EP Newsletter of the EP department
Dear Colleagues, Members of the EP Department and CERN Users,

Welcome to the 4th and last edition of the EP Newsletter this year. 2016 is almost over, and it went very fast. It has been an extremely successful year for CERN. The LHC experiments have collected more data they have ever dreamed of when starting Run 2 and the IT department had even to stock up further tapes to store the data flood. But it was not only a flood of data, these collisions were collected with excellently performing experiments and will lead the LHC into the precision measurement era. The non-LHC experiments at CERN did very well too. Just to mention a few, NA62 had a full year of running with the completed detector, the CLOUD experiment ran with an improved set up and instrumentations, and the experiments at the AD continued their progress towards precision measurements of antiprotons and antihydrogen. The ELENA ring, which will improve the performance of the AD experiments by orders of magnitude is completed and commissioning has started and HIE-ISOLDE successfully put in operation the first stage of the post-acceleration of isotopes.

We will soon close the laboratory for the Xmas break. Please respect this closure, relax with your family and if you cannot do without physics read this newsletter from home. In it you will find again a large variety of different articles reflecting the diversity of the EP department.

Finally, I would like to take this occasion to thank Panos Charitos for following the activities in our department and the many articles he has provided for the EP newsletters this year.

Happy Holidays and enjoy the Xmas break!

Manfred Krammer

EP Department Head
LHC community prepares the High Luminosity Upgrades

by D. Contardo, K. Einsweiler

With the approval of the CERN Council in June 2016, the LHC is now moving toward execution of the High Luminosity upgrades. As well, after the first step of approval by scientific committees at the end of 2015, the ATLAS and CMS collaborations were encouraged by the Resource Review Board to prepare Technical Design Reports of the experiment upgrades. These TDRs will happen in 2017 and the 3rd ECFA High-Luminosity LHC Experiments workshop in October was a new opportunity for the LHC community to address widely the preparation of the entire program.

The workshop agenda was organised to allow large attendance of all communities and to provide comprehensive and accessible information to everyone. The overviews of CERN scientific strategy, physics potential and experimental challenges for the accelerator and detectors were followed by four major discussions: The accelerator operation scenarios and their impact on experiments; the physics reach and performance; the progress on common experimental R&D; and the update of design and performance of the detector upgrades. The material for the first discussion was prepared by a new working group formed earlier this year involving experiments and accelerator, while theory and experiment colleagues had several dedicated forums to develop the new physics studies that were presented.

Recently, a new baseline for the LHC upgrade was defined, with reduced number of crab-cavities. It was shown that luminosities similar to the original design could be achieved with a relatively limited increase of 10 to 20% of the collision density along the beam axis. Two operation scenarios are considered, one with luminosity levelling at $5 \times 10^{34}$ Hz/cm$^2$ corresponding to a mean collision pileup (PU) of 140 and a density ranging from 1.1 to 1.3 per mm, and one with levelling at $7.5 \times 10^{34}$ Hz/cm$^2$, with 200 PU and a density ranging from 1.7 to 1.9 per mm. Provided the experiments can maintain good performance in these latter conditions, a 30% increase in integrated luminosity could be reached for a same operation period. For the first time, experimental simulations of the physics object reconstruction performance (for leptons, b-quarks, jets and missing transverse energy) were presented as a function of the collision density. A linear degradation of the performance is observed, rather independent of the total number of collisions, indicating that the reconstruction is mostly sensitive to the pileup of tracks.
produced near the collision of interest and wrongly assigned to this vertex. Options to reduce the collision density, such as the flat optics considered for HL-LHC operation, could therefore improve the experimental performance. Another means to reduce mis-assignment of track to interactions would be to precisely measure their arrival time in detectors (see below). New simulations will now be performed to estimate how the performance degradation with collision density propagates to benchmark physics analyses.

Physics reach at the HL-LHC depends on statistical and systematic uncertainties. The latter originate from theoretical model calculations and from experimental measurements. Tremendous progress on theory uncertainties where presented, mostly from exploitation of recent data and new orders of NLO calculations. The factor 2 improvement assumed in earlier projections of physics performance at the HL-LHC was proven to be already achieved. Several new physics projections were presented by the experiments, also including recent Run II analyses criteria and better assessment of the upgraded detector performance. Particularly, new expectations for the Higgs coupling precisions were shown, along with new fiducial and differential cross section estimates, where systematic uncertainties cancel. For new physics searches, theory perspectives building on the limits set by the current LHC results were discussed. New signal benchmarks were also evaluated; expanding the assessment of the experiment's coverage, and above all highlighting the importance to maintain highly efficient event selection and to extend the tracking acceptance in forward regions.

Several common R&D for technical solutions are ongoing in three main areas: electronic systems, cooling and mechanical structures, computing and software. These efforts benefit from specific frameworks and workshops, often federated through CERN services to the experiments. Comprehensive reports of progress were presented at the workshop and only few highlights are mentioned here. Deep investigation of radiation tolerance is of particular importance for ASIC chip technologies, especially for the 65 nm TSMC technology proposed for the most irradiated regions in the inner pixel detectors. It was shown that recent submission of demonstrator chips must soon confirm that radiation doses up to 500 Mrad, or more, could be sustained as expected. Good progresses of other common developments were also presented for new data links, power distribution systems, large power CO₂ cooling systems and light mechanical structures. Computing needs for the HL-LHC are estimated to be 50 to 100 times larger than those for Run 2, depending on pileup conditions. The projections of equipment performance versus cost indicate a gain of about 20% per year. It was however noted that substantial uncertainty on this projection are arising from present concentration and saturation of the market. In any case, the material improvements at constant cost will not be sufficient and another factor 10 gain will be needed on the computing usage itself. This appears achievable with emerging techniques for data management, multi-processor and/or accelerator usage, and new algorithmic methods. This will however require a huge effort of adaptation. The HEP Software Foundation (HSF) is proposing a framework open to the entire community to federate these efforts. A primary goal of the HSF is to prepare, by summer 2017, a white paper describing possible strategies and a roadmap toward future computing and software.

The ATLAS and CMS upgrades are driven by similar considerations for performance and operational challenges and therefore have similar scope. However, constraints from the original detectors can lead to different and complementary approaches in developing new configurations and technical solutions. It was inspiring at the workshop to compare the design options and their expected performance. Likewise, learning from the experience of ALICE and LHCb in preparing their earlier upgrades foreseen for the Long Shutdown 2 was extremely valuable. This was particularly true for tracking devices and for the new data acquisition systems (DAQ) they develop. These systems will select event only at the computing level, paving the path toward future computing and software models. The data volume and
complexity in ATLAS and CMS will not allow a full computing event selection and the improvement of the hardware trigger remains a key pre-requisite for physics. To achieve the required performance the new paradigm is to implement a hardware track reconstruction, so that they can be ready for use in tens of microseconds. In CMS, the presence of a high magnetic field has allowed to develop a new silicon-strip module concept to implement tracks in the trigger at every bunch crossing. Instead, ATLAS will have a lower rate pre-triggering based on the calorimeter and the muon detectors information before using tracks. The track information in the two approaches may be different and it will be interesting with more simulations to assess the impact on performance.

Partly because of this specific CMS concept for trigger, the two experiments have adopted different configurations for the new trackers. In the barrel, ATLAS foresees 5 layers of pixels followed by 4 layers of strips, while CMS considers 4 layers of pixels followed by 6 layers of strips. A novelty of the designs will be to tilt modules toward the interaction point at the edge of the layers, either in the pixel and/or in the strip parts. In the forward regions, both experiments will increase the coverage of the detectors with more rings/disks of pixels farther from the interaction point. Again comparing the different implementations proposed by ATLAS and CMS is enlightening in the quest for the most immaterial trackers.

In other detectors, mostly all electronics will be replaced to fulfil higher trigger rates and latency requirements. With the advent of high bandwidth data links the trend for all experiments becomes to readout the full detectors at each bunch crossing, providing full information and flexibility for triggering features deported to the back-end electronic systems.

Calorimeter upgrades are important particularly in the forward regions. It was presented that after deep investigation, ATLAS has decided to maintain the existing forward calorimeter as it is, while CMS presented progress in developing a High Granularity Calorimeter for its endcaps. This will be the first implementation in an experiment of a detector capable of 5D measurement (x,y,z,t,E) of electromagnetic and hadronic showers.

With likely operation of the HL-LHC reaching very high luminosities, precise measurement of arrival time of particles in detectors could provide a substantial new handle to mitigate the impact of the collision pileup. In the accelerator baseline scenarios, the collision time spread has a rms of about 180 ps and therefore a 30 ps resolution measurement could allow scanning a much reduced area of the z-t collision space and therefore of number of collisions. ATLAS is investigating a High Granularity Timing Detector in front of the existing forward calorimeter, with similar configuration as the CMS HGC, but with silicon sensors (LGAD) able to provide high precision timing measurements for minimum ionizing particles. CMS instead is studying a dedicated precision timing layer with full acceptance coverage in front of the barrel and endcap calorimeters. Encouraging studies of the performance benefits and of the technical feasibility where presented at the workshop.

As for the previous editions, the workshop was an inspiring exchange of information and new ideas, in a convivial atmosphere propitious to strengthen the links across the communities.

Notes: 1. https://indico.cern.ch/event/524795/timetable/
The ELENA project
by Walter Oelert, Francois Butin, Horst Breuker for the ELENA Project Team

The safety door is closed, see Figure 1. Beam can be sent to the area behind, where the mechanical construction of ELENA -- the Extra Low ENergy Antiproton ring -- was finished early November 2016. And beam - delivered for the commissioning from a special source - is arriving just in front of the ELENA ring ready to be injected.

![Image of the closed safety door of the ELENA area with "BEAM ON" and the "ELENA CLOSED" indication.](Image Credit@CERN)

Figure 1: The closed safety door of the ELENA area with “BEAM ON” and the “ELENA CLOSED” indication. (Image Credit@CERN)

The following image (Figure 2) shows the spot of the very first proton beam on the “BTV” instrument located between the injection septum and the kicker. Already three days after starting the commissioning a first coasting beam was observed for one turn and shortly after for three turns. It took only a few more days to observe the beam over several 10 s of turns. A very first success.
This remarkable milestone is certainly worth to be remembered and therefore to mark the end of the installation phase and the beginning of the commissioning of the new decelerator, a group-photo of all those people present and working for the project has been taken on Monday, November 21st 2016, and is shown in figure 3.
Back in July 8th 2014 we reported already in the EP newsletter about the ELENA project (see: [https://ep-news.web.cern.ch/content/elena-project/](https://ep-news.web.cern.ch/content/elena-project/)) which was approved by the Research Board in June 2011.

CERN has a longstanding tradition of pursuing fundamental physics on extreme low and high energy scales. The present physics knowledge is successfully described by the Standard Model along with General Relativity. In the antimatter regime many predictions of this established theory still remain experimentally unverified and one of the most fundamental open problems in physics concerns the question of asymmetry between particles and antiparticles: why is the observable and visible universe apparently composed almost entirely of matter and not of antimatter?

ELENA is a CERN project aiming to construct a small 30.4 m circumference synchrotron to further decelerate antiprotons from the Antiproton Decelerator (AD) from 5.3 MeV down to 100 keV. Whereas in 2014 only the layout of the ELENA ring could be shown, Figure 4 now presents the mechanically finished ring with nearly all its main components enclosed in the concrete shielding wall for radiation protection, all located within the AD hall.

Controlled deceleration in a synchrotron to energies as low as 100 keV and emittance reduction using electron cooling will allow the existing AD experiments to increase their antiproton capture efficiencies and renders new types of experiments possible. Unfortunately this important piece of equipment is still missing due to delivery problems but is replaced by a straight section beam pipe for closing the ring and completing the vacuum and bake out of the system. Thus the commissioning could start though without the electron cooler. Both H- ions and protons are available from an external source and later antiprotons might be delivered from the AD ring as well.

Commissioning was scheduled to take place from November 14th to the Christmas break. Unfortunately on November 26 the transformer of the source failed which will need a repair of four weeks and therefor the commissioning will continue only in February 2017 still without the electron cooler, which will be installed and tested depending on what has been achieved and on the availability of the device.
sometime in spring 2017. It should culminate in spring time 2017 with H- or p beams delivered to new experiment Gbar and somewhat later in 2017 with antiproton operation for this experiment, in parallel with continuous improvements of the commissioning conditions. In 2018 ELENA will serve exclusively Gbar whereas the other experiments will get their antiprotons still from the AD. the time consuming procedure for dismounting the present magnetic beam lines and installing new electrostatic beam lines to the existing experiments (see Figure 5) will be done during the long shut down (LS2) lasting from 2019 to 2020. Thus the sole operation of ELENA for all experiments will start most likely in 2021. ELENA will then be able to deliver beams almost simultaneously to all experiments (within one cycle up to four experiments) resulting in an important gain in total beam time for each collaboration.

Figure 5: ELENA and the beam lines to the different experiments in the AD Hall. (Image Credit@CERN)

Very visible to visitors at CERN is the construction of the new building 393. This “Antimatter Factory” hall hosts the kickers for the AD operation which had to be moved out of the AD hall in order to make place for the ELENA ring itself. In addition, it houses storage places for the experiments and a rather small workshop for fast repairs for the experiments when needed. Figure 6 depicts the outside view and a look inside.
The six experiments are named: ATRAP, ALPHA, ASACUSA, AEgIS, Gbar and BASE. Their specific properties and features can be found in CERN’s Grey Book. For instance the experiment BASE approved in 2013, reported in 2015 an improved high precision comparison of the charge/mass ratio for the antiproton-proton system with a fractional precision of 69 parts in a trillion. Moreover the collaboration has invented a novel reservoir trap technique and demonstrated very recently trapping of antiprotons for more than 1 year. Happy birthday to these exotic antiparticles!

Once low energy antiprotons are available - as provided now at the AD and even lower by ELENA in the future - they might be used either as free particles for studying the fundamental properties as charge/mass ratios and magnetic moment or investigated in bound systems, as outlined in Figure 7.
Bound states are:

i) a normal matter atom (e.g. He) with a bound antiproton replacing an electron e.g. antiprotonic helium,

ii) the exotic antihydrogen atom with an antiproton core surrounded by a positron and

iii) antihydrogen ions.

In all these cases high precision measurements in the spectroscopic and the gravitational sector investigate fundamental properties and exact interactions eventually in comparison to normal matter. Thus we might understand why there is much more matter rather than antimatter. With ELENA there is a brilliant future to come for basic antimatter-physics to be studied.
HIE-ISOLDE celebrates the end of the first stage of the energy upgrade and the great physics outcome.

by Maria Jose Garcia Borge

There was an air of celebration at CERN on Wednesday 28th September as nearly 100 invited guests gathered to mark the successful completion of phase 1 of the HIE-ISOLDE project, which aims to provide higher intensity and energy beams, up to 5.5 MeV/u, at ISOLDE. The first radioactive ion beams, which had been eagerly awaited by the ever-expanding ISOLDE scientific community, were produced on 9th September 2016. The event, organised to celebrate this significant milestone, was attended by the CERN management and the Belgian State Secretary for Scientific Policy, E. Sleurs, as well as CERN delegates, funding agency representatives and senior scientists from the now 18 member states of the ISOLDE collaboration.

The HIE-ISOLDE event was hosted by B. Blank, the ISOLDE Collaboration Committee Chair, and M.J.G. Borge, the ISOLDE Physics Leader and spokesperson. Fabiola Gianotti, Director-General, welcomed the guests to CERN and F. Bordry, CERN Director For Accelerators and Technology, gave the opening address. This was followed by a presentation by M.J.G. Borge about the ISOLDE facility, the wide range of nuclear physics research that takes place at ISOLDE and the opportunity to address new physics questions that the new energy window will provide. Y. Kadi, the HIE-ISOLDE project leader, then explained how phase 1 of the project had been achieved with successful collaboration and funding from CERN, the ISOLDE Collaboration and external sources, such as the Belgian Big Science programme, the Spanish Industry for Science programme and the EU CATHI Marie Curie Initial Training Network, as well as the CATE Consortium, which is an EU interregional program IV. The Belgian Secretary of State, E. Sleurs, congratulated the collaboration on the successful completion of phase 1 and gave an overview of the Belgian contribution to projects at CERN, in particular ISOLDE and MEDICIS. She expressed her pleasure at seeing how the investment in R&D had been so fruitful and announced a continuation of Belgian funding programmes. Guests were then given a tour of the ISOLDE facility and had the chance to meet young, dynamic members of the ISOLDE community, who
were at hand to present the experiments in which they are involved. The event came to a close with the guests visiting the Synchrocyclotron and the new CERN Microcosm exhibition.

Figure 2 3D layout of the HIE-ISOLDE post-accelerator as it looks in 2016. The REX-ISOLDE post-accelerator is at the right and two high-beta cryomodules are installed downstream of REX. Two beam transfer lines take the post-accelerated beam to the experiments: beamline XT01 is connected to the MINIBALL array and XT02 to the SEC scattering chamber. Top left: photo of the HIE-ISOLDE linac as taken in May 2016, with two cryomodules. Bottom right: layout of MINIBALL and photo of SPEDE, the electron spectrometer built in Jyväskylä.

The 2016 campaign with post-accelerated beams started on September 9th, accelerating a beam of the semi-magic (Z=50) \(^{110}\)Sn to 495 MeV (4.5 MeV/u). This first experiment addressed the determination of the transition probabilities \(2^+ \rightarrow 0^+\) that seems to differ strongly from the theoretical expectation in the light tin isotopes. The second one addressed the evolution of the quadrupole and octupole collectivity in \(^{142}\)Xe when going away from the double magic \(^{132}\)Sn. This was the heaviest nucleus accelerated in 2016. The figure shows the Doppler corrected gamma spectrum of excitation of the \(^{142}\)Xe beam at 4.5 MeV/u on a lead target compared with the equivalent spectrum obtained with REX (2.85 MeV/u) energies. With the new energies, states up to 8\(^+\) spin-parity are populated in multi-step Coulomb excitation. Following the studies done last year with \(^{74,76}\)Zn, Coulomb excitation of \(^{79}\)Zn (N=48) at 4.3 MeV/u on platinum and lead targets was studied. The aim is to understand the nature of the N=40 shell closure and how strong and large in the shell gap around the double magic \(^{78}\)Ni (Z=28, N=50). The next step was to take the superconducting cavities to maximum accelerating gradient to explore the collective \(2^+\) and \(4^+\) states of the double magic \(^{10}\)Sn (Z=50, N=82) at 5.5 MeV/u in order to get information on the two particle-two-hole cross shell configurations. The energies for each experiment were chosen to maximise cross section and at the same time to ensure that the dominating and almost exclusive process was Coulomb excitation, which interaction is well known. These experiments were performed in the beamline XT01, see figure 2, and used the workhorse MINIBALL gamma array and a combination of CD-type Si detector with the T-REX one called C-REX, both installed in the first beamline for ejectile identification. Then, the second beamline, XT02, was commissioned and at the same time used to study the resonant states in the unbound nucleus \(^{3}Li\) populated by transfer reaction (d,p) of a \(^{6}\)Li beam at 6.8 MeV/u on a deuterated target, all realised in the scattering chamber SEC. The last experiment was dedicated to the
study of the gamma-ray strength function of neutron rich nuclei in inverse kinematics. An unexpected increase in the gamma strength function at low energy has been observed in stable nuclei using the Oslo method and this enhancement could be of astrophysical relevance, if confirmed in exotic nuclei. For the first time, the Oslo method was used to study the gamma strength of exotic nuclei combining the MINIBALL array with innovative LaB$_3$ detectors. Thanks to the completion of HIE-ISOLDE stage 1, this year we have dedicated 26% of the ISOLDE beam time to nuclear structure reactions for the first time since 2012.

Figure 3  Doppler corrected gamma ray spectrum of 4.5 MeV/u $^{142}$Xe beam Coulomb excited on $^{208}$Pb target (in red) and the equivalent gamma spectrum for 2.8 MeV/u $^{142}$Xe beam on a $^{96}$Mo target (in blue). The HIE-ISOLDE project will go on to achieve energies of 7.5 MeV/u next year and 10 MeV/u before the start of the 2018 campaign, completing stage 2 of the energy upgrade. This will expand even further the possibilities for experiments at ISOLDE and keep the facility at the forefront of nuclear physics research.
LHCb searches for CP violation

by Monica Pepe Altarelli

The phenomenon of violation of invariance under CP, the combined action of charge conjugation C and parity P, which is related to the difference between properties of matter and antimatter, is one of the most fundamental problems in physics. CP violation arises in the Standard Model (SM) from a single complex phase in the Cabibbo Kobayashi Maskawa (CKM) matrix that describes the transition between up- and down-type quarks by the emission of a W boson. However, the strength of the effect in the SM is largely insufficient to explain the dominance of matter over antimatter in the present universe. This motivates the search for sources of CP violation beyond the SM, which is one of the main objectives of the LHCb experiment. LHCb has been performing many accurate measurements of CP-violating asymmetries in processes involving beauty- and charm-hadron decays to determine whether they are consistent with the CKM mechanism or whether new physics should be invoked to explain them.

CP violation was initially discovered in K meson decays and subsequently observed in B meson decays, but never in any baryon decays. In a recent LHCb paper, a search was made for CP-violating asymmetries in the decay angle distributions of \( L_b \) baryons, particles with quark content \( bud \), exploiting their large production rate at the LHC. The processes under study are the four-body decays of the \( L_b \) baryon to \( p\pi\pi\pi \) and to \( \pi\pi K^+K^- \). These are decays mediated by the weak interactions, which proceed through two different amplitudes of similar magnitude. CP violation could arise from the interference of these two amplitudes with relative phases that differ between particle and antiparticle decays, leading to differences in the \( L_b \) and \( L_b (\text{bar}) \) decay rates. A powerful tool for displaying CP violation in weak decays is the investigation of triple product asymmetries. Asymmetries of scalar triple products of final-state particle momenta in the \( L_b \) centre-of-mass frame were studied to search for CP-violating effects using the whole run 1 data sample, corresponding to an integrated luminosity of 3 fb\(^{-1}\). The results were found to be consistent with CP symmetry for the less abundant \( L_b \) baryon decaying to \( \pi\pi K^+K^- \), while evidence for CP violation in \( L_b \) baryons decaying to \( p\pi\pi\pi \) was found with a statistical significance corresponding to 3.3 standard deviations including systematic uncertainties. This represents the first evidence for CP violation in the baryon sector.
Moving to charm, charm hadrons provide the only sector involving up-type quarks where CP-violating effects are expected to be observable. This uniqueness makes the study of their properties particularly relevant. CP violation in charm is still unobserved and is predicted by the SM to be below $10^{-3}$, a precision that is now within the LHCb’s reach. The decays under study were those of the $D^0$ mesons to $K^+K^-$ and to $p\bar{p}$. Charm mesons are produced either directly in the proton-proton collisions or in the decays of heavier beauty particles. Only the first category was used in this analysis, which made use of the charge of the pion from a parent $D^*$ to $D^0\pi$ decay to distinguish between $D^0$ and $D^0$ (bar) mesons at production.

*Reconstructed invariant mass distribution for $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$ decays*
Asymmetry as a function of the proper decay time for the $D^0 \rightarrow K^+K^-$ decay mode in the two samples with magnetic field vertically upwards and downwards.

The difference of the $D^+$ and $D^-$ (bar) meson decay rates into $K^+K^-$ and to $p\bar{p}$ pairs, which is sensitive to CP violation, was measured as a function of their decay time $t$ using the whole run 1 data sample. An essential part of the analysis was the accurate, data-driven study of systematic effects that could produce small deviations from an ideally CP-symmetric detector acceptance and mimic the effect of CP violation. The results were found to be consistent with CP conservation, improving by nearly a factor two the previous world-leading measurements, also obtained by LHCb using the 2011 subsample of the current data. These are the most precise measurements of CP violation ever made in the charm sector, and are consistent with no CP violation with a precision of a few parts in $10^4$.

Notes:
[1] https://arxiv.org/abs/1609.05216 (link is external)
[2] LHCb-CONF-2016-009; LHCb-CONF-2016-010
An ambitious p-Pb data taking campaign just came to an end

by Virginia Greco

These asymmetric collisions were originally meant as a benchmark to control for background effects unrelated to the production of a quark-gluon plasma, expected in Pb-Pb collisions simply due to the use of Pb nuclei instead of protons in the collisions. Distinguishing the two classes of effects in Pb-Pb collisions is difficult, whereas the study of p-Pb collisions allows physicists to isolate them one from the other.

Event from first lead-proton run at $s_{NN}=8.16$ TeV registered by ALICE on 26 November 2016.

The fist time LHC physicists collided a beam of lead ions with one of protons was September 2012. Analysing the data collected in this run, the researchers were surprised to see, in a fraction of the collisions, the signs of a collective expansion of the system, a sort of mini-Big Bang which is a characteristic hallmark of lead-lead collisions, and is commonly associated with the quark-gluon plasma properties. A full month run of p-Pb collisions with much greater luminosity then took place in early 2013, confirming and extending those first observations.

This year an extremely ambitious and challenging schedule was launched: the proton-nucleus physics programme of 2016, spanning one month, foresees three different modes of beams.

After carefully scrutinizing all the physics programmes of the four LHC experiments, it was agreed to start this proton-nucleus physics run at $\sqrt{s_{NN}}=5.02$ TeV with beam1 being the proton and beam2 the lead ion beam, respectively. This specific run was mainly dedicated to ALICE to collect a large sample of minimum-bias events, in order to measure reference p-A data at the same energy as Pb-Pb data from previous runs. Seven days of nearly uninterrupted operation at a luminosity of 0.8 $10^{28}$ Hz/cm$^2$, which was made possible by the outstanding availability of the beams from the LHC, allowed for a total of 660 million minimum bias events to be collected, increasing the data set of 2013 of this kind of events by a factor of six. During this period, LHC produced very long fills; among these, the longest fill ever, lasting for almost 38 hours.
Just one day after the completion of the data taking at 5.02 TeV, on 18 November, the LHC delivered beams for the p-Pb run at √sNN=8.16 TeV, the highest energy ever produced by a collider for such an asymmetric system. At this energy the main focus of ALICE was on rare triggers. During a six-day data taking campaign at delivered peak luminosities varying between 1.0 - 1.5 1029 Hz/cm2, ALICE collected muon triggers resulting from a recorded integrated luminosity of 8.68 nb-1. An event display registered during this period is shown in the figure below.

Event from first lead-proton run at √sNN=8.16 TeV registered by ALICE on 18 November 2016, produced in the fill with 10 colliding bunches with the proton beam going towards the Muon Arm. Tracks triggered by a coincidence between the calorimeters (PHOS) and the muon arm in the forward direction are shown. In green the reconstructed muon track can be seen while the yellow (PHOS) towers reflect the energy registered in the calorimeters in the central barrel.

Thanks to the excellent and commendable availability of the LHC throughout 2016, all major goals in terms of data taking both in pp as well as p-Pb will be met, making it an extremely successful and productive year for ALICE! We’re very excited by the possibility in this run of studying how strongly interacting matter behaves in the simpler p-Pb system, because this could actually hold the key to understanding how the quark-gluon plasma if formed” explains Federico Antinori, spokesperson-elect for ALICE.

Lead ions have 82 times the charge and are 206.4 times more massive than protons. Colliding these asymmetric beams, with very different properties and lifetimes, leads to many challenges for the LHC accelerator physicists and operators.

An exciting period for ALICE’s researchers lies ahead.
NA61/SHINE efforts in support of the US Neutrino Physics Program

Since neutrinos are charge-less, they cannot be accelerated and steered with magnets as typically done at a particle accelerator. To create a neutrino beam, researchers accelerate charged protons and impinge them onto a fixed target of a few interaction lengths that are typically made of beryllium or carbon. The resulting particle interactions, both primary and tertiary, produce charged pions and kaons exiting the target. Physicists then focus these particles into beams, at which point they decay into daughters, including neutrinos, which roughly follow the direction of the parent. As neutrino research advances and more statistics are accumulated systematic errors become important and therefore it is essential to have a precise knowledge of parent properties to reduce the overall errors when extracting the fundamental properties of neutrinos from final data.

The NA61/SHINE experiment (offspring of NA49) was approved in October 2008. Prior to approval it took neutrino inspired data in a pilot run during September 2007, with 600,000 triggers on a thin carbon target and 200,000 triggers on the replica (long) T2K target in support of the neutrino program at JPARC (Japan). This was followed with extensive data-taking for the T2K neutrino physics program with thin (6 million triggers in 2009) and long targets (10 million triggers in 2010). The incorporation of these data into the T2K neutrino flux prediction significantly reduced the beam uncertainties and greatly enhanced the physics output of T2K. The SHINE detector was primarily designed to study strongly interacting matter, quark-gluon plasma and the production of composite particles. It can therefore reconstruct particles produced from interactions in a high track density environment with great precision (see Figure 1).

![Typical Event 60 GeV pion on Be](image)

**Figure 1: Typical Event 60 GeV pion on Be**

Due to the success of the T2K experience a new partnership between scientists from US institutions and CERN was initiated to improve flux predictions for the US neutrino program at Fermilab. Researchers from Fermilab, Los Alamos National Lab, University of Colorado, and University of Pittsburgh wishing to improve the understanding of the interactions between the protons and the target recently joined the NA61/SHINE collaboration. The collection of these precise hadro-production measurements will support Fermilab experiments such as MINOS(+), MINERnA, NOνA, and DUNE.
A pilot run took place in 2012 with the first extensive data collection phase scheduled for Fall 2015. Unfortunately the vertex magnet suffered problems with its cryogenic system. Moreover it was recommended replacing the magnet safety system before any further operation of the magnets. Therefore the 2015 run was cut short and data was collected with the vertex magnets off precluding any differential cross-section measurements. However these data sets are presently being used for determining important total cross-sections. CERN made a major effort to repair the cryo-system and build a new safety system over the winter and the magnets were successfully powered on again in May 2016. The group took their first data with a completely operational detector starting with one week in late July, and a six-week period in September-October 2016. The beam-target configurations used were: 60 GeV/c pions on carbon and beryllium, 60 GeV/c protons on carbon, beryllium, and aluminum, and 120 GeV/c protons on carbon (see Figure 2) and beryllium. For each setting 2.2 - 4 million events were recorded, close to the groups goal of ~3 million in each mode.

![Figure 2: Data collection time-line for proton on Carbon at 120 GeV mode. ~4 million triggers recorded over a 6 day period.](image)

The team hopes for at least two more years of data-taking at CERN. The plan is to take additional statistics in some of the configurations we collected in 2016 as well as other beam/target/energy combinations, including possible long targets, to allow us to fill out the matrix of primary and secondary interaction hadro-production cross-sections applicable to Fermilab neutrino beams. The design of the DUNE target should be ready by the end of the long shutdown and we hope to take data with a replica target at that time.
The W electroweak gauge boson was discovered in 1983 at the CERN SPS collider. Although the properties of the W boson have been studied for more than 30 years, precise measurement of its mass remains a major challenge.

The measurement of the W mass is a very complex measurement. Achieving a high precision in the W mass measurement requires a detailed understanding of many components, both theoretical and experimental and is of prime importance for testing the consistency of the Standard Model or any deviations thereof that could provide indirect signs of new physics.

The Standard Model precisely relates the mass of the W boson to the other SM parameters. At the loop level, the W boson mass is connected with the top quark and the Higgs boson via the radiative corrections to the W mass. In theories beyond the SM, the W mass also receives contributions from new particles.

Previous limits come from electron-positron and proton-antiproton colliders, yielding a combined world average of 80385±15 MeV, driven by the Tevatron results. This measurement is consistent with the Standard Model expectation of 80358±8 MeV. LHC energies help to improve this precision with its complementarity to the previous machine and detectors.

In principle, this measurement can be performed using different methods using transverse variables: a) the transverse momentum of the lepton, b) the neutrino transverse momentum (which is also referred sometimes to
as the missing transverse energy measured by the calorimeter) and finally the transverse mass. The combination of these measurements can improve the precision on the W mass measurement. Each of these different methods provide a different balance between the experimental and theoretical level of precision.

The W mass measurement at the LHC follows a strategy similar to the Tevatron but faces different challenges. Specifically the higher pile-up environment that affects the resolution and calibration of the jets produced in association with the W boson. More specifically, the information stored in the detector when a W is produced is a lepton and a recoiling jet, both of which need to be measured precisely. The shape of the kinematic distributions must be known below the per mil level to get <10 MeV accuracy on the W mass. To meet this challenge new techniques have being developed to calibrate the lepton momentum scale to this precision and a W-like measurement of the Z mass (using the Z events as test sample to measure the Z mass as if it was a W-like system). Consequently this also poses challenges in controlling the experimental set-up as well as in theoretical modelling.

The ATLAS collaboration reported the first measurement of the W mass using LHC proton-proton collisions data at a centre-of-mass energy of 7 TeV and corresponding to an integrated luminosity of 4.6 fb⁻¹. The measured value is 80370±19 MeV, consistent with the Standard Model prediction. It is also consistent with the combined values measured at the LEP and Tevatron colliders, and with the world average (see figure). The ATLAS result matches the best single-experiment measurement of the W mass performed by the CDF collaboration.

Probing different kinematic regions compared to the previous measurements from Tevatron (moving to 7 TeV from 2 TeV) means that the uncertainties related to the proton quark substructure are expected to be larger. The enhanced amount of heavy-quark-initiated production, and the ratio of valence and sea quarks in the proton, affect the W boson transverse momentum distribution and its polarisation. The mass measurement is thus particularly sensitive to the parton distribution functions of the proton. This is because the second generation quarks become relevant, as well as there is an ambiguity between the sea and valence quarks while valence quarks also polarise the W decay along the z-direction.

In addition, the production of the W⁺ and W⁻ is not symmetric at the LHC as it was in Tevatron where proton - antiproton beams were colliding. Therefore this is a charge dependent analysis that could lead to potentially larger theoretical uncertainties on the measurements. It required an enormous amount of effort to develop an analysis strategy that would minimise model dependence and to tune state of the art detector modelling in the whole range of the transverse momentum.

There are plans to push further for such measurements with the 13 TeV data and this is driven by the expected improvements in the physics modelling. Increased statistics that can indirectly improve not only the systematic experimental uncertainties but also the theoretical set-up for the W mass measurement. Moreover a 13 TeV measurement would probe a different kinematic region. Finally, a better knowledge of the parton distribution functions, and improved QCD and electroweak predictions of W and Z boson production are crucial for further reducing the theoretical uncertainties.
Where is Supersymmetry?
by Panos Charitos

The original ideas

The original ideas for introducing supersymmetry dates back in the 1960s when, in the context of hadron physics that was found to be approximately spin-flavour independent, a symmetry between mesons and baryons was proposed.

These ideas, largely ignored at the time, found their way through mathematical investigations related to string theory into particle physics in the 70s, where, with the development of quantum field theory, a new symmetry — supersymmetry — relating bosons to fermions on the basis of a consistent algebra was developed. Andreas Hoecker (ATLAS experiment) notes: “A long way was crossed from the first theoretical concepts, developed in parallel on both sides of the iron curtain, to formulating the phenomenology of supersymmetry”. SUSY phenomenology and predictions for experimental observations came in the later 70s with the development of the minimal supersymmetric standard model (MSSM) and the concept of the so-called “R-parity” the conservation of which would avoid proton decay. The MSSM not only duplicated the number of known particles by introducing the supersymmetric partners of the Standard Model fermions and gauge bosons, but in addition required two Higgs doublets, leading to five elementary scalar bosons, and their corresponding SUSY partners.

The MSSM provided a number of favourable features that could cure shortcomings of the Standard Model — features that were not necessarily known to the fathers of supersymmetry. Paris Sphicas from the CMS experiment notes: “Years later, we know that SUSY can address three major issues in particle physics with a single strike of its magic wand: SUSY can “explain” how the Higgs boson can be so light (despite its being some 130 proton masses, its mass is many orders of magnitude smaller than what a straightforward expectation would dictate); it provides a great candidate for dark matter (in the form of the lightest supersymmetric particle); and lastly, it seems to hint that the interactions that we have been studying in particle physics (strong, weak and electromagnetism) might just be the manifestation of one unified ‘Grand Unified Theory’.”
A primary motivation for SUSY nowadays is its effect on the mass of the Higgs boson. One of the major weaknesses of the Standard Model is the presence of very large ‘radiative’ corrections to this mass. In the absence of any new physics, up to the largest energy scales where gravity would come into play, these corrections are much, much larger than the mass of the Higgs boson itself. And this makes difficult to explain the observed mass of 125 GeV. A new mechanism — e.g. a new symmetry — can lead to a natural cancellation of these radiative corrections. SUSY achieves just that.

Another strong motivation for SUSY comes from the observation that the electroweak and strong coupling strengths seem to evolve towards each other with rising energy. Nevertheless, they do not quite meet at a single value, which would be the sign of ‘grand unification’ of the Standard Model forces. Such grand unification would not only be a beautiful generalisation of the Standard Model, but would also allow protons to decay, a property deemed necessary to generate the observed excess of baryons over anti-baryons in the universe. If SUSY materializes at energy scales of 1 TeV or so, it would modify the evolution of the couplings such that grand unification might be realised. And even more: the energy scale at which unification would occur would likely be large enough to push the lifetime of the proton beyond current experimental limits.

Finally, the third argument in favour of SUSY is that, under certain circumstances, it offers a mechanism that could explain the observed dark matter in the universe. If “R-parity” and thus the number of SUSY particles is conserved (i.e. they are only produced by Standard Model processes in pairs) then the lightest SUSY particle (LSP) could not decay to solely Standard Model particles; it would thus be stable. If this LSP is neutral and weakly interacting, it is a perfect candidate for dark matter: it could even match the required amount of dark matter that has recently been precisely determined from the data of the Planck satellite.
There remains but one question: what is the manifestation of the existence of SUSY in nature? The answer is striking: every particle of the Standard Model (SM) would have a supersymmetric analog or ‘partner’, which would be identical to the SM particle, except for its spin. Quarks, which have spin $1/2$ would have scalar (spin 0) partners, called ‘squarks’; leptons would follow suit: they would have spin-0 partners called ‘sleptons’. The situation would be almost the same for the carriers of force; there is a technical difference with respect to quark and lepton partners, in that the physical SUSY partners of the SM bosons would be admixtures of states that include the Higgs SUSY partners.

If supersymmetry were an exact symmetry, the mass of each Standard Model particle and its SUSY partner would be equal. Nature, of course tells us otherwise: there is no scalar (spin 0) particle as light as the electron, while also no other superpartners have been seen so far. Paris Sphicas explains: “This is where one has to introduce additional concepts, e.g. ‘breaking’ supersymmetry so as to make these partners much heavier than the standard model particles. There are several ways of doing this, and thus, one ends up with different ‘variants’ of SUSY. Having said this, even within any specific variant, there are still several unknowns, with the most important one being the precise mass spectrum of all the SUSY particles.” This is very important, because this spectrum governs the experimental signatures that would result from the presence of these SUSY particles. As an example, if A is heavier than B, then A can decay to other particles and B. And this is a totally different scenario than B being of higher mass than A. Another example is offered by the lifetimes: if A is short-lived we expect one set of signatures, which are very different from when it is long-lived (and in some case not decay even within the large LHC experiments).

**Experimental collider searches for SUSY…**

The hunt for SUSY has been ongoing since the 1980s, at the SPS proton–antiproton collider (with the UA1 and UA2 experiments), and the $e^+e^-$ colliders PEP (SLAC, USA), PETRA (DESY, Germany) and Tristan (KEK, Japan). This was followed by an extensive set of searches at LEP and the Tevatron up until the LHC started operation. Strong indirect limits on SUSY came from flavour physics measurements as performed, among others, at CERN by the NA48 experiment and at the SLAC and KEK B-factories. Also the non-observation of an electric dipole moment in the neutron or in atoms and precise measurements of the anomalous magnetic moment of the muon constrained SUSY models.
However, the flexibility offered by the unknown breaking mechanism allowed to tune SUSY such as to evade these constraints and still allow relatively light SUSY particles that could be produced by the LHC. Andreas Hoecker notes: “Throughout this period, and during the LHC data taking phase, the experimental searches for SUSY particles have evolved significantly”. In broad terms, one set of searches is relevant when we insist that SUSY provides a dark matter candidate. The latter being weakly interacting should escape the LHC detectors and should create a measureable momentum imbalance in the event transverse to the beam axis, much like neutrinos from decays of the W and Z bosons do. This is the famous "missing transverse momentum" signature, which has been the telltale signature of SUSY searches since the SPS. The other set of searches gives up on solving "three problems for the price of one" and allows R-parity to be broken, so that the lightest SUSY particle can decay to Standard Model particles. These searches can be more difficult, as the background from the Standard Model may be very large (as an example, the production rate for quarks is much larger than the one for squarks, since the latter are assumed to have much larger mass and have spin 0). Paris Sphicas explains: “Today, we have explored large parts of SUSY ‘parameter space’. The large centre-of-mass energy at the LHC has made the ATLAS and CMS experiments sensitive to sparticle masses that are well beyond the direct limits obtained at earlier hadron colliders. The results on electroweak SUSY production from LEP are however harder to crack. With the increasing luminosity, however, even those are giving way to the LHC results. In simple terms: we have been looking for SUSY in several scenarios, and have not found it. To quantify this null result, we calculate ‘limits’ on the SUSY particles.”

The most typical R-parity conserving models of SUSY would predict signatures with jets and missing transverse momentum at the LHC, where the jets originate from decays of pairs of squarks or gluinos, the SUSY partners of quarks and gluons, and the missing transverse momentum stems from the undetected weakly interacting lightest SUSY particles (LSP). Searches for such events have not revealed any signal and provide the strongest bounds excluding gluino masses up to 1.8 TeV depending on the details of the SUSY model assumed. Sphicas adds: “This is an example of a ‘lower limit’ on the mass. The large majority of the limits we obtain are of this type. And what is the result? Well, we conclude that the SUSY partners must have masses larger than the limits determined by the analysis.” These limits, however, are not absolute but depend on other characteristics of SUSY. As Hoecker points out: “For example, large LSP masses reduce the available phase space for missing transverse momentum in SUSY events, which deteriorates the sensitivity of the searches.”
Summary of the dedicated ATLAS searches for top squark (stop) pair production (top figure) and CMS EWKino searches (bottom figure) based on pp collision data taken at $\sqrt{s} = 13$ TeV during Run 2 of the LHC.
If one wants to tackle natural SUSY, which describes a flavour of SUSY that allows to moderate the hierarchy problem by cancelling the Higgs radiative corrections, one needs to search for light top-quark partners (top squarks, also denoted stop). Stop pair production has similar final states as top pair production with, however, additional missing transverse momentum from the two escaping LSPs but also much lower cross section (roughly six times lower if the stop had the same mass as the top quark). Highly optimised analyses searched for direct and gluino mediated stop pair production in all kinds of decay scenarios. These analyses have allowed the exclusion of stop masses of up to 900 GeV (for low-mass LSPs).

It might also occur that strongly produced SUSY particles are too heavy for the current reach of the LHC and only electroweak SUSY particles are produced. Their signatures would resemble Standard Model multi-boson production giving final states with two or more leptons, only a few jets, and missing transverse momentum. Again, ATLAS and CMS have been looking for such events in highly optimised dedicated searches with, so far, no success.

The lack of evidence has inspired the experiments to also search for SUSY in events with long-lived particles or relaxed of R-parity conservation requirement. Long-lived heavy particles are predicted in many new physics models, not only SUSY. Hoecker explains “Long-lived particles may occur if new particles can only decay through much heavier intermediate states (such as predicted in a SUSY flavour called split supersymmetry), in case of a small coupling strength (such as predicted in some gauge mediated SUSY breaking scenarios where the gravitino is the lightest SUSY particle), or if there is mass degeneracy in a cascade decay (as is present in some SUSY breaking scenarios).” The search for long-lived particles employs very interesting features of the detectors such as specific ionisation loss and time-of-flight measurements, or the reconstruction of highly displaced decay vertices, and usually requires dedicated reconstruction. Searches for R-parity violating signatures approach those for non-SUSY new phenomena such as hunts for bumps from resonances or events with many leptons or many jets, but no missing transverse momentum as the lightest SUSY particles are allowed to decay to Standard Model particles.

It is clear that, beyond its intrinsic fascination, SUSY is also a powerful tool to generate new physics models for the LHC searches. Andreas Hoecker notes: “if we see a signal in one of our SUSY searches, many additional measurements would be needed before a statement about the nature of the signal could be made.”

Lessons and next steps...

The way in which experiments search for SUSY may have changed but the motivation has stayed the same, namely, finding a solution to the hierarchy problem, to force unification and dark matter. Andreas Hoecker points out that today we have an additional reason that is the Higgs discovery at 125 GeV: “The fact there seems to be only one elementary scalar particle, the Higgs boson, and that it is light is peculiar and something that needs further exploration.”

As mentioned above, the way SUSY is probed at the LHC has evolved compared to previous experiments. Full 'top-down' models of SUSY that predict, based on a few but strong assumptions on the hidden SUSY–breaking sector, the entire SUSY particle spectrum and hence the experimental signatures, have mostly been replaced by so-called simplified models that take a more 'bottoms-up' perspective. Single SUSY processes are systematically explored in terms of the masses and mixing properties of the SUSY particles occurring in them. This allows the development of signature-based search strategies that, taken as an ensemble of many searches based on different simplified models, have been shown to adequately cover also full SUSY models. As Andreas Hoecker notes: “Simplified
models are an extremely useful tool for experimentalists. They allow us to efficiently address particular features of SUSY such as stop/sbottom production, electroweak production, compressed spectra, massive long-lived particles, R-parity violation, etc. without the need to embed these in a complete SUSY model." The term “compressed spectra" defines a particularly difficult, but theoretically well possible SUSY parameter scenario in which the produced SUSY particles have small mass differences. The consequence of such a configuration would be softer particle spectra and less missing transverse momentum. Searches for SUSY with compressed spectra need large data samples and will greatly benefit from the high-luminosity upgrade of the LHC.

There has been a tremendous effort in trying to understand whether there are loopholes in the searches, that is, whether there are regions of parameter space (i.e. of mass values of the SUSY particles) that are below the experimental limits and yet would have escaped the searches. Such scenarios have been narrowed down with the increasing data statistics and ever-improving understanding of detectors and Standard Model processes.

If by the end of the LHC programme no evidence for SUSY is seen would be a disappointment for many particle physicists. For Sphicas: “In some sense, it would be a great opportunity that nature decided not to take advantage of. Presumably, because she found an even better opportunity.”

For Hoecker: “The exclusion limits on SUSY and other new physics scenarios obtained at the LHC continue to put stress on the naturalness of the scalar sector of the Standard Model. However, although naturalness, that is the factorisation of very different distance scales, is appealing and a central concept in physics, we do not know whether Nature obeys to it for the Higgs boson. The experiments need higher luminosity and eventually higher energy to progress on this profound question.”

HL-LHC upgrade and plans for a future high-energy circular collider...

Searches for SUSY will benefit from the HL-LHC upgrade and, in particular, from a future high-energy hadron collider. Roughly, a 100 TeV collider would allow the experiments to probe SUSY particles that are ten times heavier than the LHC is currently sensitive to.

At some point in time, we will be close to the ultimate masses that the LHC can explore, and the question will become what happens next. Sphicas explains: “When we do reach that stage, the answer is simple: we will have to go higher in the masses we probe; and up to now, this has meant increasing the energy of our machines. Perhaps an example from history can help here: with the u, d and s quarks discovered, there was a solid and quite predictive theory of particles and their interactions. And in terms of ‘observables’, essentially the only measurement that did not quite fit in was some rare decays of neutral kaons. The solution to that was proposed by Glashow, Iliopoulos and Maiani (the so-called GIM mechanism). It was an elegant solution, but it demanded the presence of a fourth quark. Theory provided guidance that ‘something must happen by ~2 GeV’. And the tilde implies a rough approximation. Thankfully, the experiments at Brookhaven (S.C.C.Ting) and SLAC (B.Richter) had enough energy to produce the J/psi, the bound state of this new quark and its antiquark. The discovery is known as ‘the November revolution’ – for a revolution it was. What would have happened if the available accelerators did not have enough energy to produce these particles? I guess the next step would be to build one that could”

So you may wonder will we ever know with certainty if SUSY exists or not? “Yes, the day we discover it!” answers Sphicas. As for the other case: just like we will never know that the proton does not decay (all we can ever show is that it decays more slowly than some incredibly small rate), it is impossible to show that something does not occur in nature.

As to whether there are alternatives to SUSY? Here is a quick answer from Sphicas: “Of course there are alternative theories that try to tackle the same questions. Human imagination and more specifically
the creativity of theorists have been shown to be boundless. The one thing that can be said about SUSY is that it seems to be the only one that could solve three issues for the price of one new principle. Of course, the stress here is on the words ‘seems to be’.

The author would like to thank Andreas Hoecker (ATLAS) and Paris Sphicas (CMS) for their invaluable contribution and thoughtful comments on this article.

Latest public results for SUSY searches in the dedicated pages from the ATLAS (here) and CMS (here) experiments.

A new experiment searching for dark matter at CERN
by Stefania Pandolfi

One of the biggest puzzles in physics is that eighty-five percent of the matter in our universe is “dark”: it does not interact with the photons of the conventional electromagnetic force and is therefore invisible to our eyes and telescopes. Although the composition and origin of dark matter are a mystery, we know it exists because astronomers observe its gravitational pull on ordinary visible matter such as stars and galaxies.

Some theories suggest that, in addition to gravity, dark matter particles could interact with visible matter through a new force, which has so far escaped detection. Just as the electromagnetic force is carried by the photon, this dark force is thought to be transmitted by a particle called “dark” photon which is predicted to act as a mediator between visible and dark matter.

“To use a metaphor, an otherwise impossible dialogue between two people not speaking the same language (visible and dark matter) can be enabled by a mediator (the dark photon), who understands one language and speaks the other one,” explains Sergei Gninenko, spokesperson for the NA64 collaboration.

CERN's NA64 experiment looks for signatures of this visible-dark interaction using a simple but powerful physics concept: the conservation of energy*. A beam of electrons, whose initial energy is known very precisely, is aimed at a detector. Interactions between incoming electrons and atomic nuclei in the
detector produce visible photons. The energy of these photons is measured and it should be equivalent to that of the electrons. However, if the dark photons exist, they will escape the detector and carry away a large fraction of the initial electron energy.

**View of the NA64 experiment set-up. (Video: Noemi Caraban/CERN)**

Therefore, the signature of the dark photon is an event registered in the detector with a large amount of “missing energy” that cannot be attributed to a process involving only ordinary particles, thus providing a strong hint of the dark photon’s existence.

![Plot from::](https://arxiv.org/pdf/1610.02988v2.pdf (link is external))

*Note: [https://arxiv.org/pdf/1610.02988v2.pdf](https://arxiv.org/pdf/1610.02988v2.pdf)*

The NA64 90 % C.L. exclusion region showing also constraints from the BaBar and E787+ E949 experiments as well as muon $\alpha_\mu$ favored area. (Plot from:: [https://arxiv.org/pdf/1610.02988v2.pdf](https://arxiv.org/pdf/1610.02988v2.pdf) (link is external)).

If confirmed, the existence of the dark photon would represent a breakthrough in our understanding the longstanding dark matter mystery.

*Note: [https://arxiv.org/pdf/1610.02988v2.pdf](https://arxiv.org/pdf/1610.02988v2.pdf)*
An amazing year for the DT group

by Mar Capeans Carrido

The DT group, provides centralized resources and expertise in terms of personnel and facilities, for the development of future detector technologies, R&D and contributes to detector construction projects. Thank to the vast range of activities, infrastructure, expertise, and long-standing collaborations with CERN experiments 2016 has been an amazing year for the group. Specific partnerships for Phase 1 detector upgrades were launched with CERN teams in ALICE and LHCb are all well progressing. Moreover, detector prototyping support for the ATLAS and CMS detectors for the Phase 2 upgrade has already started. Finally, DT continues providing technical support to Small and Medium Experiments while contributions to engineering, DAQ and DCS for the CERN Neutrino Platform activities at CERN have been launched during this year.

In terms of infrastructure for the experiments, the Detector Infrastructure Section continued the modernization of magnet safety systems for the LHC experimental magnets and others such as Compass, VTX1-2, M1 and Morpurgo. The section offers also DAQ support, and the first efforts have focused on the stabilization and performance optimization of NA62 DAQ software and on taking a leading role for design of ProtoDUNE SP DAQ system.

In the Fluidics Section, on top of the regular LHC gas systems M&O responsibility, detector gas systems have been improved to adjust to new operational requirements and also to resulting in reduced costs for the experiments. Studies on the use of eco-friendly gases for LHC systems and gas analysis techniques are ongoing. A CO₂ cooling plant has been installed in CMS for the new Pixel system, and a demanding R&D programme has been launched with ATLAS and CMS to develop future large CO₂ plants for the Phase 2 Trackers. In terms of on-detector cooling, a new set of GigaTracker modules for NA62 successfully use micro-fabricated ultra thin silicon micro-plates directly bonded on to the sensors for localized cool down.

The DT irradiation facilities team has been focused on operating the PS East Area irradiation facilities (IRRAD) and the Gamma Irradiation Facility at the SPS North Area (GIF++). IRRAD had about 200 days of beam time in which 400 objects were irradiated for 28 different teams. GIF++ is being used by 20 different teams that run 24/7.

The Departmental Silicon Facility (DSF) upgraded its infrastructure in view of the high demand from LS2 and LS3 projects; a new bonding machine was acquired, and the room access policy and infrastructure modernized. The team processed 200 wire-bonding jobs for 40 different projects. The complementary Quality Assurance and Reliability Lab (QART), containing high-end QA equipment, handled about 20 expert jobs in the year.
Commissioning of the new wire Boding machine in the DT bonding lab.

The Thin-Film-Glass Facility (TFG) continued to give support to the different detector groups in terms of thin film coating and glass and ceramic machining. In 2016 several prototypes and small series have been produced for COMPASS, RD51 groups, CLOUD, and some expert consultancy was given to projects such as AWAKE.

This B-field characterization service provided magnetic field measurements developing custom mechanical setups for BELLE-II in Japan.

The Micro-Pattern Technologies (MPT) workshop activity is now more directed towards prototyping and production of detector components and detector R&D. Productions of large-size GEM foils for CMS GE1/1 and ALICE TPC have been launched, complemented with a strong industrialization effort in view of future projects. The team continued to successfully develop new detector concepts, such as micro-Rowell and embedded resistive mini pads micro-megas, that both have revealed exciting performances.

Large GEM foils produced in the EP-DT Micro-pattern Technologies workshop.
The new DT carbon-composite laboratory has produced C-prototypes for CLIC, CMS, LHCb and ATLAS.

The group has also pursued R&D on detector technologies for the interest of the overall HEP community. About 30 fellows and students work on different aspects of the DT R&D detector programme. The Solid State Detector (SSD) team is developing radiation tolerant silicon sensors for the vertex and tracking detectors for the luminosity upgrade of LHC. For example, DT participates in the evaluation of highly neutron irradiated silicon sensors for the CMS forward calorimeter concept. The SSD team also contributes to several projects within the RD50 Collaboration, such as the study of Low Gain Avalanche Detectors (LGAD) as tracking devices in high radiation environments and/or fast timing applications.

The Gaseous Detectors R&D team continues playing a major role in the RD51 Collaboration, focusing on the promotion and development of the Micro-Pattern Gaseous Detector (MPGD) technologies. The team actively supports the developments for the LHC experiments, and pursues novel R&D on precise timing with micro-megas, GEM optical readout, aging of GEM detectors, neutron detectors.

Finally the DT group contributes to future projects. R&D for the CLIC_ILD detector concept touches on vertex and high-granularity calorimeter technologies while the DT effort on micro-engineering and applications as micro-fluidics cooling as well as connectivity or development of MGy dosimetry for FCC are ongoing.

2016 has again be a year full of projects and we are looking forward to a successful continuation of all the activities in 2017!

You can follow up the activities of the EP-DT group in the group's website.
End of year news from EP-SFT

by P.Mato, J. Harvery, D. Piparo, G. Cosmo, G.Ganis, S. Gleyzer, W. Pokorski

The end of year is traditionally the time when SFT makes new releases of our main software products. It is a very busy time with everyone working energetically to meet various deadlines. All last minute changes and fixes need to be integrated and run through extensive checks to ensure that quality of the performance of the code is not compromised in all its aspects. As the new releases are getting finalised work on the rest of our projects as well as our R&D's is continuing. We are aiming to advance our various software tools as well as infrastructure we provide to the CERN experiments and collaborators. We strongly commit to educating and training students through schools such as the CERN School of computing, CERN's student program and external programs, such as Google Summer of Code.

As for any of our projects, a lot of valuable feedback is encouraged and expected from the user community in the coming weeks.

More details on some of our activities.

The scale deployment of the two main products of the CernVM ecosystem, the CernVM File System and CernVM Appliance, are such that about 350 million files - belonging to about 50 experiments - are distributed worldwide by CernVM-FS, and more than 10,000 new VMs instantiated every month to serve the needs of the LHC experiments. In 2016 the CernVM team released a new consolidated version of CernVM-FS which opens up the possibility of contributions from external collaborators to satisfy new emerging use cases, such as namespacing for data federations. Support for the CernVM appliance has been extended to cover all major cloud providers, both commercial (Google Compute Engine, Amazon Web Services, Microsoft Azure) and academic (Openstack, Cloudstack and Opennebula). In the beginning of June the team held the 2nd Users Workshop at RAL, UK. More than 40 registered participants attended and discussions were a good opportunity for developers, infrastructure maintainers and users to exchange ideas and setup new collaborations. Invited speakers from industry (IBM, VMware, Linaro, Mesosphere, Pivotal) gave dedicated talks on technology trends that were well received by the audience.

The new 2016 release of Geant4, release 10.3, consolidates further the code base for version 10 series of the Geant4 toolkit and introduces several new features, like the ability to now handle multiple actions of the same kind from the user code. The geometry modeller in release 10.3 provides improved algorithms for computing the extent of the geometrical shapes, consequently reducing the memory required for optimizing the geometry setup and providing more efficient tracking. Particle properties have been updated according to PDG-2015 and new floating level base to ions is now introduced. Electromagnetic physics processes parameters are now being handled all in a single class and can be modified via interactive UI commands. Corrections of the LPM suppression effect in electron/positron bremsstrahlung are included. The tuning of the Fritiof hadronic model has been set to the stable version of the model, based on the measurements made by LHC experiments for the hadronic showers. The
new release also includes refinements and extensions of the intra-nuclear cascade models (Bertini-like and INCL), as well as improvements both in code structure and physics of nuclear de-excitation and radioactive-decay.

ROOT Data Analysis Framework

A major version of ROOT 6, version 6.08, has been released for 2017 data taking and analysis. The new ROOT includes, among many other things, a major upgrade of the ROOT interpreter engine which allows to seamlessly interface with the most modern compilers, essential to squeeze out the last drops of performance out of recent computer architectures. The support for the expression of parallelism, both following a multithreading and multiprocessing approaches, was significantly developed. Several operations ROOT performs are now implicitly parallelised, i.e. without user intervention. Explicit parallelism is more accessible to analysers that want to speed up the study of their datasets controlling the parallelisation of their algorithms relying on ROOT. Analysis is the main focus: more tools to express analyses in form of configuration files or command line arguments have been added as well as a complete integration with the Jupyter technology. Thinking about the future, a lot of effort was put in the modernisation of the ROOT interfaces. An exciting process of development, prototyping and engagement of the users' community of experiments started to deliver new ROOT modern interfaces which will allow to further increase the productivity of the scientific community.

Machine Learning is pretty developed in ROOT. This year there were a number of major new developments. A significant update of the Toolkit for Multivariate Analysis (TMVA) happened in version 6.08, offering many new features. These include a new deep learning library that supports both NVIDIA and INTEL graphical processing units, cross-validation and hyperparameter-tuning algorithms, unsupervised learning features and interactive training and new visualizations with Jupyter notebooks. Machine learning regression capabilities have been extended and new interfaces to external machine learning tools added, such as Keras. The user interface has also been upgraded, making TMVA output more friendly. In the coming year, the plan is to continue expanding machine learning tools in ROOT, and working closely with the Inter-experimental LHC Machine Learning (IML) working group to identify areas of priority in machine learning software and tools for experiments.

AIDA 2020

The AIDA-2020 project is part of the Horizon-2020 European framework and its aim is to advance the detector technologies both on the hardware as well as the software side. The Advanced Software work-package of the AIDA-2020 project contains a number of development tasks related to the core, simulation and reconstruction software. EP/SFT is responsible for coordinating the work-package as well as in the development of two new software toolkits:

- the first of these is for modelling complex detector geometries (USolids/VecGeom) and a first version has now been released. The different algorithms used during the navigation within the geometrical structure exploit vectorisation and they show a significant performance gain with respect to existing
implementations. The new library can be used from the latest releases of Geant4 and ROOT, so that its impact can be evaluated by the experiments in realistic applications.

- the second is the Event Data Model toolkit which supports the creation of models with high-performance I/O capabilities. This is achieved by basing the design on 'Plain Old Data' concepts (POD). The first production quality version is now available and is currently used by the Future Circular Collider collaboration, whilst other LHC and Linear Collider communities are evaluating it.

The CERN Service for Web based ANalysis, SWAN, took off. It is now used by several tens of users daily and it demonstrated to shine in several occasions when it was time to deliver successful tutorials. During the Summer Students' ROOT workshop, the CERN School of Computing or the recent Statistic Academic Training, SWAN was the infrastructure used for the hands-on exercises and was able to serve up to 250 users simultaneously without showing any alteration of performance and responsiveness. A great collaboration between the SFT and IT-ST groups that delivered a high quality product!

Google Summer of Code in EP-SFT

This year was the 6th year EP-SFT has participated as a mentoring organisation in the Google Summer of Code (GSoC 2016). It was a very productive experience for students and their mentors. A number of innovative open-source software projects were completed in areas of particle and detector simulation, data analysis tools, graphics and machine learning. Two of the students working on machine learning projects were highlighted for their work by Google, and they were invited to present their projects at the Interexperimental LHC Machine Learning (IML) working group meeting in September. Next year EP-SFT is exploring the possibility of becoming a GSoC umbrella organisation via the HEP Software Foundation, possibly extending the reach of the program to the wider HEP community. We look forward to another productive Google Summer of Code program in 2017!
Physics at 100 TeV

by Panos Charitos

A report discussing the opportunities for physics discoveries with a future 100 TeV hadron circular collider was presented earlier this summer during the 2016 FCC Week.

A future hadron-hadron collider machine will be able to cover previously unexplored territory at energies never before reached in a laboratory environment. Standard Model calculations will enable precise predictions for known particles and forces in the new frontiers. The comparison of observations against predictions will allow for the structure of the Standard Model to be tested at unprecedented energies and with unparalleled precision.

If observations and predictions agree within estimated uncertainties this would provide a stunning confirmation of the present Standard Model for particle physics, that however leaves a number of questions unanswered including those on the nature of dark matter, the masses of neutrino and the observed matter/antimatter asymmetry. If on the other hand, observations do not agree with theoretical predictions this would mark the need to rethink the physics that might lie beyond the Standard Model while we might observe the rise of new phenomena. In that sense, a 100 TeV collider will push to a more fundamental understanding of the laws of nature and our understanding of how the Universe evolved after the Big Bang.

One of the most fascinating questions is related to the phase transition between unbroken and broken electroweak symmetry that took place during the Big Bang and is responsible for the baryonic asymmetry that we observe in today’s Universe. In the SM, a Higgs boson heavier than 60 GeV is too weak to generate the required asymmetry between matter and antimatter. This means that a 125 GeV Higgs boson like the one discovered at the LHC must also come with other interactions beyond the SM and additional sources of CP violation that are responsible for the observed matter/antimatter asymmetry.

The scale of these phenomena should be within few TeV; not too far from the electroweak breaking scale. Models have been proposed for these new phenomena, but their direct manifestation could escape detection at the LHC, if the masses are too large. The FCC could give a conclusive answer to the question whether the baryon asymmetry was generated at the electroweak phase transition. Likewise it is expected that a collider at 100 TeV could provide conclusive answers to the question of whether the Higgs sector is made of a single Higgs or whether there are other Higgs bosons at the TeV scale, and whether physics at the electroweak scale is responsible for dark matter.

A hadron collider at 100 TeV could allow for precise measurements of the Higgs self-interaction process, whose structure is deeply related to the origin and mass of the Higgs particle itself. Extending the study of the Higgs and its interactions with other particles of the SM to energies well above the TeV scale could provide a way to analyse in detail the mechanism underlying the breaking of the electroweak symmetry. At a more fundamental level the proposal of a 100 TeV proton-proton collider stems from the bold leap into the completely uncharted new territory that it offers, probing energy scales, where fundamental new physical principles might be at play.

The observation of Standard Model processes has an interest per se. Billions of Higgs bosons and trillions of top quarks will be produced, creating new opportunities for the study of rare decays and flavour physics within the SM which tremendously benefit from higher collision energies. The huge rates available at 100 TeV allow to push to new limits the exploration of rare phenomena (e.g. rare decays of top quarks or Higgs boson) the precision in the determination of SM parameters and the test of possible deviations from Standard Model predictions.
Standard Model processes provide a necessary reference to benchmark the performance of the detectors of future experiments both for studying SM processes with higher precision but are also key in searches for new physics. It should be noted however that one should rethink any statements about the precision of theoretical calculations in the time-window for a post-LHC facility.

The leap in energy to 100 TeV gives a huge increase in the reach for new physics that could lie beyond the Standard Model. A seven-fold increase of the centre-of-mass energies relative to the LHC with a luminosity comparable to that of the LHC increases the mass reach for new particles significantly. The possible observables that will be accessible are extensively discussed in the FCC-hh physics report.

The 100 TeV pp collider will significantly extending the energy reach allowing to hunt for new fundamental particles roughly an order of magnitude heavier than what we can possibly produce with the LHC. It may also be the case that particles currently produced at the LHC in small numbers will be produced with up to a thousand times higher rate, giving us a new window into the mechanisms at play in the evolution of our Universe and provide experimental evidence for some of the theoretical developments that try to explain the deficiencies of the Standard Model.

Finally, the FCC-hh collider is also foreseen to be used a heavy-ion collider opening the path to a heavy-ion physics programme at the FCC. The highest energy reach will offer an opportunity to push the exploration of the collective structure of matter at the most extreme density and temperature conditions to new frontiers through the study of heavy-ion collisions.

Though one has to wait for the results of the current run of the LHC, there are reasons to believe that a new description beyond the Standard Model may be required at energies up to 100 TeV and a number of different scenarios are included in the report offering a solid basis for discussing the physics possibilities and opportunities that FCC-hh could open to the international scientific community.

The findings of this report will serve as a reference for future studies and to stimulate new ideas on how to best exploit the immense potential of a future circular collider like the one studied under the FCC-hh scenario. In addition the report will serve as a baseline for the different communities (accelerator design, detector design) involved in the FCC study toward the preparation of a conceptual design report for 2019.

The first Future Circular Collider (FCC) physics workshop will take place at CERN on January 16 through 20, 2017 preceding the 2017 FCC Week that will take place in Berlin from 29 May to 02 June 2016.

The physics workshop focuses on the broad physics opportunities offered by the FCC study. All sessions will be plenary, with an emphasis on the complementarity of the different components of the programme (ee, hh and eh). Original ideas and contributions on alternative
experimental approaches in the global context of the FCC – also including physics with beam
dumps and the injector complex, and physics in the forward region – are strongly encouraged.
Please register at the workshop website.

Read more:
Become a Higgs Hunter

by Katarina Anthony,

HiggsHunters is the first mass-participation citizen science project for the Large Hadron Collider, allowing non-experts to get directly involved in physics analysis. Since its launch in 2014 on the Zooniverse platform, over 30,000 people from 179 countries have participated in the project. Their work has led to the project’s first publication on arXiv (link is external).

Citizen scientists are asked to examine ATLAS event displays, looking for “off-centre vertices” where several tracks intersect away from the central collision point. These events may indicate the presence of a new long-lived particle; such a discovery would be extremely significant to the scientific community.

Analysing event displays on the HiggsHunters website. (Image: ATLAS Experiment/CERN)

The recently-released paper shows the results of over 1.2 million event display classifications. “We found the collective ability of our volunteers to be excellent,” says Alan Barr, ATLAS physicist who led the creation of the project (University of Oxford). “Our citizen scientists are very good at pattern recognition by eye, and are able to spot ‘weird’ or unusual events that wouldn’t otherwise have been identified. In fact, for certain particle types, they were even able to identify ‘off-centre vertices’ better than existing computer algorithms.”

These results help to cement the scientific viability of citizen science projects in high-energy physics. “Even without making a discovery, our volunteers have made a great contribution,” says Barr. “We hope to feed back their results to improve our existing analysis algorithms.” Given the success, there’s plenty of opportunity for further papers from HiggsHunters.

Interested in becoming a sharp-shooting Higgs hunter? Join the project’s thriving community by visiting HiggsHunters.org
On 5 December, the 2016 LHC run came to a close, marking the end of the first full year of data-taking at a beam energy of 6.5 TeV. Over the past year, the machine delivered peak proton–proton luminosity well above design levels to ATLAS and CMS, coupled with excellent availability. ALICE and LHCb also enjoyed sustained operation at their requested levelled luminosity values. The impressive final 2016 totals of 40 fb$^{-1}$ to ATLAS and CMS, 1.9 fb$^{-1}$ to LHCb and 13.4 pb$^{-1}$ to ALICE reflect the immense amount of effort that has gone into the preparation of beam in the injectors and the performance of the accelerator systems. They also reflect the established level of understanding and control, to maximise overall performance while safely and relentlessly driving the beams through the complex operational cycle.

This level of control is shown in the flexibility of the LHC during dedicated special physics runs and a diverse and dynamic machine development programme. Special runs in 2016 included a challenging set-up with very large beams at the interaction points of ATLAS and CMS. These were needed for the forward physics experiments, ALFA, TOTEM and AFP, allowing them to successfully probe the very small angle proton–proton elastic scattering regime. However, a real demonstration of the maturity of the LHC came at the end of the year.