WELCOME

CERN Courier – digital edition

Welcome to the digital edition of the September 2015 issue of *CERN Courier*.

It is now 60 years since the antiproton was discovered at Berkeley in September 1955 and 20 years since the first antihydrogen atoms were made at CERN. Over the decades, antiprotons have become a standard tool in particle physics, and antihydrogen is now a miniature laboratory for investigations in fundamental physics, as this month's anniversary feature describes. Recently, the BASE collaboration at the Antiproton Decelerator reported on a new comparison of the proton and antiproton to test a basic symmetry. Also at CERN, the ALICE experiment is investigating how loosely bound objects, including antinuclei, can survive the hot and dense heavy-ion collisions at the LHC.

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VOLUME 55 NUMBER 7 SEPTEMBER 2015

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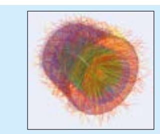

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On the cover: A 600 MeV/*c* antiproton interacts with a neon nucleus in the streamer chamber of the PS179 experiment at CERN's Low Energy Antiproton Ring (LEAR) in the 1980s. It is now 60 years since the antiproton was discovered at Berkeley and 20 years since the first antihydrogen atoms were made at LEAR (p3). (Image credit: CERN-EX-9902017.)

News

CERN

LHCb reports observation of pentaquarks

In 1964, Murray Gell-Mann and George Zweig independently predicted a substructure for hadrons: baryons would be comprised of three quarks, mesons of a quark–antiquark pair. They also said that baryons with four quarks and one antiquark were possible, as were mesons with two quarks and two antiquarks – dubbed, respectively, pentaquarks and tetraquarks, after the number of constituents. Since then, the picture for baryons and mesons has been thoroughly established within QCD, the theory of the strong interaction. Claims of the sighting of pentaquarks, meanwhile, have been thoroughly debunked. Nevertheless, their existence could cast important new light on QCD.

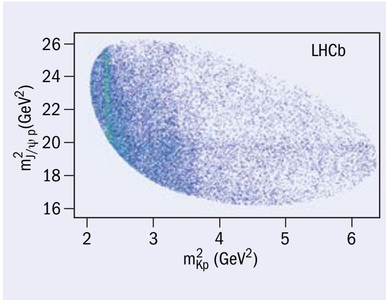
Now, the LHCb collaboration has announced the observation of two pentaquark states, P_c^+, in analysis of data collected during Run 1 of the LHC at CERN. The discovery was made during the analysis of the decay $\Lambda_b \to J/\psi K^- p$, a decay mode used in the precision measurement of the Λ_b lifetime (*CERN Courier* July/August 2013 p8). There was, however, an apparent anomaly in the pattern of these decays. The Dalitz plot, in which only 5.4% is background, shows several expected $\Lambda^* \to K^- p$ resonances as vertical bands, but there is also a horizontal band, indicative of a resonance decaying into $J/\psi p$, which was completely unexpected (figure 1).

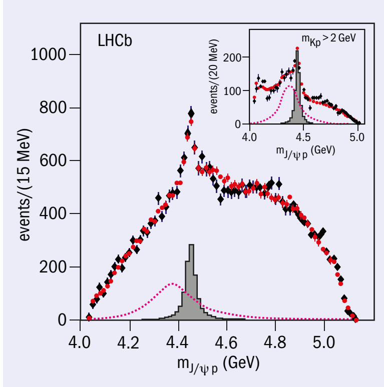
A resonance decaying into $J/\psi p$ would be a pentaquark state (with quarks $uudc\bar{c}$). So LHCb investigated more deeply, with a full six-dimensional amplitude analysis of the two interfering decay sequences: $\Lambda_b \to J/\psi \Lambda^*$, $\Lambda^* \to K^- p$, and $\Lambda_b \to P_c^+ K^-$, $P_c^+ \to J/\psi p$. This analysis not only fit the invariant mass of the decay products, the angular distributions for the decays were also fit, along with the invariant mass – this was not a simple "bump hunt".

The first attempt was to fit the data without any P_c^+ states, with the belief that the structure could be built up from Λ^* interferences. This failed. The next attempt was with one P_c^+ state, but the fit was deficient. Finally, a fit with two P_c^+ states proved to be acceptable. The masses of the states are 4380±8±29 MeV and 4449.8±1.7±2.5 MeV, with widths of 205±18±86 MeV and 39±5±19 MeV, respectively. The states have opposite parities, with one state having spin 3/2 and the other spin 5/2. The final fitted $J/\psi p$ mass spectra show the two states (figure 2). The significances of each state are more than 9σ.

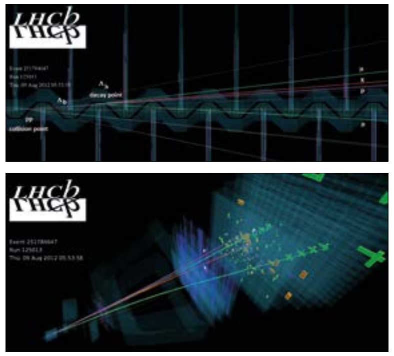
LHCb has subjected the results to a great many systematic checks. These include ensuring that tracks were not "clones" or "ghosts", splitting the data into different subsets, such as Λ_b versus $\overline{\Lambda}_b$, data from 2011 versus 2012, magnetic field up versus down, etc. All of these tests have been passed.

One interesting fact is that these pentaquarks decay into J/ψ, as do candidate states for tetraquark mesons (*CERN Courier* June 2014 p12). This suggests that two heavy quarks may be needed to provide the binding for these exotic states.





Top: Fig. 1. Dalitz plot showing $m^2(K^-p)$ versus $m^2(J/\psi p)$. The horizontal band is produced by pentaquark particles decaying into $J/\psi p$. Above: Fig. 2. The mass of the $J/\psi p$ system in $\Lambda_b \to J/\psi K^- p$ decays.



Above: Fig. 3. An example of the Λ_b decay. In the top image, the Λ_b (purple dotted line) travels 3.9 cm before it decays into $\mu^+\mu^-K^-p$, whose tracks are shown in the image below. The $\mu^+\mu^-$ are the decay products of the J/ψ.

Further reading

R Aaij *et al.* (LHCb Collaboration) 2015 arXiv:1507.03414 [hep-ex].

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CERN

Pakistan becomes associate member state of CERN

The Islamic Republic of Pakistan became an associate member state of CERN on 31 July, following notification that Pakistan has ratified an agreement signed last December, granting this status to the country (*CERN Courier* January/February 2015 p6).

Pakistan's new status will open a new era of co-operation that will strengthen the long-term partnership between CERN and the Pakistani scientific community. Associate membership will allow Pakistan to participate in the governance of CERN, through attending CERN Council meetings. Moreover, it will allow Pakistani scientists to become CERN staff members, and to participate in CERN's training and career-development programmes. Finally, it will allow Pakistani industry to bid for CERN contracts, thus opening up opportunities for industrial collaboration in areas of advanced technology.

On 16 June, an 11 T superconducting dipole-magnet model manufactured at CERN for the High-Luminosity LHC project reached record performance levels in tests in hall SM18. Its magnetic-field intensity exceeded 11 T after just six quenches – a much faster increase than in previous models. In addition, it reached 12 T – corresponding to a current of 12,800 A – which is higher than in earlier models. The new magnets, based on a niobium-tin (Nb_3Sn) superconductor, are being developed in a collaboration between Fermilab and CERN. Models constructed on both sides of the Atlantic have previously reached the required 11 T, but only after many quenches. The models are shorter than the final magnets – 2 m rather than 5.5 m – and have only a single bore, rather than two bores for the two LHC beams. (Image credit: CERN.)

Collaboration

AIDA-2020 offers support to use facilities for detector development in Europe

The Advanced European Infrastructures for Detectors and Accelerators (AIDA-2020) – the largest European-funded project for joint detector development – is making financial support available for small development teams to carry out experiments and tests at one of 10 participating European facilities. The project, which started on 1 May, will run for four years. Its main goal is to bring the community together and push detector technologies beyond current limits by sharing high-quality infrastructures provided by 57 partners from 34 countries, from Europe to Asia.

Building on the experience gained with the original AIDA project (*CERN Courier* April 2011 p6), the transnational access (TA) activities in AIDA-2020 are to enable financial support for teams to travel from one facility to another, to share existing infrastructures for efficient and reliable detector development. The support is organized around three different themes, providing access to infrastructures: the Proton Synchrotron and Super Proton Synchrotron test beams, the IRRAD proton facility and the Gamma Irradiation Facility (GIF++) at CERN; the DESY II test beam; the TRIGA reactor at the Jožef Stefan Institute; the Karlsruhe Compact Cyclotron (KAZ); the Centre de Recherches du Cyclotron at the Université catholique de Louvain (UCLouvain); the MC40 Cyclotron at the University of Birmingham; the Rudjer Boskovic Institute Accelerator Facility (RBI-AF); and the electromagnetic compatibility facility (EMClab) at the Instituto Tecnológico de Aragón (ITAINNOVA).

Access to high-energy particle beams (TA1) at CERN and DESY enables the use of test beams free-of-charge. Here the main goal is to attract more researchers to participate in beam tests, in particular supporting PhD students and postdoctoral researchers to carry out beam tests of detectors.

With the access to irradiation sources (TA2), the goal is to cover the range of particle sources needed for detector qualification for the High Luminosity LHC (HL-LHC) project. These include proton, neutron and mixed-field sources, as well as gamma irradiation. Through IRRAD, TRIGA, KAZ and MC40, it provides both the extreme fluences of up to 10^{17} neq/cm^2 required for the forward region in HL-LHC experiments, and the lower fluences of 10^{15} neq/cm^2 on 10 cm^2 objects for the outer layers of trackers. GIF++ covers irradiation of large-scale objects such as muon chambers, while the Heavy Ion Irradiation Facility at UCLouvain is available for single-event-effects tests of electronics.

The third theme provides access to new detector-testing facilities (TA3). Semiconductor detectors will be one of the main challenges at the HL-LHC. Studying their behaviour with micro-ion beams at RBI will enhance the understanding of these detectors. Electromagnetic compatibility is a key issue when detectors have to be integrated in an experiment, and prior tests in a dedicated facility such as the EMClab at ITAINNOVA will make the commissioning of detectors more efficient.

● For more details on each facility and eligibility criteria, visit aida2020.web.cern.ch/content/transnational-access.

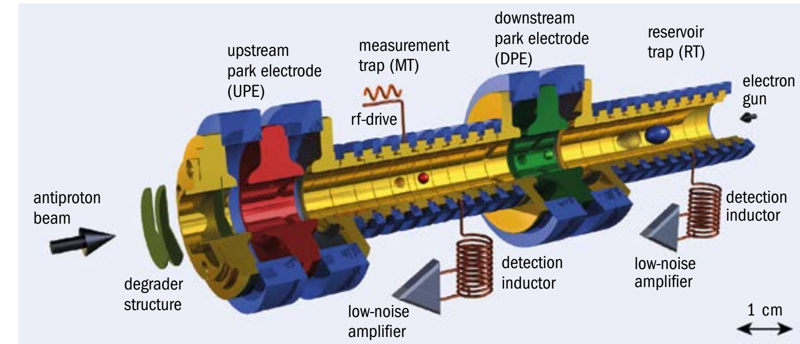
CPT

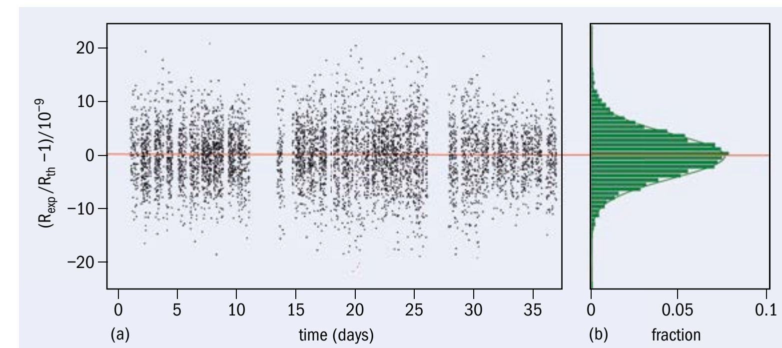
BASE compares charge-to-mass ratios of proton and antiproton to high precision

The Japanese/German BASE collaboration at CERN's Antiproton Decelerator (AD) has compared the charge-to-mass ratios of the antiproton and proton with a fractional precision of 69 parts in a trillion (ppt). This high-precision measurement was achieved by comparing the cyclotron frequencies of antiprotons and negatively charged hydrogen ions in a Penning trap. The result is consistent with charge–parity–time-reversal (CPT) invariance, which is one of the cornerstones of the Standard Model of particle physics, and constitutes the most precise test comparing baryons and antibaryons performed to date.

In their experiment, the BASE collaboration has profited from techniques pioneered in the 1990s by the TRAP collaboration at the Low Energy Antiproton Ring at CERN (see p21). The advanced cryogenic Penning-trap system used in BASE consists of four traps, two of which were used in this measurement – a measurement trap and a reservoir trap (figure 1). When the experiment receives a pulse of 5.3 MeV antiprotons from the AD, they strike the degrader structure, which is designed to slow them down, and release hydrogen. Negatively charged hydrogen ions (H^-) can form in the process, producing a composite cloud with the antiprotons that is shuttled to the reservoir trap. BASE has developed techniques to extract single antiprotons and negative hydrogen ions from this cloud whenever needed. Moreover, the reservoir has a lifetime of more than a year, making the BASE experiment almost independent from AD cycles.

Using this extraction technique, and taking the timing from the AD cycle, BASE prepares a single antiproton in the measurement trap, while an H^- ion is held in the downstream park electrode, as shown in figure 1. The cyclotron frequency of the antiproton is then measured in exactly 120 s, which corresponds to one AD cycle. The particles are subsequently exchanged by performing appropriate potential ramps, and the cyclotron frequency of the H^- ion is measured. Thus, a single comparison of the charge-to-mass ratios takes only 240 s. This is much faster than in previous experiments, enabling BASE to perform about 6500 ratio comparisons in 35 days of measurement time (figure 2). The result is a value of the ratio-comparison:





Top: Fig. 1. Schematic of the measurement (MT) and the reservoir (RT) Penning traps. Radio-frequency drives for particle manipulation are applied to the upstream correction electrode of the measurement trap. The upstream and downstream park electrodes are used for the particle shuttling scheme. The electron gun allows for electron cooling of antiprotons. The entire assembly is mounted in a cryogenic vacuum chamber. Above: Fig. 2. (a) All 6521 values of the $\bar{p}$-to-H^- cyclotron frequency ratios measured in 35 days as a function of time. (b) The measured ratios projected onto a histogram.

$(q/m)_{\bar{p}}/(q/m)_p - 1 = 1(69) \times 10^{-12}$, thus confirming CPT at the level of ppt.

The high sampling rate has also enabled the first high-resolution study of diurnal variations in a baryon/antibaryon comparison, which could be introduced by Lorentz-violating cosmic-background fields. The measurement sets constraints on such variations at the level of less than 720 ppt. In addition, by assuming that CPT invariance holds, the measurement can be interpreted as a test of the weak equivalence principle using baryonic antimatter. If matter respects weak equivalence while antimatter experiences an anomalous coupling to the gravitational field, this gravitational anomaly would contribute to a possible difference in the measured cyclotron frequencies. Thus, by following these assumptions, the result from BASE can be used to set a limit on the gravitational anomaly parameter, α_g: $|\alpha_g - 1| < 8.7 \times 10^{-7}$.

The main goal for the BASE experiment, which was approved in June 2013, is to measure the magnetic moment of the antiproton with a precision of parts per billion. Using the double Penning trap system, the collaboration recently performed the most precise measurement of the magnetic moment of the proton (*CERN Courier* July/August 2014 p8).

● **Further reading**

S Ulmer *et al.* 2015 *Nature* doi:10.1038/nature14861.

LHC EXPERIMENTS

Physics and performance in LHC Run 2

EPS-HEP 2015

EUROPEAN PHYSICAL SOCIETY HEP2015

In this issue, news from the LHC experiments focuses on a few highlights at the first big summer conference.

The year 2015 began for the ATLAS experiment with an intense phase of commissioning using cosmic-ray data and first proton–proton collisions, allowing ATLAS physicists to test the trigger and detector systems as well as to align the tracking devices. Then the collection of physics data in LHC Run 2 started in June, with proton–proton collisions at a centre-of-mass energy of 13 TeV (*CERN Courier* July/August 2015 p25). Measurements at this new high-energy frontier were among the highlights of the many results presented by the ATLAS collaboration at EPS-HEP 2015.

An important early goal for ATLAS was to record roughly 200 million inelastic proton–proton collisions with a very low level of secondary collisions within the same event ("pile-up"). This data sample allowed ATLAS physicists to perform detailed studies of the tracking system, which features a new detector, the "Insertable B-layer" (IBL). The IBL consists of a layer of millions of tiny silicon pixels mounted in the innermost heart of ATLAS at a distance of 3.3 cm from the proton beam (*CERN Courier* October 2013 p28). Together with the other tracking layers of the overall detector, the IBL allows ATLAS to measure the origin of charged particles with up to two times better precision than during the previous run. Figure 1 shows the resolution achieved for the longitudinal impact parameter of the beam.

ATLAS exploited the early data sample at 13 TeV for important physics measurements. It allowed the collaboration to characterize inelastic proton–proton collisions in terms of charged-particle production and the structure of the "underlying event" – collision remnants that are not directly related to the colliding partons in the proton. This characterization is important for validating the simulation of the high-luminosity LHC collisions, which contain up to 40 inelastic proton–proton collisions in a given event (one event involves the crossing of two proton bunches with more than 100 billion protons each). Figure 2 shows the evolution of the charged-particle multiplicity with centre-of-mass energy.

ATLAS also measured the angular correlation among pairs of the produced charged particles, confirming the appearance of a so-called "ridge" phenomenon in events with large particle multiplicity at a centre-of-mass energy of 13 TeV. The "ridge" (figure 3) consists of long-range particle–particle correlations not predicted by any of the established theoretical models describing inelastic proton–proton collisions.

After the low-luminosity phase, the LHC operators began to increase the intensity of the beams. By the time of EPS-HEP 2015, ATLAS had recorded a total luminosity of 100 pb^{-1}, of which up to 85 pb^{-1} could be exploited for physics and performance studies. ATLAS physicists measured the performance of electron, muon and τ-lepton reconstruction, the reconstruction and energy calibration of jets, and the reconstruction of "displaced" decays of long-lived particles, such as weakly decaying hadrons containing a bottom quark. The precision of the position measurements of displaced decay locations (vertices) is significantly improved by the new IBL detector.

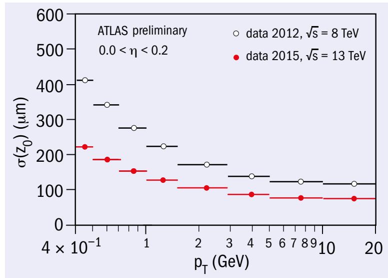
ATLAS used these data to classify the production of J/ψ particles at 13 TeV in terms of their immediate ("prompt") and delayed ("non-prompt") origin. While non-prompt J/ψ production is believed to be well understood via the decay of b hadrons, prompt production continues to be mysterious in some aspects.

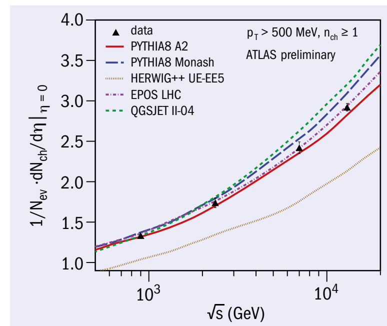
ATLAS also performed a first study of the production of energetic, isolated photons and a first cross-section measurement of inclusive jet production in 13 TeV proton–proton collisions. Both are correctly described by state-of-the-art theory.

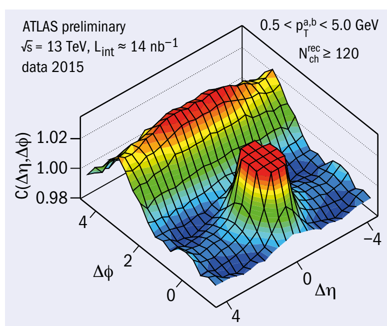
The data samples at high collision energy contain copious numbers of Z and W bosons, the mediators of the weak interaction, whose leptonic decays provide a clean signature in the detector that can be exploited for calibration purposes. ATLAS has studied the kinematic properties of these bosons, also in association with jet production. Their abundance in 13 TeV proton–proton collisions is found to be consistent with the expectation from theory. ATLAS has also observed some rare di-boson (ZZ) events, which – with a hundred times more data – should allow the direct detection of Higgs bosons. Figure 4 shows a candidate ZZ event.

In higher-energy proton collisions, the rate of particle production for many heavier particles for a given luminosity increases. The heaviest known particle, the top quark – with a mass approximately 170 times that of a proton – is predominantly produced in pairs at the LHC, and the cross-section for the production of top-quark pairs is expected to increase by a factor of 3.3 at 13 TeV, compared with the 8 TeV collisions of Run 1. ATLAS has performed an early measurement of the top-pair production cross-section in the cleanest channels where one top quark decays to an electron, an electron-neutrino and a jet containing a b-hadron ("b-jet"), while the other top-quark decays to a muon, a muon-neutrino and a b-jet. The small backgrounds from other processes in this channel allow a robust measurement with small systematic uncertainties. The measured cross-section agrees with the predicted increase of a factor of 3.3. The precision of the measurement is limited by the 9% uncertainty in luminosity, which is expected to improve significantly during the year. Figure 5 shows the evolution of the top-pair production cross-section.

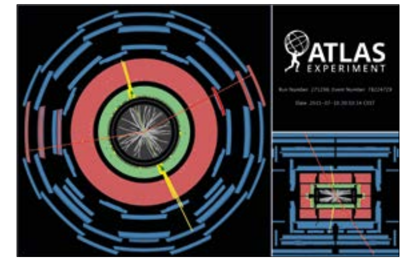
Although the available data sample does not yet allow a significant increase in the sensitivity to the most prominent new physics phenomena, ATLAS has exploited the data to perform important early measurements. The excellent detector performance has allowed the confirmation of theoretical expectations with 13 TeV proton–proton collision energies.

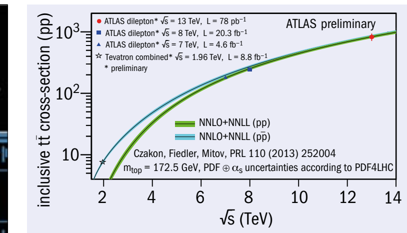






Above left: Fig. 1. Longitudinal impact-parameter resolution measured from data in 2015, $\sqrt{s} = 13$ TeV, with the Inner Detector including the IBL. Above right: Fig. 2. The average charged-particle multiplicity per unit of rapidity for $\eta = 0$ as a function of the centre-of-mass energy. Left: Fig. 3. Two-particle correlation function for charged particles having transverse momentum in the interval $0.5 < p_T < 5$ GeV and $N^{rec}_{ch} \geq 120$.





Far left: Fig. 4. Display of a Z pair-production candidate event with one Z decaying into electrons and the other Z into muons. Left: Fig. 5. Cross-section for $t\bar{t}$ pair production in pp and $p\bar{p}$ collisions, as a function of centre-of-mass energy. ATLAS results in the dilepton eμ channel at $\sqrt{s} = 13$, 8 and 7 TeV, as well as the Tevatron combination at $\sqrt{s} = 1.96$ TeV, are compared with the NNLO+NNLL theory.

Further reading

The ATLAS results at 13 TeV are summarized at https://twiki.cern.ch/twiki/bin/view/AtlasPublic/Summer2015-13TeV.

First results at 13 TeV and more from Run 1

The highlight of EPS-HEP 2015 for the CMS collaboration was the publication of the first physics result exploring the new territory at the LHC energy of 13 TeV: the measurement of the charged-hadron multiplicity (dN/dη), where η, the pseudorapidity, is a measure for the direction of the particle track. When protons collide at the LHC, more than one of their constituents (quarks or gluons) can interact with another one, so every collision produces an underlying spray of charged hadrons, such as pions and kaons, and the greater the energy, the higher the number of produced particles. Knowing precisely how many charged hadrons are created at the new collision energy is important for ensuring that the theoretical models used in the simulations employed in the physics analyses describe these underlying processes accurately. The publication from CMS at 13 TeV reports the differential multiplicity distribution for values of $\eta<2$, and a measured density for central charged hadrons (with $|\eta|<0.5$) of 5.49±0.01 (stat.)±0.17 (syst.). Figure 1 shows the differential distribution and the energy dependence of the new measurement compared with earlier data at lower energies.

CMS has, in addition, produced a full suite of performance plots covering a range of physics objects and final states, using up to 43/pb of 13 TeV data. Figure 2 shows the dimuon mass spectrum obtained from multiple trigger paths, where several resonances from the ω meson to the Z boson can be seen clearly. The B physics group in CMS has studied this spectrum in detail from the J/ψ to the Υ masses, and also the decay-time distributions for events with J/ψ or B^+ mesons. Dedicated performance plots were presented at the conference for various muon, electron and photon kinematic and identification variables, as well as the measured reconstruction and identification efficiencies. The reconstruction of several low-mass states, including K_s, Λ, D^0, D^*, B^+, B^0 and B_s, demonstrate the good performance of the CMS tracker. In addition, the position of the beam spot has been measured in all three dimensions. Simulations are already found to reproduce these physics-object data well at this early stage.

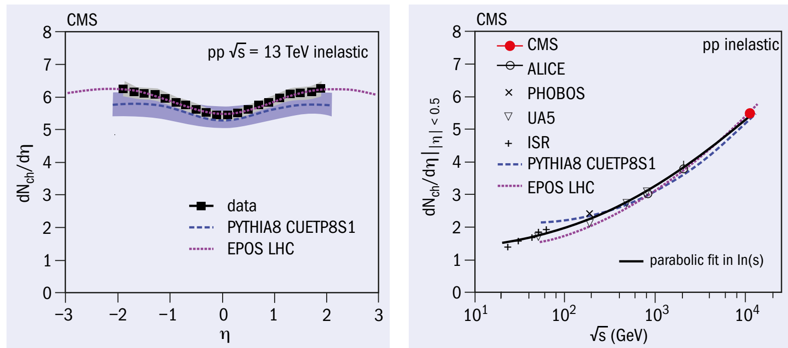


Fig. 1. Left: Measured charged-hadron production as a function of pseudorapidity. Right: The multiplicity in the central region compared with previous measurements at lower energies (CMS Collaboration 2015).

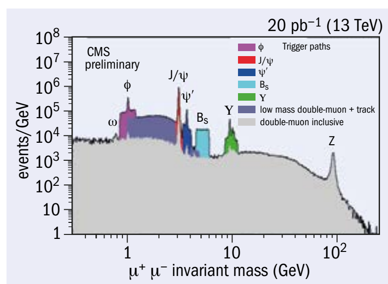


Fig. 2. The dimuon invariant-mass spectrum from several different trigger paths.

The physics groups in CMS have also started to study several processes at 13 TeV in some detail. One highlight is a first look for searches in the dijet invariant-mass spectrum, which so far reaches up to approximately 5 TeV (figure 3). Results of the same analysis on Run 1 data were released only in spring, but CMS is already continuing the search where it ended at 8 TeV up to 13 TeV, thus demonstrating the collaboration's readiness for discovery physics in the new energy regime. The TOP group has studied top–antitop ($t\bar{t}$) events in the dilepton and lepton+jet channels, in addition to taking a first look at events consistent with the production of single top quarks.

While eagerly jumping on the new data, CMS continues to produce world-class physics results on the Run 1 data collected at 7 and 8 TeV. The collaboration has recently approved more than 30 new results, which were shown at the conference. These include searches for new physics as well as precision Standard Model measurements. The results presented include measurements of the two-photon production of W-boson pairs through the interaction of two photons, the electroweak production of a W boson

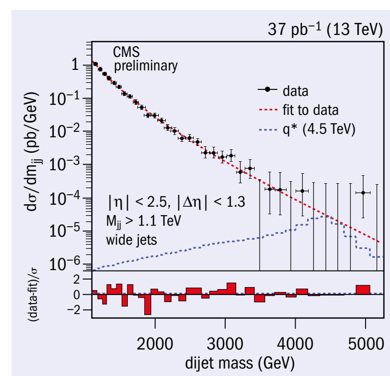


Fig. 3. The dijet invariant-mass spectrum, showing the expected signal distribution from a hypothetical particle with a mass of 4.5 TeV decaying into two jets.

accompanied by two jets, production rates for particle jets at 2.76 TeV compared with 8 TeV, as well as the production of two photons along with jets.

Discovered more than two decades ago, the top quark continues to play a vital role in physics analyses for both measurements and searches, because it is the heaviest elementary particle known so far. New CMS results with this special type of quark include measurements of the $t\bar{t}$ production rates in the fully hadronic sample, and a measurement of the $t\bar{t}+b\bar{b}$ process as well as the $t\bar{t}$ production in conjunction with a Z or W boson. In addition, searches for signs of new physics continue, most recently in the process where top decays to a charm quark and a Higgs boson, $t\rightarrow cH$, and the Higgs boson transforms to photons.

On the Higgs front itself, CMS has performed three new searches for non-Standard Model Higgs bosons containing τ leptons in the decay products, while on the supersymmetry front, analyses have looked for dark-matter candidates and other supersymmetric particles. Heavy-ion results from Run 1, using proton–proton, proton–lead and lead–lead collisions, include Υ polarization as a function of charged-particle multiplicity in proton–proton collisions, Z-boson production, jet-fragmentation functions in proton–lead collisions, and nuclear modification of Υ states in lead–lead collisions.

Further reading

CMS Collaboration 2015 arXiv:1507.05915 [hep-ex], submitted to *Phys. Lett. B*.

Performance Studies with 13 TeV data: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PublicPlotsEPS2015.

Results from Run 1 data released for EPS: https://cms-docdb.cern.ch/cgi-bin/PublicDocDB/RetrieveFile?docid=12660&filename=CMS_summary_EPSHEP15_EN_technical.pdf.

J/ψ mesons, b decays and more

At EPS-HEP 2015, the LHCb collaboration presented the first measurement of the J/ψ production cross-section in proton–proton (pp) collisions at 13 TeV. Using this measurement, they also determined the b-quark cross-section at this new, higher energy.

J/ψ mesons can be produced both "promptly", in the pp collision, and as a product of decays of B hadrons, dubbed "J/ψ-from-b". The two components are visible in figure 1, which shows the J/ψ decay-time distribution with respect to the pp collision time. The black points with error bars show the data, the solid red line indicates the best fit to the data, and the prompt J/ψ contribution is shown in blue. The black line indicates the J/ψ-from-b contribution, which falls exponentially with a time constant characteristic of the lifetime of B hadrons.

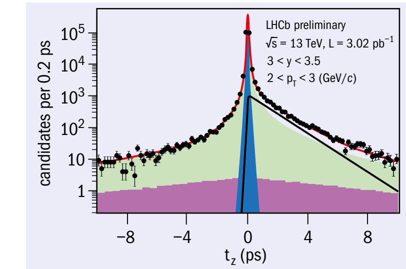
While the prompt J/ψ cross-section is interesting for constraining QCD models, the J/ψ-from-b cross-section is used to compute the b-quark pair total cross-section. The data at 13 TeV confirm the expected rise of the B-particle production rate of about a factor two with respect to 7 TeV. This increase will enable LHCb to obtain even more precise, interesting and, hopefully, surprising results in LHC Run 2.

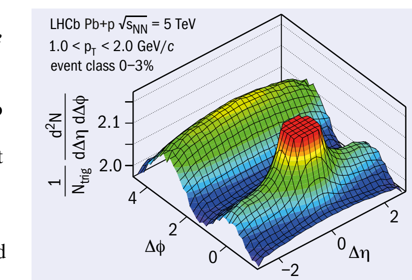
This analysis was the first to benefit from a new scheme for the LHCb software trigger that was introduced for Run 2. Splitting the event selection into two stages, it allows alignment and calibration to be performed in real time after the first stage of the software trigger and then used directly in the second stage. The same alignment and calibration information is propagated to the offline reconstruction, to ensure consistent and high-quality particle-identification information in the trigger and offline. The identical performance of the online and offline reconstruction achieved in this way offers the opportunity to perform physics analyses directly using candidates reconstructed in the trigger – the online reconstruction is used, for example, in the J/ψ cross-section measurement. The storage of only the triggered candidates leads to a reduction in the event size of an order of magnitude, permitting an increased event rate with higher efficiency.

LHCb also presented the determination based on Run 1 data of the Cabibbo–Kobayashi–Maskawa (CKM) matrix element $|V_{ub}|$, which describes the transition of a b quark to a u quark. The measurement – published during the conference in *Nature Physics* – was made by studying a decay Λ_b^0 baryon, $\Lambda_b^0\rightarrow p\mu^-\bar{\nu}_\mu$ (LHCb 2015a). The measurement of decays involving a neutrino is very challenging at a proton collider, and it was quite a surprise that this measurement could be done.

Measurements of $|V_{ub}|$ by previous experiments had returned two sets of inconsistent results, depending on the method used. Inclusive determination using all $b\rightarrow ul\nu$ transitions where l is either a muon or an electron give values of $|V_{ub}|$ above 0.004, while exclusive determinations, mainly from $B\rightarrow\pi l\nu$, yield values around 0.003. This could be explained by a new particle, in addition to the W boson, contributing to the quark transition with a right-handed current. LHCb's new measurement is of the exclusive category, but is the first to involve a baryon decay and hence a spin-1/2 particle. The result is $|V_{ub}|=(3.27\pm0.15\pm0.16\pm0.06)\times10^{-3}$, where the uncertainties are experimental, related to the theoretical calculation, and to the value of $|V_{cb}|$, respectively. This number agrees with previous exclusive determinations and is inconsistent with the hypothesis of new right-handed currents. So it still leaves the puzzle of why the inclusive and exclusive measurements do not agree. Further intensive research, both at the experimental and theoretical level, will continue to try to understand this disagreement.

While the above measurement constrains one side of the CKM unitarity triangle, the other (the third being unity) is best constrained by the B-meson oscillation frequency. LHCb presented the most precise measurement to date at the conference, using semileptonic B^0 decays. The result of (503.6±2.0±1.3) ns^{-1} is consistent with, but more precise than, the world average (LHCb 2015b).





Top: Fig. 1. Pseudo decay-time distribution of J/ψ candidates in one bin of transverse momentum p_T and rapidity. Above: Fig. 2. Two-particle correlations in azimuthal angle φ and pseudorapidity η for events recorded in the Pb+p configuration in the highest event-activity class. The near-side peak around (0,0) is truncated in the histograms.

In other highlights from Run 1, the collaboration reported new results on long-range correlations in proton–lead collisions. LHCb's latest measurements show that the so-called "ridges" seen in the most violent collisions span across even larger longitudinal distances, as figure 2 shows at Δφ=0 below the (truncated) peak at (0,0). This is the first time that the effect has been seen in the forward direction (LHCb 2015c). Moreover, because of its acceptance, the LHCb experiment distinguishes between configurations where the lead-ion enters from the front and those where it is the proton. Somewhat unexpectedly, the ridge is seen in both cases.

Further reading

LHCb Collaboration 2015a *Nature Physics* doi:10.1038/nphys3415.
LHCb Collaboration 2015b LHCb-CONF-2015-003.
LHCb Collaboration 2015c LHCb-CONF-2015-004.

ASTRONOMY

First light for the PAU camera

PAUCam, the camera for the Physics of the Accelerating Universe (PAU) project, has been successfully installed and commissioned at the William Herschel Telescope (WHT) at the Roque de los Muchachos Observatory on the island of La Palma. Installation took place on 3 June, with commissioning following during the subsequent four nights.

The innovative instrument is designed to measure precisely and efficiently the redshift of galaxies up to large distances – galaxies whose light is only now reaching Earth after starting its journey when the universe was less than half the size of what it is today. One of the primary goals of the project is to study how the expansion rate of the universe is increasing under the influence of the mysterious dark energy that makes up nearly 70% of the universe. PAUCam's competitiveness comes from its ability to obtain redshifts that are more precise than those of current photometric surveys, over a volume with a larger number density of galaxies than in spectroscopic surveys.

The camera is mounted at the prime focus of the 4 m-diameter WHT, which is part of the Isaac Newton Group of Telescopes, operated at present by a consortium between the governments of the Netherlands, Spain and the UK. The location at the prime focus of the WHT imposes severe weight limitations that are in conflict with the complexity and large size of the instrument. The solution was to build the main body of the camera with carbon fibre, with engineering developed in Spain.

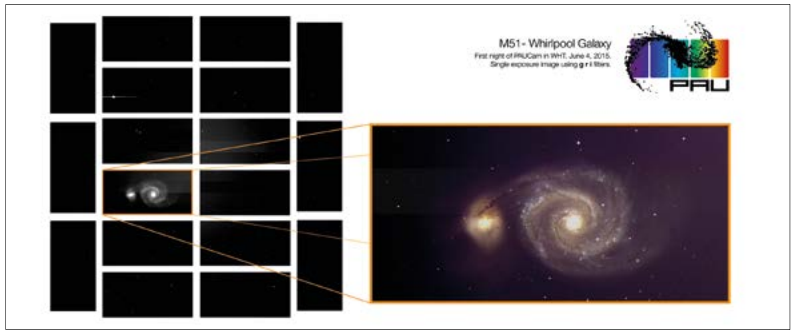
Another innovation of the camera is in the technique used to measure redshifts. With PAUCam, the redshift is measured photometrically, where the same object is imaged multiple times with its light passing through filters of different colours. PAUcam uses a set of 40 narrow-band filters, each passing light in a 10 nm-wide band, from wavelengths in the range of 450–850 nm. Another set of filters passes the light in six wider bands, named u, g, r, i, z and Y. The large number of narrow-band filters allow a determination of redshifts with a precision of 0.003(1+z), where z is the redshift parameter, or 10(1+z) Mpc, the characteristic scale of linear growth in the universe.

The photometric technique used in PAUCam contrasts with the spectroscopic technique, where the redshift of an object is determined by analysing its light through a spectrograph. The latter technique allows very precise determination of redshifts, but at the expense of much longer exposure times. Furthermore, only the spectra of previously selected objects are analysed, while the photometric technique determines, in principle, the redshift of all of the objects in the region of the sky being imaged. In the case of PAUCam, the expectation is to measure the redshift of about 50,000 objects every night of observation. The camera covers the entire field of view of the WHT (1 square degree) with a mosaic of 18 Hamamatsu Photonic red-sensitive CCDs, each with 4000 × 2000 pixels.

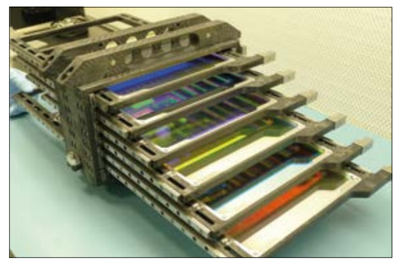
PAUCam has been designed and built over the past six years by a fruitful collaboration between astronomers, cosmologists and particle physicists in a consortium of Spanish institutions. The idea to build an instrument capable of contributing significantly to cosmological measurements arose in 2007, in the context of the Consolider Ingenio 2010 project financed by the Spanish government. This programme had as its objective the advancement in Spain of highly innovative projects.

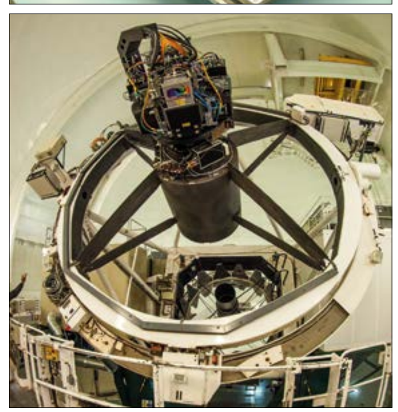
The PAUCam team is now being joined by other European groups to conduct a survey, named PAUS, with the objective of scientifically exploiting the capabilities of the camera. Aside from the survey, observation time with PAUCam will be made available to the international scientific community, for astronomical as well as cosmological measurements.

● PAUCam was designed and built by a consortium comprising the Institut de Física d'Altes Energies (IFAE), the Institut de Ciències de l'Espai (ICE-CSIC/IEEC) and the Port d'Informació Científica(PIC), all in Barcelona, and the Centro de Investigaciones Energéticas Medioambientales y Tecnológicas(CIEMAT) and the Instituto de Física Teórica (IFT-UAM/CSIC), both in Madrid.



PAUCam's 18 CCD sensors give a wide field of view, as seen in this image acquired on 6 June of M51, the Whirlpool galaxy, situated at about 23 million light-years from Earth. (Image credits: IFAE.)





Top: The filter-tray "jukebox" holding the six large-area wide-band filters. A similar jukebox, with seven trays, holds the large number of narrow-band filters, each the size of a CCD. Above: The PAUCam instrument mounted in the prime focus of the WHT.

FACILITIES

Fermilab sets neutrino-beam record

A view of the Main Injector – a powerhouse for neutrino beams. (Image credit: Fermilab.)

In June, Fermilab's Main Injector accelerator sustained a 521 kW proton beam, and set a world record for the production of high-energy neutrinos with a proton accelerator. The 120 GeV proton beam is used to provide high-energy neutrinos or antineutrinos to three experiments at the laboratory: the long-baseline experiments MINOS+ and NOvA (*CERN Courier* June 2015 p17) and the neutrino-interaction experiment MINERvA (*CERN Courier* April 2014 p26).

The record beam surpasses that of the proton beam of more than 400 kW achieved at CERN for the CERN Neutrinos to Gran Sasso (CNGS) beamline, which provided neutrinos for the ICARUS and OPERA long-baseline experiments. The highest beam powers for fixed-target proton beams are achieved with protons in the giga-electron-volt range. Both the Spallation Neutron Source at Oak Ridge National Laboratory and the cyclotron facility at the Paul Scherrer Institute in Switzerland create proton beams with powers in excess of 1 MW. In the 1990s, Los Alamos National Laboratory operated a 0.8 GeV proton beam at about 800 kW for its low-energy neutrino experiment, LSND.

The power of the proton beam is a key element in producing neutrinos at accelerators: the more protons packed in the beam, the higher the number of neutrinos and antineutrinos produced and the better the chance to record neutrino interactions. The protons strike a target to create pions and other short-lived particles; the higher the proton energy, the larger the number of pions produced. Magnetic-focusing horns direct the charged pions into a vacuum pipe that is centred along the desired neutrino-beam direction. As the pions decay, they produce neutrinos and antineutrinos that are boosted in the direction of the original pions.

Since 2011, Fermilab has made significant upgrades to its accelerators and reconfigured the complex to provide the best possible particle beams for neutrino and muon experiments. The next goal for the 3.3 km circumference Main Injector accelerator is to deliver 700 kW in 2016 – double the beam power produced in the Tevatron era.

Fermilab plans to make additional upgrades to its accelerator complex over the next decade. The Proton Improvement Project-II includes the construction of a 800 MeV superconducting linac. Its beam would enable the Main Injector to provide more than 1.2 MW of proton beam power for the international Deep Underground Neutrino Experiment (*CERN Courier* April 2015 p20).

Fermilab also operates a second neutrino beamline, powered by its 8 GeV booster accelerator. This provides neutrinos for the Short Baseline Neutrino programme, which comprises three neutrino detectors: MicroBooNE (construction complete), ICARUS (upgrades underway at CERN) and the Short Baseline Neutrino Detector (construction to start in 2016).

Sciencewatch

Compiled by John Swain, Northeastern University

Why seahorses have square tails

Most animals have tails with round cross-sections, but tails of seahorses have square ones. Michael Porter of Clemenson University in South Carolina and colleagues have now explained why. Using 3D printing to make articulated models of square and circular tails and test them, they found that while cylindrical tails could twist better, the square cross-section provides more contact area and helps the tail to relax, reducing the energy the animal has to expend to grasp things. The square cross-section is also three times stiffer and four times stronger under compression.

Why do seahorses, left, have square tails? A tail with square segments, right, creates more contact points with the surface that it is gripping, compared with a tail that has round segments. (Image credits: Florin Dumitrescu, left, and Michael Porter/Clemson University.)

● **Further reading**
M M Porter *et al.* 2015 *Science* **349** aaa6683-1.

Metal deuterium

It has long been suggested that hydrogen, under enough pressure, would become metallic, and this transition has now been seen, at least in deuterium. Marcus Knudson of Sandia National Laboratories in New Mexico and colleagues used the Sandia Z machine, which can produce currents of 20 MA and magnetic fields of 10 MG, to produce shock waves via an aluminium plate to squeeze liquid deuterium by more than 300 GPa for around a tenth of a microsecond. Between 280–305 GPa, there was an abrupt transition to a shiny metallic state. Standard hydrogen may take more effort, but this gives plenty of insight into how solid hydrogen might behave, with significant implications for ideas about gas-giant planets such as Jupiter.

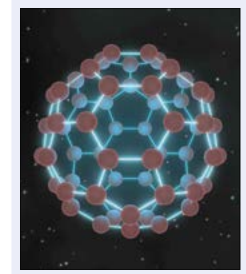
● **Further reading**
M D Knudson *et al.* 2015 *Science* **348** 1455.

Bacteria make superfluids

Genuine superfluidity is normally associated with extreme cold, but zero viscosity has come about in an unexpected way, thanks to bacteria. Harold Auradou of the University of Paris-Sud and colleagues have found that a solution with *Escherichia coli* swimming in it had a shear viscosity that depended on the concentration of bacteria. Above a threshold, they saw a "superfluid-like" transition where, macroscopically, the self-organized swimming of the bacteria overcame the dissipative effects arising from viscous loss.

● **Further reading**
H M Lopez *et al.* 2015 *Phys. Rev. Lett.* **115** 028301.

Buckyballs in space



Buckyballs are famous for their soccer-ball-like structure, with 60 carbon atoms. (Image credit: NASA/JPL-Caltech.)

Numerous "diffuse interstellar bands" (DIBs) in the absorption spectra of the interstellar medium have been puzzling astronomers since their discovery nearly 100 years ago. Now, thanks to Ewen Campbell of the University of Basel and colleagues, two infrared lines (at 9632.7±0.1 and 9577.5±0.1 Å) have been matched up with laboratory measurements of spectra of the buckminsterfullerene or "buckyball" ion C_{60}^{+} in the gas phase cooled to 5.6 K. Buckminsterfullerene has a low ionization potential, so finding it as an ion is not surprising, but the origin of the molecule itself in space and the nature of the rest of the DIBs are still mysterious.

● **Further reading**
E K Campbell *et al.* 2015 *Nature* **523** 322.

Weyl point seen

Back in 1929, Hermann Weyl proposed an equation for massless particles with a conical point in its dispersion relation – the "tip" of the mass shell, also called the "Weyl point". Neutrinos have mass, so do not fit his equation, but now the Weyl point has turned up in a solid-state system.

Following earlier theoretical suggestions, Su-Yang Xu of Princeton University and colleagues used photoemission spectroscopy to show that TaAs is a Weyl semimetal, with Weyl fermions as emergent quasiparticles. They clearly demonstrated Weyl cones and the Weyl point for propagation in the bulk, as well as Fermi arcs on the surface. The work is generating great excitement because this is, in many ways, a 3D analogue of graphene, and promises a range of applications.

● **Further reading**
S-Y Xu *et al.* 2015 *Science* DOI: 10.1126/science.aaa9297.

Mining waste

Sewage in the US could be a useful source of high-value metals. Paul Westerhoff of Arizona State University and colleagues have found that the amounts of the 13 most lucrative elements – Ag, Cu, Au, P, Fe, Pd, Mn, Zn, Ir, Al, Cd, Ti, Ga and Cr – add up to be worth a total of $280 for each tonne of sludge. This corresponds to around $8 million per million people, or more than $2.5 billion per year for the country as a whole. The metals enter the wastewater system from a variety of industries and the challenge will be to extract them from the sludge in an economical way.

● **Further reading**
P Westerhoff *et al.* 2015 *Environ. Sci. Technol.* 10.1021/es505329q.

Astrowatch

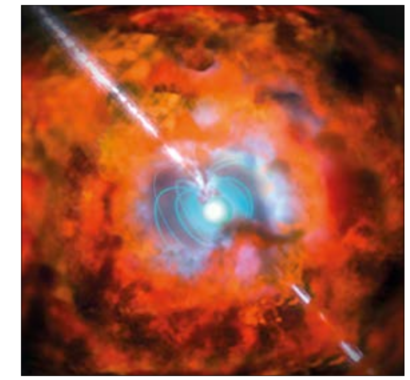
Compiled by Marc Türler, ISDC and Observatory of the University of Geneva, and CHIPP, University of Zurich

Do magnetars power hour-long gamma-ray bursts?

Based on optical observations, a team of astronomers has, for the first time, demonstrated a link between a very long-lasting gamma-ray burst (GRB) and an unusually bright supernova explosion. The results show that the supernova was not driven by radioactive decay, as expected, but most likely by the spin down of a magnetar, a neutron star with an extremely strong magnetic field.

GRBs have intrigued astronomers since their discovery nearly 50 years ago by US military satellites intended to detect nuclear test explosions conducted by the Soviet Union. Mysterious gamma-ray flashes were detected, not from Earth, but from random directions in the sky. It was only some 30 years later that the detection of their precise locations and the measurement of their redshifts by follow-up observations proved them to be very luminous events from remote galaxies. The further evidence that some of them are associated with supernova explosions settled the issue of their true nature as being a manifestation of the core collapse of a massive star (*CERN Courier* September 2003 p13).

Astronomers usually distinguish two main classes of GRBs: the short ones that flare up for less than about 2 s and the longer ones. Among the latter, there are a few outstanding bursts lasting more than 10,000 s, which have been proposed to originate in the explosion of giant stars with much larger radii (*CERN Courier* June 2013 p12). A team led by Jochen Greiner of the Max-Planck-Institut für extraterrestrische Physik in Garching, Germany, has now shown that a supernova explosion is associated with one of these rare ultra-long-duration GRBs, namely GRB 111209A. The supernova's presence has been derived from observations of the afterglow emission by two telescopes of the European Southern Observatory in Chile: the GROND instrument on the 2.2 m telescope at La Silla and the X-shooter instrument on the Very Large Telescope at Paranal.



Artist's impression of a supernova and associated gamma-ray burst driven by a magnetar, a rapidly spinning neutron star with a very strong magnetic field. (Image credit: ESO.)

The supernova's spectral and timing properties are both very peculiar. Its luminosity is intermediate between the supernovas usually associated with GRBs and a new class of super-luminous supernovas discovered in 2011. The exceptional luminosity of the latter would be due to energy injection from a rapidly rotating magnetar – a neutron star with a huge magnetic field of up to about 10^{10} T. The same process could be at play in the supernova of GRB 111209A. Indeed, the huge amount of nickel needed to explain the observed light curve by radioactive decay of ^{56}Ni is not compatible with the rather featureless spectral shape, which suggests a star of low metallicity. While Greiner and colleagues cannot prove that a magnetar is at the origin of the ultra-long GRB of 9 December 2011, nor the source of the luminous and peculiar supernova they observed, they can rule out alternative possibilities, leaving this as the most likely one.

Magnetars have already been invoked to explain the long-lasting afterglow emission of some GRBs (*CERN Courier* May 2007 p11). Now they seem to be needed to account for powering the prompt emission of some of these powerful flashes of gamma rays. Their advantage is that they would provide a continuous power supply, from hours to months, by losing rotational energy through magnetic-dipole radiation. The flexibility of the magnetar model fits peculiar GRBs and supernovas well, but what about the more standard GRBs? Could they also be powered by a new-born magnetar rather than by a black hole?

Further reading

J Greiner *et al.* 2015 *Nature* **523** 189.

Picture of the month

Welcome to Pluto! Thanks to NASA's New Horizon mission, astronomers and the general public alike now know what the dwarf planet Pluto looks like. Even with the eye of the Hubble Space Telescope, Pluto can only be seen as a little patchy marble. A journey of more than nine years was needed from Earth to this previously outermost planet – now called a dwarf planet – to take this snapshot. Unlike ESA's Rosetta spacecraft, which orbits the comet 67P/Churyumov–Gerasimenko (*CERN Courier* October 2014 p17), New Horizon was not planned to go into orbit around Pluto, but just flew by on 14 July. This high-resolution true-colour image was assembled from four images taken by the Long Range Reconnaissance Imager (LORRI). It shows a bright region in the shape of a heart contrasting with darker areas harbouring mountains rising more than 3000 m above the surface. The brightest area is an intriguing craterless, frozen plain, which is possibly still being shaped by geologic processes. (Image credit: NASA/JHUAPL/SwRI.)

CERN Courier Archive: 1972

A look back to CERN Courier vol. 12, September 1972, compiled by Peggie Rimmer

CERN News

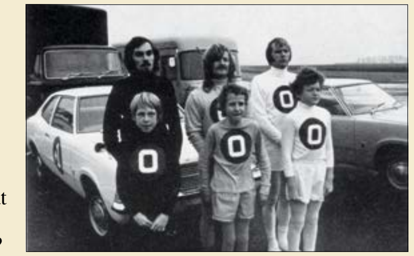
Pop physics

How to give insight into the concepts of particle physics? How to show the general public something of the inherent fascination and fundamental importance of a subject that seems so far removed from ordinary affairs and so dependent on advanced mathematics? This was the problem confronting Denis Postle of Tattooist International, the producer of a film that CERN and the British Broadcasting Corporation (BBC) have made as a co-production.

The project started nearly three years ago, after Postle had come to Geneva to make a film for the regular BBC science programme *Horizon*. This film, like others before it, talked about CERN, the machines and the physicists, but the physics remained for the most part in the background, intangible and inaccessible.

We needed a new style, a new approach, and we had to be selective in the phenomena described. It was pointless to try to cram into forty minutes of film a physics course that most students find difficult enough spread over as many months. In any case, few members of the public wish to become physicists overnight. They are interested in knowing what particle physics has to do with them, how it relates to their day-to-day affairs and what this research reveals.

In producing the film, CERN has provided the physics know-how and many people have spent a lot of time and effort in trying to explain the principal themes of present-day research in simple terms – none more so than R Hagedorn. The BBC, in the person of Peter Goodchild, editor of *Horizon*, has provided expertise on presentation and has been the final arbiter on audience acceptance. Postle as producer has turned the talk into a theme, pictures and text. Compounds have become bubble rafts, atoms concert halls, protons motorcars, pions small boys, interactions dances, and quarks a series of moves in a special game of chess. The accelerators, the ISR and the big detectors remain in the background, giving place to a machine gun and paper target that provided the participants at least with a lot of fun. The music has been composed and is played by Pete Townshend of The Who.



Shots from the CERN/BBC TV film to be released in November: hadrons (vehicles), pions (boys) and kaons (adults) prepare for interactions. The last two carry zero hadronic charge. They are black, grey and white for negative, zero, and positive electric charge. Unfortunately, from a photograph it is not possible to hear the hypercharge! (Image credits: CERN/BBC.)

Jeremy [Newson] confronts the quark model on a special chessboard.

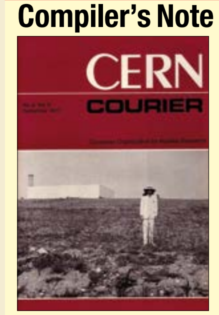
The film is meant to be entertaining but it is, nevertheless, a serious attempt to show something of the methods behind the research, and to give some impression of the surprising order and harmony underlying the disorders and divisions usually more apparent in our daily lives.

For the BBC, it represented a new approach, both in technique and organization. For Tattooist, it was a challenge to get to grips with a subject that must be one of the most difficult to portray. For CERN, it is another experiment – if not in physics, at least in physics communication.

Comment from a physicist: "We risk making high-energy physics crystal clear to the public and totally obscure to the physicist!"

● Compiled from texts on pp 288–289.

Compiler's Note



In 2012, the first Collide@CERN artist-in-residence was German-born Julius von Bismarck, and the first Dance and Performance prizewinner was Swiss choreographer Gilles Jobin. Working together, they produced *Quantum*, an ode to particle physics for six dancers. This widely acclaimed fusion of dance and lighting premiered in the CMS cavern for CERN's Open Days in September 2013, and has since been on a world tour. It can be seen on YouTube.

But this was not CERN's first foray into fusion. Forty years earlier, CERN and the BBC co-produced the TV film *Shadows of Bliss*, which aired on 2 November 1972. The audible hypercharge was presumably Pete Townshend. A rock composer of some repute, Townshend was also known as a collider, smashing his guitar against stationary targets during performances by The Who.

Many sequences were changed or dropped as a result of trial audience reactions, and a representative of the public – young poet and actor Jeremy Newson – became a permanent part of the film. Jasia Reichardt, a highly esteemed contemporary reviewer, wrote that "the film is excellent and will give a lot of pleasure to scientists as well as those completely innocent of high-energy physics." *Shadows of Bliss* can be seen at https://cds.cern.ch/record/1023489.

Among the harbingers of summer at CERN, mostly high-flying migratory physicists, is an occasional bird of paradise. One of these exotics was performance artist James Lee Byars, pictured on the *CERN Courier* cover in September 1972 and at https://cds.cern.ch/record/2012228. Just a glimpse of his distinctive plumage – flowing hair, panama hat, white suit and silver shoes – sometimes on the restaurant terrace, sometimes in a quiet corner of the site, and we knew that the sunny season had arrived!

In the steps of the antiproton

Sixty years after the discovery of the antiproton at Berkeley, a look at some of the ways that studies with antiprotons at CERN have cast light on basic physics and, in particular, on fundamental symmetries.

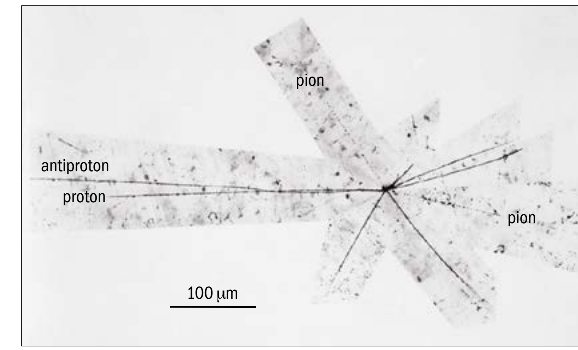


Fig. 1. One of the first annihilations of an antiproton observed at the Bevatron with a photographic emulsion. The antiproton enters from the left. The fat tracks are from slow protons or nuclear fragments, the faint tracks are from fast pions. (Image credit: O Chamberlain et al. *1956* Nuo. Cim. ***3*** *447.)*

On 21 September 1955, Owen Chamberlain, Emilio Segrè, Clyde Wiegand and Tom Ypsilantis found their first evidence of the antiproton, gathered through measurements of its momentum and its velocity. Working at what was known as the "Rad Lab" at Berkeley, they had set up their experiment at a new accelerator, the Bevatron – a proton synchrotron designed to reach an energy of 6.5 GeV, sufficient to produce an antiproton in a fixed-target experiment (*CERN Courier* November 2005 p27). Soon after, a related experiment led by Gerson Goldhaber and Edoardo Amaldi found the expected annihilation "stars", recorded in stacks of nuclear emulsions (figure 1). Forty years later, by combining antiprotons and positrons, an experiment at the Low Energy Antiproton Ring (LEAR) at CERN gathered evidence in September 1995 for the production of the first few atoms of antihydrogen.

Over the decades, antiprotons have become a standard tool for studies in particle physics; the word "antimatter" has entered into mainstream language; and antihydrogen is fast becoming a laboratory for investigations in fundamental physics. At CERN, the Antiproton Decelerator (AD) is now an important facility for studies in fundamental physics at low energies, which complement the investigations at the LHC's high-energy frontier. This article looks back at some of the highlights in the studies of the antiworld at CERN, and takes a glimpse at what lies in store at the AD.

Back at the Bevatron, the discovery of the antineutron through neutral particle annihilation followed in 1956, setting the scene for studies of real antimatter. Initially, everyone expected perfect symmetry between matter and antimatter through the combination of the operations of charge conjugation (C), parity (P) and time reversal (T). However, following the observation of CP violation in 1964, it was not obvious that nuclear forces were CPT invariant and that antinucleons should bind to build antinuclei. These doubts were laid to rest with the discovery of the antideuteron at CERN by a team led by Antonino Zichichi, and at Brookhaven by a team from Columbia University, including Leon Lederman and Sam Ting (*CERN Courier* May 2009 p15 and October 2009 p22). A decade later, evidence emerged for antihelium-3 and antitritium in the WA33 experiment at CERN's Super Proton Synchrotron, following the sighting of a few candidates at the 70 GeV proton synchrotron at the Institute for High Energy Physics near Serpukhov. More recently, the availability of colliding beams of heavy ions has led to the observation of antihelium-4 by the STAR experiment at Brookhaven's Relativistic Heavy-Ion Collider (*CERN Courier* June 2011 p8). At CERN, the ALICE experiment at the LHC observes the production of light nuclei and antinuclei with comparable masses and therefore compatible binding energies (figure 2, p22).

Exit baryonium, enter new mesons

Back in 1949, before the discovery of the antiproton, Enrico Fermi and Chen-Ning Yang predicted the existence of bound nucleon–antinucleon states (baryonium), when they noted that certain repulsive forces between two nucleons could become attractive in the nucleon–antinucleon system. Later, quark models based on duality predicted the existence of states made of two quarks and two antiquarks, which should be observed when a proton annihilates with an antiproton. In the 1970s, nuclear-potential models went on to predict a plethora of bound states and resonance excitations around the two-nucleon mass. There were indeed reports of such states, among them narrow states observed in antiproton–proton ▷

ICE, the AA and LEAR

The construction of LEAR took advantage of the antiproton facility that was built at CERN in 1980 to search for the W and Z bosons at the Super Proton Synchrotron (SPS) operating as a $\bar{p}p$ collider (*CERN Courier* December 1999 p15). The antiprotons originated when 26 GeV protons from the PS struck a target. Emerging with an average momentum of 3.5 GeV/*c*, they were collected in the Antiproton Accumulator (AA), and a pure antiproton beam with small transverse dimensions was generated by stochastic cooling. Up to 10^{12} antiprotons a day could be generated and stored. The antiprotons were then extracted and injected into the PS. After acceleration to 26 GeV, they were transferred to the SPS where they circulated in the same beam pipe as the protons, but in the opposite direction. After a final acceleration to 270 GeV, the antiprotons and protons were brought into collision.

For injection into LEAR, the 3.5 GeV/*c* antiprotons from the AA were decelerated in the PS, down to 600 MeV/*c*. Once stored in LEAR, they were further decelerated to 60 MeV/*c* and then slowly extracted with a typical intensity of 10^6/s. LEAR started up in 1982 and saw as many as 16 experiments before being decommissioned in 1996. The LEAR magnet ring lives on in the Low Energy Ion Ring, which forms part of the injection chain for heavy ions into the LHC.

LEAR also benefitted from the Initial Cooling Experiment (ICE), a storage ring designed in the late 1970s to test Simon van der Meer's idea of stochastic cooling on antiprotons, and later to investigate electron cooling. After essential modifications, the electron cooler from ICE went on to assist in cooling antiprotons at LEAR, and is now serving at CERN's current antiproton facility, the AD (*CERN Courier* September 2009 p13). ICE also contributed to measurements on antiprotons, when in August 1978, it successfully stored antiprotons at 2.1 GeV/*c* – a world first – keeping them circulating for 32 hours. The previous best experimental measurement of the antiproton lifetime, from bubble-chamber experiments, was about 10^{-4} s; now, it is known to be more than 8×10^5 years.

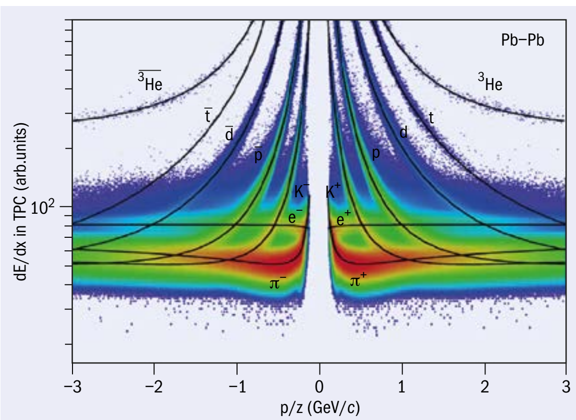


Fig. 2. Energy loss (in arbitrary units) versus momentum of negatively and positively charged particles in the ALICE time-projection chamber, showing antideuterium, antitritium and antihelium-3 in addition to electrons, pions, kaons and antiprotons, together with expectation (dashed curves). The data were taken in lead–lead collisions at 2.76 TeV. (Image credit: ALICE Collaboration.)

($\bar{p}p$) annihilation at CERN's Proton Synchrotron (PS) and in measurements of the $\bar{p}p$ cross-section as a function of energy (the S meson with a mass of 1940 MeV).

Baryonium was the main motivation for the construction at CERN of LEAR, which ran for more than a decade from 1982 to 1996 (see box). However, none of the baryonium states were confirmed at LEAR. The S meson was not observed with a sensitivity 10 times below the signal reported earlier in the $\bar{p}p$ total cross-section. Monoenergetic transitions to bound states were also not observed. The death of baryonium was a key topic for the Antiproton 86 Conference in Thessaloniki. What had happened? The high quality of the antiproton beams from LEAR meant that all of the pions had decayed. The high intensity of antiprotons (10^6/s compared with about 10^2/s in extracted beams at the PS) and a high momentum resolution of 10^{-3}–10^{-4} was crucial at low energies for antiprotons stopping with very small range-straggling.

The spectroscopy of mesons produced in $\bar{p}p$ annihilation at rest in several experiments at LEAR proved to be much more fruitful. This continued a tradition that had begun in the 1960s with antiprotons annihilating in the 81 cm Hydrogen Bubble Chamber at the PS, leading to the discovery of the E meson (E for Europe, now the η(1440)) and the D meson (now the $f_1(1285)$) in $\bar{p}p \rightarrow$ (E, D$\rightarrow K\bar{K}\pi)\pi\pi$. The former led to the long-standing controversy about the existence in this mass region of a glueball candidate – a state made only of gluons – which was observed in radiative J/ψ decay at SLAC's e^+e^- collider, SPEAR. With the start up of LEAR, the experiments ASTERIX, OBELIX, Crystal Barrel and JETSET took over the baton of meson spectroscopy in $\bar{p}p$ annihilation. ASTERIX discovered a tensor meson – the AX, now the $f_2(1565)$ – which was also reported by OBELIX; its structure is still unclear, although it could be the predicted tensor baryonium state.

Crystal Barrel specialized in the detection of multineutral events. The antiprotons were stopped in a liquid-hydrogen target and π^0 mesons were detected through their γγ decays in a barrel-shaped assembly of 1380 CsI (Tl) crystals. Figure 3 shows the detector together with a Dalitz plot of $\bar{p}p$ annihilation into $\pi^0\pi^0\pi^0$, measured by the experiment. The non-uniform distribution of events indicates the presence of intermediate resonances that decay into $\pi^0\pi^0$, such as the spin-0 mesons $f_0(980)$ and $f_0(1500)$, and the spin-2 mesons $f_2(1270)$ and $f_2(1565)$. The $f_0(1500)$ is a good candidate for a glueball.

Fundamental symmetries

The CPT theorem postulates that physical laws remain the same when the combined operation of CPT is performed. CPT invariance arises from the assumption in quantum field theories of certain requirements, such as Lorentz invariance and point-like elementary particles. However, CPT violation is possible at very small length scales, and could lead to slight differences between the properties of particles and antiparticles, such as lifetime, inertial mass and magnetic moment.

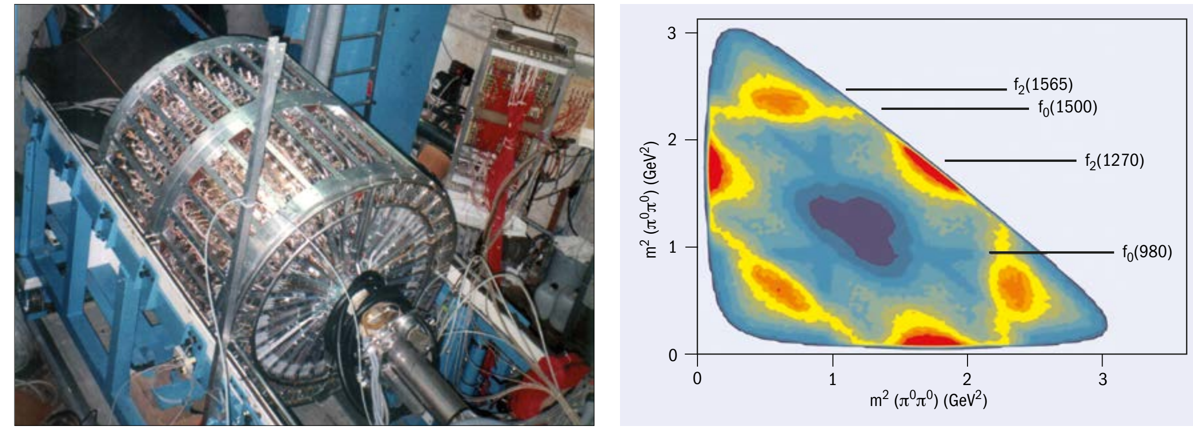


Fig. 3. Left: The Crystal Barrel experiment installed at LEAR. Right: The Dalitz plot measured by Crystal Barrel for $\bar{p}p$ annihilation into $\pi^0\pi^0\pi^0$. The bright (dark) zones correspond to high (low) event density. For symmetry reasons, there are six entries per event. (Image credits: CERN and Crystal Barrel Collaboration.)

At LEAR, the TRAP collaboration (PS196) performed a series of pioneering experiments to compare precisely the charge-to-mass ratios of the proton and antiproton, using antiprotons stored in a cold electromagnetic (Penning) trap. The signal from a single stored antiproton could be observed, and antiprotons were stored in the trap for up to two months. By measuring the cyclotron frequency of the orbiting antiprotons with an oscillator and comparing it with the cyclotron frequency of H^- ions in the same trap, the team finally achieved a result at the level of 9×10^{-11}. The experiment used H^- ions instead of protons to avoid biases when reversing the signs of the electric and magnetic fields.

Under the assumption of CPT invariance, the violation of CP symmetry first observed in the neutral kaon system in 1964 implies that T invariance is also violated. However, in 1998 the CPLEAR experiment demonstrated the violation of T in the neutral kaon system without assuming CPT conservation (*CERN Courier* March 1999 p21). The K^0 and $\bar{K}^0$ morph into one another as a function of time, and T violation implies that, at a given time t, the probability of finding a K^0 when initially a $\bar{K}^0$ was produced is not equal to the probability of finding a $\bar{K}^0$ when a K^0 was produced. CPLEAR established the identity of the initial kaon by measuring the sign of the associated charged kaon in the annihilation $\bar{p}p \rightarrow K^+\bar{K}^0\pi^-$ or $K^-K^0\pi^+$; that of the kaon at time t was inferred by detecting the decays $\bar{K}^0 \rightarrow \pi^+e^-\bar{\nu}$ and $K^0 \rightarrow \pi^-e^+\nu$. Figure 4 shows that a small asymmetry was indeed observed, consistent with expectations from CP violation, assuming CPT invariance.

The CPT theorem also predicts that matter and antimatter should have identical atomic excitation spectra. Antihydrogen – the simplest form of neutral antimatter consisting of a positron orbiting an antiproton – was observed for the first time in the PS210 experiment at LEAR. The circulating 1.9 GeV/*c* internal antiproton beam traversed a xenon-cluster jet target, allowing the possibility for an e^+e^- pair to be produced as an antiproton passed through the Coulomb field

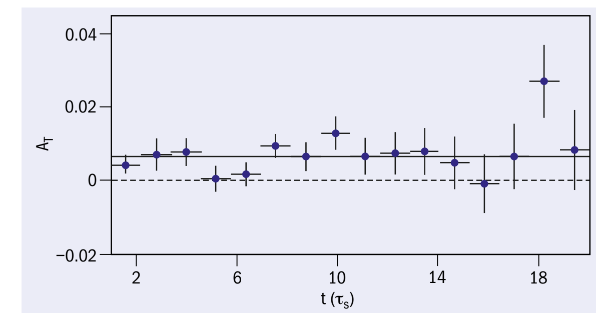
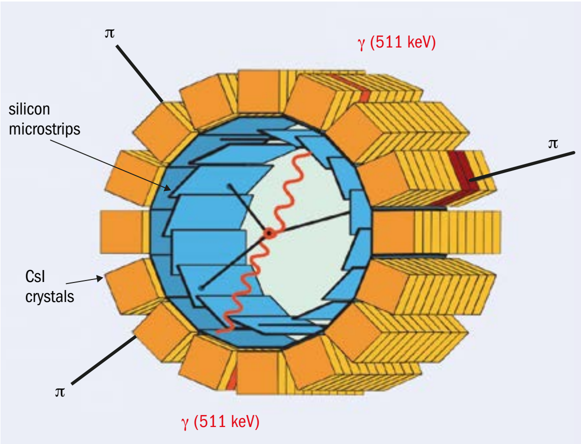


Fig. 4. The asymmetry in neutral kaon decays measured by the CPLEAR experiment, as a function of time (in units of the K_S lifetime, $\tau_S \simeq 90$ ps).

of a xenon nucleus. The e^+ could then be captured by the antiproton to form electrically neutral antihydrogen with a momentum of 1.9 GeV/*c*, which could be detected further downstream through its annihilation into pions and photons. This production process is rather rare, but nonetheless the PS210 collaboration reported evidence for nine antihydrogen atoms, following about two months of data taking in August–September 1995, and only months before LEAR was shut down. The observation of antihydrogen was confirmed two years later at Fermilab's Antiproton Accumulator, albeit with a much smaller production cross-section.

At the AD

A new chapter in the story of antihydrogen at CERN opened in 2000 with the start up of the AD, which decelerates antiprotons to 100 MeV/*c*, before extracting them for experiments on antimatter and atomic physics (*CERN Courier* November 1999 p17). The PS210 experiment had tried to make antihydrogen in flight, but to study, for example, the spectroscopy of antihydrogen, it is far more convenient to store antihydrogen atoms in electromagnetic traps, just as TRAP had done in its antiproton experiments. This ▷



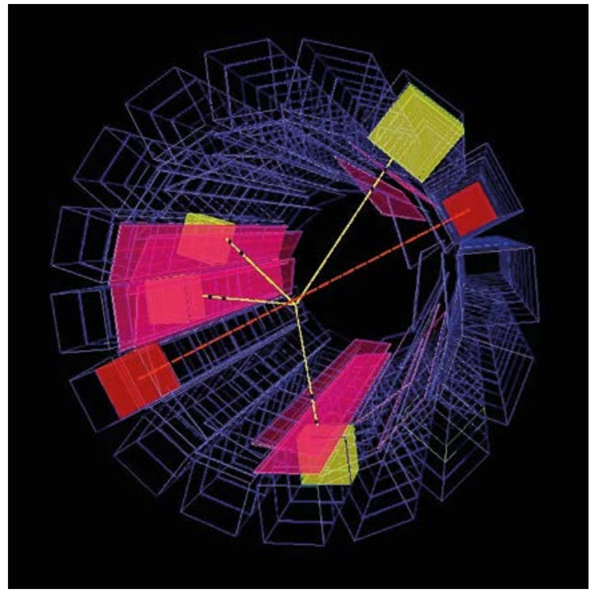


Fig. 5. Above: A diagram of the ATHENA antihydrogen detector. Right: An antihydrogen annihilation event in ATHENA, reconstructing four charged pions (yellow) and two 511 keV photons (red). (Image credits: ATHENA Collaboration.)

requires antihydrogen to be produced at very low energies, which the AD helps to achieve.

In 2002, the ATHENA and ATRAP experiments at the AD demonstrated the production of large numbers of slow antihydrogen atoms (*CERN Courier* November 2002 p5 and December 2002 p5). ATHENA used absorbing foils to reduce the energy of the antiprotons from the AD to a few kilo-electron-volts. A small fraction of the antiproton beam was then captured in a Penning trap, while positrons from a radioactive sodium source were stored in a second trap. The antiproton and positron clouds were then transferred to a third trap and made to overlap to produce electrically neutral antihydrogen, which migrated to the cryostat walls and annihilated. The antihydrogen detector contained two layers of silicon microstrips to track the charged pions from the antiproton annihilation; an array of 192 CsI crystals detected and measured the energies of the photons from the positron annihilation (figure 5). About a million antihydrogen atoms were produced during the course of the experiment, corresponding to an average rate of 10 antiatoms per second.

Antihydrogen has a magnetic dipole moment (that of the positron), which means that it can be captured in an inhomogeneous magnetic field. The first attempt to do this was carried out at the AD by the ALPHA experiment, which successfully captured 38 antihydrogen atoms in an octupolar magnetic field (*CERN Courier* March 2011 p13). The initial antihydrogen storage time of 172 ms was increased later to some 15 minutes, thus paving the way to atomic spectroscopy experiments. A sensitive test of CPT is to induce transitions from singlet to triplet spin states (hyperfine splitting, or HfS) in the antihydrogen atom, and to compare the transition energy with that for hydrogen, which is known with very high precision. ALPHA made the first successful attempts to measure the HfS with microwave radiation, managing to flip the positron spin and to eject 23 antihydrogen atoms from the trap (*CERN Courier* April 2012 p7).

An alternative approach is to perform a Stern–Gerlach-type experiment with an antihydrogen beam. The ASACUSA experiment has used an anti-Helmholtz coil (cusp trap) to exert forces on the antihydrogen atoms and to select those in a given positron spin state. The polarization can then be flipped with microwaves of the appropriate frequency. In a first successful test, 80 antihydrogen atoms were detected downstream from the production region (*CERN Courier* March 2014 p5).

The ASACUSA collaboration has also tested CPT, using antiprotons stopped in helium. The antiproton was captured by ejecting one of the two orbiting electrons, the ensuing antiprotonic helium atom being left in a high-level, long-lived atomic state that is amenable to laser excitation. By using two counter-propagating laser beams (to reduce the Doppler broadening caused by thermal motion), the group was able to determine the antiproton-to-electron mass ratio with a precision of 1.3 ppb (*CERN Courier* September 2011 p7). An earlier comparison of the charge-to-mass ratio between the proton and the antiproton had been performed with a precision of 0.09 ppb by the TRAP collaboration at LEAR, as described above. When the results from ASACUSA and TRAP are combined, the masses and charges of the proton and antiproton are determined to be equal at a level below 0.7 ppb.

CPT also requires the magnetic moment of a particle to be equal to (minus) that of its antiparticle. The BASE experiment now under way at the AD will determine the magnetic moment of the antiproton to 1 ppb by measuring the spin-dependent axial oscillation frequency in a Penning trap subjected to a strong magnetic-field gradient. The experimental approach is similar to the one used to measure the magnetic moment of the proton to a precision of 3 ppb (*CERN Courier* July/August 2014 p8). The collaboration has already compared the charge-to-mass ratios of the antiproton and proton, with a fractional precision of 6.9×10^{-11} (p7).

The weak equivalence principle (WEP), which states that all objects are accelerated in exactly the same way in gravitational fields, has never been tested with antimatter. Attempts using positrons or

antiprotons have so far failed, as a result of stray electric or magnetic fields. In contrast, the electrically neutral antihydrogen atom is an ideal probe to test the WEP. The AEgIS collaboration at the AD plans to measure the sagging of an antihydrogen beam over a distance of typically 1 m with a two-grating deflectometer. The displacement of the moiré pattern induced by gravity will be measured with high resolution (around 1 μm) by using nuclear emulsions (figure 6) – the same detection technique that was used to demonstrate the annihilation of the antiproton at the Bevatron, back in 1956.

The future is ELENA

Future experiments with antimatter at CERN will benefit from the Extra Low ENergy Antiproton (ELENA) project, which will become operational at the end of 2017. The capture efficiency of antiprotons in experiments at the AD is currently very low (less than 0.1%), because most of them are lost when degrading the 5 MeV beam from the AD to the few kilo-electron-volts required by the confinement voltage of electromagnetic traps. To overcome this, ELENA – a 30 m circumference electron-cooled storage ring that will be located in the AD hall – will decelerate antiprotons down to, typically, 100 keV. Fast extraction (as opposed to the slow extraction that was available at LEAR) is foreseen to supply the trap experiments.

One experiment that will profit from this new facility is GBAR, which also aims to measure the gravitational acceleration of antihydrogen. Positrons will be produced by a 4.3 MeV electron linac and used to create positive antihydrogen ions (i.e. an antiproton with two positrons) that can be transferred to an electromagnetic trap and cooled to 10 mK. After transfer to another trap, where one of the positrons is detached, the antihydrogen will be launched vertically with a mean velocity of about 1 m/s (*CERN Courier* March 2014 p31).

It is worth recalling that the discovery of the antiproton in Berkeley was based on some 60 antiprotons observed during a seven-hour run. The 1.2 GeV/*c* beam contained 5×10^4 more pions than antiprotons. Today, the AD delivers pure beams of some 3×10^7 antiprotons every 100 s at 100 MeV/*c*, which makes the CERN laboratory unique in the world for antimatter studies. Over the decades, antiproton beams have led to the discovery of new mesons and enabled precise tests of symmetries between matter and antimatter. Now, the properties of hydrogen and antihydrogen are being compared, and accurate tests will be performed with ELENA. The odds to see any violation of exact symmetry are slim, the CPT theorem being a fundamental law of physics. However, experience shows that – as with the surprising discovery of the non-conservation of parity in 1957 and CP violation in 1964 – experiments will, ultimately, have the last word.

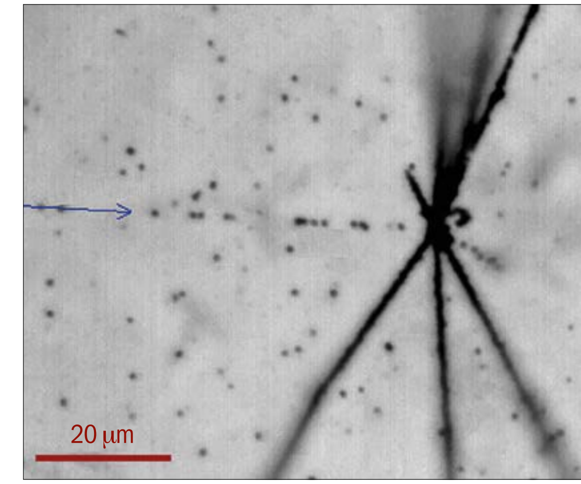


Fig. 6. The annihilation of an antiproton in an emulsion, observed in the AEgIS experiment at the AD. The faint track (blue arrow) is produced by a fast pion, while the fat tracks are from protons or nuclear fragments. (Image credit: AEgIS Collaboration.)

Further reading

For more about symmetries and the experiments described here, see *Nuclear and Particle Physics* by Claude Amsler (2015 IOP Publishing), available in print and as an ebook, see http://iopscience.iop.org/book/978-0-7503-1140-3.

Résumé

Dans le sillage de l'antiproton

Quarante ans exactement après la première observation d'antiprotons à Berkeley, une expérience menée au CERN a réuni des indices probants de la production des premiers atomes d'antihydrogène. Au fil des années, les antiprotons sont devenus un outil standard de la physique des particules ; le mot « antimatière » est entré dans le langage courant ; l'antihydrogène est en voie de devenir un véritable laboratoire de la physique fondamentale. L'article s'intéresse à certains faits marquants des recherches relatives au monde de l'antimatière au CERN, et nous en dit plus sur ce que nous pouvons attendre du Décélérateur d'antiprotons.

Claude Amsler, Albert Einstein Center for Fundamental Physics, University of Bern, and **Christine Sutton**, CERN.

CERN Courier September 2015

Heavy ions

ALICE investigates 'snowballs in hell'

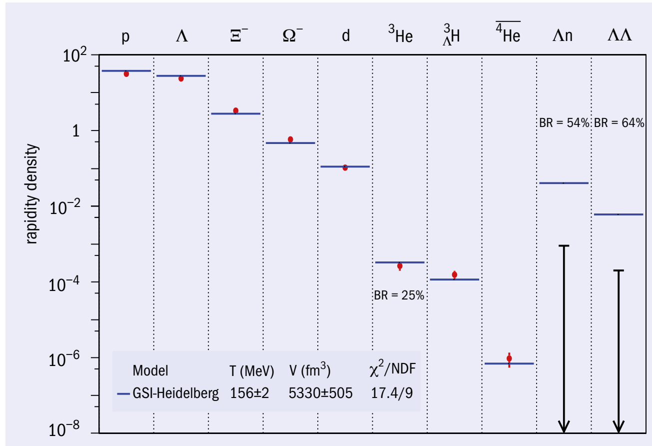
How is it that loosely bound objects are observed in high-energy nuclear collisions? The ALICE collaboration finds out.

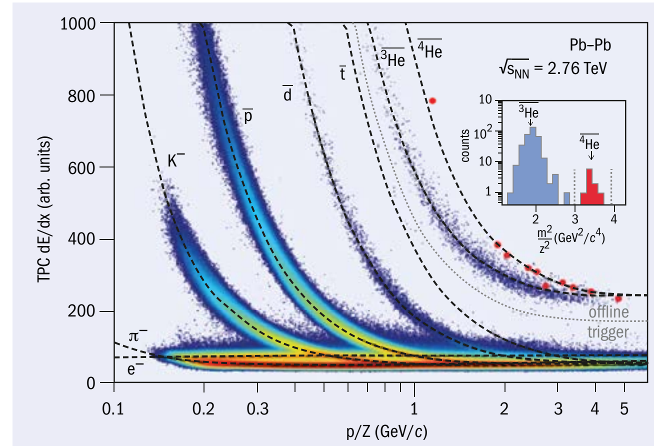
The main goal of the ALICE experiment at the LHC is to produce and study the properties of matter as it existed in the first few microseconds after the Big Bang. Such matter consists of fermions and bosons, the fundamental entities of the Standard Model. Depending on the temperature, T, only particles with mass much less than T are copious. For T < 1 GeV, or about 10^{13} K, these are the u, d and s quarks and the gluons of the strong interactions. In addition, there are of course photons, leptons and neutrinos.

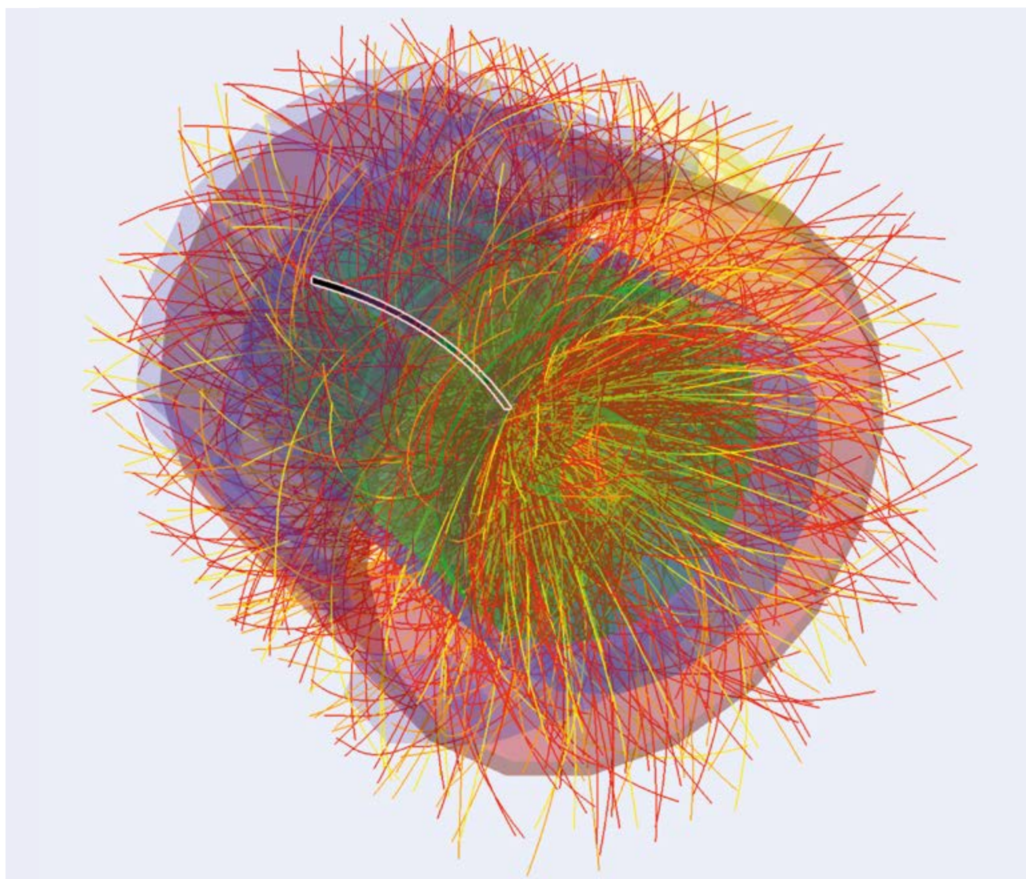
This "cosmic matter" can be produced in the laboratory by collisions at relativistic energies between very heavy atomic nuclei, such as lead at the LHC and gold at Brookhaven's Relativistic Heavy Ion Collider (RHIC). In these collisions, a fireball is formed at (initial) temperatures up to 600 MeV, with a volume exceeding 1000 fm^3 – about the volume of a lead nucleus – and with lifetimes exceeding 10 fm/*c*, about 3×10^{-23} s. This space–time volume is macroscopic for strong interactions, but charged leptons, photons and neutrinos leave the fireball without interacting and play no part in the following discussion. (However, charged leptons and photons do have a role as penetrating probes of the produced matter.) Such deconfined cosmic matter is referred to as quark–gluon plasma (QGP) because its constituents carry colour and can roam freely within the volume of the fireball. At LHC energies, the QGP comprises, in addition to gluons, essentially equal numbers of quarks and antiquarks, i.e. it carries no net baryon number, as would also have been the case in the early universe.

The produced fireball expands and cools until it reaches the (pseudo-)critical temperature, T_c, of the deconfinement–confinement transition. Solving the strong-interaction equations on a discrete space–time lattice leads, in the most recent predictions, to $T_c = 155\pm9$ MeV. The yields of hadrons produced in central lead–lead (Pb–Pb) collisions at LHC energies and measured with the ALICE detector can indeed be quantitatively understood by assuming that they all originate from a thermalized state described with a grand-canonical thermal ensemble at $T_{chem} = 156\pm2$ MeV; the "chemical freeze-out" temperature T_{chem} is therefore very close to or coincides with T_c (see figure 1). While the overall agreement between data and model predictions is excellent, there is a 2.8σ discrepancy for (anti)protons, which is currently under scrutiny. Because the volume of the fireball is fixed by the number of particles produced, the temperature T_{chem} is the principal parameter determined in the grand-canonical analysis.

Such Pb–Pb collisions produce not only hadrons in the classical sense but also composite and even fragile objects such as light nuclei (d, t, ^{3}He, ^{4}He) and light Λ-hypernuclei, along with their antiparticles. Their measured yields decrease strongly with increasing (anti)baryon number – the penalty factor for each additional (anti) baryon is about 300 – hence (anti)^{4}He production is a very rare process. Note that, because the fireball carries no net baryon number, the yields of the produced antiparticles closely coincide with the corresponding particle yields.







Anticlockwise from top left: Fig. 1. Comparison of data to thermal-model predictions. The production yields measured with ALICE are shown as red dots and the results of the calculations are shown as blue lines. The upper limits at 99% CL determined by ALICE are indicated as black arrows. For clarity, pions and kaons are left out of the comparison, but their yields also fit in very well.

Fig. 2. Event display of a central Pb–Pb collision. The highlighted black track corresponds to an anti^{4}He nucleus, identified via dE/dx and time-of-flight (see figure 3).

Fig. 3. Measured dE/dx signal in the ALICE TPC versus magnetic rigidity, together with the expected curves for negatively charged particles. The inset panel shows the time-of-flight mass measurement, which provides additional separation between anti^{3}He and anti^{4}He for tracks with p/Z > 2.3 GeV/c.

An interesting question is whether the yields of composite objects can be understood in the same grand-canonical scheme as discussed above, or whether such loosely bound objects follow a different systematics. The deuteron binding energy, for example, is only 2.23 MeV, and the energy needed to separate the Λ hyperon from a hypertriton nucleus – a bound state of a proton, neutron and Λ – is only about 130 keV, which is much smaller than the chemical freeze-out temperature, $T_{chem} = 156$ MeV.

Furthermore, the radii of such loosely bound objects are generally very large, even exceeding significantly the range of the nuclear force that binds them. The rms radius of the deuteron is 2.2 fm, for example. Even more dramatically, because of the molecular structure of the hypertriton ((p+n) + Λ), its rms radius, which in this case is the rms separation between the d nucleus and the Λ hyperon, is about 10 fm – that is, larger than the radius of the whole fireball.

Identification is the key

Before answering the question of how such exotic and fragile objects are produced, it is important to discuss how well such rare particles can be measured in the hostile environment of a Pb–Pb collision. In a central Pb–Pb collision at LHC energies, more than 15,000 charged particles are produced and up to 3000 go through the central barrel of the ALICE detector, making the task of tracking and identifying all of the different particle species quite a challenge. With ALICE, the identification of all of the produced particles and, in particular, the measurement of light nuclei and Λ-hypernuclei, is only possible because of the experiment's excellent tracking and particle-identification capabilities via dE/dx and time-of-flight measurements. This is demonstrated in figure 2, which shows an event display from the ALICE time-projection chamber (TPC) for a central Pb–Pb collision. The highlighted black track corresponds to an identified anti^{4}He track, implying that even such rare particles can be tracked with precision. Figure 3 shows the clean identification achieved for anti^{4}He particles.

At first glance it is surprising that, as figure 1 shows, the measured yields of deuterons and hypertritons and their antiparticles agree very well with the yields calculated using the approach described above for hadrons at the same chemical freeze-out temperature, $T_{chem} = 156$ MeV. This implies that the yields of these loosely bound objects are determined at the phase boundary from the QGP to a hadron gas. How is this possible for such loosely bound objects whose sizes are much larger than the inter-particle separation at the time of chemical freeze-out? ▷

Heavy ions

To understand this, thermodynamics comes to the rescue. If there are no more inelastic collisions after chemical freeze-out, then the transition from the QGP to hadronic matter is followed by an isentropic expansion (i.e. with no change in entropy). Early studies of nucleus–nucleus collisions at the Berkeley Bevalac already showed that, for systems with isentropic expansion, the entropy/net-baryon is proportional to log(d/p), implying that the yield of deuterons and antideuterons is determined by the entropy in the hot phase of the fireball. The same mechanism is at play at LHC energies: in this way, the "snowballs" can survive "hell", as the experimental data from the ALICE collaboration show.

These facts can be used to search for even more exotic states. ALICE has performed a search for two hypothetical strange dibaryon states. The first one is the H-dibaryon, which is a six-quark bound state of uuddss, first predicted by Robert Jaffe in a "bag-model" calculation in 1977. This early calculation led to a binding energy of 81 MeV. Recent non-perturbative QCD calculations (on the lattice) suggest either a loosely bound state or a resonant state above the ΛΛ threshold. The existence of double-Λ hypernuclei, such as the $^{4}_{\Lambda\Lambda}$He, reduced the allowed binding energy to a maximum of 7.3 MeV, with the most preferred value around 1 MeV. The second hypothetical bound state investigated by ALICE is a possible $\overline{\Lambda n}$ bound state.

The two searches are performed in central (0–10%) Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV in the decay modes H-dibaryon $\to \Lambda p \pi^-$ and $\overline{\Lambda n} \to \bar{d}\pi^+$. No signals are observed in either of the measured invariant-mass distributions, therefore setting upper limits for the production yields. These limits are well below the yields predicted using the grand-canonical scenario discussed above with $T_{chem} = 156$ MeV (see figure 1). In fact, the difference between the upper limit at 99% CL obtained for the $\overline{\Lambda n}$ bound state is a factor of around 50 below the prediction, whereas the factor between the upper limit at 99% CL and the model prediction for the H-dibaryon is close to 25. Given the success of the model in predicting deuteron and hypertriton yields, it appears that the existence of such bound states is very unlikely.

With the LHC's Run 2, which has just started, and much more so with the upgraded ALICE apparatus in LHC Run 3, it is expected that ALICE can measure hypernuclei with still higher masses, such as $^{4}_{\Lambda}$H and $^{4}_{\Lambda\Lambda}$H and the corresponding antiparticles. These would be the highest-mass antihypernuclei ever observed. In addition, the hypertriton measurement will be extended in the three-body decay $^{3}_{\Lambda}\mathrm{H} \to d + p + \pi^-$. The much higher statistics expected will also allow more detailed measurements, such as determination of the $^{4}\overline{\mathrm{He}}$ transverse-momentum spectrum. In addition, searches are underway for other hypothetical bound states such as Λnn or other exotic di-baryons.

In summary, the success in describing the production of different hadrons and the yields of loosely bound objects with the same temperature, T, provides strong evidence for isentropic expansion after the transition from the QGP to a hadron gas. This scenario naturally explains the observed yields for loosely bound objects. On the other hand, the upper limits obtained for the H-dibaryon and the $\overline{\Lambda n}$ bound state are well below the model prediction using the same temperature, T = 156 MeV, casting serious doubts on their existence.

The ALICE data on light (anti)nucleus production in pp, p–Pb and Pb–Pb collisions shows that very loosely bound objects are produced with significant yields for all systems, with the thermodynamic limit reached for the Pb–Pb system. The measured yields are expected to increase with beam energy similar to the way that the overall multiplicity density does. This implies significant production of antideuterons from high-energy cosmic rays, with potential consequences for searches for dark matter. Their yields can be well predicted within the scenario described here.

Further reading

For details concerning analysis and interpretation of the production of nuclei, hypertriton and exotica, see the following:

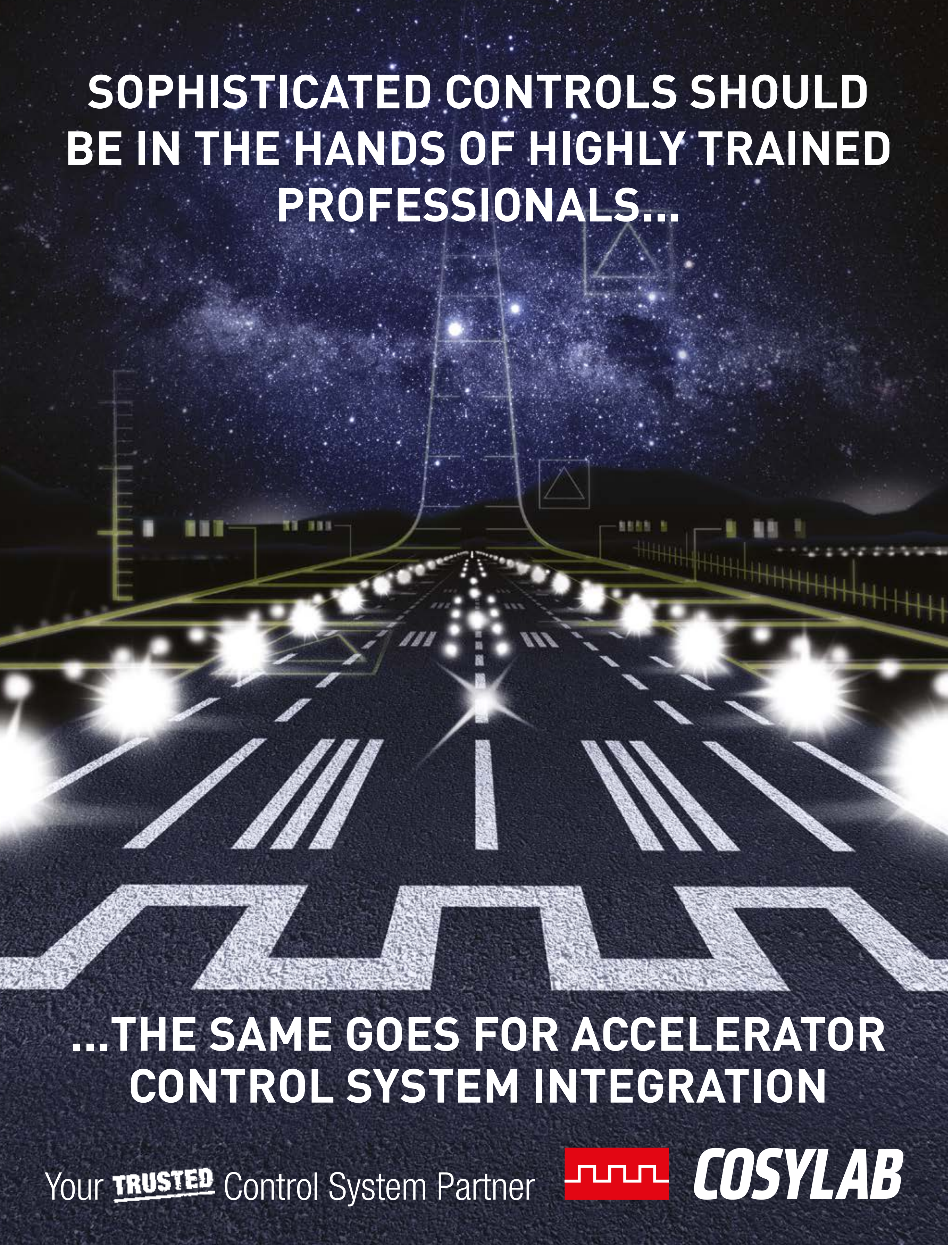
ALICE Collaboration J Adam *et al.* 2015 arXiv:1506.08951 [nucl-ex]
ALICE Collaboration J Adam *et al.* 2015 arXiv:1506.08453 [nucl-ex].
ALICE Collaboration J Adam *et al.* 2015 arXiv:1506.07499 [nucl-ex].
A Andronic *et al.* 2011 *Phys. Lett. B* **697** 203.
P Braun-Munzinger and J Stachel 2002 *J Phys. G* **28** 1971.
T Bhattacharya *et al.* 2014 *Phys. Rev. Lett.* **113** 082001.
J Stachel *et al.* 2014 *J. Phys. Conf. Ser.* **509** 012019.

Résumé

L'omelette norvégienne d'ALICE

Il n'y a pas uniquement des hadrons ordinaires dans les débris des « boules de feu » produites par les collisions d'ions lourds effectuées à l'expérience ALICE auprès du LHC ; on y trouve aussi des objets composites, aux liaisons lâches, tels que deutérons et hypernoyaux légers et leurs antiparticules. Des études montrent que la production de ces particules, telle qu'elle peut être mesurée, concorde très bien avec les résultats calculés avec la même méthode que pour les hadrons, ce qui implique que les taux de production des objets à liaison lâche sont déterminés à la limite de phase entre le plasma quark-gluon de la boule de feu et un gaz hadronique. Comment est-ce possible ? La réponse est donnée par la thermodynamique.

Peter Braun-Munzinger, EMMI, GSI, FIAS and Universität Heidelberg, **Benjamin Dönigus**, Johann Wolfgang Goethe-Universität Frankfurt, and **Nicole Löher**, TU Darmstadt, EMMI, GSI.



Massimo Tarenghi: a lifetime in the stars

The man who built the largest observatory in the world talks about his many achievements.

Massimo Tarenghi – builder of the world's biggest telescope and an accomplished photographer. (Image credit: M Struik.)

Massimo Tarenghi fell in love with astronomy at age 14, when his mother took away his stamp collection – on which he spent more time than on his schoolbooks – and gave him a book entitled *Le Stelle* (*The Stars*). By age 17, he had built his first telescope and become a well-known amateur astronomer, meriting a photo in the local daily newspaper with the headline "Massimo prefers a bigger telescope to a Ferrari." Already, his dream was "to work at the largest observatory in the world". That dream came true, because Massimo went on to build and direct the world's most powerful optical telescope, the Very Large Telescope (VLT), at the European Southern Observatory (ESO)'s Paranal Observatory in Chile.

"I was born as a guy who likes to do impossible things and I like to do them 110%," says Massimo, who decided to study physics at the University of Milan in the late 1960s "because [Giusepppe] Occhialini was the best in the world and allowed me to do a thesis in astronomy". His road to the stars began in 1970, when he gained his PhD with a thesis on the production of gamma rays by Sagittarius A – at the time a mysterious radio source, which is now known to harbour the supermassive black hole at the centre of the Milky Way. This was at the time of the first observations in X rays and in infrared of the centre of the Galaxy, and the first of many examples of far-sighted intuition in Massimo's career.

Following his PhD, Massimo convinced his colleagues at Milan to support the construction of an infrared telescope on the Gornergrat in the Swiss Alps. He was then sent to the Steward Observatory at the University of Arizona, where he did pioneering work in infrared astronomy. He quickly made himself known with a daring request for telescope time involving all of the instruments. "At that time," he recalls, "there was a clear separation between astronomy for infrared, spectroscopy or photography, and there were three levels of use of an instrument: astronomer without assistant, assistant astronomer, or general (university) public. I asked for all of the instruments – and in particular for the bolometer, which no one had ever dared ask for!" After a three-hour meeting, his proposal to observe infrared galaxies was judged "very interesting but totally crazy". So the committee suggested a compromise: 10 of his candidate objects would be observed during the telescope's spare time and then they could review the request. Massimo accepted, and two weeks later seven of his objects had been found to be infrared emitters. "So they gave me the whole bolometer three-months later. I was lucky!" he says with the same enthusiasm as the 28-year-old postdoc he was at the time.

It was, once again, pure intuition. Massimo had chosen his 10 objects based on M82, a galaxy that interacts with its larger neighbour M81. "M82 is a beautiful galaxy with explosions and I thought, when two galaxies interact, they trigger explosions. So I simply had a collection of interacting galaxies and it came out that this is just what they did." This intuition was to be confirmed by what has become a pillar of astrophysics: when two galaxies interact, the gas inside is compressed, creating a large number of new stars, which produce a large amount of infrared emission as they form.

While still in Arizona, Massimo decided to work on the optical identification of radio galaxies. "At the time, the Hercules cluster was not very well explored, with a redshift of 11,000 km/s. Compared to the well-known Coma cluster, with a redshift of 5000 km/s, it is much further and very difficult to observe between Arizona's summer storms," he explains. "Astronomers came to me saying that the cluster was 'theirs', as they had started work on it three years earlier. But they had done no observations. So I offered to collaborate, and we decided that whoever took more galaxies would be the first author on the publication. They found 19, I took all of the rest: 300." That paper is now a cornerstone in astronomy. "It was the first time we saw clearly the existence of a void in ▷

The award-winning futuristic Residencia for astronomers at Paranal, conceived by Massimo. (Image credit: ESO/M Tarenghi.)

the universe," he continues. "There was no galaxy between 6000 and 9000 km/s. Today we know this void is the remnant of the Big Bang, the structure of the anisotropy of the universe recently observed by the Planck space telescope."

Breaking records

Dubbing himself "a difficult person," Massimo broke new ground not just in the way that astronomy is done, but by bringing innovation in the way that telescopes are conceived of and built. Intuition, determination and audacity are indeed the distinctive marks of his 35-year-long career at ESO, which he joined in 1977 as a member of the Science Group, when the organization was still based at CERN (*CERN Courier* October 2012 p26). He had decided to join ESO to observe with the largest European telescope – the 3.6 m, which was just being inaugurated at ESO's site at La Silla in Chile.

"I obtained three nights for my cluster of galaxies in the Southern hemisphere," he recalls, "but I was the second official user, during the first week of observation, and nobody knew if it was going to work. I received those three nights (plus three to compensate in case of problems) because I was the only one in Europe who had experience with big telescopes. I started to complain the first night and obtained the sixth night." Massimo was then told that there would be another week of tests and he was asked if he would test the telescope, so he took the full week. "My colleagues were jealous but then were surprised that I really tested the telescope to adjust and calibrate it." After these two weeks, he went back to Geneva and told ESO's director that astronomers need to be associated with the construction of telescopes from the start. "So I created the role of 'friend of instrument' and for each instrument we associated one astronomer in charge," he explains. The role of instrument scientist, commonplace now at the large telescopes worldwide, is thus Massimo's invention.

Unsurprisingly, he then became project scientist for ESO's next telescope, the 2.2 m. Built for the Max Planck Institute, it had been destined for Namibia originally, but with Italy and Switzerland about to join ESO in 1981, the decision was taken to install it at ESO's site at La Silla. "The Italians are very aggressive astronomers," Massimo explains, "so we needed to increase telescope time, and I was asked to take the 2.2 m telescope from Heidelberg, put it in place in La Silla, and run the team." They had to do everything: they had no dome, no foundations, and a budget of only DM 5 million, which was a very limited amount compared with other projects of a similar size. But, as Massimo says, "when you have no money you do great things," and he had an idea. "I saw a thin aluminium dome on the last page of an amateur astronomers' magazine, and I asked an engineer in my team to design a scaled-down version of our dome." With the concrete foundations laid almost manually, and the help of three engineers recruited from Zeiss to build a new electronic system, they succeeded in installing the telescope for a total cost of DM 7 million.

The 2.2 m telescope saw its first light in June 1983, with a record-breaking angular resolution of 0.6 arc seconds. "The reason is simple," says Massimo. "The dome was so small that we had to move all the electronics underneath, so there was no source of heat coming from the telescope, and that's how we learnt how to remove heat from the dome." It was also the first telescope to be operated remotely. "We took the controls from the upper floor to the lower floor, and when we saw that it worked, with the software engineer we decided to do remote control from La Serena. Everybody was laughing, saying it would never work, but there was no reason it should not!" At the time, the connection was through a telephone line – not with optical fibre – and only in one direction. Massimo explains that when they needed somebody to close the dome on the other side, they used the phone to communicate from La Serena to La Silla. On the first occasion, he recalls, "I forgot the guy was still there. All night he was waiting for my call, and he waited five, six hours before he decided to call me, asking whether he could…go to the toilet!"

In 1983, Massimo was asked to be project manager for the New Technology Telescope (NTT), a 3.6 m optical telescope that saw first light six years later. With a record-breaking resolution of 0.33 arc seconds, it produced sharper images of stellar objects than ever obtained with a ground-based telescope. The NTT was the prototype for a new type of telescope that would make the VLT possible. The main revolutionary feature was the application of active optics, in which a thin and flexible primary mirror is kept in its correct shape by a support system that responds to continual real-time analysis of a stellar image. It was ESO's Ray Wilson who invented the system, but Massimo was involved from early on, and his former institute in Milan built the first test bench with which the system was shown to work in the early 1980s. The thin-mirror technology allowed by active optics was the breakthrough that enabled the construction of the next generation of much larger telescopes, in particular the VLT, built on a second ESO site in Chile, on the mountain of Cerro Paranal in the Atacama desert.

(Image credit: M Struik.)

The VLT was proposed in 1986 and approved in 1987. Massimo was given the responsibility to build it in March 1988 by ESO's director-general Herry van der Laan, and was later fully supported by the following director-general, Riccardo Giacconi. He was part of the team that decided to go from 4 m to 8 m mirrors that could be combined as an astronomical interferometer – a technique that was still in its early days. With four fixed 8.2 m-diameter Unit Telescopes (UTs) and four 1.8 m-diameter movable Auxiliary Telescopes (ATs), the VLT is today the most advanced optical observatory in the world. The UTs work either individually or in a combined mode using interferometry, while the ATs are entirely dedicated to interferometry. "I had under me 250 technicians. It was the craziest project I ever managed," Massimo remembers, "and I learnt a lesson: if you want to work in the biggest observatory in the world you have to build it!"

Building the Paranal Observatory was not just a scientific experience for Massimo, he is at also at the origin of the award-winning futuristic Residencia, chosen as the set for the James Bond film *Quantum of Solace*. "I wanted something that could make astronomers at Paranal become human again after 13 or 14 hours of observation, to experience the pleasure of water, and of green, red and all the colours missing in the desert," he explains. "This is the dream we recreated in this place, water in the desert, for the people working at the most advanced telescope in the world."

After the VLT, Massimo went on to direct another "crazy" astronomy project, the Atacama Large Millimeter/submillimeter Array (ALMA), the first truly global collaboration in astronomy (*CERN Courier* October 2007 p23). He also conducted the exploration work for the site of the next-generation facility, the European Extremely Large Telescope (E-ELT), with a record-breaking 39 m-diameter mirror. Construction work started at the Cerro Armazones, the chosen site for E-ELT, in March 2014. Massimo, who celebrated his 70th birthday at the end of July, officially retired from ESO in 2013, but he has not stopped working for European astronomy. He still commutes between the ESO sites in Chile, Santiago and Munich, supporting ESO's public-relations activities in Chile – and spending endless nights photographing the unique sky above the Atacama desert.

Résumé

Massimo Tarenghi : une vie parmi les étoiles

Massimo Tarenghi est tombé amoureux de l'astronomie à l'âge de 14 ans, le jour où sa mère lui a confisqué sa collection de timbres pour lui donner un livre intitulé Le Stelle *(« Les étoiles »). À 17 ans, il avait construit son premier télescope et son rêve était déjà de « travailler dans le plus grand observatoire du monde ». Son rêve s'est réalisé puisqu'il a fini par construire et diriger le télescope optique le plus puissant jamais produit, le* Very Large Telescope *(VLT), à l'observatoire Paranal (Chili), dépendant de l'Observatoire européen austral (ESO). Il évoque ici les nombreux défis qu'il a dû relever au cours de sa carrière.*

Paola Catapano, CERN, met with Massimo Tarenghi during a visit to the Paranal observatory in July.

Faces & Places

CO-OPERATION

Sri Lanka strengthens partnership with CERN

CERN and Sri Lanka have formed a partnership with the aim of formalizing and broadening their co-operation. To this end, CERN's director-general, Rolf Heuer, and Sri Lanka's permanent representative at the United Nations in Geneva, Ravinatha Aryasinha, signed an expression of interest on 25 June 2015.

The agreement incorporates Sri Lanka in CERN's High School Teachers and Summer Student programmes. It also aims at preparing a platform that will allow more scientists from Sri Lanka to participate in CERN's cutting-edge research programmes. Several scientists from Sri Lankan universities have already participated in LHC experiments within frameworks such as sabbatical leave, while others have participated as visiting scientists employed by universities in other countries. To allow for broader and more sustained participation, discussions have begun on forming a "cluster" of Sri Lankan universities and research institutes with the aim of joining one of the LHC collaborations.

Sri Lanka is the most recent Asian country to have strengthened its partnership with CERN. Others include those as diverse as Bangladesh, Thailand, Indonesia and Mongolia.

Ravinatha Aryasinha, left, and Rolf Heuer, signing the expression of interest. (Image credit: CERN-PHOTO-201506-146-7.)

APPOINTMENT

Amber Boehnlein takes charge of IT at Jefferson Lab

Amber Boehnlein. (Image credit: Jefferson Lab.)

Amber Boehnlein is the new chief information officer (CIO) at Jefferson Lab. As CIO, she is responsible for the Information Technology (IT) Division as well as the IT systems, including scientific data analysis, high-performance computing, IT infrastructure and cyber security.

Boehnlein arrived at Jefferson Lab in June, having led the Computing Division at SLAC from 2011. At SLAC she gained expertise in computational physics relevant to light sources and large-scale databases for astrophysics, as well as overseeing the hardware computing systems for the high-energy physics programme. Prior to her time at SLAC, she served a three-year assignment as the US Department of Energy's Office of High Energy Physics programme manager for the US Large Hadron Collider Detector Operations programme.

Having gained a PhD in physics in 1990 at Florida State University, Boehnlein was a member of the DØ collaboration at Fermilab from 1991 to 2013, and served as the collaboration's computing and software co-ordinator from 1999 to 2006. As a staff scientist in the Computing Division at Fermilab, she was responsible for the computing and application support for all Fermilab-based experiments.

AWARDS

CERN receives Hermes Innovation award

CERN's leading role in international scientific co-operation has been recognized with a 2015 Hermes Innovation award. The European Institute for Creative Strategies and Innovation makes the awards for "humanistic innovation" annually to selected organizations and companies that have excelled in offering more satisfaction to society through their products and services. The awards, which are linked to up to eight themes, are named after Hermes – in Greek mythology an ingenious and inventive god who supports human ventures.

● For more about the event, see www.rencontre-innovation.com/.

Frédérick Bordry, centre with the Hermes award, Marc Giget, right, and Sylvie Borzakian, left, respectively, founder/president and director of the Club de Paris des Directeurs de l'Innovation and the European Institute for Creative Strategies and Innovation. (Image credit: M Iesci/Hermes Award.)

Philippe Lebrun honoured by the cryogenic community

CERN's Philippe Lebrun has received the prestigious Samuel C Collins Award from the Cryogenic Engineering Conference. Named after the American physicist who developed the first practical helium liquefiers, the award is given to an individual "who has remarkably devoted themselves in the identification and solution of cryogenic engineering problems, and has subsequently demonstrated their concern for the cryogenic community with their dedicated and unselfish professional service and leadership to this community".

Lebrun conducted the R&D on the superfluid helium cryogenic system for the LHC. He then led CERN's Accelerator Technology Department during the construction of the machine, and played a major role during the construction of the cryogenic high-field magnets. He received the award during the 2015 Cryogenic Engineering Conference and International Cryogenic Materials Conference, which took place on 28 June–2 July in Tucson.

Philippe Lebrun, right, receiving the award from Ray Radebaugh, chair of the Awards Committee of the Cryogenic Engineering Conference and a former recipient of the award. (Image credit: Werner K Huget.)

Della Negra and Virdee receive awards for leadership

The "founding fathers" of CMS, Michel Della Negra of CERN and now Imperial College, and Tejinder Virdee of Imperial College, have been awarded, respectively, the 2014 André Lagarrigue Prize and the 2015 Glazebrook Prize.

Della Negra is cited as "a leader with a deep understanding of physics, in Lagarrigue's lineage" and for his "outstanding qualities as a builder of experimental devices of great complexity" in his role as a major player in the discoveries at CERN of the W, Z and Higgs bosons.

Virdee is cited for "his leadership of the CMS experiment at the LHC, where evidence for the Higgs boson was revealed after 20 years of research" and for "his prominent role in the innovative design and lengthy construction of the CMS experiment, in particular the scintillating-crystal-based electromagnetic calorimeter, a vital piece of the 'toolkit' necessary to discover the Higgs boson".

Michel Della Negra, right, and Tejinder Virdee, recipients, respectively, of the Lagarrigue award and the Glazebrook prize, in the CMS control room in 2008. (Image credit: CERN.)

Della Negra started his career at the Collège de France with a thesis in 1967 on a bubble-chamber study of proton–antiproton annihilations at rest. He then pursued physics at the Intersecting Storage Rings at CERN, where he convinced the Split Field Magnet collaboration to focus on high-p_T physics. Having there demonstrated the capabilities of a 4π multi-purpose detector, he became involved in the proposed proton–antiproton collider in the Super Proton Synchrotron, and made decisive contributions to the design of UA1 – another 4π detector.

Virdee carried out his graduate studies at Imperial College London, on the hybrid bubble-chamber at SLAC. In 1979, as a CERN fellow he worked on the NA14 photo-production experiment, where the fractional electric charge of the quarks was measured. Virdee also collaborated on the UA1 experiment at CERN. His keen interest in hadron-collider physics and precision calorimetry in UA1 led to his prominent role in the CMS experiment.

Della Negra and Virdee were among the first physicists to support the project that became the LHC. In 1989, they started thinking of a 4π detector for the new machine, based on a strong magnetic field produced by a large solenoid capable of containing the inner tracker and the calorimeters. Della Negra focused on the optimization of the muon and trigger systems, and Virdee on a high-precision electromagnetic calorimeter, with a view to discovering the Higgs boson through its decay into four muons and two photons.

In 1992, Della Negra was elected the CMS collaboration's first spokesperson, with Virdee as his deputy, until 2006. This period saw the conception, R&D and prototyping, and much construction of the CMS experiment. During this period, Della Negra and Virdee took many critical and difficult decisions to ensure the optimal performance and success of the CMS experiment. In 2006, Virdee was elected spokesperson for three years, during which he oversaw the complex task of the completion of construction, installation and commissioning underground, and the first collision data-taking. The discovery of the Higgs boson by both the ATLAS and CMS experiments at the LHC was announced in July 2012.

The Lagarrigue award, established in 2005 under the aegis of the French Physical Society, pays tribute to André Lagarrigue, director of the Laboratory of Linear Accelerator (LAL, Orsay) from 1969 to 1975, who had a major role in the discovery of neutral weak interactions with the Gargamelle bubble-chamber at CERN. Co-funded by the CEA, CERN, Ecole Polytechnique, IN2P3-CNRS, LAL and Université Paris-Sud, the prize is awarded every two years.

The Glazebrook medal and prize is a premier award of the UK's Institute of Physics (IOP), and is named after its first president.

Faces & Places

IOP recognizes work in deep-inelastic scattering

For distinguished work in particle physics, Amanda Cooper-Sarkar of Oxford University has been awarded the IOP's Chadwick Medal and prize. She receives the award for "her study of deep-inelastic scattering [DIS] of leptons on nuclei, which has revealed the internal structure of the proton". As a world expert in DIS, her career has covered all forms of lepton–proton scattering and the study of QCD to elucidate the structure of the nucleon.

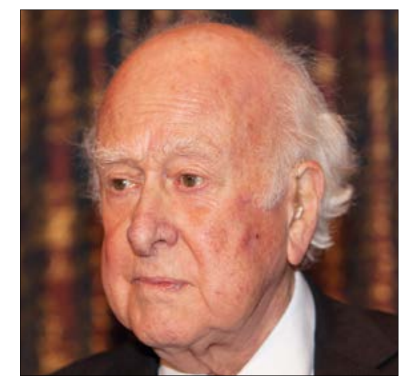
Cooper-Sarkar has distinguished herself in devising techniques to distil the experimental data into knowledge that could be interpreted and extrapolated in QCD. She was recently a leading figure in preparing the final papers in the area of DIS from the Hadron Electron Ring Accelerator at DESY, and also plays a leading role in the ATLAS groups at CERN that are making new measurements of the proton's structure function.

Amanda Cooper-Sarkar receives the IOP's Chadwick Medal. (Image credit: University of Oxford.)

The Royal Society honours particle physics

Peter Higgs, professor emeritus at the University of Edinburgh, has joined the ranks of Charles Darwin, Humphry Davy and Albert Einstein by winning the world's oldest scientific prize, the Royal Society's Copley Medal, which was first awarded in 1731. Higgs receives the 2015 award for his work that contributed to what is known as the Brout–Englert–Higgs (BEH) mechanism, which endows fundamental particles with mass. The particle known as the Higgs boson – the emissary of this mechanism – was discovered by the ATLAS and CMS experiments at the LHC in 2012.

The Royal Society has also recognized research in particle physics and at the LHC with the awarding of one its Royal Medals to Chris Llewellyn Smith, who was director-general of CERN from 1994 to 1998. Llewellyn Smith is honoured for "his major contributions to the development of the Standard Model, particularly his success in making the case for the building of the Large Hadron Collider". The Royal Medals, founded by King George IV in 1825, are awarded for the most important contributions in the physical, biological and applied sciences.



A Copley Medal for Peter Higgs, top, and a Royal Medal for Chris Llewellyn Smith, above. (Image credits: B Nyman, top, and C Llewellyn Smith.)

OUTREACH

MoEDAL takes monopoles to London

The MoEDAL experiment at the LHC and its "Monopole Quest" were on show at the Royal Society's 2015 Summer Science Exhibition on 30 June–5 July. The week-long display of the most exciting cutting-edge science and technology in the UK took place, as customary, at the society's base in London. The exhibition featured 22 exhibits, where hundreds of visitors could meet the scientists, try some of the hands-on activities or attend inspiring talks and events.

Visitors to the MoEDAL exhibit could design their own monopole detector, take part in the "Citizen Science" project to search online for monopole tracks in exposed MoEDAL plastic nuclear-track detectors, and test MoEDAL trapping volumes for captured monopoles. They could also visualize a Dirac monopole and investigate radioactivity on their mobile phones using a MoEDAL TimePix Chip. Involvement was awarded with gifts and prizes, which included a MoEDAL medal. There was fun for all, including the team looking after the exhibit, despite the unusual London temperatures that soared to higher than 30 °C.

Members of the MoEDAL team at the Royal Society Summer Exhibition (with their MoEDAL medals), on shift at the first formal soirée. Left to right: Arttu Rajantie and Edward Gillman of Imperial College London, Mairi Sakellariadou of King's College London, James Pinfold of the University of Alberta, and Anna Evans, Caitlin Cooke and Becky Parker of the Simon Langton School. (Image credit: Courtesy J Pinfold.)

● The MoEDAL groups involved in proposing, designing and eventually staffing the exhibit were from Imperial College London, King's College London, CERN, the University of Alberta, Langton Star Centre and the Simon Langton Grammar School for Boys.

CONFERENCE

QCD-Montpellier celebrates 30th anniversary

Every one to two years, Montpellier hosts the International Conference in Quantum Chromodynamics (QCD). Initiated in 1985 by Stephan Narison, director of research of the French National Research Centre for Scientific Research at the Laboratory of Universe and Particles of Montpellier, as a conference on non-perturbative methods, it took on the name QCD in 1990, and since 2001 has alternated with the International High-Energy Conference (HEPMAD) in Madagascar. This year, QCD-Montpellier celebrated its 30th anniversary at its 18th edition, which took place on 29 June–3 July.

During its 30 years, the conference has welcomed many world experts to Montpellier, including Nobel prizewinners – Jack Steinberger attended in 1997, David Gross in 1998 and Gerard 't Hooft in 1998 and 2002 – as well as winners of the J J Sakurai prize: Stanley Brodsky in 1990 and 2014, Mikhail Shifman in 2008 and 2010, and Valentin Zakharov, who has been a member of the International Committee and regular participant since 1996.

The conference also provides training for doctoral students and young postdocs, who are often present and talk for the first time in front of international QCD experts. The meeting's size of around 100 attendees, with equal numbers of theorists and experimentalists, allows participants to interact in a relaxed atmosphere, created by the well-organized social events and by the beauty of Montpellier and its surroundings, which favour discussions and the initiation of future collaborations.

Participants at QCD 15. (Image credit: alizé photo.)

Unlike other workshops, QCD-Montpellier covers all aspects of QCD including those related to searches for new physics beyond the Standard Model. It is also a meeting where new experimental results are often presented before the large international particle-physics conferences – or at the same time, as with the special session that took place on 4 July 2012 to present the Higgs discovery by ATLAS and CMS by video conference.

● For more on QCD 15, visit www.lupm.univ-montp2.fr/users/qcd/qcd15/Welcome.html. For HEPAMD 15, which will take place on 17–22 September, see www.lupm.univ-montp2.fr/users/qcd/hepmad15/Welcome.html.

ANNIVERSARY

Conference celebrates 60 years of Yang–Mills theories

On 1 October 1954, *Physical Review* published the seminal paper by Chen-Ning Yang and Robert Mills that was to become a cornerstone of theoretical physics. The Yang–Mills gauge field theory laid the foundation of the Standard Model of particle physics, and also went on to have widespread applications in statistical physics, condensed-matter physics, atomic and nonlinear optics and nonlinear systems. In May, the Institute of Advances Studies, Nanyang Technological University in Singapore, held a major conference on "60 years of Yang–Mills gauge field theories", attracting more than 180 participants from around the world.

Many eminent speakers attended to present results related to Yang–Mills gauge theories, including, in particular, Yang himself. (Sadly, Mills died in 1999.) The presentations included interdisciplinary talks by Paul Chu on "A possible paradigm shift in the search for higher T_c", Robert Crease on "Yang–Mills for historians and philosophers" and Antti Niemi on "Folding proteins at the speed of life". There were also interesting reminiscences by Yu Shi and Zhong-Qi Ma of the immense contributions by Yang to physics in general. In addition, David Gross, Michael Fisher and Yang gave public lectures on personal perspectives on physics.

Because the famous paper was written when Yang and Mills shared an office during the summer at Brookhaven Laboratory, the conference also included a round-table discussion on the role of regional labs and hubs in promoting collaboration in theoretical and fundamental physics. Various suggestions were made during the discussion, including strong arguments for creating an Asian version of CERN, where Asian countries could work with scientists from the rest of the world to uncover new levels of fundamental physics.

● For more about the conference, see www.ntu.edu.sg/ias/upcomingevents/Yang-Mills60/. The proceedings will be published by World Scientific.

Participants surround Chen-Ning Yang, centre front. (Image credit: Institute of Advanced Studies, Nanyang Technological University.)

VISIT

The prime minister of the Italian Republic, **Matteo Renzi**, visited CERN on 7 July, accompanied by Italy's minister for education, university and research, **Stefania Giannini**. They were welcomed by members of the CERN management together with **Carlo Rubbia**, former director-general and senator for life of the Italian Republic. During the visit they toured the ATLAS control room, as well as the ATLAS experimental area and the LHC tunnel, before meeting Italian physicists working at CERN. Left to right: Sergio Bertolucci, CERN's director for research and scientific computing, Matteo Renzi, Fabiola Gianotti, director-general designate at CERN, Stefania Giannini, Rolf Heuer, CERN's director-general, and Carlo Rubbia. (Image credit: CERN-PHOTO-201507-150 – 103.)

OBITUARIES

Bernard Hyams 1925–2015

Bernard Hyams. (Image credit: Vincent Chabaud.)

Bernard Hyams, a distinguished scientist who worked at CERN for 32 years, died on 15 May at the age of 90.

Bernard began his research career in Patrick Blackett's Laboratory at Manchester University, where he joined the teaching staff in 1950 and worked on a magnetic spectrograph to measure the momentum of single cosmic-ray particles. He went on to lead the group that set up a cosmic-ray experiment at the Pic du Midi Observatory, which in 1953–1955 observed eight well-identified unstable particles having properties consistent with the $K\mu$. He submitted his PhD thesis, on a search for antiproton production by high-energy cosmic-ray particles, in 1955.

Visiting CERN on sabbatical in 1958, Bernard participated in an experiment conducted in the Lötschberg Tunnel in the Swiss Alps, which showed that the nucleon lives longer than 2×10^{26} years – a subject that was to gain importance many years later. He accepted a staff appointment at CERN in 1959 and performed one of the first experiments at the Proton Synchrotron (PS), demonstrating that in pion decay the muon's spin behaves as expected. After studying vector-meson decays into muon pairs, he then spent several years working on precision measurements with pions. In the mid-1960s, together with Ulrich Stierlin of MPI Munich, he organized a group specializing in meson spectroscopy, which as the CERN–Munich collaboration, went on to perform a long series of experiments at the PS, well into the 1970s.

When the Intersecting Storage Rings (ISR) started operation at CERN early in 1971, there was no experiment in place that was capable of looking for quarks, even though the ISR were constructed as a "discovery machine". So Bernard acted decisively, supporting a small and mostly young team of physicists who proposed a relatively simple experiment to search for the putative particles, which many people expected to be discovered at the ISR. Thanks to Bernard's leadership, the ISR Committee swiftly approved the experiment, R402, which – unsurprisingly with hindsight – found no candidates.

Around 1974, the CERN–Munich group joined forces with others to form the long-lasting Amsterdam–CERN–Cracow–Munich–Oxford–Rutherford (ACCMOR) collaboration, which performed a well-known series of experiments at the Super Proton Synchrotron, first in the West Area (WA3), before moving to the North Area (NA11 and NA32). With the discovery of charmed particles, Bernard became interested in the study of their decays using silicon-microstrip detectors, which were implemented in the NA32 experiment.

In the early 1980s, he became a pioneer of the use of silicon microstrips for high-precision vertex measurements at particle colliders, in particular applying the technique in the DELPHI detector at CERN's Large Electron–Positron (LEP) collider. During a sabbatical year at SLAC, in collaboration with Sherwood Parker and James Walker, he developed a VLSI chip for microstrip read-out, allowing compact vertex detectors to be built for collider experiments. The proposal for the DELPHI device was put forward, and part of the microvertex detector collected data during the first LEP run in August 1989. It was completed for the next running period in 1990 and upgraded successfully a number of times.

While continuing his research work, Bernard was also leader of CERN's Experimental Physics Division from 1984 to 1987. Overall, he spent 32 years at CERN before retiring in April 1990. In 2002, he received the title of Honorary Professor of the Institute of Nuclear Physics at Cracow for his role in bringing Cracow's physicists into modern experiments at CERN. The *laudatio* forms an excellent tribute to Bernard's career in general, recognizing "his outstanding achievements in experimental particle physics, his role in introducing many scientists to the mysteries of modern physics and his great contribution to the development of scientific collaboration between CERN and national physics institutions".

Discussing a physics project with Bernard was always special. With his brilliant mind he would quickly grasp the essential points, making suggestions for improvements or criticizing, if warranted, with his keen British sense of humour. He was always attentive to the feelings of others, and visibly enjoyed CERN's exciting research atmosphere and the contact with younger colleagues. Because of his wisdom and generosity, many requested his advice, especially when difficult decisions had to be taken. He was scrupulously fair and never pushed himself to the forefront, preferring to work hard in the shadows for the good of the collaboration. It was a privilege to know and work with him. His influence went far beyond the boundaries of CERN, and all of his colleagues, no matter where located, remember him as a great friend who will be sorely missed.

Bernard was very attached to his family, from his wife Hanna to his granddaughter Solongo. He died just one month after his beloved wife, surrounded by his family.

Our warmest thoughts and sympathy go to them and to the many others who have shared an important part of their professional lives with Bernard.

● *His friends and colleagues.*

Yanglai Cho 1932–2015

Yanglai Cho, a principal member of the small dedicated team that brought the Advanced Photon Source (APS) to Argonne National Laboratory, passed away on 14 June. He was 82 years of age.

Cho received his BS in physics from Seoul National University in 1956, his Master's from Brigham Young University in 1958 and his PhD from the Carnegie Institute of Technology in 1966. He was also an instructor in the physics department at Vassar College from 1960 to 1962. In 1967, he joined the Carnegie Institute of Technology as a research physicist, and began his long and distinguished career at Argonne the same year, starting as a research associate. His earliest roots at Argonne were in high-energy physics, studying $K\pi$ scattering on the Zero Gradient Synchrotron (ZGS).

Developing an interest in accelerator science in the early 1970s, Cho undertook physics studies on the performance and upgrade of the ZGS. He became director of the accelerator group of the ZGS, and was responsible for the commissioning of the Intense Pulsed Neutron Source there – the first slow neutron source based on a proton synchrotron. His career at Argonne was interrupted briefly in 1983–1985, when he went on assignment to the University of Wisconsin's Synchrotron Research Center, first as associate director for accelerator technology then as acting director.

In 1983, a committee on major materials facilities commissioned by the US Department of Energy recommended the construction of a synchrotron light source operating in the 6 GeV range. Cho pointed out to Kenneth Kliewer, at the time Argonne's associate laboratory director for physical research, that Argonne was a natural site for the facility and that it should be pursued. Kliewer agreed, and Cho became one of the major drivers throughout the design, construction, commissioning and successful operation of what became the APS.

Yanglai Cho. (Image credit: ANL.)

He served as project director in the formative years of the APS, and then became deputy associate laboratory director. He was technical director of the Spallation Neutron Source at Oak Ridge National Laboratory from 1999 to 2001 during the facility's early development, where he made the successful case for the first use of superconducting technology in a high-power proton linac.

Upon retiring from Argonne, Cho chaired the Technical Advisory Committee for the Facility for Antiproton and Ion Research in Darmstadt. He also chaired numerous international conferences on accelerator science and technology, and had a leading role in facilitating the joint proposal between two agencies in the Japanese government that gave rise to the Japan Proton Accelerator Research Complex. He was the author of numerous peer-reviewed publications, and was awarded the University of Chicago Distinguished Performance Award by Argonne in 1986.

Cho also helped to initiate several other accelerator projects, particularly in Korea. Both the Pohang Light Source at Pohang University of Science and Technology and the Korea Multi-purpose Accelerator Project at the Korea Atomic Energy Research Institute benefited greatly from his initial design concepts and subsequent suggestions. He left his mark in his homeland, where all of his friends will forever miss his great humanity.

Yanglai Cho had tremendous energy and dedication, and a remarkable combination of technical brilliance and practicality. He leaves an important legacy.

● *Based – with permission – on the obituary published on the APS website: www1.aps.anl.gov/APS-News/Yanglai-Cho-a-Founder-of-the-APS-Dies-at-82.*

NEW PRODUCTS

FLIR Systems has announced a new version 4.2 of its ResearchIR thermal-imaging software. ResearchIR 4.2 provides researchers with a powerful tool for viewing, acquiring, analysing, and sharing thermal data captured with FLIR's scientific and R&D cameras. For the first time, it gives users direct access to MATLAB scripts within ResearchIR, allowing users to access their customized MatLab scripts directly for specially tailored image-analysis and processing tasks. For further information, tel +32 3665 5100, e-mail flir@flir.com or visit www.flir.com.

Intersil Corporation has announced the first 60 V synchronous buck controller able to bypass the intermediate step-down conversion stage traditionally employed in industrial applications. The ISL8117 synchronous step-down PWM controller's low-duty cycle (40 ns minimum on time) enables the direct step-down conversion from 48 V to a 1 V point-of-load. This technical achievement makes it possible for designers to reduce system complexity in infrastructure applications. For more information, contact Mark Alden, tel +1 408 546 3402, e-mail malden@intersil.com or visit www.intersil.com/products/isl8117.

Narda Safety Test Solutions has launched a new FFT analyser for low-frequency electromagnetic fields. The EHP-50F measures and analyses electric- and magnetic-field strengths in the frequency range 1 Hz to 400 kHz, and evaluates the results in accordance with current human safety standards. Narda has also expanded the features of its Interference and Direction Analyser, providing spectrograms with a time resolution of as fine as 1 μs. This means that interference and hidden transmitters with rapidly changing frequencies can be analysed and then localized with subsequent operating steps. For more information, tel +49 7121/97 32 0, e-mail info.narda-de@L-3com.com or visit www.narda-sts.com.

The **ORTEC Products Group** of AMETEK Advanced Measurement Technology has announced the release of Profile "SP" Series P-type high-purity germanium (HPGe) detectors, providing premium resolution at low to medium energies for a range of demanding, radiation-detection applications. The detectors employ a low-noise back contact combined with a semi-planar crystal geometry. The proprietary back contact of the Profile "SP" improves energy resolution at lower energies, while supporting the same resolution at higher energies. SP detectors also feature a stable, thin front-contact, allowing warm storage, simplified detector handling and lower associated storage costs. For more information, tel +1 865 482 4411, or visit www.ortec-online.com.

XP Power has announced the DDC15 and DDC30 series of low-profile 15 W and 30 W DIN-rail format DC–DC converters. The range is designed to offer additional voltages in DIN rail-power systems, provide isolated outputs and noise immunity or support battery-powered or battery-backed applications. The single output converters accommodate a 4:1 input range from 9–36 VDC, suiting 12 or 24 VDC nominal input. Both series are available with a choice of a 5, 9, 12, 15 or 24 VDC nominal output. The DDC15 model is available with a 3.3 VDC output. Input-to-output isolation is 1500 VDC. For further information, contact Steve Head, tel +44 118 984 5515, e-mail shead@xppower.com or visit www.xppower.com.

Recruitment

For advertising enquiries, contact *CERN Courier* recruitment/classified, IOP Publishing, Temple Circus, Temple Way, Bristol BS1 6HG, UK.
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The MAP-fis Physics Doctoral Program, a joint initiative of three major Portuguese Universities, Minho, Aveiro and Porto, is announcing 8 first year PhD scholarships for the 2015-2016 edition. Recognized as program of excellence by Portugal's National Science Foundation (FCT), MAP-fis joins three Physics Departments and 6 research centers. Fellowships include a monthly stipend and tuition fees.

MAP-fis constitutes a unified effort to prepare highly qualified human resources in Physics and an effort to strengthen research in this area in these universities. It is supported by an academic staff of about 130 faculty members, and a total of 280 PhD researchers working in 6 Research Centers.

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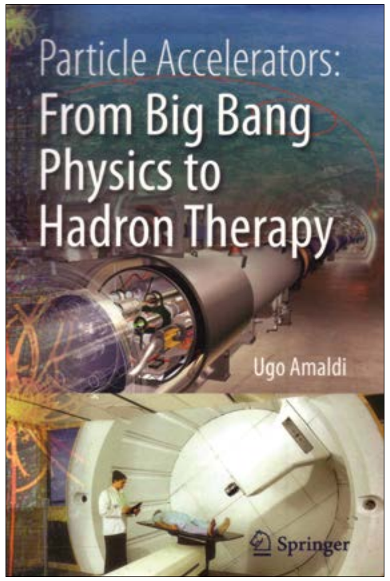
- Meteorology and Oceanography.

For more information, and to apply, see the MAP-fis site **http://www.map.edu.pt/fis/**.

Applications are opened until September 14, 2015.

Bookshelf



Particle Accelerators: From Big Bang Physics to Hadron Therapy

By Ugo Amaldi
Springer
Paperback: £19.99 €36.01 $34.99
E-book: £14.99 €29.74 $19.99
Also available at the CERN bookshop

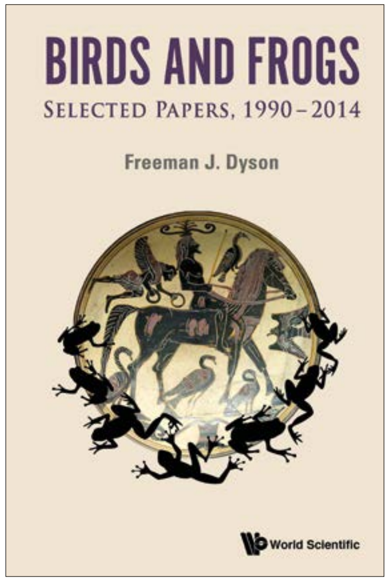
There was a time when books on particle physics for the non-expert were a rarity; not quite as rare as Higgs bosons, but certainly as rare as heavy quarks. Then, rather as the "November revolution" of 1974 heralded in the new era of charm, beauty and top, so the construction of the LHC became the harbinger of a wealth of "popular" books on particle physics, and the quest to find the final piece of the Standard Model and what lies beyond. These books can be excellent in what they set out to do, but few venture where Ugo Amaldi goes – to look at the basic tools that have made this whole adventure possible, and in particular, the accelerators and their builders. Without the cyclotron and its descendants, there would be no Standard Model, no CERN, no LHC. Nor would there be the applications, particularly in medicine, which Amaldi himself has done so much to bring about.

As the son of Edoardo Amaldi, one of CERN's "founding fathers", Ugo Amaldi must have the history of particle physics in his bones, and he writes with feeling about the development of particle accelerators, introducing each chapter with personal touches – photos of roads at CERN named after important protagonists, anecdotes of his personal experience, quotes from people he admires. There is a passion here that makes the book interesting even for those who already know the basic story. Indeed, while particle physicists may not be the main audience the author had in mind, they can still learn from many chapters, "speed-reading" the parts they are familiar with, then dwelling on some of the historical gems – such as the rather sad story of the co-inventor of strong focusing, Nick Christofilos, about whom I had previously known little beyond his being Greek and a lift engineer.

For the non-expert, the book has much to absorb, the result of containing quite a thorough mini-introduction to the Standard Model and beyond – the author's inner particle physicist could clearly not resist. Yet it is worth persevering and reaching the chapters on "accelerators that care", to use Amaldi's phrase, to discover the medical applications of the 21st century.

So, this is a book for everyone, and in particular, I believe, for young people. Books like this inspired my studies, and I would like to think that Amaldi will inspire others with his passion for physics.

● *Christine Sutton, CERN.*



Birds and Frogs: Selected Papers, 1990–2014

By Freeman J Dyson
World Scientific
Hardback: £38
Paperback: £18

Birds and Frogs is a wonderful collection of essays and papers by Freeman Dyson from 1990 to 2014, and a sequel to a volume of earlier papers. It consists of a short introductory section followed by four more: "Talks about Science", "Memoirs", "Politics and History" and "Technical Papers".

The book takes its title from one of the "Talks about Science", in which Dyson classifies mathematicians – and, I would add, physicists – as either "birds" or "frogs". He writes: "Birds fly high in the air and survey broad vistas of mathematics out to the far horizon. They delight in concepts that unify our thinking and bring together diverse problems from different parts of the landscape. Frogs live in the mud below and see only the flowers that grow nearby. They delight in the details of particular objects, and they solve problems one at a time. I happen to be a frog, but many of my best friends are birds." This section contains a wealth of fascinating thoughts on, for example, the origins of life, resistance to new ideas in physics, and the nature of computation in the human brain.

Despite his claim to be a frog, much of the book is written with a bird's-eye view. Dyson is perhaps uniquely placed among living scientists in having been privy to much that went on in the early days of quantum field theory, and to have met and be able to write about personal experiences with many of our modern-day heroes. In the "Memoirs" section, and elsewhere, he offers insights not only into their work, but also their lives and beliefs.

"Politics and History" ranges from science and religion to ethics, and education from the points of view of Tolstoy and Napoleon. His recollections and observations about the Second World War are as unique as they are fascinating. Ultimately, he shares spectacular and optimistic visions for our future as a species that can spread life throughout the universe.

It is the section on "Technical Papers" that shows Dyson the frog. Here, number theory, bounds on variation of the fine structure constant, detectability of gravitons and game theory all appear.

Whether you're a frog or a bird or neither – Dyson has a penchant for classifying things into a small number of categories, often just two – you are certain to find much to delight you in this eclectic and yet somehow unified collection.

● *John Swain, Northeastern University.*

Bookshelf

Books received

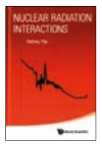
Cosmic Ray Origin: Beyond the Standard Models
By Omar Tibolla et al. (eds)
Elsevier
Nuclear Physics B (Proc. Suppl.) 256–257 (2014)

Where do cosmic rays, discovered more than a century ago, come from? The standard model of their origin points to natural particle accelerators in the form of shock waves in supernova remnants, but there is mounting experimental evidence that there are other sources. This conference brought together a range of experts to examine the evidence and to consider some of the key questions. What other sources might there be in the Galaxy? What causes the knee? Where (in energy) is the transition to an extragalactic component? What extragalactic sources are conceivable?

International Seminars on Nuclear War and Planetary Emergencies 46th Session: The Role of Science in the Third Millennium
By A Zichichi and R Ragani (eds)
World Scientific
Hardback: £98
E-book: £74

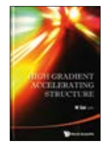
The 46th Session of the International Seminars on Nuclear War and Planetary Emergencies, held in Erice, Sicily, gathered again, in 2013, more than 100 scientists from 43 countries. This is the latest output from an interdisciplinary effort that has been going on for the past 32 years, to examine and analyse planetary problems that are followed up, throughout the year, by the World Federation of Scientists' Permanent Monitoring Panels.

Nuclear Radiation Interactions
By Sidney Yip
World Scientific
Hardback: £49

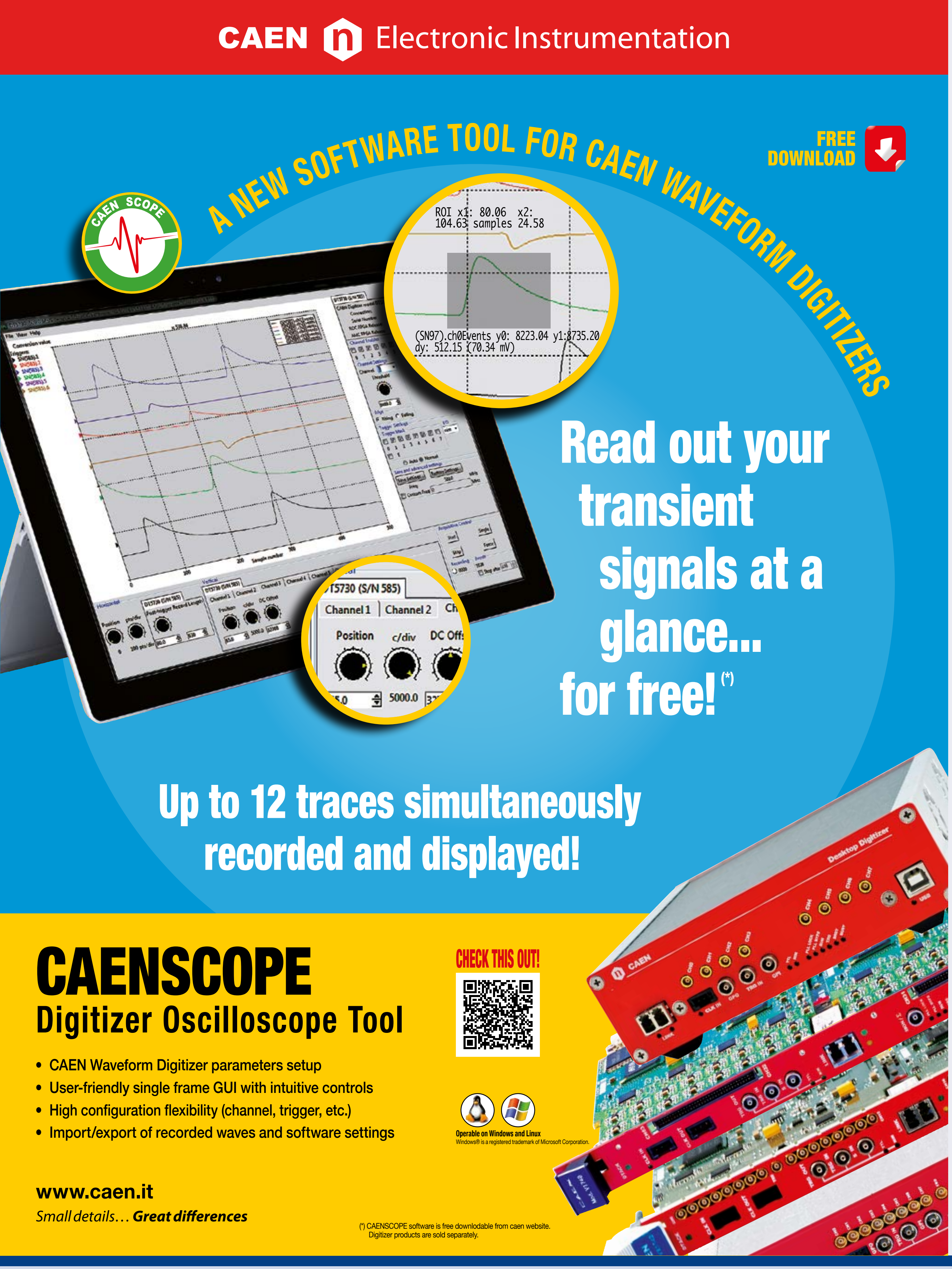


Based on a first-year graduate-level course that the author taught in the Department of Nuclear Science and Engineering at MIT, this book differs from traditional nuclear-physics texts for a nuclear-engineering curriculum by emphasizing the understanding of nuclear radiations and their interactions with matter. In generating nuclear radiations and using them for beneficial purposes, scientists and engineers must understand the properties of the radiations and how they interact with their surroundings. Hence, radiation interaction is the essence of this book.

High Gradient Accelerating Structure
By W Gai (ed.)
World Scientific
Hardback: £65
E-book: £49



This proceedings volume, for the symposium in honour of Juwen Wang's 70th anniversary, is dedicated to his many important achievements in the field of accelerator physics. Wang has been a key member of SLAC for many years, working on accelerating structures for linear colliders, up to and including the CLIC project at CERN, as well as the Linac Coherent Light Source at SLAC. The book includes discussions of recent advances and challenging problems by experts in the field of high-gradient accelerating structures.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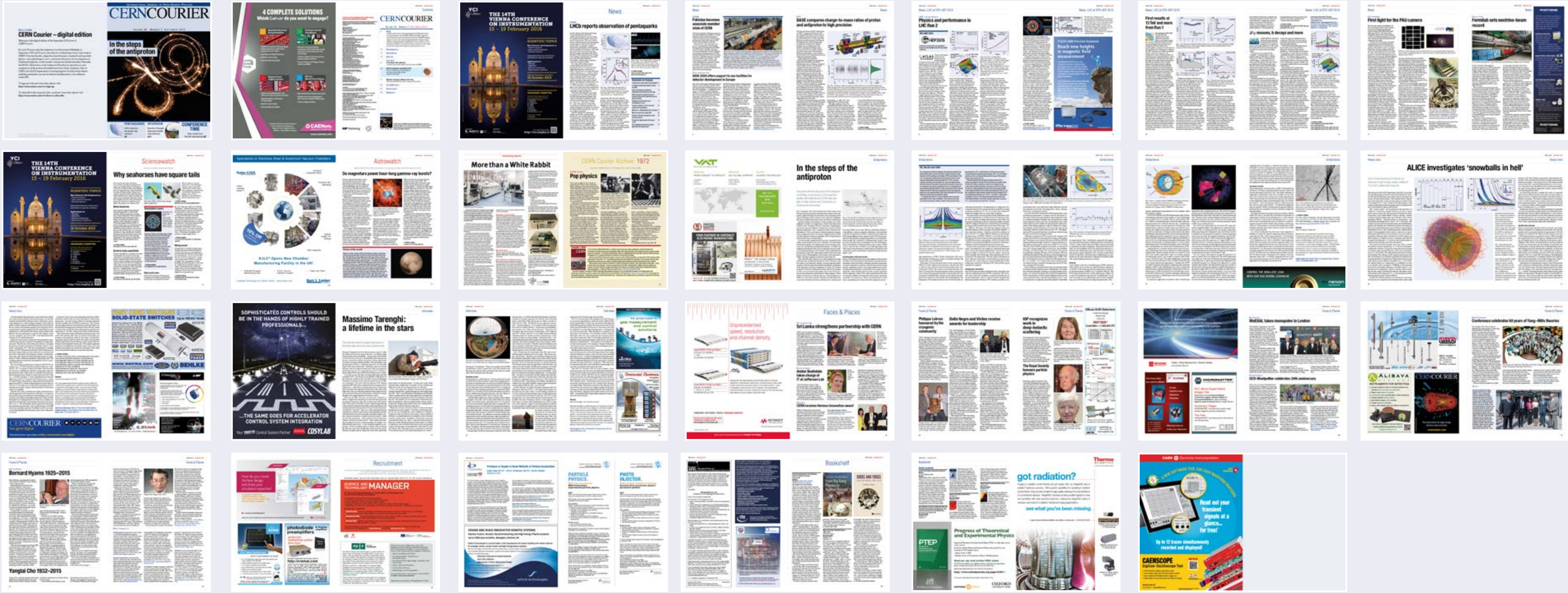

CERNCOURIER

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