WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the July/August 2020 issue of *CERN Courier*.

From giant detectors at the receiving end of artificial neutrino beams to vast sub-ice or subsea arrays and smaller setups investigating whether neutrinos are Majorana particles, neutrino experiments span an enormous range of types, scales and locations. Today, as explored in this issue, a new generation of reactor and accelerator experiments – including DUNE in the US, Hyper-Kamiokande in Japan and JUNO in China – are gearing up to complete the measurements of neutrino-oscillation parameters and establish the neutrino mass ordering. Meanwhile, a series of shorter baseline experiments are scrutinising the three-neutrino paradigm.

Coordinated global action has seen Europe, via the CERN neutrino platform, participate in the long-baseline neutrino programmes in Japan and the US. This has proved a major success. The 2020 update of the European strategy for particle physics, released on 19 June, recommends that the neutrino platform receives continued support. Its highest priority recommendations are to pursue an electron–positron Higgs factory to follow the LHC, and that Europe explores the feasibility of a future energy-frontier hadron collider with a Higgs factory as a possible first stage. These are exciting times, and this month's Viewpoint also calls on particle physicists to highlight the broader socioeconomic impact of our field.

Elsewhere in this issue: a global network of ultra-sensitive magnetometers called GNOME homes in on exotic fields; neutron facilities prepare to study the structure of SARS-CoV-2; graphene-based Hall probes trialled at CERN; reports on the virtual IPAC and LHCP events; CLOUD experiment breaks new ground in atmospheric science; and much more.

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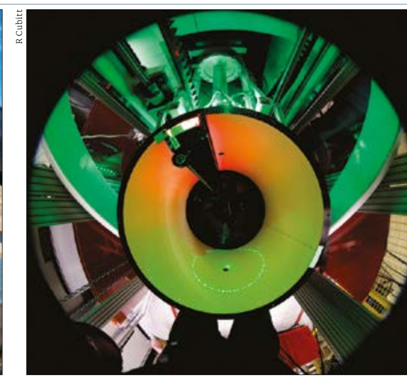
IN THIS ISSUE

VOLUME 60 NUMBER 4 JULY/AUGUST 2020


J Goodman

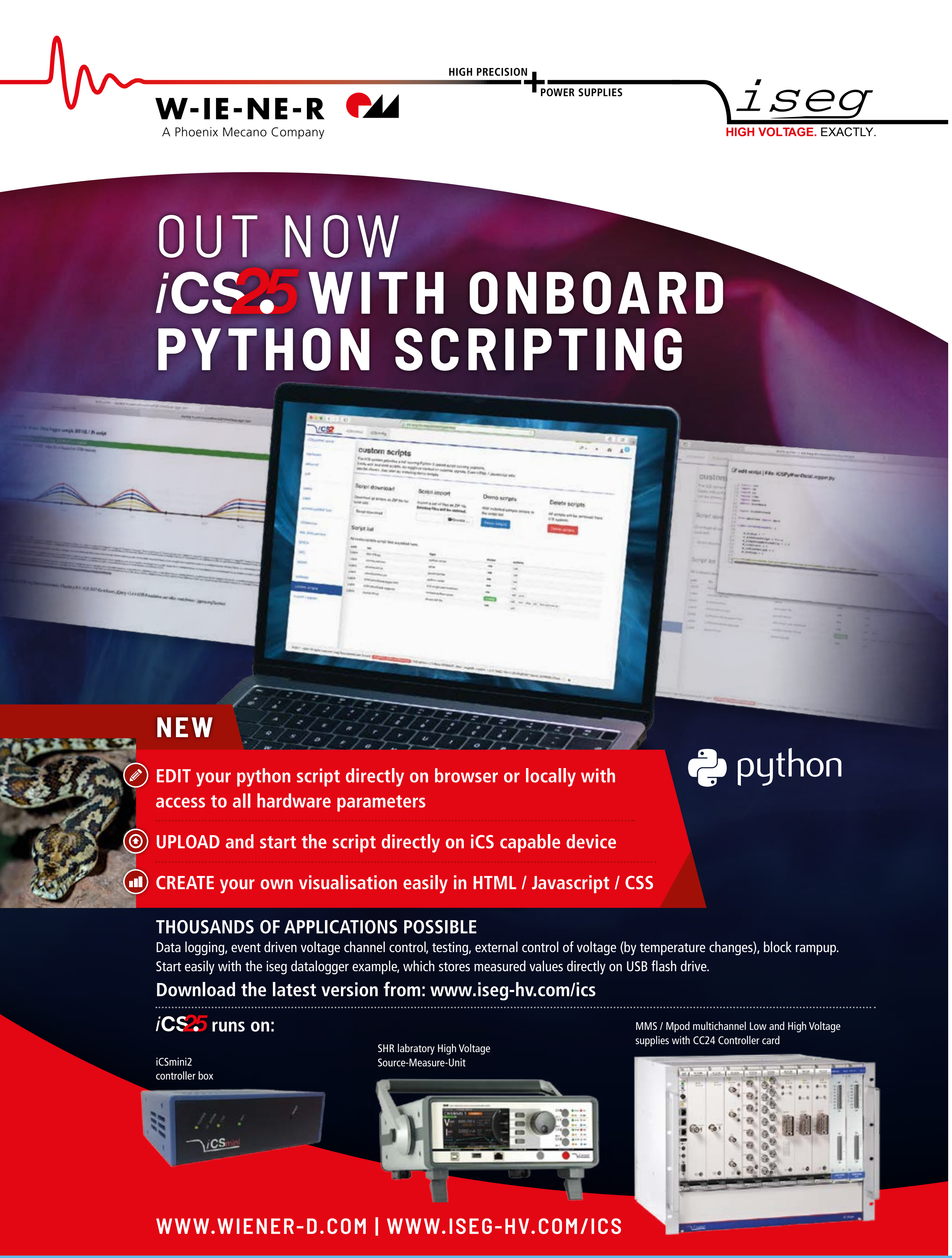
HAWC eye *Gamma-ray observations are being pushed above 100 TeV.* **12**


R Cubitt

I spy *Neutron diffraction offers unique advantages for studying SARS-CoV-2.* **43**


M Brice/CERN-PHOTO-200906-179-2

Hold on tight *How fundamental research drives socioeconomic progress.* **47**



FROM THE EDITOR

A neutrino success story

Matthew Chalmers
Editor

In the 64 years since the direct discovery of the neutrino from a reactor source, experiments with reactor, solar, accelerator, atmospheric, cosmic and geological neutrinos have taken physicists ever closer to this most ethereal of Standard Model particles. The revelation that neutrinos have mass, confirmed in the 1990s via the discovery of neutrino oscillations, also launched promising theoretical speculations on the existence of particles beyond the Standard Model.

Today, as our cover feature explores, a new generation of reactor and accelerator experiments are gearing up to complete the measurements of oscillation parameters (p32). A priority is the complex phase of the mixing matrix, which encodes potential leptonic CP violation (p40) and for which the T2K experiment in Japan recently published hints (p8), while another target is the neutrino mass ordering. Three upcoming mega-projects – DUNE in the US, Hyper-Kamiokande in Japan and JUNO in China – have these enigmas firmly in their sights. Meanwhile, a series of shorter-baseline experiments are to scrutinise the three-neutrino paradigm.

From giant detectors at the receiving end of artificial neutrino beams to vast sub-ice or subsea arrays and smaller setups investigating whether neutrinos are Majorana particles, neutrino experiments span an enormous range of types, scales and locations. Their latest results will be showcased at Neutrino2020, which was getting under way in a fully virtual format as the *Courier* went to press.

It would be difficult to design two long-baseline accelerator-neutrino experiments more different than Hyper-Kamiokande and DUNE

Coordinated action

Following the recommendations of the 2013 update of the European strategy for particle physics, Europe chose to participate in the long-baseline neutrino programmes in Japan and the US rather than pursue its own facility, instead building reciprocal support for the HL-LHC. This coordinated action, via the CERN neutrino platform, has proved a major success. It has provided a large-scale demonstration of DUNE's kiloton-scale liquid-argon time-projection chambers and the refurbishment of ICARUS for use in the Fermilab short-baseline programme, and has seen the development of the BabyMIND magnetic spectrometer and contributions to T2K's near-detector ND280 and its upgrade. ND280, which was built inside the magnet from the UA1 experiment in a collaboration with CERN dating from much earlier, is vital for reducing neutrino-interaction systematics, while the NA61 experiment at CERN is helping to improve neutrino-flux predictions. A strong need exists for further such experiments if maximal physics is to be extracted from DUNE and Hyper-Kamiokande.


M Brice/CERN

Neutrino platform *ProtoDUNE modules in CERN's EHN1 hall.*

The recent go-ahead for Hyper-Kamiokande in Japan, along with the continuing uncertainty over the International Linear Collider sited there, have slightly obscured the neat global vision of particle physicists back in 2013 of a world with an intensity frontier in the US, a precision frontier in Japan, and an energy frontier in Europe. But it would be difficult to design two long-baseline accelerator-neutrino experiments more different than Hyper-Kamiokande and DUNE, and that brings richer physics opportunities. The 2020 update of the European strategy for particle physics, which was released just as the *Courier* went to press (p7), envisions Europe retaining its leadership at the energy frontier and identifies an electron–positron Higgs factory as the highest priority next collider, whether in Europe or Asia. Appropriately, it recommends that Europe, and CERN through the neutrino platform, should continue to support neutrino projects in Japan and the US for the benefit of the worldwide neutrino community.

Reporting on international high-energy physics

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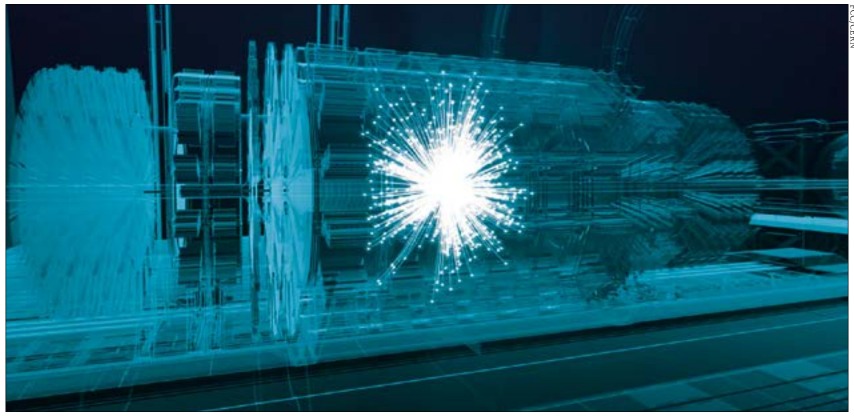
NEWS ANALYSIS

Policy

European strategy update released

The discovery of the Higgs boson by the ATLAS and CMS collaborations at the LHC in 2012 marked a turning point in particle physics. Not only was it the last of the Standard Model particles to be found, but it is completely different to any particle seen before: a fundamental scalar, with profound connections to the structure of the vacuum. Extensive measurements so far suggest that the particle is the simplest possible version that nature permits. But the study of the Higgs boson is still in its infancy and its properties present enigmas, including why it is so light, which the Standard Model cannot explain. Particle physics is entering a new era of exploration to address these and other outstanding questions, including unknowns in the universe at large, such as the nature of dark matter.



Outlining the future *An artist's impression of a particle collision taking place at a future circular collider, which is one of the highest priority recommendations of the ESPPU.*

The 2020 update of the European strategy for particle physics (ESPPU), which was released on 19 June during the 199th session of the CERN Council, sets out an ambitious programme to carry the field deep into the 21st century. Following two years of discussion and consultation with particle physicists in Europe and beyond, the ESPPU has identified an electron–positron Higgs factory as the highest priority collider after the LHC. The ultra-clean collision environment of such a machine (which could start operation at CERN within a timescale of less than 10 years after the full exploitation of the high-luminosity LHC in the late 2030s) will enable dramatic progress in mapping the diverse interactions between the Higgs boson and other particles, and form an essential part of a research programme that includes exploration of the flavour puzzle and the neutrino sector.

Unprecedented scales

To prepare for the longer term, the ESPPU prioritises that Europe, together with its international partners, explore the technical and financial feasibility of a future proton–proton collider at CERN with a centre-of-mass energy of at least 100 TeV. In addition to allowing searches for new phenomena at unprecedented scales, this machine would enable the detailed study of how the Higgs boson interacts with itself – offering a deeper understanding of the electroweak phase transition in the early universe, after which the vacuum gained a non-zero expectation value and particles were able to acquire mass.

We have started to concretely shape CERN's future after the LHC

"We have started to concretely shape CERN's future after the LHC, which is a difficult task because of the different paths available," said Ursula Bassler, president of the CERN Council.

The strategy update is the second since the process was launched in 2005, serving as a guideline to CERN and enabling a coherent science policy in Europe. Building on the previous strategy update in 2013, the 2020 update states that the successful completion of the high-luminosity LHC should remain the focal point of European particle physics, together with continued innovation in experimental techniques. Europe, via the CERN neutrino platform, should also continue to support the Long Baseline Neutrino Facility in the US and neutrino projects in Japan. Diverse projects that are complementary to collider experiments are an essential pillar of the ESPPU recommendations, which urge European laboratories to support experiments enabling, for example, precise investigations of flavour physics and electric or magnetic dipole moments, and searches for axions, dark-sector candidates and feebly interacting particles.

Cooperative programmes between CERN and research centres and national institutes in Europe should be strengthened and expanded, in addition to building strong collaborations with the astroparticle and nuclear physics communities.

Exploring the next frontier

The 2013 ESPPU recommended that options for CERN's next machine after the LHC be explored. Today, there are four possible options for a Higgs factory in different regions of the world: an International Linear Collider (ILC) in Japan, a Compact Linear Collider (CLIC) at CERN, a Future Circular Collider (FCC-ee) at CERN and a Circular Electron Positron Collider in China. As Higgs factories, the ESPPU finds all four to have comparable reach, albeit with different time schedules and with differing potentials for the study of physics topics at other energies. While not specifying which facility should be built, the ESPPU states that the large circular tunnel necessary for a future hadron collider at CERN would also provide the infrastructure needed for FCC-ee as a possible first step. In addition to serving as a Higgs factory, FCC-ee is able to provide huge numbers of weak vector bosons and their decay products that would enable precision tests of electroweak physics and the investigation of the flavour puzzle.

Considering colliders at the energy frontier, a 3 TeV CLIC and a 100 TeV ▷

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circular hadron collider (FCC-hh) were explored in depth. While the proposed 380 GeV CLIC also offers a Higgs factory as a first stage, the dramatic increase in energy possible with a future hadron collider compared to the LHC has led the ESPPU to consider this technology as the most promising for a future energy-frontier facility. A feasibility study into building such a machine at CERN with FCC-ee as a possible first stage is to be established as a global endeavour and completed on the timescale of the next strategy update later this decade. It is also expected that Europe invests further in R&D for the high-field superconducting magnets for FCC-hh while retaining a programme in the advanced accelerator technology developed for CLIC, which also has significant potential applications beyond high-energy physics.

The report notes that the timely realisation of the ILC in Japan would be compatible with this strategy and, in that case, European particle physicists would wish to collaborate. "The natural next step is to explore the feasibility of the highest priority recommendations, while continuing to pursue a diverse programme of high-impact projects," explains Halina Abramowicz, chair of the European Strategy Group, which was charged with organising the 2020 update. "Europe should keep the door open to participate in other headline projects which will serve the field as a whole."

Ramping up accelerator R&D

To achieve the ambitious ESPPU goals, particle physicists are urged to undertake vigorous R&D on advanced accelerator technologies, which also drive many other fields of science, industry and society, notes the report. Europe should develop a technology roadmap, taking into account synergies with international partners and other communities such as photon and neutron science, fusion energy and industry. In addition to high-field magnets, the roadmap should include R&D for plasma-acceleration schemes, an international design study for a muon collider, and R&D on energy-recovery linacs.

The ESPPU recommendations strongly emphasise the need to continue with efforts to minimise the environmental impact of accelerator facilities and maximise the energy efficiency of future projects. Europe should also continue to vigorously support theoretical research covering the full spectrum of particle physics, pursuing new research directions and links with cosmology, astroparticle physics and nuclear physics. The development of software and computing infrastructures that exploit recent advances in information technology and data science are also to be pursued in collaboration with other fields of science and industry, while particle physicists should forge stronger relations with the European Commission and continue their leadership in promoting open science.

Europe should keep the door open to participate in other headline projects

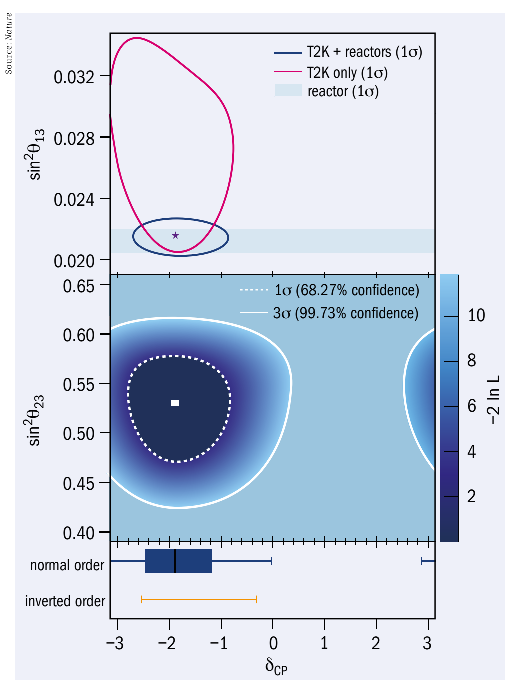
"It is an historic day for CERN and for particle physics in Europe and beyond. We are all very excited and we are ready to work on the implementation of this very ambitious but cautious plan," said CERN Director-General Fabiola Gianotti following the unanimous adoption of the resolution to update the strategy by the CERN Council's national representatives. "We will continue to invest in strong cooperative programmes between CERN and other research institutes in CERN's member states and beyond. These collaborations are key to sustained scientific and technological progress, and bring many societal benefits."

Neutrinos

Neutrino oscillations constrain leptonic CP violation

In April, the T2K (Tokai to Kamioka) collaboration in Japan reported the strongest hint so far that charge-parity (CP) symmetry is violated by the weak interactions of leptons. Based on an analysis of nine years of neutrino-oscillation data, the T2K results exclude a substantial parameter space for δ_{CP}, the phase thought to govern leptonic CP violation, at 3σ confidence. While further data are required to confirm the findings, the result strengthens previous observations and offers hope for a future discovery of leptonic CP violation at next-generation long-baseline neutrino-oscillation experiments due to come online this decade (see p32).

Discovered in 1964, CP violation has so far only been observed in the weak interactions of quarks, mostly recently in the charm system by the LHCb collaboration. Since the size of the effect in quarks is too small to explain the observed matter-antimatter disparity in the universe, finding additional sources of CP violation is one of the outstanding mysteries in particle physics. The quantum mixing of neutrino flavours as neutrinos travel over large distances provides a way to probe another potential source of CP



Statistical strike *After applying external reactor-neutrino constraints (top), T2K has achieved the first closed 3σ confidence interval on δ_{CP} (middle). In the bottom panel, 1σ (box and line) and 3σ (error bar) confidence intervals for δ_{CP} are plotted for the two possible neutrino mass orderings.*

violation: a complex phase, δ_{CP}, in the neutrino mixing matrix (see p40). Though models indicate that no value of δ_{CP} could explain the cosmological matter-antimatter asymmetry without new physics, the observation of leptonic CP violation would make models such as leptogenesis, which feature heavy Majorana partners for the Standard Model neutrinos, more plausible.

The T2K experiment uses the Super Kamiokande detector to observe neutrinos and antineutrinos generated by a proton beam at the J-PARC accelerator facility 295 km away. As the beam travels through Earth, a fraction of muon neutrinos oscillate into electron neutrinos that are recorded via nuclear-recoil interactions in Super Kamiokande's 50,000 tonne tank of ultrapure water, where the charged lepton generated by the weak interaction creates a ▷

Cherenkov ring that can be distinguished as being created by an electron or muon. By changing the polarity of J-PARC's magnetic focusing horn, this oscillation can be compared to its CP-mirror process. Since the beam-line and detector components are made out of matter and not antimatter, the observation of neutrinos is enhanced compared to antineutrinos.

The δ_{CP} parameter is a cyclic phase: if $\delta_{CP} = 0$ or $\pm\pi$, then neutrinos and antineutrinos change from muon to electron types in the same way during oscillation; any other value would enhance the oscillations of either neutrinos or antineutrinos, violating CP symmetry. Analysing data with 1.49×10^{21} and 1.64×10^{21} protons on target in neutrino- and antineutrino-beam mode, respectively, T2K observed 90 electron-neutrino candidates and 15 electron-antineutrino candidates. This may be compared with the 56 and 22 events expected for maximal electron-antineutrino enhancement ($\delta_{CP} = +\pi/2$), and the 82 and 17 events expected for maximal electron-neutrino enhancement ($\delta_{CP} = -\pi/2$). Being most compatible with the latter scenario, the T2K data disfavour almost half of the possible values of δ_{CP} – including $\delta_{CP} = 0$, when averaged over other oscillation parameters – at 3σ confidence. For the statistically favoured "normal" neutrino-mass ordering, the measured 3σ confidence-level interval for δ_{CP} is [−3.41, −0.03], while for the "inverted" mass ordering (in which the first mass splitting is greater than the second) it is [−2.54, −0.32], with no parameter space inside the 1σ bound (see figure).

"Our results show the strongest constraint yet on the parameter governing CP violation in neutrino oscillations, one of the few parameters governing fundamental particle interactions that has not yet been precisely measured," says T2K international co-spokesperson Federico Sanchez of the University of Geneva. "These results indicate that CP violation in neutrino mixing may be large, and T2K looks forward to continued operation with the prospect of establishing evidence for CP violation in neutrino oscillations."

Finding additional sources of CP violation is one of the outstanding mysteries in particle physics

To further improve the experimental sensitivity to a potential CP-violating effect, the collaboration plans to upgrade the ND280 near detector to reduce systematic uncertainties and to accumulate more data, while J-PARC will increase the beam intensity by upgrading its accelerator and beam line. Future neutrino CP violation measurements at DUNE and Hyper-Kamiokande are expected to determine the exact degree of CP violation in the neutrino system.

Further reading

T2K Collaboration 2020 *Nature* **580** 339.

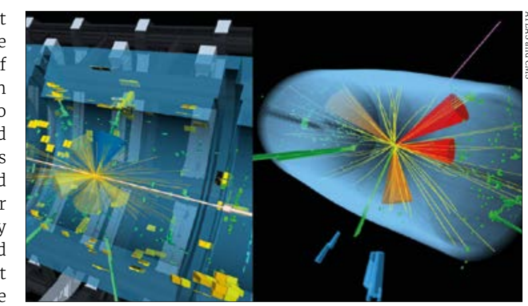
Higgs physics

First foray into CP symmetry of top-Higgs interactions

One of the many doors to new physics that has been opened by the discovery of the Higgs boson concerns the possibility of finding charge-parity violation (CPV) in Higgs-boson interactions. Were CPV to be observed in the Higgs sector, it would be an unambiguous indication of physics beyond the Standard Model (SM), and could have important ramifications for understanding the baryon asymmetry of the universe. Recently, the ATLAS and CMS collaborations reported their first forays into this area by measuring the CP structure of interactions between the Higgs boson and top quarks.

While CPV is well established in the weak interactions of quarks, and is explained in the SM by the existence of a phase in the CKM matrix, the amount of CPV observed is many orders of magnitude too small to account for the observed cosmological matter-antimatter imbalance. Searching for additional sources of CPV is a major programme in particle physics, with a moderate-significance hint among lepton interactions recently announced by the T2K collaboration (see story above). It is likely that sources of CPV from phenomena beyond the scope of the SM are needed, and the detailed properties of the Higgs sector are one of several possible hiding places.

Based on the full LHC Run-2 dataset, ATLAS and CMS studied events where the Higgs boson is produced in association with one or two top quarks before decaying into two photons. The latter (ttH) process, which accounts for around 1% of the Higgs bosons produced at the LHC, was observed by both collaborations in 2018. But the tH production channel is predicted to be about six times rarer. This is due to destructive interference between higher order diagrams involving W bosons, and makes the tH process particularly sensitive to new-physics processes.



Seeking asymmetry *Higgs-top interactions recorded by the ATLAS and CMS detectors.*

According to the SM, the Higgs boson is "CP even" – that is, it is possible to rotate-away any CP-odd phase from the scalar mass term. Previous probes of the interaction between the Higgs and vector bosons by CMS and ATLAS support the CP-even nature of the Higgs boson, determining its quantum numbers to be most consistent with $J^{PC} = 0^{++}$, though small CP-odd contributions from a more complex coupling structure are not excluded. The presence of a CP-odd component, together with the dominant CP-even one, would imply CPV, altering the kinematic properties of the ttH process and modifying tH production. Exploring the CP properties of these interactions is non-trivial, and requires the full capacities of the detectors and analysis techniques.

The collaborations employed machine-learning algorithms to disentangle the relative fractions of the CP-even and CP-odd components of top-Higgs interactions. The CMS collaboration observed ttH production at a significance of 6.6σ, and excluded a pure CP-odd structure of the top-Higgs Yukawa coupling at 3.2σ. The ratio of the measured ttH production rate to the predicted production rate was found by CMS to be 1.38 with an uncertainty of about 25%. ATLAS data also show agreement with the SM. Assuming a CP-even coupling, ATLAS observed ttH with a significance of 5.2σ. Comparing the strength of the CP-even and CP-odd components, the collaboration favours a CP-mixing angle very close to 0 (indicating no CPV) and excludes a pure CP-odd coupling at 3.9σ. ATLAS did not observe tH production, setting an upper limit on its rate of 12 times the SM expectation.

In addition to further probing the CP properties of the top-Higgs interaction with larger data samples, ATLAS and CMS are searching in other Higgs-boson interactions for signs of CPV.

Further reading

ATLAS Collab. 2020 arXiv:2004.04545.
CMS Collab. 2020 arXiv:2003.10866.

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ATMOSPHERIC SCIENCE

CLOUD clarifies cause of urban smog

Urban particle pollution ranks fifth in the risk factors for mortality worldwide, and is a growing problem in many built-up areas. In a result that could help shape policies for reducing such pollution, the CLOUD collaboration at CERN has uncovered a new mechanism that drives winter smog episodes in cities.

Winter urban smog episodes occur when new particles form in polluted air trapped below a temperature inversion: warm air above the inversion inhibits convection, causing pollution to build up near the ground. However, how additional aerosol particles form and grow in this highly polluted air has puzzled researchers because they should be rapidly lost through scavenging by pre-existing aerosol particles. CLOUD, which uses an ultraclean cloud chamber situated in a beamline at CERN's Proton Synchrotron to study the formation of aerosol particles and their effect on clouds and climate, has found that ammonia and nitric acid can provide the answer.

Deriving in cities mainly from vehicle emissions, ammonia and nitric acid were previously thought to play a passive role in particle formation, simply exchanging with ammonium nitrate in the particles. However, the new CLOUD study finds that small inhomogeneities in the concentrations of ammonia and nitric acid can drive the growth rates of newly formed particles up to more than 100 times faster than seen before, but only in short spurts that have previously escaped detection. These ultrafast growth rates are sufficient to rapidly transform the newly formed particles to larger sizes, where they are less prone to being lost through scavenging, leading to a dense smog episode with a high number of particles.

H Cawley

Clearer view *Large-eddy simulations of urban flow patterns depicting pollution inhomogeneities superimposed on a composite London skyline.*

"Although the emission of nitrogen oxides is regulated, ammonia emissions are not and may even be increasing with the latest catalytic converters used in gasoline and diesel vehicles," explains CLOUD spokesperson Jasper Kirkby. "Our study shows that regulating ammonia emissions from vehicles could contribute to reducing urban smog."

• *CLOUD's science is described in depth in our interview with Jasper Kirkby on p48.*

Further reading

CLOUD Collab. 2020 *Nature* **581** 184.

APPLICATIONS

Graphene trialled at CERN for magnetic measurements

First isolated in 2004 by physicists at the University of Manchester using pieces of sticky tape and a graphite block, the one-atom-thick carbon allotrope graphene has been touted as a wonder material on account of its exceptional electrical, thermal and physical properties. Turning these properties into scalable commercial devices has proved challenging, however, which makes a recently agreed collaboration between CERN and UK firm Paragraf on graphene-based Hall-probe sensors especially novel.

With particle accelerators requiring large numbers of normal and superconducting magnets, high-precision and reliable magnetic measurements are essential. While the workhorse for these measurements is the rotating-coil magnetometer with a resolution limit of the order of 10^{-8} Vs, the most important tool for local field mapping is the Hall probe, which passes electrical current proportional to the field strength when the sensor is perpendicular to a magnetic field. However, measurement uncertainties in the 10^{-4} range required for determining field multipoles are difficult to obtain, even with the state-of-the-art devices. False signals caused by non-perpendicular field components in the three-dimensional sensing region of existing Hall probes can increase the measurement uncertainty, requiring complex and time-consuming calibration and processing to separate true signals from systematic errors. With an active sensing component made of atomically thin graphene, which is effectively two-dimensional, a graphene-based Hall probe in principle suffers negligible planar Hall effects and therefore could enable higher precision mapping of local magnetic fields.

Paragraf/CERN

2D sense *Paragraf and CERN scientists setting up the graphene Hall sensor for performance evaluation in the reference dipole magnet of CERN's magnetic measurement section.*

Stephan Russenschuck, head of the magnetic measurement section at CERN, spotted the potential of graphene-based Hall probes when he heard about a talk given by Paragraf – a recent spin-out from the department of materials science at the University of Cambridge – at a magnetic measurement conference in December 2018. This led to a collaboration, formalised between CERN and Paragraf in April, which has seen several graphene sensors installed and tested at CERN during the past year. The firm sought to develop and test the device ahead of a full product launch by the end of this year, and the results so far, based on well-calibrated field measurements in CERN's reference magnets, have been very promising. "The collaboration has proved that the sensor has no planar effect," says Paragraf's Ellie Galanis. "This was a learning step. There is probably no other facility in the world to be able to confirm this, so the project has been a big win on both sides."

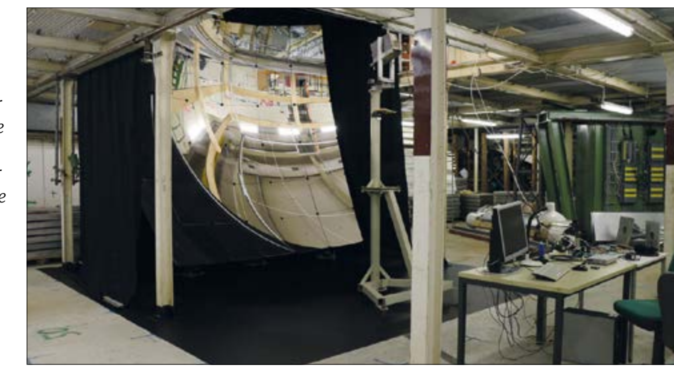
There is probably no other facility in the world to be able to confirm this, so the project has been a big win on both sides

The graphene Hall sensor also operates over a wide temperature range, down to liquid-helium temperatures at which superconducting magnets in the LHC operate. "How these sensors behave at cryogenic temperatures is very interesting," says Russenschuck. "Usually the operation of Hall sensors at cryogenic temperatures requires careful calibration and *in situ* cross-calibration with fluxmetric methods. Moreover, we are now exploring the sensors on a rotating shaft, which could be a breakthrough for extracting local, transversal field harmonics. Graphene sensors could get rid of the spurious modes that come from nonlinearities and planar effects."

CERN and Paragraf, which has patented a scalable process for depositing two-dimensional materials directly onto semiconductor-compatible substrates, plan to release a joint white paper communicating the results so far and detailing the sensor's performance across a range of magnetic fields.

DARK MATTER

Funky physics at KIT



KIT

Dark reflections *The FUNK experimental area, where the black-painted floor can be seen with the photomultiplier tube–camera pillar at the centre and the mirror on the left.*

Using a large spherical mirror as an electromagnetic dark-matter antenna, a novel experiment at Karlsruhe Institute of Technology (KIT) called FUNK – Finding U(1)s of a Novel Kind – has set an improved limit on the existence of hidden photons as candidates for dark matter.

Despite overwhelming astronomical evidence for the existence of dark matter, direct searches for dark-matter particles at colliders and dedicated nuclear-recoil experiments have so far come up empty handed. With these searches being mostly sensitive to heavy dark-matter particles, namely weakly interacting massive particles (WIMPs), the search for alternative light dark-matter candidates is growing in momentum. Hidden photons, a cold, ultralight dark-matter candidate, arise in extensions of the Standard Model that contain a new U(1) gauge symmetry and are expected to couple very weakly to charged particles via kinetic mixing with regular photons. Laboratory experiments that are sensitive to such hidden or dark photons include helioscopes such as the CAST experiment at CERN, and "light-shining-through-a-wall" methods such as the ALPS experiment at DESY.

FUNK exploits a novel "dish antenna" method first proposed in 2012, whereby a hidden photon crossing a metallic spherical mirror surface would cause faint electromagnetic waves to be emitted almost perpendicularly to the mirror surface, and be focused on the radius point. The experiment was conceived in 2013 at a workshop at DESY when it was realised that there was a perfectly suited mirror – a prototype for the Pierre Auger Observatory with a surface area of 14 m² – in the basement of KIT. Various photodetectors placed at the radius point allow FUNK to search for a signal in different wavelength ranges, corresponding to different hidden-photon masses. The dark-matter nature of a possible signal can then be verified by observing small daily and seasonal movements of the spot around the radius point as Earth moves through the dark-matter field. The broadband dish-antenna technique is able to scan hidden photons over a large parameter space.

The mass range of viable hidden-photon dark matter is huge

Completed in 2018, the experiment took data during last year in several month-long runs using low-noise photomultiplier tubes. In the mass range 2.5–7 eV, the data exclude a hidden-photon coupling stronger than 10^{-12} in kinetic mixing. "This is competitive with limits derived from astrophysical results and partially exceeds those from other existing direct-detection experiments," says FUNK principal investigator Ralph Engel of KIT.

So far, two other experiments of this type have reported search results for hidden photons in this energy range – the dish-antenna at the University of Tokyo and the SHUKET experiment at Paris-Saclay – though FUNK's factor-of-10 larger mirror surface brings a greater experimental sensitivity, says the team. Other experiments, such as NA64 at CERN which employs missing-energy techniques, are setting stringent bounds on the strength of dark-photon couplings for masses in the MeV range and above.

"The mass range of viable hidden-photon dark matter is huge," says FUNK collaborator Joerg Jaeckel of Heidelberg University. "For this reason, techniques that can scan over a large parameter space are especially useful, even if they cannot explore couplings as small as is possible with some other dedicated methods. A future exploitation of the setup in other wavelength ranges is possible, and FUNK therefore carries an enormous physics potential."

Further reading

A Andrianavalomahefa *et al.* 2020 arXiv:2003.13144.

D Horns *et al.* 2013 *J. Cosmol. Astropart. Phys.* **1304** 016.

CERNCOURIER
VOLUME 60 NUMBER 4 JULY/AUGUST 2020

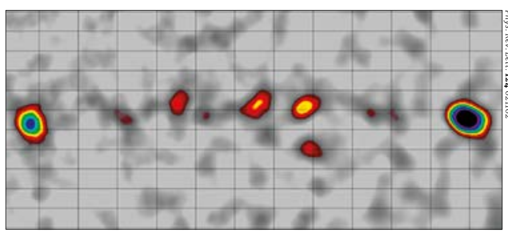
Astrowatch

100 TeV photons test Lorentz invariance

Over the past decades, the photon emission from astronomical objects has been measured across 20 orders of magnitude in energy, from radio up to TeV gamma rays. This has not only led to many astronomical discoveries, but also, thanks to the extreme distances and energies involved, allowed researchers to test some of the fundamental tenets of physics. For example, the 2017 joint measurement of gravitational waves and gamma rays from a binary neutron-star merger made it possible to determine the speed of gravity with a precision of less than 10^{-16} compared to the speed of light. Now, the High-Altitude Water Cherenkov (HAWC) collaboration has pushed the energy of gamma-ray observations into new territory, placing constraints on Lorentz-invariance violation (LIV) that are up to two orders of magnitude tighter than before.

Models incorporating LIV allow for modifications to the standard energy–momentum relationship dictated by special relativity, predicting phenomenological effects such as photon decay and photon splitting. Even if the probability for a photon to decay through such effects is small, the large distances involved in astrophysical measurements in principle allow experiments to detect it. The most striking implication would be the existence of a cutoff in the energy spectrum above which photons would decay while travelling towards Earth. Simply by detecting gamma-ray photons above the expected cutoff would put strong constraints on LIV.

HAWC collab.



Phys. Rev. Lett. 124 021102

High altitude *Several different sources are observed by the HAWC observatory (top) to emit photons at energies exceeding 56 TeV. The bright source on the right of the lower image is the strongest contributor to the LIV limit.*

Expensive and complex

Increasing the energy limit for photons with which we observe the universe is, however, challenging. Since the flux of a typical source, such as a neutron star, decreases rapidly, ever-larger detectors are needed to probe higher energies. Photons with energies of hundreds of GeV can still be directly detected using satellite-based detectors equipped with tracking and calorimetry. However, these instruments, such as the US–European Fermi-LAT detector and the Chinese–European DAMPE detector, require a mass of several tonnes, making launching them expensive and complex. To get to even higher energies, ground-based detectors, which detect gamma rays through the showers they induce in Earth's atmosphere, are more popular. But their indirect detection and the large background coming from cosmic rays make such measurements difficult.

Recently, significant improvements have been made in ground-based detector technology and data analysis. The Japanese–Chinese Tibet air shower gamma-ray experiment ASγ, a Cherenkov-based detector array built at an altitude of 4 km in Yangbajing, added underground muon detectors to allow hadronic air showers to be differentiated from photon-induced ones via the difference in muon content, and improved data-analysis techniques to more accurately remove the isotropic all-sky background. In 2019, this enabled the ASγ team to observe a source at energies above 100 TeV for the first time. This measurement was soon followed by measurements of nine different sources above 56 TeV by the HAWC observatory located at 4 km altitude in the mountains near Puebla, Mexico. These new measurements of astrophysical sources, which are likely all pulsars, could not only lead to an answer of the question as to where the highest energy (PeV and above) cosmic rays are produced, but could also allow new constraints to be placed on LIV. The spectra of four sources studied by the collaboration did not show any signs of a cutoff, allowing HAWC to exclude the LIV energy scale to 2.2×10^{31} eV – an improvement of one-to-two orders of magnitude over previous limits.

Pushing the limits

It is likely that LIV will be further constrained in the near future, as a range of new high-energy gamma-ray detectors are developed. Perhaps the most powerful of these is the Large High Altitude Air Shower Observatory (LHAASO) located in the mountains of the Sichuan province of China, the first stage of which commenced data-taking in 2018. Once finished, LHAASO will be close to two orders of magnitude more sensitive than HAWC at 100 TeV and capable of pushing the photon energy into the PeV range. Additionally, the limit of direct-detection measurements will be pushed beyond that from Fermi-LAT and DAMPE by the Chinese European High Energy cosmic Radiation Detector (HERD), a 1.8 tonne calorimeter surrounded by a tracker scheduled for launch in 2025, which is foreseen to be able to directly detect photons up to 100 TeV.

Further reading

HAWC Collab. 2020 *Phys. Rev. Lett.* **124** 021102.
HAWC Collab. 2020 *Phys. Rev. Lett.* **124** 131101.
Tibet ASγ Collab. 2019 *Phys. Rev. Lett.* **123** 051101.

NEWS DIGEST

M Brice/CERN-PHOTO-201911-394-28

Mark Bissell (University of Manchester) inspects the CRIS setup at CERN.

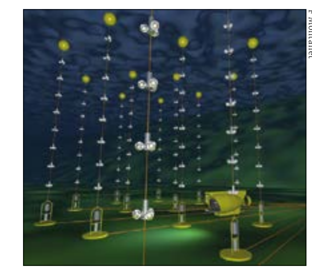
Radioactive spectroscopy
A team at CERN's ISOLDE facility has staked a claim to the first laser-spectroscopy measurements of a short-lived radioactive molecule, opening new opportunities to test physics beyond the Standard Model (BSM). A Proton Synchrotron Booster beam collided with a uranium-carbide target to produce radioactive radium isotopes that formed radioactive radium-monofluoride (RaF) ions in a fluoride-rich gas surrounding the target. By using ISOLDE's collinear resonance ionisation spectroscopy (CRIS) setup, the team was able to identify the low-lying energy levels of RaF and demonstrate that it can be laser cooled for future precision studies, as implied by theoretical calculations. Radioactive molecules promise high sensitivity to BSM physics as certain isotopes exhibit deformations such as nuclear pear shapes, which should amplify non-standard effects (*Nature* **581** 396).

Anyon statistics observed
In 3D space, the many-body wave function accumulates a phase 0 or π when two particles are exchanged, the basis of a fundamental classification of particles as bosons or fermions. In 1982 Frank Wilczek showed that in two dimensions other phases can be realised too, defining types of elementary excitations that lie somewhere between the boson and fermion extremes. Scientists in Paris have now detected denizens of this third kingdom of particles for the first time (*Science* **368** 173). The team used the quantum Hall effect to build an anyon collider in a 2D electron gas, and observed correlations corresponding to "fractional" statistics with a phase of $\pi/3$. Anyons are the most recent of a growing list of fundamental ideas observed first as an emergent phenomenon in a condensed-matter system.

Thoroughly modern Millikan
A dark sector could be introduced into the Standard Model via a new gauge field, the dark photon, which can transform back and forth into ordinary photons. Should the dark photon be massless, dark-sector particles that couple to it should also have small effective electric charges. In 2017 a prototype scintillator-bar array called the milliQan demonstrator was installed 33 m from the interaction point of the CMS experiment at the LHC, to fill a high-mass gap in searches for such particles. The team has now reported a first search using the prototype. The results match the ArgoNeuT collaboration's leading exclusion of new particles with a charge of more than about 0.1e and a mass of a few GeV (arXiv:2005.06518), and the team is now pursuing an optimised detector with 100 times the mass.

Pionic helium sighted in Villigen
Researchers have used an intense pion beam at the Paul Scherrer Institute in Villigen, Switzerland, and equipment constructed at CERN via the ASACUSA collaboration, to synthesise pionic helium atoms (*Nature* **581** 37). The team attempted to excite pionic orbital transitions in the metastable $He^{2+}e^-\pi^-$ atom using lasers, with the resonance evidenced by neutron, proton and deuteron fragments from the resulting electromagnetic cascade and fission. After several surprising null observations, a transition was excited at 1631 nm – a wavelength used for optical-fibre telecommunication, thus affording the researchers access to superior optical devices. Laser spectroscopy of mesonic atoms could place upper limits on exotic forces, claims the team.

Multimessenger non-coincidences
The ANTARES collaboration, which operates a neutrino telescope 2.5 km under the Mediterranean Sea, has reported a search for neutrino counterparts to six gravitational-wave events thought to originate in the coalescence of binary black holes observed by LIGO or Virgo between June and August



F Montanet

A visualisation of the ANTARES detector.

2017 (*Eur. Phys. J. C* **80** 487). While previous analyses included only upward-going muon neutrinos, the new result includes all flavours and the whole sky. The search for prompt neutrino emission within ±500 seconds of the events yielded no candidates. Though neutrino counterparts are not expected in typical binary-black-hole mergers, systems with asymmetric or very large masses are less well understood theoretically.

AMS continues to surprise
The Alpha Magnetic Spectrometer (AMS) experiment on the International Space Station has published the first measurements of the rigidity (p/q) dependence of the flux of heavy species of cosmic rays. Following previous unexpected results from AMS, the rigidity dependences of neon, magnesium and silicon nuclei were found to be both identical and markedly different from helium, carbon and oxygen cosmic rays above 86.5 GV (*Phys. Rev. Lett.* **124** 211102). The new AMS data, which comprise about two million cosmic rays of each species, suggest a new subdivision of primary cosmic rays into at least two distinct classes.

Quark-matter cores
Astroparticle theorists have uncovered evidence that matter in the interior of maximally massive stable neutron stars (NSs) may exist in the deconfined phase of quantum chromodynamics. The team used gravitational waves from NS mergers and electromagnetic observations of binary systems with a pulsar (a highly magnetised rotating NS) to constrain theoretical models. While $1.4M_\odot$ NSs are still expected to have neutron cores, quark-matter cores should now be considered the standard scenario for NSs of around $2M_\odot$, say the authors (*Nat. Phys.* doi:10.1038/s41567-020-0914-9).

Milestone for open science
Researchers at CERN can now publish open-access in 42 of the journals of the publishing arm of the UK Institute of Physics, IOP Publishing, which also publishes this magazine. The agreement includes authors with a secondary affiliation to CERN and CERN experimental collaborations, and the CC-BY license will allow authors to retain copyright. This is the 10th arrangement of its kind for IOP Publishing, and the first for CERN, marking a milestone towards extending the open dissemination of its research. The agreement builds on the CERN-hosted $SCOAP^3$ initiative, which in 2014 established free and immediate open access to published articles as the standard in particle physics.

ENERGY FRONTIERS

Reports from the Large Hadron Collider experiments

CMS

Vector-boson scattering probes quartic coupling

The electroweak (EW) sector of the Standard Model (SM) predicts self-interactions between W and Z gauge bosons through triple and quartic gauge couplings. Following first measurements at LEP and at the Tevatron during the 1990s, these interactions are now a core part of the LHC physics programme, as they offer key insights into EW symmetry breaking, which, in the case of the SM, causes the W and Z bosons to acquire mass as a result of the Brout–Englert–Higgs mechanism. The quartic coupling can be probed at colliders via rare processes such as tri-boson production, which the CMS collaboration observed for the first time earlier this year, and vector-boson scattering (VBS).

The scattering of longitudinally polarised W and Z bosons is a particularly interesting probe of the SM, as its tree-level amplitudes would violate unitarity at high energies without delicate cancellations from quartic gauge couplings and Higgs-boson contributions. Thus, the study of VBS processes provides key insight into the quartic gauge couplings as well as the Higgs sector. These processes offer sensitivity to enhancements caused by models of physics beyond the SM, which modify the Higgs sector with additional Higgs bosons contributing to VBS.

Vector-boson scattering is characterised by the presence of two forward jets, with a large di-jet invariant mass and a large rapidity separation. CMS previously reported the first observation of same-sign $W^\pm W^\pm$ production using the data collected in 2016. The same-sign $W^\pm W^\pm$ process is chosen because of the smaller background yield from other SM processes compared to the opposite-sign $W^\pm W^\mp$ process. The collaboration has now updated this analysis and performed new studies of the EW production of two jets produced in association with WZ, and ZZ boson pairs using data collected between 2016 and 2018 at a centre-of-mass energy of 13 TeV, corresponding to 137 fb^{-1}. Vector-boson pairs were selected by their decays to electrons and muons. The $W^\pm W^\pm$ and WZ production modes were studied by simultaneously measuring their production cross sections using several kinematical observables. The measured total cross section for $W^\pm W^\pm$ production of 3.98 ± 0.45 (± 0.37 stat. only) fb is the most accurate to date, with a precision of roughly 10%. No deviation from SM predictions is evident.

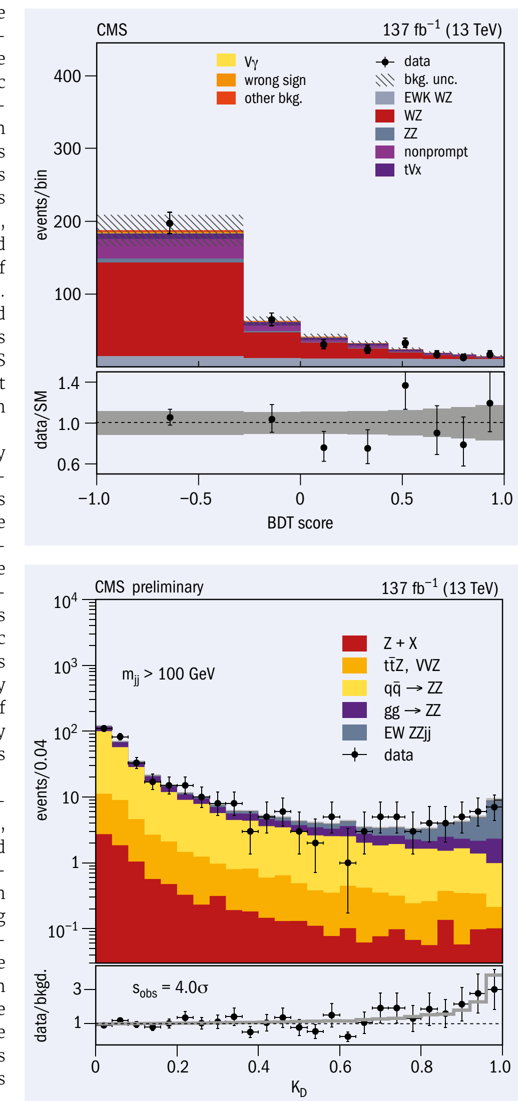


Fig. 1. *Distributions of the boosted-decision-tree score in the WZ signal region (top) and the matrix-element discriminant in the ZZ signal region (bottom). The lower panels show the ratios of data to the SM and background-only predictions, respectively. The grey band shows the uncertainty on the predicted yields. The grey line is the ratio of the total fit to its background-only component.*

Though the contribution from background processes induced by the strong interaction is considerably larger in the WZ and ZZ final states, the scattering centre-of-mass energy and the polarisation of the final-state bosons can be measured as these final states can be more fully reconstructed than in $W^\pm W^\pm$ production. To optimally isolate signal from background, the kinematical information of the WZ and ZZ candidate events is exploited with a boosted decision tree and matrix element likelihood techniques, respectively (see figure). The observed statistical significances for the WZ and ZZ processes are 6.8 and 4.0 standard deviations, respectively, in line with the expected SM significances of 5.3 and 3.5 standard deviations. The possible presence of anomalous quartic gauge couplings could result in an excess of events with respect to the SM predictions. Strong new constraints on the structure of quartic gauge couplings have been set within the framework of dimension-eight effective-field-theory operators.

The observation of the EW production of $W^\pm W^\pm$, WZ and ZZ boson pairs is an essential milestone towards precision tests of VBS at the LHC, and there is much more to be learned from the future LHC Run-3 data. The High-Luminosity LHC should allow for very precise investigations of VBS, including finding evidence for the scattering of longitudinally polarised W bosons.

Further reading

CMS Collab. 2020 arXiv:2005.01173.
CMS Collab. 2020 CMS-PAS-SMP-20-001.
CMS Collab. 2020 CMS-PAS-SMP-19-014.

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IOP Publishing

LHCb

LHCb interrogates X(3872) line shape

In 2003 the Belle collaboration reported the discovery of a mysterious new hadron, the X(3872), in the decay $B^+ \to X(3872)K^+$. Their analysis suggested an extremely small width, consistent with zero, and a mass remarkably close to the sum of the masses of the D^0 and D^{*0} mesons. The particle's existence was later confirmed by the CDF, D0 and BaBar experiments. LHCb first reported studies of the X(3872) in the data sample taken in 2010, and later unambiguously determined its quantum numbers to be 1^{++}, leading the Particle Data Group to change the name of the particle to $\chi_{c1}(3872)$.

The nature of this state is still unclear. Until now, only an upper limit on the width of the $\chi_{c1}(3872)$ of 1.2 MeV has been available. No conventional hadron is expected to have such a narrow width in this part of the otherwise very well understood charmonium spectrum. Among the possible explanations are that it is a tetraquark, a molecular state, a hybrid state where the gluon field contributes to its quantum numbers, or a glueball without any valence quarks at all. A mixture of these explanations is also possible.

The LHCb collaboration has now published two new measurements of the width of the $\chi_{c1}(3872)$, based on minimally overlapping data sets. The first uses Run-1 data corresponding to an integrated luminosity of $3\,fb^{-1}$, in which $(15.5 \pm 0.4) \times 10^3$ $\chi_{c1}(3872)$ particles were selected inclusively from the decays of hadrons containing b quarks. The second analysis selected $(4.23 \pm 0.07) \times 10^3$ fully reconstructed $B^+ \to \chi_{c1}(3872)K^+$ decays from the full Run 1–2 data set, which corresponds to an integrated luminosity of $9\,fb^{-1}$. In both cases, the $\chi_{c1}(3872)$ particles were reconstructed through decays to the final state $J/\psi\pi^+\pi^-$. For the first time the measured Breit–Wigner width was found to be non-zero, with a value close to the previous upper limit from Belle (see figure).

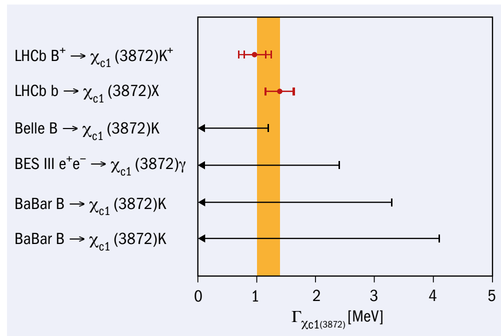

Fig. 1. *New LHCb constraints on the Breit–Wigner width of the $\chi_{c1}(3872)$ state (red) and previous upper limits at the 90% confidence level. The orange band shows the average of the two LHCb measurements.*

Combining the two analyses, the mass of the $\chi_{c1}(3872)$ was found to be 3871.64 ± 0.06 MeV – just 70 ± 120 keV below the $D^0\bar{D}^{*0}$ threshold. The proximity of the $\chi_{c1}(3872)$ to this threshold puts a question mark on measuring the width using a simple fit to the well-known Breit–Wigner function, as this approach neglects potential distortions. Conversely, a precise measurement of the line shape could help elucidate the nature of the $\chi_{c1}(3872)$. This has led LHCb to explore a more sophisticated Flatté parametrisation and report a measurement of the $\chi_{c1}(3872)$ line shape with this model, including the pole positions of the complex amplitude. The results favour the interpretation of the state as a quasi-bound $D^0\bar{D}^{*0}$ molecule, but other possibilities cannot yet be ruled out. Further studies are ongoing. Physicists from other collaborations are also keenly interested in the nature of the $\chi_{c1}(3872)$, and the very recent observation by CMS of the decay process $B_s^0 \to \chi_{c1}(3872)\phi$ suggests another laboratory for studying its properties.

Further reading

LHCb Collab. 2020 arXiv:2005.13419.
LHCb Collab. 2020 arXiv:2005.13422.

ALICE

Common baryon source found in proton collisions

High-energy hadronic collisions, such as those delivered by the LHC, result in the production of a large number of particles. Particle pairs produced close together in both coordinate and momentum space are subject to final-state effects, such as quantum statistics, Coulomb forces and, in the case of hadrons, strong interactions. Femtoscopy uses the correlation of such pairs in momentum space to gain insights into the interaction potential and the spatial extent of an effective particle-emitting source.

Abundantly produced pion pairs are used to assess the size and evolution of the high-density and strongly interacting quark–gluon plasmas, which are formed in heavy-ion collisions. Recently, high-multiplicity pp collisions at the LHC have raised the possibility of observing collective effects similar to those seen in heavy-ion collisions, motivating detailed investigations of the particle source in such systems as well. A universal description of the emission source for all baryon species, independent of the specific quark composition, would open new possibilities to study the baryon–baryon interaction, and would impose strong constraints on particle-production models.

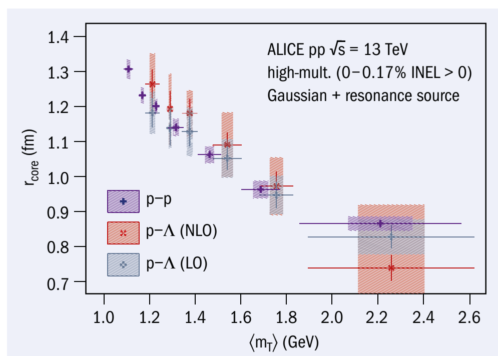

Fig. 1. *The Gaussian core radius as a function of the transverse mass of the p–p and p–Λ pairs, extracted from femtoscopic fits to the ALICE data. The scaling is observed independently of the interaction model used to describe the p–Λ interaction (leading or next-to-leading order chiral-effective-field-theory calculations).*

The ALICE collaboration has recently used p–p and p–Λ pairs to perform the first study of the particle-emitting source for baryons produced in pp collisions. The chosen data sample isolates the 1.7 permille highest-multiplicity collisions in the 13 TeV data set, yielding events with 30 to 40 charged particles reconstructed, on average, per unit of rapidity. The yields of protons and Λ baryons are dominated by contributions from short-lived resonances, accounting for about two thirds of all produced particles. A basic thermal model (the statistical hadronisation model) was used to estimate the number and composition of these resonances, indicating that the average lifetime of those feeding to protons (1.7 fm) is significantly shorter than those feeding to Λ baryons (4.7 fm) – this would have led to a substantial broadening of the source shape if not properly accounted for. An explicit treatment of the effect of short-lived resonances was developed by assuming that all primordial particles and resonances are emitted from ▷ a common core source with a Gaussian shape. The core source was then folded with the exponential tails introduced by the resonance decays. The resulting root-mean-square width of the Gaussian core scales from 1.3 fm to 0.85 fm as a function of an increase in the pair's transverse mass (m_T) from 1.1 to 2.2 GeV, for both p–p and p–Λ pairs (see figure). The transverse mass of a particle is its total energy in a coordinate system in which its velocity is zero along the beam axis. The two systems exhibit a common scaling of the source size, indicating a common emission source for all baryons. The observed scaling of the source size with m_T is very similar to that observed in heavy-ion collisions, wherein the effect is attributed to the collective evolution of the system.

This result is a milestone in the field of correlation studies, as it directly relates to important topics in physics. The common source size observed for p–p and p–Λ pairs implies that the spatial- temporal properties of the hadronisation process are independent of the particle species.

This result is a milestone in the field of correlation studies

This observation can be exploited by coalescence models studying the production of light nuclei, such as deuterons or ^{3}He, in hadronic collisions. Moreover, the femtoscopy formalism relates the emission source to the interaction potential between pairs of particles, enabling the study of the strong nuclear force between hadrons, such as p–K⁻, p–Ξ⁻, p–Ω⁻ and Λ–Λ, with unprecedented precision.

Further reading

ALICE Collab. 2020 arXiv:2004.08018.

ATLAS

LEP-era universality discrepancy unravelled

The family of charged leptons is composed of the electron, muon (μ) and tau lepton (τ). According to the Standard Model (SM), these particles only differ in their mass: the muon is heavier than the electron and the tau lepton is heavier than the muon. A remarkable feature of the SM is that each flavour is equally likely to interact with a W boson. This is known as lepton flavour universality.

In a new ATLAS measurement, a novel technique using events with top-quark pairs has been exploited to test the ratio of probabilities for tau leptons and muons to be produced in on-shell W boson decays, R(τ/μ). In the SM, R(τ/μ) is expected to be unity, but a longstanding tension with this prediction has existed since the LEP era in the 1990s, where, from a combination of the four experiments, R(τ/μ) was measured to be 1.070 ± 0.026, deviating from the SM expectation by 2.7σ. This strongly motivated the need for new measurements with higher precision. If the LEP result was confirmed it would correspond to an unambiguous discovery of beyond-the-SM physics.

To conclusively prove either that the LEP discrepancy is real or that it was just a statistical fluctuation, a precision of at least 1–2% is required – something previously not thought possible at a hadron collider like the LHC, where inclusive W bosons, albeit produced abundantly, suffer from large backgrounds and kinematic biases due to the online selection in the trigger. The key to achieving this is to obtain a sample of muons and tau leptons from W boson decays that is as insensitive as possible to the details of the trigger and object reconstruction used to select them. ATLAS has achieved this by exploiting both the LHC's large sample of more than 100 million top-quark pairs produced in the latest run, and the fact that top quarks decay exclusively to a W boson and a quark. In a tag-and-probe approach, one W boson is used to select the events and the other is used, independently of the first, to measure the fractions of decays to tau leptons and muons.

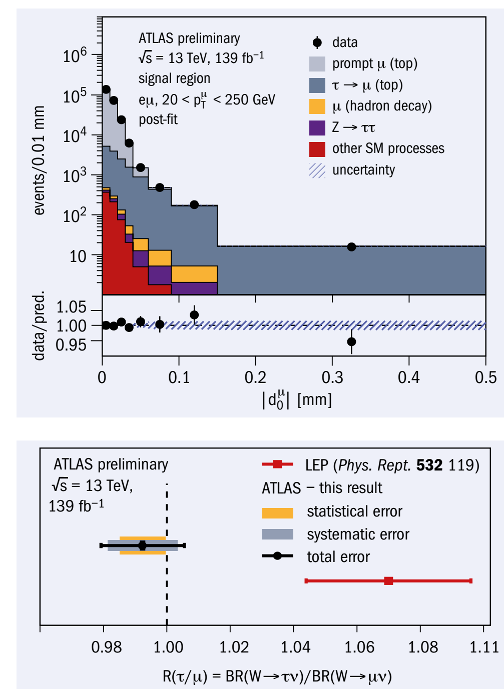

Fig. 1. *Top: an example $|d_0^\mu|$ distribution (in the electron tagging channel for the highest p_T^μ bin) after the fit to data has been performed, showing the separation power between prompt μ and τ → μ contributions. Bottom: a comparison of this measurement to that from LEP. The vertical dashed line indicates equal branching ratios (SM value) to different lepton flavours.*

The analysis focuses on tau-lepton decays to a muon, rather than hadronic tau-lepton decays that are more complicated to reconstruct, thus reducing the systematic uncertainties associated with object reconstruction. The tau-lepton lifetime and its lower momentum decay products are exploited by the precise muon reconstruction available from the ATLAS detector to separate muons from tau-lepton decays and muons produced directly by a W decay (so-called prompt muons). Specifically, the absolute distance of closest approach of muon tracks in the plane perpendicular to the beam line, $|d_0^\mu|$ (as shown in the top figure), and the transverse momentum, p_T^μ, of the muons, are used to isolate these contributions. These variables, in particular $|d_0^\mu|$, are calibrated using a pure sample of prompt muons from $Z \to \mu\mu$ data.

The extraction of R(τ/μ) is performed using a fit to $|d_0^\mu|$ and p_T^μ, where the cancellation of several systematic uncertainties is observed as they are correlated between the prompt μ and τ → μ contributions. This includes uncertainties related to jet reconstruction, flavour tagging and trigger efficiencies. As a result, the measurement obtains very high precision, surpassing that of the previous LEP measurement.

The measured value is R(τ/μ) = 0.992 ± 0.013 [± 0.007 (stat) ± 0.011 (syst)], forming the most precise measurement of this ratio, with an uncertainty half the size of that from the combination of LEP results (see bottom figure). This is in agreement with the Standard Model expectation and suggests that the previous LEP discrepancy may be due to a fluctuation.

Though surviving this latest test, the principle of lepton flavour universality will not quite be out of the woods until the anomalies in B-meson decays recorded by the LHCb experiment (*CERN Courier* May/June 2020 p10) have also been definitively probed.

Further reading

ATLAS Collab. 2020 ATLAS-CONF-2020-014.
LEP Electroweak Working Group 2013 *Phys. Rept.* **532** 119; arXiv:1302.3415.

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FIELD NOTES

Reports from events, conferences and meetings

IPAC'20

IPAC goes virtual

More than 3000 accelerator specialists gathered in cyberspace from 11 to 14 May for the 11th International Particle Accelerator Conference (IPAC). The conference was originally destined for the GANIL laboratory in Caen, a charming city in Normandy, and host to the flagship radioactive-ion-beam facility SPIRAL-2, but the coronavirus pandemic forced the cancellation of the in-person meeting and the French institutes CNRS/IN2P3, CEA/IRFU, GANIL, Soleil and ESRF agreed to organise a virtual conference. Oral presentations and the accelerator-prize session were maintained, though unfortunately the poster and industry sessions had to be cancelled. The scientific programme committee whittled down more than 2000 proposals for talks into 77 presentations, which garnered more than 43,000 video views across 60 countries, making IPAC'20 an involuntary pioneer of virtual conferencing and a lighthouse of science during the lockdown.

IPAC'2020

Live around the world *A selection of more than 3000 registered participants at IPAC'20's online closing session.*

Top of the talks

IPAC'20's success relied on a programme of recent technical highlights, new developments and future plans in the accelerator world. Weighing in at 1998 views, the most popular talk of the conference was by Ben Shepherd from STFC's Daresbury Laboratory in the UK, who spoke on high-technology permanent magnets. Accelerators not only accelerate ensembles of particles, but also use strong magnetic fields to guide and focus them into very small volumes, typically just micro or nanometres in size. Recent trends indicate increasing usage of permanent magnets that provide strong fields but do not require external power, and can provide outstanding field quality. Describing the major advances for permanent magnets in terms of production, radiation resistance, tolerances and field tuning, Shepherd presented high-tech devices developed and used for the SIRIUS, ESRF-EBS, SPRING-8, CBETA, SOLEIL and CUBE-ECRIS facilities, and also presented the Zero-Power Tunable Optics (ZEPTO) collaboration between STFC and CERN, which offers 15–60 T/m tunability in quadrupoles and 0.46–1.1 T in dipoles.

The seven IPAC'20 presentations with the most views included four by outstanding female scientists. CERN Director-General Fabiola Gianotti presented strategic considerations for future accelerator-based particle physics. While pointing out the importance of Europe participating in projects elsewhere in the world, she made the strong point that CERN should host an ambitious future collider, and discussed the options being considered, pointing to the update of the European Strategy for Particle Physics soon to be approved by the CERN Council. Sarah Cousineau from Oak Ridge reported on accelerator R&D as a driver for science in general, pointing out that accelerators have directly contributed to more than 25 Nobel prizes, including the Higgs-boson discovery at the LHC in 2012. The development of superconducting accelerator technology has enabled projects for colliders, photon science, nuclear physics and neutron spallation sources around the world, with several light sources and neutron facilities currently engaged in COVID-19 studies (see p43).

The benefits of accelerator-based photon science for society were also emphasised by Jerry Hastings from Stanford University and SLAC, who presented the tremendous progress in structural biology driven by accelerator-based X-ray sources, and noted that research can be continued during COVID-19 times thanks to the remote synchrotron access pioneered at SSRL. Stressing the value of international collaboration, Hastings presented the outcome of an international X-ray facilities meeting that took place in April and defined an action plan for ensuring the best possible support to COVID-19 research.

Recent trends indicate increasing usage of permanent magnets

GANIL director Alahari Navin presented new horizons in nuclear science, reviewing facilities around the world and presenting his own laboratory's latest activities. GANIL has now started commissioning SPIRAL-2, which will allow users to explore the as-yet unknown properties of exotic nuclei near the limits of the periodic table, and has performed its initial science experiment. Liu Lin from LNLS in Brazil presented the commissioning results for the new fourth-generation SIRIUS light source, showing that the functionality of the facility has already been demonstrated by storing 15 mA of beam current. Last, but not least in the top-seven most-viewed talks, Anke-Susanne Müller from KIT presented the status of the study for a 100 km Future Circular Collider – just one of the options for an ambitious post-LHC project at CERN.

Many other highlights from the accelerator field were presented during IPAC'20. Kyo Shibata (KEK) discussed the progress in physics data-taking at the SuperKEKB factory, where the Belle II experiment recently reported its first result. Ferdinand Willeke (BNL) presented

CERNCOURIER Volume 60 Number 4 July/August 2020
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the electron–ion collider approved to be built at BNL, Porntip Sudmuang (SLRI) showed construction plans for a new light source in Thailand, and Mohammad Eshraqi (ESS) discussed the construction of the European Spallation Source in Sweden. At the research frontier towards compact accelerators, Chang Hee Nam (IBS, Korea) explained prospects for laser-driven GeV-electron beams from plasma-wakefield accelerators and Arnd Specka (LLR/CNRS) showed plans for the compact European plasma-accelerator facility EuPRAXIA, which is entering its next phase after successful completion of a conceptual design report. The accelerator-applications session rounded the picture off with presentations by Annalisa Patriarca (Institut Curie) on accelerator challenges in a new radiation-therapy technique called FLASH, in which ultra-fast delivery of radiation dose reduces damage to healthy tissue; by Charlotte Duchemin (CERN) on the production of non-conventional radionuclides for medical research at the MEDICIS hadron-beam facility; by Toms Torims (Riga Technical University) on the treatment of marine exhaust gases using electron beams; and by Adrian Fabich (SCK-CEN) on proton-driven nuclear-waste transmutation.

SPIRAL-2 will explore exotic nuclei near the limits of the periodic table

To the credit of the French organisers, the virtual setup worked seamlessly. The concept relied on pre-recorded presentations and a text-driven chat function that allowed registered participants to join from time zones across the world. Activating the sessions in half-day steps preserved the appearance of live presentations to some degree, before a final live session, during which the four prizes of the accelerator group of the European Physical Society were awarded.

Mike Seidel *PSI and EPFL,* **Ralph Aßmann** *DESY and* **Frédéric Chautard** *GANIL.*

LHCP CONFERENCE

LHC physics shines amid COVID-19 crisis

The eighth Large Hadron Collider Physics (LHCP) conference, originally scheduled to be held in Paris, was hosted as a fully online conference from 25 to 30 May. To enable broad participation, the organisers waived the registration fee and, with the help of technical support from CERN, hosted about 1300 registered participants from 56 countries, with attendees actively engaging via Zoom webinars. Even a poster session was possible, with 50 junior attendees from all over the world presenting their work via meeting rooms and video recordings. The organisers must be complimented for organising a pioneering virtual conference that succeeded in bringing the LHC community together, in larger and more diverse numbers than at previous editions.

LHCP

Brainpower *A cross section of online delegates at LCHP 2020.*

Enhanced sensitivity

LHCP'20 presentations covered a wide assortment of topics and several new results with significantly enhanced sensitivity than was previously possible. These included both precision measurements with excellent potential to uncover discrepancies that can be explained only by physics beyond the Standard Model (SM) and direct searches using innovative techniques and advanced analysis methods to look for new particles.

The first observation of the combined production of three massive vector bosons (VVV with V = W or Z) was reported by the CMS experiment (see also p17). In the nearly 40 years that have followed the discovery of the W and Z boson, their properties have been measured very precisely, including via "diboson" measurements of the simultaneous production of two vector bosons. However, "triboson" simultaneous production of three massive vector bosons has eluded us so far, as the cross sections are small and the background contributions are rather large. Such measurements are crucial, both to test the underlying theory and to probe non-standard interactions. For example, if new physics beyond the SM is present at high mass scales not far above 1 TeV, then cross-section measurements for triboson final states might deviate from SM predictions. The CMS experiment took advantage of the large Run-2 dataset and machine-learning techniques to search for these rare processes. Leveraging the relatively background-free leptonic final states, CMS collaborators were able to combine searches for different decay modes and different types of triboson production (WWW, WWZ, WZZ and ZZZ) to achieve the first observation of combined heavy triboson production (with an observed significance of 5.7 standard deviations), and at the same time evidence for WWW and WWZ production with observed significances of 3.3 and 3.4 standard deviations, respectively. While the results obtained so far are in agreement with SM predictions, more data is needed for the individual measurements of the WZZ and ZZZ processes.

The first evidence for four-top-quark production was announced by ATLAS. The top-quark discovery in 1995 launched a rich programme of top-quark studies that includes precision measurements of its properties as well as the observation of single-top-quark production. In particular, since the large mass of the top quark is a result of its interaction with the Higgs field, studies of rare processes such as the simultaneous production of four top quarks can provide insights into the properties of the Higgs boson. Within the SM, this process is extremely rare, occurring just once for every 70,000 pairs of top quarks created at the LHC; on the other hand, numerous extensions of the SM predict exotic particles that couple to top quarks and lead to significantly higher production rates. The ATLAS experiment performed this challenging measurement using the full Run-2 dataset using sophisticated techniques and machine-learning methods applied to the multilepton final state to obtain strong evidence for this process. The observed signal significance was found to be 4.3 standard deviations, in excess of the expected sensitivity of 2.4, assuming SM four-top-quark-production properties. While the measured value of the cross section was found to be consistent with the SM prediction within 1.7 standard deviations, the data collected during Run 3 will shed further light on this rare process.

The first observation of the combined production of three massive vector bosons was reported by CMS

The LHCb collaboration presented, with unprecedented precision, measurements of two properties of the mysterious X(3872) particle. Originally discovered by the Belle experiment in 2003 as a narrow state in the $J/\psi\pi^+\pi^-$ mass spectrum of $B^+ \to J/\psi\pi^+\pi^-K^+$ decays, this particle has puzzled particle physicists ever since. The nature of the state is still unclear and several hypotheses have been proposed, such as it being an exotic tetraquark (a system of four quarks bound together), a two-quark hadron, or a molecular state consisting of two D mesons. LHCb collaborators reported the most precise mass measurement yet, and measured, for the first time, and with five standard-deviations significance, the width of the resonance (see p18). Though the results favour its interpretation as a quasi-bound $D^0\bar{D}^{*0}$ molecule, more data and additional analyses are needed to rule out other hypotheses.

ALICE and the dark sector

The ALICE collaboration presented a first measurement of the inelastic low-energy antideuteron cross section using p–Pb collisions at a centre-of-mass energy per nucleon–nucleon pair of 5.02 TeV. Low-energy antideuterons (composed of an antiproton and an antineutron) are predicted by some models to be a promising probe for indirect dark-matter searches. In particular, antideuterons could be produced during the annihilation or decay of neutralinos or sneutrinos, which are hypothetical dark-matter candidates. Contributions from cosmic-ray interactions in the low-energy range below 1–2 GeV per nucleon are expected to be small. ALICE collaborators used a novel technique that utilised the detector material as an absorber for antideuterons to measure the production and annihilation rates of low-energy antideuterons. The results from this measurement can be used in propagation models of antideuterons within the interstellar medium for interpreting dark-matter searches, including intriguing results from the AMS experiment. Future analyses with higher statistics will improve the modelling and extend these studies to heavier antinuclei.

The above are just a few of the many excellent results that were presented at LHCP'20. The extraordinary performance of the LHC coupled with progress reported by the theory community, and the excellent data collected by the experiments, has inspired LHC physicists to continue with their rich harvest of physics results, despite the current world crisis. Results presented at the conference showed that huge progress has been made on several fronts, and that Run 3 and the High-Luminosity LHC upgrade programme will enable further exploration of particle physics at the energy frontier.

Tulika Bose *University of Wisconsin-Madison.*

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SENSING A PASSAGE THROUGH THE UNKNOWN

A global network of ultra-sensitive optical atomic magnetometers – GNOME – has begun its search for exotic fields beyond the Standard Model.

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Long shot *Previous precision measurements could have missed exotic transient phenomena.*

Since the inception of the Standard Model (SM) of particle physics half a century ago, experiments of all shapes and sizes have put it to increasingly stringent tests. The largest and most well-known are collider experiments, which in particular have enabled the direct discovery of various SM particles. Another approach utilises the tools of atomic physics. The relentless improvement in the precision of tools and techniques of atomic physics, both experimental and theoretical, has led to the verification of the SM's predictions with ever greater accuracy. Examples include measurements of atomic parity violation that reveal the effects of the Z boson on atomic states, and measurements of atomic energy levels that verify the predictions of quantum electrodynamics (QED). Precision atomic physics experiments also include a vast array of searches for effects predicted by theories beyond-the-SM (BSM), such as fifth forces and permanent electric dipole moments that violate parity- and time-reversal symmetry. These tests probe potentially subtle yet constant (or controllable) changes of atomic properties that can be revealed by averaging away noise and controlling systematic errors.

But what if the glimpses of BSM physics that atomic spectroscopists have so painstakingly searched for over the past decades are not effects that persist over the many weeks or months of a typical measurement campaign, but rather transient events that occur only sporadically? For example, might not cataclysmic astrophysical events such as black-hole mergers or supernova explosions produce hypothetical ultralight bosonic fields impossible to generate in the laboratory? Or might not Earth occasionally pass through some invisible "cloud" of a substance (such as dark matter) produced in the early universe? Such transient phenomena could easily be missed by experimenters when data are averaged over long times to increase the signal-to-noise ratio.

Detecting such unconventional events represents several challenges. If a transient signal heralding new physics was observed with a single detector, it would be exceedingly difficult to confidently distinguish the exotic-physics signal from the many sources of noise that plague precision atomic physics measurements. However, if transient interactions occur over a global scale, a network of such detectors geographically distributed over Earth could search for specific patterns in the timing and amplitude of such signals that would be unlikely to occur randomly. By correlating the readouts of many detectors, local effects can be filtered away and exotic physics could

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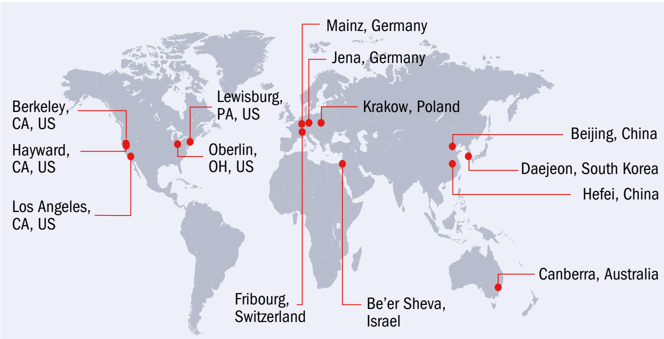


Correlated *The Global Network of Optical Magnetometers to search for Exotic physics (GNOME) is specifically designed to search for global-scale transient or oscillating events resulting from the coupling between atomic spins and beyond-the-Standard-Model fields.*

be distinguished from mundane physics.

This idea forms the basis for the Global Network of Optical Magnetometers to search for Exotic physics (GNOME), an international collaboration involving 14 institutions from all over the world (see "Correlated" figure). Such an idea, like so many others in physics, is not entirely new. The same concept is at the heart of the worldwide network of interferometers used to observe gravitational waves (LIGO, Virgo, GEO, KAGRA, TAMA, CLIO), and the global network of proton-precession magnetometers used to monitor geomagnetic and solar activity. What distinguishes GNOME from other global sensor networks is that it is specifically dedicated to searching for signals from BSM physics that have evaded detection in earlier experiments.

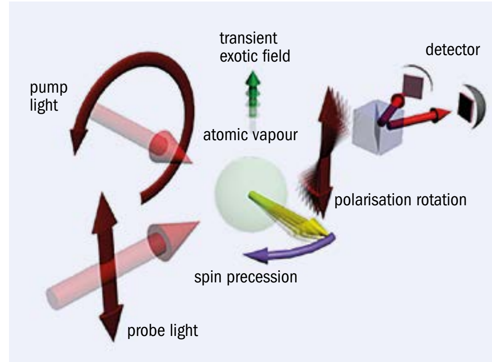
GNOME is a growing network of more than a dozen optical atomic magnetometers, with stations in Europe, North America, Asia and Australia. The project was proposed in 2012 by a team of physicists from the University of California at Berkeley, Jagiellonian University, California State University – East Bay, and the Perimeter Institute. The network started taking preliminary data in 2013, with the first dedicated science-run beginning in 2017. With more data on the way, the GNOME collaboration, consisting of more than 50 scientists from around the world, is presently combing the data for signs of the unexpected, with its first results expected later this year.

Exotic-physics detectors

Optical atomic magnetometers (OAMs) are among the most sensitive devices for measuring magnetic fields. However, the atomic vapours that are the heart of GNOME's OAMs are placed inside multi-layer shielding systems, reducing the effects of external magnetic fields by a factor of more than a million. Thus, in spite of using extremely sensitive magnetometers, GNOME sensors are largely insensitive to magnetic signals. The reasoning is that many BSM theories predict the existence of exotic fields that couple to atomic spins and would penetrate through magnetic shields largely unaffected. Since the OAM signal is proportional to the spin-dependent energy shift regardless of whether or not a magnetic field causes the energy shift, OAMs – even enclosed within magnetic shields – are sensitive to a broad class of exotic fields.

If such exotic fields exist, their coupling to atomic spins must be extremely feeble

The basic principle behind OAM operation (see "Optical rotation" figure) involves optically measuring spin-

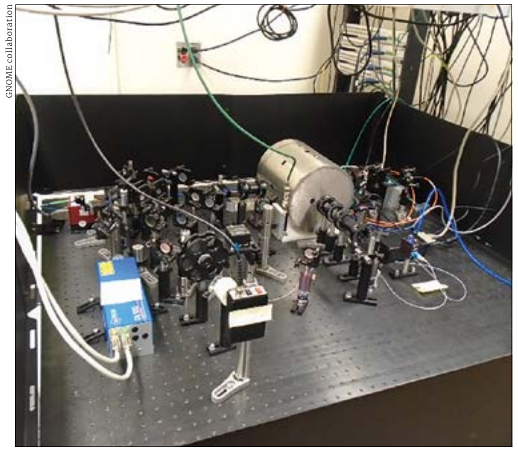


Optical rotation *In a GNOME optical atomic magnetometer, linearly polarised light optically pumps atomic-spin alignment along the light polarisation axis, making the atomic vapour optically anisotropic. If a transient torque from an exotic field causes the spins to precess, the axis of the optical anisotropy, parallel to the spin alignment, also rotates. This causes optical rotation of the light polarisation, which can be precisely measured with a polarimeter.*

dependent energy shifts by controlling and monitoring an ensemble of atomic spins via angular momentum exchange between the atoms and light. The high efficiency of optical pumping and probing of atomic spin ensembles, along with a wide array of clever techniques to minimise atomic spin relaxation (even at high atomic vapour densities), have enabled OAMs to achieve sensitivities to spin-dependent energy shifts at levels well below 10^{-20} eV after only one second of integration. One of the 14 OAM installations, at California State University – East Bay, is shown in the "Benchtop physics" image.

However, one might wonder: do any of the theoretical scenarios suggesting the existence of exotic fields predict signals detectable by a magnetometer network while also evading all existing astrophysical and laboratory constraints? This is not a trivial requirement, since previous high-precision atomic spectroscopy experiments have established stringent limits on BSM physics. In fact, OAM techniques have been used by a number of research groups (including our own) over the past several decades to search for spin-dependent energy shifts caused by exotic fields sourced by nearby masses or polarised spins. Closely related work has ruled out vast areas of BSM parameter space by comparing measurements of hyperfine structure in simple hydrogen-like atoms to QED calculations. Furthermore, if exotic fields do exist and couple strongly enough to atomic spins, they could cause noticeable cooling of stars and affect the dynamics of supernovae. So far, all laboratory experiments have produced null results and all astrophysical observations are consistent with the SM. Thus if such exotic fields exist, their coupling to atomic spins must be extremely feeble.

Despite these constraints and requirements, theoretical scenarios both consistent with existing constraints and that predict effects measurable with GNOME do exist. Prime examples, and the present targets of the GNOME

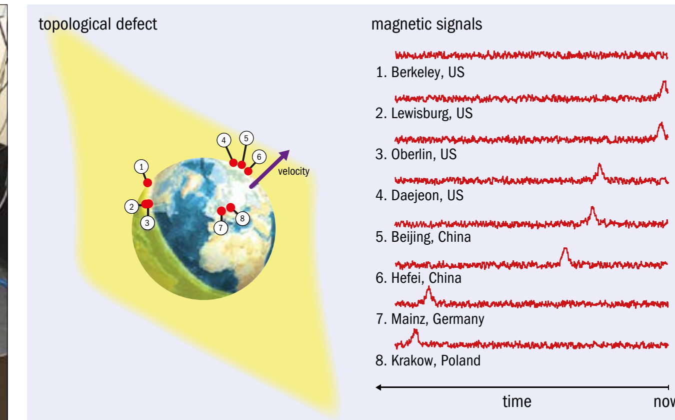


Benchtop physics *The OAM setup at the GNOME station at California State University – East Bay in Hayward, California.*

collaboration's search efforts, are ultralight bosonic fields. A canonical example of an ultralight boson is the axion. The axion emerged from an elegant solution, proposed by Roberto Peccei and Helen Quinn in the late 1970s, to the strong-CP problem. The Peccei–Quinn mechanism explains the mystery of why the strong interaction, to the highest precision we can measure, respects the combined CP symmetry whereas quantum chromodynamics naturally accommodates CP violation at a level ten orders of magnitude larger than present constraints. If CP violation in the strong interaction can be described not by a constant term but rather by a dynamical (axion) field, it could be significantly suppressed by spontaneous symmetry breaking at a high energy scale. If the symmetry breaking scale is at the grand-unification-theory (GUT) scale (~10^{16} GeV), the axion mass is around 10^{-10} eV, and at the Planck scale (10^{19} GeV) around 10^{-13} eV – both many orders of magnitude less massive than even neutrinos. Searching for ultralight axions therefore offers the exciting possibility of probing physics at the GUT and Planck scales, far beyond the direct reach of any existing collider.

Beyond the Standard Model

In addition to the axion, there are a wide range of other hypothetical ultralight bosons that couple to atomic spins and could generate signals potentially detectable with GNOME. Many theories predict the existence of spin-0 bosons with properties similar to the axion (so-called axion-like particles, ALPs). A prominent example is the relaxion, proposed by Peter Graham, David Kaplan and Surjeet Rajendran to explain the hierarchy problem: the mystery of why the electroweak force is about 24 orders-of-magnitude stronger than the gravitational force. In 2010, Asimina Arvanitaki and colleagues found that string theory suggests the existence of many ALPs of widely varying masses, from 10^{-33} eV to 10^{-10} eV. From the perspective of BSM theories, ultralight bosons are ubiquitous. Some predict ALPs such as "familons", "majorons" and "arions". Others predict new ultralight spin-1 bosons such as dark and hidden



New domains *An artist's rendition of the Earth passing through a topological defect of an axion-like field in the form of a "domain wall" (left). As various GNOME stations pass through the topological defect, signals appear in the OAM data at particular times (right), normalised so that the apparent signals have the same amplitude and sign.*

photons. There is even a possibility of exotic spin-0 or spin-1 gravitons: while the graviton for a quantum theory of gravity matching that described by general relativity must be spin-2, alternative gravity theories (for example torsion gravity and scalar-vector-tensor gravity) predict additional spin-0 and/or spin-1 gravitons.

It also turns out that such ultralight bosons could explain dark matter. Most searches for ultralight bosonic dark matter assume the bosons to be approximately uniformly distributed throughout the dark matter halo that envelopes the Milky Way. However, in some theoretical scenarios, the ultralight bosons can clump together into bosonic "stars" due to self-interactions. In other scenarios, due to a non-trivial vacuum energy landscape, the ultralight bosons could take the form of "topological" defects, such as domain walls that separate regions of space with different vacuum states of the bosonic field (see "New domains" figure). In either of these cases, the mass-energy associated with ultralight bosonic dark matter would be concentrated in large composite structures that Earth might only occasionally encounter, leading to the sort of transient signals that GNOME is designed to search for.

Yet another possibility is that intense bursts of ultralight bosonic fields might be generated by cataclysmic astrophysical events such as black-hole mergers. Much of the underlying physics of coalescing singularities is unknown, possibly involving quantum-gravity effects far beyond the reach of high-energy experiments on Earth, and it turns out that quantum gravity theories generally predict the existence of ultralight bosons. Furthermore, if ultralight bosons exist, they may tend to condense in gravitationally bound halos around black holes. In these scenarios, a sizable fraction of the energy released when black holes merge could plausibly be emitted in the form of ultralight bosonic fields. If the energy density of the ultralight bosonic field is large enough, networks of atomic sensors like GNOME might be able to detect a signal.

In order to use OAMs to search for exotic fields, the effects of environmental magnetic noise must be reduced, controlled, or cancelled. Even though the GNOME magnetometers are enclosed in multi-layer magnetic shields so that signals from external electromagnetic fields are

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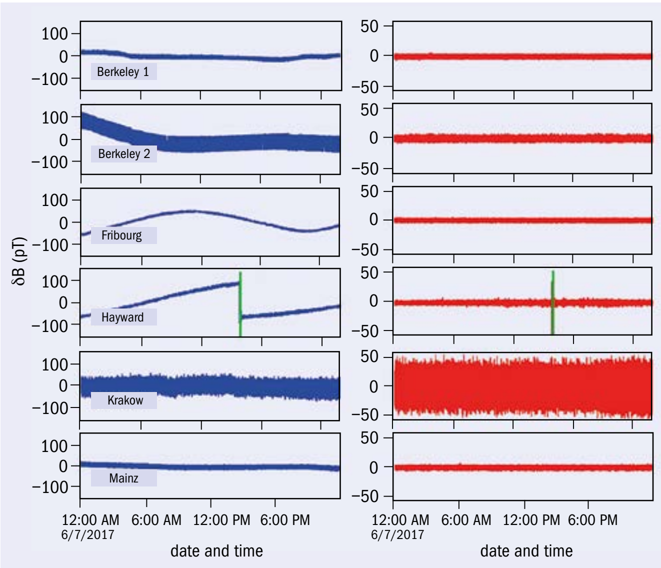


Afach et al. 2018

Spurious signals *Sample data for the apparent magnetic field deviation from the mean (δB) from several GNOME stations. The blue traces (left) show the raw data and the red traces (right) show the data after high-pass and notch filters are applied to remove slow drifts and noise at line frequencies (50 or 60 Hz). An event flagged by auxiliary sensors as spurious is highlighted in green on the plots of the data from Hayward.*

significantly suppressed, there is a wide variety of phenomena that can mimic the sorts of signals one would expect from ultralight bosonic fields. These include vibrations, laser instabilities, and noise in the circuitry used for data acquisition. To combat these spurious signals, each GNOME station uses auxiliary sensors to monitor electromagnetic fields outside the shields (which could leak inside the shields at a far-reduced level), accelerations and rotations of the apparatus, and overall magnetometer performance. If the auxiliary sensors indicate data may be suspect, the data are flagged and ignored in the analysis (see "Spurious signals" figure).

GNOME data that have passed this initial quality check can then be scanned to see if there are signals matching the patterns expected based on various exotic physics hypotheses. For example, to test the hypothesis that dark matter takes the form of ALP domain walls, one searches for a signal pattern resulting from the passage of Earth through an astronomical-sized plane having a finite thickness given by the ALP's Compton wavelength. The relative velocity between the domain wall and Earth is unknown, but can be assumed to be randomly drawn from the velocity distribution of virialised dark matter, having an average speed of about one thousandth the speed of light. The relative timing of signals appearing in different GNOME magnetometers should be consistent with a single velocity v: i.e. nearby stations (in the direction of the wall propagation) should detect signals with smaller delays and stations that are far apart should detect signals with larger delays, and furthermore the time delays should occur in a sensible sequence. The energy shift that could lead to a detectable signal in GNOME magnetometers is caused by an interaction of the domain-wall field ϕ with the atomic spin S whose strength is proportional to the scalar product of the spin with the gradient of the field, $S \cdot \nabla\phi$. The gradient of the domain-wall field $\nabla\phi$ is proportional to its momentum relative to S, and hence the signals appearing in different GNOME magnetometers are proportional to $S \cdot v$. Both the signal-timing pattern and the signal-amplitude pattern should be consistent with a single value of v; signals inconsistent with such a pattern can be rejected as noise.

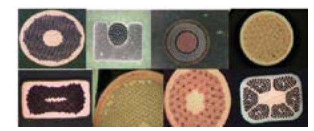
To claim discovery of a signal heralding BSM physics, detections must be compared to the background rate of spurious false-positive events consistent with the expected signal pattern but not generated by exotic physics. The false-positive rate can be estimated by analysing time-shifted data: the data stream from each GNOME magnetometer is shifted in time relative to the others by an amount much larger than any delays resulting from propagation of ultralight bosonic fields through Earth. Such time-shifted data can be assumed to be free of exotic-physics signals, so any detections are necessarily false positives: merely random coincidences due to noise. When the GNOME data are analysed without timeshifts, to be regarded as an indication of BSM physics, the signal amplitude must surpass the 5σ threshold as compared to the background determined with the time-shifted data. This means that, for a year-long data set, an event due to noise coincidentally matching the assumed signal pattern throughout the network would occur only once every 3.5 million years.

Inspiring efforts

Having already collected over a year of data, and with more on the way, the GNOME collaboration is presently combining the data for signs of BSM physics. New results based on recent GNOME science runs are expected in 2020. This would represent the first ever search for such transient exotic spin-dependent effects. Improvements in magnetometer sensitivity, signal characterisation, and data-analysis techniques are expected to improve on these initial results over the next several years. Significantly, GNOME has inspired similar efforts using other networks of precision quantum sensors: atomic clocks, interferometers, cavities, superconducting gravimeters, etc. In fact, the results of searches for exotic transient signals using clock networks have already been reported in the literature, constraining significant parameter space for various BSM scenarios. We would suggest that all experimentalists should seriously consider accurately time-stamping, storing, and sharing their data so that searches for correlated signals due to exotic physics can be conducted *a posteriori*. One never knows what nature might be hiding just beyond the frontier of the precision of past measurements. ●

Further reading

S Afach *et al.* 2018 *Phys. Dark Universe* **22** 162.
D Budker and A Derevianko 2015 *Phys. Today* **68** 10.
C Dailey *et al.* 2020 arXiv:2002.04352.
A Derevianko and M Pospelov 2014 *Nat. Phys.* **10** 933.
D F Jackson Kimball *et al.* 2018 *Phys. Rev. D* **97** 043002.
H Masia-Roig *et al.* 2020 *Phys. Dark Universe* **28** 100494.
M Pospelov *et al.* 2013 *Phys. Rev. Lett.* **110** 021803.
S Pustelny *et al.* 2013 *Annalen der Physik* **525** 659.
B M Roberts *et al.* 2017 *Nat. Commun.* **8** 1.
M S Safronova *et al.* 2018 *Rev. Mod. Phys.* **90** 025008.
P Wcisło *et al.* 2016 *Nat. Astron.* **1** 1.



TUNING IN TO NEUTRINOS

A new generation of accelerator and reactor experiments is opening an era of high-precision neutrino measurements to tackle questions such as leptonic CP violation, the mass hierarchy and the possibility of a fourth "sterile" neutrino, writes Mark Rayner.

In traditional Balinese music, instruments are made in pairs, with one tuned slightly higher in frequency than its twin. The notes are indistinguishable to the human ear when played together, but the sound recedes and swells a couple of times each second, encouraging meditation. This is a beating effect: fast oscillations at the mean frequency inside a slowly oscillating envelope. Similar physics is at play in neutrino oscillations. Rather than sound intensity, it's the probability to observe a neutrino with its initial flavour that oscillates. The difference is how long it takes for the interference to make itself felt. When Balinese musicians strike a pair of metallophones, the notes take just a handful of periods to drift out of phase. By contrast, it takes more than 10^{20} de Broglie wavelengths and hundreds of kilometres for neutrinos to oscillate in experiments like the planned mega-projects Hyper-Kamiokande and DUNE.

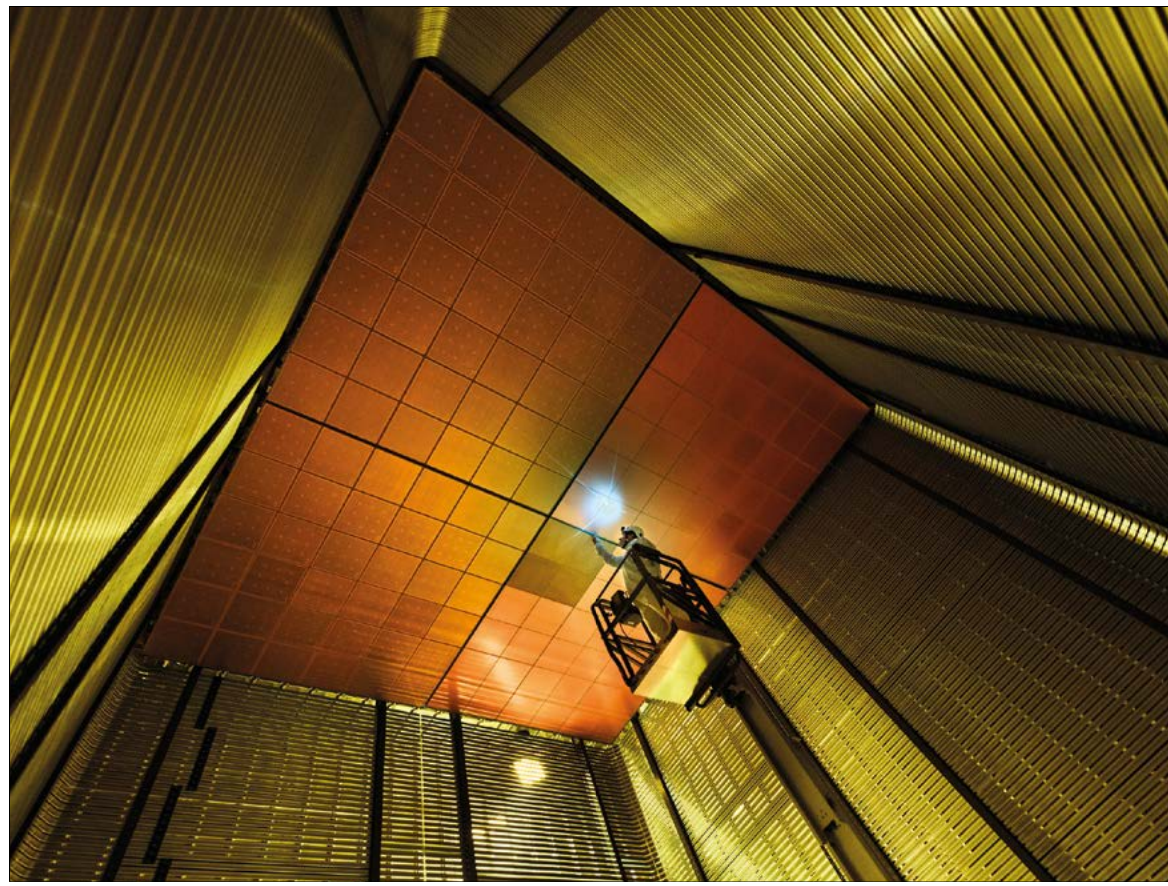
Neutrino oscillations revealed a rare chink in the armour of the Standard Model: neutrinos are not massless, but are evolving superpositions of at least three mass eigenstates with distinct energies. A neutrino is therefore like three notes played together: frequencies so close, given the as-yet immeasurably small masses involved, that they are not just indistinguishable to the ear, but inseparable according to the uncertainty principle. As neutrinos are always ultra-relativistic, the energies of the mass eigenstates differ only due to tiny mass contributions of $m^2/2E$. As the mass eigenstates propagate, phase differences develop between them proportional to squared-mass splittings Δm^2. The sought-after oscillations range from a few metres to the diameter of Earth.

Orthogonal mixtures

The neutrino physics of the latter third of the 20th century was bookended by two anomalies that uncloaked these effects. In 1968 Ray Davis's observation of a deficit of solar neutrinos prompted Bruno Pontecorvo to make public his conjecture that neutrinos might oscillate. Thirty years later, the Super-Kamiokande collaboration's analysis of a deficit of atmospheric muon neutrinos from the other side of the planet posthumously vindicated the visionary Italian, and later Soviet, theorist's speculation. Subsequent observations have revealed that electron, muon and tau neutrinos are orthogonal mixtures of mass eigenstates ν_1 and ν_2, separated by a small so-called solar splitting Δm^2_{21}, and ν_3, which is separated from that pair by a larger "atmospheric" splitting usually quantified by Δm^2_{32} (see "Little and large" figure, p34). It is not yet known if ν_3 is the lightest or the heaviest of the trio. This is called the mass-hierarchy problem.

THE AUTHOR

Mark Rayner *associate editor.*



M Brice/CERN-PHOTO-201902-023-1

Golden opportunity *Liquid-argon time-projection chambers can serve as both target and tracker for neutrino interactions. Here, an engineer is pictured adjusting the charge-readout plane of the DUNE experiment's dual-phase prototype detector at CERN.*

"In the first two decades of the 21st century we have achieved a rather accurate picture of neutrino masses and mixings," says theorist Pilar Hernández of the University of Valencia, "but the ordering of the neutrino states is unknown, the mass of the lightest state is unknown and we still do not know if the neutrino mixing matrix has imaginary entries, which could signal the breaking of CP symmetry," she explains. "The very different mixing patterns in quarks and leptons could hint at a symmetry relating families, and a more accurate exploration of the lepton-mixing pattern and the neutrino ordering in future experiments will be essential to reveal any such symmetry pattern."

Today, experiments designed to constrain neutrino mixing tend to dispense with astrophysical neutrinos in favour of more controllable accelerator and reactor sources. The experiments span more than four orders of magnitude in size and energy and fall into three groups (see "Not natural" figure on p34). Much of the limelight is taken by experiments that are sensitive to the large mass splitting Δm^2_{32}, which include both a cluster of current (such as T2K) and future (such as DUNE) accelerator-neutrino experiments with long baselines and high energies, and a high-performing trio of reactor-neutrino experiments (Daya Bay, RENO and Double Chooz) with a baseline of about a kilometre, operating just above the threshold for inverse beta decay. The second group is a beautiful pair of long-baseline reactor-neutrino experiments (KamLAND and the soon-to-be-commissioned JUNO), which join experiments with solar neutrinos in having sensitivity to the smaller squared-mass splitting Δm^2_{21}. Finally, the third group is a host of short-baseline accelerator-neutrino experiments and very-short-baseline reactor neutrino experiments that are chasing tantalising hints of a fourth "sterile" neutrino (with no Standard-Model gauge interactions), which is split from the others by a squared-mass splitting of the order of 1 eV^2.

The zeitgeist began to shift to artificially produced neutrinos

Artificial sources

Experiments with artificial sources of neutrinos have a storied history, dating from the 1950s, when physicists toyed with the idea of detecting neutrinos created in the explosion of a nuclear bomb, and eventually observed them streaming from nuclear reactors. The 1960s saw the invention of the accelerator neutrino. Here, proton beams smashed into fixed targets to create a decaying debris of charged pions and their concomitant muon neutrinos. The 1970s transformed these neutrinos into beams by focusing the charged pions with magnetic horns, leading to the discovery of weak neutral currents and insights into the structure of nucleons. It was not until the turn of the century, however, that the zeitgeist of neutrino-oscillation studies began to shift from naturally to artificially produced neutrinos. Just a year after the publication of the Super-Kamiokande collaboration's seminal 1998 paper on atmospheric-neutrino oscillations, Japanese experimenters trained a new accelerator-neutrino beam on the detector.

Operating from 1999 to 2006, the KEK-to-Kamioka (K2K) experiment sent a beam of muon neutrinos from the KEK laboratory in Tsukuba to the Super-Kamiokande detector, 250 km away under Mount Ikeno on the other side of

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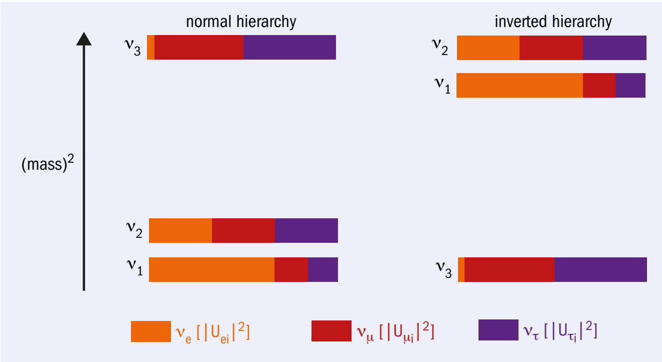
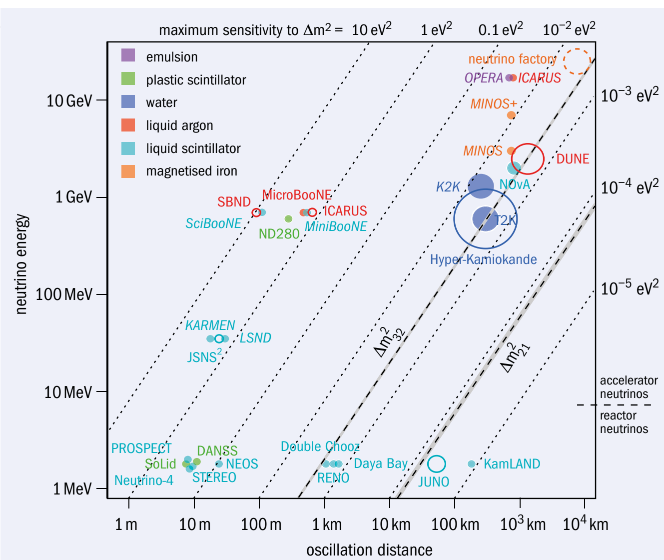
VOLUME 60 NUMBER 4 JULY/AUGUST 2020



Little and large *A narrow splitting between neutrino mass eigenstates, Δm^2_{21}, is known to be about $+7.4\times10^{-5}$ eV^2, and a larger splitting, Δm^2_{32}, is known to be approximately 2.5×10^{-3} eV^2 in magnitude, though its sign is unknown. The colours roughly indicate coupling to the charged leptons.*



Not natural *Neutrino-oscillation experiments using neutrinos from nuclear reactors or accelerator beams, as a function of the distance from source to detector and the peak energy of the neutrinos. Open markers indicate future projects (for detectors in excess of 5 kton, the area of the marker is proportional to the detector mass) and italics indicate completed experiments. The experiments are coloured according to target material. The "magic-baseline" neutrino factory proposed in the 2011 international design study is plotted for reference.*

Honshu. K2K confirmed that muon neutrinos "disappear" as a function of propagation distance over energy. The experiments together supported the hypothesis of an oscillation to tau neutrinos, which could not be directly detected at that energy. By increasing the beam energy well above the tau-lepton mass, the CERN Neutrinos to Gran Sasso (CNGS) project, which ran from 2006 to 2012, confirmed the oscillation to tau neutrinos by directly observing tau leptons in the OPERA detector. Meanwhile, the Main Injector Neutrino Oscillation Search (MINOS), which sent muon neutrinos from Fermilab to northern Minnesota from 2005 to 2012, made world-leading measurements of the parameters describing the oscillation.

With $\nu_\mu \to \nu_\tau$ oscillations established, the next generation of experiments innovated in search of a subtler effect. T2K (K2K's successor, with the beam now originating at J-PARC in Tokai) and NOvA (which analyses oscillations over the longer baseline of 810 km between Fermilab and Ash River, Minnesota) both have far detectors offset by a few degrees from the direction of the peak flux of the beams. This squeezes the phase space for the pion decays, resulting in an almost mono-energetic flux of neutrinos. Here, a quirk of the mixing conspires to make the musical analogy of a pair of metallophones particularly strong: to a good approximation, the muon neutrinos ring out with two frequencies of roughly equal amplitude, to yield an almost perfect disappearance of muon neutrinos – and maximum sensitivity to the appearance of electron neutrinos.

Testing CP symmetry

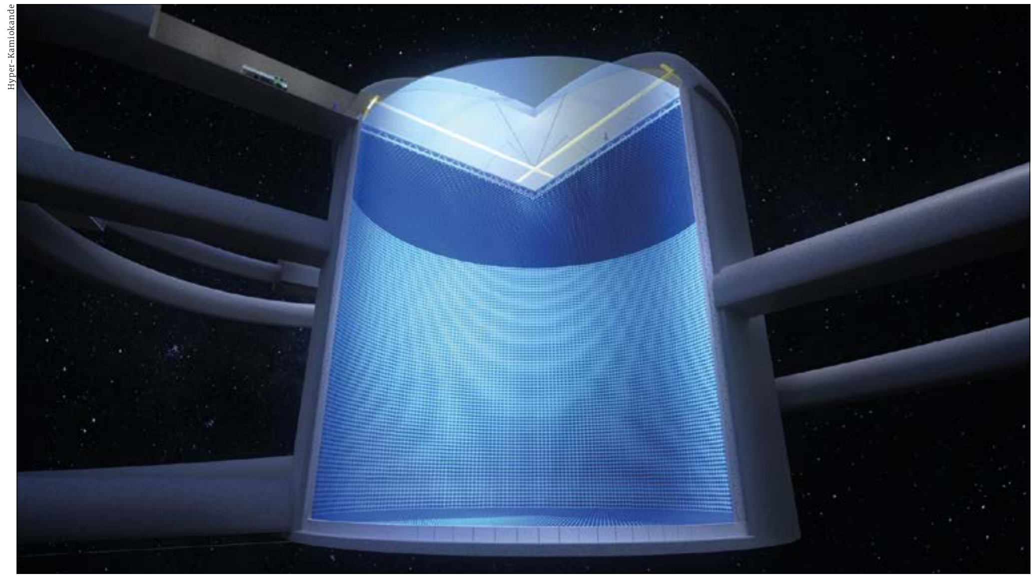
The three neutrino mass eigenstates mix to make electron, muon and tau neutrinos according to the Pontecorvo–Maki–Nakagawa–Sakata (PMNS) matrix, which describes three rotations and a complex phase δ_{CP} that can cause charge–parity (CP) violation – a question of paramount importance in the field due to its relevance to the unknown origin of the matter–antimatter asymmetry in the universe (see p40). Whatever the value of the complex phase, leptonic CP violation can only be observed if all three of the angles in the PMNS matrix are non-zero. Experiments with atmospheric and solar neutrinos demonstrated this for two of the angles. At the beginning of the last decade, short-baseline reactor-neutrino experiments in China (Daya Bay), Korea (RENO) and France (Double Chooz) were in a race with T2K to establish if the third angle, which leads to a coupling between ν_3 and electrons, was also non-zero. In the reactor experiments this would be seen as a small deficit of electron antineutrinos a kilometre or so from the reactors; in T2K the smoking gun would be the appearance of a small number of electron neutrinos not present in the initial muon-neutrino-dominated beam.

After data taking was cut short by the great Sendai earthquake and tsunami of March 2011, T2K published evidence for the appearance of six electron-neutrino events, over the expected background of 1.5 ± 0.3 in the case of no coupling. Alongside a single tau-neutrino candidate in OPERA, these were the first neutrinos seen to appear in a detector with a new flavour, as previous signals had always registered a deficit of an expected flavour. In the closing days of the year, Double Chooz published evidence for 4121 electron-antineutrino events, under the expected tally for no coupling of 4344 ± 165, reinforcing T2K's 2.5σ indication. Daya Bay and RENO put the matter to bed the following spring, with 5σ evidence apiece that the ν_3–electron coupling was indeed non-zero. The key innovation for the reactor experiments was to minimise troublesome flux and interaction systematics by also placing detectors close to the reactors.

Since then, T2K and NOvA, which began taking data in 2014, have been chasing leptonic CP violation – an analysis that is out of the reach of reactor experiments, as δ_{CP} does not affect disappearance probabilities. By switching the polarity of the magnetic horn, the experiments can compare the probabilities for the CP-mirror oscillations $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ directly. NOvA data are inconclusive at present. T2K data currently err towards near maximal CP violation in the vicinity of $\delta_{CP} = -\pi/2$. The latest analysis, published in April, disfavours leptonic CP conservation ($\delta_{CP} = 0, \pm\pi$) at 2σ significance for all possible mixing parameter values (see p8). Statistical uncertainty is the biggest limiting factor.

Major upgrades planned for T2K next year target statistical, interaction-model and detector uncertainties. A substantial increase in beam intensity will be accompanied by a new fine-grained scintillating target for the ND280 near-detector complex, which will lower the energy threshold to reconstruct tracks. New transverse TPCs will improve ND280's acceptance at high angles, yielding a better cancellation of systematic errors with the far detector, Super-Kamiokande, which is being upgraded by loading 0.01% gadolinium salts into the otherwise ultrapure water. As in reactor-neutrino detectors, this will provide a tag for antineutrino events, to improve sample purities in the search for leptonic CP violation.

T2K and NOvA both plan to roughly double their current data sets, and are working together on a joint fit, in a bid to better understand correlations between systematic uncertainties, and break degeneracies between measurements of CP violation and the mass hierarchy. If the CP-violating phase is indeed maximal, as suggested by the recent T2K result, the experiments may be able to exclude CP conservation with more than 99% confidence. "At this point we will be in a transition from a statistics-dominated to a systematics-dominated result," says T2K spokesperson Atsuko Ichikawa of the University of Kyoto. "It is difficult to say, but our sensitivity will likely be limited at this stage by a convolution of neutrino-interaction and flux systematics."



Not super but hyper *A visualisation of the Hyper-Kamiokande detector – a 260,000 tonne gadolinium-doped water-Cherenkov detector with a fiducial volume 8.4 times greater than its predecessor. Excavation of the cavern has already begun.*

The next generation

Two long-baseline accelerator-neutrino experiments roughly an order of magnitude larger in cost and detector mass than T2K and NOvA have received green lights from the Japanese and US governments: Hyper-Kamiokande and DUNE. One of their primary missions is to resolve the question of leptonic CP violation.

Hyper-Kamiokande will adopt the same approach as T2K, but will benefit from major upgrades to the beam and the near and far detectors in addition to those currently underway in the present T2K upgrade. To improve the treatment of systematic errors, the suite of near detectors will be complemented by an ingenious new gadolinated water-Cherenkov detector at an intermediate baseline: by spanning a range of off-axis angles, it will drive down interaction-model systematics by exploiting previously neglected information on the how the flux varies as a function of the angle relative to the centre of the beam. Hyper-Kamiokande's increased statistical reach will also be impressive. The power of the Japan Proton Accelerator Research Complex (J-PARC) beam will be increased from its current value of 0.5 MW up to 1.3 MW, and the new far detector will be filled with 260,000 tonnes of ultrapure water, yielding a fiducial volume 8.4 times larger than that of Super-Kamiokande. Procurement of the photo-multiplier tubes will begin this year, and the five-year-long excavation of the cavern has already begun. Data taking is scheduled to commence in 2027. "The expected precision on δ_{CP} is 10–20 degrees, depending on its true value," says Hyper-Kamiokande international co-spokesperson Francesca di Lodovico of King's College, London.

In the US, the Deep Underground Neutrino Experiment (DUNE) will exploit the liquid-argon–TPC technology first deployed on a large scale by ICARUS – OPERA's sister detector in the CNGS project. The idea for the technology dates back to 1977, when Carlo Rubbia proposed using liquid

Muon neutrinos ring out with two frequencies of roughly equal amplitude, to yield almost perfect disappearance

CERNCOURIER
VOLUME 60 NUMBER 4 JULY/AUGUST 2020
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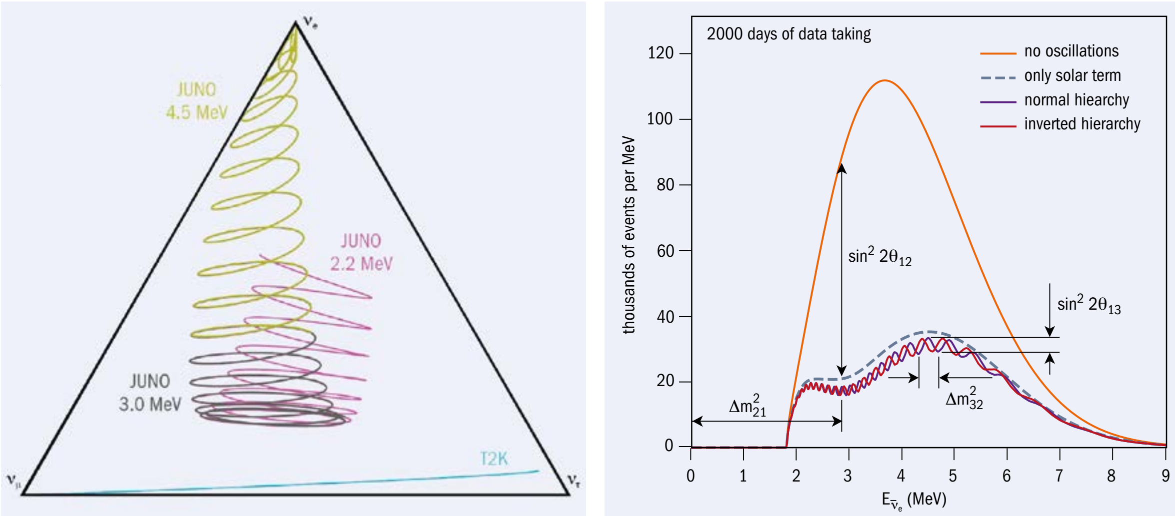

JUNO

An oscillation within an oscillation *Left: the evolution of the fraction of each flavour in the wavefunction of electron antineutrinos as they traverse the 53 km from a nuclear reactor to the JUNO detector at three different energies. The fine oscillations due to Δm^2_{32} are plotted coiling in the sense corresponding to the normal mass hierarchy. The evolution of a muon neutrino in the T2K experiment is plotted for reference. Right: JUNO plans to distinguish the mass hierarchy through exquisite energy resolution.*

rather than gaseous argon as a drift medium for ionisation electrons. Given liquid-argon's higher density, such detectors can serve as both target and tracker, providing high-resolution 3D images of the interactions – an invaluable tool for reducing systematics related to the murky world of neutrino–nucleus interactions.

Spectacular performance

The technology is currently being developed in two prototype detectors at CERN. The first hones ICARUS's single-phase approach. "The performance of the prototype has been absolutely spectacular, exceeding everyone's expectations," says DUNE co-spokesperson Ed Blucher of the University of Chicago. "After almost two years of operation, we are confident that the liquid-argon technology is ready to be deployed at the huge scale of the DUNE detectors." In parallel, the second prototype is testing a newer dual-phase concept. In this design, ionisation charges drift through an additional layer of gaseous argon before reaching the readout plane. The signal can be amplified here, potentially easing noise requirements for the readout electronics, and increasing the maximum size of the detector. The dual-phase prototype was filled with argon in summer 2019 and is now recording tracks.

A rich programme of short-baseline experiments promises to confirm or exclude hints of a fourth sterile neutrino

The final detectors will have about twice the height and 10 to 20 times the footprint. Following the construction of an initial single-phase unit, the DUNE collaboration will likely pick a mix of liquid-argon technologies to complete their roster of four 10 kton far-detector modules, set to be installed a kilometre underground at the Sanford Underground Research Laboratory in Lead, South Dakota. Site preparation and pre-excavation activities began in 2017, and full excavation work is expected to begin soon, with the goal that data-taking begin during the second half of this decade. Work on the near-detector site and the "PIP-II" upgrade to Fermilab's accelerator complex began last year.

Though similar to Hyper-Kamiokande at first glance, DUNE's approach is distinct and complementary. With beam energy and baseline both four times greater, DUNE will have greater sensitivity to flavour-dependent coherent-forward-scattering with electrons in Earth's crust – an effect that modifies oscillation probabilities differently depending on the mass hierarchy. With the Fermilab beam directed straight at the detector rather than off-axis, a broader range of neutrino energies will allow DUNE to observe the oscillation pattern from the first to the second oscillation maximum, and simultaneously fit all but the solar mixing parameters. And with detector, flux and interaction uncertainties all distinct, a joint analysis of both experiments' data could break degeneracies and drive down systematics.

"If CP violation is maximal and the experiments collect data as anticipated, DUNE and Hyper-Kamiokande should both approach 5σ significance for the exclusion of leptonic CP conservation in about five years," estimates DUNE co-spokesperson Stefan Söldner-Rembold of the University of Manchester, noting that the experiments will also be highly complementary for non-accelerator topics. The most striking example is supernova-burst neutrinos, he says, referring to a genre of neutrinos only observed once so far, during 15 seconds in 1987, when neutrinos from a supernova in the Large Magellanic Cloud passed through the Earth. "While DUNE is primarily sensitive to electron neutrinos, Hyper-Kamiokande will be sensitive to electron antineutrinos. The difference between the timing distributions of these samples encodes key information about the dynamics of the supernova explosion." Hyper-Kamiokande spokesperson Masato Shiozawa of ICRR Tokyo also emphasises the broad scope of the physics programmes. "Our studies

JUNO

Call to ordering *Excavation of the cavern for the JUNO experiment, a 20 kton liquid-scintillator detector located 700 m beneath the Dashi hill in Guangdong, China, is almost complete.*

will also encompass proton decay, high-precision measurements of solar neutrinos, supernova-relic neutrinos, dark-matter searches, the possible detection of solar-flare neutrinos and neutrino geophysics."

Half a century since Ray Davis and two co-authors published evidence for a 60% deficit in the flux of solar neutrinos compared to John Bahcall's prediction, DUNE already boasts more than a thousand collaborators, and Hyper-Kamiokande's detector mass is set to be 500 times greater than Davis's tank of liquid tetrachloroethylene. If Ray Davis was the conductor who set the orchestra in motion, then these large experiments fill out the massed ranks of the violin section, poised to deliver what may well be the most stirring passage of the neutrino-oscillation symphony. But other sections of the orchestra also have important parts to play.

Mass hierarchy

The question of the neutrino mass hierarchy will soon be addressed by the Jiangmen Underground Neutrino Observatory (JUNO) experiment, which is currently under construction in China. The project is an evolution of the Daya Bay experiment, and will seek to measure a deficit of electron antineutrinos 53 km from the Yangjiang and Taishan nuclear-power plants. As the reactor neutrinos travel, the small kilometre-scale oscillation observed by Daya Bay will continue to undulate with the same wavelength, revealed in JUNO as "fast" oscillations on a slower and deeper first oscillation maximum due to the smaller solar mass splitting Δm^2_{21} (see "An oscillation within an oscillation" figure).

"JUNO can determine the neutrino mass hierarchy in an unambiguous and definite way, independent from the CP phase and matter effects, unlike other experiments using accelerator or atmospheric neutrinos," says spokesperson Yifang Wang of the Chinese Academy of Sciences in Beijing. "In six years of data taking, the statistical significance will be higher than 3σ."

JUNO has completed most of the digging of the underground laboratory, and equipment for the production and purification of liquid scintillator is being fabricated. A total of 18,000 20-inch photomultiplier tubes and 26,000 3-inch photomultiplier tubes have been delivered, and most of them have been tested and accepted, explains Wang. The installation of the detector is scheduled to begin next year. JUNO will arguably be at the vanguard of a precision era for the physics of neutrino oscillations, equipped to measure the mass splittings and the solar mixing parameters to better than 1% precision – an improvement of about one order of magnitude over previous results, and even better than the quark sector, claims Wang, somewhat provocatively. "JUNO's capabilities for supernova-burst neutrinos, diffused supernova neutrinos and geoneutrinos are unprecedented, and it can be upgraded to be a world-best double-beta-decay detector once the mass hierarchy is measured."

With JUNO, Hyper-Kamiokande and DUNE now joining a growing ensemble of experiments, the unresolved leitmotifs of the three-neutrino paradigm may find resolution this decade, or soon after. But theory and experiment both hint, quite independently, that nature may have a scherzo twist in store before the grand finale.

A rich programme of short-baseline experiments promises to bolster or exclude experimental hints of a fourth sterile neutrino with a relatively large mixing with the electron neutrino that have dogged the field since the late 1990s. Four anomalies stack up as more or less consistent among themselves. The first, which emerged in the mid-1990s at Los Alamos's Liquid Scintillator Neutrino

CERNCOURIER
VOLUME 60 NUMBER 4 JULY/AUGUST 2020
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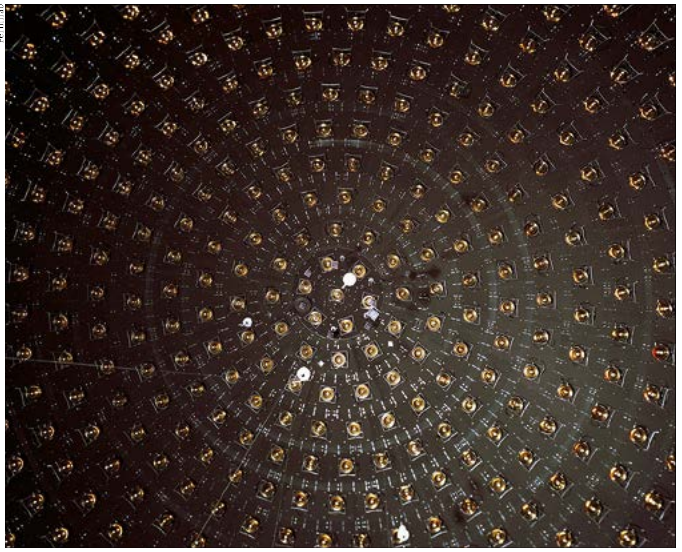


Fermilab

Sterile suggestion *In 2018 the MiniBooNE collaboration reported evidence for an excess 381.2 ± 85.2 electron–neutrino events in their detector (pictured), compared to expected rates.*

Detector (LSND), is an excess of electron antineutrinos that is potentially consistent with oscillations involving a sterile neutrino at a mass splitting $\Delta m^2 \sim 1\,eV^2$. Two other quite disparate anomalies since then – a few-percent deficit in the expected flux from nuclear reactors, and a deficit in the number of electron neutrinos from radioactive decays in liquid-gallium solar-neutrino detectors – could be explained in the same way. The fourth anomaly, from Fermilab's MiniBooNE experiment, which sought to replicate the LSND effect at a longer baseline and a higher energy, is the most recent: a sizeable excess of both electron neutrinos and antineutrinos, though at a lower energy than expected. It's important to note, however, that experiments including KARMEN, MINOS+ and IceCube have reported null searches for sterile neutrinos that fit the required description. Such a particle would also stand in tension with cosmology, notes phenomenologist Silvia Pascoli of Durham University, as models predict it would make too large a contribution to hot dark matter in the universe today, unless non-standard scenarios are invoked.

Three different types of experiment covering three orders of magnitude in baseline are now seeking to settle the sterile-neutrino question in the next decade. A smattering of reactor-neutrino experiments a mere 10 metres or so from the source will directly probe the reactor anomaly at $\Delta m^2 \sim 1\,eV^2$. The data reported so far are intriguing. Korea's NEOS experiment and Russia's DANSS experiment report siren signals between 1 and $2\,eV^2$, and NEUTRINO-4, also based in Russia, reports a seemingly outlandish signal, indicative of very large mixing, at $7\,eV^2$. In parallel, J-PARC's JSNS[2] experiment is gearing up to try to reproduce the LSND effect using accelerator neutrinos at the same energy and baseline. Finally, Fermilab's short-baseline programme will thoroughly address a notable weakness of both LSND and MiniBooNE: the lack of a near detector.

The Fermilab programme will combine three liquid-argon TPCs – a bespoke new short-baseline detector (SBND), the existing MicroBooNE detector, and the refurbished ICARUS detector – to resolve the LSND anomaly once and for all. SBND is currently under construction, MicroBooNE is operational, and ICARUS, removed from its berth at Gran Sasso and shipped to the US in 2017, has been installed at Fermilab, following work on the detector at CERN. "The short-baseline neutrino programme at Fermilab has made tremendous technical progress in the past year," says ICARUS spokesperson and Nobel laureate Carlo Rubbia, noting that the detector will be commissioned as soon as circumstances allow, given the coronavirus pandemic. "Once both ICARUS and SBND are in operation, it will take less than three years with the nominal beam intensity to settle the question of whether neutrinos have an even more mysterious character than we thought."

Outside of the purview of oscillation experiments with artificially produced neutrinos, astrophysical observatories will scale a staggering energy range, from the PeV-scale neutrinos reported by IceCube at the South Pole, down, perhaps, to the few-hundred-μeV cosmic neutrino background sought by experiments such as PTOLEMY in the US. Meanwhile, the KATRIN experiment in Germany is zeroing in on the edges of beta-decay distributions to set an absolute scale for the mass of the peculiar mixture of mass eigenstates that make up an electron antineutrino (*CERN Courier* January/February 2020 p28). At the same time, a host of experiments are searching for neutrinoless double-beta decay – a process that can only occur if the neutrino is its own antiparticle. Discovering such a Majorana nature for the neutrino would turn the Standard Model on its head, and offer grist for the mill of theorists seeking to explain the tininess of neutrino masses, by balancing them against still-to-be-discovered heavy neutral leptons.

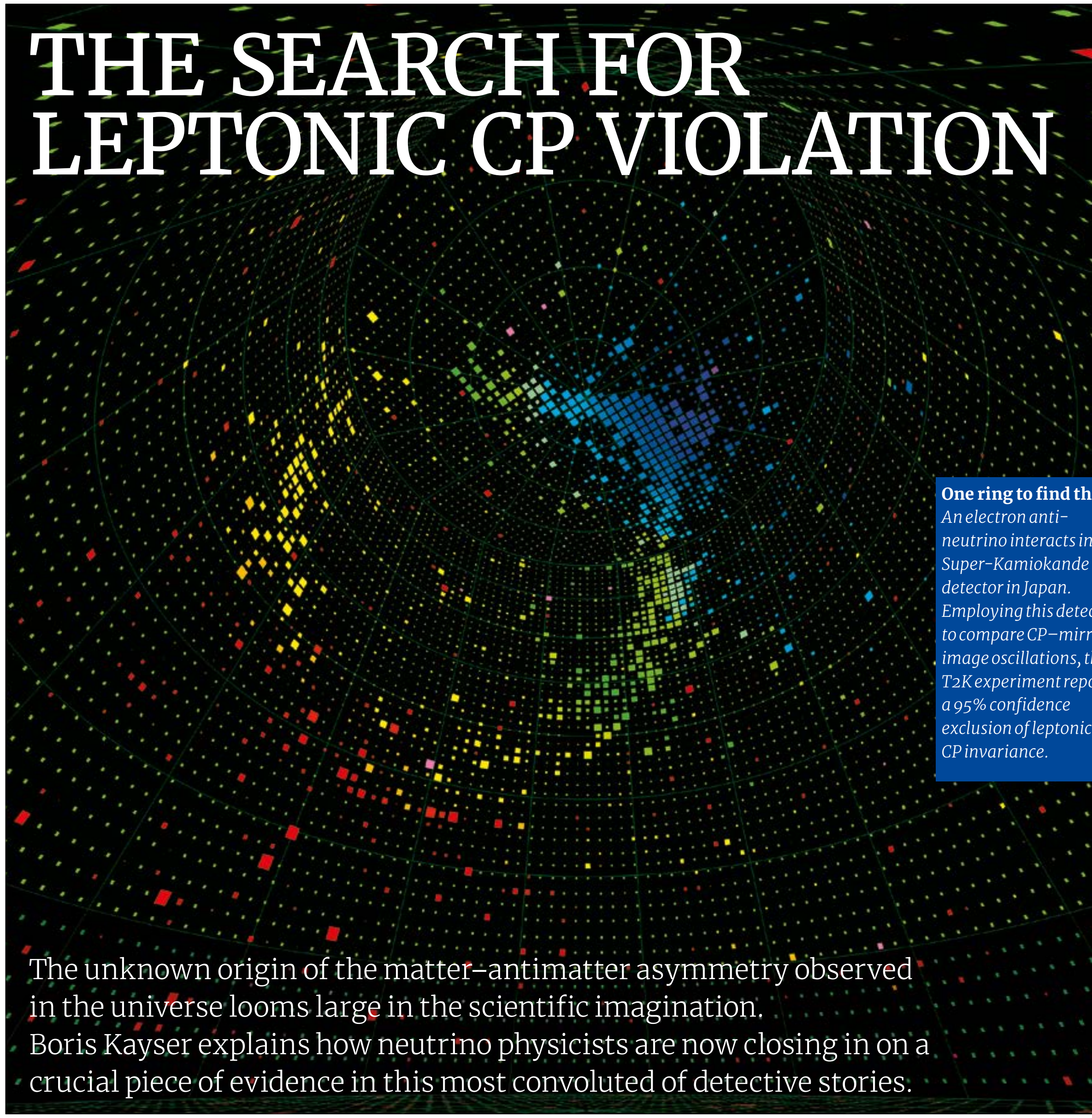
Indispensable input

According to Mikhail Shaposhnikov of the Swiss Federal Institute of Technology in Lausanne, current and future reactor- and accelerator-neutrino experiments will provide an indispensable input for understanding neutrino physics. And not in isolation. "To reach a complete picture, we also need to know the mechanism for neutrino-mass generation and its energy scale, and the most important question here is the scale of masses of new neutrino states: if lighter than a few GeV, these particles can be searched for at new experiments at the intensity frontier, such as SHiP, and at precision experiments looking for rare decays of mesons, such as Belle II, LHCb and NA62, while the heavier states may be accessible at ATLAS and CMS, and at future circular colliders," explains Shaposhnikov. "These new particles can be the key in solving all the observational problems of the Standard Model, and require a consolidated effort of neutrino experiments, accelerator-based experiments and cosmological observations. Of course, it remains to be seen if this dream scenario can indeed be realised in the coming 20 years." •

Further reading

F Close 2012 *Neutrino* Oxford University Press.
C Giunti and T Lasserre 2019 *Ann. Rev. Nucl. Part. Sci.* **69** 163.

THE SEARCH FOR LEPTONIC CP VIOLATION



One ring to find them *An electron anti-neutrino interacts in the Super-Kamiokande detector in Japan. Employing this detector to compare CP-mirror-image oscillations, the T2K experiment reported a 95% confidence exclusion of leptonic CP invariance.*

Super-Kamiokande

The unknown origin of the matter–antimatter asymmetry observed in the universe looms large in the scientific imagination. Boris Kayser explains how neutrino physicists are now closing in on a crucial piece of evidence in this most convoluted of detective stories.

Luckily for us, there is presently almost no antimatter in the universe. This makes it possible for us – made of matter – to live without being annihilated in matter–antimatter encounters. However, cosmology tells us that just after the cosmic Big Bang, the universe contained equal amounts of matter and antimatter. Obviously, for the universe to have evolved from that early state to the present one, which contains quite unequal amounts of matter and antimatter, the two must behave differently. This implies that the symmetry CP (charge conjugation × parity) must be violated. That is, there must be physical systems whose behaviour changes if we replace every particle by its antiparticle, and interchange left and right.

In 1964, Cronin, Fitch and colleagues discovered that CP is indeed violated, in the decays of neutral kaons to pions – a phenomenon that later became understood in terms of the behaviour of quarks. By now, we have observed quark CP violation in the strange sector, the beauty sector and most recently in the charm sector (*CERN Courier* May/June 2019 p7). The observations of CP violation in B (beauty) meson decays have been particularly illuminating. Everything we know about quark CP violation is consistent with the hypothesis that this violation arises from a single complex phase in the quark mixing matrix. This matrix gives the amplitude for any particular negatively-charged quark, whether down, strange or bottom, to convert via a weak interaction into any particular positively-charged quark, be it up, charm or top. Just two parameters in the quark mixing matrix, ρ and η, whose relative size determines the complex phase, account very successfully for numerous quark phenomena, including both CP-violating ones and others. This is impressively demonstrated by a plot of all the experimental constraints on these two parameters (figure 1). All the constraints intersect at a common point.

THE AUTHOR
Boris Kayser *Fermilab.*

Of course, precisely which (ρ, η) point is consistent with all the data is not important. Lincoln Wolfenstein, who created the quark-mixing-matrix parametrisation that includes ρ and η, was known to say: "Look, I invented ρ and η, and I don't care what their values are, so why should you?"

Having observed CP violation among quarks in numerous laboratory experiments of today, we might be tempted to think that we understand how CP violation in the early universe could have changed the world from one with equal quantities of matter and antimatter to one in which matter dominates very heavily over antimatter. However, scenarios that tie early-universe CP violation to that seen among the quarks today, and do not add new physics to the Standard Model of the elementary particles, yield too small a present-day matter–antimatter asymmetry. This leads one to wonder whether early-universe CP violation involving leptons, rather than quarks, might have led to the present dominance of matter over antimatter. This possibility is envisaged by leptogenesis, a scenario in which heavy neutral leptons that were their own antiparticles lived briefly in the early universe, but then underwent CP-asymmetric decays, creating a world with unequal numbers of particles and antiparticles. Such heavy neutral leptons are predicted by "see-saw" models, which explain the extreme lightness of the known neutrinos in terms of the extreme heaviness of the postulated heavy neutral leptons. Leptogenesis can successfully account for the observed size of the present matter–antimatter asymmetry.

Deniable plausibility

In the straightforward version of this picture, the heavy neutral leptons are too massive to be observable at the LHC or any foreseen collider. However, since leptogenesis requires leptonic CP violation, observing this violation in the behaviour of the currently observed leptons would make it more plausible that leptogenesis was indeed the mechanism through which the present matter–antimatter asymmetry of the universe arose. Needless to say, observing leptonic CP violation would also reveal that the breaking of CP symmetry, which before 1964 one might have imagined to be an unbroken, fundamental symmetry of nature, is not something special to the quarks, but is participated in by all the constituents of matter.

To find out if leptons violate CP, we are searching for what is traditionally described as a difference between the behaviour of neutrinos and that of antineutrinos. This description is fine if neutrinos are Dirac particles – that is, particles that are distinct from their antiparticles. However, many theorists strongly suspect that neutrinos are actually Majorana particles – that is, particles that are identical to their antiparticles. In that case, the traditional description of the search for leptonic CP violation is clearly inapplicable, since then the neutrinos and the antineutrinos are the same objects. However, the actual experimental approach that is being pursued is a perfectly valid probe of leptonic CP violation regardless of whether neutrinos are of Dirac or of Majorana character. In fact, this approach is completely insensitive to which of these two possibilities nature has chosen.

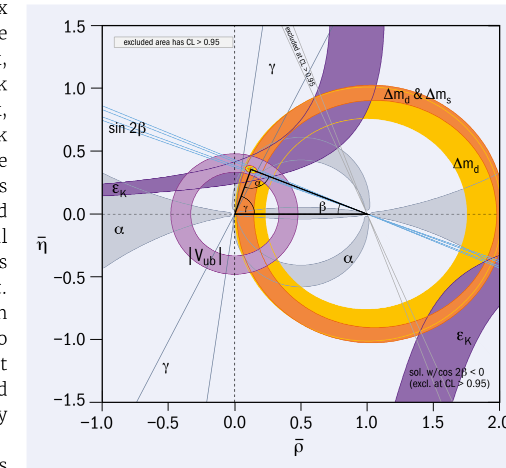


Fig. 1. *All the experimental constraints on the quark-mixing parameters relating to CP violation intersect at a single point at the apex of the black triangle. (Reproduced from PDG* Phys. Rev. D *2018* **98** *030001 p234)*

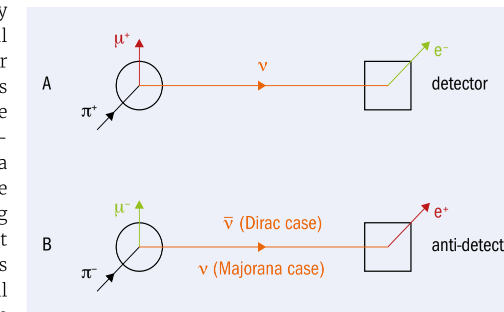
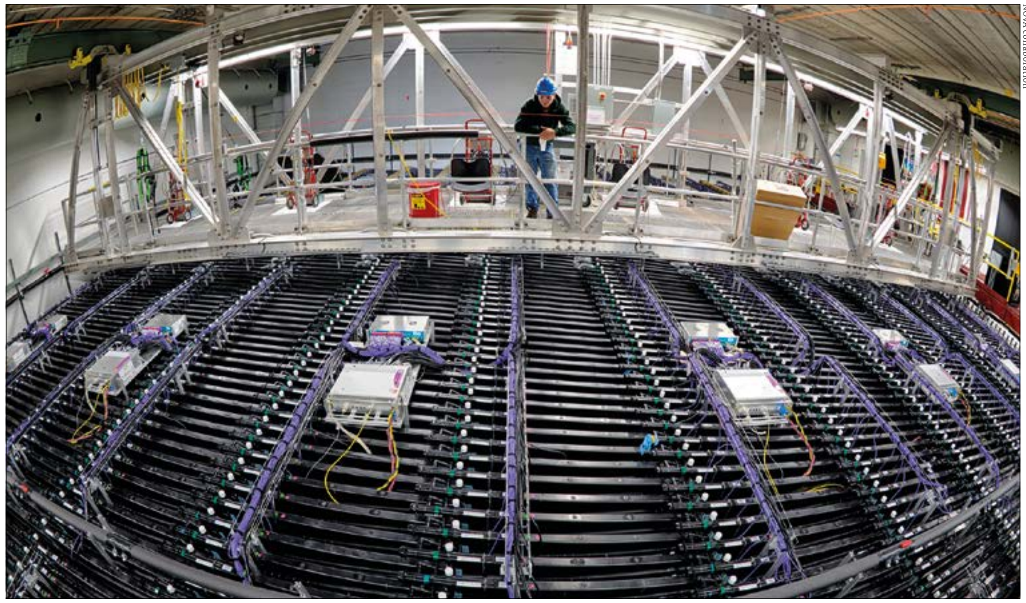


Fig. 2. *The pursuit of leptonic CP violation is based on comparing the rates for two CP-mirror-image processes.*

Through a glass darkly

The pursuit of leptonic CP violation is based on comparing the rates for two CP mirror-image processes (figure 2). In process A, the initial state is a π^+ and an undisturbed detector. The final state consists of a μ^+, an e^-, and a nucleus in the detector that has been struck by an intermediate-state neutrino beam particle that travelled a long distance from its source to the detector. Since the neutrino was born together with a muon, but produced an electron in the detector, and the probability for this to have happened oscillates as a function of the distance

Leptogenesis can account for the matter–antimatter asymmetry



NOvA collaboration

Super NOvA *A 14 kton stack of scintillating cells filled with mineral oil, the NOvA far detector, at Ash River, Minnesota, searches for neutrino oscillations using an accelerator beam created 810 km away at Fermilab, near Chicago.*

the neutrino travels divided by its energy, the process is commonly referred to as muon-neutrino to electron-neutrino oscillation.

In process B, the initial and final states are the same as in process A, but with every particle replaced by its antiparticle. In addition, owing to the character of the weak interactions, the helicity (the projection of the spin along the momentum) of every fermion is reversed, so that left and right are interchanged. Thus, regardless of whether neutrinos are identical to their antiparticles, processes A and B are CP mirror images, so if their rates are unequal, CP invariance is violated. Moreover, since the probability of a neutrino oscillation involves the weak interactions of leptons, but not those of quarks, this violation of CP invariance must come from the weak interactions of leptons.

Of course, we cannot employ an anti-detector in process B in practice. However, the experiment can legitimately use the same detector in both processes. To do that, it must take into account the difference between the cross sections for the beam particles in processes A and B to interact in this detector. Once that is done, the comparison of the rates for processes A and B remains a valid probe of CP non-invariance.

The matrix reloaded

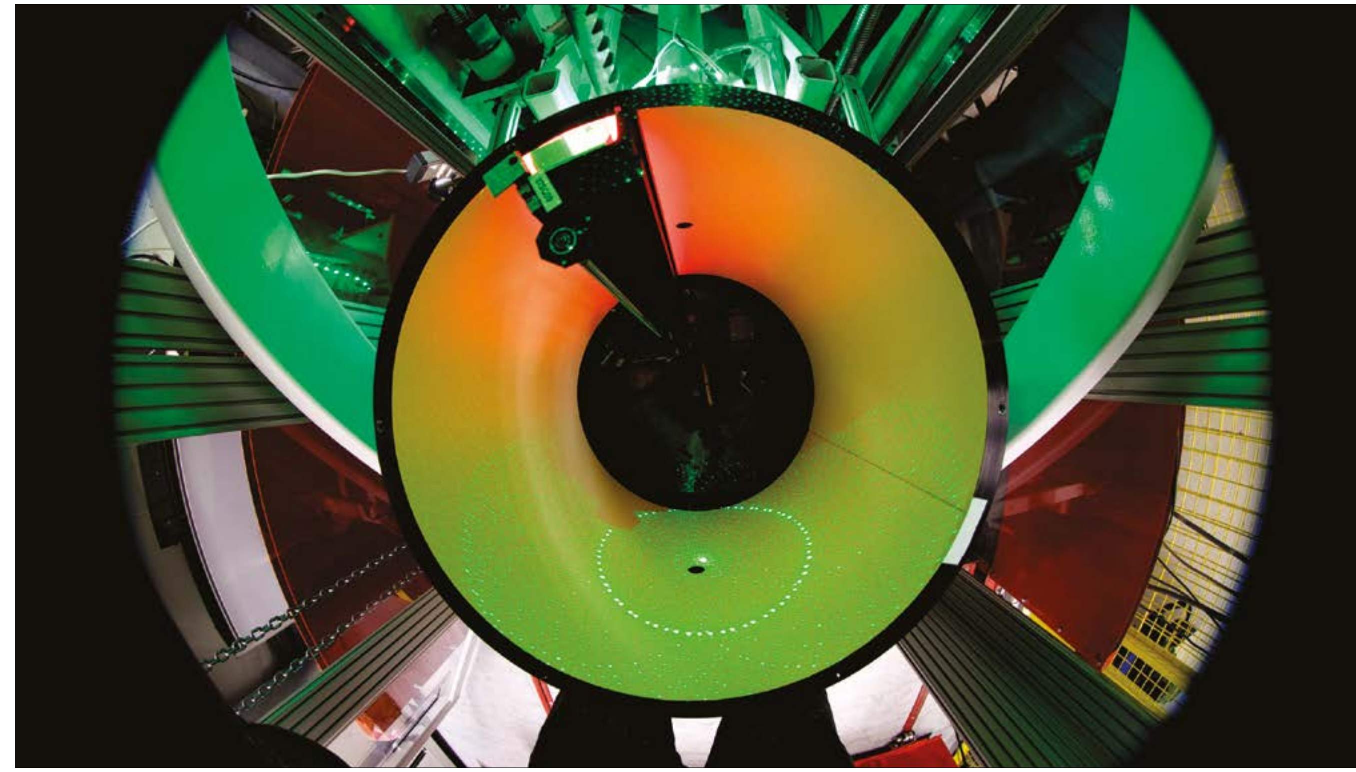
Just as quark CP violation arises from a complex phase in the quark mixing matrix, so leptonic CP violation in neutrino oscillation can arise from a complex phase, δ_{CP}, in the leptonic mixing matrix, which is the leptonic analogue of the quark mixing matrix. However, if, as suggested by several short-baseline oscillation experiments, there exist not only the three well-established neutrinos, but also additional so-called "sterile" neutrinos that do not participate in Standard Model weak interactions, then the leptonic mixing matrix is larger than the quark one. As a result, while the quark mixing matrix is permitted to contain just one complex phase, its leptonic analogue may contain multiple complex phases that can contribute to CP violation in neutrino oscillations.

T2K excludes the complete absence of leptonic CP violation at 95% confidence

Leptonic CP violation is being sought by two current neutrino-oscillation experiments. The NOvA experiment in the US has reported results that are consistent with either the presence or absence of CP violation. The T2K experiment in Japan reports that the complete absence of CP violation is excluded at 95% confidence (see p8). Assuming that the leptonic mixing matrix is the same size as the quark one, so that it may contain only one complex phase relevant to neutrino oscillations, the T2K data show a preference for values of that phase, δ_{CP}, that correspond to near maximal CP violation. Of course, as Lincoln Wolfenstein would doubtless point out, the precise value of δ_{CP} is not important. What counts is the extremely interesting experimental finding that the behaviour of leptons may very well violate CP. In the future, the oscillation experiments Hyper-Kamiokande in Japan and DUNE in the US will probe leptonic CP violation with greater sensitivity, and should be capable of observing it even if it should prove to be fairly small (see p32).

By searching for leptonic CP violation, we hope to find out whether the breaking of CP symmetry occurs among all the constituents of matter, including both the leptons and the quarks, or whether it is a feature that is special to the quarks. If leptonic CP violation should be definitively shown to exist, this violation might be related to the reason that the universe contains matter, but almost no antimatter, so that life is possible. ●

Further reading
The NOvA Collaboration 2019 *Phys. Rev. Lett.* **123** 151803.
The T2K Collaboration 2020 *Nature* **580** 339.



An eye for structure *The LADI instrument at the ILL, a quasi-Laue neutron diffractometer used for single-crystal studies of biological macromolecules at high resolution. Neutron Laue diffraction patterns are recorded on a cylindrical detector, allowing the determination of protein structures including the locations of hydrogen/deuterium atoms. (Credit: R Cubitt)*

NEUTRON SOURCES JOIN THE FIGHT AGAINST COVID-19

Advanced neutron facilities such as the Institut Laue-Langevin are gearing up to enable a deeper understanding of the structural workings of SARS-CoV-2.

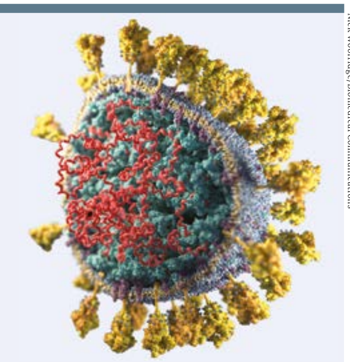
The global scientific community has mobilised at an unprecedented rate in response to the COVID-19 pandemic, beyond just pharmaceutical and medical researchers. The world's most powerful analytical tools, including neutron sources, harbour the unique ability to reveal the invisible, structural workings of the virus – which will be essential to developing effective treatments. Since the outbreak of the pandemic, researchers worldwide have been using large-scale research infrastructures such as synchrotron X-ray radiation sources (*CERN Courier* May/June 2020 p29), as well as cryogenic electron microscopy (cryo-EM) and nuclear magnetic resonance (NMR) facilities, to determine the 3D structures of proteins of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), which can lead to COVID-19 respiratory disease, and to identify potential drugs that can bind to these proteins in order to disable the viral machinery. This effort has already delivered a large number of structures and increased our understanding of what potential drug candidates might look like in a remarkably short amount of time, with the number increasing each week.

COVID-19 impacted the operation of all advanced neutron sources worldwide. With one exception (ANSTO in Australia, which continued the production of radioisotopes) all of

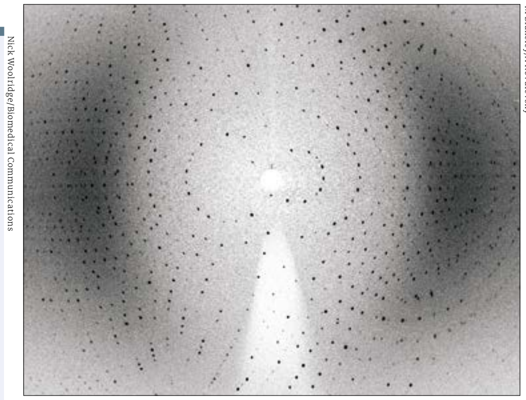
THE AUTHORS
Matthew Blakeley and **Helmut Schober** *Institut Laue-Langevin.*

Structural power

Determining the biological structures that make up a virus such as SARS-CoV-2 (pictured) allows scientists to see what they look like in three dimensions and to understand better how they function, speeding up the design of more effective anti-viral drugs. Knowledge of the structures highlights which parts are the most important: for example, once researchers know what the active site in an enzyme looks like, they can try to design drugs that fit well into the active site – the classic "lock-and-key" analogy. This is also useful in the development of vaccines. Knowledge of the structural components that make up a virus are important since vaccines are often made from weakened or killed forms of the microbe, its toxins, or one of its surface proteins.



Nick Woolridge/Biomedical Communications



M Blakeley/A Kovalevsky

Neutron diffraction *A neutron Laue diffraction pattern from a crystal of HIV-1 protease in complex with a clinical inhibitor collected using the LADI instrument at ILL.*

them were shut down in the context of national lockdowns aimed at reducing the spread of the disease. The neutron community, however, lost no time in preparing for the resumption of activities. Some facilities like Oak Ridge National Laboratory (ORNL) in the US have now restarted operation of their sources exclusively for COVID-19 studies. Here in Europe, while waiting (impatiently) for the restart of neutron facilities such as the Institut Laue-Langevin (ILL) in Grenoble, which is scheduled to be operational by mid-August, scientists have been actively pursuing SARS-CoV-2-related projects. Special research teams on the ILL site have been preparing for experiments using a range of neutron-scattering techniques including diffraction, small-angle neutron scattering, reflectometry and spectroscopy. Neutrons bring to the table what other probes cannot, and are set to make an important contribution to the fight against SARS-CoV-2.

Unique characteristics

Discovered almost 90 years ago, the neutron has been put to a multitude of uses to help researchers understand the structure and behaviour of condensed-matter. These applications include a steadily growing number of investigations into biological systems. For the reasons explained below, these investigations are complementary to the use of X-rays, NMR and cryo-EM. The necessary infrastructure for neutron-scattering experiments is provided to the academic and industrial user communities by a global network of advanced neutron sources. Leading European neutron facilities include the ILL in Grenoble, France, MLZ in Garching, Germany, ISIS in Didcot, UK, and PSI in Villigen, Switzerland. The new European flagship neutron source – the European Spallation Source (ESS) – is under construction in Lund, Sweden.

Neutrons are a particularly powerful tool for the study of biological macromolecules in solutions, crystals and partially ordered systems. Their neutrality means neutrons can penetrate deep into matter without damaging the samples, so that experiments can be performed at room temperature, much closer to physiological temperatures.

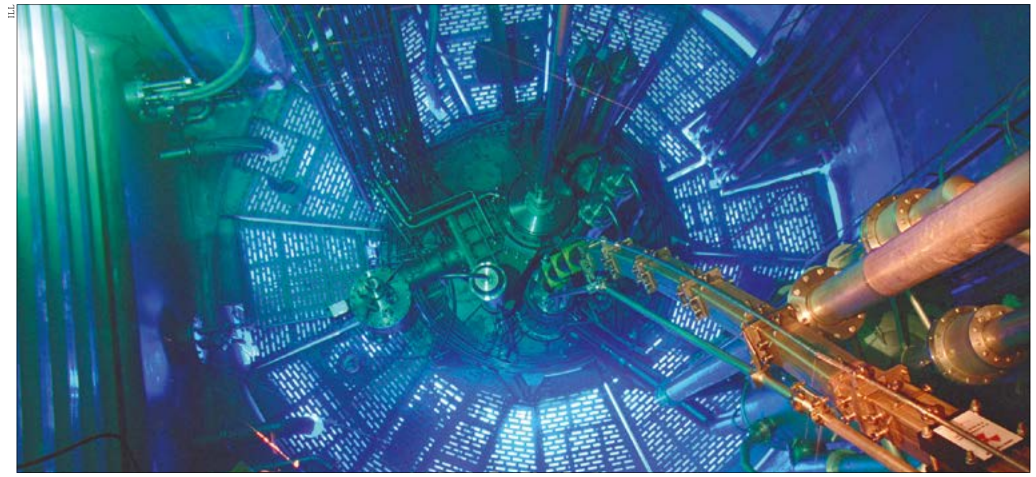
Neutrons can penetrate deep into matter without damaging the samples

Furthermore, in contrast to X-rays, which are scattered by electrons, neutrons are scattered by atomic nuclei, and so neutron-scattering lengths show no correlation with the number of electrons, but rather depend on nuclear forces, which can even vary between different isotopes. As such, while hydrogen (H) scatters X-rays very weakly, and protons (H^+) do not scatter X-rays at all, with neutrons hydrogen scatters at a similar level to the other common elements (C, N, O, S, P) of biological macromolecules, allowing them to be located. Moreover, since hydrogen and its isotope deuterium (^{2}H/D) exhibit different scattering lengths and signs, this can be exploited in neutron studies to enhance the visibility of specific structural features by substituting one isotope for the other. Examples of this include small-angle neutron scattering (SANS) studies of macromolecular structures that provide low-resolution 3D information on molecular shape without the need for crystallization, and neutron-crystallography studies of proteins that provide high-resolution structures of proteins, including the locations of individual hydrogen atoms that have been exchanged for deuterium to make them particularly visible. Indeed, neutron crystallography can provide unique information on the chemistry occurring within biological macromolecules, such as enzymes, as recent studies on HIV-1 protease, an enzyme essential for the life-cycle of the HIV virus, illustrate.

Treating and stopping COVID-19

Proteases are like biological scissors that cleave polypeptide chains – the primary structure of proteins – at precise locations. If the cleavage is inhibited, for example, by appropriate anti-viral drugs, then so-called poly-proteins remain in their original state and the machinery of virus replication is blocked. For the treatment to be efficient this inhibition has to be robust—that is, the drug occupying the active site should be strongly bound, ideally to atoms in the main chain of the protease. This will increase the likelihood that treatments are effective in the long run, despite mutations of the enzyme, since mutations occur only within the side chains of the enzyme. Neutron research, therefore,

ILL



High flux *The ILL reactor, which typically operates four 50-day cycles per year for user experiments, provides the most intense continuous neutron flux in the world: 1.5×10^{15} neutrons per second per cm^2, with a thermal power of 58.3 MW.*

provides essential input into the long-term development of pharmaceuticals. This role will be further enhanced in the context of advanced computer-aided drug development that will rely on an orchestrated combination of high-power computing, artificial intelligence and broad-band experimental data on structures.

Neutron crystallography data add supplementary structural information to X-ray data by providing key details regarding hydrogen atoms and protons, which are critical players in the binding of such drugs to their target enzyme through hydrogen bonding, and revealing important details of protein chemistry that help researchers decipher the exact enzyme catalytic pathway. In this way, neutron crystallography data can be hugely beneficial towards understanding how these enzymes function and the design of more effective medications to target them. For example, in the study of complexes between HIV-1 protease – the enzyme responsible for maturation of virus particles into infectious HIV virions – and drug molecules, neutrons can reveal hydrogen-bonding interactions that offer ways to enhance drug-binding and reduce drug-resistance of anti-retroviral therapies.

More than half of the SARS-CoV-2-related structures determined thus far are high-resolution X-ray structures of the virus's main protease, with the majority of these bound to potential inhibitors. One of the main challenges for performing neutron crystallography is that larger crystals are required than for comparable X-ray crystallography studies, owing to the lower flux of neutron beams relative to X-ray beam intensities. Nevertheless, given the benefits provided by the visualisation of hydrogen-bonding networks for understanding drug-binding, scientists have been optimising crystallisation conditions for the growth of larger crystals, in combination with the production of fully deuterated protein in preparation for neutron crystallography experiments in the near future. Currently, teams at ORNL, ILL and the DEMAX facility in Sweden are growing crystals for SARS-CoV-2 investigations.

Proteases are, however, not the only proteins where neutron crystallography can provide essential information. For example, the spike protein (S-protein) of SARS-CoV-2 that is responsible for mediating the attachment and entry into human cells is of great relevance for developing therapeutic defence strategies against the virus. Here, neutron crystallography can potentially provide unique information about the specific domain of the S-protein where the virus binds to human cell receptors. Comparison of the structure of this region between different variations of coronavirus (SARS-CoV-2 and SARS-CoV) obtained using X-rays suggests small alterations to the amino-acid sequence may enhance the binding affinity of the S-protein to the human receptor hACE2, making SARS-CoV-2 more infectious. Neutron studies will provide further insight into this binding, which is crucial for the attachment of the virus. These experiments are scheduled to take place, e.g. at ILL and ORNL (and possibly MLZ), as soon as large enough crystals have been grown.

The big picture

Biological systems have a hierarchy of structures: starting from molecules that assemble into structures such as proteins; these form complexes which, as supramolecular arrangements like membranes, are the building blocks of cells. These are of course the building blocks of our bodies. Every part of this huge machinery is subject to continuous reorganisation. To understand the functioning, or in the case of a disease, the malfunctioning of a biological system, we therefore must get insight into the biological mechanism on all of these different length scales.

When it comes to studying the function of larger biological complexes such as assembled viruses, SANS becomes an important analytical tool. The technique's capacity to distinguish specific regions (RNA, proteins and lipids) of the virus – thanks to advanced deuteration methods – enables researchers to map out the arrangement of the various components, contributing invaluable information to structural studies of SARS-CoV-2. While other analytical techniques provide the detailed atomic-resolution structure of small biological assemblies, neutron scattering allows researchers to pan back to see the larger

CERNCOURIER
VOLUME 60 NUMBER 4 JULY/AUGUST 2020
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picture of full molecular complexes, at lower resolution. Neutron scattering is also uniquely suited to determining the structure of functional membrane proteins in physiological conditions. Neutron scattering will therefore make it possible to map out the structure of the complex formed by the S-protein and the hACE2 receptor.

Last but not least, a full understanding of the virus's life cycle requires the study of the interaction of the virus with the cell membrane, and the mechanism it uses to penetrate the host cell. SARS-CoV-2 is a virus, like HIV, that possesses a viral envelope composed of lipids, proteins and sugars. By providing information on its molecular structure and composition, the technique of neutron reflectometry – whereby highly collimated neutrons are incident on a flat surface and the intensity of reflected radiation is measured as a function of angle or neutron wavelength – helps to elucidate the precise mechanism the virus uses to penetrate the cell. Like in the case of SANS, the strength of neutron reflectometry relies on the fact that it provides a different contrast to X-rays, and that this contrast can be varied via deuteration allowing, for example, to distinguish a protein inserted into the membrane from the membrane itself. Regarding SARS-CoV-2, this implies that neutron reflectometry can in fact provide detailed structural information on the interaction of small protein fragments, so-called peptides, that mimic the S-protein and that are believed to be responsible for binding with the receptor of the host cell. Defining this mechanism, which is decisive for the infection, will be essential to controlling the virus and its potential future mutations in the long term.

Neutron scattering is also uniquely suited to determining the structure of functional membrane proteins

Tool of choice

And we should not forget that viruses in their physiological environments are highly dynamic systems. Knowing how they move, deform and cluster is essential for optimising diagnostic and therapeutic treatments. Neutron spectroscopy, which is ideally suited to follow the motion of matter from small chemical groups to large macromolecular assemblies, is the tool of choice to provide this information.

The League of Advanced European Neutron Sources (*CERN Courier* May/June 2020 p49) has rapidly mobilised to conduct all relevant experiments. We are equally in close contact with our international partners, some of whom have, or are just in the process of, reopening their facilities. Scientists have to make sure that each research subject is provided with the best-suited analytical tool – in other words, those that have the samples will be given the necessary beam time. Neutron facilities are fast-adapting with special access channels to beam time having been implemented to allow the scientific community to respond without delay to the challenge posed by COVID-19. ●

A price worth paying

Large research infrastructures are essential drivers of economic progress, and particle physicists have a duty to make this message loud and clear, argues Rolf Heuer.

M Brice/CERN

Rolf-Dieter Heuer *was CERN Director-General from 2009 to 2015.*

Science, from the immutable logic of its mathematical underpinnings to the more fluid realms of the social sciences, has carried us from our humble origins to an understanding of such esoteric notions as gravitation and quantum mechanics. This knowledge has been applied to develop devices such as GPS trackers and smartphones – a story repeated in countless domains for a century or more – and it has delivered new tools for basic research along the way in a virtuous circle.

While it is undeniable that science has led us to a better world than that inhabited by our ancestors, and that it will continue to deliver intellectual, utilitarian and economic progress, advancement is not always linear. Research has led us up blind alleys, and taken wrong turnings, yet its strength is its ability to process data, to self-correct and to form choices based on the best available evidence. The current coronavirus pandemic could prove to be a great educator in the methods of science, demonstrating how the right course of action evolves as the evidence accumulates. We've seen all too clearly how badly things can go wrong when individuals and governments fail to grasp the importance of evidence-based decision making.

Fundamental science has to make its case not only on the basis of cultural wealth, but also in terms of socioeconomic benefit. In particle physics, we also have no shortage of examples. These go well beyond the web, although an economic impact assessment of that particular invention is one that I would be very interested in seeing. As of 2014, there were some 42,200 particle accelerators worldwide, 64% of which were used in industry, a third for medical purposes and just 3% in research – not bad for a technology invented for fundamental exploration. It's a similar story for techniques developed for particle detection, which have found their way into numerous applications, especially in medicine and biology.

Fundamental research is every bit as important as directed research

Deep impact *Projects such as the LHC deliver global visibility and impact.*

The benefits of Big Science for economic prosperity become more pertinent if we consider the cumulative contributions to the 21st-century knowledge economy, which relies heavily on research and innovation. In 2018, more than 40% of the CERN budget was returned to industry in its member-state countries through the procurement of supplies and services, generating corollary benefits such as opening new markets. Increasing efforts, for example by the European Commission, to require research infrastructures to estimate their socioeconomic impact are a welcome opportunity to quantify and demonstrate our impact.

CERN has been subject to economic impact assessments since the 1970s, with one recent cost–benefit analysis of the LHC, conducted by economists at the University of Milan, concluding with 92% probability that benefits exceed costs, even when attaching the very conservative figure of zero to the value of the organisation's scientific discoveries. More recent studies (*CERN Courier* September 2018 p51) by the Milan group, focusing on the High-Luminosity LHC, revealed a quantifiable return to society well in excess of the project's costs, again, not including its scientific output. Extrapolating these results, the authors show that future colliders at CERN would bring similar societal benefits on an even bigger scale.

Across physics more broadly, a 2019 report commissioned by the European Physical Society found that physics-based industries generate more than 16% of total turnover and 12% of overall employment in Europe – representing a net annual contribution of at least €1.45 trillion, and topping contributions from the financial services and retail sectors (*CERN Courier* January/February 2020 p9).

Of course, there are some who feel that limited resources for science should be deployed in areas such as addressing climate change, rather than blue-sky research. These views can be persuasive, but are misleading. Fundamental research is every bit as important as directed research, and through the virtuous circle of science, they are mutually dependent. The open questions and mind-bending concepts explored by particle physics and astronomy also serve to draw bright young minds into science, even if individuals go on to work in other areas. Surveys of the career paths taken by PhD students working on CERN experiments fully bear this out (*CERN Courier* April 2019 p55).

In April 2020, as a curtain-raiser to the update of the European Strategy for Particle Physics, *Nature Physics* published a series of articles about potential future directions for CERN. An editorial pointed out the strong scientific and utilitarian case for future colliders, concluding that: "Even if the associated price tag may seem high – roughly as high as that of the Tokyo Olympic Games – it is one worth paying." This is precisely the kind of argument that we as a community should be prepared to make if we are to ensure continuing exploration of fundamental physics in the 21st century and beyond.

CERNCOURIER
VOLUME 60 NUMBER 4 JULY/AUGUST 2020
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OPINION INTERVIEW

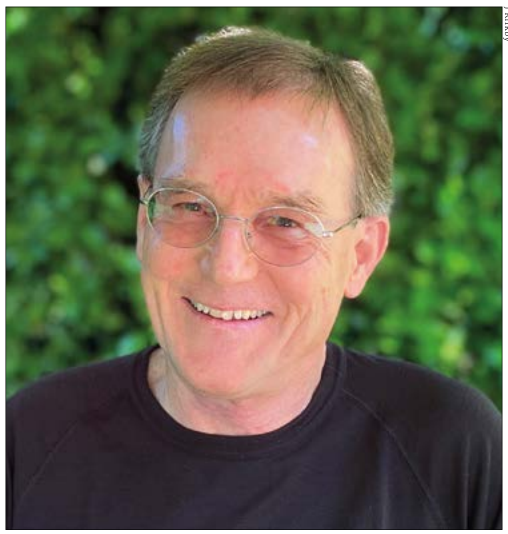
Lofty thinking

CERN's Cosmics Leaving Outdoor Droplets (CLOUD) experiment has merged the best of particle physics and atmospheric science into a novel experimental approach. Spokesperson **Jasper Kirkby** argues that this interdisciplinarity could benefit climate modelling, too.

What, in a nutshell, is CLOUD?

It's basically a cloud chamber, but not a conventional one as used in particle physics. We realistically simulate selected atmospheric environments in an ultraclean chamber and study the formation of aerosol particles from trace vapours, and how they grow to become the seeds for cloud droplets. We can precisely control all the conditions found throughout the atmosphere such as gas concentrations, temperature, ultraviolet illumination and "cosmic ray" intensity with a beam from CERN's Proton Synchrotron (PS). The aerosol processes we study in CLOUD are poorly known yet climatically important because they create the seeds for more than 50% of global cloud droplets.

We have 22 institutes and the crème de la crème of European and US atmospheric and aerosol scientists. It's a fabulous mixture of physicists and chemists, and the skills we've learned from particle physics in terms of cooperating and pooling resources have been incredibly important for the success of CLOUD. It's the CERN model, the CERN culture that we've conveyed to another discipline. We implemented the best of CERN's know-how in ultra-clean materials and built the cleanest atmospheric chamber in the world.



J Kirkby

Interdisciplinary *Jasper Kirkby at his home in May 2020.*

How did CLOUD get off the ground?

The idea came to me in 1997 during a lecture at CERN given by Nigel Calder, a former editor of *New Scientist* magazine, who pointed out a new result from satellite data about possible links between cosmic rays and cloud formation. That Christmas, while we visited relatives in Paris, I read a lot of related papers and came up with the idea to test the cosmic ray–cloud link at CERN with an experiment I named CLOUD. I did not want to ride into another field telling those guys how to do their stuff, so I wrote a note of my ideas and started to make contact with the atmospheric community in Europe and build support from lab directors in particle physics. I managed to assemble a dream team to propose the experiment to CERN. The hard part was convincing CERN that they should do this crazy experiment. We proposed it in 2000 and it was finally approved in 2006, which I think is a record for CERN to approve an experiment. There were some people in the climate community who were against the idea that cosmic rays could influence clouds. But we persevered and, once approved, things went very fast. We started taking data in 2009 and have been in discovery mode ever since.

> **In CLOUD you're the theorist and the experimentalist at the same time – like it was in the early days of particle physics**

Do you consider yourself a particle physicist or an atmospheric scientist?

An experimental physicist! My training and my love is particle physics, but judging by the papers I write and review, I am now an atmospheric scientist. It was not difficult to make this transition. It was a case of going back to my undergraduate physics and high-school chemistry and learning on the job. It's also very rewarding. We do experiments, like we all do at CERN, on a 24/7 basis, but with CLOUD I can calculate things in my notebook and see the science that we are doing, so we know immediately what the new stuff is and we can adapt our experiments continuously during our run.

On the other hand, in particle physics the detectors are running all the time but we really don't know what is in the data without years of very careful analysis afterwards, so there is this decoupling of the result from the actual measurement. Also, in CLOUD we don't need a separate discipline to tell us about the underlying theory or beauty of what we are doing. In CLOUD you're the theorist and the experimentalist at the same time – like it was in the early days of particle physics.

How would you compare the Standard Model to state-of-the-art climate models?

It's night and day. The Standard Model (SM) is such a well formed theory and remarkably high-quality quantitatively that we can see incredibly subtle signals in detectors against a background of something that is extremely well understood. Climate models, on the other hand, are trying to simulate a very complex system about what's happening on Earth's surface, involving energy exchanges between the atmosphere, the oceans, the biosphere, the cryosphere … and the influence of human beings. The models involve many parameters that are poorly understood, so modellers have to make plausible yet uncertain choices. As a result, there is much more flexibility in climate models, whereas there is almost none in the SM. Unfortunately, this flexibility means that the predictive power of such models is much weaker than it is in particle physics.

There are skills such as the handling of data, statistics and software optimisation where particle physics is probably the leading science in the world, so I would love to see CERN sponsor a workshop where the two communities could exchange ideas and perhaps even begin to collaborate. This is what CLOUD has done. It's politically correct to talk about the power of interdisciplinary research, but it's very difficult in practical terms – especially when it comes to funding because experiments often fall into the cracks between funding agencies.

M Brice, J Ordan/CERN

On cloud nine *Kirkby on the roof of the CLOUD detector in CERN's East Hall back in 2018.*

How has CLOUD's focus evolved during a decade of running?

CLOUD was designed to explore whether variations of cosmic rays in the atmosphere affect clouds and climate, and that's still a major goal. What I didn't realise at the beginning is how important aerosol–particle formation is for climate and health, and just how much is not yet understood. The largest uncertainty facing predictions of global warming is not due to a lack of understanding about greenhouse gases, but about how much aerosols and clouds have increased since pre-industrial times from human activities. Aerosol changes have offset some of the warming from greenhouse gases but we don't know by how much – it could have offset almost nothing, or as much as one half of the warming effect. Consequently, when we project forwards, we don't know how much Earth will warm later this century to better than a factor of three.

Many of our experiments are now aimed at reducing the aerosol uncertainties in anthropogenic climate change. Since all CLOUD experiments are performed under different ionisation conditions, we are also able to quantify the effect of cosmic rays on the process under study. A third major focus concerns the formation of smog under polluted urban conditions.

> **Many of our experiments are now aimed at reducing the aerosol uncertainties in anthropogenic climate change**

What have CLOUD's biggest contributions been?

We have made several major discoveries and it's hard to rank them. Our latest result (p10) on the role of ammonia and nitric acid in urban environments is very important for human health. We have found that ammonia and nitric acid can drive the growth rates of newly formed particles up to more than 100 times faster than seen before, but only in short spurts that have previously escaped detection. This can explain the puzzling observation of bursts of new particles that form and grow under highly polluted urban conditions, producing winter smog episodes. An earlier CLOUD result, also in *Nature*, showed that a few parts-per-trillion of amine vapours lead to extremely rapid formation of sulphuric acid particles, limited only by the kinetic collision rate. We had a huge fight with one of the referees of this paper, who claimed that it couldn't be atmospherically important because no-one had previously observed it. Finally, a paper appeared in *Science* last year showing that sulphuric acid–amine nucleation is the key process driving new particle formation in Chinese megacities.

A big result from the point of view of climate change came in 2016 when we showed that trees alone are capable of producing abundant particles and thus cloud seeds. Prior to that it was thought that sulphuric acid was essential to form aerosol particles. Since sulphuric acid was five times lower in the pre-industrial atmosphere, climate models assumed that clouds were fewer and thinner back then. This is important because the pre-industrial era is the baseline aerosol state from which we assess anthropogenic impacts. The fact that biogenic vapours make lots of aerosols and cloud droplets reduces the contrast in cloud coverage (and thus the amount of cooling offset) between then and now. The formation rate of these pure biogenic particles is enhanced by up to a factor 100 by galactic cosmic rays, so the pristine pre-industrial atmosphere was more sensitive to cosmic rays than today's polluted atmosphere.

There was an important result the very first week we turned on CLOUD, when we saw that sulphuric acid does not nucleate on its own but requires ammonia. Before CLOUD started, people were measuring particles but they weren't able to measure the molecular composition, so many experiments were being fooled by unknown contaminants.

Have CLOUD results impacted climate policy?

The global climate models that inform the Intergovernmental Panel on Climate Change (IPCC) have begun to incorporate CLOUD aerosol

CERNCOURIER
Volume 60 Number 4 July/August 2020
IOP Publishing

parameterisations, and they are impacting estimates of Earth's climate sensitivity. The IPCC assessments are hugely impressive works of the highest scientific quality. Yet, there is something of a disconnect between what climate modellers do and what we do in the experimental and observational world. The modellers tend to work in national centres and connect with experiments through the latter's publications, at the end of the chain. I would like to see much closer linkage between the models and the measurements, as we do in particle physics where there is a fluid connection between theory, experiment and modelling. We do this already in CLOUD, where we have several institutes who are primarily working on regional and global aerosol–cloud models.

What's next on CLOUD's horizon?
The East Hall at the PS is being completely rebuilt during CERN's current long shutdown, but the CLOUD chamber itself is pretty much the only item that is untouched. When the East Area is rebuilt there will be a new beamline and a new experimental zone for CLOUD. We think we have a 10-year programme ahead to address the questions we want to and to settle the cosmic ray–cloud–climate question. That will take me up to just over 80 years old!

Will humanity succeed in preventing catastrophic climate change?
I am an optimist, so I believe there is always a way out of everything. It's very understandable that people want to freeze the exact temperature of Earth as it is now because we don't want to see a flood or desert in our back garden. But I'm afraid that's not how Earth is, even without the anthropogenic influence. Earth has gone through much larger natural climate oscillations, even on the recent timescale of homo sapiens. That being said, I think Earth's climate is fundamentally stable. Oceans cover two thirds of Earth's surface and their latent heat of vaporisation is a huge stabiliser of climate – they have never evaporated nor completely frozen over. Also, only around 2% of CO_2 is in the atmosphere and most of the rest is dissolved in the oceans, so eventually, over the course of several centuries, CO_2 in the atmosphere will equilibrate at near pre-industrial levels. The current warming is an important change – and some argue it could produce a climate tipping point – but Earth has gone through larger changes in the past and life has continued. So we should not be too pessimistic about Earth's future. And we shouldn't conflate pollution and climate change. Reducing pollution is an absolute no brainer, but environmental pollution is a separate issue from climate change and should be treated as such.

Interview by **Paola Catapano** *and* **Matthew Chalmers** *CERN.*

OPINION REVIEWS

Fiction, in theory

Big Bang
By Irène Jacob
Éditions Albin Michel (in French)

French actor Irène Jacob rose to international acclaim for her role in the 1991 film *The Double Life of Véronique*. She is the daughter of Maurice Jacob (1933–2007), a French theoretical physicist and head of CERN's theory division from 1982 to 1988. Her new novel, *Big Bang*, is a fictionalised account of the daughter of a renowned physicist coming to terms with the death of her father and the arrival of her second child. Keen to demonstrate the artistic beauty of science, she is also a patron of the Physics of the Universe Endowment Fund established in Paris by George Smoot.

When Irène Jacob recites from her book, it is more than a reading, it's a performance. That much is not surprising: she is after all the much-feted actor in the subtly reflective 1990s films of Krzysztof Kieślowski. What did come as a surprise to this reader is just how beautifully she writes. With an easy grace and fluidity, she weaves together threads of her life, of life in general, and of the vast mysteries of the universe

Billed as a novel, *Big Bang* comes across more as a memoir, and that's no accident. The author's aim was to use her entourage, somewhat disguised, to tell a universal story of the human condition. Names are changed, Irène's well-known physicist father becoming René, for example, one of his middle names. The true chronology of events is not strictly observed, and maybe there's some invention, but behind the storytelling there is nevertheless a touching portrait of a very real family. The backdrop to the opening scenes is CERN, more specifically the corridors of the theory division in the 1970s and 1980s, a regular stomping ground for the young Irène. The reader discovers the wonders of physics through the wide-open eyes of a seven-year-old child. Later on, that child-become-adult reflects on other wonders – those related to the circle of life. The book ties all this together, seen from the point in space–time at which Irène has to reconcile her father's passing with her own impending motherhood.


SJ Hertzog/CERN-PHOTO-202002-036-2

Double life *Irène Jacob reads an excerpt from* Big Bang.

For those who remember the CERN of the 1980s, the story begins with an opportunity to rediscover old friends and places. For those not familiar with particle physics, it offers a glimpse into the field, to those who devote their lives to it, and to those who share their lives with them. The initial chapters open the door to Irène Jacob's world, just a crack.

The atmosphere soon changes, though, as she flings the door wide open. More than once I found myself wondering whether I had the right to be there: inside Irène Jacob's life, dreams and nightmares. It is a remarkably intimate account, looking deep into what it is to be human. Highs and lows, loves and laughs, kindnesses and hurts, even tragedies, all play a part. Irène Jacob's fictionalised family suffers much, yet although Irène holds nothing back, *Big Bang* is essentially an optimistic, life-affirming tale.

Science makes repeated cameo appearances. There's a passage in which René is driving home from hospital after welcoming his first child into the world. Distracted by emotion, he's struck by a great insight and has to pull over and tell someone. How often does that happen in the creative process? Biochemist Kary Mullis tells a similar story in his memoirs. In his case, the idea for polymerase chain reaction came to him at the end of hot May day on Highway 128 with his girlfriend asleep next to him in the passenger seat of his little silver Honda. Mullis got the Nobel prize. Both had a profound impact on their fields

Alice in Wonderland is a charmingly recurrent theme, particularly the Cheshire cat. Very often, a passage ends with nothing left but an enigmatic smile, a metaphor for life in the quantum world, where believing in six impossible things before breakfast is almost a prerequisite.

Big Bang is not a page turner. Instead, each chapter is a beautifully formed vignette of family life. Take, for example, the passage that begins with a quote from Niels Bohr taken from René's manuscript, *Des Quarks et des Hommes* (published as *Au Coeur de la Matière*). Bohr can be paraphrased as saying: the opposite of a profound truth is another profound truth. As the passage moves on, it plays with this theme, ending with the conclusion: if my story does not stand up, it's because reality is very small. And if my story is very small, it is because reality does not stand up.

Whatever the author's wish, *Big Bang* comes across as an admirably honest family portrait, at times uncomfortably so. It's a portrait that goes much deeper than the silver screen or the hallowed halls of academia. The cast of *Big Bang* is a very human family, and one that this reader came to like very much.

James Gillies *CERN.*

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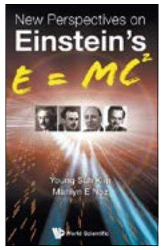
New Perspectives on Einstein's E = mc²

Young Suh Kim and Marilyn E Noz

World Scientific



New Perspectives on Einstein's E = mc² mixes historical notes with theoretical aspects of the Lorentz group that impact relativity and quantum mechanics. The title is a little perplexing, however, as one can hardly expect nowadays to discover new perspectives on an equation such as $E = mc^2$. The book's true aim is to convey to a broader audience the formal work done by the authors on group theory. Therefore, a better-suited title may have been "Group theoretical perspectives on relativity", or even, more poetically, "When Wigner met Einstein".

The first third of the book is an essay on Einstein's life, with historical notes on topics discussed in the subsequent chapters, which are more mathematical and draw heavily on publications by the authors – a well-established writing team who have co-authored many papers relating to group theory. The initial part is easy to read and includes entertaining stories, such as Einstein's mistakes when filing his US tax declaration. Einstein, according to this story, was calculating his taxes erroneously, but the US taxpayer agency was kind enough not to raise the issue. The reader has to be warned, however, that the authors, professors at the University of Maryland and New York University, have a tendency to make questionable statements about certain aspects of the development of physics that may not be backed up by the relevant literature, and may even contradict known facts. They have a repeated tendency to interpret the development of physical theories in terms of a Hegelian synthesis of a thesis and an antithesis, without any cited sources in support, which seems, in most cases, to be a somewhat arbitrary *a posteriori* assessment.

There is a sharp distinction in the style of the second part of the book, which requires training in physics or maths at advanced undergraduate level. These chapters begin with a discussion of the Lorentz group. The interest then quickly shifts to Wigner's "little groups", which are subgroups of the Lorentz group with the property of leaving the momentum of a system invariant. Armed with this mathematical machinery, the authors proceed to Dirac spinors and give a Lorentz-invariant formulation of the harmonic oscillator that is eventually applied to the parton model. The last chapter is devoted to a short discussion on optical applications of the concepts advanced previously. Unfortunately, the book finishes abruptly at this point, without a much-needed final chapter to summarise the material and discuss future work, which, the previous chapters imply, should be plentiful.

Young Suh Kim and Marilyn Noz's book may struggle to find its audience. The contrast between the lay and expert parts of this short book, and the very specialised topics it explores, do not make it suitable for a university course, though sections could be incorporated as additional material. It may well serve, however, as an interesting pastime for mathematically inclined audiences who will certainly appreciate the formalism and clarity of the presentation of the mathematics.

Nikolaos Rompotis *University of Liverpool.*

Surveying the surveyors

The need at CERN to align components within a fraction of a millimetre demands skills and tools beyond the scope of normal surveyor jobs.

J-F Fuchs

Fieldwork *Alban Vieille of the accelerators, survey and geodesy section aligning a LHC collimator.*

A career as a surveyor offers the best of two worlds, thinks Dominique Missiaen, a senior member of CERN's survey, mechatronics and measurements (SMM) group: "I wanted to be a surveyor because I felt I would like to be inside part of the time and outside the other, though being at CERN is the opposite because the field is in the tunnels!" After qualifying as a surveyor and spending time doing metrology for a cement plant in Burma and for the Sorbonne in Paris, Missiaen arrived at CERN as a stagier in 1986. He never left, starting in a staff position working on the alignment of the pre-injector for LEP, then of LEP itself, and then leading the internal metrology of the magnets for the LHC. From 2009–2018 he was in charge of the whole survey section, and since last year has a new role as a coordinator for special projects, such as the development of a train to remotely survey the magnets in the arcs of the LHC.

"Being a surveyor at CERN is completely different to other surveying jobs," explains Missiaen. "We are asked to align components within a couple of tenths of a millimetre, whereas in the normal world they tend to work with an accuracy of 1–2 cm, so we have to develop new and special techniques."

We see the physics results as a success that we share in too

A history of precision

When building the Proton Synchrotron in the 1950s, engineers needed an instrument to align components to 50 microns in the horizontal plane. A device to measure such distances did not exist on the market, so the early CERN team invented the "distinvar" – an instrument to ensure the nominal tension of an invar wire while measuring the small length to be added to obtain the distance between two points. It was still used as recently as 10 years ago, says Missiaen. Another "stretched wire" technique developed for the ISR in the 1960s and still in use today replaces small-angle measurements by a short-distance measurement: instead of measuring the angle between two directions, AB and AC, using a theodolite, it measures the distance between the point B and the line AC. The AC line is realised by a nylon wire, while the distance is measured using a device invented at CERN called the "ecartometer".

Invention and innovation haven't stopped. The SMM group recently adapted a metrology technique called frequency sweeping interferometry for use in a cryogenic environment to align components inside the sealed cryostats of the future High-Luminosity LHC (HL-LHC), which contract by up to 12 mm when cooled to operational temperatures. Another recent innovation, in collaboration with the Institute of Plasma Physics in Prague that came about while developing the challenging alignment system for HIE-ISOLDE, is a non-diffractive laser beam with a central axis that diverges by just a few mm over distances of several hundred metres and which can "reconstruct" itself after meeting an obstacle.

The specialised nature of surveying at CERN means the team has to spend a lot of time finding the right people and training newcomers. "It's hard to measure at this level and to maintain the accuracy over long distances, so when we recruit we look for people who have a feeling for this level of precision," says Missiaen, adding that a constant feed of students is important. "Every year I go back to my engineering school and give a talk about metrology, geodesy and topometry at CERN so that the students understand there is something special they can do in their career. Some are not interested at all, while others are very interested – I never find students in between!"

CERN's SMM group has more than 120 people, with around 35 staff members. Contractors push the numbers up further during periods such as the current long-shutdown two (LS2), during which the group is tasked with measuring all the components of the LHC in the radial and vertical direction. "It takes two years," says Jean-Frederic Fuchs, who is section leader for accelerators, survey and geodesy. "During a technical stop, we are in

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charge of the 3D-position determination of the components in the tunnels and their alignment at the level of a few tenths of a millimetre. There is a huge number of various accelerator elements along the 63 km of beam lines at CERN."

Fuchs did his master's thesis at CERN in the domain of photogrammetry and then left to work in Portugal, where he was in charge of guiding a tunnel-boring machine for a railway project. He returned to CERN in the early 2000s as a fellow, followed by a position as a project associate working on the assembly and alignment of the CMS experiment. He then left to join EDF where he worked on metrology inside nuclear power plants, finally returning to CERN as a staff member in 2011 working on accelerator alignment. "I too sought a career in which I didn't have to spend too much time in the office. I also liked the balance between measurements and calculations. Using theodolites and other equipment to get the data is just one aspect of a surveyor's job – post-treatment of the data and planning for measurement campaigns is also a big part of what we do."

With experience in both experiment and accelerator alignment, Fuchs knows all too well the importance of surveying at CERN. Some areas of the LHC tunnel are moving by about 1 mm per year due to underground movement inside the rock. The tunnel is rising at point 5 (where CMS is located) and falling between P7 and P8, near ATLAS, while the huge mass of the LHC experiments largely keeps them at the same vertical position, therefore requiring significant realignment of the LHC magnets. During LS2, the SMM group plans to lower the LHC at point 5 by 3 mm to better match the CMS interaction point by adjusting jacks that allow the LHC to be raised or lowered by around 20 mm in each direction. For newer installations, the movement can be much greater. For example, LINAC4 has moved up by 5 mm in the source area, leading to a slope that must be corrected. The new beam-dump tunnels in the LHC and the freshly excavated HL-LHC tunnels in points 1 and 5 are also moving slightly compared to the main LHC tunnel. "Today we almost know all the places where it moves," says Fuchs. "For sure, if you want to run the LHC for another 18 years there will be a lot of measurement and realignment work to be done." His team also works closely with machine physicists to compare its measurements to those performed with the beams themselves.

It is clear that CERN's accelerator infrastructure could not function at the level it does without the field and office work of surveyors. "We see the physics results as a success that we share in too," says Missiaen. "When the LHC turned on you couldn't know if a mistake had been made somewhere, so in seeing the beam go from one point to another, we take pride that we have made that possible."

Matthew Chalmers *editor.*

Appointments and awards

New director at PSI

Christian Rüegg, a solid-state physicist with a research focus on quantum phenomena in magnetism, took up the position of director of the Paul Scherrer Institute (PSI) in Switzerland on 1 April, succeeding Joël Mesot. In addition to its advanced X-ray and spallation-neutron sources, PSI is host to rare-decay experiments such as MEG II (*CERN Courier* May/Jun 2019 p45) and Mu3e, and has a strong programme of searches for new physics using high-intensity, low-momentum pion and muon beams and ultracold neutrons. Earlier this year, a team used pion beams at PSI to make the first

Scanderbeg Sauer Photography

spectroscopic measurements of exotic pionic-helium atoms (see p15).

Oxford University

Burrows heads JAI

Philip Burrows of the University of Oxford has been appointed director of the John Adams Institute for Accelerator Science (JAI), a three-institute centre of excellence for advanced accelerator science and technology based at: the University of Oxford; Royal Holloway, University of London; and Imperial College. JAI's core R&D programme covers beam dynamics, beam instrumentation, feedback and control, RF systems, metrology and alignment systems, lasers and plasmas, and medical beamlines. The institute currently comprises 20 faculty, 29 staff and 39 PhD students, with an additional 33 staff from the UK's national laboratories and CERN being affiliated with its research and teaching programmes.

Turok takes up Higgs chair

Theorist Neil Turok, previously director of the Perimeter Institute in Canada, has taken up the inaugural Higgs Chair at the Higgs Centre for Theoretical Physics (HCTP) at the University

Perimeter Institute

of Edinburgh. Building on the scientific legacy of Peter Higgs, the HCTP was established in 2012 with a vision to create bridges between disciplines and combine graduate-school education with research. Turok plans to promote new research directions including the application of real-time path integrals in general relativity, and to lead a considerable expansion of the centre's activities, including new faculty positions and fellowships.

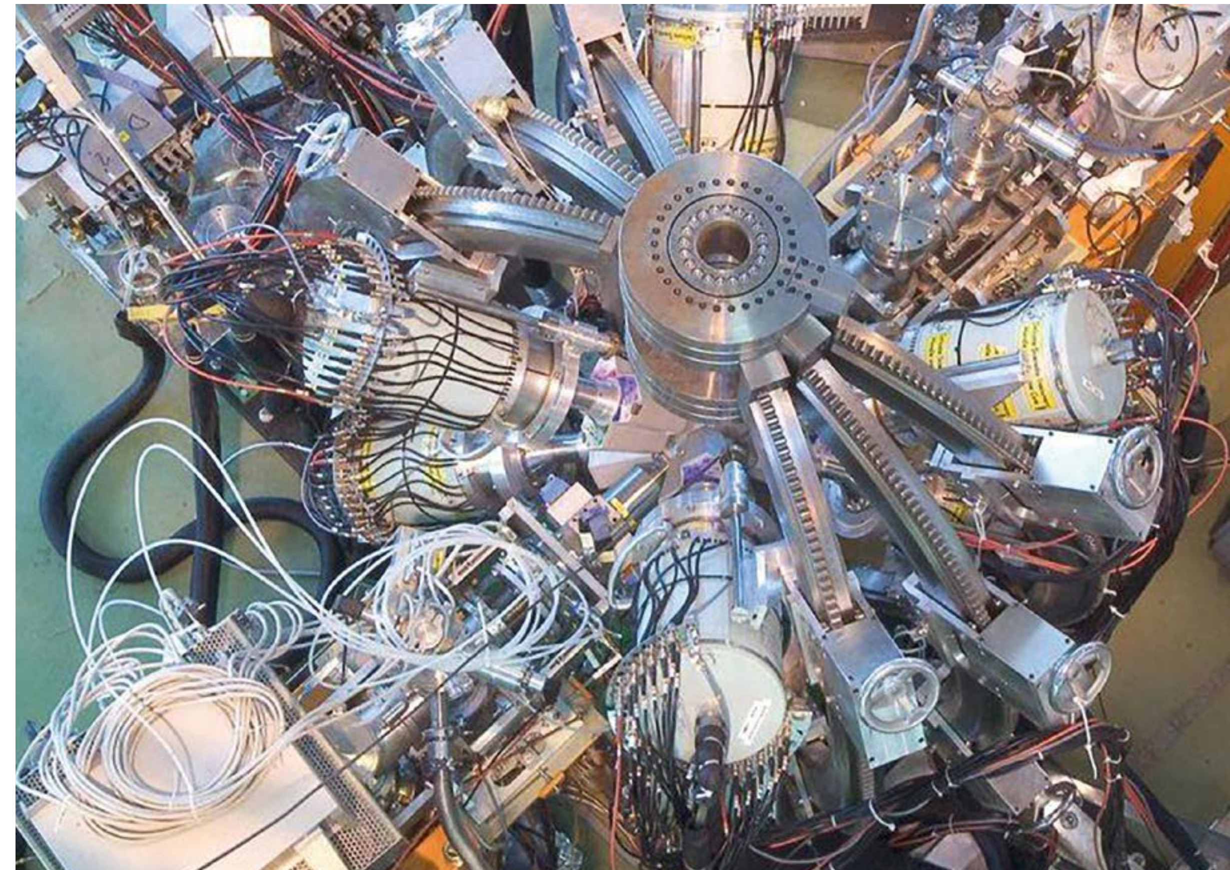
First Olga Igonkina travel grant awarded

Viacheslav Matiunin, a PhD student in experimental physics at ITEP Moscow, has received the first Olga Igonkina travel grant for Russian talent in physics. The €2000 award was established in memory of the late Russian–Dutch particle physicist Olga "Olya" Igonkina, a member of the ATLAS experiment and Nikhef staff who passed away last year at the age of 45. Announced in May, Nikhef has also established, in Igonkina's memory, a new

Nikhef

three-year fellowship for a female post-doc researcher intended to encourage talented female physicists to pursue a career in science.

RECRUITMENT



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For our location in Hamburg we are seeking:

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DESY.

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The position

You are invited to take an active role in one or more of the following areas at Hamburg:

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- Preparations for future particle physics experiments, in particular detector and technology development
- Scientific computing
- Accelerator development

Requirements

- Ph.D. in physics completed within the last four years
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DESY-Fellowships are awarded for a duration of 2 years with the possibility of prolongation by one additional year.

Futher informations and a link to the submission system for your application and the references can be found here:
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Please note that it is the applicants responsibility that all material, including letter of references, reach DESY before the deadline for the application to be considered.

Salary and benefits are commensurate with those of public service organisations in Germany. Classification is based upon qualifications and assigned duties. Handicapped persons 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. Vacant positions at DESY are in general open to part-time work. During each application procedure DESY will assess whether the post can be filled with part-time employees.

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Faculty Position in the Medical Physics group at the Institute of Physics, Pontificia Universidad Católica de Chile.

The Institute of Physics at Pontificia Universidad Católica de Chile invites applications for a tenure-track full time faculty position at the Assistant Professor level in Medical Physics or a closely related field. We are looking for candidates with a strong background and research expertise in any subfield of physics applied to medical diagnosis and treatment and open to collaborate in interdisciplinary teams. A Ph.D. degree in Physics or a closely related field is required. Postdoctoral experience is desirable.

The successful candidate is expected to be able to teach in Spanish after one year. Applications must include curriculum vitae, list of publications, statements of proposed research and teaching interests, and two recommendation letters.
The recommendation letters must be sent directly by the referees to the e-mail provided below.

The successful candidate is expected to establish independent research. The complete application should be sent by e-mail by July 31st, 2020 to the Search Committee at submit2020@fis.puc.cl.

ELI Beamlines research centre in Dolní Břežany is part of pan-European Extreme Light Infrastructure supporting scientific excellence in Europe by making available its capacities to the best scientific teams across the world. The ELI Beamlines is part of the Institute of Physics of the Czech Academy of Sciences. The High Field Initiative project at the ELI-BL is established to be the leading project in the high field science.

The HiFI-ERT (Excellence Research Team) recruits a scientist for developing theory and computer simulations on the following activities:

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Further questions on scientific project can be addressed to Sergei Bulanov (sergei.bulanov@eli-beams.eu)

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Applications, containing CV, cover letter, contacts of references, and any other material the candidate considers relevant, should be sent to Mrs. Jana Ženíšková, HR specialist (jana.zeniskova@eli-beams.eu, +420 - 601560322).

Information regarding the personal data processing and access to the personal data at the IoP CAS can be found on: https://www.fzu.cz/en/processing-of-personal-data.

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Image: NASA astronauts repair the Hubble Space Telescope

PEOPLE OBITUARIES

Pierre Lazeyras 1931–2020

Talent, tenacity and warmth

Pierre Lazeyras, who played leading roles in the ALEPH experiment, neutrino beams and silicon detectors during a 35-year-long career at CERN, passed away on 4 April aged 88.

Pierre graduated from the École supérieure de physique et chimie industrielle (ESPCI) in Paris in 1954 and, after working in Anatole Abragam's group at CEA Saclay, he joined CERN as a staff member in October 1961. He was one of the early collaborators in the Track Chamber (TC) division, which built the two-metre bubble chamber and the Big European Bubble Chamber (BEBC). In parallel, he headed the team that developed one of the first superconducting bending magnets for BEBC's "beam s3".

Pierre directed the TC SPS neutrino beam group from 1972, which included the construction of the horns, the 185 m-long iron muon shielding and the beam monitoring, for which silicon-diode particle detectors were employed. After some initial teething troubles, the SPS neutrino beams operated for nearly 20 years without major problems. The silicon monitors were found to be more precise than the early gas-filled ion chambers, and this was the beginning of the era of silicon micro-strip detectors. Pierre encouraged the microelectronics developments for this new technology and its integrated read-out circuits. These advances also came just in time for the UA2 experiment at the SPS and for wider applications in the LEP experiments.

Pierre was instrumental in the formation and success of ALEPH. From the conception of the experiment in 1982 right through to the LEP2 phase in 1996, he was ALEPH technical coordinator – a role that was quite new to those of us coming from smaller experiments. Pierre made sure we were realistic in our ambitions and our estimates of the difficulties and planning constraints, and we owe it mainly to him that the various parts of ALEPH were assembled without major problems. He was always available for advice even if, in his careful and reserved style, he did not try to direct or micro-manage everything.


Pierre at his retirement party in 1996.

In addition to being responsible for general safety in the experiment (which had no major incidents during its 11 years of operation), Pierre ensured that the construction of ALEPH was completed within budget. He also played an essential role at a crucial moment for the experiment in the early 1990s: the problem with the superconducting magnet cryostat. Under Pierre's supervision, a vacuum leak was located, close to the edge of the magnet, and the cryostat then underwent "surgery" using a milling machine suspended from a crane. It was a wonderful exercise in imagination and, to the relief of all, a complete success. Pierre had always insisted that such a huge superconducting magnet and cryostat inherently constituted a fragile device, and had objected to the idea of warming up the magnet during annual shutdowns, citing the mechanical stress resulting from this procedure. He was absolutely right.

Pierre was also involved in the design of the large stabilised superconductors for the LHC-experiment magnets and served as a member of the magnet advisory group of the LHC into his retirement, his wisdom being highly appreciated. He was also an active member of the CERN Staff Association. Following his retirement in 1996, he joined the *Groupement des Anciens* and was a representative on the CERN health insurance supervisory committee, where his advice and opinions were always wise and measured.

Pierre was not only highly talented and used his experience most effectively, he was also a warm person, someone on whom one could always rely. He would always tell you straight how things were and then suggest how any problems could be tackled. A typical remark by Pierre would be: "Ask me to approve or reject your ideas, do not ask me what work I have for you." We will remember him as a very dear friend and colleague.

His friends and colleagues *at CERN.*

Aldo Michelini 1930–2020

A respected leader

Aldo Michelini, who led OPAL and other important experiments at CERN, passed away at Easter at the age of 89. He was known as much for his kindness and care for his colleagues, particularly those embarking on their careers, as for the physics at which he excelled.

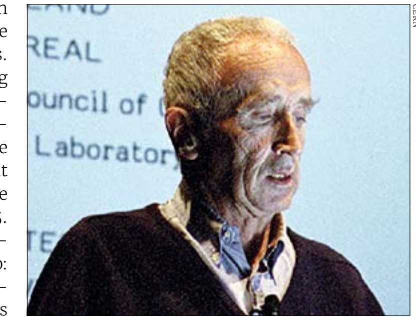
Aldo first came to CERN in 1960, bringing experience from several tracking-chamber experiments, including a stint with Jack Steinberger at Columbia University, and he lost no time in making an impact. One of his earliest contributions was to equip CERN's Wilson chamber magnet with spark chambers, which he then used as part of a CERN/ETH/Imperial College/Saclay collaboration to measure properties of the K^0_S meson and $p\bar{p}$ and K^-p charge-exchange interactions using a polarised target.

As the 1960s advanced, Aldo formed a partnership and life-long friendship with his compatriot, Mario Morpurgo, who was an early pioneer of superconducting magnet technology. The two were part of the small team spearheading the development of the Omega spectrometer, a general-purpose device built around a large superconducting magnet that could be arranged and configured according to the physics to be studied. Omega was initially equipped with spark chambers and installed on a PS beamline, receiving its first beam in 1972, and moved to the SPS in 1976 where it became the backbone of the fixed-target programme there for 20 years.

In 1973, Aldo headed a similar project to build a general-purpose spectrometer for the North Area. This became NA3, which was the first experiment to receive beam in the new SPS hadron hall, EHN1, in May 1978. NA3 embarked on ▷

a programme of high-mass dimuon production with π^+, π^-, K^+, K^-, p and $\bar{p}$ beams, enabling the first observation of upsilon production by pions. It also probed the structure of the incoming particles via the Drell–Yan process. The spectrometer carried out a string of valuable experiments under Aldo's guidance until 1981, when he became spokesperson of the OPAL experiment being planned for LEP. Aldo remained at the helm of OPAL right up to his retirement in 1995.

OPAL was built around tried and tested technology, including a paradoxical novelty for Morpurgo: a warm magnet. Huge for its time, with a collaboration of some 300 people, OPAL was nevertheless the smallest of the four LEP experiments. It was a scale that lent itself well to Aldo's unique style of management – leading through example and consensus. Colleagues remember him smiling and looking very worried, or more often than not, the other way around. This was strangely motivational, with team members striving to make him smile more and worry less. His personality shaped the unique OPAL team spirit. Despite his gentle nature, Aldo was more than capable of making tough choices, and winning over those who might initially have disagreed with him.


Aldo Michelini during the LEPfest in October 2000.

When OPAL detected the first Z boson at LEP on 13 August 1989, Aldo was heard to remark that the young people had taken over. The average age of those in the control room that day was well under 30, and that youthfulness was no accident. Aldo actively supported the young members of the collaboration, making sure that they were visible at collaboration meetings and conferences. He also imbued them and the whole collaboration with a culture of never publishing even preliminary results before being absolutely certain of them. As a result, OPAL's scientists built a strong reputation, with many conference conversations including the words, "let's wait and see what OPAL has to say". Aldo's faith in the younger generation was rewarded by some 300 successful PhD theses from OPAL, while more than 100 CERN fellows passed through the collaboration over its lifetime.

Aldo was a great leader, commanding respect and affection in equal measure. That the collaboration was still able to gather more than 100 members in 2019 to celebrate the 30th anniversary of that first Z decay is testimony to the kind of person Aldo was, and to the spirit that he engendered. Although he was unable to attend that gathering, he sent a message, and was loudly cheered. He will be sorely missed.

Rolf Heuer, **David Plane** *and* **Mette Stuwe** *CERN (retired) and* **James Gillies** *CERN.*

Adolf Minten 1931–2020

A scientific and technical authority

Distinguished CERN physicist Adolf Minten passed away on 21 March at the age of 88.

After graduating from the University of Bonn, where he worked in the team of Wolfgang Paul on the 500 MeV electron synchrotron, Adolf joined the CERN Track Chamber division in 1962. Working under Charles Peyrou, he set up beamlines for the two-metre bubble chamber and actively participated in its broad physics programme. Another important milestone of his career was his time as a visiting scientist at SLAC from 1966 to 1967, where he took part in the early experiments on hadron electro-production and electron scattering at the new two-mile accelerator.

Adolf returned to CERN at a time of decisive developments in accelerator and detector technologies. In parallel to his continued participation in bubble-chamber experiments, he became interested in the physics programme of the Intersecting Storage Rings, the world's first proton–proton collider, which started operation in 1971. To cope with the high interaction rates expected at this new machine, the development of track detectors focused on the multi-wire proportional chamber (MWPC) developed by Georges Charpak. One of the designs was a large multi-purpose spectrometer called the split-field magnet (SFM). At that time, a large-scale application of the revolutionary MWPC technology, hitherto available only in single-wire devices or small-surface detectors, presented a formidable challenge. In 1969, Adolf became responsible for the construction of the SFM facility, which covered the full solid angle with an unprecedented 300 m² detector surface, and 70,000 wires and electronics channels. Major detector, electronics and software developments were needed to bring this project into operation in 1974.


Adolf Minten addressing the crowd at one of the famous EF division parties.

In 1975, to prepare for the next generation of experiments at the new SPS machine, the CERN management proposed the creation of a new Experimental Facilities (EF) division. Adolf was elected to lead the new EF division, a position that required a combination of strong scientific and technical authority, and in which he commanded the unreserved respect of his collaborators. Following support provided to the major facilities for the SPS fixed-target programme, such as BEBC, the Omega spectrometer and the neutrino, muon and other experiments, his new division soon became involved in the successful experiments at the SPS proton–antiproton collider.

In 1984 Adolf stepped down from his position as EF division leader and joined the ALEPH experiment at LEP. The LEP experiments were a quantum leap in size and complexity when compared to previous experiments, and demanded new organisational structures. As head of the ALEPH steering committee, Adolf was instrumental in setting up an organisation whose role he compared to an "orchestra, where it is not sufficient that all the instruments be properly tuned, they must also harmonise". However, his true role of an "elder statesman" went far beyond organisational responsibilities; equally important were his human qualities, which were remarkable indeed and for which he was respected by both young and old.

Adolf maintained a constant interest in DESY, where he was highly appreciated. In 1981 Bjorn Wiik's study group had finished the HERA design report, and DESY set up an international evaluation committee to analyse it in detail. Adolf was invited to chair this committee. Its positive recommendation was a significant step towards the approval of the HERA project. He chaired the DESY scientific council from 1987 until 1990, during the main construction phase of the storage rings and the H1 and ZEUS multi-purpose detectors.

Adolf retired from CERN in 1996. We remember him as a supremely well-organised scientist of deep and incisive intelligence, unafraid to challenge and question preconceived ideas, and always inspiring others to do the same. At the same time, he was a modest person who cared profoundly for all the people around him, and their families.

His friends and colleagues.

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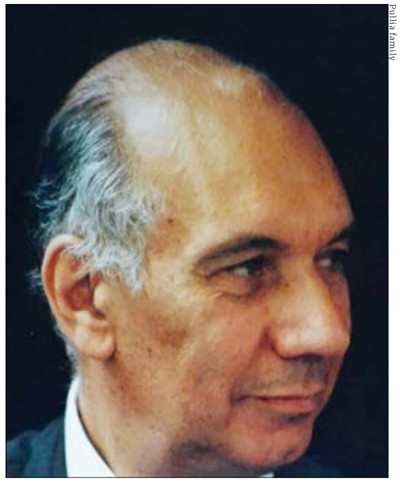
Antonino Pullia 1935–2020

From neutral currents to dark matter

Antonino Pullia, who passed away in April aged 84, was a student of Giuseppe Occhialini at the University of Milan and obtained his laurea in 1959. For the next 60 years he devoted himself to teaching, administration and the rich physics research programmes at the INFN and the universities of Milan and Milano-Bicocca, playing a major role in establishing the new physics department at the latter. He had a great passion for teaching undergraduates, continuing well into retirement.

Pullia's research ranged over many topics including neutrino physics, proton decay, double-beta decay, DELPHI at LEP, CMS at LHC and dark-matter searches. He also played a prominent role in the discovery of neutral currents at CERN using the Gargamelle bubble chamber.

In March 1972 he presented the vertex distribution of possible neutral-current events that had no lepton candidate but one or more pions. The distribution was seen to be uniform, just like the events with muon candidates, leading immediately to the formation of working groups concentrating on neutral-current searches in both hadronic and purely leptonic modes. After a remarkable scanning and measurement effort many candidates for neutral currents had been found, but the burning issue was the size of the background due to neutron interactions. Pullia recognised the importance of a special class of events, namely genuine neutrino events with a detected final-state muon and a neutron emitted at the interaction vertex and detected downstream in the visible part of the bubble chamber. Such events were rare, but very valuable, since in this case the downstream event was surely induced by a neutron. It was clear that the major source of background neutrons was coming from neutrino events in the material surrounding Gargamelle. With this knowledge, it turned out that the predicted background was far too small to explain the observed number of neutral-current candidates and thus, at the end of July 1973, the collaboration was able to announce the great discovery of neutral currents. The Italian Physical Society awarded the 2011 Fermi prize to Pullia in recognition of his important contribution.



Tonino Pullia played a prominent role in the discovery of neutral currents at CERN.

He was always extremely kind and open to alternative views

At the beginning of the 1980s Tonino, as he was known, joined the DELPHI collaboration at LEP where he worked with his group on the construction of the electromagnetic calorimeter, along with the reconstruction and analysis software. The Milan group, under his constant support, was extremely active in DELPHI, proposing many original analyses, as well as many PhD and master theses, contributing to the exceptionally rich LEP physics results.

In 2012 Tonino became interested in the detection of dark matter, deciding to resurrect a special type of bubble chamber developed 50 years ago – called "the Geyser" – which is remarkable in its simplicity. With no moving parts, and the ability to reset itself a few seconds after a bubble is formed, the device was ideal for underground experiments. He also formed the MOSCAB collaboration, which successfully produced a small detector with the required superheat needed for dark-matter searches.

Each of us who had the privilege to work with, or simply to talk to, Tonino has been enlightened in some way in our efforts to have a deeper understanding of fundamental physics. He was always extremely kind and open to alternative views. We will sadly miss him for his human qualities, and as a physicist.

His friends and colleagues.

Teresa Rodrigo Anoro 1956–2020

Shaping Spanish particle physics

Teresa Rodrigo Anoro, professor of atomic and nuclear physics at the University of Cantabria, passed away at her home on 20 April after a long illness. She was a leading figure within the particle-physics community and played a key role in shaping Spanish particle-physics policy, with an emphasis on promoting the participation of women in science.

After her bachelor's degree in physics from the University of Zaragoza, Teresa joined the high-energy physics group of La Junta de Energía Nuclear in Madrid (currently CIEMAT), earning a PhD in 1985 with a thesis on the production of strange particles at the NA23 experiment at CERN. She then moved to CERN to participate in the development of the Uranium-TMP calorimeter for the upgrade of the UA1 experiment, where she started her personal journey towards finding the top quark. This eventually brought her to the CDF experiment at Fermilab, where she carried out the detailed modelling of the W+jet background, a crucial input to the top's discovery. In 1994 she took up a faculty position at the Instituto de Física de Cantabria (IFCA) in Santander, incorporating the IFCA group into both the CDF experiment and the newly formed CMS collaboration at CERN. Under her direction, the group continued her study of the properties of the top quark and opened up a new line of research towards the discovery of the Higgs boson.

More recently, moving away from hadron beams for the first time, Teresa promoted new approaches to the search for light dark-matter at the DAMIC experiment. She was well aware of the importance of technology development and detector building in high-energy physics and orchestrated her group's contribution to the construction of the CMS muon spectrometer, in particular its muon alignment system, and to the building of CDF's time-of-flight detector.

Teresa's scientific insight and strong commitment to whatever endeavour she was engaged in were recognised by the international community: she was elected chair of the CMS collaboration board (2011–2012) and served as a member of several scientific ▷

policy committees, including the European Physical Society HEPP board (2006–2013) and the CERN scientific policy committee (2012–2017). Outside academia, she was a member of several Spanish ministerial scientific panels and of the technical and research panel of the Princesa de Asturias awards. She also held an honorary doctorate from the Menéndez Pelayo International University, received the silver medal of the University of Cantabria and the first Julio Peláez award for female pioneers in science, among other recognitions.

Teresa's influence on the Santander HEP group and the IFCA institute that she directed until a few months before her death remains very visible. During her tenure, the group grew considerably and greatly expanded its activities. The institute was awarded the greatest distinction of excellence of the Spanish science system, the Maria de Maeztu grant, and the gender-equality prize awarded by the Spanish National Research Council.

Teresa Anoro in the CMS control room.

Those of us who were fortunate enough to know Teresa and to share some of her scientific passions, are aware of how kind, approachable, righteous and sympathetic she was, though with a strong character that came from her deep honesty. Teresa's legacy stands as a testament to her leadership, her vision and her ability to mentor rising colleagues. She will be sorely missed.

Her colleagues and friends.

Danila Tlisov 1983–2020

A unique mix of strengths

Danila Tlisov, a member of the CMS collaboration at CERN, passed away on 14 April in Russia due to complications associated with COVID-19. He was just 36 years old.

Danila joined the INR Moscow group in 2010 as a young researcher after graduating with honours from Moscow State University and defending his dissertation. Following his contributions to early heavy-neutrino searches, he started to work on the CMS hadron calorimeter (HCAL) subsystem in 2012. Danila served as the hub of the multi-national CMS HCAL upgrade effort, leading the CERN-based team that received individual components from India, Russia, Turkey and the US, and assembling them into a working detector. Danila recently brought his unique mix of strengths to the CMS HCAL management team as deputy project manager and a member of the CMS management.

In the physics analysis realm, Danila worked with the University of Rochester group on a measurement of the electroweak mixing angle using the forward–backward asymmetry in Drell–Yan events, where he focused on critical improvements to the calibration of the electron-energy measurements in challenging regions of Drell–Yan kinematic phase space.

Danila Tlisov was instrumental in the CMS HCAL upgrade.

CMS friends and colleagues remember fondly the warm smile and incredibly effective leadership of Danila. His practical know-how and excellent judgement were critical as we worked together through the tough challenges of a major detector upgrade.

Danila was an accomplished backcountry touring skier. Because of his great physical strength and focus on climbing, it was often said that he may have been faster going uphill than downhill, and that is saying a lot.

Among his many colleagues, Danila will be remembered for his pleasant, cheerful disposition, even during times of intense pressure. He challenged us with his brilliant ideas, guided students with patience and grace, and inspired us all. He will be sorely missed.

His colleagues and friends *from the CMS collaboration.*

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BACKGROUND

Notes and observations from the high-energy physics community

Particle of doubt


In DUNE *David Ibbett (left), alongside fellow artists in residence Patrick Gallagher and Chris Klapper, in front of part of DUNE's short-baseline detector.*

Contemporary classical music is the latest addition to Fermilab's rich cultural life in physics. Inaugural guest-composer David Ibbett's latest oeuvre, *Particle of Doubt*, is a sonification of the evolving flavour fractions in the neutrino beam of the lab's flagship long-baseline neutrino facility, which is preparing to send a beam 810 km from Chicago to the DUNE detector in South Dakota (see p32). Violin, viola and cello parts map the fractions of the electron, muon and tau eigenstates to the pitch of the melody, while flutes play rhythms taken from an estimate of the three neutrino masses – assuming normal ordering. "You should be massless like rays of light," sings soprano Beth Sterling, as the wavefunction evolves. "You should be changeless, but the change gives us hope that we'll know where we came from," she continues, referring to the potential of the DUNE experiment to quantify leptonic CP violation. "I don't often write lyrics," explains Ibbett, "but was so moved by what I've learned about neutrinos, the infinitesimally small particles that raise such huge questions, that the song found its way into existence." The piece will premiere in full in a live concert 2021.

116 591 810 (43) × 10⁻¹¹

The predicted muon anomalous magnetic moment based on a new consensus from the theory community (arXiv:2006.04822), which is lower than the current experimental value by 3.7 standard deviations

Les Horribles Cernettes reunite online

Dedicated in solidarity to everyone in lockdown around the world due to COVID-19, CERN's infamous musical spinout *Les Horribles Cernettes* – famous for such earworms as "Collider", "Strong Interactions" and "Microwave Love" – have released "The Lockdown Song" on YouTube. "I'm running out of protons now the synchrotron's shut," sing the self-styled world's only high-energy rock band (clockwise from top left: Colette Marx-Neilsen, Angela Higney, Michele de Gennaro and Lynn Veronneau).

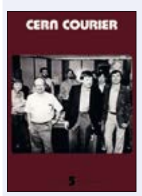
From the archive: July/August 1980

CERN unlocked


Left: Research DG Léon Van Hove fires the starting pistol; middle: the runners get under way; right: Executive DG John Adams presents the Challenge Trophy.

First collisions in the Berkeley/Stanford PEP electron–positron storage ring on 4 May were celebrated on the cover of *CERN Courier* July/August 1980. Also reported was a world record in centre-of-mass energies on 21 May, when CERN's Intersecting Storage Rings collided two beams of 62 GeV alpha particles.

Then, June saw an event we can only dream of during these locked-down days. Not a first but a 10th – CERN's annual relay race. Were you there? Did you run? Did you drop the baton? To paraphrase Baron Pierre de Coubertin: "The most important thing in the CERN race is not winning but taking part …"



Pictured above are some reminders of that sunny day when the Laboratory, with double Directors-General and staff physically distanced across two sites, indulged in some social gathering. The race would have had its Golden Jubilee in 2020 but … here's to taking part in the renormalised 50th in 2021.

● Based on *CERN Courier* July/August 1980, pp187–188, p194 and p206.

Media corner

"Maiman's letter consists of two simple figures and fewer than 300 words, and – unlike many modern submissions – there is no concluding paragraph announcing the many scientific and technological advances the finding may lead to."

From an editorial in ***Nature Reviews Physics*** (vol 2, p221) celebrating 60 years of the laser, proposed by Theodore Maiman in a paper titled "Stimulated optical radiation in ruby".

"We think sub-surface firn is the culprit."

Ian Shoemaker of Virginia Tech, quoted in ***New Atlas*** (11 June), proposing that two bizarre, but apparently neutrino-like, high-energy events recorded at the South Pole by the ANITA balloon experiment in 2016 and 2018, may have been caused by reflections of Askaryan-effect radio waves at density interfaces between layers of compressed snow, or firn.

"I think we're seeing a real change here in what particle physics is about. It's not about adding more particles to a long list of particles; it's about how does the universe really operate in a fundamental way to produce what we see today?"

Fermilab's Joe Lykken quoted in an article about neutrino physics in ***Gizmodo*** (20 May).

"It wasn't a hard decision for arXiv to join the strike."

Astroparticle physicist Eleonora Presani, executive director of the arXiv e-print repository, quoted in ***Nature*** (9 June) on the decision by many academics and organisations to cease research activities on 10 June to reflect on systemic inequalities in science.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