EP Newsletter of the EP department

A ground-breaking ceremony was held on the 15th of June, to celebrate the start of civil engineering work for a major upgrade to the LHC . When completed in 2026, the HL-LHC will produce a five to seven times higher rate of proton-proton collisions, providing better statistics and powering new discoveries that could answer the fundamental questions about our universe. The highlight of the first run of the LHC was the observation of a Higgs boson in 2012, and it has also provided a wealth of measurements of electroweak and QCD processes. However, we have only scratched the surface of the ultimate physics potential of the LHC. There are still many open fundamental questions in particle physics that can be addressed by increasing the luminosity of the collider.

The increase in the number of collisions in HL-LHC, means more observations of rare phenomena and more chances for discovery. As an example, the upgrade will increase the number of Higgs bosons that can be produced by the LHC from 1.2 million to 15 million. The HL-LHC data will enable the improvement of the precision on Higgs boson couplings by a factor of 2 to 3 with respect to the previous LHC running.

Furthermore, extensive searches of SUSY particles have found no compelling evidence so far, thus putting stringent limits on the masses of the potential supersymmetric partners. Supersymmetric models motivate a large set of searches, including those for strongly produced supersymmetric particles. The higher luminosity of the LHC will allow to search for rare processes including third generation squarks, electroweak-inos and particles predicted by various compressed SUSY models.

Other exotic models of new physics have been explored including particles to explain the observed light mass of the Higgs and signatures that could account for the mysterious dark matter. The LHC probes various types of interactions and dark matter can be detected by tagging SM particles in the detector and identifying the recoiling dark matter particles from a missing transverse energy signature. These searches can benefit from the higher statistics available at the HL-LHC - that will allow to discern signals from the noisy background - and will complement the direct astroparticle searches for dark matter. The tenfold larger dataset of HL-LHC results in a 20% approximately increase in mass reach while it would also allow detailed studies of any newly discovered particle in the next runs of the LHC.

The main pillars of its physics programme are precision measurements of the Standard Model including the Higgs boson, searches for new physics through the study of rare processes, searches for new heavy states, and measurements of the properties of any newly discovered particles. The imbalance between matter and anti-matter in the universe is a big open issue for flavour physics. Finally, there may be a new weakly interacting massive particle to explain the existence of Dark Matter. If evidence of deviations from the Standard Model are seen before the upgrade, the HL-LHC will allow further scrutiny of the new landscape of particle physics. In the absence of any such hint, the ten-fold increase in data will push the sensitivity for new physics into uncharted territory.

"The High-Luminosity LHC will extend the LHC's reach beyond its initial mission, bringing new opportunities for discovery, measuring the properties of particles such as the Higgs boson with greater precision and exploring the fundamental constituents of the universe ever more profoundly," mentioned CERN's Director-General Fabiola Gianotti during the ceremony.

Moreover, HL-LHC will allow to push many of the technologies needed for any future energy and intensity frontier collider that could come after the completion of the LHC's scientific programme in 2036. Since 2010, scientists, engineers and technicians from all over the world, have been conducting R&D on new technologies that would make operations at the HL-LHC possible. The project will involve the replacement of high-tech accelerator components along 1.2 kilometres of the machine. Indeed High Luminosity LHC (HL-LHC), relies on a number of key innovative technologies, representing exceptional technological challenges, such as cutting-edge 11-12 tesla superconducting magnets, very compact superconducting cavities for beam rotation with ultra-precise phase control, new technology for beam collimation and 300 m long high-power superconducting links with negligible energy dissipation, able to carry currents of record intensities to the accelerator, up to 100,000 amps, over 100 metres.

“We have to innovate in many fields, developing cutting-edge technologies for magnets, the optics of the accelerator, superconducting radiofrequency cavities, and superconducting links,” explained Lucio Rossi, Head of the High-Luminosity LHC project. HL-LHC will also see the construction of new buildings, shafts, caverns and underground galleries, as well as tunnels and halls to house the new cryogenic equipment, as well as power supplies and cooling and ventilation kit.

All these technologies have been explored since 2011 in the framework of the HiLumi LHC Design Study - partly financed by the European Commission's FP7 programme. HiLumi LHC brought together a large number of laboratories from CERN’s member states, as well as from Russia, Japan and the US. American institutes participated in the project with the support of the US LHC Accelerator Research Program (LARP), funded by the U.S. Department of Energy. Some 200 scientists from 20 countries collaborated on this first successful phase.

Moreover, the LHC experiments plan their major upgrades to fully exploit the opportunities offered by the increased luminosity. The expected average number of simultaneous proton-proton (pp) collisions (pile-up) will increase from 40 to up to 200, making each event much larger in size and much more complex to record and analyse. Faster detectors and readout electronics, as well as sophisticated trigger systems to efficiently identify physics signatures, will be required. Finally, the detectors will need to tolerate a substantial radiation dose.

During the civil engineering work, the LHC will continue to operate, with two long technical stop periods that will allow preparations and installations to be made for high luminosity alongside yearly regular maintenance activities. After completion of this major upgrade, the LHC is expected to produce data in high-luminosity mode from 2026 onwards. By pushing the frontiers of accelerator and detector technology, it will also pave the way for future higher-energy accelerators. “Audacity underpins the history of CERN and the High-Luminosity LHC writes a new chapter, building a bridge to the future,” said CERN’s Director for Accelerators and Technology, Frédérick Bordry. “It will allow new research and with its new innovative technologies, it is also a window to the accelerators of the future and to new applications for society.

Further reading:

1. HL-LHC Preliminary Design Report: https://cds.cern.ch/record/2116337?ln=el

2. HL-LHC website: http://hilumilhc.web.cern.ch

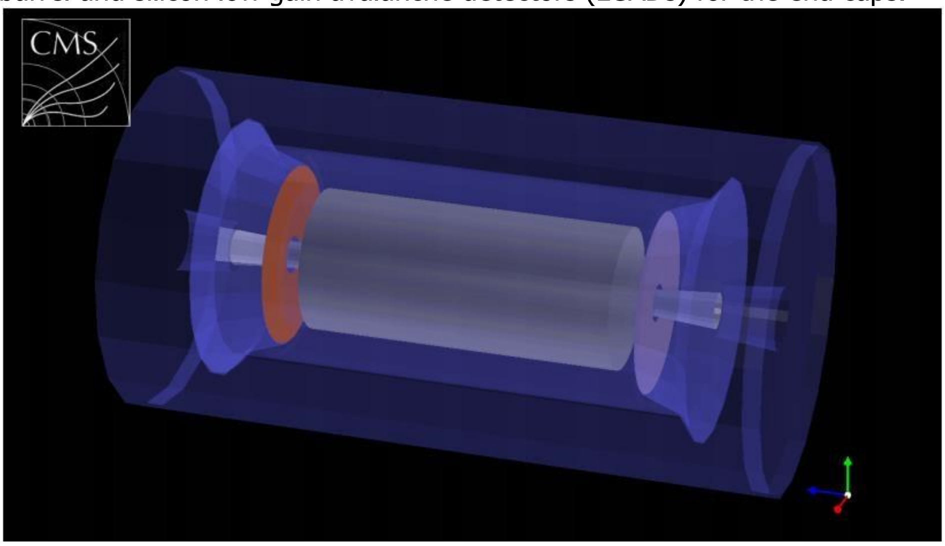
Precise timing detectors for the LHC experiments

The ATLAS and CMS experiments physics programme at the HL-LHC will target a very wide range of measurements, including in-depth studies of the Higgs boson properties and direct searches for physics beyond the standard model (BSM). Timing detectors will help improve vertex identification, acceptance extension for isolated objects, improved missing transverse momentum resolution, and pileup jet rate reduction that make a significant impact on the their physics programme across several channels. The characterization of the Higgs boson properties, with precision measurements of the Higgs boson couplings to standard model (SM) particles, and the search for rare SM and BSM decays, will benefit from timing detectors. In addition, the proposed detectors will increase the sensitivity to several searches for new phenomena that are part of the HL-LHC scientific programme, including many SUSY models. Finally, the precise track-time reconstruction opens a new avenue in searches for neutral long lived particles (LLPs), postulated in many extensions of the Standard Model and ALP searches.

CMS and ATLAS experiments have recently been approved for their technical proposal for timing detectors [CERN-LHCC-2017-027] and [CERN-LHCC-2018-023] and should submit their technical design reports by the first quarter of 2019.

CMS timing detectors at HL-LHC and the pileup combat

The CMS collaboration submitted a technical proposal for a dedicated timing detector aimed at providing timing information with about 30 ps resolution for charged tracks. This MIP Timing Detector (MTD) will complement the timing capabilities for photons in the electromagnetic calorimeters and for hadron showers in the forward region of the upgraded CMS experiment. The MTD will consist in a single layer providing timing in the barrel and the end cap region, with an angular coverage up to a pseudorapidity $|\eta|<3.0$. Radiation tolerance, integration, services, and schedule constraints, as well as cost considerations, lead to the choice of LYSO crystals read out by silicon photomultipliers (SiPMs) for the barrel and silicon low gain avalanche detectors (LGADs) for the end caps.

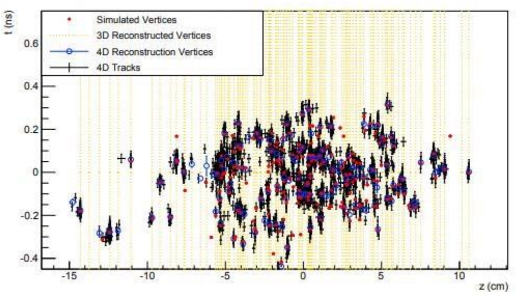


A simplified GEANT geometry of the timing layer implemented in CMSSW for simulation studies comprises a LYSO barrel (grey cylinder), at the interface between the Tracker and the ECAL, and two silicon endcap (orange discs) timing layers in front of the CE calorimeter.

The CMS experimental program at the HL-LHC, which include the precision characterization of the Higgs boson as well as searches of particles and processes not included in the so-called standard model of particle interactions, will benefit greatly from the increased luminosity provided by the upgrade of the LHC accelerator complex. However, particle reconstruction and correct assignment to primary interaction vertices in the presence of as many as 200 concurrent collisions per beam crossing (pileup events) represents a formidable challenge to the LHC detectors that must be overcome in order to harvest that benefit.

Pileup mitigation typically relies upon the removal from relevant quantities of charged tracks inconsistent with the vertex of interest, and of neutral deposits in the calorimeters with ansatz-based statistical inference techniques like PUPPI. Time tagging of minimum ionizing particles (MIPs) produced in LHC collisions provides further discrimination of interaction vertices in the same 25 ns bunch crossing beyond spatial tracking algorithms. According to preliminary simulation studies, a timing resolution of about 30 ps, about one sixth of the time spread of the LHC luminous region, holds the promise to recover the track purity of vertices of current LHC conditions, offsetting the performance degradation due to event pileup experienced in several observables.

The event display in the left panel of Fig.1, for instance, visually illustrates the power of space-time reconstruction in 200 pileup collisions, with a time-aware extension (4D) of the vertex reconstruction used by the CMS experiment. On average, the instances of vertex merging are reduced from 15% in space to 1% in space-time. Another measure of the performance improvement is illustrated in the right panel of Fig.1, showing the rate of tracks from pileup vertices incorrectly associated with the hard interaction vertex as a function of the line density of vertices. The rate of incorrect associations increases with the line density, as vertices start to overlap within a window for track-to-vertex association optimized for the 3D reconstruction. The addition of track-time information reduces the wrong associations at the typical vertex densities planned for HL-LHC operation (1.4-1.9 mm^{-1}) to a level comparable to those observed without timing at the LHC vertex density of to about 0.3 mm^{-1}



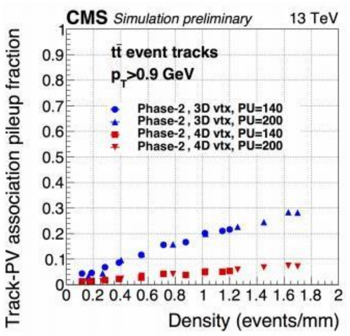


Fig.1 - Left: Simulated (red-dots) and reconstructed vertices (blue) and tracks (black) in 200 pileup collisions using 4D tracking; vertices merged in 3D (yellow lines) are separated in 4D. Right: Rate of tracks from pileup vertices incorrectly associated with the primary vertex as a function of the vertex density.

Preliminary studies show that time cleaning substantially improves the reconstruction of final state observables relevant for the identification of processes with Higgs boson production and decays. The performance of b-jet identification, which relies on vertex reconstruction, is enhanced. The removal of pileup tracks from the isolation cones improves the identification efficiency for isolated leptons and photons. Similarly, the reconstruction of spatially extended objects and global event quantities that are vulnerable to the pileup, such as jets and the missing transverse momentum, is improved. Efficiency gains at the single-object level compound in multi-object final states – such as Higgs boson decays to four leptons, di-Higgs boson events or events where the Higgs boson is produced in association with other particles – providing potential gains, at constant rate of reducible backgrounds, of about 20-30% across all measurements. In addition, the ability to reconstruct the time of displaced vertices will provide enhanced capability in the search of long-lived particles (LLPs), with the ability of resonance reconstruction of the LLPs mass. The projected performance gains, for a 30 ps precision and hermetic coverage up to $|\eta|<3$, are summarized in Table 1.

Signal	Physics measurement	MTD Impact
$H\rightarrow\gamma\gamma$ $H\rightarrow$4leptons	**+25%** statistical precision on xsecs → Couplings	Isolation Vertex identification
VBF+$H\rightarrow\tau\tau$	**+30%** statistical precision on xsecs → Couplings	Isolation VBF tagging, MET
HH	**+20%** gain in signal yield → Consolidate searches	Isolation, b-tagging
EWK SUSY	**40%** reducible background reduction → +150 GeV mass reach	MET
Long Lived Particles (LLP)	Peaking Mass Reconstruction → Unique discovery potential	β_{LLP} from timing of displaced vertices

The gain in sensitivity corresponds to a 20-30% gain in effective integrated luminosity and is equivalent to an additional 3 years of operation of the HL-LHC complex.

The barrel compartment of the MTD can be seen, in simplistic terms, as an optimization for charged track detection of existing detector and read-out chips developed for TOF-PET scanners, with specific customization of the geometry of the scintillation tiles and of the SiPMs. The high-rate and high-fluence environment of the HL-LHC, as well as the large detector area and the integration constraints, however, present a formidable challenge that will be addressed in a two-year long R&D and engineering phase, followed by three years of construction. The readout chip will be a high-rate evolution of the TOFPET2, including baseline subtraction to mitigate the impact of the radiation-induced SiPM noise.

The endcap compartment of the MTD, with LGADs, will be the first large-area timing detector is based on silicon sensors, with a total surface of 12 m^2. The key reason for this choice is the required radiation hardness to withstand a fluence that is up to one order of magnitude larger than in the barrel. The development of multi-pad sensors of a few 10 cm^2 size with the required radiation tolerance, response uniformity, and fill factor is the focus of the next three-year long R&D and engineering phase. This challenge is paired by, and the R&D tightly intertwined with, the development of an ASIC read-out chip of excellent timing capability, low power consumption, and good radiation tolerance. The chip will be designed in the 65 nm technology, leveraging on the success of the RD53 collaboration.

The barrel and endcap detectors are more complex than just their front-end components: cooling, clock distribution, mechanics, and power need to take up the gauntlet of designing a thin, noise-free, power-hungry set of services to make the MTD a success.

All in all, the R&D phase to demonstrate technologies and the detector concept is in full progress and is planned to continue throughout 2018, with the Technical Design Report (TDR) anticipated for the end of 2018. An engineering and prototyping phase, culminating in the delivery of the Engineering Design Reports (EDR), will follow.

ATLAS High Granularity Timing Detector

A High-Granularity Timing Detector (HGTD) using Low Gain Avalanche Diodes (LGAD) is proposed for the ATLAS phase 2 upgrade. Aiming to provide a time resolution of 30 ps /track in the region of 2.4<h<4.0 throughout the entire duration of the HL-LHC program it will provide a powerful way to mitigate pile-up, one of the main experimental challenges for the HL-LHC physics programme

HGTD will measure the time of individual tracks with a precision of 6 times better than the spread of the collision time, allowing to distinguish between collisions occurring very close in space but wellseparated in time, as illustrated in Figure 2. This new detector will significantly improve the track-tovertex association in the forward region, compensating for the reduced longitudinal impact parameter resolution of tracks reconstructed by the ITk tracker at large pseudorapidities. Rejecting pileup tracks with the new capability provided by HGTD improves the rejection of pileup jets by ~ a factor of 2 (for a hard-scatter jet efficiency of 98%), the lepton isolation efficiency increases by 14%, the light- jet rejection at a b-jet efficiency of 70% improves by a factor of 1.5 as seen in Figure 3.

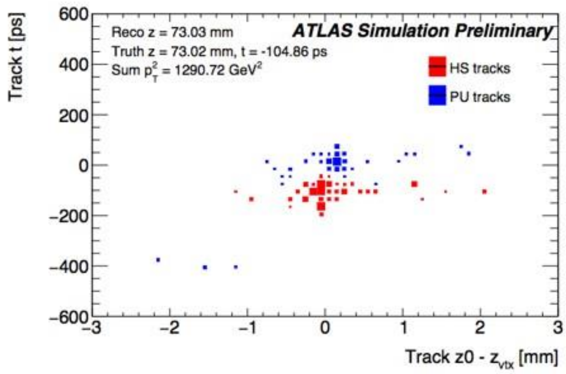
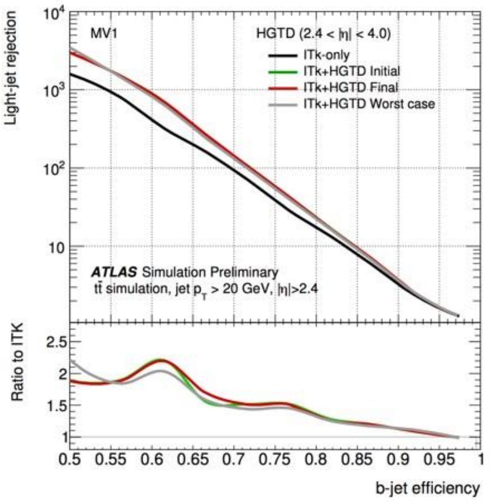


Figure 2: Example of reconstructed times and z positions of the pT-weighted tracks associated to the hard-scatter vertex of an event with a VBF-produced Higgs boson decaying invisibly (H → Z(vv)Z(vv)) with ⟨μ⟩ = 200. While superimposed along z, they two interactions are well separated in time.



(a) Light-jet rejection

Figure 3: Light-jet rejection versus *b*-tagging efficiency for the MV1 tagger using $t\bar{t}$ events at ⟨μ⟩ = 200 for different scenarios: start and end of the HL-LHC and in a pessimistic scenario where the time resolution of 30ps/track would be degraded by a factor of 2.

These improvements in object reconstruction performance translate into important sensitivity gains and enhance the reach of the HL-LHC physics program in the forward region. The signal strength determination for VBF-produced Higgs bosons decaying to H→WW and the signal significance for the tH(H → $b\bar{b}$) are expected to improve by about 10 %. An improvement of 11% on the experimental uncertainty on the weak mixing angle sin(theta) can be achieved through the improved electron isolation performance in the forward region. Furthermore, the HGTD provides unique capabilities to measure the online and offline luminosity with high accuracy. It can also provide a minimum-bias trigger at L0 and possibilities for improved pileup mitigation in both the L0 and high-level trigger systems.

HGTD **Detector**

Reaching a 30 ps/track time resolution at mip amplitude in a harsh radiation environment is an ambitious goal and R&D on sensors and electronics have been quite intensive. In addition the design of the HGTD has limited available space allocated in the ATLAS experiment.

HGTD is a very thin, disk-shaped planar detector with 75 mm thickness in the Z direction and a radial coverage of 110 < R < 1000 mm, including the active area, peripheral electronics and the vessel needed to keep it at -30^{o} C, see Figure 4. It will be installed between the ITK and the endcap-forward calorimeters, in the place presently occupied by the Minimum Bias Scintillator trigger counters, at a distance of +/- 3.5m from the interaction point.

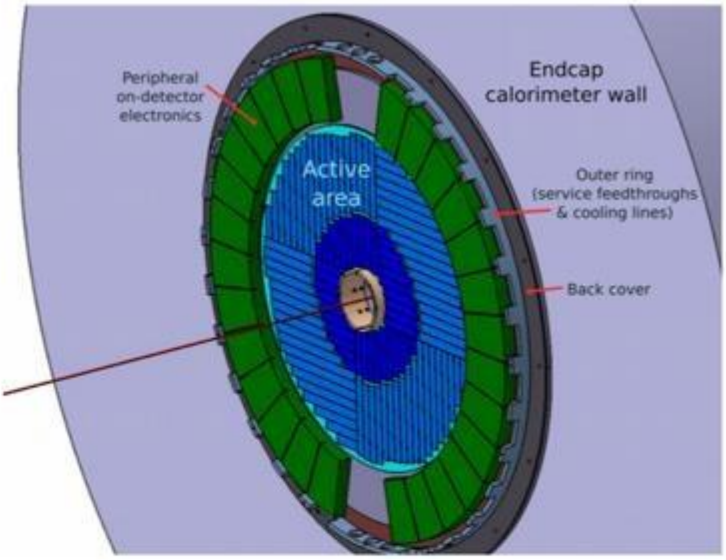


Figure 4: Illustration of the HGTD, showing the peripheral on-detector electronics (in green) and the active area (in blue).

In order to keep a 30ps/track during it's full life time, two double sided layers of LGAD will equip each forward region with an optimized overlap to achieve 3 hits per track in the inner ring (3.2<h<4.0) exposed to highest irradiation doses, and 2 hits/track in the external ring covering 2.4<h<3.2. The inefficiency due to non-instrumented zones, is expected to be less than 1% and the fraction of events with 0 hits should not exceed 2-3%.

A replacement of the inner ring (dark blue region in Figure 4), corresponding to 30% of the full active area, is needed at the middle life time of the HL-LHC to limit the radiation levels to a maximum of $3.7 x 10^{15}$ neq/cm^2 and 4.0 MGy, including safety factors. The sensors will have a granularity of 1.3×1.3 mm^2, a trade-off between occupancy and time resolution on one side (leading to small pad) and efficiency on the other side (leading to larger pad and fill factor). The sensor, of size of 2x4 cm^2 , will be bump bonded to two 225 channels ASICs and read along X or Y axis with flexible printed board up to the large radius. The signals will then be transmitted at various speeds depending on the radial position of the ASIC through optical links to the ATLAS USA15 electronics cavern. This part of the electronic is quite similar to the one used for the ATLAS ITk strips upgrade (DC/C converter and power supply, lpGBT, VL+ optical modules)

A total of 6.3 m^2 modules are needed to equip the full detector to be readout by 3.54 Million channels. This new detector proposal is the result of ~3 years of active R&D especially on sensors and front-end electronics, detailed below, undertaken by ~20 Institutes and ~ 120 people from all around the word.

Ongoing R&D activities on HGTD sensors and ASICs

In close collaboration with RD50 and CNM/HPK manufacturers, an extensive R&D programme started ~ 3 years ago and is progressing quickly towards real size sensor pads and arrays. Those are being irradiated and tested in collaborating Institutes and then tested in beam tests, mostly at CERN/SPS H6 with pion beams [1].

Before irradiation, time resolution as good as 30 ps is obtained with gain up to 50 with 50 mm thickness LGADs, see Figure 5. Under irradiation, the observed degradation the time resolution is attributed to a decrease of the gain caused by the loss of the effective doping concentration in the multiplication layer up to $1x10^{15}$ n/cm^2. Beyond this fluence there is no more avalanche region but some gain from the bulk. Figure 6 shows the time resolution as a function of neutron fluence of LGAD single pads produced by HPK with a thickness of 35 and 50 mm thickness. The timing resolution per track at the maximum expected fluence will be ~ 50 ps per hit. Therefore, maintaining a timing resolution of the order of 30 ps for the entire life of the HGTD should be possible with three effective layers at low radius and two layers elsewhere. Further R&D is on-going in close contact with CNM and HPK to improve the radiation hardness.

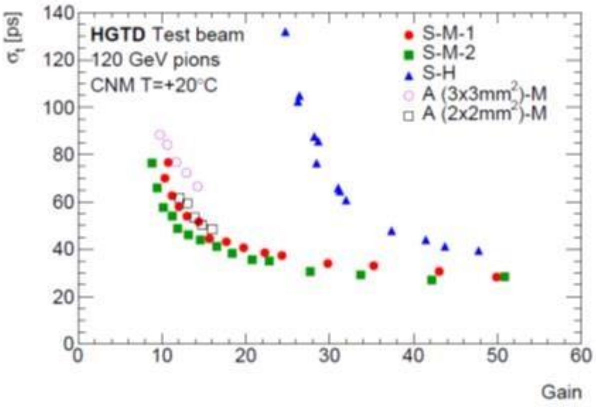


Figure 5: Time resolution vs. gain for non irradiated single pad sensors (S, 1.3x1.3 mm2) and arrays (A) from CNM with various doping (M, H).

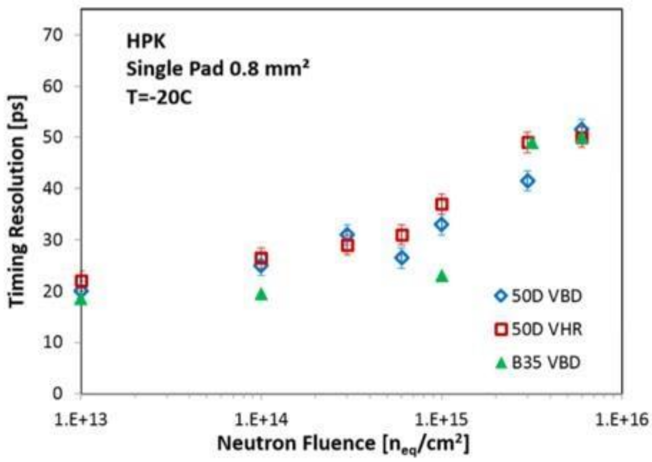


Figure 6: Time resolution vs. neutron fluence of LGAD single pad sensors produced by HPK with a thickness of 50 mm (50D) and 35 mm (B35).

Another major R&D activity is the ASIC-ALTIROC development. The main requirements are driven by the targeted 30 ps time resolution per mip after irradiation. The electronics jitter contribution should be < 25 ps for a charge equivalent to a mip (10fC) while withstanding 4 MGy and have a power dissipation < 300 mW/cm^2 to keep the cooling power budget to 25 KW maximum for the total detector. The ASIC in 130 nm CMOS technology from TSMC will contain 225 channels with a preamplifier, followed by a discriminator and Time-to-Digital Converters (TDC) for the digitization of Time-of-Arrival (TOA) and Time-Over-Threshold measurements. A Local FIFO memory is also included, storing the information until the trigger signal. The time information is transferred to the data acquisition system only upon L0/L1 trigger reception In order to measure the online bunch-bybunch luminosity each ASIC of the outer ring will transmit at 40 MHz the total number of hits. A first prototype of the analog part has shown already promising jitter results on test bench (< 20 ps at 10 fC) and will be further tested with beam. A second prototype including the TDCs and the memory, looking as a complete pixel readout, is submitted middle of June.

The clock distribution is also a challenge issue of this detector. A common working ATLAS/CMS group, led by CERN-EP-ESE-BE, has just started to evaluate the various contribution to the clock instability in term of jitter and wander. The current HGTD strategy is to bring the clock through the lpGBT and correct the T0 of each channel using the quite large bandwidth data information online and offline.

In summary, an optimized baseline concept driven by the best compromise between performance and cost is summarized in the HGTD Technical Proposal submitted to the LHCC in November 2017 and with final approval expected in the coming weeks. If successful the Technical Design Report is expected for the first quarter of 2019. The R&D activities are expected to continue up to the end of 2020, followed by construction phase in 2021-2025 and final installation in the ATLAS cavern in summer 2025.

[1]: "Beam test measurements of Low Gain Avalanche Detector single pads and arrays for the ATLAS High Granularity Timing Detector", submitted to JINST (archive link: https://arxiv.org/abs/1804.00622)

Further reading:

1. CMS Timing Detector Technical Proposal: https://cds.cern.ch/record/2296612

ProtoDUNE gets ready for first tests at CERN

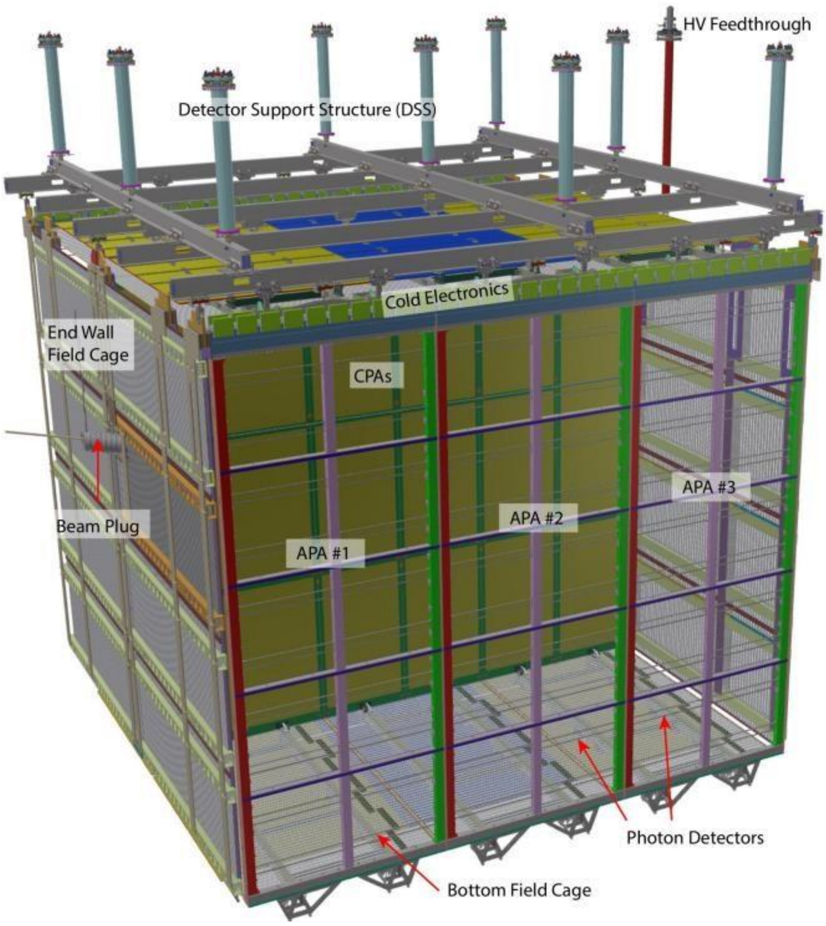
Neutrino Platform
NEUTRINO GROUP *by*
Panos Charitos

Last year has been particularly busy in CERN's EHN1 test facility in the north area of the Prévessin site, as work is ongoing for the construction of the two ProtoDUNE detectors. The two prototypes test different concepts of the future Deep Underground Neutrino Experiment (DUNE) detector, planned to start operations by 2024 as part of Fermilab's Long Baseline Neutrino Facility (LBNF). Each of them is a 11x11x11-metre Liquid Argon Time Projection Chamber, with a single- (SP) or dual-phase (DP) configuration that will soon be filled with 800 tons of liquid argon (LAr). Despite their large dimensions, they are mini models of the four DUNE far detectors.

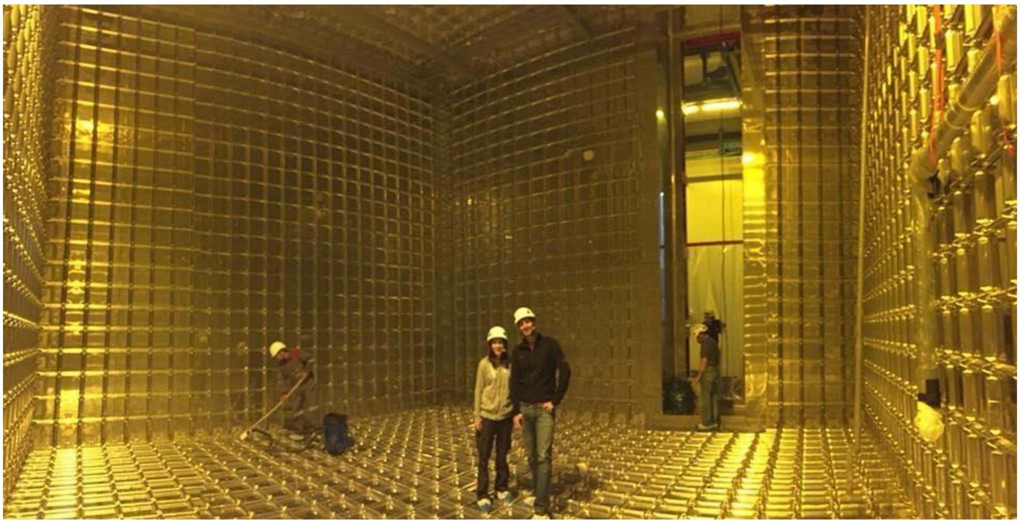
Following a well-coordinated international effort the detectors were assembled in the two cryostats at CERN and the first tests will start this August. The team plans to start with test beam data for the characterisation of the performance of the detector, followed by months of cosmic data taking to establish the long term stability of the complete system.

Success of the ProtoDUNE is key in developing and testing the required technologies of the TPC detector of the future DUNE detector and demonstrate the production and integration schemes. Professor Christos Touramanis, University of Liverpool, one of the coordinators of the single-phase prototype explains: "The results will allow validating the technologies used and provide invaluable feedback in the technical design review of DUNE in spring 2019. Therefore the team faced a rather tight timeline to provide the required data for the DUNE TDR review that will consequently allow onset of DUNE construction by 2020."

A major challenge for ProtoDUNE, given its large dimensions, is the cryostat. The ProtoDUNE cryostat - the largest ever constructed for a particle physics experiment - has been built at CERN. A major difficulty stems from the fact that the cryostat contains the liquid argon as well as the detectors and read-out electronics while very good insulation and high purity is required. To meet this challenge, the collaboration explored a novel technological solution inspired by the liquified-natural-gas (LNG) shipping industry. The patent is based on a membrane-type containment system with two cryogenic liners that support and insulate the liquid cargo. CERN established a fruitful collaboration with Gaztransport & Technigaz (GTT), a firm that deploys LNG in about 80% of all transport ships worldwide, thanks to which the same patent was available for the ProtoDUNE cryostat. Following the success of this project, the same cryostat will serve as a prototype for the cryostat of the DUNE far detector.



The ProtoDUNE-SP TPC. The beam enters from the left into the nearside (Saleve-side) drift volume through the Beam Plug.



A Greek engineer, a Turkish, an American and an Italian physicist and a Spanish worker in the completed ProtoDUNE-SP cryostat. International cooperation in science, what CERN does best in the last 63 years (Image Credits: Prof. Christos Touramanis).

The ProtoDUNE detector uses the state-of-the-art time projection technology of Liquid Argon TPC (LAr TPC), to capture 3D images of particle tracks created in neutrino interactions. The technology, originally proposed by Carlo Rubbia in 1977, was conceived as a tool for a uniform imaging with high accuracy of massive volumes. The operational principle is based on the fact that in highly purified liquid argon ionization tracks can be transported, practically undistorted, by a uniform electric field over macroscopic distances. The ionization electrons are drifted with a constant electric field away from the cathode plane and towards the segmented anode plane.

The DUNE collaboration plans to use the Liquid Argon TPC technology for the massive and extremely sensitive DUNE Far Detector. The reference design is based on a single-phase readout, similarly to the one applied in ICARUS and MicroBooNE, where the readout anode is composed of wire planes in the liquid argon volume. A second design adopts a dual-phase approach, in which the ionization charges are extracted, amplified and detected in gaseous argon (GAr) lying above the volume of liquid argon. Clearly, one of the goals of the project is to validate how LAr TPC can scale up in the dimensions of DUNE as well as other alternative technologies for the DUNE far detector.

"As Liquid argon technology is sufficiently new it is highly desirable to perform a large-scale test of single phase ProtoDUNE, to reduce risks associated with the operation of the DUNE far detector" explains Prof. Touramanis . "ProtoDUNE-SP is pushing the limits of LAr TPC technology with key dimensions and technological solutions crucial for de-risking the scaling of the ICARUS technology" and adds "measuring and understanding the TPC performance will help to remove any risks related to the project and to move forward with the submission of the Technical Design Report (TDR) of the DUNE far detector". Moreover, these tests will demonstrate the ability to construct this detector in a technically and financially feasible way. Although there are several single-phase LAr TPCs in operation or under construction (MicroBooNE, SBND, ICARUS), the design for the DUNE far detector includes various specific features that have not been field-tested.

The single-phase ProtoDUNE has the longest drift distance between cathode and anode planes of 3.6 m compared to 1.5 m in ICARUS and 2.6 m in MicroBooNE. Moreover, its drift volumes of 155.5 m^3, exceeding the 86.4 m^3 ones of ICARUS and the 62.2 m^3 of the single drift volume of MicroBooNE, thus paving the way to the 10−kt LArTPCs foreseen in the final DUNE far detector. For the TPC of the ProtoDUNE-single phase (protoDUNE-SP), a critical component was the delivery of the Anode Plane Assembly (APA) modules at CERN and their successful integration in the TPC/Cryostat.

The ProtoDUNE SP detector consists of six APA modules (6 m high and 2.3 m wide) each of which uses approximately 24 kilometers of precisely tensioned, closely spaced, continuously wound wire. Four of the six ProtoDUNE-SP APAs were constructed at PSL (Wisconsin) and two at Daresbury (UK) using identical semi-automatic wiring machines and "process carts". The wire screen, receive an induced signal, recorded by the electronics and then send to computer farms, allowing to study the neutrino interactions. This is why precision in positioning and tension of the wires is critical, as well as electrical continuity and isolation.

The DUNE APAs installed inside the cold-box. APAs is one of the key novelties of proto-DUNE. The detector consists of six APA modules (6 m high and 2.3 m wide) each of which uses approximately 24 kilometers of precisely tensioned (Image credits: Prof. Christos Touramanis).

The photo-detector system, developed by a collaboration of US and Brazilian institutes, is another important part of the protoDUNE TPC. The scintillation light from the liquid argon allows defining the reference time, i.e the time at which the particle crossed the detector volume. However, though liquid argon is a good scintillator, it emits photons in the far ultraviolet (~128 nm), which doesn't match the sensitivity of most photodetectors. Therefore, the photon detection in ProtoDUNE is done using lightguide, installed between the wire planes of APA, coated with a wavelength shifter, which absorbs the UV light and re-emits in the visible. This secondary emission is then detected by "silicon photomultipliers" (SiPM) and the analog signals are transferred outside the cryostat and read by dedicated electronics operating at room temperature.

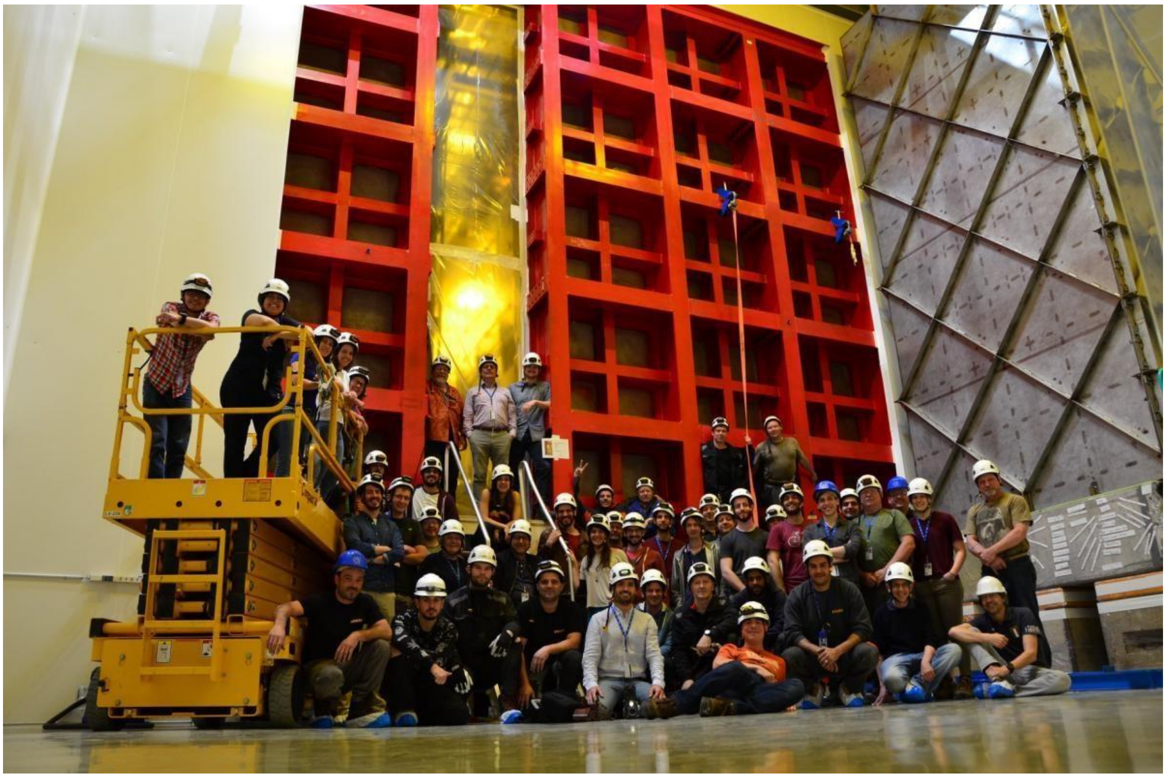
Single-phase liquid argon TPCs don't allow for charge multiplication to achieve high signal-to-noise ratio. This means that the protoDUNE electronics have to be as close as possible to the actual wires electrodes and inside the cryostat. Therefore the team had to develop electronics able to achieve high performances and very low noise levels, while coping with the very low temperatures of the liquid argon.

Finally, an important development has been the design of the DAQ system in collaboration between CERN, UK and US institutes. Presently, two readout technologies are employed for the cold electronics: the CERN's Front-End Link EXchange (FELIX) system and the SLAC RCE system. One out of six ProtoDUNE TPC Anode Plane Assemblies is read out using FELIX, a project initially developed within the ATLAS Collaboration. Its purpose is to facilitate the development of high-bandwidth readout, needed for the High-Luminosity LHC, presently planned to start in 2026. DAQ is designed for an average record rate of 34 Gb/sec and is located next to the detector. The DAQ system is connected to the CERN IT infrastructure, with a dedicated line of 20Gb/s installed and running since August 2017.

Today, all the elements of the TPC and the cold electronics have been produced in parallel to the integration of the detector at CERN achieving a just-in-time delivery mode of operation. Within only a year, the production of all components was completed and their integration in the proto-DUNE SP started early this year. Furthermore, power, signal and data connections to the outside are done with cables running through one dedicated feedthrough on the cryostat roof for each APA.

"In the last months, the progress in the construction and test of the various components of the second DUNE prototype detector at CERN has changed gear," said Filippo Resnati, the technical coordinator of the Neutrino Platform at CERN. The field cage is fully installed and has been tested at 150,000 volts. In June, the first 3-meter-by-3-meter signal-amplification system was ready for extensive test in realistic thermodynamic conditions. Light readout, electronics, data acquisition and detector control systems are in very good shape too."

The installation of the detector will be completed in fall of this year. The team aims to have a complete, fully equipped tested detector filled with Liquid Argon and ready for commissioning by August 2018, to start the first tests with the dedicated H4 line, spanning a range of particle types and energies. At the same time, a second beam line (H2) can provide beam to the ProtoDUNE dual phase prototype. These tests will allow measuring charged particle cross sections in argon, at energies relevant to DUNE neutrino interactions, while also advancing the state of the art LAr event reconstruction algorithms and software suites. The test-beam data will involve strong feedback between reconstruction, detector simulation, and hadronic modelling. Touramanis notes: "The beam tests will give us precise measurements of how sub-GeV particles interact with Argon which will then feed the Monte Carlo for DUNE far detector thus allowing for improved modelling and simulations and consequently a more rigorous physics analysis". The beam tests will run until mid-November and after that, the team will start a cosmic data taking campaign while trying to extract the performance characterisation results that are required for the DUNE TDR in early 2019. Due to some delays for the dual phase prototype, that detector is now aiming to be ready for tests with cosmic rays by the end of the year."



The ProtoDUNERs at CERN in front of the cold box that houses the new ProtoDUNE detector (Image Credits: ProtoDUNE Collaboration).

Closing of the ProtoDUNE cryostat. The detector system is ready for the first test beam in August.

DUNE marks the evolution of neutrino physics as a global enterprise. Almost five years ago the leaderships of Fermilab, CERN and KEK realised that a long baseline neutrino facility offers a good physics case that could attract senior researchers and early-career scientists from all over the world. This was also reflected in the last European Strategy update where it was clearly stated that CERN should contribute to neutrino physics done at any place in the planet. This helped to bring CERN's expertise in the game while CERN also offered the platform for all its member states to work together and integrate in DUNE. This was instrumental for the success of the project as it might have been more difficult for each country to join individually. For Touramanis, ProtoDUNE already reflects a sociological evolution of the neutrino community: "a paradigm change in the way neutrino science is done; we saw the transition from the previously fragmented communities to a 1000-strong, truly global collaboration where people thought globally and were able to interact beyond borders and any form of boundaries".

The unprecedented event reconstruction capability offered by the ProtoDUNE LAr TPC combined with the lessons from the first beam tests of the detector at CERN will open the way to a truly rich programme of new physics investigations into particle interaction processes.

Towards an FCC-hh Detector Magnet System

Superconducting Magnets
Detector Design FCC

*by **Erwin Bielert, on behalf of the FCC-hh detector magnet working group***

The Future Circular Collider (FCC) study is well on its way, and will culminate in the publication of the Conceptual Design Report (CDR) early 2019. The most ambitious proposed future machine is a hadron-hadron accelerator (FCC-hh) of 100 km in circumference foreseeing proton-proton collisions at a center of mass energy of 100 TeV. This collision energy is about 7 times higher than the presently largest and most powerful machine, the LHC, can deliver. This factor 7 has a huge impact on the design of the accelerator, as new technologies are required, as well as the exploration of a new realm in dimensions. Besides the collider, the increased energy also has a significant impact on the design of the experiments for measuring tracks and momenta of the particles created during the collisions. This impact is not only on the design of the various detectors for tracking and calorimetry and their readout, but also on the magnet system as the key ingredient for bending charged particles, thereby identifying their charge and momentum. The superconducting detector magnets have to provide a higher magnetic field over a larger tracking distance and this thus implies much larger detector dimensions, meaning a new challenge for the magnet designers!

Recent developments

Last year, Tom Taylor presented a nice historic overview in the CERN Courier about superconducting magnets and their technological development. In addition Akira Yamamoto reviewed the main steps in the development of superconducting detector magnets at the 2017 European Conference on Applied Superconductivity in Geneva, see the EPnewsletter. Both refer to a proposed "twin solenoid" magnet system for the FCC-hh generalpurpose experiment. More details of this design by Matthias Mentink can be found in a 2014 EPnewsletter. However, the crystallization process of the baseline detector went on, as presented in several publications. Most recently, the FCC-hh detector magnet working group provided an entertaining overview of the evolution of the design towards a smaller, simpler and especially more cost-effective solution. The result is the new CDR-ready baseline detector and its magnet system shown in Figure 1, comprising a 20 meter long central solenoid with 10 m free bore, delivering 4 T in the center at the interaction point. It is accompanied by two smaller solenoids at either end covering the forward directions and delivering 3.2 T on beam axis in a 5 m free bore across 4 m.

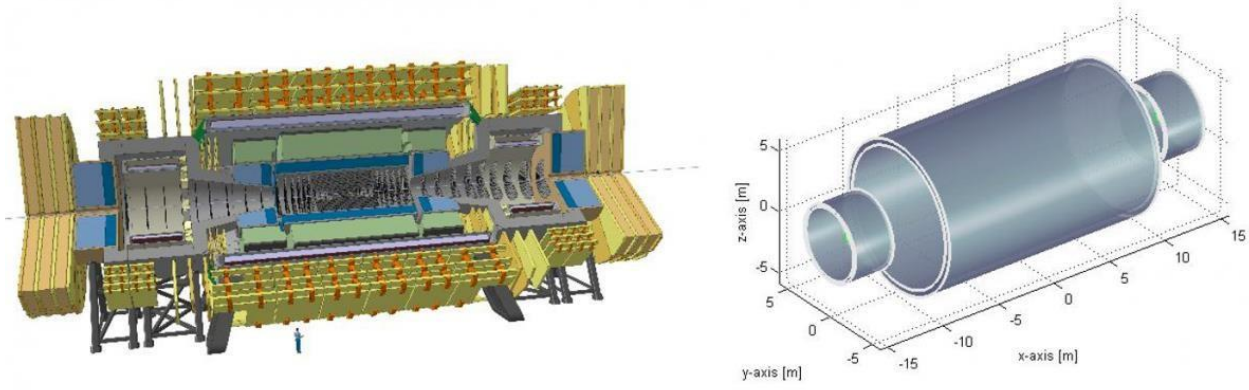


Figure 1. FCC-hh detector overview (left) and superconducting magnet system cold masses (right).

Baseline and options

Since the main solenoid is the largest single part of the detector system, installation scenarios have to be developed properly. The diameter of the main shaft to the experimental cavern needs to have a minimum size to allow for the lowering of the solenoid with axis vertical where after it is turned 90 degree to its operational position. Also the cranes need to be able to handle at least 2.5 kt, to safely deal with the heavy magnet system components and calorimeter units as well. Installation steps discussed in detail during the FCC week 2017 in Berlin have not been significantly changed since.

Besides delivering 4 tesla magnetic field in the very large volume, the magnet system has to operate reliably and inherently safely. Like for any other superconducting system, not only a proper magnetic performance must be demonstrated but also electrically, thermally and mechanically the design has to be sound. The stored energy over the cold mass is 12 kJ/kg, which is comparable to the CMS solenoid today. However, the 12.5 GJ stored energy of the much larger FCC-hh system is unprecedented for a detector.

Large scale magnets like this one make use of active as well as passive quench protection meaning that part of the energy is extracted from the system and the remaining energy is absorbed by the cold mass itself. Therefore, the cold mass mainly consists of aluminium alloy rather than superconducting cable. To spread the energy as homogenous as possible, quench heaters are foreseen in both the main solenoid and in the forward solenoids. When the system is working properly, 73% of the energy is extracted and the peak temperature in the main coil will be at 60 K level, while the forward solenoids can reach 90 K. Failing quench heaters will result in much higher, but still safe temperatures of about 130-140 K.

Optional for the baseline is replacing the forward solenoids by forward dipole coils. For particles created during the collisions in IP, moving in a direction with a very small angle relative to the beam, the magnetic field is almost parallel to the trajectory and therefore the Lorentz force acting on these particles very small. The result is almost straight trajectories for which it is very difficult to measure the particle's momentum. This is also the main reason why solenoids are usually used in collider experiments: for most of the angles, the field is reasonably perpendicular to the trajectories of the particles created during the collisions.

For high pseudo rapidity particles flying at low angle in the forward direction, more parallel to the particle beam, a forward dipole magnet may be an interesting option despite their obvious technical disadvantages. One drawback is that a forward dipole magnet breaks the rotationally symmetric system, and causes a large torque additional to the already huge forces, and it has negative impact on the particle beam as well that would require corrections. The system of cold masses with this option on is shown in Figure 2, alongside the impact of a magnetic dipole field on the integrated magnetic field along the trajectories for several pseudo-rapidities (eta).

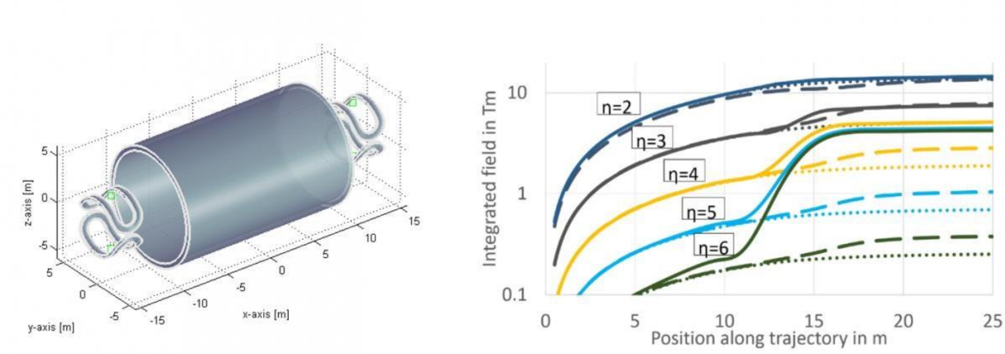


Figure 2. Superconducting cold mass of main solenoid accompanied by two forward dipole coils (left) and the impact forward dipole coils would have on the integrated magnetic field as a function of distance along the trajectory for several pseudo-rapidities.

A novel design for which targeted R&D is required is also part of the overall investigation for FCC detector magnets. Extremely thin in terms of material build and radiation transparent coils would allow for advanced experiments. Since magnetic field is not required in the volume of the calorimeters, but in the inner trackers only, ideally the solenoid would be placed in between inner tracker and calorimeters. The argument against is that energy measurements get disturbed by the presence of too much material used to build the magnet cold mass and cryostat. So the challenge is to develop a next generation of ultra-thin solenoids with less than one unit of radiation length. Interesting steps forward have been taken, new ideas are being tested and results can be expected in the years to come.

Conclusion

To conclude, it has been shown design-wise that it is technically possible to construct a record size detector solenoid, 20 m long, 10 m free bore, with a stored energy of 13 GJ. There are still many challenges for the years to come.

Fundamental physics research, in particular particle physics, has always pushed the performance of superconductors, either for accelerator magnets or for detector magnets. There has always been, and this project shows that there continues to be, a demand for better performing superconductors, the understanding of their behaviour under ever more extreme conditions of electromagnetic forces, high radiation levels and thermal cycling from room to cryogenic temperature.

RD53: Making the challenging pixel detector chips for the Phase-II upgrades of ATLAS and CMS

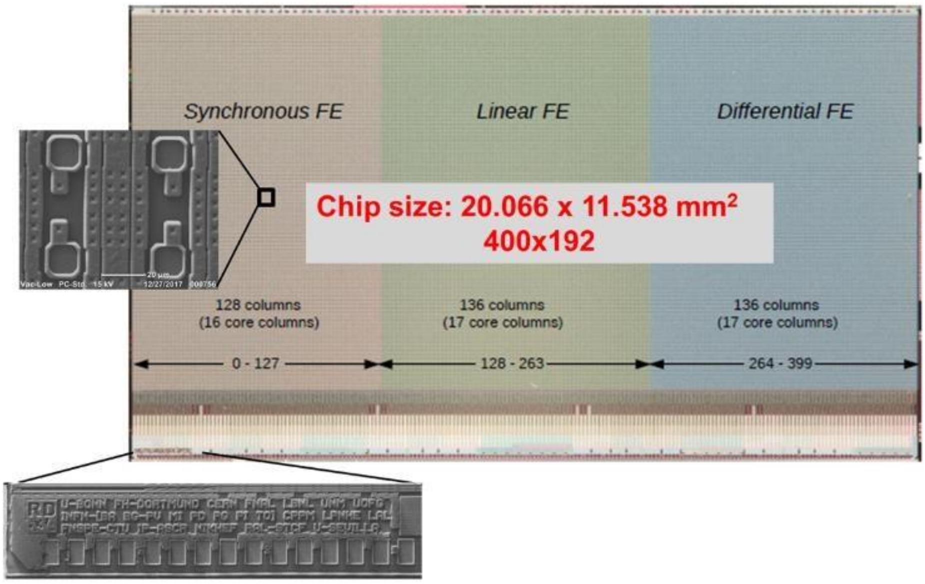
by ***Jorgen Christiansen***

The RD53 collaboration has developed over the last five years the foundations to make the extremely challenging pixel detector chips for the Phase-II pixel upgrades of ATLAS and CMS. A large-scale demonstrator chip, called RD53A, was produced last year and during the last six months has been undergoing successful extended tests. The design of the final production versions of the pixel chips for the two experiments is currently ongoing and the scheduled submission is for next year.

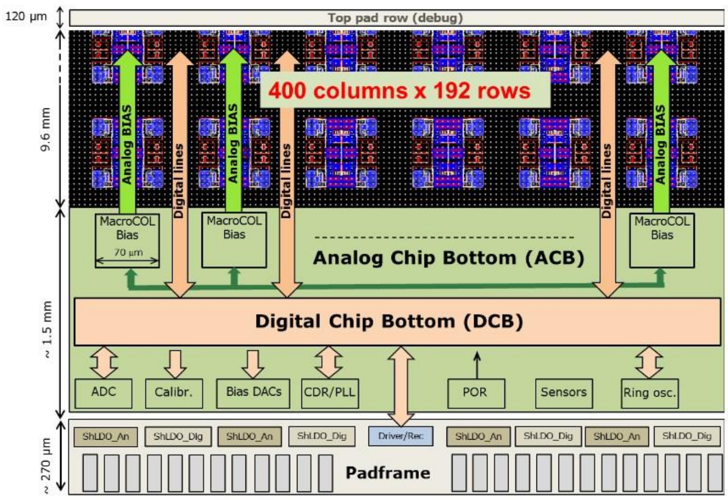
Higher resolution tracking with pixel detectors will be vital to reconstruct events at the high collision rates at the HL-LHC with the very high track densities expected (thousands per 25ns bunch crossing). The successful use of hybrid pixel detectors in the current LHC experiments has been a major achievement enabling a rich and successful physics program. Next generation pixel detectors pose new major challenges that require significant advances in many aspects of pixel detectors, starting with their highly integrated readout electronics.

The HL-LHC pixel upgrades requires ~5 times higher granularity (pixel size of 50x50um^2), at an order of magnitude higher hit rates of up to of 3GHz/cm2, with analog charge readout to get very good tracking resolution. To perform efficient event selection, under the very challenging conditions of the HL-LHC, trigger rates will be increased by an order of magnitude and the trigger latency increased by a factor ~5. This combination of requirements pose severe challenges for the pixel readout integrated circuit being located in the most hostile environment ever at the heart of the experiments with radiation levels reaching 1Grad over ten years for the inner most pixel layers. This must in addition be obtained at reduced material budget, requiring the use of a novel serial powering concept, with complete power regulation and power conditioning on the pixel chip itself, in combination with highly efficient CO_2 cooling systems.

The RD53 collaboration has during its first three years developed and prototyped a multitude of required basic building blocks (analog front-ends, DACs, ADC, shunt-LDO power regulator, etc.) in the chosen 65nm CMOS technology, which was new to our community. Different chip architectures have been evaluated and extensively simulated with a dedicated RD53 pixel chip simulation and verification framework. Finally, a large effort has been invested to get a better understanding of radiation effects in the extremely hostile radiation environment in the pixel detectors. Analog and digital test chips have been designed and characterized for radiation effects at different biasing and temperature conditions. Radiation damage above 100Mrad levels can be severe, especially for small transistors required in high-density digital logic and data buffering. It was realized that effective radiation damage can become both reduced or amplified by annealing depending strongly on annealing conditions (biasing and temperature). The fact that the pixel detectors will be operating cold (-20°C), and only biased/powered when cooled, will play a major role in limiting effective radiation damage. This allows pixel chips to be made with appropriate design techniques to tolerate at least 500Mrad, implying that inner pixel layers may have to be exchanged after five years of operation. Further extensive radiation tests of the RD53A demonstrator will show if it is viable to have complex mixed signal pixel chips operating up to 1Grad.

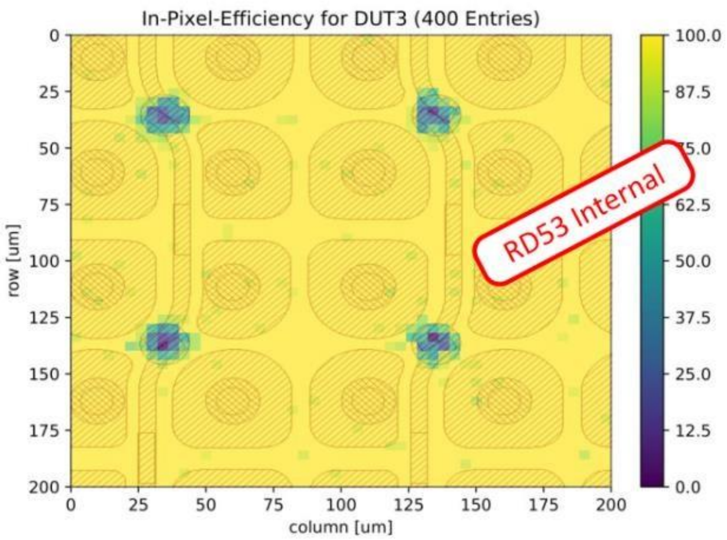


A picture of the RD53A chip.



The block diagram of the RD53A chip

The last two years have been focused on designing and submitting the RD53A demonstrator pixel chip. This demonstrator chip is designed as being a full sized pixel chip with all main/critical functions included. In the end the chip was submitted as a half-sized chip (2cm x 1cm) to allow mask sharing with another large tracker chip, the CMS MPA chip, as mask costs of a modern 65nm CMOS technology is significant. The RD53A chip contains specific test functions to allow direct comparisons of three alternative implementations of low power analog front-ends and dedicated functions to measure radiation effects. The RD53A chip has since the beginning of this year been extensively tested by the RD53 community and has been found fully functional. Chips and RD53 developed test systems are now being distributed across the ATLAS and CMS pixel communities for extensive testing, characterization and verification of pixel sensors, serial powering and realistic pixel modules for large-scale pixel detector system tests.



First preliminary test of a pixel sensor detection efficiency, with the RD53A chip in a CERN test beam in May 2018. The observed holes on hit efficiency is due to a specific biasing applied to tests the behaviour of the pixel sensor. as expected the hit efficiency under this specific biasing condition is low at these areas, validating the behaviour of the RD53A chip down to the sub-pixel level.

Concurrently to testing the RD53A chip, the RD53 chip design team has prepared an improved design framework to make the final production chips for both ATLAS and CMS. Since the foundation of the RD53 collaboration in 2013, some of the requirements from the two experiments have evolved differently (e.g. trigger rates and latencies). It has been determined that an appropriate common architecture can accommodate such differences. Differences in the pixel detector layouts of the two experiments (e.g. CMS pixel detector being closer to beam, ATLAS pixel detector being bigger, etc.) dictates that dedicated pixel chips of different size and aspect ratio are required. The improved RD53 design framework can map the common pixel chip architecture into two chip implementations of different size, controlled by a few key parameters in design generation and verification scripts. Both chips could in principle be submitted at the same time but it has been decided to time skew the two submissions to reduce cost risks related to potential design problems. The ATLAS sized chip will be submitted ~mid 2019 and after basic verification of this chip (also by CMS groups) the CMS sized chip will be submitted ~end 2019.

The RD53 collaboration consists of 22 institutes across the European and American continents. Designing, verifying and testing so challenging complex mixed signal chips across so many different groups, people and experiment boundaries has been a challenging but also a very rewarding experience for everybody taking part in this. There has been a lot of exchange of experience and ideas during the years, which has benefitted significantly the two pixel projects and everybody contributing to this. An excellent collaboration spirit, weekly and well-organized meetings combined with getting the core design team together at CERN for several months before the RD53A submission has been the recipe to make this successful.

RD53 institutes: Aragon, Bari, Bergamo-Pavia, Bergen, Bonn, CERN, CPPM, Fermilab, LALOrsay, LBNL, LPNHE Paris, Milano, NIKHEF, New Mexico, Padua, Perugia, Pisa, Prague, RAL, Santa-Cruz, Seville, Torino.

A new era for calorimetry?

CMS

*by **David Barney***

Motivation

In the mid-1990s the design of the CMS detector was being finalized, culminating in the relevant Technical Design Reports at the end of the decade. This was followed by the start of construction. The main constraints at the time were radiation tolerance and immunity to the effects of pileup. The detectors were designed to withstand the radiation (neutron fluence and ionizing dose) from accumulating ~500fb^{-1} of 14 TeV proton-proton collisions (spread over ~10 years of operation) with a pileup of 20-25 events. The LHC is well on its way to accumulating hundreds of fb^{-1} and may reach the 500fb^{-1} by LS3. But the pileup is already averaging about double the original design. It is a testament to the original detector designs and the ingenuity of the physicists/engineers that operate and maintain them that this huge pileup can be mitigated and the underlying physics uncovered, even at the trigger level. The challenges of the High-Luminosity phase of the LHC are similar, but far more extreme: CMS must perform well after an integrated luminosity of ~3000 fb^{-1} with a pileup of between 140 and 200. Whilst some of the existing detectors – mainly those in the barrel region – can withstand the increased radiation, the challenge of the pileup – particularly at trigger level – requires new electronics for all detectors. And in the endcaps (pseudorapidity > 1.5) only the forward calorimeter (known as HF) [1] will survive the radiation and continue to perform well. The silicon tracker (pixels and strips) will be replaced in LS3, along with the main endcap calorimeters: the ECAL (homogeneous electromagnetic calorimeter, based largely on lead tungstate scintillating crystals with vacuum phototriode light detection) and HCAL (sampling hadronic calorimeter based on plastic scintillating tiles, wavelength-shifting fibres and SiPM light detection). In 2015 the CMS Collaboration decided to replace these detectors with the High Granularity Calorimeter (HGCAL), to be installed in LS3.

Overview of HGCAL

The HGCAL is one of the most ambitious detector projects ever undertaken, due to the combination of extremely high readout and trigger granularity coupled with the harsh radiation environment of the CMS endcaps during the high-luminosity phase of LHC. The starting point was to identify radiationtolerant materials. As the radiation field changes by 4-5 orders of magnitude over the Z-η region covered by HGCAL (reaching ~10^{16} cm^{-2} 1 MeV-neutron equivalent and 2 MGy in the hottest region at the end of HL-LHC), two materials have been selected: silicon in the high-fluence (and dose) region; plastic scintillator tiles in the less harsh regions. To mitigate the effects of radiation damage to the silicon, it must be cooled to about -30°C: the coolant chosen is bi-phase CO_2, profiting from the same developments for phase-2 Trackers etc. Cooling the entire HGCAL to this temperature is also beneficial to the scintillator part, as it allows on-tile silicon photomultipliers (SiPMs) to be used for light detection.

The HGCAL will be realized as a 52-layer sampling calorimeter, as shown schematically in figure 1 along with relevant parameters.

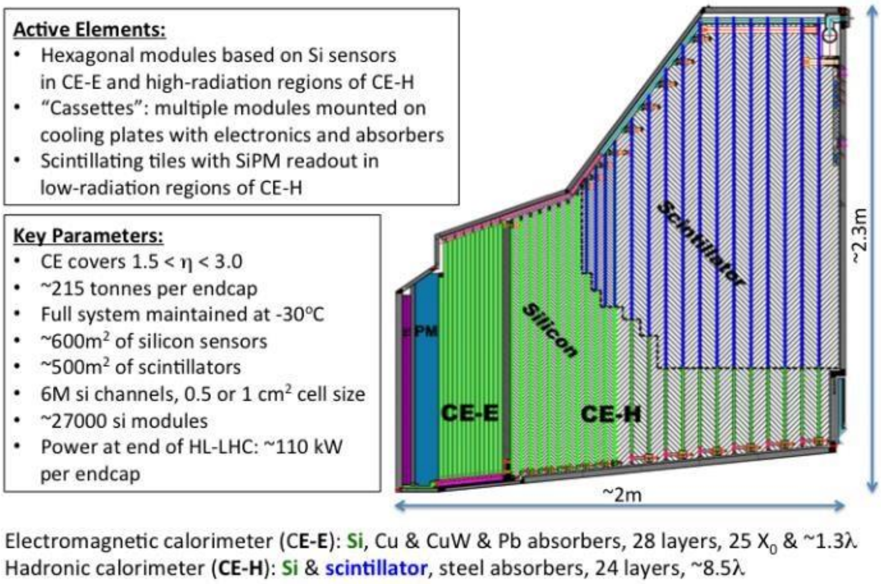


Figure1: Schematic transverse slice of the HGCAL.

The first 28 layers form the electromagnetic section of the calorimeter and are based on hexagonal modules, comprising hexagonal silicon sensors (maximizing the useable surface of 8" circular silicon wafers) divided into hexagonal cells, glued to high-density copper-tungsten alloy (25%:75%) baseplates on one side, and PCBs containing the front-end ASICs on the other side. Three different thicknesses of silicon are used: 120μm in the highest-fluence regions; 200μm in the medium-fluence regions, and 300μm in the remainder. The sensors are divided into hexagonal cells of ~0.5cm² (for the thinnest sensors) and ~1.1cm² for the others. These cell sizes are chosen as a compromise between cell capacitance (which influences the noise) and channel count. The modules are attached to either side of a copper plate that has an embedded pipe carrying the CO_2, in order to cool the silicon sensors and evacuate the heat generated by the front-end electronics. Motherboards, containing dataconcentrator ASICs and links to the off-detector electronics, are plugged into the hexagonal modules. Lead plates, sandwiched between thin steel sheets, are placed on either side of the double-sided module-copper-module assembly, to form self-supporting "cassettes". Each cassette covers 60o in phi and has an overall thickness (including absorbers, cooling, modules and services) of about 25mm – one of the major challenges of HGCAL.

The following 8 layers are similar, forming the front part of the hadronic section of HGCAL, but are single-sided and using a lighter baseplate (carbon fibre or copper – to be decided) for the modules and stainless steel as main absorber. The final 16 layers each incorporate silicon modules in the low-radius (high radiation) region and scintillator tiles with on-tile SiPM light detection in the high-radius region. The use of both detector technologies optimizes the overall cost of the HGCAL whilst maintaining excellent long-term performance. Again, stainless steel is used as the main absorber.

Wherever possible "generic" electronics components will be used, such as the lpGBT chipset, Versatile Link++ and FEAST DC/DC system. These will be complemented by custom ASICs at the front-end, for signal processing, analog-to-digital conversion, data storage, trigger-primitive generation and data concentration.

Prototype tests, and expected performance

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A program of prototype development began in 2016. Hexagonal silicon sensors, cut from 6” wafers, were produced and built into modules, to evaluate the feasibility of the overall design and study the performance in beams at FNAL and CERN. An existing front-end ASIC was used in 2016, the Skiroc2 chip originally developed for the CALICE collaboration. Although not really suited to LHC operation, the silicon modules performed well, with measured longitudinal/transverse shower shapes agreeing very well with simulation. The performance, in terms of position, energy and timing resolution all agreed with simulation, despite fewer layers being used in the beam tests than will be used in reality. In 2017 a new ASIC was available – the Skiroc2-CMS, including many of the features of the final desired front-end ASIC: ~20ns shaping time, low noise, large dynamic range obtained through the use of “standard” amplifier stages plus a Time-over-Threshold technique for large signals, and a Time-ofArrival circuit with ~50ps accuracy in order to help mitigate in-time pileup. A prototype module, showing the through-hole wire-bonding used to connect the PCB to the silicon below, is shown in figure 2.

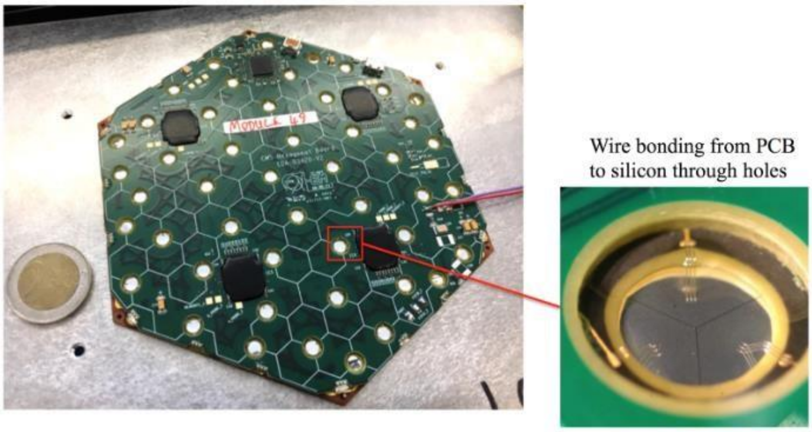


Figure 2: Prototype 6” hexagonal silicon module, with zoom showing wire bonding from PCB to silicon.

A 25 X_0 electromagnetic section and 4λ hadronic section were formed from layers of silicon modules and appropriate absorbers. And for the first time a scintillator+SiPM rear hadronic section was included in the beam tests: a slightly modified version of the CALICE AHCAL. Again the performance was as expected, both for electromagnetic and hadronic showers, giving confidence in the overall design and in the simulation. Figure 3 shows the MIP signal (used for calibrating the silicon and scintillators) as well as the transverse spread (data and simulation) of hadron showers, as measured at CERN in 2017.

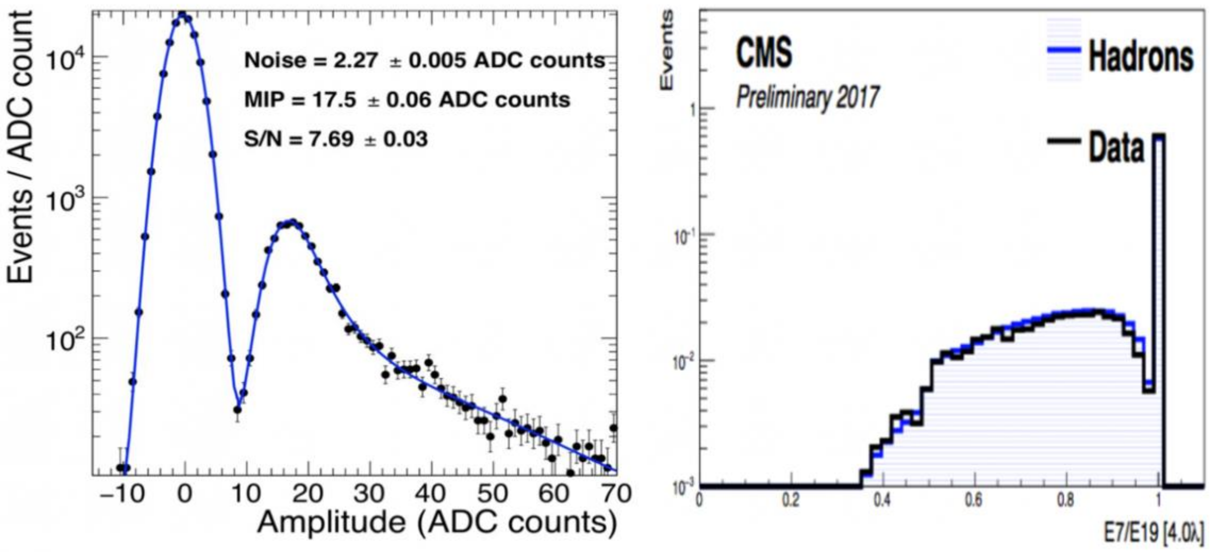


Figure 3: Mip signal (left) and transverse hadronic shower shape (right) as measured in beams at CERN in 2017.

The simulation was used to predict the performance of the HGCAL in CMS. Although the reconstruction algorithms are in an early stage of development, the expected performance in terms of energy resolution, particle identification and triggering are all comparable to the present CMS endcap calorimeters, even in the presence of 200 pileup events and after 3000 fb^{-1}. The readout/triggering granularity and timing resolution for showers are key elements leading to this performance. Figure 4 shows the expected energy resolution for electrons, showing an insensitivity to pileup and a constant term (the most relevant in the endcaps) of around 1%. Also shown is a plot of the mass spectra of $H\rightarrow\gamma\gamma$ events in the presence of 200 pileup, where both photons are in the HGCAL and have not converted in the Tracker.

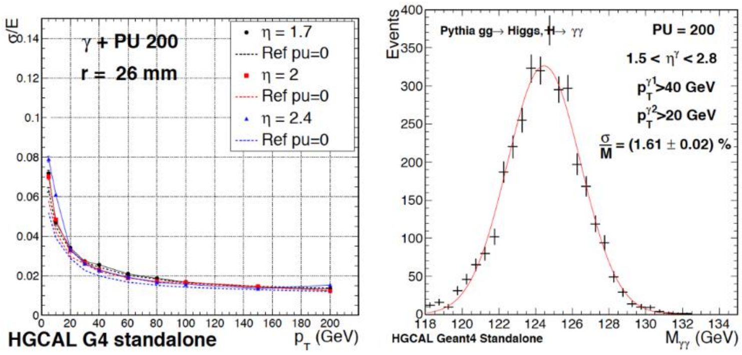


Figure 4: Expected electron energy resolution (left) and $H\rightarrow\gamma\gamma$ mass resolution (right) for the HGCAL with 200 pileup.

Outlook

The HGCAL TDR (CERN-LHCC-2017-023) was approved in April 2018. The next years will be extremely challenging in terms of engineering of all types, to finalize the mechanics, on-detector electronics, services and off-detector readout/trigger boards. In parallel, the triggering, reconstruction and clustering algorithms (in 5 dimensions – X, Y, Z, E, t) will be optimized, adding to information from the new Tracker and new/existing Muon systems, to give an unprecedented "particle flow" picture of the complex events expected at HL-LHC.

Several groups in EP are playing key roles in the development of HGCAL, including EP-CMX, EP-CMG and EP-CMO inside the CMS team, as well as EP-DT, EP-ESE and EP-LCD.

DT group present its annual report

DT

*by **Burkhard Schmidt (EP-DT)***

The EP-DT group has published its Annual Report where key activities throughout 2017 are summarized and a description is given of how the group is organized and interacts with the detector physics community.

The Detector Technologies group participates in the development, construction, operation and maintenance of particle detectors for experiments at CERN. The group is engaged in several detector projects for LHC and non-LHC experiments, operates services open to all CERN users for detector operation, research & development, and is involved in R&D projects on new detector technologies and related infrastructures. Expertise in many different domains crucial for advanced detector-systems is available in the DT group. Among these are fine mechanics, engineering, micro-fabrication, thin film coatings, optics, a silicon facility with a wire-bonding and quality assurance lab, irradiation facilities, magnet support and B-field mapping, instrumentation and controls, gas and cooling systems for particle detectors. DT runs several mechanical workshops with conventional and CNC machines and equipment for specialized machining for scintillators, glass and ceramics.

Agreements for the upgrades of the LHC experiments, established in previous years are now being executed. During 2017 the contributions to the ALICE and LHCb upgrades entered into the production phase. The involvement of the EP-DT group in the phase II upgrades of the ATLAS and CMS trackers, where the engineering and detector prototyping phase is still ongoing, increased in 2017. DT staff plays also important coordination roles in NA62 and CLOUD and has also started during 2017 to provide support to ISOLDE and the SHiP project. Important contributions at the level of mechanical engineering, DAQ and controls have been made to the Neutrino platform, and the support to the LCD project continued. The group also pursues R&D on detector technologies and detector infrastructure systems for the interest of the overall HEP community.

The 2017 Annual Report can be found HERE.

Connecting the dots: applying deep learning techniques in HEP

ATLAS CMS

*by **Panos Charitos***

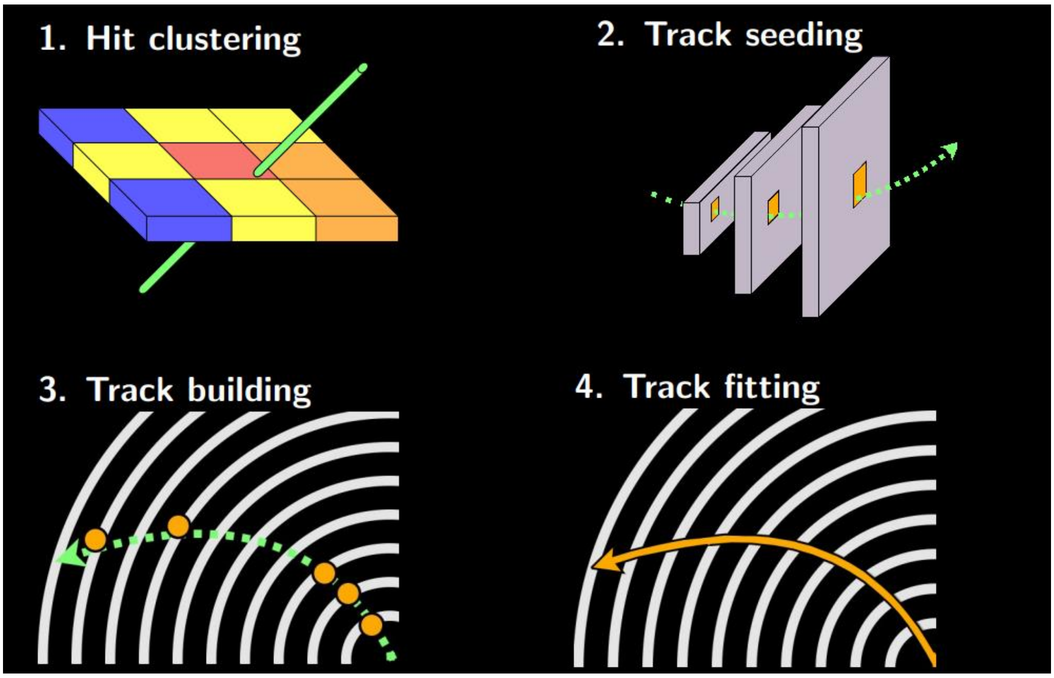
With massive amounts of computational power, machines can now recognize objects and translate speech in real time. Deep-learning software attempts to mimic the activity in layers of neurons in the neocortex, the wrinkly 80 percent of the brain where thinking occurs. The software learns, to recognize patterns in digital representations of sounds or images while it can also be used to analyse the data collected by the detectors of the LHC experiments.

Beginning around the time of the Higgs discovery, the data analysis world outside high energy physics saw a resurgence in interest in machine learning, driven in part by new and innovative approaches to training neural networks.

These new “deep” networks were able to label raw data with much better accuracy than previous carefully hand-crafted algorithms.s. Deep Learning over the past few years given rise to a massive collection of ideas and techniques that were previously either unknown or thought to be untenable.

The ATLAS and CMS experiments at the LHC search for new particles, rare processes and short-lived particles. Challenges in these searches stem from the required statistics and the backgrounds that could hide signals of new physics. These challenges drive a need to explore how advanced machine-learning methods could apply to improve the analysis of data recorded by the experiments.

Presently the experiments select interesting events - at the level of the so-called High-Level Triggering - by reconstructing the trajectory of each particle using the raw data from the silicon layers of the inner tracker. Raw data from the detector are processed to obtain hit clusters, formed by nearby silicon pixels that see a signal. The cluster shape depends both on the particle, on its trajectory and on the module that has been hit. In that sense, track reconstruction by its nature is a combinatorial problem that requires great computational resources. It is implemented as an iterative algorithm that allows to first search for easy tracks, eliminate from the successive searches the hits associated with the found tracks, and look for the more difficult tracks in successive steps.



Stages of track reconstruction (Image credit: joona.havukainen@helsinki.fi).
Perhaps, one of the most challenging, albeit very interesting challenges for machine learning techniques, is the study of jets originating from heavy flavour quarks (b/c "tagging") which at the same time is one of the crucial objects to search for new physics. A variety of b-tagging algorithms has been developed by CMS to select b-quark jets based on variables such as the impact parameters of the charged-particle tracks, the properties of reconstructed decay vertices, and the presence or absence of a lepton, or combinations thereof. These algorithms heavily rely on machine learning tools and are thus natural candidates for advanced tools like deep neural networks.

Starting with improved b-jet tagging techniques the method can also be applied in jets containing W, Z or top particles. Markus Stoye, a CMS physicist and Professor at Imperial College London, leads the effort of applying deep learning algorithms to interpret data recorded by the CMS detector. In the last two years, the team has applied deep learning techniques to tackle the challenges of studying the jets of particles produced at the LHC Run 2.

Boosted objects like jets can have a large number of tracks in a small section of the tracker and thus reconstructing these is difficult as allowing shared hits increases reconstruction of fake and duplicate tracks. A neural network classifier identifies if hits are caused by single or multiple tracks and it has been shown to increase tracking efficiency in dense regions. Moreover, the use of deep neural networks (DNN) instead of boosted decision trees (BDT) as classifiers can further improve the efficiency and reduce the fraction of "fake" tracks.

The new generation of b tagging algorithms have shown significantly improved performance compared to previous b-taggers. Stoye explains: "A variety of b tagging algorithms has been developed at CMS to select b-quark jets based on variables such as the impact parameters of the charged-particle tracks, the properties of reconstructed decay vertices, and the presence or absence of a lepton."

Following an initial training period to familiarize with the concepts and available tools he helped form a group within the CMS collaboration. The success of the deep learning approach resulted in a great team and today more than ten people work to push further deep learning techniques in the analysis of CMS data. "Currently, we design a neural network architecture DeepCSV that can do simultaneously the formerly independent steps that are followed in the analysis of jets, e.g. variable design per particle and track selection. The input to the deep learning algorithm are the constituents of the jet, meaning all its particles and secondary vertices". These adds up to about 1000 features and if you use a general dense deep neural network, you might have 10.000.000 to minimize in your optimization. Based on some assumptions stemming from the physics describing these interactions you can reduce the complexity bringing this number down to 250.000.

In contrast to the other algorithms, it uses properties of all charged and neutral particle-flow candidates, as well as of secondary vertices within the jet, without a b-tagging specific preselection. The neural network consists of multiple 1x1 convolutional layers for each input collection. Their output goes to recurrent layers, followed by several densely connected layers. So far, in the CMS simulations, this algorithm outperforms the other taggers significantly, especially for high-pt jets, which could lead to improved sensitivity in searches for new physics with high energetic b jets in the final state.

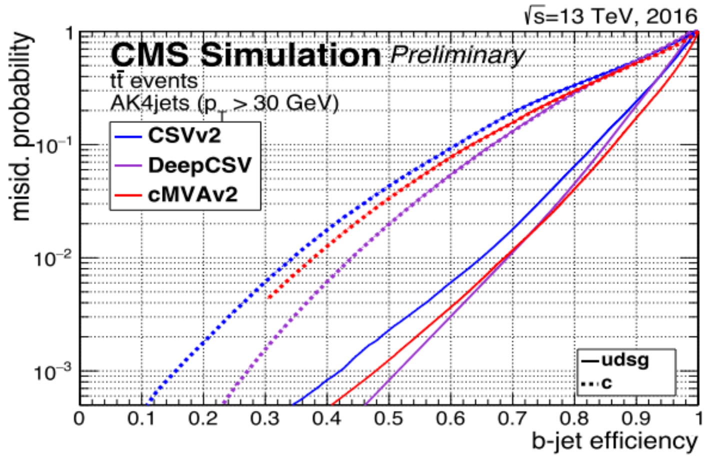


Figure 1. Performance of the b jet identification efficiency algorithms demonstrating the probability for non-b jets to be misidentified as b jet as a function of the efficiency to correctly identify b jets. DeepCSV significantly better than CSVv2 in ~every b jet efficiency value versus both light and c jet misidentification (as b jets) probability.

Deep learning techniques have achieved great results in pattern recognition tasks. "In this process one has to understand both the architectures that are available as well as the physics problems that one aims to address. Markus comments: "We input pretty complete information about the particles to the algorithm and gradually the neural network starts becomes able to figure out itself what is most important for the analysis" and continues: "We know that we have better tagging following the copious efforts of the past nine months. Thanks to the neural network technique there is an acceleration in the way we improve on these fields compared to the past though this is not to undermine all past efforts and the way in which they pushed our understanding."

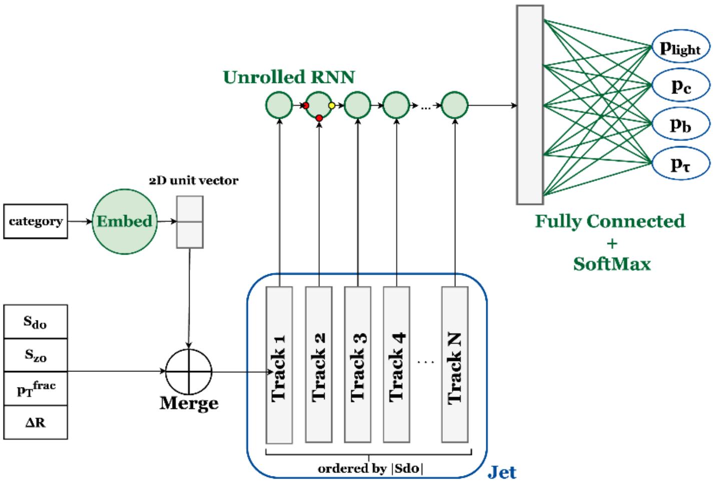
Regarding future steps, the team plans to develop ways to reduce systematic uncertainties. Markus explains: "Presently there are different approaches on that within data science and this is an aspect that we presently focus. It is a major branch of research in data science called domain adaptation while it will be a major step in developing new techniques".

Machine learning has also been a part of the ATLAS physics program since the beginning of LHC data taking. "Neural networks, while basic by today's standards, were part of b-quark identification since first data in 2009" note David Rousseau and Dan Guest, ATLAS ML conveners. "Boosted Decision Trees (BDT), a relatively simple algorithm, have been the most frequently used algorithm while since 2012, ATLAS uses these algorithms not only to identify visible particles, but also to better measure them".

Once the particles emerging from the collisions are identified and measured, and the event saved on disk, physicists have to sift through billions of events to find and study the rarest unstable particles such as the Higgs boson. Machine Learning did not have a major role in ATLAS for the Higgs boson discovery in 2012, however the BDT technique has had major impact on the study of the more difficult channels that were later discovered: the Higgs boson decaying to tau leptons, to b-quarks, the separation of different Higgs boson production mechanisms and very recently the direct observation of the coupling of the Higgs boson to the top quark. Regression techniques were used, e.g., for the calibration of electrons and photons with impact on the resolution of the Higgs peak and on the measurement of its mass.

Recently ATLAS physicists have put these new algorithms to work on their data. The ATLAS detector consists of millions of individual sensors, which must work in unison to detect hints of new particles. Conventional event reconstruction relies on many hand-crafted algorithms, which first distil the millions of raw sensor outputs down to hundreds of physical objects, and then further summarize these objects as a few variables in each collision. BDTs are still useful as the final step, when objects must be classified from a dozen of variables. But more modern machine learning, with its ability to distil very complicated information into a few meaningful quantities, has opened new doors.

Thanks to modern neural networks, physical objects like jets and electrons may soon be identified directly from raw data. For example, calorimeters measure energies in discrete cells, and are somewhat analogous to cameras measuring light in pixels, meaning that image processing techniques can be adapted to our calorimeters. Moreover, Recurrent Neural Network, initially developed for text analysis (where sentences have variable number of words), can be used to analyse a bunch of tracks in a jet. As the machines advance, ATLAS physicists ask more sophisticated questions. With the help of generative networks, for example, physicists can invert the particle classification problem to simulate realistic physics instead.



Schematic of RNN for b tagging in ATLAS.

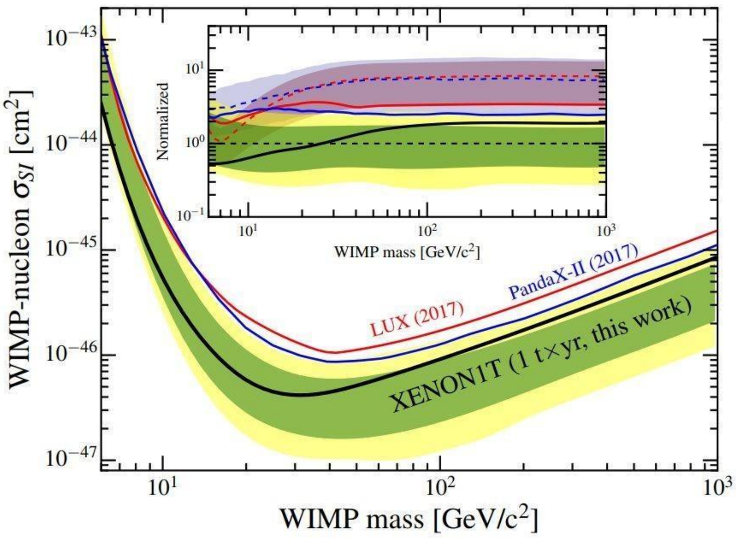
"But we can't do it all on our own! None of these modern advances would be possible without help from outside software engineers, industry data scientists, and academic machine learning researchers." says David Rousseau. To help bring new ideas to High Energy Physics, ATLAS is in the process of releasing curated datasets to the public. ATLAS also recently set up a mechanism to "embed" Machine Learning researchers in the collaboration, giving them access to internal software and simulated data. Thus they can collaborate directly with ATLAS physicists and eventually publish their results together with the ATLAS collaboration.

The author would like to warmly thank Markus Stoye (CMS) as well as David Rousseau and Dan Guest (ATLAS) for their invaluable contributions and comments

XENON1T probes deeper into Dark Matter WIMPs

Dark Matter seminar

XENON1T probes deeper into Dark Matter WIMPs, with 1300 kg of cold Xe atoms
Results from XENON1T, the world's largest and most sensitive detector dedicated to a direct search for Dark Matter in the form of Weakly Interacting Massive Particles (WIMPs), were reported on the 28th May, by the spokesperson, Prof. Elena Aprile of Columbia University, in a seminar at the hosting laboratory, the INFN Laboratori Nazionali del Gran Sasso (LNGS), in Italy. The international collaboration of more than 165 researchers from 27 institutions, has successfully operated XENON1T, collecting an unprecedentedly large exposure of about 1 tonne x year with a 3D imaging liquid xenon time projection chamber. The data are consistent with the expectation from background, and place the most stringent limit on spin-independent interactions of WIMPs with ordinary matter for a WIMP mass higher than 6 GeV/c². The sensitivity achieved with XENON1T is almost four orders of magnitude better than that of XENON10, the first detector of the XENON Dark Matter project, which has been hosted at LNGS since 2005. Steadily increasing the fiducial target mass from the initial 5 kg to the current 1300 kg, while simultaneously decreasing the background rate by a factor 5000, the XENON collaboration has continued to be at the forefront of Dark Matter direct detection, probing deeper into the WIMP parameter space.



Shown are the limits on WIMP interactions, derived from one year of XENON1T data. The inset compares our limit and sensitivity with the limit and sensitivities of previous experiments.
WIMPs are a class of Dark Matter candidates which are being frantically searched with experiments at the Large Hadron Collider, in space, and on Earth. Even though about a billion WIMPs are expected to cross a surface of one square meter per second on Earth, they are extremely difficult to detect. Results from XENON1T show that WIMPs, if they indeed comprise the Dark Matter in our galaxy, will result in a rare signal, so rare that even the largest detector built so far can not see it directly. XENON1T is a cylindrical detector of approximately one meter height and diameter, filled with liquid xenon at 95°C, with a density three times that of water. In XENON1T, the signature of a WIMP interaction with xenon atoms is a tiny flash of scintillation light and a handful of ionization electrons, which themselves are turned into flashes of light. Both light signals are simultaneously recorded with ultra-sensitive photodetectors, giving the energy and 3D spatial information on an event-by-event basis.
In developing this unique type of detector to search for a rare WIMP signal, many challenges had to be overcome; first and foremost the reduction of the overwhelmingly large background from many

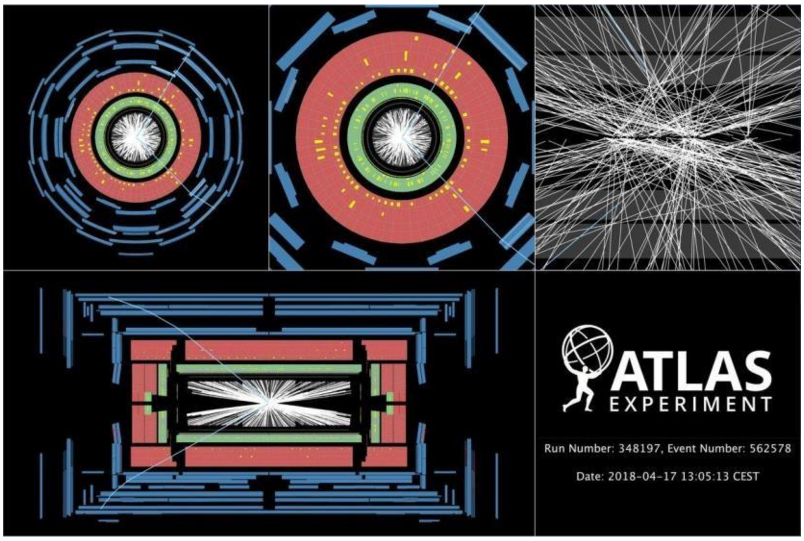
sources, from radioactivity to cosmic rays. Today, XENON1T is the largest Dark Matter experiment with the lowest background ever measured, counting a mere 630 events in one year and one tonne of xenon in the energy region of interest for a WIMP search. The search results, submitted to Physical Review Letters, are based on 1300 kg out of the total 2000 kg active xenon target and 279 days of data, making it the first WIMP search with a noble liquid target exposure of 1.0 tonne x year. Only two background events were expected in the innermost, cleanest region of the detector, but none were detected, setting the most stringent limit on WIMPs with masses above 6 GeV/c^2 to date. XENON1T continues to acquire high quality data and the search will continue until it will be upgraded with a larger mass detector, being developed by the collaboration. With another factor of four increase in fiducial target mass, and ten times less background rate, XENONnT will be ready in 2019 for a new exploration of particle Dark Matter at a level of sensitivity nobody imagined when the project started in 2002.

New season starts for the LHC experiments *by* ***Panos Charitos***

The last 2017 proton-proton collisions took place on 28 November and the LHC machine was shut down during the winter period to allow for planned technical interventions while the LHC experiments profit from this period to perform maintenance work on many sub-detectors.

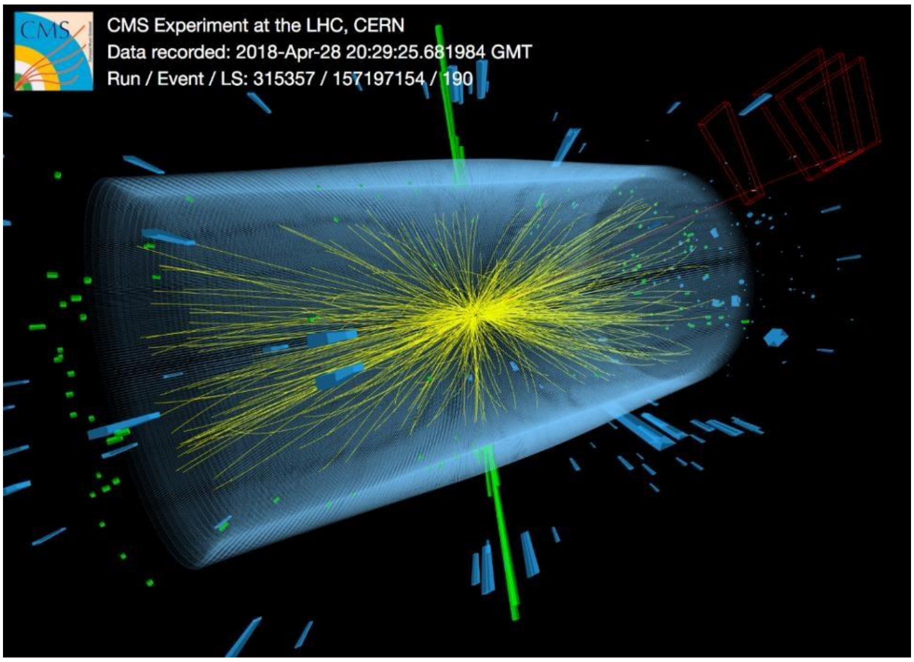
Four months later proton beams were back at the LHC. The re-commissioning of the accelerator has proceeded very smoothly and first collisions arrived earlier than initially expected. Last April, a small number of bunches were injected to deliver test collisions inside the four LHC experiments. LHC operators declared stable beams on the 17 April and over the next days they stepwise increased the number of protons bunches per beam. On the 28 April they reached 1200 bunches. This was a crucial step in the intensity ramp up of the LHC towards the optimal running configuration – which foresees 2556 bunches per beam.

ATLAS and CMS, the two “general-purpose” detectors, will continue to probe the properties of the Higgs boson as its peculiar properties call for further exploration including its interaction with all the other particles of the Standard Model.



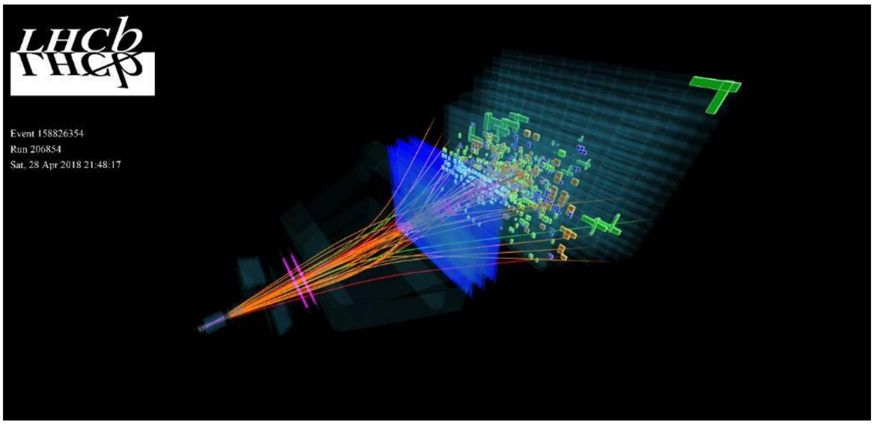
An event recorded by ATLAS earlier in April, from some of the first collisions of the year with three proton bunches circulating in the LHC (Image: ATLAS/CERN)

Since the Higgs boson discovery, physicists have studied its behaviour and interactions with other particles, which have so far shown good agreement with the Standard Model. Searches will also continue for supersymmetric partners of the familiar bosons and fermions that are predicted to exist by a family of theories known as supersymmetry, which might provide us with a candidate for a dark-matter particle. ATLAS, CMS and LHCb are also searching for hints of dark matter through other means, and will add the forthcoming trove of data to their stockpiles as they advance their explorations.

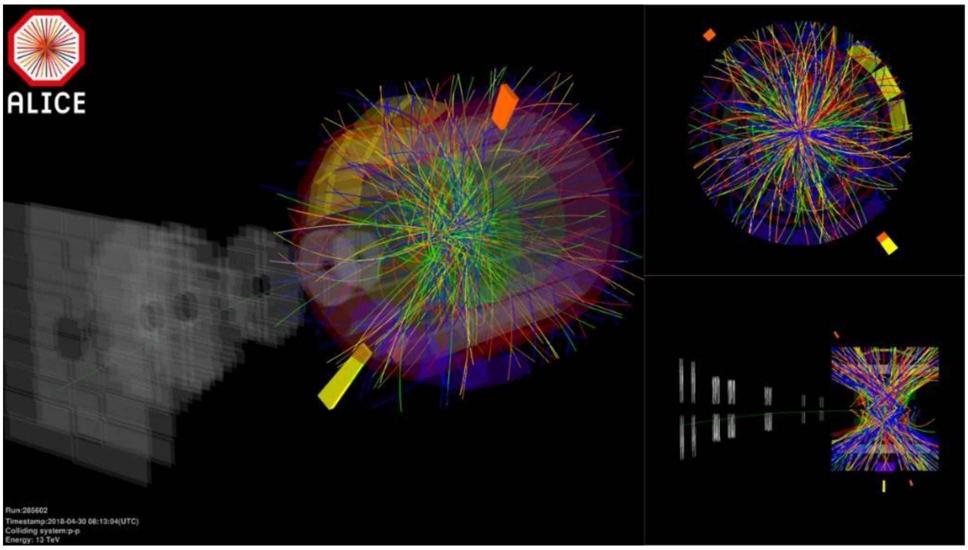


Collisions with 1200 bunches of protons in each beam, recorded by the CMS detector in April 2018. The yellow lines represent reconstructed particle trajectories in the tracker, the green and blue rectangles represent energy deposits in the calorimeters, and the long red lines represent reconstructed muon trajectories (Image: Tom McCauley/CMS/CERN).

Among other searches, LHCb will continue to seek a solution to the problem of matter-antimatter asymmetry, as the Standard Model cannot adequately explain the observed abundance of matter in the universe. When matter was formed in the Big Bang, there should have been an equal amount of antimatter accompanying it; each matter-antimatter pair should then have annihilated upon contact, leaving us with a universe without stars or human beings to observe them.



ALICE, the LHC’s heavy-ion specialist, focuses on collisions of lead nuclei in order to study the strong interaction and the quark-gluon plasma. It also records proton-proton collisions to continue its investigation of the properties of collision events that contain a large number of particles produced at the same time and to serve as a baseline with which to compare lead-lead collisions.



A proton-proton collision event at a centre-of-mass energy of 13 TeV, recorded by ALICE on 30 April 2018, one of the first with proton beams containing 1200 bunches (see image above). Over the last month, ALICE carried out a few tests, starting from the timing calibration of some of the subdetectors. Data were taken with a set of triggers and special setups, as requested by some detector groups: in particular, the Electromagnetic calorimeter (EMCal) and the Di-Jet Calorimeter (DCal). A few more special setups will be used in the following weeks, before starting a long data taking period with a fixed trigger configuration, which will hopefully last for some months.

The LHC operators will keep ramping up the number of bunches, aiming to hit 2556 bunches in total. This will help them achieve their target of 60 inverse femtobarns (fb^{-1}) of proton-proton collisions this year delivered to both ATLAS and CMS, 20% more than the 50 fb^{-1} achieved in 2017. In simple terms, each inverse femtobarn can correspond to up to 100 million million (10^{14}) individual collisions between protons. The proton-proton run will be followed by the first heavy-ion run since 2016; the LHC will inject and collide lead nuclei at the end of the year.

On 5 May, during the last steps of the intensity ramp-up, when the average peak luminosity for ATLAS and CMS was close to 2.1×10^{34} $cm^{-2}s^{-1}$, while on the 11th of May, the integrated luminosity for ATLAS and CMS was already at 6.91 fb^{-1} (of the 60 fb^{-1} planned for 2018) equalling or even surpassing the record peak luminosity of 2017. From now on, the LHC is in production mode for physics. The operation of the machine will be consolidated in parallel, meaning that the machine settings will be further tweaked, beam life times optimised, performance stabilised and, if possible, increased.

This is the last year with collisions before the LHC enters a period of hibernation until spring 2021 (Long Shutdown 2), during which the machine and the experiments will be upgraded. All four experiments will therefore hope to maximise their data-collection efficiency to keep themselves occupied with many analyses and new results over the two-year shutdown, using high-quality data collected this year.

DsTau project: study of tau-neutrino production at the CERN SPS

CERN

by ***Akitaka Ariga and Tomoko Ariga (for the DsTau collaboration)***

DsTau is a new project which has been proposed at the CERN SPS to study tau-neutrino (ν_τ) production [1] with the aim of providing important data for future ν_τ measurements.

Indications of possible lepton non-universality have been recently reported by several experiments, including studies of B meson decays [2], that showed enhancements of phenomena involving τ and ν_τ. These results may indicate new physics effects between heavy flavour quarks and leptons. One approach to investigate these anomalies is to study neutrino scattering. If there are additional particles mediating the interactions between heavy quarks and heavy leptons, an increase in the $\nu_\tau$cross section would be suggestive evidence of new physics. However, to date, experimental results on the ν_τ cross section are too poor to probe these questions [3]. A new precise measurement of the ν_τ cross section is necessary to test new physics effects in ν_τ –nucleon CC interactions. This measurement also has practical importance for neutrino oscillation experiments and astrophysical ν_τ observations

The concept of ν_τ cross section measurement in a nonoscillated ν_τ beam is shown in Fig. 1. The dominant source of ν_τ is the sequential decay of Ds mesons, $D^+_s \rightarrow \tau^+ \nu_\tau \rightarrow X \bar{\nu}_\tau \nu_\tau$ and $D^-_s \rightarrow \tau^- \bar{\nu}_\tau \rightarrow X \nu_\tau \bar{\nu}_\tau$, produced in high-energy proton interactions. However, there is no experimental measurement of the Ds differential production cross section in fixedtarget experiments using proton beams, which leads to a large systematic uncertainty on the ν_τ flux estimation. This was the main source of error in the ν_τ cross section measurement [3] at >50%, larger than the 33% relative statistical uncertainty due to the limited number of detected events (nine in total). While the statistical uncertainty is expected to be reduced down to the 2% level in future ν_τ programs as already incorporated in the SHiP project [4], it is vital to reduce the uncertainty of the ν_τ flux prior to such high statistics experiments.

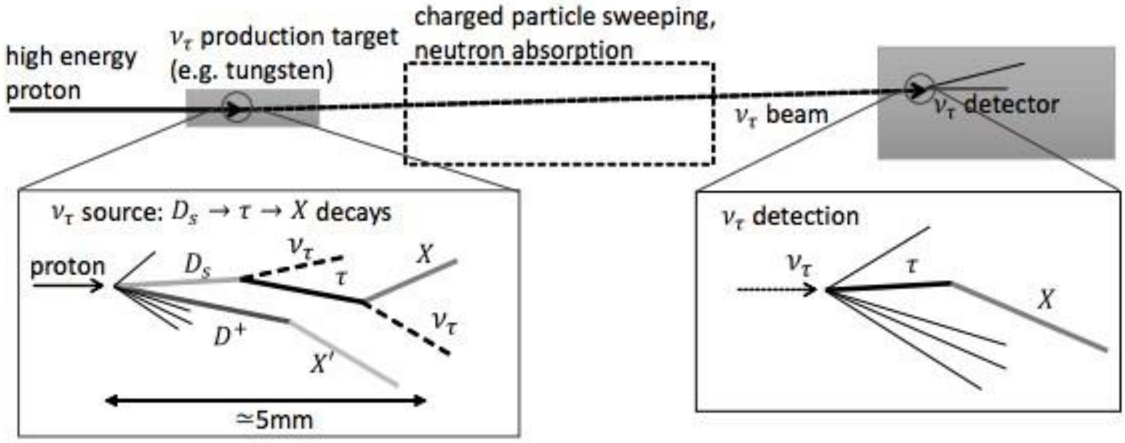


Figure 1: Concept of ν_τ cross section measurement.

The DsTau project aims to reduce the systematic uncertainty in the cross section measurement from >50% to 10%. This will be achieved by detecting 1000 Ds → τ → X events and thus measuring the Ds differential production cross section in 400 GeV proton interactions. This double decay occurs at a distance of ~5 mm. The challenge of this measurement is the detection of the 1 tiny kink angle of the Ds → τ decay, which has a mean kink angle of 7 mrad. For this purpose, emulsion detectors with nanometric precision readout will be used. The emulsion detector has a position resolution of 50 nm [5], which leads to an intrinsic angular resolution of 0.35 mrad with a 200-µmthick plastic base layer (Fig. 2 left). As shown in Fig. 2 right, each detector unit comprises a 500 µm-thick tungsten target, followed by 10 emulsion films interleaved with 200 µm-thick plastic sheets acting as high-precision particle trackers as well as decay volumes for short-lived particles

A module is made of ten such units followed by an ECC to measure the momenta of the daughter particles. A total of 370 modules will be exposed to the 400 GeV proton beam from SPS at a density of 105protons/cm2 uniformly on the module surface. 4.6×10^9 protons on target will be collected, yielding to 2.3×10^8 proton interactions in the tungsten plates, and 1000 detected Ds → τ decays.

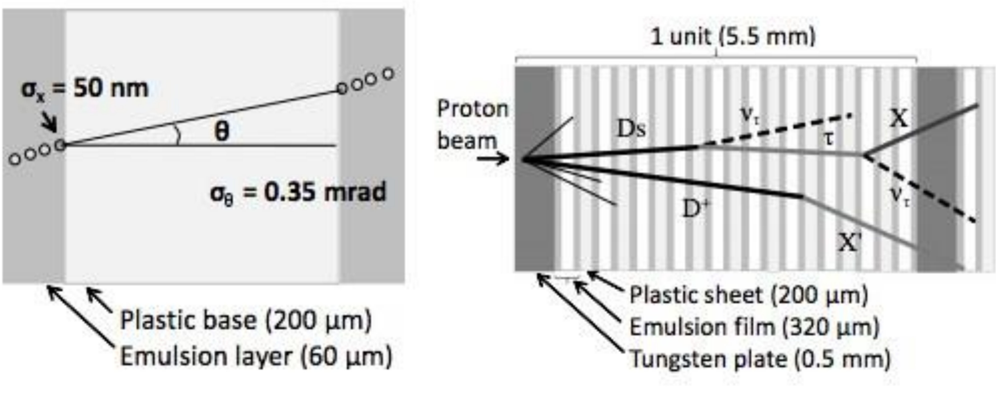


Figure 2: Left: Schematic of the angular measurement in an emulsion film. An angular precision of 0.35 mrad can be achieved by a single emulsion film. Right: A schematic of topology of $D_s \to \tau \to X$ double-kink events in the detector.

The data analysis will require the full area scanning of the 1000 m^2 emulsion surface by the world's fastest readout system, the Hyper Track Selector (HTS) [6]. After detecting τ decay topologies, events will be analysed by dedicated high-precision systems using a piezo-based highprecision

Zaxis, allowing emulsion hits to be measured with nanometric resolution. To study the differential production cross section of D_s mesons, the momentum of the D_s meson (PD_s) must be measured. Because Ds mesons decay quickly and the invisible $\nu\tau$'s escape measurement, the direct measurement of PD_s is not possible. However, the peculiar event topology gives us indications of PD_s . For example, Ds → $\tau\nu_\tau$ is a two-body decay with well-defined decay momentum. Therefore, the kink angle of $D_s \rightarrow \tau$ is a good indicator of PD_s . Because the $D_s \rightarrow \tau \rightarrow X$ decay topology has two kink angles ($\theta D_s \rightarrow \tau$, $\theta_\tau \rightarrow X$) and two flight lengths (F LDs→τ , F Lτ→X), the combination of these four variables effectively provides an estimate of PD_s . A machine-learning algorithm was trained with a simulated sample (τ → 1 prong) using the four variables to estimate PD_s , the result of which is shown in Figure 3. The momentum resolution is estimated to be 18%.
In addition to the primary aim of measuring Ds production, analysing 2.3×108 proton interactions, combined with the high yield of 105 charmed decays produced as by-products, will enable the extraction of additional physical quantities such as the interaction length of charmed hadrons, the Λc production rates and the search of super-nuclei.

Two test beam campaigns were performed in November 2016 and May 2017 at the CERN SPS. The upper left panel of Figure 4 shows the detector setup at the H4 beamline. To analyse the data, a new tracking algorithm has been developed to reconstruct tracks in the extremely high track density of $O(10^5$–10^6) protons/cm^2 , which is 1000 times higher than that of OPERA. An example of the reconstructed data from the detector is shown in the upper right panel of Figure 4. A systematic search of the decay topologies of charmed particles was applied and the first double charm event is shown in the lower panel of Figure 4, proving that analyses of short-lived particles in actual experimental conditions are possible.

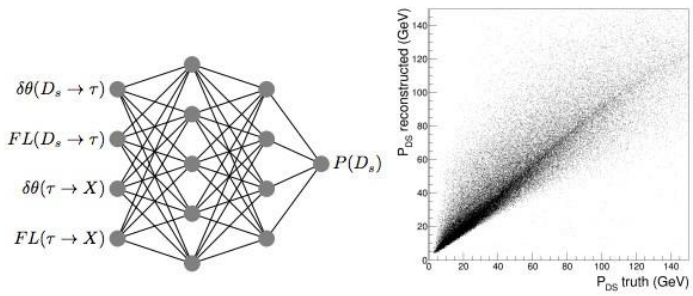


Figure 3: Left: Design of a neutral network for reconstruction of the D_s momentum from the topological variables $\theta_{D_s \to \tau}$, $\theta_{\tau \to X}$, $FL_{D_s \to \tau}$, $FL_{\tau \to X}$. Right: Reconstructed D_s momenta versus true momenta. A gaussian fit of $\Delta P/P$ provides σ of 18%.

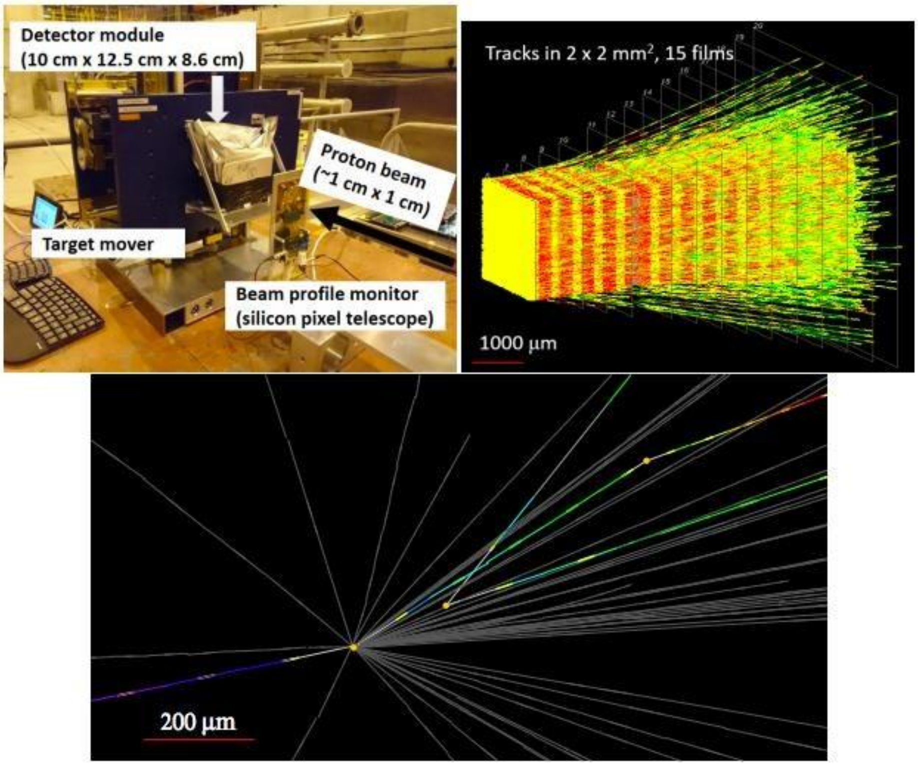


Figure 4: Top-left: Photo of the detector setup for the test beam campaign at the CERN SPS H4 beamline. The detector module was driven by a target stage so that it was uniformly exposed to the proton beam at a density of 10^5 protons/cm^2. Top-right: An example of the track data reconstructed in 2×2 mm^2 and 15 films. About 15,000 tracks are reconstructed in this volume. Bottom: A double charm event with a neutral 2-prong (vee) and a charged 1-prong (kink) topology (tilted view).

The CERN-SPSC approved a pilot run in 2018, and recommended beam time for a physics run in 2021. We are currently producing emulsion films for 30 detector modules for the pilot run in August 2018. This is primarily intended to provide a test of large data taking and an estimation of the background, but which also already allows us to re-evaluate the ν_τ cross section measured by DONUT by significantly reducing the overall systematic uncertainty. With the outcome of the physics run, DsTau will provide essential inputs for future tau neutrino experiments and pave a way for the search of new physics effects in ν_τ –nucleon interactions.

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Cloud(y) climate studies at CERN

DT
CLOUD SME *by*
Stefan Weber

Continuous improvements to the CLOUD facility as well as to the instruments combined with the state of the art know-how available at CERN have enabled a steady increase in the measurement capabilities and resulted in numerous high impact publications. This combination reflects CLOUD's world leading role in experimental laboratory studies of atmospheric aerosol nucleation and growth.

Cloud studies under tightly controlled conditions the numerous different parameters as well as a great number of processes, happening in the atmosphere that lead to cloud formation and therefore significantly influence earth’s climate. The understanding of the interplay and the influence of the different parameters is fundamentally important to understand climate change and further improve climate predictions.

The constant evolution of the Cloud experimental area from 2009 to nowadays is shown in fig. 1. Cloud's chamber is hosted at T11 in the PS Easthall (building 157) and this adds another outstanding feature as the 3.5 GeV π-beam can be used to simulate the impact of galactic cosmic rays. Furthermore it allows to study the effect of ionizing radiation on aerosol and cloud formation.

Figure 1. Evolution of the CLOUD experimental area from CLOUD01 in 2009 (left) to CLOUD11 in 2016 (right). As the photos show, safety aspects (e.g. wearing of helmets) have evolved, too.

In recent years, the focus was twofold and driven by a great interest in pristine and urban environments. The former typically investigates processes happening in boreal forests and marine environments, while the latter is concerned with more polluted and purely anthropogenic causes. A detailed physics overview was already given by the spokesperson of Cloud, Jasper Kirkby, in an issue of the EP newsletter in 2016. CLOUD’s first measurement campaign in 2018 is now in June-July. This is a technical run and devoted to the sharpening of our understanding of the measurement facility itself. This year's main campaign will start in autumn and has a similar goal as previous campaigns, namely to study the precursors responsible for clouds. On the contrary, in the following Cloudy campaign in 2019 we will change our focus towards the microphysical processes during cloud formation itself.

The achievements of the CLOUD collaboration, its unique scientific possibilities and focus made possible to receive a grant for a third Marie Curie Innovative Training Network, financed by the European

Commission. The Cloud-MOTION ITN is a multi-site network of 15 Ph.D. students distributed over 10 institutes across Europe with two fo them located at CERN.

Using the excellent capabilities of the CLOUD facility, researches will be able to perform detailed and high-precision studies on the role of atmospheric aerosols in cloud formation and consequently in climate change as members of a distributed network of collaborators. They will gather data from a wide range of instruments and by combining and analysing them will try to answer some of the key questions related to aerosol formation and its potential impact in climate change. Furthermore, their research also focuses on the formation of aerosol nucleus and growth both in pristine and urban environments, significantly adding to our knowledge on the role that a growing urban environment might play. Last but not least, another important aspect is the formation of ice on glassy Secondary Organic Aerosol that can act as Ice Nucleating Particles.

Due to the wide variety of instruments using different software and data formats a particularly delicate issue is the inclusion of all instruments into the same Data Acquisition System. Another complication is added by the need for ‘quasi’ real-time on-line monitoring and data analysis. This is required, since the exact parameter choice for the next measurements is decided on a day to day basis and based on the most recent data taken.

Besides that, a better understanding of the chamber characteristics is required to increase the precision of the aerosol physics measurements. Effort is now being put to measure the mixing time and possible non-uniformities of gases and ions inside the chamber.

The CLOUD collaboration aims to maintain and strengthen its leading role in experimental laboratory studies on atmospheric aerosol and cloud formation, and ultimately to improve understanding of the climate change. The CLOUD facility at CERN has proven to be an excellent platform for this task while continue training the next generation of scientists to tackle these questions.

A bright future for the development of microelectronics at CERN

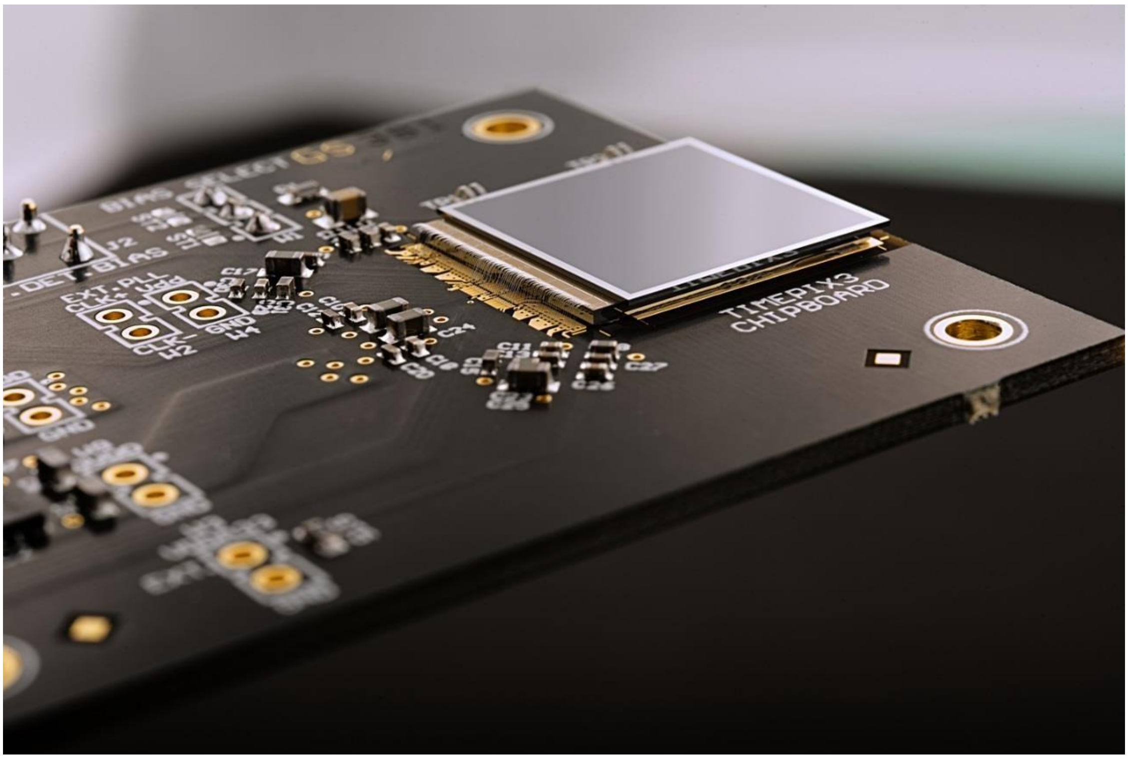
microelectronics
ESE
*by **Panos Charitos***

During the 2018 FCC week in Amsterdam, Michael Campbell (EP-ESE) gave a presentation on the “Present and future of microelectronics”. Following an informative review of ASICs used in the LHC run one systems, he tried to distinguish recent trends in ASIC design for HEP experiments and discussed possibly relevant technologies for experiments at future colliders, such as the FCC.

Campbell noted that radiation hard ASIC’s are essential for the present day LHC detectors and highlighted some on-going developments, most of which concern tracking detectors to aimed at reaching the even higher performances required by the high-luminosity LHC (HL-LHC) upgrade.

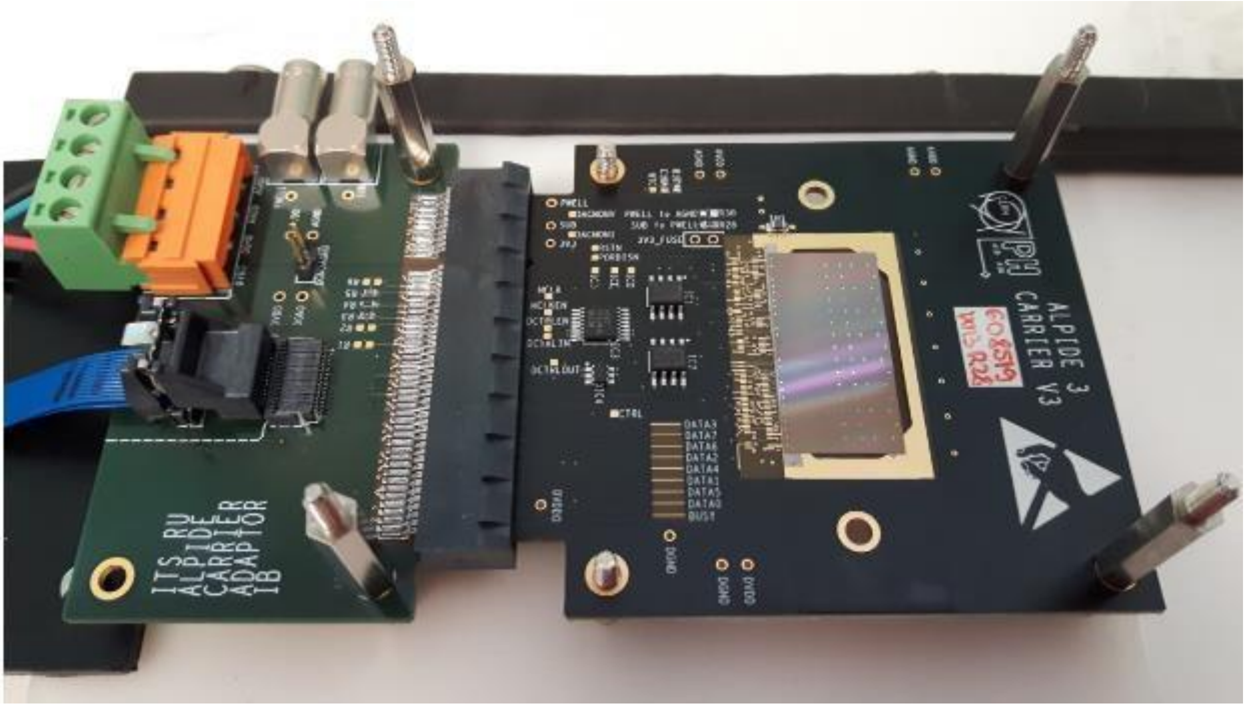
A critical requirement for modern high-energy-physics detectors is to maximize the interaction of the particles flying out from the collision point with the active part of the sensors while at the same time minimizing their interaction with auxiliary material such as cables, cooling and mechanical infrastructure.

Detectors with millions of channels profit from developments in microelectronics that allowed the read-out circuit of each detector to be designed to provide optimal signal-to-noise characteristics with minimal power consumption. In addition, high-speed links and monitoring electronics could be highly optimized to provide the best solution for system builders. Campbell emphasized that these developments, crucial for the physics searches of the LHC experiments - were not evident from the beginning and significant progress has been achieved thanks to the collaborative efforts of microelectronics specialists at CERN and those from other HEP groups.



The Timepix3 chip is a multipurpose hybrid pixel detector developed within the Medipix3 Collaborations, having applications within medical imaging, education, space dosimetry and material analysis.

Continuing the long road that started in the late 1990’s with the development of the first ALICE readout chip based on hybrid pixel technology, a novel concept is being applied for the LS2 upgrade of the ALICE Inner Tracking System (ITS). The so-called ALPIDE chip is based on monolithic pixel technology that is applied for the first time at a large scale at the LHC. Several previous technologies (hybrid pixels, silicon drift detectors and silicon strip detectors) have been replaced by a single technology. This unified approach resulting on the order of > 1000 wafers making the development attractive to the supplier while significantly reducing the cost for the experiment.



The ALPIDE chip, a innovative monolithic silicon pixel sensor developed at CERN for the ALICE ITS upgrade

A wealth of developments is currently ongoing also for the microelectronics of the other LHC experiments aimed at coping with the challenging environment of the HL-LHC. For the new silicon tracker being developed for CMS, pixel-strip and strip-strip modules are used to extract track stubs locally and contribute to the L1 trigger decision. The LHCb VELO upgrade permits trigger free operation of a tracking system for the first time at LHC. In RD-53, which is developing a hybrid pixel readout chip for the ATLAS and CMS upgrades, on-pixel buffering becomes essential for dealing with the extreme hit rates foreseen. Finally, another key development related to the HLLHC upgrade is lpGBT, based on a 65nm CMOS, like many of the developments mentioned here.

In every case (i.e. VELOpix, CMS tracker, RD-53 and lpGBT) high level behavioural simulations are essential in identifying the most appropriate choice of architecture. Sophisticated simulation tools are used throughout the design and verification processes and large expert teams are needed. For example, in the case of RD-53 the design effort involved more than 10 designers and a total of more than 30 man years while the entire design team spent some months at CERN; a crucial step for the successful completion of the chip.

Campbell then discussed where developments in the HEP ASIC design community stood with respect to work in groups outside the field. Although many leading academic and industry groups are working on technologies of 10nm feature size and below, there is still quite some activity on the 65nm process, which is the main workhorse of the HEP community at present. That being said, he pointed out that the ALICE SPD pixel readout chip (250nm feature size) was submitted to foundry in 1999, the same year that Intel launched its processor using the same feature size. Since then we, as a community, have fallen far behind the mainstream: the Intel processor using the 65nm feature size was launched already in 2006!

The very latest CMOS processes offer many opportunities and challenges for the teams working on the development of microelectronics. In particular, FinFET transistors have already replaced planar CMOS transistors in the most recent processes. Their tolerance to radiation damage is for now largely unknown but first measurements leave little room for optimism (see presentation by

G. Borghello at the FCC week 2018). This means that for the high levels of radiation foreseen in future high-energy colliders, new approaches involving replaceable ASICs may have to be considered seriously. Wafer level chip stacking permits the hybridization of CMOS sensor and readout chips at a much lower cost per assembly than the current bump bonding techniques used for hybrid pixel detectors. However, accessing such processes usually requires sizable orders. In Campbell's opinion accessing these processes may require a major cultural shift in our community whereby large teams are formed to provide homogeneous ASIC solutions in a given, wellsupported technology. The design of a large tracking system presents an optimistic scenario as it could cover a large area (of the order of 1000m^2) resulting in a need for tens of thousands of wafers. This wafer volume may render our community a more attractive client for the suppliers of leading edge technologies - a modern wafer production facility can produce ~ 1M wafers starts per year.

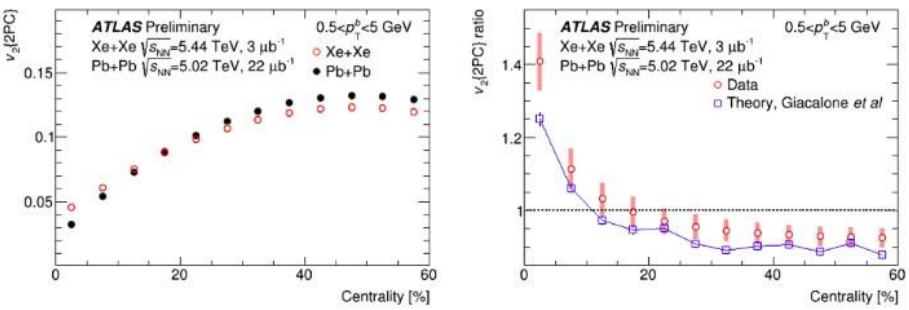
Radiation tolerance requirement is strongly machine dependent. Reference TID levels correspond to the innermost tracker layer (note that in some cases the forward calorimeters might be exposed to larger doses, such as in FCC-hh) [image from Federico Faccio]. The future is bright, if challenging. Opportunities exist to achieve unprecedented spatial and timing precision even in an environment of very dense hits. Depending on the choice of future collider, radiation tolerance may continue to be a specific challenge for our community. But from past experience we know that adapting new technologies will be essential to yielding the best physics outcome from the new colliders. Getting organized in terms of foundry access, tools, training and forming and maintaining large expert teams are among the challenges faced by our ASIC design community.

CERN experiments presented their latest results from the study of lead-ion collisions at the annual Quark Matter conference, that was held this year in Venice, Italy. The programme includes a plethora of presentations on a variety of topics, spanning QCD at high temperature, QGP in small systems, initial state physics, collective dynamics, correlations and fluctuations, electroweak probes, jets, quarkonia and others. All experiments report highly subtle measurements, bringing heavy-ion physics into a new era of high precision studies.

Heavy ion collisions at the Large Hadron Collider (LHC) energies result in a hot, dense medium called the quark-gluon plasma (QGP), in which the primary constituents are thought to be quarks and gluons. The study of these collisions is expected to shed more light on the strong interaction and how quarks and gluons interact to form stable particles. Moreover, the LHC experiments presented results from asymmetric collisions of lead ions with protons while for the first time Xe-Xe collisions produced at the LHC during a short test run in 2017. By comparing the result of pp, pPb and PbPb collisions physicists are able to study the role that the size of the colliding system plays in the final results.

ATLAS

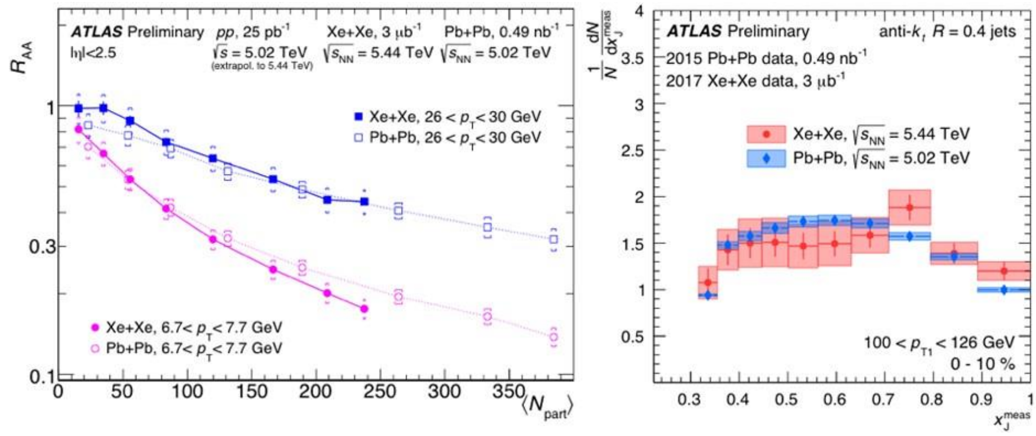
In new results presented at the Quark Matter 2018 conference, ATLAS has studied “collective flow” and “jet quenching” in both xenon-xenon and lead-lead collisions. Comparisons of elliptic flow measurements in xenon-xenon and lead-lead collisions provide a unique opportunity to study viscous effects in the hydrodynamic expansion of the QGP, as well as the effects of event-by-event fluctuations in the collision geometry. These fluctuations are expected to be larger in xenon collisions compared to lead ions resulting in an enhancement of the observed flow. A counterbalancing effect comes from viscous effects that weakn the amplitude of the flow in peripheral collisions and furthermore in xenon collisions where there are larger spatial variations. Results confirming the above assumption were presented in Quark Matter 2018.



Left: charged particle v2 measured in xenon-xenon and lead-lead collisions as a function of centrality. Right: ratio of xenon to lead-ion v2 values compared to theoretical predictions. The

error bars and bands indicate statistical and systematic uncertainties, respectively. (Image: ATLAS Collaboration/CERN).

Another interesting result from the comparison of xenon with lead ion collisions is the different in the so-called jet quenching, one of the characteristic signature of QGP formation. Jet quenching may be weakened in xenon collisions due to the reduced density of the QGP and the smaller path lengths of the partons in the plasma compared to the larger lead collisions. The reduction is quantified by RAA, the ratio of particle yields as a function of transverse momentum in nuclear collisions to that in protonproton collisions, scaled by a factor that accounts for the flux of colliding quarks and gluons from each nucleus. The charged hadron RAA measured in xenon-xenon and lead-lead collisions are compared in the figures below as a function of the number of nucleons, the number of participating nucleons. It was shown that the xenon and lead results are similar, but slightly more suppression is observed in the xenon collisions, suggesting that the overlap geometry is not the only feature which determines the precise amount of jet quenching.



Charged hadron nuclear modification factor as a function of the number of nucleons (Npart) for xenon and lead-lead collisions in two different hadron pT intervals (left). Dijet xJ distributions in the 10% most central xenon-xenon and lead-lead collisions (right). (Image: ATLAS Collaboration/CERN).

Another interesting result from ATLAS reported during QM18 comes from the study of the quark-gluon plasma using muon pairs produced by two photons during ultra-peripheral collisions. To study dimuons in lead-lead collision data, ATLAS analysed two variables characterizing the kinematic properties of the two oppositely-charged muons, namely “acoplanarity” and “momentum asymmetry”. The “acoplanarity” variable measures how much the two muons are not back-to-back. The “momentum asymmetry” variable reflects the relative difference in the transverse momenta of the muons, or the momentum that is perpendicular to the beam line. Both quantities are large for muons decaying from heavy flavor mesons, while both are nearly zero for the gamma-gamma process. For some years, it remained an open question whether dileptons from photon-photon interactions could be observed in more typical high-multiplicity interactions of heavy ions and, if so, whether they would be sensitive to the dramatically increased charge density inside the QGP.

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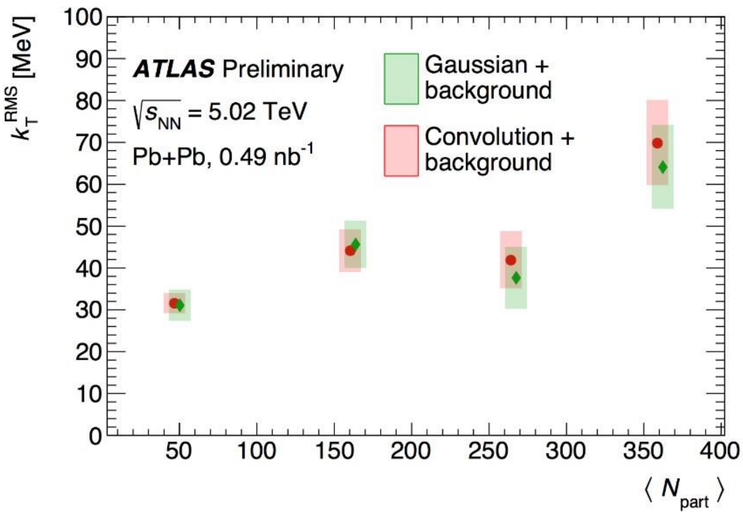


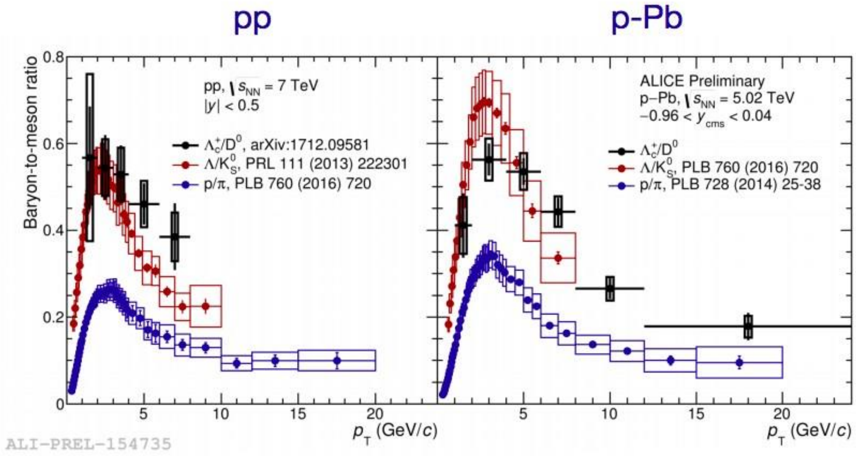
The root-mean-square of the distribution of additional transverse momentum broadening, relative to the muon direction. Results are shown as a function of the number of participating nucleons, with peripheral events on the left and central events on the right. (Image: ATLAS Collaboration/CERN).

During QM18, ATLAS also presented final results on quarkonium suppression in PbPb collisions, with particular attention to contributions from prompt quarkonia, produced directly in the plasma, and particles that result from the decay of B mesons, typically outside the medium. A new technique of correlating harmonic amplitudes and transverse momentum in PbPb collisions is presented.

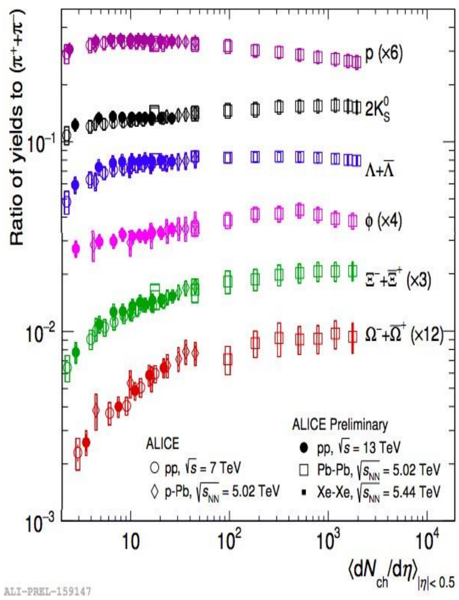
ALICE

ALICE, the LHC's dedicated experiment for the study of heavy-ion collisions presented a wealth of new measurements exploring the different stages of the atomic nuclei collisions as they form QGP and shedding light on the mechanisms of QCD. More than 70 new preliminary results were reviewed and approved for the conference and 16 new papers were published on time to be presented. Of particular interest are new measurements of how ordinary particles emerge when the QGP cools down and reverts to more standard forms of matter.

New results on heavy flavour production in p-Pb collisions show that the charmed baryon production rate is much larger than was expected from electron-positron collisions, and the baryon-to-meson ratio is characterized by a maximum at intermediate p_T, which is also seen for light flavour baryon-to-meson ratios. This suggests that there is a common production mechanism for light flavour baryons such as protons and Λ baryon and for the charmed Λ_c baryon. A first result of Λ_c baryon production in Pb-Pb collisions was presented, which also shows a large baryon/meson ratio. Improving the precision of these measurements is one of the goals of the ALICE detector upgrade programme, which was discussed in another session.

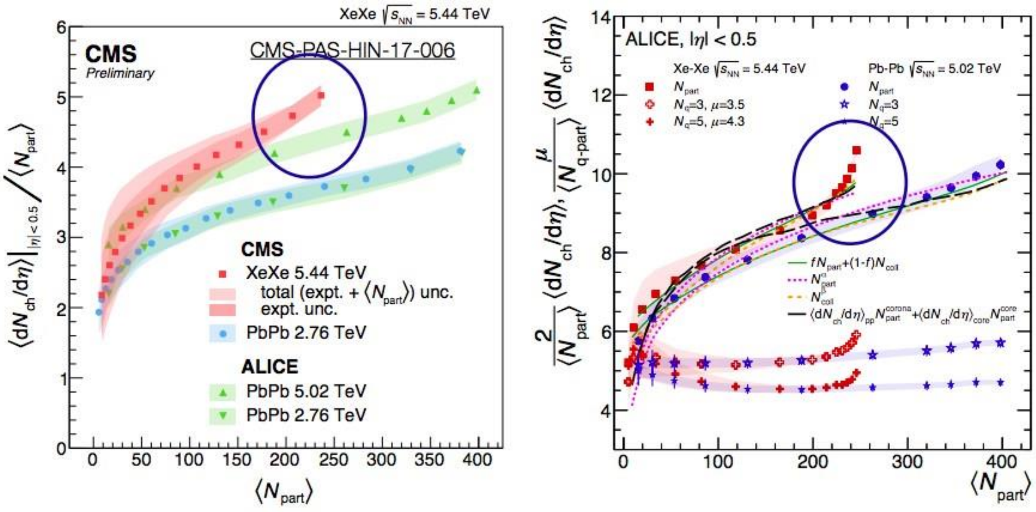


Heavy quark baryon/meson ratio similar to *Λ*/K.



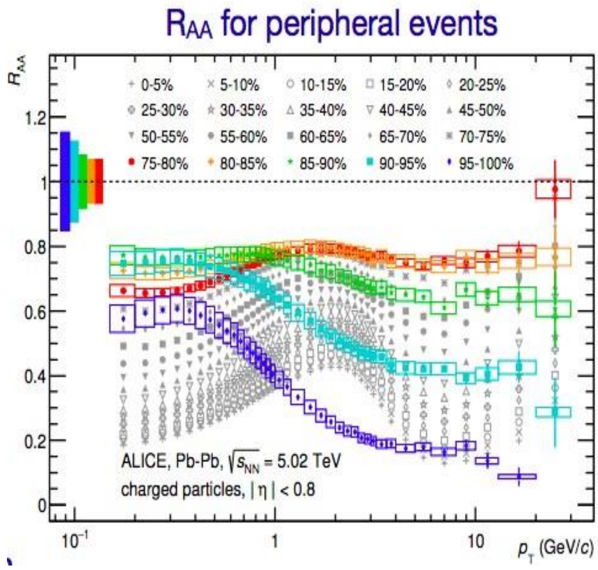
Increase of strange baryon production observed in pp, pPb and PbPb collisions.

Moreover, the collaboration presented the latest results on the production of particles ranging from photons to nuclei and hypernuclei. New studies were also presented on the dependence of particle production on the size of the colliding system, including new measurements on the data from a short run in 2017 in which nuclei of xenon, instead of protons or lead nuclei, were accelerated in the LHC. The relative abundances of light flavour hadrons in the new Xe-Xe data confirm the previously-established picture that particle chemistry depends mostly on final state particle multiplicity at LHC energies. Finally, for high-momentum particle production, a similar nuclear modification factor in Xe and Pb was measured when comparing collisions with the same multiplicity. This is qualitatively in line with expectations, since parton energy loss depends on the density and the volume of the system, but more detailed model comparisons are being pursued.



Multiplicity/Npart 'scales' (approximately) between XeXe and PbPb with data suggesting a sharper increase for central collisions that needs to be further investigated.

Another intriguing result comes from a dedicated study of the nuclear modification factor (RAA) of peripheral PbPb collisions shows that, while the suppression of high-momentum particle production that is associated with parton energy loss initially decreases when the collisions become less central, it increases again for very peripheral collisions. This non-monotonic behaviour suggests that there is a different mechanism that suppresses high-momentum particle production in very peripheral collisions; one possible explanation is that the individual nucleon-nucleon collisions in the nuclear collision have larger impact parameters and that this reduces the number of parton scatterings, and thus the particle production at high transverse momentum. It is also relevant for the interpretation of collisions of small systems, where the observed azimuthal anisotropy suggests that final state interactions are important, but no suppression of final state particle production is found.



Nuclear modification factor for peripheral events showing evidence of increasing in very peripheral collisions.

ALICE also presented a first attempt to measure azimuthal anisotropy of direct photons at the LHC, which probes the time evolution of the temperature and pressure in the Quark Gluon Plasma. The measured signal is large, suggesting the importance of late emission of photons. However, the uncertainties are still sizeable and further improvements are needed to firmly establish this conclusion.

Finally, ALICE presented new results on the nuclear modification factor for jets, as well as studies of the substructure of jets, which aim to be directly sensitive to the radiation of gluons by fast partons as they go through the plasma. A suppression of large-angle symmetric splittings is found, which suggests that partons in a parton shower interact independently with the Quark Gluon Plasma if the angle between them is large enough.

CMS

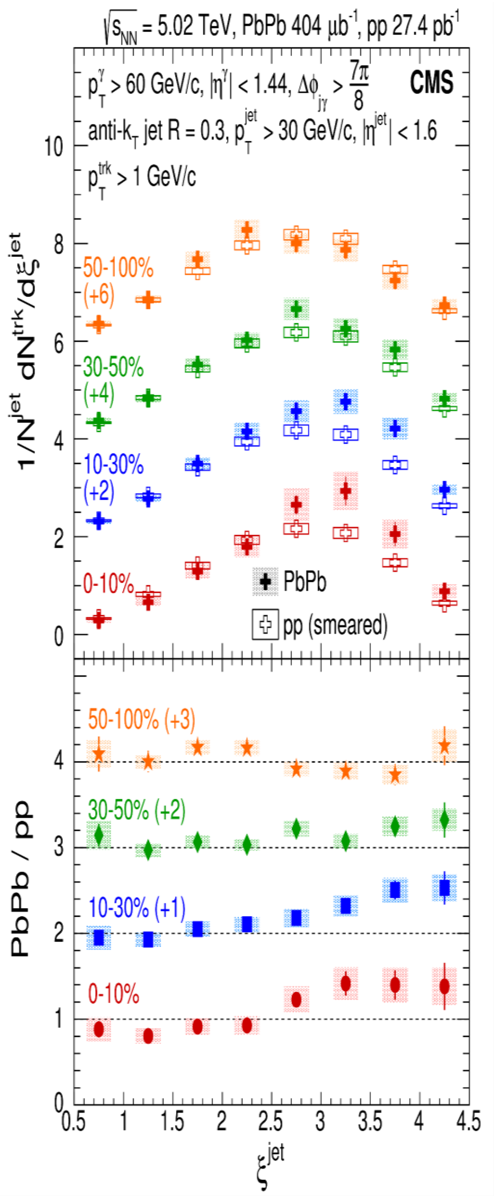
The CMS collaboration came to this year’s Quark Matter conference with fourteen new results, never shown before, and five other results recently submitted for publication. The majority of them exploit the high luminosity 8.16 TeV pPb, and 5.02 TeV pp and PbPb data delivered by the LHC in 2016 and 2015, respectively. Three of the analyses use the XeXe data at 5.44 TeV delivered during a 1 day run in October 2017.

The XeXe data show that the charged-particle production depends on collision geometry, not the system size. CMS continues to investigate collective effects (in which many particles in the event are correlated) in small systems, searching for the onset of these effects in events with a small multiplicity and also for similar effects in events which produce particles with relatively large mass or momentum. Significant v2 (a measure of azimuthal anisotropy) is observed in high-multiplicity pPb collisions for particles with either a single charm quark (D0) or a charm-anticharm pair (J/Psi). CMS reports also the first v3 measurement using 4-particle cumulants in pPb collisions, providing further evidence that v2 and v3 in pPb collisions are caused by initial state fluctuations.

CMS continues to perform increasingly detailed studies of the jet-quenching phenomenon, which gives rise to the striking dijet pT asymmetries observed in PbPb collisions (CMS collaboration 2011). Tracing the fate of energy lost by hard-scattered partons in the dense QGP remains a fascinating challenge for the field.The first measurement was reported of the detailed shapes of jets (sprays of particles created by a high momentum quark or gluon) in events with a back-to-back photon+jet pair. The results show that some of the energy in the core of the jet is redistributed to large distances from the jet axis. At the same time, the analysis of jet substructure shows that the overall distribution of particles in the core itself is hardly affected by the medium. For heavy quark studies, the first measurement of the radial profile of D mesons in jets in heavy ion collisions is reported. CMS continues to enrich its program of studying b (beauty) quarks, by adding the first measurement of Bs mesons and D mesons from the decay of beauty hadrons (called non-prompt D). For particles with charm-anticharm pairs, the measurement of Psi(2S) and J/psi mesons in PbPb, pPb, and pp collisions at 5.02 TeV reveals that the production of the Psi(2S) is suppressed with respect to J/psi in both pPb and PbPb.

The distribution of jet-correlated charged-particle tracks with $|\Delta\phi|<|\Delta\phi|< 1.0$ as a function of $\Delta\eta\Delta\eta$ in pp (top left) and PbPb (middle row) collisions. The PbPb results are shown for different centrality regions. The bottom row shows the difference between the PbPb and pp data.

The nPDFs are studied at high precision using W bosons and pairs of jets in pPb collisions at 8.16 and 5.02 TeV, respectively. The W boson results constrain the quark and antiquark nPDFs, while the dijet results represent the first evidence that the gluons which carry a large longitudinal momentum fraction in lead ions are strongly modified. CMS reported also on the scattering of a photon from one Pb nucleus off of a photon from the other (so called light-by-light scattering) in ultra-peripheral PbPb collisions.

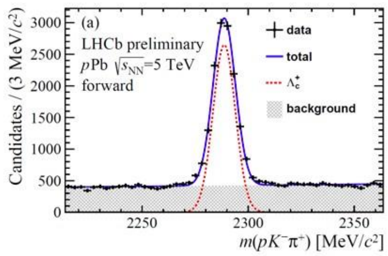


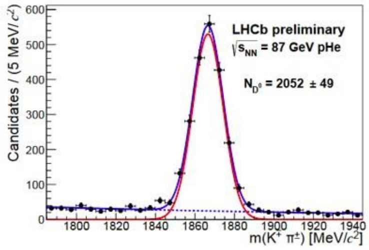
The fragmentation functions of jets associated with isolated photons are measured for the first time in pp and PbPb data, using CMS samples collected at centre-of-mass energy of 5.02 TeV as function of the ξ^{jet} parameter. When compared to the results found using pp data, the ξjet and ξTγ distributions in central PbPb collisions show an excess of low-pT particles and a depletion of high-pT particles inside the jet.

This measurement shows for the first time the in-medium parton shower modifications for events with well-defined initial parton kinematics, and constitutes a clear reference for testing theoretical models of the parton?s passage through the QGP.

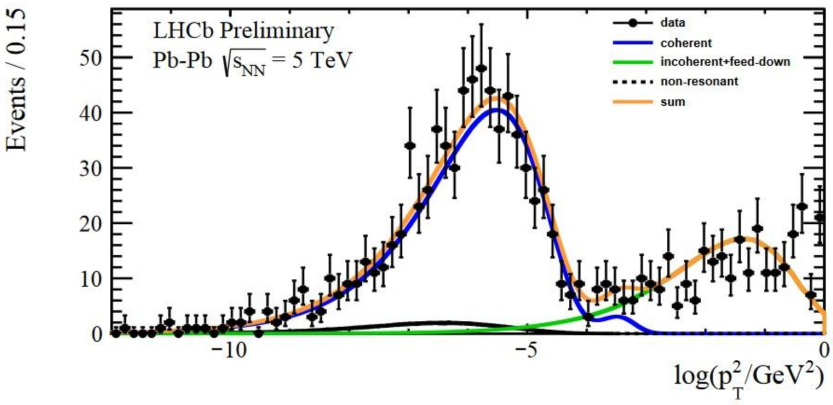
LHCb

The LHCb collaboration presented a wide range of results on charm production in various types of collisions. These include the production of the Λc baryon in pPb collisions and of D0 and J/ψ mesons in the fixed-target collisions with He and Ar. The production of heavy quarks in nucleus-nucleus interactions is well suited to the study of the transition between ordinary hadronic matter and the hot and dense Quark-Gluon Plasma (QGP). The production of J/ψ mesons in nucleus-nucleus interactions, its possible suppression in the quark-gluon medium and/or later charm-anti-charm quark recombination are all studied in order to shed light into the mechanisms governing such a phase transition. The LHCb pPb and fixed-target results utilising proton interactions with different nuclei at different energies provide precious reference results in conditions in which the formation of the QGP is not expected. The images below show a signal mass peak of Λc baryons decaying into a proton, a K and a π (above left) as well as of D0 mesons decaying into a K and a π (above right).



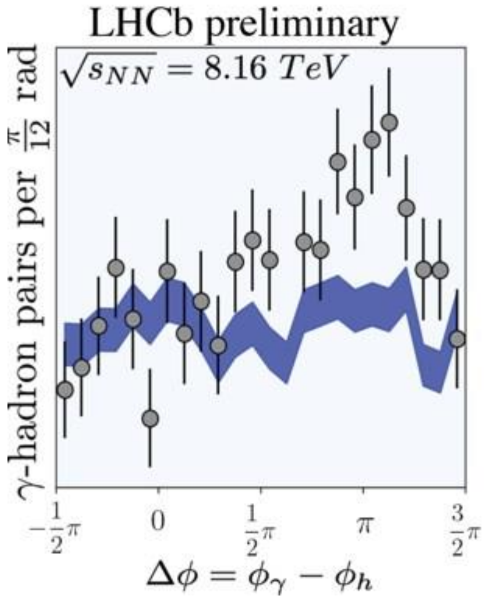


In ultra-relativistic heavy nuclei PbPb collisions, two-photon and photonuclear interactions are enhanced in ultra-peripheral collisions (UPC). The collisions are either coherent, where the photon couples coherently to all nucleons, or incoherent, where the photon couples to a single nucleon. In the case of coherent J/ψ production in UPC, the photon-lead interaction can be modelled by the exchange of a colourless propagator, identified as a single object called a Pomeron, that interacts with the photon. The LHCb collaboration reported the cross-section measurement of coherent J/ψ production in PbPb collisions at 5 TeV and compared this to predictions from different phenomenological models.



The image shows that the coherent J/ψ production (blue line) can be clearly separated from the other contributions in the natural logarithm of the J/ψ transverse momentum squared distribution.

High-energy collisions involving ions have the best chance to produce gluon condensates, where the gluon wave functions start to overlap producing a collective behaviour. Saturated gluons are expected to be observed only at small angles relative to the beam axes, where the number and the size of the gluons are the largest. LHCb has the unique capability of measuring photons coming from these high density gluon regions and the announcement of initial measurements of these photons caused a lot of excitement. It is the first indication that gluons can be probed in this region, never achieved by any experiment so far.



The image shows the angular distribution between isolated photons and other particles taken during the 2016 pPb run. he peak at the angle π indicates the presence of photons from gluons. The blue band is the background from other processes.

Quark Matter 2018 meeting was the latest in a long line of this venerable conference series, which has played a central role in defining the field of relativistic heavy ion physics. The foreseen detector upgrades will increase the experiment's capabilities to search for new phenomena and shed light in the understanding of the QCD mechanisms in the new era of HL-LHC. This embarrassment of experimental riches will be well-served by a new level of quantitative theoretical understanding made available by increased computational resources, new algorithms, and developing sophistication in techniques and modeling. These are promising sign of a bright future for the heavy-ion community that keeps growing and making the most of CERN's accelerator complex.