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WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the June 2018 issue of *CERN Courier*.

During the past five years, rapid progress in R&D has been made towards the next generation of circular colliders that would take up the Large Hadron Collider's mantle in fundamental exploration. Two major studies on opposite sides of the planet are under way, both of which envisage a 100 km-circumference tunnel that could house an electron–positron collider for precision measurements and a proton–proton collider at a new energy frontier. The Future Circular Collider (FCC) study imagines such a facility being built at CERN, while physicists in China are considering several sites for the Circular Electron Positron Collider (CEPC). The proposals are part of a broader machine landscape that includes the International Linear Collider and the Compact Linear Collider, which will be a focus of discussions at the upcoming update of the European Strategy for Particle Physics. Meanwhile, the LHC's 2018 physics programme is in full swing and SuperKEKB has achieved its first collisions at the KEK laboratory in Japan. Finally, delving into some of the advanced technologies underpinning modern accelerators, this month's cover feature takes us to the heart of CERN's vacuum group.

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Contents

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

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On the cover: View of the inner surface of a beam-screen prototype designed for the new HL-LHC triplet magnets. (Image credit: CERN.)

Viewpoint

Colliding visions drive success

Bids for major projects in Europe and China are reminiscent of the competition between the LHC and SSC.

FCC study/CERN

A simulation of the 100 km-circumference tunnel that could host different particle colliders explored by the FCC study.

By Geoffrey Taylor

With each new high-energy accelerator, a question arises: is this the largest facility that we can conceive of being built? Although accelerator experts have never lost their astounding capacity for innovation when it comes to building the next collider, it is the necessary political will required to fund multi-billion-dollar science projects that remains the big unknown. Yet, giant facilities have succeeded in the past.

CERN's Large Hadron Collider (LHC) was Europe's answer to a long-standing transatlantic competition for the high-energy frontier. The US Superconducting Super Collider (SSC) had been designed to operate at 40 TeV – an enormous step – while the LHC was proposed at lower energy to fit into the existing LEP tunnel, compensating with higher luminosity. The cancellation of the SSC in 1993 ensured that the LHC would take up the high-energy mantle. Meanwhile, the 2 TeV Tevatron at Fermilab continued operations, giving the LHC real competition in the search for the Higgs boson.

Overcoming many challenges to the LHC's construction, CERN wrestled back the energy frontier with magnificent success, crowned in 2012 by the Higgs-boson discovery. The machine and its approved high-luminosity upgrade will maintain Europe's leadership into the 2030s. But what then?

The proposed Future Circular Collider (FCC) aims to keep CERN at the energy frontier via a 100 km-circumference ring capable of housing a 100 TeV proton collider (see p15). It may well proceed via an intermediate 90–365 GeV electron–positron collider (FCC-ee), bringing incredible precision to measurements of the Higgs boson and backing up the discovery at the LHC in much the same way that LEP did after the discoveries of the Z and W bosons at the Sp$\bar{p}$S.

Whilst CERN physicists and partners wish for continued leadership from their stable base, global competition is tilting towards Asia, where two major proposals are progressing towards approval: the 250 GeV International Linear Collider (ILC) in Japan, and the 250 GeV Circular Electron-Positron Collider (CEPC) in China (p21). The ILC requires major international participation, whilst CEPC (which, like FCC, could proceed to a high-energy proton collider) will be largely nationally resourced.

In principle, FCC-ee and the CEPC are direct competitors. For that matter the ILC is too, and CERN is also developing the Compact Linear Collider (CLIC) with a much higher energy reach. All would produce a very large sample of Higgs bosons in a clean environment. Uniquely, linear machines can in principle be upgraded by extending their length or increasing the gradient of their accelerating cavities. Circular machines, with the radius fixed at construction, require stronger magnets and increased power to push up their energy.

The existence of the Chinese and CERN bids is reminiscent of the competitive LHC–SSC era. Again, while the physics potential of each machine is similar, their political, economic and social environments are quite different. This time it is the new economic power of China, with a government focussed on international leadership in a range of endeavours, that is impacting future planning in the field.

The ILC and CEPC have such different development pathways – and with China increasing the size of the international high-energy physics pie, not just re-slicing it – that both could be important. For a 100 TeV proton collider, perhaps the massive development and production of the necessary superconducting magnets can be limited to one facility, freeing up international resources to explore more compact and efficient acceleration techniques for the future. CERN clearly has the experience and leadership in high-energy proton colliders.

The lesson from the LHC–SSC story is the need for persistence, international collaboration and endorsement, stability, innovation and a long-term vision – characteristics that underpin CERN's successes. In Asia too, where long-term vision is the cultural norm, effective decadal planning is expected and recognised as critical amongst high-energy physics leaders. Surely international resources can be optimised to ensure our field remains active and relevant in the decades to come.

Geoffrey Taylor is chair of the International Committee for Future Accelerators and director of the ARC Centre of Excellence for Particle Physics at the Terascale (CoEPP) at the University of Melbourne.

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News

KEK

SuperKEKB steps out at the intensity frontier

On 26 April the SuperKEKB accelerator at the KEK laboratory in Japan collided its first beams of electrons and positrons, marking the start of an ambitious data-taking campaign that will allow ultraprecise measurements of Standard Model (SM) parameters.

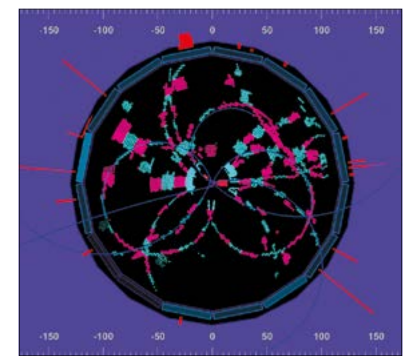

Celebrating first collisions in the Belle II control room.

These are the first particle collisions at KEK in eight years, following the closure in 2010 of the KEKB machine to prepare for its next phase. Many subsystems of the accelerator had to be upgraded, the most important involving the use of nanobeam technology to squeeze the vertical beam size at the interaction point to around 50 nm – 20 times smaller than it was at KEKB. This required a complicated system of superconducting final-focus magnets and low-emittance beams (*CERN Courier* September 2016 p32).

SuperKEKB will work at the so-called intensity frontier to produce copious amounts of B and D mesons and τ leptons, enabling precise measurements of rare decays that test the SM with unprecedented sensitivity. Since the first beams were stored over a month ago, KEK teams have worked to tune the two beams for first collisions at the centre of the Belle II detector – the "super-B factory" upgrade of its predecessor, Belle. When fully commissioned, Belle II will detect and reconstruct events at the much higher rates provided by the 40-fold higher design luminosity of SuperKEKB compared to KEKB. The Belle II outer detector is already in place, but the full inner detector will not be installed until the end of the year, and the first physics run with the complete detector is projected to start in February 2019.

In 2009 KEKB achieved a record instantaneous luminosity of $2.1 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$, but SuperKEKB is targeting $8 \times 10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$. The huge increase is projected to deliver to Belle II a dataset of about 50 billion $B\bar{B}$ meson pairs – 50 times larger than the entire data sample of the KEKB/Belle project – in about 10 years of operation.

According to Belle II spokesperson Tom Browder, it is not realistic to expect design luminosity straight away. "There will be a number of steps as the beam is progressively squeezed to smaller and smaller sizes, and we fight through each new technical challenge with nanobeams," he explains. "Our luminosity profile assumes that we progressively resolve these problems at the same rate as KEKB or PEP-II [at SLAC]. In this sense, our programme resembles that of the LHC."


A hadronic event spotted by the Belle II detector at 2.27 a.m. on 26 April.

Belle II has physics goals related to those of the LHCb experiment (*CERN Courier* April 2018 p23), set against the relatively cleaner environment of electron–positron collisions but with a lower production rate of heavy hadrons with respect to the LHC collisions. Examples include investigating whether there are new CP-violating phases in the quark sector, whether there are sources of lepton-flavour violation (LFV) beyond the SM, whether there is a dark sector of particle physics at the same mass scale as ordinary matter, and whether there are flavour-changing neutral currents beyond the SM. Browder says the Belle II collaboration expects to work on all of the goals, especially on LFV studies, and to catch up with LHCb on certain measurements as soon as a significant amount of luminosity is achieved. "Even with the very early data samples, the team should be able to make impactful results on the dark sector and new hadrons," he says.

Sommaire en français

LHC

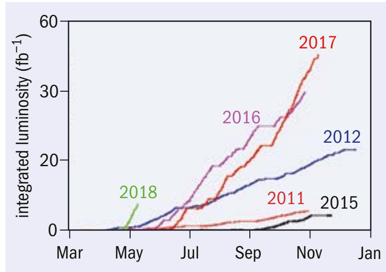
LHC physics soars ahead

On 28 April, 13 days ahead of schedule, operators at CERN's Large Hadron Collider (LHC) successfully injected 1200 bunches of protons into the machine and brought them into collision – formally marking the beginning of the LHC's 2018 physics season, and the final leg of Run 2.

Stable beams were first declared on 17 April, when the LHC experiments started to take data with three bunches per beam at very low luminosities. A stepwise increase of the number of bunches resulted in the maximum number of 2556 bunches per beam being reached on 5 May.

During the last steps of the intensity ramp-up, the average peak luminosity for ATLAS and CMS was close to $2.1\times10^{34}\,cm^{-2}\,s^{-1}$ – equalling or even surpassing the record peak luminosity with stable beams reached in 2017 – although the final calibration of the luminosity measurements still needs to be performed.

For the rest of the year, the LHC is dedicated to production mode for physics, with the operation of the machine being consolidated in parallel. As the *Courier* went to press in mid-May, the integrated luminosity for ATLAS and CMS had already surpassed $10\,fb^{-1}$ (with a target of $60\,fb^{-1}$ planned for 2018).



The 2018 integrated-luminosity curve (green) shows an early and steep increase, but beware: planned technical stops, machine-development sessions and special physics runs will introduce plateaus as the year progresses.

The faster-than-anticipated commissioning phase of the 2018 LHC restart has led to a revised machine schedule: the LHC will provide 131 days of physics operations with 25 ns-spaced proton beams, 17 days of special runs with protons, and 24 days of lead–lead collisions at the end of the year (the proton run will finish on 28 October). From December, the machine will enter Long Shutdown 2 in preparation for its high-luminosity upgrade.

DAΦNE

KLOE-2 completes data-taking at Frascati Φ-factory

On 30 March the KLOE-2 experiment concluded its data-taking campaign at the electron–positron collider DAΦNE at the INFN National Laboratory of Frascati (LNF), Italy. This marks the conclusion of a two-decades long period of activity at the Frascati lab, which began with the first data collected by KLOE in 1999 and then continued with KLOE-2 since November 2014. In total, an integrated luminosity of around $8\,fb^{-1}$ (corresponding to around 24 billion ϕ-mesons) was acquired, representing the largest ever sample collected at the ϕ-resonance peak.

In terms of machine physics, the KLOE/DAΦNE programme has brought a wealth of results and a few world firsts. The KLOE-2 run saw the first application of the "crab-waist" concept – an interaction scheme developed in Frascati with the transverse dimensions of the beams and their crossing angle tuned to maximise the machine luminosity – in the presence of a high-field detector solenoid. The implementation of this innovative configuration by the DAΦNE team allowed KLOE-2 to collect an integrated luminosity of $5.5\,fb^{-1}$ in a period of just over three years.

Record performances in terms of peak luminosity ($2.4\times10^{32}\,cm^{-2}\,s^{-1}$) and maximum daily integrated luminosity ($14\,pb^{-1}$/day) have been achieved for an electron–positron collider running at such centre-of-mass energies (approximately 1 GeV).

LNF

The KLOE/KLOE-2 and DAΦNE teams marked the end of an era on 30 March.

The general-purpose KLOE detector, comprising a 4 m-diameter drift chamber surrounded by a lead-scintillating-fibre electromagnetic calorimeter with very good energy and timing performance at low energies, underwent several upgrades including a cylindrical gas-electron-multiplier (GEM) detector for the inner tracker. To improve its vertex reconstruction capabilities near the interaction region, KLOE-2 was the first high-energy experiment using GEM technology with a cylindrical geometry – a novel idea that was developed at LNF.

Together with its predecessor KLOE, the KLOE-2 data sample is rich in physics. The analysis of KLOE data provided, and continues to provide, a variety of significant results on: neutral and charged kaon properties; tests of discrete symmetries; tests of the unitary of the quark mixing matrix; light-scalar-meson spectroscopy; η-meson decays; hadronic cross sections and the anomalous magnetic moment (g-2) of the muon; and searches for dark photons.

Analyses of the KLOE-2 data is ongoing, in particular extending the KLOE physics programme in precision tests of fundamental discrete symmetries and the quantum coherence of entangled neutral kaon pairs. The roughly 60-strong collaboration will also study rare K_S and η-meson decays and strong interactions in low-energy processes, in addition to $\gamma\gamma$ physics and the search for possible manifestations of dark matter.

Overall, the KLOE programme has involved hundreds of Italian and foreign physicists in a challenging human and scientific enterprise. But activities at the DAΦNE accelerator complex do not stop here. They are now continuing with the PADME and Siddharta-2 experiments, designed to search for dark photons and to study exotic atoms and strong interactions at low energies, respectively. Frascati Laboratory is also planning to revamp the DAΦNE complex, becoming a world-class test facility for R&D in accelerator physics, and is applying to host the future EuPRAXIA infrastructure for a European plasma-based free-electron Laser.

"The KLOE experiment has been a scientific milestone for the laboratory and for particle physics," says LNF director, Pierluigi Campana. "DAΦNE will continue to produce physics for PADME and Siddharta-2, and we are thinking towards its future after 2020."

Neutrinos

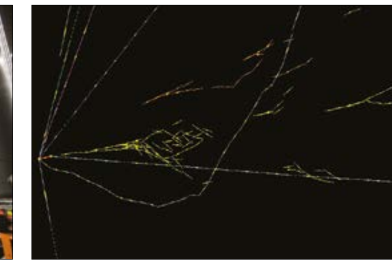
OPERA concludes on tau appearance

The OPERA experiment, located at the Gran Sasso Laboratory of the Italian National Institute for Nuclear Physics (INFN), was designed to conclusively prove that muon-neutrinos can oscillate into tau-neutrinos by studying beams of muons sent from CERN 730 km away.

In a paper published on 22 May, describing the very final results of the experiment on neutrino oscillations, the OPERA collaboration has reported the observation of a total of 10 candidate events for a muon-to tau-neutrino conversion. This result demonstrates unambiguously that muons morph into tau neutrinos on their way from CERN to Gran Sasso.

The OPERA collaboration observed the first tau-neutrino event (evidence of muon-neutrino oscillation) in 2010, followed by four additional events reported between 2012 and 2015. A new analysis strategy applied to the full data sample collected between 2008 and 2012 led to the new total of 10 candidate events, with an extremely high level of significance. "We also report the first direct observation of the tau-neutrino lepton number, the parameter that discriminates neutrinos from antineutrinos," says Giovanni de Lellis, OPERA spokesperson. "It is extremely gratifying to see today that our legacy results largely exceed the level of confidence we had envisaged in the experiment proposal."

INFN



The OPERA detector (left) and an event display showing a muon-to-tau neutrino conversion (right).

Beyond its contribution to neutrino physics, OPERA pioneered the use of large-scale emulsion films with fully automated and high-speed readout technologies with submicrometre accuracy. These technologies are now used in a wide range of other scientific areas, from dark-matter searches to investigations of volcanoes, and from the optimisation of hadron therapy for cancer treatment to the exploration of secret chambers in the Great Pyramid. The OPERA collaboration has also made its data public through the CERN open data portal, allowing researchers outside the collaboration to conduct novel research and offering tools such as a visualiser to help adapt the datasets for educational use.

Further reading

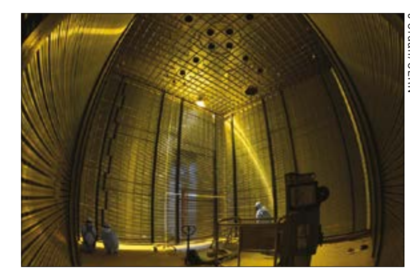
OPERA Collaboration 2018 *Phys. Rev. Lett.* **120** 211801.

US and India team up on neutrino physics

On 16 April, US energy secretary Rick Perry and Indian Atomic Energy Secretary Sekhar Basu signed an agreement in New Delhi to expand the two countries' collaboration in neutrino science. It opens the way for jointly advancing the Long-Baseline Neutrino Facility (LBNF) and the international Deep Underground Neutrino Experiment (DUNE) in the US and the India-based Neutrino Observatory (INO).

More than 1000 scientists from over 170 institutions in 31 countries work on LBNF/DUNE, construction for which got under way in July 2017. The project will direct the world's most intense beams of neutrinos from Fermilab accelerators (driven by the new PIP-II machine) to detectors 1300 km away. INO scientists, meanwhile, will observe neutrinos that are produced in Earth's atmosphere. Scientists from more than 20 institutions are working on INO, which is currently going through approval procedures.

The India–US agreement builds on one signed in 2013 authorising the joint development and construction of particle-accelerator components. Scientists from four institutions in India – BARC in Mumbai, IUAC in New Delhi, RRCAT in Indore and VECC in Kolkata – are contributing to the design and construction of magnets and superconducting particle-accelerator components for PIP-II at Fermilab and the next generation of particle accelerators in India.



J Ordan/CERN

Inside the final structure of the protoDUNE module at CERN, which is soon to undergo its first beam tests.

Under the new agreement, US and Indian institutions will expand this to include neutrino research projects. DUNE, located about 1.5 km underground, will use almost 70,000 tonnes of liquid argon to detect neutrinos; and an additional detector will measure the neutrino beam at Fermilab as it leaves the accelerator complex. Prototype neutrino detectors are already under construction at CERN, which is also a partner in LBNF/DUNE. INO will use a different technology: an iron calorimeter. Its detector will feature what could be the world's biggest magnet, allowing INO to be the first experiment able to distinguish signals produced by atmospheric neutrinos and antineutrinos produced when cosmic rays strike the atmosphere.

More than a dozen Indian institutions are involved in the collaboration on neutrino research. According to former INO spokesperson Naba Mondal of the Saha Institute of Nuclear Physics, "this agreement is a positive step towards making INO a global centre for fundamental research. Students working at INO will get opportunities to interact with international experts."

LHC EXPERIMENTS

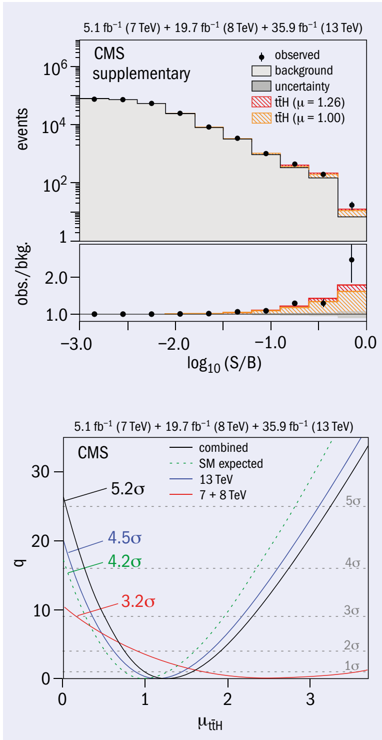
Higgs boson reaches the top

The CMS collaboration has published the first direct observation of the coupling between the Higgs boson and the top quark, offering an important probe of the consistency of the Standard Model (SM). In the SM, the Higgs boson interacts with fermions via a Yukawa coupling, the strength of which is proportional to the fermion mass. Since the top quark is the heaviest particle in the SM, its coupling to the Higgs boson is expected to be the largest and thus the dominant contribution to many loop processes, making it a sensitive probe of hypothetical new physics.

The associated production of a Higgs boson with a top quark–antiquark pair ($t\bar{t}H$) is the best direct probe of the top-Higgs Yukawa coupling with minimal model dependence, and thus a crucial element to verify the SM nature of the Higgs boson. However, its small production rate – constituting only about 1% of the total Higgs production cross-section – makes the $t\bar{t}H$ measurement a considerable challenge.

The CMS and ATLAS collaborations reported first evidence for the process last year, based on LHC data collected at a centre-of-mass energy of 13 TeV (*CERN Courier* May 2017 p49 and December 2017 p12). The first observation, constituting statistical significance above five standard deviations, is based on an analysis of the full 2016 CMS dataset recorded at an energy of 13 TeV and by combining these results with those collected at lower energies.

The $t\bar{t}H$ process gives rise to a wide variety of final states, and the new CMS analysis combines results from a number of them. Top quarks decay almost exclusively to a bottom quark (b) and a W boson, the latter subsequently decaying either to a quark and an antiquark or to a charged lepton and its associated neutrino. The Higgs-boson decay channels include the decay to a bb quark pair, a $\tau^+\tau^-$ lepton pair, a photon pair, and combinations of quarks and leptons from the decay of intermediate on- or off-shell W and Z bosons. These five Higgs-boson decay channels were analysed by CMS using sophisticated methods, such as multivariate techniques, to separate signal from background events. Each channel poses different experimental challenges: the bb channel has the largest rate but suffers from a large background of events containing a top-quark pair and jets, while the photon and Z-boson pair channels offer the highest signal-to-background ratio at a very small rate.



Top: distribution of all events as a function of $\log_{10}$ S/B, where S and B are the expected signal and background yields, respectively, evaluated for each bin in the combined likelihood analysis. The signal contribution is shown for both the SM expectation ($\mu = 1.0$) and the value measured in data ($\mu = 1.26$). Bottom: the likelihood-ratio test statistic q as a function of the $t\bar{t}H$ signal-strength modifier, μ, at 7+8 TeV and at 13 TeV, separately, and their combination. The expected SM result for the combination is also shown. The horizontal dashed lines indicate the p-values for the background-only hypothesis expressed in the number of standard deviations.

CMS observed an excess of events with respect to the background-only hypothesis at a significance of 5.2 standard deviations. The measured values of the signal strength in the considered channels are consistent with each other, and a combined value of $1.26 +0.31/-0.26$ times the SM expectation is obtained (see figure). The measured production rate is thus consistent with the SM prediction within one standard deviation. The result establishes the direct Yukawa coupling of the Higgs boson to the top quark, marking an important milestone in our understanding of the properties of the Higgs boson.

Further reading

CMS Collaboration 2018 arXiv:1804.02610 (accepted by *Phys. Rev. Lett.*).
CMS Collaboration 2018 arXiv:1803.05485 (submitted to *J. High Energy Phys*).
ATLAS Collaboration 2018 *Phys. Rev. D* **97** 072003.

ALICE probes partons inside lead nuclei

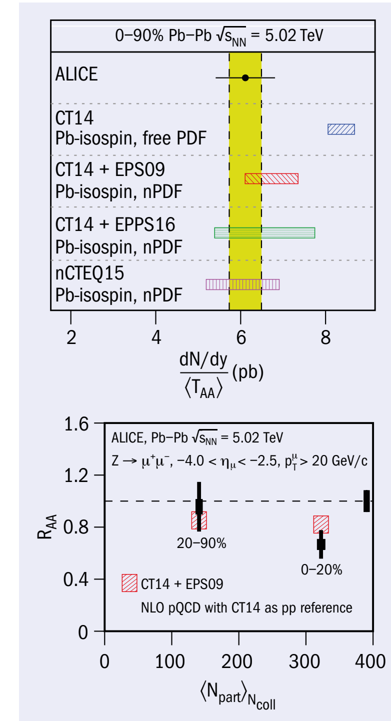
The large centre-of-mass energy and luminosity of the LHC have made possible the first measurements of electroweak-boson production in ultrarelativistic heavy-ion collisions. The production cross sections for such processes in proton–proton (pp) collisions are known with high precision, and indeed have been suggested as "standard candles" for luminosity measurements at the LHC. Since the electroweak bosons and their leptonic decay products do not interact strongly with the hot and dense quark–gluon matter produced in heavy-ion collisions, they can also be used as a reference in this environment. Here, the production rates of W and Z bosons directly probe initial-state effects, such as the u- and d-quark density (isospin) and the difference between the parton density functions (PDFs) of nucleons that are bound in nuclei and those that are free. These effects are studied by comparing the measurements in lead–lead (PbPb) collisions to the results from pp collisions, taking their different collision-impact parameters into account.

The ALICE experiment has measured, ▷

for the first time, Z-boson production at large rapidity in PbPb collisions at a centre-of-mass energy of 5.02 TeV per nucleon pair (figure, top). The measurement was compared with theoretical calculations at next-to-leading order, considering a combination of proton and neutron PDFs to account for the isospin of the lead nucleus. Those calculations that include a nuclear modification of the PDFs (through three different parameterisations) describe the data well, while the calculation using free proton and neutron PDFs overestimates the data by 2.3 standard deviations.

The Z production rate was studied as a function of rapidity and collision centrality. To study the radial dependence of the nuclear effects, the data sample was divided into two different centrality classes and the nuclear modification factor R_{AA} was evaluated by dividing the normalised yields by the theoretical pp cross-section reference (figure, bottom). The measurements are well described by the calculations using an impact-parameter-dependent nuclear PDF, and the data point in the 0–20% most central collisions deviates from the predictions with free PDFs by three standard deviations.

The Z-boson measurements at large rapidity in PbPb collisions at LHC energies are well-described by calculations that include nuclear modifications of the PDFs. These have been inferred mostly from deep-inelastic scattering experiments at lower energies, while the predictions using free PDFs deviate from data. The data from the upcoming PbPb data-taking period in November will allow ALICE to improve the precision of the electroweak-boson measurements and provide more precise information on the modification of PDFs in nuclei.



Top: invariant yield of dimuons from Z-boson production in the rapidity range $2.5 < y < 4.0$ divided by the average nuclear overlap function in the 0–90% centrality class in PbPb collisions at 5.02 TeV. The horizontal bar represents the statistical uncertainty, while the yellow band represents the systematic uncertainty, and the result is compared to theoretical calculations with and without nuclear modification of the PDFs. Bottom: nuclear modification factor as a function of the collision centrality: vertical error bars are statistical, while boxes represent systematic uncertainties.

Further reading

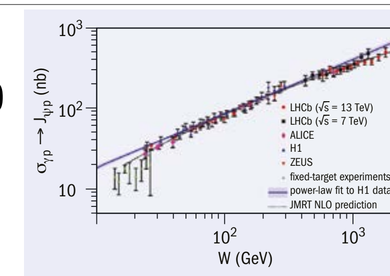
ALICE Collaboration 2018 *Phys. Lett. B* **780** 372.

Central exclusive production at LHCb

Four years ago, LHCb measured the central exclusive production (CEP) of J/ψ and $\psi(2S)$ mesons at a centre-of-mass energy of 7 TeV (*CERN Courier* March 2014 p7). In CEP, two incoming protons emerge intact from the collision, with a central system created by the fusion of two propagators that do not contain colour (e.g. photons or pomerons). This results in an unusual final state for hadron collisions with just a few particles detected: in the case of J/ψ and $\psi(2S)$ mesons, it leads to the characteristic signature of two muons from the meson decay and no other observed activity in the event.

A major background to this process is due to collisions where the protons dissociate but the remnants travel close to the beamline and thus remain undetected. To address this, the LHCb collaboration designed and built a new detector called HeRSCheL, which was installed at the beginning of 2015 in the LHC tunnel. It consists of 20 square plastic scintillators approximately 30 cm wide placed just outside the vacuum pipe at distances up to 114 m from the interaction point. Whilst LHCb is fully instrumented in the pseudorapidity region $2 < \eta < 5$, HeRSCheL significantly extends the sensitivity to $5 < |\eta| < 10$ and therefore improves the precision with which the experiment can observe CEP processes.

LHCb has now taken advantage of the extra reach to measure J/ψ and $\psi(2S)$ CEP in 13 TeV proton–proton collisions. By including HeRSCheL, backgrounds have been reduced by a factor of two compared to the measurement at 7 TeV. Furthermore, by comparing events with and without activity in HeRSCheL, a much better understanding of those backgrounds has been achieved, resulting in an improved precision.



Photoproduction cross section for J/ψ mesons as a function of the proton–photon centre-of-mass energy from various experiments.

The figure shows the derived photoproduction cross section for J/ψ mesons as a function of the proton–photon centre-of-mass energy for LHCb data at 7 and 13 TeV, with good agreement observed compared to theoretical predictions. Also shown are ALICE results in proton–lead collisions and HERA (H1 and Zeus) results at lower energies. The shaded band is a power-law extrapolation of the HERA data, which is seen to be inconsistent with the data at the highest energies.

Measurements of the CEP process can be used to test perturbative QCD predictions as well as to improve our understanding of the distribution of gluons inside the proton. This new measurement paves the way to future CEP analyses at LHCb and beyond, not only using proton–proton but also heavy-ion collisions.

Further reading

K C Akiba *et al.* 2018 *J. Instrum.* **13** P04017.
S P Jones *et al.* 2013 *J. High Energy Phys.* **11** 085.
LHCb Collaboration 2018 LHCb-PAPER-2018-011.

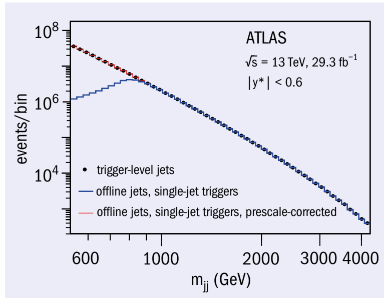
News

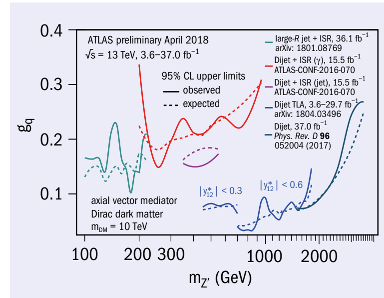
Trigger-level searches for low-mass dijet resonances

The LHC is not only the highest-energy collider ever built, it also delivers proton–proton collisions at a much higher rate than any machine before. The LHC detectors measure each of these events in unprecedented detail, generating enormous volumes of data. To cope, the experiments apply tight online filters (triggers) that identify events of interest for subsequent analysis. Despite careful trigger design, however, it is inevitable that some potentially interesting events are discarded.

The LHC-experiment collaborations have devised strategies to get around this, allowing them to record much larger event samples for certain physics channels. One such strategy is the ATLAS trigger-object level analysis (TLA), which consists of a search for new particles with masses below the TeV scale decaying to a pair of quarks or gluons. The analysis uses selective readout to reduce the event size and therefore allow more events to be recorded, increasing the sensitivity to new physics in domains where rates of Standard Model (SM) background processes are very large.

Dijet searches look for a resonance in the two-jet invariant mass spectrum. The strong-interaction multi-jet background is expected to be smoothly falling, thus a bump-like structure would be a clear sign of a deviation from the SM prediction. As the invariant mass decreases, the rate of multi-jet events increases steeply – to the point where, in the sub-TeV mass range, the data-taking system of ATLAS cannot handle the full rate due to limited data-storage resources. Instead, the ATLAS trigger system discards most of the events in this mass range, reducing the sensitivity to low-mass dijet resonances.





The compact TLA data format records approximately 1% of the nominal event size at a much higher rate than standard data-taking. As a result, more data are recorded at lower dijet invariant mass (left). The large TLA dataset allows ATLAS to set its strongest limits on resonances decaying to quarks in the mass range between 450 GeV and 1 TeV (right).

By recording only the final-state objects used to make the trigger decision, however, this limitation can be bypassed. For a dijet-resonance search, the only necessary ATLAS detector signals are the calorimeter information used to reconstruct the jets. This compact data format records far less information for each event, about 1% of the usual amount, allowing ATLAS to record dijet events at a rate 20 times larger than what is possible with standard data-taking (figure, left).

While the TLA technique gives access to physics at lower thresholds, the ATLAS detector information for these events is incomplete. Dedicated reconstruction and calibration techniques had to be developed to deal with the partial event information and, as a result, the invariant mass computed from TLA jets is comparable to that using jets reconstructed from the full detector readout within 0.05%.

The data recorded by ATLAS in 2015 and 2016 at a centre-of-mass energy of 13 TeV did not reveal any bump-like structure in the TLA dijet spectrum. The unprecedented statistical precision allowed ATLAS to set its strongest limits on resonances decaying to quarks in the mass range between 450 GeV and 1 TeV (figure, right). The analysis is sensitive to new particles that could mediate interactions between the SM particles and a dark sector, and to other new resonances at the electroweak scale. This analysis probes an important mass region that could not otherwise be explored in this final state with comparable sensitivity.

ATLAS joins CMS and LHCb with an analysis technique that requires fewer storage resources to collect more LHC data. The technique will be extended in the future, with upgraded trigger farms and detectors making tracking information available at early trigger levels. It will thus play an important role at LHC Run 3 and at the high-luminosity LHC upgrade.

Further reading

ATLAS Collaboration 2018 arXiv:1804.03496.
ATLAS Collaboration 2017 ATL-DAQ-PUB-2017-003.
CMS Collaboration 2016 arXiv:1611.03568.
LHCb Collaboration 2016 arXiv:1604.05596.

Sciencewatch

Compiled by John Swain, Northeastern University

Endless recycling possibilities

Easily recyclable polymers, which could be broken down into their constituent monomers and then repolymerised, would potentially help to solve the global plastic-waste problem. Jian-Bo Zhu and colleagues of Colorado State University have developed a polymer system based on γ-butyrolactone (GBL) that renders the usually nonpolymerisable GBL ring easily polymerisable at room temperature and under solvent-free conditions. The polymer has high molecular weight, thermal stability and crystallinity, and can be repeatedly converted back into its monomers by thermolysis or chemolysis, ready to be used again as a raw material.


iStock/apomares

The easily recyclable polymer system developed by Zhu and colleagues could help to fix the global plastic-waste problem.

Further reading

J-B Zhu *et al.* 2018 *Science* **360** 398.

20-qubit entanglement

For quantum computing to reach its full potential, the critical benchmark to push is the number of quantum-entangled qubits. Nicolai Friis of the Austrian Academy of Sciences and colleagues now report entangled states in a fully controlled 20-qubit system using trapped atomic ions as the qubits. The previous largest number of entangled qubits was 14, but even modest improvements in how many qubits can be entangled can lead to vast increases in computational power. The team observed genuine multipartite entanglement in all neighbouring qubit pairs and triplets, in most quadruplets, and in some quintuplets. Genuine multipartite entanglement in larger qubit groups in their system remains to be demonstrated.

Further reading

N Friis *et al.* 2018 *Phys. Rev. X* **8** 021012.

Two new time crystals

Time crystals – structures whose lowest-energy configurations are periodic in time rather than space – were first experimentally demonstrated in 2017 in (spatially) disordered systems. Two independent teams have now added spin systems periodically driven by NMR pulses to the list of systems that can host time crystals. Jared Rovny and colleagues of Yale University used radio-frequency (RF) pulses to periodically rotate the spins of phosphorus-31 nuclei inside a crystal of ammonium dihydrogen phosphate, finding that the spins displayed time-crystal behaviour, oscillating at twice the period of the pulse sequence. In a distinct NMR experiment, Soham Pal and colleagues at the Indian Institute of Science Education and Research found time-crystal behaviour in a liquid, using molecules with a central spin surrounded by several satellite spins and subjecting the molecules to an RF pulse sequence.

Further reading

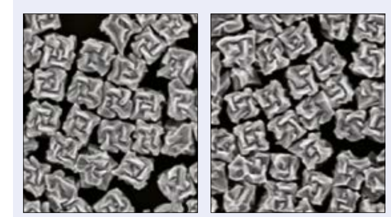
J Rovny *et al.* 2018 *Phys. Rev. Lett.* **120** 180603; *Phys. Rev. B* **97** 184301.
S Pal *et al.* 2018 *Phys. Rev. Lett.* **120** 180602.

From amino acids to gold

Chiral nanoparticles have several potential applications, such as in optical devices and sensors. But it can be tricky to prepare them, particularly from crystalline metals. A novel idea uses the chirality of amino acids to make chiral plasmonic gold nanoparticles. Hye-Eun Lee of Seoul National University and colleagues used chiral (L or D) amino acids on "seed" nanoparticles to favour one chirality over the other as the seeds grew. The resulting nanoparticles have a twisted morphology that gives them a strong chiral plasmonic optical activity with a so-called dissymmetry factor of 0.2, even when the particles are dispersed randomly in solution.

Further reading

H-E Lee *et al.* 2018 *Nature* **556** 360.



Scanning electron microscope images of chiral gold nanoparticles grown in the presence of L (left) or D (right) amino acids.

Randomness from starlight

John von Neumann once said "Anyone who attempts to generate random numbers by deterministic means is, of course, living in a state of sin." Enter Calvin Leung from Harvey Mudd College in California and colleagues. In earlier work, Leung and co-workers used light coming from stars in the Milky Way to develop a random-number generator to assign detector settings for a so-called Bell experiment, which tests the quantum nature of a system. This allowed them to rule out any local correlations between the particles and detectors used in the experiment going back 600 years into the past. The team has now used (distant) quasars to push this time frame back to near the beginning of the universe.

Further reading

C Leung *et al.* 2018 *Phys. Rev. A* **97** 042120.

New Bose–Einstein condensate

Tommi Hakala and colleagues of the Aalto University School of Science have made a new type of Bose–Einstein condensate, in which the condensate particles are surface plasmon polaritons – a mixture of light and electrons. The researchers produced the condensate using a periodic array of gold nanoparticles overlaid with dye molecules and optically pumped from one edge. The condensate emerges in less than a picosecond, which is far shorter than typical condensation times, and unlike most other condensates it forms at room temperature. These features might make this new form of condensate a promising system for future light-based technologies.

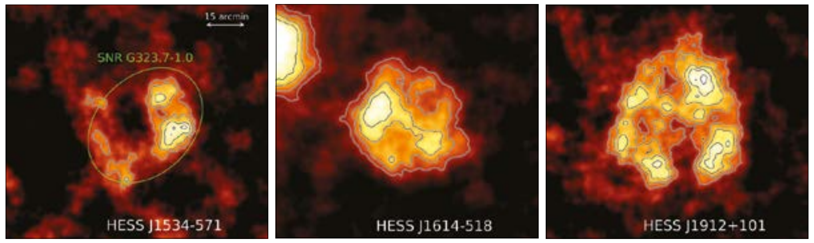
Further reading

T K Hakala *et al.* 2018 *Nat. Phys.* doi:10.1038/s41567-018-0109-9.

Astrowatch

Compiled by Merlin Kole, Department of Particle Physics, University of Geneva

HESS proves the power of TeV astronomy



Surface-brightness maps of the three supernova-remnant candidates detected by HESS in our galactic plane. The green ellipse denotes the radio counterpart of HESS J1534-571.

For hundreds of years, discoveries in astronomy were all made in the visible part of the electromagnetic spectrum. This changed in the past century when new objects started being discovered at both longer wavelengths, such as radio, and shorter wavelengths, up to gamma-ray wavelengths corresponding to GeV energies. The 21st century then saw another extension of the range of astronomical observations with the birth of TeV astronomy.

The High Energy Stereoscopic System (HESS) – an array of five telescopes located in Namibia in operation since 2002 – was the first large ground-based telescope capable of measuring TeV photons (followed shortly afterwards by the MAGIC observatory in the Canary Islands and, later, VERITAS in Arizona). To celebrate its 15th anniversary, the HESS collaboration has published its largest set of scientific results to date in a special edition of *Astronomy and Astrophysics*. Among them is the detection of three new candidates for supernova remnants that, despite being almost the size of the full Moon on the sky, had thus far escaped detection.

Supernova remnants are what's left after massive stars die. They are the prime suspect for producing the bulk of cosmic rays in the Milky Way and are the means by which chemical elements produced by supernovae are spread in the interstellar medium. They are therefore of great interest for different fields in astrophysics.

HESS observes the Milky Way in the energy range 0.03–100 TeV, but its telescopes do not directly detect TeV photons. Rather, they measure the Cherenkov radiation produced by showers of particles generated when these photons enter Earth's atmosphere. The energy and direction of the primary TeV photons can then be determined from the shape and direction of the Cherenkov radiation.

Using the characteristics of known TeV-emitting supernova remnants, such as their shell-like shape, the HESS search revealed three new objects at gamma-ray wavelengths, prompting the team to search for counterparts of these objects in other wavelengths. Only one, called HESS J1534-571 (figure, left), could be connected to a radio source and thus be classified as a supernova remnant. For the two other sources, HESS J1614-518 and HESS J1912+101, no clear counterparts were found. These objects thus remain candidates for supernova remnants.

The lack of an X-ray counterpart to these sources could have implications for cosmic-ray acceleration mechanisms. The cosmic rays thought to originate from supernova remnants should be directly connected to the production of high-energy photons. If the emission of TeV photons is a result of low-energy photons being scattered by high-energy cosmic-ray electrons originating from a supernova remnant (as described by leptonic emission models), soft X-rays would also be produced while such electrons travelled through magnetic fields around the remnant. The lack of detection of such X-rays could therefore indicate that the TeV photons are not linked to such scattering but are instead associated with the decay of high-energy cosmic-ray pions produced around the remnant, as described by hadronic emission models. Searches in the X-ray band with more sensitive instruments than those available today are required to confirm this possibility and bring deeper insight into the link between supernova remnants and cosmic rays.

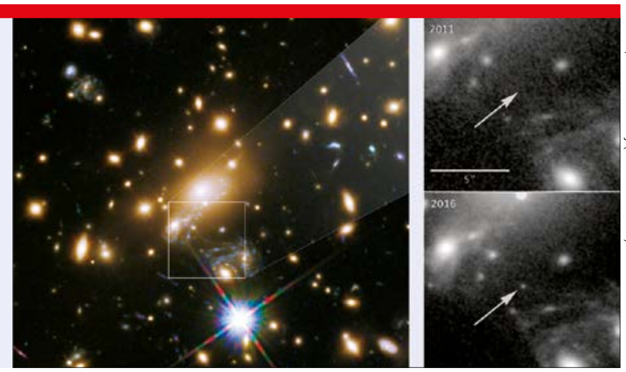
The new supernova-remnant detections by HESS demonstrate the power of TeV astronomy to identify new objects. The latest findings increase the anticipation for a range of discoveries from the future Cherenkov Telescope Array (CTA). With more than 100 telescopes, CTA will be more sensitive to TeV photons than HESS, and it is expected to substantially increase the number of detected supernova remnants in the Milky Way.

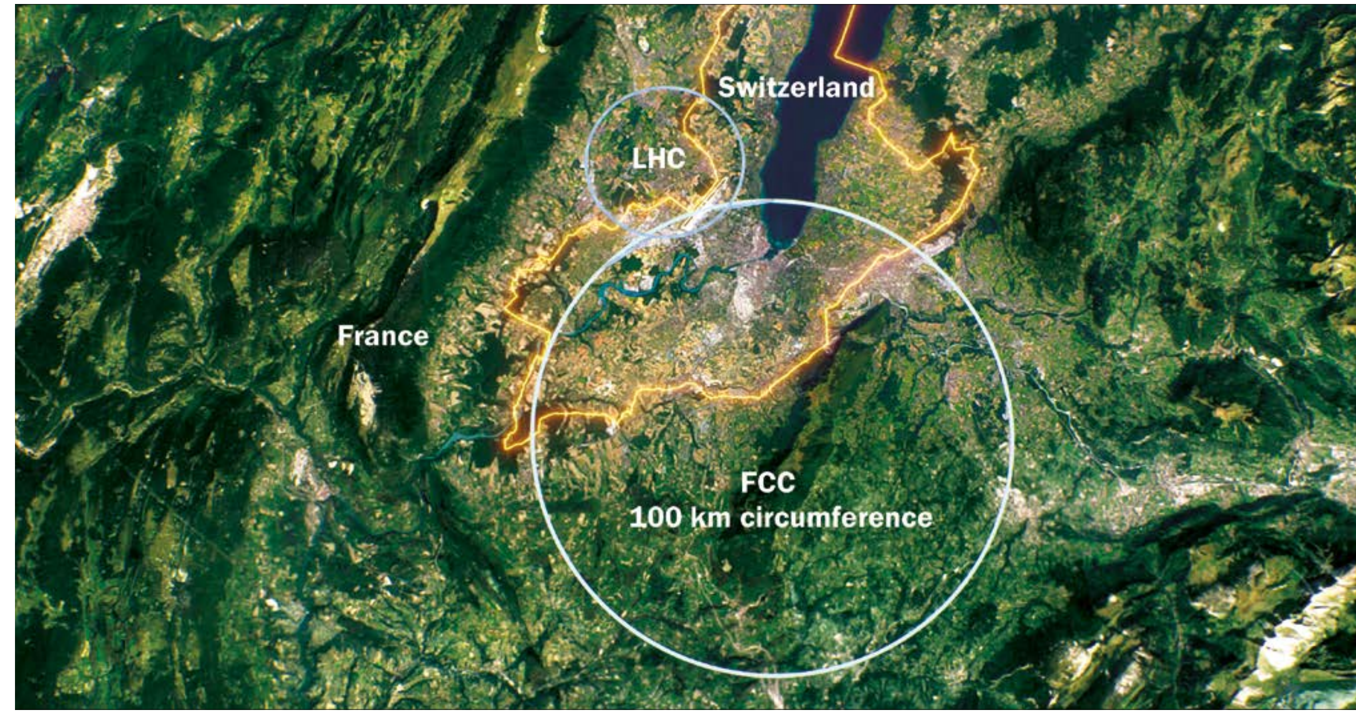
Further reading

HESS Collaboration 2018 *Astron. Astrophys.* **612** A8.

Picture of the month

Although barely noticeable in this image of a massive galaxy cluster (left), which was taken with the Hubble Space Telescope, the small blue dot in the centre of the inset could be the farthest star ever observed. The source appeared to come out of nowhere: it was visible in 2016 (bottom right) but not in 2011 (top right). Such transients are typically associated with supernovae, but the spectrum and variability of the source seem to agree much more with those of a distant blue supergiant star magnified 2000 times by the gravitational lensing of the foreground galaxy cluster. If this interpretation is correct, the star, now called Icarus, would be the farthest star ever seen, with a light-travel distance of about nine billion light years.





CERN thinks bigger

"What is the origin of the universe? This very simple question lies at the heart of all your work and forms the basis of the ambitions for the Future Circular Collider study." – José van Dijck, president of the Royal Netherlands Academy of Arts and Sciences.

It is almost six years since the CMS and ATLAS collaborations jointly announced the discovery of the Higgs boson, the last of the Standard Model particles predicted to exist. Yet deep questions in particle physics remain unsolved and precise measurements of the Higgs boson are one of many ways to search for answers that could point to new physics beyond the Standard Model. Experiments at higher energies than those available at the LHC could conclusively determine which, if any, of the many theories describing this new physics is realised and reveal the nature of the dark sector of the universe.

The Future Circular Collider (FCC) study, which was formally launched in 2014, would see a 100 km-circumference tunnel built at CERN to host post-LHC colliders. The goals of this international project include precision measurements of the Higgs self-interaction, whose structure is deeply related to the origin of mass and to the breaking of the electroweak symmetry. More generally, the FCC offers a leap into completely uncharted territory, from delivering mind-boggling statistics of 5×10^{12} Z decays all the way up to proton–proton collisions at an energy of 100 TeV (*CERN Courier* May 2017 p34).

Deriving from proposals formulated as early as 2010, the FCC study has made rapid progress in R&D across the many domains of this mammoth technological effort, and attracted a growing international community. Scientists and engineers from around the world gathered in Amsterdam from 9–13 April for the 2018 FCC collaboration week to identify key objectives for the FCC's Conceptual Design Report (CDR), which is due by the end of this year. Advances in theoretical studies and detector techniques presented during the conference demonstrated that the machines envisaged by the FCC study could investigate some of the most compelling issues of particle physics in the decades following the LHC, while at the same time driving a major training, technological and industrial programme.

Image above: the FCC would build on CERN's existing accelerator network and be fed particles by the LHC. (Image credit: CERN.)

CERN Courier June 2018
Future colliders

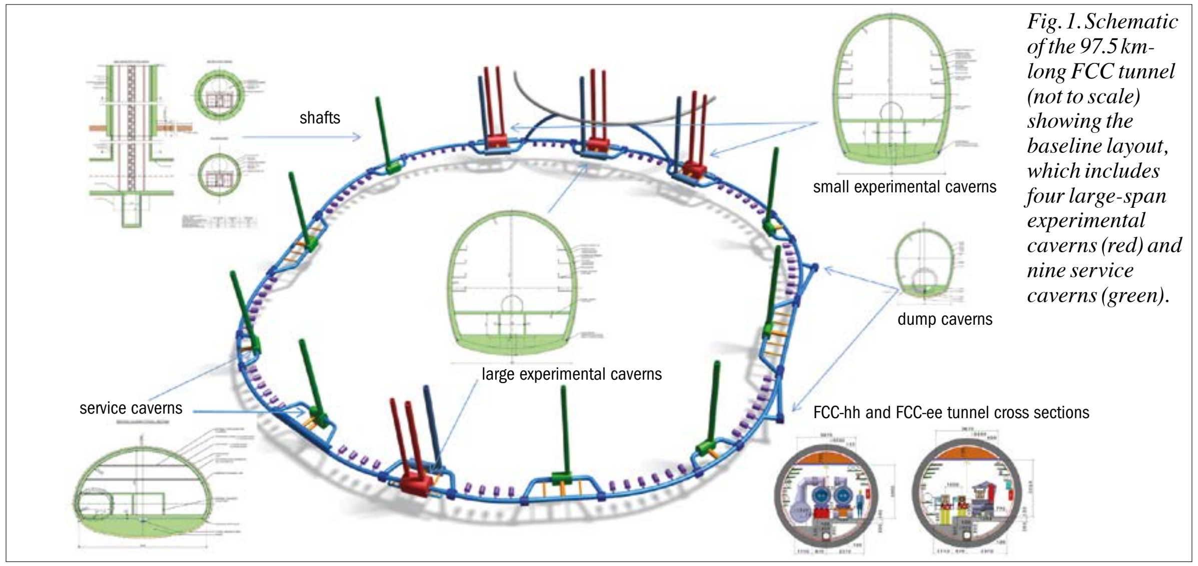


Fig. 1. Schematic of the 97.5 km-long FCC tunnel (not to scale) showing the baseline layout, which includes four large-span experimental caverns (red) and nine service caverns (green).

As with other major proposals for post-LHC machines at CERN and elsewhere, the FCC is currently at the exploratory stage. Its predecessors, the Large Electron Positron collider (LEP) and the LHC were, and are, massive endeavours offering a fruitful physics programme spanning more than 60 years: from the first concept of LEP to the future full exploitation of the high-luminosity LHC upgrade. The timescales of high-energy physics are such that we need to start the process of designing, and understanding what would be required to build, the next generation of circular colliders now if they are to come into operation soon after the completion of the high-luminosity LHC's research programme in the late 2030s.

Following earlier investigations and projects – such as the ELOISATRON in Italy and the Superconducting Super Collider and Very Large Lepton Collider (VLLC)/Very Large Hadron Collider (VLHC) in the US – the first studies in Europe for a future circular collider started in 2010 and 2011, respectively, for new high-energy proton and lepton colliders at CERN. The lepton collider had three variants: LEP3 (a new electron–positron collider in the LHC tunnel), DLEP (a new collider roughly double the size of LEP) and the 80 km circumference "TLEP" (triple the size of LEP). As was the case for LEP and LHC, and also proposed by the VLLC/VLHC study in around 2001, both the lepton and hadron machines could be housed successively in a new, large tunnel.

Amalgamation

In early 2014 the lepton- and proton-collider design efforts were formally combined under the umbrella of the FCC study. First civil engineering studies in 2012 and 2014 revealed that a tunnel of 80–100 km is geologically preferred in the Lake Geneva basin, and a circumference of about 100 km has become the FCC target. In 2013 the Institute for High-Energy Physics in Beijing initiated a similar design study for a Higgs factory in China (CEPC) that would be succeeded by a high-energy proton–proton collider called SppC (see p21). Initially a CEPC tunnel circumference of 54 km and a proton collider reaching collision energies of 70 TeV were being considered, but since 2017 the CEPC tunnel circumference has also been set at 100 km.

The FCC study envisages, as a potential first step, an electron–positron collider (FCC-ee) that could scrutinise the Higgs boson and the electroweak scale. The remarkable precision of LEP has been instrumental in confirming the Standard Model and in tightly constraining the masses of the top quark and of the Higgs Boson. The FCC-ee builds upon this tradition. Operating at four different energies for precision measurements of the Z, W and Higgs bosons and the top quark, FCC-ee represents a significant advance in terms of technology and design parameters. The total scientific programme could span a period of 14 years, the first eight dedicated to Z, W and Higgs measurements followed by a high-energy upgrade to a top-quark factory.

With produced samples of 5×10^{12} Z bosons, 10^{8} W pairs, 10^{6} Higgs and top pairs, FCC-ee will allow searches for rare phenomena that can reveal new physics, while as an exploratory machine it would have sensitivity to new particles that might either be extremely heavy or that could interact too weakly with ordinary matter to be otherwise seen. The extraordinary precision of FCC-ee (1 ppm precision on the Z mass, 7 ppm precision on the W mass) backed up by unique measurements of additional inputs to the calculations (such as the top-quark mass) will allow typical sensitivity to particles as massive as 50 TeV or to couplings many orders of magnitude smaller than those of normal particles. While presenting considerable challenges, the design and technology for FCC-ee are solid and the machine could be built so as to start physics as soon as the LHC's high-luminosity upgrade (HL-LHC) has completed its programme.

The mammoth proton–proton collider (FCC-hh) would operate at seven times the LHC energy, and deliver about 10 times more integrated luminosity. During its planned 25 years of data-taking, more than 10^{10} Higgs bosons will be created, which will be 100 times more than that achieved by the end of the (HL-)LHC operation. These additional statistics will enable the FCC-hh experiments to improve the separation of Higgs signals from the huge backgrounds that affect most LHC studies. The discovery reach for high-mass particles – such as Z′ and W′ gauge bosons corresponding to new fundamental forces, or particles like gluinos and squarks that appear in supersymmetric theories – will increase by a factor five or more, depending on the luminosity. The new energy regime will allow us to exclude many theories relying on weakly interacting massive particles, guaranteeing a discovery or excluding a vast portion of the parameter space, and explore fully the electroweak symmetry-breaking mechanism.

Operating the FCC-hh machine with heavy ions generates even more extreme collisions, leading to the creation of a quark–gluon plasma with larger initial density and temperature than those previously observed at RHIC and LHC. This system, in comparison to that produced at the LHC, represents the universe at an earlier, hotter stage of its evolution, allowing a better understanding of quantum chromodynamics and shedding light on the question of how quarks combine to form more stable particles. The FCC complex could also host a proton–electron mode (FCC-he) to explore the secrets of the structure of matter by means of an electron super microscope using deep-inelastic electron–proton (ep) scattering with unprecedented energies and luminosities. Finally, the FCC study also pursues the design of a 27 TeV proton–proton collider in the LHC tunnel (the so-called High Energy LHC, HE-LHC) based on the same 16 T superconducting niobium-tin magnet technology as intended for FCC.

Fig. 2. Left: winding of the enhanced racetrack model coil (RMC) for FCC-hh 16 T magnets with Nb_3Sn superconducting cable at CERN. Right: A 1 m-long prototype of the FCC-ee dipole magnet. The proposed design considerably reduces the power consumption and the total amount of material required. For example, a machine three times longer than LEP will only require around 35% more steel.

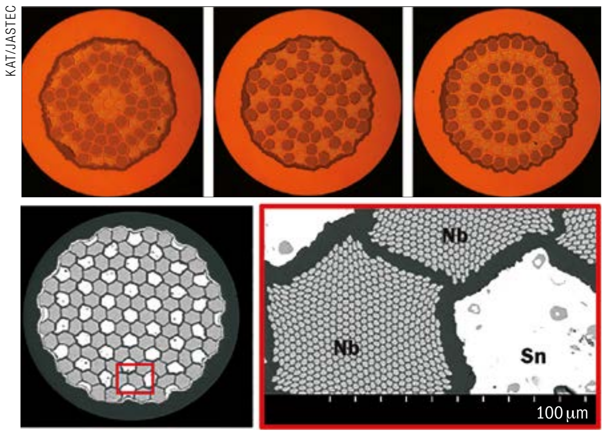


Fig. 3. Cross-sections of prototype Nb_3Sn wires developed in collaboration with CERN as part of the FCC conductor development programme. Top: optical micrographs of wires from Kiswire Advanced Technology. Bottom: electron micrographs showing a wire developed by JASTEC in collaboration with KEK. Both show the unreacted wire before the heat treatment to form the Nb_3Sn compound from the niobium filaments and tin.

New thinking required

Conceiving and designing an FCC-class accelerator poses tantalising challenges with respect to infrastructure and operations. Since the launch of the study, a major focus of the civil-engineering team has been locating the machine in the optimal position, as well as developing a design that could host the different collider modes in a combination of underground and surface structures.

The civil-engineering requirements for the FCC include approximately 115 km of tunnelling, of which 97.75 km is a 5.5 m-diameter machine tunnel, and the remainder is a combination of bypass, injection and dump tunnels. In addition, four experimental caverns and 12 service caverns are needed, while a total of 22 shafts will connect the underground facilities with the surface (figure 1). The current baseline position successfully fulfils many of the desired criteria, such as a reduction in the total shaft length, a maximum amount of tunnelling in the stable molasses rock, and a minimum amount of excavation in karstic limestone and moraines. Detailed underground surveys, as previously done for the LHC and HL-LHC, are needed to confirm the different soil types and identify potential problems before the proposed location can be firmly validated.

Significant progress has been made over the past year to assess and minimise environmental impact, opting for smart "green" solutions based on the development of new technologies. Among all proposed, future electron–positron colliders, FCC-ee offers by far the highest luminosity at the lowest electric input power up to the top quark threshold, partly thanks to more efficient superconducting radiofrequency cavities, new klystrons and novel designs for the dipole (figure 2) and quadrupole magnets. Similar considerations apply to the design of FCC-hh, which spans a wide range of proton collision energies yet should draw a total electric power similar to the FCC-ee.

FCC Week 2018 saw significant progress in the development of detector designs both for FCC-ee and FCC-hh. For the lepton collider, a detector inspired by the Compact Linear Collider (CLIC) with an all-silicon tracker and a 3D-imaging calorimeter, and an alternative novel detector approach (called International Detector for Electron-positron Accelerator, or IDEA) combine different philosophies with bold technologies. For IDEA, the vertex detector would be silicon-based using the Monolithic Active Pixel Sensor (MAPS) technology developed for the ALICE inner-tracker upgrade, while a large wire chamber inspired by DAFNE's KLOE experiment would provide the central tracking. Perhaps the most innovative concept of IDEA is the dual-readout copper calorimeter. All in all, the basic detector components are based on proven techniques and work is in progress, including test beam sessions foreseen at CERN in the summer, to optimise their designs.

The increased energy of FCC-hh also has a huge impact on the design of the various detectors for tracking and calorimetry and their readout electronics, as well as the magnet system for bending charged particles and identifying their properties. The superconducting detector magnets of the FCC-hh experiments should provide a higher magnetic field over a larger tracking distance than currently achieved by the LHC experiments, and this poses a new challenge for magnet designers. The FCC-hh baseline design foresees a very large main solenoid (with a free bore of 10 m and a length of 20 m) providing a field of 4 T and forward solenoids at both ends. For FCC-ee, an ultra-thin 2 T magnet concept is being studied with a free bore of 4.4 m and a length of 6 m.

Core technology

Advanced superconducting technology is at the core of the FCC study. Two of the major technological challenges for an energy-frontier machine are the development of more powerful dipole magnets (16 T, which is around twice that of the LHC) and a new generation of superconductors able to meet the FCC requirements. CERN has launched a 16 T magnet programme, in coordination with a US programme targeting 15 T, and an ambitious FCC conductor development programme with research institutes and industry distributed around the world (*CERN Courier* May 2018 p40).

Niobium-tin (Nb_3Sn) is the workhorse of the FCC magnet development programme. The first breakthrough results of this effort came in 2015, when a Nb_3Sn magnet in Racetrack Model Coil (RMC) configuration reached a field of 16.2 T (*CERN Courier* November 2015 p8). The next goal is to create an enhanced RMC (ERMC) reaching a mid-plane field of 16 T with a 10% margin at a temperature of 4.2 K. The first ERMC coil was successfully wound at CERN in April this year (figure 2, left picture) and a demonstrator unit will be available by the end of the summer. The high-field magnets of the proposed FCC-hh collider would require 7000–9000 tonnes of Nb_3Sn superconducting wire, with major implications for the superconductivity industry, while boosting the applications of this technology in domains outside high-energy physics.

The FCC conductor development programme aims, over an initial four-year period, to meet the challenging requirements of the FCC high-field magnets. The first results are very promising: within only one year, the Nb_3Sn superconducting wires produced by various international partners have achieved the same performance as the HL-LHC wire (figure 3), and there are strong indicators that it


F Marhauser/Jlab

Fig. 4. The 802 MHz five-cell RF cavity, produced in a partnership between JLAB and CERN, has achieved accelerating fields exceeding the FCC requirements.


CERN

Fig. 5. First beam screens for a high-energy FCC proton–proton collider. Based on a novel vacuum system with improved heat transfer, lower impedance, improved pumping and feasible manufacturing, the design mitigates the formation of electron clouds and removes the much higher synchrotron-radiation power.

will be feasible to meet the even more ambitious wire targets (in terms of performance and cost) for FCC. The FCC magnet development programme will require six tonnes of superconducting wire over the next five years for the construction of R&D and model magnets, representing a substantial opportunity for wire manufacturers in Europe and beyond. CERN has also launched a Marie-Curie training network called EASITrain to advance our knowledge on superconducting materials and take into account large-scale industrialisation (*CERN Courier* September 2017 p31).

Another key technology for FCC is advanced superconducting radio-frequency (RF) cavities. A series of cavity designs comprising single-cell, four-cell 400 MHz and five-cell 800 MHz cavities are being developed, in collaboration with LNL-INFN in Italy and JLAB in the US, to cover the different operation energies foreseen for FCC-ee (figure 4). Recent progress in superconducting RF cavities at CERN has been fascinating, and a concrete R&D programme is under way (*CERN Courier* April 2018 p26). The technology of superconducting niobium-coated copper cavities, already employed at LEP and LHC, is rapidly advancing, achieving, for FCC-ee, a performance at 4.5 K that is competitive to niobium radiofrequency cavities at 2 K.

Current results from niobium-copper cavities installed in HIE-ISOLDE demonstrate the outstanding performance of this technology, achieving peak surface fields of 60 MV/m. Another key development is the rapid shaping of cavities using novel hydro-hydraulic forming, a technique developed in collaboration with

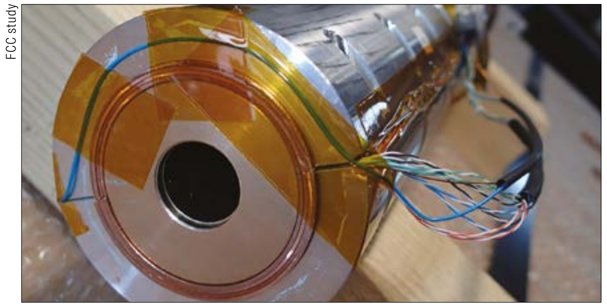

FCC study

Fig. 6. Test setup of a 3.2 mm-thick superconducting shield, that can shield a field of 3.1 T, for the high-field extraction septum magnet of the FCC-hh machine.


E Burrillon

Fig. 7. Researchers, academics and industry representatives from around the globe gathered in Amsterdam in April to discuss the status of the FCC study, in preparation for the publication of a conceptual design report at the end of the year.

the France-headquartered firm Bmax, and promising results from sputtering tests with Nb_3Sn films for even more efficient RF cavities. In addition, new klystron bunching technologies that can increase RF power production efficiency up to 90% (compared to the present average of 65%) are being developed in collaboration with the CLIC team. Finally, prototypes of the low-field low-power (and low-cost) twin-aperture dipole and quadrupole magnets for the FCC-ee arcs have been built and tested at CERN.

All in all, the new challenges of the FCC compared to the LHC and LEP call for a number of novel, special technologies that will allow a reliable and sustainable operation. New extraction systems, kickers and collimators to control the beam, powerful vacuum systems and novel approaches to deal with beam effects at the new regime of FCC, are but a few examples. These efforts have already resulted in a new beam-screen design (figure 5) to cope with the high synchrotron radiation of energetic proton beams, the first prototypes of which are currently under test at the Karlsruhe Research Accelerator (KARA) in Germany. Among other first pieces of hardware paving the way for FCC are the first prototypes of a superconducting shield septum magnet (figure 6) and an innovative method of laser surface treatment to suppress the electron clouds so easily induced by the intense FCC-hh beams, which is also under consideration for the HL-LHC.

Cooling the detector and accelerator magnets is another major challenge for a research infrastructure of this size, requiring huge cryogenic refrigeration capacity below 2 K. In collaboration with specialised industrial partners, significant studies of turbo compressors and also new mixtures of coolants have been carried out. A prototyping phase is to be launched after the completion of the forthcoming CDR.

Winning multinational cooperation

A collider that significantly extends the energy reach of the LHC requires multi-year and multinational cooperation, given the daunting magnitude of the resources needed. The high and growing number of young participants during the annual FCC meetings is a positive indicator for the future of the study. Moreover, the participation of a large number of industries in the FCC study and the supporting Horizon 2020 projects is not a surprise. After all, many of these challenges are also opportunities for technological breakthroughs, as confirmed by past large-scale scientific projects.

The wealth of results presented during the FCC Week 2018 will help inform the update of the European Strategy for Particle Physics, written input for which is required by the end of the year (*CERN Courier* April 2018 p7). As CERN Director-General Fabiola Gianotti remarked during the opening session of the Amsterdam event, "I cannot see a more natural and better place than CERN to host future circular colliders of the complexity of the FCC, given CERN's demonstrated expertise in building and operating high-energy accelerators, the existing powerful accelerator complex, and the available infrastructure that we continue to upgrade." The laboratory's long history and strong expertise in all the necessary technical domains, as well as its ability to foster international collaborations that amplify the impact of such large-scale projects, provide the ideal base from which to mount the post-LHC adventure.

Further reading

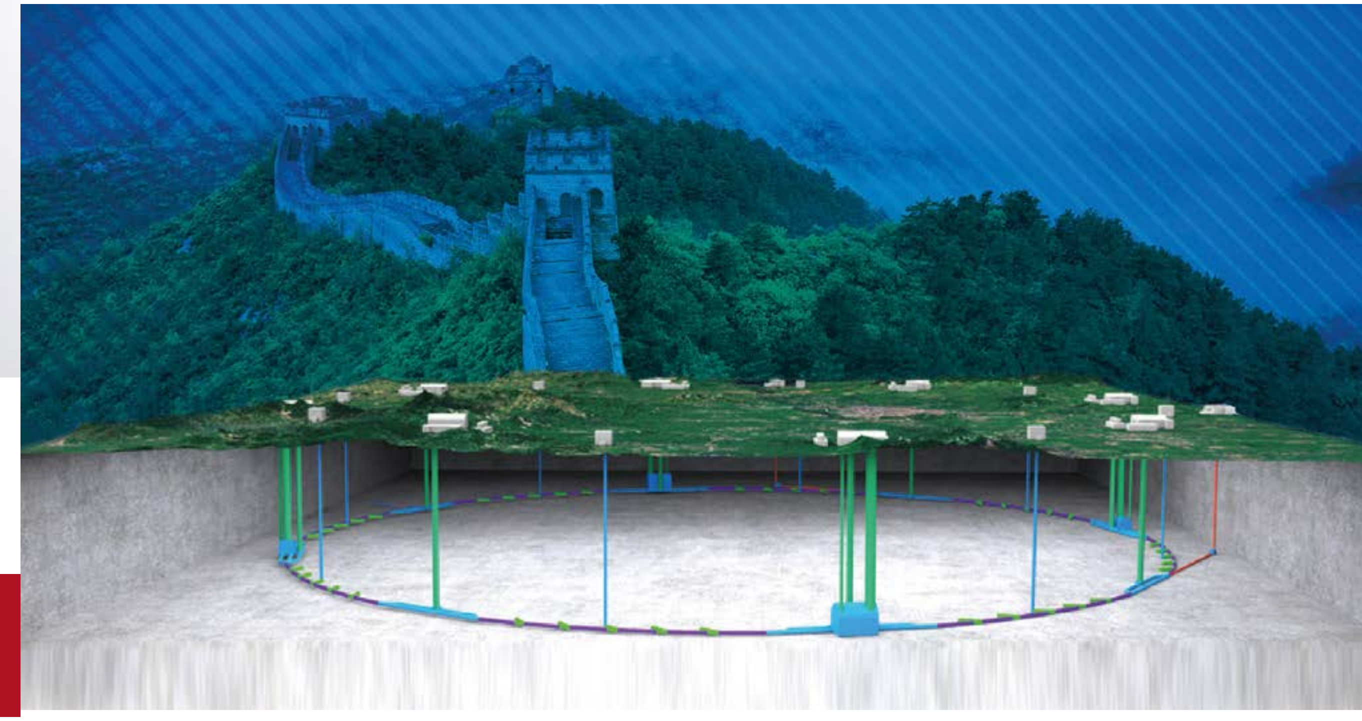
A Blondel and F Zimmermann 2011 arXiv:1112.2518.
F Zimmermann 2013 EuCARD-REP-2013-008.
J Gao 2017 *Int. J. Mod. Phys. A* **32** 1746003.
M Benedikt and F Zimmermann 2016 *J. Korean Phys. Soc.* **69** 893.
M Mangano (ed.) 2017 arXiv:1710.06353.
M Bicer *et al.* 2014 *J. High Energy Phys.* **1** 164.
J Ellis *et al.* 1998 CERN-SL-98-004-AP ; CERN-EP-98-003 ; CERN-TH-98-033.
T Sen and J Norem 2002 *Phys. Rev.* Spec. *Top. Accel. Beams* **5** 031001.

Résumé

Le CERN voit grand

L'étude sur un futur collisionneur circulaire (FCC), lancée en 2014, imagine la construction au CERN d'un tunnel de 100 km de circonférence pour accueillir les collisionneurs qui succéderont au LHC. Ce projet international promet des mesures précises du boson de Higgs, et plus généralement une plongée dans un territoire entièrement inexploré, grâce à des collisions proton–proton à une énergie de 100 TeV. S'appuyant sur des propositions formulées en 2010 déjà, la R&D associée à l'étude FCC a progressé rapidement. Des scientifiques et des ingénieurs du monde entier se sont réunis à Amsterdam, du 9 au 13 avril, pour la semaine de la collaboration FCC 2018, afin de définir les objectifs clés pour le rapport préliminaire de conception sur le FCC, qui doit être présenté d'ici à la fin de cette année.

Frank Zimmermann and **Michael Benedikt**, CERN.



China's bid for a circular electron–positron collider

Physicists in China have completed a conceptual design report for a 100 km-circumference collider that, in conjunction with a possible linear collider in Japan, would open a new era for high-energy physics in Asia.

Chinese accelerator-based research in high-energy physics is a relatively recent affair. It began in earnest in October 1984 with the construction of the 240 m-circumference Beijing Electron Positron Collider (BEPC) at the Institute of High Energy Physics. BEPC's first collisions took place in 1988 at a centre-of-mass energy of 1.89 GeV. At the time, SLAC in the US and CERN in Europe were operating their more energetic PEP and LEP electron–positron colliders, respectively, while the lower-energy electron–positron machines ADONE (Frascati), DORIS (DESY) and VEPP-4 (BINP Novosibirsk) were also in operation.

Beginning in 2006, the BEPCII upgrade project saw the previous machine replaced with a double-ring scheme capable of colliding electrons and positrons at the same beam energy as that of BEPC but with a luminosity 100 times higher (10^{33} cm^{-2} s^{-1}). BEPCII, whose collisions are recorded by the Beijing Spectrometer III (BES III) detector, switched on two years later and continues to produce results today, with a particular focus on the study of charm and light-hadron decays. China also undertakes non-accelerator-based research in high-energy physics via the Daya Bay neutrino experiment, which was approved in 2006 and announced the first observation of the neutrino mixing angle θ_{13} in March 2012.

Image above: several sites in China are currently under study for a possible 100 km-circumference collider. (All image credits: IHEP.)

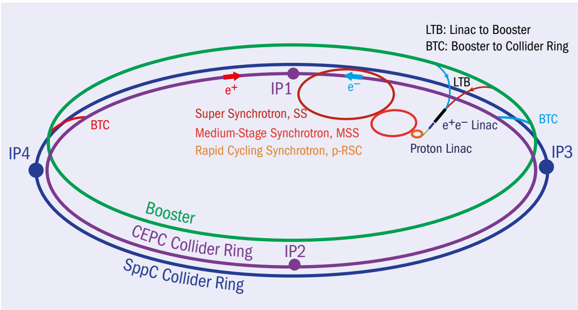


Fig. 1. The overall CEPC-SppC schematic layout.

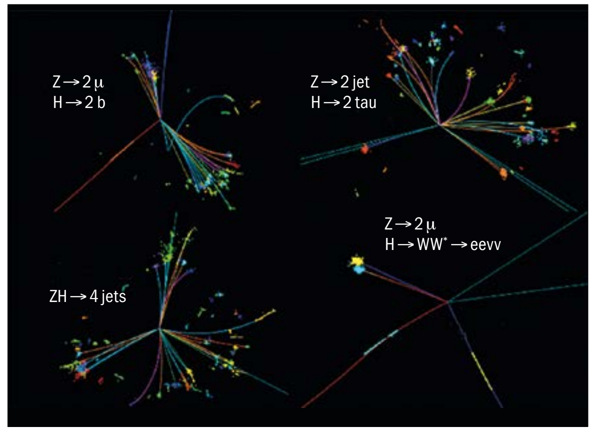


Fig. 2. Simulated Higgs-boson signals with different decay final states for 240 GeV electron–positron collisions envisaged at CEPC, using a PFA-oriented detector design.

The discovery of the Higgs boson at CERN's Large Hadron Collider in July 2012 raises new opportunities for a large-scale accelerator. Thanks to the low mass of the Higgs, it is possible to produce it in the relatively clean environment of a circular electron–positron collider – in addition to linear electron–positron colliders such as the International Linear Collider (ILC) and the Compact Linear Collider (CLIC) – with reasonable luminosity, technology, cost and power consumption. The Higgs boson is the cornerstone of the Standard Model (SM), yet is also responsible for most of its mysteries: the naturalness problem, the mass-hierarchy problem and the vacuum-stability problem, among others. Therefore, precise measurements of the Higgs boson serve as excellent probes of the fundamental physics principles underlying the SM and of exploration beyond the SM.

In September 2012, Chinese scientists proposed a 50–70 km circumference 240 GeV Circular Electron Positron Collider (CEPC) in China, serving two large detectors for Higgs studies. The tunnel for such a machine could also host a Super Proton Proton Collider (SppC) to reach energies beyond the LHC (figure 1). CERN is also developing, via the Future Circular Collider (FCC) study, a proposal for a large (100 km circumference) tunnel, which could host high-energy electron–positron (FCC-ee), proton–proton (FCC-hh) or electron–proton (FCC-he) colliders (see p15). Progress in both projects is proceeding fast, although many open questions remain – not least how to organise and fund these next great steps in our exploration of fundamental particles.

Precision leap

CEPC is a Higgs factory capable of producing one million clean Higgs bosons over a 10 year period. As a result, the couplings between the Higgs boson and other particles could be determined to an accuracy of 0.1–1% – roughly one order of magnitude better than that expected of the high-luminosity LHC upgrade and challenging the most advanced next-to-next-to-leading-order SM calculations (figure 2). By lowering the centre-of-mass energy to that of the Z pole at around 90 GeV, without the need to change hardware, CEPC could produce at least 10 billion Z bosons per year. As a super Z – and W – factory, CEPC would shed light on rare decays and heavy-flavour physics and mark a factor-10 leap in the precision of electroweak measurements.

The latest CEPC baseline design is a 100 km double ring (figure 3, left) with a single-beam synchrotron-radiation power of 30 MW at the Higgs pole, and with the same superconducting radio-frequency accelerator system for both electron and positron beams. CEPC could work both at Higgs- and Z-pole energies with a luminosity of $2 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$ and $16 \times 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$, respectively. The alternative design of CEPC is based on a so-called advanced partial double-ring scheme (figure 3, right) with the aim of reducing the construction cost. Preliminary designs for the two CEPC detectors are shown in figure 4.

Concerning the SppC baseline, it has been decided to start with 12 T dipole magnets made from iron-based high-temperature superconductors to allow proton–proton collisions at a centre-of-mass energy of 75 TeV and a luminosity of $10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$. The SppC SC magnet design is different to the Nb_3Sn-based magnets planned by the FCC-hh study, which are targeting a field of 16 T to allow protons to collide at a centre-of-mass energy of 100 TeV. The Chinese design also envisages an upgrade to 20 T magnets, which will take the SppC collision energy to beyond 100 TeV. Discovered just over a decade ago, iron-based superconductors have a much higher superconducting transition temperature than conventional superconductors, and therefore promise to reduce the cost of the magnets to an affordable level. To conduct the relevant R&D, a national network in China has been established and already more than 100 m of iron-based conductor cable has been fabricated.

The CEPC is designed as a facility where both machines can coexist in the same tunnel (figure 5). It will have a total of four detector experimental halls, each with a floor area of 2000 m^2 – two for CEPC and another two for SppC experiments. The tunnel is around 6 m wide and 4.8 m high, hosting the CEPC main ring (comprising two beam pipes), the CEPC booster and SppC. The SppC will be positioned outside of CEPC to accommodate other collision modes, such as an electron–proton, in the far future. The FCC study, which is aiming to complete a Conceptual Design Report (CDR) by the end of the year, adopts a similar staged approach (see p15).

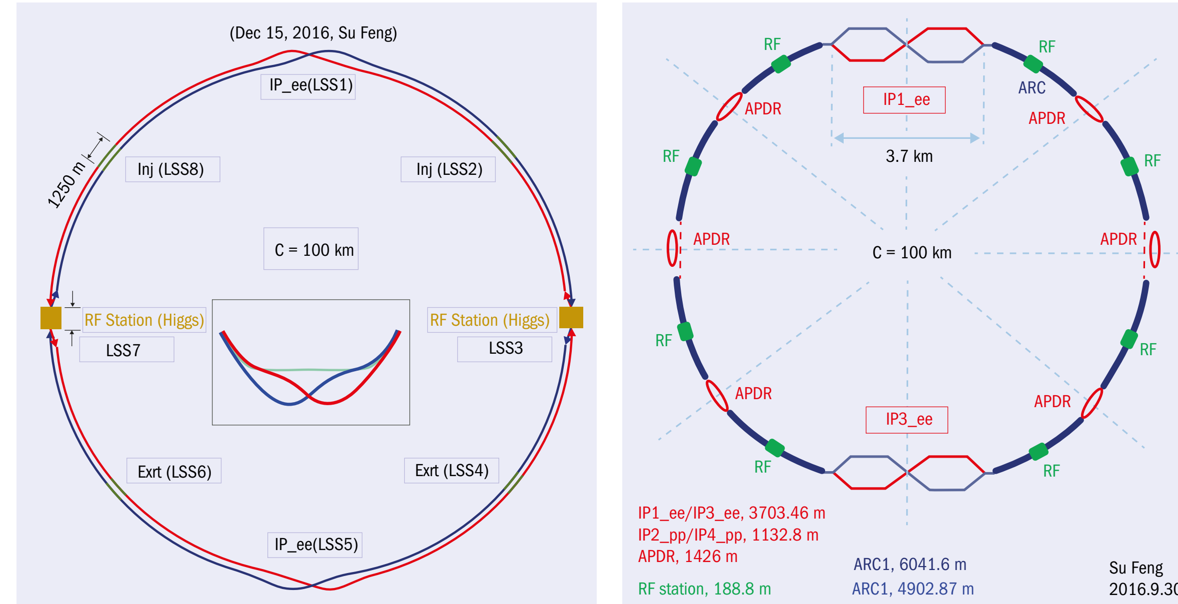


Fig. 3. Schematic layouts of the CEPC baseline (left, consisting of a double ring) and alternative (right, "advanced partial double-ring") designs. While the latter is cheaper, requiring just 30% of the ring to be dualled, it is limited in luminosity at the Z-pole energy.

China on track

Since the first CEPC proposal, momentum has grown. In June 2013, the 464th Fragrant Hill Meeting (a national meeting series started in 1994 for the long-term strategic development of China's science and technology) was held in Beijing and devoted to developing China's high-energy physics following the discovery of the Higgs boson. Two consensuses were reached: the first was to support the ILC and participate in its construction with in-kind contributions, with R&D funds to be requested from the Chinese government; the second was a recognition that a circular electron–positron Higgs factory – the next collider after BEPCII in China – and a Super proton–proton collider built afterwards in the same tunnel is an important historical opportunity for fundamental science.

In 2014, the International Committee for Future Accelerators (ICFA) released statements supporting studies of energy-frontier circular colliders and encouraged global coordination. ICFA continues to support international studies of circular colliders, in addition to support for linear machines, reflecting the strategic vision of the international high-energy community. In April 2016, during the AsiaHEP and Asian Committee for Future Accelerators (ACFA) meeting in Kyoto, positive statements were made regarding the ILC and a China-led effort on CEPC-SppC. In September that year, at a meeting of the Chinese Physics Society, it was concluded that CEPC is the first option for a future high-energy accelerator project in China, with the strategic aim of making it a large international scientific project. Pre-conceptual design reports (pre-CDRs) for CEPC-SppC were completed at the beginning of 2015 with an international review, based on a single ring-based "pretzel" orbit scheme. A CEPC International Advisory Committee (IAC) was established and, in 2016, the Chinese Ministry of Science and Technology (MOST) allocated 36 million RMB (€4.6 million) for the CEPC study, and in 2018 another 32 million RMB (€4.1 million) has been approved by MOST.

Ensuring that a large future circular collider maximises its luminosity is a major challenge. The CEPC project has studied the use of a crab-waist collision scheme, which is also being studied for FCC-ee. Each of the double-ring schemes for CEPC have been studied systematically with the aim of comparing the luminosity potentials. On 15 January last year, CEPC-SppC baseline and alternative designs for the CDR were decided, laying the ground for the completion of the CEPC CDR at the end of 2017. Following an international review in June, the CEPC CDR will be published in July 2018.

While technical R&D continues – both for the CEPC machine and its two large detectors – a crucial issue is how to pay for such a major international project. In addition to the initial funding from MOST, other potential channels include the National Science Foundation of China (NSFC), the Chinese Academy of Sciences (CAS) and local governments. For example, two years ago Beijing Municipal allocated more than 500 million RMB (€65 million) to the Institute of High Energy Physics for superconducting RF development, and in 2018 CAS plans to allocate 200 million RMB (€26 million) to study high-temperature superconductors

The discovery of the Higgs boson at CERN's Large Hadron Collider raises new opportunities for a large-scale accelerator.

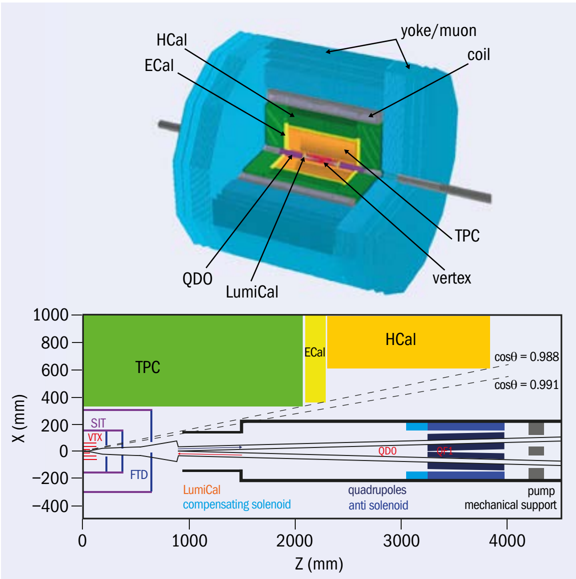


Fig. 4. CEPC detector and machine-detector-interface schematic layout. From inner to outer directions, the detector comprises: a vertex system; silicon inner tracker; time projection chamber (TPC); silicon external tracker; electromagnetic calorimeter (ECAL); hadronic calorimeter (HCAL); and a solenoid.

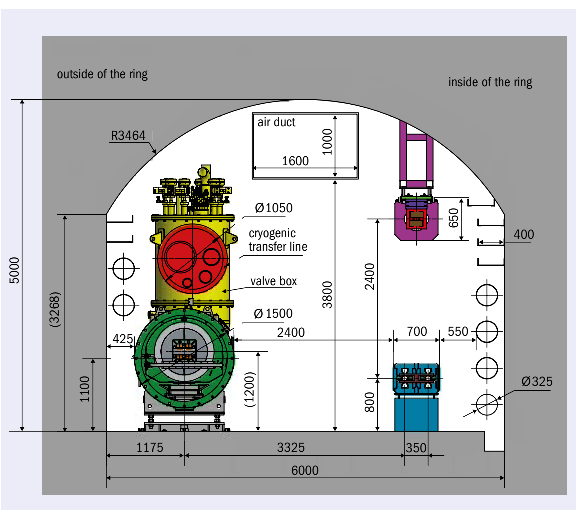


Fig. 5. CEPC-SppC tunnel layout, showing CEPC (right) on the inside the ring and the much larger SppC on the outer side.

for magnets, including studies in materials science, industry and projects such as SppC. While not specifically intended for CEPC-SppC, such investments will have strong synergies with high-energy physics and, in November 2017, the CEPC-SppC Industrial Promotion Consortium was established with the aim of supporting mutual efforts between CEPC-SppC and industry.

A five-year-long Technical Design Report (TDR) effort to optimise the CEPC-SppC design and technologies, and prepare for industrial production, started this year. Construction of CEPC could begin as early as 2022 and be completed by the end of the decade. CEPC would operate for about 10 years, while SppC is planned to start construction in around 2040 and be completed by the mid-2040s. The CEPC-SppC TDR phase after the CDR is critical, both for key-component R&D and industrialisation. R&D has already started towards high-Q, high-field 1.3 GHz and 650 MHz superconducting cavities; 650 MHz high-power high-efficiency klystrons; 12 kW cryogenic systems, 12 T iron-based high temperature superconducting dipoles, and other enabling technologies. Construction of a new 4500 m^2 superconducting RF facility in Beijing called the Platform of Advanced Photon Source began in May 2017 to be completed in 2020, and could serve as a supporting facility for different projects.

International ambition

CEPC-SppC is a Chinese-proposed project to be built in China, but its nature is an international collaboration for the high-energy physics community worldwide. Following the creation of the CEPC-SppC IAC in 2015, more than 20 MoUs have been signed with many institutes and universities around the world, such as the Budker Institute of Nuclear Physics (BINP; Russia); National Research Nuclear University MEPhI (Moscow, Russia) and the University of Rostock (Germany).

In August 2017, ICFA endorsed an ILC operating at a centre-of-mass energy of 250 GeV (ILC250), with energy-upgrade possibilities in the future (*CERN Courier* January/February 2018 p7). Although CEPC and ILC250 start with the same energy to study the Higgs boson, the ultimate goals are totally different from each other: SppC is for a 100 TeV proton–proton collider and ILC is a 1 TeV (maximum) electron–positron collider. The existence of both, however, would offer a highly complementary physics programme operating for a period of decades. The specific feature of CEPC is its small-scale superconducting RF system, (and its relatively large AC power consumption (300 MW for CEPC compared to 110 MW for ILC250). As for the cost, CEPC in its first phase includes part of the cost of SppC for its long tunnel, whereas ILC would upgrade its energy by increasing tunnel length accordingly later.

Deciding where to site the CEPC-SppC involves numerous considerations. Technical criteria are roughly quantified as follows: earthquake intensity less than seven on the Richter scale; earthquake acceleration less than 0.1 g; ground surface-vibration amplitude less than 20 nm at 1–100 Hz; granite bedrock around 50–100 m deep, and others. The site-selection process started in February 2015, and so far six sites have been considered: Qinhuangdao in Hebei Province; Huangling county in Shanxi Province; Shenshan Special District in Guangdong Province; Baoding (Xiongan) in Heibei Province; Huzhou in Zhejiang Province and Changchun in Jilin Province, where the first three sites have been prospected underground (figure 6). More sites, such as Huzhou in Zhejiang Province, will be considered in the future before a final selection decision. According to Chinese civil construction companies involved in the siting process, a 100 km tunnel will take less than five years to dig using drill-and-blast methods, and around

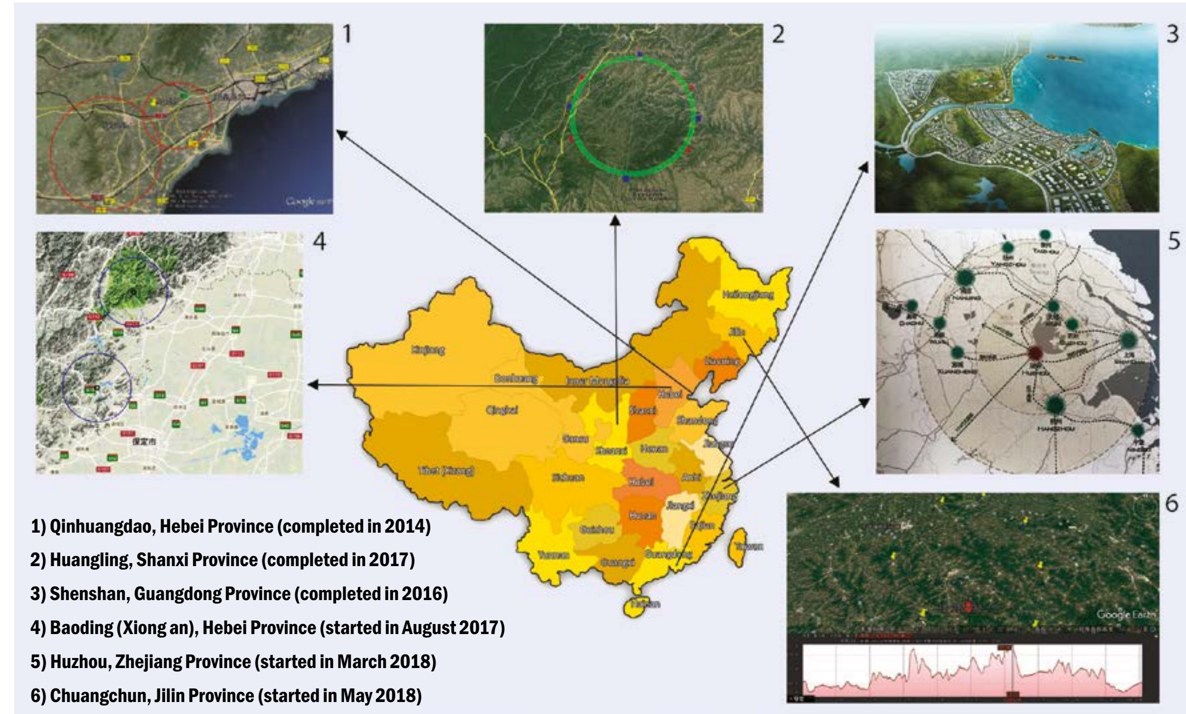


Fig. 6. The CEPC-SppC site-selection status in China.

three years if a tunnel boring machine is employed.

2018 is a milestone year for Higgs factories in Asia. As CEPC completes its CDR, the global high-energy physics community is waiting for a potential positive declaration from the Japanese government, by the end of the year, on their intention to host ILC250 in Japan, upgradable to higher energies. It is also a key moment for high-energy physics in Europe. FCC will complete its CDR by the end of the year, while CLIC released an updated 380 GeV baseline-staging scenario (*CERN Courier* November 2016 p20), and the European Strategy for Particle Physics update process will get under way (*CERN Courier* April 2018 p7). Hopefully, both ILC250 and CEPC-SppC will be included in the update together with FCC, while with respect to the US strategy we are looking forward to the next "P5" meeting following the European update.

During the past five years, CEPC-SppC has kept to schedule both in design and R&D, together with strong team development and international collaboration. On 28 March this year, the Chinese government announced the "Implementation method to support China-initiated large international science projects and plans", with the goal of identifying between three and five preparatory projects, one or two of which will be put to construction, by 2020. Hopefully, CEPC will be among those selected.

• Further reading

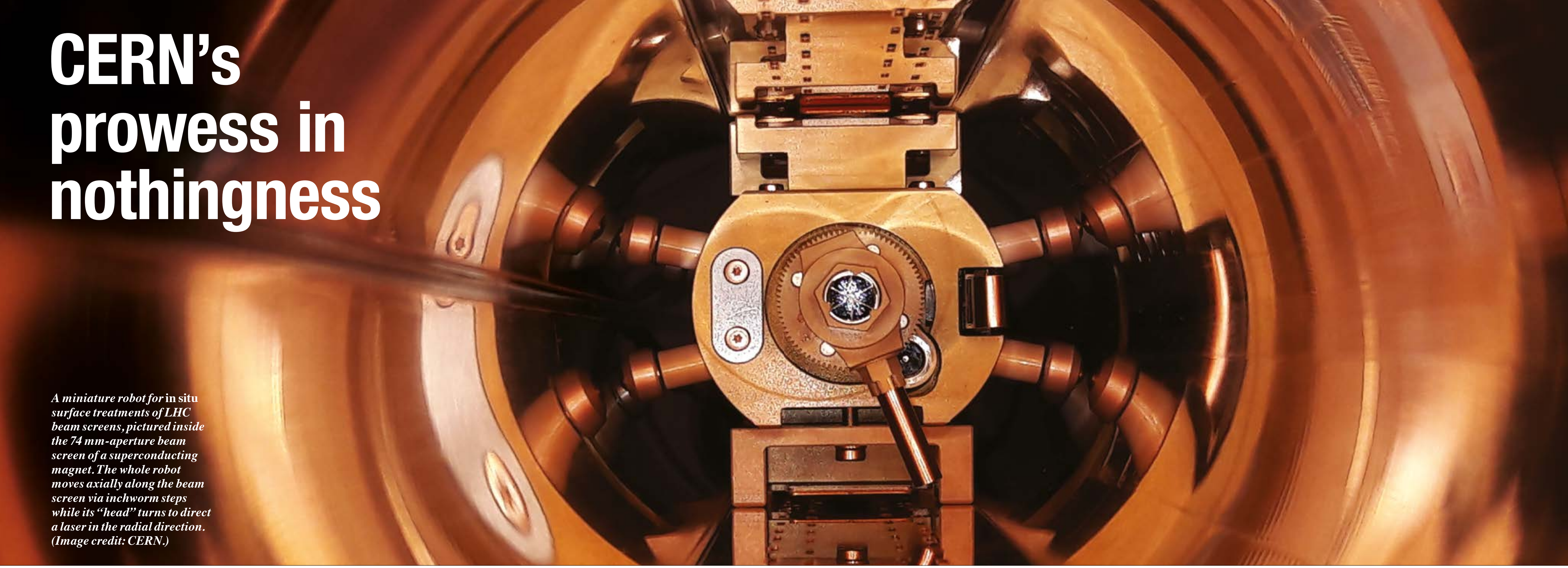
http://cepc.ihep.ac.cn/preCDR/volume.html.
http://cepc.ihep.ac.cn/Progress%20Report.pdf.
T J Bian 2017 *Int. J. Mod. Phys. A* **32** 1746009.
J Gao 2016 IHEP-AC-LC 2016-002.
J Gao 2017 *Int. J. Mod. Phys. A* **32** 1746003.
F Su 2017 *Int. J. Mod. Phys. A* **32** 1746005.
D Wang 2017 *Int. J. Mod. Phys. A* **32** 1746006.
Y F Wang 2018 Talk given at FCC Week 2018, Amsterdam.
Y W Wang 2017 *Int. J. Mod. Phys. A* **32** 1746004.

Résumé

La Chine candidate pour un collisionneur circulaire électron-positon

La découverte du boson de Higgs et de sa masse relativement faible fait naître de nouvelles perspectives pour les grands accélérateurs. En septembre 2012, des scientifiques chinois ont proposé un collisionneur électron-positon circulaire (CEPC) de 240 GeV, d'une circonférence de 50 à 70 km, qui serait situé en Chine et permettrait de réaliser des mesures de précision du boson de Higgs. Le tunnel qui serait construit pour cette machine pourrait également accueillir un supercollisionneur proton-proton (SppC), qui viserait à atteindre de nouvelles frontières d'énergie. Le projet du CEPC progresse rapidement, une étude préliminaire de conception devant être publiée en juillet. Ce projet et un éventuel collisionneur linéaire au Japon pourraient marquer le début d'une nouvelle ère pour la physique des hautes énergies en Asie.

Jie Gao, Institute of High Energy Physics and Chinese Academy of Sciences, University of Chinese Academy of Sciences.



CERN's prowess in nothingness

A miniature robot for in situ *surface treatments of LHC beam screens, pictured inside the 74 mm-aperture beam screen of a superconducting magnet. The whole robot moves axially along the beam screen via inchworm steps while its "head" turns to direct a laser in the radial direction. (Image credit: CERN.)*

A constant flow of challenging projects, a wealth of in-house expertise and the freedom to explore ideas make CERN a unique laboratory for vacuum technology for particle physics and beyond.

From freeze-dried foods to flat-panel displays and space simulation, vacuum technology is essential in many fields of research and industry. Globally, vacuum technologies represent a multi-billion-dollar, and growing, market. However, it is only when vacuum is applied to particle accelerators for high-energy physics that the technology displays its full complexity and multidisciplinary nature – which bears little resemblance to the common perception of vacuum as being just about pumps and valves.

Particle beams require extremely low pressure in the pipes in which they travel to ensure that their lifetime is not limited by interactions with residual gas molecules and to minimise backgrounds in the physics detectors. The peculiarity of particle accelerators is that the particle beam itself is the cause of the main source of gas: ions, protons and electrons interact with the wall of the vacuum vessels and extract gas molecules, either due to direct beam losses or mediated by photons (synchrotron radiation) and electrons (for example by "multipacting").

Nowadays, vacuum technology for particle accelerators is focused on this key challenge: understand, simulate, control and mitigate the direct and indirect effects of particle beams on material surfaces. It is thanks to major advances made at CERN and elsewhere in this area that machines such as the LHC are able to achieve the high beam stability that they do.

Since it is in the few-nanometre-thick top slice of materials that vacuum technology concentrates most effort, CERN has merged in the same group: surface-physics specialists, thin-film coating experts and galvanic-treatment professionals, together with teams of designers and colleagues dedicated to the operation of large vacuum equipment. Bringing this expertise together "under one roof" makes CERN one of the world's leading R&D centres for extreme vacuum technology, contributing to major existing and future accelerator projects at CERN and beyond.

Intersecting history

Vacuum technology for particle accelerators has been pioneered by CERN since its early days, with the Intersecting Storage Rings (ISR) bringing the most important breakthroughs. At the turn of the 1960s and 1970s, this technological marvel – the world's first hadron collider – required proton beams of unprecedented intensity (of the order of 10 A) and extremely low vacuum pressures in the interaction areas (below 10^{-11} mbar). The former challenge stimulated studies about ion instabilities and led to innovative surface treatments – for instance glow-discharge cleaning – to mitigate the effects. The low-vacuum requirement, on the other hand, drove the development of materials and their treatments – both chemical and thermal – in addition to novel high-performance cryogenic pumps and vacuum gauges that are still in use today. The technological successes of the ISR also allowed a direct measurement in the laboratory of the lowest ever achieved pressure at room temperature, 2×10^{-14} mbar, a record that still stands today.

The Large Electron Positron collider (LEP) inspired the next chapter in CERN's vacuum story. Even though LEP's residual gas density and current intensities were less demanding than those of the ISR, the exceptional length and the intense synchrotron-light power distributed along its 27 km ring triggered the need for unconventional solutions at reasonable cost. Responding to this challenge, the LEP vacuum team developed extruded aluminium vacuum chambers and introduced, for the first time, linear pumping by non-evaporable getter (NEG) strips.

In parallel, LEP project leader Emilio Picasso launched another fruitful development that led to the production of the first superconducting radio-frequency (RF) cavities based on niobium thin-film coating on copper substrates. The ability to attain very low vacuum gained with the ISR, the acquired knowledge in film deposition, and the impressive results obtained in surface treatments of copper were the ingredients for success. The present accelerating RF cavities of the LHC and HIE-ISOLDE (figure 1, overleaf) are essentially based on the expertise assimilated for LEP (*CERN Courier* May 2018 p26).

The coexistence in the same team of both NEG and thin-film expertise was the seed for another breakthrough in vacuum technology: NEG thin-film coatings, driven by the LHC project requirements and the vision of LHC project leader Lyn Evans. The NEG material, a micron-thick coating made of a mixture of titanium, zirconium and vanadium, is deposited onto the inner wall of vacuum chambers and, after activation by heating in the accelerator, provides pumping for most of the gas species present in accelerators. The Low Energy Ion Ring (LEIR) was the first CERN accelerator to implement extensive NEG coating in around 2006. For the LHC, one of the technology's key benefits is its low secondary-electron emission, which suppresses the growth of electron clouds in the room-temperature part of the machine (figure 2, overleaf).

Studying clouds

Electron clouds had to be studied in depth for the LHC. CERN's vacuum experts provided direct measurements of the effect in the Super Proton Synchrotron (SPS) with LHC beams, contributing to a deeper understanding of electron emission from technical surfaces over a large range of temperatures. New concepts for vacuum systems at cryogenic temperatures were invented, in particular the beam screen. Conceived at BINP (Russia) and further developed at

CERN

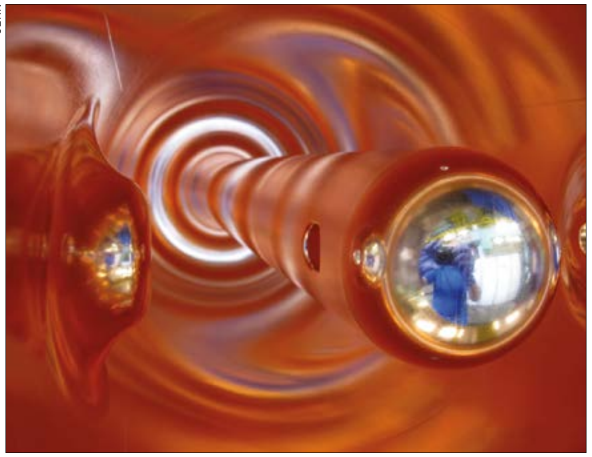


Fig. 1. The copper substrate of the HIE-ISOLDE superconducting radio-frequency cavities. The surface treatment of copper is one of the most important competences needed to achieve the required performance.

CERN

Fig. 2. The central beam pipe of CMS is entirely coated with NEG materials on the inside to ensure the lowest possible beam-gas background to the detector and suppress electron-cloud development.

CERN, this key technology is essential in keeping the gas density stable and to reduce the heat load to the 1.9 K cold-mass temperature of the magnets. This non-exhaustive series of advancements is another example of how CERN's vacuum success is driven by the often daunting requirements of new projects to pursue fundamental research.

Preparing for the HL-LHC

As the LHC restarts this year for the final stage of Run 2 at a collision energy of 13 TeV, preparations for the high-luminosity LHC (HL-LHC) upgrade are getting under way. The more intense beams of HL-LHC will amplify the effect of electron clouds on both the beam stability and the thermal load to the cryogenic systems. While NEG coatings are very effective in eradicating electron multipacting, their application is limited for room-temperature beam pipes that needed to be heated ("bakeable" in vacuum jargon) to around 200 °C to activate them. Therefore, an alternative strategy has to be found for the parts of the accelerators that cannot be heated, for example those in the superconducting magnets of the LHC and the vacuum chambers in the SPS.

Thin-film coatings made from carbon offer a solution. The idea originated at CERN in 2006 following the observation that beam-scrubbed surfaces – those that have been cleared of trapped gas molecules which increase electron-cloud effects – are enriched in graphite-like carbon. During the past 10 years, this material has been the subject of intense study at CERN. Carbon's characteristics at cryogenic temperatures are extremely interesting in terms of gas adsorption and electron emission, and the material has already been deposited on tens of SPS vacuum chambers within the LHC Injectors Upgrade project (*CERN Courier* October 2017 p32). By far, the HL-LHC project presents the most challenging activity in the coming years, namely the coating of the beam screens inserted in the triplet magnets to be situated on both sides of the four LHC experiments to squeeze the protons into tighter bunches. A dedicated sputtering source has been developed that allows alternate deposition of titanium, to improve adherence, and carbon. At the end of the process, the latter layer will be just 50 nm thick.

By far, the HL-LHC project presents the most challenging activity in the coming years.

Another idea to fight electron clouds for the HL-LHC, originally proposed by researchers at the STFC Accelerator Science and Technology Centre (ASTeC) and the University of Dundee in the UK, involves laser-treating surfaces to make them more rough: secondary electrons are intercepted by the surrounding surfaces and cannot be accelerated by the beam. In collaboration with UK researchers and GE Inspection Robotics, CERN's vacuum team has recently developed a miniature robot that can direct the laser onto the LHC beam screen (image on pp26–27). The possibility of *in situ* surface treatments by lasers opens new perspectives for vacuum technology in the next decades, including studies for future circular colliders.

An additional drawback of the HL-LHC's intense beams is the higher rate of induced radioactivity in certain locations: the extremities of the detectors, owing to the higher flux of interaction debris, and the collimation areas due to the increased proton losses. To minimise the integrated radioactive dose received by personnel during interventions, it is necessary to properly design all components and define a layout that facilitates and accelerates all manual operations. Since a large fraction of the intervention time is taken up by connecting pieces of equipment, remote assembling and disassembling of flanges is a key area for potential improvements.

One interesting idea that is being developed by CERN's vacuum team, in collaboration with the University of Calabria (Italy), concerns shape-memory alloys. Given appropriate thermomechanical pre-treatment, a ring of such materials delivers radial forces that tighten the connection between two metallic pipes: heating provokes the clamping, while cooling generates the unclamping. Both actions can be easily implemented remotely, reducing human intervention significantly. Although the invention was motivated by the HL-LHC, it has other applications that are not yet fully exploited, such as flanges for radioactive-beam accelerators and, more generally, the coupling of pipes made of different materials.

M Brice/CERN

Fig. 3. Prototype of a NEG-coated vacuum chamber produced by copper electroforming and coated using a sacrificial mandrel. The technique is applicable to a wide range of diameters and lengths.

CERN

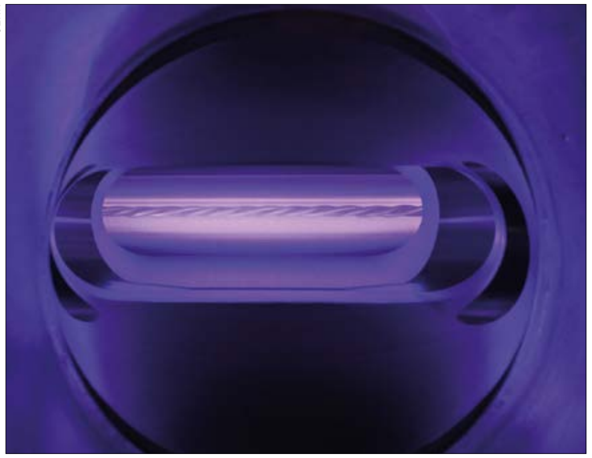


Fig. 4. NEG thin-film coating of the ELENA vacuum chambers at CERN's Antiproton Decelerator. The blue light is the effect of the ionisation of the coating process gas. The target material is three intertwisted elemental wires of titanium, zirconium and vanadium.

Synchrotron applications

Technology advancement sometimes verges off from its initial goals, and this phenomenon is clearly illustrated by one of our most recent innovations. In the main linac of the Compact Linear Collider (CLIC), which envisages a high-energy linear electron-positron collider, the quadrupole magnets need a beam pipe with a very small diameter (about 8 mm) and pressures in the ultra-high vacuum range. The vacuum requirement can be obtained by NEG-coating the vacuum vessel, but the coating process in such a high aspect-ratio geometry is not easy due to the very small space available for the material source and the plasma needed for its sputtering.

This troublesome issue has been solved by a complete change of the production process: the NEG material is no longer directly coated on the wall of the tiny pipe, but instead is coated on the external wall of a sacrificial mandrel made of high-purity aluminium (figure 3). On the top of the coated mandrel, the beam pipe is made by copper electroforming, a well-known electrolytic technique, and on the last production step the mandrel is dissolved chemically by a caustic soda solution. This production process has no limitations in the diameter of the coated beam pipe, and even non-cylindrical geometries can be conceived. The flanges can be assembled during electroforming so that welding or brazing is no longer necessary.

It turns out that the CLIC requirement is common with that of next-generation synchrotron-light sources. For these accelerators, future constraints for vacuum technology are quite clear: very compact magnets with magnetic poles as close as possible to the beam – to reduce costs and improve beam performance – call for very-small-diameter vacuum pipes (less than 5 mm in diameter and more than 2 m long). CERN has already produced prototypes that should fit with these requirements. Indeed, the collaboration between the CERN vacuum group and vacuum experts of light sources has a long history. It started with the need for photon beams for the study of vacuum chambers for LEP and beam screens for the LHC, and continued with NEG coating as an efficient choice for reducing residual gas density – a typical example is MAX IV, for which CERN was closely involved (*CERN Courier* September 2017 p38). The new way to produce small-diameter beam pipes represents another step in this fruitful collaboration.

Further technology transfer has come from the sophisticated simulations necessary for the HL-LHC and the Future Circular Collider study. A typical example is the integration of electromagnetic and thermomechanical phenomena during a magnet quench to assess the integrity of the vacuum vessel. Another example is the simulation of gas-density and photon-impingement profiles by Monte Carlo methods. These simulation codes have found a large variety of applications well beyond the accelerator field, from the coating of electronic devices to space simulation. For the latter, codes have been used to model the random motion and migration of any chemical species present on the surfaces of satellites at the time of their launch, which is a critical step for future missions to Mars looking for traces of organic compounds.

Of course, the main objective of the CERN vacuum group is the operation of CERN's accelerators, in particular those in the LHC chain. Here, the relationship with industry is key because the vacuum industry across CERN's Member and Associate Member states provides us with state-of-art components, valves, pumps, gauges and control equipment that have contributed to the high reliability of our vacuum systems. On the other hand, the LHC gives high visibility to industrial products that, in turn, can be beneficial for the image of our industrial partners. Collaborating with industry is a win–win situation.

The variety of projects and activities performed at CERN provide us with a continuous stimulation to improve and extend our competences in vacuum technology. The fervour of new collider concepts and experimental approaches in the physics community drives us towards innovation. Other typical examples are antimatter physics, which requires very low gas density (figure 4), and radioactive-beam physics that imposes severe controls on contamination and gas exhausting. New challenges are already visible at the horizon, for example physics with gas targets, higher-energy beams in the LHC, and coating beam pipes with high-temperature superconductors to reduce beam impedance..

An orthogonal driver of innovation is reducing the costs and operational downtime of CERN's accelerators. In the long term, our dream is to avoid bakeout of vacuum systems so that very low pressure can be attained without the heavy operation of heating the vacuum vessels *in situ*, principally to remove water vapour. Such advances are possible only if the puzzling interaction between water molecules and technical materials is understood, where again only a very thin layer on top of material surfaces makes the difference. Achieving ultra-high vacuum in a matter of a few hours at a reduced cost would also have an impact well beyond the high-energy physics community. This and other challenges at CERN will guarantee that we continue to push the limits of vacuum technology well into the 21st century.

Résumé

Les prouesses du CERN dans le vide

À l'échelle mondiale, les technologies du vide représentent un marché de plusieurs milliards de dollars, mais ce n'est que lorsque le vide est utilisé pour des accélérateurs de particules destinés à la physique des hautes énergies que cette technologie révèle toute sa complexité et sa nature multidisciplinaire. Le CERN a réuni des spécialistes de la physique des surfaces, des experts des revêtements en couche mince et des professionnels des traitements galvaniques, ainsi que des équipes de concepteurs et d'autres spécialistes qui se consacrent au fonctionnement de grands équipements pour le vide. Avec toutes ces compétences spécialisées réunies sous le même toit, et le flux constant de projets complexes exigés par la recherche fondamentale auquel il doit faire face, le CERN est devenu l'un des centres de R&D les plus éminents au monde pour les technologies du vide poussé.

Paolo Chiggiato, CERN.

Faces & Places

Appointments

Tanaka to head SLAC neutrino group

Neutrino physicist Hirohisa Tanaka has moved from the University of Toronto (Canada) to SLAC National Accelerator Laboratory in the US to expand the lab's role in the Deep Underground Neutrino Experiment (DUNE). The experiment, which will study neutrinos produced by Fermilab's Long-Baseline Neutrino Facility approximately 1300 km away, is due to start up in the mid-2020s and will address critical issues such as whether CP violation exists in the neutrino sector and what is the hierarchy of the neutrino masses.

Tanaka completed his PhD at SLAC in 2002 and went on to work on neutrino experiments at Fermilab (MiniBooNE) and J-PARC (T2K). The SLAC group's growing activities include developing the data readout and reconstruction for liquid-argon detectors like those used in DUNE, and the design of the near detector at Fermilab.

"If we're lucky, we may see the first hints of asymmetries between neutrinos and antineutrinos with current experiments," says Tanaka. "In the long run, DUNE will give us the definite answers due to its longer baseline and higher-power neutrino beam."

D Harmer/SLAC

Tanaka is to head a group studying data from DUNE.

SESAME appoints technical director

The third-generation light source SESAME in Jordan has appointed Riccardo Bartolini as technical director, overseeing the facility's infrastructure through its start-up phase. Bartolini's experience ranges from synchrotron light sources to free-electron lasers and colliders. While serving as SESAME's technical director, he will divide his time between Jordan and the UK's Diamond Light Source, where he is head of the accelerator physics group, and will be on leave from the John Adams Institute at the University of Oxford.

"It is great to be part of a project that promotes science and peace, and it is a privilege to carry on the work done by my predecessors Einfeld, Vignola, Nadji and Huttel," he said.

SESAME was established under the auspices of UNESCO in 2002 and is modeled closely on CERN. It produced "first light" in 2017 and, last month, inaugurated a second beamline (*CERN Courier* March 2017 p8).

ILSF

Riccardo Bartolini will oversee SESAME's infrastructure.

Awards

Four winners of 2018 Edison Volta Prize

The 2018 European Physical Society (EPS) Edison Volta Prize, organised in conjunction with the Fondazione Alessandro Volta and energy firm Edison S.p.A., has been awarded to four gravitational-wave researchers. Alain Brillet (Observatoire de la Cote d'Azur, Nice, France), Karsten Danzmann (Max-Planck-Institut für Gravitationsphysik and Leibniz University, Hannover, Germany), Adalberto Giazotto (INFN, Pisa) and Jim Hough (University of Glasgow, UK) were recognised "for the development, in their respective countries, of key technologies and innovative experimental solutions, that enabled the advanced interferometric gravitational-wave detectors LIGO and Virgo to detect the first gravitational-wave signals from mergers of black holes and of neutron stars." The EPS Edison Volta Prize is given biennially to individuals or groups of up to three people. Giazotto (*CERN Courier* April 2018 p55) was awarded posthumously.

Gravitational-wave researchers (left to right) Alain Brillet, Karsten Danzmann, Adalberto Giazotto and Jim Hough. Image credits (from left to right): M Perciballi, A Hindemith, INFN, University of Glasgow.

Accelerator awards presented at IPAC

On 3 May, during a ceremony at the International Particle Accelerator Conference in Vancouver (p36), the American Physical Society (APS) and the Institute of Electrical and Electronics Engineers (IEEE) presented their 2018 awards recognising excellence in the accelerator field.

The recipient of the 2018 thesis award granted by the APS division of physics of beams is Sergey Antipov of CERN, who was honoured "for experimental studies and analysis of the electron cloud build-up and corresponding instability in accelerators with combined function magnets and for the development of an effective mitigation technique applied in Fermilab's recycler ring". Also receiving his certificate was last year's thesis-award recipient Spencer Gessner of SLAC National Accelerator Laboratory, who was cited for "an original theoretical treatment and an experimental demonstration of accelerating positrons in a hollow channel plasma wakefield accelerator". Alexander Wu Chao of SLAC National Accelerator Laboratory, winner of the prestigious 2018 APS Robert R. Wilson Prize for Achievement announced late last year (*CERN Courier* December 2017 p35), also received his award during the Vancouver ceremony.

From left to right: Hermann Grunder, Sandra Biedron, Martina Martinello and Sergey Antipov at the Vancouver ceremony. (Image credits: IPAC18.)

The IEEE Particle Accelerator Science and Technology (PAST) award, made on behalf of IEEE's nuclear and plasma sciences society, is given to individuals who have made outstanding contributions to accelerator science and technology. Hermann Grunder, director emeritus at Argonne National Laboratory in the US, was honoured "for his far-reaching contributions to accelerator science and technology", which span nuclear physics, high-energy and heavy-ion accelerators, and applications of accelerators in medical research. Sandra Biedron of the University of New Mexico received the award "for broad impact in accelerator science and technology", which includes contributions to the FERMI@Elettra free-electron laser in Italy, and R&D in advanced controls, novel diagnostics and high-power electron guns.

The 2018 PAST Doctoral Student Award, in recognition of significant and innovative technical contributions to the field of particle accelerator science and technology, was presented to Martina Martinello of Fermilab "for contributions to physical understanding of limiting factors in SRF cavities".

Panjab University honours Virdee

On 4 March, CMS physicist Tejinder (Jim) Virdee of Imperial College, London, was awarded an honorary doctorate by Panjab University, India, in recognition of his outstanding contribution to the LHC's CMS experiment. Between 1993 and 2006, Virdee was the deputy spokesperson of CMS and, later, spokesperson for three years from 2007. He played a crucial role in all phases of the CMS experiment since its formation and, during the experiment's early period, travelled widely to engage, excite and invite the participation of physicists from around the world.

Panjab University

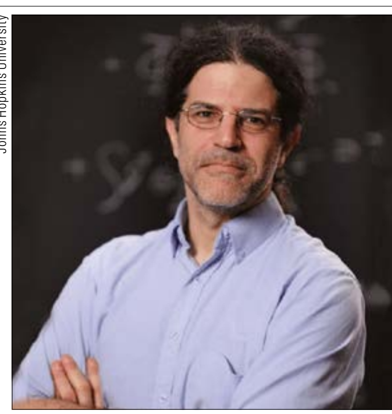
From right to left: Virdee, Venkaiah Naidu, vice-president of India and chancellor of the university, and vice-chancellor Arun Grover.

Kaplan wins for *Particle Fever*

A documentary about the Large Hadron Collider (LHC) has won producer David Kaplan, a theorist at Johns Hopkins University in the US, the 2018 Andrew Gemant Award. The annual prize, awarded by the American Institute of Physics, recognises contributions to the cultural, artistic and human dimensions of physics and includes a cash sum of $5000 and a grant of $3000 to further the public communication of physics. *Particle Fever* follows six physicists during the LHC switch-on, and the film has won multiple awards since its launch in 2013. Kaplan, whose research interests include the Higgs boson and dark matter, completed a year of film school before pursuing physics at the University of California, Berkeley.

"I wanted to give the experiential version of the story where people would learn the science only because it was a key part of the narrative – it wasn't the goal to teach them physics. You can't learn particle physics in 90 minutes, but you can experience the process of it," he says.

Johns Hopkins University



Kaplan has won many accolades for his film covering the switch-on of the LHC.

OUTREACH

Brazil signs up to IPPOG collaboration

The International Particle Physics Outreach Group (IPPOG) has welcomed Brazil as a new member, boosting efforts to expand the group's international impact on scientific outreach. Established 20 years ago as a European network, IPPOG has grown to a global network that involves countries, laboratories and scientific collaborations active in particle physics. It is best known for its international masterclasses programme, which evolved in the late 1990s from national outreach efforts. Following the model of collaboration in experimental particle physics, IPPOG became a formal scientific collaboration based on a memorandum of understanding (MoU) in 2017 (*CERN Courier* March 2017 p5).

C Marcelloni

Ignacio de Bediaga Hickman (left), chair of the Brazilian national network for high-energy physics RENAFAE, signing the MoU on 26 April with IPPOG chairs Hans Peter Beck (right) and Steve Goldfarb.

Brazil, which will be officially represented in IPPOG by Marcelo Munhoz of the University of São Paulo, is one of several countries to formally join the collaboration in recent months. In April, at the 15th IPPOG collaboration meeting in Pisa, two further countries – Slovenia and the Czech Republic – confirmed their membership, while Greece and Austria are finalising the process to sign IPPOG's MoU. That will bring IPPOG's total number of members to 26 – including the Belle II experiment, which has just started operations at KEK in Japan (see p7).

J A Cardoso

A book launched at CERN on 26 April in the presence of Pedro Afonso Comissário, ambassador of Mozambique to the United Nations, provides a glimpse into CERN's nature as a centre of knowledge creation and a true melting pot of skills. Devised, edited and assembled by Marilena Streit-Bianchi, a former member of staff, CERN: Science Bridging Cultures *brings together texts written by CERN scientists, project leaders, department heads and directors. It contains illustrations by the Mozambican artist Justino António Cardoso and has been translated into several languages.*

ANNIVERSARY

ALICE marks quarter century

Speakers at the jubilee event, clockwise from top left: Chris Fabjan (ALICE technical coordinator from 2001 to 2007), Emanuele Quercigh (first chair of the collaboration board), Luciano Musa (project leader of the inner tracking system), and Jürgen Schukraft (spokesperson from 1992 to 2010). (Image credits: V Greco/CERN.)

On 21 March, members of the ALICE collaboration celebrated 25 years since the experiment was founded. On 1 March 1993, the recently formed ALICE collaboration submitted a letter of intent to the CERN Large Hadron Collider (LHC) committee, proposing the construction of a heavy-ion experiment dedicated to the study of strongly interacting matter produced in nucleus–nucleus collisions. The effort has been rewarded with major advances in our understanding of the quark–gluon plasma and with the discovery of new phenomena, such as the detection of collective effects and strangeness enhancement in small collision systems (*CERN Courier* April 2017 p26). The ATLAS and CMS collaborations celebrated their 25th birthdays in October.

MEETINGS

Accelerator aficionados meet in Vancouver

The 9th International Particle Accelerator Conference (IPAC18) was held in Vancouver, Canada, from 29 April to 4 May. Hosted by TRIUMF and jointly sponsored by the IEEE Nuclear and Plasma Sciences Society and the APS Division of Physics of Beams, the event attracted more than 1210 delegates from 31 countries, plus 80 industry exhibits staff. The scientific programme included 63 invited talks and 62 contributed orals, organised according to eight main classes. While impossible to summarise the full programme in a short article, below are some of the highlights from IPAC18 that demonstrate the breadth and vibrancy of the accelerator field at this time.

A foray into the future of accelerators by Stephen Brooks of Brookhaven National Laboratory was a walk on the wild side. The idea of a single-particle collider was presented as a possibility to achieve diffraction-limited TeV beams to bridge the potential "energy desert" between current technology and the next energy regime of interest. Relevant technological and theoretical challenges were discussed, including multiple ideas for overcoming emittance growth from synchrotron radiation, focusing beams (via gravitational lensing!) and obtaining nucleus-level alignment, as was how to reduce the cost of future accelerators.

The rise of X-ray free-electron lasers in the past decade, opening new scientific avenues in areas highly related to wider society, was a strong theme of the conference. In addition, in the session devoted to photon sources and electron accelerators, Michael Spata described the Jefferson Laboratory's 12 GeV upgrade of CEBAF, which began full-power operation in April after overcoming numerous challenges (including installation and operation of a new 4 kW helium liquefier, and field-emission limitations in the cryomodules). James Rosenzweig (UCLA) described progress towards an all-optical "fifth-generation" light source. Here, a TW laser pulse would be split into two, with half being used to accelerate high-quality electron bunches as they co-propagate in a tapered undulator, and the other half striking the accelerated electron beam head on so that the back-scattered photons are shifted to much shorter wavelengths. The scheme could lead to a compact, tunable multi-MeV gamma-ray source, and successful demonstrations have already taken place at the RUBICONICS test stand at UCLA.

Concerning novel particle sources and acceleration techniques, plasma-wakefield

IPAC18

IPAC18 attracted more than 1210 delegates and 80 industry exhibits.

acceleration featured large. CERN's Marlene Turner described progress at the AWAKE experiment, which aims to use a high-energy proton beam to generate a plasma wake that is then used to accelerate an electron beam. Last year, the AWAKE team demonstrated self-modulation of the proton beam and measured the formation of the plasma wakefield. Now the team has installed the equipment to test the acceleration of an injected electron beam, which is expected to be completed in 2018. Felicie Albert of Lawrence Livermore National Laboratory also described the use of laser-wakefield technology to generate betatron X rays, which could enable new measurements at X-ray free-electron lasers.

With IPAC18 coinciding with TRIUMF's 50th anniversary (*CERN Courier* May 2018 p31), laboratory director Jonathan Bagger described the evolution of TRIUMF from its founding in 1968 by three local universities to the present-day set-up with 20 member universities, users drawn from 38 countries and an annual budget of CA$100 million. Also in the hadron-accelerator session was a talk by Sergei Nagaitsev of Fermilab about the path to the Long-Baseline Neutrino Facility, which is actually three parallel paths: one for the proton beams (PIP-II), one for the detector which will be located in the Homestake mine in South Dakota (DUNE) 1300 km away, and one for the facilities at Fermilab and Homestake. The three projects will engage more than 175 institutions from around the world with the aim of investigating leptonic CP violation and the mass hierarchy in the neutrino sector. The International Facility for Antiproton and Ion Research (FAIR) under construction in Germany (*CERN Courier* July/August 2007 p4) was another focus of this session, with Mei Bai of GSI Darmstadt summarising the significant upgrade of the heavy-ion synchrotron SIS18 that will drive the world's most intense uranium beams for future FAIR operation.

In the session devoted to beam dynamics and electromagnetic fields, Valery Telnov (Budker Institute) introduced a cautionary note about bremsstrahlung at the interaction points of future electron–positron colliders (such as FCC-ee) that will impact beam lifetimes whereas present-generation colliders (such as SuperKEKB) are dominated by synchrotron radiation in the arcs. Tessa Charles of the University of Melbourne, meanwhile, introduced the method of "caustics" to understand and optimise longitudinal beam-dynamics problems, such as how to minimise coherent synchrotron radiation effects in recirculation arcs.

The proton linac for the European Spallation Source (ESS) under construction in Sweden was presented by Morten Jensen during the session on accelerator technology. He outlined the variety of radio-frequency (RF) power sources used in the ESS proton linac and the development of the first-ever MW-class "inductive out tubes" for the linac's high-beta cavities, which have been tested at CERN and reached record-beating performances of 1.2 MW output for 8.3 kW input power. Pending the development of a production series, the accelerator community may have a new RF workhorse.

As indicated, these are just a few of the many scientific highlights from IPAC18. Industry was also a major presence. In an industry panel discussion, speakers talked about successful models for technology transfer, while talks such as that from Will Kleeven (IBA) described the Rhodotron compact industrial CW electron accelerator producing intense beams with energies in the range from around 1 to 10 MeV, which has key industry applications including polymer cross-linking, sterilisation, food treatment and container security scanning.

IPAC is committed to welcoming young researchers, offering more than 100 student grants and heavily discounted fees for all students. Almost 1500 posters were presented by authors from 233 institutions over four days. The regional attendance distribution was 24% from Asia, 41% from Europe and 35% from the Americas, demonstrating the truly international nature of our field. The 10th IPAC will take place in Melbourne, Australia, on 19–24 May 2019.

● *Shane Koscielniak (TRIUMF) and Tor Raubenheimer (SLAC), IPAC18 chairs.*

The history and future of the PHYSTAT series

Most particle-physics conferences emphasise the results of physics analyses. The PHYSTAT series is different: speakers are told not to bother about the actual results, but are reminded that the main topics of interest are the statistical techniques used, the resulting uncertainty on measurements, and how systematics are incorporated. What makes good statistical practice so important is that particle-physics experiments are expensive in human effort, time and money. It is thus very worthwhile to use reliable statistical techniques to extract the maximum information from data (but no more).

Banff International Research Station

Is there a significant peak in the background? Participants at the 2010 PHYSTAT workshop in Banff, Canada, appear to be looking the wrong way to see it.

Origins

Late in 1999, I had the idea of a meeting devoted solely to statistical issues, and in particular to confidence intervals and upper limits for parameters of interest. With the help of CERN's statistics guru Fred James, a meeting was organised at CERN in January 2000 and attracted 180 participants. It was quickly followed by a similar one at Fermilab in the US, and further meetings took place at Durham (2002), SLAC (2003) and Oxford (2005). These workshops dealt with general statistical issues in particle physics, such as: multivariate methods for separating signal from background; comparisons between Bayesian and frequentist approaches; blind analyses; treatment of systematics; p-values or likelihood ratios for hypothesis testing; goodness-of-fit techniques; the "look elsewhere" effect; and how to combine results from different analyses.

Subsequent meetings were devoted to topics in specific areas within high-energy physics. Thus, in 2007 and 2011, CERN hosted two more meetings focusing on issues relevant for data analysis at the Large Hadron Collider (LHC), and particularly on searches for new physics. At the 2011 meeting, a whole day was devoted to unfolding, that is, correcting observed data for detector smearing effects. More recently, two PHYSTAT-ν workshops took place at the Institute for Physics and Mathematics of the Universe in Japan (2016) and at Fermilab (2017). They concentrated on issues that arise in analysing data from neutrino experiments, which are now reaching exciting levels of precision. In between these events, there were two smaller workshops at the Banff International Research Station in Canada, which featured the "Banff Challenges" – in which participants were asked to decide which of many simulated data sets contained a possible signal of new physics.

The PHYSTAT workshops have largely avoided having parallel sessions so that participants have the opportunity to hear all of the talks. From the very first meetings, the atmosphere has been enhanced by the presence of statisticians; more than 50 have participated in the various meetings over the years. Most of the workshops start with a statistics lecture at an introductory level to help people with less experience in this field understand the subsequent talks and discussions. The final pair of summary talks are then traditionally given by a statistician and a particle physicist.

A key role

PHYSTAT has played a role in the evolution of the way particle physicists employ statistical methods in their research, and has also had a real influence on specific topics. For instance, at the SLAC meeting in 2003, Jerry Friedman (a SLAC statistician who was previously a particle physicist) spoke about boosted decision trees for separating signal from background; such algorithms are now very commonly used for event selection in particle physics. Another example is unfolding, which was discussed at the 2011 meeting at CERN; the Lausanne statistician Victor Panaretos spoke about theoretical aspects, and subsequently his then student Mikael Kuusela became part of the CMS experiment, and has provided much valuable input to analyses involving unfolding. PHYSTAT is also one of the factors that has helped in raising the level of respectability with which statistics is regarded by particle physicists. Thus, graduate summer schools (such as those organised by CERN) now have lecture courses on statistics, some conferences include plenary talks, and books on particle-physics methodology have chapters devoted to statistics. With the growth in size and complexity of data in this field, a thorough grounding in statistics is going to become even more important.

Recently, Olaf Behnke of DESY in Hamburg has taken over the organisation and planning of the PHYSTAT programme and already there are ideas regarding having a monthly lecture series, a further PHYSTAT-ν workshop at CERN in January 2019 and a PHYSTAT-LHC meeting in autumn 2019, and possibly one devoted to statistical issues in dark-matter experiments. In all probability, the future of PHYSTAT is bright.

● *Louis Lyons, Imperial College, London, and University of Oxford, UK.*

Antimatter research leaps ahead


L Hilico

Participants of the 2018 Low Energy Antiproton Physics conference in Paris.

The 13th Low Energy Antiproton Physics (LEAP) conference was held from 12–16 March at the Sorbonne University International Conference Center in Paris. A large part of the conference focused on experiments at the CERN Antiproton Decelerator (AD), in particular the outstanding results recently obtained by ALPHA and BASE.

One of the main goals of this field is to explain the lack of antimatter observed in the present universe, which demands that physicists look for any difference between matter and antimatter, apart from their quantum numbers. Specifically, experiments at the AD make ultra-precise measurements to test charge-party-time (CPT) invariance and soon, via the free-fall of antihydrogen atoms, the gravitational equivalence principle to look for any differences between matter and antimatter that would point to new physics.

The March meeting began with talks about antimatter in space. AMS-02 results, based on a sample of 3.49×10^5 antiprotons detected during the past four years onboard the International Space Station, showed that antiprotons, protons and positrons have the same rigidity spectrum in the energy range 60–500 GeV. This is not expected in the case of pure secondary production and could be a hint of dark-matter interactions (*CERN Courier* December 2016 p31). The development of facilities at the AD, including the new ELENA facility, and at the Facility for Antiproton and Ion Research Facility (FAIR), were also described. FAIR, under construction in Darmstadt, Germany, will increase the antiproton flux by at least a factor of 10 compared to ELENA and allow new physics studies focusing, for example, on the interactions between antimatter and radioactive beams (*CERN Courier* July/August 2017 p41).

Talks covering experimental results and the theory of antiproton interactions with matter, and the study of the physics of antihydrogen, were complemented with discussions on other types of antimatter systems, such as purely leptonic positronium and muonium. Measurements of these systems offer tests of CPT in a different sector, but their short-lived nature could make experiments here even more challenging than those on antihydrogen.

Stefan Ulmer and Christian Smorra from the AD's BASE experiment described how they managed to keep antiprotons in a magnetic trap for more than 400 days under an astonishingly low pressure of 5×10^{-19} mbar. There is no gauge to measure such a value, only the lifetime of antiprotons and the probability of annihilation with residual gas in the trap. The feat allowed the team to set the best direct limit so far on the lifetime of the antiproton: 21.7 years (indirect observations from astrophysics indicate an antiproton lifetime in the megayear range). The BASE measurement of the proton-to-antiproton charge over mass ratio (*CERN Courier* September 2015 p7) is consistent with CPT invariance and, with a precision of 0.69×10^{-12}, it is the most stringent test of CPT with baryons. The BASE comparison of the magnetic moment of the proton and the antiproton at the level of 2×10^{-10} is another impressive achievement and is also consistent with CPT (*CERN Courier* March 2017 p7).

Three new results from ALPHA, which has now achieved stable operation in the manipulation of antihydrogen atoms that has allowed spectroscopy to be performed on 15,000 antiatoms, were also presented. Tim Friesen presented the hyperfine spectrum and Takamasa Momose presented the spectroscopy of the 1S–2P transition. Chris Rasmussen presented the 1S–2S lineshape, which gives a resonant frequency consistent with that of hydrogen at a precision of 2×10^{-12} or an energy level of 2×10^{-20} GeV, already exceeding the precision on the mass difference between neutral kaons and antikaons. ALPHA's rapid progress suggests hydrogen-like precision in antihydrogen is achievable, opening unprecedented tests of CPT symmetry (*CERN Courier* March 2018 p30).

The next edition of the LEAP conference will take place at Berkeley in the US in August 2020. Given the recent pace of research in this relatively new field of fundamental exploration, we can look forward to a wealth of new results between now and then.

● *Patrice Pérez, CEA Saclay.*

FCC presents at tunnel congress

FCC study

John Osborne presenting the FCC study at the 2018 World Tunnel Congress.

The World Tunnel Congress (WTC) brings together leading tunnel and underground-space experts from all around the world. This year, the congress was held in Dubai from 21 to 26 April and was attended by nearly 2000 professionals, with case studies illuminating the latest trends and innovations and discussions about the role of tunnels in supporting future sustainable cities. CERN's Future Circular Collider (FCC) study – which is exploring the possibility of a 100 km-circumference collider (see p15) – would require one of the world's largest ever underground projects, generating great interest from WTC delegates.

The extensive underground tunnel works required for FCC were presented by John Osborne from CERN and by Werner Dallapiazza from ILF Consulting, who have been tasked with performing a cost and schedule study for the civil-engineering aspects of the FCC study.

The FCC could provide a facility able to host machines in several different collider modes, as well as four very large experimental caverns and service caverns at depths of up to approximately 300 m below the surface. The key challenges for civil engineering come from the difficult geology under Lake Geneva, the river Arve crossing and the area where the river Rhone exits the Geneva basin. In addition, solutions for the 9.2 million cubic metres of excavated rock and other environmental issues need to be studied further.

● *John Osborne, CERN.*

Letter

Renaming the Pauli principle

The feature "Putting the Pauli exclusion principle on trial" (*CERN Courier* March 2018 p35) was extremely interesting, describing highly accurate experiments that have put severe limits on the possible violation of the Pauli principle. Testing this sacrosanct principle reminds me that, at CERN, we test charge-parity-time (CPT) invariance with antinuclei and antiatoms.

Two points struck me from the article. First, the authors say, rightly, that 50 years ago Freeman Dyson and Andrew Lenard proved that the "stability of matter" follows from the Pauli Principle. However, this proof was very complex and, in 1975, Elliott Lieb and Walter Thirring produced a much simpler proof that also gave almost realistic numbers for the binding energy and the minimum volume occupied by a neutral assembly of charged particles (*Phys. Rev Lett.* **36** 687). I am slightly astonished that the authors do not quote this paper, especially since one of the authors is from Vienna and I believed that Thirring was well known in this city.

The second point is historical and concerns the "modern form" of the Pauli principle expressed via the asymmetry of the wave function, as described by the authors. When Pauli proposed the exclusion principle in 1925, the Schrödinger equation did not exist; Pauli was thinking in terms of an independent particle model where particles could be given definite quantum numbers. My late friend, the great theoretician Vladimir Glaser, told me that it was in fact Heisenberg who at the same time understood the usefulness of generalising the Schrödinger equation to N particles and replaced the Pauli principle by the requirement of the asymmetry of the wave function with respect to the exchange of electrons (including spin). We all know how important the generalisation of the Schrödinger equation was to N particles since it allows one to calculate the binding energy of any atomic or molecular system, given enough computing power. The Schrödinger equation has even been used to calculate the masses of hadrons considered as systems of quarks, its only defect being that it is nonrelativistic.

These facts are confirmed in the book called *Out the Crystal Maze* (Oxford University Press, 1997), which gives references to three fundamental papers of Heisenberg: two on the many-body problem in quantum mechanics (*Z. für Physik* **38** 411 and *Z. für Physik* **41** 239) and one on ions with two electrons (*Z für Physik* **39** 1926). Frankly, it is too late, but I think that one should rename the Pauli principle as the Pauli–Heisenberg principle.

● *André Martin, formerly CERN.*

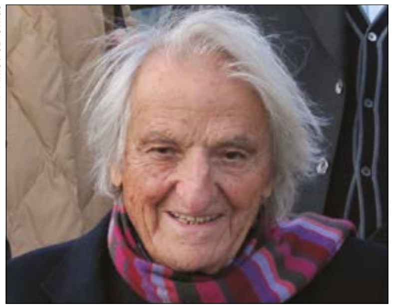
Obituaries

Enzo Bertolini 1932–2017

Born in Verona, Italy, on 4 May 1932, Enzo Bertolini graduated in electrical engineering and, subsequently, in applied nuclear physics at the University of Padua in 1959. He then started his research work at CERN in the field of high-energy physics. There he worked with a talented young man named Carlo Rubbia, and the pair carried out some important work for the epoch – for example, determining the muon total capture rate in liquid hydrogen.

In 1962 Bertolini moved to Frascati (ENEA, Italy) to work on plasma physics and explore electricity generation via a magnetic-hydrodynamic generator. From 1973 to 1997 he was a member of the directorate of the EU JET project based in the UK, where eventually he became chief engineer. JET is currently the most important experiment in the world for the study of fusion energy: in 1991 it produced a small amount of fusion power (1.7 MW) for the first time on Earth, rising to 16 MW in 1997. These results have been instrumental in the design and construction of ITER, which should prove the feasibility of a thermonuclear reactor for the production of electricity.

F Fillietroz-Onlus



Bertolini worked across many physics fields.

In his many fields of expertise – particle physics, electricity generation, plasma physics, fusion, astronomy and astrophysics – Bertolini presented at international conferences and published more than 120 scientific papers. In 1969 he started his collaboration with the University of California at Davis and Santa Barbara, first as visiting professor and, from 1988, as adjunct professor, teaching in the field of energy conversion. From 1999 to 2007 he served as consultant for the government of South Korea in the field of fusion energy. He has also been on scientific and technical committees at CERN (including contributions for the design of the ATLAS experiment at LHC), the Italian Space Agency, and more recently he was an evaluator of research proposals for the EU Framework Programme. From 2006 to 2016 he was director of the Fondazione Clément Fillietroz-ONLUS (Aosta Valley, Italy), operating the Astronomical Observatory of the Autonomous Region of the Aosta Valley and the Planetarium of Lignan.

Enzo Bertolini passed away in his home in the Aosta Valley on 30 June last year. He was a true "man of science".

● *Jean Marc Christille and his colleagues at Lignan.*

Ferdinand Hahn 1959–2018

It was with great sadness that we learned that Ferdi Hahn passed away on 4 March. He was an enthusiastic and highly skilled colleague, and an openhearted friend.

Ferdi first came to CERN in 1987 as technical student of the University of Wuppertal, when he joined the barrel-RICH project for the DELPHI experiment at LEP. As part of his diploma thesis, he participated in the photon detector project, SYBIL, a TPC-like drift chamber with single photoelectron detection, which was a prototype of the DELPHI barrel-RICH system.

Here, Ferdi became very much acquainted with all hardware and software aspects of such a test program, both in the innumerable technical matters and in the analysis of the data taken. From 1990, as a CERN fellow, he was heavily involved in the commissioning of the drift tubes of the RICH detector, a particularity of the DELPHI experiment, followed by the development of the temperature control of the barrel RICH. A specific part of the detector was not delivered in time, so Ferdi immediately drove 800 km to the company and back again to allow the start of data taking on time in 1989. Later, Ferdi completed his PhD with a measurement of the differential cross-sections of charged kaons and protons using the DELPHI detector, taking advantage of the unique RICH system.

Private collection

Ferdi played major roles in the DELPHI and NA62 experiments.

In 1995 Ferdi joined the CERN physics department as a member of the DELPHI gas group. As section leader in the support groups to CERN experiments and deputy group leader of the DELPHI detector unit, he perfected the operation of the many and complex DELPHI gas systems. He also structured the LHC experiments gas working-group, which led to a professional and efficient system for all LHC detectors.

After having led the detector technology group of the physics department between 2007 and 2008, Ferdi then took over the technical coordination of the NA62 experiment with considerable commitment and great competence in many experimental aspects. Through the preparation of the Technical Design Report and the coordination of the entire installation of the experiment, his exquisite ability to bring collaborators from all kinds of cultures together was clearly an asset for the success of the project.

Knowing that the NA62 experiment was operating smoothly, Ferdi happily agreed to support the physics department as deputy head in 2015. As part of the management, he was in charge of the coordination of the technical groups in the department, including the planning of personnel. With his pleasant manner, patience and exemplary communication skills, he solved numerous tricky problems.

Ferdi was treasured as a close colleague by many; it was a pleasure to work with him. His open character and smile made it easy to discuss subjects, even when they involved complicated issues. He was enthusiastic and full of energy, always ready to help. His friendly way of dealing with people was backed up by a deep competence in technical issues. He was one of a kind and will be sadly missed.

● *His friends and colleagues.*

Vincenzo Palmieri 1962–2018

Vincenzo Palmieri, one of the most active members of the superconducting radio-frequency (SRF) community, passed away on 16 March. Vincenzo graduated *cum laude* in physics at the University of Naples Federico II in 1987, and started his career in the group of Cristoforo Benvenuti at CERN, as a technical student. Then he was hired by INFN in Legnaro to develop techniques to sputter quarter-wave cavities for the ALPI accelerator, where he founded and was responsible for the Laboratory of Superconductivity and Surface treatments.

Vincenzo was a unique character in the SRF community, always giving inspiring seminars and colouring them with unconventional pictures and videos. He had an out-of-the-ordinary energy that has pushed the entire community to look for new ideas and challenges.

He also had countless interests outside physics, from bonsai art and languages to chess, table tennis and graphology. He was always motivated to share his knowledge and train young researchers, and proposed and directed a master's course at the University of Padua in surface treatments for industrial applications. He was convinced of the necessity for science to meet industry, making him one of the pioneers of technology transfer in the accelerator community.

C Pira

Vincenzo was an expert in superconducting RF.

Vincenzo was the inventor of several breakthrough techniques in SRF. This includes the development of seamless cavities by spinning and of various chemical treatments to reduce the cost and environmental impact while improving cavity performances.

He collaborated with numerous institutes across the world, including CERN and DESY, contributed to more than 280 publications, held three patents and was the supervisor and tutor of about 100 theses. He also drove many contract agreements between research institutes and industries.

Vincenzo leaves a large community of colleagues, students and friends with a legacy of inventions, anecdotes and an inextinguishable example of enthusiasm, integrity and love for science. Our thoughts go to his wife Emanuela and his daughters Eulalia and Ludmilla, who were always the first and constant topic of conversation with his friends.

● *His friends and colleagues.*

Richard Taylor 1929–2018

Richard E Taylor died at the age of 88 on 22 February at his home on the Stanford campus in the US. Taylor was the co-recipient of the 1990 Nobel Prize in Physics, along with Henry Kendall and Jerome Friedman of MIT, for their discoveries of scaling in deep-inelastic electron–proton scattering. It was these results that led to the experimental demonstration of the existence of quarks.

Taylor was born in Medicine Hat, Alberta, Canada, to Clarence and Delia Taylor. He was interested in a career as a surgeon, but an early explosion while using a chemistry set as a child cost him parts of two fingers and the thumb on his left hand – and thus pushed him towards a career in science. He was an undergraduate at the University of Alberta, receiving a bachelor and then master of science in 1952. At Alberta, he married Rita Bonneau in 1951.

Taylor then went to Stanford, working at the Stanford High Energy Physics Laboratory (HEPL). In 1958, he was invited by colleagues at École Normale Supérieure in Orsay to work on experiments for their new accelerator at the Laboratoire de l'Accelerateur Lineare. After three years, he returned to the US, spending a year at Lawrence Berkeley National Laboratory. He then returned to Stanford to complete his PhD under Robert Mosely in 1962. Wolfgang Panofsky invited him to join the core group building the Stanford Linear Accelerator Center (SLAC), roughly 1 km west of the main Stanford campus. Taylor was given responsibility for the "Beam Switchyard" at the end of the linear accelerator that analysed and steered beams to experiments and for the large "End Station A" and its electron spectrometers. Taylor organised a talented group at SLAC including David Coward and Herbert (Hobie) DeStaebler, which carried out the design and construction of these major facilities. The three electron spectrometers with momentum ranges centered around 1.6, 8 and 20 GeV/c made the critical measurements that established SLAC in the forefront of particle physics.

SLAC

Taylor helped establish the reality of quarks.

Taylor led his group at SLAC into a collaboration with Caltech and MIT that foresaw the rise of powerful particle-physics collaborations now at the scale of a few thousand physicists for the major LHC experiments. That collaboration proposed and carried out a series of experiments beginning with the elastic scattering of electrons off protons at high momentum transfer in 1967. The measurements extended those made by Richard Hofstadter at HEPL, but led to no surprises.

The proposal for deep-inelastic scattering had no mention of point-like particles in the nucleon. The inelastic cross sections beyond the nucleon resonances were unexpectedly large and flat with increasing momentum transfer, especially when compared to elastic scattering. The data also displayed a simplifying feature called scaling – a prediction by Bjorken from current algebra – suggesting that deep-inelastic cross sections could be expressed as a function of one kinematic variable. These results were extended by Taylor's group and MIT into more kinematic regions and to studies of the neutron with a deuterium target. ▷

Faces & Places

At the "Rochester Conference" in Vienna in 1968, Panofsky summed up the first public results of the experiments with the comment: "Therefore, theoretical speculations are focused on the possibility that these data might give evidence on the behaviour of point-like, charged structures within the nucleon." Following a visit to SLAC in August 1968, Richard Feynman introduced his "naïve parton theory" in which electrons scattered from point-like free partons give both the observed weak momentum-transfer dependence and scaling. Subsequent experiments by Taylor and collaborators allowed the two nucleon structure functions to be separated, determining that the partons were spin-½ particles. Evaluations of sum rules derived by Bjorken and Kurt Gottfried were consistent with charge assignments in the nascent quark model. Finally, the Gargamelle neutrino and antineutrino results at CERN confirmed the Gell-Mann–Zweig quark model, and these experiments collectively gave rise to the Standard Model of particle physics.

Taylor's connections to Paris, and later DESY and CERN, continued as a theme through his life. He was awarded a doctorate (Honoris Causa) by the Université de Paris-Sud. After becoming a member of the SLAC faculty in 1968, Taylor won a Guggenheim fellowship and spent a sabbatical year at CERN. He received an Alexander von Humboldt award and spent the 1981–1982 academic year at DESY. Taylor's group at SLAC was a lively place, with many young European visitors who became staunch colleagues and friends.

In 1978, an experiment at SLAC led by Charles Prescott and Taylor demonstrated parity violation in polarised electron–deuterium scattering – a very challenging experiment that followed negative results from atomic-physics experiments. Parity violation was the essential component of the unification of the electromagnetic and weak interactions, another key chunk of the Standard Model that led to the Nobel Prize for Sheldon Glashow, Abdus Salam and Steven Weinberg in 1979.

Taylor also was awarded the W K H Panofsky Prize, and was a fellow of the American Physical Society, American Association for the Advancement of Science, Royal Society and the Royal Society of Canada. He was also a member of the American Academy of Arts and Sciences and the Canadian Association of Physics, a foreign associate of the National Academy of Science, and Companion of the Order of Canada.

Taylor stayed rooted to his Canadian origins, often vacationing in Medicine Hat where he maintained a home and enjoyed fly fishing in the local streams. He always saw himself as an experimentalist, saying in a 2008 Nobel-prize interview: "My job was to measure things and to make sure that the measurements were right. It is the job of the theoretical community to understand why things are the way that I see them when I do experiments."

Taylor was a large man and pretended to enjoy a reputation of being somewhat fierce. His friends and colleagues all knew him as a gentle soul, caring deeply for SLAC and always promoting the younger generations of scientists. He is survived by his wife Rita and son Ted.

● *Martin Breidenbach and Charles Prescott, SLAC National Accelerator Laboratory.*

Bookshelf

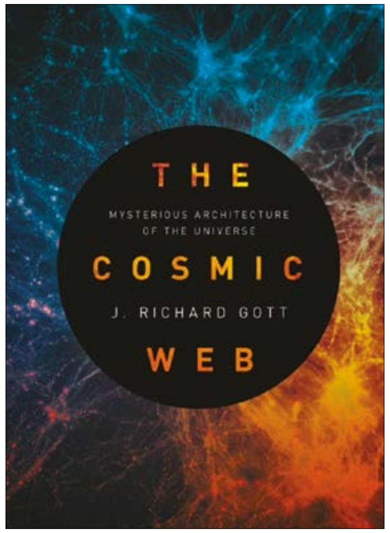
Compiled by Virginia Greco, CERN

The Cosmic Web

By John Richard Gott

Princeton University Press

The observation of the night sky is as old as humankind itself. Cosmology, however, has only achieved the status of "science" in the past century or so. In this book, Gott accompanies the reader through the birth of this new science and our growing understanding of the universe as a whole, starting from the observation by Hubble and others in the 1920s that distant galaxies are receding away from us. This was one of the most important discoveries in the history of science because it shifted the position of humans farther away from the centre of the cosmos and showed that the universe is not eternal, but had a beginning. The philosophical implications were hard to digest, even for Einstein, who invented the cosmological constant such that his equations of general relativity could have a static solution.



Following the first observations of distant galaxies, astronomers began to draw a comprehensive map of the observable universe. They played the same role as the explorers travelling around our planet, except that they could only sit where they were and receive light from distant objects, like the faded photography of a lost past.

After an introduction to the early days of cosmology, the book becomes more personal, and the reader feels drawn in to the excitement of actually doing research. Gott's account of cosmology is given through the lens of his own research, making the book slightly biased towards the physics of the large-scale structure of the universe, but also more focused and definitely captivating for the reader.

The overarching theme of the book is the quest to understand the shape of the "cosmic web", which is the distribution of galaxies and voids in a universe that is homogeneous only on very large scales. Tiny fluctuations in the matter density, ultimately quantum in origin, grow via gravity to weave the web.

In graduate school, under the supervision of Jim Gunn, Gott wrote his most cited paper, proposing a mathematical model of the gravitational collapse of small density fluctuations. Here, the readers are given a flavour of the way real research is carried out. The author describes in detail the physics involved in the topic, as well as how the article was born and completed and how it took on a life of its own to become a classic.

The author's investigation of the large-scale structure intertwines with his passion for topology. He was fascinated by polyhedrons with an infinite number of faces, which were the subject of an award-winning project that he developed in high school and of his first scientific article published in a mathematics journal.

At the time, when astronomical surveys were covering only a small portion of the sky, it was unclear how the cosmic structures assembled. American cosmologists thought that galaxies gathered in isolated clusters floating in a low-density universe, like meatballs in a soup. On the other hand, Soviet scientists maintained that the universe was made up of a connected structure of walls and filaments, where voids appear like holes in a Swiss cheese.

Does the 3D map of the universe resemble a meatball stew or a Swiss cheese? Neither, Gott says. With his collaborators, he proposed that the cosmic web is topologically like a sponge, where voids and galaxy clusters form two interlocking regions, much like the infinite polyhedrons Gott studied in his youth.

The reader is given clear and mathematically precise descriptions of the methods used to demonstrate the idea, which was later confirmed by deeper and larger astronomical observations (in 3D), and by the analysis of the cosmic microwave background (in 2D). By that time, we had the theory of cosmological inflation to explain a few of the puzzles regarding the origin of the universe. Remarkably, inflation predicts tiny quantum fluctuations in the fabric of space–time, giving rise to a symmetry between higher and lower density perturbations, leading to the observed sponge-like topology.

Therefore, by the end of the 20th century, the pieces of our understanding of the universe were falling into place and, in 1998, the discovery that the universe is accelerating allowed us to start thinking about the ultimate fate of the cosmos. This is the subject of the last chapter, an interesting mix of sound predictions (for the next trillion years) and speculative ideas (in a future so far away that it is hard to think about), ending the book with a question – rather than an exclamation – mark.

This is not only a good popular science book that achieves a balance between mathematical precision and a layperson's intuition. It is also a text about the day-to-day life of a researcher, describing details of how science is actually done, the excitement of discovery and the disappointment of following a wrong path. It is a book for readers curious about cosmology, for researchers in other fields, and for young scientists, who will be inspired by an elder one to pursue the fascinating exploration of nature.

Guido D'Amico, CERN

Calorimetry: Energy Measurement in Particle Physics (2nd edition)

By Richard Wigmans

Oxford Science Publications

Also available at the CERN bookshop

When the first edition of this book appeared in 2000, it established itself as "the bible of calorimetry" – not only because of the exhaustive approach to this subtle area of detection, but also because its author enjoyed worldwide recognition within the field. Wigmans gained it thanks to his ground-breaking work on the quantitative understanding of so-called compensating calorimeters (i.e. how to equalise the response of such detectors for electromagnetic and hadronic interactions) and to the leading role he played in designing and operating large detectors that are still considered to be state of the art.

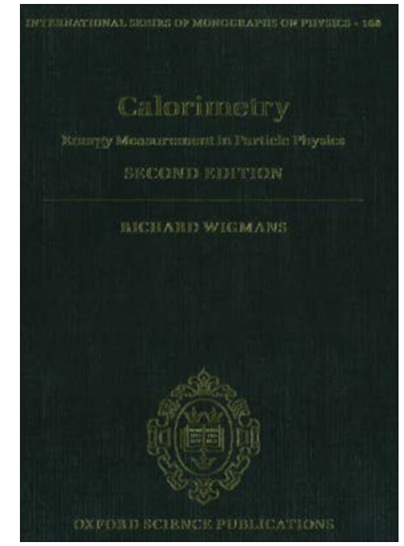
As with the real Bible, which underwent several revisions, this book has been reviewed in depth and published in a second edition. The author has updated it to take into account the last 16 years of progress in the field and to improve its impact as a reference for both students and practitioners.

At first look, one immediately notices that considerable work has been put into improving the quality of the graphics and figures – introducing colours where appropriate – and this new edition is available as an e-book. But there is much more to this updated version.

Chapters two to six, in which the fundamentals of calorimetry are discussed, follow the same thorough structure of the first edition, but they include new insights and use more recent data for illustration, mostly coming from the LHC experiments. Chapters one (Seventy Years of Calorimetry), seven (Performance of Calorimeter Systems) and 11 (Contributions of Calorimetry to the Advancement of Science) have also been brought up to date. Chapters eight, nine and (to a large extent) 10 are brand new and, in my opinion, represent the real added value of this new edition. In particular, chapter eight (New Calorimeter Techniques) discusses the two most relevant innovations introduced in the field during the past decade: dual-readout calorimetry (DRC) and particle-flow analysis (PFA).

The concept of DRC is elaborated upon to circumvent the limitations of compensating hadron calorimeters. Their performances depend crucially on the detection of the abundant contribution of the neutrons produced in the hadronic shower development, which in turn requires the use of heavy absorbers and a small sampling fraction – with the consequent loss of resolution for electromagnetic showers – as well as a relatively large signal-integration time and volume. In DRCs, signals coming from scintillation and Cherenkov processes provide complementary information about the shower development and allow the measurement of the electromagnetic fraction of hadron showers event by event, thus eliminating the effects of fluctuations on calorimeter performance. This concept is discussed in depth and predictions are compared with R&D results on prototypes, providing a convincing experimental demonstration of this novel technique. Although no full-scale calorimeter of this type has been built so far, the results obtained with real detectors, combined with Monte Carlo simulations, have outlined the breakthrough power of this idea, which has all the potential to rival the performances of the best compensating calorimeters, with much better energy resolution for electromagnetic showers. It is very stimulating food for thought for whoever is poised to design next-generation calorimeters.

The other important topic discussed in chapter eight, PFA, is a completely different method that is being used to improve calorimeter performances for jets. It is based on the combined use of a precision tracker and a high-granularity calorimeter, which



measures the momentum of charged-jet particles and the energy of neutral particles, respectively. High granularity is mandatory to avoid double counting of the charged particles already measured by the tracker. The topic is treated in great detail, with abundant examples of the application of this technique in real experiments, and its pros and cons are discussed in view of future large-scale detector systems.

As an example, the idea that one can relax the requirements on the calorimeters, since they measure on average only one third of the particles in a jet while the remaining two thirds are very well measured by the tracker, is strongly questioned because the jet-energy resolution would be dominated by the fluctuations in the fraction of the total jet energy that is carried by the charged fragments.

Chapter nine (Analysis and Interpretation of Test Beam Data) is a brand-new addition that I find extremely illuminating and will be valuable for more than just newcomers to the field. By going through it, I have retraced the path of some of my mistakes when dealing with calorimeters, which are complex and subtly deceptive detectors, often exhibiting counterintuitive properties.

Finally, chapter 10 (Calorimeters for Measuring Natural Phenomena) is a tribute to the realisation and successful employment of calorimetric systems to the study of natural phenomena (neutrinos, cosmic rays) in the Antarctica, the Mediterranean Sea and the Argentinian pampa, inside a variety of mountains and deep mines, and in space.

In summary, this second edition of *Calorimetry* fully meets the ambitious goals of its author: it is a well written and pleasant book, a reference manual for both beginners and experts, and a source of inspiration for future developments in the field.

Sergio Bertolucci, University of Bologna

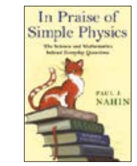
Books received

In Praise of Simple Physics: The Science and Mathematics behind Everyday Questions

By Paul J Nahin

Princeton

Also available at the CERN bookshop



In this book, popular-science writer Paul Nahin presents a collection of everyday situations in which the application of simple physical principles and a bit of mathematics can make us understand how things work. His aim is to take these scientific disciplines closer to the layperson and, at the same time, show them the wonder lying behind many aspects of reality that are often taken for granted.

The problems presented and explained are very diverse, ranging from how to extract more energy from renewable sources, how best to catch a baseball, to how to measure gravity in one's garage and why the sky is dark at night. These topics are treated in an informal and entertaining way, but without waiving the maths. In fact, as the author himself highlights, he is interested in keeping the discussions simple, but not so simple that they are simply wrong. The whole point of the book is actually to show how physics and some calculus can explain many of the things that we commonly encounter.

Engaging and humorous, this text will appeal to non-experts with some background in maths and physics. It is suited to students at any level beyond the last years of high school, as well as to practising scientists who might discover alternative, clever ways to solve (and explain) everyday physics problems.

The Black Book of Quantum Chromodynamics: A Primer for the LHC Era

By J Campbell, J Huston and F Krauss

Oxford University Press

Also available at the CERN bookshop

This book provides a comprehensive overview of the physics of the strong interaction, which is necessary to analyse and understand the results of current experiments at particle accelerators. In particular, the authors aim to show how to apply the

Bookshelf

framework of perturbative theory in the context of the strong interaction, to the prediction as well as correct interpretation of signals and backgrounds at the Large Hadron Collider (LHC).

The book consists of three parts. In the first, after a brief introduction to the LHC and the present hot topics in particle physics, a general picture of high-energy interactions involving hadrons in the initial state is developed. The relevant terminology and techniques are reviewed and worked out using standard examples.

The second part is dedicated to a more detailed discussion of various aspects of the perturbative treatment of the strong interaction in hadronic reactions. Finally, in the last section, experimental findings are confronted with theoretical predictions.

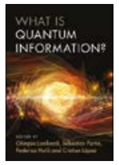
Primarily addressed at graduate students and young researchers, this book can also be a helpful reference for advanced scientists. In fact, it can provide the right level of knowledge for theorists to understand data more in depth and for experimentalists to be able to recognise the advantages and disadvantages of different theoretical descriptions.

The reader is assumed to be familiar with concepts of particle physics such as the calculation of Feynman diagrams at tree level and the evaluation of cross sections through phase space integration with analytical terms. However, a short review of these topics is given in the appendices.

What is Quantum Information?

By O Lombardi, S Fortin, F Holik and C López (eds.)

Cambridge University Press



This book debates the topic of quantum information from both a physical and philosophical perspective, addressing the main questions about its nature. At present, different interpretations of the notion of information coexist and quantum mechanics brings in many puzzles; as a consequence, says the author, there is not yet a generally agreed upon answer to the question "what is quantum information?".

The chapters are organised in three parts. The first is dedicated to presenting various interpretations of the concept of information and addressing the question of the existence of two qualitatively different kinds of information (classical and quantum). The links between this concept and other notions, such as knowledge, representation, interpretation and manipulation, are discussed as well.

The second part is devoted to the relationship between informational and quantum issues, and deals with the entanglement of quantum states and the notion of pragmatic information. Finally, the third part analyses how probability and correlation underlie the concept of information in different problem domains, as well as the issue of the ontological status of quantum information.

Providing an interdisciplinary examination of quantum information science, this book is aimed at philosophers of science, quantum physicists and information-technology experts who are interested in delving into the multiple conceptual and philosophical problems inherent to this recently born field of research.

Recruitment

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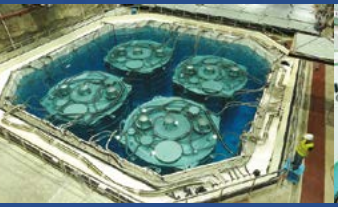
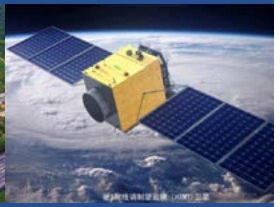
IHEP RECRUITMENT OF OVERSEAS HIGH-LEVEL TALENTS

INSTITUTE OF HIGH ENERGY PHYSICS, CHINESE ACADEMY OF SCIENCES



The Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences (CAS) invites applications for permanent staff positions at all levels. IHEP is a comprehensive research laboratory for particle and astroparticle physics, accelerator physics and technology, radiation technologies and applications, as well as for nuclear analytical techniques and interdisciplinary research.

For More Information: **http://english.ihep.cas.cn/**

Recruitment Objectives:

Based on the needs of the research areas and the disciplines development of IHEP, we are now publicly recruiting overseas outstanding talents and scholars of relevant disciplines who possess research abilities and innovation awareness.

Programs:

1 National "Thousand Talents Program" (full time & part time programs) for established scientists
2 National "Thousand Young Talents Program" for outstanding junior scientists
3 Pioneer "Hundred Talents Program" of CAS for outstanding junior scientists, excellent junior detector or accelerator experts
4 "Outstanding Talents Program" of IHEP for scientific research or technical talents

Research Areas:

Experimental Particle and Nuclear Physics, Theoretical Physics, Astronomy and Astrophysics, Nuclear Technology, Accelerators, Neutron physics, Condensed matter physics, Chemistry, Biochemistry and Molecular Biology, Biophysics, Computing, Multidisciplinary Research.

Contact:

Office of Human Resources, Institute of High Energy Physics, Chinese Academy of Sciences
E-mail: lianggj@ihep.ac.cn **Tel:** (86)010-88233157 **Fax:** (86)010-88233102
Address: No. 19 (B), Yuquan Road, Shijingshan District, Beijing (Postcode: 100049)

Applications should include a CV, an outline of academic accomplishments, description of current research and plan for future research, 3 – 5 published papers representative of your work, and a record of citations for your work. You should arrange for 3 letters of reference from experts in your field to be sent by post or email (established scientists are not requested).

For detailed information, please visit **http://english.ihep.cas.cn/doc/2649.html**

The ELI (Extreme Light Infrastructure) Project is an integral part of the European plan to build the next generation of large research facilities. ELI-Beamlines as a cutting edge laser facility is currently being constructed near Prague, Czech Republic. ELI will be delivering ultra-short, ultra-intense laser pulses lasting typically a few tens of femtoseconds with peak power projected to reach 10 PW. It will make available time synchronized laser beams over a wide range of intensities for multi-disciplinary applications in physics, medicine, biology, material science etc. The high intensities of the laser pulse will be also used for generating secondary sources of e- and p+ and high-energy photons. Our research groups are expanding and recruiting physicists and engineers.

In our team we therefore have the following positions available:

- Junior Scientist
- Senior Scientist
- Laser Physicist
- Junior Engineer
- Senior Engineer
- Vacuum Technician
- Mechanical Designer
- Control System Specialist
- Safety Engineer
- Optical Engineer
- X-ray Scientist
- Opto-mechanics

For more information see our website www.eli-beams.eu and send your application, please.

eli beamlines

MINISTRY OF EDUCATION, YOUTH AND SPORTS

EUROPEAN UNION
European Structural and Investing Funds
Operational Programme Research, Development and Education

UNIVERSITÄT BONN

The Department of Physics and Astronomy in the Faculty of Mathematics and Natural Sciences of the University of Bonn invites applications for a

Professorship (W2 Tenure Track W3) for Experimental Physics Strong Interaction Physics

at the Helmholtz-Institut für Strahlen- und Kernphysik.

Hadron physics together with elementary particle physics is one of the main research areas of the Physics Department of the university. The experimental groups conduct research at the local accelerator ELSA as well as at external laboratories with the experiments PANDA at FAIR, ALICE, COMPASS and ATLAS at CERN, and Belle/Belle2 at KEK.

The research focus of the professorship is expected to be in the field of exotic states of the strong interaction and should extend and strengthen the existing research activities in the area of meson and/or baryon spectroscopy. Possible research topics are: the spectroscopy of hadrons with heavy quarks, exotic quark configurations or gluonic degrees of freedom. Candidates should have an outstanding research profile in developing and building detector systems as well as in data analysis.

The candidate is expected to contribute significantly to the new "Research and Technology Centre Detector Physics" (FTD) at the University of Bonn. Participation in new collaborative research projects is desired as well as a collaboration with the CRC 110 "Symmetries and the Emergence of Structure in QCD".

Teaching at the usual level for such a professorship is required.

The conditions of employment are according to *§ 36 Hochschulgesetz NRW.*

The University of Bonn is committed to diversity and equal opportunity. It is certified as a family-friendly university and has a dual career program. It aims to increase the proportion of women in areas where women are under-represented and to promote their careers in particular. It therefore urges women with relevant qualifications to apply. Applications will be handled in accordance with the *Landesgleichstellungsgesetz* (State Equality Act). Applications from suitable individuals with a certified serious disability and those of equal status are particularly welcome.

Applicants are invited to send the usual documents electronically (curriculum vitae, summary of research interests, list of publications, copies of all university certificates) by **July 1st, 2018** to the Chairperson of the Department of Physics and Astronomy: fachgruppe@physik-astro.uni-bonn.de.

UNIVERSITÄT BONN

The Department of Physics and Astronomy in the Faculty of Mathematics and Natural Sciences of the University of Bonn invites applications for a

Professorship (W2) for Experimental Physics Particle Physics

at the Physikalisches Institut.

Particle Physics is one of the three main research areas of the Department of Physics and Astronomy at the University of Bonn. The experimental particle physics groups are engaged in research at external accelerators with the experiments Belle/Belle II in Japan, ATLAS, ALICE and COMPASS at CERN, PANDA at FAIR as well as experiments at the university's own accelerator ELSA. The department wants to strengthen its research in experimental particle physics, in particular in the area of B-meson physics. Candidates should have experience in experiments with B mesons and be interested in making strong contributions to the research program of the Belle II experiment at the SuperKEKB B-factory in Japan. Possible areas of research at Belle II include precision measurements of fundamental parameters of the Standard Model, semileptonic and rare decays, CP violation, and indirect searches for new phenomena in B decays. An active participation in coordinated research activities would be very welcome.

Successful candidates should be able to teach experimental physics in its full breadth and have an outstanding track record in data analysis and development and construction of experiments at particle accelerators. The candidate is expected to contribute significantly to the new "Research and Technology Centre Detector Physics" (FTD) at the University of Bonn

The conditions of employment are according to *§ 36 Hochschulgesetz NRW.*

The University of Bonn is committed to diversity and equal opportunity. It is certified as a family-friendly university and has a dual career program. It aims to increase the proportion of women in areas where women are under-represented and to promote their careers in particular. It therefore urges women with relevant qualifications to apply. Applications will be handled in accordance with the *Landesgleichstellungsgesetz* (State Equality Act). Applications from suitable individuals with a certified serious disability and those of equal status are particularly welcome.

Applicants are invited to send the usual documents electronically (curriculum vitae, summary of research interests, list of publications, copies of all university certificates) by **June 15th, 2018** to the Chairperson of the Department of Physics and Astronomy: fachgruppe@physik-astro.uni-bonn.de

CERN Courier Archive: 1975

A look back to CERN Courier vol. 15, June 1975, compiled by Peggie Rimmer

Around the Laboratories

Fourth CERN-JINR School

The picture shows N N Bogolubov, Director of Dubna (third from left) with W Jentschke (sixth from left) and L D Soloviev, Director of IHEP Serpukhov (second from left).

The fourth Joint JINR-CERN School of Physics, generally regarded as the most successful yet, took place at Alushta in the Crimea, USSR, from 14 to 28 May 1975. About 60 students attended from Dubna and its Member States and 35 from CERN and its Member States. Lecturers from Western Europe were C Michael from the University of Liverpool, L Montanet and W Jentschke from CERN, and B Wiik from DESY.

● Compiled from texts on p191.

Los Alamos

First patient irradiations

The use of particle beams for cancer therapy has been studied for 10 years. In May, preliminary results of the first-ever patient irradiations using negative pion beams were reported at a meeting in San Juan, Puerto Rico.

Irradiations on two patients exhibiting tumour nodules in the skin began in October 1974 at the Los Alamos 800 MeV proton linear accelerator, LAMPF. They were conducted by the Cancer Research and Treatment Center of the University of New Mexico in collaboration with the LAMPF team.

The paper to the American Radium Society reported no unusual reactions from the treatment. It seems that pions can achieve an equivalent effect on tumour tissue with about half the X-ray dose needed and less damage on normal skin in the irradiated areas.

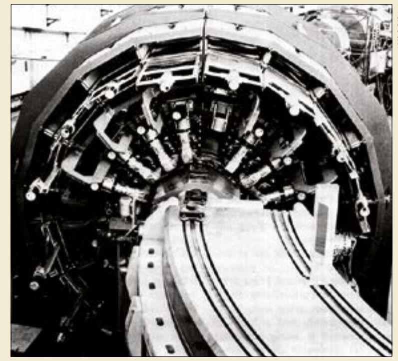
● Compiled from texts on p93.

Frascati

Adone and the new particles

When news of the discovery of the 3.1 GeV particle [the J/ψ charm/anti-charm meson] reached physicists at Adone, the e^+e^- storage ring at Frascati, an intense programme was started to push beam energies above the nominal top energy of 1.5 GeV per beam. Thanks to the joint efforts of the machine group and experimental teams, a clear signal of the new particle was observed within a few days (*CERN Courier* December 1974 p417).

Simultaneous measurements of the total and the leptonic cross sections give information on the intrinsic width of the particle (linked to its stability). The Frascati group have now published results indicating a total width less than 100 keV. At present an extensive search is in progress for narrow resonances in the mass range 1.90 to 3.15 GeV.



Frascati

The detection system of the "baryon–antibaryon" group recently completed at the Adone storage ring at Frascati. It incorporates lead glass counters, set up by the Stony Brook component of the collaboration, used in studying the energy distribution of gammas emerging from the decay of the newly discovered 3.1 GeV particle.

● Compiled from texts on pp193–194.

ECFA urges European e^+e^- ring

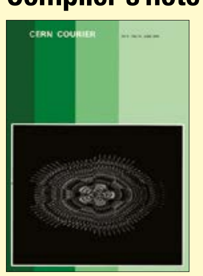
At a Plenary Meeting on 6 June, ECFA, the European Committee for Future Activities (formerly the European Committee for Future Accelerators), passed a resolution in support of the construction of a higher energy e^+e^- storage ring in Europe.

The statement reads — "ECFA considers that i) electron–positron storage rings with centre of mass energy above 20 GeV would be an extremely valuable addition to European high energy physics facilities, complementing existing proton accelerators and national electron–positron facilities at lower energies, ii) it is of primary importance that such a project is realised with minimum delay, iii) the exploitation of the storage rings should be open to the European scientific community, iv) there should be no duplication of similar accelerators within Europe. If the laboratories concerned agree, ECFA will study and make recommendations about the international exploitation of such a facility."

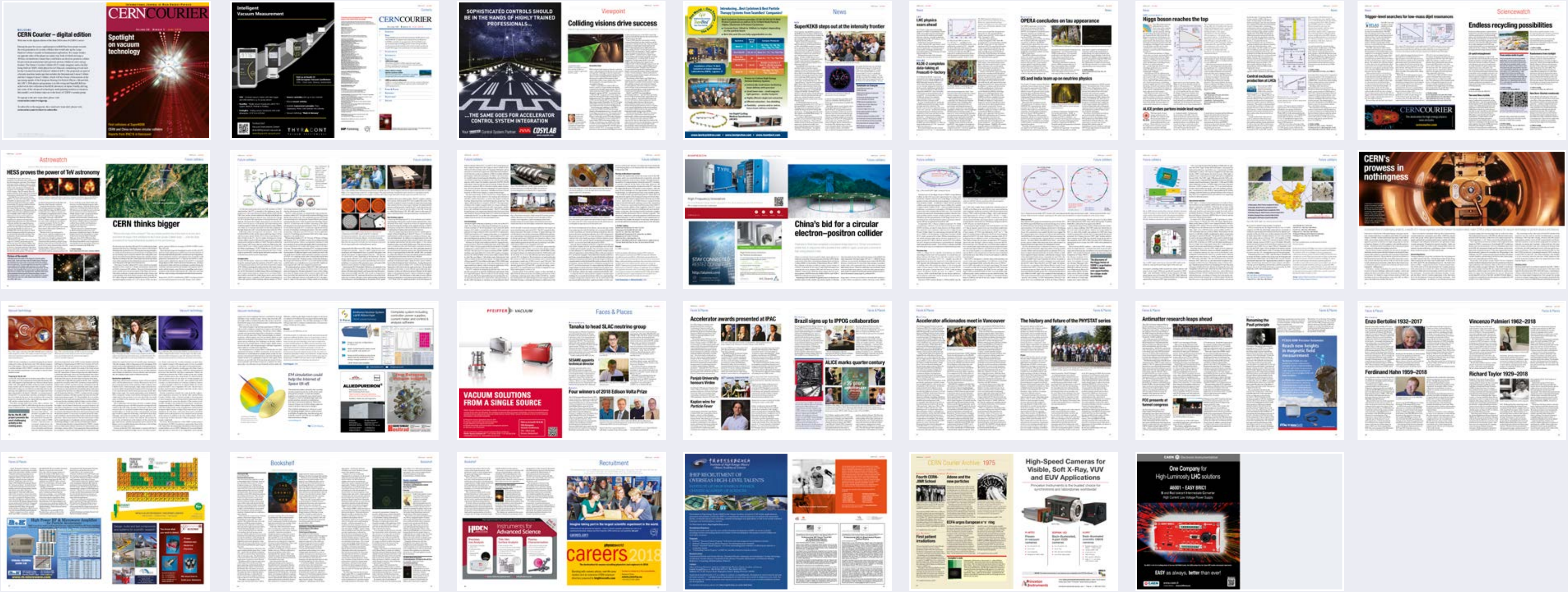
Concern for an early start on one of two European projects under discussion, PETRA [DESY] and EPIC [Rutherford Laboratory], is related to an equivalent USA project at Berkeley/Stanford, PEP. The new particle discoveries hold out the tantalising prospect that the first machine to operate could cream off some spectacular physics.

● Compiled from texts on p198.

Compiler's note



Following the 1974 discovery of charm at the e^+e^- collider SPEAR at SLAC (and at BNL, using a proton beam from the Alternating Gradient Synchrotron), there was indeed more spectacular physics to come from a lepton collider – the ground-breaking discovery of the gluon at PETRA. In 1976 a trio of CERN theorists, John Ellis, Mary Gaillard and Graham Ross, suggested that gluon bremsstrahlung might appear in 3-jet events from e^+e^- annihilation. In 1979, within a year of PETRA commissioning, all four experiments – Mark J, JADE, PLUTO and TASSO – had evidence for the existence of this hitherto hypothetical particle, the first gauge boson to be detected after the photon.



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Contents