WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the January/February 2017 issue of *CERN Courier*.

The detection of gravitational waves by the twin aLIGO detectors, announced in February last year, is one of the most significant discoveries in physics for decades. It is also further spectacular confirmation of Einstein's theory of gravity, general relativity. Although the existence of gravitational waves had already been established from precise measurements of pulsars, their direct detection by interferometers opens a new vista on the universe. This issue of *CERN Courier* explores what we can expect from the new era of gravitational-wave astronomy, from understanding the internal machinery of black holes to probing the very early universe, and describes the remarkable technological feat that enabled aLIGO to detect a displacement 200 times smaller than the proton radius. We also survey the broader experimental status of general relativity, which enters its second century without any signs of cracking. Upcoming experiments at CERN's Antiproton Decelerator are about to test the gravitational free-fall of antiatoms, while searches for extra dimensions at the Large Hadron Collider continue to place tight constraints on more exotic models of gravity. Despite being the first force to be tamed by mathematics, gravity is still riddled with enigmas. Dark energy and dark matter are among them, but perhaps the deepest mystery of all is how gravity relates to the other three forces – a challenge that has outfoxed the best minds for the best part of a century.

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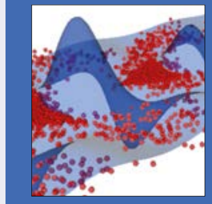
THE GRAVITY ISSUE



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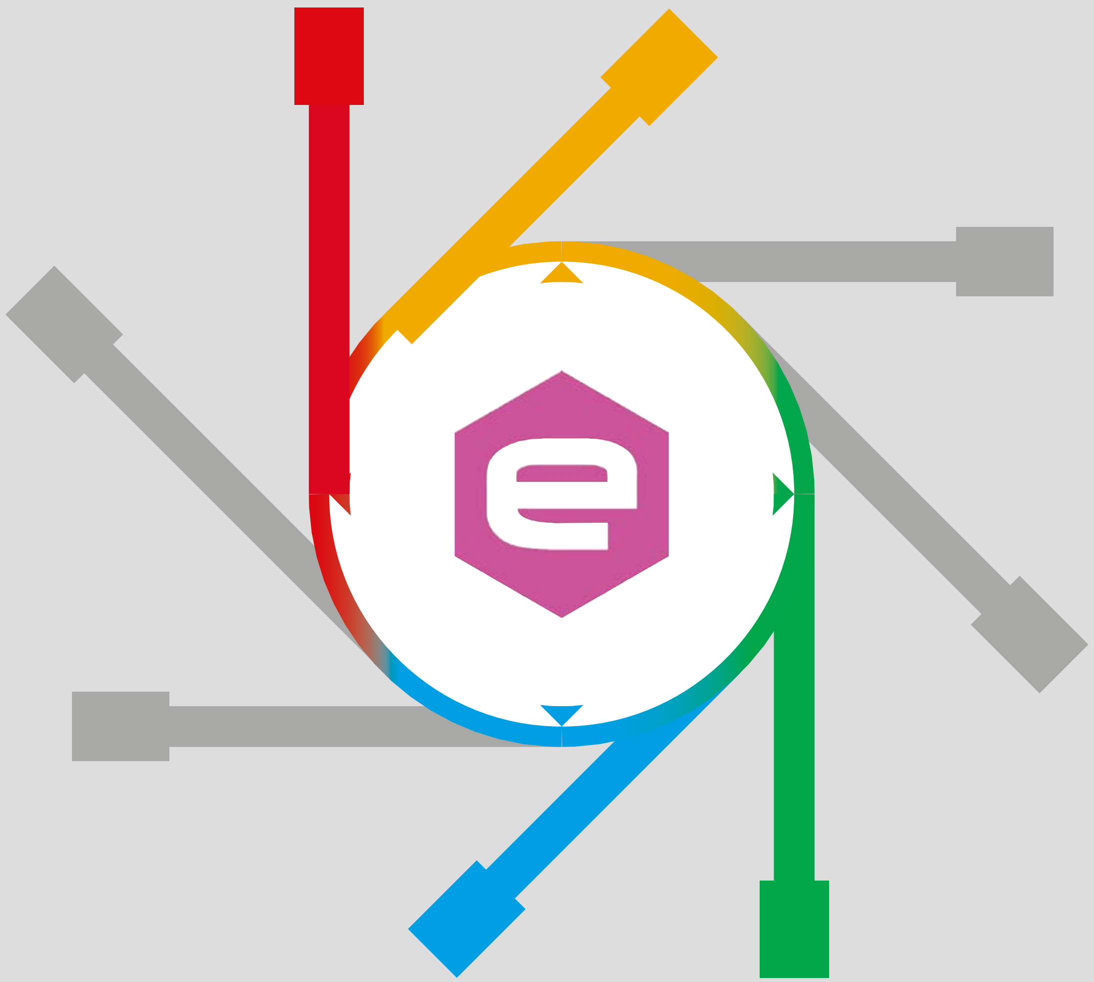

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Covering current developments in high-energy physics and related fields worldwide

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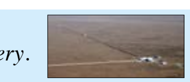

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On the cover: Newton's apple, an icon for gravity. (Image credit: Graphic treatment by Mathew Ward.)

Viewpoint

Unity through global science

CERN's enlargement policy will help particle physics adapt to an evolving global environment.

M Brice/CERN

CERN's geographical enlargement policy of 2010 has been turned into a strategy to help secure the long-term future of particle physics.

By Emmanuel Tsesmelis

CERN's Large Hadron Collider (LHC) and its discovery of the Higgs boson in 2012 have launched a new era of research in particle physics. The LHC and its upgrades will chart the course of the field for many years to come, and CERN is therefore in a unique position to help shape the long-term future of particle physics. In view of this, CERN is exploring two different and challenging projects: the Compact Linear Collider (CLIC) and a Future Circular Collider (FCC).

These developments are taking place at a time when facilities for high-energy physics, as for other branches of science, are becoming larger and more complex as well as requiring more resources. Funding for the field is not increasing in many countries and the timescale for projects is becoming longer, resulting in fewer facilities being realised. Particle physics must adapt to this evolving reality by fostering greater co-ordination and collaboration on a global scale. This goes hand in hand with CERN's tradition of networking with worldwide partners.

In 2010, CERN Council approved a radical shift in CERN's membership policy that opened full membership to non-European states, irrespective of their geographical location. At the same time, Council introduced the status of associate membership to facilitate the accession of new members, including countries outside of Europe that might not command sufficient resources to sustain full membership (*CERN Courier* December 2014 p58).

Geographical enlargement is part of the effort to secure the future of the laboratory, and the process has been gradual and measured. Israel became CERN's 21st Member State in 2014 while Romania joined as the 22nd Member State in 2016. Cyprus and Serbia are presently associate members in the pre-stage to membership, while Pakistan, Turkey and Ukraine are associate members. Late last year, agreements with Slovenia for associate membership in the pre-stage to membership and with India for associate membership were signed (see p7). Brazil, Croatia, Lithuania and Russia have also applied for associate membership.

CERN builds on a long tradition of a global engagement. The Organization has formal relations with non-member states (NMS) via bilateral International Co-operation Agreements (ICAs), currently in force with 47 countries. Out of a total of about 12,700 users at CERN, the participation of NMS users is now almost 40% – the majority of which are researchers from the US and Russia working on the LHC. The overall NMS participation in the non-LHC research programme is currently about 20%. Financial resources for research programmes, notably maintenance and operation costs for the LHC experiments, are shared between the Member States, the associate members and the NMS. In addition, there is increasing interest in collaboration on accelerator R&D and related technologies, focusing on the LHC's luminosity upgrades and also on the FCC and CLIC studies. The number of states involved in such activities is already growing beyond the restricted circle of NMS that contributed to the LHC accelerator construction. The increasingly global interest in CERN also translates into a rising demand for CERN's education and training programmes – falling within CERN's mission of helping build capacity in countries that are developing their particle-physics communities.

The geographical enlargement policy of 2010 offers important opportunities for the future of the Organization. Now, CERN has developed it into a strategy, presented to Council in March 2016, to ensure that geographical enlargement consolidates the institutional base and thus reinforces the long-term scientific aspirations of CERN. Enlargement is not an aim in and of itself. Rather, the focus is on strengthening relations with countries that can bring scientific and technological expertise to CERN and can, in turn, benefit from closer engagement.

It is essential that membership and associate membership are beneficial to particle physics in individual countries, and that governments continue to invest in the growth of national communities. At the same time, enlargement should not hinder the operational efficiency of the laboratory. CERN's engagement with prospective members and associate members is clearly oriented towards these objectives, mindful that investigating the unification of the fundamental forces of nature requires uniting scientific efforts on a global scale.

Emmanuel Tsesmelis is an experimental particle physicist who is head of relations with associate Member States and non-Member States at CERN. (Image credit: CERN.)

News

INTERNATIONAL

India to become associate Member State

CERN

CERN Director-General Fabiola Gianotti (left) signs the agreement with Sekhar Basu.

On 21 November, CERN signed an agreement with Sekhar Basu, chairman of the Atomic Energy Commission (AEC) and secretary of the Department of Atomic Energy (DAE) of the government of India, to admit India as an associate Member State.

India has been a partner of CERN for more than 50 years, during which it has made substantial contributions to the construction of the LHC and to the ALICE and CMS experiments, as well as Tier-2 centres for the Worldwide LHC Computing Grid. A co-operation agreement was signed in 1991, but India's relationship with CERN goes back much further, with Indian institutes having provided components for the LEP collider and one of its four detectors, L3, in addition to the WA93 and WA89 detectors. The success of the DAE–CERN partnership regarding the LHC has also led to co-operation on novel accelerator technologies through DAE's participation in CERN's Linac4, SPL and CTF3 projects. India also participates in the COMPASS, ISOLDE and nTOF experiments at CERN.

In recognition of these substantial contributions, India was granted observer status at CERN Council in 2002. When it enters into force, associate membership will allow India to take part in CERN Council meetings and its committees, and will make Indian scientists eligible for staff appointments. "Becoming associate member of CERN will enhance participation of young scientists and engineers in various CERN projects and bring back knowledge for deployment in the domestic programmes," says Basu. "It will also provide opportunities to Indian industries to participate directly in CERN projects."

Slovenia to become associate Member State in pre-stage to membership

CERN Council has voted unanimously to admit the Republic of Slovenia to associate membership in the pre-stage to CERN membership. Slovenia's membership will facilitate, strengthen and broaden the participation and activities of Slovenian scientists, said Slovenian minister Maja Makovec Brenčič, and give Slovenian industry full access to CERN procurement orders. "Slovenia is also aware of the CERN offerings in the areas of education and public outreach, and we are therefore looking forward to become eligible for participation in CERN's fellows, associate and student programmes."

Slovenian physicists have participated in the LHC's ATLAS experiment for the past 20 years, focusing on silicon tracking, protection devices and computing at the Slovenian Tier-2 data centre. However, Slovenian physicists contributed to CERN long before Slovenia became an independent state in 1991, participating in an experiment at LEAR and the DELPHI experiment at LEP. In 1991, CERN and the Executive Council of the Assembly of the Republic of Slovenia signed a co-operation agreement, and in 2009 Slovenia applied to become a Member State.

Maja Makovec Brenčič, Slovenian minister of education, science and sport (left), signs the agreement with CERN Director-General Fabiola Gianotti on 16 December.

Following internal approval procedures, Slovenia will join Cyprus and Serbia as an associate Member State in the pre-stage to membership. At the earliest two years thereafter, Council will decide on the admission of Slovenia to full membership. "It is a great pleasure to welcome Slovenia into our ever-growing CERN family as an associate Member State in the pre-stage to membership," says CERN Director-General Fabiola Gianotti.

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Antimatter

Antihydrogen atoms show their colour

M Brice, CERN

ALPHA uses a laser system to interrogate the electronic states of antihydrogen.

Following 20 years of research and development by the CERN antimatter community, the ALPHA collaboration has reported the first ever measurement of the optical spectrum of an antimatter atom. The result, published in *Nature* in December, involves technological developments that open a completely new era in high-precision antimatter research.

Comprising a single electron orbiting a single proton, hydrogen is the simplest and most well-understood atom, and has played a central role in fundamental physics for more than a century. Its spectrum is characterised by well-known spectral lines at certain wavelengths, corresponding to the emission of photons when electrons jump between different orbits. Measurements of the hydrogen spectrum agree with the predictions of quantum electrodynamics at the level of a few parts in 10^{15}, and CPT invariance requires that antihydrogen has exactly the same spectrum.

The ALPHA team has now succeeded in observing the first spectral line in an atom of antihydrogen, made up of an antiproton and a positron. The measurement concerned the 1S–2S transition, which has a lifetime on the order of a tenth of a second and therefore leads to a narrow spectral line that is particularly suitable for precision measurements. The measurement was found to be in agreement with the hydrogen spectrum, and therefore consistent with CPT invariance, with a relative precision of around 2×10^{-10}.

Comparing the spectra of hydrogen and antihydrogen was one of the main scientific motivations for CERN's Antiproton Decelerator (AD), since it offers an extraordinary new tool to test whether matter behaves differently from antimatter and thus test the robustness of the Standard Model. The ALPHA collaboration, which expects to improve the precision of its measurements, generates roughly 25,000 antihydrogen atoms per trial by mixing antiprotons from the AD with positrons. Around 14 antiatoms per trial are trapped and interrogated by a laser at a precisely tuned frequency to measure their internal states.

Low-energy antihydrogen was first synthesised by the ATHENA collaboration in 2002, later repeated by the ATRAP, ALPHA and ASACUSA collaborations, and ALPHA trapped the first antihydrogen atoms in 2010. The new result, along with recent limits on the antiproton–electron mass ratio by the ASACUSA collaboration and antiproton charge-to-mass ratio by the BASE collaboration, demonstrates that tests of fundamental symmetries with antimatter at CERN are maturing rapidly.

● Further reading

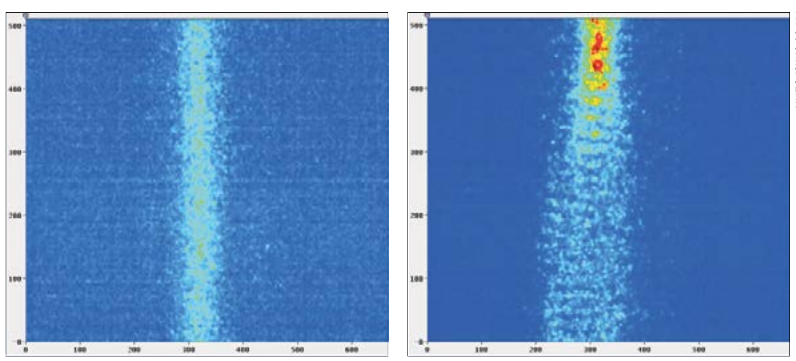
ALPHA Collaboration 2016 doi:10.1038/nature21040.

ASACUSA Collaboration 2016 *Science* **354** 610.

BASE Collaboration 2015 *Nature* **524** 196.

Accelerator technology

AWAKE makes waves



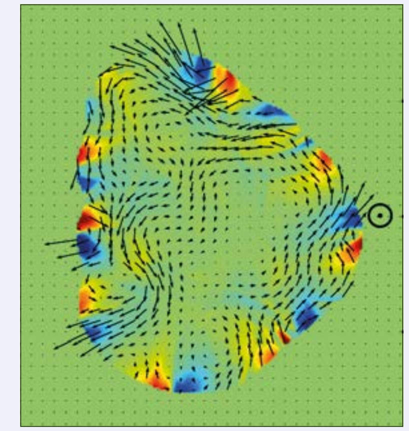
A Petrenko/CERN

Comparison of the proton-bunch longitudinal profile (left, no plasma) with the profile for a bunch passing through plasma (right), showing the strong modulation of the bunch.

In early December, the AWAKE collaboration made an important step towards a pioneering accelerator technology that would reduce the size and cost of particle accelerators. Having commissioned the facility with first beam in November, the team has now installed a plasma cell and observed a strong modulation of high-energy proton bunches as they pass through it. This signals the generation of very strong electric fields that could be used to accelerate electrons to high energies over short distances.

AWAKE (Advanced Proton Driven Plasma Wakefield Acceleration Experiment) is the first facility to investigate the use of plasma wakefields driven by proton beams. The experiment involves injecting a "drive" bunch of protons from CERN's Super Proton Synchrotron (SPS) into a 10 m-long tube containing a plasma. The bunch then splits into a series of smaller bunches via a process called self-modulation, generating a strong wakefield as they move through the plasma. "Although plasma-wakefield technology has been explored for many years, AWAKE is the first experiment to use protons as a driver – which, given the high energy of the SPS, can drive wakefields over much longer distances compared with electron- or laser-based schemes," says AWAKE spokesperson Allen Caldwell of the Max Planck Institute for Physics in Munich.

While it has long been known that plasmas may provide an alternative to traditional accelerating methods based on RF cavities, turning this concept into a practical device is a major challenge. The next step for the AWAKE collaboration is to inject a second beam of electrons, the "witness" beam, which is accelerated by the wakefield just as a surfer accelerates by riding a wave. "To have observed indications for the first time of proton-bunch self-modulation, after just a few days of tests, is an excellent achievement. It's down to a very motivated and dedicated team," says Edda Gschwendtner, CERN AWAKE project leader.



L Pang et al. 2016 *Phys. Rev. Lett.* **117** 192301

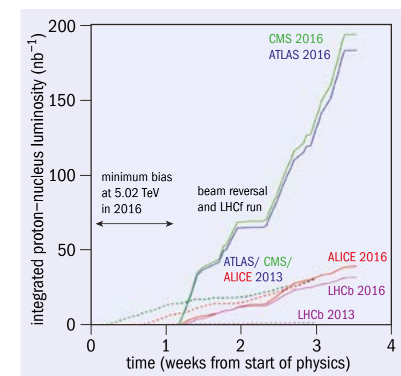
Powerful supercomputer simulations of colliding atomic nuclei have provided new insights about quark–gluon plasma (QGP), a superhot fluid of de-confined partons produced in heavy-ion collisions at the LHC and at RHIC, Brookhaven National Laboratory. Shown in the image are the transverse (arrows) and longitudinal vorticity (contour) distributions of a strongly coupled quark–gluon plasma in the transverse plane at forward spatial rapidity. The coupling between spin and local vorticity shifts the energy level of fermions, leading to different phase-space distributions for fermions with different spin states and therefore spin polarisation along the direction of the local vorticity.

The international team responsible for the work, which involved weeks of processing on a GPU cluster, suggests that longitudinal spin correlations can be used to study the vortex structure of the expanding QGP in high-energy heavy-ion collisions. Different from global transverse polarisation, the longitudinal spin correlation does not decrease with beam energy or vanish in event averages. This provides a unique opportunity to study the local fluid vorticity of the QGP at LHC energies, concludes the team. "We can think about this as opening a completely new window of looking at quark–gluon plasmas, and how to study them," says team member Xin-Nian Wang at the Central China Normal University and Lawrence Berkeley National Laboratory.

LHC news

Proton–lead run tops record year of LHC operations

On 26 October, the LHC completed its 2016 proton–proton operations at a collision energy of 13 TeV, during which it exceeded the design value of the luminosity and broke many other records (*CERN Courier* December 2016 p5). As in most years, the machine was then reconfigured for a month-long heavy-ion run, devoted this year to colliding beams of protons (p) and lead nuclei (Pb). Following a feasibility test in 2012 and an initial month-long run in 2013, pPb collisions remain a novel mode of operation at the LHC. Despite this novelty, the LHC team was able to deliver enormous data sets to the experiments for the investigation of extreme nuclear matter during the 2016 run.



Integrated luminosity versus time since the start of physics, comparing the 2013 run at 5.02 TeV (dashed lines) with the 8.16 TeV part of the 2016 run (solid lines).

Asymmetric proton–nucleus collisions were originally seen as a means to disentangle cold from hot nuclear-matter effects studied in lead–lead collisions. Surprisingly, a more complex picture emerged following the pPb results of 2012 and 2013. For 2016, the LHC experiments requested a variety of apparently incompatible operating conditions, according to their diverse capabilities and physics programmes. Careful analysis of the beam physics and operational requirements led to an ambitious schedule comprising three different beam modes that could potentially fulfil all requests.

Following a technical stop, the first set-up for pPb collisions at a centre-of-mass energy for colliding nucleon pairs of 5.02 TeV started on 5 November and physics data-taking started on 10 November. This run was mainly dedicated to the LHC's ALICE experiment to increase an earlier collected sample of minimum-bias events. The other experiments also participated, with LHCb studying collisions between protons and a target of helium gas. As foreseen, the beam lifetimes were extremely long, allowing seven days of nearly uninterrupted running at a constant levelled luminosity of $0.8 \times 10^{28}\,cm^{-2}s^{-1}$. A total of 660 million minimum-bias events were collected, increasing by a factor six the data set from 2013. One of the first fills also turned out to be the longest LHC fill ever, lasting almost 38 hours.

Just one day after the 5.02 TeV run ended, the second set-up involving new high-luminosity beam optics was complete and the LHC delivered pPb collisions at an energy of 8.16 TeV. This is the highest energy ever produced by a collider for such an asymmetric system, and included a short run for the LHCf experiment and also a third run in which the directions of the Pb and p beams were reversed. Thanks to the superb performance of the injectors and numerous improvements in the LHC, the luminosity soared to $9 \times 10^{29}\,cm^{-2}s^{-1}$, which is 7.8 times the design value set some years ago. The luminosity could have been pushed even further had the intense flux of lead beam fragments from the collisions not risked quenching nearby magnets. On 4 December, the LHC was switched back to 5.02 TeV for a final 20 hours of pPb data taking, delivering a further 120 million minimum-bias events for ALICE.

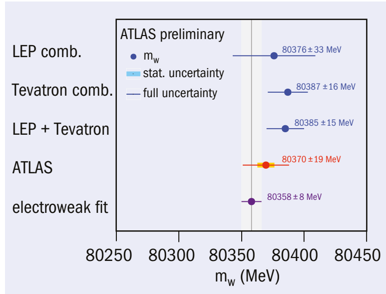
That such a complex run could be implemented in such a short time was a triumph for the LHC and all those concerned with its design, construction and operation. Every one of the high-priority goals, plus some subsidiary ones, for ATLAS, CMS, ALICE and LHCb were comfortably exceeded. CMS recorded an integrated luminosity of nearly 200 nb^{-1} at 8.16 TeV, representing a six-fold increase of the sample collected from the first pPb run in 2013 at 5 TeV, and allowing the collaboration to investigate the behaviour of hard probes in high-multiplicity pPb collisions (see article on p11). ATLAS recorded a similar data set, while ALICE and LHCb each received totals well over 30 nb^{-1} at 8.16 TeV in the two beam directions.

LHC EXPERIMENTS

ATLAS makes precision measurement of W mass

A precise measurement of the mass of the W boson, which was discovered at CERN in 1983, is vital because it is closely related to the masses of the top quark and the Higgs boson. Measuring the W mass tests this prediction and thus the self-consistency of the Standard Model (SM), since any deviation from theory would be a sign of new physics. The W mass was measured previously at CERN's Large Electron–Positron (LEP) collider and Fermilab's proton–antiproton collider, the Tevatron, yielding a world average of 80.385±0.015 GeV, which is consistent with the SM constraints of 80.358±0.008 GeV.

The ATLAS collaboration has now reported the first measurement of the W mass at the LHC, based on proton–proton collisions at a centre-of-mass energy of 7 TeV (corresponding to an integrated luminosity of 4.6 fb^{-1}). The measured value, 80.370±0.019 GeV, matches the precision of the best single-experiment measurement of the W mass performed by the Tevatron's CDF experiment, and is consistent with both the SM prediction and combined measurements (see figure).



ATLAS measurement of the W mass is compared to the SM prediction from the electroweak fit, and to the combined values measured at LEP and at the Tevatron collider.

Measuring the W mass is more challenging at the LHC compared with LEP and the Tevatron because there are a large number of interactions per beam crossing and significant contributions to W production from second-generation quarks (strange and charm). ATLAS measured the W mass by reconstructing the kinematic properties of leptonic decays, in which a W produces an electron or muon and a neutrino in the final state.

The analysis required a highly accurate calibration of the detector response, which was achieved via the large sample of Z-boson events and the precise knowledge of the Z mass. Accurate predictions of the W-boson production and decay properties are also crucial at a proton–proton collider. The enhanced amount of heavy-quark-initiated production and the ratio of valence and sea quarks in the proton affect the W boson's transverse-momentum distribution and its polarisation, which makes the measurement sensitive to the parton distribution functions of the proton. To address these issues, ATLAS combined the most advanced theoretical predictions with experimental constraints from precise measurements of Z- and W-boson differential cross-sections and of Z-boson transverse momentum and polarisation.

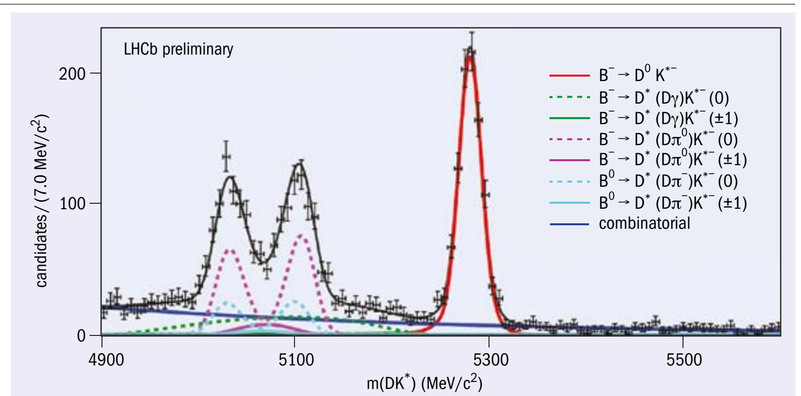
Future analysis of larger data samples at the LHC would allow the reduction of the statistical uncertainty and of several experimental systematic uncertainties. Finally, a better knowledge of the parton distribution functions and improved QCD and electroweak predictions of W- and Z-boson production are crucial to further reduce the theoretical uncertainties.

● Further reading

ATLAS Collaboration 2016 CERN-EP-2016-305 & ATLAS-CONF-2016-113.

Run 2 promises a harvest of beauty for LHCb

The first b-physics analysis using data from LHC Run 2, which began in 2015 with proton–proton collisions at an energy of 13 TeV, shows great promise for the physics programme of LHCb. During 2015 and 2016, the experiment collected a data sample corresponding to an integrated luminosity of about 2 fb^{-1}. Although this value is smaller than the total integrated luminosity collected in the three years of Run 1 (3 fb^{-1}), the significant increase of the LHC energy in Run 2 has almost doubled the production cross-section of beauty particles. Furthermore, the experiment has improved the performance of its trigger system and particle-identification capabilities. Once such an increase is taken into account, along with improvements in the trigger strategy and in the particle identification of the experiment, LHCb has already more than doubled the statistics of beauty particles on tape with respect to Run 1.



The new measurement concerns the process $B^- \to D^0 K^{*-}$ (red), where the D^0 decays into two-body final states consisting of charged π and/or K mesons. The powerful background suppression of the LHCb detector allows the signal to be isolated with extremely high purity.

The new analysis is based on 1 fb^{-1} of available data, aiming to measure the angle γ of the CKM unitarity triangle using $B^- \to D^0 K^{*-}$ decays. While $B^- \to D^0 K^-$ decays have been extensively studied in the past, this is the first time the $B^- \to D^0 K^{*-}$ mode has been investigated. The analysis, first presented at CKM2016 (see p52), allows the LHCb collaboration to cross-check expectations for the increase of signal yields in Run 2 using real data. A significant increase, roughly corresponding to a factor three, is observed per unit of integrated luminosity. This demonstrates that the experiment has benefitted from the increase in b-production cross-section, but also that the trigger of the detector performs better than in Run 1. Although the statistical uncertainty on γ from this measurement alone is still large, the sensitivity will be improved by the addition of more data, as well as by the use of other D-meson decay modes. This bodes well for future measurements of γ to be performed in this and other decay modes with the full Run 2 data set.

Measurements of the angle γ are of great importance because it is the least well-known angle of the unitarity triangle. The latest combination from direct measurements with charged and neutral B-meson decays and a variety of D-meson final states, all performed with Run 1 data, yielded a central value of 72±7 degrees. LHCb's ultimate aim, following detector upgrades relevant for LHC Run 3, is to determine γ with a precision below 1°, providing a powerful test of the Standard Model.

● Further reading

LHCb Collaboration 2016 LHCb-PAPER-2016-032, arXiv:1611.03076.

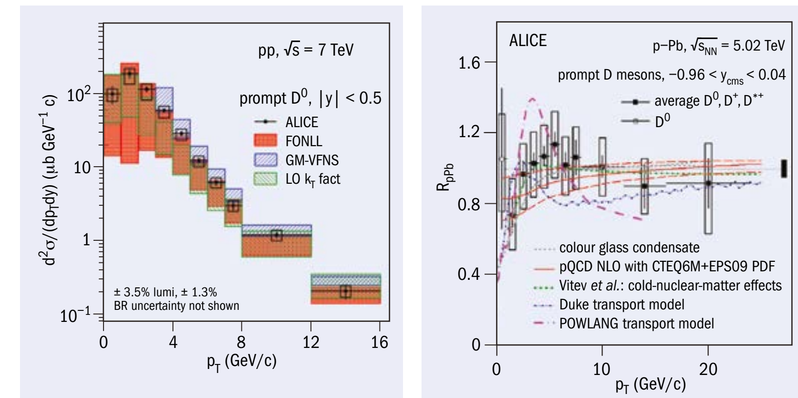
LHCb Collaboration 2016 LHCb-CONF-2016-014.

ALICE zeroes in on cold-matter effects

Measuring the production cross-section of charm hadrons in proton–proton collisions provides an important test of perturbative quantum chromodynamics (QCD). In proton–nucleus collisions, "cold-matter" effects related to the presence of nuclei in the colliding system are expected to modify the production cross-section and the transverse-momentum distribution of open-charm hadrons. Assessing such effects is thus crucial for interpreting the results from heavy-ion collisions, where a hot and dense medium of deconfined partons – the quark–gluon plasma (QGP) – is formed.

Previously, ALICE measured D-meson production in proton–lead collisions and found no substantial modification relative to proton–proton interactions within the kinematic range of the measurement (covering a transverse momentum, p_T, between one and 24 GeV/c at mid-rapidity). Most cold-nuclear-matter effects are expected to modify charm production at low p_T, but no measurement of D-meson production down to zero transverse momentum was performed at mid-rapidity at LHC energies.

Recently the ALICE collaboration extended the measurement of the D^0-meson cross-section down to zero p_T in proton–proton collisions at 7 TeV and in proton–lead collisions at 5.02 TeV. In contrast to previous ALICE publications, the analysis relied on estimating and subtracting the combinatorial background without having to reconstruct the D^0 decay vertex. This allowed the first measurement of the D^0 signal in the interval $0 < p_T < 1$ GeV/c and a significant reduction of the uncertainties in the interval $1 < p_T < 2$ GeV/c compared with previous results.



The cross-section for open-charm production in proton–proton data (left) agrees within uncertainties with three different perturbative QCD calculations. The nuclear modification factor R_{pPb} (right) is compatible with unity within uncertainties, indicating that cold-nuclear-matter effects are small in this kinematic range.

The current precision of the measurement does not yet confirm the role of the different nuclear effects or the possible presence of additional hot-medium effects. However, applied to larger data sets in the future, the analysis technique will provide insight into the physics-rich region close to $p_T = 0$.

● Further reading

ALICE Collaboration 2014 *Phys. Rev. Lett.* **113** 232301.

ALICE Collaboration 2016 arXiv:1605.07569.

Protons probe quark–gluon plasma at CMS

Proton–nucleus collisions provide a crucial tool to investigate the quark–gluon plasma (QGP), a state of nuclear matter with a high energy density spread over a relatively large volume. Although proton–lead (pPb) collision systems have been considered to be too small and dilute to themselves form a QGP, they have served as a reference in the search for QGP signatures in the collisions of two heavy ions. Nonetheless, in the first-ever pPb collisions at the LHC, collected in 2013, the CMS experiment observed QGP-like features in very high multiplicity pPb events.

Subsequent studies have supported the hypothesis that a dense, QGP-like medium may be formed in high multiplicity pPb systems. However, several key signatures of a dense QGP medium, observed in PbPb collisions, remain unestablished for pPb events. These unestablished signatures include the loss of energy ▷

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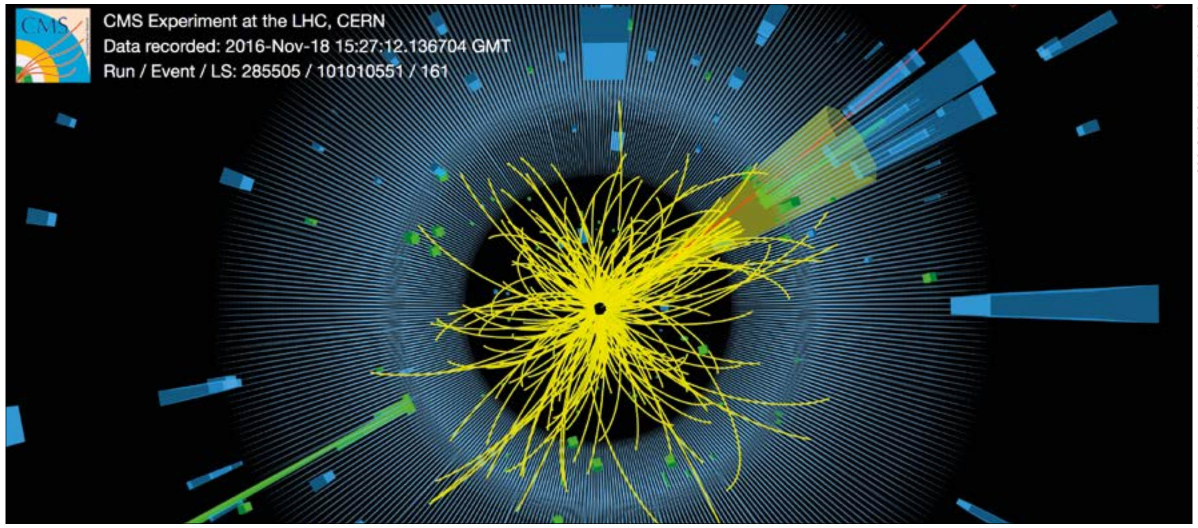
News



CMS-PHO-EVENTS-2016-009

Event with a high-energy photon candidate (green tower) and a high-energy b-jet candidate (green cone and towers contained therein). The photon and the jet are nearly back-to-back.

from high-energy quarks and gluons ("jet quenching") and the suppression of quarkonium states (J/ψ and ϒ mesons). A hint of a stronger suppression of ϒ(2S) mesons compared to ϒ(1S) mesons is observed in the 2013 pPb data, but a conclusive comparison with PbPb data at similar high multiplicities has not been possible because of limited statistical precision in the pPb data.

At the end of 2016, CMS again collected pPb collisions, with a higher energy and a larger accumulated data sample than in 2013. The experiment is thus poised to relaunch its comprehensive search for QPG signatures in high multiplicity pPb systems. Compared to 2013, the yields of relevant events (see figure) are enhanced by a factor of 20–30. This will enable many new studies that might provide conclusive results on the formation of QGP in pPb events.

Further reading

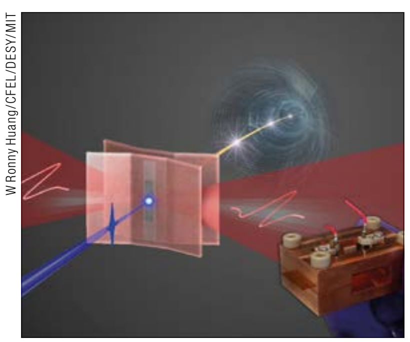
CMS Collaboration 2013 *Phys. Lett. B* **718** 795.
CMS Collaboration 2014 *JHEP* **04** 103.

ACCELERATOR TECHNOLOGY

Electron gun shrunk to matchbox size

An interdisciplinary team of researchers from DESY in Germany and MIT in the US has built a new kind of electron gun that is about the size of a matchbox. The new device uses laser-generated terahertz radiation, rather than traditional radio-frequency fields, to accelerate electrons from rest. Since terahertz radiation has a much shorter wavelength than radio waves, the new device measures just 34 × 24.5 × 16.8 mm – compared with the size of a car for traditional state-of-the-art electron guns.

This device reached an accelerating gradient of 350 MV per metre, which the team says is almost twice that of current electron guns. "We achieved an acceleration of a dense packet of 250,000 electrons from rest to 0.5 keV with minimal energy spread," explains lead author W Ronny Huang of MIT, who carried out the work at the Center for Free-Electron Laser



W Ronny Huang/CFEL/DESY/MIT

A UV pulse (blue) back-illuminates the gun photocathode, producing a high-density electron bunch inside the gun that is immediately accelerated by ultra-intense single-cycle terahertz pulses to energies approaching 1 keV.

Science in Hamburg. The electron beams emerging from the device could already be used for low-energy electron diffraction experiments, he says, and will also have applications in ultrafast electron diffraction or for injecting electrons into linacs and X-ray light sources.

Further reading

W R Huang *et al.* 2016 *Optica* DOI:10.1364/OPTICA.3.001209.

***Les physiciens des particules du monde entier sont invités** à apporter leurs contributions au CERN Courier, en français ou en anglais. Les articles retenus seront publiés dans la langue d'origine. Si vous souhaitez proposer un article, faites part de vos suggestions à la rédaction à l'adresse cern.courier@cern.ch.*

CERN Courier welcomes contributions from the international particle-physics community. These can be written in English or French, and will be published in the same language. If you have a suggestion for an article, please send proposals to the editor at cern.courier@cern.ch.

Sciencewatch

Compiled by John Swain, Northeastern University

Linking sound with meaning

A study of nearly two thirds of the world's 6000+ languages has revealed widespread associations between the sounds of words and their meanings. It has long been known that when people are shown pictures of an amorphous blob and a star-like shape and are asked which one is likely named "bouba" and which one "kiki", speakers of different languages consistently associate the blob with the former word and the star with the latter. Damián Blasi of the University of Zurich and colleagues have now found that a large proportion of 100 basic vocabulary items have strong associations with specific speech sounds across continents and linguistic families. The distributions of the associations with time and location suggest that many words arose independently, potentially revealing deep connections between the developments of languages.

Words for "tongue" tend to contain the letters i or u, "round" often appears with r, and "small" with i.

Further reading

D Blasi *et al.* 2016 *PNAS* **113** 10818.

Cosmic rays make more muons

Researchers at the Pierre Auger Observatory in Argentina have measured the longitudinal and lateral distributions of ultra-high-energy cosmic-ray air showers with primary energies of 6–16 EeV (corresponding to centre-of-mass energies of 110–170 TeV). The average shower is 1.33±0.16 and 1.61±0.21 times larger than predicted from the leading LHC-tuned models EPOS-LHC and QGSJetII-04, respectively, corresponding to an excess of muons. This suggests either flaws in the underlying models or a more fundamental change in physics at these energies.

Further reading

A Aab *et al.* 2016 *Phys. Rev. Lett.* **117** 192001.

Statistical mechanics of consciousness

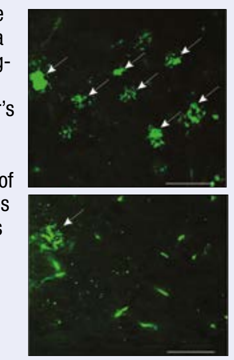
Ramon Guevara Erra of the Université Paris Descartes and colleagues have reported a new insight into the nature of consciousness. The researchers recorded the brain activity of people while they were sleeping, awake, and having epileptic seizures. They found that normal wakeful states are characterised by the greatest number of interactions between brain networks, equating to the highest entropy values. This means there is higher information content in the networks associated with conscious states and suggests that consciousness could be the result of optimising information processing.

Further reading

R Guevarra Eva *et al.* 2016 *Phys. Rev. E* **94** 052402.

LEDs for Alzheimer's

Researchers in the US have unveiled a non-invasive, drug-free approach to treating Alzheimer's disease, based on flickering LEDs. Hannah Iaccarino of MIT and colleagues showed that levels of beta-amyloid plaque of the type associated with Alzheimer's in mice are reduced by exposure to flickering LED light at frequencies of 40 Hz. This corresponds to the gamma-frequency range of brainwaves (25–80 Hz), which in normal brain function is associated with attention, perception and memory. One hour of exposure to the light reduced beta-amyloid plaque by an impressive 40–50%. Levels of abnormally modified Tau protein, also associated with Alzheimer's disease, were also reduced. Other frequencies between 20 and 80 Hz were ineffective. Clinical trials with humans are now being planned.



The brain of a mouse after seven days of one-hour per day in the dark (top) or exposure to a 40 Hz flicker (bottom), showing plaques (white arrows). The scale bar is 50 μm.

Further reading

H Iaccarino *et al.* 2016 *Nature* **540** 230.

An antidote to carbon monoxide

For the first time, an antidote has been found to carbon-monoxide poisoning. Ling Wang and Qinzi Xu of the University of Pittsburgh in Pennsylvania and collaborators gave mice air containing 3% carbon monoxide for 4.5 minutes, which would kill most humans. The mice recovered when given a modified neuroglobin (a protein found in the brain and retina that protects cells by binding with oxygen and nitric oxide) that was engineered to bind to carbon monoxide 500 times more tightly than it binds to hemoglobin. The US Food and Drug Administration has promised an expedited review of the work.

Further reading

I Azarov *et al.* 2016 *Sci. Transl. Med.* **8** 368ra173.

Flying to reduce jet lag

Joseph Bass of Northwestern University in Chicago and colleagues have made the surprising finding that flying can sometimes reduce jet lag. After observing daily cycles in blood and tissue oxygen levels in mice kept on a normal light–dark cycle, the team found that if the mice were subjected to a six-hour-long change in light cycle that corresponded to flying east on a jet, those kept in a low concentration of oxygen adapted more quickly. The mechanism involves changing the amount of HIF1α, which is required for oxygen levels to entrain the circadian clock.

Further reading

C Peek *et al.* 2016 *Cell Metabolism* DOI:10.1016/j.cmet.2016.09.010.

Astrowatch

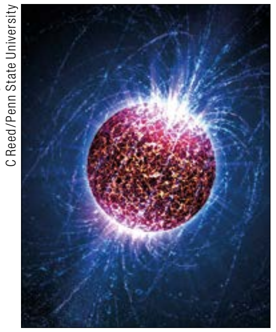
Compiled by Marc Türler, ISDC and Observatory of the University of Geneva, and CHIPP, University of Zurich

Compact star hints at vacuum polarisation

By studying an isolated neutron star, astronomers may have found the first observational indication of a strange quantum effect called vacuum birefringence, which was predicted in the 1930s by Werner Heisenberg and Hans Heinrich Euler.

Neutron stars are the very dense remnant cores of massive stars – at least 10 times more massive than our Sun – that have exploded as supernovae at the ends of their lives. In the 1990s, the Germany-led ROSAT space mission for soft X-ray astronomy discovered a new class of seven neutron stars that are known as the Magnificent Seven. The faint isolated objects emit pulses of X-rays every three to 11 seconds or so, but unlike most pulsars they have no detectable radio emission. The ultra-dense stars have an extremely high dipolar magnetic field (of the order 10^{9}–10^{10} T) and display an almost perfect black-body emission, making them unique laboratories to study neutron-star cooling processes.

A team led by Roberto Mignani from INAF Milan in Italy and the University of Zielona Gora, Poland, used ESO's Very Large Telescope (VLT) at the Paranal Observatory in Chile to observe the neutron star RX J1856.5-3754. Despite being the brightest of the Magnificent Seven and located only around 400 light-years from Earth, its extreme dimness is at the limit of the VLT's current capabilities to measure polarisation. The aim of the measurement was to detect a quantum effect predicted 80 years ago: since the vacuum is full of virtual particles that appear and vanish, a very strong magnetic field could polarise empty space and hence also light passing through it. Vacuum birefringence is too weak to be observed in laboratory experiments, but the phenomenon should be visible in the very strong magnetic fields around neutron stars.



C Reed/Penn State University

Artist's illustration of an isolated neutron star with an extreme magnetic field able to polarise empty space and light passing through it.

After careful analysis of the VLT data, Mignani and collaborators detected a significant degree (16%) of linear polarisation, which they say is likely due to vacuum birefringence occurring in the empty space surrounding RX J1856.5-3754. They claim that such a level of polarisation is not easily explained by other sources. For example, the contribution from dust grains in the interstellar medium were estimated to be less than 1%, which was corroborated by the detection of almost zero polarisation in the light from 42 nearby stars. The genuine thermal radiation of the neutron star is also expected to be polarised by its surface magnetic field, but this effect should cancel out if the emission comes from the entire surface of the neutron star over which the magnetic-field direction changes substantially.

The polarisation measurement in this neutron star constitutes the very first observational support for the predictions of QED vacuum polarisation effects. ESO's future European Extremely Large Telescope will allow astronomers to study this effect around many more neutron stars, while the advent of X-ray polarimetric space missions offers another perspective to this new field of research.

Further reading

R Mignani 2016 *MNRAS* **465** 492.

Picture of the month

This beautiful image displays IC 405, known as the Flaming Star Nebula, in the constellation of Auriga some 1500 light-years away. Many hundreds of stars are visible in the extremely sharp view, which was taken at the 2800 m-high Mount Lemmon Sky Center Observatory in Arizona, US. The bright star visible left of centre is AE Aurigae, which was not born in this nebula but most likely in the famous Orion Nebula, from where it was ejected in a multiple star interaction. Over millions of years, the runaway star has already covered 40° on the sky relative to its birthplace. The intense ultraviolet emission of the high-speed star ionises hydrogen atoms, which then recombine and emit the characteristic reddish glow of such nebulae. Dusty filaments are seen in blue because they reflect the blue and ultraviolet stellar light. AE Aurigae, which is at the limit of what can be seen by the naked eye, will continue its run around the sky for some time, before exploding as a supernova.

A Block/Mount Lemmon Sky Center/University of Arizona

Gravitational-wave astronomy

The dawn of a new era

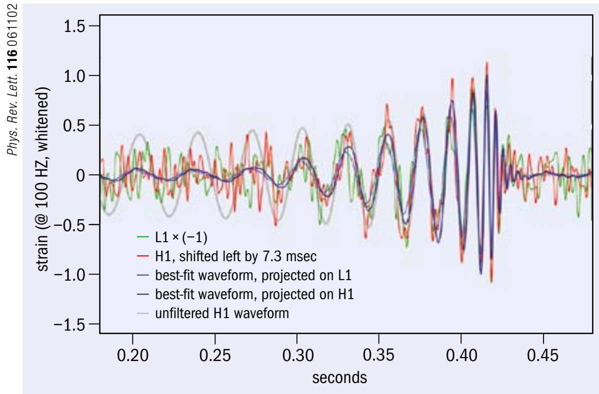
From the extreme dynamics of black holes to the beginning of the universe itself, the detection of gravitational waves has opened a profound new vista on nature.

One of the greatest scientific discoveries of the century took place on 14 September 2015. At 09.50 UTC on that day, a train of gravitational waves launched by two colliding black holes 1.4 billion light-years away passed by the Advanced Laser Interferometer Gravitational-wave Observatory (aLIGO) in Louisiana, US, causing a fractional variation in the distance between the mirrors of about one part in 10^{21}. Just 7 ms later, the same event – dubbed GW150914 – was picked up by the twin aLIGO detector in Washington 3000 km away (figure 1, overleaf). A second black-hole coalescence was observed on 26 December 2015 (GW151226) and a third candidate event was also recorded, although its statistical significance was not high enough to claim a detection. A search that had gone on for half a century had finally met with success, ushering in the new era of gravitational-wave astronomy.

Black holes are the simplest physical objects in the universe: they are made purely from warped space and time and are fully described by their mass and intrinsic rotation, or spin. The gravitational-wave train emitted by coalescing binary black holes comprises three main stages: a long "inspiral" phase, where gravitational waves slowly and steadily drain the energy and angular momentum from the orbiting black-hole pair; the "plunge and merger", where black holes move at almost the speed of light and then coalesce into the newly formed black hole; and the "ringdown" stage during which the remnant black hole settles to a stationary configuration (figure 2, overleaf). Each dynamical stage contains fingerprints of the astrophysical source, which can be identified by first tracking the phase and amplitude of the gravitational-wave train and then by comparing it with highly accurate predictions from general relativity.

aLIGO employs waveform models built by combining analytical and numerical relativity. The long, early inspiral phase, characterised by a weak gravitational field and low velocities, is well described by the post-Newtonian formalism (which expands the

An artist's impression of the gravitational-wave universe inspired by the aLIGO discovery. (Image credit: Penelope Rose Cowley.) ▷

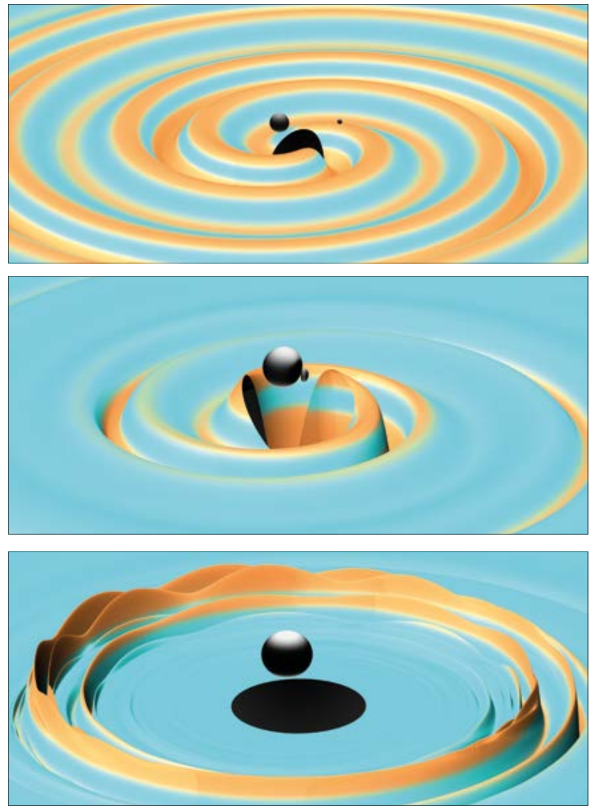


Phys. Rev. Lett. **116** 061102

Fig. 1. The gravitational-wave event GW150914 observed by aLIGO's Livingston (green) and Hanford (red) detectors, also showing best-fit templates computed by combining analytical and numerical relativity. Data for H1 are shifted by about 7 ms to account for the time of travel between the detectors.

Einstein field equation and the gravitational radiation in powers of v/c, but loses accuracy as the two bodies come closer and closer). Numerical relativity provides the most accurate solution for the last stages of inspiral, plunge, merger and ringdown, but such models are time-consuming to produce – the state-of-the-art code of the Simulating eXtreme Spacetimes collaboration took three weeks and 20,000 CPU hours to compute the gravitational waveform for the event GW150914 and three months and 70,000 CPU hours for GW151226.

A few hundred thousand different waveforms were used as templates by aLIGO during the first observing run, covering compact binaries with total masses 2–100 times that of the Sun and mass ratios up to 1:99. Novel approaches to the two-body problem that extend post-Newtonian theory into the strong-field regime and combine it with numerical relativity had to be developed to provide aLIGO with accurate and efficient waveform models, which were based on several decades of steady work in general relativity (figure 3). Further theoretical work will be needed to deal with more sensitive searches in the future if we want to take full advantage of the discovery potential of gravitational-wave astronomy.



Max Planck Institute for Gravitational Physics/Simulating eXtreme Spacetimes project

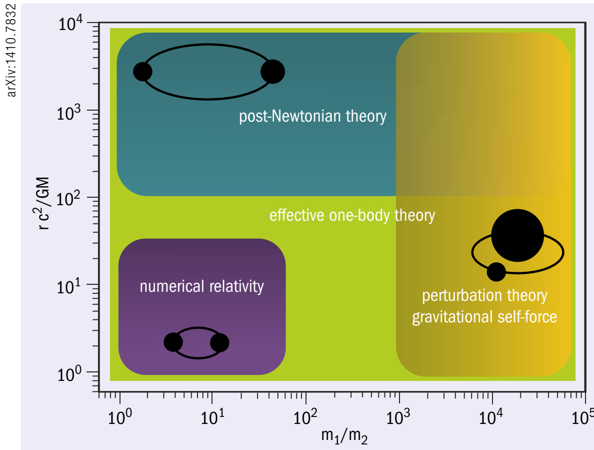
Fig. 2. Numerical simulations of the binary black-hole coalescence of the gravitational-wave event GW150914.

aLIGO's first black holes

The two gravitational-wave signals observed by aLIGO have different morphologies that reveal quite distinct binary black-hole sources. GW150914 is thought to be composed of two stellar black holes with masses 36 M_{Sun} and 29 M_{Sun}, which formed a black hole of about 62 M_{Sun} rotating at almost 70% of its maximal rotation speed, while GW151226 had lower black-hole masses (of about 14 M_{Sun} and 8 M_{Sun}) and merged in a 21 M_{Sun} black-hole remnant. Although the binary's individual masses for GW151226 have larger uncertainties compared with GW150914 (since the former happened at a higher frequency where aLIGO sensitivity degrades), the analysis ruled out the possibility that the lower-mass object in GW151226 was a neutron star. A follow-up analysis also revealed that the individual black holes had spins less than 70% of the maximal value, and that at least one of the black holes in GW151226 was rotating at 20% of its maximal value or faster. Finally, the aLIGO data show that the binaries that produced GW150914 and GW151226 were at comparable distances from the Earth and that the peak of the gravitational-wave luminosity was about 3×10^{56} erg/sec, making them by far the most luminous transient events in the universe.

Owing to the signal's length and the particular orientation of the binary plane with respect to the aLIGO detectors, no information about the spin precession of the system could be extracted. It has therefore not yet been possible to determine the precise astrophysical production route for these objects. Whereas the predictions for the rate of binary black-hole mergers from astrophysical-formation mechanisms traditionally vary by several orders of magnitude, the aLIGO detections so far have already established the rate to be somewhat on the high side of the range predicted by astrophysical models at 9–240 per Gpc^3 per year. Larger black-hole masses and higher coalescence rates raise the interesting possibility that a stochastic background of gravitational waves composed of unresolved signals from binary black-hole mergers could be observed when aLIGO reaches its design sensitivity in 2019.

The sky localisation of GW150914 and GW151226, which is mainly determined by recording the time delays of the signals arriving at the interferometers, extended over several hundred square degrees. This can be compared with the 0.2 square degrees covered by the full Moon as seen from the Earth, and makes it very hard to search for an electromagnetic counterpart to black-hole mergers. Nevertheless, the aLIGO results kicked off the first campaign for possible electromagnetic counterparts of gravitational-wave signals, involving almost 20 astronomical facilities spanning the gamma-ray, X-ray, optical, infrared and radio regions of the spectrum. No convincing evidence of electromagnetic signals emitted by GW150914 and GW151226 was found, in line with expectations from standard astrophysical scenarios. Deviations from the standard scenario may arise if one considers dark electromagnetic sectors, spinning black holes with strong magnetic fields that need to be sustained until merger, and black holes surrounded by clouds of axions (see p45).

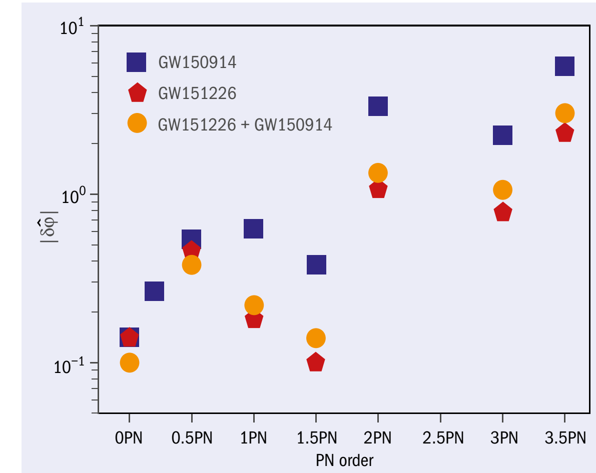


arXiv:1410.7832

Fig. 3. Current range of validity of the main analytical and numerical methods to solve the two-body problem. The horizontal axis shows the binary mass ratio, while the vertical axis shows the radial separation between the two black holes in the binary.

aLIGO's observations allow us to test general relativity in the so-far-unexplored, highly dynamical and strong-field gravity regime. As the two black holes that emitted GW150914 and GW151226 started to merge, the binary's orbital period varied considerably and the phase of the gravitational-wave signal changed accordingly. It is possible to obtain an analytical representation of the phase evolution in post-Newtonian theory, in which the coefficients describe a plethora of dynamical and radiative physical effects, and long-term timing observations of binary pulsars have placed precise bounds on the leading-order post-Newtonian coefficients. However, the new aLIGO observations have put the most stringent limits on higher post-Newtonian terms – setting upper bounds as low as 10% for some coefficients (figure 4). It was even possible to investigate potential deviations during the non-perturbative coalescence phase, and again general relativity passed this test without doubt.

The first aLIGO observations could neither test the second law of black-hole mechanics, which states that the black-hole entropy cannot decrease, nor the "no-hair" theorem, which says that a black hole is only described by mass and spin, for which we require to extract the mass and spin of the final black hole from the data. But we expect that future, multiple gravitational-wave detections with higher signal-to-noise ratios will shed light on these important theoretical questions. Despite those limitations, aLIGO has provided the most convincing evidence to date that stellar-mass compact objects in our universe with masses larger than roughly five solar masses are described by black holes: that is, by the solutions to the Einstein field equations (see p21).



2016 Phys. Rev. X **6** 041015

Fig. 4. The 90%-credible upper bounds on deviations in the post-Newtonian coefficients from GW150914 and GW151226, and the joint upper bounds from the two detections.

From binaries to cosmology

During its first observation run, lasting from mid-September 2015 to mid-January 2016, aLIGO did not detect gravitational waves from binaries composed of either two neutron stars, or a black hole and a neutron star. Nevertheless, it set the most stringent upper limits on the rates of such processes: 12.6×10^3 and 3.6×10^3 per Gpc^3 per year, respectively. The aLIGO rates imply that we expect to detect those binary systems a few years after aLIGO and the French–Italian experiment Virgo reach their design sensitivity. Observing gravitational waves from binaries made up of matter is exciting because it allows us to infer the neutron-star equation of state and also to unveil the possible origin of short-hard gamma-ray bursts (GRBs) – enormous bursts of electromagnetic radiation observed in distant galaxies.

Gravitational waves provide us with a pristine snapshot of the source.

Neutron stars are extremely dense objects that form when massive stars run out of nuclear fuel and collapse. The density in the core is expected to be more than 10^{14} times the density of the Sun, at which the standard structure of nuclear matter breaks down and new phases of matter such as superfluidity and superconductivity may appear. All mass and spin parameters being equal, ▷

the gravitational-wave train emitted by a binary containing a neutron star differs from the one emitted by two black holes only in the late inspiral phase, when the neutron star is tidally deformed or disrupted. By tracking the gravitational-wave phase it will be possible to measure the tidal deformability parameter, which contains information about the neutron-star interior, and ultimately to discriminate between some equations of state. The merger of double neutron stars and/or black-hole–neutron-star binaries is currently considered the most likely source of short-hard GRBs, and we expect a plethora of electromagnetic signals from the coalescence of such compact objects that will test the short-hard GRB/binary-merger paradigm.

Bursts of gravitational waves lasting for tenths of milliseconds are also produced during the catastrophic final moments of all stars, when the stellar core undergoes a sudden collapse (or supernova explosion) to a neutron star or a black hole. At design sensitivity, aLIGO and Virgo could detect bursts from the core's "bounce", provided that the supernova took place in the Milky Way or neighbouring galaxies, with more extreme emission scenarios observable to much further distances. Highly magnetised rotating neutron stars called pulsars are also promising astrophysical sources of gravitational waves. Mountains just a few centimetres in height on the crust of pulsars can cause the variation in time of the pulsar's quadrupole moment, producing a continuous gravitational-wave train at twice the rotation frequency of the pulsar. The most recent LIGO all-sky searches and targeted observations of known pulsars have already started to invade the parameter space of astrophysical interest, setting new upper limits on the source's ellipticity, which depends on the neutron-star's equation of state.

Lastly, several physical mechanisms in the early universe could have produced gravitational waves, such as cosmic inflation, first-order phase transitions and vibrations of fundamental and/or cosmic strings. Being that gravitational waves are almost unaffected by matter, they provide us with a pristine snapshot of the source at the time they were produced. Thus, gravitational waves may unveil a period in the history of the universe around its birth that we cannot otherwise access. The first observation run of aLIGO has set the most stringent constraints on the stochastic gravitational-wave background, which is generally expressed by the dimensionless energy density of gravitational waves, of $< 1.7 \times 10^{-7}$. Digging deeper, at design sensitivity aLIGO is expected to reach a value of 10^{-9}, while next-generation detectors such as the Einstein Telescope and the Cosmic Explorer may achieve values as low as 10^{-13} – just two orders of magnitude above the background predicted by the standard "slow-roll" inflationary scenario.

Grand view

The sensitivity of existing interferometer experiments on Earth will be improved in the next 5–10 years by employing a quantum-optics phenomenon called squeezed light. This will reduce the sky-localisation errors of coalescing binaries, provide a better measurement of tidal effects and the neutron-star equation of state in binary mergers, and enhance our chances of observing gravitational waves from pulsars and supernovae. The ability to identify the source of gravitational waves will also improve over time, as upgraded and new gravitational-wave observatories come online.

Furthermore, pulsar signals offer an alternative Pulsar Timing Array (PTA) detection scheme that is currently operating. Gravitational waves passing through pulsars and the Earth would modify the time of arrival of the pulses, and searches for correlated signatures in the pulses' times of arrival from the most stable known pulsars by PTA projects could detect the stochastic gravitational-wave background from unresolved supermassive binary black-hole inspirals in the 10^{-9}–10^{-7} Hz frequency region. Results from the North-American NANOGrav, European EPTA and Australian PPTA collaborations have already set interesting upper limits on the astrophysical background, and could achieve a detection in the next five years.

The past year has been a milestone for gravitational-wave research in space, with the results of the LISA Pathfinder mission published in June 2016 exceeding all expectations and proving that LISA, planned for 2034, will work successfully (see p34). LISA would be sensitive to gravitational waves between 10^{-4}–10^{-2} Hz, thus detecting sources different from the ones observed on the Earth such as supermassive binary black holes, extreme mass-ratio inspirals, and the astrophysical stochastic background from white-dwarf binaries in our galaxy. In the meantime, a new ground facility to be built in 10–15 years – such as the Einstein Telescope in Europe and the Cosmic Explorer in the US – will be required to maximise the scientific potential of gravitational-wave physics and astrophysics. These future detectors will allow such high sensitivity to binary coalescences that we can probe binary black holes in all our universe, enabling the most exquisite tests of general relativity in the highly dynamical, strong-field regime. That will challenge our current knowledge of gravity, fundamental and nuclear physics, unveiling the nature of the most extreme objects in our universe.

• Further reading

M Armano *et al.* 2016 *Phys. Rev. Lett.* **116** 231101.
LIGO Scientific and Virgo Collaborations 2016 *Phys. Rev. Lett.* **116** 061102.
LIGO Scientific and Virgo Collaborations 2016 *Phys. Rev. Lett.* **116** 241103.
LIGO Scientific and Virgo Collaborations 2016 *Phys. Rev. Lett.* **116** 221101.
LIGO Scientific and Virgo Collaborations 2016 *Phys. Rev. X* **6** 041015.
LIGO Scientific and Virgo Collaborations 2016 *Living Rev. Relat.* **19** 1.

Résumé

Le début d'une ère nouvelle

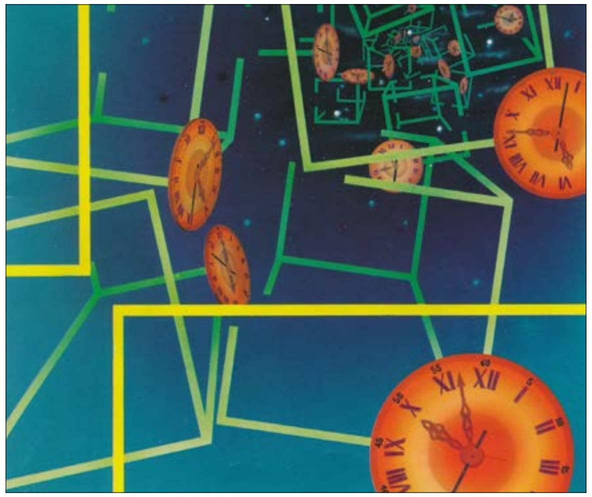
L'une des plus grandes découvertes scientifiques de notre siècle a eu lieu le 14 septembre 2015, lorsqu'un train d'ondes gravitationnelles issu de la collision de deux trous noirs, à 1,4 milliard d'années-lumière de la Terre, est passé à travers l'expérience aLIGO. Cet événement a marqué la fin d'une quête qui avait duré un demi-siècle, et l'entrée dans la nouvelle ère de l'astronomie des ondes gravitationnelles. La capacité que nous avons à présent d'observer l'Univers à l'aide des ondes gravitationnelles remettra en question notre connaissance actuelle de la gravité et de la physique fondamentale, car elle pourrait dévoiler la nature des objets les plus extrêmes que nous connaissons et peut-être faire la lumière sur l'origine de l'Univers lui-même. Et ce n'est là qu'un début.

Alessandra Buonanno, Max Planck Institute for Gravitational Physics, Germany, and University of Maryland, US.

General relativity at 100

Einstein's masterpiece has passed every test thrown at it, most recently with the discovery of gravitational waves, but it is vital that we submit our century-old theory of gravity to further precision experiments.

Einstein's long path towards general relativity (GR) began in 1907, just two years after he created special relativity (SR), when the following apparently trivial idea occurred to him: "If a person falls freely, he will not feel his own weight." Although it was long known that all bodies fall in the same way in a gravitational field, Einstein raised this thought to the level of a postulate: the equivalence principle, which states that there is complete physical equivalence between a homogeneous gravitational field and an accelerated reference frame. After eight years of hard work and deep thinking, in November 1915 he succeeded in extracting from this postulate a revolutionary theory of space, time and gravity. In GR, our best description of gravity, space–time ceases to be an absolute, non-dynamical framework as envisaged by the Newtonian view, and instead becomes a dynamical structure that is deformed by the presence of mass-energy.


Gravity warps space and time. (Image credit: Isaïe Correia.)

GR has led to profound new predictions and insights that underpin modern astrophysics and cosmology, and which also play a central role in attempts to unify gravity with other interactions. By contrast to GR, our current description of the fundamental constituents of matter and of their non-gravitational interactions – the Standard Model (SM) – is given by a quantum theory of interacting particles of spins 0, ½ and 1 that evolve within the fixed, non-dynamical Minkowski space–time of SR. The contrast between the homogeneous, rigid and matter-independent space–time of SR and the inhomogeneous, matter-deformed space–time of GR is illustrated in figure 1 (overleaf).

The universality of the coupling of gravity to matter (which is the most general form of the equivalence principle) has many observable consequences such as: constancy of the physical constants; local isotropy of space; local Lorentz invariance; universality of free fall and universality of gravitational redshift. Many of these have been verified to high accuracy. For instance, the universality of the acceleration of free fall has been verified on Earth at the 10^{-13} level, while the local isotropy of space has been verified at the 10^{-22} level. Einstein's field equations (see panel overleaf) also predict many specific deviations from Newtonian gravity that can be tested in the weak-field, quasi-stationary regime appropriate to experiments performed in the solar system. Two of these tests – Mercury's perihelion advance, and light deflection by the Sun – were successfully performed, although with limited precision, soon after the discovery of GR. Since then, many high-precision tests of such post-Newtonian gravity have been performed in the solar system, and GR has passed each of them with flying colours.

Precision tests

Similar to what is done in precision electroweak experiments, it is useful to quantify the significance of precision gravitational experiments by parameterising plausible deviations from GR. The simplest, and most conservative, deviation from Einstein's pure spin-2 theory is defined by adding a long-range (massless) spin-0 field, ϕ, coupled to the trace of the energy-momentum tensor. The most general such theory respecting the universality of gravitational coupling contains an arbitrary function of the scalar field defining the "observable metric" to which the SM matter is minimally and universally coupled.

In the weak-field slow-motion limit, appropriate to describing gravitational experiments in the solar system, the addition of ϕ modifies Einstein's predictions only through the appearance of two dimensionless parameters, $\bar{\gamma}$ and $\bar{\beta}$. The best current limits on these "post-Einstein" parameters are, respectively, $(2.1 \pm 2.3) \times 10^{-5}$ (deduced from the additional Doppler shift ▷

General relativity makes waves

There are two equivalent ways of characterising general relativity (GR). One describes gravity as a universal deformation of the Minkowski metric, which defines a local squared interval between two infinitesimally close space–time points and, consequently, the infinitesimal light cones describing the local propagation of massless particles. The metric field $g_{\mu\nu}$ is assumed in GR to be universally and minimally coupled to all the particles of the Standard Model (SM), and to satisfy Einstein's field equations:

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}.$$

Here, $R_{\mu\nu}$ denotes the Ricci curvature (a nonlinear combination of $g_{\mu\nu}$ and of its first and second derivatives), $T_{\mu\nu}$ is the stress-energy tensor of the SM particles (and fields), and G denotes Newton's gravitational constant.

The second way of defining GR, as proven by Richard Feynman, Steven Weinberg, Stanley Deser and others, states that it is the unique, consistent, local, special-relativistic theory of a massless spin-2 field. It is then found that the couplings of the spin-2 field to the SM matter are necessarily equivalent to a universal coupling to a "deformed" space–time metric, and that the propagation and self-couplings of the spin-2 field are necessarily described by Einstein's equations.

Following the example of Maxwell, who had found that the electromagnetic-field equations admit propagating waves as solutions, Einstein found that the GR field equations admit propagating gravitational waves (GWs). He did so by considering the weak-field limit ($g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$) of his equations, namely,

$$\Box \bar{h}_{\mu\nu} - \partial_\mu H_\nu - \partial_\nu H_\mu = -\frac{16\pi G}{c^4} T_{\mu\nu},$$

where $\bar{h}_{\mu\nu} = h_{\mu\nu} - ½h\,\eta_{\mu\nu}$. When choosing the co-ordinate system so as to satisfy the gravitational analogue of the Lorenz gauge condition, so that $H_\mu = \partial_\nu \bar{h}_{\mu\nu} = 0$, the linearised field equations simplify to the diagonal inhomogeneous wave equation, which can be solved by retarded potentials.

There are two main results that derive from this wave equation: first, a GW is locally described by a plane wave with two transverse tensorial polarisations (corresponding to the two helicity states of the massless spin-2 graviton) and travelling at the velocity of light; second, a slowly moving, non self-gravitating source predominantly emits a quadupolar GW.

experienced by radio-wave beams connecting the Earth to the Cassini spacecraft when they passed near the Sun) and $< 7 \times 10^{-5}$, from a study of the global sensitivity of planetary ephemerides to post-Einstein parameters.

In the regime of radiative and/or strong gravitational fields, by contrast, pulsars (rotating neutron stars emitting a beam of radio waves) in gravitationally bound orbits have provided crucial tests of GR. In particular, measurements of the decay in the orbital period of binary pulsars have provided direct experimental confirmation of the propagation properties of the gravitational field. Theoretical studies of binaries in GR have shown that the finite velocity of propagation of the gravitational interaction between the pulsar and its companion generates damping-like terms at order $(v/c)^5$ in the equations of motion that lead to a small orbital period decay. This has been observed in more than four different systems

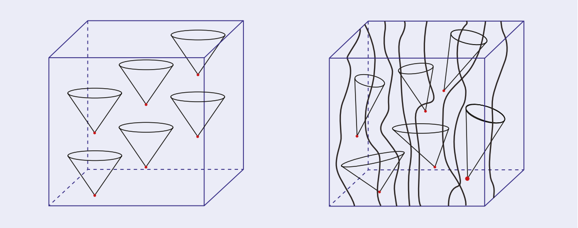


Fig. 1. The non-dynamical Minkowski space–time of SR (left) and its regular array of light cones compared to the dynamical, matter-deformed space–time of GR and its field of local light cones (right). GR has been submitted, with striking success, to many high-precision experimental tests.

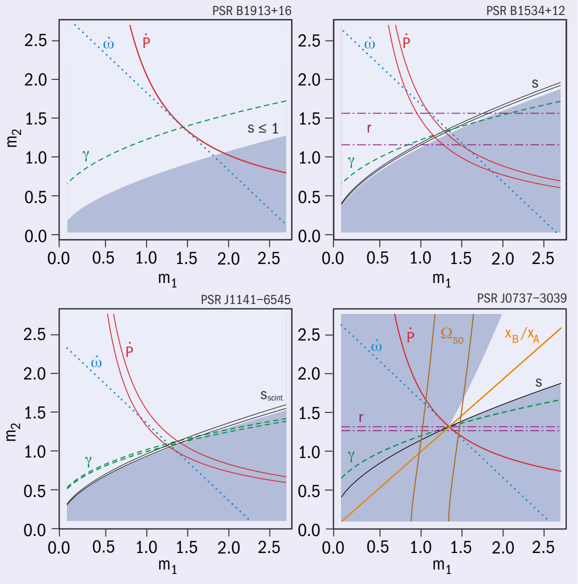
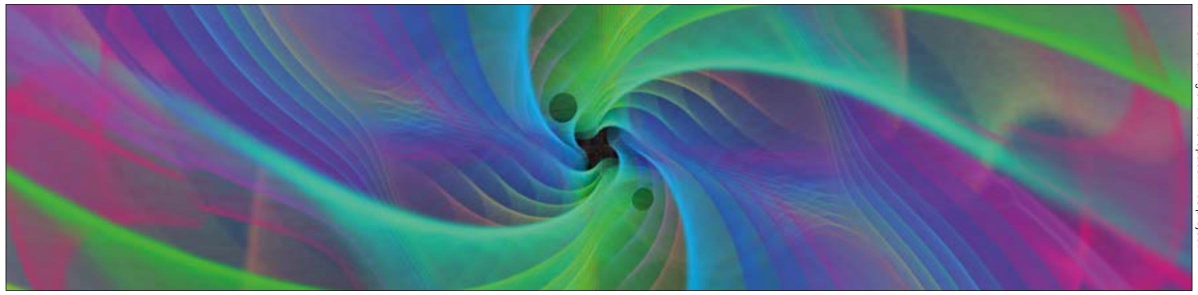


Fig. 2. Illustration of the 11 tests of relativistic gravity obtained in the four known binary pulsar systems. Each curve (or strip) in the mass plane corresponds to the interpretation, within GR, of some observable timing parameter. The shaded regions correspond to s > 1, which is theoretically excluded.

since the discovery of binary pulsars in 1974, providing direct proof of the reality of gravitational radiation. Measurements of the arrival times of pulsar signals have also allowed precision tests of the quasi-stationary strong-field regime of GR, since their values may depend both on the unknown masses of the binary system and on the theory of gravity used to describe the strong self-gravity of the pulsar and its companion (figure 2).

The radiation revelation

Einstein realised that his field equations had wave-like solutions in two papers in June 1916 and January 1918 (see panel left). For many years, however, the emission of gravitational waves (GWs) by known sources was viewed as being too weak to be of physical significance.



MPI/Simulating eXtreme Spacetimes project

In addition, several authors – including Einstein himself – had voiced doubts about the existence of GWs in fully nonlinear GR.

The situation changed in the early 1960s when Joseph Weber understood that GWs arriving on Earth would have observable effects and developed sensitive resonant detectors ("Weber bars") to search for them. Then, prompted by Weber's experimental effort, Freeman Dyson realised that, when applying the quadupolar energy-loss formula derived by Einstein to binary systems made of neutron stars, "the loss of energy by gravitational radiation will bring the two stars closer with ever-increasing speed, until in the last second of their lives they plunge together and release a gravitational flash at a frequency of about 200 cycles and of unimaginable intensity." The vision of Dyson has recently been realised thanks, on the one hand, to the experimental development of drastically more sensitive non-resonant kilometre-scale interferometric detectors and, on the other hand, to theoretical advances that allowed one to predict in advance the accurate shape of the GW signals emitted by coalescing systems of neutron stars and black holes (BHs).

The recent observations of the LIGO interferometers have provided the first detection of GWs in the wave zone. They also provide the first direct evidence of the existence of BHs via the observation of their merger, followed by an abrupt shut-off of the GW signal, in complete accord with the GR predictions.

BHs are perhaps the most extraordinary consequence of GR, because of the extreme distortion of space and time that they exhibit. In January 1916, Karl Schwarzschild published the first exact solution of the (vacuum) Einstein equations, supposedly describing the gravitational field of a "mass point" in GR. It took about 50 years to fully grasp the meaning and astrophysical plausibility of these Schwarzschild BHs. Two of the key contributions that led to our current understanding of BHs came from Oppenheimer and Snyder, who in 1939 suggested that a neutron star exceeding its maximum possible mass will undergo gravitational collapse and thereby form a BH, and from Kerr 25 years later, who discovered a generalisation of the Schwarzschild solution describing a BH endowed both with mass and spin.

Another remarkable consequence of GR is theoretical cosmology, namely the possibility of describing the kinematics and the dynamics of the whole material universe. The field of relativistic cosmology was ushered in by a 1917 paper by Einstein. Another key contribution was the 1924 paper of Friedmann that described general families of spatially curved, expanding or contracting homogeneous cosmological models. The Friedmann models still constitute the background models of the current, inhomogeneous

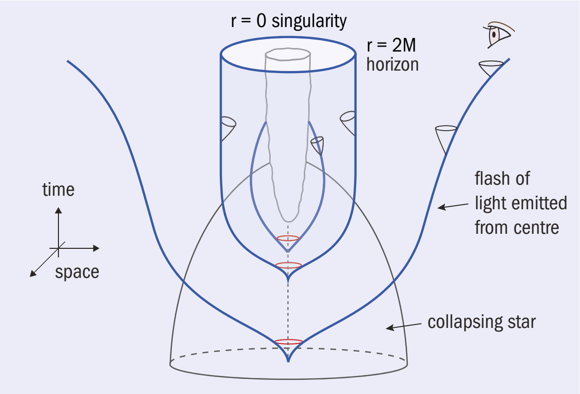


Fig. 3. (Top) Simulation of a black-hole merger based on numerical GR. (Bottom) The gravitational collapse of a star leading to the formation of a BH horizon, a hypersurface in space–time that is everywhere tangent to the light cone and whose 2D spatial sections approach asymptotically (in the future) the r = 2GM/c² 2-sphere of a Schwarzschild solution.

cosmologies. Quantitative confirmations of GR on cosmological scales have also been obtained, notably through the observation of a variety of gravitational lensing systems.

Dark clouds ahead

In conclusion, all present experimental gravitational data (universality of free fall, post-Newtonian gravity, radiative and strong-field effects in binary pulsars, GW emission by coalescing BHs and gravitational lensing) have been found to be compatible with the predictions of Einstein's theory. There are also strong constraints on sub-millimetre modifications of Newtonian gravity from torsion-balance tests of the inverse square law.

One might, however, wish to keep in mind the presence of two dark clouds in our current cosmology, namely the need to assume that most of the stress-energy tensor that has to be put on the right-hand side of the GR field equations to account for the current observations is made of yet unseen types of matter: dark matter and a "cosmological constant". It has been suggested that these signal a breakdown of Einstein's gravitation at large scales, although no convincing theoretical modification of GR at large distances has yet been put forward.

GWs, BHs and dynamical cosmological models have become essential elements of our description of the macroscopic universe. ▷

General relativity

The recent and bright beginning of GW astronomy suggests that GR will be an essential tool for discovering new aspects of the universe (see p16). A century after its inception, GR has established itself as the standard theoretical description of gravity, with applications ranging from the Global Positioning System and the dynamics of the solar system, to the realm of galaxies and the primordial universe.

However, in addition to the "dark clouds" of dark matter and energy, GR also poses some theoretical challenges. There are both classical challenges (notably the formation of space-like singularities inside BHs), and quantum ones (namely the non-renormalisability of quantum gravity – see p27). It is probable that a full resolution of these challenges will be reached only through a suitable extension of GR, and possibly through its unification with the current "spin ≤ 1" description of particle physics, as suggested both by supergravity and by superstring theory.

It is therefore vital that we continue to submit GR to experimental tests of increasing precision. The foundational stone of GR, the equivalence principle, is currently being probed in space at the 10^{-15} level by the MICROSCOPE satellite mission of ONERA and CNES. The observation of a deviation of the universality of free fall would imply that Einstein's purely geometrical description of gravity needs to be completed by including new long-range fields coupled to bulk matter. Such an experimental clue would be most valuable to indicate the road towards a more encompassing physical theory.

Further reading

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Résumé

La relativité générale fête ses 100 ans

Au cours des cent dernières années, la théorie de la gravité d'Einstein a donné naissance à de nouvelles prédictions et idées essentielles, qui sont à la base de l'astrophysique et de la cosmologie modernes. La plupart ont été confirmées par l'expérience avec une précision stupéfiante, et la détection des ondes gravitationnelles a été la cerise sur le gâteau pour la relativité générale. Mais l'horizon se charge de nuages menaçants. En plus de difficultés pour rendre compte de la matière noire et de l'énergie noire, la relativité générale pose des problèmes théoriques qui pourraient n'être résolus que par une extension appropriée de la théorie, et peut-être par son unification avec la physique des particules, comme le suggèrent les théories de la supergravité et des supercordes.

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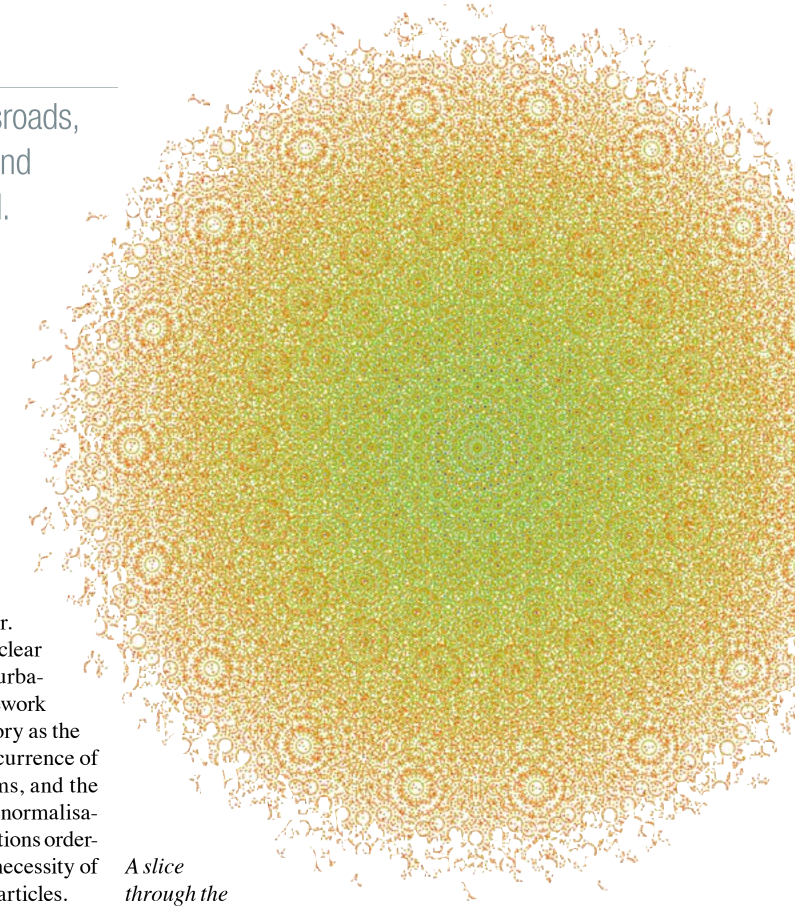
Gravity's quantum side

Theoretical physics has arrived at crossroads, with no clues so far as to what lies beyond general relativity or the Standard Model. If we are ever to break through this impasse, we need to borrow from Einstein's epochal feats.



A slice through the root space of the symmetry group E10, a possible symmetry for quantum gravity. Each point is associated with one or more independent symmetry operations – similar to the flavour SU(3) root diagram for the meson octet, but vastly more complicated. There are infinitely many such layers, and the number of symmetry operations grows exponentially as one penetrates deeper and deeper into the E10 Lie algebra. (Image credit: T Nutma.)

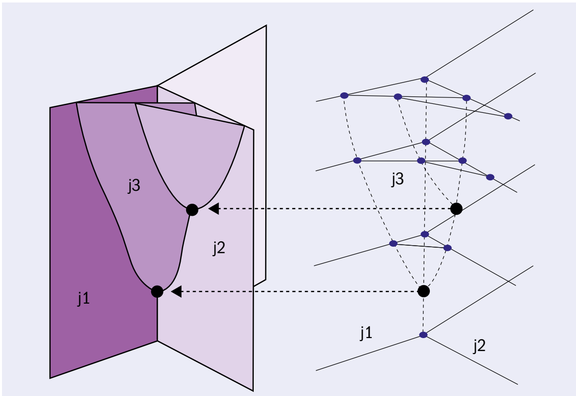
There is little doubt that, in spite of their overwhelming success in describing phenomena over a vast range of distances, general relativity (GR) and the Standard Model (SM) of particle physics are incomplete theories. Concerning the SM, the problem is often cast in terms of the remaining open issues in particle physics, such as its failure to account for the origin of the matter–antimatter asymmetry or the nature of dark matter. But the real problem with the SM is theoretical: it is not clear whether it makes sense at all as a theory beyond perturbation theory, and these doubts extend to the whole framework of quantum field theory (QFT) (with perturbation theory as the main tool to extract quantitative predictions). The occurrence of "ultraviolet" (UV) divergences in Feynman diagrams, and the need for an elaborate mathematical procedure called renormalisation to remove these infinities and make testable predictions order-by-order in perturbation theory, strongly point to the necessity of some other and more complete theory of elementary particles.

On the GR side, we are faced with a similar dilemma. Like the SM, GR works extremely well in its domain of applicability and has so far passed all experimental tests with flying colours, most recently and impressively with the direct detection of gravitational waves (see p21). Nevertheless, the need for a theory beyond Einstein is plainly evident from the existence of space–time singularities such as those occurring inside black holes or at the moment of the Big Bang. Such singularities are an unavoidable consequence of Einstein's equations, and the failure of GR to provide an answer calls into question the very conceptual foundations of the theory.

Unlike quantum theory, which is rooted in probability and uncertainty, GR is based on notions of smoothness and geometry and is therefore subject to classical determinism. Near a space–time singularity, however, the description of space–time as a continuum is expected to break down. Likewise, the assumption that elementary particles are point-like, a cornerstone of QFT and the reason for the occurrence of ultraviolet infinities in the SM, is expected to fail in such extreme circumstances.

Applying conventional particle-physics wisdom to Einstein's theory by quantising small fluctuations of the metric field (corresponding to gravitational waves) cannot help either, since it produces non-renormalisable infinities that undermine the predictive power of perturbatively quantised GR.

In the face of these problems, there is a wide consensus that the outstanding problems of both the SM and GR can only be overcome by a more complete and deeper theory: a theory of quantum ▷



If quantum space is made of web-like structures (spin networks), as postulated by LQG-like approaches, a spin foam describes the quantum evolution of such spin networks in time. In the abstract description, the ambient space–time in which the spin foam is "embedded" is simply not there, since all of the geometry resides on the spin foam.

gravity (QG) that possibly unifies gravity with the other fundamental interactions in nature. But how are we to approach this challenge?

Planck-scale physics

Unlike with quantum mechanics, whose development was driven by the need to explain observed phenomena such as the existence of spectral lines in atomic physics, nature gives us very few hints of where to look for QG effects. One main obstacle is the sheer smallness of the Planck length, of the order 10^{-33} cm, which is the scale at which QG effects are expected to become visible (conversely, in terms of energy, the relevant scale is 10^{19} GeV, which is 15 orders of magnitude greater than the energy range accessible to the LHC). There is no hope of ever directly measuring genuine QG effects in the laboratory: with zillions of gravitons in even the weakest burst of gravitational waves, realising the gravitational analogue of the photoelectric effect will forever remain a dream.

One can nevertheless speculate that QG might manifest itself indirectly, for instance via measurable features in the cosmic microwave background, or cumulative effects originating from a more granular or "foamy" space–time. Alternatively, perhaps a framework will emerge that provides a compelling explanation for inflation, dark energy and the origin of the universe. Although not completely hopeless, available proposals typically do not allow one to unambiguously discriminate between very different approaches, for instance when contrarian schemes like string theory and loop quantum gravity vie to explain features of the early universe. And even if evidence for new effects was found in, say, cosmic-ray physics, these might very well admit conventional explanations.

All of the important questions remain wide open.

In the search for a consistent theory of QG, it therefore seems that we have no other choice but to try to emulate Einstein's epochal feat of creating a new theory out of purely theoretical considerations.

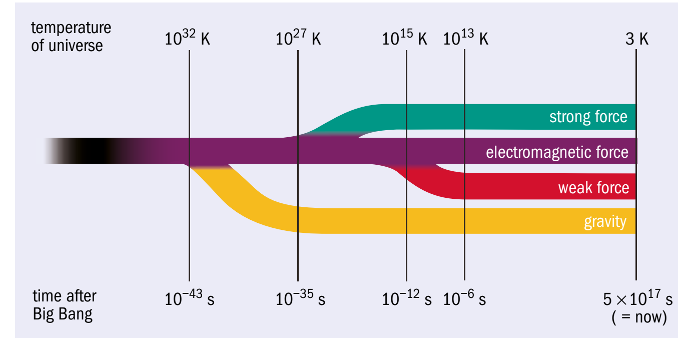
Emulating Einstein

Yet, after more than 40 years of unprecedented collective intellectual effort, different points of view have given rise to a growing diversification of approaches to QG – with no convergence in sight. It seems that theoretical physics has arrived at crossroads, with nature remaining tight-lipped about what comes after Einstein and the SM. There is currently no evidence whatsoever for any of the numerous QG schemes that have been proposed – no signs of low-energy supersymmetry, large extra dimensions or "stringy" excitations have been seen at the LHC so far. The situation is no better for approaches that do not even attempt to make predictions that could be tested at the LHC.

Existing approaches to QG fall roughly into two categories, reflecting a basic schism that has developed in the community. One is based on the assumption that Einstein's theory can stand on its own feet, even when confronted with quantum mechanics. This would imply that QG is nothing more than the non-perturbative quantisation of Einstein's theory and that GR, suitably treated and eventually complemented by the SM, correctly describes the physical degrees of freedom also at the very smallest distances. The earliest incarnation of this approach goes back to the pioneering work of John Wheeler and Bryce DeWitt in the early 1960s, who derived a GR analogue of the Schrödinger equation in which the "wave function of the universe" encodes the entire information about the universe as a quantum system. Alas, the non-renormalisable infinities resurface in a different guise: the Wheeler–DeWitt equation is so ill-defined mathematically that no one until now has been able to make sense of it beyond mere heuristics. More recent variants of this approach in the framework of loop quantum gravity (LQG), spin foams and group field theory replace the space–time metric by new variables (Ashtekar variables, or holonomies and fluxes) in a renewed attempt to overcome the mathematical difficulties.

The opposite attitude is that GR is only an effective low-energy theory arising from a more fundamental Planck-scale theory, whose basic degrees of freedom are very different from GR or quantum field theory. In this view, GR and space–time itself are assumed to be emergent, much like macroscopic physics emerges from the quantum world of atoms and molecules. The perceived need to replace Einstein's theory by some other and more fundamental theory, having led to the development of supersymmetry and supergravity, is the basic hypothesis underlying superstring theory (see p41). Superstring theory is the leading contender for a perturbatively finite theory of QG, and widely considered the most promising possible pathway from QG to SM physics. This approach has spawned a hugely varied set of activities and produced many important ideas. Most notable among these, the AdS/CFT correspondence posits that the physics that takes place in some volume can be fully encoded in the surface bounding that volume, as for a hologram, and consequently that QG in the bulk should be equivalent to a pure quantum field theory on its boundary.

Apart from numerous technical and conceptual issues, there remain major questions for all approaches to QG. For LQG-like or "canonical" approaches, the main unsolved problems concern the emergence of classical space–time and the Einstein field equations in the semiclassical limit, and their inability to recover standard QFT results such as anomalies. On the other side, a main shortcoming is the "background dependence" of the quantisation procedure, for which both supergravity and string theory have to rely on perturbative expansions about some given space–time background geometry. In fact, in its presently known form, string theory cannot even be formulated without reference to a specific space–time background.



The success of symmetry has fuelled hopes that we might ultimately understand the evolution of the universe from its beginning as a symmetry-breaking cascade, where at each step more and more of the initial symmetry is lost as the universe expands and cools down. In this view, the unsymmetrical world that we see around us is only the broken phase of a highly symmetrical theory at the origin of the universe, when forces, matter and space–time were unified into a single entity. However, this picture has so far been validated only up to energy scales accessible to the LHC, or equivalently distances down to 10^{-18} cm.

These fundamentally different viewpoints also offer different perspectives on how to address the non-renormalisability of Einstein's theory, and consequently on the need (or not) for unification. Supergravity and superstring theory try to eliminate the infinities of the perturbatively quantised theory, in particular by including fermionic matter in Einstein's theory, thus providing a *raison d'être* for the existence of matter in the world. They therefore automatically arrive at some kind of unification of gravity, space–time and matter. By contrast, canonical approaches attribute the ultraviolet infinities to basic deficiencies of the perturbative treatment. However, to reconcile this view with semiclassical gravity, they will have to invoke some mechanism – a version of Weinberg's asymptotic safety – to save the theory from the abyss of non-renormalisability.

Conceptual challenges

Beyond the mathematical difficulties to formulating QG, there are a host of issues of a more conceptual nature that are shared by all approaches. Perhaps the most important concerns the very ground rules of quantum mechanics: even if we could properly define and solve the Wheeler–DeWitt equation, how are we to interpret the resulting wave function of the universe? After all, the latter pretends to describe the universe in its entirety, but in the absence of outside classical observers, the Copenhagen interpretation of quantum mechanics clearly becomes untenable. On a slightly less grand scale, there are also unresolved issues related to the possible loss of information in connection with the Hawking evaporation of black holes.

A further question that any theory of QG must eventually answer concerns the texture of space–time at the Planck scale: do there exist "space–time atoms" or, more specifically, web-like structures like spin networks and spin foams, as claimed by LQG-like approaches? (see diagram on previous page) Or does the space–time continuum get dissolved into a gas of strings and branes, as suggested by some variants of string theory, or emerge from holographic entanglement, as advocated by AdS/CFT aficionados? There is certainly no lack of enticing ideas, but without a firm guiding principle and the prospect of making a falsifiable prediction, such speculations may well end up in the nirvana of undecidable propositions and untestable expectations.

Why then consider unification? Perhaps the strongest argument in favour of unification is that the underlying principle of symmetry has so far guided the development of modern physics from Maxwell's theory to GR all the way to Yang–Mills theories and the SM (see diagram above). It is therefore reasonable to suppose that unification and symmetry may also point the way to a consistent theory of QG. This point of view is reinforced by the fact that the SM, although only a partially unified theory, does already afford glimpses of trans-Planckian physics, independently of whether new physics shows up at the LHC or not. This is because the requirements of renormalisability and vanishing gauge anomalies put very strong constraints on the particle content of the SM, which are indeed in perfect agreement with what we see in detectors. There would be no more convincing vindication of a theory of QG than its ability to predict the matter content of the world (see panel overleaf).

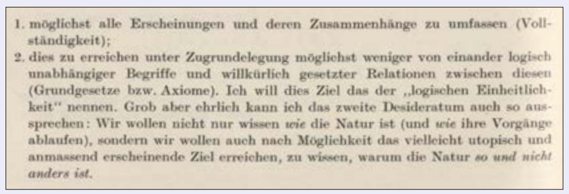
In search of SUSY

Among the promising ideas that have emerged over the past decades, arguably the most beautiful and far reaching is supersymmetry. It represents a new type of symmetry that relates bosons and fermions, thus unifying forces (mediated by vector bosons) with matter (quarks and leptons), and which endows space–time with extra fermionic dimensions. Supersymmetry is very natural from the point of view of cancelling divergences because bosons and fermions generally contribute with opposite signs to loop diagrams. This aspect means that low-energy ($N = 1$) supersymmetry can stabilise the electroweak scale with regard to the Planck scale, thereby alleviating the so-called hierarchy problem via the cancellation of quadratic divergences. These models predict the existence of a mirror world of superpartners that differ from the SM particles only by their opposite statistics (and their mass), but otherwise have identical internal quantum numbers.

To the great disappointment of many, experimental searches at the LHC so far have found no evidence for the superpartners predicted by $N = 1$ supersymmetry. However, there is no reason to give up on the idea of supersymmetry as such, since the refutation of low-energy supersymmetry would only mean that the most simple-minded way of implementing this idea does not work. Indeed, the ▷

Einstein on unification

It is well known that Albert Einstein spent much of the latter part of his life vainly searching for unification, although disregarding the nuclear forces and certainly with no intention of reconciling quantum mechanics and GR. Already in 1929, he published a paper on the unified theory (pictured below). In this paper, he states with wonderful and characteristic lucidity what the criteria should be of a "good" unified theory: to describe as far as possible all phenomena and their inherent links, and to do so on the basis of a minimal number of assumptions and logically independent basic concepts. The second of these goals (also known as the principle of Occam's razor) refers to "logical unity", and goes on to say: "Roughly but truthfully, one might say: we not only want to understand how nature works, but we are also after the perhaps utopian and presumptuous goal of understanding why nature is the way it is and not otherwise."


1. möglichst alle Erscheinungen und deren Zusammenhänge zu umfassen (Vollständigkeit);
2. dies zu erreichen unter Zugrundelegung möglichst weniger von einander logisch unabhängiger Begriffe und willkürlich gesetzter Relationen zwischen diesen (Grundgesetze bzw. Axiome). Ich will dies Ziel das der „logischen Einheitlichkeit" nennen. Grob aber ehrlich kann ich das zweite Desideratum auch so aussprechen: Wir wollen nicht nur wissen *wie* die Natur ist (und *wie* ihre Vorgänge ablaufen), sondern wir wollen auch nach Möglichkeit das vielleicht utopisch und anmassend erscheinende Ziel erreichen, zu wissen, warum die Natur *so und nicht anders ist*.

An extract from Einstein's 1929 paper in which he set out his approach to unification. (From a contribution to a commemorative publication for Aurel Stodola, Zurich, 1929.)

initial excitement about supersymmetry in the 1970s had nothing to do with the hierarchy problem, but rather because it offered a way to circumvent the so-called Coleman–Mandula no-go theorem – a beautiful possibility that is precisely not realised by the models currently being tested at the LHC.

In fact, the reduplication of internal quantum numbers predicted by $N = 1$ supersymmetry is avoided in theories with extended ($N > 1$) supersymmetry. Among all supersymmetric theories, maximal $N = 8$ supergravity stands out as the most symmetric. Its status with regard to perturbative finiteness is still unclear, although recent work has revealed amazing and unexpected cancellations. However, there is one very strange agreement between this theory and observation, first emphasised by Gell-Mann: the number of spin-1/2 fermions remaining after complete breaking of supersymmetry is $48 = 3 \times 16$, equal to the number of quarks and leptons (including right-handed neutrinos) in three generations (see p41). To go beyond the partial matching of quantum numbers achieved so far will, however, require some completely new insights, especially concerning the emergence of chiral gauge interactions.

Then again, perhaps supersymmetry is not the end of the story. There is plenty of evidence that another type of symmetry may be equally important, namely duality symmetry. The first example of such a symmetry, electromagnetic duality, was discovered by Dirac in 1931. He realised that Maxwell's equations in vacuum are invariant under rotations of the electric and magnetic fields into one another – an insight that led him to predict the existence of magnetic monopoles. While magnetic monopoles have not been seen, duality symmetries have turned out to be ubiquitous in supergravity and string theory, and they also reveal a fascinating and unsuspected link with the so-called exceptional Lie groups.

More recently, hints of an enormous symmetry enhancement have also appeared in a completely different place, namely the study of cosmological solutions of Einstein's equations near a space-like singularity. This mathematical analysis has revealed tantalising evidence of a truly exceptional infinite-dimensional duality symmetry, which goes by the name of E10, and which "opens up" as one gets close to the cosmological (Big Bang) singularity (see image p27). Could it be that the near-singularity limit can tell us about the underlying symmetries of QG in a similar way as the high-energy limit of gauge theories informs us about the symmetries of the SM? One can validly argue that this huge and monstrously complex symmetry knows everything about maximal supersymmetry and the finite-dimensional dualities identified so far. Equally important, and unlike conventional supersymmetry, E10 may continue to make sense in the Planck regime where conventional notions of space and time are expected to break down. For this reason, duality symmetry could even supersede supersymmetry as a unifying principle.

Outstanding questions

Our summary, then, is very simple: all of the important questions in QG remain wide open, despite a great deal of effort and numerous promising ideas. In the light of this conclusion, the LHC will continue to play a crucial role in advancing our understanding of how everything fits together, no matter what the final outcome of the experiments will be. This is especially true if nature chooses not to abide by current theoretical preferences and expectations.

Over the past decades, we have learnt that the SM is a most economical and tightly knit structure, and there is now mounting evidence that minor modifications may suffice for it to survive to the highest energies. To look for such subtle deviations will therefore be a main task for the LHC in the years ahead. If our view of the Planck scale remains unobstructed by intermediate scales, the popular model-builders' strategy of adding ever more unseen particles and couplings may come to an end. In that case, the challenge of explaining the structure of the low-energy world from a Planck-scale theory of quantum gravity looms larger than ever.

Résumé

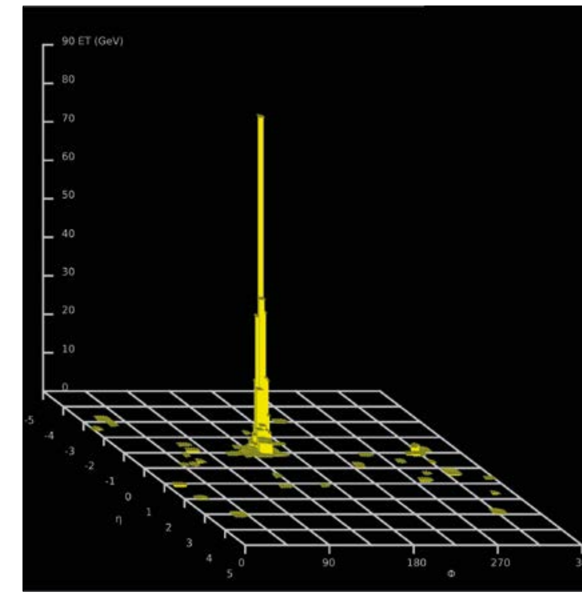
La face quantique de la gravité

La physique théorique est à la croisée des chemins, et nul ne sait pour l'instant ce qui se trouve au-delà de la relativité générale ou du Modèle standard. Il est admis que nous ne pourrons progresser qu'avec une théorie plus complète de la gravité quantique, qui unifierait peut-être la gravité avec les autres interactions fondamentales de la nature. Or, après plus de 40 ans d'un effort intellectuel collectif sans précédent, les approches de la gravité quantique sont toujours plus diversifiées et aucune convergence n'est en vue. Si nous voulons sortir un jour de cette impasse, nous devrons nous inspirer des prouesses historiques d'Einstein.

Hermann Nicolai, Max Planck Institute for Gravitational Physics, Potsdam, Germany.

The LHC's extra dimension

The discovery of additional space–time dimensions would revolutionise physics, but after 20 years of dedicated searches at particle colliders, we have turned up empty handed.



The presence of a large extra dimension could produce a clear missing-energy signal in the LHC detectors, as shown here for an ATLAS event recorded in 2011 with a missing transverse energy of 523 GeV.

At 10.00 a.m. on 9 August 2016, physicists gathered at the Sheraton hotel in Chicago for the "Beyond the Standard Model" session at the ICHEP conference. The mood was one of slight disappointment. An excess of "diphoton" events at a mass of 750 GeV reported by the LHC's ATLAS and CMS experiments in 2015 had not shown up in the 2016 data, ending a burst of activity that saw some 540 phenomenology papers uploaded to the arXiv preprint server in a period of just eight months. Among the proposed explanations for the putative new high-mass resonance were extra space–time dimensions, an idea that has been around since Theodor Kaluza and Oscar Klein attempted to unify the electromagnetic and gravitational forces a century ago.

In the modern language of string theory, extra dimensions are required to ensure the mathematical consistency of the theory. They are typically thought to be very small, close to the Planck length (10^{-35} m). In the 1990s, however, theorists trying to solve problems with supersymmetry suggested that some of these extra dimensions could be as large as 10^{-19} m, corresponding to an energy scale in the TeV range. In 1998, as proposed by Arkani-Hamed and co-workers, theories emerged with even larger extra dimensions, which predicted detectable effects in contemporary collider experiments. In such large extra-dimension (LED) scenarios, gravity can become stronger than we perceive in 3D due to the increased space available. In addition to showing us an entirely different view of the universe, extra dimensions offer an elegant solution to the so-called hierarchy problem, which arises because the Planck scale (where gravity becomes as strong as the other three forces) is 17 orders of magnitude larger than the electroweak scale.

Particle physicists normally ignore gravity because it is feeble compared with the other three forces. In theories where gravity gets stronger at small distances due to the opening of extra dimensions, however, it can catch up and lead to phenomena at colliders with high enough rates that they can be measured in experiments. The possibility of having extra space dimensions at the TeV scale was a game changer. Scientists from experiments at the LEP, Tevatron and HERA colliders quickly produced tailored searches for signals for this new beyond-the-Standard Model (SM) physics scenario. No evidence was found in their accumulated data, setting lower limits on the scale of extra dimensions of around 1 TeV.

The possibility of having extra space dimensions at the TeV scale was a game changer.

By the turn of the century, a number of possible new experimental signatures had been identified for extra-dimension searches, many of which were studied in detail while assessing the physics performance of the LHC experiments. For the case of LEDs, where gravity is the only force that can expand in these dimensions, high-energy collider experiments were just one approach. Smaller "tabletop" scale experiments aiming to measure the strength of gravity at sub-millimetre distances were also in pursuit of extra dimensions, but no deviation from the Newtonian law has been observed to date. In addition, there were also significant constraints from astrophysics processes on the possible number and size of these dimensions.

Enter the LHC

Analysis strategies to search for extra dimensions have been deployed from the beginning of high-energy LHC operations in 2010, and the recent increase in the LHC's collision energy to ▷

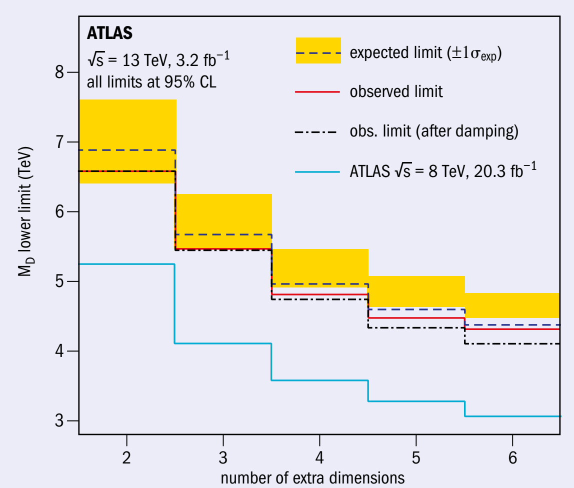


Fig. 1. Recent mono-jet searches at ATLAS have pushed possible extra-dimension scales to values beyond 5–7 TeV, depending on the number of assumed large extra dimensions available for gravity to expand into.

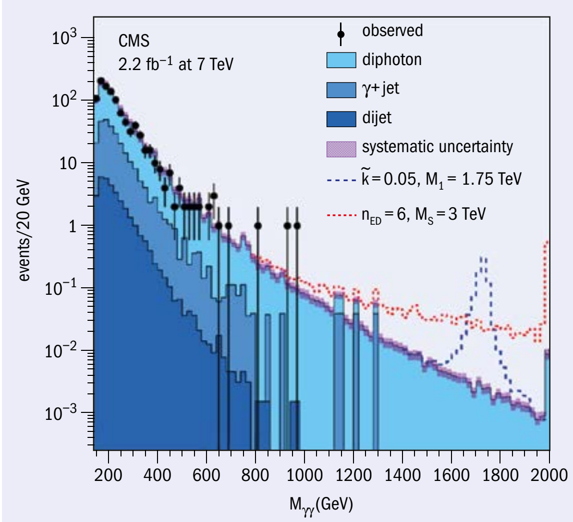


Fig. 2. Observed event yields and background expectations as a function of the diphoton invariant mass for an early extra-dimension study at the LHC. The simulated distributions for two extra-dimension model signal hypotheses are shown as dotted (LED) and dashed (RS) lines.

13 TeV has extended the search window considerably. Although no positive signal of the presence of extra dimensions has been observed so far, a big leap forward has been taken in excluding large portions of the TeV scale phase-space where extra dimensions could live.

A particular feature of LED-type searches is the production of a single very energetic "mono-object" that does not balance the transverse momentum carried by anything else emerging from the collision (as would be required by momentum and energy conservation). Examples of such objects are particle jets, very energetic photons or heavy W and Z vector bosons. Such collisions only appear to be imbalanced, however, because the emerging jet or boson is balanced by a graviton that escapes detection. Hence SM processes such as the production of a jet plus a Z boson that decays into neutrinos can mimic a graviton production signal. The absence of any excess in the mono-jet or mono-photon event channels at the LHC has put stringent limits on LEDs (figure 1), with 2010 data already bypassing previous collider search limits. LEDs can also manifest themselves as a new contribution to the continuum in the invariant mass spectrum of two energetic photons (figure 2) or fermions (dileptons or dijets). Here too, though, no signals have been observed, and the LHC has now excluded such contributions for extra-dimension scales up to several TeV.

In 1999, another extra-dimension scenario was proposed by Randall and Sundrum (RS), which led to a quite different phenomenology compared with that expected from LEDs. In its simplest form, the RS idea contains two fundamental 3D branes: one on which most if not all SM particles live, and one on which gravity lives. Gravity is assumed to be intrinsically strong, but the warped space between the two branes makes it appear weak on the brane where we live. The experimental signature of such scenarios is the production of so-called Kaluza–Klein (spin-2 graviton) resonances that can be observed in the invariant mass spectra of difermions or dibosons. The most accessible spectra to the LHC experiments include the diphoton and dilepton spectra, in which no new resonance signal has been found, and at present the limits on putative Kaluza–Klein gravitons are about 4 TeV, depending on RS-model parameters. Analyses of dijet final states provide even more stringent limits of up to 7 TeV. Further extensions of the RS model, in particular the production of top quark–antiquark resonances, offer a more sensitive signature, but despite intense searches, no signal has been detected.

The initial high enthusiasm for extra-dimension theories has waned.

Searching in the dark

At the start of 2000, it was realised that large or warped extra dimensions could lead to a new type of signature at the LHC: microscopic black holes. These can form when two colliding partons come close enough to each other, namely to within the Schwarzschild radius or black-hole event horizon, and can be as large as a femtometre in the presence of TeV-scale extra dimensions at the LHC. Such microscopic black holes would evaporate via Hawking radiation on time scales of around 10^{-27} s, way before they could suck up any matter, and provide an ideal opportunity to study quantum gravity in the laboratory.

Black holes that are produced with a mass significantly above the formation threshold are expected to evaporate in high-energy multi-particle final states leading to plenty of particle jets, leptons, photons and even Higgs particles. Searches for such energetic multi-object final states in excess of the SM expectation have been performed since the first collisions at the LHC at 7 TeV, but none have been found. If black holes are produced closer to the formation threshold, these would be expected to decay in a much smaller final-state topology, for instance into dijets. The CMS and ATLAS experiments have been looking for all of these final states up until the latest 13 TeV data (figure 3), but no signal has been observed so far for black-hole masses up to about 9 TeV.

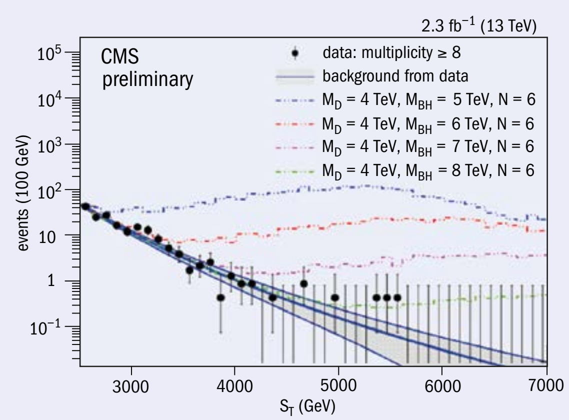


Fig. 3. Distributions of the total transverse energy for events with eight high-p_T objects. Observed data are shown by points, while the solid blue lines show the main background estimation along with the uncertainty band. The predictions for several semiclassical black-hole signals are also shown.

Several other possible incarnations of extra-dimension theories have been proposed and searched for at the LHC. So-called TeV-type extra dimensions allow for more SM particles, for example partners of the heavy W and Z bosons, to enter in the bulk, and these would show up as high-mass resonances in dilepton and other invariant mass spectra. These new resonances have a spin equal to one, and hence such signatures could be more tedious to detect because they can interfere with the SM Drell–Yan production background. Nevertheless, no such resonances have been discovered so far.

In so-called universal extra-dimension (UED) scenarios, all particles have states that can go into the bulk. If this scenario is correct, a completely new particle spectrum of partners of the SM particles should show up at the LHC at high masses. Although this looks very much like what would be expected from supersymmetry, where all known SM particles have partners, the Kaluza–Klein partners would have exactly the same spin as their SM partners, whereas supersymmetry transforms bosons into fermions and vice versa. Alas, no new particles either for Kaluza–Klein partners or supersymmetry candidates have been observed, pushing the lower mass limits beyond 1 TeV for certain particle types.

Final hope

Collider data so far have not yet given us any sign of the existence of extra dimensions, or for that matter a sign that gravity is becoming strong at the TeV scale. It is possible that, even if they exist, the extra dimensions could be as small as predicted by string theory, in which case they would not be able to solve the hierarchy problem. The idea is still very much alive, however, and searches will continue as more data are recorded at the LHC.

Even excellent and attractive ideas always need confirmation from data, and inevitably the initial high enthusiasm for extra-dimension theories may have waned somewhat in recent years. Although such confirmation could come from the next generation of colliders, such as possible higher-energy machines, there is unfortunately no guarantee. It could be that we have to turn to even more outlandish ideas to progress further.

• Further reading

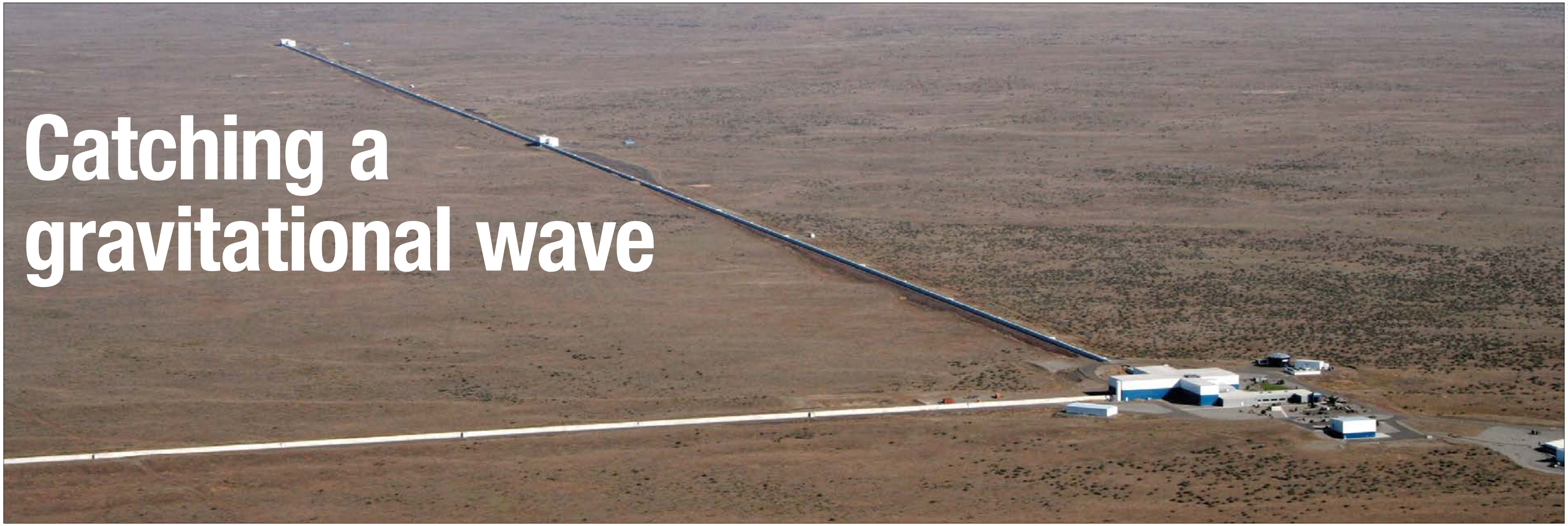
ATLAS results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/ExoticsPublicResults.
CMS results: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsEXO.
I Antoniadis 1990 *Phys. Lett. B* **246** 377.
N Arkani-Hamed *et al.* 1998 *Phys. Lett. B* **429** 263.
S Dimopoulos and G Landsberg 2001 *Phys. Rev. Lett.* **87** 161602.
L Randall and R Sundrum 1999 *Phys. Rev. Lett.* **83** 3370.

Résumé

La dimension supplémentaire du LHC

La physique des particules ignore généralement la gravité, car elle est très faible en comparaison des trois autres forces. Toutefois, les théories mettant en jeu des dimensions supplémentaires de l'espace, développées à la fin des années 1990, prédisent que la gravité n'est pas du tout ce qu'elle semble être, et qu'elle pourrait causer des phénomènes exotiques dans des collisionneurs, comme des trous noirs microscopiques. La recherche de dimensions supplémentaires a été menée dès le début de l'exploitation du LHC, en 2010. Aucun signal positif n'a été observé jusqu'ici, mais les expériences ATLAS et CMS ont déjà éliminé de grandes parties de l'espace de phase à l'échelle du TeV, et les recherches se poursuivront à mesure que davantage de données seront enregistrées au LHC et dans les futures machines.

Albert De Roeck, CERN, and **Greg Landsberg**, Brown University.



Catching a gravitational wave

More than a billion years ago, two black holes of about 36 and 29 solar masses merged to form a black hole of 62 solar masses. The remaining mass was emitted as gravitational waves, which were detected by the aLIGO detectors (shown is the Hanford site) on 14 September 2015.

The LIGO experiment has started its second observation run, with further upgrades in store and several other gravitational-wave observatories planned.

Gravitational waves alternatively compress and stretch space–time as they propagate, exerting tidal forces on all objects in their path. Detectors such as Advanced LIGO (aLIGO) search for this subtle distortion of space–time by measuring the relative separation of mirrors at the ends of long perpendicular arms, which form a simple Michelson interferometer with Fabry–Perot cavities in the arms: a beam splitter directs laser light to mirrors at the ends of the arms and the reflected light is recombined to produce an interference pattern. When a gravitational wave passes through the detector, the strain it exerts changes the relative lengths of the arms and causes the interference pattern to change.

The arms of the aLIGO detectors are each 4 km long to help maximise the measured length change. Even on this scale, however, the induced length changes are tiny: the first detected gravitational waves, from the merger of two black holes, changed the arm length of the aLIGO detectors by just 4×10^{-18} m, which is approximately 200 times smaller than the proton radius. Achieving the fantastically high sensitivity required to detect this event was the culmination of decades of research and development.

Battling noise

The idea of using an interferometer to detect gravitational waves was first concretely proposed in the 1970s and full-scale detectors began to be constructed in the mid-1990s, including GEO600 in Germany, Virgo in Italy and the LIGO project in the US. LIGO consists of detectors at two sites separated by about 3000 km – Hanford (in Washington state) and Livingston in Louisiana – and undertook its first science runs in 2002–2008. Following a major upgrade, the observatory restarted in September 2015 as aLIGO with an initial sensitivity four times greater than its predecessor. Since the detectors measure strain in space–time, the effective increase in volume, or event rate, of aLIGO is a factor 4^3 higher.

A major issue facing aLIGO designers is to isolate the detectors from various noise sources. At a frequency of around 10 Hz, the motion of the Earth's surface or seismic noise is about 10 orders of magnitude larger than required, with the seismic noise falling off at higher frequencies. A powerful solution is to suspend the mirrors as pendulums: a pendulum acts as a low-pass filter, providing significant reductions in motion at frequencies above the pendulum frequency. In aLIGO, a chain of four suspended masses is used to provide a factor 10^7 reduction in seismic motion. In addition, the entire suspension is attached to an advanced seismic isolation system using a variety of active and passive techniques, which further isolate noise by a factor 1000. At 10 Hz, and in the absence of other noise sources, these systems could already increase the sensitivity of the detectors to roughly 10^{-19} m/√(Hz).

A factor-two improvement over the aLIGO design sensitivity could be achieved.

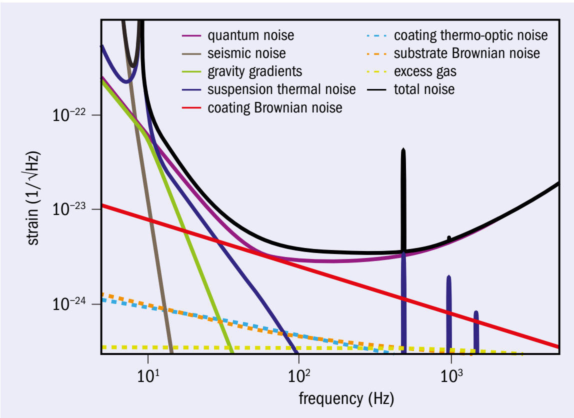
At even lower frequencies (10 μHz), the daily tides stretch and shrink the Earth by the order of 0.4 mm over 4 km.

Another source of low-frequency noise arises from moving mass interacting with the detector mirrors via the Newtonian inverse square law. The dominant source of this noise is from surface seismic waves, which can produce density fluctuations of the Earth's surface close to the interferometer mirrors and result in a fluctuating gravitational force on them. While methods of monitoring and subtracting this noise are being investigated, the performance of Earth-based detectors is likely to always be limited at frequencies below 1 Hz by this noise source.

Thermal noise associated with the thermal energy of the mirrors and their suspensions can also cause the mirrors to move, providing a significant noise source at low-to-mid-range frequencies. The magnitude of thermal noise is related to the mechanical loss of the materials: similar to a high-quality wine glass, a material with a low loss will ring for a long time with a pure note because most of the thermal motion is confined to frequencies close to the resonance. For this reason, aLIGO uses fibres fabricated from fused silica – a type of very pure glass with very low mechanical loss – for the final stage of the mirror suspension. Pioneered in the GEO600 detector near Hanover in Germany, the use of silica fibres in place of the steel wires used in the initial LIGO detectors significantly reduces thermal noise from suspension.

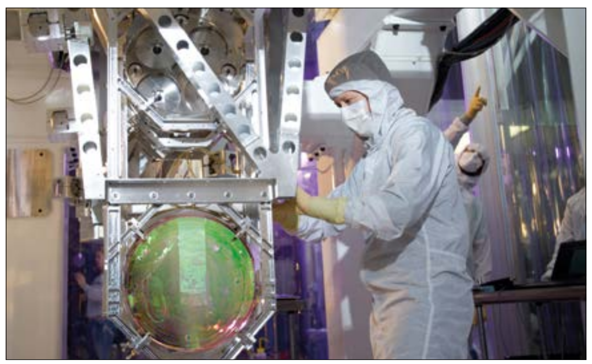
Low-loss fused silica is also used for the 40 kg interferometer mirrors, which use multi-layered optical coatings to achieve the high reflectivity required. For aLIGO, a new optical coating was ▷

LIGO Lab



The design sensitivity of aLIGO, showing the dominant noise sources.

LIGO Lab



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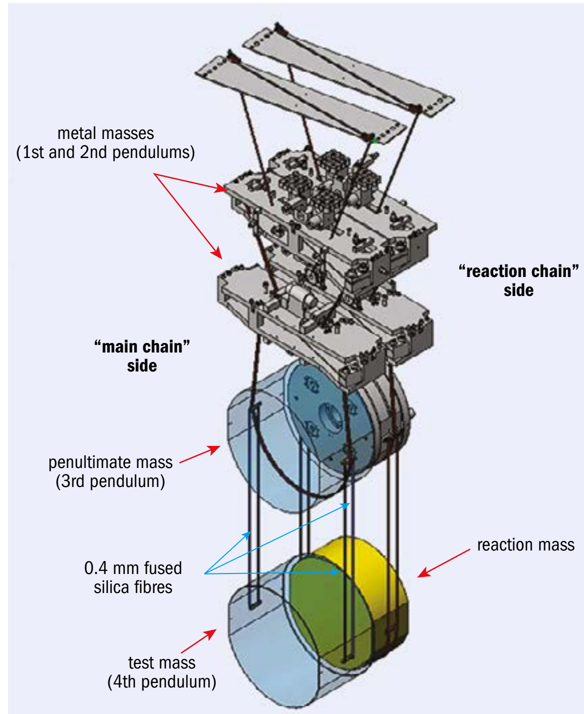


Left and above: aLIGO uses a chain of four suspended masses to provide a factor 10^7 reduction in seismic motion. To achieve this level of shielding, each of aLIGO's 40 kg test masses is suspended within a 360 kg quadruple pendulum system.

developed comprising a stack of alternating layers of silica and titania-doped "tantala", reducing the coating thermal noise by about 20%. However, at the aLIGO design sensitivity (which is roughly 10 times higher than the initial aLIGO set-up) thermal noise will be the limiting noise source at frequencies of around 60 Hz – close to the frequency at which the detectors are most sensitive.

aLIGO also has much reduced quantum noise compared with the original LIGO. This noise source has two components: radiation-pressure noise and shot noise. The former results from fluctuations in the number of photons hitting the detector mirrors, which is more significant at lower frequencies, and has been reduced by using mirrors four times heavier than the initial LIGO mirrors. Photon shot noise, resulting from statistical fluctuations in the number of photons at the output of the detector, limits sensitivity at higher frequencies. Since shot noise is inversely proportional to the square root of the power, it can be reduced by using higher laser power. In the first observing run of aLIGO, 100 kW of laser power was circulating in the detector arms, with the potential to increase it to up to 750 kW in future runs. Optical cavities are also used to store light in the arms and build up laser power.

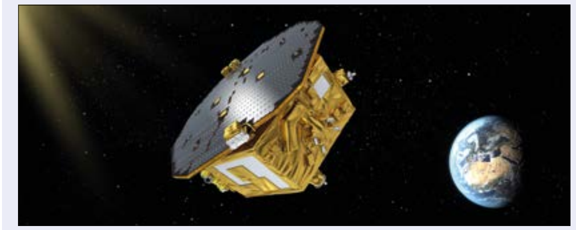
In addition to reductions in these fundamental noise sources, many other technological improvements were required to reduce more technical noise sources. Improvements over the initial LIGO detector included a thermal compensation system to reduce thermal lensing effects in the optics, reduced electronic noise in control circuits and finer polishing of the mirror substrates to reduce the amount of scattered light in the detectors.

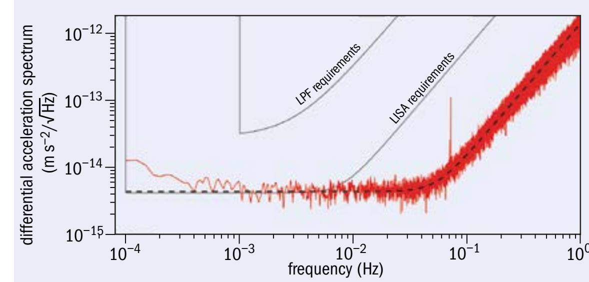
Upgrades on the ground

Having detected their first gravitational wave almost as soon as they switched on in September 2015, followed by a further event a few months later, the aLIGO detectors began their second observation run on 30 November. Dubbed "O2", it is scheduled to last for six months. More observation runs are envisaged, with more upgrades in sensitivity taking place between them.

The next major upgrade, expected in around 2018, will see the injection of "squeezed light" to further reduce quantum noise. However, to gain the maximum sensitivity improvement from squeezing, a reduction in coating thermal noise is also likely to be required. With these and other relatively short-term upgrades, it is expected that a factor-two improvement over the aLIGO design sensitivity could be achieved. This would allow events such as the first detection to be observed with a signal-to-noise ratio almost 10 times better than the initial result. Further improvements in sensitivity will almost certainly require more extensive upgrades or new facilities, possibly involving longer detectors or cryogenic cooling of the mirrors.

aLIGO is expected to soon be joined in observing runs by





*Initial results from LISA Pathfinder show that the technology is close to meeting requirements for a full gravitational-wave detector in space (*Phys. Rev. Lett. **116** 231101*). At frequencies above 60 mHz, its precision is only limited by the sensing noise of the laser measurement system, while at lower frequencies of 1–60 mHz, control over the test masses is limited by the residual (and decreasing) small number of gas molecules bouncing off them. Frequencies below 1 mHz exhibit noise as a result of keeping the craft's solar panels pointing towards the Sun, most of which is removable.*

Advanced Virgo, giving a network of three geographically separated detectors and thus improving our ability to locate the position of gravitational-wave sources on the sky. Discussions are also under way for an aLIGO site in India. In Japan, the KAGRA detector is under construction: this detector will use cryogenic cooling to reduce thermal noise and is located underground to reduce seismic and gravity gradient effects. When complete, KAGRA is expected to have similar sensitivity to aLIGO.

Longer term, in Europe a detector known as the Einstein Telescope (ET) has been proposed to provide a factor 10 more sensitivity than aLIGO. ET would not only have arms measuring 10 km long but would take a new approach to noise reduction using two very different detectors: a high-power room-temperature interferometer optimised for sensitivity at high frequencies, where shot noise limits performance, and a low-power cryogenic interferometer optimised for sensitivity at low frequencies (where performance is limited by thermal noise). ET would require significant changes in detector technology and also be constructed underground to reduce the effect of seismic noise and gravity-gradient noise on low-frequency sensitivity.

The final frontier

Obtaining significantly improved sensitivity at lower frequencies is difficult on Earth because they are swamped by local mass motion. Gaining sensitivity at very low frequencies, which is where we must look for signals from massive black-hole collisions and other sources that will provide exquisite science results, is only likely to be achieved in space. This concept has been on the table since the 1970s and has evolved into the Laser Interferometer Space Antenna (LISA) project, which is led by the European Space Agency (ESA) with contributions from 14 European countries and the US.

A survey mission called LISA Pathfinder was launched on 3 December 2015 from French Guiana. It is currently located 1.5 million km away at the first Earth–Sun Lagrange point, and will take data until the end of May 2017. The aim of LISA Pathfinder was to demonstrate technologies for a space-borne gravitational-wave detector based on the same measurement philosophy as that used by ground-based detectors. The mission has clearly demonstrated that we can place test masses (gold–platinum cubes with 46 mm sides separated by 38 cm) into free fall, such that the only varying force acting on them is gravity. It has also validated a host of complementary techniques, including: operating a drag-free spacecraft using cold gas thrusters; electrostatic control of free-floating test masses; short-arm interferometry and test-mass charge control. When combined, these novel features allow differential accelerometry at the 10^{-15} g level, which is the sensitivity needed for a space-borne gravitational-wave detector. Indeed, if Pathfinder test-mass technology were used to build a full-scale LISA detector, it would recover almost all of the science originally anticipated for LISA without any further improvements.

The success of Pathfinder, coming hot on the heels of the detection of gravitational waves, is a major boost for the international gravitational-wave community. It comes at an exceptional time for the field, with ESA currently inviting proposals for the third of its Cosmic Vision "large missions" programme. Developments are now needed to move from LISA Pathfinder to LISA proper, but these are now well understood and technology development programmes are planned and under way. The timeline for this mission leads to a launch in the early 2030s and the success of Pathfinder means we can look forward with excitement to the fantastic science that will result.

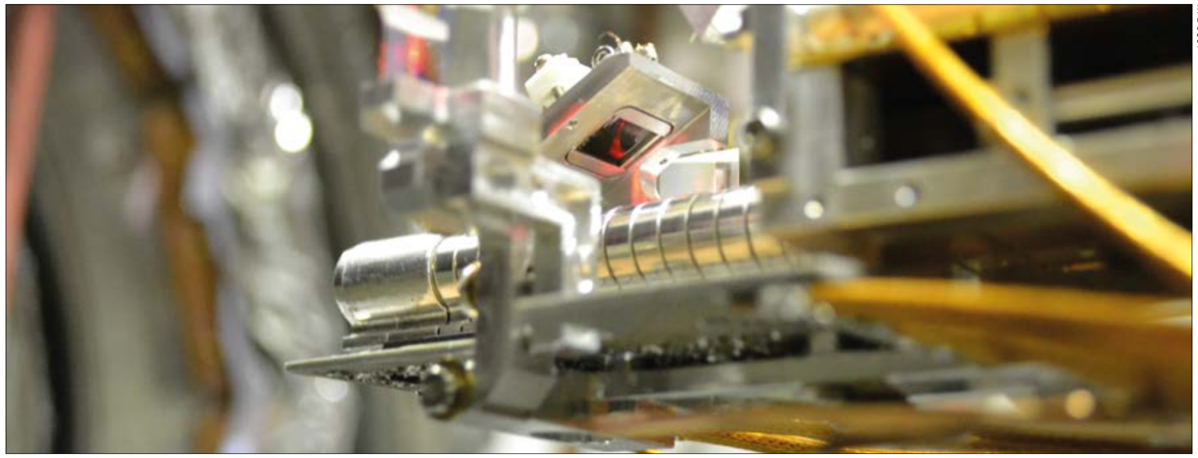
Résumé

Comment attraper une onde gravitationnelle

L'expérience aLIGO, qui a réalisé la première détection d'ondes gravitationnelles l'année passée, a entamé sa deuxième campagne d'observation. Des améliorations sont prévues pour le futur, et d'autres observatoires terrestres sont également en projet dans le monde. À cela s'ajoute le succès de la mission LISA, de bon augure pour un futur détecteur d'ondes gravitationnelles dans l'espace. La sensibilité extraordinairement élevée qu'il a fallu atteindre pour détecter les infimes déplacements causés par les ondes gravitationnelles (plus de 200 fois plus petits que le rayon d'un proton) a été l'aboutissement de dizaines d'années de recherche et de développement dans la réduction du bruit et l'amélioration de l'optique.

Iain Martin, **Christian Killow** and **Giles Hammond**, Institute for Gravitational Research, University of Glasgow, UK.

Does antimatter fall up?



M Doser

The AEgIS flight tube from which atoms of antihydrogen will be fired to test if antimatter falls under gravity the same way matter does.

Three CERN experiments are preparing to measure the gravitational behaviour of antihydrogen.

Measuring the effect of gravity on antimatter is a long-standing story. It started with a project at Stanford in 1968 that attempted to measure the free fall of positrons, but a trial experiment with electrons showed that environmental effects swamped the effect of gravity and the final experiment was not performed. In the 1990s, the PS200 experiment at CERN's LEAR facility attempted the same feat with antiprotons, but the project ended with the termination of LEAR before any robust measurement could be made. To date, indirect measurements have set limits on the deviation from standard gravity at the level of 10^{-6}.

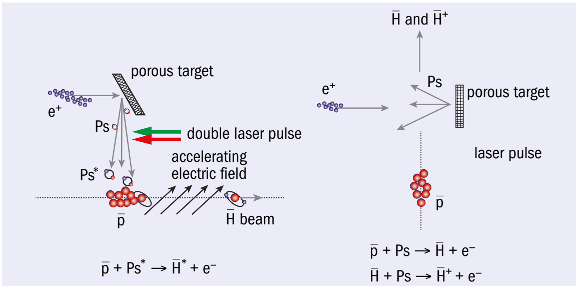
Thanks to advances in cooling and trapping technology, and the construction of a new synchrotron at CERN called ELENA, three collaborations are now preparing experiments at CERN's Antiproton Decelerator (AD) facility to measure the behaviour of antihydrogen (a positron orbiting an antiproton) under gravity. The ALPHA experiment has already analysed its data on the trapping of antihydrogen atoms to set upper limits on differences in the free-fall rate of matter and antimatter, and is now designing a new set-up. AEgIS is currently putting its apparatus through its paces, while GBAR will start installation in 2017.

Given that most of the mass of antinuclei comes from massless gluons, it is extremely unlikely that antimatter experiences an opposite gravitational force to matter and therefore "falls" up. Nevertheless, precise measurements of the free fall of antiatoms could reveal subtle differences that point to a crack in our current understanding.

Violating equivalence

To date, most efforts at the AD have focused on looking for CPT violation by comparing the spectroscopy of antihydrogen to its well-known matter counterpart, hydrogen. Now we are in a position to test Einstein's equivalence principle with antimatter by directly measuring the free fall of antiatoms on Earth. The equivalence principle is the keystone of general relativity and states that all particles with the same initial position and velocity should follow the same trajectories in a given gravitational field. On the other hand, quantum theories such as supersymmetry or superstrings do not necessarily lead to an equivalent force on matter and antimatter (technically, the terms related to gravity in the Lagrangians are not bound to be the same for matter and antimatter). This is also the case when Lorentz-symmetry violating terms are included in the Standard Model of particle physics.

Any difference seen in the behaviour of antimatter and matter with respect to gravity would mean that the equivalence principle is not perfect and force us to understand quantum effects in the gravitational arena. Experiments performed with free-falling matter atoms have so far found no difference to that of macroscopic objects. Such tests have set limits at the level of one part in 10^{13}, but have not yet been able to test the equivalence principle at the level where supersymmetric or other quantum effects would appear. Since the amplitude of these effects could be different for antimatter, the AD experiments might have a better opportunity ▷



The production of antihydrogen in AEgIS (left) and GBAR (right) is performed via the interaction of antiprotons with positronium (Ps). In AEgIS, a plasma of antiprotons at rest in a Penning trap is showered with excited positronium atoms, producing excited antihydrogen atoms that are accelerated to form a beam. In GBAR, a dense positronium cloud is traversed by a beam of antiprotons to produce antihydrogen atoms and ions.

to test such quantum effects. Any difference would probably not change anything in the observable universe, but it would point to the necessity of having a quantum theory of gravity.

AEgIS plans to measure the vertical deviation of a pulsed horizontal beam of cold antihydrogen atoms, generated by bringing laser-excited positronium moving at several km/s into contact with cold antiprotons, travelling with a velocity of a few hundred m/s. The resulting highly excited antihydrogen atoms are then accelerated horizontally and a moiré deflectometer used to measure the vertical deviation, which is expected to be a few microns given the approximately 1 m-long flight tube of AEgIS. Reaching the lowest possible antiproton temperature minimises the divergence of the beam and therefore maximises the flux of antihydrogen atoms that end up on the downstream detector.

In GBAR, which takes advantage of advances in ion-cooling techniques, antihydrogen ions ($\bar{H}^+$) are produced with velocities of the order of 0.5 m/s. In a second step, the anti-ions will be stripped of one positron to give an ultra-slow neutral antiatom that is allowed to enter free fall. The time of free fall over a height of 20 cm is as long as 200 ms, which is easily measurable. These numbers correspond to the gravitational acceleration known for matter atoms, and the expected sensitivity to small deviations is 1% in the first phase of operation.

The ALPHA-g experiment will release antihydrogen atoms from a vertical magnetic atom trap and record their positions when they annihilate on the walls of the experiment. In a proof-of-principle experiment using the original ALPHA atom trap, the acceleration of antihydrogen atoms by gravity was constrained to lie anywhere between –110 g and 65 g. ALPHA-g improves on this original demonstration by orienting the trap vertically, thereby enabling better control of the antiatom release and improving sensitivity to the vertical annihilation position. In the new arrangement, antihydrogen gravitation can be measured at the 10% level, which would already settle the question of whether antimatter falls up or down, but improvements in cooling techniques will allow measurements at the 1% level. A long-term aspiration of the ALPHA-g project is to use techniques that cause antihydrogen atoms to interact with a beam of photons, promising a sensitivity in the 10^{-6} range.

Cooling matter

In the case of AEgIS, the deflectometer principle that underpins the measurement has already been demonstrated with matter atoms and with antiprotons, while the time-of-flight measurement is straightforward in the case of GBAR. The difficulty for the experiments lies in preparing sufficient numbers of antiatoms at the required low velocities. ALPHA has already demonstrated trapping of several hundred antiatoms at a temperature below 0.5 K, corresponding to random velocities of the order 10 m/s. The antiatoms are formed by letting the antiprotons traverse a plasma of positrons located within the same Penning trap.

A different scheme is used in AEgIS and GBAR to form and possibly cool the antiatoms and anti-ions. In AEgIS, antiprotons are cooled within a Penning trap and receive a shower of positronium atoms (bound e^+e^- pairs) to form the antiatoms. These are then slightly accelerated by electric fields (which act on the atoms' induced electric-dipole moments) so that they exit the charged particle trap axially in the form of a neutral beam. For GBAR, the antiproton beam traverses a cloud of positronium to form the anti-ions, which are then cooled to a few μK by forcing them to interact with laser-cooled beryllium ions.

In this race towards low energies, ALPHA and AEgIS are located on the beam at the AD, which delivers 5 MeV antiprotons. While AEgIS is already commissioning its dedicated gravity experiment, ALPHA will move from spectroscopy to gravity in the coming months. GBAR, which will be the first experiment to make use of the beam delivered by ELENA, is now beginning installation and expects first attempts at anti-ion production in 2018. ELENA will decelerate antiprotons coming from the AD from 5 MeV to just 100 keV, making it more efficient to trap and store antimatter. Following commissioning first with protons and then with hydrogen ions, ELENA should receive its first antiprotons in the middle of 2017 (*CERN Courier* December 2016 p16). Along with precision tests of CPT invariance, this facility will help to ensure that any differences in the gravitational antics of antimatter are not missed.

Résumé

L'antimatière tombe-t-elle vers le haut ?

Le principe d'équivalence est au centre de la théorie de la relativité générale ; selon ce principe, testé avec une précision toujours plus fine au cours des dernières décennies, toute la matière tombe à la même vitesse. Trois collaborations (ALPHA, AEgIS et GBAR) préparent actuellement des expériences auprès du Décélérateur d'antiprotons du CERN afin de vérifier si ce principe est valable également pour l'antimatière, en mesurant la manière dont les atomes d'antihydrogène tombent sous l'effet de la gravité. Toute différence par rapport à des atomes d'hydrogène normal suggérerait que des effets quantiques entrent en ligne de compte ; nous aurions alors besoin d'une théorie quantique de la gravité.

Patrice Perez, CEA-Irfu Saclay, **Michael Doser**, CERN, and **William Bertsche**, University of Manchester.

The many lives of supergravity

Forty years after theorists married general relativity with supersymmetry, supergravity continues to carve out new directions in the search for a unified theory.

The early 1970s was a pivotal period in the history of particle physics. Following the discovery of asymptotic freedom and the Brout–Englert–Higgs mechanism a few years earlier, it was the time when the Standard Model (SM) of electroweak and strong interactions came into being. After decades of empirical verification, the theory received a final spectacular confirmation with the discovery of the Higgs boson at CERN in 2012, and its formulation has also been recognised by Nobel prizes awarded to theoretical physics in 1979, 1999, 2004 and 2013.

It was clear from the start, however, that the SM, a spontaneously broken gauge theory, had two major shortcomings. First, it is not a truly unified theory because the gluons of the strong (colour) force and the photons of electromagnetism do not emerge from a common symmetry. Second, it leaves aside gravity, the other fundamental force of nature, which is based on the gauge principle of general co-ordinate transformations and is described by general relativity (GR).

In the early 1970s, grand unified theories (GUTs), based on larger gauge symmetries that include the SM's "SU(3) × SU(2) × U(1)" structure, did unify colour and charge – thereby uniting the strong and electroweak interactions. However, they relied on a huge new energy scale (~10^{16} GeV), just a few orders of magnitude below the Planck scale of gravity (~10^{19} GeV) and far above the electroweak Fermi scale (~10^{2} GeV), and on new particles carrying both colour and electroweak charges. As a result, GUTs made the stunning prediction that the proton might decay at detectable rates, which was eventually excluded by underground experiments, and their two widely separated cut-off scales introduced a "hierarchy problem" that called for some kind of stabilisation mechanism.

A possible solution came from a parallel but unrelated development. In 1973, Julius Wess and Bruno Zumino unveiled a new symmetry of 4D quantum field theory: supersymmetry, which interchanges bosons and fermions and, as would be better appreciated later, can also conspire to stabilise scale hierarchies. Supersymmetry was inspired by "dual resonance models", an early version of string theory pioneered by Gabriele Veneziano and extended by André Neveu, Pierre Ramond and John Schwarz. Earlier work done in France by Jean-Loup Gervais and Benji Sakita, and in the Soviet Union by Yuri Golfand and Evgeny Likhtman, and by Dmitry Volkov and Vladimir Akulov, had anticipated some of supersymmetry's salient features.

An exact supersymmetry would require the existence of ▷

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Participants of the first workshop on supergravity, held at Stony Brook in September 1979. (From P Van Nieuwenhuizen and D Freedman ed 1979 Supergravity. Proceedings, Workshop At Stony Brook, 27–29 September 1979 *(North-Holland).)*

superpartners in the SM, but it would also imply mass degeneracies between the known particles and their superpartners. This option has been ruled out over the years by several experiments at CERN, Fermilab and elsewhere, and therefore supersymmetry can be at best broken, with superpartner masses that seem to lie beyond the TeV energy region currently explored at the LHC. Moreover, a spontaneous breaking of supersymmetry would imply the existence of additional massless ("Goldstone") fermions.

Supergravity, the supersymmetric extension of GR, came to the rescue in this respect. It predicted the existence of a new particle of spin 3/2 called the gravitino that would receive a mass in the broken phase. In this fashion, one or more gravitinos could be potentially very heavy, while the additional massless fermions would be "eaten" – much as it occurs for part of the Higgs doublet in the SM.

Seeking unification

Supergravity, especially when formulated in higher dimensions, was the first concrete realisation of Einstein's dream of a unified field theory (see diagram opposite). Although the unification of gravity with other forces was the central theme for Einstein during the last part of his life, the beautiful equations of GR were for him a source of frustration. For 30 years he was disturbed by what he considered a deep flaw: one side of the equations contained the curvature of space–time, which he regarded as "marble", while the other contained the matter energy, which he compared to "wood". In retrospect, Einstein wanted to turn "wood" into "marble", but after special and general relativity he failed in this third great endeavour.

GR has, however, proved to be an inestimable source of deep insights for unification. A close scrutiny of general co-ordinate transformations led Theodor Kaluza and Oskar Klein (KK), in the 1920s and 1930s, to link electromagnetism and its Maxwell potentials to internal circle rotations, what we now call a U(1) gauge symmetry. In retrospect, more general rotations could also have led to the Yang–Mills theory, which is a pillar of the SM. According to KK, Maxwell's theory could be a mere byproduct of gravity, provided the universe contains one microscopic extra dimension beyond time and the three observable spatial ones. In this 5D picture, the photon arises from a portion of the metric tensor – the "marble" in GR – with one "leg" along space–time and the other along the extra dimensions.

Supergravity follows in this tradition: the gravitino is the gauge field of supersymmetry, just like the photon is the gauge field of internal circle rotations. If one or more local supersymmetries (whose number will be denoted by N) accompany general co-ordinate transformations, they grant the consistency of gravitino interactions. In a subclass of "pure" supergravity models, supersymmetry also allows one to connect "marble" and "wood" and therefore goes well beyond the KK mechanism, which does not link Bose and Fermi fields. Curiously, while GR can be formulated in any number of dimensions, seven additional spatial dimensions, at most, are allowed in supergravity due to intricacies of the Fermi–Bose matching.

Last year marked the 40th anniversary of the discovery of supergravity. At its heart lie some of the most beautiful ideas in theoretical physics, and therefore over the years this theory has managed to display different facets or has lived different parallel lives.

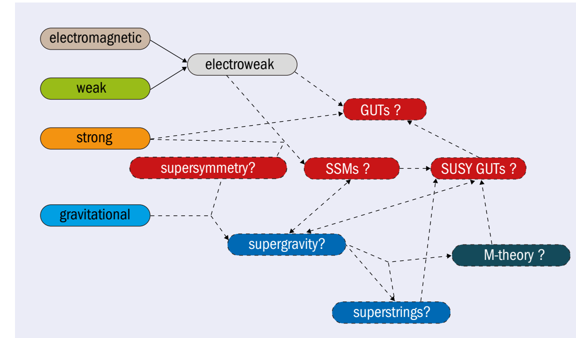
Construction begins

The first instance of supergravity, containing a single gravitino (N = 1), was built in the spring of 1976 by Daniel Freedman, Peter van Nieuwenhuizen and one of us (SF). Shortly afterwards, the result was recovered by Stanley Deser and Bruno Zumino, in a simpler and elegant way that extended the first-order ("Palatini") formalism of GR. Further simplifications emerged once the significance of local supersymmetry was better appreciated. Meanwhile, the "spinning string" – the descendant of dual resonance models that we have already met – was connected to space–time supersymmetry via the so-called Gliozzi–Scherk–Olive (GSO) projection, which reflects a subtle interplay between spin-statistics and strings in space–time. The low-energy spectrum of the resulting models pointed to previously unknown 10D versions of supergravity, which would include the counterparts of several gravitinos, and also to a 4D Yang–Mills theory that is invariant under four distinct supersymmetries (N = 4). A first extended (N = 2) version of 4D supergravity involving two gravitinos came to light shortly after.

When SF visited Caltech in the autumn of 1976, he became aware that Murray Gell-Mann had already worked out many consequences of supersymmetry. In particular, Gell-Mann had realised that the largest "pure" 4D supergravity theory, in which all forces would be connected to the conventional graviton, would include eight gravitinos. Moreover, this N = 8 theory could also allow an SO(8) gauge symmetry, the rotation group in eight dimensions (see table opposite). Although SO(8) would not suffice to accommodate the SU(3) × SU(2) × U(1) symmetry group of the SM, the full interplay between supergravity and supersymmetric matter soon found a proper setting in string theory, as we shall see.

Attaining a deeper theoretical understanding of broken supersymmetry in supergravity appears crucial today.

The following years, 1977 and 1978, were most productive and drew many people into the field. Important developments followed readily, including the discovery of reformulations where N = 1 4D supersymmetry is manifest. This technical step was vital to simplify more general constructions involving matter, since only this minimal form of supersymmetry is directly compatible with the chiral (parity-violating) interactions of the SM. Indeed, by the early 1980s, theorists managed to construct complete couplings of supergravity to matter for N = 1 and even for N = 2.



Current attempts to unify the fundamental interactions.

N	helicity content
1	$[(2), (\frac{3}{2})]$
2	$[(2), 2(\frac{3}{2}), (1)]$
3	$[(2), 3(\frac{3}{2}), 3(1), (\frac{1}{2})]$
4	$[(2), 4(\frac{3}{2}), 6(1), 4(\frac{1}{2}), 2(0)]$
5	$[(2), 5(\frac{3}{2}), 10(1), 11(\frac{1}{2}), 10(0)]$
6	$[(2), 6(\frac{3}{2}), 16(1), 26(\frac{1}{2}), 30(0)]$
8	$[(2), 8(\frac{3}{2}), 28(1), 56(\frac{1}{2}), 70(0)]$

The particles of "pure" supergravity theories in four dimensions, which coincide for N = 7, 8. Here (0) indicates a scalar, (1/2) a Majorana fermion, (1) a vector, (3/2) a gravitino and (2) the graviton. The numbers not within brackets indicate particle multiplicities.

The maximal, pure N = 8 4D supergravity was also derived, via a circle KK reduction, in 1978 by Eugene Cremmer and Bernard Julia. This followed their remarkable construction, with Joel Scherk, of the unique 11D form of supergravity, which displayed a particularly simple structure where a single gravitino accounts for eight 4D ones. In contrast, the N = 8 model is a theory of unprecedented complication. It was built after an inspired guess about the interactions of its 70 scalar fields (see table) and a judicious use of generalised dualities, which extend the manifest symmetry of the Maxwell equations under the interchange of electric and magnetic fields. The N = 8 supergravity with SO(8) gauge symmetry foreseen by Gell-Mann was then constructed by Bernard de Wit and Hermann Nicolai. It revealed a negative vacuum energy, and thus an anti-de Sitter (AdS) vacuum, and was later connected to 11D supergravity via a sphere KK reduction. Regarding the ultraviolet behaviour of supergravity theories, which was vigorously investigated soon after the original discovery, no divergences were found, at one loop, in the "pure" models, and many more unexpected cancellations of divergences have since come to light. The case of N = 8 supergravity is still unsettled, and some authors still expect that this maximal theory be finite to all orders.

The string revolution

Following the discovery of supergravity, the GSO projection opened the way to connect "spinning strings", or string theory as they came to be known collectively, to supersymmetry. Although the link between strings and gravity had been foreseen by Scherk and Schwarz, and independently by Tamiaki Yoneya, it was only a decade later, in 1984, that widespread activity in this direction began. This followed Schwarz and Michael Green's unexpected discovery that gauge and gravitational anomalies cancel in all versions of 10D supersymmetric string theory. Anomalies – quantum violations of classical symmetries – are very troublesome when they concern gauge interactions, and their cancellation is a fundamental consistency condition that is automatically granted in the SM by its known particle content.

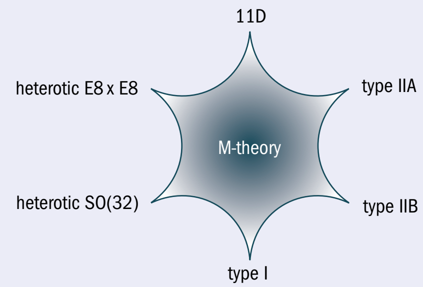
Anomaly cancellation left just five possible versions of string theory in 10 dimensions: two "heterotic" theories of closed strings, where the SU(3) × SU(2) × U(1) symmetry of the SM is extended to the larger groups SO(32) or E8 × E8; an SO(32) "type-I" theory involving both open and closed strings, akin to segments and circles, respectively; and two other very different and naively less interesting theories called IIA and IIB. At low energies, supergravity emerges from all of these theories in its different 10D realisations, opening up unprecedented avenues for linking 10D strings to the interactions of particle physics. Moreover, the extended nature of strings made all of these enticing scenarios free of the ultraviolet problems of gravity.

Following this 1984 "first superstring revolution", one might well say that supergravity officially started a second life as a low-energy manifestation of string theory. Anomaly cancellation had somehow connected Einstein's "marble" and "wood" in a miraculous way dictated by quantum consistency, and definite KK scenarios soon emerged that could recover from string theory both the SM gauge group and its chiral, parity-violating interactions. Remarkably, this construction relied on a specific class of 6D internal manifolds called Calabi–Yau spaces that had been widely studied in mathematics, thereby merging 4D supergravity with algebraic geometry. Calabi–Yau spaces led naturally, in four dimensions, to a GUT gauge group E6, which was known to connect to the SM with right-handed neutrinos, also providing realisations of the see-saw mechanism.

A third life

The early 1990s were marked by many investigations of black-hole-like solutions in supergravity, which soon unveiled new aspects of string theory. Just like the Maxwell field is related to point particles, some of the fields in 10D supergravity are related to extended objects, generically dubbed "p-branes" (p = 0 for particles, p = 1 for strings, p = 2 for membranes, and so on). String theory, being based at low energies on supergravity, therefore could not be merely a theory of strings. Rather, as had been strongly advocated over the years by ▷

M-theory revealed a unique, if elusive, underlying principle connecting the known types of string theory, since the six theories at the edges of the diagram are all equivalent. The sides of the diagram reflect different duality links. Some were inspired by supergravity, while the others had already surfaced in the late 1980s. They are beyond its reach but find their rationale in the "T-duality" link between strings in large and small KK volumes, and in the "orientifold" link proposed by one of us (AS).



Michael Duff and Paul Townsend, we face a far more complicated soup of strings and more general p-branes. A novel ingredient was a special class of p-branes, the D-branes, whose role was clarified by Joseph Polchinski, but the electric-magnetic dualities of the low-energy supergravity remained the key tool to analyse the system. The end result, in the mid 1990s, was the awesome, if still somewhat vague, unified picture called M-theory, which was largely due to Edward Witten and marked the "second superstring revolution". Twenty years after its inception, supergravity thus started a third parallel life, as a deep probe into the mysteries of string theory.

The late 1990s witnessed the emergence of a new duality. The AdS/CFT correspondence, pioneered by Juan Maldacena, is a profound equivalence between supergravity and strings in AdS and conformal field theory (CFT) on its boundary, which connects theories living in different dimensions. This "third superstring revolution" brought to the forefront the AdS versions of supergravity, which thus started a new life as a unique tool to probe quantum field theory in unusual regimes. The last two decades have witnessed many applications of AdS/CFT outside of its original realm. These have touched upon fluid dynamics, quark–gluon plasma, and more recently condensed-matter physics, providing a number of useful insights on strongly coupled matter systems. Perhaps more unexpectedly, AdS/CFT duality has stimulated work related to scattering amplitudes, which may also shed light on the old issue of the ultraviolet behaviour of supergravity. The reverse programme of gaining information about gravity from gauge dynamics has proved harder, and it is difficult to foresee where the next insights will come from. Above all, there is a pressing need to highlight the geometrical principles and the deep symmetries underlying string theory, which have proved elusive over the years.

The interplay between particle physics and cosmology is a natural arena to explore consequences of supergravity. Recent experiments probing the cosmic microwave background, and in particular the results of the Planck mission, lend support to inflationary models of the early universe. An elusive particle, the inflaton, could have driven this primordial acceleration, and although our current grasp of string theory does not allow a detailed analysis of the problem, supergravity can provide fundamental clues on this and the subsequent particle-physics epochs.

Supersymmetry was inevitably broken in a de Sitter-like inflationary phase, where superpartners of the inflaton tend to experience instabilities. The novel ingredient that appears to get around these problems is non-linear supersymmetry, whose foundations lie in the prescient 1973 work of Volkov and Akulov. Non-linear supersymmetry arises when superpartners are exceedingly massive, and seems to play an intriguing role in string theory. The current lack of signals for supersymmetry at the LHC makes one wonder whether it might also hold a prominent place in an eventual picture of particle physics. This resonates with the idea of "split supersymmetry", which allows for large mass splittings among superpartners and can be accommodated in supergravity at the price of reconsidering hierarchy issues.

In conclusion, attaining a deeper theoretical understanding of broken supersymmetry in supergravity appears crucial today. In breaking supersymmetry, one is confronted with important conceptual challenges: the resulting vacua are deeply affected by quantum fluctuations, and this reverberates on old conundrums related to dark energy and the cosmological constant. There are even signs that this type of investigation could shed light on the backbone of string theory, and supergravity may also have something to say about dark matter, which might be accounted for by gravitinos or other light superpartners. We are confident that supergravity will lead us farther once more.

• Further reading

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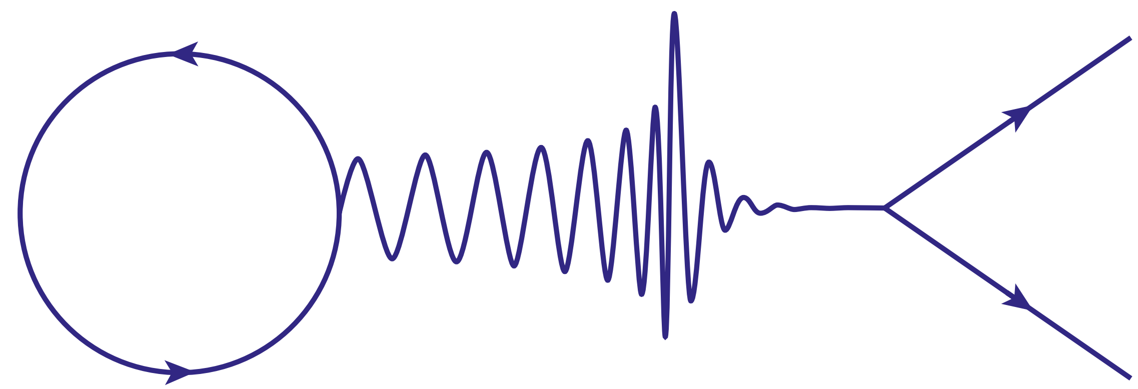
Résumé
Les multiples vies de la supergravité

Quarante ans après le mariage célébré par les théoriciens entre la relativité générale et la supersymétrie, la supergravité continue d'ouvrir de nouvelles voies dans la quête d'une théorie unifiée. La supergravité, qui repose sur quelques-unes des plus belles idées de la physique théorique, a dévoilé au fil des années plusieurs de ses facettes. En particulier, la supergravité s'est révélée être une manifestation à faible énergie de la théorie des cordes, et un outil essentiel pour l'étude des objets étendus appelés branes. S'il n'y a toujours pas de preuve de l'existence de la supersymétrie, la supergravité se porte toujours à merveille.

Sergio Ferrara, CERN and INFN Frascati, and **Augusto Sagnotti**, Scuola Normale Superiore and INFN Pisa.

Linking waves to particles

Gravitational waves do not just tell us about the largest objects in the universe – they may also shed light on searches for dark matter, new light fields and other microscopic phenomena.



Gravitational waves could provide a link between strong gravity (left) and particle physics (right).

Black holes are arguably humankind's most intriguing intellectual construction. Featuring a curvature singularity where space–time "ends" and tidal forces are infinite, black-hole interiors cannot be properly understood without a quantum theory of gravity. They are defined by an event horizon – a surface beyond which nothing escapes to the outside – and an exterior region called a photosphere, which is able to trap light rays. These uncommon properties explain why black holes were basically ignored for half a century, considered little more than a bizarre mathematical solution of Einstein's equations but one without counterpart in nature.

LIGO's discovery of gravitational waves provides the strongest evidence to date for the existence of black holes, but these tiny distortions of space–time have much more to tell us. Gravitational waves offer a unique way to test the basic tenets of general relativity, some of which have been taken for granted without observations. Are black holes the simplest possible macroscopic objects? Do event horizons and black holes really exist, or is their formation halted by some as-yet unknown mechanism? In addition, gravitational waves can tell us if gravitons are massless and if extra-light degrees of freedom fill the universe, as predicted in the 1970s by Peccei and Quinn in an attempt to explain the smallness of the neutron electric-dipole moment, and more recently by string theory. Ultralight fields affect the evolution of black holes and their gravitational-wave emission in a dramatic way that should be testable with upcoming gravitational-wave observatories.

The existence of black holes

The standard criterion with which to identify a black hole is straightforward: if an object is dark, massive and compact, it's a black hole. But are there other objects which could satisfy the same criteria? Ordinary stars are bright, while neutron stars have at most three solar masses and therefore neither is able to explain observations of very massive dark objects. In recent years, however, unknown physics and quantum effects in particular have been invoked that change the structure of the horizon, replacing it by a hard surface. In this scenario, the exterior region – including the photosphere – would remain unchanged, but black holes would be replaced by very compact, dark stars. These stars could be made of normal matter under extraordinary quantum conditions or of exotic matter such as new scalar particles that may form "boson stars".

Unfortunately, the formation of objects invoking poorly understood quantum effects is difficult to study. The collapse of scalar fields, on the other hand, can theoretically allow boson stars to form, and these may become more compact and massive through mergers. Interestingly, there is mounting evidence that compact objects without horizons but with a photosphere are unstable, ruling out entire classes of alternatives that have been put forward.

Gravitational waves might soon provide a definite answer to such questions. Although current gravitational-wave detections are not proof for the existence of black holes, they are a strong indicator that photospheres exist. Whereas observations of electromagnetic ▷

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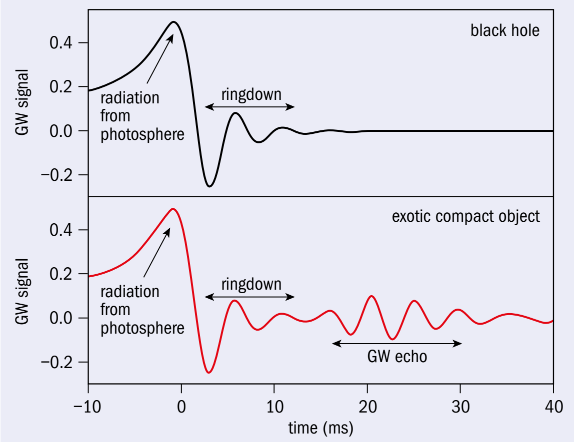

Fig. 1. Typical gravitational-wave signal generated by a small star falling into a massive compact object with (top) and without (bottom) a horizon. In the latter case, "echoes" of gravitational waves appear at late time and provide a smoking gun for putative quantum effects that halt the gravitational collapse.

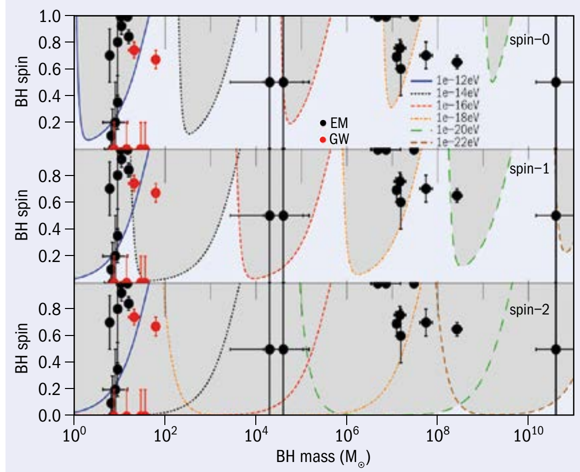

Fig. 2. Exclusion plots in the black-hole mass-spin plane for ultralight scalar (top), vector (middle) and tensor (bottom) fields, showing electromagnetic (black) and gravitational-wave (red) observations. Above each curve (grey), superradiance would spin the black hole down to the threshold, whereas below the curve accretion is dominant and there is no spin-down effect.

processes in the vicinities of black holes only probe the region outside of the photosphere, gravitational waves are sensitive to the entire space–time and are our best probe of strong-field regions.

A typical gravitational-wave signal generated by a small star falling head-on into a massive black hole looks like that in figure 1. As the star crosses the photosphere, a burst of radiation is emitted and a sequence of pulses dubbed "quasinormal ringing" follow, determined by the characteristic modes of the black hole. But if the star falls into a quantum-corrected or exotic compact object with no horizon, part of the burst generated during the crossing of the photosphere reflects back at the object surface. The resulting signal in a detector would thus initially look the same, but be followed by lower amplitude "echoes" trapped between the photosphere and the surface of the object (figure 1, lower panel). These echoes, although tricky to dig out in noisy data, would be a smoking gun for new physics. With increasing sensitivity in detectors such as LIGO and Virgo, observations will be pushing back the object's surface closer to the horizon, perhaps even to the point where we can detect the echo of quantum effects.

Dark questions

Understanding strong-field gravity with gravitational waves can also test the nature of dark matter. Although dark matter may interact very feebly with Standard Model particles, according to Einstein's equivalence principle it must fall just like any other particle. If dark matter is composed of ultralight fields, as recent studies argue, then black holes may serve as excellent dark-matter detectors. You might ask how a monstrous, supermassive black hole could ever be sensitive to ultralight fields. The answer lies in superradiant resonances. When black holes rotate, as most do, they display an interesting effect discovered in the 1970s called superradiance: if one shines a low-frequency lamp on a rotating black hole, the scattered beam is brighter. This happens at the expense of the hole's kinetic energy, causing the spin of the black-hole to decrease.

Not only electromagnetic waves, but also gravitational waves and any other bosonic field can be amplified by a rotating black hole. In addition, if the field is massive, low-energy fluctuations are trapped near the horizon and are forced to interact repeatedly with the black hole, producing an instability. This instability extracts rotational energy and transfers it to the field, which grows exponentially in amplitude and forms a rotating cloud around the black hole. For a one-million solar-mass black hole and a scalar field with a mass of 10^{-16} eV, the timescale for this to take place is less than two minutes. Therefore, the very existence of ultralight fields is constrained by the observation of spinning black holes. With this technique, one can place unprecedented bounds on the mass of axion-like particles, another popular candidate for dark matter. For example, we know from current astrophysical observations that the mass of dark photons must be smaller than 10^{-20} eV, which is 100 times better than accelerator bounds. The technique relies only on measurements of the mass and spin of black holes, which will be known with unprecedented precision with future gravitational-wave observations.

Superradiance, together with current electromagnetic observations of spinning black holes, can also be used to constrain the mass of the graviton, since any massive boson would trigger superradiant instabilities. Spin measurements of the supermassive black hole in galaxy Fairall 9 requires the mass of the graviton to be lighter than 5×10^{-23} eV – an impressive number which is even more stringent than the bound recently placed by LIGO.

Gravitational waves can also test the nature of dark matter.

Gravitational lighthouses

Furthermore, numerical simulations suggest that the superradiant instability mechanism eventually causes a slowly evolving and non-symmetric cloud to form around the black hole, emitting periodic gravitational waves like a gravitational "lighthouse". This would not only mean that black holes are not as simple as we thought, but lead to a definite prediction: some black holes should be emitting nearly monochromatic gravitational waves whose frequency is dictated only by the field's mass. This raises terrific opportunities for gravitational-wave science: not only can gravitational waves provide the first direct evidence of ultralight fields and of possible new effects near the horizon, but they also carry detailed information about the black-hole mass and spin. If light fields exist, the observation of a few hundred black holes should show "gaps" in the mass-spin plane corresponding to regions where spinning black holes are too unstable to exist.

This is a surprising application of gravitational science, which can be used to investigate the existence of new particles such as those possibly contributing to the dark matter. The idea of using observations of supermassive black holes to provide new insights not accessible in laboratory experiments would certainly be exciting. Perhaps these new frontiers in gravitational-wave astrophysics, in addition to probing the most extreme objects, will also give us a clearer understanding of the microscopic universe.

Further reading

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Résumé

Lier les ondes aux particules

La découverte des ondes gravitationnelles par LIGO fournit l'indice le plus probant jusqu'ici de l'existence des trous noirs, mais ces distorsions de l'espace-temps ont bien d'autres choses à nous apprendre. Elles nous offrent un moyen sans égal de vérifier si les trous noirs sont les objets macroscopiques les plus simples possible, si les horizons des événements existent vraiment, et si les gravitons n'ont effectivement pas de masse. Élément peut-être encore plus surprenant, les ondes gravitationnelles pourraient révéler la nature de la matière noire et l'existence de champs scalaires légers – ce qui établirait un lien entre la physique des particules et les objets les plus extrêmes de l'Univers.

Vitor Cardoso, Universidade de Lisboa, and **Paolo Pani**, Sapienza University of Rome.

Faces & Places

APPOINTMENTS

New management at linear collider

Shinichiro Michizono from KEK has been appointed as associate director for the International Linear Collider (ILC), taking over from Mike Harrison, while Jim Brau of the University of Oregon has replaced Hitoshi Yamamoto as associate director for physics and detectors. The Linear Collider collaboration, which encompasses the ILC and CLIC, has recently been granted a further three-year mandate by the International Committee for Future Accelerators.

LCC

K James/University of Oregon

Incoming associate directors Shinichiro Michizono (left) and Jim Brau.

ESO appoints astronomer Barcons as new director general

The council of the European Southern Observatory (ESO), which builds and operates some of the world's most powerful ground-based telescopes, has appointed Xavier Barcons as its next director general. The 57 year-old astronomer will take up his new position on 1 September 2017, when the current director general Tim de Zeeuw completes his mandate. He began his career as a physicist, completing a PhD on hot plasmas.

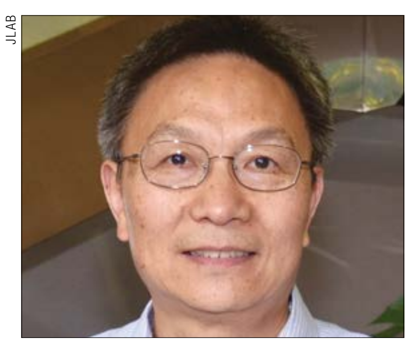
ESO/F J Carrera

Xavier Barcons will become the new ESO director later in the year.

Next theory leader for Jefferson Lab

In October 2016, Jianwei Qiu joined the Thomas Jefferson National Accelerator Facility as its new associate director for theoretical and computational physics. Qiu, whose research focus is QCD and its applications in both high-energy particle and nuclear physics, will oversee a broad programme of theoretical research in support of the physics studied with the Continuous Electron Beam Accelerator Facility (CEBAF).

JLAB



Qiu, who previously led the nuclear theory group at Brookhaven National Laboratory.

LHC operations changes hands

Rende Steerenberg has been appointed head of operations in CERN's Beams Department, effective from 1 January 2017. He takes over from Mike Lamont, who has been in the role since 2009 and oversaw operations from the LHC's rollercoaster start-up to its latest record performance. Lamont remains deputy group leader of the Beams Department.

N Steerenberg

Rende Steerenberg, previously deputy operations group leader.

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Awards

Heuer given highest French honour


CERN

Former CERN Director-General Rolf-Dieter Heuer has been appointed Chevalier de la Légion d'Honneur (Knight of the Legion of Honour), one of the highest recognitions of achievement in France. Heuer, who is currently president of the German Physical Society (DPG) and president-elect of the SESAME Council, among other roles, was presented with the medal on 22 November at the residence of the French permanent representative in Geneva.

Rolf Heuer with French ambassador Elisabeth Laurin.

String theorists snare Breakthrough Prize


Getty images

Andrew Strominger, Joseph Polchinski and Cumrun Vafa (left to right) at the award ceremony.

The 2017 Breakthrough Prize in Fundamental Physics has been awarded to Joseph Polchinski, University of California at Santa Barbara, and Andrew Strominger and Cumrun Vafa of Harvard University. The three winners, who received the $3 million award at a glitzy ceremony in San Francisco on 4 December, have made important contributions to fundamental physics including quantum gravity and string theory. Polchinski was recognised in particular for his discovery of D-branes, while the citation for Strominger and Vafa included their derivation of the Bekenstein–Hawking area-entropy relation, which unified the laws of thermodynamics and black-hole dynamics.

Recipients of the previously announced Special Prize in Fundamental Physics – Ronald Drever and Kip Thorne of Caltech and Rainer Weiss of MIT, who were recognised in May along with the entire LIGO team for the discovery of gravitational waves – were also present. A further prize, the $100,000 New Horizons in Physics Prize, went to six early-career physicists: Asimina Arvanitaki (Perimeter Institute), Peter Graham (Stanford University) and Surjeet Rajendran (University of California, Berkeley); Simone Giombi (Princeton University) and Xi Yin (Harvard University); and Frans Pretorius (Princeton).

This year's Breakthrough Prize, which was founded in 2012 by Sergey Brin, Anne Wojcicki, Yuri and Julia Milner, Mark Zuckerberg and Priscilla Chan, saw $25 million in prizes awarded for achievements in the life sciences, fundamental physics and mathematics.

Humboldt award for Brookhaven physicist

On 30 November, the Alexander von Humboldt Foundation in Bonn, Germany, granted a Humboldt Research Award to Raju Venugopalan, a senior physicist at Brookhaven National Laboratory and Stony Brook University. The €60,000 award recognises Venugopalan's achievements in theoretical nuclear physics, and comes with the opportunity to collaborate with German researchers at Heidelberg University and elsewhere.


BNL

Venugopalan joined Brookhaven in 1998.

Atomic pioneer wins presidential medal

US physicist and science policy adviser to the US government, Richard Garwin, was awarded the Presidential Medal of Freedom at a White House ceremony on 22 November. The award is the highest honour that the US government can confer to civilians. Garwin was recognised for his long career in research and invention, which saw him play a leading role in the development of the hydrogen bomb, and for his advice to policy makers.

Introducing Garwin, President Obama remarked: "Dick's not only an architect of the atomic age. Reconnaissance satellites, the MRI, GPS technology, the touchscreen all bear his fingerprints – he even patented a mussel washer for shellfish. Dick has advised nearly every president since Eisenhower, often rather bluntly. Enrico Fermi, also a pretty smart guy, is said to have called Dick the only true genius he ever met."


The White House

Richard Garwin was one of 21 recipients of the 2016 Presidential Medal of Freedom.

Neutrino physicist takes up Pascal Chair


RCNS/Tohoku University

Fumihiko Suekane wins the French award.

Fumihiko Suekane of Tohoku University, Japan, has been awarded a 2016 Blaise Pascal Chair to further his research into neutrinos. Established in 1996, and named after the 17th-century French polymath Blaise Pascal, the €200,000 grant allows researchers from abroad to work on a scientific project in an institution in the Ile-de-France region. Suekane will spend a year working at the Astroparticle and Cosmology Laboratory in Paris, where he will focus on R&D for novel neutrino detectors and measurements of reactor neutrinos.

Visits


M Brice/CERN

President of the Republic of Poland, **Andrzej Duda**, visited CERN on 15 November and toured the CERN Control Centre.


S Bennett/CERN

Director of SLAC National Accelerator Laboratory in the US, **Chi-Chang Kao**, signed the guestbook with CERN Director-General Fabiola Gianotti on 23 November.

Russian Academy of Sciences elects theorists as latest new members

In late 2016, theorists Mikhail Danilov, from the Lebedev Institute in Moscow, Sergio Ferrara from CERN and David Gross from the Kavli Institute for Theoretical Physics and the University of California in Santa Barbara were elected as members of the Russian Academy of Sciences. Established in 1724, the body has more than 2000 members.

Conferences

Triangulating in Mumbai

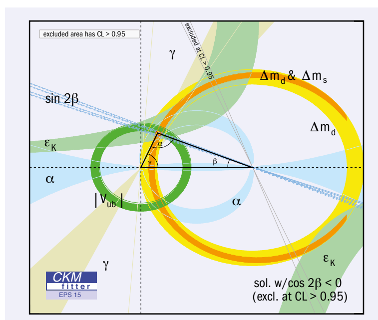
From 28 November to 2 December, more than 200 flavour physicists gathered at the Tata Institute of Fundamental Research in Mumbai for the 9th International Workshop on the Cabibbo–Kobayashi–Maskawa Unitarity Triangle (CKM2016). The workshop focuses on weak transitions of quarks from one flavour to another, as described by the CKM matrix, and on the charge–parity (CP) violation present in these transitions, as visualised by the unitarity triangle (UT). Input from theory, particularly lattice QCD, is vital to fully leverage the power of such measurements.

It is an exciting time for flavour physics. The mass scales potentially involved in such weak processes are much higher than those that can be directly probed at the LHC, due to the presence of quantum loops that mediate many of the processes of interest, such as $B_{(s)}^0 - \bar{B}_{(s)}^0$ mixing. Compared with the absence of new particles so far at the energy frontier, LHCb and other B factories already have significant hints of deviations between measurements and Standard Model (SM) predictions.

An example is the persistent discrepancy in the measured differential distributions of the decay products of the rare flavour-changing neutral-current process $B^0 \to K^{*0}\mu^+\mu^-$, first reported by the LHCb collaboration in 2015. A highlight of CKM2016 was the presentation of first results of the same distributions from the Belle experiment in Japan, which also included the related but previously unmeasured process $B^0 \to K^{*0}e^+e^-$. The Belle results are more compatible with those of LHCb than the SM, further supporting the idea that new physics may be manifesting itself, via interference effects, in these observables. Progress on measuring CP violation in B decays was also reported, with LHCb presenting the first evidence for time-dependent CP violation in the decay of B_s^0 mesons in two separate final states, $D_s^+K^-$ and K^+K^-. The latter involves loop diagrams allowing a new-physics-sensitive determination of a UT angle (γ) that can be compared to a tree-level SM determination in the decay $B^- \to D^0K^-$.

TIFR Photography Section

CKM2016 participants at the Tata Institute of Fundamental Research in Mumbai.



The sides, angles and height of the unitarity triangle constitute a highly overconstrained system where small deviations from predictions would indicate the presence of non-SM physics.

For the first time, LHCb also presented results with data from LHC Run 2, which is ultimately expected to increase the size of the LHCb data samples by approximately a factor four. Longer term, the Belle II experiment based at the SuperKEKB collider recently enjoyed its first beam, and will begin its full physics programme in 2018. By 2024, Belle II should have collected 50 times more data than Belle, allowing unprecedented tests of rare B-meson decays and precision CP-violation measurements. On the same timescale, the LHCb upgrade will also be in full swing, with the goal of increasing the data size by least a factor 10 compared to Run 1 and Run 2. Plans for a second LHCb upgrade presented at the meeting would allow LHCb, given the long-term future of the LHC, to run at much higher instantaneous luminosities to yield an enormous data set by 2035.

With more data the puzzles of flavour physics will be resolved thanks to the ongoing programme of LHCb, imminent results from rare-kaon-decay experiments (KOTO and NA62), and the Belle II/LHCb upgrade projects. No doubt there will be more revealing results by the time of the next CKM workshop, to be held in Heidelberg in September 2018.

● www.tifr.res.in/~ckm16.

PSI event probes the low-energy frontier

While there are many conferences focusing on physics at the high-energy frontier, the triennial PSI workshop at the Paul Scherrer Institute (PSI) in Switzerland concerns searches for new phenomena at non-collider experiments. These are complementary to direct searches at the LHC and often cover a parameter space that is beyond the reach of the LHC or even future colliders.

The fourth workshop in this series, PSI2016, took place from 16–21 October and attracted more than 170 physicists. Theoretical overviews covered: precision QED calculations; beyond-the-Standard-Model implications of electric-dipole-moment (EDM) searches; axions and other light exotic particles; flavour symmetries; the muon g-2 problem; NLO calculations of the rare muon decay $\mu \to e e \nu \nu$; and possible models to explain the exciting flavour anomalies presently seen in B decays. On the experimental side, several new results were presented.

Fundamental neutron physics featured prominently, ranging from cold-neutron-beam experiments to those with stored ultracold neutrons at facilities such as ILL, PSI, LANL, TRIUMF and Mainz. Key experiments are measurements of the neutron lifetime, searches for a permanent EDM, measurements of beta-decay correlations and searches for exotic interactions. The future European Spallation Source in Sweden will also allow a new and much improved search for neutron–antineutron oscillations. Atomic physics and related methods offer unprecedented sensitivity to fundamental-physics aspects ranging from QED tests, parity violation in weak interactions, EDM and exotic physics to dark-matter (DM) and dark-energy searches. With the absence of signals from direct DM searches so far, light and ultralight DM is a focus of several upcoming experiments. Atomic physics also comprises precision spectroscopy of exotic atoms, and several highlight talks included the ongoing efforts at CERN's Antiproton Decelerator with antihydrogen and with light muonic atoms at J-PARC and at PSI. For antiprotons and nuclei, impressive results from recent Penning-trap mass and g-factor measurements were presented with impacts on CPT tests, bound-state QED tests and more.

Major international efforts are under way at PSI ($\mu \to e\gamma$, $\mu \to eee$), FNAL and J-PARC ($\mu \to e$ conversion) devoted to muons and their lepton-flavour violating decays, and the upcoming muon g-2 experiments at FNAL and J-PARC have reported impressive progress. Last but not least, rare kaon decays (at CERN and J-PARC), new long-baseline neutrino oscillation results, developments towards direct neutrino-mass measurements, and CP and CPT tests with B mesons were reported. The field of low-energy precision physics has grown fast over the past few years, and participants plan to meet again at PSI in 2019.

S Ritt/PSI

Attendees enjoy a music event at PSI2016, which comprised 65 plenary talks.

Correction

The Compiler's Note in the December 2016 issue of the *Courier* (p50) inadvertently reported that the touchscreen and tracker ball used at the SPS were inventions of an individual.

Such projects are, of course, team efforts, sometimes involving industry, and useful products emerge and evolve over time and place. Credit should have been more fairly attributed to reflect the history of these important CERN devices.

Nanotechnology meets HEP in Darmstadt

The fields of nanomaterials and nanotechnology are quickly evolving, with discoveries frequently reported across a wide range of applications including nanoelectronics, sensor technologies, drug delivery and robotics, in addition to the energy and healthcare sectors.

At an academia–industry event on 20–21 October at GSI in Darmstadt, Germany, co-organised by the technology-transfer network HEPTech, delegates explored novel connections between nanotechnology and high-energy physics (HEP).

The forum included an overview of the recent experiments at DESY's hard X-ray source PETRA III, which allows the investigation of physical and chemical processes *in situ* and under working conditions and serves a large user community in many fields including nanotechnology. Thermal-scanning probe lithography, an increasingly reliable method for rapid and low-cost prototyping of 2D and quasi-3D structures, was also discussed. Much attention was paid to the production and application of nanostructures, where the achievements of the Ion Beam Center at Helmholtz-Zentrum Dresden-Rossendorf in surface nanostructuring and nanopatterning were introduced.

UK firm Hardide Coatings Ltd presented its advanced surface-coating technology, the core of which are nano-structured tungsten-carbide-based coatings that have promising applications in HEP and vacuum engineering. Industry also presented ion-track technology, which is being used to synthesise 3D interconnected nanowire networks in micro-batteries or gas sensors, among other applications. Neutron-research infrastructures and large-scale synchrotrons are emerging as highly suitable platforms for the advanced characterisation of micro- and nano-electronic devices, and the audience heard the latest developments from the IRT Nanoelec Platform for Advanced Characterisation of Grenoble.

The meeting addressed how collaboration between academia and industry in the nanotechnology arena can best serve the needs of HEP, with CERN presenting applications in gaseous detectors using the charge-transfer properties of graphene. The technology-transfer office at DESY also shared its experience in developing a marketing strategy for promoting the services of the DESY NanoLab to companies. Both academia and industry representatives left the event with a set of contacts and collaboration arrangements.

GSI

70 participants from 11 countries attended the event and 30 bilateral meetings took place.

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Super future for medical accelerators

On 24–25 November, academics and leading companies in the field of superconductivity met in Madrid, Spain, to explore the technical challenges of applying new accelerator technology to medicine. Organised by CIEMAT in collaboration with HEPTech, EUCARD2, CDTI, GSI and the Enterprise Europe Network, the event brought together 120 participants from 19 countries to focus on radioisotope production, particle therapy and gantries.

Superconductivity has a range of applications in energy, medicine, fusion and high-energy physics (HEP). The latter are illustrated by CERN's high-luminosity LHC (HL-LHC), now near construction with superconducting magnets made from advanced Nb_3Sn technology capable of 12 T fields. The HL-LHC demands greatly advanced superconducting cavities with more efficient and higher-gradient RF systems, plus the development of new devices such as crab cavities that can deflect or rotate single bunches of protons.

On the industry side, new superconducting technology is ready to go into production for medical applications. A dedicated session presented novel developments in cyclotron production, illustrated by the AMIT project of CIEMAT (based on a cyclotron with a compact superconducting design that will be able to produce low-to-moderate rates of dose-on-demand ^{11}C and ^{18}F) and the French industry–academia LOTUS project system, which features a compact 12 MeV superconducting helium-free magnet cyclotron suitable for the production of these isotopes in addition to ^{68}Ga. Antaya Science and Technology, meanwhile, reported on the development of a portable high-field superconducting cyclotron for the production of ammonia-13N in near proximity to the PET cameras. The meeting also heard from MEDICIS, the new facility under construction at CERN that will extend the capabilities of the ISOLDE radioactive ion-beam facility for production of radiopharmaceuticals and develop new accelerator technologies for medical applications (*CERN Courier* October 2016 p28).

PSI

A proton-therapy gantry facility at the Paul Scherrer Institute.

Concerning particle therapy, industry presented medical accelerators such as the MEVION S250 – a proton-therapy system based on a gantry-mounted 250 MeV superconducting synchrocyclotron that weighs less than 15 tonnes and generates magnetic fields in excess of 10 T. Global medical-technology company IBA described its two main superconducting cyclotrons for particle therapy: the Cyclone 400 for proton/carbon therapy and the S2C2 dedicated to proton therapy, with a particular emphasis on their superconducting coil systems. IBA also introduced the latest developments concerning ProteusONE – a single-room system that delivers the most clinically advanced form of proton-radiation therapy. Researchers from MIT in the US presented a novel compact superconducting synchrocyclotron based on an ironless magnet with a much reduced weight, while the TERA Foundation in Italy is developing superconducting technology for "cyclinacs" – accelerators that combine a cyclotron injector and a linac booster.

Finally, the session on gantries covered developments such as a superconducting bending-magnet section for future compact isocentric gantries by researchers at the Paul Scherrer Institute, and a superconducting rotating gantry for carbon radiotherapy designed by the Japanese National Institute of Radiological Sciences. With demand for medical isotopes and advanced cancer therapy rising, we can look forward to rich collaborations between accelerator physics and the medical community in the coming years.

Higgs Couplings 2016

R Kish/SLAC

Higgs experts from theory and experiment at Higgs Couplings 2016.

The fifth in the series of Higgs Couplings workshops, which began just after the Higgs-boson discovery in 2012 to bring together theorists and experimentalists, was held at SLAC on 9–12 November and drew 148 participants from five continents.

Discussions focused on lessons from the current round of LHC analyses that could be applied to future data. Modelling of signal and background is already limiting for some measurements, and new theoretical results and strategies were presented. Other key issues were the use of vector-boson fusion production as a tool, and the power and complementarity of diverse searches for heavy Higgs bosons.

Two new themes emerged at the meeting. The first was the possibility of exotic decays of the 125 GeV Higgs boson. These include not only Higgs decays to invisible particles but also decays to lighter Higgs particles, light quarks and leptons (possibly with flavour violation) and new, long-lived particles. A number of searches from ATLAS and CMS reported their first results. The workshop also debated the application of effective field theory as a framework for parametrising precise Higgs measurements.

The 6th Higgs Couplings meeting will be held in Heidelberg on 6–10 November 2017. We look forward to new ideas for the creative use of the large data samples of Higgs bosons that will become available as the LHC programme continues.

Hard probe for QCD matter

Xi-Chang Chen

Hard Probe 2016 attracted a record number of participants.

The 8th International Conference on Hard and Electromagnetic Probes of High-energy Nuclear Collisions (Hard Probes 2016) was held in Wuhan, China, on 23–27 September. Hard and electromagnetic probes are powerful tools for the study of the novel properties of hot and dense QCD matter created in high-energy nucleus–nucleus collisions, and have provided much important evidence for the formation of quark–gluon plasma (QGP) in heavy-ion collisions at RHIC and the LHC.

Hard Probe 2016 attracted close to 300 participants from 28 countries. The main topics discussed were: jet production and modification in QCD matter; high transverse-momentum hadron spectra and correlations; jet-induced medium excitations; jet properties in small systems; heavy flavour hadrons and quarkonia; photons and dileptons and initial states and related topics. The most recent experimental progress on hard and electromagnetic probes from the ALICE, ATLAS, CMS, LHCb, PHENIX and STAR collaborations, together with many new exciting theoretical and phenomenological developments, were discussed. The next Hard Probe conference will be held in Aix Les Bains, France, in 2018.

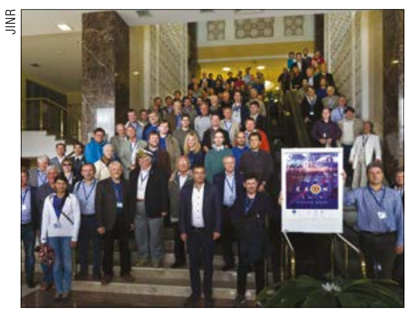
Exotic nuclei and super-heavy elements

The International Symposium on EXOtic Nuclei (EXON-2016), took place from 5–9 September in Kazan, Russia, attracting around 170 nuclear experts from 20 countries. The scientific programme focused on recent experiments on the synthesis and study of new super-heavy elements, the discovery of which demonstrates the efficiency of international co-operation.

Interesting results were obtained in joint experiments on chemical identification of elements 112 and 114 performed at JINR (Russia), the GSI (Germany) and the Paul Scherrer Institute (Switzerland). A vivid example of co-operation with US scientists is an experiment on the synthesis of element 117 held at the cyclotron of JINR. Recently, the International Union of Pure and Applied Chemistry approved the discovery of the new elements with atomic numbers 113 ("nihonian"), 115 ("moscovium"), 117 ("tennessine") and 118 ("oganesson").

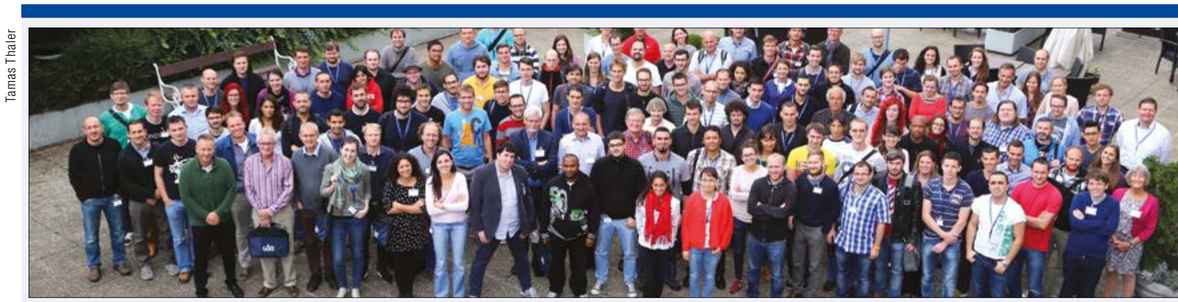
Five laboratories, which are the co-founders of the symposium, are now creating a new generation of accelerators for the synthesis and study of new exotic nuclei. Projects such as SPIRAL2, RIKEN RI Beam Factory, FAIR, DRIBs, NICA and FRIB will allow us to delve further into the upper limits of the periodic table.

JINR



Participants of the VIII International Symposium on EXOtic Nuclei.

Tamas Thaler



The CERN Accelerator School (CAS) and the Wigner Research Centre for Physics jointly organised an introduction-to-accelerator-physics course in Budapest, Hungary, from 2–14 October, attended by more than 120 participants spanning 28 nationalities. This year, CAS will organise a specialised course on beam injection, extraction and transfer (to be held in Erice, Sicily, from 10–19 March) and a second specialised course on vacuum for particle accelerators (near Lund, Sweden, from 6–16 June). The next course on advanced-accelerator physics will be held in the UK in early September, and a Joint International Accelerator School on RF technology will be held in Hayama, Japan, from 16–26 October (www.cern.ch/schools/CAS).

Obituaries

Ovsat Abdinov 1944–2016

Ovsat Abdinov, member of the Azerbaijan National Academy of Sciences (ANAS), died on 29 October at the age of 72, after a long illness. He was born in Belokan city, Azerbaijan, graduated from Baku State University in 1966, and defended his PhD thesis in 1972.

It is impossible to overstate the impact that Abdinov had in the creation and development of high-energy physics in Azerbaijan. His wide knowledge, inexhaustible energy, talent in organisation and search for young specialists led to the creation of his own school in this field that serves as an example for future generations.

Scientifically, Abdinov's main interest was the theoretical description of hadron-nuclear interaction processes. He was the first to propose a hypothesis of the cluster formation in light nuclei, which was later experimentally proven. The laboratory he headed at ANAS Institute of Physics collaborated initially with the Joint Institute for Nuclear Research (JINR) in Dubna and the Institute of High Energy Physics (IHEP) in Serpukhov, both in Russia, followed by CERN.


Gökhan Ünel

Ovsat Abdinov had a major impact on high-energy physics in Azerbaijan.

The creation and expansion of relations between Azerbaijan and CERN paved the way for the participation of Azerbaijan scientists in the LHC, but this did not interrupt connections with Dubna: Abdinov was a staff member of JINR, deputy of authorised representative of the government of Azerbaijan Republic in JINR, and a member of JINR Scientific Council.

The creation of Azerbaijan's first Worldwide LHC Computing Grid segment also owes its thanks to Abdinov.

Abdinov was a famous scientific representative of the Azerbaijan intelligentsia. He was an organiser and invited speaker at international conferences, a presenter of high-level reports and the winner of numerous research grants both in the former Soviet Union and in Azerbaijan. He dedicated almost 20 years of his scientific activity to investigations carried out within the ATLAS collaboration. We hope that his work will be continued by his scientific heirs and further benefit Azerbaijan high-energy physics.

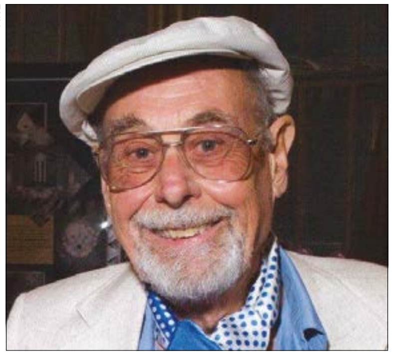
● *His colleagues.*

Malcolm Derrick 1933–2016

Malcolm Derrick, a long-time leader in the Argonne high-energy physics (HEP) division, passed away on 31 October after a long illness. Born in Hull, UK, in 1933, Malcolm received his BSc and PhD degrees in physics from the University of Birmingham. After working on the cyclotron at Carnegie Tech, he moved to Oxford University in 1962 to help establish a bubble-chamber group working at CERN. In 1963 he moved to Argonne National Laboratory to work on the 12 GeV ZGS synchrotron then in construction.

While working on several bubble-chamber experiments with the 30 inch chamber, Malcolm's main interest was in establishing a programme of neutrino physics using the 12 foot bubble-chamber then being built. He was spokesman for the first experiment using the deuterium-filled chamber, which produced several important results including the first measurement of the axial-vector form factor in muon neutrino–neutron quasi-elastic scattering. This result was verified by later BNL and FNAL experiments.

Malcolm served on two occasions as HEP division director and was always a source of good career advice. He enthusiastically supported the division's collaboration with the University of Minnesota to build an underground detector to search for proton decay in the Soudan Mine in Minnesota. This resulted in a rich programme of neutrino physics with a series of multi-kiloton detectors and in new underground laboratories at Soudan, using both atmospheric neutrinos and Fermilab neutrino beams. The important physics produced by the MINOS programme is the direct result of these early experiments.


ANL

Malcolm Derrick was a long-time CERN collaborator.

After the closure of the ZGS programme, Malcolm initiated Argonne participation in two important experiments: HRS at the PEP collider at SLAC, where he proposed using the superconducting magnet of the 12 foot bubble chamber as the solenoid for the HRS spectrometer, and the ZEUS experiment at the HERA collider in DESY. Malcolm took sabbatical leave at University College London and later at DESY, where he served as physics chairman and oversaw such activities as physics publications. A gifted speaker, he served on several review committees and was a HEPAP member and an active participant in the Snowmass Conferences. He retired in 2006.

Besides being a brilliant physicist, Malcolm had a knack for entertaining his guests with stories about his life and endless anecdotes about history and philosophy. His spare time was spent reading good books, fine dining and listening to classical music. Malcolm leaves behind his wife Eva and his many children and grandchildren. He will be missed by all who knew and loved him.

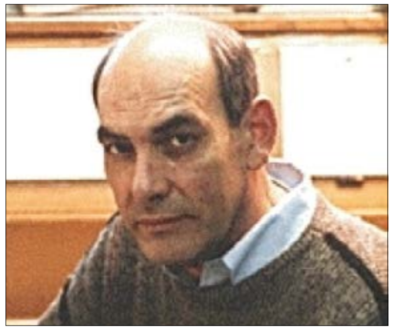
● *His colleagues.*

Valery Khovanskiy 1940–2016

Russian physicist Valery Dmitrievich Khovanskiy passed away in Moscow on 7 September. A veteran of Russian experimental high-energy physics and long-time leader of the ITEP team in ATLAS, he will be remembered not only as an energetic contributor to the CERN neutrino and LHC programmes, but also as an honest and principled person who loved science and life.

Valery was born in Sverdlovsk in the former USSR, and received his PhD (for the study of cumulative effects in πN-interactions) at the Institute of Experimental and Theoretical Physics (ITEP, Moscow) in 1969. Since then, his main scientific interests were in the fields of neutrino physics, novel particle-detection methods and hadron collider physics.

In the first Russian accelerator neutrino experiment at the Serpukhov 70 GeV proton synchrotron (IHEP-ITEP, 1970–1978), Valery lead the detector construction and studied neutrino and antineutrino interactions to validate the then very young quark-parton model. In the late 1970s, Valery joined the CERN experimental neutrino programme at the SPS and PS, and became one of the senior scientists of the CHARM, PS-181, CHARM-2 and CHORUS experiments devoted to a systematic study of neutral currents, and the search for new particles and neutrino oscillations. From 1990 onwards, he participated in the ATLAS experiment. His group was active in the preparation of the Letter of Intent, working on the concept of radiation-resistant forward calorimeters, and, from 1995 to 2009, worked on the construction and commissioning of the ATLAS liquid-argon forward calorimeters, providing the major part of the tungsten electrodes.



Khovanskiy at CERN in the late 1990s.

From 1995 to 2012, Valery was the leader of the neutrino-physics laboratory at ITEP. He served on the LHCC from 1992 to 1994 and for a long period on the Russian government's commission on fundamental research. He was also one of the founders and lecturers of the famous ITEP Winter School of Physics.

Valery had a vivid individuality and was invariably good humoured. His many pupils, colleagues and friends admired him and he will be very much missed.

● *His friends and colleagues, ITEP and ATLAS.*

Ted Wilson 1938–2016

Edmund (Ted) Wilson, a well-known figure in the world of particle accelerators and former director of the CERN Accelerator School (CAS), died after a short illness on 3 November.

The son of a schoolteacher in Liverpool, UK, he graduated in physics at the University of Oxford in 1959 and immediately joined the nearby Rutherford Appleton Laboratory. His first stay at CERN was in 1962–1963 and he returned in 1967 as a fellow, working in Werner Hardt's group on the design of the booster for the new large synchrotron: the "300 GeV" machine, later to become the Super Proton Synchrotron (SPS). He became the right-hand man of John Adams in 1969, helping him to prepare the project for approval by CERN Council, which was given in 1971. He became one of the first staff members of the new "300 GeV laboratory" set up for the construction of the SPS.

In 1973–1974, at the request of Adams, Ted spent a sabbatical year at Fermilab to work on the commissioning of the "main ring", a machine very similar to the SPS. The lessons he learnt there would prove essential for the smooth commissioning of the SPS, for which he was responsible a few years later. Following the approval in 1978 of the bold proposal of Carlo Rubbia to turn the SPS into a part-time proton–antiproton collider, Ted started working on how to convert the machine from a synchrotron to a storage ring. He later worked on the design and construction of CERN's antiproton complex: first the antiproton accumulator, to which a second ring, the antiproton collector, was later added.


Alex Wilson

Accelerator physicist Ted Wilson.

Ted was a natural and gifted teacher. During the days of SPS construction he ran a series of courses on accelerator theory for members of the 300 GeV laboratory, which evolved into the book *An Introduction to Particle Accelerators*. Following his appointment as CAS director in 1992, he was responsible for organising 25 schools, in addition to special schools in India, China and Japan. He also coauthored a fascinating book on the history of particle accelerators and their applications: *Engines of Discovery, a Century of Particle Accelerators*.

On his retirement, Ted renewed his association with Oxford University by becoming a guest professor at the John Adams Institute of Accelerator Physics, where he taught and supervised students. He has helped to bring on a new generation of machine builders.

Ted Wilson will be sorely missed by the world's accelerator community. He will always be remembered for his impish smile and his dry sense of humour. He is survived by his wife Monika, his three children and five grandchildren.

● *His friends and colleagues.*

CERNCOURIER

Volume 57 Number 1 January/February 2017

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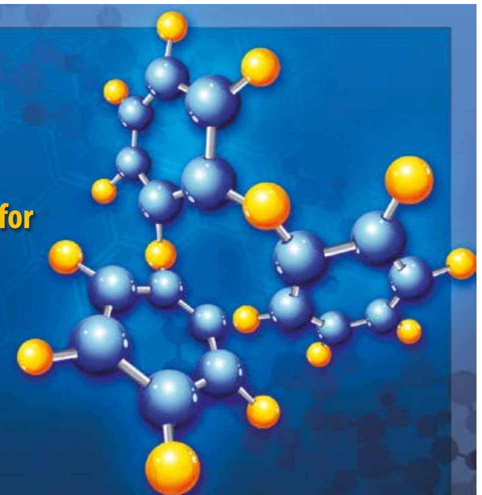
Oak Ridge National Laboratory



The Neutron Sciences Directorate invites applicants for Research Accelerator Division Director (RAD)

In this executive leadership role, you will lead an organization of approximately 240 staff and $93M in annual funding to enable neutron science research in support of Department of Energy (DOE) missions. The RAD Director reports to the Associate Laboratory Director for Neutron Sciences and represents the ORNL core capability of accelerator science and technology. This position also directs the technical initiatives necessary to maintain pre-eminent standing in high power hadron linear accelerators, and supports cutting edge neutron scattering science. Broad experience in both accelerator science and operations in a fast-paced, multi-disciplinary environment is essential. The successful candidate will be expected to ensure the Spallation Neutron Source accelerator and target complex maintain a world-leading position in pulsed accelerator-based neutron sources by sustaining highly reliable operation (>90% against schedule) for over 5000 hours per year at a beam power of 1.4 MW, and contribute to projects aimed at doubling beam power and neutron scattering capacity.

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Pontificia Universidad Catolica de Chile

Instituto de Física
Facultad de Física

Two Faculty Positions in experimental or computational Plasma Physics

$Attractive | South America | 07 Dec 2016

The Institute of Physics of the Pontificia Universidad Católica de Chile invites applications for two tenure-track faculty positions at the Assistant Professor level, to begin as early as August 2017.

A Ph. D. degree in physics is required and postdoctoral experience is expected. The successful candidate is expected to establish a leading research program in the areas relevant to the Plasma Physics group, as well as teach at the undergraduate and graduate levels. One of the selected candidates is expected to develop research in experimental Plasma Physics, with particular emphasis in dense transient plasmas. A good working knowledge of pulsed power technology and electronics together with plasma diagnostics is advantageous. The area of research expertise of the second selected candidate could be either in experimental plasma physics applied to materials science or biomedicine, or to computational Plasma Physics related to transient high energy density plasmas.

Applications should include a letter of application, curriculum vitae, list of publications, and statements of past and proposed research and teaching interests. Furthermore, at least two confidential letters of reference must be sent directly by the referees. All the documents should be sent by email before February 28, 2017 to the Head of the Selection Committee, Prof. Heman Bhuyan, **hbhuyan@fis.puc.cl**.

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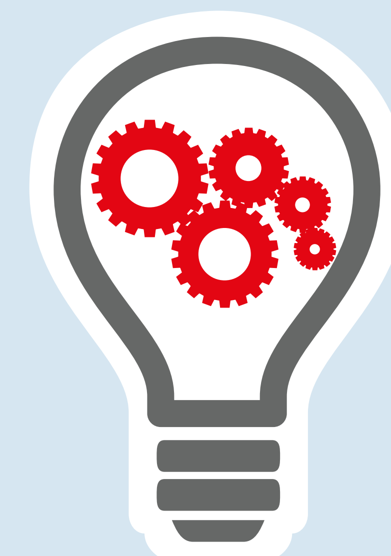
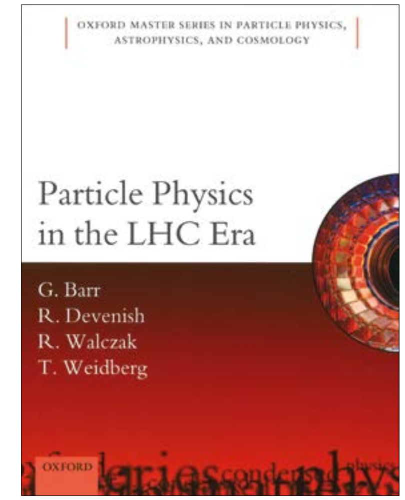


The jobs site for physics and engineering

Bookshelf

Compiled by Virginia Greco, CERN

Particle Physics in the LHC Era
By G Barr, D Devenish, R Walczak and T Weidberg
Oxford University Press



This book's aim, as stated in the introduction, is to provide a practical introduction to particle physics in the LHC era at the level of an advanced undergraduate or introductory graduate course. Indeed, in its almost 400 pages, it covers a wide range of topics, from instrumentation and detector technologies to some mathematical techniques and the traditional particle-physics topics that are usually included in similar textbooks. It hovers, by design, at the border between the established textbooks aimed at undergraduates and the more advanced graduate texts that often start with quantum field theory.

Following the introduction, the book commences with a three-chapter sequence with somewhat technical content. Chapter 2, dedicated to mathematical methods, covers discrete symmetries, angular momentum and rotations in space, Lorentz invariance and the calculation of phase-space factors, decay widths and cross-sections, and concludes with a brief review of group theory. Chapter 3, on accelerators, includes a concise yet clear description of the basic concepts and terminology often encountered by students starting to work on experiments but not readily available. The topics include synchronicity, beam optics, Q values and beam tunes, luminosity, and even some characteristics of past accelerators. Chapter 4 is on particle detectors. Beyond the standard topics expected in such an overview, e.g. the interaction of particles and radiation with matter, the chapter includes topics that are usually neglected, including short presentations on signal generation, triggering of experiments and the selection of a magnetic field. As would be expected, calorimetry is well covered, as are tracking detectors, to which an extensive description, including an introduction to solid-state detectors, is included. The topics and detector examples provided are too centred on the LHC and its experiments, though.

Chapter 5, on the static quark model, is the first "particle-physics-proper" section. It's a clear and self-contained introduction to mesons and baryons, with a modern perspective. The authors have decided to include heavy quarks (with the exception of the top quark) and their mesons and baryons, and the result is a full overview for the reader. Finally, chapter 6 on relativistic quantum mechanics concludes what could be called the first part of the book on "concepts, tools and methods". There is a modern angle in this chapter: as an example, Weyl spinors are introduced and used, along with the associated Lorentz transforms and spin matrices. This material is better absorbed by graduate students. The rest of the chapter covers the traditional Klein–Gordon and Dirac equations, and introduces the electromagnetic interaction. It concludes with a short introduction to gauge symmetry.

Chapters 7–10 constitute a second part that concentrates on particle physics. Chapter 7, on weak interactions, covers all of the material from the four-point Fermi interaction to the Standard Model (SM), although without symmetry breaking. The descriptions of V–A, parity violation and the weak interactions of quarks, the CKM matrix and hadron decays via the weak interaction are clear, as is the extended introduction of $SU(2) \times U(1)$ symmetry as the basis of the SM. Chapter 8, on experimental tests of electroweak theory, is one of the more modern presentations of the topics covered: it starts with neutrino interactions and charged and neutral currents, and moves to Z physics and then WW production at LEP. It includes some experimental aspects such as the use of resonant depolarisation for the precise determination of the LEP beam energy. Moving away from convention, the discovery of the W and Z bosons at the CERN SPS is left for after the LEP presentation. The chapter concludes with a brief presentation of the discovery of the top quark and some later results from the Tevatron.

Chapter 9, on dynamic quarks, breaks the flow slightly. It contains Rutherford scattering, the quark–parton model and neutrino interactions, and concludes its first part with electron–nucleon deep inelastic scattering. This is a departure from standard practice in most textbooks. The second part of the chapter is on the introduction of colour, QCD, parton distribution functions and hadron–hadron collisions, and the Drell–Yan process. The material, which is extensive but presented quite briefly, is more appropriate for undergraduates.

Chapters 10 (oscillations and CP violation in meson systems) and 11 (neutrino oscillations) are great introductions to physics mixing, both in the quark and the lepton sector. The discussion in chapter 10 is modern, with results from experiments at LEP, the B factories and hadron colliders. Chapter 11 has one of the best summaries on neutrino physics for this level: it starts with the first evidence of mixing in atmospheric neutrinos, and proceeds to laboratory experiments, and then the MSW effect, solar-neutrino oscillations and then three-flavour oscillations, concluding with the measurement of θ_{13}. This chapter is a novel and useful addition to the textbook.

Chapter 12 is on the Higgs boson. It starts with a short introduction to spontaneous symmetry breaking and proceeds to a description of the discovery of the Higgs boson by the ATLAS and CMS experiments. The material, with the exception of a section on the statistical significance, which is too short and ill-placed to be useful, is at the right level for the advanced-undergraduate-to-graduate student audience.

The book concludes with chapter 13 on the LHC and BSM (physics Beyond the Standard Model). It has an interesting selection of topics, including expected ones like supersymmetry and some unexpected ones (for a textbook) like the search for new contact interactions and new resonances. The approach is quite experimental in that only the motivation for new phenomena is presented, and the theory is skipped. It is nevertheless a useful introduction to the subject, adequate for motivating students to explore further.

Overall, the book achieves its goal of bridging the gap between undergraduate and graduate textbooks. The descriptions of the various topics are mostly clear, although at times too short. In a formal course, the tutor would probably choose to cover the material in a slightly different mix to the order it is presented here, combining material from the first part (chapters 2–6) and the second ▷

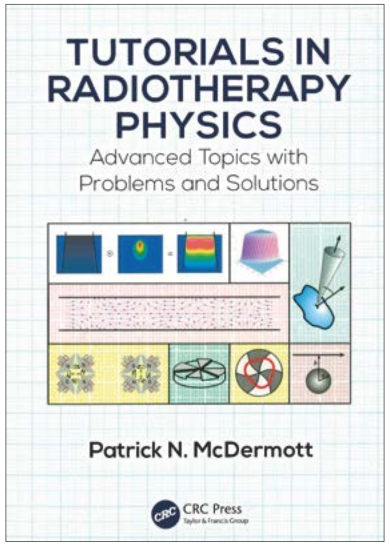
part (mainly chapters 7–10). In summary, this is a welcome, useful and modern addition to the current list of textbooks in particle physics.

● *Paraskevas Sphicas, CERN, and University of Athens, Greece.*

Tutorials in Radiotherapy Physics: Advanced Topics with Problems and Solutions

By Patrick N McDermott

CRC Press



This book addresses five selected physics topics in modern cancer radiation therapy. Examining them in more detail than can be found in standard medical-physics textbooks, the author has also formulated and solved a large number of exercises that are provided at the end of each chapter, together with a detailed bibliography.

Despite its title, the book is not a substitute for comprehensive textbooks in medical-radiation physics, rather it complements them. It is therefore of interest to experienced medical physicists who would like to better understand the physics of their daily work, as well as to young researchers approaching this discipline for the first time, often following a PhD in particle physics.

The first section deals with the main tool of modern cancer radiation therapy: the electron linear accelerator (linac). Starting from the basics of electrodynamics, travelling- and standing-wave linear accelerators are discussed together with resonating cavities. Particular care is given to mathematical formulations and to the definition of symbols. This chapter could also appeal to accelerator physicists willing to know more about electron acceleration at energies of a few MeV.

Proton therapy, which is generally considered an advanced topic in medical radiation therapy, is approached in a somewhat easier way. Starting from an historical introduction, emphasis is given to accelerators and to dose-distribution systems, with a glimpse of future developments. It is a pity that carbon-ion therapy is not mentioned and that active dose-distribution systems are not discussed in more detail.

The two topics that follow address the daily work of the medical physicist. Dose-computation algorithms are treated following a careful mathematical formulation complemented by examples and references to practical cases. Deterministic radiation transport is introduced, starting from the basic quantities used in medical radiation physics. The transport and Fermi–Eyges equations are then derived and discussed.

The last theme, tumour control and normal tissue complications, is the most relevant for the patient. Is the therapy effective? What is the quality of life after treatment? The answers to these questions may be searched for using the bridge that connects physics to medicine. To accomplish this task, models are necessary. Starting from the concepts of probability and of dose-volume histograms, empirical and mechanistic models are presented together with the serial and parallel architecture of the organs in the human body.

The application of radiation physics to medicine is an expanding multidisciplinary field based on knowledge, tools and techniques derived from nuclear and particle physics. This book will therefore appeal not only to curious medical physicists and scientists active in the field, but also to physicists in general who – as the author comments – "like understanding".

● *Saverio Braccini, AEC-LHEP, University of Bern, Switzerland.*

Books received

Lectures in Nonlinear Mechanics and Chaos Theory

By Albert W Stetz

World Scientific

This concise book provides a rigorous introduction to the theory of nonlinear mechanics and chaos, suitable for students across physics, mathematics and engineering.

Nonlinear dynamics treats problems that cannot be "solved", in the sense that it is not possible to derive equations of motion that describe the positions of the various parts of a system as functions of time using standard analytic functions. If, on one side, the formulations of mechanics of Lagrange and Hamilton lead to systems that cannot be solved in the usual sense of the word, perturbation theory, in turn, fails in providing approximate solutions because of the problem of small dividers. This is the path that led originally to the discovery of chaos, and it is the one that the author pursues in the book.

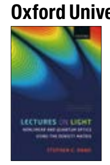
The first part is dedicated to the basic concepts of the Lagrangian and Hamiltonian formulation of mechanics, and to canonical transformations. The author then deals with more advanced topics, including Liouville's theorem and perturbation theory. In the third part of the book, the modern theory of chaos is introduced. The author describes chaotic motion using the tools of discrete maps and Poincaré sections, along with the Poincaré–Birkhoff and Kolmogorov–Arnold–Moser (KAM) theorems and their applications.

Each chapter is accompanied by a set of problems, with the last section providing more advanced projects that require some expertise in computing. As a conclusion, an appendix discusses the relevance of the KAM theorem to the ergodic hypothesis and the second law of thermodynamics.

Lectures on Light: Nonlinear and Quantum Optics using the Density Matrix (2nd edition)

By Stephen C Rand

Oxford University Press



The aim of this book is to bridge the gap between introductory quantum mechanics and the most recent advances in modern optics.

The author opts for an unconventional approach. Rather than providing an exhaustive treatment, he introduces a single analytic tool – the density matrix – to analyse complex optical phenomena and applies it to a wide range of problems. Among the many mathematical tools available to treat nonlinear and quantum optics, he chooses the density matrix because it is extremely versatile and applicable virtually to any problem. In particular, it is well suited for dealing with coherence in isolated or interactive systems, and allows researchers to ignore parts of a problem that appear irrelevant.

After covering the basics, the book quickly passes to more sophisticated topics. It starts with the simplest systems (stationary two-level atoms) and then introduces atomic motion and additional energy levels, and continues with a discussion of coherence effects effects (of first-, second- and third-order).

Finally, a section is dedicated to selected examples from recent research topics in which the use of the density matrix is profitable, including laser tweezers, laser cooling, coherent population trapping and transfer, optical magnetism, electromagnetically induced transparency, squeezed light and quantum information processing.

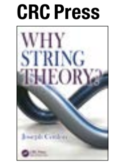
The text is based on two decades of lectures and is oriented to graduate students not only of traditional disciplines such as physics, chemistry, electrical engineering and materials science, but also of interdisciplinary courses such as biophysics, biomedicine and photochemistry.

In this second revised edition, new sections on quantum interference, Fano resonances, optical magnetism, quantum computation, laser cooling of solids, and irreducible representation of magnetic interactions have been included, along with more than 40 new problems.

Why String Theory?

By Joseph Conlon

CRC Press



As the author himself states, the primary aim of this book is to explain why so many scientists choose to work on a theory that has no direct experimental support and is unlikely to have so anytime soon.

String theory, the origins of which date back to 1968, has developed into a major component of theoretical particle physics. It is most famous as a theory of quantum gravity and as a candidate unified theory of fundamental interactions at the smallest scales – so small that, unfortunately, we cannot directly test it with experiments.

Although string theory is built on a very solid mathematical basis and allows rigorous calculations, the author uses almost no equations. Rather than a textbook, this is a book on the history, science and philosophy lying behind a fascinating and speculative theory.

In the first part, the theory of quantum-mechanical relativistic strings is placed within the broader context of theoretical particle physics, and ultimately science in general. It is then discussed why there is still a need for ideas and paradigms that go beyond what we already know, and why string theory is a candidate for being a global theory that includes all others. Following this, the author describes the motivation driving this field and how this has evolved during the past 50 years. In particular, he dedicates various chapters to the connections of string theory with quantum field theory, mathematics, cosmology, particle physics and quantum gravity.

The last part of the book discusses the social aspects of science: the diverse ways of approaching the topic as well as various personal driving forces. A chapter is also dedicated to the most significant criticisms of string theory, to which the author provides a reply.

The book is intended to appeal to laypersons interested in fundamental physics as well as to physics students, so the author chooses to avoid mathematical formulations of the theory. However, the risk is that the book is then not sufficiently clear and explanatory to be an easy read for non-experts, nor technical and detailed enough to appeal to students.

Exactly Solvable Models in Many-Body Theory

By N H March and G G N Angilella

World Scientific

Following their previous book on many-body theory, the authors have written a new volume focused on exactly solvable models, to add to the literature in this field. Several theoretical models are presented for selected systems in condensed states of matter – including solid, liquid and disordered states – and for systems of few or many bodies.

The book starts with an introduction to low-order density matrices, then discusses exactly or nearly exactly solvable models for several few-particle systems. The material is arranged according to the statistics of these particle assemblies, going from small clusters of fermions to small clusters of bosons – with specific reference to Efimov trimers in nuclear and condensed-matter assemblies – to anyon statistics.

The second group of chapters is dedicated to models for selected many-body systems in condensed matter, where particular attention is given to superconductivity and superfluidity, and to isolated impurities in a solid. Pair-potential and many-body force models for liquids are also discussed, as well as disorder and its implications for transport in solids.

The authors then deal with more general topics, in particular statistical field theory (discussing some specific models and critical exponents) and relativistic field theory. Open problems in quantum gravity are also briefly reviewed in the concluding chapter, and several appendices are included at the end of the book.

CERN Courier Archive: 1974

A look back to CERN Courier vol. 14, February 1974, compiled by Peggie Rimmer

News

All the world's a hadron

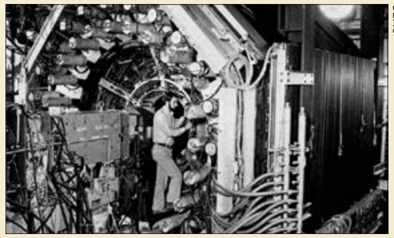
Following the coming into operation of the 6 GeV Bevatron at Berkeley in February 1954, the particle population explosion defied understanding. Then came a beautiful application of unitary symmetry theory, which grouped particles in an orderly way with well-defined relationships between them. Noting an absent member in one of these groups, the omega minus was predicted and, in February 1964, Brookhaven identified this particle, crowning one of the great achievements of high-energy physics.

The famous quark hypothesis is one attempt to explain the particle grouping and relationships. It postulates three types of fractionally charged particles [up, down and strange] coming together in different ways to build up the multitude of discovered hadrons (which respond to the strong interaction). However, quarks have never been isolated as separate entities despite a multitude of searches, and some results do not line up precisely with predictions.

The past 10 years have seen no let-up in the accumulation of fresh information. This has been particularly true of recent years when the opening up of new energy ranges has produced fascinating results. The 76 GeV proton synchrotron at Serpukhov, the CERN Intersecting Storage Rings [ISR], and the 400 GeV proton synchrotron at NAL Batavia have all contributed something new. Fresh surprises from experiments on electron–positron storage rings were reported by B Richter (SLAC) at the American Physical Society Meeting in Chicago, 4–7 February.

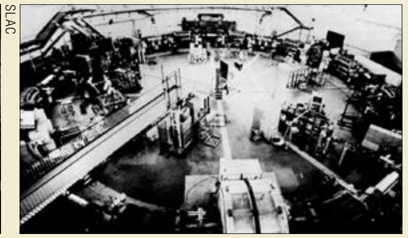
The high-energy collision of an electron and a positron brings matter and antimatter together, resulting in annihilation into energy. This energy (photons) can convert into hadrons (predominantly pions). Thus hadrons emerge from lepton collisions.

The first inkling that things were going adrift came from experiments at the electron–positron storage ring ADONE at Frascati. Measurements indicated the hadron-production cross-section up to 3 GeV centre-of-mass energy is over twice that expected. A few measurements with electrons and positrons at energies up to 5 GeV centre of mass then came from the Cambridge bypass. They were very much higher than predictions, but the accelerator was closed down before they could be checked. In recent months the same energy range has been covered at the electron–positron storage ring [SPEAR] at Stanford. Experiments there have resoundingly confirmed the Cambridge measurements and completely overthrown our understanding of what is going on.



SLAC

The detection system surrounding a beam collision region at SPEAR, used in gathering the new astonishing results on hadron production.



Frascati

The ADONE storage ring at Frascati, where combined electron–positron energies of up to 3 GeV had already indicated that the hadron-production cross-section was high.

The total cross-section for the production of hadrons is about 25 nb and is virtually constant over energies up to 5 GeV. This is in complete contradiction to the prediction of the quark model, which says that the cross-section should fall off as the square of the energy.

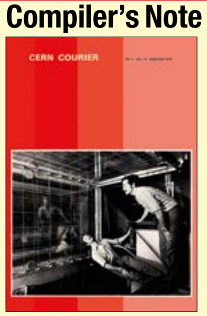
The quark model gets another jolt when the total cross-section for producing hadrons is compared with that for producing pairs of muons. The simple quark model says the ratio should be constant at 2/3, independent of energy. ADONE results had already upset the apple cart but they were still compatible with a more complicated variant of the quark model involving "coloured" quarks (introducing a property for the quarks like an ultra-strangeness). The coloured variant still insisted on a constant value for the ratio, this time of 2. But the Cambridge and SPEAR measurements can be explained by no quark model, no matter how coloured. They show the ratio rising with increasing energy and by 5 GeV it has reached a value of about 6.

The results can also be applied subversively to another revered concept – scaling. Scaling makes it possible to predict the energy distribution of the hadrons at any energy once they have been measured at another energy. It has worked beautifully in studies of lepton–hadron interactions, for example the elastic scattering of electrons off nucleons. Why then does scaling not apply for electron–positron collisions?

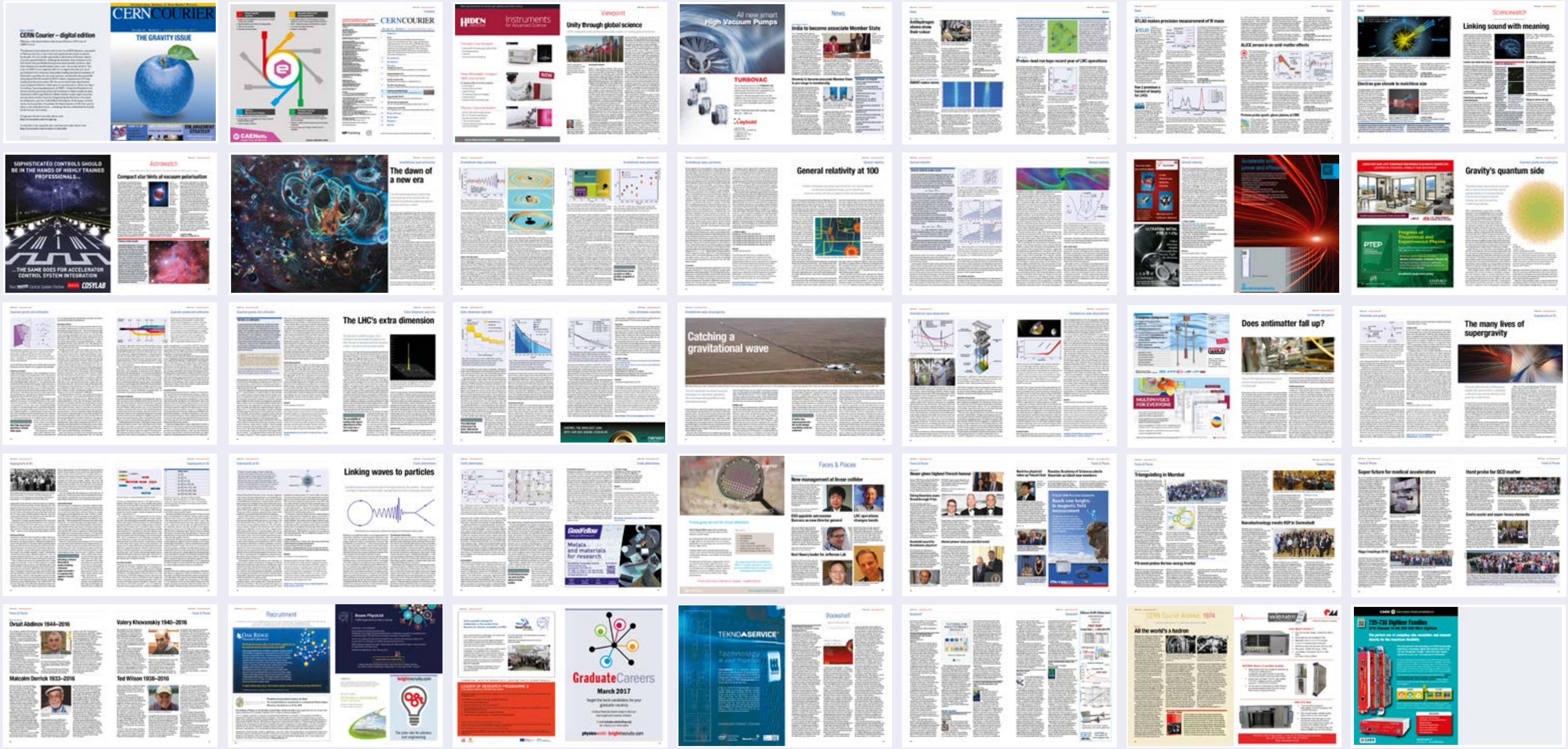
It is also intriguing that the hadron energy distribution from electron–positron collisions looks like that in very high energy proton collisions, such as pion production data at 90° in the centre of mass at NAL and the ISR. It is as if the electron is sensitive to the strong interaction within a tiny radius of 10^{-16} cm. So, is even the best-known lepton really a hadron at heart?

● Compiled from texts on pp39–42.

Compiler's Note



In 1964, Gell-Mann and Zweig proposed a quark model of hadrons, purely for bookkeeping purposes. But increasing accelerator energies brought growing evidence that the hypothetical up, down and strange quarks were in fact real and point-like. For example, particles with high transverse momentum were emerging from proton–proton collisions at the ISR, reminiscent of the large-angle scattering of alpha particles that led to Rutherford's discovery of the atomic nucleus. The GIM mechanism, proposed by Glashow, Iliopoulos and Maiani in 1970, required the existence of a fourth, heavier quark, and by the end of 1974 it had been identified, by Richter at SLAC and Ting at BNL, in the charm/anticharm J/ψ meson. And with real quarks, there was no need for hadronic leptons.



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