WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the May/June 2021 issue of *CERN Courier*.

In April, a keenly awaited measurement from Fermilab strengthened the longstanding tension between the measured and predicted values of the muon's anomalous magnetic moment, generating media coverage worldwide (p7). Physicists now look forward to further data (p49) and to a deeper understanding of the tricky QCD calculations (p25) before weighing up possible signs of new physics.

Meanwhile, in March, a new LHCb measurement of a parameter called R_K, which compares the rate of certain B-meson decays to muons and electrons, reinforces hints that lepton-flavour universality may be violated in the B sector (p17).

Also generating headlines this spring were the discovery of the odderon 50 years after its prediction (p8), and the demonstration of laser-cooled antihydrogen by the ALPHA collaboration (p9).

Elsewhere in this issue: upgrades to the beam-intercepting devices at the heart of CERN's accelerator complex (p38); ALICE makes strides towards understanding the extreme conditions of the early universe (p31); news from Moriond (p21); careers advice from accelerator physicist Suzie Sheehy (p52); assessing the economic impact of particle physics (p55); and much more.

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May/June 2021 cerncourier.com
Reporting on international high-energy physics

MUON g-2
MEASUREMENT OF THE MOMENT

Laser-cooled antihydrogen
Flavour anomalies back in the spotlight
Odderon finally discovered

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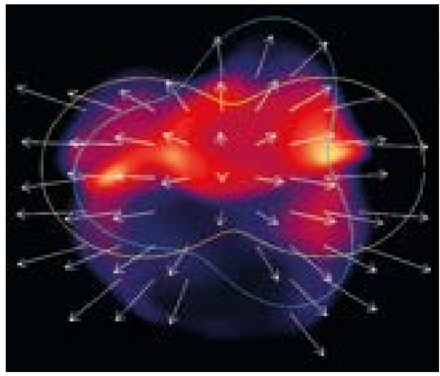
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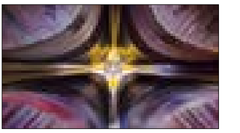
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FROM THE EDITOR

Muons making headlines

Matthew Chalmers
Editor

Ever since it turned up unexpectedly in cosmic rays 85 years ago, the muon has been a source of intrigue, famously prompting Isidor Isaac Rabi to exclaim "Who ordered that?" Similar to the electron in all but mass, it was the harbinger of a second generation of fermions and arguably marked the beginning of modern particle physics. Two results reported in this issue show that interest in the muon is far from over.

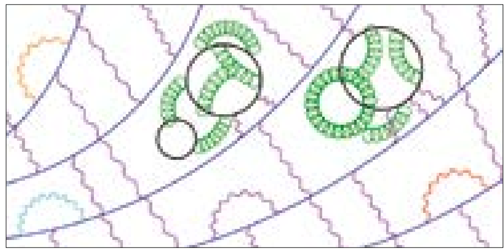
Keenly awaited measurements of the muon's anomalous magnetic moment announced by Fermilab on 7 April (p7) reinforce the anomaly reported by a previous experiment at Brookhaven 20 years ago. Currently, theory and experiment, both known to a precision of better than one part per million, stand 4.2σ apart. Meanwhile, a new LHCb measurement of a parameter called R_K, which compares the rate of certain B-meson decays to muons and to electrons, strengthens hints that lepton-flavour universality (LFU) is violated in the B sector (p17). The latest R_K result lies 3.1σ from the Standard Model, constituting the first single-measurement "evidence" for LFU violation, and fitting a pattern of flavour anomalies seen by LHCb in recent years.

Given the many channels studied in particle physics, 3σ effects come and go all the time. There is also no *a priori* reason to expect these particular departures from the Standard Model. The R_K anomaly involves a change of quark flavour whereas g–2 doesn't, note theorists, and there is no truly model-independent connection between them. Scalar leptoquarks and new gauge forces have been invoked to explain the anomalies, and further such efforts, requiring varying feats of acrobatics, are sure to be uploaded to the arXiv preprint server in the coming weeks and months.

Early days

Clearly it is far too soon to tell if something is amiss with the muon. But the fact that both anomalies are in the muon sector, and that fresh data have caused them to grow rather than fade, has generated a buzz in the community, and seen particle physicists' Twitter channels trend with the hashtag #CautiouslyExcited. The good news is that more measurements are on the way.

Clearly it is far too soon to tell if something is amiss with the muon



M Rayner/CERN

Freewheelin' *Artistic sketch of muons (blue) interacting with a magnetic field (purple), including "g–2" contributions, which are the subject of intense theoretical efforts (p25).*

Fermilab is at the very beginning of a campaign that will ultimately reduce the muon g–2 uncertainty by a factor of at least three, while a completely independent measurement is expected from J-PARC in Japan. If something is indeed going on with the muon's g-factor, it will only be natural that interest in a wider muon experimental programme is heightened. This includes Mu2e at Fermilab, Mu3e and muEDM at PSI, and COMET at J-PARC. A proposed experiment at CERN – where the first g–2 measurements were made 60 years ago (p49) – called MUonE aims to precisely determine the leading hadronic contribution to the g–2 measurement, while theoretical calculations relevant to muon g–2 are an exciting work in progress (p25).

Regarding the flavour anomalies, for which the accompanying theoretical calculations are comparatively much cleaner, new LHCb measurements of R_K-related observables are in development, with LHC Run 3 to bring further statistical power. The recently started Belle II experiment at SuperKEKB in Japan is also building up a dataset that will provide a crucial independent check of the LHCb results in the coming years, while CMS and ATLAS are poised to contribute.

One way or another, the current picture should start to come into focus towards the middle of the decade, around the time when decisions about the next major collider could be taken.

Reporting on international high-energy physics

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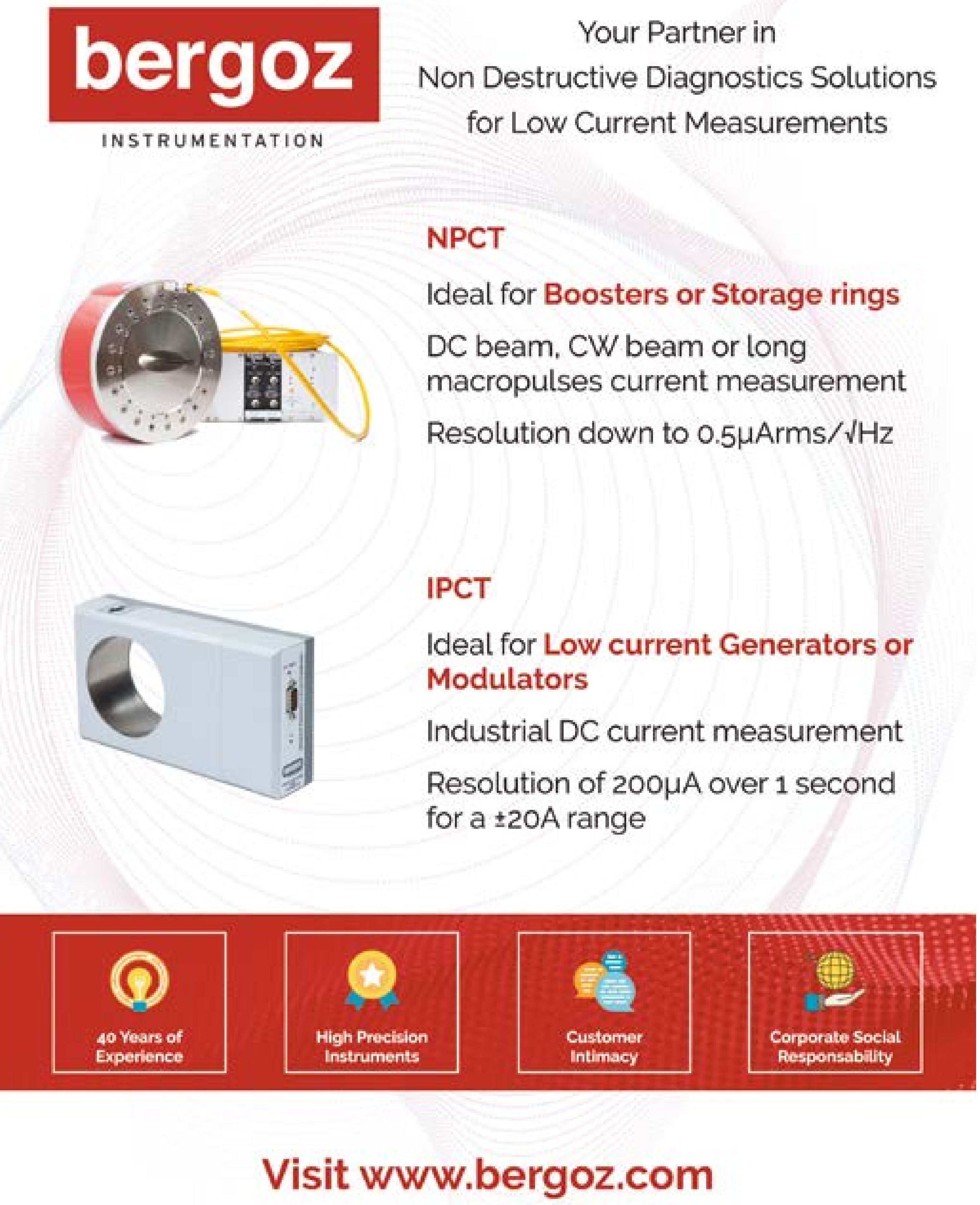


NEWS ANALYSIS

SEARCHES FOR NEW PHYSICS

Fermilab strengthens muon g–2 anomaly

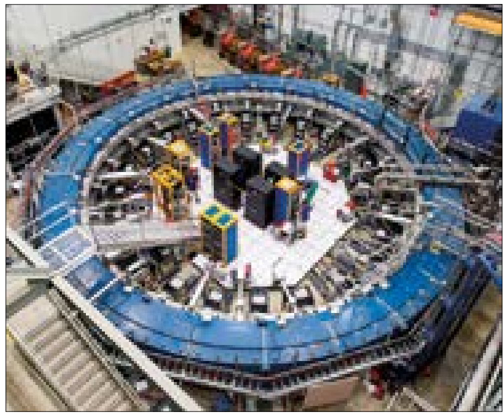
Hotly anticipated results from the first run of the muon g–2 experiment at Fermilab were announced on 7 April, increasing the tension between measurements and theoretical calculations. The last time this ultra-precise measurement was performed, at Brookhaven National Laboratory 20 years ago, it disagreed with the Standard Model (SM) by 3.7σ. After almost eight years of work rebuilding the Brookhaven experiment at Fermilab and analysing its first data, the muon's anomalous magnetic moment has been measured to be $116592040(54)\times10^{-11}$. The result is in agreement with the Brookhaven measurement and is 3.3σ greater than the SM prediction: $116591810(43)\times10^{-11}$. Combined with the Brookhaven result, the world-average value for the anomalous magnetic moment of the muon is $116592061(41)\times10^{-11}$, representing a 4.2σ departure from the SM.

"Today is an extraordinary day, long awaited not only by us but by the whole international physics community," says Graziano Venanzoni of the INFN, who is co-spokesperson of the Fermilab muon g–2 collaboration.

The Fermilab result was unblinded during a Zoom meeting on 25 February in the presence of 200 collaborators. It was an emotional moment, says Venanzoni. The analysis took almost three years from data taking to the release of the result, and the collaboration decided to unblind only when all the steps were completed and there were no outstanding questions.

Experiment reincarnated

The previous Brookhaven measurement left physicists pondering whether the presence of unknown particles in loops could be affecting the muon's behaviour. It was clear that further measurements were needed, and in the summer of 2013 the experiment's 14 m-diameter, 1.45 T superconducting magnet was transported from Brookhaven to Fermilab to build a reincarnated muon g–2 experiment. The Fermilab team reassembled the magnet and spent a year "shimming" its field, making it three times more uniform than the one it created at Brookhaven. Along with a new beamline to deliver a purer muon beam, thereby suppressing the pion contamination that challenged the Brookhaven measurement, Fermilab's muon g–2 set up required entirely new instrumentation and calibration systems, along with new detectors and a control room.



R Hahn/Fermilab

Momentary laps *The 14 m-diameter muon g–2 ring in its detector hall at Fermilab.*

When a muon travels in a strong external magnetic field, the direction of its magnetic moment precesses at a rate that depends on its strength, g. The Dirac equation predicts that fermions have a g-factor equal to two. But higher order loops add an "anomalous" moment, $a_\mu = (g-2)/2$, which can be calculated extremely precisely. At Fermilab, muons with an energy of about 3.1 GeV are vertically focused in the storage ring via quadrupoles, and their precession frequency is determined from decays to electrons using 24 electromagnetic calorimeters located along the ring's inner circumference. The collaboration took its first dataset in 2018, with more than eight billion muon decays resulting in an overall uncertainty approximately 15% better than Brookhaven's. Data analysis on the second and third runs is already under way, while a fourth run is ongoing and a fifth is planned. The collaboration is targeting a final precision of around 0.14 ppm.

"So far we have analysed less than 6% of the data that the experiment will eventually collect," said Fermilab's Chris Polly, a co-spokesperson for the current experiment and a graduate student on the Brookhaven experiment. "Although these first results are telling us that there is an intriguing difference with the Standard Model, we will learn much more in the next couple of years."

Theory baseline

Developments in the theory community are equally vital (p25). The Fermilab muon g–2 collaboration takes as its theory baseline the value obtained last year by the Muon g–2 Theory Initiative. Uncertainties in the calculation are dominated by hadronic contributions, in particular a term called the hadronic vacuum polarisation (HVP). The Theory Initiative incorporates the HVP value obtained by well-established "dispersive methods", which combine fundamental properties of quantum field theory with experimental measurements of low-energy hadronic processes. An alternative approach gaining traction is to calculate the HVP contribution using lattice QCD. In a paper published in *Nature* on the same day as the Fermilab announcement, one group reported a lattice HVP calculation with a much reduced uncertainty that is in 2σ tension with the dispersive approach; if adopted, it would substantially reduce the tension with experimental measurements.

"Given the complexity of the computations, independent results from different lattice groups with commensurate uncertainties are needed to test and check the lattice calculations against each other," read a statement from the Muon g–2 Theory Initiative steering committee. "Being entirely based on Standard Model theory, once the lattice results are well tested and precise enough, they will play an important role in understanding how new physics enters into the discrepancy."

Further reading

T Aoyama *et al.* 2020 *Phys. Rept.* **887** 1.
S Borsanyi *et al.* 2021 *Nature* doi:10.1038/s41586-021-03418-1.
Muon g–2 Collaboration 2021 *Phys. Rev. Lett.* **126** 141801.

STRONG INTERACTIONS

Elusive odderon finally discovered

M Brice/CERN-PHOTO-201609-210-4

Excavating odderons *Part of the TOTEM installation in the LHC tunnel 220 m downstream from the CMS experiment.*

The TOTEM collaboration at the LHC, along with the DØ collaboration at the former Tevatron collider at Fermilab, have announced the discovery of the odderon – an elusive odd-numbered gluon state predicted almost 50 years ago. The result was presented on 5 March during the LHC Forward Physics meeting at CERN, and follows the joint publication of a CERN/Fermilab preprint by TOTEM and DØ reporting the observation in December 2020.

"This result probes the deepest features of quantum chromodynamics, notably that gluons interact between themselves and that an odd number of gluons are able to be 'colourless', thus shielding the strong interaction," says TOTEM spokesperson Simone Giani of CERN. "A notable feature of this work is that the results are produced by joining the LHC and Tevatron data at different energies."

States comprising two, three or more gluons are termed "glueballs", and are peculiar objects made only of the carriers of the strong force. The idea for the odderon was introduced in 1973 in the framework of "Regge theory", and was named two years later in a paper by Joynson, Leader, Nicolescu and Lopez. With the advent of quantum chromodynamics (QCD), the existence of the odderon as a kind of virtual glueball became a firm prediction. But proving its existence has been a major experimental challenge, requiring detailed measurements of protons as they glance off one another in high-energy collisions.

Deviation measurement

While most high-energy collisions cause protons to break into their constituent quarks and gluons, roughly 25% are elastic collisions where the protons remain intact but emerge on slightly different paths (deviating by around a millimetre over a distance of 200 m at the LHC). TOTEM measures these small deviations in proton–proton (pp) scattering using two detectors located 220 m on either side of the CMS experiment, while DØ employed a similar setup at the Tevatron proton–antiproton ($p\bar{p}$) collider.

At low energies, differences in pp vs $p\bar{p}$ scattering are due to the exchange of virtual mesons. At multi-TeV energies, on the other hand, proton interactions are expected to be mediated purely by gluons. In particular, elastic scattering at low-momentum transfer and high energies has long been explained by the exchange of a pomeron – a colour-neutral virtual glueball made up of two gluons.

However, in 2018 TOTEM reported measurements at high energies that could not easily be explained by this traditional picture. Instead, a further QCD object with an odd charge-congugation quantum number C seemed to be at play, supporting models in which a glueball containing at least three gluons was being exchanged. The discrepancy came to light via measurements of a parameter called ρ, which represents the ratio of the real and imaginary parts of the forward elastic-scattering amplitude when there is minimal momentum exchange between the colliding protons and thus almost no deviation in their trajectories. The 2018 results were sufficient to claim evidence for the odderon, although not yet its definitive observation.

The new work is based on a model-independent analysis of data at medium-range momenta transfer. The TOTEM and DØ teams compared LHC pp data (recorded at collision energies of 2.76, 7, 8 and 13 TeV and extrapolated to 1.96 TeV), with Tevatron $p\bar{p}$ data measured at 1.96 TeV. The odderon would be expected to contribute with different signs to pp and $p\bar{p}$ scattering. Supporting this picture, the two data sets disagree at the 3.4σ level, providing evidence for the t-channel exchange of a colourless, C-odd gluonic compound. "When combined with the ρ and total cross-section result at 13 TeV, the significance is in the range $5.2–5.7\sigma$ and thus constitutes the first experimental observation of the odderon," said Christophe Royon of University of Kansas, who presented the results on behalf of DØ and TOTEM in March. "This is a major discovery by CERN/Fermilab."

This is a major discovery by CERN/Fermilab

In addition to the new TOTEM–DØ model-independent study, several theoretical papers based on data from the ISR, SPS, Tevatron and LHC, and model-dependent inputs, provide additional evidence supporting the conclusion that the odderon exists.

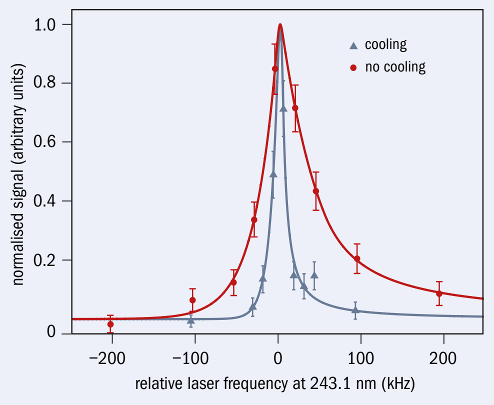
"The independent experimental evidence in the measurements of the ρ parameter and differential elastic cross section make it likely that we are indeed seeing signals of the odderon here," says theorist Carlo Ewerz of GSI Helmholtz Centre for Heavy Ion Research and Heidelberg University in Germany. "In these cases the odderon is only one among several contributions, and a very small one, so it is very impressive that the TOTEM and DØ collaborations could finally isolate an odderon signal in these challenging measurements. Dedicated searches for odderon effects in exclusive processes at the LHC and at the future Electron-Ion Collider will be crucial in order to determine its properties in detail and thus to understand why it had escaped detection for almost 50 years."

Further reading

DØ and TOTEM Collaborations 2020 arXiv:2012.03981.
TOTEM Collab. 2019 *Eur. Phys. J. C* **79** 785.
D Joynson *et al.* 1975 *Nuovo Cimento A* **30** 345.

ANTIMATTER

Laser-cooled antihydrogen takes ALPHA into new realm



Source: *Nature* **592** 35

Slimming down *Antihydrogen's 1S–2S spectral line measured with (grey) and without (red) the application of laser cooling. The narrowing occurs because the colder atoms spend more time in the laser field each time they pass through the beam, reducing the so-called transit-time broadening. Using thousands of trapped antihydrogen atoms, ALPHA is now able to record such a spectral line in a single day; the equivalent result from 2017 (see text) took 10 weeks.*

After many years of research and development, the ALPHA collaboration has succeeded in laser-cooling antihydrogen – opening the door to considerably more precise measurements of antihydrogen's internal structure and gravitational interactions. The seminal result, reported on 31 March in *Nature*, could also lead to the creation of antimatter molecules and the development of antiatom interferometry, explains ALPHA spokesperson Jeffrey Hangst. "This is by far the most difficult experiment we have ever done," he says. "We're over the moon. About a decade ago, laser cooling of antimatter was in the realm of science fiction."

The ALPHA collaboration synthesises antihydrogen from cryogenic plasmas of antiprotons and positrons at CERN's Antiproton Decelerator (AD), storing the antiatoms in a magnetic trap. Lasers with particular frequencies are then used to measure the antiatoms' spectral response. Finding any slight difference between spectral transitions in antimatter and matter would challenge charge–parity–time symmetry, and perhaps cast light on the cosmological imbalance of matter and antimatter.

Following the first antihydrogen spectroscopy by ALPHA in 2012, in 2017 the collaboration measured the spectral structure of the antihydrogen 1S–2S transition with an outstanding precision of 2×10^{-12} – marking a milestone in the AD's scientific programme. The following year, the team determined antihydrogen's 1S–2P "Lyman-alpha" transition with a precision of a few parts in a hundred million, showing that it agrees with the prediction for the equivalent transition hydrogen to a precision of 5×10^{-8}. However, to push the precision of spectroscopic measurements further, and to allow future measurements of the behaviour of antihydrogen in Earth's gravitational field, the kinetic energy of the antiatoms must be lowered.

In their new study, the ALPHA researchers were able to laser-cool a sample of magnetically trapped antihydrogen atoms by repeatedly driving the antiatoms from the 1S to the 2P state using a pulsed laser with a frequency slightly below that of the transition between them. After illuminating the trapped antiatoms for several hours, the researchers observed a more than 10-fold decrease in their median kinetic energy, with many of the antiatoms attaining energies below 1 μeV. Subsequent spectroscopic measurements of the 1S–2S transition revealed that the cooling resulted in a spectral line about four times narrower than that observed without laser cooling – a proof-of-principle of the laser-cooling technique, with further statistics needed to improve the precision of the previous 1S–2S measurement (see figure).

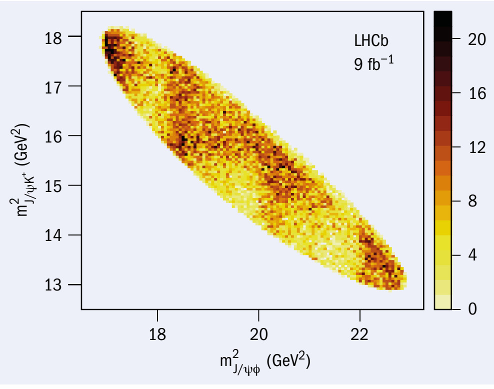
"Historically, researchers have struggled to laser-cool normal hydrogen, so this has been a bit of a crazy dream for us for many years," says Makoto Fujiwara, who proposed the use of a pulsed laser to cool trapped antihydrogen in ALPHA. "Now, we can dream of even crazier things with antimatter."

Further reading

The ALPHA Collaboration 2021 *Nature* **592** 35.

HADRON SPECTROSCOPY

LHCb observes four new tetraquarks



LHCb collaboration

Mountain ridges *A Dalitz plot of 24,000 $B^+ \to J/\psi\phi K^+$ decays, where vertical and horizontal bands reveal the presence of intermediate particles.*

The LHCb collaboration has added four new exotic particles to the growing list of hadrons discovered so far at the LHC. In a paper posted to the arXiv preprint server on 2 March, the collaboration reports the observation of two tetraquarks with a new quark content ($c\bar{c}u\bar{s}$): a narrow one, $Z_{cs}(4000)^+$, and a broader one $Z_{cs}(4220)^+$. Two other new tetraquarks, X(4685) and X(4630), with a quark content $c\bar{c}s\bar{s}$, were also observed. The results, which emerged thanks to adding the statistical power from LHC Run 2 to previous datasets, follow four tetraquarks discovered by the collaboration in 2016 and provide grist for the mill of theorists seeking to explain the nature of tetraquark binding mechanisms.

The new exotic states were observed in an almost pure sample of 24,000 $B^+ \to J/\psi\phi K^+$ decays, which, as a three-body decay, may be visualised using a Dalitz plot (see "Mountain ridges" figure). Horizontal and vertical bands indicate the temporary production of tetraquark resonances, which subsequently decay to a J/ψ meson and a K^+ meson or a J/ψ meson and a ϕ meson, respectively. The most prominent vertical bands correspond to four $c\bar{c}s\bar{s}$ tetraquarks that were first observed in June 2016. The collaboration has now resolved two new horizontal bands corresponding to the $c\bar{c}u\bar{s}$ states, and two additional vertical bands corresponding to the $c\bar{c}s\bar{s}$ states.

The results have already triggered theoretical head scratching. In November, the BESIII collaboration at the Beijing Electron–Positron Collider II reported the discovery of the first candidate for a charged hidden-charm tetraquark with strangeness, tentatively dubbed $Z_{cs}(3985)^-$. It is unclear whether the new $Z_{cs}(4000)^+$ tetraquark can be identified with this state, say physicists. Though their masses are consistent, the width of the BESIII particle is 10 times smaller. ▷

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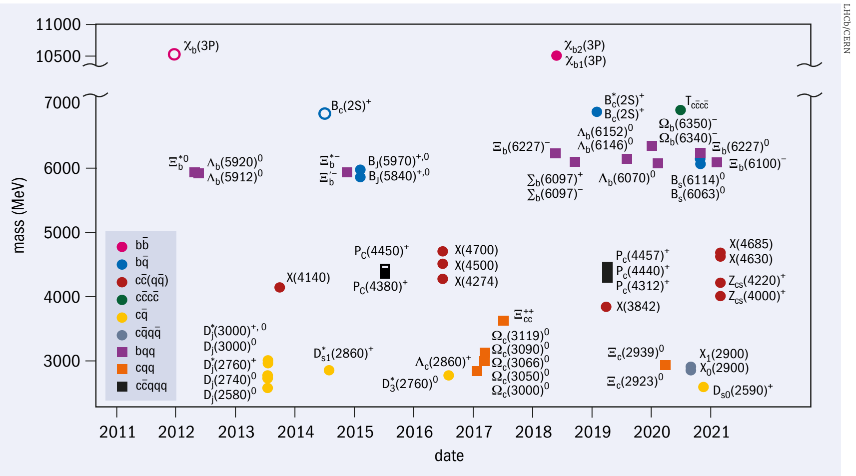
"These states may have very different inner structures," says lead analyst Liming Zhang of the LHCb collaboration. "The one seen by BESIII is a narrow and longer-lived particle, and is easier to understand with a nuclear-like hadronic molecular picture, where two hadrons interact via a residual strong force. The one we observed is much broader, which would make it more natural to interpret as a compact multiquark candidate."

The new observations take the tally of new hadronic states discovered at the LHC – which includes several pentaquarks as well as rare and excited mesons and baryons – to 59 (see "Diagram of discovery" figure). Though quantum chromodynamics naturally allows the existence of states beyond conventional two- and three-quark mesons and baryons, the detailed mechanisms responsible for binding multi-quark states are still largely mysterious. Tetraquarks, for example, could be tightly bound pairs of diquarks or loosely bound meson–meson molecules – or even both, depending on the production process (*CERN Courier* Sept/Oct 2020 p25).

"Who would have guessed we'd find so many exotic hadrons?" says former LHCb physics coordinator Patrick Koppenburg, who put the plot together. "I hope that they bring us to a better modelling of the strong interaction, which is very much needed to understand, for instance, the anomalies we see in B-meson decays."



LHCb/CERN

Diagram of discovery *The ATLAS, CMS and LHCb collaborations have discovered 59 new hadronic states so far.*

Further reading

LHCb Collab. 2021 arXiv:2103.01803.

ACCELERATORS

High-power linac shows promise for ADS technology

Physicists at the Institute of Modern Physics (IMP) in Lanzhou, China, have achieved a significant milestone towards an accelerator-driven sub-critical system – a proposed technology for sustainable fission energy. In February the institute's prototype front-end linac for the China Accelerator Driven Subcritical System (C-ADS) reached its design goal with the successful commissioning of a 10 mA, 205 kW continuous-wave (CW) proton beam at an energy of 20 MeV. The result breaks the world record for a high-power CW superconducting linac, says Yuan He, director of IMP's Linac Center: "This result consists of 10 years of hard work by IMP scientists, and brings the realisation of an actual ADS facility one step closer to the world."

The ADS concept, which was proposed by Carlo Rubbia at CERN in late 1990s, offers a potential technology for nuclear-waste transmutation and the development of safe, sustainable nuclear power. The idea is to sustain fission reactions in a subcritical reactor core with neutrons generated by directing a high-energy proton or electron beam, which can be switched on or off at will, at a heavy-metal spallation target. Such a system could run on non-fissile thorium fuel, which is more abundant than uranium and produces less waste. The challenge is to design an accelerator with the required beam power and long-term reliability, for which a superconducting proton linac is a promising candidate.

In 2011 a team at IMP launched a programme to build a superconducting proton linac (named CAFe) with an unprecedented 10 mA beam current. It was upgraded in 2018 by replacing the radio-frequency quadrupole and a cryo-module, but the team faced difficulties in reaching the design goals. Challenges including beam-loss control and detection, heavy beam loading and rapid fault recovery were finally overcome in early 2021, enabling the 38 m-long facility to achieve its design performance at the start of the Chinese new year. CAFe's beam availability during long-term, high-power operation was measured to be 93–96%, indicating high reliability: 12 hours of operation at 174 kW/10 mA and 108 hours at 126 kW/7.3 mA.


IMP

On track *The CAFe proton linac in China, which reached its design performance in early 2021.*

The full C-ADS project is expected to be completed this decade. A similar project called MYRRHA is under way at SCK CEN in Belgium, the front-end linac for which recently entered construction. Other ADS projects are under study in Japan, India and other countries.

"CAFe is the world's first CW superconducting proton linac stepping into the hundred-kilowatt level," says He. "The successful operation of the 10 mA beam meets the beam-intensity requirement for an experimental ADS demo facility – a breakthrough for ADS linac development and an outstanding achievement in the accelerator field."

COMPUTING

CMS seeks support for Lebanese colleagues

The CMS collaboration, in partnership with the Geneva-based Sharing Knowledge Foundation, has launched a fundraising initiative to support the Lebanese scientific community during an especially difficult period. Lebanon signed an international cooperation agreement with CERN in 2016, which triggered a strong development of the country's contributions to CERN projects, particularly to the CMS experiment through the affiliation of four of its top universities. Yet the country is dealing with an unprecedented economic crisis, food shortages, Syrian refugees and the COVID-19 pandemic, all in the aftermath of the Beirut port explosion in August 2020.

"Even the most resilient higher-education institutions in Lebanon are struggling to survive," says CMS collaborator Martin Gastal of CERN, who initiated the fundraising activity in March. "Despite these challenges, the Lebanese scientific community has reaffirmed its commitment to CERN and CMS, but it needs support."


M Alali

Strong ties *Young Lebanese scientists at CERN.*

One project, High-Performance Computing for Lebanon (HPC4L), which was initiated to build Lebanon's research capacity while contributing as a Tier-2 centre to the analysis of CMS data, is particularly at risk. HPC4L was due to benefit from servers donated by CERN to Lebanon, and from the transfer of CERN and CMS knowledge and expertise to train a dedicated support team that will run a high-performance computing facility there. But the hardware has been unable to be shipped from CERN because of a lack of available funding. CMS and the Sharing Knowledge Foundation are therefore fundraising to cover the shipping costs of the donated hardware, to purchase hardware to allow its installation, and to support Lebanese experts while they are trained at CERN by the CMS offline computing team.

"At this pivotal moment, every effort to help Lebanon counts," says Gastal. "CMS is reaching out for donations to support this initiative, to help both the Lebanese research community and the country itself."

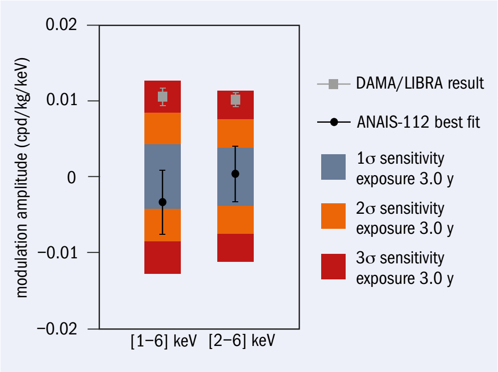
- More information, including how to get involved, can be found at: cern.ch/fundraiser-lebanon.

CERNCOURIER
VOLUME 61 NUMBER 3 MAY/JUNE 2021
IOP Publishing

ASTROWATCH

ANAIS challenges DAMA dark-matter claim

ANAIS



Source: arXiv:2103.01175

Still in the dark *Photomultiplier tubes for ANAIS inside their shielding blocks and (right) a comparison between the ANAIS and DAMA/LIBRA results.*

Despite the strong indirect evidence for the existence of dark matter, a plethora of direct searches have not resulted in a positive detection. The exception to this are the famous results from the DAMA/NaI experiment at Gran Sasso underground laboratory in Italy, first reported in the late 1990s, which show a modulating signal compatible with Earth moving through a region containing weakly interacting massive particles (WIMPs). These results were backed-up more recently with measurements from the follow-up DAMA/LIBRA detector. Combining the data in 2018, the evidence reported for a dark-matter signal is as high as 13σ. Now, the Annual modulation with NaI Scintillators (ANAIS) collaboration, which aims to directly reproduce the DAMA results using the same detector concept, has published the results from their first three years of operations. The results, which were presented at Rencontres de Moriond, show a clear contradiction with DAMA, indicating that we are still no closer to finding dark matter.

The DAMA results are based on searches for an annual modulation in the interaction rate of WIMPs in a detector comprising NaI crystals. First theoretically proposed in 1986 by Andrzej Drukier, Katherine Freese and David Spergel, this modulation is a result of the difference in velocity of Earth with respect to the dark-matter halo of the galaxy. On 2 June the velocities of Earth and the Sun are aligned with respect to the galaxy, whereas half a year later they are oppositely aligned, resulting in a lower cross section for WIMPs with a detector placed on Earth. Although this method has advantages compared to more direct detection methods, it requires that other potential sources of such a seasonal modulation be ruled out. Despite the significant modulation with the correct phase observed by DAMA, its results were not immediately accepted as a clear signal of dark matter due to the remaining possibility of instrumental effects, seasonal background modulation or artifacts from the analysis.

Controlling the data

Over the years the significance of the DAMA results has continued to increase while other dark-matter searches, in particular with the XENON1T and LUX experiments, found no evidence of WIMPs capable of explaining the DAMA results. The fact that only the final analysis products from DAMA have been made public has also hampered attempts to prove or disprove alternative origins of the modulation. To overcome this, the ANAIS collaboration set out to reproduce the data with an independent detector intentionally similar to DAMA, consisting of NaI(Tl) scintillators read out by photomultipliers placed in the Canfranc Underground Laboratory deep beneath the Pyrenees in northern Spain. Using this method ANAIS can rule out any instrument-induced effects while producing data in a controlled way and studying it in detail with different analysis procedures.

The first three years of ANAIS data have now been unblinded, and the results were posted on arXiv on 1 March. None of the analysis methods used show any signs of a modulation, with a statistical analysis ruling out the DAMA results at 99% confidence. The results therefore narrow down the possible causes of the modulation observed by DAMA to either differences in the detector compared to ANAIS, or in the analysis method. One specific issue raised by the ANAIS collaboration regards the background-subtraction method. In the DAMA results the mean background rate for each year is subtracted from the raw data for that full year. In case the background during that year is not constant, however, this will produce an artificial saw-tooth shape which, with the limited statistics, can be fitted with a sinusoidal. This effect was already pointed out in a publication by a group from INFN in 2020, which showed how a slowly increasing background is capable of producing the exact modulation observed by DAMA. The ANAIS collaboration describes their background in detail, shows that it is indeed not constant, and provides suggestions for a more robust handling of the background.

The ANAIS results also agree with the first results published by the COSINE-100 collaboration

The ANAIS results also agree with the first results published by the COSINE-100 collaboration in 2019 which, again using a NaI-based detector, found no evidence of a yearly modulation. Thanks to the continued experimental efforts of these two groups, and with the ANAIS collaboration planning to make their data public to allow independent analyses, the more than 20 year-old DAMA anomaly looks likely to be settled in the next few years.

Further reading

J Amaré *et al.* 2021 arXiv:2103.01175.
D Buttazzo *et al.* 2020 *JHEP* **04** 137.
COSINE-100 Collab. 2018 *Nature* **564** 83.

CERNCOURIER
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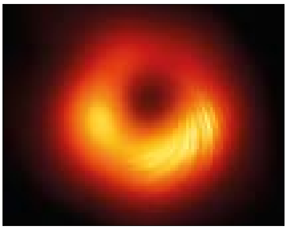
NEWS DIGEST

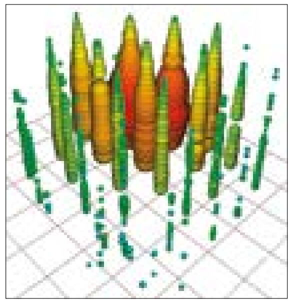

EHT Collaboration

M87 in polarised light.

Polarisation at the event horizon
Two years after intriguing the world with an intensity map of light from the massive object at the centre of the supergiant galaxy M87, the Event Horizon Telescope collaboration has added polarisation information to the image (see figure). It is the first time astronomers have been able to measure polarisation this close to the edge of a black hole (*ApJL* **910** L12). Only theoretical models featuring light emission by strongly magnetised gas can explain observations at the event horizon, notes a separate theory paper by the collaboration (*ApJL* **910** L13). To study its primary targets – M87 and Sagittarius A*, the much smaller black hole at the centre of the Milky Way – the collaboration must wait for good weather at eight telescopes around the world, and then mail the hard drives to analysis locations.

Baikal–GVD launched
In March researchers in Russia inaugurated the Baikal Deep Underwater Neutrino Telescope (Baikal–GVD) – a km^3-scale facility situated up to 1.3 km below Lake Baikal, the largest freshwater lake in the world. When complete, it will contain 20 detector clusters each comprising 288 (36×8 strings) glass spheres housing photomultiplier tubes. With eight clusters installed so far, the facility is 40% complete. Already the largest neutrino telescope in the Northern Hemisphere, Baikal–GVD will search for high-energy cosmic neutrinos by detecting Cherenkov light generated by their interactions.

IceCube sees Glashow resonance
In 1960 Sheldon Glashow predicted that a then-unknown W^- boson could be resonantly produced by a high-energy electron antineutrino interacting with an atomic electron (*Phys. Rev.* **118** 316). Glashow could not have imagined that this particle, discovered at CERN in 1983, would have a mass of 80 GeV, and require a neutrino with an energy of 6.3 PeV to be produced on-shell in an interaction with an electron at rest. The IceCube collaboration, which operates an enormous detector encased in Antarctic ice, has now uncovered one such event in data from 2016 – one of only three neutrinos to be detected with an energy in excess of 5 PeV (*Nature* **591** 220).


IceCube

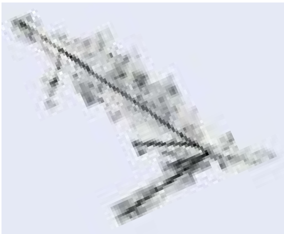
The Glashow "Hydrangea" event.

Gender irrelevant in physics tests
A team of education researchers and physicists from the University of Texas and Texas A&M University report that gender is not a strong factor leading to differences in student performance. The 12-year study of algebra- and calculus-based classical mechanics and electromagnetism courses looked for discrepancies between the exam performance of male and female physics students. A few differences were seen, such as women outperforming men in algebra-based mechanics, but the effects are small, and at most weakly dependent on gender, write the authors (*Phys. Rev. Phys. Educ. Res.* **17** 010106).

Muon detection in cargo
A team headed by Francesco Riggi at the University of Catania has developed a new way to detect nuclear materials in cargo ships using cosmic muons. Muon tomography is a well-documented technique that offers a promising way to detect the presence of hidden quantities of dense materials inside large volumes. Since cosmic muons are relatively rare, however, long scanning times are required. Riggi and collaborators developed a full-scale muon tomograph prototype with a sensing area of $18\,m^2$ and used it to inspect a full-scale container in which a $0.004\,m^2$ lead block was placed. A multi-parametric "POCA" analysis of incoming and outgoing muon tracks allowed a real-time analysis of the collected events, showing promise for practical applications, says the team (*EPJ Plus* **136** 139).

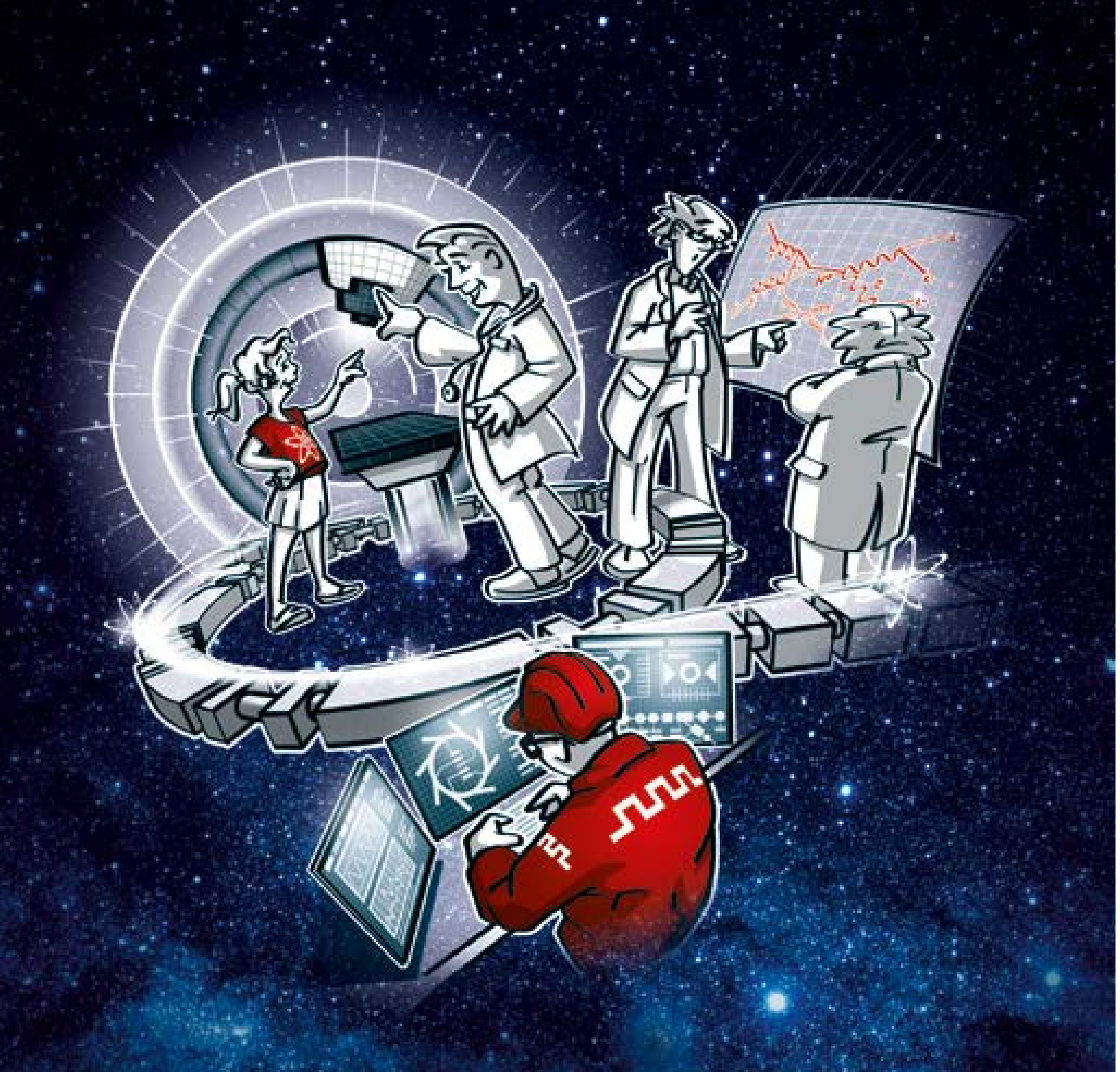
Antimatter on the move
In March, CERN approved the development of two new experiments to transport antiprotons from CERN's Antimatter Factory to other facilities. BASE-STEP, a variant of the BASE experiment, will feature two Penning traps to receive and release antiprotons and has been designed to be carried to a facility at CERN or elsewhere to allow higher-precision antiproton measurements. PUMA will transport antiprotons to CERN's nuclear-physics facility ISOLDE, for the investigation of exotic nuclear-physics phenomena. It will consist of a first trapping zone to stop antiprotons, and a second trapping zone to host collisions between the antiprotons and radioactive atomic nuclei that are routinely produced at ISOLDE but decay too rapidly to be transported anywhere themselves.

Doubly strange hypernucleus seen
J-PARC's E07 collaboration has detected a short-lived nucleus containing two strange quarks. The Japan-based team directed a beam of K mesons into a diamond target to produce Ξ^- (dss) hyperons which then traversed a stack of photographic sheets, extracting an event named "IBUKI" for a Honshu mountain (image below), where a hyperon briefly bonded with a nitrogen nucleus to create a doubly strange hypernucleus. The team determined that Ξ hyperons bind to nitrogen nuclei with an energy of about 1.27 MeV, likely corresponding to a nuclear 1p state, in agreement with predictions (*Phys. Rev. Lett.* **126** 062501). In a separate result, the team observed the same hypernucleus decaying into two ^{5}He hypernuclei with a binding energy of 6.27 MeV, corresponding to the more strongly bound 1s state (arXiv:2103.08793).


J-PARC E07 Collaboration

The "IBUKI" event.

Quasi-Majorana claim retracted
The authors of a 2018 *Nature* article have retracted their claim to have observed "quantised Majorana conductance" – a sign of superconductor analogues to Majorana fermions that have potential applications in quantum computing (*Nature* **591** E30). After inconsistencies in the original analysis were pointed out, the authors reanalysed their results and established that the data in two of their figures had been unnecessarily corrected for charge jumps, invalidating their original claim. The retraction does not invalidate previous findings that excitations with the properties of Majorana fermions exist in condensed-matter systems.



ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

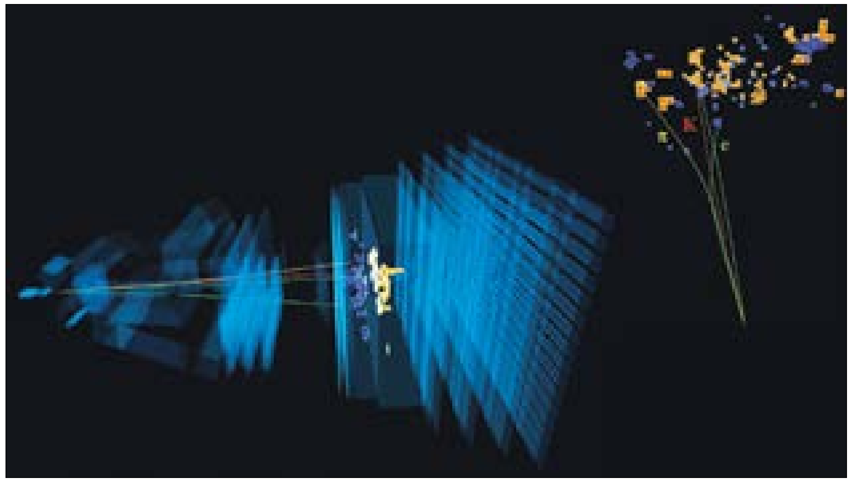
LHCb

New data strengthens R_K flavour anomaly

The principle that the charged leptons have identical electroweak interaction strengths is a distinctive feature of the Standard Model (SM). However, this lepton-flavour universality (LFU) is an accidental symmetry in the SM, which may not hold in theories beyond the SM (*CERN Courier* May/June 2019 p33). The LHCb collaboration has used a number of rare decays mediated by flavour-changing neutral currents, where the SM contribution is suppressed, to test for deviations from LFU. During the past few years, these and other measurements, together with results from B-factories, hint at possible departures from the SM.

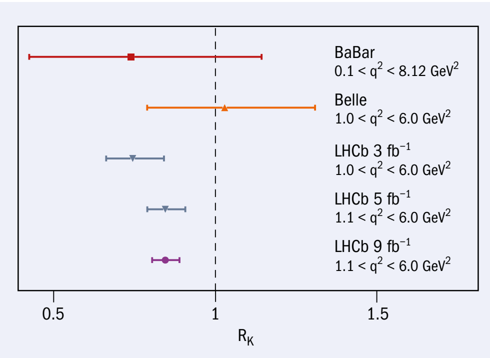
In a new measurement of a LFU-sensitive parameter "R_K" with increased precision and statistical power, reported at the Rencontres de Moriond, LHCb has strengthened the significance of the flavour anomalies. The value R_K probes the ratio of B-meson decays to muons and electrons: $R_K = BR(B^+ \rightarrow K^+\mu^+\mu^-)/BR(B^+ \rightarrow K^+e^+e^-)$. Testing LFU in such $b \rightarrow s\ell^+\ell^-$ transitions has the advantage that not only are SM contributions suppressed, but the theoretical predictions are very precise. Therefore, any significant deviation of R_K from unity would imply physics beyond the SM.

The experimental challenge lies in the fact that, while electrons and muons interact via the electroweak force in the same way, the small electron mass means that it interacts with detector material much more than muons. For example, electrons radiate a significant number of bremsstrahlung photons when traversing the LHCb detector, which degrades reconstruction efficiency and signal resolution compared to muons. The key to control this effect is to use the decays $J/\psi \rightarrow e^+e^-$ and $J/\psi \rightarrow \mu^+\mu^-$, which are known to have the same decay probability and can be used to calibrate and test electron reconstruction efficiencies. High precision tests with the J/ψ are compatible with LFU, which provides a powerful cross-check on the experimental analysis.



LHCb

Sensitive test *The decay of a B^0 meson to a K^{*0} and an electron–positron pair.*



LHCb

Fig. 1. *Comparison between R_K measurements. In addition to the LHCb result, the measurements by the BaBar and Belle collaborations, which combine $B^+ \rightarrow K^+\ell^+\ell^-$ and $B^0 \rightarrow K^0_S\ell^+\ell^-$ decays, are shown.*

Previous LHCb measurements of R_K and R_{K*} (which probes $B^0 \rightarrow K^{0*}\ell^+\ell^-$ decays) in 2019 and 2017, respectively, provide hints of deviations from unity (*CERN Courier* May/June 2019 p9). The latest analysis of R_K, which uses the full dataset collected by the experiment in Run 1 and Run 2 of the LHC, represents a substantial improvement in precision on the previous measurement (see figure 1) thanks to doubling the dataset. The R_K ratio is measured to be three standard deviations from the SM prediction (see figure 1). This is the first time that a departure from LFU above this level has been seen in any individual B-meson decay, with a value of $R_K = 0.846^{+0.042}_{-0.039}$ (stat.) $^{+0.013}_{-0.012}$ (syst.).

Although it is too early to conclude anything definitive at this stage, this deviation is consistent with a pattern of anomalies that have manifested themselves in $b \rightarrow s\,\ell^+\ell^-$ and similar processes over the course of the past decade. In particular, the strengthening R_K anomaly may be considered alongside hints from other measurements of these transitions, including angular asymmetries and decay rates.

The LHCb experiment is well placed to clarify the potential existence of new-physics effects in these decays. Updates on a suite of $b \rightarrow s\,\ell^+\ell^-$ related measurements with the full Run 1 and Run 2 dataset are underway. A major upgrade to the detector during the ongoing second long shutdown of the LHC will offer a step change in precision in Run 3 and beyond.

Further reading

LHCb Collaboration 2021 arXiv:2103.11769.

ATLAS

Higgsinos under the microscope

The Higgs boson was hypothesised to explain electroweak symmetry breaking nearly 50 years before its discovery. Its eventual discovery at the LHC took half a century of innovative accelerator and detector development, and extensive data analysis. Today, several outstanding questions in particle physics could be answered by higgsinos – theorised supersymmetric partners of an extended Higgs field. The higgsinos are a triplet of electroweak states, two neutral and one charged. If the lightest neutral state is stable, it can provide an explanation of astronomically observed dark matter. Furthermore, an intimate connection between higgsinos and the Higgs boson could explain why the mass of the Higgs boson is so much lighter than suggested by theoretical arguments. While higgsinos may not be much heavier than the Higgs boson, they would be produced more rarely and are significantly more challenging to find, especially if they are the only supersymmetric particles near the electroweak scale.

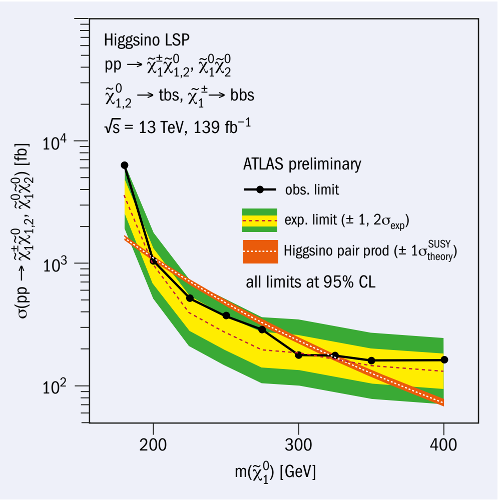


Fig. 1. *The excluded cross-section of the lightest higgsino as a function of its hypothetical mass (black), for the case wherein the lightest higgsino decays to three quarks. The orange line shows the theoretical rate of higgsino production. Higgsino masses between 200 and 320 GeV are ruled out by this search.*

The ATLAS collaboration recently released a set of results based on the full LHC Run 2 dataset that explore some of the most challenging experimental scenarios involving higgsinos. Each result tests different assumptions. Owing to quantum degeneracy, the higgsinos mix with other supersymmetric electroweak states, the wino and the bino, to form the physical particles that would be observed by the experiment. The mass difference between the lightest neutral and charged states, ∆m, depends on this mixing. Depending on the model assumptions, the phenomenology varies dramatically, requiring different analysis techniques and stimulating the development of new tools.

If ∆m is only a few hundred MeV, the small phase space suppresses the decay from the heavier states to the lightest one. The long-lived charged state flies partway through the inner tracker before decaying, and its short track can be measured. A search targeting this anomalous "disappearing track" signature was performed by exploiting novel requirements on the quality of the signal candidate and the ability of the ATLAS inner detectors to reconstruct short tracks. Finding that the number of short tracks is as expected from background processes alone, this search rules out higgsinos with lifetimes of a fraction of a nanosecond for masses up to 210 GeV.

If higgsinos mix somewhat with other supersymmetric electroweak states, they will decay promptly to the lightest stable higgsino and low-energy Standard Model particles. These soft decay products are extremely challenging to detect at the LHC, and ATLAS has performed several searches for events with two or three leptons to maximise the sensitivity to different values of ∆m. Each search features innovative optimisation and powerful discriminants to reject background. For the first time, ATLAS has performed a statistical combination of these searches, constraining higgsino masses to be larger than 150 GeV for ∆m above 2 GeV.

A final result targets higgsinos in models in which the lightest supersymmetric particle is not stable. In these scenarios, higgsinos may decay to triplets of quarks. A search designed around an adversarial neural network and employing a completely data-driven background estimation technique was developed to distinguish these rare decays from the overwhelming multi-jet background. This search is the first at the LHC to obtain sensitivity to this higgsino model, and rules out scenarios of the pair production of higgsinos with masses between 200 and 320 GeV (figure 1).

Together, these searches set significant constraints on higgsino masses, and for certain parameters provide the first extension of sensitivity since LEP. With the development of new techniques and more data to come, ATLAS will continue to seek higgsinos at higher masses, and to test other theoretical and experimental assumptions.

Further reading

ATLAS Collab. 2021 SUSY-2019-09.
ATLAS Collab. 2021 ATLAS-CONF-2021-007.
ATLAS Collab. 2021 ATLAS-CONF-2021-016.

CMS

New excited beauty-strange baryon observed

Beauty baryons are a subject of great interest at the LHC, offering unique insights into the nature of the strong interaction and the mechanisms by which hadrons are formed. While the ground states Λ_b^0, $\Sigma_b^{\pm}$, Ξ_b^-, Ξ_b^0, Ω_b^- were observed at the Tevatron at Fermilab and the SPS at CERN, the LHC's higher energy and orders-of-magnitude larger integrated luminosity have allowed the discovery of more than a dozen excited beauty baryon states among the 59 new hadrons observed at the LHC so far (see p9).

Many hadrons with one c or b quark are quite similar. Interchanging heavy-quark flavours does not significantly change the physics predicted by effective models assuming "heavy quark symmetry". The well-established charm baryons and their excitations therefore provide excellent input for theories modelling the less well understood spectrum of beauty-baryons. A number of the lightest excited b baryons, such as $\Lambda_b(5912)^0$, $\Lambda_b(5920)^0$, and several excited Ξ_b and Ω_b^- states, have been observed, and are consistent with their charm partners. By contrast, however, heavier excitations, such as the $\Lambda_b(6072)^0$ and $\Xi_b(6227)$ isodoublet (particles that differ only by an up or down quark), cannot yet be readily associated with charmed partners.

The $\Xi_b(6100)^-$ might also shed light on the nature of previous discoveries

The first particle observed by the CMS experiment, in 2012, was the beauty-strange baryon $\Xi_b(5945)^0$ (*CERN Courier* June 2012 p6). It is consistent with being the beauty partner of the $\Xi_c(2645)^+$ with spin-parity $3/2^+$, while the $\Xi_b(5955)^-$ ▷ and $\Xi_b(5935)^-$ states observed by LHCb are its isospin partner and the beauty partner of the $\Xi_c'^0$, respectively. The charm sector also suggests the existence of prominent heavier isodoublets, called Ξ_b^{**}: the lightest orbital Ξ_b excitations with orbital momentum between a light diquark (a pairing of a s quark with either a d or a u quark) and a heavy b quark. The isodoublet with spin-parity $1/2^-$ decays into $\Xi_b' \pi^{\pm}$ and the one with $3/2^-$ into $\Xi_b^* \pi^{\pm}$.

The CMS collaboration has now observed such a baryon, $\Xi_b(6100)^-$, via the decay sequence $\Xi_b(6100)^- \to \Xi_b(5945)^0\pi^- \to \Xi_b^- \pi^+ \pi^-$. The new state's measured mass is 6100.3 ± 0.6 MeV, and the upper limit on its natural width is 1.9 MeV at 95% confidence level. The Ξ_b^- ground state was reconstructed in two channels: $J/\psi\, \Xi^-$ and $J/\psi\, \Lambda\, K^-$. The latter channel also includes partially reconstructed $J/\psi\, \Sigma^0\, K^-$ (where the photon from the $\Sigma^0 \to \Lambda\, \gamma$ decay is too soft to be reconstructed).

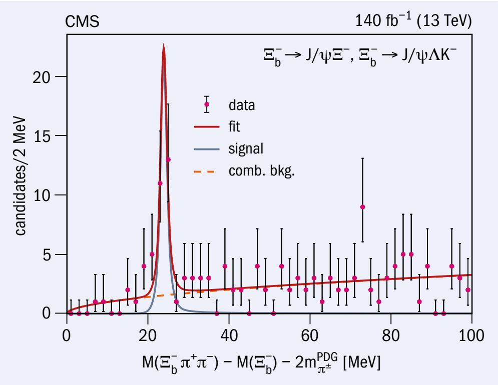


Fig. 1. *The reconstructed invariant mass difference distribution of the selected $\Xi_b^-\, \pi^+\, \pi^-$ candidates. The observed peak at 24.14 ± 0.22 MeV, with respect to the Ξ_b^- and di-pion mass, corresponds to a new Ξ_b^{**-} particle with a mass of 6100.3 ± 0.6 MeV. The inclusion of charge-conjugated states is implied throughout the text.*

The observation of this baryon and the measurement of its properties are useful for distinguishing between different theoretical models predicting the excited beauty baryon states. It is curious to note that if the $\Xi_b(6100)^-$ baryon were only 13 MeV heavier, a tiny 0.2% change, it would be above the $\Lambda_b^0 K^-$ mass threshold and could decay to this final state. The $\Xi_b(6100)^-$ might also shed light on the nature of previous discoveries: if it is the $3/2^-$ member of the lightest orbital excitation isodoublet, then the $\Xi_b(6227)$ isodoublet recently found by the LHCb collaboration could be the $3/2^-$ orbital excitation of Ξ_b' or Ξ_b^* baryons.

Further reading

CMS Collab. 2021 arXiv:2102.04524 (submitted to *Phys. Rev. Lett.*).

ALICE

Light neutral mesons probed to high p_T

Neutral pion (π^0) and eta-meson (η) production cross sections at midrapidity have recently been measured up to unprecedentedly high transverse momenta (p_T) in proton–proton (pp) and proton–lead (p–Pb) collisions at $\sqrt{s_{NN}} = 8$ and 8.16 TeV, respectively. The mesons were reconstructed in the two-photon decay channel for p_T from 0.5 and 1 GeV up to 200 and 50 GeV for π^0 and η mesons, respectively. The high momentum reach for the π^0 measurement was achieved by identifying two-photon showers reconstructed as a single energy deposit in the ALICE electromagnetic calorimeter.

In pp collisions, measurements of identified hadron spectra are used to constrain perturbative predictions from quantum chromodynamics (QCD). At large momentum transfer (Q^2), one relies in these perturbative approximations of QCD (pQCD) on the factorisation of computable short-range parton scattering processes such as quark–quark, quark–gluon and gluon–gluon scatterings from long-range properties of QCD that need experimental input. These properties are modelled by parton distribution functions (PDFs), which describe the fractional-momentum (x) distributions of quarks and gluons within the proton, and fragmentation functions, which describe the fractional-momentum distribution of quarks or gluons for hadrons of a certain species.

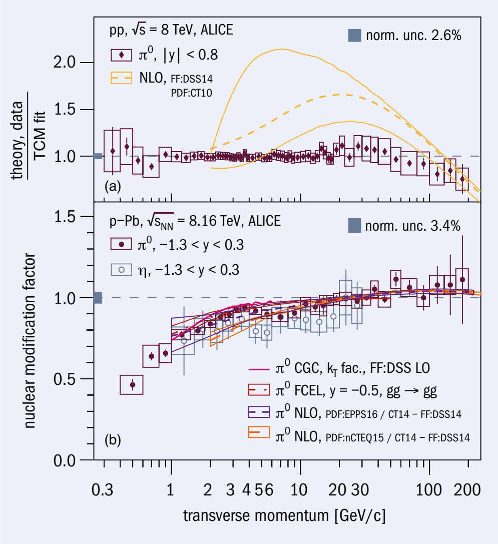


Fig. 1. *(a) Neutral pion cross section compared to NLO pQCD calculations in pp collisions at 8 TeV, normalised to a phenomenological two-component model (TCM) fit of the data. (b) Nuclear modification factor of π^0 and η mesons in p–Pb collisions at 8.16 TeV compared to calculations based on NLO pQCD with nuclear PDFs, the Color Glass Condensate (CGC) framework, and pQCD with final-state energy loss (FCEL).*

In p–Pb collisions, nuclear effects are expected to significantly affect particle production, in particular at small parton fractional momentum x, compared to pp collisions. Modification at low p_T (~1 GeV), usually attributed to nuclear shadowing (*CERN Courier* March/April 2021 p19), can be parameterised by nuclear parton distribution functions (nPDFs). However, since high parton densities are reached at the LHC, the Colour Glass Condensate (CGC) framework is also applicable at low p_T (x values as small as ~5×10^{-4}), which predicts strong particle suppression due to saturation of the parton phase space in nuclei. Above momenta of about 10 GeV/c, measurements in p–Pb collisions can also be sensitive to the energy loss of the outgoing partons in nuclear matter.

The nuclear modification factor (R_{pPb}), shown in the lower panel of the figure, was measured as the ratio of the cross sections in p–Pb and pp collisions normalised by the atomic mass number. Below 10 GeV, R_{pPb} is found to be smaller than unity, while above 10 GeV it is consistent with unity. The measurement is described by calculations over the full transverse momentum range and provides further constraints to the nPDF parameterisations for lower than about 5 GeV. The direct comparison of the neutral pion cross section in pp collisions at 8 TeV, with pQCD calculations shown in the upper panel of the figure, reveals differences in the low to intermediate p_T range, which, however, cancel in R_{pPb}, since similar differences are also present for the p–Pb cross section. Future high-precision measurements are ongoing using the large dataset from pp collisions at 13 TeV, providing further constraints to pQCD calculations.

Further reading

ALICE Collab. 2021 arXiv:2104.03116.

CERNCOURIER
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Advertisement

ARMCO® Pure Iron – a benchmark for manifold Big Science projects

Highest quality for DC magnets
The use of iron for particle accelerator magnets, instruments or passive magnetic shielding must meet the advanced requirements of unalloyed soft magnetic steel. Numerous projects and developments in science, therapy and analytics have now proven the unrivalled quality of ARMCO® Pure Iron. In the last decade, a profound material knowledge has been established and excellent magnetic properties confirmed for a broad range of shapes, dimensions and delivery conditions. AK Steel International is proud to provide the key details from the major projects below.

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As emphasised by CERN, ARMCO® Pure Iron undergoes purification during melting using special refining techniques, resulting in a minimum iron content of 99.85 weight%. After solidification it has a particularly homogeneous composition with regard to impurity distribution. A maximum carbon content of 0.010% is specified, and in most flat-rolled or forged conditions, as in DC electromagnets, the grade exhibits a carbon content of 0.005% or below. With the existing capabilities of producing flat-rolled items, the carbon content has not exceeded 0.0023%, with an average value of 0.0013% over several years of production. Very low values of oxygen, sulphur, nitrogen and cobalt are confirmed, as well as full transformation, homogeneity and freedom from pores and inclusions. Due to the particularly low carbon content, the microstructure is composed of 100% ferrite.

Benchmark for synchrotrons
As well as collider projects, ARMCO® Pure Iron has been specified for numerous synchrotron rings to secure the required magnet performance at optimised power

Source: CERN. Copyright retained

An example of an MQXF magnet. ARMCO® Pure Iron is specified for LARP low-beta quadrupole master keys, yokes and load pads.

utilisation. A novel approach has been implemented by processing a total of 600 tonnes of customised ARMCO® Pure Iron flat items for the integrated magnet design of the MAX IV and SOLARIS light sources. More recently, it was decided at Argonne National Laboratory to utilise the material's specific combination of magnetic permeability and lot-to-lot repeatability for the MI and M2 magnets of the local Advanced Photon Source upgrade. Similarly, hot-rolled heavy plates and forged bars have been used for manufacturing positron damping-ring magnets for the SLAC FACET-II facility. Here, the introduction of the Pure Iron AME grade for large forgings has provided a highly transformed ultra-pure iron option at increased dimensions. Overall, several magnet engineers and manufacturers who specialise in synchrotron-light-source equipment have utilised both ARMCO® Pure Iron and Pure Iron AME for manifold project work worldwide.

The power of a well-defined field
CERN Courier has previously reported on the Baby MIND neutrino detector (www.cerncourier.com/a/baby-mind-takes-first-steps), where large-area elements are made from customised ARMCO® Pure Iron heavy plates. For the DUNE/LBNF neutrino experiment, cold-rolled sheets of the same grade were selected for the beamline magnets in the framework of the current Fermilab collaborations. Moreover, experiments with neutral particles require ARMCO® Pure Iron for magnetic shielding in the vicinity of high-Tesla instrumentation such as the aSPECT spectrometer or for applying a very uniform magnetic field to SANS, as occurred in the Larmor project.

It is worth noting that an increasing number of cyclotron types for particle therapy and radioisotope production benefit from the specification of ARMCO® Pure Iron, covering numerous developments in medical technology and academia worldwide. In addition, projects in fusion-energy research make use of the specific magnetic permeability wherever related requirements for magnets or shielding apply.

AK Steel International has access to results from magnetic characterisation and from accompanying tests in various conditions of ARMCO® Pure Iron and its variants. A detailed reference list for the above-mentioned magnet projects is available on request, based on an article by A Parrella, P Arpaia, M Buzio *et al.* (2019 *IEEE Transactions on Magnetics* **55** 2001004). Designers who intend to unambiguously define this grade in their specifications are recommended to use the designation "ARMCO Pure Iron".

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FIELD NOTES

Reports from events, conferences and meetings

RENCONTRES DE MORIOND

Anomalies intrigue at Moriond

The electroweak session of the Rencontres de Moriond convened more than 200 participants virtually from 22 to 27 March in a new format, with pre-recorded plenary talks and group-chat channels that went online in advance of live discussion sessions. The following week, the QCD and high-energy interactions session took place with a more conventional virtual organisation.

The highlight of both conferences was the new LHCb result on R_K based on the full Run 1 and Run 2 data, and corresponding to an integrated luminosity of 9 fb^{-1}, which led to the claim of the first evidence for lepton-flavour-universality (LFU) violation from a single measurement. R_K is the ratio of the branching fractions for the decays $B^+ \to K^+ \mu^+ \mu^-$ and $B^+ \to K^+ e^+ e^-$. LHCb measured this ratio to be 3.1σ below unity, despite the fact that the two branching fractions are expected to be equal by virtue of the well-established property of lepton universality (see p17). Coupled with previously reported anomalies of angular variables and the R_{K*}, R_D and R_{D*} branching-fraction ratios by several experiments, it further reinforces the indications that LFU may be violated in the B sector. Global fits and possible theoretical interpretations with new particles were also discussed.

M Brice/CERN-PHOTO-201812-329-10

Anomalies in focus
An experimental update from LHCb (pictured) on the flavour anomalies and a lattice-QCD update on the anomalous magnetic moment of the muon provoked frank debate at the Rencontres de Moriond.

Important contributions

Results from Belle II and BES III were reported. Some of the highlights were a first measurement of the $B^+ \to K^+ \nu\bar{\nu}$ decay and the most stringent limits to date for masses of between 0.2 and 1 GeV from Belle II, based on the first data they collected, and searches for LFU violation in the charm sector from BES III that for the moment give negative results. Belle II is expected to give important contributions to the LFU studies soon and to accumulate an integrated luminosity of 50 ab^{-1} 10 years from now.

ATLAS and CMS presented tens of new results each on Standard Model (SM) measurements and searches for new phenomena in the two conferences. Highlights included the CMS measurement of the W leptonic and hadronic branching fraction with an accuracy larger than that measured at LEP for the branching fractions of the electron and muon, and the updated ATLAS evidence of the four-top-production measurement at 4.7σ (with 2.6σ expected). ATLAS and CMS have not yet found any indications of new physics but continue to perform many searches, expanding the scope to as-yet unexplored areas, and many improved limits on new-physics scenarios were reported for the first time at both conference sessions.

Several results and prospects of electroweak precision measurements were presented and discussed, including a new measurement of the fine structure constant with a precision of 80 parts per trillion, and a measurement of the null electric dipole moment of the neutron with an uncertainty of 1.1×10^{-26} e·cm. Theoretical predictions of $(g-2)_\mu$ were discussed, including the recent lattice calculation from the Budapest–Marseille–Wuppertal group of the hadronic-vacuum-polarisation contribution, which, if used in comparison with the experimental measurement, would bring the tension with the $(g-2)_\mu$ prediction to within 2σ.

In the neutrino session, the most relevant recent new results of last year were discussed. KATRIN reported updated upper limits on the neutrino mass, obtained from the direct measurement of the endpoint of the electron spectrum of the tritium β decay, while T2K showed the most recent results concerning CP violation in the neutrino sector, obtained from the simultaneous measurement of the ν_μ and $\bar{\nu}_\mu$ disappearance, and ν_e and $\bar{\nu}_e$ appearance. The measurement disfavours at 90% CL the CP-conserving values 0 and π of the CP-violating parameter of the neutrino mixing matrix, δ_{CP}, and all values between 0 and π.

The quest for dark matter is in full swing and is expanding on all fronts. XENON1T updated delegates on an intriguing small excess in the low-energy part of the electron-recoil spectrum, from 1 to 7 keV, which could be interpreted as originating from new particles but that is also consistent with an increased background from tritium contamination. Upcoming new data from the upgraded XENONnT detector are expected to be able to disentangle the different possibilities, should the excess be confirmed. The Axion Dark Matter eXperiment (ADMX) is by far the most sensitive experiment to detect axions ▷

in the explored range around 2 µeV. ADMX showed near-future prospects and the plans for upgrading the detector to scan a much wider mass range, up to 20 µeV, in the next few years. The search for dark matter also continues at accelerators, where it could be directly produced or be detected in the decays of SM particles such as the Higgs boson.

ATLAS and CMS also presented new results at the Moriond QCD and high-energy-interactions conference. Highlights of the new results are: the ATLAS full Run-2 search for double-Higgs-boson production in the bbγγ channel, which yielded the tightest constraints to date on the Higgs-boson self-coupling, and the measurement of the top-quark mass by CMS in the single-top-production channel that for the first time reached an accuracy of less than 1 GeV, now becoming relevant to future top-mass combinations. Several recent heavy-ion results were also presented by the LHC experiments, and by STAR and PHENIX at RHIC, in the dedicated heavy-ion session. One highlight was a result from ALICE on the measurement of the Λ_c^+ transverse-momentum spectrum and the Λ_c^+/D^0 ratio in pp and p–Pb collisions, showing discrepancies with perturbative QCD predictions.

The quest for dark matter is in full swing and is expanding on all fronts

The above is only a snapshot of the many interesting results presented at this year's Rencontres de Moriond, representing the hard work and dedication of countless physicists, many at the early-career stage. As ever, the SM stands strong, though intriguing results provoked lively debate during many a virtual discussion.

Marco Pieri *University of California, San Diego.*

NeuTel 2021

NeuTel as vibrant as ever

The XIX International Workshop on Neutrino Telescopes (NeuTel) attracted 1000 physicists online from 18 to 26 February, under the organisation of INFN Sezione di Padova and the Department of Physics and Astronomy of the University of Padova.

The opening session featured presentations by Sheldon Lee Glashow, on the past and future of neutrino science, Carlo Rubbia, on searches for neutrino anomalies, and Barry Barish, on the present and future of gravitational-wave detection. This session was a propitious moment for IceCube principal investigator Francis Halzen to give a "heads-up" on the first observation, in the South-Pole detector, of a so-called Glashow resonance – the interaction of an electron antineutrino with an atomic electron to produce a real W boson, as the eponymous theorist predicted back in 1960. According to Glashow's calculations, the energy at which the resonance shall happen depends on the mass of the W boson, which was discovered in 1983 by Rubbia and his team.

The first edition of NeuTel saw the birth of the idea of instrumenting a large volume of Antarctic ice to capture high-energy neutrinos – a "Deo volente" (God willing) detector, as Halzen and collaborators then dubbed it. Thirty-three years later, as the detection of a Glashow resonance demonstrates, it is possible to precisely calibrate the absolute energy scale of these gigantic instruments for cosmic particles, and we have achieved several independent proofs of the existence of high-energy cosmic neutrinos, including first confirmations by ANTARES and Baikal-GVD.


Y Makino/IceCube/NSF

South Pole shifters *The IceCube observatory unearthed a "Glashow resonance" 61 years after the event was hypothesised and 33 years after the detector was conceived at the first NeuTel.*

Astrophysical models describing the connections between cosmic neutrinos, photons and cosmic rays were discussed in depth, with special emphasis on blazars, starburst galaxies and tidal-distribution events. Perspectives for future global multi-messenger observations and campaigns, including gravitational waves and networks of neutrino instruments over a broad range of energies, were illustrated, anticipating core-collapse supernovae as the most promising sources. The future of astroparticle physics relies upon very large infrastructures and collaborative efforts on a planetary scale. Next-generation neutrino telescopes might follow different strategic developments. Extremely large volumes, equipped with cosmic-ray-background veto techniques and complementary radio-sensitive installations might be the key to achieving high statistics and high-precision measurements over a large energy range, given limited sky coverage. Alternatively, a network of intermediate-scale installations, like KM3NeT, distributed over the planet and based on existing or future infrastructures, might be better suited for population studies of transient phenomena. Efforts are currently being undertaken along both paths, with a newborn project, P-ONE, exploiting existing deep-underwater Canadian infrastructures for science to operate strings of photomultipliers.

T2K and NOvA did not update last summer's leptonic-CP-violation results. The tension of their measurements creates counter-intuitive fit values when a combination is tried, as discussed by Antonio Marrone of the University of Bari. The most striking example is the neutrino mass hierarchy: both experiments in their own fits favour a normal hierarchy, but their combination, with a tension in the value of the CP phase, favours an inverted hierarchy.

The founder of the Borexino experiment, Gianpaolo Bellini, discussed the results of the experiment together with the latest exciting measurements of the CNO cycle in the Sun. DUNE, Hyper-K, and JUNO presented progress towards the realisation of these leading projects, and speakers discussed their potential in many aspects of new-physics searches, astrophysics investigations and neutrino-oscillation sensitivities. The latest results of the reactor-neutrino experiment Neutrino-4, which about one year ago claimed 3.2σ evidence for an oscillation anomaly that could be induced by sterile neutrinos, were discussed in a dedicated session. Both ICARUS and KATRIN presented their sensitivities to this signal in two completely different setups.

Marc Kamionkowski (John Hopkins University) and Silvia Galli (Institut d'Astrophysique de Paris) both provided an update on the "Hubble tension": an approximately 4σ difference in the Hubble constant when determined from angular temperature fluctuations in the cosmic microwave background (probing the expansion rate when the universe was approximately 380,000 years old) and observing the recession velocity of supernovae (which provides its current value). This Hubble tension could hint at new physics modifying the thermal history of our universe, such as massive neutrinos that influence the early-time measurement of the Hubble parameter.

Elisa Bernardini *and* **Francesco D'Eramo** *University of Padova and INFN-Padova, and* **Mauro Mezzetto** *INFN-Padova.*

6TH LHC REINTERPRETATION WORKSHOP

LHC reinterpreters think long-term

The ATLAS, CMS and LHCb collaborations perform precise measurements of Standard Model (SM) processes and direct searches for physics beyond the Standard Model (BSM) in a vast variety of channels. Despite the multitude of BSM scenarios tested this way by the experiments, it still constitutes only a small subset of the possible theories and parameter combinations to which the experiments are sensitive. The (re)interpretation of the LHC results in order to fully understand their implications for new physics has become a very active field, with close theory–experiment interaction and with new computational tools and related infrastructure being developed.

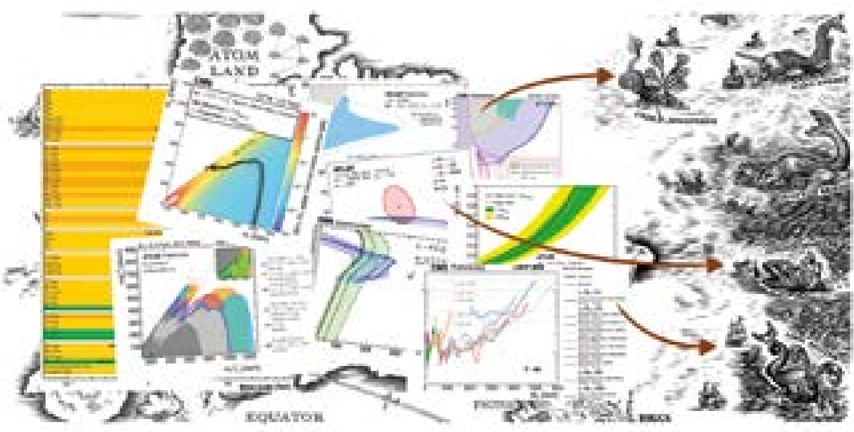

Illustration (c) C. Wormell from "A Map of the Invisible" by J. Butterworth

Embarrassment of riches *ATLAS, CMS and LHCb are sensitive to a far greater set of theories and parameter combinations than have so far been tested.*

From 15 to 19 February, almost 300 theorists and experimental physicists gathered for a week-long online workshop to discuss the latest developments. The topics covered ranged from advances in public software packages for reinterpretation to the provision of detailed analysis information by the experiments, from phenomenological studies to global fits, and from long-term preservation to public data.

Open likelihoods

One of the leading questions throughout the workshop was that of public likelihoods. The statistical model of an experimental analysis provides its complete mathematical description; it is essential information for determining the compatibility of the observations with theoretical predictions. In his keynote talk "Open science needs open likelihoods", Harrison Prosper (Florida State University) explained why it is in our scientific interest to make the publication of full likelihoods routine and straightforward. The ATLAS collaboration has recently made an important step in this direction by releasing full likelihoods in a JSON format, which provides background estimates, changes under systematic variations, and observed data counts at the same fidelity as used in the experiment, as presented by Eric Schanet (LMU Munich). Matthew Feickert (University of Illinois) and colleagues gave a detailed tutorial on how to use these likelihoods with the pyhf python package. Two public reinterpretation tools, MadAnalysis5 presented by Jack Araz (IPPP Durham) and SModelS presented by Andre Lessa (UFABC Santo Andre) can already make use of pyhf and JSON likelihoods, and others are to follow. An alternative approach to the plain-text JSON serialisation is to encode the experimental likelihood functions in deep neural networks, as discussed by Andrea Coccaro (INFN Genova) who presented the DNNLikelihood framework. Several more contributions from CMS, LHCb and from theorists addressed the question of how to present and use likelihood information, and this will certainly stay an active topic at future workshops.

A novelty for the Reinterpretation workshop was that the discussion was extended to experiences and best practices beyond the LHC, to see how experiments in other fields address the need for publicly released data and reusable results. This included presentations on dark-matter direct detection, the high-intensity frontier, and neutrino oscillation experiments. Supporting Prosper's call for data reusability 40 years into the future – "for science 2061" – Eligio Lisi (INFN Bari) pointed out the challenges met in reinterpreting the 1998 Super-Kamiokande data, initially published in terms of the then-sufficient two-flavour neutrino-oscillation paradigm, in terms of contemporary three-neutrino descriptions, and beyond. On the astrophysics side, the LIGO and Virgo collaborations actively pursue an open-science programme. Here, Agata Trovato (APC Paris) presented the Gravitational Wave Open Science Center, giving details on the available data, on their format and on the tools to access them. An open-data policy also exists at the LHC, spearheaded by the CMS collaboration, and Edgar Carrera Jarrin (USF Quito) shared experiences from the first CMS open-data workshop.

The question of making research data findable, accessible, interoperable and reusable is a burning one throughout modern science

The question of making research data findable, accessible, interoperable and reusable ("FAIR" in short) is a burning one throughout modern science. In a keynote talk, the head of the GO FAIR Foundation, Barend Mons, explained the FAIR Guiding Principles together with the technical and social aspects of FAIR data management and data reuse, using the example of COVID-19 disease modelling. There is much to be learned here for our field.

The wrap-up session revolved around the question of how to implement the recommendations of the Reinterpretation workshop in a more systematic way. An important aspect here is the proper recognition, within the collaborations as well as the community at large, of the additional work required to this end. More rigorous citation of HEPData entries by theorists may help in this regard. Moreover, a "Reinterpretation: Auxiliary Material Presentation" (RAMP) seminar series will be launched to give more visibility and explicit recognition to the efforts of preparing and providing extensive material for reinterpretation. The first RAMP meetings took place on 9 and 23 April.

Sabine Kraml *LPSC Grenoble.*

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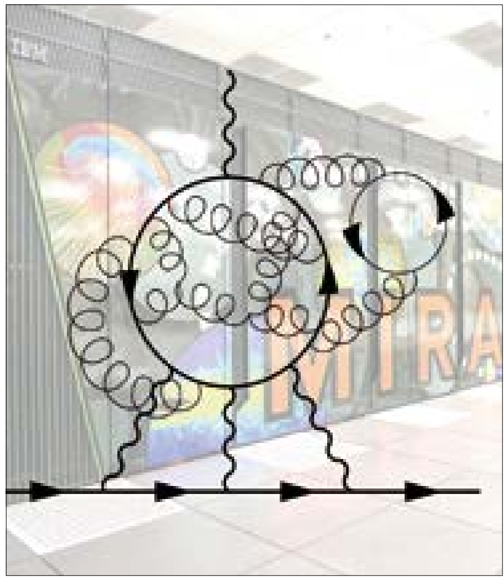
ANOMALOUS MOMENT FOR THE MUON



L Jin

Thanks to new theory calculations and keenly awaited measurements of the magnetic moment of the muon, a longstanding anomaly may soon be resolved either in favour of new physics or the Standard Model.

A fermion's spin tends to twist to align with a magnetic field – an effect that becomes dramatically macroscopic when electron spins twist together in a ferromagnet. Microscopically, the tiny magnetic moment of a fermion interacts with the external magnetic field through absorption of photons that comprise the field. Quantifying this picture, the Dirac equation predicts fermion magnetic moments to be precisely two in units of Bohr magnetons, e/2m. But virtual lines and loops add an additional 0.1% or so to this value, giving rise to an "anomalous" contribution known as "g–2" to the particle's magnetic moment, caused by quantum fluctuations. Calculated to tenth order in quantum electrodynamics (QED), and verified experimentally to about two parts in 10^{10}, the electron's magnetic moment is one of the most precisely known numbers in the physical sciences. While also measured precisely, the magnetic moment of the muon, however, is in tension with the Standard Model.

Tricky comparison

The anomalous magnetic moment of the muon was first measured at CERN in 1959, and prior to 2021, was most recently measured by the E821 experiment at Brookhaven National Laboratory (BNL) 16 years ago. The comparison between theory and data is much trickier than for electrons. Being short-lived, muons are less suited to experiments with Penning traps, whereby stable charged particles are confined using static electric and magnetic fields, and the trapped particles are then cooled to allow precise measurements of their properties. Instead, experiments infer how quickly muon spins precess in a storage ring – a situation similar to the wobbling of a spinning top, where information on the muon's advancing spin is encoded in the direction of the electron that is emitted when it decays. Theoretical calculations are also more challenging, as hadronic contributions are no longer so heavily suppressed when they emerge as virtual particles from the more massive muon.

All told, our knowledge of the anomalous magnetic moment of the muon is currently three orders of magnitude less precise than for electrons. And while everything tallies up, more or less, for the electron, BNL's longstanding measurement of the magnetic moment of the muon is 3.7σ greater than the Standard Model prediction (see panel "Rising to the moment"). The possibility that the discrepancy could be due to virtual contributions from as-yet-undiscovered particles demands ever more precise theoretical calculations. This need is now more pressing than ever, given the increased precision of the experimental value expected in the next few years from the Muon g–2 collaboration at Fermilab in the US and other experiments such as the Muon g–2/EDM collaboration at J-PARC in Japan. Hotly anticipated results from the first data run at Fermilab's E989 experiment were released on 7 April. The new result is completely consistent with the BNL value but with a slightly smaller error, leading to a slightly larger discrepancy of 4.2σ with the Standard Model when the measurements are combined (see p7).

Hadronic vacuum polarisation

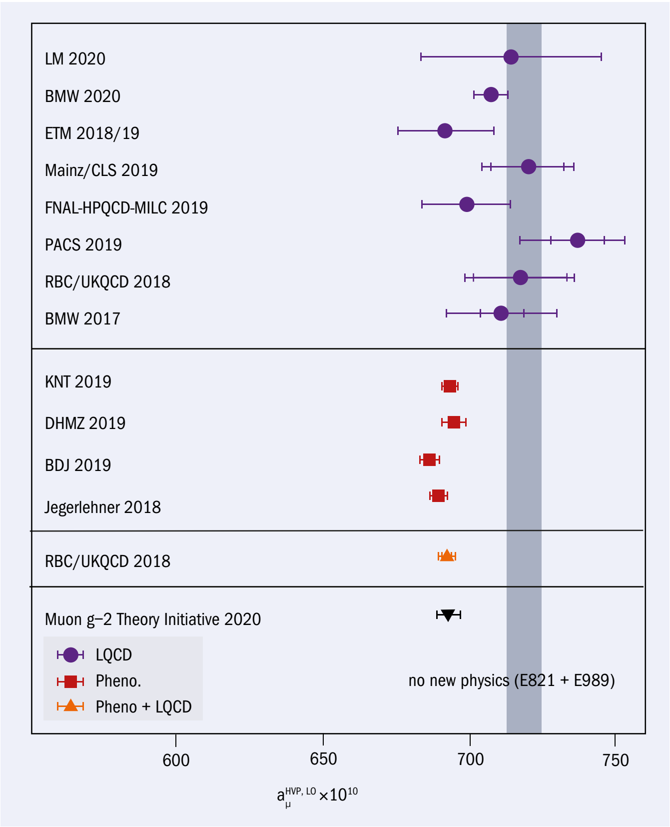
The value of the muon anomaly, a_μ, is an important test of the Standard Model because currently it is known very precisely – to roughly 0.5 parts per million (ppm) – in both experiment and theory. QED dominates the value of a_μ, but due to the non-perturbative nature of QCD it is strong interactions that contribute most to the error. The theoretical uncertainty on the anomalous magnetic moment of the muon is currently dominated by so-called hadronic vacuum polarisation (HVP) diagrams. In HVP, a virtual photon briefly explodes into a "hadronic blob", before being reabsorbed, while the magnetic-field photon is simultaneously absorbed by the muon. While of

Challenging calculation

It took a billion core-hours on the Mira supercomputer to compute the hadronic light-by-light contribution to the muon's magnetic moment.

THE AUTHORS

Thomas Blum and **Luchang Jin** *University of Connecticut, and* **Christoph Lehner** *University of Regensburg.*



Off the mark *Values of the leading-order hadronic vacuum-polarisation contribution to the anomalous magnetic moment of the muon,* $a_\mu^{HVP,LO}$ *(×* 10^{10}*). The purple circles indicate independent lattice–QCD calculations; the red squares show results from dispersion relations and the experimental cross-sections for* e^+e^- *annihilation; the orange triangle shows a combined value where contributions are taken from the most precise parts of data-driven and lattice results of Jegerlehner 2018 and RBC/UKQCD 2018, respectively; and the black triangle shows the theoretical value currently being used for experimental comparisons with E821 and E989. The grey band indicates the value needed to bring the SM into agreement with the measurements by the BNL and Fermilab experiments (plot adapted from T Aoyama* et al. *2020).*

order α^2 in QED, it is all orders in QCD, making for very difficult calculations.

Historically, and into the present, HVP is calculated using a dispersion relation and experimental data for the cross section for $e^+e^- \rightarrow$ hadrons. This idea was born of necessity almost 60 years ago, before QCD was even on the scene, let alone calculable. The key realisation is that the imaginary part of the vacuum polarisation is directly related to the hadronic cross section via the optical theorem of wave-scattering theory; a dispersion relation then relates the imaginary part to the real part. The cross section is determined over a relatively wide range of energies, in both exclusive and inclusive channels. The dominant contribution – about three quarters – comes from the $e^+e^- \rightarrow \pi^+\pi^-$ channel, which peaks at the rho meson mass, 775 MeV. Though the integral converges rapidly with increasing energy, data are needed over a relatively broad region to obtain the necessary precision. Above the τ mass, QCD perturbation theory hones the calculation.

Several groups have computed the HVP contribution in this way, and recently a consensus value has been produced as part of the worldwide Muon g–2 Theory Initiative. The error stands at about 0.58% and is the dominant part of the theory error. It is worth noting that a significant part of the error arises from a tension between the most precise measurements, by the BaBar and KLOE experiments, around the rho-meson peak. New measurements, including those from experiments at Novosibirsk, Russia and Japan's Belle II experiment, may help resolve the inconsistency in the current data and reduce the error by a factor of two or so.

The alternative approach, of calculating the HVP contribution from first principles using lattice QCD, is not yet at the same level of precision, but is getting there. Consistency between the two approaches will be crucial for any claim of new physics.

Lattice QCD

Kenneth Wilson formulated lattice gauge theory in 1974 as a means to rid quantum field theories of their notorious infinities – a process known as regulating the theory – while maintaining exact gauge invariance, but without using perturbation theory. Lattice QCD calculations involve the very large dimensional integration of path integrals in QCD. Because of confinement, a perturbative treatment including physical hadronic states is not possible, so the complete integral, regulated properly in a discrete, finite volume, is done numerically by Monte Carlo integration.

Lattice QCD has made significant improvements over the last several years, both in methodology and invested computing time. Recently developed methods (which rely on low-lying eigenmodes of the Dirac operator to speed up calculations) have been especially important for muon-anomaly calculations. By allowing state-of-the-art calculations using physical masses, they remove a significant systematic: the so-called chiral extrapolation for the light quarks. The remaining systematic errors arise from the finite volume and non-zero lattice spacing employed in the simulations. These are handled by doing multiple simulations and extrapolating to the infinite-volume and zero-lattice-spacing limits.

The HVP contribution can readily be computed using lattice QCD in Euclidean space with space-like four-momenta in the photon loop, thus yielding the real part of the HVP directly. The dispersive result is currently more precise (see "Off the mark" figure"), but further improvements will depend on consistent new e^+e^- scattering datasets.

Rapid progress in the last few years has resulted in first lattice results with sub-percent uncertainty, closing in on the precision of the dispersive approach. Since these lattice calculations are very involved and still maturing, it will be crucial to monitor the emerging picture once several precise results with different systematic approaches are available. It will be particularly important to aim for statistics-dominated errors to make it more straightforward to quantitatively interpret the resulting agreement with the no-new-physics scenario or the dispersive results. In the shorter term, it will also be crucial to cross-check between different lattice and dispersive results using additional observables, for example based on the vector–vector correlators.

With improved lattice calculations in the pipeline from a number of groups, the tension between lattice QCD and phenomenological calculations may well be resolved before the Fermilab and J-PARC experiments announce their final results. Interestingly, there is a new lattice result with sub-percent precision (BMW 2020) that is in agreement both with the no-new-physics point within 1.3σ, and with the dispersive-data-driven result within 2.1σ. Barring a significant re-evaluation of the phenomenological calculation, however, HVP does not appear to be the source of the discrepancy with experiments.

The next most likely Standard Model process to explain the muon anomaly is hadronic light-by-light scattering. Though it occurs less frequently since it includes an extra virtual photon compared to the HVP contribution, it is much less well known, with comparable uncertainties to HVP.

Hadronic light-by-light scattering

In hadronic light-by-light scattering (HLbL), the magnetic field interacts not with the muon, but with a hadronic "blob", which is connected to the muon by three virtual photons. (The interaction of the four photons via the hadronic blob gives HLbL its name.) A miscalculation of the HLbL contribution has often been proposed as the source of the apparently anomalous measurement of the muon anomaly by BNL's E821 collaboration.

Since the so-called Glasgow consensus (the fruit of a 2009 workshop) first established a value more than 10 years ago, significant progress has been made on the analytic computation of the HLbL scattering contribution. In particular, a dispersive analysis of the most important hadronic channels has been carried out, including the leading pion–pole, sub-leading pion loop and rescattering diagrams including heavier pseudoscalars. These calculations are analogous in spirit to the dispersive HVP calculations, but are more complicated, and the experimental measurements are more difficult because form factors with one or two virtual photons are required.

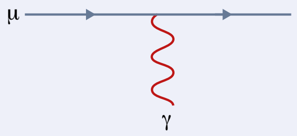
The project to calculate the HLbL contribution using lattice QCD began more than 10 years ago, and many improvements to the method have been made to reduce both statistical and systematic errors since then. Last year we published, with colleagues Norman Christ, Taku Izubuchi and Masashi Hayakawa, the first ever lattice–QCD calculation of the HLbL contribution with all errors controlled, finding $a_\mu^{\text{HLbL, lattice}} = (78.7 \pm 30.6\,(\text{stat}) \pm 17.7\,(\text{sys})) \times 10^{-11}$. The calculation was not easy: it took four years and a billion core-hours on the Mira supercomputer at Argonne National Laboratory's Large Computing Facility.

Our lattice HLbL calculations are quite consistent with the analytic and data-driven result, which is approximately a factor of two more precise. Combining the results

Rising to the moment

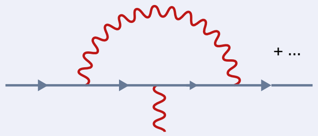
In the Standard Model, the magnetic moment of the muon is computed order-by-order in powers of α for QED (each virtual photon represents a factor of α), and to all orders in α_s for QCD.

At the lowest order in QED, the Dirac term (pictured right) accounts for precisely two Bohr magnetons and arises purely from the muon (μ) and the real external photon (γ) representing the magnetic field.



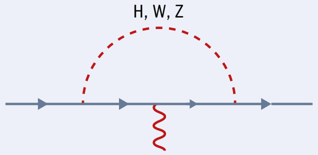
At higher orders in QED, virtual Standard Model particles, depicted by lines forming loops, contribute to a fractional increase of a_μ with respect to that value: the so-called anomalous magnetic moment of the muon. It is defined to be $a_\mu = (g-2)/2$, where g is the gyromagnetic ratio of the muon – the number of Bohr magnetons, e/2m, which make up the muon's magnetic moment. According to the Dirac equation, g = 2, but radiative corrections increase its value.

The biggest contribution is from the Schwinger term (pictured right, O(α)) and higher-order QED diagrams.



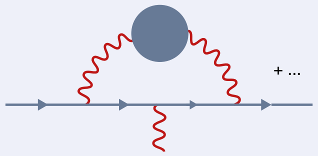
$$a_\mu^{\text{QED}} = (116\,584\,718.931 \pm 0.104) \times 10^{-11}$$

Electroweak lines (pictured right) also make a well-defined contribution. These diagrams are suppressed by the heavy masses of the Higgs, W and Z bosons.



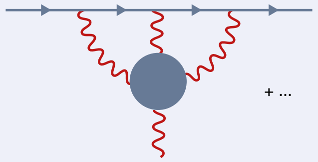
$$a_\mu^{\text{EW}} = (153.6 \pm 1.0) \times 10^{-11}$$

The biggest QCD contribution is due to hadronic vacuum polarisation (HVP) diagrams. These are computed from leading order (pictured right, O(α^2)), with one "hadronic blob" at all orders in α_s (shaded) up to next-to-next-to-leading order (NNLO, O(α^4), with three hadronic blobs) in the HVP.



$a_\mu^{\text{HVP}} \times 10^{11}$	LO	NLO	NNLO
e^+e^- data	6931 ± 40	−98 ± 7	12 ± 1
Lattice QCD	7116 ± 184		

Hadronic light-by-light scattering (HLbL, pictured right at O(α^3) and all orders in α_s (shaded)), makes a smaller contribution but with a larger fractional uncertainty.



$a_\mu^{\text{HLbL}} \times 10^{11}$	LO	NLO
Phenomenology	92 ± 19	2 ± 1
Lattice QCD	79 ± 35	

Neglecting lattice–QCD calculations for the HVP in favour of those based on e^+e^- data and phenomenology, the total anomalous magnetic moment is given by

$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{HVP}} + a_\mu^{\text{HLbL}} = (116\,591\,810 \pm 43) \times 10^{-11}.$$

This is somewhat below the combined value from the E821 experiment at BNL in 2004 and the E989 experiment at Fermilab in 2021.

$$a_\mu^{\text{exp}} = (116\,592\,061 \pm 41) \times 10^{-11}$$

The discrepancy has roughly 4.2σ significance:

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (251 \pm 59) \times 10^{-11}.$$

leads to $a_\mu^{\mathrm{HLbL}} = (90 \pm 17) \times 10^{-11}$, which means the very difficult HLbL contribution cannot explain the Standard Model discrepancy with experiment. To make such a strong conclusion, however, it is necessary to have consistent results from at least two completely different methods of calculating this challenging non-perturbative quantity.

New physics?

If current theory calculations of the muon anomaly hold up, and the new experiments reduce its uncertainty by the hoped-for factor of four, then a new-physics explanation will become impossible to ignore. The idea would be to add particles and interactions that have not yet been observed but may soon be discovered at the LHC or in future experiments. New particles would be expected to contribute to the anomaly through Feynman diagrams similar to the Standard Model topographies (see "Rising to the moment" panel).

The most commonly considered new-physics explanation is supersymmetry, but the increasingly stringent lower limits placed on the masses of super-partners by the LHC experiments make it increasingly difficult to explain the muon anomaly. Other theories could do the job too. One popular idea that could also explain persistent anomalies in the b-quark sector is heavy scalar leptoquarks, which mediate a new interaction allowing leptons and quarks to change into each other. Another option involves scenarios whereby the Standard Model Higgs boson is accompanied by a heavier Higgs-like boson.

Calculations of the anomalous magnetic moment of the muon are not finished

The calculations of the anomalous magnetic moment of the muon are not finished. As a systematically improvable method, we expect more precise lattice determinations of the hadronic contributions in the near future. Increasingly powerful algorithms and hardware resources will further improve precision on the lattice side, and new experimental measurements and analysis methods will do the same for dispersive studies of the HVP and HLbL contributions.

To confidently discover new physics requires that these two independent approaches to the Standard Model value agree. With the first new results on the experimental value of the muon anomaly in almost two decades showing perfect agreement with the old value, we anxiously await more precise measurements in the near future. Our hope is that the clash of theory and experiment will be the beginning of an exciting new chapter of particle physics, heralding new discoveries at current and future particle colliders. ●

Further reading

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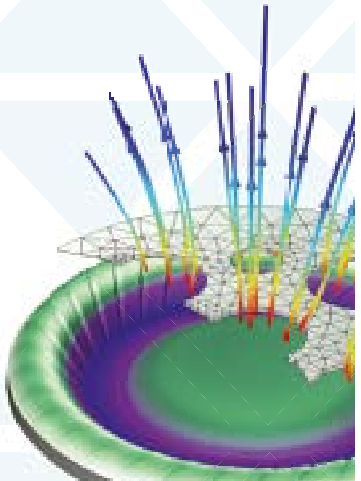

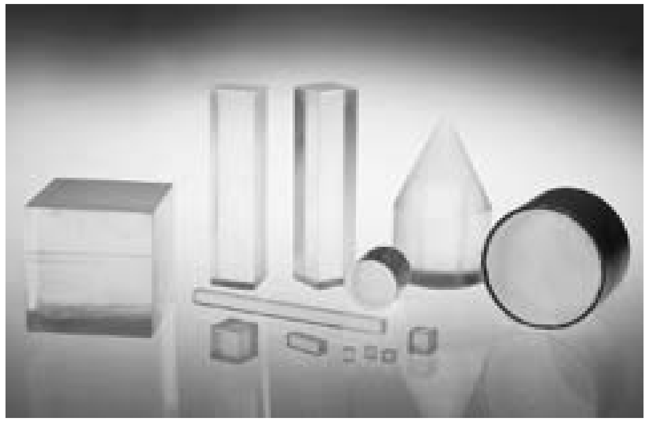

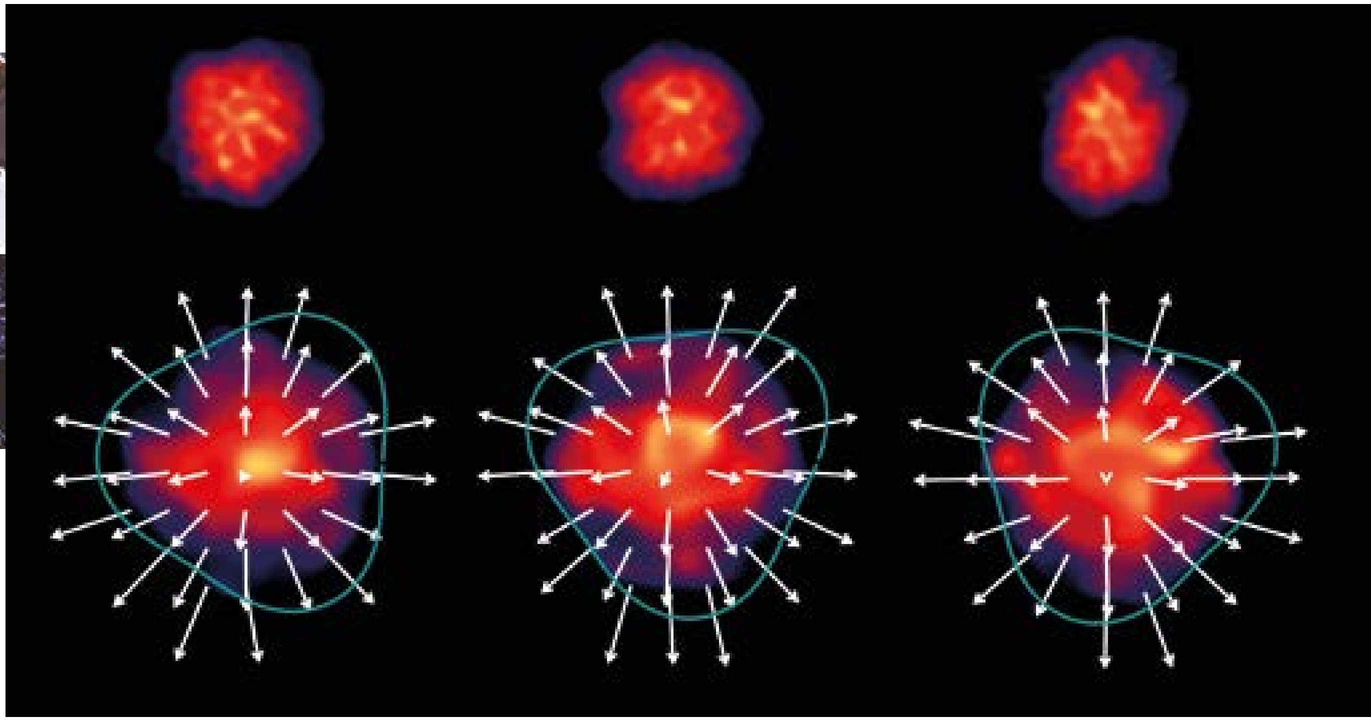

Evolving fluctuations *Three droplets of quark–gluon plasma, simulated at 6 and 38 yoctoseconds (10^{-24} s) after head-on collisions between lead ions in the LHC. (Credit: MUSIC arXiv:1209.6330)*

GOING WITH THE FLOW

The ALICE experiment is making strides towards understanding how charm and beauty quarks flow within cooling droplets of quark–gluon plasma at the LHC, shedding light on the extreme conditions of the early universe.

Microseconds after the Big Bang, quarks and gluons roamed freely. As the universe expanded, this quark–gluon plasma (QGP) cooled. When the temperature dropped to roughly a hundred thousand times that in the core of the Sun, hadrons formed. Today, this phase transition is reproduced in the heart of detectors at the LHC when lead ions careen into each other at high energy.

The experimental quest for the QGP started in the 1980s using fixed-target collisions at the Alternating Gradient Synchrotron at Brookhaven National Laboratory (BNL) and the Super Proton Synchrotron at CERN. This side of the millennium, collider experiments have provided a big jump in energy, first at the Relativistic Heavy Ion Collider (RHIC) at BNL, and now at the LHC. Both facilities allow a thorough investigation of the QGP at different points on the still-mysterious phase diagram of quantum chromodynamics.

Among the most striking features of the QGP formed at the LHC is the development of "collective" phenomena, as spatial anisotropies are transformed by pressure gradients into momentum anisotropies. The ALICE experiment is designed to study the collective behaviour of the torrent of particles created in the hadronisation of QGP droplets. Following detailed studies of the "flow" of the abundant light hadrons that are produced, ALICE has recently demonstrated, alongside certain competitive measurements by CMS and ATLAS, the flow of heavy-flavour (HF) hadrons – particles that probe the entire lifetime of a droplet of QGP.

A perfect fluid

The QGP created in lead–ion collisions at the LHC is made up of thousands of quarks and gluons – far too many quantum fields to keep track of in a simulation. In the early 2000s,

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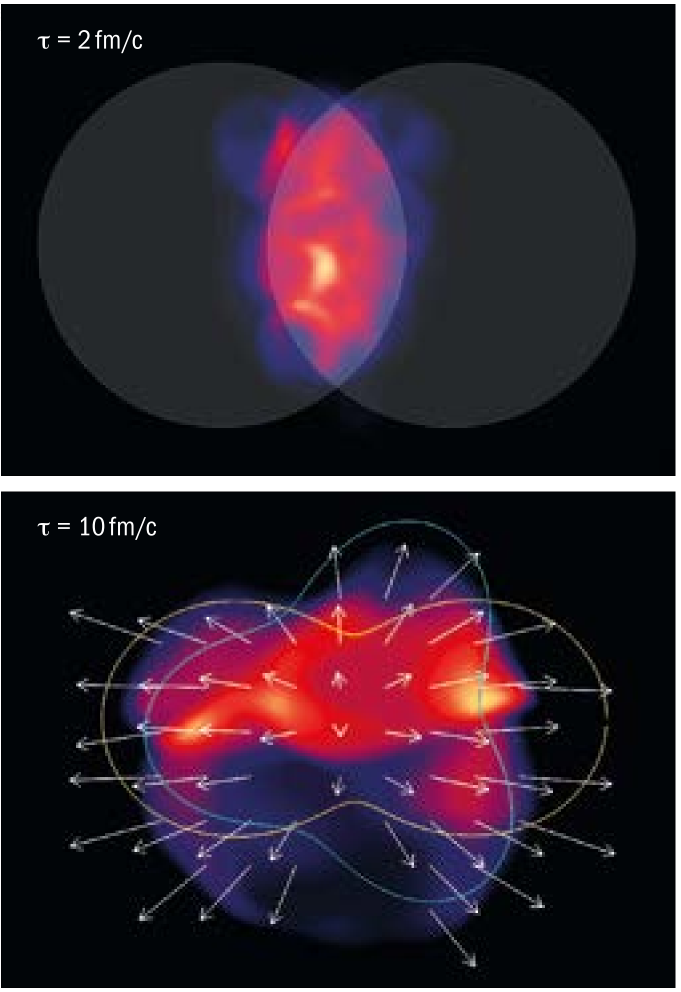
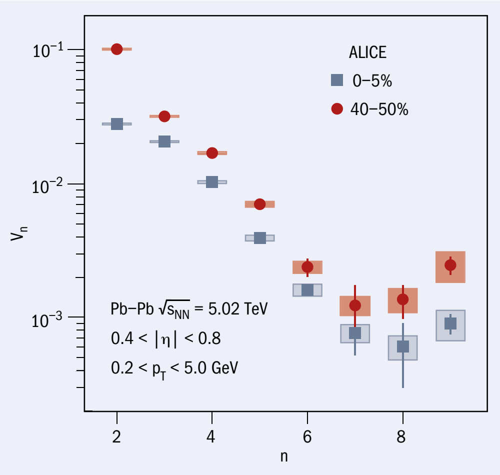


MUSIC arXiv:1209.6330

Noncentral collision *An illustration of the evolving energy density of the QGP created in a noncentral collision. Pressure gradients act on the initial geometrical anisotropy to create a final velocity field (arrows), which may be decomposed into elliptic (yellow), triangular (teal) and higher order components. Hydrodynamic calculations were performed using the MUSIC software package.*

however, measurements at RHIC revealed that the QGP has a simplifying property: it is a near perfect fluid, with a very low viscosity, as indicated by observations of the highest collective flows allowable in viscous hydrodynamic simulations. More precisely, its shear viscosity-to-entropy ratio – the generalisation of the non-relativistic kinematic viscosity – appears to be only a little above the conjectured quantum limit of $1/4\pi$ derived using holographic gravity (AdS/CFT) duality. As the QGP is a near-perfect fluid, its expansion can be modelled using a few local quantities such as energy density, velocity and temperature.

In noncentral heavy-ion collisions, the overlap region between the two incoming nuclei has an almond shape, which naturally imprints a spatial anisotropy to the initial state of the system: the QGP is less elongated along the symmetry plane that connects the centres of the colliding nuclei. As the system evolves, interactions push the QGP more strongly along the shorter symmetry-plane axis than along the longer one (see "Noncentral collision" figure). This is called elliptic flow.



ALICE arxiv:2002.00633

Light-flavour flow *ALICE has measured significant values for the flow anisotropy coefficients* (v_n) *of charged hadrons up to ninth order* $(n = 9)$ *– a nine-pronged Fourier component in transverse-momentum space. Measurements are plotted here for head-on "central" collisions (grey), and glancing 40–50% centrality collisions between lead nuclei (red).*

Density fluctuations in the initial state may also lead to other anisotropic flows in the velocity field of the QGP. Triangular flow, for example, pushes the system along three axes. In general, this collective motion is decomposed as $1+2\sum_{n=1}^{\infty} v_n \cos(n(\varphi-\Psi_n))$, where v_n are harmonic coefficients, φ is the azimuthal angle of the final-state particles in transverse-momentum (p_T) space, and Ψ_n are the orientation of the symmetry planes. v_1, which is expected to be negligible at mid-rapidity, is "directed flow" towards a single maximum, while v_2 and v_3 signal elliptic and triangular flows. The LHC's impressive luminosity has allowed ALICE to measure significant values for the flow of light-flavour hadrons up to v_9 (see "Light-flavour flow" figure).

The importance of being heavy

The bulk of the QGP is composed of thermally produced gluons and light quarks. By contrast, thermal HF production is negligible as the typical temperature of the system created in heavy-ion collisions is a few hundred MeV – significantly below the mass of a charm or beauty quark–antiquark pair. HF quarks are instead created in quark–antiquark pairs in early hard-scattering processes on shorter timescales than the QGP formation time, and experience the whole evolution of the system.

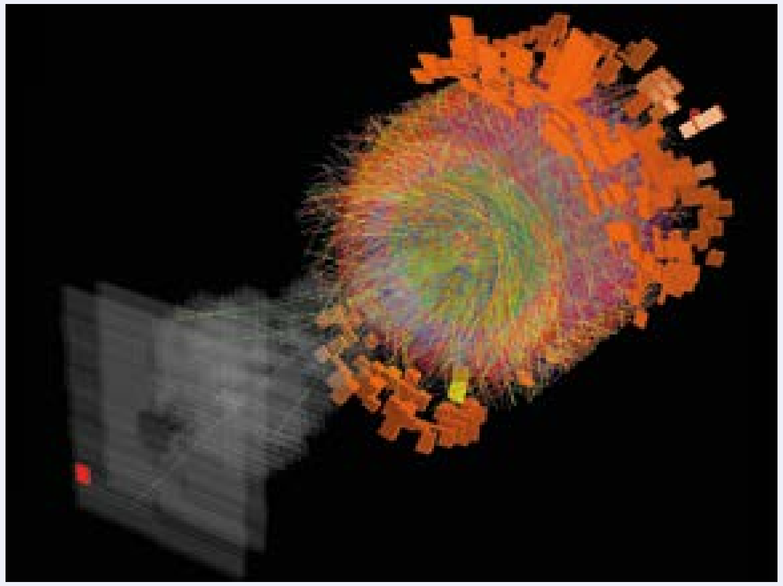
Heavy quarks are therefore powerful probes of properties of the QGP. As they traverse the medium, they interact with its constituents, gaining or losing energy depending on their momenta. High-momentum HF quarks lose energy via both elastic (collisional) and inelastic (gluon radiation) processes. Low-momentum HF quarks are swept along with the flow of the medium, partially thermalising with it via multiple interactions. The thermalisation time is inversely proportional to the particle's mass, and so a higher degree of thermalisation is expected for charm than for beauty. Subsequent hadronisation brings additional complexity: as colour-charged quarks arrange themselves in colour-neutral hadrons, extra contributions to their flow arise from the influence of the surrounding medium when they coalesce with nearby light quarks.

ALICE in action

The geometrical overlap between the two colliding nuclei varies from head-on collisions that produce a huge number of particles, sending several thousand hadrons flying to ALICE's detectors ("0% centrality", as a percentile of the hadronic cross section) to peripheral collisions where the two nuclei barely overlap ("100% centrality"). Since the initial geometry is not directly experimentally accessible, centrality is estimated using either the total particle multiplicity or the energy deposited in the detectors.

Among the cloud of particles are a handful of open and hidden heavy-flavour hadrons that are reconstructed from their decay products using tracking, particle-identification and decay-vertex reconstruction. Charm mesons are reconstructed through hadronic decay channels using the central barrel detectors. Open beauty hadrons are also reconstructed in the central barrel using their semileptonic decay to an electron as a proxy. Compelling evidence of heavy-quark energy loss in a deconfined strongly interacting matter is provided by the suppression of high-p_T open heavy-flavour hadron yields in central nucleus–nucleus collisions relative to proton–proton collisions (after scaling by the average number of binary nucleon–nucleon collisions).

A small fraction of the initially created heavy-quark pairs will bind together to form charmonium $(c-\bar{c})$ or bottomonium $(b-\bar{b})$ states that are reconstructed in the forward muon spectrometer using their decay channel to two muons. Charmonium states were among the first proposed probes of the deconfinement of the QGP. The potential between the heavy quark and antiquark pair is partially screened by the high density of colour charges in the QGP, leading to a suppression of the production of charmonium states. Interestingly, however, ALICE observes less suppression of the J/ψ in lead–lead collisions than is seen at the lower collision energies of RHIC, despite the increased density of colour charges at higher collision energies. This effect may be understood as due to J/ψ regeneration as the copiously produced charm quarks and antiquarks recombine. By contrast, bottomonia are not expected to have a large regeneration contribution due to the larger mass and thus lower production cross section of the beauty quark.



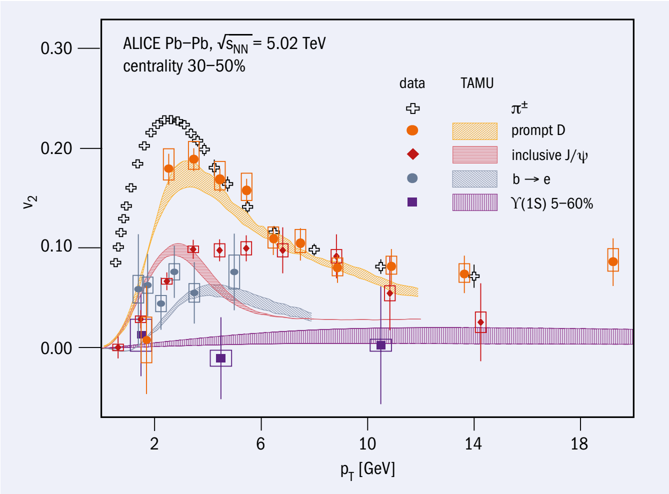
ALICE

High multiplicity *Lead–ion collisions can generate thousands of hadrons.*

In the past two years, the ALICE collaboration has measured the elliptic and triangular flow coefficients of HF hadrons with open and hidden charm and beauty. The results are currently unique in both scope and transverse-momentum coverage, and depend on the simultaneous reconstruction of thousands of particles in the ALICE detectors (see "ALICE in action" panel). In each case, these HF flows should be compared to the flow of the abundant light-particle species such as charged pions. Within the hydrodynamic description, particles originating from the thermally expanding medium at relatively low transverse momenta typically exhibit flow coefficients that increase with transverse momentum. Faster particles also interact with the medium, but might not reach thermal equilibrium. For these particles, an azimuthal anisotropy develops due to the shorter length of medium they traverse along the symmetry plane, but it is not as large, and anisotropy coefficients are expected to fall with increasing transverse momentum. When thermal equilibrium is achieved, it imprints the same velocity field to all particles: the result is a mass hierarchy wherein heavier particles exhibit lower flow coefficients for a given transverse momentum.

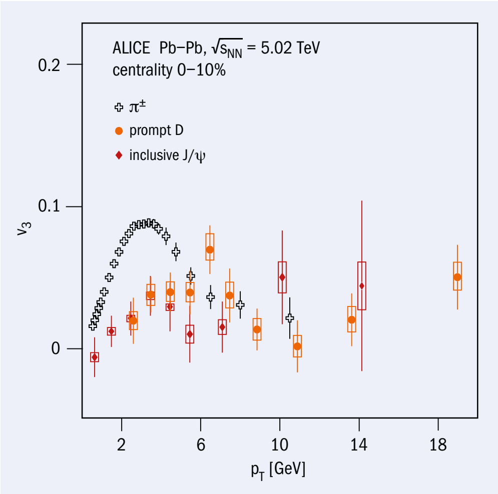
D mesons are the lightest and most abundant hadrons formed from a heavy quark, and are key to understanding the dynamics of charm quarks in the collision. A substantial anisotropy is observed for D mesons in non-central collisions (see "Elliptic flow" figure). As expected, the measured p_T dependence is similar to that for light particles, suggesting that D mesons are strongly affected by the surrounding medium, participating in

Heavy quarks are powerful probes of properties of the QGP



ALICE/arXiv:1905.09216/arXiv:1504.00670

Elliptic flow *ALICE measurements of differential elliptic-flow coefficients for charged pions, D mesons, J/ψ mesons, electrons from beauty-hadron decays and ϒ(1S) mesons in semi-central (30–50% centrality) lead–lead collisions at 5.02 TeV. Predictions from the TAMU model of HF transport are plotted for comparison.*



ALICE

Triangular flow *ALICE measurements of differential triangular-flow coefficients for charged pions, D mesons and J/ψ mesons in central (0–10% centrality) lead–lead collisions at 5.02 TeV.*

the collective motion of the QGP and reaching a high degree of thermalisation. J/ψ mesons, which do not contain light-flavour quarks, also exhibit significant positive elliptic flow with a similar p_T shape. Open beauty hadrons, whose mass is dominated by the b quark, are also seen to flow, and in the low to intermediate p_T region, below 4 GeV, an apparent mass hierarchy is seen: the lighter the particle, the greater the elliptic flow, as expected in a hydrodynamical description of QGP evolution. Above 6 GeV, the elliptic flows of the three particles converge, perhaps as a result of energy loss as energetic partons move through the QGP. In contrast to the other particles, ϒ mesons do not show any significant elliptic flow. This is not surprising as the transverse momentum of peak elliptic flow is expected to scale with the mass of the particle according to the hydrodynamic description of the evolution of the QGP – for ϒ mesons that should be beyond 10 GeV, where the uncertainties are currently large.

Theoretical descriptions of elliptic flow are also making progress. Models of HF flow need to include a realistic hydrodynamic expansion of the QGP, the interaction of the heavy quarks with the medium via collisional and radiative processes, and the hadronisation of heavy quarks via both fragmentation and coalescence. For example, the "TAMU" model describes the measurements of the D mesons and electrons from beauty-hadron decays reasonably well, but shows some tension with the measurement of J/ψ at intermediate and high transverse momenta, perhaps indicating that a mechanism related to parton energy loss is not included.

Currently ongoing upgrades to ALICE will extend its unique advantages in track reconstruction at low momenta

Triangular flow

Triangular flow is observed for D and J/ψ mesons in central collisions, demonstrating that energy-density fluctuations in the initial state have a measurable effect on the heavy quark sector (see "Triangular flow" figure). These measurements of a triangular flow of open- and hidden-charm mesons pose new challenges to models describing HF interactions in the QGP: models now need to account not only for the properties of the medium and the transport of the HF quarks through it, but also for fluctuations in the initial conditions of the heavy-ion collisions.

In the coming years, measurements of HF flow will continue to strongly constrain models of the QGP. It is now clear that charm quarks take part in the collective motion of the medium and partially thermalise. More data is needed to make firm conclusions about open and hidden beauty hadrons. All four LHC experiments will study how heavy quarks diffuse in a colour-deconfined and hydrodynamically expanding medium with the greater luminosities set to be delivered in LHC Run 3 and Run 4. Currently ongoing upgrades to ALICE will extend its unique advantages in track reconstruction at low momenta, and upgrades to LHCb will allow this asymmetric experiment to study non-central collisions in Run 3. In the next long shutdown of the LHC, upgrades to CMS and ATLAS will then extend their already impressive flow measurements to be competitive with ALICE in the crucial low transverse momentum domain, inching us closer to understanding both the early universe and the phase diagram of quantum chromodynamics. ●

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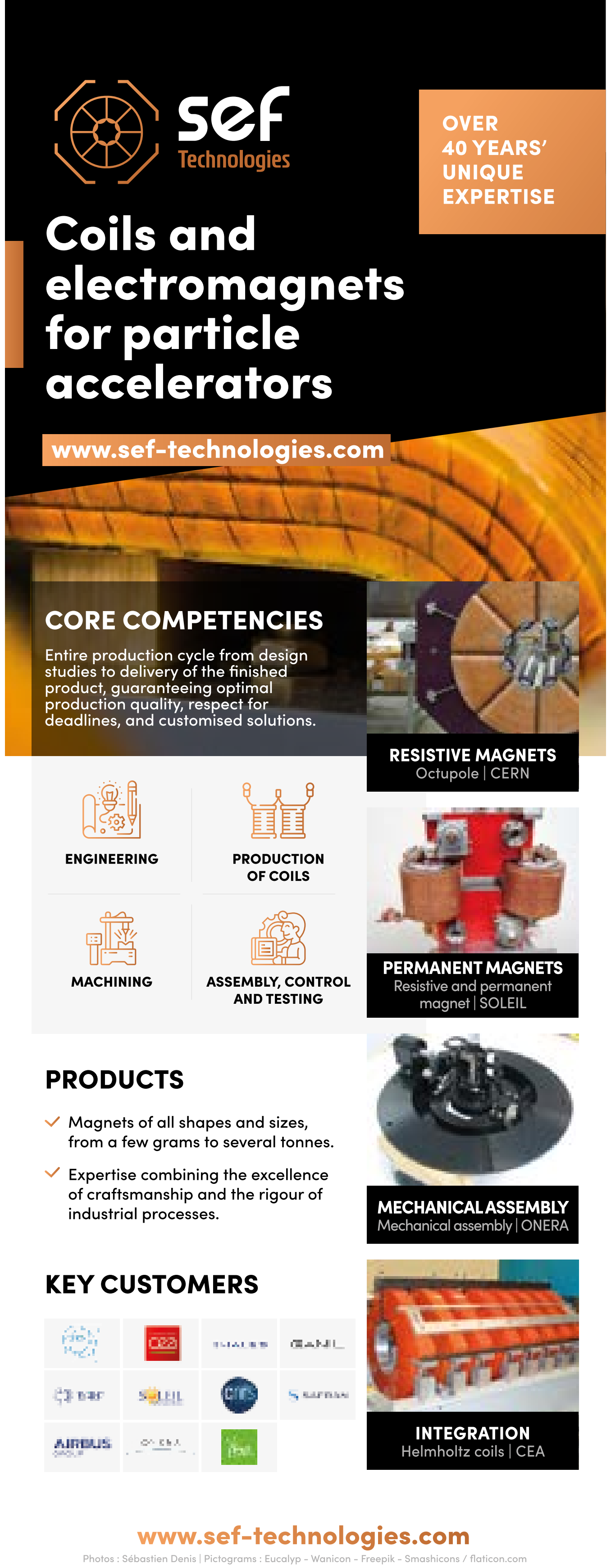

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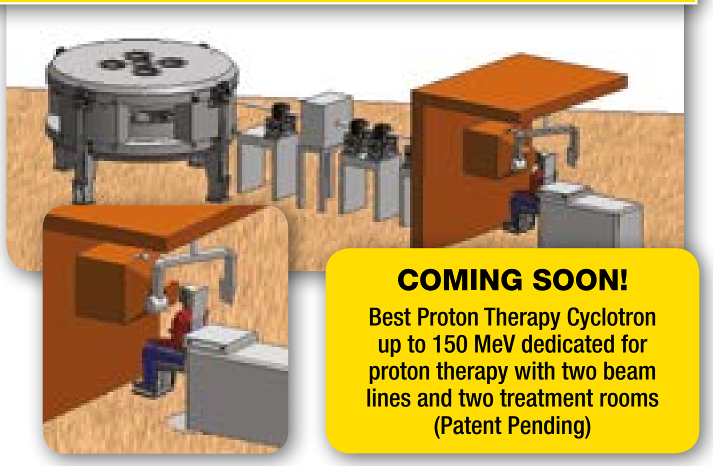

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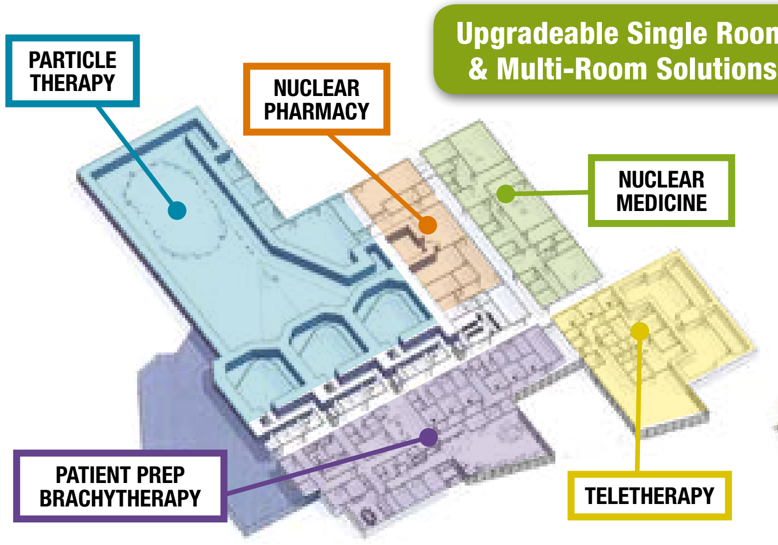

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INTERCEPTING THE BEAMS

From targets to absorbers, beam-intercepting devices are vital to CERN's accelerator complex.
Marco Calviani describes the major upgrades taking place to prepare for the high-luminosity LHC, and the challenges posed by future projects.

Imagine standing in the LHC tunnel when the machine is operating. Proton beams are circulating around the 27 km ring more than 11,000 times per second, colliding at four points to generate showers of particles that are recorded by ATLAS, CMS, ALICE, LHCb and other detectors. After a few hours of operation, the colliding beams need to be disposed of to allow a new physics fill. Operators in the CERN control centre instruct beam-transfer equipment to shunt the circulating beams into external trajectories that transport them away from the cryogenic superconducting magnets. Each beam exits the ring and travel for 600 metres in a straight line before reaching a compact cavern housing a large steel cylinder roughly 9 m long, 70 cm in diameter and containing about 4.4 tonnes of graphitic material. Huge forces are generated in the impact. If you could witness the event up close, you would hear a massive "bang" – like a bell – generated by the sudden expansion and successive contraction of the steel shell.

What you will have witnessed is a beam-intercepting system in action. Of course, experiencing a beam dump in person is not possible, due to the large amount of radiation generated in the impact, which is one of the reasons why access to high-energy accelerators is strictly forbidden during operation.

Beam-intercepting systems are essential devices designed to absorb the energy and power of a particle beam. Generally, they are classified in three categories depending on their use: particle-producing devices, such as targets; systems for beam cleaning and control, such as collimators or scrapers; and those with safety functions, such as beam dumps or beam stoppers. During the current long-shutdown 2 (LS2), several major projects have been undertaken to upgrade some of the hundreds of beam-intercepting systems across CERN's accelerator complex, in particular to prepare the laboratory for the high-luminosity LHC era.

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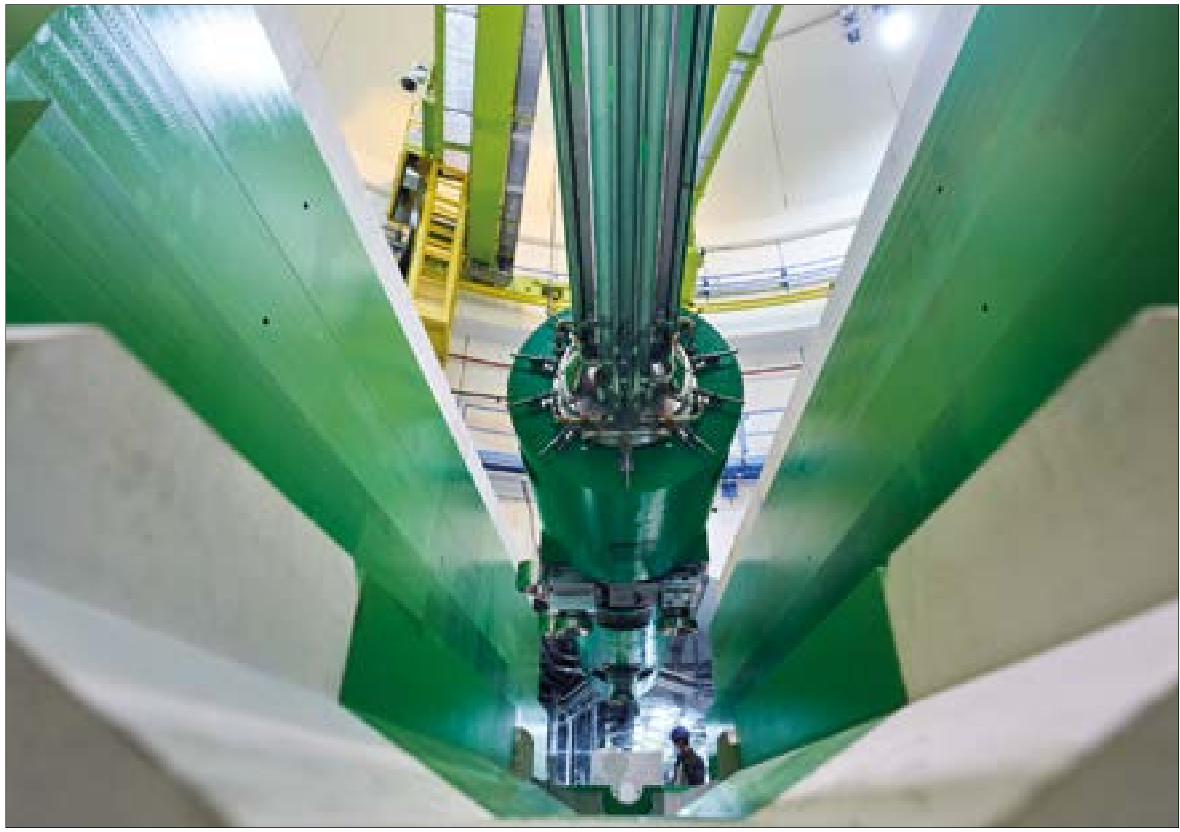


J Ordan/CERN-PHOTO-202010-134-24

Structural integrity *The new Super Proton Synchrotron internal beam dump being installed inside its shielding in October 2020.*

M Brice & J Ordan/CERN-PHOTO-202103-037-7

End of the line *The upgraded LHC beam dump, capable of absorbing 560 MJ of kinetic energy in a period of 86 µs, installed in its shielding in March 2021.*

Withstanding stress

Beam-intercepting devices have to withstand enormous mechanical and thermally-induced stresses. In the case of the LHC beam dump, for example, upgrades of the LHC injectors will deliver a beam which at high energy will have a kinetic energy equivalent to 560 MJ during LHC Run 3, roughly corresponding to the energy required to melt 2.7 tonnes of copper. Released in a period of just 86 µs, this corresponds to a peak power of 6.3 TW or, put differently, 8.6 billion horse power.

In general, the energy deposited in beam-intercepting devices is directly proportional to the beam energy, its intensity and the beam-spot size, as well as to the density of the absorbing material. From the point of view of materials, this energy is transformed into heat. In a beam dump, for example, the collision volume (which is usually much smaller than the beam-intercepting device itself) is heated to temperatures of 1500 C or more. This heat causes the small volume to try to expand but, because the surrounding area has a much lower temperature, there is no room for expansion. Instead, the hot volume pushes against the colder surrounding area, risking breaking the structure. To reach a sufficient attenuation, due to the high energy of the beams in CERN's accelerators, we need devices that in some cases are several metres long.

Beam-intercepting devices must be able to withstand routine operation and also accident scenarios, where they serve to protect more delicate equipment such as cryomagnets. Amongst the many challenges that need to be faced are operation under ultra-high-vacuum conditions, and maintaining integrity and functionality when enduring energy densities up to several kJ/cm^3 or power densities up to several MW/cm^3. For physics applications, optimisation processes have led to the use of low-strength materials, such as pure lead for the generation of neutrons at the n_TOF facility or iridium and tantalum for the generation of antiprotons at the Antiproton Decelerator (AD) facility.

Preparing for HL-LHC

The LHC Injectors Upgrade (LIU) Project, which was launched in 2010 and for which the hardware was installed during LS2, will allow beams with a higher intensity and a smaller spot size to be injected into the LHC. This is a precondition for the full execution of the High-Luminosity LHC (HL-LHC), which will enable a large increase in the integrated luminosity collected by the experiments. To

M Brice/CERN-PHOTO-202007-102-3

J Ordan/CERN-PHOTO-201911-382-21

New collimators *Left: new dispersion-suppressor collimators being installed near ALICE in 2020, where they will clean beam losses at the HL-LHC. Right: checks during collimator installation in one of the SPS-to-LHC transfer lines in November 2019, as part of the LHC Injector Upgrade Project.*

The LHC Injector Upgrade Project will allow beams with a higher intensity and a smaller spot size to be injected into the LHC

safely protect sensitive equipment in the accelerator chain, the project required a series of new devices in the injector complex from the PS Booster to the SPS, including new beam-intercepting devices. One example is the new SPS internal beam dump, the so-called TIDVG (Target Internal Dump Vertical Graphite), which was installed in straight-section five of the SPS during 2020 (see “Structural integrity” image). The main challenge faced for this device was the need to dissipate a large amount of power from the device rapidly and efficiently to avoid reaching temperatures not acceptable by the beam-dump materials.

The TIDVG is used to dispose of the SPS circulating beam whenever necessary, for example in case of emergency during LHC beam-setup, filling or machine-development periods, and to dispose of the part of the beam dedicated to fixed-target experiments that remains after the slow-extraction process. Aiming at reducing the energy density deposited in the dump core’s absorbing material (and hence minimising the associated thermo-mechanical stresses), the beam is diluted by kicker magnets, producing a sinusoidal pattern on the front of the first absorbing block. The dump is designed to absorb all beam energies in the SPS, from 14 GeV (injection from the PS) to 450 GeV.

With respect to the pre-LS2 device, the beam power to be absorbed by the dump will be four-times higher, with an average power of 300 kW. To reduce the local energy deposition whilst maintaining the total required beam absorption, the length of the new dump has been increased by 70 cm, leading to a 5 m-long dump. The dump blocks are arranged so that the density of the absorbing materials increases as the beam passes through the device: 4.4 m of isostatic graphite, 20 cm of a molybdenum alloy and 40 cm of pure tungsten. This ensures that the stresses associated with the resulting thermal gradients are kept within acceptable values. The core of the component, which receives the highest thermal load, is cooled directly by a dedicated copper-alloy jacket surrounding the blocks, which can only release their heat through the contact with the jacket; to maximise the thermal conductivity at the interfaces between the stainless-steel cooling pipes and the copper alloy, these materials are diffusion-bonded by means of hot isostatic pressing. The entire core is embedded in an air-cooled, seamless 15 mm-thick stainless-steel hollow cylinder. Due to the high activation of the dump expected after operation, in addition to the first cast-iron shielding, the assembly is surrounded by a massive, multi-layered external shield comprising an inner layer of 50 cm of concrete, followed by 1 m of cast iron and an external layer 40 cm of marble. Marble is used on the three sides accessible by personnel to minimise the residual dose rate in the vicinity after short cool-down times.

Collimator system upgrades

Beam collimators and masks are essential components in accelerator systems. They act as intermediate absorbers and dilutors of the beam in case of beam losses, minimising the thermal energy received by components such as superconducting magnets (leading to quench) or delicate materials in the LHC experiments. The other function of the collimators is to clean up the halo of the beam, by removing particles moving away from the correct orbit. Collimators generally consist of two jaws – moveable blocks of robust materials – that close around the beam to clean it of stray particles. More than 100 of these vital devices are placed around the LHC in critical locations.

The jaw materials can withstand extreme temperatures and stresses (resulting in deposited energy densities up to 6 kJ/cm^3), while maintaining – at least for the LHC collimators – good electrical conductivity to reduce the impedance contribution to the machine. Several developments were incorporated in the SPS-to-LHC transfer line collimators built in the framework of the LIU project, as well as in the LHC collimators for the HL-LHC. For the former, dedicated and extremely robust 3D carbon-composite materials were developed at CERN in collaboration with European industry, while for the latter, dedicated molybdenum carbide-graphite composites were developed, again in collaboration with European firms. For these cases, more than 30 new collimators have been built and installed in the SPS and LHC during LS2 (see “New collimators” image).

LHC beam-dump upgrades

Several challenges associated with the LHC beam dump system had to be overcome, especially on the dump-block itself: it needs to be ready at any time to accept protons, from injection at 450 GeV up to top energy (6.5 TeV, with up to 7 TeV in the future); it must be reliable (~200 dump events per year); and it must accept fast-extracted beams, given that the entire LHC ring is emptied in just 86 µs. At 560 MJ, the projected stored beam energy during Run 3 will also be 75% higher than it was during Run 2.

The dump core (around 8 m long) consists of a sandwich of graphitic materials of sufficiently low density to limit the temperature rise – and therefore the resulting thermal-induced stresses – in the material (see “End of the line” image). The graphite is contained in a 12 mm-thick special stainless-steel grade (see “Dump upgrades” image) and the assembly is surrounded by shielding blocks. Roughly 75% (±430 MJ) of the energy that gets deposited by either electromagnetic shower and ionisation losses of hadrons and muons is deposited in the graphite, while around 5% (±25 MJ) is deposited in the thin steel vessel, and the remaining energy is deposited in the shielding assembly. Despite the very low density (1.1 g/cm^3) employed in the middle section of the core, temperatures up to 1000 C have been reached during Run 2. From Run 3, temperatures up to 1500 C will be reached. These temperatures could be much higher if it were not for the fact that the beam is “painted” on the face of the dump by means of dilution kickers situated hundreds of metres upstream. The dump must also guarantee its structural integrity even in the case of failures of these dilution systems.

Although the steel vessel is responsible for absorbing just 5% of the deposited energy, the short timescales involved lead to a semi-instantaneous rise in temperature of more than 150 C, generating accelerations up to 2000 g and forces of several hundred tonnes. Following the operational experience during LHC Run 1 and Run 2, during LS2 several upgrades have been implemented on the dump. These include complex instrumentation to yield information and operational feedback during Run 3, until 2025. In the later HL-LHC era, the dump will have to absorb an additional 50% more energy per dump than during Run 3 (up to 750 MJ/dump), presenting one of numerous beam-interception challenges to be faced.

M Brice/CERN-PHOTO-202009-112-4

Dump upgrades *Upgraded LHC external dumps with new instrumentation, beam windows and support systems being fitted into their new frames, ready for installation.*

S Hertzog/CERN-PHOTO-202101-003-11

Neutron production target *Welding of the upstream cover and proton window on n_TOF’s third generation lead-based neutron spallation target.*

Fixed-target challenges

Beyond the LHC, challenging conditions are also encountered for antiproton production at CERN’s Antiproton Decelerator (AD), which serves several antimatter experiments. In this case, high-density materials are required to make sources as point-like as possible to improve the capture capabilities of the downstream magnetic-horn focusing system. Energy densities up to 7 kJ/cm^3 and temperatures up to 2500 C are reached in refractory materials such as iridium, tantalum and tungsten. Such intense energy densities and the large gradients resulting from the very small transverse beam size generate large thermal stresses and produce damage in the target material, which must be minimised to maintain the reliability of the AD’s physics programme. To this end, a new air-cooled antiproton production target will be installed


J Ordan & S Herztog/CERN-PHOTO-201905-140-1

Material integrity test *Preparation for irradiation of graphite and copper alloy for the HL-LHC injection dump (TDIS) at the HiRadMat facility in 2018.*


J Ordan/CERN-PHOTO-201808-199-6

Beam-dump facility *Installation of the tantalum-clad pure tungsten block in the Beam Dump Facility prototype target assembly, before testing with proton beam, in 2018.*

in the antiproton target area this year. Similar challenges are faced when producing neutrons for the n_TOF facility: in this case a new nitrogen-cooled pure lead spallation target weighing roughly 1.5 tonnes will be commissioned this year, ready to produce neutrons spanning 11 orders of magnitude in energy, from 25 meV to several GeV (see "Neutron production target" image).

Reliability is a key aspect in the construction of beam-intercepting devices, not just because machine operation strongly depends on them, but because replacing devices is not easy due to their residual radioactivation after operation. But how do we know that new devices will fulfill their function successfully once installed in the machine? CERN's HiRadMat facility, which allows single proton pulse testing using a high-intensity beam from the SPS, is one solution. Extremely high energy densities can be reached in test materials and in complex systems, allowing the experimental teams to investigate – in a controlled manner – the behaviour of materials or complex mechanical systems when impacted by proton (or ion) beams. During the past few years, the facility was heavily employed by both CERN and external teams from laboratories such as STFC, Fermilab, KEK and GSI, testing materials from graphite to copper and iridium across the whole spectrum of densities (see "Material integrity test" image). To be able to correctly predict the behaviour of materials when impacted by protons and other charged particles, a full understanding of thermo-physical and material properties is mandatory. Examples of critical properties include the coefficient of thermal expansion, heat capacity, thermal and electrical conductivity as well as the Young's modulus and yield strength, as well as their temperature dependence.

Dealing with radiation damage is becoming increasingly important as facilities move to higher beam intensities and energies, presenting potential show-stoppers for some beam-intercepting devices. To better understand and predict the radiation response of materials, the RaDIATE collaboration was founded in 2012, bringing together the high-energy physics, nuclear and related communities. The collaboration's research includes determining the effect of high-energy proton irradiation on the mechanical properties of potential target and beam-window materials, and developing our understanding via micro-structural studies. The goal is to enable accurate lifetime predictions for materials subjected to beam impact, to design robust components for high-intensity beams, and to develop new materials to extend lifetimes. CERN is partner to this collaboration, as well as Fermilab, STFC/UKRI, Oak Ridge, KEK, Pacific Northwest National Laboratory, and other institutions and laboratories worldwide.

Future projects

High-energy physics laboratories across the world are pursuing new energy and/or intensity frontiers, either with hadron or lepton machines. In all cases, whether collider physics or fixed-target, neutrino or beam-dump experiments, beam-intercepting devices are at the heart of accelerator operations. For the proposed 100 km-circumference Future Circular Collider (FCC), several challenges have already been identified. Owing to the small emittances and high luminosities involved in a first electron–positron FCC phase, the positron source system, and its target and capture system, will require dedicated R&D and testing as well as the two lepton dumps. FCC's proton–proton phase, further in the future, will draw on lessons from the HL-LHC operation, but it will also operate at uncharted energy densities for beam-intercepting devices, both for beam cleaning and shaping collimators as well as for the beam dumps.

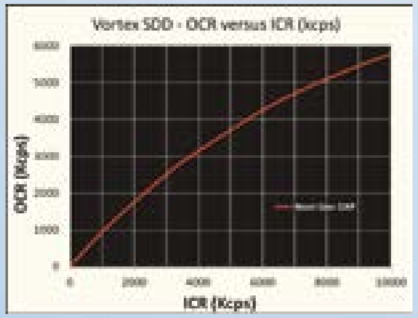
The recently launched muon-collider initiative, meanwhile, will require a target system capable of providing copious amounts of muons generated either by proton beams or electrons impacting on a target, depending on the scheme under consideration. For the former, beams of several MW could collide on a production target, which will have to be very efficient to produce muons of the required momenta while being sufficiently reliable to operate without failure for long periods. The muon collider target and front-end systems will also require magnets and shielding to be located quite close to the production target and will have to cope with radiation load and heat deposition. These challenges will be tackled extensively in the next few years, both from a physics and engineering perspective.

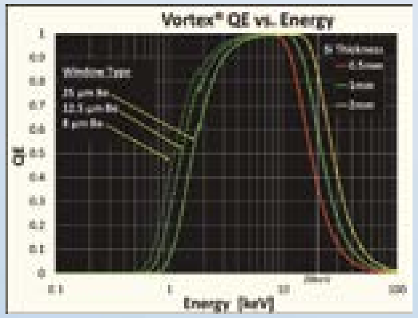
As one of the front-runner projects in the Physics Beyond Colliders initiative, the proposed Beam Dump Facility at CERN would require the construction of a general-purpose high-intensity and high-energy fixed-target complex, initially foreseen to be exploited by the Search for Hidden Particles (SHiP) experiment. At the heart of the installation resides a target/dump assembly that can safely absorb the full high-intensity 400 GeV/c SPS beam, while maximising the production of charm and beauty mesons and using high-Z materials, such as pure tungsten and molybdenum alloy, to reduce muon background for the downstream experiment. The nature of the beam pulse induces very high temperature excursions between pulses (up to 100 °C), leading to considerable thermally induced stresses and long-term fatigue considerations. The high average power deposited on target (305 kW) also creates a challenge for heat removal. A prototype target was built and tested at the end of 2018, at one tenth of the nominal power but able to reach the equivalent energy densities and thermal stresses (see "Beam-dump facility" image).

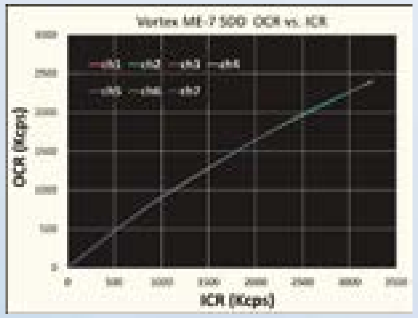
Human efforts

The development, construction and operation of successful beam-intercepting devices require extensive knowledge and skills, ranging from mechanical and nuclear engineering, to physics, vacuum technologies and advanced production techniques. Technicians also constitute the backbone of the design, assembly and installation of such equipment. International exchanges with experts in the fields and with laboratories working with similar challenges is essential, as is cross-discipline collaboration, for example in aerospace, nuclear and advanced materials. In addition, universities provide key students and personnel capable of mastering and developing these techniques both at CERN and in CERN's member states' laboratories and industries. This intense multidisciplinary effort is vital to successfully tackle the challenges related to current and future high-energy and high-intensity facilities and infrastructures, as well as to develop systems with broader societal impact, for example in X-ray synchrotrons, medical linacs, and the production of radioisotopes for nuclear medicine. ●

Successful beam-intercepting devices require extensive knowledge and skills







PHYSICS FLIES HIGH AT SINP

Eduard Boos and Victor Savrin look back at 75 years of developments at Russia's Skobeltsyn Institute of Nuclear Physics, which range from pioneering satellite experiments to participation in the LHC-experiment upgrades.


MSU photo archive

Close neighbours *The main building of SINP MSU (foreground) against the background of Moscow State University and its spire.*

The Skobeltsyn Institute of Nuclear Physics (SINP) was established at Lomonosov Moscow State University (MSU) on 1 February 1946, in pursuance of a decree of the government of the USSR. SINP MSU was created as a new type of institute, in which the principles of integrating higher education and fundamental science were prioritised. Its initiator and first director was Soviet physicist Dmitri Vladimirovich Skobeltsyn, who was known for his pioneering use of the cloud chamber to study the Compton effect in 1923 – aiding the discovery of the positron less than a decade later.

It is no coincidence that SINP MSU was established in the immediate aftermath of the Second World War, following the first use of nuclear weapons in conflict. The institute was created on the basis that it would train personnel who would specialise in nuclear science and technology, after the country realised that there was a shortage of specialists in the field. Thanks to strong leadership from Skobeltsyn and one of his former pupils, Sergei Nikolaevich Vernov, SINP MSU quickly gained recognition in the country. As soon as 1949, the government designated it a leading research institute. By this time a 72 cm cyclotron was already in use, the first to be used in a higher education institute in the USSR.

Skobeltsyn and Vernov continued with their high ambitions as they expanded the facility to the Lenin Hills, along with other scientific departments in MSU. Proposed in 1949 and opened in 1953, the new building in Moscow was granted approval to build a set of accelerators and a special installation for studying extensive air showers (EASs). The first accelerator built there was a 120 cm cyclotron, and its first outstanding scientific achievement was the discovery by A F Tulinov of the so-called "shadow effect" in nuclear reactions on single crystals, which makes it possible to study nuclear reactions at ultra-short time intervals. Significant scientific successes were associated with the commissioning of a unique installation, the EAS-MSU, at the end of the 1950s for the study of ultra-high-energy cosmic rays. Several results were obtained through a new method for studying EASs in the region of 10^{15}–10^{17} eV, leading to the discovery of the famous "knee" in the energy spectrum of primary cosmic rays .

The space race

1949 marked SINP MSU's entrance into astrophysics and, in particular, satellite technology. The USSR's launch of Sputnik 1, Earth's first artificial satellite, in 1957 gave Vernov, an enthusiastic experimentalist who had previously researched cosmic rays in the Earth's stratosphere, the opportunity to study outer-atmosphere cosmic rays. This led to the installation of a Geiger counter on the Sputnik 2 satellite and a scintillation counter on Sputnik 3, to enable radiation experiments. Vernov's experiments on Sputnik 2 enabled the first detection of the outer radiation belt. However, this was not confirmed until 1958 by the US's Explorer 1, which carried an instrument designed and

THE AUTHORS
Eduard Boos *and* **Victor Savrin** *SINP MSU.*


MSU photo archive

Vernov's legacy *On 28 April 2016 the Lomonosov satellite was launched aboard the Soyuz carrier rocket, marking the first launch from the new Russian Vostochny Cosmodrome.*

built by James Van Allen. Sputnik 3 confirmed the existence of an inner radiation belt, having received information from Australia and South America, as well as from sea-based stations.

Vernov, who was Skobeltsyn's successor as SINP director in 1960–1982, later worked on the "Electron" and "Proton" series of satellites, which studied the radiation-belt structure, energy spectra and temporal variations associated with geomagnetic activity. This led to pioneering results on the spectrum and composition of galactic cosmic rays, and to the first model of radiation distribution in near-Earth space in the USSR.

SINP MSU has carried on Vernov's cosmic legacy by continuing to develop equipment for satellites. Since 2005 the institute has developed its own space programme through the university satellites Tatiana-Universitetsky and Tatiana-2, as well as the Vernov satellite. These satellites led to new phenomena such as ultraviolet flashes from the atmosphere being discovered. In 2016 a tracking system for ultraviolet rays was installed on board the Lomonosov satellite (see "Vernov's legacy" image), developed at SINP MSU under the guidance of former director Mikhail Igorevich Panasyuk. This allowed fluorescence light radiated by EASs of ultra-high-energy cosmic rays to be measured for the first time, and prompt-emission observations of multi-wavelength gamma-ray bursts. The leading role of the entire mission of the Lomonosov satellite belongs to the current rector of MSU, Victor Sadovnichy.

High-energy exploration

In 1968, under strong endorsement by Vernov and the director of a new Russian accelerator centre in Protvino, Anatoly Alekseyevich Longunov (who went on to be MSU rector from 1977 to 1991), a department of high-energy physics was established under the leadership of V G Shevchenko at SINP MSU, and the following year it was decided that a high-energy laboratory would be established at MSU. Throughout the years to follow, collaborations with laboratories in USSR and across the world, including CERN, Fermilab, DESY and the Joint Institute for Nuclear Research (JINR), lead the department to be at the forefront of the field.

At the end of the 1970s a centre was created at SINP MSU for bubble-chamber film analysis. At the time it was one of the largest automated complexes for processing and analysing information from large tracking detectors in the country. In collaboration with other institutes worldwide, staff at the institute studied soft hadronic processes in the energy range 12–350 GeV at a number of large facilities, including the Mirabelle Hydrogen Bubble Chamber and European Hybrid Spectrometer.

Extensive and unique experimental data have been obtained on the characteristics of multiple hadron productions, including fragmentation distributions. Throughout the years, exclusive reaction channels, angular and momentum correlations of secondary particles, resonance production processes and annihilation processes were also investigated. These results have made it possible to reliably test the predictions of phenomenological models, including the dual-parton model and the quark–gluon string model, based on the fundamental theoretical scheme of dual-topological unitarisation.

For the first time in Russia, together with a number of scientific and technical enterprises with the leading role of the SINP MSU, an integrated system has now been created for the development, design, mass production and testing of large silicon solid and microstrip detectors. On this basis, at the turn of the millennium a hadron–electron separator was built for the ZEUS experiment at HERA, DESY.

The institute delved into theoretical studies in 1983, with the establishment of the laboratory of symbolic computations in high-energy physics and, in 1990, the department of theoretical high-energy physics. One of its most striking achievements was the creation of the CompHEP software package, which has received global recognition for its ability to automate calculations of collisions between elementary particles and their decays within the framework of gauge theories. This is freely available and allows physicists (even those with little computer experience) to calculate cross sections and construct various distributions for collision processes within the Standard Model and its extensions. Members of the department later went on to make a significant contribution to the creation of a Tier-2 Grid computer segment in Russia for processing and storing data from the LHC detectors.

Over the past 35 years of research in the field of particle accelerators at SINP MSU, research has moved from the development of large accelerator complexes for fundamental research, to now focusing on the creation and production of applied accelerators for security systems, industry and medicine.

Teaching legacy

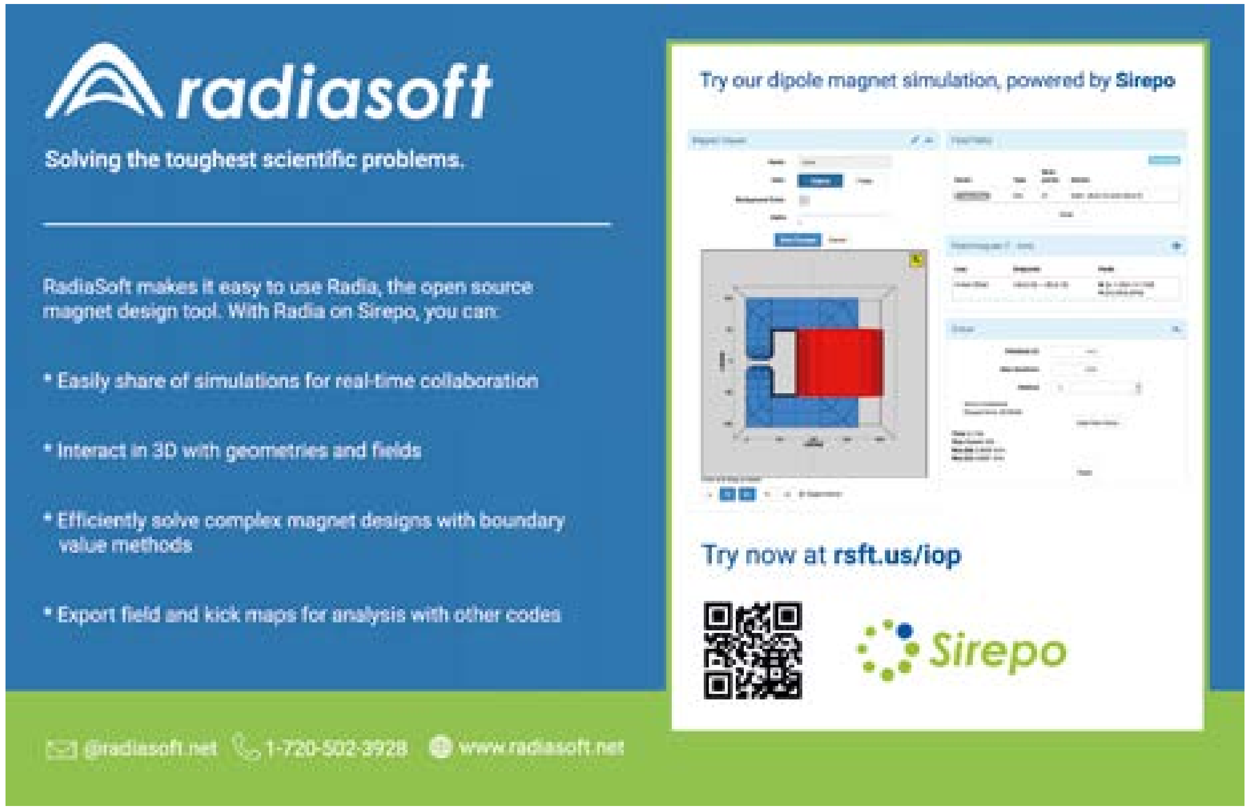
Throughout its 75 years, SINP MSU has also nurtured thousands of students. In 1961 a new branch of SINP MSU, the department for nuclear research, was established in Dubna. It became the basis for training students from the MSU physics faculty in nuclear physics using the capabilities of the largest international scientific centre in Russia – JINR. The department, which is still going strong today, teaches with a hands-on approach, with students attending lectures by leading JINR scientists and taking part in practical training held at the JINR laboratories.

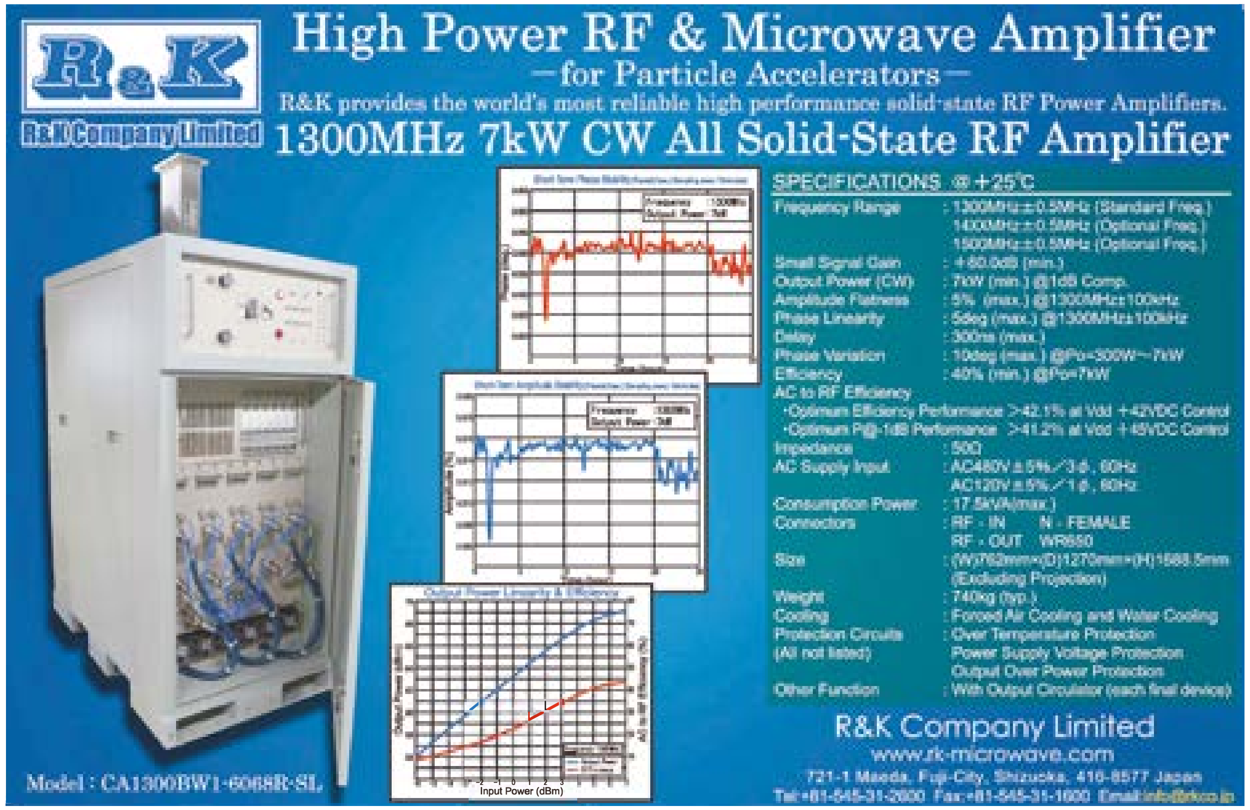
The institute is currently participating in the upgrade of the LHC detectors (CMS, ATLAS, LHCb) for the HL-LHC project, as well as in projects within the Physics Beyond Colliders initiative (e.g. NA64, SHiP). These actions are under the umbrella of a 2019 cooperation agreement between CERN and Russia concerning high-energy physics and other domains of mutual interest. Looking even further ahead, SINP MSU scientists are also working on the development of research programmes for future collider projects such as the FCC, CLIC and ILC. Furthermore, the institute is involved in the upcoming NICA Complex in Russia, which plans to finish construction in 2022.

After 75 years, the institute is still as relevant as ever, and whatever the next chapter of particle physics will be, SINP MSU will be involved. ●


MSU photo archive

CERN collaboration *A visit of former CERN Director-General Rolf Heuer (fourth from right) to Lomonosov Moscow State University in 2011.*

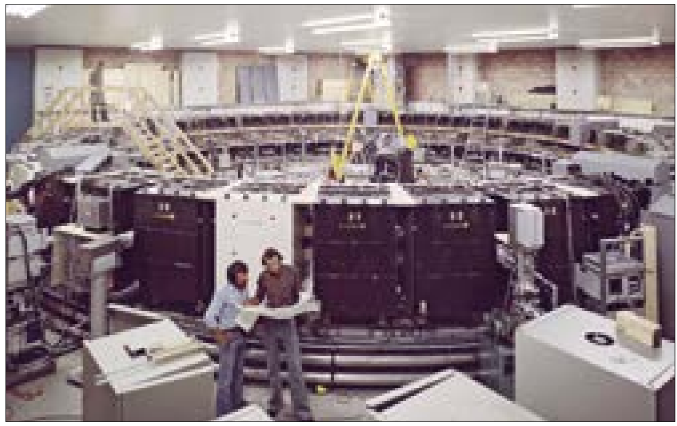




OPINION COMMENT

Muon g–2: the promise of a generation

The long-awaited g–2 result from Fermilab offers a moment to reflect on the perseverance and tight collaboration required by theorists and experimentalists to deliver progress, write Themis Bowcock and Mark Lancaster.


Pioneering *The CERN g–2 storage ring, which entered operation in 1974.*

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U. Liverpool

Themis Bowcock, *University of Liverpool, is a member of the LHCb and Muon g–2 collaborations.*


Fermilab

Mark Lancaster, *University of Manchester, is a former Muon g–2 spokesperson and a member of the Mu2e collaboration.*

It has been almost a century since Dirac formulated his famous equation, and 75 years since the first QED calculations by Schwinger, Tomonaga and Feynman were used to explain the small deviations in hydrogen's hyperfine structure. These calculations also predicted that deviations from Dirac's prediction $a = (g-2)/2$, where g is the gyromagnetic ratio $e/2m_e$, should be non-zero and thus "anomalous". The result is famously engraved on Schwinger's tombstone, standing as a monument to the importance of this result and a marker of things to come.

In January 1957 Garwin and collaborators at Columbia published the first measurements of g for the recently discovered muon, accurate to 5%, followed two months later by Cassels and collaborators at Liverpool with uncertainties of less than 1%. Leon Lederman is credited with initiating the CERN campaign of g–2 experiments from 1959 to 1979, starting with a borrowed 83×52×10 cm magnet from Liverpool and ending with a dedicated storage ring and a precision of better than 10 ppm.

Why was CERN so interested in the muon? In a 1981 review, Combley, Farley and Picasso commented that the CERN results for a_μ had a higher sensitivity to new physics by "a modification to the photon propagator or new couplings" by a factor $(m_\mu/m_e)^2$. Revealing a deeper interest, they also admitted "... this activity has brought us no nearer to the understanding of the muon mass [200 times that of the electron]."

With the end of the CERN muon programme, focus turned to Brookhaven and the E821 experiment, which took up the challenge of measuring a_μ 20 times more precisely, providing sensitivity to virtual particles with masses beyond the reach of the colliders at the time. In 2004 the E821 collaboration delivered on its promise, reporting results accurate to about 0.6 ppm. At the time this showed a $2-3\sigma$ discrepancy with respect to the Standard Model (SM) – tantalising, but far from conclusive.

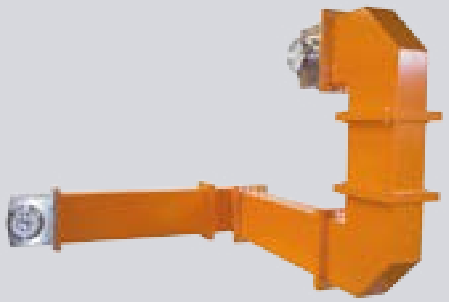
Spectacular progress

The theoretical calculation of g–2 made spectacular progress in step with experiment. Almost eclipsed by the epic 2012 achievement of calculating the QED contributions to five loops from 12,672 Feynman diagrams, huge advances in calculating the hadronic vacuum polarisation contributions to a_μ have been made. A reappraisal of the E821 data using this information suggested at least a 3.5σ discrepancy with the SM. It was this that provided the impetus to Lee Roberts and colleagues to build the improved muon g–2 experiments at Fermilab, the first results from which are described in this issue (see p7), and at J-PARC. Full results from the Fermilab experiment alone should reduce the a_μ uncertainties by at least another factor of three – down to a level that really challenges what we know about the SM.

Of course, the interpretation of the new results relies on the choice of theory baseline. For example, one could choose, as the Fermilab experiment has, to use the consensus "International Theory Initiative" expectation for a_μ. One could also take into account the new results provided by LHCb's recent R_K measurement (see p17), which hint that muons might behave differently than electrons. There will inevitably be speculation over the coming months about the right approach. Whatever one's choice, muon g–2 is a clear demonstration that theory and experiment must progress hand in hand.

Perhaps the most important lesson is the continued cross-fertilisation and impetus to the physics delivered both at CERN and at Fermilab by recent results. The g–2 experiment, an international collaboration between dozens of labs and universities in seven countries, has benefited from students who cut their teeth on LHC experiments. Likewise, students who have worked at the precision frontier at Fermilab are now armed with the expertise of making blinded ppm measurements and are keen to see how they can make new measurements at CERN, for example at the proposed MUonE experiment, or at other muon experiments due to come online this decade (see p5).

"It remains to be seen whether or not future refinement of the [SM] will call for the discerning scrutiny of further measurements of even greater precision," concluded Combley, Farley and Picasso in their 1981 review – a wise comment that is now being addressed.



OPINION
INTERVIEW

Making a difference

Accelerator physicist and science communicator **Suzie Sheehy** discusses her work, her new book, and how to increase the appeal of a research career.

How did you end up as an accelerator physicist?
Somewhat accidentally, because I didn't even know that being a researcher in physics was a thing you could be until my second year of university. It was around then that I realised that someone like me could ask questions that didn't have answers. That hooked my interest. My first project was in nuclear physics, and it involved using a particle accelerator for an experiment. I then attended the CERN summer student programme, working on ATLAS, which was my first proper exposure to the technology of particle physics. When it came to the time to do my PhD in around 2006, I had the choice to either stay in Melbourne to do particle physics, or go to Oxford, which had a strong accelerator programme. When I learned they were designing accelerators for cancer treatment, it blew my mind! I took the leap and decided to move to the other side of the world.

What did you do as a postdoc?
I was lucky enough to get an 1851 Royal Commission Fellowship, which allowed me to start an independent research programme. It was a bit of a baptism of fire, as I had been working on medical machines but then moved to high-intensity proton accelerators. I was looking at fixed-field alternating gradient accelerators and their application to things like accelerator-driven reactors. After a while I found myself spending a lot of time building sophisticated simulations, and was getting a bit bored of computing. So I started a couple of collaborations with some teams in Japan – one of which was using ion traps to mimic the dynamics of particle beams at very high intensity. What I found really interesting is how beams behave at a fundamental level, and I am currently working on upgrading a small experiment called IBEX to test a new type of optics called non-linear integral optics, which is a focus of Fermilab at the moment.

Charles Henderson Photography

Focused *Suzie Sheehy divides her time between her research groups at the University of Oxford and the University of Melbourne.*

And now you're back in the medical arena?
Yes – a few years ago I started working with people from CERN and the UK on compact medical accelerators for low- and middle-income countries. Then in 2019 I felt the pull to return to Australia to grow accelerator physics there. They have accelerators and facilities but didn't have a strong academic accelerator community, so I am building up a group at Melbourne University that has a medical applications focus, but also looks at other areas. After 20 years of pushing for a proton therapy centre here, the first one is now being built.

How and when did your career in science communication take off?
I was doing things like stage shows for primary-school children when I was a first-year undergraduate. I have always seen it as part of the process of being a scientist. Before my PhD I worked in a science museum and, while at Oxford, I started an outreach programme called Accelerate! that took live science shows to some 30,000 students in its first two years and is still running. From there, it sort of branched out. I did more public lectures, but also a little bit of TV, radio and some writing.

Any advice for physicists who want to get into communication?
You need to build a portfolio, and demonstrate that you have a range of different styles, delivery modes and use language that people understand. The other thing that really helped me was working with professional organisations such as the Royal Institution in London. It does take a lot of time to do both your research and academic job well, and also do the communication well. A lot of my communication is about my research field – so luckily they enrich each other. I think my communication has the potential to have a much bigger societal impact than my research, so I am very serious about it. The first time someone pointed a video camera at me I was terrified. Now I can say what I want to say. We shouldn't underestimate how much the public wants to hear from real working scientists, so keeping a very strong research base keeps my authenticity and credibility.

What is your work/life balance like?
I am not a fan of the term "work/life balance" as it tends to imply that one is necessarily in conflict with the other. I think it's important to set up a kind of work/life integration that supports well-being while allowing you to do the work you want to do. When I was invited back to Melbourne

to build an accelerator group, I'd just started a new research group in Oxford. I stepped down my teaching and we agreed that I would take periods of sabbatical to spend time in Melbourne until I finished my experiment. I have been so incredibly grateful to everyone on both sides for their understanding. Key to that has been learning how other people's expectations affect you and finding a way to filter them out and drive your own goals. Working in two completely different time zones, it would be easy to work ridiculously long days, so I have had to learn to protect my health. The hardest thing, and I think a lot of early/mid-career researchers will relate to this, is that academia is an infinite job: you will never do enough for someone to tell you that you have done enough. The pressure always feels like it's increasing, especially when you are a post-doc or on tenure track, or in the process of establishing a new group or lab. You have to learn how to take care of your mental health and well-being so that you don't burn out. With everything else that's going on in the world right now, this is even more important.

You are active in trying to raise the profile of women in physics. What does this involve on a practical level?

There has been a lot of focus for many years in getting more women into subjects like physics. My view is that whenever I meet young people they're interested already. In many countries the gender balance at undergraduate level is similar. So what's happening instead is that we are pushing women and minorities out. My focus, within my sphere of influence, is to make sure that the culture that I am perpetuating and the values that I hold within my research groups are well defined and communicated.

I kind of pulled back from active engagement in panel sessions and things like that a number of years ago, because I realised that the most important way I can contribute is by being the best scientist that I can be. The fact that I happen to have a public profile is great in that it makes people aware that people like me exist. One of the things that has helped me the most is to build a really great community of peers of other women in physics. I think for the first seven or eight years of my career, when imposter syndrome was strong and I questioned if I fitted in, I realised that I didn't have a single direct female colleague. With most people in my field being men, it's likely that when choosing a speaker, for example, the first person we think of is male. Taking time to be well-networked with women in the field is incredibly important in that regard. Today, I find that creating the right environment means that people will seek out my research group because they hear it's a nice place to be. Students today are much savvier with this stuff – they can tell toxic professors a mile away. I am trying to show them that there is a way of doing research that doesn't involve the horrible sides to it. Research is hard enough already, so why make it harder?

Katherine Leedale

Reaching out *Sheehy delivering a Friday Evening Discourse at the Royal Institution.*

Tell us about your debut book *The Matter of Everything*?

It's published by Bloomsbury (UK/Commonwealth) and Knopf (US) and is due out in early 2022. Its subtitle is "The 12 experiments that made the modern world", starting with the cathode-ray tube and going all the way through to the LHC and what might come next. It's told from the perspective of an experimental physicist. What isn't always captured in popular physics books is how science is actually done, but it's very human to feel like you're failing in the lab. I also delve into what first interested me in accelerators, specifically the things that have emerged unexpectedly from these research areas. People think that Apple invented everything in the iPhone, but if it wasn't for curiosity-driven physics experiments then it wouldn't be possible. On a personal note, as I went through these stories in the field, often in the biographies and the acknowledgments, I would end up going down these rabbit holes of women whose careers were cut short because they got married and had to quit their job. It's been lovely to have the opportunity to learn that these women were there, and it wasn't just white men.

> You have to learn how to take care of your mental health and well-being so that you don't burn out

Do you have a preference as to which collider should come next after the LHC?

I think it should be one of the linear ones. The size of future circular colliders and the timescales involved are quite overwhelming, and you have to wonder if the politics might change throughout the project. A linear machine such as the ILC is more ready to go, if the money and will was there. But I also think there is value in the diversity of the technology. The scaling of SLAC's linear electron machine, for example, really pushed the industrialisation of that accelerator technology – which is part of the reason why we have 3 GHz electron accelerators now in every hospital. There will be other implications to what we build, other than physics results – even though the decisions will be made on the physics.

What do you say to students considering a career in particle physics?

I will answer that from the perspective of the accelerator field, which is very exciting. If you look historically, new technologies have always driven new discoveries. The accelerator field is going through an interesting "technology discovery phase", for example with laser-driven plasma accelerators, so there will be huge changes to what we are doing in 10–15 years' time that could blow the decisions surrounding future colliders out of the water. This happened in the 1960s in the era of proton accelerators, where suddenly there was a new technology and it meant you could build machines with a much higher energy with smaller magnets, and suddenly the people who took that risk were the ones who ended up pushing the field forward. I sometimes feel experimental and theoretical physicists are slightly disconnected to what's going on with accelerator physics now. When making future decisions, people should attend accelerator conferences… it may influence their choices.

Interview by **Matthew Chalmers**.

Calculating the curiosity windfall

The Economics of Big Science: Essays by Leading Scientists and Policymakers

Edited by Hans Peter Beck and Panagiotis Charitos

Springer

Recent decades have seen an emphasis on the market and social value of fundamental science. Increasingly, researchers must demonstrate the benefits of their work beyond the generation of pure scientific knowledge, and the cultural benefits of peaceful and open international collaboration.

This timely collection of short essays by leading scientific managers and policymakers, which emerged from a workshop held during Future Circular Collider (FCC) Week 2019, brings the interconnectedness of fundamental science and economics into focus. Its 18 contributions range from procurement to knowledge transfer, and from global-impact assessments to case studies from CERN, SKA, the ESS and ESA, with a foreword by former CERN Director-General Rolf Heuer. As such, it constitutes an important contribution to the literature and a guide for future projects such as a post-LHC collider.

As the number and size of research infrastructures (RIs) has grown over the years, describes CERN's head of industry, procurement and knowledge transfer, Thierry Lagrange, the will to push the frontier of knowledge has required significant additional public spending linked to the development and upgrade of high-tech instruments, and increased maintenance costs. The socioeconomic returns to society are clear, he says. But these benefits are not generated automatically: they require a thriving ecosystem that transfers knowledge and technologies to society, aided by entities such as CERN's knowledge transfer group and business incubation centres.

Multi-billion public investments in RIs are justified given their crucial and multifaceted role in society, asserts director-general for research and innovation in the European Commission Margarida Ribeiro. She argues that new RIs need to be closely integrated into the European landscape, with plans put in place for international governance structures, adequate long-term funding, closer engagement with industry, and methodologies for assessing RI impact. All contributors acknowledge the importance of this latter point. While physicists would no doubt prefer to go back to the pre-Cold War days of doing science for science's sake, argues ESS director John Womersley, without the ability to articulate the socioeconomic justifications of fundamental science as a driver of prosperity, jobs, innovation, startups and as solutions to challenges such as climate change and the environment, it is only going to become more difficult for projects to get funding.


CERN-PHOTO-201804-088-10

Profitable prototype? *Advanced magnet R&D for a proposed future collider at CERN, in 2018.*


Springer

A future collider is a case in point. Johannes Gutleber of CERN and the FCC study describes several recent studies seeking to quantify the socioeconomic value of the LHC and its proposed successor, the FCC, with training and industrial innovation emerging as the most important generators of impact. The rising interest in the type of RI benefits that emerge and how they can be maximised and redistributed to society, he writes, is giving rise to a new field of interdisciplinary research, bringing together economists, social scientists, historians and philosophers of science, and policymakers.

Nowhere is this better illustrated than the ongoing programme led by economists at the University of Milan, described in two chapters by Florio Massimo and Andrea Bastianin. A recent social cost-benefit analysis of the HL-LHC, for example, conservatively estimates that every €1 of costs returns €1.2 to society, while a similar study concerning the FCC estimates the benefit/cost ratio to be even higher, at 1.8. Florio argues that CERN and big science more generally are ideal testing grounds for theoretical and empirical economic models, while demonstrating the positive net impact that large colliders have for society. His 2019 book *Investing in Science: Social Cost-Benefit Analysis of Research Infrastructures* (MIT Press) explores this point in depth (*CERN Courier* September 2018 p51), and is another must-read in this growing interdisciplinary area. Completing the series of essays on impact evaluation, Philip Amison of the UK's Science and Technology Facilities Council reviews the findings of a report published last year capturing the benefits of CERN membership (*CERN Courier* September/October 2020 p9).

The final part of the volume focuses on the question "Who benefits from such large public investments in science?", and addresses the contribution of big science to social justice and inequalities. Carsten Welsch of the University of Liverpool/Cockcroft Institute argues that fundamental science should not be considered as a distant activity, illustrating the point convincingly via the approximately 50,000 particle accelerators currently used in industry, medical treatments and research worldwide.

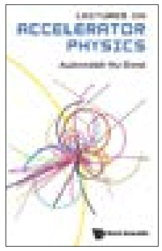
The grand ideas and open questions in particle physics and cosmology already inspire many young people to enter STEM subjects, while technological spin-offs such as medical treatments, big-data handling, and radio-frequency technology are also often communicated. Less well known are the significant but harder-to-quantify economic benefits of big science. This volume is therefore essential reading, not just for government ministers and policymakers, but for physicists and others working in curiosity-driven research who need to convey the immense benefits of their work beyond pure knowledge.

Matthew Chalmers *editor.*

Lectures on Accelerator Physics

By Alexander Wu Chao

World Scientific



World Scientific

Alex Chao, one of the leading practitioners in the field, has written an introductory textbook on accelerator physics. It is a lucid and insightful presentation of the principles behind the workings of modern accelerators, touching on a multitude of aspects, from elegant mathematical concepts and fundamental electromagnetism to charged-particle optics and the stability of charged particle beams. At the same time, numerous practical examples illustrate key concepts employed in the most advanced machines currently in operation, from high-energy colliders to free-electron lasers.

The author is careful to keep the text rigorous, yet not to overload it with formal derivations, and exhibits a keen sense for finding simple, convincing arguments to introduce the basic physics. A large number of homework problems (most of them with solutions) facilitate the stated aim to stimulate thinking. The variety of these is the fruit of extensive teaching experience. The book assumes only a basic understanding of special relativity and electromagnetism, while readers with advanced language skills will benefit from occasional remarks in Chinese, mainly philosophical in nature (translated in most cases). The present reviewer could not help wondering about the missed punchlines.

This book is a veritable "All you wanted to know about accelerators physics but were afraid to ask"

Beginners and advanced students alike will find pleasure in striking derivations of basic properties of simple physical systems by dimensional analysis. Students will also find the presentation on the use of phase-space (coordinate-momentum space) concepts in classical mechanics capable of clearing the fog in their heads. In particular, an insightful presentation of transverse and longitudinal phase-space manipulation techniques provides modern-day examples of advanced designs. Furthermore, an important discussion on "symplecticity" and Liouville's theorem – ideas that yield powerful constraints on the evolution of dynamical systems – lets physics ideas stand out against the background of formal mathematics. The discussion should help students avoid imagining typical unphysical ideas such as beams focused to infinitesimally small dimensions: the infamous "death rays" first dreamt up in the 1920s and 1930s. The treatment of the stability criteria for linear and non-linear systems, in the latter case introducing the notion of dynamical aperture (the stable region of phase space in a circular accelerator), serves as a concrete illustration of these deep and beautiful concepts of classical mechanics.

The physics of synchrotron radiation and its detailed effects on beam dynamics of charged-particle beams provide the essentials for understanding the properties of lepton and future very-high-energy hadron colliders. *Lectures on Accelerator Physics* also describes the necessary fundamentals of accelerator-based synchrotron light sources, reaching as far as the physics principles of free-electron lasers and diffraction-limited storage rings.

A chapter on collective instability introduces some of the most important effects related to the stability of beams as multi-particle systems. A number of essential effects, including head-tail instability and the Landau damping mechanism, which play a crucial role in the operation of present and future particle accelerators and colliders, are explained with great elegance. The beginner, armed with the insights gained from these lectures, is well advised to turn to Chao's classic 1993 text *Physics of Collective Beam Instabilities in High Energy Accelerators* for a more in-depth treatment of these phenomena.

This book is a veritable "All you wanted to know about accelerators physics but were afraid to ask". It is a compilation of ideas, and can be used as a less dry companion to yet another classic compilation, in this case of formulas: the *Handbook of Accelerator Physics and Engineering*, edited by Chao and Maury Tigner.

Lenny Rivkin *Paul Scherrer Institute.*

A day with particles

Screened at GeekFestToronto, and directed by Vojtech Pleskot, Martin Rybar and Daniel Scheirich

Outreach must continue, even in a pandemic: if visitors can't come to the lab, we need to find ways to bring the lab to them. Few outreach initiatives do this as charmingly as *A day with particles* – a short independent film by three ATLAS physicists at Charles University in Prague. Mixing hand-drawn animations, deft sound design and a brisk script targeted at viewers with no knowledge of physics, the 30 minute film follows a day in the life of postdoc Vojtech Pleskot. In its latest pitstop in a worldwide tour of indie film festivals, it won "BEST of FEST (Top Geek)" last week at GeekFestToronto.

"We just want to show that scientists are absolutely normal people, and that no one needs to fear them," says Pleskot, who wrote and directed the film alongside producer Martin Rybar and animator Daniel Scheirich. The three physicists produced the film with no funding and no prior expertise, beating off competition from well funded projects to win the Canadian award. Even within the vibrant but specialist niche of high-energy-physics geekery, competition included *The world of thinking*, featuring interviews with Ed Witten, Freeman Dyson and others, and a professionally produced film dramatising a love letter from Richard Feynman to his late wife Arline, who passed away while he was working on the Manhattan Project. But Pleskot, Rybar and Scheirich won the judges over with their idiosyncratic distillation of life at the rock-face of discovery. "We want to break stereotypes about scientists," adds Pleskot.

V Plesko, M Rybar and D Scheirich

Not pocket-sized *A still shot of Daniel Scheirich's art from* A day with particles.

Not every stereotype is broken, and there is room to quibble about some of the details, but grassroots projects such as *A day with particles* boast a quirky authenticity, and is well placed to connect emotionally with non-physicists. The film is beautifully paced. Wide-eyed enthusiasm for physics cuts to an adorable glimpse of Pleskot's two "cute little particles" having breakfast. A rapid hop from Democritus to Rutherford to the LHC cuts to tracking shots of Pleskot making his way through the streets of Prague to the university. The realities of phone conferences, failed grid jobs and being late for lab demonstrations are interwoven with a grad student dancing to discuss her analysis, conversations on free-diving with turtles and the stories of beloved professors recalling life in the communist era. Life as a physicist is good. And life as a physicist is really like this, they insist. "I hope that science communicators will share it far and wide," says Connie Potter (CERN and ATLAS), who commissioned the film for the 2020 edition of ICHEP.

A day with particles will next be considered at the World of Film International Festival in Glasgow in June, where it has been selected as a semi-finalist.

Mark Rayner *associate editor.*

Harnessing the CERN model

Experimental physicist Paul Lecoq's half-century-long career illustrates the power of CERN in fostering international collaboration, writes Craig Edwards.

Shanghai City Hall

Political presence *The 1982 dinner where Paul Lecoq (third from right) and Sam Ting (fifth from right) met with Jiang Zemin (fourth from right), who later went on to become the president of China. Also pictured are members of the Shanghai Institute of Ceramics (to the left of Ting), and L3 collaborators Hans Rykaczewski and Michel Lebeau (to the right of Lecoq).*

CERN's international relationships are central to its work, and a perfect example of nations coming together for the purpose of peaceful research, regardless of external politics. Through working in China during the 1980s and the Soviet Union/Russia in the early 1990s, physicist Paul Lecoq's long career is testament to CERN's influence and standing.

Originally interested in astrophysics, Lecoq completed a PhD in nuclear physics in Montreal in 1972. After finishing his military service, during which he taught nuclear physics at the French Navy School, he came across an advertisement for a fellowship position at CERN. It was the start of a 47-year-long journey with the organisation. "I thought, why not?" Lecoq recalls. "CERN was not my initial target, but I thought it would be a very good place to go. Also, I liked skiing and mountains."

Royal treatment

During his third year as a fellow, a staff position opened for the upcoming European Hybrid Spectrometer (EHS), which would test CERN's potential for collaboration beyond its core member states. "The idea was to make a complex multi-detector system, which would be a multi-institute collaboration, with each institute having the responsibility to build one detector," says Lecoq. One of these institutes was based in Japan, allowing the exchange of personnel. Lecoq was one of the first to benefit from this agreement and, thanks to CERN's already substantial image, he was very well-received. "At the time, people were travelling much less than now, and Japan was more isolated. I was welcomed by the president of the university and had a very nice reception almost every day." It was an early sign of things to come for Lecoq.

During the lifetime of the EHS, a "supergroup" of CERN staff was formed whose main role was to support partners across the world while also building part of the experiment. By the time the Large Electron–Positron Collider (LEP) came to fruition it was clear that it would also benefit from this successful approach. At that time, Sam Ting had been asked to propose an experiment for LEP by then Director-General Herwig Schopper, which would become the L3 experiment, and with the EHS coming to an end, says Lecoq, it was natural that the EHS supergroup was transferred to Ting. Through friends working in material science, Lecoq caught wind of the new scintillator crystal (BGO) that was being proposed for L3 – an idea that would see him link up with Ting and spend much of the next few years in China.

This is something unique about CERN, where you can meet fantastic people that can completely change your life

BGO crystals had not yet been used in particle physics, and had only existed in a few small samples, but L3 needed more than 1 m^3 of coverage. After sampling and testing the first crystal samples, Lecoq presented his findings at an L3 collaboration meeting. "At the end of the meeting, Ting pointed his finger in my direction and asked if I was free on Saturday. I responded, 'yes sir'. Then he turned to his secretary and said, 'book a flight ticket to Shanghai – this guy is coming with me!'"

Unknown to Lecoq upon his arrival in China, Ting had already prepared the possibility to develop the technology for the mass production of BGO crystals there, and wanted Lecoq to oversee this production. BGO was soon recognised as a crystal that could be produced in large quantities in a reliable and cost-effective way, and it has since been used in a generation of PET scanners. Lecoq was impressed by the authority Ting held in China. "The second day we were in China, we, well Ting, had been invited by the mayor of Shanghai for a dinner to discuss the opportunity for the experiment." The mayor was Jiang Zemin, who only a few years later became China's president. "I have been very lucky to have several opportunities like this in my career. This is something unique about CERN, where you can meet fantastic people that can completely change your life. It was also an interesting period when China was slowly opening up to the world – on my first trip everyone was in Mao suits, and in the next three to five years I could see a tremendous change that was so impressive."

Lecoq's journeyman career did not stop there. With LEP finishing towards the turn of the millennium and LHC preparations in full swing, his expertise was needed for the production of lead tungstate (PWO) crystals for CMS's electromagnetic calorimeter. This time, however, Russia was the base of operations, and the 1.2 m^3 of BGO crystal for L3 became more than 10 m^3 of PWO for CMS. As with his spell in China, Lecoq was in Russia during a politically uncertain time, with his arrival shortly following the fall of the Berlin Wall. "There was no system anymore. But there was still very strong intellectual activity, with scientists at an incredible level, and there was still a lot of production infrastructure for military interest."

At the time, lithium niobate, a crystal very similar to PWO, was being exploited for radar communication and missile guidance, says Lecoq, and the country had a valuable (but unknown to the public) production-infrastructure in place. With the disarray at the end of the Cold War, the European Commission set up a system, along with Canada, Japan and the US, called the International Science and Technology Center (ISTC), whose role was to transfer the Soviet Union's military industry into civil application. Lecoq was able to meet with ISTC and gain €7 million in funding to support PWO crystal production for CMS. Again, he stresses, this only happened due to the stature of CERN. "I could not have done that if I had been working only as a French scientist. CERN has the diplomatic contact with the European Commission and different governments, and that made it a lot easier." Lecoq was responsible for choosing where the crystal production would take place. "These top-level scientists working in the military areas felt isolated, especially in a country that was in a period of collapse, so they were more than happy not only to have an opportunity to do their job under better conditions, but also to have the contacts. It was interesting not only at the scientific level, but on a human level too."

Crystal clear

Back at CERN, Lecoq realised that introducing a new scintillating crystal, optimising its performance to the harsh operating conditions of the LHC, and developing mass-production technologies to produce large amounts of crystal in a reliable and cost-effective way, was a formidable challenge that could not be dealt with only by particle physicists. Therefore, in 1991, he decided to establish the Crystal Clear multidisciplinary collaboration, gathering experts in material science, crystal-growth, luminescence, solid-state physics and beyond. Here again, he says, the attractiveness of CERN as an internationally recognised research centre was a great help to convince institutes all over the world, some not connected to particle physics at all, to join the collaboration. Crystal Clear is still running today, and celebrating its 30th anniversary.

Through developing international connections in unexpected places, Lecoq's career has helped build sustained connections for CERN in some of the world's largest and fruitfully scientific places. Now retired, he is a distinguished professor at the Polytechnic University in Valencia, where he has set up a public-private partnership laboratory for metamaterial-based scintillators and photodetectors, to aid a new generation of ionisation radiation detectors for medical imaging and other applications. Even now, he is able to flex the muscles of the CERN model by keeping in close contact with the organisation.

"My career at CERN has been extremely rich. I have changed so much in the countries I've worked with and the scientific aspect, too. It could only have been possible at CERN."

Craig Edwards *(based on an interview between Paul Lecoq and the Office for CERN Alumni Relations).*

Appointments and awards

Smith leads TRIUMF

Nigel Smith has been announced as the next director of TRIUMF, Canada's leading particle accelerator centre.


SNOLAB

The appointment follows the departure of Jonathan Bagger, who became CEO of the American Physical Society in January. Smith, who has served as SNOLAB director since 2009, has previously worked as a research associate at Imperial College London and as group leader in dark-matter research at the STFC Rutherford Appleton Laboratory. His five-year term as TRIUMF director begins on 17 May and spans an important time as the laboratory aims to complete two major projects: the Advanced Rare Isotope Laboratory (ARIEL) and the Institute for Advanced Medical Isotopes (IAMI).

French Physical Society appoints Wormser

The French Physical Society (SFP) has appointed particle physicist Guy Wormser as its new president for the period 2021–2023. Wormser has spent his career at the Linear Accelerator Laboratory (LAL) at Orsay, which recently merged with neighbouring laboratories to become the Irène-Joliot Curie Physics of Two Infinities Lab (IJCLab), and was director of LAL from 2005–2011. He also represented France at the European Committee for Future Accelerators from 2013 to 2019 and has been involved in the LHCb experiment since 2013. Wormser's term will encompass the 150th anniversary of the SFP in 2023.


G Wormser

New ATLAS management

The ATLAS collaboration announced its new management team on 1 March. Former deputy spokesperson Andreas Hoecker (pictured), who has been part of the collaboration since 2005, replaces Karl Jakobs to become the fifth ATLAS spokesperson since the collaboration's establishment in 1992. Marumi Kado (University of Rome I and INFN Rome) joins Manuella Vincter (Carleton University) as deputy spokesperson, while technical coordinator Ludovico Pontecorvo (CERN), resource coordinator David Francis (CERN) and upgrade coordinator Francesco Lanni (Brookhaven National Laboratory) also continue in their roles. The new management team will guide the collaboration for the next two years, overseeing the final push before LHC Run 3 in 2022 and preparing for future high-luminosity LHC operations.


C Nellist

Collide Residency Award

Arts at CERN announced in February that Black Quantum Futurism, a multidisciplinary collaboration between Camae Ayewa (above left) and Rasheedah Phillips (above right), has been awarded the Collide Residency Award. The duo explores the intersections of futurism, creative media, DIY-aesthetics and activism in marginalised communities "through an alternative temporal lens".


K Foto

A two-month residency at CERN this year, followed by one month at the Hangar Visual Arts Research and Production Centre in Barcelona, will see Ayewa and Phillips produce a new artwork based on their proposal "CPT Symmetry and Violations". Collide is an annual competition that invites artists from across the world to submit proposals for a research-led residency based on interactions with CERN's scientific community. This year a total of 564 project proposals were received from 79 countries.

2020 Wu-Ki Tung Award

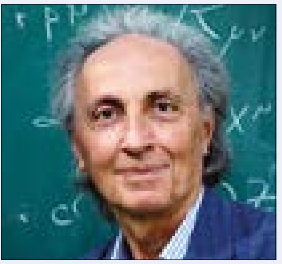
Theorist Bernhard Mistlberger (SLAC) has been granted the 2020 Wu-Ki Tung Award for Early-Career Research on QCD, "for pioneering theoretical computations of multi-loop radiative contributions for precision Higgs and electroweak physics at hadron colliders". The $5000 award, given annually to a young physicist performing either experimental or theoretical research on QCD, was established by the CTEQ (Collaborative Theoretical and Experimental studies of QCD) collaboration in 2014 to honour the legacy of Wu-Ki Tung, one of the leading researchers on QCD, and the founder of CTEQ.


B Mistlberger

Trio wins Galileo Medal

The 2021 Galileo Galilei Medal has been awarded to theorists (below, from top to bottom) Alessandra Buonanno (Max Planck Institute), Thibault Damour (Institut des Hautes Études Scientifiques) and Frans Pretorius (Princeton University) "for the fundamental understanding of sources of gravitational radiation by complementary analytic and numerical techniques, enabling predictions that have been confirmed by gravitational-wave observations and are now key tools in this new branch of astronomy". The award was established in 2018 by the National Institute for Nuclear Physics (INFN) and the Galileo Galilei Institute, and is given to scientists who, in the 25 years before the date of the award, have achieved outstanding results in the areas of theoretical physics of interest to the INFN.


T Rinaldo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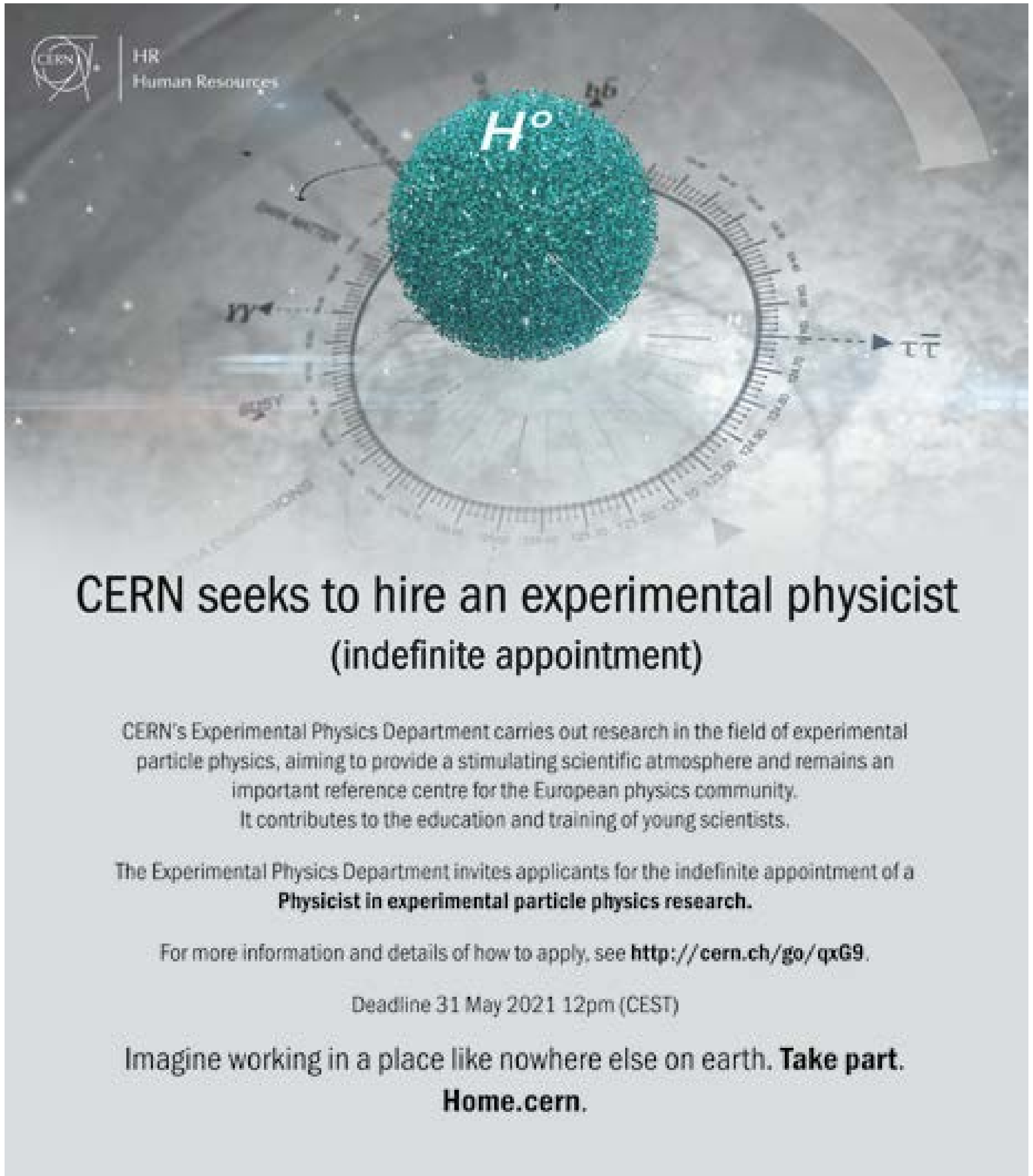

CERN seeks to hire an experimental physicist (indefinite appointment)

CERN's Experimental Physics Department carries out research in the field of experimental particle physics, aiming to provide a stimulating scientific atmosphere and remains an important reference centre for the European physics community. It contributes to the education and training of young scientists.

The Experimental Physics Department invites applicants for the indefinite appointment of a **Physicist in experimental particle physics research.**

For more information and details of how to apply, see **http://cern.ch/go/qxG9**.

Deadline 31 May 2021 12pm (CEST)

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European Physical Society
more than ideas

The European Physical Society (EPS) is a non-profit association that advocates and promotes physics research and its contributions to the economic, technological, social and cultural advancement in Europe. Federating 42 national Member Societies, institutional and corporate Members from academia and industry, and more than 3'500 Individual Members, the EPS represents a community of more than 130'000 scientists. The scientific activities of the EPS are organised through 18 Divisions and Groups covering all branches of physics. The seat of the Society is in Mulhouse (France). Detailed information about the EPS can be found on www.eps.org.

THE EPS IS SEEKING A NEW SECRETARY GENERAL

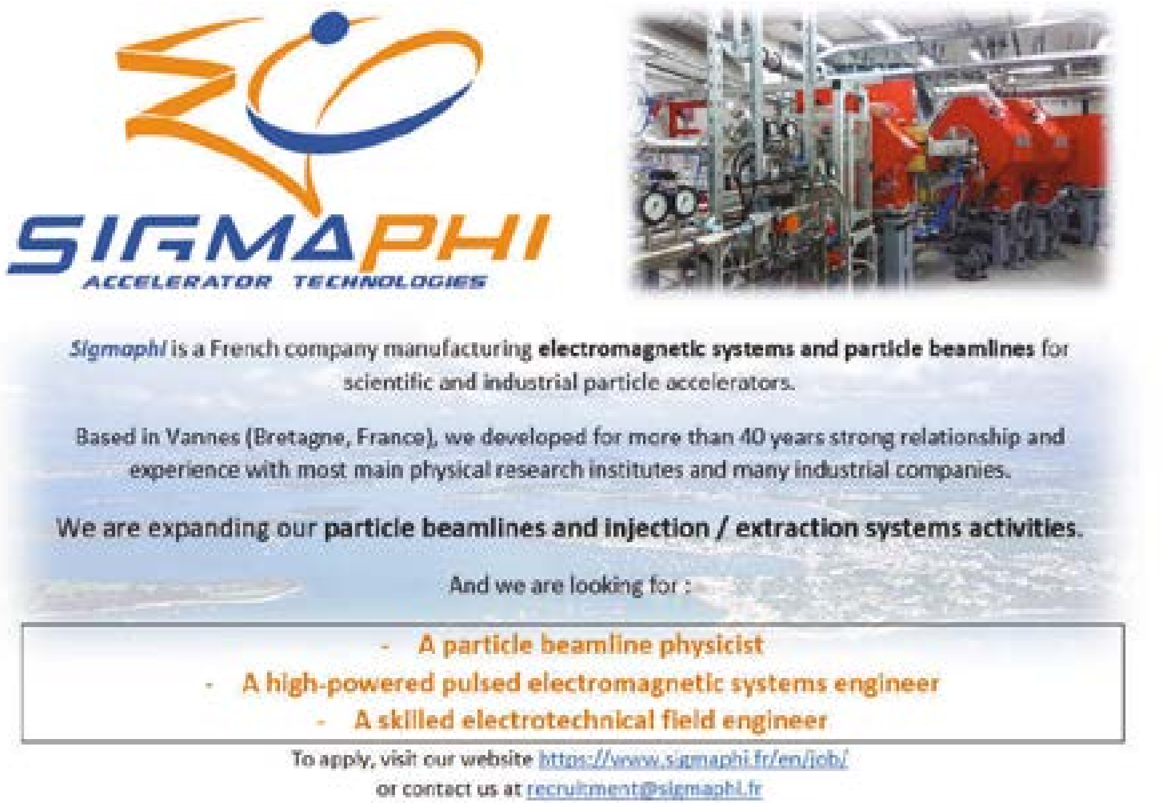
to succeed the present Secretary General who plans to retire in spring 2023. Employment is expected to begin in autumn 2022 to allow for a thorough on-the-job training.

- The Secretary General heads the EPS Secretariat which supports the activities of the President, the Vice President, the Executive Committee, and all other bodies of the Society.

The person to be recruited should have a university degree, preferably in physics or another field in natural sciences, with several years of experience in science management and administration. A degree in political science, business administration or similar may also be suitable.

- The Secretary General shall be responsible for all administrative and financial matters of the EPS. The person supports the activities of the President, the Vice President, the Executive Committee, and all other bodies of the Society.
- The EPS is looking for a dynamic personality with leadership experience, excellent social and communication skills, and a strong interest in science policy and science advocacy, in particular at the European level. An enthusiastic commitment to the mission of the Society is expected. The position requires fluency in English, a working knowledge of French, flexible working hours, and availability to travel. A complete job description is available at ***https://www.eps.org/recruitment***.
- The EPS offers competitive employment conditions commensurate with age and experience, in an attractive environment close to the French-German-Swiss border triangle. The financial conditions will be based on the salary grid of public research institutions in France.

Applications with a detailed letter of motivation and a Curriculum Vitae should be addressed not later than 30 June, 2021 to the EPS President, Dr. Luc Bergé (***president@eps.org***). Further information may also be obtained from the present Secretary-General David Lee (***d.lee@eps.org***).



SIGMAPHI
ACCELERATOR TECHNOLOGIES

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PhD student for dosimetry and beam diagnostics at PITZ

DESY.

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The position

- Simulate beam interactions using software packages such as GEANT
- Prototype and test several sensors for dosimetry, including CMOS imaging sensors (CIS)
- Implement the sensors and readout in PITZ and test them with the unique beam properties available
- Optimise beam dynamics and test with phantoms to optimise the delivered dose
- Analyze experimental data and compare with simulation results
- Participate in shift operation for accelerator R&D at PITZ

Requirements

- Excellent university degree in experimental physics, with very good knowledge in detector physics and corresponding simulations or equivalent qualification
- Strong background in numerical and statistical methods
- Good knowledge in experimental characterization of particle beams; good programming skills
- Knowledge in beam dynamics simulations/radiation physics/dosimetry is of advantage
- Very good command of English is required and knowledge of German is of advantage
- Excellent teamwork abilities in an international environment

For further information please contact Dr. Steven Worm at +49 33762 7-7208 (steven.worm@desy.de).

The position is limited to 3 years.
Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Persons with disabilities will be given preference to other equally qualified applicants. DESY operates flexible work schemes. DESY is an equal opportunity, affirmative action employer and encourages applications from women.

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Human Resources Department | Code: APDO002/2021
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Deadline for applications: Until the position is filled.

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Please see the complete posting at https://www.jlab.org/job-openings.

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SEIT 1386

The Department of Physics and Astronomy at Heidelberg University invites applications for a

FULL PROFESSORSHIP (W3) IN THEORETICAL PHYSICS (F/M/D)

Candidates (f/m/d) should have a leading international research profile in the broader area of quantum field theory/cosmology (succession Christof Wetterich). They should contribute to our understanding of fundamental physical law by applying and developing modern theoretical methods. The candidates' research should have connections to and complement the work of established groups at our Theory Institute and Physics Department. Teaching Theoretical Physics at all levels is a central part of this position.

Prerequisites for application are a university degree, a doctoral degree and (in accordance with Article 47, Paragraph 2 of the Higher Education Law of the Federal State of Baden-Württemberg) a habilitation, a successfully evaluated junior professorship, or equivalent qualifications.

Applications should include a CV, a statement of research interests, a brief description of future research plans, a list of publications and a summary of teaching experience. They should be sent electronically (single PDF) only. All materials must be received no later than **May 16, 2021** at Ruprecht-Karls-Universität Heidelberg, Dekan der Fakultät für Physik und Astronomie, Prof. Dr. Tilman Plehn, Im Neuenheimer Feld 226, D-69120 Heidelberg, e-mail: dekanat@physik.uni-heidelberg.de.

We ask for your understanding that application documents received will not be returned.

Heidelberg University stands for equal opportunities and diversity. Qualified female candidates are especially invited to apply. Disabled persons will be given preference if they are equally qualified. Information on the application process and the collection of personal data is available at www.uni-heidelberg.de/stellenmarkt.

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Candidates (f/m/d) are expected to develop a strong research program in experimental particle physics by searching for physics beyond the Standard Model through precision measurements. Possible subject areas could be dark matter and axion searches, collider or non-collider based neutrino physics, or research at high-intensity low-energy beams. The position is located at the Kirchhoff-Institut für Physik (KIP) and aims to complement our efforts in high-energy particle physics at the LHC. It will be embedded in an active research environment on experimental and theoretical particle physics both at Heidelberg University and the Max-Planck-Institut für Kernphysik (MPIK).

The professorship is based within the Department for Physics and Astronomy and duties include teaching of experimental physics in its full breadth at the undergraduate and graduate levels. The group will participate in the graduate education program within the Heidelberg Graduate School for Physics (HGSFP).

Prerequisites for application are a university degree, a doctoral degree and (in accordance with Article 47, Paragraph 2 of the Higher Education Law of the Federal State of Baden-Württemberg) a habilitation, a successfully evaluated junior professorship, or equivalent qualifications.

Applications should include a CV, a statement of research interests, a brief description of future research plans, a list of publications and a summary of teaching experience. They should be sent electronically (PDF) only. All materials must be received no later than **16.05.2021** at Ruprecht-Karls-Universität Heidelberg, Dekan der Fakultät für Physik und Astronomie, Prof. Dr. Tilman Plehn, Im Neuenheimer Feld 226, D-69120 Heidelberg, e-mail: dekanat@physik.uni-heidelberg.de.

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PEOPLE OBITUARIES

Samoil Mihelevich Bilenky 1928–2020

A pioneer of neutrino physics

Eminent Russian theorist Samoil Mihelevich Bilenky, one of the founders of modern neutrino physics, passed away on 5 November 2020. A teacher of a generation of particle physicists, not only in Russia but also in many Eastern European countries and later in Western Europe, Samoil Bilenky played a leading role in the evolution of neutrino physics to the present day.

Bilenky was born in Zmerinka, Ukraine, to an engineering family. He graduated in 1952 *cum laude* from the renowned Moscow Engineering Physics Institute. His thesis adviser was Isaak Pomeranchuk. The same year, Bilenky got a permanent position at the Institute for Nuclear Problems in Dubna, near Moscow, which in 1956 became the Joint Institute for Nuclear Research (JINR), and ever since was a staff member at JINR. He obtained his PhD in 1957 for applications of the dispersion-relation theory to weak-interaction processes. In a subsequent series of articles, Bilenky discovered a general connection between polarisation effects and internal parities of particles in scattering processes and proposed a method for determining the parities of strange particles, later used in experiments at Berkeley and CERN. These articles also initiated the development of the polarised proton-target technique.

Bilenky's most prominent contributions are in the field of neutrino physics. In a fruitful collaboration and co-authorship with the Italian/Soviet physicist Bruno Pontecorvo, which started in the early 1970s, he developed the theory of neutrino oscillations in vacuum and laid the foundations of the phenomenological theory of neutrino mixing, on which every theoretical model of neutrino mass generation (including grand unified theories) is based. After Pontecorvo's passing in 1993, Bilenky continued to make original and insightful contributions to the development of neutrino physics. For his devotion to the studies of neutrinos, which he called "the most interesting among the elementary particles", and – in view of the fact that neutrino properties suggest the existence of physics beyond the Standard Model – "a gift of nature", his long-term friend and renowned particle physicist Jose Bernabeu proposed once, jokingly, that Bilenky should be called "Mister Neutrino".


JINR

Bilenky helped lay the foundations of the phenomenological theory of neutrino mixing.

Bilenky was an excellent teacher, mentor and inspiration for many young researchers in the field of elementary particle and neutrino physics. His lectures on different topics in theoretical particle physics at Moscow University, where he taught for 30 years, and on neutrino physics at various international schools, were characterised by remarkable clarity. This made him a sought-after speaker and he was invited and gave lectures at universities across Europe. Bilenky initiated and was a tireless organiser of the well-known Pontecorvo Neutrino Physics School.

For his research and teaching activities Bilenky received many recognitions: the Russian state medal "For distinguished service to the State", the International Bruno Pontecorvo Prize, the Humboldt Prize, and the Medal of First Degree of the Faculty of Physics and Mathematics of Charles University in Prague, among others. He also wrote five books on particle-physics theory, which have helped and continue to help many young scientists enter into the fascinating fields of modern particle and neutrino physics.

Bilenky attracted people with his kind and obliging character, and had collaborators and friends in many countries. His warmth and benevolent personality embodied the best humanistic and cultural traditions of the Russian intelligentsia to which Samoil Mihelevich Bilenky belonged. We shall miss him.

His colleagues and friends.

Arnulfo Zepeda Domínguez 1943–2020

Promoting Mexican particle physics

Born in 1943 in San Luis de Potosí, Mexico, Arnulfo Zepeda graduated in nuclear engineering at the University of Prague in 1967. He then joined Cinvestav (Centro de Investigación y de Estudios Avanzados of Instituto Politécnico Nacional), where he obtained a PhD in physics in 1970, and then Rockefeller University where he obtained a PhD in elementary particle physics in 1972.

Arnulfo's initial interest was in theoretical particle physics and he became known for his studies in chiral symmetry breaking, nucleon form factors and the up-quark mass. He created a young and very active particle-physics group at Cinvestav and became one of the leading figures in theoretical physics in Mexico and Latin America.

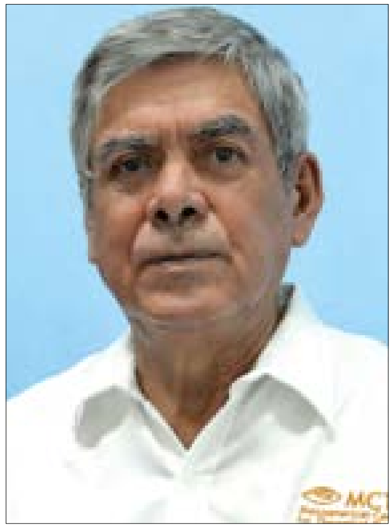
In the late 1990s Arnulfo's attention turned to ultra-high-energy cosmic rays. Leading Mexico's participation in the construction and exploitation of the Auger Observatory in Argentina, he contributed significantly to important discoveries such as establishing the GZK ultra-high-energy cutoff, the nuclear composition of ultra-high-energy cosmic rays and the observation of possible point-like cosmic-ray sources. His activities in this field continued in Mexico with the promotion of the HAWC gamma-ray observatory and participation in its collaboration board.

At the beginning of the new millennium, Arnulfo was among the initiators of the participation of Mexican scientists in CERN's experimental programmes, in particular the ALICE experiment. In 2002 he formally joined ALICE, where he was involved in the installation of the ACORDE detector that has acted as a cosmic-ray trigger. ACORDE not only provided precious calibration data but also, together with other ALICE sub-detectors, precise information on cosmic rays with primary energies in the range 10^{15}–10^{17} eV. ▷

Arnulfo was an associate (1982–1988) and senior associate (1998–2003) to ICTP, Trieste, and was elected fellow of the American Physical Society in 1993 for his original research in high-energy physics and phenomenology, his leadership in high-energy physics in México, and for initiatives in promoting closer communication among physicists in North America. Contributing greatly to the advancement of physics in Mexico and Latin America, he founded the Escuela Mexicana de Partículas y Campos, chaired the División de Partículas y Campos of the Sociedad Mexicana de Física (SMF) in 1991–1992, and was president of SMF between 1992 and 1994. He also directed more than 30 theses and was considered an enthusiastic and outstanding professor, devoted to his students.

In the years 2005 to 2016 Arnulfo promoted Europe–Latin America scientific exchanges as a member of the executive board of two European Commission projects: HELEN (High Energy Physics Latin-American European Network) and EPLANET (European Particle Physics Latin American Network). These projects have mobilised exchanges for more than 3000 person-months, making it possible for physicists from Latin America to participate significantly in the discoveries made at the LHC. In his later years, Arnulfo was the founding director of MAIS (Meso American Institute for Science) at the Universidad Autónoma de Chiapas – an initiative started by ICTP to establish a network of partner UNESCO institutes around the globe. Arnulfo took this task with great enthusiasm, moving there from 2011 to 2018, and MAIS was established as a category-two UNESCO institute in 2020.

Arnulfo's broad and deep scientific interests and his human qualities have been instrumental in the growth of high-energy and astroparticle physics in Mexico in recent decades, and raised the profile of the Mexican scientific community at the international level, both at CERN and in international cosmic-ray experiments. He was an excellent scientist and a precious friend for many of us at CERN.


MAIS

Arnulfo was instrumental in the growth of high-energy and astroparticle physics in Mexico.

Paolo Giubellino *GSI-FAIR*, **Luciano Maiani** *Università di Roma*, **Luciano Musa** *CERN and* **Veronica Riquer** *Università di Roma.*

ROGER J N PHILLIPS 1931–2020

An eminent phenomenologist


Family photograph

Roger Phillips was renowned for his deep understanding of particle-physics models.

The eminent theoretical physicist Roger Julian Noel Phillips died peacefully on 4 September 2020, aged 89, at his home in Abingdon, UK. Roger was educated at Trinity College, Cambridge, where he received his PhD in 1955. His thesis advisor was Paul Dirac. Roger transferred from the Harwell theory group to the Rutherford Appleton Laboratory in 1962, where he led the theoretical high-energy physics group to international prominence. He also held visiting appointments at CERN, Berkeley, Madison and Riverside.

Roger was a giant in particle-physics phenomenology and his book *Collider Physics* (Addison-Wesley, 1987), co-authored with his longstanding collaborator Vernon Barger, remains a classic. In 1990 Roger was awarded the Ernest Rutherford Medal and Prize of the UK's Institute of Physics. To experimenters, he was one of the rocks upon whom the UK high-energy physics community was built. To theorists, he was renowned for his deep understanding of particle-physics models.

A career-long collaboration across the Atlantic with Barger ensued from their sharing an office at CERN in 1967. Their initial focus was the Regge-pole model to describe high-energy scattering of hadrons. Subsequently they inferred the momentum distribution of the light quarks and gluons from deep-inelastic scattering data and made studies to identify the charm-quark signal in a Fermilab neutrino experiment.

In 1980 Phillips and collaborators discovered the resonance in neutrino oscillations when neutrinos propagate long distances through matter. This work is the basis of the ongoing Fermilab long-baseline neutrino programme that will make precision determinations of neutrino masses and mixing. From 1983 Phillips and his collaborators developed pioneering strategies in collider physics for finding the W boson, the top quark, the Higgs boson and searches for physics beyond the Standard Model. In an influential 1990 publication, Phillips, Hewett and Barger showed that the decay of a b-quark to an s-quark and a photon is a highly sensitive probe of a charged Higgs boson through its one-loop virtual contribution.

There are symmetries in mathematics which are like aspects of dreaming

After retiring in 1997, Roger maintained an active interest in particle physics. He struggled with Parkinson's disease in recent years but continued to live with determination, wit and cheer. He joked that his Parkinson's tremor made his mouse and keyboard run wild: "I know that an infinite number of random monkeys can eventually write Shakespeare, but I can't wait that long!" One of his very last whispers to his son David was: "There are symmetries in mathematics which are like aspects of dreaming." He did great things with his brain when he was alive that will continue, as he donated his to the Parkinson's UK Brain Bank.

Roger was highly respected for his intellectual brilliance, physics leadership and immense integrity, but also for his modesty and generosity in going out of his way to help others. He was a delight to work with and an inspiration to all who knew him. He is missed by his many friends around the world.

Vernon Barger *University of Wisconsin-Madison.*

PIERLUIGI RIBONI 1935–2020

A great CERN engineer


Family photograph

Pierluigi helped design gantries for hadron therapy in his later years.

Pierluigi Riboni passed away in Geneva on 9 November, aged 85, as a consequence of COVID-19. Born in Pavia, Italy, he graduated from Milan Polytechnic in 1961 as a mechanical engineer. After working a few years for Montecatini in Portomarghera near Venice, he joined CERN as the head of the mechanics group in the engineering division. Initially his work focused on supporting the PS groups and, in particular, concerning the vacuum systems. In the 1970s he also contributed to the design of ESO's 3.6 m telescope.

During the early 1990s Riboni became the head of CERN's central machines shop, which is responsible for supporting the accelerators and detectors by supplying machines and material from conceptual design to quality-controlled end products. Personnel shortages during these times meant that he often had to face the "making or buying" dilemma, leading Riboni to become increasingly involved with technology-transfer to industry. For nearly 20 years he co-organised the industry sessions of the biannual Conference on Astroparticle, Particle Physics, Detectors and Medical Applications, held in Como, Italy. The conference became an important venue for knowledge exchange for several hundred scientists, engineers, managers and administrators of research institutions.

Pierluigi remained active long into his retirement, in particular contributing to CERN's activities. He was one of the first engineers involved in the CMS detector, and continued to contribute through an association with ETH-Zurich, focusing on the production of the superconducting cable of the solenoid and on the manufacturing of four grease pads. In 2002 he joined the TERA Foundation, which collaborates with CERN in the development of the techniques for hadron therapy, and contributed to the mechanical design of both high-frequency proton accelerators and gantries that support magnetic beam lines and rotate around the patient bed. In particular, he designed a gantry that weighed 25 tonnes, which was 10 times less than the existing ones. The report on SIGRUM – the Superconducting Ion Gantry with Riboni's Unconventional Mechanics – was presented a few days after he left us to the international advisory committee set-up by CERN, CNAO, INFN and MedAustron.

Pierluigi's cultural background covered philosophy, politics, economics and architecture. His vast knowledge originated from both an unbound curiosity and a great interest in learning. He also had a passion for athletics, tennis and skiing, balancing his intellectual interests with his physical wellbeing. His life choices were characterised by an absolute optimism, which allowed him to maintain a positive attitude towards all professional and personal challenges. He had a gentleman's attitude in his relations with people, and he always encouraged and supported younger collaborators.

Pierluigi is among the best Italian engineers who contributed to the successes of CERN. He will be missed by his family, friends and his collaborators but will always live in our memories.

His friends and colleagues.

HAROLD KLEIN TICHO 1921–2020

A remarkable life well-lived


C Pansing

Harold Ticho was part of the team working on Berkeley's Bevatron.

Harold Klein Ticho, who was born in Brno, Czechoslovakia in 1921, passed away peacefully on 3 November 2020 in La Jolla, California, surrounded by his loving family. He was a little more than a month under 99 years of a well-lived life.

Harold was the eldest son of well-to-do parents. From the age of 12 he experienced many momentous changes that testified to his family's resilience during a time of great personal and global upheaval. His younger brother Leo passed away in 1933 from a childhood illness. Shortly after the Anschluss in 1938 when living near the Austrian border, Harold's mother sent him to a Swiss boarding school to get him safely out of the country. By the time they were reunited in the US in 1940, Harold was enrolled at the University of Chicago. He became a US citizen in 1944.

Harold obtained his bachelor's degree in physics in 1942, his master's in 1944 and his PhD in 1949. Over the years he had the opportunity to work with the greatest minds in his field such as Enrico Fermi at institutes including Fermilab, Berkeley and CERN. Aged 27, he became a lecturer and later professor at the University of California at Los Angeles, the beginning of his tenure with the UC system that would continue through becoming dean of the physics department, professor and later vice chancellor at UC San Diego. In between, he held multiple Guggenheim fellowships, a visiting professorship at Stanford and a sabbatical position at CERN.

As a researcher, educator and university administrator, Harold's contributions were extraordinary. His research in experimental particle physics paved the way to the quark model of the nucleon, his contributions being essential to the work of the Nobel Prize-winning team of Luis Alvarez. He continued to leave his mark in science education well into his 80s with the UC San Diego public television science programme he developed for budding young scientists.

Harold was not only resilient and remarkably accomplished, he also had matchless integrity, rationality, objectivity, generosity and strong moral character. Unusually he excelled not only in physics, but also in the more pragmatic and political field of university administration. He tempered all with a gentle and often mischievous sense of humour, and a great love of his family, classical music, opera and theatre. His methodical nature was contrasted with his spontaneous wit, and other surprising traits like putting his foot to the floor when driving in his Alfa Romeo, and his almost reckless and frenzied cooking, pan clanging and tomato-sauce flinging when he made his signature dish of veal parmigiana. In his 90s, he became a San Diego Padres fan and lectured on the application of physics to baseball. He also used some inexpensive binder clips and post-it notes placed on the pendulum of his early 19th-century Morbier grandfather clock to synchronise it with atomic time.

Harold was a gem of a man. In keeping with Harold's wishes, his family asks that anyone who wants to honour his memory make a contribution to the Global Union of Scientists for Peace and The Humane Society.

Cynthia Pansing *West Stockbridge, MA.*

CERNCOURIER
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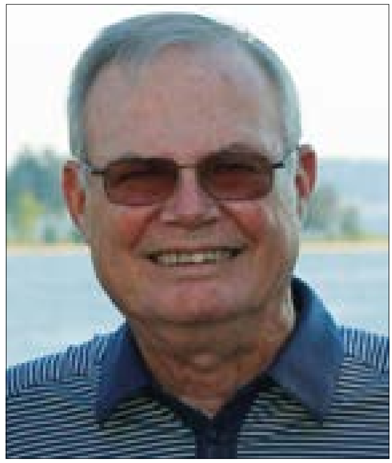
Philip Karl Williams 1939–2021

An exemplary research director

Theorist Philip Karl Williams passed away in the Washington, DC area on 19 January. Born in Tulsa, Oklahoma, he completed a bachelor's degree at Rice University in 1961, a PhD in physics at Indiana University in 1965, and a research associateship at the University of Michigan from 1965 to 1967. Following his postdoctoral training, he moved to Florida State University where he was promoted to associate professor with tenure in 1973. While at Florida, PK, as he was known to friends and colleagues, was best known for his theoretical formulations of pion physics in $\pi\pi$ scattering with absorption, that came to be known as the Williams model.

In 1979 PK chose to enter government service with the Department of Energy (DOE) office of high-energy physics, located near Washington, DC, where he soon became the director of an approximately $100 million university research programme – a position that he held until his retirement in late 2008. In addition to this key managerial role, PK also made significant contributions to other agency activities, which included serving as executive secretary of the high-energy physics advisory panel (HEPAP), executive secretary of the US/Russia joint co-ordinating committee on fundamental properties of matter, executive secretary of the US/Japan committee on high-energy physics, and chair of the scientific assessment group for experiments in non-accelerator physics. In well-deserved recognition of his many contributions, in 2003 PK was elected as a fellow of the American Physical Society.


P Williams

Williams was respected for his faithful stewardship of the DOE university research programme.

At the DOE, he served as mentor to newer programme managers, clarifying how the programme was envisioned and the considerations for funding. He cared deeply about the university researchers funded via the programme and was always ready to discuss their needs for carrying out their research.

However, for many of us, PK will be long remembered and respected for his faithful stewardship of the DOE university research programme in high-energy physics, and for his yearly site visits throughout the community to keep abreast of activities and to meet young postdocs and students. Through good times and bad, he was always helpful and supportive. We fondly remember his visit to CERN where he met many US physicists and encouraged them to work hard and not get discouraged by being in big collaborations. We will miss him greatly.

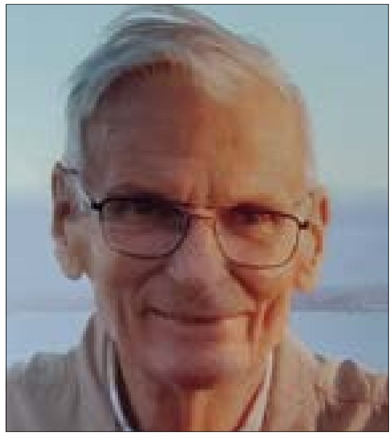
Vasken *and* **Sharon Hagopian** *Florida State University,* **Randy Ruchti** *Notre Dame University and* **Kathleen Turner** *US DOE.*

Roland Windmolders 1940–2020

A great collaborator

Roland Windmolders died suddenly on 27 November 2020 in Prévessin, France. Of Belgian nationality, Roland completed his university education at the University of Louvain, first in civil engineering and then in mathematics and physics. Aged 27 he defended his PhD in particle physics at Louvain with the highest distinction. At the end of the 1960s, Roland spent a year at Berkeley, after which he became an assistant in the faculty of science at the University of Mons, where he assumed several teaching responsibilities. From 1971 to 1976 his work was connected with the Mirabelle bubble chamber and studies of kaon–proton and antiproton–proton interactions, working with physics communities across the world.

In 1975 Roland married Magdeleine. For about 10 years they lived in Belgium and then moved to Prévessin, to be closer to CERN, as Roland became more and more involved in CERN's experiments, while still affiliated to the University of Mons. He joined the European Muon Collaboration (EMC), eventually becoming its longest-serving member. The EMC was a collaboration of more than 100 physicists – which was considered large in the 1980s – formed to study the nucleon and nuclei parton structure. Roland brought with him wide experience and knowledge of high-energy interactions, acquired from bubble-chamber experiments. He once said with great satisfaction: "In this subject, you can precisely calculate everything." The EMC made several fundamental discoveries, such as the "EMC effect" and the proton spin puzzle. Roland continued to work on muon physics within the New Muon Collaboration, the Spin Muon Collaboration and then COMPASS, which is still running. He continued to work with COMPASS until his retirement in 2018, and kept in contact with the collaboration thereafter.


CERN

Roland Windmolders was a true "enlightenment" man.

Roland was a true scientist and a great collaborator: his contribution to deep-inelastic physics experiments cannot be overstated. His profound understanding of all details of deep inelastic scattering experiments and data analysis consistently allowed him to find new solutions to physics problems. Calm, friendly and shy, Roland attracted discussions and debates at all moments, coffee breaks in particular. He never applied for or agreed to take on any high-level positions; his leading role in physics was, in spite of that, never questioned. His style was to work quietly in the background without fuss.

Roland was a thorough gentleman who got things done. He was always willing to help and to advise others, and his help was often sought. He was a true "enlightenment" man: cultivated and sophisticated in the arts, literature and history, which he systematically explored during his many travels. In particular, he had an intimate knowledge of CERN's surrounding region, which he was always willing to share with his colleagues to help them appreciate the beauties of the region. He will be dearly missed.

His colleagues and friends.

BACKGROUND

Notes and observations from the high-energy physics community

Wu honoured by US postal service

USPS

Chien-Shiung Wu adorns a new commemorative US Postal Service stamp, becoming the first Chinese American physicist, and third female physicist (the others being Maria Goeppert Mayer and Sally Ride), to receive the honour. Wu, who passed away in 1997 aged 84, worked for the Manhattan Project before joining Columbia University, where she made groundbreaking studies of beta decay. Her most definitive achievement was her 1956 experiment with ^{60}Co nuclei, which showed that parity is violated by the weak interaction. The discovery resulted in the award of the 1957 Nobel Prize in Physics to theorists Lee and Yang, but the prize committee did not acknowledge Wu's work.

From the archive: June 1981

Beyond the Standard Model

CERN 380.12.86

A module of the detector to be used in the Mont Blanc tunnel.

Following the success of the unification of electromagnetic and weak forces, theorists have proposed a unification of the electroweak and strong forces. This [Grand Unification] theory predicts the unstable proton. Current thinking gives protons a lifetime of around 10^{31} years. Such rare decays – about one per hundred kilograms of matter per century – require large, "passive" detectors, situated deep underground to screen off stray cosmic muons and neutrinos.

In the US, Irvine/Michigan/Brookhaven and Harvard/Purdue/Wisconsin groups are assembling detectors, while in Europe an experiment is being prepared by a CERN/Frascati/Milan/Torino collaboration for installation in the Mont Blanc tunnel.

The Italian Government has approved a project to be built as an international laboratory under the Gran Sasso mountain some 150 km from Rome, capable of housing 10,000 ton detectors.

In Japan, a Tokyo/KEK/Tsukuba project, with a 1000 ton detector 1000 m below ground, is expected to be operational by April 1982.

● Based on text from pp195–196 of *CERN Courier* June 1981.

Compiler's note

None of these mammoths, nor any of their successors to date, have observed proton decay, and the inferred half-life is now at least 10^{34} years. With the age of the universe estimated at some 1.4×10^{10} years, maybe protons are forever. But, large detectors deep underground, water or ice are good at registering naturally occurring exotic events, and their discovery of trans-flavour neutrinos has exposed another lacuna in the Standard Model (SM). Identity oscillations among the three neutrino types can only occur if they have mass, but the SM Higgs field does not naturally provide mass for neutrinos. And solving this mystery may also solve another, the lack of antimatter in the universe.

Th Swapland

VOL.1 ... No.1 APRIL 1, 2021 ZERO DOLLARS

R$_K$ opens; All eyes on g−2 IPA next week

SN/ES 73.2 +4σ | KOTO 2.1 × 10^{-9} <2σ | EDGES 0.52 −2σ | LHCb 0.846 −3σ

Archaeologists Unearth & Translate Ancient Codes

Opinions & Local News

Making a splash

On 1 April, particle physicists at Harvard took a sideways glance at the field by publishing "The arXiv digest you wish you had every day" (arXiv:2103.17198). Leading with a finance-themed take on the R_K and muon g–2 updates, the fake journal carries classified ads for a box of dark-matter models ("FREE!! Accidentally acquired too many of them. Fair condition, may require some tuning…"), supersymmetry ("Beautiful and mint condition, but we just never got the chance to use it… No strings attached…"), along with career opportunities for a data scientist ("Sell your soul, but not completely…") and a wordsmith "to help us GAUGE: Generate Acronyms for Upcoming Galaxy-probing Experiments", ending with a crossword to rival even that of this magazine.

Media corner

"I believe we should commit to a CERN for AI, and locate it in the most competitive AI region of Europe."

Jörgen Warborn, an MEP with the European People's Party, quoted in *Science|Business* (25 March).

"We were actually shaking when we first looked at the results, we were that excited."

LHCb researcher **Mitesh Patel** speaking to *BBC News* about the latest measurement of R_K (23 March).

"It's all about physics and most physical laws are not that difficult – the trick is to make them work for you and not against you."

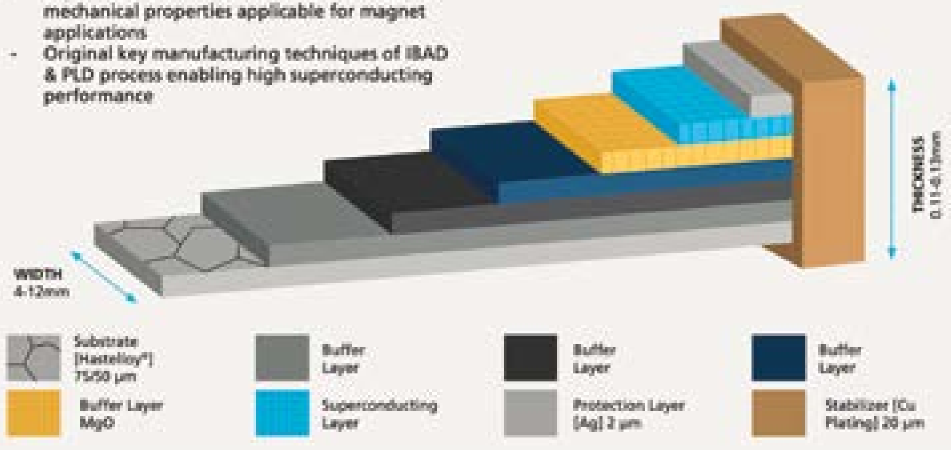
Peter Berdowski, CEO of Boskalis, the company in charge of moving the Ever Given container ship in the Suez Canal, quoted in *France 24* (30 March).

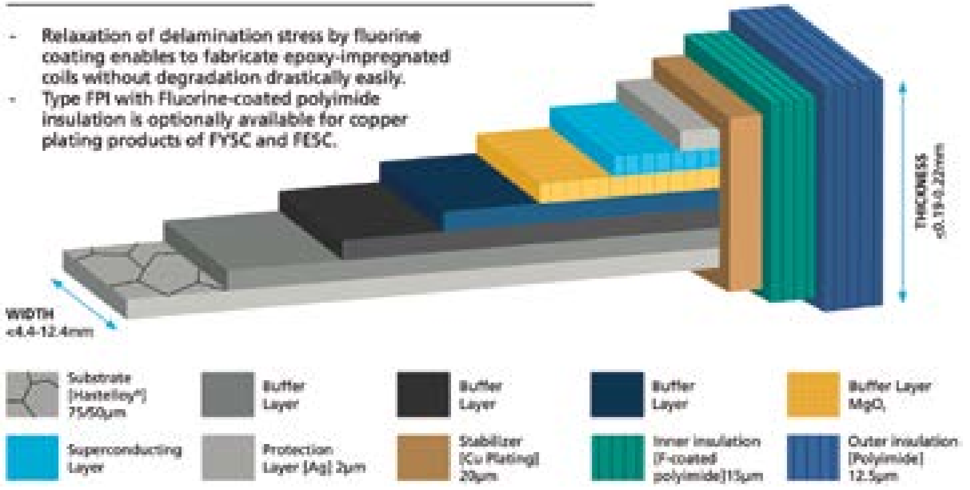
"So, when you see someone bemoaning the woes of fundamental physics, take them seriously – but don't let it get you down. Just find a good article on condensed-matter physics and read that."

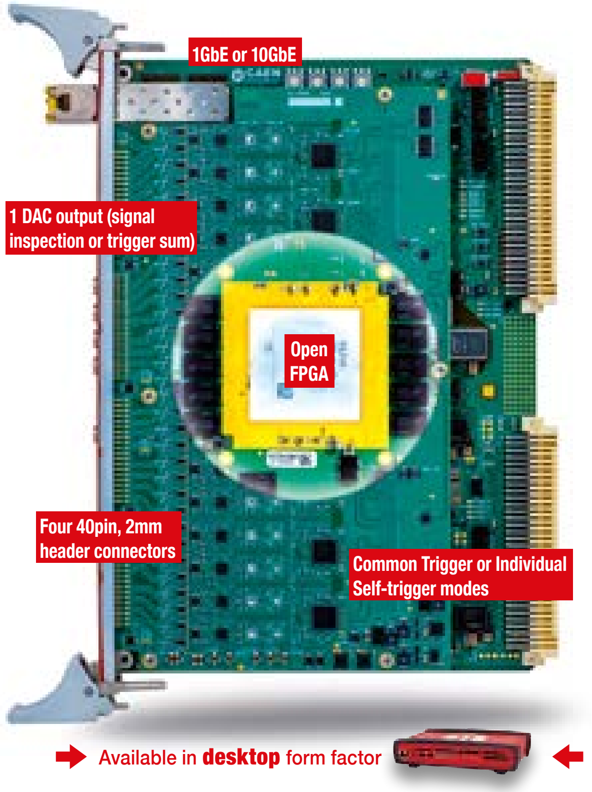
Mathematical physicist **John Baez** writing in *Nautilus* (24 February) about "the joy of condensed matter".

"The countries and regions that invested in fundamental research and technology are the ones that are now global powers."

ALPHA-collaboration member **Muhammad Sameed** speaking to *The Express Tribune* (4 April) about CERN and laser-cooled antihydrogen.



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1 DAC output (signal inspection or trigger sum)
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Common Trigger or Individual Self-trigger modes
Available in **desktop** form factor