WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the April 2017 issue of *CERN Courier*.

Few scientific disciplines enjoy such a close connection with mathematics as particle physics, and at the heart of this relationship lies quantum field theory. Quantum electrodynamics famously predicts quantities, such as the anomalous magnetic moment of the electron, which agree with observations at the level of 10 decimal places, while the Higgs boson existed on paper half a century before the Large Hadron Collider (LHC) flushed it out for real. Driven by the strong performance of the LHC experiments, there has been a burst of activity in recent months concerning next-to-next-to-leading order (NNLO) calculations in quantum chromodynamics to ensure that theory keeps up with the precision of LHC measurements. As the cover feature in this issue explains, cracking the complex NNLO problem demands novel algorithms, mathematical ingenuity and computational muscle. Theorists are also trying to make sense of a number of "exotic" hadrons that have turned up in recent years in experiments such as LHCb and which do not naturally fit the simple quark model. Sticking with the strong-force theme, we also report on 30 years of heavy-ion physics and how recent measurements at the LHC and RHIC are closing in on the evolution of the quark–gluon plasma. Finally, we describe new forward detectors that from this year will allow the LHC to analyse photon–photon collisions in the ongoing search for new physics.

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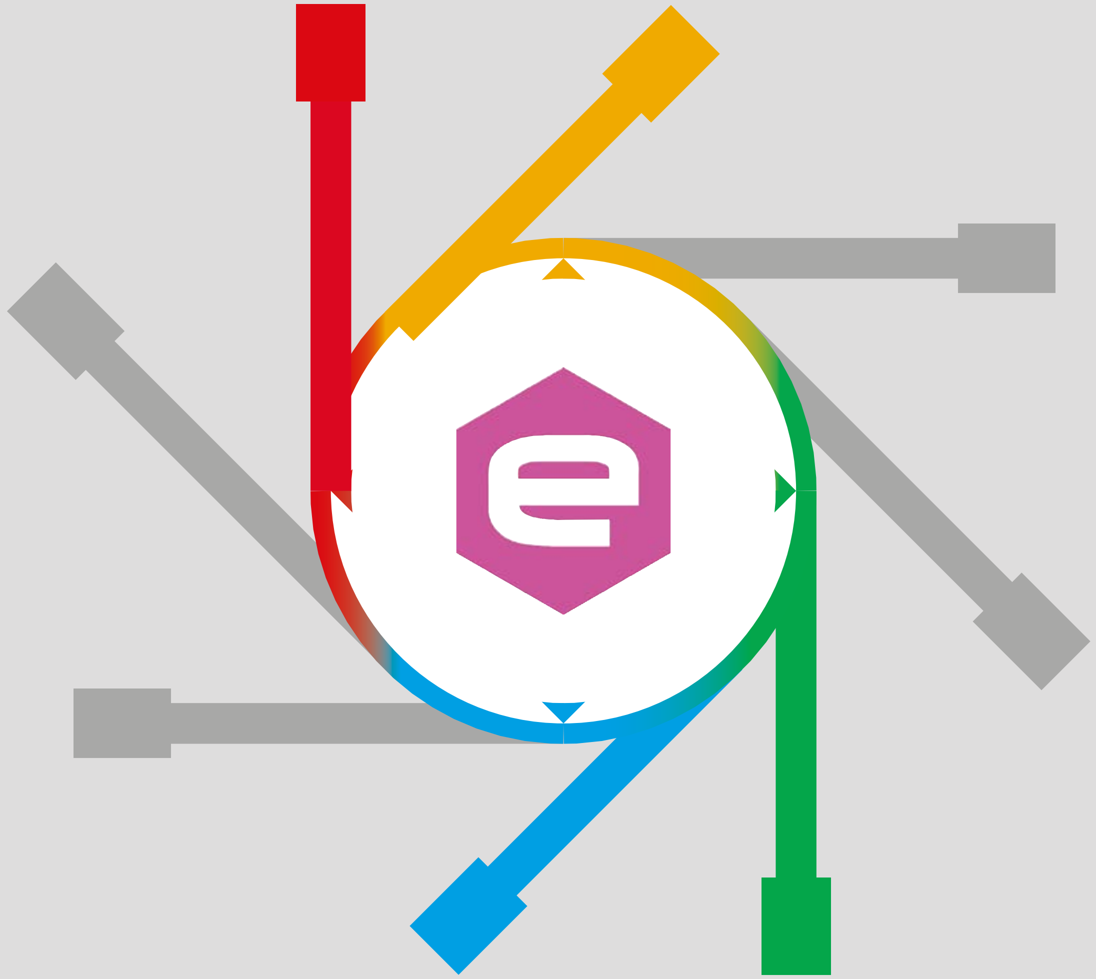

Covering current developments in high-energy physics and related fields worldwide

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On the cover: Graphic treatment of NNLO diagrams relevant to LHC physics. (Image credit: Daniel Dominguez.)

Viewpoint

Accelerating gender equality

The growing numbers of female colleagues at CERN marks significant changes in attitude.

We all need to join forces to assure CERN's ongoing commitment to diversity.

Sudeshna Datta-Cockerill is the CERN ombudsperson. She has worked at CERN for 41 years as HR adviser, head of learning and development, diversity programme leader, and member of the HR management board. She was CERN's first equal opportunities officer (1996–2003).

By Sudeshna Datta-Cockerill

When I started working at CERN in 1976, women were a relatively rare sight. The few women who did work here generally held administrative roles, many having started with the incongruous job title of "scanning girls", regardless of the age at which they had been recruited. Back then it was quite normal to walk into a workshop and find pictures of naked females on the walls, and everyday sexism was common. I recall once being told that women couldn't possibly do night shifts in the control room. The reason, a male colleague explained, was to avoid mysterious calls in the middle of the night: "What if there was a problem and she has to call a physicist? What would his wife think?"

Such attitudes were not just true of CERN, of course, and things have changed significantly since then. Even as recently as 1995, less than three per cent of CERN research and applied physicists were female, whereas today that number is around 18 per cent. Similar increases have been seen across engineering and technician roles, and CERN now has its first female Director-General.

It was in 1996 that CERN launched its equal opportunities (EO) programme. I was appointed as the first EO officer, and the following year an EO advisory panel was created. Many a meeting was taken up by educating male colleagues about the lasting effects of sexist behaviour through the personal experiences of their female counterparts. The EO programme adopted a four-pronged strategy focusing on recruitment, career development, work environment and harassment. On recruitment we took a firm stand against quotas, recommending instead thorough monitoring that would ensure reasonable proportions of qualified women were shortlisted for interview.

Equitable recruitment practices that we take for granted today were then the subject of much debate. The multicultural nature of CERN brought added complexity, as people's notions of acceptable behaviour varied greatly. We were often accused of exaggerating the need for gender-neutral language or reproached for no longer having a sense of humour. Although some women colleagues found themselves in the uncomfortable situation of wishing to support EO initiatives while not wishing to risk the perception of tokenism or positive discrimination, many became vital allies in moving the EO agenda forward. Whether it was a question of work–life balance or simply accepting women in all job categories, a great deal of effort was invested to overcome resistance born of years of habit. It has only been over time that the proportion of female scientists at CERN has risen to match the numbers in society, as reflected by our world-wide user community.

CERN's EO programme itself has also evolved into today's diversity programme, which was launched in 2010 together with a newly created ombudsperson function and a formal harassment investigation panel. The CERN code of conduct was also produced at this time. The growing numbers of female colleagues in all fields at CERN is living proof that we have come a long way in the last two decades. But gender equality means more than just gender parity. While continuing our efforts to encourage female students to pursue science and to employ our colleagues through equitable recruitment practices, we should ask if we are doing everything possible to promote a mindset that enables all our colleagues to contribute as equals.

The last six years have seen approximately equal numbers of male and female visitors to the ombud office. However, when mapped against the corresponding staff-member populations, there are proportionally three-to-four times more women than men consulting the ombudsperson. A similar pattern is seen in other international organisations where women are a minority, and is mirrored by the proportionally higher number of females who participate in CERN's "diversity in action" workshops. Although the issues raised by women are essentially the same as those faced by their male colleagues, a closer examination reveals examples of stereotyping and unconscious bias that suggests ours is not yet a completely level playing field.

Not only is it difficult for the majority to recognise the insidious barriers of organisational culture faced by minority groups, it is sometimes equally difficult for those within the minority to bring these aspects to light. If we are to ensure that our work environment is equally supportive to all, the experience of women needs to be shared with a wider audience including their male colleagues. We all need to join forces to assure CERN's ongoing commitment to diversity.

News

INTERNATIONAL

Sri Lanka signs International Co-operation Agreement with CERN


M Brice/CERN

Susil Premajayantha and Charlotte Warakaulle with the signed documents.

On 8 February, Sri Lanka and CERN entered into an International Co-operation Agreement (ICA) concerning scientific and technical co-operation in high-energy physics. The agreement was signed by Susil Premajayantha, Sri Lanka's hon. minister of science, technology and research, and Charlotte Warakaulle, CERN's director for international relations.

The new agreement follows an Expression of Interest signed in June 2015 by Sri Lanka ambassador Ravinatha Aryasinha and the then Director-General Rolf-Dieter Heuer, which already incorporated Sri Lanka into CERN's high-school teacher and summer-student programmes. Previously, scientists from Sri Lankan universities have participated in LHC experiments within the frameworks of sabbatical leave or similar programmes, whereas others have participated as visiting scientists employed by universities in a third country.

With the partnership now formalised via the new ICA, students, scientists, engineers and research institutes in Sri Lanka will be able to benefit from broader and more sustained participation in CERN, and thus be exposed to cutting-edge technology and research in high-energy physics.

"ICAs help to strengthen the global network for particle physics, which is essential for the future of the discipline and for fundamental research more generally," says Warakaulle. "It is significant to see that a smaller, developing country is emphasising fundamental research and making the connection with CERN a priority. It testifies to an understanding of the value of fundamental research, which is commendable in a country that is facing other challenges. It also further enhances the CERN connection with South Asia, following the associate memberships of Pakistan and India."

COMPUTING

European computing cloud takes off

A European scheme to make publicly funded scientific data openly available has entered its first phase of development, with CERN one of several organisations poised to test the new technology. Launched in January and led by the UK's Science and Technology Facilities Council, a €10 million two-year pilot project funded by the European Commission marks the first step towards the ambitious European Open Science Cloud (EOSC) project. With more than 30 organisations involved, the aim of the EOSC is to establish a Europe-wide data environment to allow scientists across the continent to exchange and analyse data. As well as providing the basis for better scientific research and making more efficient use of data resources, the open-data ethos promises to address societal challenges such as public-health or environmental emergencies, where easy access to reliable research data may improve response times.

The pilot phase of the EOSC aims to ▷

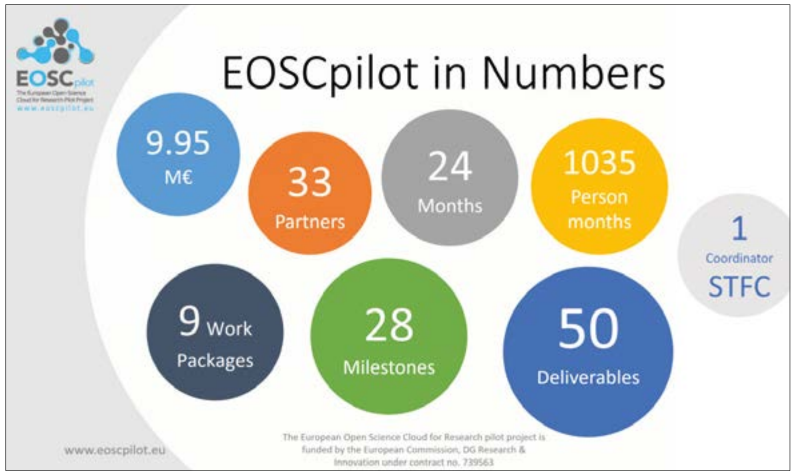
Sommaire en français

establish a governance framework and build the trust and skills required. Specifically, the pilot will encourage selected communities to develop demonstrators to showcase EOSC's potential across various research areas including life sciences, energy, climate science, material science and the humanities. Given the intense computing requirements of high-energy physics, CERN is playing an important role in the pilot project.

The CERN demonstrator aims to show that the basic requirements for the capture and long-term preservation of particle-physics data, documentation, software and the environment in which it runs can be satisfied by the EOSC pilot. "The purpose of CERN's involvement in the pilot is not to demonstrate that the EOSC can handle the complex and demanding requirements of LHC data-taking, reconstruction, distribution, re-processing and analysis," explains Jamie Shiers of CERN's IT department. "The motivation for long-term data preservation is for reuse and sharing."

Propelled by the growing IT needs of the LHC and experience gained by deploying scientific workloads on commercial cloud services, explains Bob Jones of CERN's IT department, CERN proposed a model for a European science cloud some years ago. In 2015 this model was expanded and endorsed by members of EIROforum. "The rapid expanse in the quantities of open data being produced by science is stretching the underlying IT services," says Jones. "The Helix Nebula Science Cloud, led by CERN, is already working with leading commercial cloud service providers to support this growing need for a wide range of scientific use cases."

The challenging EOSC project, which raises issues such as service integration, intellectual property, legal responsibility and service quality, complements the work of the Research Data Alliance and builds on the European Strategy Forum on Research Infrastructure (ESFRI) road map. "Our goal is to make science more efficient and productive and let millions of researchers share and analyse research data in a trusted environment across technologies, disciplines and borders," says Carlos Moedas, EC commissioner for research, science and innovation.



Scope of the pilot phase for the European Open Science Cloud.

FACILITIES

Milestone for US dark-matter detector

The US Department of Energy (DOE) has formally approved a key construction milestone for the LUX-ZEPLIN (LZ) experiment, propelling the project towards its April 2020 goal for completion. On 9 February the project passed a DOE review and approval stage known as "Critical Decision 3", which accepts the final design and formally launches construction. The LZ detector, which will be built roughly 1.5 km underground at the Sanford Underground Research Facility in South Dakota and be filled with 10 tonnes of liquid xenon to detect dark-matter interactions, is considered one of the best bets to determine whether dark-matter candidates known as WIMPs exist.

The project stems from the merger of two previous experiments: LUX (Large Underground Xenon) and ZEPLIN (ZonEd Proportional scintillation in LIquid Noble gases). It was first approved in 2014 and currently has about 250 participating scientists in 37 institutions in the US, UK, Portugal, Russia and Korea. The detector is expected to be at least 50 times more sensitive to finding signals from dark-matter particles than its predecessor LUX, and will compete with other liquid-xenon experiments under development worldwide in the race to detect dark matter. A planned upgrade to the current XENON1T experiment (called XENONnT) at Gran Sasso National Laboratory in Italy and China's plans to advance the PandaX-II detector, for instance, are both expected to have a similar schedule and scale to LZ.

The LZ collaboration plans to release a Technical Design Report later this year. "We will try to go as fast as we can to have everything completed by April 2020," says LZ project director Murdock Gilchriese. "We got a very strong endorsement to go fast and to be first."

LBNL

Photomultiplier tubes surrounded by polytetrafluoroethylene for the LZ experiment, which is managed by Lawrence Berkeley National Laboratory.

POLICY

European organisations uphold scientific values

More than 50 science organisations in Europe have written an open letter expressing concern about the impact of recent US policies on science, research and innovation. The 10 February letter, which was organised by EuroScience (founder of the EuroScience Open Forum, ESOF), asks that the principles and values that underpin scientific progress are upheld. It is addressed to the presidents of the European Council and European Commission, and prime ministers and science ministers in individual European countries.

The European Physical Society (EPS) is among the many signatories of the letter, as are the Marie Curie Alumni Association, the Royal Society and the Royal Swedish Academy of Sciences. Explaining the decision to sign, outgoing EPS president Christophe Rossel says: "Science was and will never be restrained by physical, cultural and political barriers. In our globalised world, where international scientific collaboration has become the rule, there is no place for discrimination and censorship. Any measure that restricts the freedom of movement and communication of our US colleagues will have a profound impact on science and innovation in Europe and other continents."

Three chief concerns are outlined in the letter: the recent Executive Order discriminating against persons on the basis of their nationality; indications that US government scientists might be affected by new policies that limit their communication with the press; and the unwarranted credibility given to views that are not based on facts and sound evidence in areas such as climate science. It states that all of these are at odds with the principles of transparency, open communication and the mobility of scholars and scientists, "which are vital to scientific progress and to the benefit of our societies, economies and cultures deriving from it".

In response to recent US policies, European science organisations seek to maintain a global science system based on core principles.

LHC NEWS

Chamonix event prepares for LHC's future

2016 was a remarkably successful year for CERN's Large Hadron Collider (LHC), marked by excellent peak performance, good availability and operational flexibility (*CERN Courier* December 2016 p5). Targeting further improvement, a thorough review of LHC operation and system performance was the focus of discussions in the first phase of the annual LHC performance workshop, which took place from 23 to 26 January in Chamonix, France.

Experts from the accelerator sector, CERN management and members of the CERN Machine Advisory Committee explored the operational scenarios for the remainder of Run 2 and made preliminary decisions regarding optics and machine parameters. Beam is due back in the LHC this year at the beginning of May, and the rest of the year will essentially be dedicated to proton–proton physics, with the usual mix of machine development and special physics runs. By quantifying the limitations to peak luminosity from electron-cloud effects, the cryogenics system and other factors, luminosity estimates for the coming years were also drawn up: in 2017, the peak luminosity should be at least $1.7 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ and the integrated luminosity target for ATLAS and CMS is $45\,\mathrm{fb}^{-1}$.

One open question about future LHC operations concerns the increase of the beam energy from 6.5 to 7 TeV per beam, which would see the machine reach its design specification. To gain input on high-field magnet behaviour, a dipole training campaign was conducted at the start of the year-end technical stop (*CERN Courier* March 2017 p9). Experience from this and previous training campaigns was reviewed and the duration, timing and associated risks of pushing up to 7 TeV – including implications for other accelerator systems, such as the LHC beam dump – were explored. There will be no change of beam energy in 2017 and 2018. The goal is to prepare the LHC to run at 14 TeV during Run 3 with the experiments expressing a clear preference to make the change in energy in a single step.

Regarding the longer-term future of the LHC, the High-Luminosity LHC (HL-LHC) demands challenging proton and ion beam parameters from the injector complex. The LHC injector upgrade (LIU) project is charged with planning and executing wide-ranging upgrades to the complex to meet these requirements. Both the LIU and HL-LHC projects have come through a recent cost-and-schedule review, and at present are fully funded and on schedule. The injector upgrades will be deployed during Long Shutdown 2 (LS2) in 2019/2020, while the HL-LHC will see the major part of its upgrades implemented in LS3, which is due to start in 2024.

With only two more years of operation before the next long shutdown, planning for LS2 is already well advanced. For the LHC itself, LS2 will not require the same level of intervention as seen in LS1. Nonetheless, here is still a major amount of work planned across the complex including major upgrades to the injectors in the framework of LIU, and significant upgrades to the LHC experiments.

The exploitation of the LHC and the injector complex has been impressive recently, but work across the Organization continues unabated in the push to get the best out of the LHC in both the medium and long term.

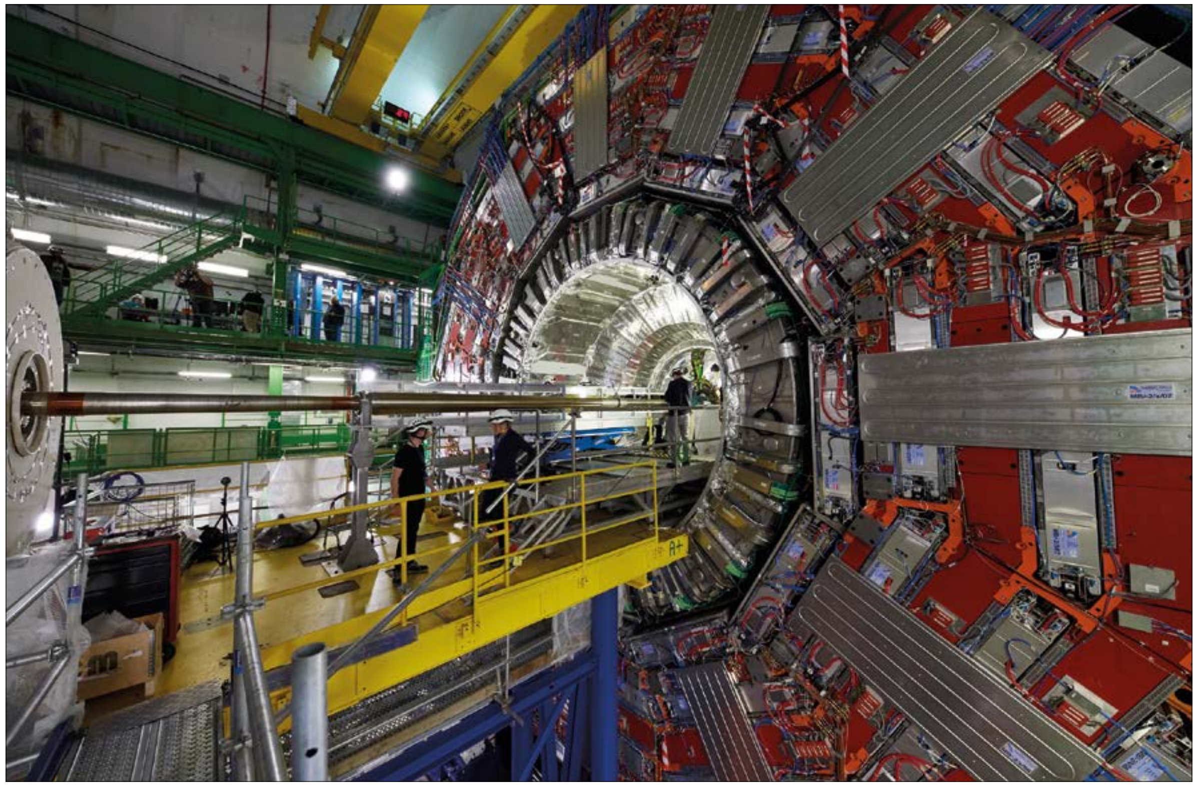
CERN

Beam is due back in the LHC in May.

LHC EXPERIMENTS

CMS undergoes tracker transplant

M Brice/CERN



(Above and below) The new silicon pixel tracker being installed in the central region of the CMS detector.

At the beginning of March, the CMS collaboration successfully replaced the heart of its detector: the pixel tracker. This innermost layer of the CMS detector, a cylindrical device containing 124 million sensitive silicon sensors that record the trajectories of charged particles, is the first to be encountered by debris from the LHC's collisions.

The original three-layer 64 Mpix tracker, which has been in place since the LHC started operations in 2008, was designed for a lower collision rate than the LHC will deliver in the coming years. Its replacement contains an additional layer and has its first layer placed closer to the interaction point. This will enable CMS to cope with the harsher collision environment of future LHC runs, for which the detector has to simultaneously handle the products from a large number of simultaneous collisions.

M Brice/CERN

The new pixel detector will also be better at pinpointing where individual collisions occurred and will therefore enhance the precision with which predictions of the Standard Model can be tested.

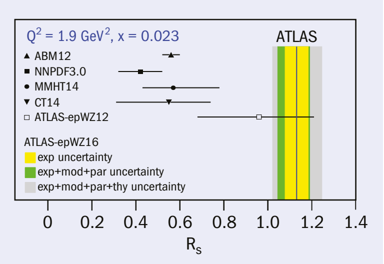
After a week of intense activity, and a few frayed nerves, the new subdetector was safely in place by 8 March. After testing is complete, CMS will be closed ready for the LHC to return to action in May.

ATLAS reveals more strangeness in the proton

The excellent theoretical understanding of the production of electroweak W and Z gauge bosons in proton–proton collisions at the LHC makes these "standard-candle" processes ideal for studying the detailed performance of the ATLAS detector, and thus improves the precision on measurements. Specifically, differences in the couplings of the W^+, W^-, Z and γ^* bosons to quarks and antiquarks appear as differences in rapidity distributions that reveal additional information about the structure of the proton.

Protons are often considered to be composed of two up quarks and one down quark, but when probed at small distances they reveal additional content. This includes a "sea" of up and down quarks, strange quarks from the heavier second generation of particles, and the gluons that bind the quarks together into the proton.

The ATLAS collaboration has now shed light on the least-known component of the proton – its content of strange quarks – based on sub-per-cent measurements of the kinematic dependencies of the W and Z boson cross-sections using LHC data recorded in 2011 at an energy of 7 TeV. Previous determinations of the strange-quark content of the proton were based on neutrino scattering, in which charged-current interaction muons from the fragmentation of charm quarks were detected. Contrary to theoretical expectations, these data revealed a suppression of strange quarks relative to the up and down quarks.



Comparison of the ATLAS strangeness suppression factor R_s with various predictions at the point of maximum sensitivity (corresponding to a scale of $Q^2 = 1.9$ GeV^2 and a proton momentum fraction of quarks of $x = 0.023$).

Gaining further insight into the proton structure using inclusive W and Z boson production required significant experimental improvements, with painstaking calibration efforts revealing detection efficiencies in real and simulated data at the per-mille level using both the electron and muon channels. Indeed, thanks to these studies, the ATLAS data provided a new test of electron–muon universality in the weak-interaction sector that is in excellent agreement with the Standard Model at the sub-per-cent level.

The combined electron and muon data, including the correlations of systematic uncertainties, were compared to predictions performed at next-to-next-to leading order (NNLO) in QCD and next-to-leading order in electroweak theory. Using various parton distribution functions, the comparisons revealed significant tensions between measurement and theory. Interpreting HERA-inclusive deep-inelastic-scattering data including the ATLAS data in an NNLO QCD fit pointed to a new sensitivity to the strangeness suppression factor $R_s = (s+\bar{s})/(\bar{d}+\bar{u})$, as shown in the figure. The data confirm with significantly improved precision the previous ATLAS determination of an unsuppressed strange-quark content (shown as ATLAS-epWZ12) based on 2010 data.

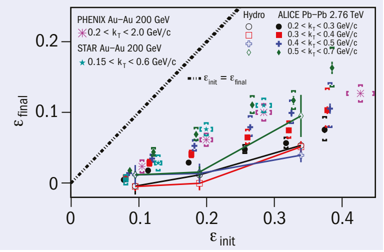
The result may have important implications for further precision measurements of Standard Model parameters, in particular the mass of the W boson and the weak-mixing angle, since these are affected by the second generation of quarks. The ATLAS measurement challenges the current paradigm of a suppression of the strange- compared to other light-quark distributions, but the quest continues.

- **Further reading**

ATLAS Collaboration 2016 arXiv:1612.03016.

ALICE measures shape of the QGP fireball at freeze-out

Heavy-ion collisions at LHC energies create a hot and dense medium of deconfined quarks and gluons, known as the quark–gluon plasma (QGP). The QGP fireball first expands, cools and then freezes out into a collection of final-state hadrons. Correlations between the free particles carry information about the space–time extent of the emitting source, and are imprinted on the final-state spectra due to a quantum-mechanical interference effect. To measure these correlations and to determine the space–time parameters of the source, physicists utilise Hanbury Brown and Twiss (HBT) interferometry, a technique first used in astronomy for determining the angular sizes of stars. Using azimuthally differential HBT interferometry, the ALICE collaboration has recently measured the shape of the fireball at freeze-out.



Freeze-out eccentricity measured for different ranges of pair transverse momentum as a function of initial-state eccentricity obtained from Monte Carlo models for six centrality ranges, 0–5%, 5–10%, 10–20%, 20–30 %, 30–40 % and 40–50%.

In a non-central collision, the nuclear overlap region is almond shaped with the longer axis oriented perpendicular to the reaction plane (defined by the impact parameter and the beam direction). The spatial anisotropies in the initial state are converted, via pressure gradients, to momentum anisotropies, leading to anisotropic particle flow. The magnitudes of the momentum anisotropies are quantified by the so-called v_n coefficients, where the second harmonic coefficient (v_2) is generated from the system's approximately elliptic shape. This is usually called elliptic flow, and the direction of the strongest component of elliptic flow is defined as the elliptic-flow plane.

The HBT radius, measured as a function of the pair-emission azimuth relative to the elliptic-flow plane, exhibits oscillations and thus provides information on the eccentricity of the source at freeze-out, when the

▷

particles cease to interact. The source eccentricity at freeze-out can be estimated from oscillations of the HBT radius at low pion-pair transverse momentum. ALICE has measured the pion HBT-radius oscillations for different transverse-momentum ranges as a function of centrality in lead–lead collisions at an energy of 2.76 TeV per nucleon pair and plotted the results as a function of the initial eccentricity (see figure on previous page).

The final eccentricities are significantly below the initial eccentricities due to a larger expansion in the in-plane direction. The freeze-out eccentricities measured by ALICE are smaller than those measured at RHIC energies, likely reflecting the longer lifetime of the system at the LHC. Hydrodynamic calculations performed for similar centralities and pair transverse-momentum ranges as in the ALICE experiment show a similar trend, but predict smaller final-source eccentricity corresponding to a more spherical source.

The final-state source eccentricity remains positive for all the pair transverse-momentum ranges, indicating that even after a stronger expansion in the in-plane direction, the pion source at freeze-out is still elongated in the out-of-plane direction. In the future, the ALICE collaboration intends to measure the azimuthal dependence of the HBT radii relative to the higher-harmonic ($n \geq 3$) flow planes, which is directly sensitive to anisotropies in the system's collective velocity fields.

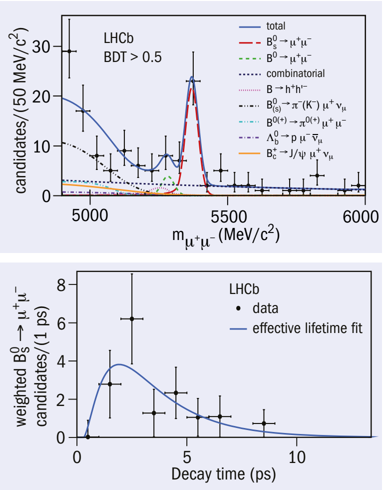
● Further reading

ALICE Collaboration 2017 arXiv:1702.01612.

Rare decay puts Standard Model on the spot

The decay rate of the B^0_s meson to two muons is a flagship measurement in flavour physics. It is extremely rare and well predicted in the Standard Model (SM), with a branching fraction of $(3.65\pm0.23)\times10^{-9}$. It proceeds via a loop diagram that involves the heaviest known particles: the Z and W bosons and the top quark. Any unknown heavier particles that exist are likely to also contribute to this decay, which makes it a very sensitive probe of physics beyond the SM. After three decades of unsuccessful searches, the observation of the decay was first announced in a joint paper in *Nature* in 2015 by the CMS and LHCb collaborations using LHC data from Run 1.

Recently the LHCb collaboration reported an improved analysis of this decay with data from 2015 and 2016 added to the Run-1 sample. Work during the long shutdown allowed significant improvements to be made in background rejection, which increased the experiment's sensitivity. The $B^0_s \to \mu^+\mu^-$ peak is clearly visible in the resulting mass plot, with a small bump possibly due to the B^0 meson to its left (see figure, top). The significance of the former is 7.8σ, corresponding to the first observation of this decay by a single experiment. At just 1.6σ, the B^0 peak is not significant.



Mass fit of dimuon candidates in the high-purity region of the machine-learning algorithm output (top), and decay-time distribution of background-subtracted $B^0_s \to \mu^+\mu^-$ signal with lifetime fit superimposed (below).

Using the well-known decays $B^0 \to K^+\pi^-$ and $B^+ \to J/\psi K^+$ to calibrate and normalise the efficiencies, the $B^0_s \to \mu^+\mu^-$ branching fraction is measured to be $(3.0\pm0.6)\times10^{-9}$, which is the most precise measurement to date. Although consistent with the SM, the experimental precision still has to improve before it matches the present theoretical accuracy.

For the first time, LHCb also measured the effective lifetime of the $B^0_s \to \mu^+\mu^-$ decay. The B_s meson system has much in common with that of the K^0 meson, in that it exhibits a heavier long-lived state and a lighter shorter-lived state. Only the former is allowed to decay into $\mu^+\mu^-$ in the SM, but that may not be the case in other scenarios. The contributions of the two states can be disentangled by fitting a single exponential to the lifetime distribution (figure, below). The fitted effective lifetime is consistent within 1σ with the hypothesis of only the heavier state contributing, and within 1.4σ of the opposite. While this result does not yet tell us anything about new physics, it allows the sensitivity to be extrapolated to larger data samples. With the 300 fb^{-1} integrated-luminosity target of the LHCb phase-II upgrade, the two states could be disentangled at the 5σ level and thus provide a new and important test of the SM.

● Further reading

LHCb Collaboration 2017 LHCb-PAPER-2017-001.
De Bruyn *et al.* 2012 *Phys. Rev. Lett.* **109** 041801.

DARK MATTER

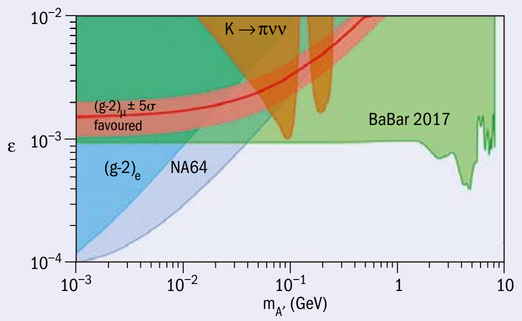
BaBar casts further doubt on dark photons

Dark photons, are hypothetical low-mass spin-1 particles that couple to dark matter but have vanishing couplings with normal matter. Such a boson, which may be associated with a U(1) gauge symmetry in the dark sector and mix kinetically with the Standard Model photon, offers an explanation for puzzling astrophysical observations such as the positron abundance in cosmic rays reported by the PAMELA satellite. Dark photons have also been invoked as possible explanations to the muon g-2 anomaly.

Based on single-photon events in 53 fb^{-1} of e^+e^- collision data collected at the PEP-II B factory in SLAC, California, the BaBar collaboration has now completed a thorough search for these particles (A') via the process $e^+e^- \to \gamma A'$. The search was based on the assumption that the dark photon decays almost entirely to dark-matter particles and therefore that no energy would be deposited in the BaBar detector from its decay products. Finding no evidence for such processes, the analysis places 90% confidence-level upper limits on the coupling strength of A' to e^+e^- for dark photons lighter than 8 GeV. In particular, the BaBar limits exclude values of the A' coupling suggested by the dark-photon interpretation of the muon g-2 anomaly, as well as a broad range of parameters for dark-sector models (see figure).

"This paper is the final word from BaBar on a search where the dark photon decays invisibly," says BaBar spokesperson Michael Roney. "But we are continuing to search for dark photons and other dark-sector particles that have visible decay modes."

The BaBar result follows another direct search for sub-GeV dark photons carried out recently by CERN's NA64 experiment, in which electrons incident on an active target probe the process $e^-Z \to e^-ZA'$. Again, no evidence for such decays was found, and NA64 was able to exclude dark photons with a mass less than around 0.1 GeV.



Regions of the dark-photon parameter space (mixing strength versus mass) excluded by BaBar (green) compared with the previous constraints. The new analysis rules out dark-photon coupling as the explanation for the muon (g-2) anomaly and places stringent constraints on dark-sector models.

"The thing is, there are dark photons and dark photons," says theorist Sean Carroll of Caltech, who has worked on dark-photon models. "In contrast to massless dark photons, which are analogous to ordinary photons, this experiment constrains a slightly different idea of dark force-carrying particles that are associated with a broken symmetry, which therefore get a mass and then can decay. They are more like 'dark Z bosons' than dark photons."

● Further reading

BaBar Collaboration 2017 arXiv:1702.03327.
NA64 Collaboration 2017 *Phys. Rev. Lett.* **118** 011802.

***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.*

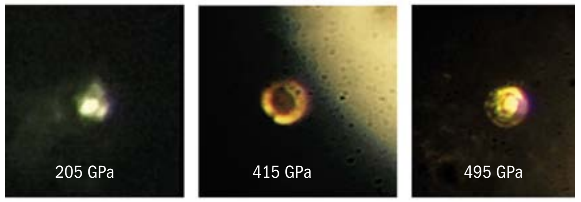
CERN Courier welcomes contributions from the international particle-physics community. These can be written in English or French, and will be published in the same language. If you have a suggestion for an article, please send proposals to the editor at cern.courier@cern.ch.

Sciencewatch

Compiled by John Swain, Northeastern University

Metallic hydrogen claimed

It has long been expected that hydrogen becomes metallic under sufficient pressure, and researchers have been edging closer to its production. Now, Ranga Dias and Isaac Silvera of Harvard University in the US report that they have finally observed the bizarre quantum state. Squeezed in a diamond-anvil cell to a pressure of 495 GPa, hydrogen becomes a shiny metal with a plasma frequency of 32.5±2.1 eV at a temperature of 5.5 K – a transition predicted more than 80 years ago by Wigner and Huntington. The metal may be metastable, remaining metallic when the pressure is removed, similarly to how diamond is formed at high pressures and retains its form under normal conditions. If metastable, it could have applications as a rocket fuel far more powerful than liquid hydrogen and oxygen, and may even be superconducting at room temperature.



Photos of a microscopic sample of hydrogen within a circular gasket at increasing pressures, showing the transition from a transparent (left) to opaque (centre) and reflective (right) state.

● **Further reading**
R Dias and I Silvera 2017 *Science* DOI: 10.1126/science.aal1579.

Time crystals

Time crystals are a new form of non-equilibrium matter that has periodic motion even in its ground state. Norman Yao of the University of California, Berkeley, and colleagues have published detailed instructions for how to make them and measure their properties, leading two groups to report experimental realisations: J Zhang of the University of Maryland and colleagues via a chain of trapped ions, and Soonwon Choi of Harvard University and colleagues, via an ensemble of dipolar-spin impurities in diamond. These are the first materials to break time-translation symmetry in a way that is analogous to the breaking of space-translation symmetry in crystals, opening a new chapter in experimental condensed-matter physics.

● **Further reading**
S Choi *et al.* 2016 arXiv:1610.08057v1.
N Yao *et al.* 2017 *Phys. Rev. Lett.* **118** 030401.
J Zhang *et al.* 2016 arXiv:1609.08684v1.

Cosmic Bell test

Bell's inequality, which provides a test of whether a system is quantum or classical, is usually derived on the assumption that there are no correlations between the experimenter's choice of measurement settings or anything else that could causally affect the outcomes. This leaves open the possibility that an unknown cause affects both the choice of settings and measurements before each trial – typically as little as microseconds before in experimental tests. A new "cosmic Bell test" by Johannes Handsteiner of the Institute for Quantum Optics and Quantum information in Vienna and colleagues uses light from distant astronomical sources to produce the settings. The work pushes back the most recent time that any local-realistic influences could have produced the observed Bell inequality violation by about 16 orders of magnitude, or approximately 600 years.

● **Further reading**
J Handsteiner *et al.* 2017 *Phys. Rev. Lett.* **118** 060401.

Human–pig genetics

The first successful human–animal hybrid has been created: a mixture of human and pig. Jun Wu of the Salk Institute in the US and colleagues built on previous work making chimeras from mice and rats, and managed to put human cells into developing pig embryos. The embryos were then inserted into adult pigs, which carried them for three to four weeks, after which they were removed and studied. Although considered controversial, the work demonstrates that human cells can be made to survive and grow inside of a host animal, bolstering hopes for better ways to make organs without the need for human donors.

The observations raise the possibility of generating transplantable human tissue.

● **Further reading**
Jun Wu *et al.* 2017 *Cell* **168** 473.

Giant quantum computer

An ambitious proposal suggests that a giant quantum computer able to solve currently computationally unsolvable problems such as factoring large numbers could be built based on existing technology. Winfried Hensiger of the University of Sussex in the UK and colleagues propose a football-field-sized microwave-coupled trapped-ion quantum computer using thousands of hand-sized modules, each containing 2500 trapped-ion qubits, which could be joined to make an arbitrarily large computer. To factor a 2048 bit (617 digit)-long number (a task impossible on classical computers today) would need, including error correction, some two billion qubit ions, and the calculation would take around 110 days. Quantum computing might start to develop along lines similar to experimental high-energy physics with large facilities funded by international collaborations.

● **Further reading**
B Leksitch *et al.* 2017 *Sci. Adv.* **3** e1601540.

Astrowatch

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

Gravitational lens challenges cosmic expansion

Using galaxies as vast gravitational lenses, an international group of astronomers has made an independent measurement of how fast the universe is expanding. The newly measured expansion rate is consistent with earlier findings in the local universe based on more traditional methods, but intriguingly remains higher than the value derived by the Planck satellite – a tension that could hint at new physics.

The rate at which the universe is expanding, defined by the Hubble constant, is one of the fundamental quantities in cosmology and is usually determined by techniques that use Cepheid variables and supernovae as points of reference. A group of astronomers from the H0LiCOW collaboration led by Sherry Suyu of the Max Planck Institute for Astrophysics in Germany, ASIAA in Taiwan and the Technical University of Munich, used gravitational lensing to provide an independent measurement of this constant. The gravitational lens is made of a galaxy that deforms space–time and hence bends the light travelling from a background quasar, which is an extremely luminous and variable galaxy core. This bending results in multiple images, as seen from Earth, of the same quasar that are almost perfectly aligned with the lensing galaxy (see image).

While being simple in theory, in practice the new technique is rather complex. A straightforward equation relates the Hubble constant to the length of the deflected light rays between the quasar and Earth. Since the brightness of a quasar changes over time, astronomers can see the different images of the quasar flicker at different times, and the delays between them depend on the lengths of the paths the light has taken. Deriving the Hubble constant therefore depends on very precise modelling of the distribution of the mass in the lensing galaxy, as well as on several hundred accurate measurements of the multiple images of the quasar to derive its variability pattern over many years.


ESA/Hubble, NASA, Suyu *et al.*

The Hubble constant was derived by studying a gravitational lens called HE 0435-1223. The foreground galaxy creates four almost evenly distributed images of the distant quasar around it.

This complexity explains why the measurement of the Hubble constant – reported in a separate publication by H0LiCOW collaborator Vivien Bonvin from the EPFL in Switzerland and co-workers – relies on a total of four papers by the H0LiCOW collaboration. The obtained value of $H_0 = 71.9 \pm 2.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ is in excellent agreement with other recent determinations in the local universe using classical cosmic-distance ladder methods. One of these, by Adam Riess and collaborators, finds an even higher value of the Hubble constant ($H_0 = 73.2 \pm 1.7\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$) and has therefore triggered a lot of interest in recent months.

The reason is that such values are in tension with the precise determination of the Hubble constant by the Planck satellite. Assuming standard "Lambda Cold Dark Matter" cosmology, the Planck collaboration derived from the cosmic-microwave-background radiation a value of $H_0 = 67.9 \pm 1.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ (*CERN Courier* May 2013 p12). The discrepancy between Planck's probe of the early universe and local values of the Hubble constant could be an indication that we are missing a vital ingredient in our current understanding of the universe.

A possible explanation of this discrepancy, according to Riess and colleagues, could involve an additional source of dark radiation in the early universe, corresponding to a significant increase in the effective number of neutrino species. It will be interesting to follow this debate in the coming years, when new observing facilities and also new parallax measurements of Cepheid stars by the Gaia satellite will reduce the uncertainty of the Hubble constant determination to a per cent or less.

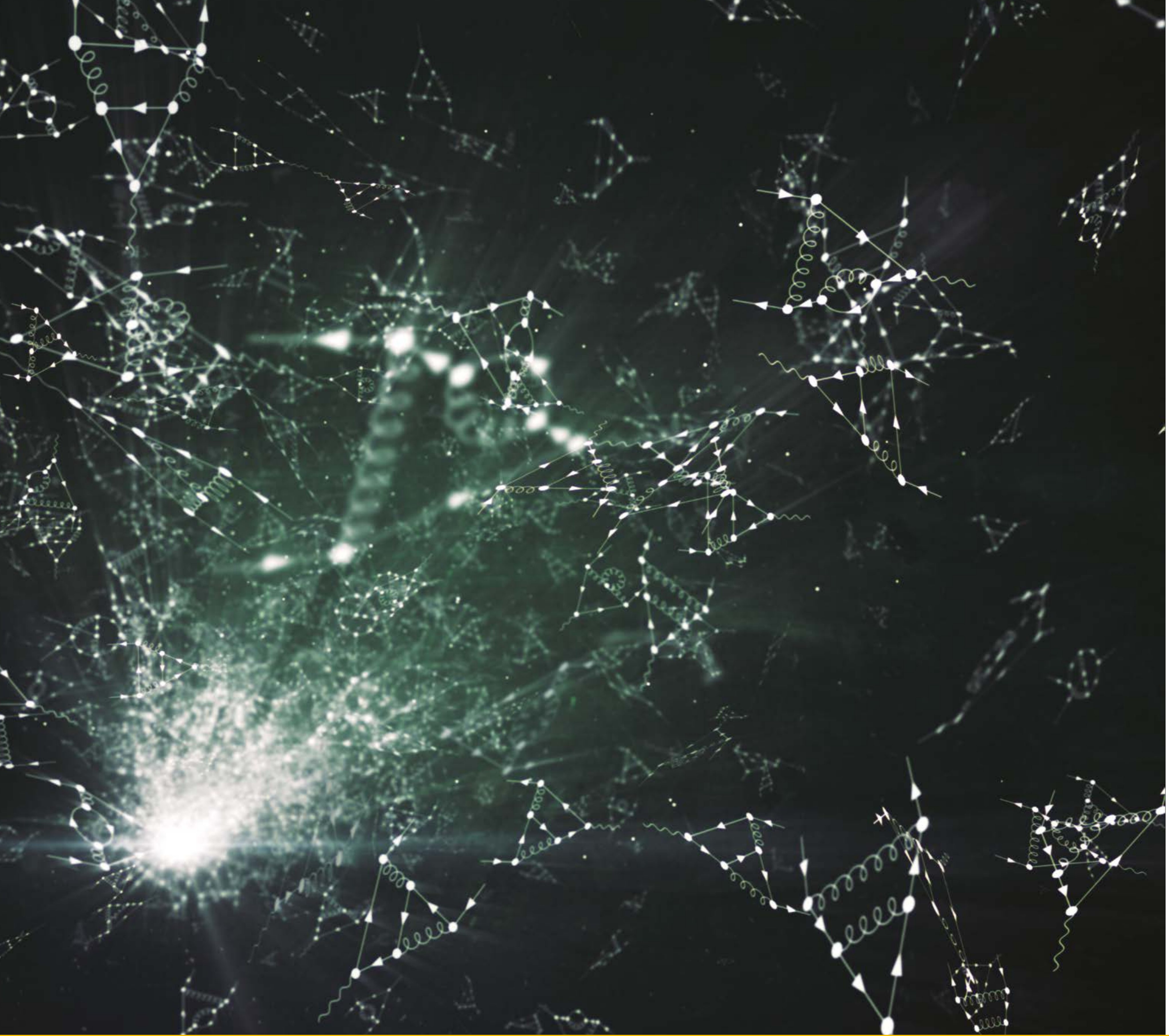
● **Further reading**

V Bonvin *et al.* 2017 *MNRAS* **465** 4914.
A Riess *et al.* 2016 *ApJ* **826** 56.

Picture of the month

The night sky holds many stunning views, and this is certainly one of them. This pair of galaxies called Arp 142 is better known as the Porpoise Galaxy, although it rather looks like a penguin guarding its egg. Reprocessed recently, this image by the Hubble Space Telescope reveals in magnificent detail the strange shape of a former normal spiral galaxy (NGC 2936, on top) now stretched and twisted by the gravitational force of its elliptical companion (NGC 2937, below). The blue skin of the "penguin" comes from massive, young and hot stars recently formed by gas compression due to the gravitation interaction. On the contrary, the white colour of the "egg" means that there is currently very little gas and star-forming activity in this galaxy, which is mainly composed of old stars. The brownish dust lines artistically cross near the penguin's eye, which is the core of the spiral galaxy and likely the last part to be disrupted in the merging process foreseen in about a billion years from now, far away in the Hydra constellation.


NASA, ESA, Hubble, HLA; Reprocessing & Copyright: Raul Villaverde



The two-loop explosion

During the past two years there has been a burst of activity in next-to-next-to-leading order calculations to ensure that theory keeps up with the increasing precision of LHC measurements.

Studying matter at the highest energies possible has transformed our understanding of the microscopic world. CERN's Large Hadron Collider (LHC), which generates proton collisions at the highest energy ever produced in a laboratory (13 TeV), provides a controlled environment in which to search for new phenomena and to address fundamental questions about the nature of the interactions between elementary particles. Specifically, the LHC's main detectors – ATLAS, CMS, LHCb and ALICE – allow us to measure the cross-sections of elementary processes with remarkable precision. A great challenge for theorists is to match the experimental precision with accurate theoretical predictions. This is necessary to establish the Higgs sector of the Standard Model of particle physics and to look for deviations that could signal the existence of new particles or forces. Pushing our current capabilities further is key to the success of the LHC physics programme.

Underpinning the prediction of LHC observables at the highest levels of precision are perturbative computations of cross-sections. Perturbative calculations have been carried out since the early days of quantum electrodynamics (QED) in the 1940s. Here, the smallness of the QED coupling constant is exploited to allow the expressions for physical quantities to be expanded in terms of the coupling constant – giving rise to a series of terms with decreasing magnitude. The first example of such a calculation was the one-loop QED correction to the magnetic moment of the electron, which was carried out by Schwinger in 1948. It demonstrated for the first time that QED was in agreement with the experimental discovery of the anomalous magnetic moment of the electron, g_e-2 (the latter quantity was dubbed "anomalous" precisely because, prior to Schwinger's calculation, it did not agree with predictions from Dirac's theory). In 1957, Sommerfeld and Petermann computed the two-loop correction, and it

▷

Next-to-next-to-leading order (NNLO) Feynman diagrams relevant to the LHC physics programme. (Image credit: Daniel Dominguez, CERN.)

took another 40 years until, in 1996, Laporta and Remiddi computed analytically the three-loop corrections to g_e-2 and, 10 years later, even the four- and five-loop corrections were computed numerically by Kinoshita *et al*. The calculation of QED corrections is supplemented with predictions for electroweak and hadronic effects, and makes g_e-2 one of the best known quantities today. Since g_e-2 is also measured with remarkable precision, it provides the best determination of the fine-structure constant with an error of about 0.25 ppb. This determination agrees with other determinations, which reach an accuracy of 0.66 ppb, showcasing the remarkable success of quantum field theory in describing material reality.

In the case of proton–proton collisions at the LHC, the dominant processes involve quantum chromodynamics (QCD). Although in general the calculations are more complex than in QED due to the non-abelian nature of this interaction, i.e. the self-coupling of gluons, the fact that the QCD coupling constant is small at the high energies relevant to the LHC means that perturbative methods are possible. In practice, all of the Feynman diagrams that correspond to the lowest-order process are drawn by considering all possible ways in which a given final state can be produced. For instance, in the case of Drell–Yan production at the LHC, the only lowest-order diagram involves an incoming quark and an incoming antiquark from the proton beams, which annihilate to produce a Z, γ^* or a W boson, which then decays into leptons. Using the Feynman rules, such pictorial descriptions can be turned into quantum-mechanical amplitudes. The cross-section can then be computed as the square of the amplitude, integrated over the phase space and appropriately summing and averaging over quantum numbers.

This lowest-order description is very crude, however, since it does not account for the fact that quarks tend to radiate gluons. To incorporate such higher-order quantum corrections, next-to-leading order (NLO) calculations that describe the radiation of one additional gluon are required. This gluon can either be real, giving rise to a particle that is recorded by a detector, or virtual, corresponding to a quantum-mechanical fluctuation that is emitted and reabsorbed. Both contributions are divergent because they become infinite in the limit when the energy of the gluon is infinitesimally small, or when the gluon is exactly collinear to one of the emitting quarks. When real and virtual corrections are combined, however, these divergences cancel out. This is a consequence of the so-called Kinoshita–Lee–Nauenberg theorem, which states that low-energy (infrared) divergences must cancel in physical (measurable) quantities.

Even if divergences cancel in the final result, a procedure to handle divergences in intermediate steps of the calculations is still needed. How to do this at the level of NLO corrections has been well understood for a number of years. The first successes of NLO QCD calculations came in the 1990s with the comparison of Drell–Yan particle-production data recorded by CERN's SPS and Fermilab's Tevatron experiments to leading-order and NLO QCD predictions, which had first been computed in 1979 by Altarelli, Ellis and Martinelli. The comparison revealed unequivocally that NLO corrections are required to describe Drell–Yan data, and marked the first great success of perturbative QCD (figure 1).

Compared to NLO calculations, NNLO are substantially more complex.

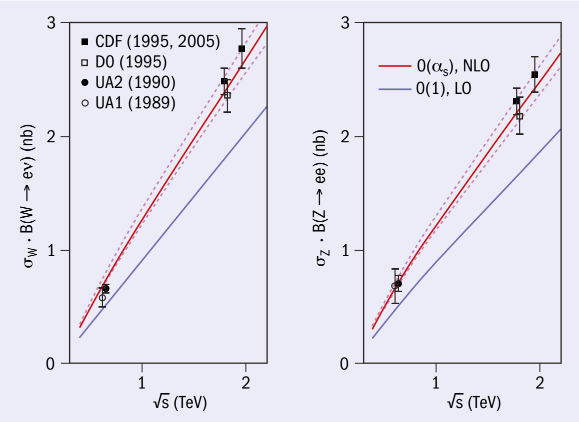


Fig. 1. Comparison of inclusive W-production (left) and Z-production (right) data with leading-order (blue) and NLO (red, with uncertainty in pink) predictions.

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Things have changed a lot since then. Today, NLO corrections have been calculated for a large class of processes relevant to the LHC programme, and several tools have been developed to even compute them in a fully automated way. As a result, the problem of NLO QCD calculations is considered solved and comparing these to data has become standard in current LHC data analysis. Thanks to the impressive precision now being attained by the LHC experiments, however, we are now being taken into the complex realm of higher-order calculations.

The NNLO explosion

The new frontier in perturbative QCD is the calculation of next-to-next-to-leading order (NNLO) corrections. At the level of diagrams, the picture is once again pretty simple: at NNLO level, it is not just one extra particle emission but two extra emissions that are accounted for. These emissions can be two real partons (quarks or gluons), a real parton and a virtual one, or two virtual partons.

The first NNLO computation for a collider process concerned "inclusive" Drell–Yan production, by Hamberg, Van Neerven and Matsuura in 1991. Motivated by the SPS and Tevatron data, and also by the planned LHC and SSC experiments, this was a pioneering calculation that was performed analytically. The second NNLO calculation, in 2002, was for inclusive Higgs production in gluon–gluon fusion by Harlander and Kilgore. Inclusive calculations refer only to the total cross-section for producing a Higgs boson or a Drell–Yan pair without any restriction on where these particles end up, which is not measurable because detectors do not cover the entire phase space such as the region close to the beam.

The first "exclusive" NNLO calculations, which allow kinematic cuts to be applied to the final state, started to appear in 2004 for Drell–Yan and Higgs production. These calculations were motivated by the need to predict quantities that can be directly measured, rather then relying on extrapolations to describe the effects of experimental cuts. The years 2004–2011 saw more activity, but limited progress: all calculations were essentially limited to "2 → 1" scattering processes, in essence Higgs and Drell–Yan production, as well as Higgs production in association with a Drell–Yan pair. From a QCD point of view, the latter process is simply off-shell Drell–Yan production in which the vector boson radiates a Higgs. A few 2 → 2 calculations started to appear in 2012, most notably top-pair production and the production of a pair of vector bosons. It is only in the past two years, however, that we have witnessed an explosion of NNLO calculations (figure 2). Today, all 2 → 2 Standard Model LHC scattering processes are known to NNLO, thanks to remarkable progress in the calculation of two-loop integrals and in the development of procedures to handle intermediate divergences.

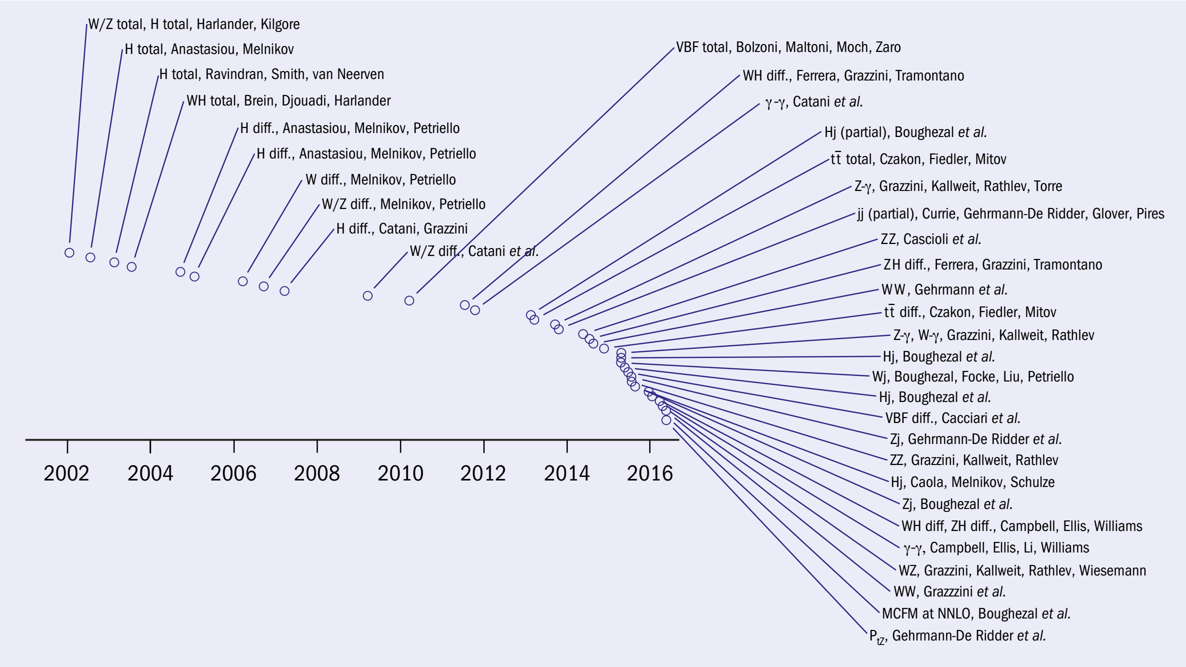

Fig. 2. The completion date and main authors of various NNLO calculations, with vertical separations for display purposes.

From the talk given by G P Salam at the 2016 LHCP conference.

Compared to NLO calculations, NNLO calculations are substantially more complex. Two main difficulties must be faced: loop integrals and divergences. Two-loop integrals have been calculated in the past by explicitly performing the multi-dimensional integration, in which each loop gives rise to a "D-dimensional" integration. For simple cases, analytical expressions can be found, but in many cases only numerical results can be obtained for these integrals. The complexity increases with the number of dimensions (i.e. the number of loops) and with the number of Lorentz-invariant scales involved in the process (i.e. the number of particles involved, and in particular the number of massive particles).

Recently, new approaches to these loop integrals have been suggested. In particular, it has been known since the late 1990s that integrals can be treated as variables entering a set of differential equations, but solutions to those equations remained complicated and could be found only on a case-by-case basis. A revolution came about just three years ago when it was realised that the differential equations can be organised in a simple form that makes finding solutions, i.e. finding expressions for the wanted two-loop integrals, a manageable problem. Practically, the set of multi-loop integrals to be computed can be regarded as a set of vectors. Decomposing these vectors in a convenient set of basis vectors can lead to significant simplifications of the differential equations, and concrete criteria were proposed for finding an optimal basis. The very important NNLO calculations of diboson production have benefitted from this technology.

Currently, when only virtual massless particles are involved and up to a total of four external particles are considered, the two-loop integral problem is considered solved, or at least solvable. However, when massive particles circulate in the loop, as is the case for a number of LHC processes, the integrals give rise to a new class of functions, elliptic functions, and it is not yet understood how to solve the associated differential equations. Hence, for processes with internal massive particles we still face a conceptual bottleneck. Overcoming this will be very important for Higgs studies at large transverse momentum, where the top loop to which the Higgs couples is resolved. The calculation of these integrals is today an area with tight connections to more formal and mathematical areas, leading to close collaborations between the high-energy physics and the mathematical/formal-oriented communities.

The second main difficulty in NNLO calculations is that, as at NLO, individual contributions are divergent in the infrared region, i.e. when particles have a very small momentum or become collinear with respect to one another, and the structure of these singularities is now considerably more complex because of the extra particle radiated at NNLO. All singularities cancel when ▷

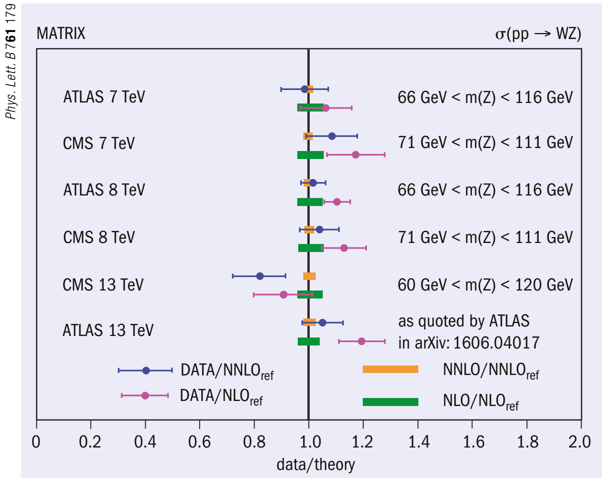

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Fig. 3. Comparison of LHC data for the WZ production cross-section versus NLO (magenta) and NNLO QCD (blue) predictions.

all contributions are combined, but to have exclusive predictions it is necessary to cancel the singularities before performing integrations over the phase space. Compared to NLO, where systematic ways to treat these intermediate divergences have been known for many years, the problem is more difficult at NNLO because there are more divergent configurations and different divergences overlap. The past few years have seen remarkable developments in the understanding and treatment of infrared singularities in NNLO computations of cross-sections, and a range of methods based on different physical ideas have been successfully applied.

Beyond NNLO

Is the field of precision calculations close to coming to an end? The answer is, of course, no. First, while the problem of cancelling singularities is in principle solved in a generic way, in practice all methods have been applied to $2 \to 2$ processes only, and no $2 \to 3$ cross-section calculation is foreseen in the near future. For instance, the very important processes of three-jet production or Higgs production in association with a top-quark pair are known to NLO accuracy only. Similarly, two-loop pentagon integrals required for the calculation of $2 \to 3$ scatterings are at the frontier of what can be done today. Furthermore, most of the existing NNLO computer codes require extremely long runs on large computer farms, with typical run times of several CPU years. It could be argued that this is not an issue in an age of large computer farms and parallel processing and when CPU time is expected to become cheaper over the years, however, the number of phenomenological studies that can be done with a theory prediction is much larger when calculations can be performed quickly on a single machine. Hence, in the coming years NNLO calculations will be scrutinised and compared in terms of their performances. Ultimately, only one or a few of the many existing methods to perform integrals and to treat intermediate divergences is likely to take over.

Given how hard and time-consuming NNLO calculations are, we should also ask if it is worth the effort. A comparison with data for the diboson (WZ) production process at different LHC beam energies to NLO and NNLO calculations (figure 3) provides an indication of the answer. It is clear that LHC data already indicate a clear preference for NNLO QCD predictions and that, once more data are accumulated, NLO will likely be insufficient. While it is early days for NNLO phenomenology, the same conclusion applies to other measurements examined so far.

In the past, accurate precision measurements have provided a strong motivation to push the precision of theoretical predictions. On the other side, very precise theory predictions have stimulated even more precise measurements. Today, the accuracy reached by LHC measurements is by far better than what anybody could have predicted when the LHC was designed. For instance, the Z transverse momentum spectrum reaches an accuracy of better than a per cent over a large range of transverse momentum values, which will be important to further constrain parton-distribution functions, and the mass of the W boson, which enters precision tests of the Standard Model, is measured with better than 20 MeV accuracy. In the future, one should expect that high-precision theoretical predictions will push the experimental precision beyond today's foreseeable boundaries. This will usher in the next phase in perturbative QCD calculations: next-to-next-to-next-to-leading order, or N^{3}LO.

Today we have two pioneering calculations beyond NNLO: the N^{3}LO calculation of inclusive Higgs production (in the large top-mass approximation), and the N^{3}LO calculation of inclusive vector-boson-fusion Higgs production. Both calculations are inclusive over radiation, exactly in the same way that the first NNLO calculations were. These calculations are now suggestive of a good convergence of the perturbative expansion, meaning that the N^{3}LO correction is very small and that the N^{3}LO result lies well within the theoretical uncertainty band of the NNLO result. Turning these calculations into fully exclusive predictions is the next theoretical challenge.

● Further reading

T Aoyama *et al.* 2012 *Phys. Rev. Lett.* **109** 111807.
T Becher 2016 arXiv:1607.01165.
C Duhr 2014 arXiv:1411.7538.
J M Henn 2013 *Phys. Rev. Lett.* **110** 251601.
M Passera 2005 *J. Phys. G* **31** R75.

Résumé

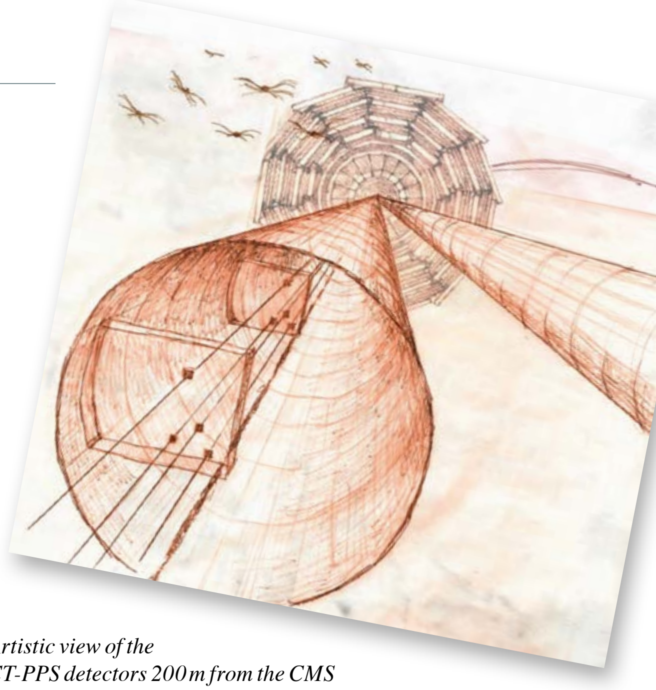
L'explosion des doubles boucles

Ces deux dernières années, l'univers des calculs de l'ordre sous-sous-dominant (NNLO) a connu une activité frénétique, qui visait à permettre à la théorie de tenir le rythme des expériences. Les prédictions sur les observations du LHC s'appuient sur des calculs perturbatifs des sections efficaces, et les corrections NLO ont déjà été calculées pour une grande partie des processus pertinents pour le programme du LHC. Or, étant donné la précision impressionnante qu'atteignent à présent les expériences LHC, nous nous retrouvons maintenant dans le royaume complexe des calculs d'ordre plus élevé, où l'activité a explosé ces derniers mois.

Giulia Zanderighi, CERN and University of Oxford.

Looking forward to photon–photon physics

Precision spectrometers situated on either side of the LHC's CMS experiment will probe the quartic couplings of electroweak bosons and other signs of new physics.



Artistic view of the CT-PPS detectors 200 m from the CMS detector, showing the silicon pixels inside the Roman pots. (Image credit: Sergio Cittolin.)

As its name suggests, the Large Hadron Collider (LHC) at CERN smashes hadrons into one another – protons, to be precise. The energy from these collisions gets converted into matter, producing new particles that allow us to explore matter at the smallest scales. The LHC does not fire protons into one another individually; instead, they are circulated in approximately 2000 bunches each containing around 100 billion protons. When two bunches are focused magnetically to cross each other in the centre of detectors such as CMS and ATLAS, only 30 or so protons actually collide. The rest continue to fly through the LHC unimpeded until the next time that two bunches cross.

Occasionally, something very different happens. If two protons travelling in opposite directions pass very close to one another, photons radiated from each proton can collide and produce new particles. The two parent protons remain completely intact, continuing their path in the LHC, but the photon–photon interaction removes a fraction of their initial energy and causes them to be slightly deflected from their original trajectories. By identifying the deflected protons, one can determine whether such photon interactions took place and effectively turn the LHC into a photon collider. It is also possible for the two protons to exchange pairs of gluons, which is another interesting process.

The idea of tagging deflected protons has been pursued at previous colliders, and also at the LHC back in 2012 and 2015 using only low-intensity beams. The proposal to pursue this type of physics with the LHC's CMS and/or ATLAS experiments was first presented many years ago, but the project (under the name FP420) did not materialise.

A new project called the CMS-TOTEM Precision Proton Spectrometer (CT-PPS) has now taken up the challenge of making photon–photon physics possible at the LHC when operating at nominal luminosity. While CMS is a general-purpose detector for LHC physics, CT-PPS uses two sets of detectors placed 200 m either side of the CMS interaction point to measure protons in the forward direction. A parallel project called ATLAS Forward Physics (AFP) is also being developed by ATLAS, and both experiments aim to be in operation throughout this year's LHC proton–proton run.

Light collisions

Despite photons being electrically neutral, the Standard Model (SM) allows two photons to interact via the exchange of virtual charged particles. Several final states are possible (figure 1, overleaf), including a pair of photons. The latter process ($\gamma\gamma \to \gamma\gamma$, or "light-by-light scattering") has been known since the development of quantum electrodynamics (QED) and tested indirectly in several experiments, but the first direct evidence came last year from ATLAS in low-luminosity measurements of lead–lead collisions (*CERN Courier* December 2016 p9). Since the probability of emitting photons scales with the square of the electrical charge, the cross-section for lead–lead collisions is significantly higher than for proton–proton collisions. By searching for two photons and nothing else in the central detector and using kinematics cut to suppress backgrounds, the invariant mass of the two photons was in the region of 10 GeV. The measured cross-section was compatible with the QED prediction and, since ▷

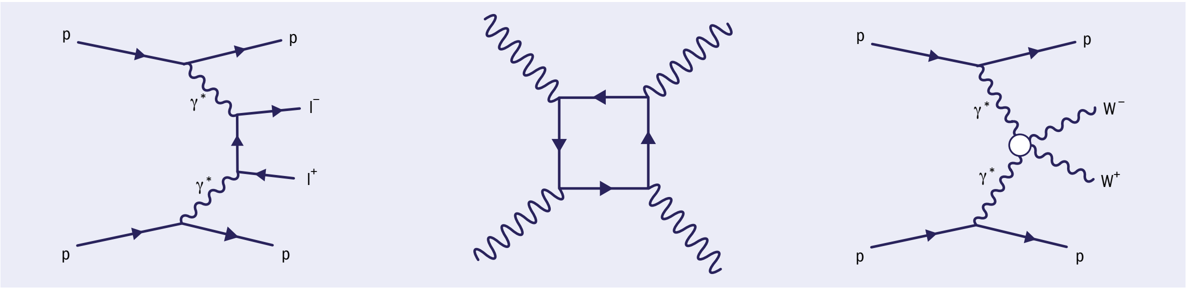


Fig. 1. The interaction between two photons can produce a lepton pair of opposite charge (left), while light-by-light scattering (middle) involves a loop of virtual charged particles and therefore the corresponding cross-section is very low. Two photons may also interact with two W bosons in a quartic vertex (right), which is a four-point interaction. The white circle suggests the interesting possibility that this interaction involves new particles of high mass or new couplings.

no deviations are expected in this low-mass range, the ATLAS result was interesting but somewhat expected.

In forward experiments such as CT-PPS and AFP, however, the high-luminosity proton collisions allow a much higher mass region to be probed – between 300 GeV and 2 TeV in the case of CT-PPS. Proton tagging is possible because centrally produced high-mass systems cause the protons to lose enough energy to be deflected into the CT-PPS detectors. The study of photon interactions in this region could therefore provide new insights about the electroweak interaction, in particular the quartic gauge couplings predicted by the SM. These are interactions where two photons annihilate upon collision to produce two W bosons, implying four particles at the same vertex in a Feynman diagram (figure 1). Deviations from the SM prediction would point to new physics in the same way as the observations of deviations from the quartic coupling in Fermi's beta-decay theory in the 1930s were the forerunner to the discovery of the W boson 50 years later.

If there are new particles with masses above 300 GeV, CT-PPS could also improve CMS's general discovery potential. For example, diphoton resonances at high mass have a very clean signature almost free of any background. Thus, in addition to precision electroweak tests, forward experiments such as CT-PPS provide an important cross-check of "bumps" in invariant mass distributions by offering complementary information about the production mechanism, coupling and quantum numbers of a possible new resonance. An example of this complementarity concerns the now-infamous 750 GeV bump in the diphoton invariant-mass distributions from the LHC's 2015 data set. Although the bump turned out to be a statistical effect, it provided strong motivation to advance the CT-PPS physics programme at the time. Were similar bumps to be observed by CMS and ATLAS in future, CT-PPS and AFP will play an important role in determining whether a real resonance is responsible for the excesses seen in the data.

Photon–photon collisions have been a topic of some interest for many decades.

Forward thinking

Given their potential for revealing new physics, photon–photon collisions have been a topic of some interest for many decades. For example, photon–photon collisions were studied at CERN's Large Electron Positron (LEP), while studies at DESY's HERA and Fermilab's Tevatron colliders concentrated on interactions of protons through the exchange of gluons to probe quantum chromodynamics in the non-perturbative regime. The LHC achieves a much higher energy and luminosity than LEP, but at the price of colliding particles that are not elementary. Therefore, the elementary interactions between gluons and quarks do not have well-defined energies and the interaction products include the remnants of the two protons, making physics analyses more difficult in general.

Proton-tagged photon collisions at the LHC, on the other hand, are very clean. Since photons are elementary particles and there are no proton remnants, the photon–photon collision energy at the LHC is precisely defined by the kinematics of the two tagged protons. In conjunction with CT-PPS, CMS can therefore probe anomalous quartic couplings with much better sensitivity than before.

The physics we are interested in corresponds to the process $pp \rightarrow ppX$, where the "pp" part is measured by the CT-PPS detectors and the system "X" is measured in the other CMS subdetectors. In the case of the quartic coupling $\gamma\gamma WW$, for instance, the process is $pp \rightarrow ppWW$. The two photons that merge into two W are not measured directly, but energy-momentum conservation allows all of the kinematic properties of the WW pair to be deduced much more precisely from the CT-PPS proton measurements than could be achieved from the measurements of W decay products with the CMS detector alone.

The CT-PPS detectors are located on either side of CMS, 200 m from the interaction point. They rely on objects called Roman Pots (RP), which are cylinders that allow small detectors to be moved into the LHC beam pipe so that they sit a mere few mm from the beam. The RPs of TOTEM are designed to operate under special LHC runs with a small number of collisions per second. However, the physics goals of CT-PPS require the RPs to operate during normal CMS data-taking, when the LHC provides a much higher number of collisions per second. The first and most important goal of the CT-PPS project was therefore to demonstrate that the detectors could operate successfully only a few millimetres from the LHC's high-intensity beams. The final demonstration happened between April and May 2016, and the green light for CT-PPS operation in regular high-luminosity LHC running was given the following month.

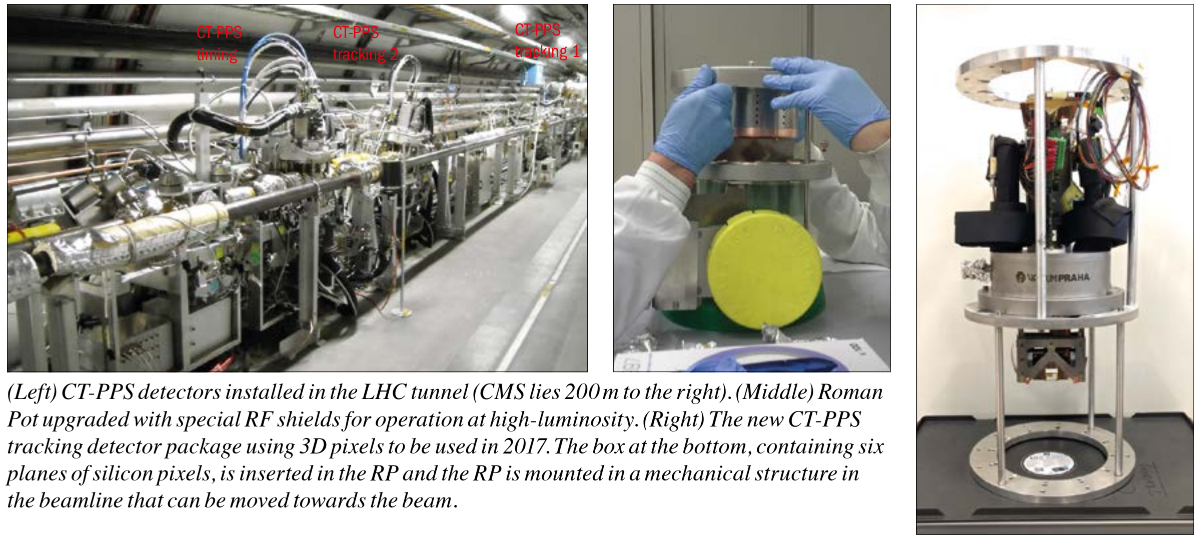


Image credits: CERN

(Left) CT-PPS detectors installed in the LHC tunnel (CMS lies 200 m to the right). (Middle) Roman Pot upgraded with special RF shields for operation at high-luminosity. (Right) The new CT-PPS tracking detector package using 3D pixels to be used in 2017. The box at the bottom, containing six planes of silicon pixels, is inserted in the RP and the RP is mounted in a mechanical structure in the beamline that can be moved towards the beam.

Success so far

The CT-PPS project redesigned the RPs to suit these harsh operating conditions. In collaboration with LHC teams, they also conducted a thorough programme of RP insertions at increasingly closer distances to the beam, measuring its impact on beam monitors. Great care must be taken not to disrupt the beam, since if the protons start to scrape the RPs there would be an increase in secondary particles that would trigger a beam dump. In 2016, CT-PPS used non-final detectors to collect 15.2 fb^{-1} of data integrated in the CMS data set. CT-PPS has proven for the first time the feasibility of operating a near-beam proton spectrometer at high luminosity on a regular basis and has paved the way for other such spectrometers.

CT-PPS is also facing big challenges in the development of the final detectors. The tracking detectors have a surface area of just 2 cm^2 and reside in two RPs located 10 m apart on either side of the collision point (for a total of four stations). Six planes of silicon pixels on each station will detect the track of the flying protons to provide direction information, and the magnetic field of the LHC's magnets will serve as the proton-deflecting field. The devices themselves have to sustain exceedingly high radiation fluxes given their proximity to the beam: a proton fluence in excess of 5×10^{15} particles/cm^2 is expected after an integrated luminosity of 100 fb^{-1}. CMS's own tracker will not face these radiation conditions until the HL-LHC enters operation in the mid 2020s.

From 2017 onwards, CT-PPS will be using new 3D pixel technology that has been developed in view of upgrades to the CMS tracker and therefore provide valuable experience with the new sensors. The project also relies on high-precision timing detectors. CT-PPS matches the primary vertex of the collision measured in the central detector with the vertex position obtained from the difference of the time-of-arrival to the two protons, so that it can reject the background from spurious collisions piling up in the same bunch crossing. A time precision of 20 ps makes it possible to estimate the z-vertex with the 3 mm accuracy needed to reduce the background sufficiently. The timing detectors had used diamond sensors in 2016 and will add silicon low-gain avalanche diodes this year. Again, the experience acquired in a high-rate and high-radiation environment will be most valuable for CMS upgrades for HL-LHC.

Meanwhile, the ATLAS collaboration installed one arm of the AFP experiment in early 2016 and has taken data in special low-luminosity runs to study diffraction. The second AFP arm, with horizontal RP stations similar to those of CT-PPS, has also since been installed and its four-layer 3D silicon pixel detectors and new Cherenkov-based time-of-flight detectors are being assembled. They will be installed and commissioned before the LHC restarts in May this year. Like CT-PPS, AFP aims to participate in high-luminosity running throughout the year, with both operating in tandem to enhance the LHC's search for new physics.

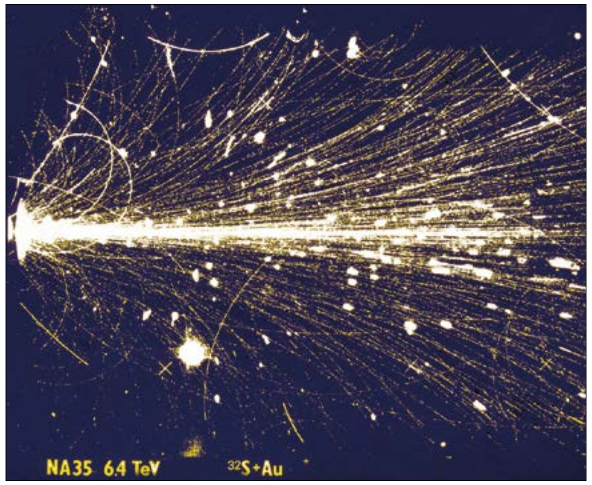
Résumé

La physique des collisions de photons bientôt d'actualité

Le LHC fait normalement entrer en collision des protons avec d'autres protons. Or, si deux protons circulant dans des sens opposés passent très près l'un de l'autre, les photons alors émis par chacun des protons peuvent entrer en collision et produire de nouvelles particules. Des spectromètres de précision situés en amont et en aval de l'expérience CMS et un projet semblable en cours de réalisation auprès d'ATLAS enregistreront ces événements afin de partir en quête des couplages quartiques des bosons électrofaibles et d'autres signes d'une nouvelle physique. Les deux dispositifs seront installés et mis en service avant le redémarrage du LHC au mois de mai prochain.

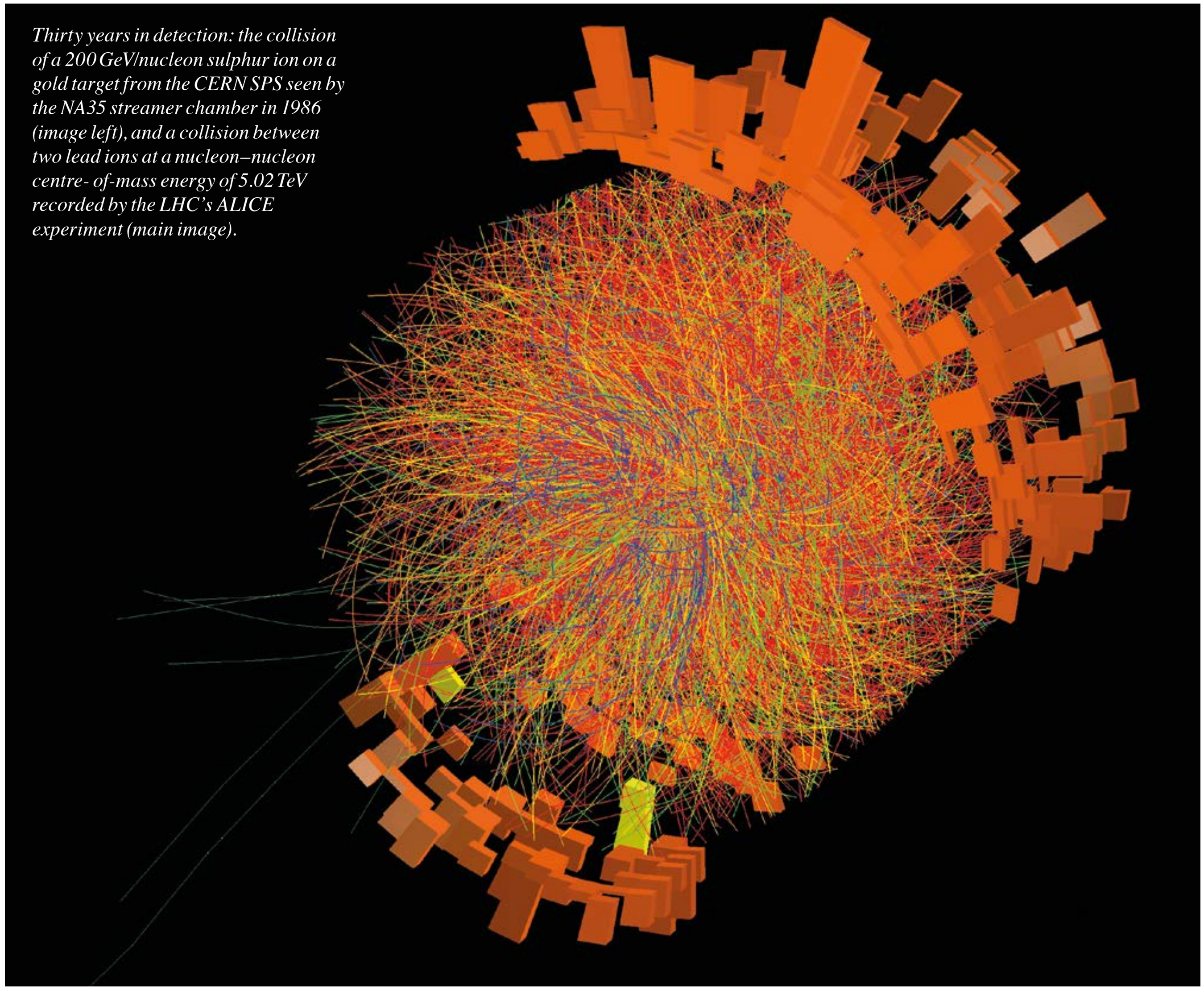
Achintya Rao, UWE Bristol, and **Joao Varela**, LIP.

A 30-year adventure with heavy ions



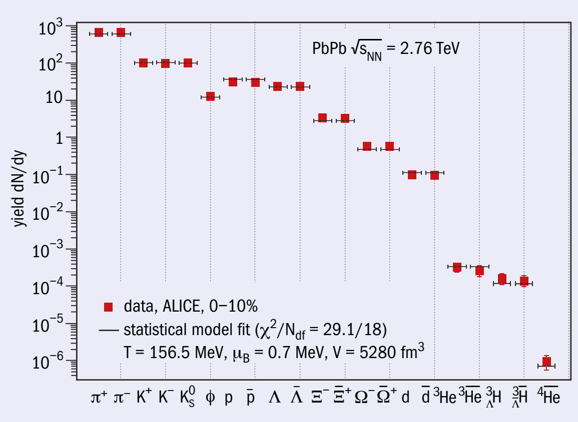
CERN EX-38-7-91

Three decades since the first ultrarelativistic collisions were produced at CERN, the field of heavy-ion physics could be about to enter a new paradigm.



Thirty years in detection: the collision of a 200 GeV/nucleon sulphur ion on a gold target from the CERN SPS seen by the NA35 streamer chamber in 1986 (image left), and a collision between two lead ions at a nucleon–nucleon centre- of-mass energy of 5.02 TeV recorded by the LHC's ALICE experiment (main image).

F Ronchetti/CERN



arXiv:1611.01347

During hadronisation of the QGP, final states range from non-strange and strange mesons and baryons to light nuclei. The data were recorded by ALICE in central lead–lead collisions at an energy of 2.76 TeV and fitted with a grand canonical thermal model with a temperature of 156 MeV.

Heavy-ion and proton–proton collisions at ultrarelativistic energies provide a unique system with which to investigate the dynamics of matter in the early universe. By generating an incredibly hot and dense "fireball" of fundamental particles, such collisions allow us to recreate the extreme conditions of the universe during its first tens of microseconds of existence.

Given that the universe did not become transparent until roughly 370,000 years after the Big Bang, this epoch in its history lies completely out of reach to observational astronomy. According to the Standard Model of particle physics, the emergence of elementary particles and forces took place via a succession of symmetry-breaking mechanisms at different energy scales as the universe expanded and cooled. In the early universe, matter was made of freely roaming quarks – which formed the quark–gluon plasma (QGP) – in addition to leptons and gauge bosons. The QGP cooled down until hadrons including baryons such as neutrons and protons were formed. Photons continued interacting with charged particles until most of the matter became bound in neutral atoms, after which they were set free to form today's cosmic microwave background.

During the past 30 years, a succession of collider experiments and impressive theoretical achievements have driven immense progress in the field of high-energy heavy-ion physics. Not only do these results shed new light on the dynamics of matter in the early universe, they probe fundamental predictions about the strong nuclear force governed by quantum chromodynamics (QCD).

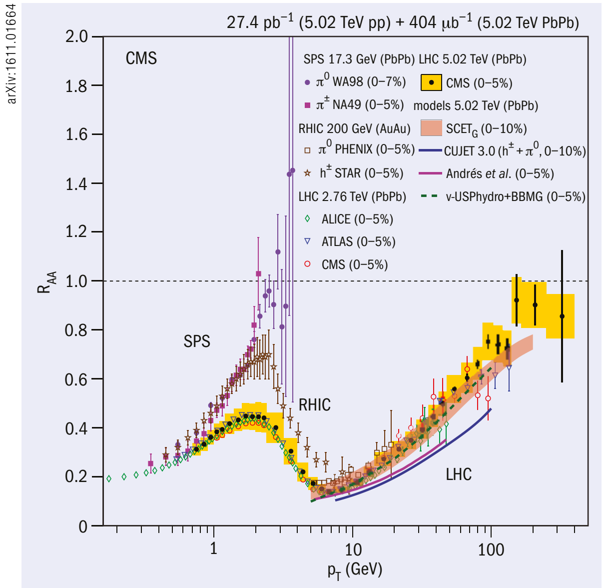
Surprises galore

We have come a long way from the early belief in the 1970s that this early phase in the universe, recreated by colliding heavy ions at continuously increasing energies, comprised a gas of quarks and gluons. This is what was expected following asymptotic freedom, a feature of QCD that explains how the interaction between two quarks becomes asymptotically weaker as the distance between them decreases. But it took three major colliders on both sides of the Atlantic to find out what was really going on during these extreme initial moments.

The first big result came from CERN in 2000, when it was announced that heavy-ion collisions generated by the Super Proton Synchrotron (SPS) had created a new state of matter. CERN's then Director-General, Luciano Maiani, worded the discovery as follows: From the combined data presented by the seven CERN experiments dedicated to the heavy-ion programme has emerged the clear picture that a new state of colour-deconfined matter has been created in the early stage of the collision that develops into a collective expansion of the fireball in the later stages.

This finding confirmed a fundamental prediction of QCD: above a critical temperature, quarks are no longer confined in hadrons. The CERN announcement was, however, only the beginning of our exploration into strongly interacting matter. The same year, the baton was passed to the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory in the US. Just five years after the CERN announcement, the remarkable data collected at RHIC demonstrated that a change of paradigm for strongly interacting matter was needed. The QGP that had been created in RHIC's STAR and PHENIX experiments did not have the properties of a perfect gas. Rather, it showed all the properties of a perfect liquid: a strongly interacting fluid with minimal mean free path.

With RHIC continuing to produce data, in 2010 CERN rejoined the heavy-ion programme with the newly operational Large Hadron Collider (LHC) and the dedicated heavy-ion experiment ALICE, ATLAS, CMS and, more recently, LHCb. This machine marked a factor 25 jump in collision energy compared with RHIC, and its experiments confirmed with unprecedented precision the STAR and PHENIX findings. The LHC also offered new opportunities to explore deconfined matter in great detail, with the goal of understanding how the dynamics of matter emerge from the fundamental properties of the strong interaction and from the quark infrastructure of particles. More recently, and surprisingly, LHC ▷



Measurements of the nuclear modification factors as a function of transverse momentum in central heavy-ion collisions at four different centre-of-mass energies, for neutral pions (SPS, RHIC), charged hadrons ($h^\pm$) (SPS, RHIC), and charged particles (LHC). Values of $R_{AA} < 1$ indicate that high-energy partons lose energy while traversing the QGP and thus carry information about its colour-charge density.

data are pointing to unexpected similarities between observables measured in heavy-ion collisions and those measured in proton–lead or in high-multiplicity proton–proton collisions, perhaps hinting at yet another change of paradigm.

The past 30 years have been an arduous path where every step both reveals more knowledge to us while simultaneously generating new riddles. To mark the important achievements so far and to discuss the long and thrilling future of heavy-ion physics, more than 400 physicists met at CERN on 9 November last year to review what can be considered as one of the most vigorous fields at the forefront of the high-energy physics programme.

A fitting celebration

Although accelerators had been working with electrons and protons for many decades, it was in 1974 when the Bevalac at Lawrence Berkeley Laboratory accelerated the first ions to relativistic energies (approximately 2 GeV per nucleon) and led to further programmes at BNL and CERN. The Bevalac beams were not energetic enough to create the necessary energy densities for the QGP to form, and it required the ingenuity of accelerator physicists and the remarkable development of electron cyclotron resonance (ECR) sources during the 1980s to take the decisive step toward "ultrarelativistic" energies.

The idea to launch an experimental heavy-ion programme at CERN came shortly after the SPS had enabled the discovery of the W and Z bosons in 1983. As the then CERN Director-General Herwig Schopper recalled at the November workshop, the 1980s were not the best time to initiate new projects. The CERN budget was severely cut and the laboratory was very much focused on the construction of the Large Electron–Positron Collider (LEP). Despite this, Schopper bravely decided to give heavy-ion physics a chance. He was motivated by arguments put forth by Reinhardt Stock, Hans Specht, Rudolf Bock, William Willis and several other leading physicists, but the main arguments that convinced him came from Tsung Dao Lee during a VIP lunch at CERN. Schopper recalled: "I knew [Lee] from the parity-violation experiment. He had no direct personal interest and his physics motivation sounded convincing. The main argument he put forward was to find the theoretically predicted quark–gluon plasma, which played an important role in the development of the universe."

When, in October 1986, oxygen-16 ions were successfully accelerated by the SPS and fired into a fixed target of gold, the heavy-ion programme began with a disparate ensemble of detectors recuperated from earlier high-energy experiments. Six different experiments were hatched, each with a different profile adapted to hunt the variety of observables predicted to accompany the QGP phase transition: WA80 "Plastic Ball"; the NA34/2 HELIOS; the NA35 streamer chamber; NA36; WA85/94; and the NA38 muon-pair spectrometer.

In 1987, together with the increase of energy and the acceleration of sulphur beams, second-generation experiments containing innovative detector technologies were launched. Among these were: NA49 with an ambitious time projection chamber; CERES and its double ring imaging Cherenkov detectors; NA57 and its silicon tracking; and NA44, which contained a focusing spectrometer that made use of cesium-iodide photocathodes for the first time. The number of aficionados of this new and intriguing field of investigation grew rapidly from a few hundred initial physicists to the several thousand from all over the world who work on today's LHC, SPS and RHIC heavy-ion facilities.

State of the art

Today, heavy-ion science is a thriving field of research, and it is notable that it is the common denominator in the physics programmes of all four major LHC experiments. On one hand, we have entered a phase of precision measurements of the QGP properties, while on the other hand the surprising similarities between proton–proton and proton–nucleon collisions observed at the LHC lead us to question if the same dynamics are at work in light and heavy systems. As demonstrated at the Quark Matter 2017 conference (see p39), many new results are generating discussion. On the experimental side, these are based on a wealth of high-quality data collected both at LHC and RHIC for a variety of collision systems and energies, coupled with inventive analysis tools. On the theory side, particular progress has been made in relativistic hydrodynamics calculations. Among many new and creative theoretical concepts is the non-perturbative formulation of string theory, which along with the "AdS/CFT" correspondence provides tools to perform calculations for the QGP in the strongly coupled regime.

Quarkonia states, another hard probe, have also revealed rich dynamics.

On 9 November 2016, more than 400 physicists came to CERN to celebrate three decades of heavy-ion physics.

Macroscopic properties of the QGP such as its density and viscosity can now be determined with increasing precision by studying how the QGP, modelled by hydrodynamics, transports a perturbation. Measurements include the value of high-order flow coefficients and nonlinear mode mixing, while the value of η/S (shear viscosity over entropy density) and its temperature dependence have been pinned down within a factor two or less to 1/4π – which is the conjectured minimal value for a perfect quantum fluid.

The microscopic structure of the QGP remains to be established, with the help of hard probes to provide the required resolving power. Here, jet quenching has already become a mundane phenomenon with which to study the content and dynamics of the QGP. In turn, the same studies also hint at the ability of the QGP to resolve the partonic shower. Quarkonia states, another hard probe, have also revealed rich dynamics. Their collision energy and transverse-momentum-dependent production can be understood in terms of two competing mechanisms: suppression due to resonance melting by colour screening and regeneration due to coalescence of free heavy-flavour quarks, both providing evidence for deconfinement. In addition, a flow signal has been measured for open and hidden charmed mesons, raising the question of whether charm quarks participate in the collective dynamics of the medium.

In general, the composition of the final hadronic state of the collision is quite well explained, assuming hadrons are formed in a thermalised state with a temperature that closely matches the temperature predicted for the QGP phase transition to the hadronic phase. Surprisingly, fragile objects such as light nuclei appear to be produced and to survive at temperatures several times larger than their binding energy. The possibility that nuclei were formed at the phase transition to hadrons, and not later via coalescence, would be an interesting complement to baryogenesis.

Strong future

As far as the next decades are concerned, in view of the achievements realised in the past years and the remaining open questions, it is a safe bet that heavy-ion physics will continue to be a vigorous field of research on both sides of the Atlantic. What are the relevant degrees of freedom of the QGP: perturbative partons, pseudo-particles, collective excitation of colour fields? Which dynamics drive the collision towards the formation of the QGP on timescales of a trillionth of a trillionth of a second, and in systems as small as a proton–proton collision? At which energy and which size does collectivity and statistical behaviour step in, and is chiral symmetry restored in the QGP?

These are some of the unanswered questions in the heavy-ion field. Existing and planned facilities that offer varying collision systems combined with ever more sophisticated detectors and strong collaborations between the theory and experiment communities are key to answering them. Based on what we are seeing currently, heavy-ion veteran Reinhard Stock commented that we could be about to enter a new paradigm with impact across high-energy physics. That would perhaps reveal QCD to be some sort of low-energy limit to a more fundamental theory.

● Further reading

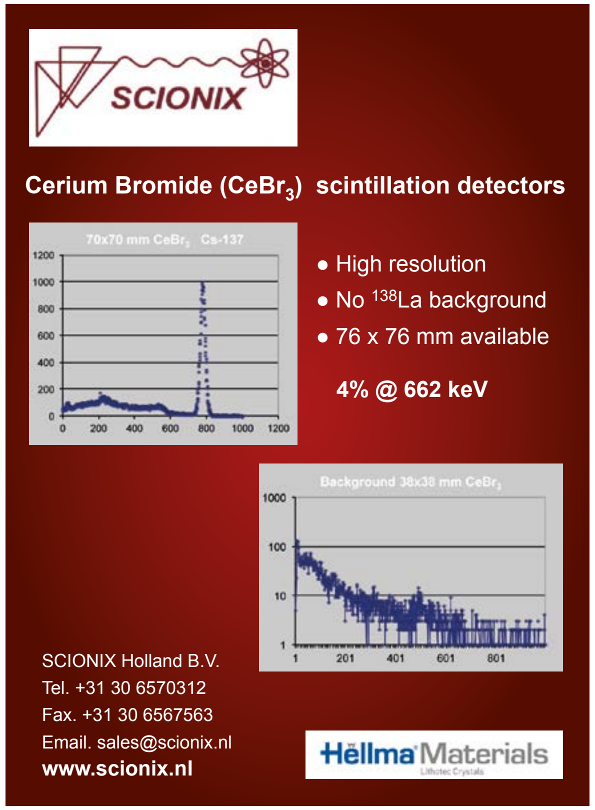
30 Years of Heavy ions: ...what next? indico.cern.ch/event/457044/timetable.

Résumé

Ions lourds : l'aventure dure depuis 30 ans

Trente ans après la production des premières collisions ultra-relativistes au CERN, l'étude de la physique des ions lourds est toujours d'actualité. Les collisions de haute énergie entre des ions lourds et entre des protons constituent un système unique où étudier la dynamique de la matière dans l'univers primordial et tester les prédictions fondamentales de la chromodynamique quantique. Une série d'expériences faisant appel à des collisionneurs et de prédictions théoriques remarquables ont permis de jeter un nouvel éclairage sur le plasma quarks-gluons et ont révélé qu'il a les propriétés d'un liquide parfait ; des mesures récentes laissent penser que ce domaine de recherche pourrait être au seuil d'un nouveau changement de paradigme.

Guy Paic, UNAM, Mexico, and **Yves Schutz**, IPHC, Strasbourg.




C Marcelloni/CERN

The LHCb detector at CERN is one of several experiments where unusual hadrons have appeared in the past few years.

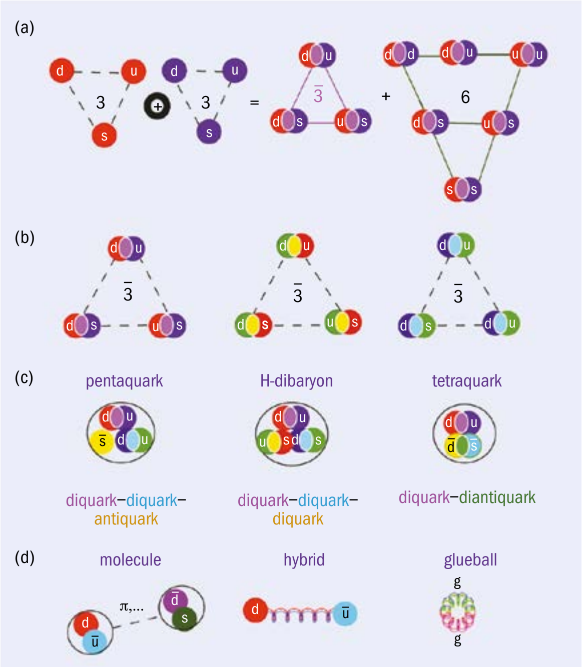
Exotic hadrons bend the rules

Half a century after the quark model was devised, a number of hadrons have been discovered that appear to challenge its axioms.

Fifty years have passed since Dick Dalitz presented his explicit constituent-quark model at the 1966 International Conference on High Energy Physics in Berkeley, US. Murray Gell Mann and George Zweig independently introduced the quark concept in 1964, and the idea had also been anticipated by André Petermann in a little-known paper received by *Nuclear Physics* in 1963. But it was Dalitz who developed the model and considered excitations of quarks by analogy with the behaviour of nucleons in atomic nuclei. His primary focus was on the spectroscopy of baryons, which were interpreted as bound states of three quarks. Dalitz realised that the restrictions enforced by the Pauli exclusion principle led to a distinct pattern of supermultiplets. Today, this simple model remains in excellent agreement with experiments, in particular for mesons that comprise a quark–antiquark pair.

Despite its success in matching empirical data, the theoretical underpinning of this non-relativistic model for light hadrons has always been unclear. One of the remarkable features of hadron spectroscopy is that, half a century after the invention of the constituent-quark model, the particle data tables are filled with states that fit with a non-relativistic spectrum almost to the exclusion of anything else. Quarks are but a few MeV in mass, and are therefore surely relativistic when confined within the 1 fm radius of a proton, yet the constituent-quark model treats them as if relativity plays no role.

▷



Front. Phys. **10** 101401

Fig. 1. Some of the ways in which QCD allows quarks to arrange into hadrons: (a) a red and blue quark triplet produces a magenta (anti-green) antitriplet and sextet; (b) three anticoloured diquark antitriplets; (c) exotic, colour-singlet states formed from quarks, antiquarks, diquarks and diantiquarks; and (d) other possible multiquark/gluon systems.

In the case of mesons, which fit the quark model arguably even better than baryons, this incongruity is especially significant. When Dalitz spoke in 1966, it made sense to emphasise baryons because they outnumbered the known mesons at that time. Following the discovery of charm and heavy flavours in the late 1970s, however, the spectroscopy of mesons flourished and the correlations among a meson's spin (J), parity (P) and charge conjugation (C) were also found to be in accord with those of a non-relativistic system.

Following Dalitz's description of the baryon spectrum, Greenberg, Nambu, Lipkin and others noted that the model's ad-hoc correlation of baryon spins with the constraints of the Pauli principle required some novel degree of freedom, which we call "colour". The advent of quantum chromodynamics (QCD) in the 1970s provided the rationale for this concept, explaining the existence of quark–antiquark or three-quark combinations in terms of colour-singlet clusters. But QCD did not explain the non-relativistic pattern of these states. Feynman, who in his final years devoted his attention to this issue, asserted: "The [non-relativistic] quark model is correct as it explains so much data. It is for theorists to explain why." Today, physicists still await this explanation. Yet the empirical guide of the quark model is so well established that hadrons outside of this straitjacket are deemed "exotic".

Although the restriction to colour singlets within QCD explains the existence of $q\bar{q}$ and qqq hadrons, it raised the question of why the spectroscopy of QCD is so meagre. Colour singlets also allow combinations of quarks and antiquarks ("tetraquark" mesons), four quarks and an antiquark ("pentaquark" baryons), in addition to states comprised solely of gluons ("glueballs"). Furthermore, combinations called "hybrids" in which the gluonic fields entrapping the quark and antiquark are themselves excited are also theoretically possible within QCD (figure 1). Glueballs, tetraquarks and hybrid mesons, predicted in the late 1970s, can form correlations among a meson's J, P and C quantum numbers that are forbidden by the non-relativistic model. Indeed, it is the lack of any empirical evidence for such exotic states in the meson spectrum that helped to establish the constituent-quark model in the first place. It is therefore ironic that searches for such states at modern experiments are now being used to establish the dynamic role of gluonic excitations in hadron spectroscopy.

Although QCD is well tested to high precision in the perturbative regime, where it is now an essential tool in the planning and interpretation of experiments, its implications for the strong-interaction limit are far less understood. Forty years after its discovery, and notwithstanding the advent of lattice QCD, hadron physics is still led by empirical data, from which clues to novel properties in the strong interactions may emerge. The search for exotic hadrons is an essential part of this strategy, and in recent years several new hadrons have been discovered that do not fit well within the traditional quark model.

Strange sightings

With hindsight, one of the first clues to the existence of quarks came in the 1950s from measurements of cosmic-ray interactions in the atmosphere, which revealed hadrons with unusual production and decay properties. These "strange" hadrons, we now know, contain one or more strange quarks or strange antiquarks, yet history has left us with a perverse convention whereby strange quarks are deemed to carry negative strangeness, and strange antiquarks are positive. Thus mesons can have one unit of strangeness, in either positive or negative amounts, while baryons can have strangeness –1, –2 or –3 (antibaryons, in turn, can have positive strangeness).

A baryon with positive strangeness (or an antibaryon with negative strangeness) is therefore classed as exotic. The minimal configuration for such a baryon would involve four quarks together with the strange antiquark, giving a total of five and the technically incorrect name of "pentaquark". A claim to have found such a state – the θ(1540) – made headlines nearly two decades ago but is now widely disregarded. The scepticism was not that a pentaquark exists, since QCD can accommodate such a state, but that it appeared to be anomalously stable. More recently, the LHCb experiment at CERN's Large Hadron Collider (LHC) reported decays of the Λ_b pentaquark-like baryon that revealed similar structures with a mass of around 4.4 GeV (*CERN Courier* September 2015 p5). These have normal strong-interaction lifetimes and have been interpreted as clusters of three quarks plus a charm–anticharm pair. Whether these are genuinely compact pentaquarks, or instead bound states of a charmed baryon and a meson or some other dynamic artefact, they do appear to qualify as "exotic" in that they do not fit easily into a traditional three-constituent picture.

The empirical guide of the quark model is so well established that hadrons outside of this straitjacket are deemed "exotic".

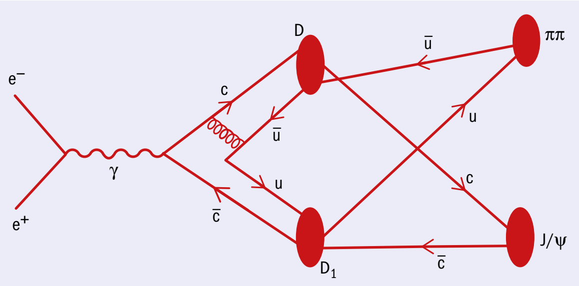
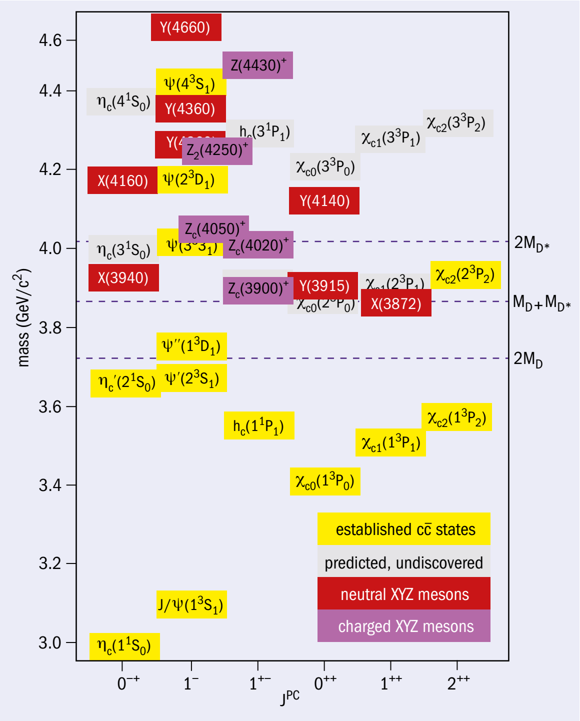


Fig. 2. At 4.6 GeV, e^+e^- annihilation produces DD_1 at threshold. The $(c\bar{u})(\bar{c}u)$ content rearranges into $(c\bar{c})(u\bar{u}) \to J/\psi\pi\pi$.

There have also been interesting meson sightings at lepton colliders in recent decades. Electron–positron annihilation above energies of 4 GeV in numerous experiments reveals a series of peaks in the total cross-section that are consistent with radial excitations of the fundamental $c\bar{c}$ J/ψ meson: the ψ(2S), ψ(4040), ψ(4160) and ψ(4415), which are non-exotic and fit within the non-relativistic spectrum. Evidence for exotic mesons has come from data on specific final states, notably those containing a J/ψ with one or more pions, which have revealed several novel states. Historically, the first clue for an exotic charmonium meson of this type above a mass of 4 GeV came around a decade ago from the BaBar experiment at SLAC in the US. Analysing the process $e^+e^- \to J/\psi\pi\pi$, researchers there found a clear resonant-like structure dubbed Y(4260), which has no place in the $q\bar{q}$ spectrum because its mass lies between the ψ(4160) and ψ(4415) $c\bar{c}$ states. More remarkably, this state decays into charmonium and pions with a standard strong-interaction width of the order of 100 MeV rather than 100 keV, which is more typical for such a channel.

The clue to the nature of this meson appears to be that the mass of the Y meson (4260 MeV) is near the threshold for the production of DD_1 – the combination of pseudoscalar (D) and axial (D_1) charmed mesons (figure 2). This is the first channel in e^+e^- annihilation where charmed meson pairs can be produced with no orbital angular momentum (i.e. via S-wave processes). Thus at threshold there is no angular-momentum barrier against a DD_1 pair being created effectively at rest, and rearranging their constituents into the form of J/ψ and light flavours (the latter then seeding pions). Thus the structure could simply be a threshold effect rather than a true resonance, or an exotic "molecule" made of D and D_1 charmed mesons.

The decay of the Y(4260) into J/ψππ reveals a manifestly exotic structure. The $J/\psi\pi^\pm$ channel is electrically charged with a pronounced peak called Z(3900), as reported by both the BESIII experiment in China and Belle in Japan in 2013. Another sharp peak observed by BESIII – the Z(4020) – appears in the flavour-exotic channel containing a pion and a charmonium meson. Since it can carry electric charge, this state must contain $u\bar{d}$ (or $d\bar{u}$) in addition to its $c\bar{c}$ content, and therefore cannot be explained as a bound state of a single quark and antiquark. In principle, these states should be accessible in decays of B mesons, but there is no sign of them so far.



Front. Phys. **10** 101401

Fig. 3. The spectrum of charmonium and charmonium-like candidates.

Nonetheless, B decays are a source of further exotic structures. For example, the invariant-mass spectrum of $B \to K\pi^\pm\psi(2S)$ contains a structure called the Z(4430) observed by Belle and LHCb in the $\psi(2S)\pi$ invariant-mass spectrum, which contains both hidden charm and isospin and hence must contain (at least) two quarks and two antiquarks. These features first need to be established as genuine and not artefacts associated with some specific production process. Their appearance and decay in other channels would help in this regard, while the observation of analogous signals for other combinations of flavour may also signpost the underlying dynamics. If real, these states are the product of charmonium $c\bar{c}$ and light-quark basis states (a summary of charmonium candidates can be seen in figure 3).

Proceed with caution

It is clear that peaks are being found that cannot be interpreted as qqq or $q\bar{q}$ clusters. But one should not leap to the conclusion that we have discovered some fundamentally novel state built from, say, diquarks and antidiquarks or, for baryons, a pentaquark. A $qq\bar{q}\bar{q}$ "tetraquark", for example, looks less exotic when trivially rewritten as $q\bar{q}\,q\bar{q}$, which is suggestive of two bound conventional mesons. ▷

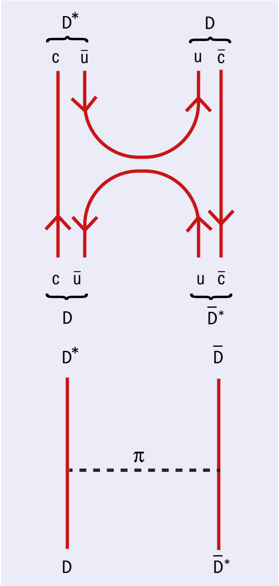


Fig. 4. "Deusons" arise from pion exchange. Pion exchange is the source of an attractive force between D and $\bar{D}$ or $\bar{D}$ and D* charmed mesons. This also occurs between D and D* analogous to the case of the deuteron.*

Indeed, these could be the two mesons in the invariant mass of which the peak was seen. Unless the peak is seen in different channels, and ideally in different production mechanisms, one should be cautious.

For example, when three or more hadrons are produced in a single decay it is common to discover peaks in invariant-mass spectra just above the two-body thresholds. These are not resonances, although papers on the arXiv preprint server are full of models built on the assumption that they are. Instead, the peaks likely arise due to competition between two effects. First, phase space opens up for the production of the two-body channel, but as the invariant mass increases, the chance of this exclusive two-body mode dies off because the probability for the wavefunctions of the two hadrons to overlap decreases. Any peak seen within a few hundred MeV of such a threshold is most likely to be the accidental result of this phenomenon. Such "cusps" have been proposed as explanations of several recent exotic candidates, such as the Z(3900) and Z(10610) spotted at BESIII and Belle, among others. Whether the tetraquark candidates X(4274), X(4500) and X(4700) recently observed at LHCb, in addition to the X(4140) found by the CDF experiment at Fermilab in 2009, herald the birth of a new QCD spectroscopy or are examples of more mundane dynamics such as cusps, is also the subject of considerable debate. In short, if a peak occurs above a two-body threshold in a single channel: beware.

Enter the deuson

More interesting for exotic-hadron studies are peaks that lie just below threshold. Such states are well known in the baryon sector, the deuteron being a good example. The nuclear force driven by pion exchange that binds neutrons and protons inside the atomic nucleus should also occur between pairs of mesons, at least for those that are stable on the timescale of the strong interaction. Thus on purely phenomenological and conservative grounds, we should anticipate meson molecules (or, by analogy with the deuteron, "deusons"), which would take us beyond the simple quark-model spectroscopy. The Y(4260) could be an example of such a state, since both DD_1 and D^*D_0 S-wave thresholds lie in this region and pion exchange may play a role in linking the two channels (figure 4). If these states are indeed deusons then there should also be partners with isospin. Establishing whether these structures are singletons or have siblings is therefore another important step in identifying their dynamical origins.

The first sign of deusons may be expected in the axial-vector channel formed from a pseudoscalar and vector charmed (or bottom) meson. This is because pion exchange can occur between a pair of vector mesons or as an exchange force between a pseudoscalar-vector combination, but not within a state of two pseudoscalars as this would violate parity conservation. The enigmatic state X(3872), which was first observed in B decays by Belle in 2003 and occurs at the $D_0\,\bar{D}^{*0}$ + cc threshold, has long been a prime candidate for a deuson. If so, there should be analogous states in the $B\bar{B}^*$ as well as charm-bottom flavour mixtures and perhaps siblings with two units of charm or bottom. Whether these states have charged partners is one of many model-dependent details. That some of these states should occur seems unavoidable, however, and if doubly charmed states exist they should be produced at the LHC.

Whereas for baryons the attractive forces arise in the exchange or "t channel", for pairs of mesons there can also be contributions due to $q\bar{q}$ annihilation in the direct s-channel. In QCD this can also mask the search for glueballs: for example, the scalar glueball of lattice QCD predicted at a mass of around 1.5 GeV mixes with the nonet of scalar $q\bar{q}$ states in this very region. The pattern of these scalars empirically is consistent with such dynamics.

Scalar mesons are interesting not least because the theoretical interest in multiquark or molecular states originated in such particles 40 years ago, after Robert Jaffe noticed that the chromomagnetic QCD forces are powerfully attractive in the nonet of light-flavoured scalar mesons. Intriguingly, this idea has remained consistent with the observed nonet of scalars below 1 GeV ever since. The main question that remains unresolved is to what extent these states are dominantly formed from coloured diquarks and their antidiquarks, or are better described as molecular states formed from colour-singlet π and K mesons.

LHCb in particular has shown that it is possible to identify light scalars among the decay debris of heavy-flavoured mesons, offering a new opportunity to investigate their nature and dynamics. Indeed, the kinematic reach of the LHC potentially enables a multitude of information to be obtained about heavy-flavoured mesons in both conventional and exotic combinations. We might therefore hope that information about exotic mesons will be extended into different flavour sectors to help identify the source of the binding.

Remarkably robust

In general, the simple $q\bar{q}$ picture of mesons appears to remain remarkably robust so long as there are no nearby prominent channels for pair production of hadrons in the S-wave channel. "Exotic" mesons and baryons seem to correlate with some S-wave channel sharing quantum numbers with a nominal $q\bar{q}$ state and causing the appearance of a state near the corresponding S-wave threshold. In some of these cases, but not all, the familiar forces of conventional nuclear physics play a role, and the multi-particle events at the LHC have the kinematic reach to include all combinations of non-strange, strange, charm and bottom mesons. How many of these can in practice be identified is the challenge, but identifying the dynamics of states "beyond $q\bar{q}$" may depend on it.

In conclusion, these exotic states need to be studied in different production mechanisms and in a variety of decay channels. A genuine resonant state should appear in different modes, whereas a structure that appears in a single production mechanism and a unique decay channel is suggestive of some dynamical feature that is not truly resonant. While interesting in its own right, such a state is not "exotic" in the sense of hadron spectroscopy.

As for truly exotic states, there are different levels of exoticity. For flavoured hadrons: the least exotic are meson analogues of nuclei – "deusons" driven by pion exchange between pairs of mesons. Next are "hybrids": states anticipated in QCD where the gluonic degrees of freedom are excited in the presence of quarks and/or antiquarks. Finally, the most exotic of all would be colour-singlet combinations of compact diquarks, which are allowed in principle by QCD and would lead to a rich spectroscopy. At present their status is like the search for extraterrestrial life: while one feels that in the richness of nature such entities must exist, they seem reluctant to reveal themselves.

● Further reading

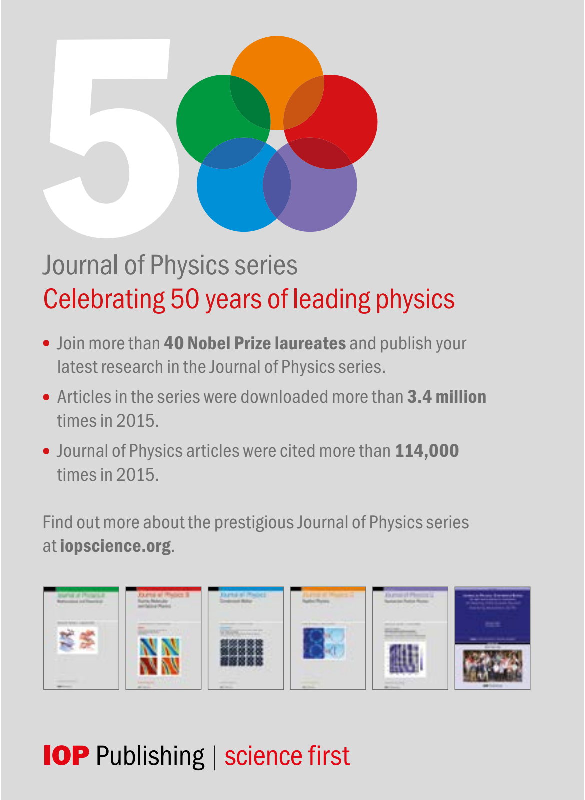
F Close 2017 *The New Cosmic Onion: Quarks and the Nature of the Universe* (Taylor and Francis).
S L Olsen 2015 *Front. Phys.* **10** 101401.
A Petermann 1965 *Nucl. Phys.* **63** 349.

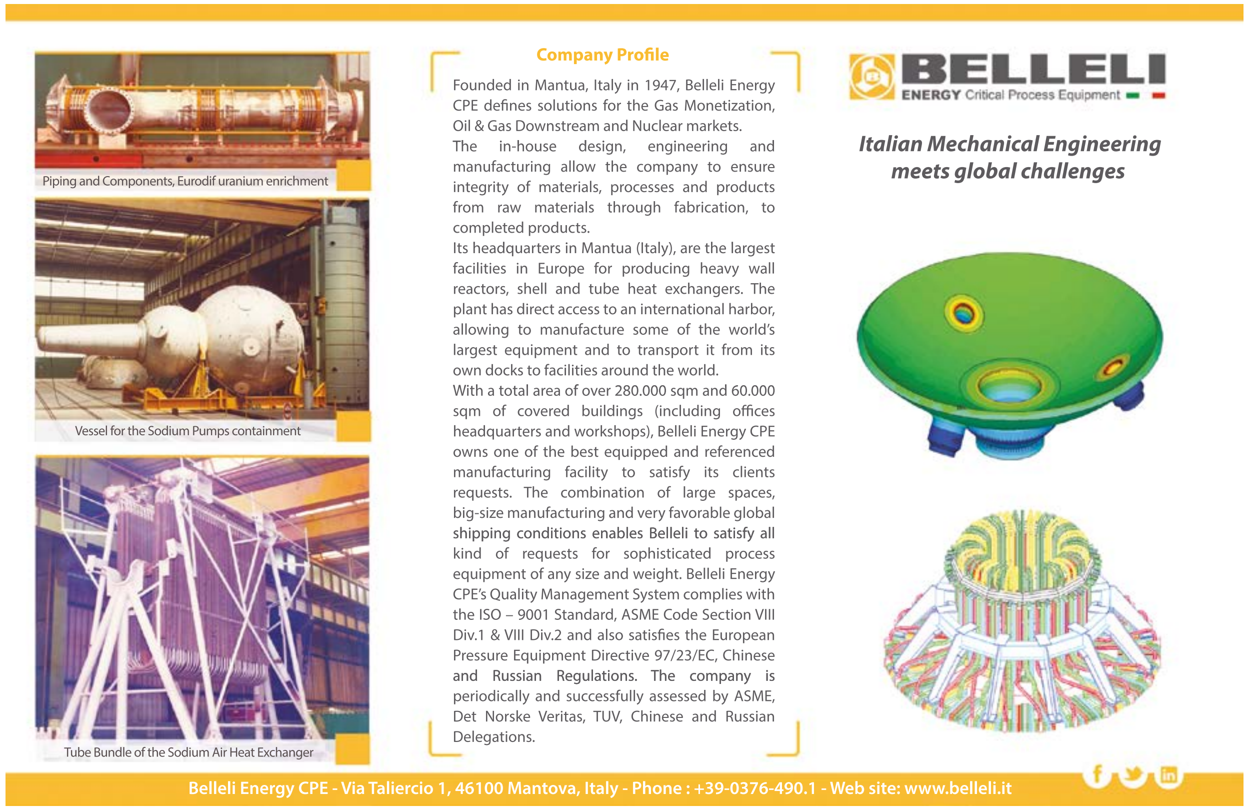
Résumé

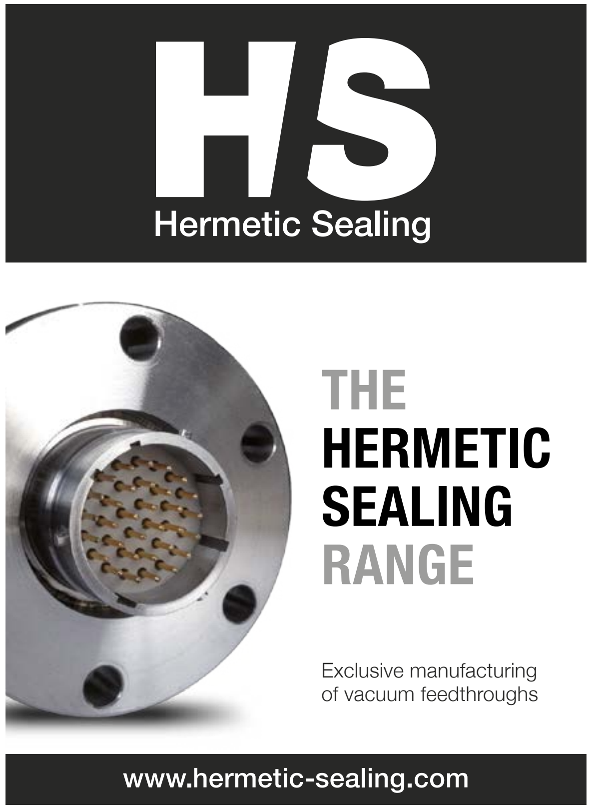
Les hadrons exotiques font plier les règles

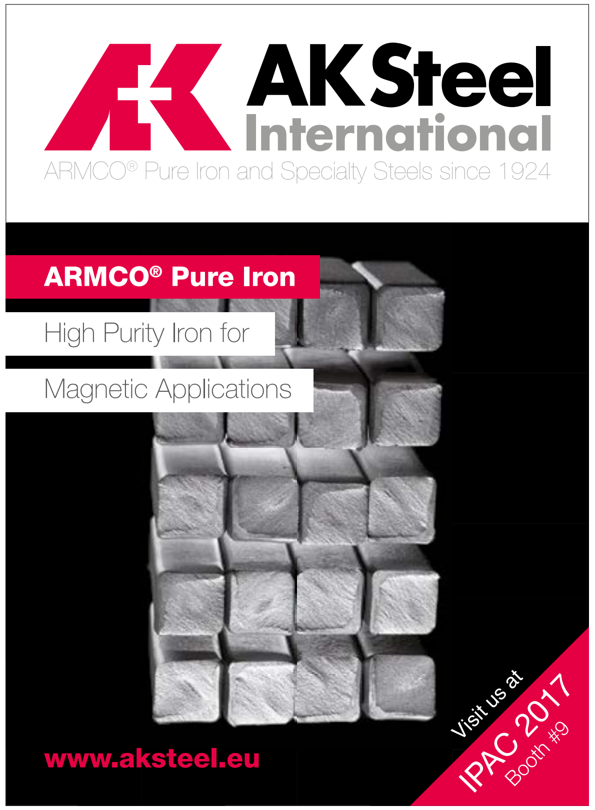
50 ans après la création du modèle des quarks, certains hadrons semblent défier ses axiomes. Si la correspondance avec les données empiriques est une réussite, la fondation théorique de ce modèle non relativiste pour les hadrons légers n'a toutefois jamais été claire. Les résultats d'expériences telles que BESIII, Belle et LHCb indiquent des pics qui ne peuvent pas être interprétés comme des états traditionnels à deux ou à trois quarks. Il ne faudrait toutefois pas en conclure hâtivement la découvert d'un état fondamentalement nouveau formé de diquarks et d'antidiquarks ou, pour les baryons, un pentaquark. Ces états exotiques doivent d'abord être étudiés dans différents mécanismes de production et divers canaux de désintégration. D'ici-là, ils garderont le même statut que la vie extraterrestre : même si nous imaginons que ces êtres doivent exister dans la richesse de la nature, ils semblent vouloir rester cachés.

Frank Close, University of Oxford, UK.









Faces & Places

APPOINTMENTS

New director for Jefferson Lab

Accelerator physicist Stuart Henderson, 53, has been named the fourth director of the Thomas Jefferson National Accelerator Facility in Virginia, US. Currently director of the Advanced Photon Source upgrade project at Argonne National Laboratory, he will start his new role on 3 April. Prior to joining Argonne, Henderson was associate laboratory director for accelerators at Fermilab and before that he spent almost a decade at Oak Ridge National Laboratory's Spallation Neutron Source (SNS), where he led the transition to successful user operations at megawatt-beam power levels.

Henderson replaces Hugh Montgomery, who came to Jefferson Lab as director in 2008 from Fermilab and will continue his association with the facility as director emeritus. Jefferson Lab has enjoyed significant growth in recent years, which includes the $338 million 12 GeV Upgrade Project and construction of a $70 million addition to the lab's engineering and design facilities. "I'm thrilled to be taking the helm of Jefferson Lab, particularly at this time of tremendous opportunity and potential," says Henderson. "Jefferson Lab plays a very special role in furthering the Department of Energy mission, both through its operation of a world-class nuclear-physics research facility, and through its world-renowned technology capabilities."


Argonne National Laboratory

Stuart Henderson has extensive experience with US national laboratories.

Rüdiger Voss next president of EPS

Former CERN staff member Rüdiger Voss has been appointed president of the European Physical Society (EPS), beginning 1 April and effective for two years. Established in 1968, the EPS represents 42 national physical societies, which in turn represent more than 120,000 members. It has a similar number of associate members – mostly major research institutions such as CERN – and about 3500 individual members.

Voss, who completed a PhD in deep inelastic muon–nucleon scattering at CERN's SPS in 1982, joined CERN as a research physicist in 1987. Following various group-leader positions in the experimental-physics division, in 2009 he became a senior adviser for international relations and then head of the unit from 2013 to 2015.

Among his many goals as EPS president, Voss wants to strengthen global co-operation and networks and raise the voice of science in the face of Europe's changing political landscape, which he says poses severe threats to cross-border collaboration, the mobility of students and researchers, and equal access to European funding and infrastructures. "The EPS, representing a scientific discipline with a highly developed culture of international collaboration, has a special responsibility to voice a strong opinion in this discussion," he says. "This concern is not unique to physics, and needs to be addressed by the scientific community at large." (See "European organisations uphold scientific values" on p9.)


CERN

Voss, the latest voice of the EPS.

AWARDS

Neutrino trio wins 2016 Pontecorvo Prize

The Joint Institute for Nuclear Research (JINR) in Dubna, Russia, has selected the winners of the Bruno Pontecorvo Prize, which is awarded each year for significant advances in elementary particle physics. The 2016 recipients, who are recognised for their outstanding contributions to the study of neutrino oscillations and to the measurement of the θ_{13} mixing angle using the Daya Bay, RENO and T2K experiments, are: Yifang Wang of the Institute of High Energy Physics in Beijing, China; Soo-Bong Kim of Seoul National University, South Korea; and Koichiro Nishikawa of the KEK Laboratory in Tsukuba, Japan.

Wang pioneered the Daya Bay neutrino oscillation experiment in China, while Kim is spokesperson for the Reactor Experiment for Neutrino Oscillation (RENO) in South Korea and Nishikawa is the founding spokesperson of the T2K and K2K experiments in Japan. The 2016 prizewinners will receive the award at a ceremony in September.

Bruno Pontecorvo died in 1993 at Dubna, and the prize was instituted in his memory two years afterwards. It was Pontecorvo who in 1957 suggested that neutrinos might change from one type to another. The experimental discovery of neutrino oscillation half a century later by Super-Kamiokande and the Sudbury Neutrino Observatory was recognised with the 2015 Nobel Prize for Physics.


(Left to right) Yifang Wang, Soo-Bong Kim and Koichiro Nishikawa.

Image credits: (left to right) CERN; ESRF; Fermilab

EPS announces accelerator prizes

The European Physical Society (EPS) accelerator group has announced the winners of the 2017 accelerator prizes, to be presented on 18 May during the International Particle Accelerator Conference (IPAC17) in Copenhagen.

Lyn Evans of CERN receives the Rolf Wideröe Prize for outstanding work in the accelerator field. He is rewarded for his many major accomplishments in the field of accelerator design, construction and operation, in particular his contributions to the SPS and his leadership of the design and construction of the LHC. Research at the SPS led to the discovery of the W and Z bosons, while the LHC uncovered the Higgs boson in 2012.

The Gersch Budker Prize for a recent significant, original contribution to the accelerator field goes to Pantaleo Raimondi of the ESRF in Grenoble in recognition of his invention of a new storage-ring lattice called the "hybrid multi-bend achromat". The novel design will reduce the emittance of the ESRF light source by a factor of 30 and has also been adopted as the basis for the design of several other next-generation light sources.

Finally, the Frank Sacherer Prize recognising an individual in the early part of his or her career goes to Anna Grassellino of Fermilab, for her major impact on the field of superconducting RF technology. The techniques of nitrogen doping and "nitrogen infusion" developed by Grassellino have already been applied to accelerator projects and have the potential to significantly reduce the cryogenic load and improve the energy efficiency of superconducting linacs.

(Top, left to right) EPS prizewinners Lyn Evans, Pantaleo Raimondi and Anna Grassellino.

AAAS honours Kurt Gottfried

Kurt Gottfried, professor emeritus of physics at Cornell University and a renowned authority on nuclear-arms control, has been awarded the 2016 Scientific Freedom and Responsibility Award from the American Association for the Advancement of Science (AAAS). Gottfried, an expert in quantum theory who was a visiting scientist at CERN in the 1960s, was honoured "for his long and distinguished career as a 'civic scientist', through his advocacy for arms control, human rights and integrity in the use of science in public policymaking".

Cornell University

Gottfried helped to found the Union of Concerned Scientists.

Julius Wess Award for detector work

Robert Klanner of the University of Hamburg and DESY has been nominated for the 2016 Julius Wess Award for outstanding achievements in elementary particle and astroparticle physics. The award, established in 2008 by the KIT Elementary Particle and Astroparticle Physics Center, recognises Klanner's fundamental contributions to the development of silicon-microstrip detectors, in particular for achieving the resolution required to reconstruct secondary vertices from the decay of heavy-flavoured hadrons. In the early 1980s, together with Gerhard Lutz and the late Josef Kemmer, Klanner used planar processes to build a silicon-strip detector, and in doing so initiated the culture of flavour-tagging in particle physics.

DESY

Klanner's work led to the rapid development of micro-structured silicon detectors.

CONFERENCES

Highlights from Quark Matter 2017

C Behnke/GSI

Quark Matter 2017 participants at the Hyatt Regency Chicago in February.

The 26th Quark Matter conference, devoted to ultra-relativistic nucleus–nucleus collisions, was held in Chicago on 5–11 February. Following a pre-conference student day that attracted nearly 400 young scientists, the main event had more than 700 registered participants. Overviews of the most recent results from experiments, spanning the entire energy range from the SIS 100 accelerator at GSI Darmstadt to the highest energies at CERN's LHC, were followed by almost 200 parallel presentations, 30 plenary talks and a session with more than 300 posters.

Nucleus–nucleus collisions have long been known to display characteristic signatures of collectivity, and this was one of the main themes at the Chicago event. Collectivity is typically quantified in terms of flow coefficients, v_n, where n corresponds to a particular harmonic in the azimuthal distributions of produced particles. Since the first LHC proton–lead run in 2013, it has been known that sizeable v_n are also observed in proton–lead collisions and even in detailed analyses of high-multiplicity proton–proton collisions.

At this year's conference, the LHC's ALICE experiment presented novel results on identified particle flow. The data show that ϕ mesons flow like pions and kaons, that heavy-flavoured D mesons display sizable collectivity above 10 GeV and that even J/ψ mesons partake in collective motion in lead–lead collisions. Both ALICE and CMS also presented novel analyses of the correlations between different flow coefficients, while CMS quantified the differences between D-meson flow and light-hadron flow for v_2 and v_3, which inform us about differences in the interactions of light partons and heavy quarks with the hot medium. ATLAS showed new results on heavy-flavour flow in proton–lead collisions. These results were complemented by more detailed analyses from RHIC in the US, revealing the mass ordering of flow coefficients and heavy-flavour flow measured by the STAR experiment, and small-system collectivity including proton–gold, deuteron–gold and helium–gold collisions measured by PHENIX.

Theory-overview talks focused on the validity of relativistic fluid dynamic simulations supplemented with realistic initial conditions and properties of the hot-partonic and the hadronic phases. The extent to which the simulations can account for collectivity in soft-particle production, and in particular how global Bayesian analyses that are novel for this field can be used to zoom in on fundamental properties of the quark–gluon plasma, was the subject of many parallel talks. In addition to details of these analyses, the Chicago conference discussed the new challenges for theory and experimental analyses that arise from characterising and understanding collectivity in smaller systems. ▷

Another highlight of the event was progress on the topic of hard probes. Since the first experiments at RHIC, it has been known that the yield of high-p_T final-state hadrons is suppressed or "quenched" by a factor of around five in central heavy-ion collisions. Measurements at the LHC have extended the dynamic range of these measurements and have gradually made a whole new set of jet-based probes available. The last two years have also seen a strong push towards analysing jet substructures with modern analysis techniques, and Quark Matter 2017 featured the first detailed public discussion of such developments. For instance, researchers are exploring novel opportunities for characterising jet-medium interactions and medium-induced parton splittings based on so-called "groomed" jet variables, such as the groomed z_g distributions measured by CMS and STAR or jet-mass measurements presented by ALICE.

Apart from these new observables, a number of well-known measurements have been repeated using the much larger data samples of LHC Run 2 to improve the measured kinematic ranges and statistical accuracy. In particular, ATLAS showed nuclear modification factors for jets that reveal a factor of two suppression for jets with a transverse energy up to 1 TeV, while both ATLAS and CMS presented much improved measurements of the energy imbalance for photon jets and CMS presented Z-boson-jet pairs, which provide precise information about the probability distribution for energy loss. An exciting future perspective is that a detailed analysis of the softening of jet fragmentation may provide experimental access to the microscopic mechanisms underlying equilibration processes in the hot and dense medium.

There were many further highlights at Quark Matter 2017. Results ranged from the ATLAS measurement of dijet photoproduction in ultra-peripheral collisions, which may yield novel constraints on the nuclear dependence of parton distribution functions, to new precision measurements of the sequential suppression of bottomonium states at CMS. New results from RHIC also included a first measurement of the charmed Λ_c baryon by the STAR experiment, which provides a new way to test hadronisation models. We also saw the first measurements of net particle moments by ALICE, which provide a critical reference for fluctuation measurements in the RHIC beam-energy scan.

Space was also given to discussions of the physics plans for the LHC heavy-ion programme in Run 3 and beyond, as well as the planning for the new "sPHENIX" detector at RHIC that has recently passed an important review and is expected to take first beam in 2022. Participants now have 15 months to consider the presented results and make progress before the next Quark Matter meeting in Venice in May 2018.

Slush brings scientists and entrepreneurs closer

With an astonishing 17,500 attendees, one million livestream viewers and thousands of participating start-up companies and venture capitalists, Slush is Europe's leading entrepreneurship event. Among accredited business founders and investors, CERN was invited to give a keynote speech at the 2016 edition of the annual event, held in Helsinki, Finland, at the start of December. With Slush aiming to aid the next generation of world-conquering companies and CERN aiming to find answers to fundamental questions about the universe, you might wonder what these two organisations have in common.

Although there has traditionally existed a gap between science and entrepreneurship, both communities have started to realise that the benefits of co-operating are reciprocal. One of the ways innovations and know-how can be applied more generally is through starting new ventures, and CERN is committed to building a culture of entrepreneurship among its scientists and engineers to help maximise the impact of CERN on society. Vice versa, new initiatives such as Slush Science Track have brought academic research into the spotlight by gathering top-quality research and offering a €100,000 prize for the best basic research presented. Slush underpins its initiative by remarking that "all inventions come from science, and that today's findings will lead to products years later".

P Kauttu

Marthe Dehli of CERN's Knowledge Transfer Group was a keynote speaker at Slush Science Track in December.

Antwerp workshop sets reference

At the beginning of November, at the Resummation, Evolution, Factorization (REF) meeting, about 40, mostly young, scientists met in Antwerp in Belgium to discuss limitations in present calculations and simulations concerned with Standard Model processes. These limitations, which concern the physics programme both at the LHC and at future lepton–hadron colliders, come from neglecting the transverse momenta that arise in the QCD evolution of initial-state partons during collisions. Very small transverse momenta shed light on the intrinsic hadronic structure, while large transverse momenta can change the kinematics of processes significantly. In the usual collinear evolution and parton-distribution functions, these transverse momenta are not considered explicitly.

P Van Mechelen

Participants at the 2016 REF workshop.

One of the highlights of the workshop was the determination of the very first complete transverse-momentum-dependent parton distributions, which are valid over the full range of momentum accessible at the LHC. Progress has been reported in the region of very small longitudinal momenta, where saturation effects typically appear. New tools for transverse-momentum-dependent parton distributions (TMDs) were reported, including a complete library containing all publicly available TMDs and visualisation tools.

The REF workshop series, which started in 2014, is unique because it addresses questions from high-energy particle collisions together with issues coming from the non-perturbative structure of hadrons. These are very new and exciting attempts to describe in a uniform manner the low- and high-energy behaviour of particle collisions, which has much impact on the precision of LHC predictions. Although still a small community, the range of applications of TMD approaches cover the most interesting and important regions where resummation to all orders in perturbation theory is relevant, and which is the major focus of new and challenging Standard Model measurements at the LHC. The next edition of the REF workshop will be held in Madrid, Spain, from 13 to 17 November 2017.

Celebrating a decade of high-end computer algebra

Precision calculations of scattering processes at high-energy colliders such as the LHC rely on advances in computer algebra to process the enormous number of higher-loop Feynman integrals. For the past 10 years, the DESY theory group at Zeuthen has collaborated in this field with mathematicians from the Research Institute of Symbolic Computation (RISC) at Johannes Kepler University (JKU) in Linz. During the collaboration, various symbolic summation and integration packages, as well as those for related special functions, have been created. These are publically available and offer broad automation of analytic Feynman integral calculations for two- and three-loop integrals.

To mark the 10th anniversary of this successful partnership, a one-day workshop took place at Hagenberg Castle in Austria on 7 February, during which representatives of DESY and JKU extended their collaboration agreement for a further five years. The directors of research at Wolfram Research and MapleSoft also contributed reports on the latest versions of Mathematica and Maple, while special lectures were delivered about summation theory, elliptic solutions, precision calculations for the LHC and new developments in q-series.

C Koutschan

(From left to right) Joachim Mnich (DESY), Peter Paule (RISC), Johannes Blümlein (DESY), Carsten Schneider (RISC) and Alexander Egyed (JKU).

Correction

A photograph on p41 of the March issue shows Claude Trudelle, Québec delegate general for Germany, Austria and Switzerland, and not Rémi Quirion as stated in the caption.

Visits

S Bennett/CERN

Director-general of the United Nations Office, **Michael Møller**, visited CERN on 6 February with other heads of United Nations agencies, during which they toured the ATLAS cavern and visited the LHC tunnel.

S Bennett, CERN

Marie-Christine Marghem, Belgian minister for energy, environment and sustainable development, came to CERN on 20 February. Following a tour of CMS, she signed the guestbook with (left to right): CERN director for accelerators and technology Frédérick Bordry, Belgian ambassador to the UN Geert Muylle, CERN Director-General Fabiola Gianotti, and CERN director for research and computing Eckhard Elsen.

S Bennett/CERN

Ofir Akunis, minister of science, technology and space in Israel, visited CERN on 22 February, during which he toured ATLAS with former experiment spokesperson Peter Jenni (left).

M Brice/CERN

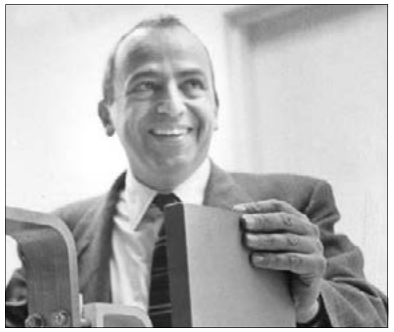
Edgars Rinkēvičs, minister of foreign affairs for the Republic of Latvia, came to CERN on 27 February and visited the CMS experiment. He signed the guestbook with CERN director for international relations Charlotte Warakaulle and non-Member State adviser Christoph Schaefer.

OBITUARIES

Ned Goldwasser 1919–2016

Edwin Goldwasser, deputy director of Fermilab when the laboratory was founded in 1967, died on 14 December at the age of 97. Goldwasser oversaw the construction of Fermilab (or the National Accelerator Laboratory, as it was then known), completing it on time and under budget. He also scheduled its experimental programme, managed its programme Advisory Committee and implemented its groundbreaking equal-employment programme. Goldwasser remained as the laboratory's deputy director until 1978, taking an extended leave of absence from the University of Illinois to serve at the new facility.

"When Ned took leave from the University of Illinois to help create Fermilab from green fields, the project took on new dimensions: a truly effective course for the variety of people to build it, and a dedication to make it both fruitful for its users and attractive for the professional development of its staff," says emeritus professor of the University of Illinois Ralph Simmons. "All this was combined with contagious yet critical enthusiasm for the discoveries made possible."


Fermilab

Ned Goldwasser in 1967 at the National Accelerator Laboratory.

After setting Fermilab firmly on its feet, Goldwasser returned to the University of Illinois in 1978 as vice chancellor for research and dean of the graduate college. In 1986, he took another extended leave to join the central design group of the proposed Superconducting Super Collider facility, where he served as associate director until 1988. In 1990, following his retirement from the university, he was appointed a distinguished scholar at the California Institute of Technology (Caltech) to work on the LIGO project.

Goldwasser did his undergraduate work at Harvard University. Following service as a physicist with the US Navy, he received his PhD in physics from the University of California, Berkeley, then served a year on the faculty there before moving to the University of Illinois in 1951.

"Ned was a natural leader, who was instrumental in making Fermilab a place where both physics and physicists thrived," says Barry Barish, professor emeritus of physics at Caltech and the first director of LIGO. "I will personally miss his wisdom and guidance. In every way, Ned was a class act."

● *Based on an article written for the Fermilab website, news.fnal.gov.*

Hans Jürgen Hilke 1938–2016

Hans Jürgen Hilke, a true experimental physicist and an inspirational colleague, passed away on 15 October. He completed his diploma thesis in 1965 at Hamburg University, then went to CERN to develop a bubble chamber activated by the wave pattern produced from an ultrasonic quartz oscillator. Having earned his doctorate in 1969, he soon became engaged in the construction of the external muon identifier for the Big European Bubble Chamber (BEBC). After completing the project and having operated the detector for its first exposures, Hans Jürgen took a sabbatical at the University of California, Berkeley, where he worked on time-projection chambers (TPCs). While at Berkeley, he became engaged in the most challenging aspect of large-TPC design, leaving his characteristic imprint of good judgement and technical prowess on the complex TPC read-out planes, in particular. Despite the chaotic environment of a pioneering enterprise, Hans Jürgen's unflappable and gracious perspective was highly appreciated by all involved.

Experimental physicist Hans Jürgen Hilke.

The experience he gained in working with TPCs motivated Hans Jürgen to introduce this technology to the experiments at CERN's Large Electron–Positron Collider, in particular DELPHI (for which in 1980 he became technical co-ordinator). The successes of the complex DELPHI detector are in large part due to Hans Jürgen's drive, care and attention to detail. In 1989, at the start up of data-taking, the collaboration encountered many unexplained cut-offs of the superconducting magnet coils, which constituted the world's largest solenoid at that time. After many unsuccessful attempts by the constructor, Hans Jürgen discovered and understood the origin of these cut-offs, and in a couple of days DELPHI was able to take data.

From 1991 to 1994 he was deputy leader of CERN's experimental-physics division, with particular responsibility for the mechanical and electronics engineering groups.

In January 1997 he joined the LHCb experiment, where he took over the function of technical co-ordinator and immediately became heavily involved in preparing various Technical Design Reports. Working in his usual energetic and passionate manner, Hans Jürgen quickly became familiar with the experiment and played a crucial role in strengthening its capabilities in several areas such as the magnet, photon detectors in the ring imaging Cherenkov detectors, and the muon system. He also took responsibility in financial matters and safety, and undoubtedly played a significant part in the success of the LHCb experiment.

Besides his scientific qualities, his integrity and honest character were always very much appreciated. Hans Jürgen was always ready to hear different opinions and did not hesitate to take difficult decisions. His extensive knowledge and experience with various detector technologies paired with his co-ordination skills earned him credibility and authority. Colleagues who had the pleasure to work closely with Hans Jürgen will never forget him and his intellectual honesty, directness of speech and dedication to CERN and its experiments.

In his private life, Hans Jürgen's wide interests, his love of classical music and great care in all personal relations were a continuous inspiration to his family and friends. Our deepest sympathy goes to his wife, children, brother and their families.

● *His friends and colleagues.*

Jean Yoccoz 1925–2016

Jean Yoccoz, one of the pioneering directors of the French National Institute for Nuclear Physics and Particle Physics (IN2P3), passed away on 30 December at the age of 91.

Born into a modest peasant family in Savoie, Yoccoz succeeded brilliantly in his studies and was admitted to Ecole Normale Supérieure in Paris. Attracted by theoretical nuclear physics, he entered Frédéric Joliot's laboratory in Collège de France and then joined Rudolf Peierls at the University of Birmingham in the UK, where he undertook a PhD that established the link between the shell and Bohr–Mottelson models of the nucleus. The 1957 Peierls–Yoccoz paper continues to be regularly cited today. Having been appointed professor at the University of Strasbourg, he continued his research and in 1966 moved to Grenoble University. However, it was high-level scientific management to which Yoccoz would orientate his career and invest his intellectual talents to the benefit of our community.

At the end of the 1960s there was great debate in France concerning the organisation of particle physics and whether a national accelerator programme could still be afforded. After eight years of unsuccessful attempts, the IN2P3 institute was created in 1971 (without a high-energy machine) to co-ordinate and support research done in the many French laboratories involved in nuclear and particle physics. Its first director, Jean Teillac, immediately called on Jean Yoccoz as a deputy, and in 1975 Yoccoz became the next director – a position he held until 1983.


N G and S Yoccoz

Jean Yoccoz, an exemplary director for IN2P3.

The early years of IN2P3 were very important to establish an efficient structure allowing laboratories to retain their identities while also being integrated within prioritised large projects. One of the aims was to achieve high visibility for French particle physicists on the international scene, and Yoccoz's vision turned out to be correct. It led during his mandate to the launching of large programmes at CERN on the SPS and later on LEP, but also with the first large-scale experiment to be installed abroad (CELLO at DESY, Hamburg). In 1982, Yoccoz signed an agreement with then CERN Director-General Herwig Schopper for the construction of the LEP linac injector at the Laboratoire de l'Accélérateur Linéaire (LAL, Orsay). Yoccoz was also instrumental in shaping a new landscape for nuclear physics with the creation of the IN2P3-CEA national laboratories Saturne at Saclay and GANIL in Caen with competitive accelerators.

We remember Jean Yoccoz as an exemplary director for IN2P3. He steered the institute through occasionally difficult times when he had to defend its specificity and the need for large resources, including highly qualified technical personnel. His human qualities were recognised by all. He could interact with people whatever their level in the same benevolent spirit. He knew how to listen, but his decisions were always firm and clear.

In the last months of his life, Jean Yoccoz was deeply affected by the loss of his son Jean-Christophe, a mathematician and winner of the Fields Medal who died prematurely last September. Our condolences go to his family, particularly his two sons Nigel Gilles and Serge.

● *Michel Davier.*

Recruitment

For advertising enquiries, contact *CERN Courier* recruitment/classified, IOP Publishing, Temple Circus, Temple Way, Bristol BS1 6HG, UK.
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SFB 1258 Neutrinos Dark Matter Messengers

Several PhD Positions at the Technical University of Munich (TUM) on Experimental and Theoretical Aspects of Neutrinos and Dark Matter

We are looking for highly qualified and motivated students holding an MSc or equivalent degree in physics or astrophysics to pursue doctoral research at the Munich School on Neutrinos and Dark Matter.

The School is an Integrated Research Training Group within the recently founded SFB1258 "Neutrinos and Dark Matter in Astro- and Particle Physics" (www.sfb1258.de). SFB1258 is based at the Technical University of Munich (TUM) in collaboration with the Max-Planck-Institut für Physik (MPP), Max-Planck-Institut für Extraterrestrische Physik (MPE), Max-Planck-Institut für Astrophysik (MPA), European Southern Observatory (ESO), and the Institut für Hochenergiephysik (HEPHY) der Österreichischen Akademie der Wissenschaften.

We are offering PhD positions in Physics on various experimental as well as theoretical topics on neutrino properties, neutrino astronomy at low and high energies, the particle nature of dark matter, axion searches, and supernovae processes including the investigation of stellar matter.

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For further information and application details please visit: http://www.sfb1258.de/graduate-school/

KEK, High Energy Accelerator Research Organization

Call for Nomination for Next Director-General of KEK

KEK, High Energy Accelerator Research Organization, invites nominations for the next Director-General whose term will begin April 1, 2018.

In view of his/her role that presides over the business of KEK as a representative of the Inter-University Research Institute Corporation, nominees shall be:

1) persons of noble character, with relevant knowledge and experience and having abilities to manage its educational and research activities properly and effectively.
2) persons expected to promote with long-term vision and strong scientific leadership, the highly advanced, internationalized, and inter-disciplinary research activities of KEK by getting support from the public.
3) persons expected to establish and carry out the medium-term goals and plans.

The term of appointment is three years until March 31, 2021 and shall be eligible for reappointment only twice. Thus, he/she may not remain in office continuously over a period 9 years.

We widely accept the nomination of the candidates regardless of their nationalities.

We would like to ask you to recommend the best person who satisfies requirements for the position written above.

Nomination should be accompanied by:
1) letter of recommendation, 2) brief personal history of the candidate, and 3) list of major achievements (publications, academic papers, commendations and membership of councils, etc.). The nomination should be submitted to the following address no later than May 31, 2017:

- Documents should be written either in English or in Japanese.
- Forms and details are available at: https://www.kek.jp/en/NewsRoom/Release/20170301090000/

Takayuki Sumiyoshi
The Chair of Director-General Selection Committee
High Energy Accelerator Research Organization

Inquiries concerning the nomination should be addressed to:
General Affairs Division
General Management Department
KEK, High Energy Accelerator Research Organization
1-1 Oho, Tsukuba, Japan 305-0801

Tel +81-29-864-5114 Fax +81-29-864-5560

Email: kek.dgsc@ml.post.kek.jp

UNIVERSITÉ DE GENÈVE

The Faculty of Science of the University of Geneva invites applications for a position as

FULL or ASSOCIATE PROFESSOR in neutrino physics

ASSIGNMENT:
This full-time appointment includes teaching physics at bachelor, master and postgraduate level as well as supervising master and doctoral theses.

The candidate will develop original research at the international level in his/her field of expertise and secure external funding. He/she will also take on organizational and administrative duties.

We are seeking a candidate with a proven international scientific reputation, with a wide range of skills and knowledge, including a very good understanding of the physics of neutrinos, the ability to coordinate a research group and to initiate communication and outreach programs for the University.

REQUIRED QUALIFICATIONS:
PhD in physics or equivalent.

Strong track record in research and experience in the management of research groups and in teaching. Publications in high-ranked international journals.

STARTING DATE: 01.08.2018 or upon mutual agreement
Applications including: cover letter, detailed CV together with a list of publications, copy of highest degrees/diploma, research and teaching statements, list of referees who can later be contacted directly by the search committee.

Recommendation letters are not requested for now.

Applications should be submitted exclusively on-line to the University website at the address https://jobs.unige.ch before July 31st, 2017 (0:00 Geneva time).

APPLICATIONS SENT BY EMAIL SHALL NOT BE ACCEPTED.

Complementary information may be obtained at the following e-mail address: scienceopenings@unige.ch.

In a perspective of parity, applications by women are particularly encouraged and welcome.

Bookshelf

Compiled by Virginia Greco, CERN

Infinitesimal: How a Dangerous Mathematical Theory Shaped the Modern World

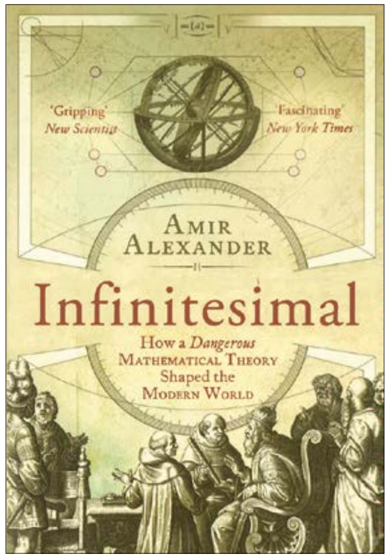
By Amir Alexander

One World

Lying midway between the history and the philosophy of science, this book illuminates a fascinating period in European history during which mathematics clashed with common thought and religion. Set in the late 16th and early 17th centuries, it describes how the concept of infinitesimals – a quantity that is explicitly nonzero and yet smaller than any measurable quantity – took a central role in the debate between ancient medieval ideas and the new ideas arising from the Renaissance. The former were represented by immutable divine order and the principle of authority, the latter by social change and experimentation.

The idea of indivisible quantities and their use in geometry and arithmetic, which had already been developed by ancient Greek mathematicians, underwent its own renaissance 500 years ago, at the same time as Martin Luther launched the Reformation. The consequences for mathematics and physics were enormous, giving rise to unprecedented scientific progress that continued for the following decades and centuries. But even more striking is that the new way of thinking built around the concept of infinitesimals crossed the borders of science and strongly influenced society, up to the point that mathematics became the main focus of the struggle between the old and new orders.

This book is divided into two parts, each devoted to a particular geographical area and period in which this battle took place. The first part leads the reader to late 16th century Italy, where the flourishing and creative ideas of the Renaissance had given birth to a prolific number of mathematicians and scientists. Here, the prominent figure of Galileo Galilei – together with Evangelista Torricelli, Bonaventura Cavalieri and others – was at the forefront of the new mathematical approach involving the concept of infinitesimals. This established the basis of inductive reasoning, which makes broad generalisations from specific observations, and led to a new science founded on experience. On the opposite side, the religious congregation of the Jesuits used these same mathematical developments in its fight against heresy and the Reformation. To them, the traditional mathematical approach was a solid basis for the absolute truth represented by the Catholic faith and the authority of the Pope. The fierce opposition of the Jesuit mathematicians led Galileo and the "infinitesimalists" to damnation, with irreparable consequences for the ancient tradition of Italian mathematicians.



The second part of the book moves the reader to 17th century England, just after the English Civil War in the years of Cromwell's republic and the Restoration. In that context, the new ideas represented by infinitesimals were not only condemned by the Anglican Church but also opposed by political powers. Here, the leading figure of Thomas Hobbes took the stage in the fight against the indivisibles and the inductive method. For him, traditional Euclidean geometry – which, contrary to induction, used deduction to achieve any result from a few basic statements – was the highest expression of an ordered philosophical system and a model for a perfect state. Hobbes was also concerned about the threat to the principle of authority that emanated from traditional mathematical thought. In his struggle against infinitesimals, he was confronted by the members of the newly founded Royal Society, eager for scientific progress. Among them was John Wallis, who considered mathematical knowledge as a "down–up" inductive system in which calculus played the role of experiments in physics. Solving many of the toughest mathematical problems of his times by infinitesimal procedures, Wallis defeated traditional geometry – and Thomas Hobbes with it. The triumph of Wallis made way for scientific progress and the advance of thought that opened the door to the Enlightenment.

This book is excellently written and its mathematical concepts are clearly explained, making it fully accessible to a general audience. With his fascinating narrative, the author intrigues the reader, depicting the historical background and, in particular, recounting the plots of the Holy See, the Jesuits' fight for power, the Reformation, the absolutist power of the kings, and the early steps of Europeans towards democracy and freedom of thought. The book includes extensive notes at the end, a useful index of concepts, a timeline and a "*dramatis personae*" section, which is divided between "infinitesimalists" and "non-infinitesimalists". Finally, the images and portraits included in the book enhance the enjoyment for the reader.

● *Pablo Fernández Martínez, CERN.*

The Many Faces of Maxwell, Dirac and Einstein Equations: A Clifford Bundle Approach (2nd edition)

By Waldyr A Rodrigues Jr and Edmundo Capelas de Oliveira

Springer

In theoretical physics, hardly anything is better known than the Einstein, Maxwell and Dirac equations. The Dirac and Maxwell equations (as well as the analogous Yang–Mills equations) form the basis of the modern description of matter via the electrodynamic, weak and strong interactions, while Einstein's equations of special and general relativity are the foundations of the theory of gravity. Taken together, these three equations cover scales from the subatomic to the large-scale universe, and are the pillars on which the standard models of cosmology and particle physics are built. Although they constitute core information for theoretical physicists, they are rarely, if ever, presented together.

This book aims to remedy the situation by providing a full description of the Dirac, Maxwell and Einstein equations. The authors go further, however, by presenting the equations in several different forms. Their aim is twofold. On one hand, different expressions of these famous formulae may help readers to view a given equation from new and possibly more fruitful perspectives (when the Maxwell equations are written in the form of the Navier–Stokes equations, for instance, they allow a hydrodynamic interpretation of the electrodynamic field). On the other hand, casting different

▷

CERN COURIER
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IOP Publishing

Bookshelf

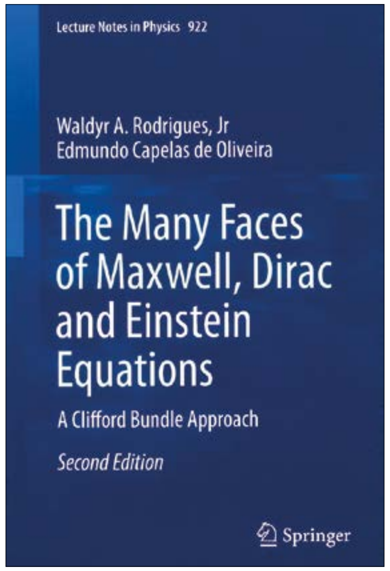
equations in similar forms may shed light on the quest for unification – as happens, for example, when the authors rewrite Maxwell's equations in Dirac-like form and use this to launch a digression on supersymmetry.

Another feature of the book concerns concepts in differential geometry that are widely used in mathematics but about which there is little knowledge in theoretical physics. An example is the torsion of space–time: general differential manifolds are naturally equipped with a torsion in addition to the well-known curvature, and torsion also enters into the description of Lie algebras, yet the torsional completion of Einstein gravity, for instance, has been investigated very little. In the book, the authors take care of this issue by presenting the most general differential geometry of space–time with curvature and torsion. They then use this to understand conservation laws, more specifically to better grasp the conditions under which these conservation laws may or may not fail. Trivially, a genuine conservation law expresses the fact that a certain quantity is constant over time, but in differential geometry there is no clear and unambiguous way to define an absolute time.

As an additional important point, the book contains a thorough discussion about the role of active transformations for physical fields (to be distinguished from passive transformations, which are simply a change in co-ordinates). Active transformations are fundamental, both to define the transformation properties of specific fields and also to investigate their properties from a purely kinematic point of view without involving field equations. A section is also devoted to exotic or new physical fields, such as the recently introduced "ELKO" field.

Aside from purely mathematical treatments, the book contains useful comments about fundamental principles (such as the equivalence principle) and physical effects (such as the Sagnac effect). The authors also pay attention to clarifying certain erroneous concepts that are widespread in physics, such as assigning a nonzero rest mass to the photon.

In summary, the book is well suited for anyone who has an interest in the differential geometry of twisted–curved space–time manifolds, and who is willing to work on generalisations of gravity, electrodynamics and spinor field theories (including supersymmetry and exotic physics) from a mathematical perspective. Perhaps the only feature that might discourage a potential reader, which the authors themselves acknowledge in the introduction, is the considerable amount of sophisticated formalism and mathematical notation. But this is the price one has to pay for such a vast and comprehensive discussion about the most fundamental tools in theoretical physics.


Lecture Notes in Physics 922

Waldyr A. Rodrigues, Jr
Edmundo Capelas de Oliveira

The Many Faces of Maxwell, Dirac and Einstein Equations

A Clifford Bundle Approach

Second Edition

Springer

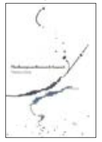
- *Luca Fabbri, INFN Bologna, Italy.*

Books received

The European Research Council

By Thomas König

Polity Press



Established in 2007 to fund frontier-research projects, the European Research Council (ERC) has quickly become a fundamental instrument of science policy at European level, as well as a quality standard for academic research. This book traces the history of the creation and development of the ERC, drawing on the first-hand knowledge of the author, who was scientific adviser to the president of the ERC for four years. It covers the period between the early 2000s – when a group of strong-minded scientists pushed the idea of allocating (more) money to research projects selected for the quality of the proposals, judged by independent, competent and impartial reviewers – and when the first ERC programme cycle was concluded in 2013.

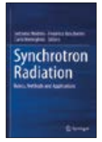
The author is particularly interested in the politics behind those events and shows how the ERC could translate into reality thanks to the fact that the European Commission decided to support it, using a much more strategic, planned and technical approach. He also describes the way that the ERC was implemented and the creation of its scientific council, discusses the "hybrid" nature of the ERC – being somewhere between a programme and an institution – and the consequent frictions in its early days, as well as the process to establish a procedure for selecting applications for funding.

While telling the story of the ERC from a critical perspective and examining its challenges and achievements, the book also offers a view of the relationship between science and policy in the 21st century.

Synchrotron Radiation: Basics, Methods and Applications

By S Mobilio, F Boscherini and C Meneghini (eds)

Springer


Synchrotron Radiation

Observed for the first time in 1947 – and long considered as a problem for particle physics as it can cause particle beams to lose energy – synchrotron radiation is today a fundamental tool for characterising nanostructures and advanced materials. Thanks to its characteristics in terms of brilliance, spectral range, time structure and coherence, it is extensively applied in many scientific fields, spanning material science, chemistry, nanotechnology, earth and environmental sciences, biology, medical applications, and even archaeology and cultural heritage.

The book reports the lecture notes of lessons held at the 12th edition of the School on Synchrotron Radiation, held in Trieste, Italy, in 2013 and organised by the Italian Synchrotron Radiation Society in collaboration with Elettra-Sincrotrone Trieste. The book is organised in four parts. The first describes the emission of synchrotron and free-electron laser sources, as well as the basic aspects of beamline instrumentation. In the second part, the fundamental interactions between electromagnetic radiation and matter are illustrated. The third part discusses the most important experimental methods, including different types of spectroscopy, diffraction and scattering, microscopy and imaging techniques. An overview of the numerous applications of these techniques to various research fields is then given in the fourth section. In this, a chapter is also dedicated to the new generation of synchrotron radiation sources, based on free-electron lasers, which are opening the way to new applications and more precise measurements.

This comprehensive book is aimed at both PhD students and more experienced researchers, since it not only provides an introduction to the field but also discusses relevant topics of interest in depth.

Inside Story

On the road with the Bonn Show

A strong storyline and a bit of humour, not to mention good old-fashioned advertising, go a long way when engaging new audiences with particle physics.

(Top) Maike Hansen and Lorenzo Ubaldi collide two boxes full of coloured balls to show the need for bunches in the LHC beams. (Above) The wooden scattering experiment built in Bonn, in which the distribution of scattered steel balls in the pockets at the edge can be used to infer the shape of the scattering centre (here triangular).

Boarding the ferry in Puttgarden, on the small island of Fehmarn in northern Germany, last September, I looked across the water to Denmark. We had two vans full of physics equipment, a minibus, 17 physics students, one postdoc, two technicians, two professors, and of course the bus driver – a real entourage! We were travelling to Copenhagen under invitation from the Niels Bohr Institute, and subsequently to Odense, to perform our new particle-physics show. We were road hardened after trips to Oxford and London in the UK in 2014, and Padua and Trieste in Italy the following year. In March 2016, we even went to Beijing to teach Bonn-show physics to students at Peking University and the Chinese Academy of Science. Every country is a new physics challenge, a new adventure, and has led to many interesting interactions. Denmark, here we come!

The Bonn Physics Show was established in 2001 with the goal of doing something different from the "lectures with demonstrations" format of traditional particle-physics shows.

For the past 15 years we have been successfully performing the Bonn show, mainly devoted to classical physics aimed at a younger audience, and our approach has evolved with our experiences. In 2012, as part of a large research grant from the German physical society (DFG), we received support to take a brand new particle-physics Bonn show on tour that is rooted in storytelling.

A big challenge for a modern physics show is to find appropriate demonstrations, since few real effects can be seen on stage. From our previous shows on particle physics, one performed at CERN in French in 2010, we had a first set of experiments. Inspired by a simpler model at DESY, for example, we built a new wooden scattering experiment (pictured). We also designed our own electrically driven linear and circular accelerators, as well as an experiment showing real antimatter on stage using a β^+ source, a Geiger counter and a strong permanent magnet.

A big challenge for a modern physics show is to find appropriate demonstrations.

For the new show, besides adding novel experiments, we wanted to make it more like a play to better capture the audience's attention. At the end of 2013, I sat down and drafted a story that takes two heroes time-travelling through the history of particle physics, encountering many physics greats along the way who explain the physics with the help of 25 live experiments. This first draft was much improved in extensive rehearsals. We created the character of a caretaker as the master of time travel, adding a lighter element and bringing a common thread to the play. We also added many verbal and physical jokes to make the shows both fun and educational (the script and detailed descriptions of the experiments can be found at arXiv:1607.07478).

We premiered the performance in the physics department at Oxford University in March 2014. The shows in the UK went well, but were not full. One reason was that schools there seem to have such a tight curriculum that there is little time for excursions. We also realised that we could improve the way the shows were advertised. For the Italy trip in 2014, I went to Padua two months before and gave a colloquium attended by all of the regional high-school physics teachers, in addition to members of the university physics department. Two months later, in the department's beautiful lecture hall, the shows were all packed – apparently only Ed Witten drew a larger crowd – and were a resounding success. Within our team the Padua performance has taken on a mythical status for the wonderful rapport we had with the audience – there was a tremendous atmosphere.

Denmark brought further highlights. The four Copenhagen performances last year were all booked out, mainly with high-school children. For the first time, two non-Bonn students, one from Harvard and one from Tel Aviv, were part of our team. We also incorporated a few Bonn undergraduates. In February 2016, the DFG grant was renewed for another four years. We are now looking forward to more exciting trips, such as to Valencia and Barcelona in Spain in September.

The past 15 years have been full of exciting interactions with the Bonn physics students and with audiences in many countries. Not only has it been rewarding in itself, it has stimulated and benefitted my own research in theoretical physics.

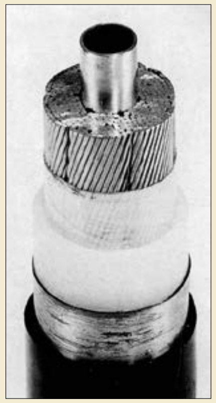
- *Herbi Dreiner, University of Bonn.*

CERN Courier Archive: 1974

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

CERN

Meeting on Technology arising from High Energy Physics


CERN 106.7.68

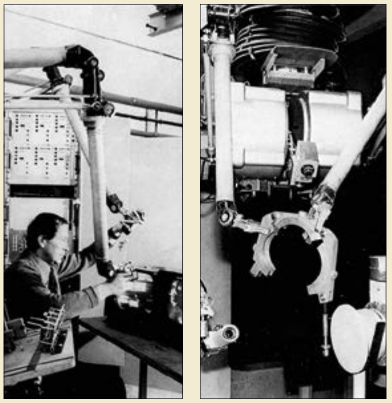
The water-cooled cable developed to power the magnets of the Intersecting Storage Rings. It is a high current conductor but is flexible and can be transported on a drum and cut to size where it is to be used.

One problem was to design terminations where the cables join the magnets because water leakage in high voltage conditions could lead to breakdown. A method was evolved whereby the lug is crimped to the cable with a hydraulically operated tool and then insulated with radiation resistant epoxy resin.


CERN 391.10.73

Construction of the electrostatic septum for the beam ejection system of the SPS. Its special feature is a precisely aligned plane of thin wires individually held taut across the aperture where the protons pass by means of springs. On the left, the wires are already in place. On the right, a new frame of wires is being positioned and the springs which will hold them can be seen protruding below on each side.

Having a plane of wires under tension avoids the possibility of distortion if a foil was used as the septum and minimises the volume of matter which is put in the way of the protons. In the event of a wire breaking, the springs will pull it out of the path of the beam.


CERN 392.2.74

Any radioactive environment prevents human intervention. However, conventional remote handling manipulators used in reactor and radiochemical laboratories are not appropriate at accelerators because of the distances involved. A variant was therefore tried at the PS.

The switch operated electric arm, mounted on a crane bridge, could travel around the ring with its cables being automatically plugged in at connection boxes around the accelerator tunnel wall. The manipulator is surveyed by TV cameras, as seen here, and can be operated up to 40 m from a plug-in box. It is controlled by an operator located at the centre of the accelerator ring.

The prototype proved useful for many jobs such as remote dosimetry, beam loss detection and dismantling radioactive components. It was clear, however, that higher speed and versatility was needed.

From 24–26 April, CERN is the scene of a "Meeting on Technology". Over 300 participants, including industrialists, directors of applied research, senior staff from technical universities, science journalists, etc, are invited to three days of review talks on advanced technology and the opportunity of touring 250 exhibits of equipment and techniques.

The main purpose of CERN is to provide Europe's scientists with first class facilities for high-energy physics research. In so doing, it is a strong stimulus and support to the quality of physics in Europe and of science education in the European universities where most of the physicists using CERN are based.

A second purpose, predominant at the time of CERN's formation 20 years ago, is the welding together of the efforts of many European countries to work for common aims. This purpose remains valid today and also seems well fulfilled.

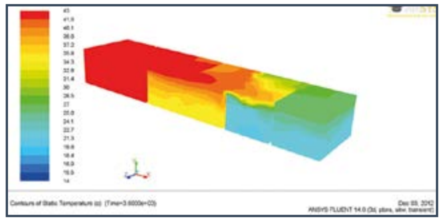
However, a great deal of advanced technology is involved in carrying out high-energy physics and, although knowledge of CERN's work is freely available, not much has so far been done to project this knowledge to people who could find it useful.

In the April meeting, a kind of "technological accounting" exercise, CERN will spread out some of the achievements from the European high-energy physics programme. The emphasis will be on straightforward presentation, without trying to anticipate possible applications.

● Compiled from texts on pp120–121, 126–127.

Compiler's Note

Amid the turmoil of today's world, CERN continues to fulfil the mission enshrined in its 1954 Convention. The lab now has an impressive administrative infrastructure for knowledge transfer across a broad front, from high-school teacher training to high-tech industrial collaboration. In addition, a regular series of exhibitions are organised whereby industries showcase their products at CERN and interact with in-house experts and clients. While spin-off into nuclear medicine and global networking is well known, the images shown here are some examples of the kind of pioneering techniques, rather than technologies, that can also find applications beyond the laboratory.



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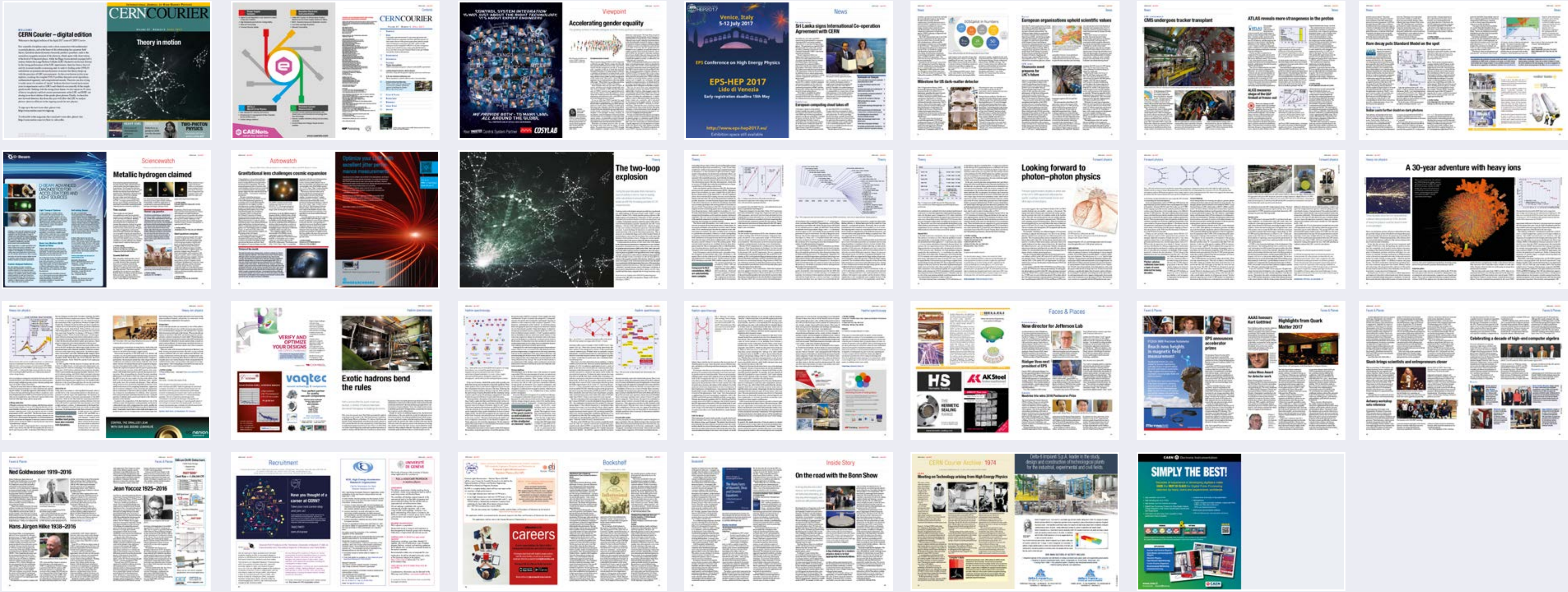

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