EP Newsletter of the EP department

A word from the Head of the EP department - December 2018

Editorial
by Manfred Krammer
PDF version


Dear Colleagues, dear Members of the EP Department and CERN Users,

Welcome to the last EP newsletter of 2018. This year has been another great year for CERN. The LHC run has broken again all records, both for the proton-proton run, as well as for the heavy ion run in the last month. The LHC experiments have now accumulated an enormous data set, which will keep them busy analysing for some time. With the last beam dump on December 10, Run 2 has finished and we entered Long Shutdown 2. This means there will be no beam for the next two years. It is the period many colleagues have worked towards, when preparing the components for the upgrade of their experiments. In particular ALICE and LHCb will undertake many changes to almost all of their detector components. You will find more details on the planned upgrades in this newsletter.

Another article in the newsletter explains another success of 2018: the completion of the large ProtoDUNE single-phase liquid argon detector. Perfectly on schedule the detector became operational and first tracks were observed using the SPS beam. Also just in time for this newsletter we have completed our study for Strategic R&D on Technologies for Future Experiments. In two workshops and many meetings we have defined what we believe are the crucial EP R&D lines for detectors, electronics and software for all future experiments. The article in the newsletter gives an overview and links you to the full document.

You will find many more articles, interviews and the introduction of new staff and fellows in EP in this newsletter. Take your time during the holiday break to enjoy reading them.

Finally, I would like to wish all of you Happy Holidays and a very Successful Year 2019! Recharge your batteries during the break and enjoy your time with your family.

Manfred Krammer

EP Department Head

Setting a roadmap for future detector technologies

DT
by Panos Charitos (CERN)
PDF version

The effort to address the remaining open questions of the Standard Model lies at the core of the HL-LHC physics programme and informs current design studies for post-LHC colliders (CLIC, FCC-ee, FCC-hh) as well as new fixed target experiments explored under the Physics Beyond Collider initiative.

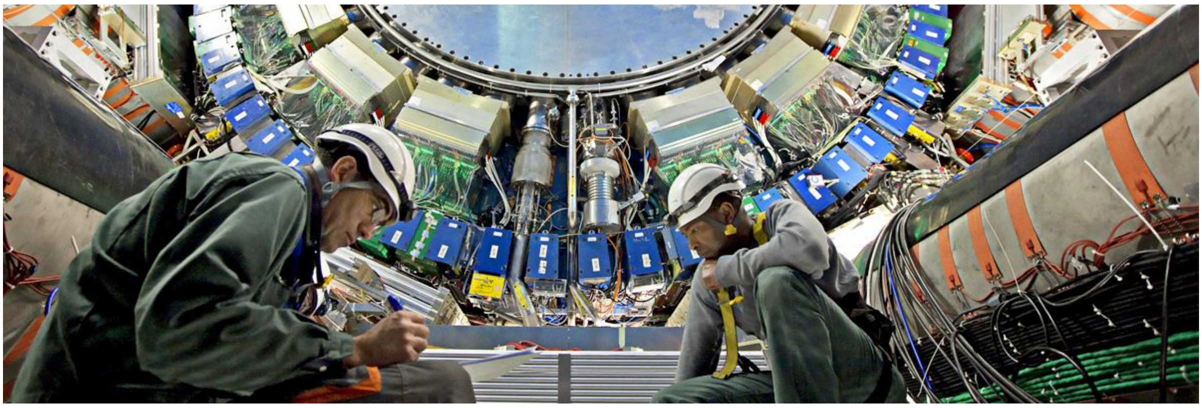
To meet the experimental challenges posed by these design studies, CERN's EP department is preparing to launch a rigorous R&D programme. This will be an initially five-year long initiative (2020-2024) covering a wide range of detector related technologies, including also novel electronics, mechanical structures, magnets and the related software.

In September 2018, during an open meeting at CERN the different groups working on detector R&D met to present their R&D plans and to conclude on a number of open issues before drafting the final report that will document key priorities and set concrete milestones. Manfred Krammer, head of the EP department stressed in his opening talk: "We must urgently identify relevant domains for future R&D. concentrating on the most important technologies, rather than on concrete detector applications".

The workshop offered the opportunity to conclude on a number of R&D topics identified in the previous meetings. Experts from the eight working groups presented concise summaries of ongoing research efforts and discussed the next steps to tackle the challenges lying ahead. In the case of hadron colliders they are mainly related to the very high pile-up, the high radiation loads and need for faster throughput of larger amounts of data. At the precision frontier, covered by proposals for lepton colliders, very low material budget and high granularity calorimeters are needed. Finally, the cooling and powering systems, software needs, refined mechanics and sophisticated electronics and detector magnets are key topics that add to the versatility of the discussed R&D programme.

Previous similar initiatives, the DRDC project in the 1990s and the White Paper R&D programme (2008-2011) have been instrumental in providing the technologies presently in use at the LHC experiments and their foreseen upgrades. Among the recent successes are the validation of the CMOS 130 nm technology, the GEM single mask technique, radiation hard optical links, the CernVM virtual machine environment and DC-DC converters.

During the meeting, conversations focused on the different available options in detector technologies, the predictions for the development of future electronics including also forecasts from the industry and alternative cooling and engineering options. Key for the success of this programme is to enable efficient cooperation between external groups from universities and other research centres and unleash the potential for further cross-fertilization with other industries that have similar challenges.



Since the first edition of this workshop, in March 2018, the working groups prepared concrete working plans while they had the chance to iterate on them together and identify possible collaboration and other areas where synergies could boost future work. Christian Joram, deputy Head of EP department and organizer of the workshop notes: "This R&D programme aims to accelerate the development of new technologies. Considering the number and complexity of the challenges ahead, this initiative is just timely".

The results of this R&D will be building blocks, demonstrators and prototypes, which will form the technological basis for new experiments and experiment upgrades beyond the LHC Phase-II upgrades scheduled for the long shutdown LS3. Planning today these R&D efforts is vital for the success of future experiments that could cope with different physics requirements.

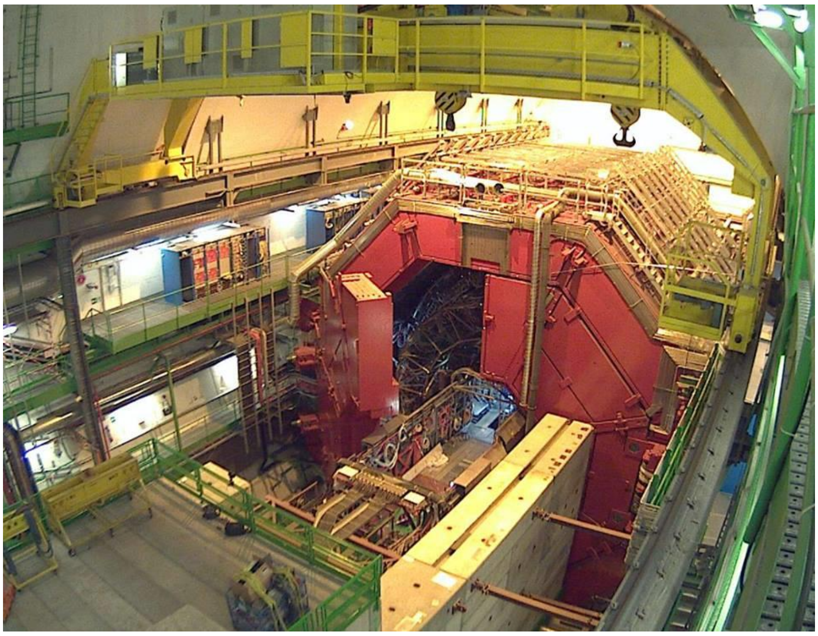
CERN's contributions and collaborations with numerous institutes offers a precious experience, and guarantees the ability to be at the forefront of technological disruption in detector technologies since the beginning. The required R&D work will be carried out jointly with external groups from universities and research labs while special focus will also be given to the industrialization of these technologies in partnership with the industry.

Launching today a clear and wide R&D programme for future projects can guarantee the success of this effort and attract more institutes, including industries/domains that had not previously collaborated with CERN. The recent workshop highlighted the tremendous potential, which is documented in a public report that can be found HERE.

A short summary of the final report will serve as input to the European Strategy Group in view of the 2020 update of the European Strategy for Particle Physics.

"New" ALICE in development during LS2

ALICE
by Virginia Greco (ALICE Experiment, CERN)
PDF version



The ALICE solenoid re-opens its door as the collaboration prepares for the detector upgrade planned for LS2.

At 6 a.m. of December 3, 2018, the LHC expert team switched off the engine of the biggest particle accelerator of the world, which will rest for the next two years before entering a new phase of operation. Starting from March 2021, in fact, the LHC will deliver collisions at increased luminosity, allowing the experiments to collect much more data in less time and, thus, to study rare phenomena.

The higher luminosity will certainly benefit ALICE, the LHC experiment dedicated to the study of the strong interaction and of the Quark-Gluon-Plasma (QGP), a state of matter which prevailed in the first instants of the universe and is recreated in droplets at the LHC by colliding lead ions. During Run 3, indeed, the interaction rate of lead ions will be gradually increased to reach about 50 kHz, i.e. an instantaneous luminosity of L= $6x10^{27}$ $cm^{-2}s^{-1}$. This will allow ALICE to accumulate more than $10nb^{-1}$ of Pb-Pb collisions. Data samples of pp and p-Pb collisions will also be collected to measure the same observables in different interaction systems.

To exploit the incredible scientific potential of Run 3 and subsequent HL-LHC operations and to be able to study rare processes, the ALICE collaboration is currently implementing a major upgrade of its detector, data- taking and data-processing systems.

The current Inner Tracking System (ITS), which is the heart of the detector, will be replaced by a brand-new one composed by seven layers of silicon pixel detectors. A compact pixel sensor chip (ALPIDE), based on the Monolithic Active Pixel Sensors (MAPS) technology, has been developed for this upgrade. The new ITS will improve dramatically the resolution of the detector and its ability to reconstruct the particle trajectories.

Mounting of a module of the New Inner Tracking System (ITS) of ALICE, which will be installed in the heart of the experiment in 2020

A novel Muon Forward Tracker (MFT), implementing the same custom ALPIDE chip, will also be installed in the forward region of the detector. Thanks to its excellent spatial resolution, not only will ALICE be more sensitive to several measurements, but also able to access new ones that are currently beyond reach.

A new Fast Interaction Trigger (FIT) detector will also replace three current forward detectors, with the aim of providing the minimum-bias trigger and excellent time resolution for identifying decay vertices.

ALICE Time Projection Chamber (TPC), the largest in the world at nearly 100 cubic metres, will also be upgraded during LS2.

The increased collision rate also requires a major upgrade of the ALICE TPC. The current detector is limited by its read-out chambers, which are based on multi-wire proportional chamber (MWPC) technology. Thus, they will be replaced with multi-stage gas electron multiplier (GEM) chambers, the development of which has required intense R&D activities. The TPC upgrade will increase the read-out rate of the detector by about two orders of magnitude, while preserving its excellent tracking and particle identification capabilities.

A new computing facility to perform online and offline operations on the data is also being installed at the experimental site.

Whereas the machine will sleep, this long shut down period will be nothing but quiet for all the engineers and physicists who will work on a tight schedule to make the ALICE experiment ready for the next challenges.

The LS2 period for the ATLAS detector

ATLAS
by Ludovico Pontecorvo (ATLAS experiment, CERN)
PDF version

The main upgrade activities are all aimed at enhancing the capability of the detector to trigger more efficiently on leptonic and hadronic signatures. In particular it is essential to preserve the ability to trigger efficiently on electron and muons with transverse momentum of ~20 GeV. With the instantaneous luminosity expected for Run 3, this implies to improve the selectivity of the trigger system.

To improve the selectivity of the electron trigger, the amount of information used for the trigger decision will be drastically increased. In fact, up to now, the very fine-grained information produced by the electromagnetic calorimeter is grouped in “trigger towers” of relatively big size, to limit the number of trigger channels (Fig. 1).

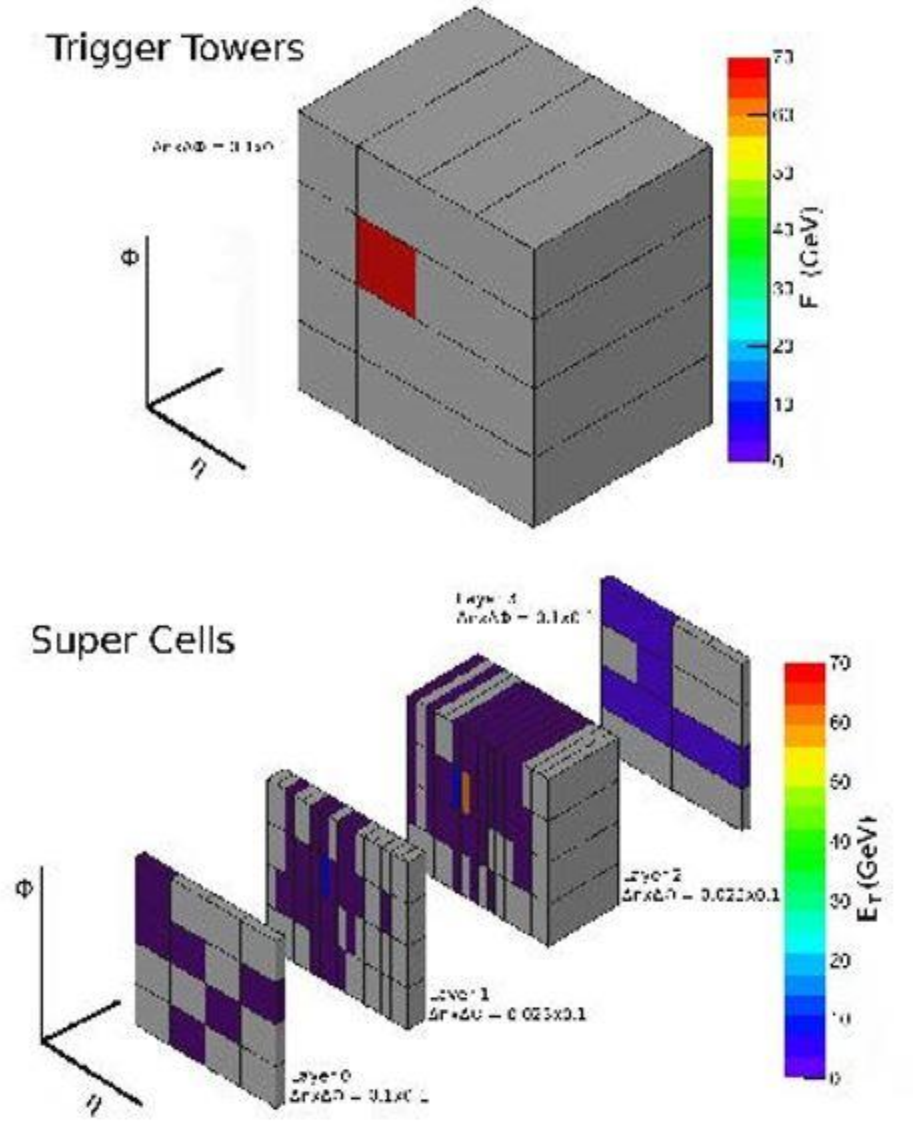


Figure 1: The so-called trigger towers in which information is stored by the ATLAS electromagnetic calorimeter.

This was needed in the original design of ATLAS (1995-2000) to limit the cost and the amount of cables. Nowadays the technological evolution in electronics and in data transmission with optical fibers allows the transmission of a much larger amount of information at a reasonable cost. By replacing some components of the front end electronics of the LAr electromagnetic calorimeter, the level of segmentation available at the trigger level will be increased fourfold, improving the ability to reject jets and preserve electron and photons, while keeping the trigger rate at the current level (see Fig. 2).

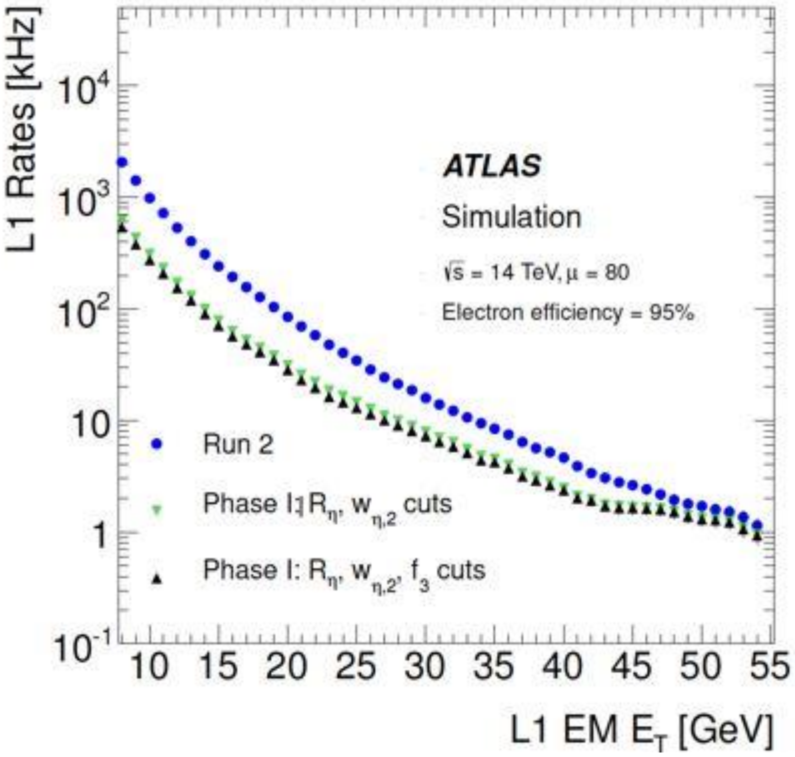


Figure 2: The foreseen improvement of the ability to reject jets and preserve electron and photons by the scheduled upgrade of the LAr electromagnetic calorimeter.

The Trigger and Data acquisition (TDAQ) systems will also be upgraded by introducing new electronics boards aimed at analyzing the more granular trigger information coming from the detector. To this end, three different types of boards have been designed and are in fabrication: the eFex (electron feature extractor), jFex (Jet Feature extractor) and gFex (Global feature extractor). These new boards will be installed and commissioned together with all the other read-out and trigger electronic boards that complete the TDAQ upgrade, throughout the whole LS2 period.

The inner layer of the forward region of the ATLAS muon spectrometer is being upgraded with the construction of the so-called New Small Wheels (NSW), as shown in Fig. 3. below.

Both tracking capabilities in presence of large background and triggering capabilities will be improved with respect to the present Small Wheel, introducing new detector technologies Micromegas and sTGC. Both technologies will be able to withstand the higher flux of neutrons and photons expected to be created in the LHC interactions, which will produce counting rates as high as 15-20 kHz/cm^2 in the inner part of the NSW, and deliver trigger information at the first-level trigger.

The main aim of the NSW is to reduce the fake muon triggers in the forward region and improve the sharpness of the trigger threshold drastically, allowing the same selection power as the present High Level Trigger (HLT=computing farm) at the first-level trigger (made in hardware). This will be achieved by measuring precisely the angle of the muon candidate at the NSW location, together with the measurement of the candidate muon's direction in the Big Wheel, after being deflected by the strong magnetic field of the End Cap Toroid.

Other smaller upgrades will be deployed during LS2, including the installation of 16 new muon chambers made of small-tube Monitor Drift Chambers (sMDT) and Resistive Plate Chambers (RPC) in the inner layer of the barrel spectrometer.

The organization of the LS2 period is a very complex exercise in which the maintenance needs of the detectors and of the main general infrastructures (electric distribution cooling and ventilation, detector cooling) have to be combined with the plans of installation of the upgrades previously described.

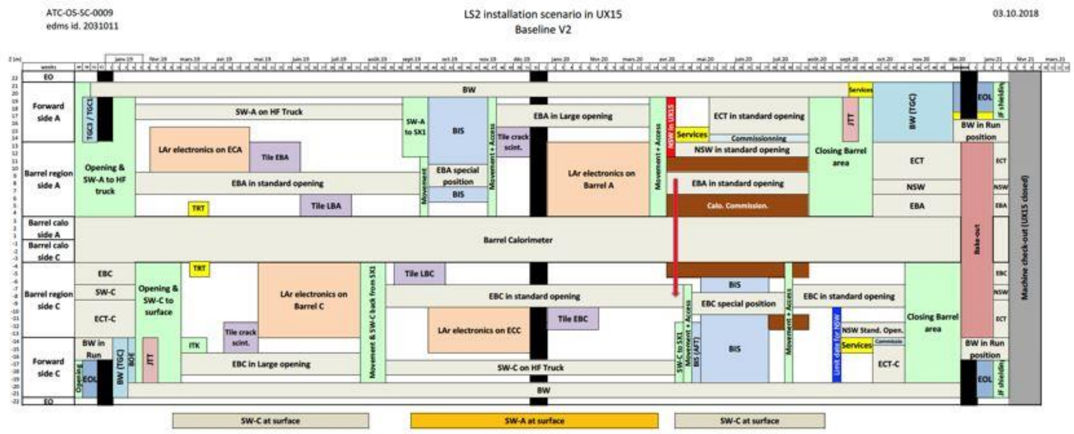


Figure 4 shows a sketch of the activities scheduled during LS2 for both sides of the detector (side A and Side C).

After a first period devoted to the opening of the detector and the maintenance of the forward muon spectrometer, the first big non-standard operation will be to bring to the surface the Small Wheel on side C. This operation will already be performed in January 2019. Having the detector fully open on side C will allow us to make a very important test for the installation of the new all-silicon inner tracker (ITk) which is scheduled to be installed during the shutdown LS3 in the framework of the Phase II upgrade. On side A the upgrade of the LAr Calorimeter electronics will start in February 2019 (End Cap A) and will continue almost continuously for about one year on the other parts of the EM calorimeter (Barrel C, End Cap C and Barrel A). The work consists in dismounting all the front-end boards from their crates, modifying both the boards and the crates, and re-installing the modified boards in their original position. This work will entail the creation of specific access to the LAr Front End crates. The maintenance of the Tile calorimeter and of the Inner Detector (ID) will be done in parallel. A very important part of the maintenance of these two systems and also of the LAr Calorimeter is the search for leaks in the front-end cooling system. During Run 2 several leaks in each of these systems were discovered but could not be fixed as the detector was closed. The Tile calorimeter group is planning the overhaul of all the connectors in the cooling loops of the front-end electronics in order to have a more robust cooling system during Run 3. In parallel and for the whole LS2 period, a large campaign of search and repair of gas leaks in the RPCs, that are the triggering chambers in the muon barrel, will take place.

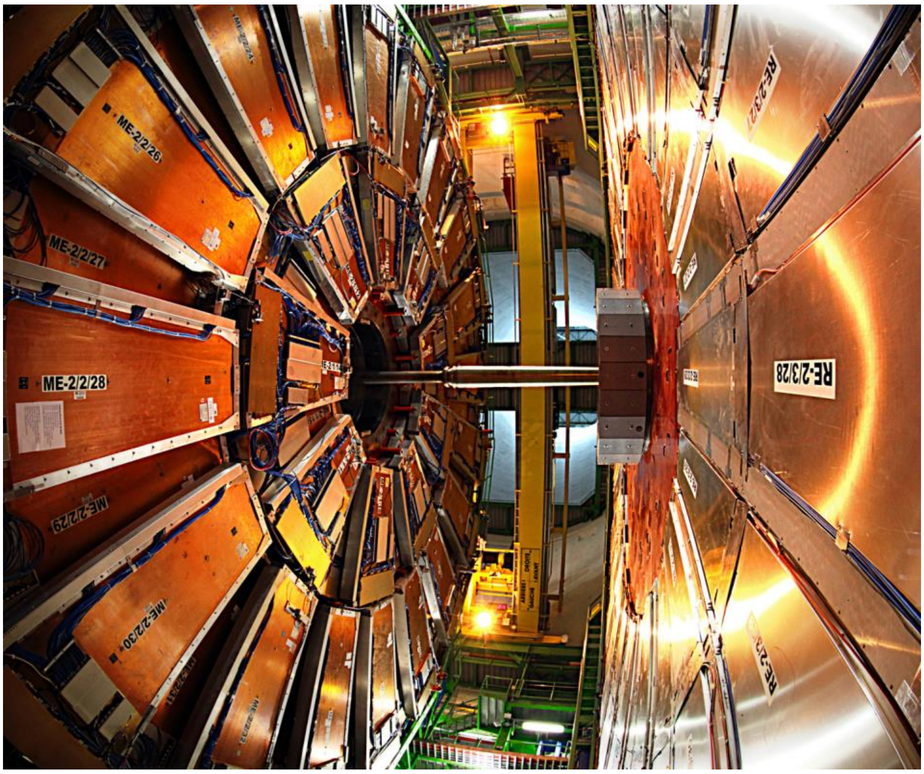
In August 2019 the Small Wheel C is scheduled to be lowered down again, to allow the Small Wheel A to come to the surface. This operation is needed to start the installation on side A of the new muon barrel chambers, and in preparation of the installation of the New Small Wheel A that is expected in April 2020. In the same period, all the optical transmission boards of the Pixel detector will have to be changed, since they showed a large failure rate during Run 2. After these installations, there will be a long period of commissioning of all the upgraded detectors (LAr electronics, New Small Wheel A, Muon Barrel Chambers, new TDAQ systems) and the preparation for the installation of the second NSW (Side C), for which a new movement to the surface of the Small Wheel C is needed. Before the installation of the NSW C the new muon barrel chambers will be installed on side C. Finally, the NSW C should be installed in the fall of 2020. At that moment the closing process will start and will last for about three months, including the bake-out of the beam pipe, which is a very delicate and potentially dangerous operation for the pixel detectors of the inner tracker.

At the end of LS2, ATLAS will be ready to take data in Run 3 with a renewed and better performing detector.

CMS upgrade plans for LS2

CMS
by Panos Charitos
PDF version

To achieve the full benefit of the HL-LHC, CMS must continue to be able to reconstruct at the much higher luminosity all the standard physics analysis objects with high efficiency, low fake rate, and high resolution. Excellent electron, photon, and muon reconstruction is needed for Higgs decays to $\gamma\gamma$, ZZ^* and $WW*$ and to observe Higgs decays to $\mu^+\mu^-$. The dominant decay mode of the Higgs boson to bottom quark, only recently observed at the LHC, requires excellent b-quark tagging capabilities and consequently, continued precision reconstruction of primary and secondary vertices. Overall, precision measurements of rare decays that are well-predicted in the SM is another approach to discovering new physics. Moreover the search for SUSY particles will continue based on the latest stringent limits from Run 1 and Run 2 data. If new physics is present it might either enhance or suppress the rate of these decays. Finally, the HL-LHC will allow to increase the precision in the values of a number of SM parameters that appear in a number of models predicting new physics. High-precision measurement of S.M backgrounds will contribute significantly to the robustness of our current searches for beyond the Standard Model physics.



The HL-LHC will integrate ten times more luminosity than the LHC, posing significant challenges for radiation tolerance and event pileup for the CMS subdetectors. Following a number of studies for all CMS sub-systems, it is very clear that the tracker and the endcap calorimeters must be entirely replaced during LS3. This means that a lot of engineering and pre-production process must start during LS2 including detailed simulations of the detectors performance, the radiation hardness of the electronics and addressing any mechanical issues while responding to cooling needs and achieving a reduced material budget. Several other upgrades or preparations of the detector infrastructure and services will take place in LS2 to be ready for the major installations of components in LS3.

The collaboration has already taken the first steps towards LS2 with the installation of a new narrower beam-pipe. The new beam-pipe will allow the pixel detector to reach closer to the interaction point. As a next step, the cylindrical section of the beam-pipe will be extended opening more space for the phase-2 pixel detector to be installed in LS3. In addition, CMS will install a new GEM muon detector layer in the inner ring of the first endcap disk and lay services for the future improved Resistive Plate Chambers of the muon detector.

Moreover, during LS2 there will be major work on primary infrastructures such as power and cooling, new electronics racks and a new hydraulic opening system for the detector. The LS2 schedule is now fully established, with a critical path starting with the pixel-detector and beam-pipe removal in January/February and extending through the muon system upgrade and maintenance (until May/June 2020), installation of the Phase-II beam-pipe (July/September 2020) plus the revised Phase-I pixel detector (October 2020), and, after closing the magnet yoke, re-commissioning of the magnet with the upgraded powering system in December 2020. The other LS2 activities, including the barrel hadron calorimeter work, will take place in the shadow of this critical path.

As part of its HL-LHC upgrade programme, the CMS Collaboration has also proposed a high granularity calorimeter (HGCAL) to replace the existing endcap calorimeters in LS3. The existing forward calorimeters, the electromagnetic calorimeter based on lead tungstate crystals (EE) and the plastic scintillator based hadron calorimeter (HE), were designed for an integrated luminosity of 500 fb^{-1}. However, during the HL-LHC this system must have the ability to withstand integrated radiation levels that are ten times higher than anticipated in the original CMS design.

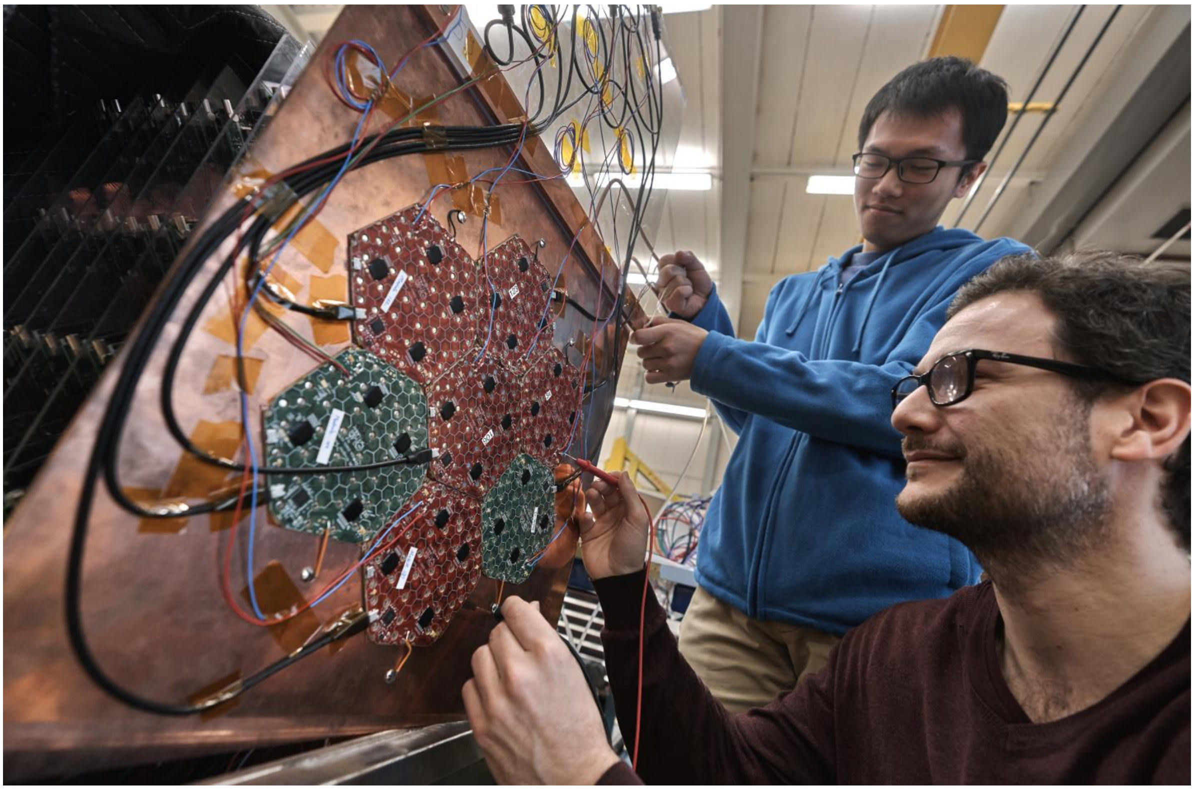


Figure 1: Ongoing tests on the modules of the High Granularity Calorimeter. Intense R&D is foreseen during LS2 to ensure that the new detector will be ready for installation during LS3.

The R&D carried out has demonstrated that silicon sensors could indeed tolerate such levels and have been chosen for the active material for the bulk of the upgrade of the endcap calorimeters. Efficient operation also means that they should be cooled down and operated at around -30^{0}C The proposed design for the new HGCAL is based on silicon sensors as active material in the front sections and plastic scintillator tiles, with the scintillation light read out by SiPMs, towards the rear (that also need to be operated at -30^{0}C). The designed HGCAL will feature unprecedented transverse and longitudinal segmentation for both electromagnetic and hadronic compartments.

The various muon systems detectors, (i.e. Drift Tubes (DT) and Resistive Plate Chambers (RPC) in the barrel, and Cathode Strip Chambers (CSC) and RPCs in the endcaps) are expected to tolerate the increased radiation levels during Phase II without major degradation. Therefore there is no plan to replace these detectors, but further measurements are underway to confirm their radiation tolerance margins.

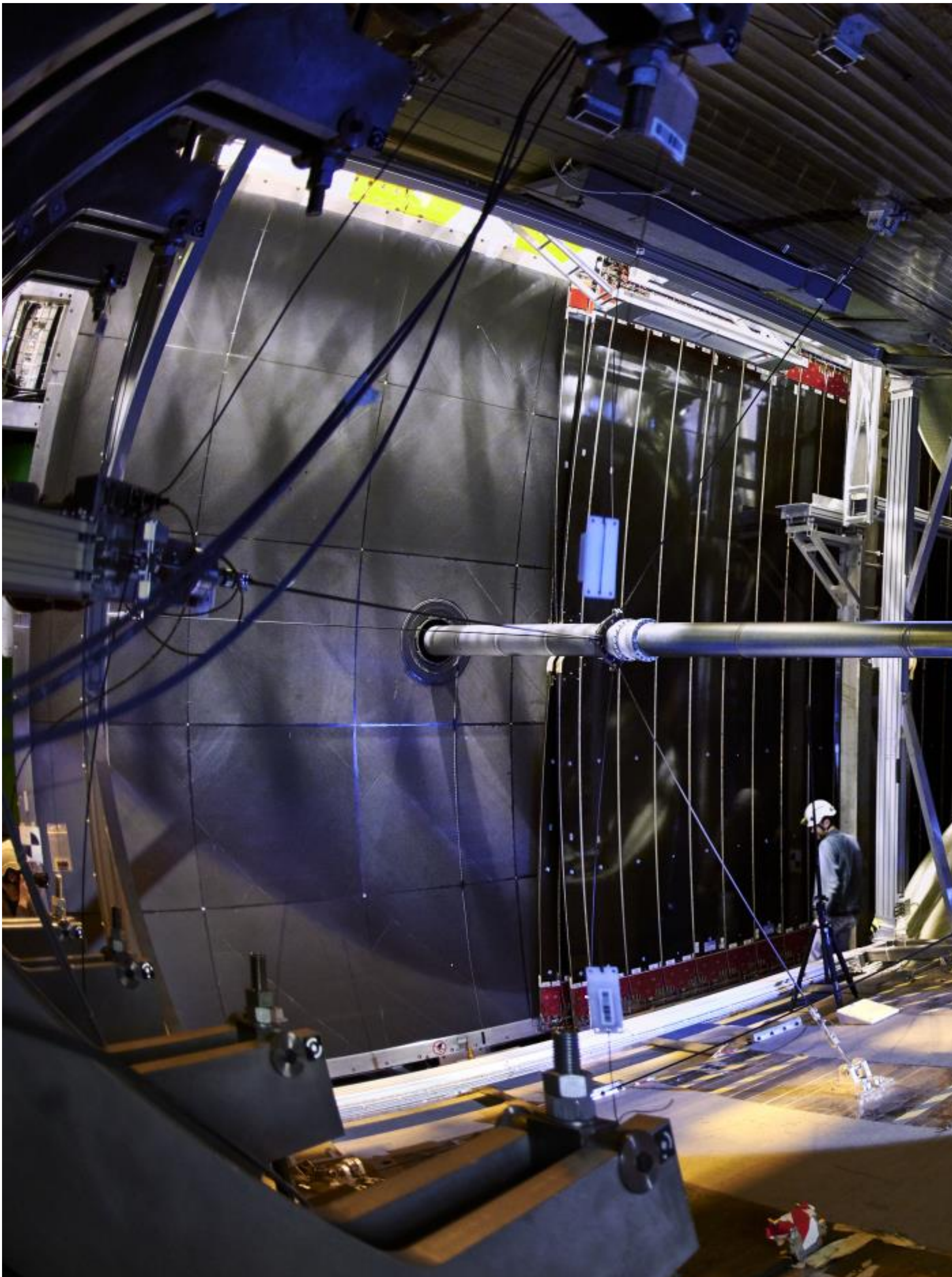
Moreover, CMS collaboration plans to upgrades of all the readout electronics to allow for efficient data taking up to an average pileup of 200. With this possibility, CMS has also intensified a program of R&D into the use of precision timing to help solve the problem of vertex association for neutral particles. With proper design of the barrel and endcap readout electronics shower energy deposits can be timed with a precision substantially lower than the predicted energy spread; CMS can reduce the impact of pileup by selecting only those energy deposits consistent with occurring at the same time. Finally, a new hardware trigger system is foreseen to maintain similar physics acceptance as in Run 1 and Run 2. This specification can be easily accommodated in the design of all new detector readout electronics.

The timely completion of the intense LS2 program is critical for a successful CMS Phase-II upgrade in the following years including the HL-LHC phase of the LHC!

LHCb plans for major upgrade during LS2

LHCb
by Panos Charitos & Massimiliano Ferro-Luzzi
PDF version

During the previous LHC runs, the LHCb experiment collected 10 fb^{-1} and performed many important measurement in the heavy flavour sector. However, many crucial measurements are statistically limited, with experimental precision not directly comparable to the uncertainty of the theoretical predictions. In order to significantly increase the statistical precision on theoretically clean observables in the heavy flavour sector, the level of collected data must be increased much beyond the 1 fb^{-1} per year. This drives the LHCb detector upgrade that will allow to operate at a constant instantaneous luminosity of $2\times10^{33} cm^{-2} s^{-1}$ during a period of ten years, corresponding to about 50 fb^{-1} of collected data; about ten times the current design luminosity.

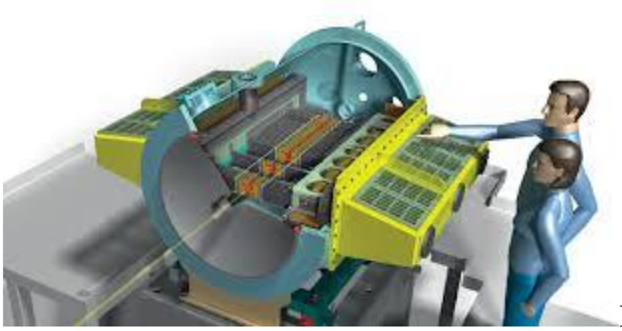


Opening of the LHCb detector as technicla teams prepare for the LS2 upgrade.

To reach the desired performance, all the front-end electronics as well as the detector components with embedded electronics need to be replaced. The current hardware-based trigger will be replaced with a fully software-based trigger, allowing to overcome the current limit of 1 MHz and perform full reconstruction at a rate of 30 MHz to meet the above mentioned requirements.

Moreover, to cope with the data flow of 4 TB/s from 2021 onward, the LHCb data acquisition system is being completely renewed. Data will travel from the underground hall via ~9000 three hundred metre-long optical fibres, into the front-end computers located at the surface in a brand new data centre at the Ferney Voltaire site of LHCb. There, ~500 powerful and custom-made PCIe40 boards will receive the data and transfer to the farm containing thousands of processing cores.

The LHCb detector will undergo a significant upgrade in parallel to the trigger system upgrade, to meet the renewed experimental challenges due the increased luminosity. Higher granularity and radiation tolerance are key elements to push the performance. The trigger hardware equipment will be removed, namely the Scintillating Pad Detector (SPD), PreShower detector (PS) and first Muon station (M1). Moreover new front-end and readout electronics have been designed for the calorimeter and muon detectors allowing to cope with the substantially higher rates of radiation and will be installed throughout 2019.



In the cavern, the LHCb detector halves have just been opened sideways to allow for the temporary beam pipe removal and the start of detector dismantling. The Vertex Locator (VELO), which allows for precise measurement of primary and displaced vertices of short living particles, is one of the detectors that will be upgraded in LS2. The new VELO consists of 26 tracking layers based on 50x50 μm^2 pixel technology offering better hit resolution and simpler track reconstruction. Moreover, the new VELO will be installed closer to the beam axis, moving from the current 8.4 mm to 5.1 mm, which means that particles will see more detector material before reaching the first layer of the detector. This poses significant design challenges as the VELO performance is key for determining the resolution on the measurement of the impact parameters of the particles. A new chip, the VELOPIX, was developed and produced for this purpose (read HERE). The new chip collects signal hits from 65,536 pixels (256 x 256) and sends zero suppressed data at the staggering rate of up to 15 Gb/s. Being in vacuum, the dissipated power (about 1 W per chip) must be very efficiently removed.

Achieving a temperature of -20 °C at the silicon pixel sensor is absolutely vital, since these sensors will receive the heaviest irradiation of all LHC detectors envisaged so far (including ATLAS and CMS Phase II upgrades) and thermal run-away must be prevented by efficient cooling. A cooling substrate, using cutting-edge silicon technology, was developed for this purpose. An optimized array of microchannels (of just 200 µm width and 120 µm depth) is trenched out of a 260 µm thick silicon wafer by lithographic techniques and then bonded to a mating wafer of 140 µm thick thickness.

The Ring Imaging Cherenkov (RICH) detector remains, as before, composed of two systems: RICH1, located between the interaction point and the dipole magnet, and a RICH2 located after the magnet, between the tracking stations and calorimeter system. RICH1 allows one to discriminate kaons from pions in the low momentum range, while RICH2 performs particle identification in the high momentum range. Furthermore, the mirror system, required to deflect and focus the Cherenkov photons onto the photodetector planes will be replaced with new one that has been optimized for the much increased particle densities of the upgrade running conditions. The large mirrors have been produced and are now being coated at CERN. RICH detector columns are composed of 6 photo-detector modules (PDM), each of these containing 4 elementary cells, the basic building block of the RICH detector.

The Upstream Tracker (UT), will replace the Tracker Turicensis (TT) mounted just between RICH1 and the start of the dipole magnet. The new detector will play an important role in the High-Level Trigger (HLT) tracking, providing a fast estimate of the momentum of charged particles and allowing rejection of low-momentum tracks, thus speeding up the track reconstruction algorithm by a factor of three compared to the current tracking strategy. Due to its improved acceptance coverage at small angles will also achieve higher trigger efficiency. UT also has finer granularity, improved radiation hardness, and new front-end electronics that will allow a full 40 MHz readout. To counter the effects of irradiation a strong R&D programme was launched in 2014 resulting in a number of new technologies including electronics, connecting cables and an efficient cooling scheme. UT will be contained in a thermal enclosure and cooled to approximately -5 °C using a carbon dioxide evaporative cooling system. Lightweight staves, with a carbon foam back plane and embedded cooling pipe, are "dressed" with flex cables and instrumented with 14 modules, each composed of a polyimid hybrid, a boron nitride stiffener and a 300 µm thick Si sensor.

Another formidable challenge for the LHCb collaboration is the SciFi tracker, given the size and complexity of this project, but also because it is the first time that this technology will be used for such a large-area detector and in such a radiation-hard environment. The detector has twelve layers, used for track reconstruction after the magnet region. Following a copious R&D effort in the past year, the detector has been built and is ready to be installed later in 2019. The fibres will be readout by SiPMs placed on the top and on the bottom of the detector layers, reading arrays of 50x50 μm^2 sized pixels grouped in arrays of 128 channels and cooled down to -40C.

To avoid water condensation near or around the detector, while avoiding conflicts with neighbouring modules, a sophisticated and high-performance cooling enclosure was designed. These are the last elements to be assembled on the five-meter modules before installation on the supporting C-shaped frames, which are being built at this moment

The installation of the LHCb upgraded detector will take place during the LHC Long Shutdown 2. In 2018 the old sub-detectors will be removed, and in 2019 the Upgrade ones will be installed in order to be ready for the LHC Run 3, in 2020-2021.

Further Reading

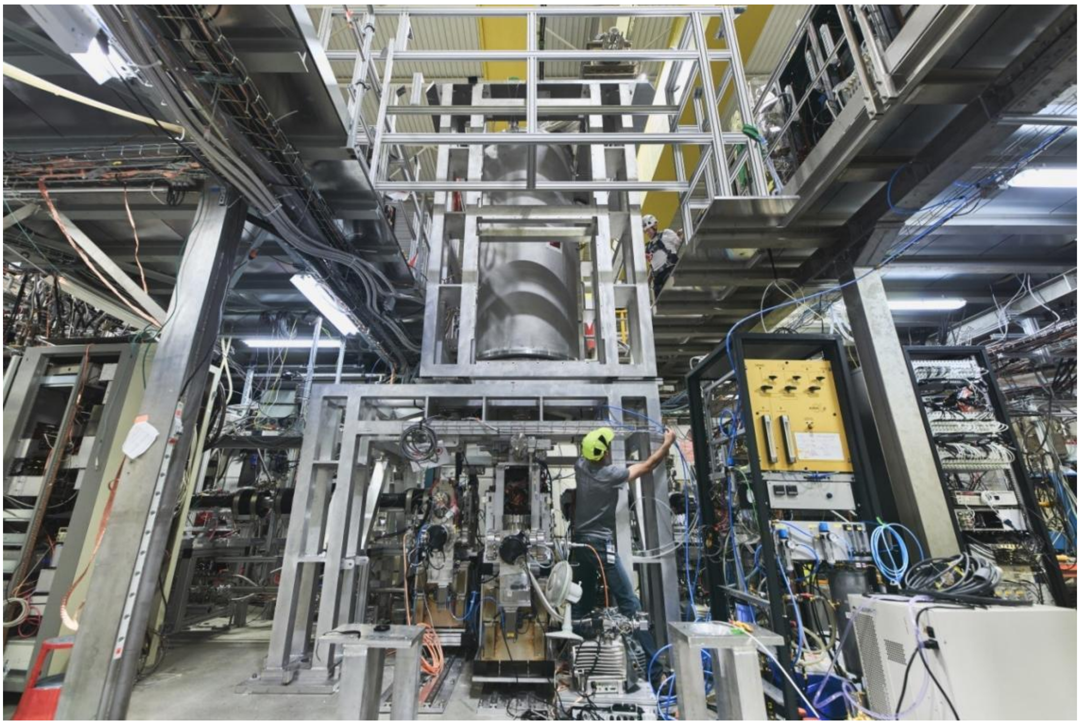
[1] Letter of Intent for the LHCb Upgrade, CERN-LHCC-2011-001 ; Expression of Interest for an LHCb Upgrade, CERN-LHCC-2008-007.

[2] Framework TDR for the LHCb Upgrade: Technical Design Report, CERN-LHCC-2012-007.

ALPHA-g sees its first antiparticles: does antimatter fall up or down?

ALPHA-g
SME
by Niels Masden and Claudio Lenz Cesaron on behalf of ALPHA
PDF version

The ALPHA collaboration working on antihydrogen at the Antiproton Decelerator (AD) in building 193 has successfully expanded their setup with new devices. The previous setup consisted of a positron accumulation device, accumulating positrons from a sodium radiative source, a dedicated catching trap to receive antiprotons from the AD and the antihydrogen synthesis and trapping device called ALPHA-2.



The ALPHA-2 device has seen a string of successes in recent years, the latest being the observation of laser spectra of the 1S-2S and 1S-2P transitions in antihydrogen. The former led to the most accurate measurement on antimatter ever achieved with an accuracy of 12 significant digits in the transition frequency, and the latter paves the way to laser-cooling amongst other things.

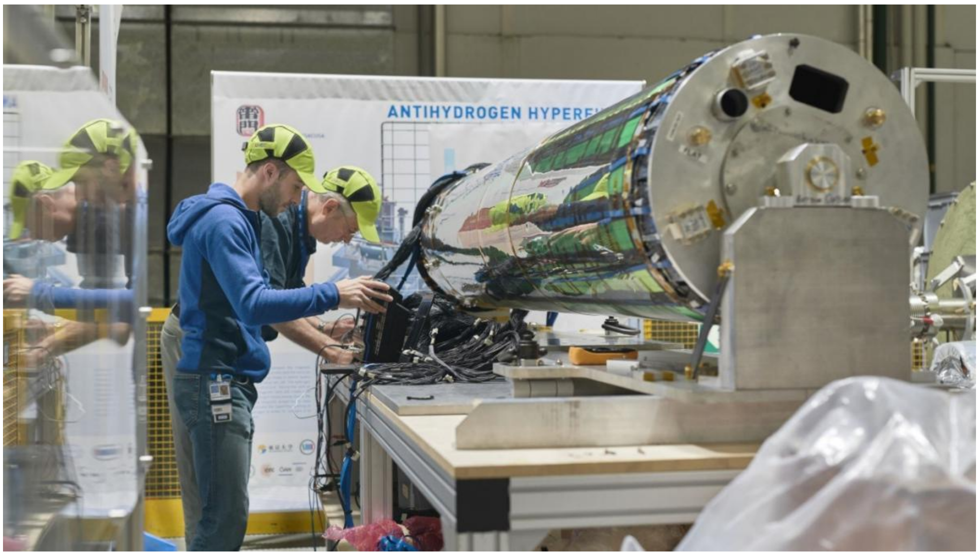


Figure 1: The Barrel Scintillator for ALPHA-g Experiment is composed of 64 trapezoidal scintillating bars arranged in a barrel shape. Each bar is readout at each end with SiPM sensors for a total of 128 channels.

In an ambitious effort to expand the discovery potential, ALPHA has added a new device called ALPHA-g to the setup. ALPHA-g is, to put it simply, a vertical (and longer) version of ALPHA-2 that will allow measurement of Earth's gravitational acceleration on the cold neutral antihydrogen atom by slowly releasing the atoms from a magnetic trap and monitoring their escape downwards or upwards with an imaging annihilation detector.

To make this installation possible ALPHA first pushed their positron accumulator about 7 meter downstream and installed a low energy beamline that would allow to continue the transport of positrons to ALPHA-2 while also allowing the transport of positrons and antiprotons to ALPHA-g that was subsequently installed above this beamline.

Figure 2: Insertion of the ALPHA-g cryostat with the antihydrogen trap magnets into the centre of the main solenoid, radial TPC and barrel scintillator.

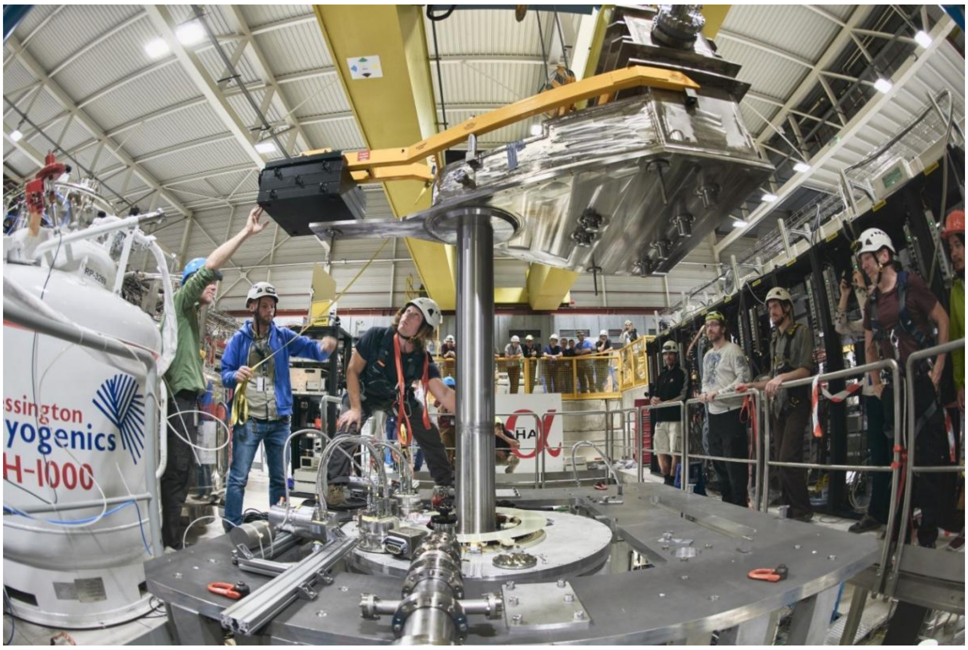


Figure 3: Insertion of the detector assembly (radial TPC and barrel scintillator) into the main ALPHA-g solenoid

Installation of ALPHA-g finished at about the same time that the AD returned from a technical stop due to problems with the electron cooler, and the apparatus was commissioned with particles during the last three weeks of beam from the AD. Both antiprotons and positrons were transported to and recaptured in ALPHA-g during this time, and brought to interact, though a small leak in the cryostat prevented temperatures low enough for antihydrogen to be observed. However, the new radial time projection chamber detector and barrel-shaped scintillator were commissioned and detected their first antiproton annihilations.

This successful commissioning should allow ALPHA to observe antimatter atoms falling under the effect of gravity in 2021 when antiprotons return, by then delivered to the experiment by the new extra low energy antiproton ring ELENA. "Does antimatter fall up or down?" is an old speculation that deserves a straight experimental answer that ALPHA-g should achieve in its initial exploration.

The MoEDAL Experiment at the Discovery Frontier

SME
MoEDAL
by James Pinfold for the MoEDAL collaboration
PDF version

MoEDAL, the LHC's newest experiment [1], that started official data taking in 2015, is different to other collider detectors. It is currently comprised of passive tracking, using plastic Nuclear Track Detectors (NTDs) and trapping sub-detectors that are capable of retaining a permanent direct record of discovery and even capturing new particles for further study in the laboratory. It also has a small TimePix pixel device array for monitoring beam-related backgrounds. MoEDAL is designed to only detect anomalously ionizing avatars of new physics and is insensitive to Standard Model physics signals. Thus, it can to operate without an electronic trigger. A full GEANT4 model of MoEDAL is now available. A visualization of this model is shown in Figure 1.

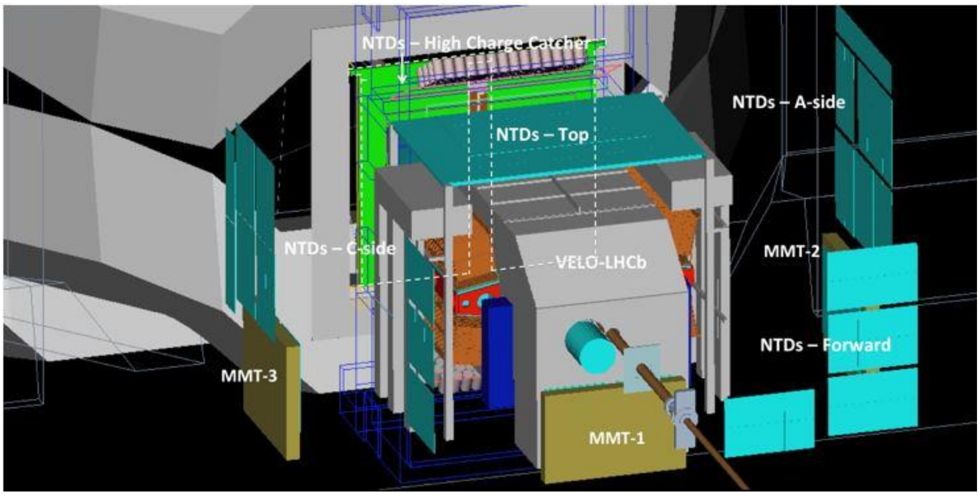


Figure 1. A visualization of the Geant4 simulation of the MoEDAL experiment, represented using Geant4's PANORAMIX.

One of the primary aims of the General Purpose LHC Detectors (GPDs), ATLAS and CMS, was to discover the Higgs boson and study its properties as precisely as possible. As we all know the discovery a new particle by ATLAS and CMS, which is now largely identified with the Standard Model Higgs boson, was announced in 2012 [2]. In a similar way the main aim of the MoEDAL experiment is to search for the Magnetic Monopole. The main modern conception of the magnetic monopole is that it is a topological "excitation" in the Higgs field of the underlying theory. In this way the main physics aims of the GPDs and MoEDAL are complementary. Their experimental sensitivity is also complementary in that GPDs have limited sensitivity to Highly Ionizing Particles (HIPs), which MoEDAL is designed to detect. On the other hand MoEDAL cannot detect the decays of new particles into Standard Model states.

MoEDAL published its first physics result based on data taken with the prototype trapping detector in 2016 [3]. In this case the characteristic magnetic field of a monopole captured in the trapping detector was sought using the SQUID magnetometer facility at ETH Zurich. A null result allowed MoEDAL to place the world's best limits on magnetic monopoles with multiple (Dirac) charge (g_D). Our first result using data taken during LHC's Run-2 was published in 2017 [4] and a result with higher luminosity came out in 2018 [5]. In this paper we presented experimental limits on the direct search for spin-1 monopoles for the first time. The Run-2 data allowed MoEDAL to improve the mass limit for spin-1/2 monopoles to as much as roughly 1.6 TeV. Also, the limit on multiply charged monopoles was pushed to $5g_D$. A summary of MoEDAL results compared to those obtained by the ATLAS and CDF experiments is shown in Figure 2.

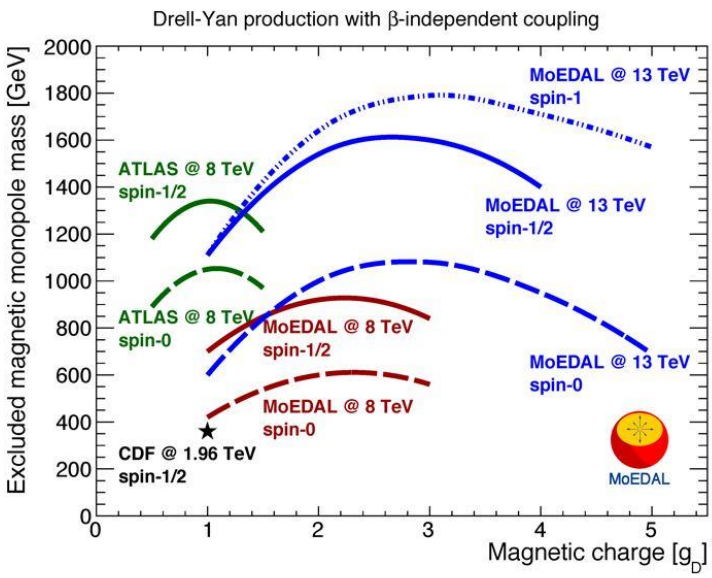


Figure 2. A comparison of the mass versus magnetic charge limits achieved at the Tevatron and the LHC.

Another unique feature of the MoEDAL experiment is the level of fruitful cooperation between experimentalists and theoreticians. One example of this partnership is a paper published in 2018 [6] by MoEDAL authors, where the phenomenology of photon-fusion and DY production of spin 0, ½, 1 monopoles was studied in detail - for the cases where the monopole coupling is velocity-dependent or velocity-independent. Duality arguments were used to justify an effective monopole-velocity-dependent charge in the monopole-matter scattering processes. A magnetic-moment term proportional to a new parameter κ is added to the effective theory to enrich the monopole phenomenology describing the interactions of monopoles with photons. As we lack a fundamental microscopic theory of magnetic poles, such an addition appears reasonable. This creates a dependence of the scattering amplitudes of processes on this parameter. The κ parameter is proposed as a tool for monopole searches which can be tuned to explore different models.

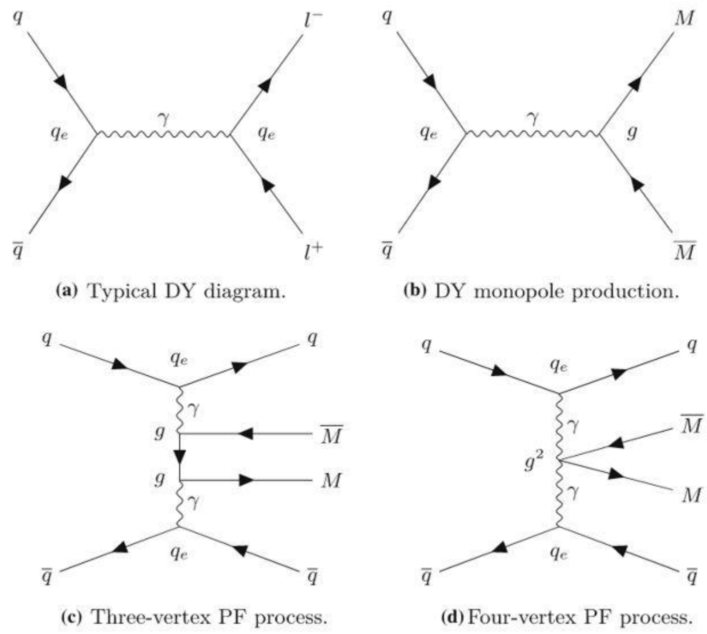


Figure 3. Feynman-like tree-level diagrams for production processes of a monopole pairs via a Drell-Yan –Yan process (b) and monopole-antimonopole pair production via photon fusion (c) & (d).

We are now poised to publish result on the search for monopoles produced via photon fusion as well as the Drell-Yan mechanism, informed by the above-mentioned phenomenological work. The Feynman diagrams describing these processes are shown in Figure 3. In addition, we are completing the search for highly electrically charged particles during LHC's Run-1, the first result that utilizes MoEDAL's NTDs. This is another arena where we expect MoEDAL to be extremely competitive with other collider limits. The delay in producing this first NTD result was due to the need to formulate our own custom alcohol "cocktail", which we add to our etchant to improve the visibility of the etch pits. This was necessary since the commercial product that we used formerly is no longer available. Actually, we eventually discovered a mix that gives even better results than the original. Now MoEDAL's NTD sub-detector is truly in business.

Late in 2017, we installed a prototype of a new sub-detector called MAPP (MoEDAL Apparatus for Penetrating Particles) in the UGC1 gallery in the LHCb/MoEDAL cavern. This gallery runs diagonally away from the main LHC tunnel, in the plane of the machine, as shown in Figure 4. The MAPP detector can be anything from 30 m to 55 m distant from the intersection point (IP8). The size of the gallery is such that it is always possible to have a 6 m-10 m decay zone in front of MAPP wherever it is placed along the gallery. The intervening rock serves to shield the detector from Standard Model backgrounds originating from IP8. The high-energy muons that do penetrate can be used to calibrate the detector.

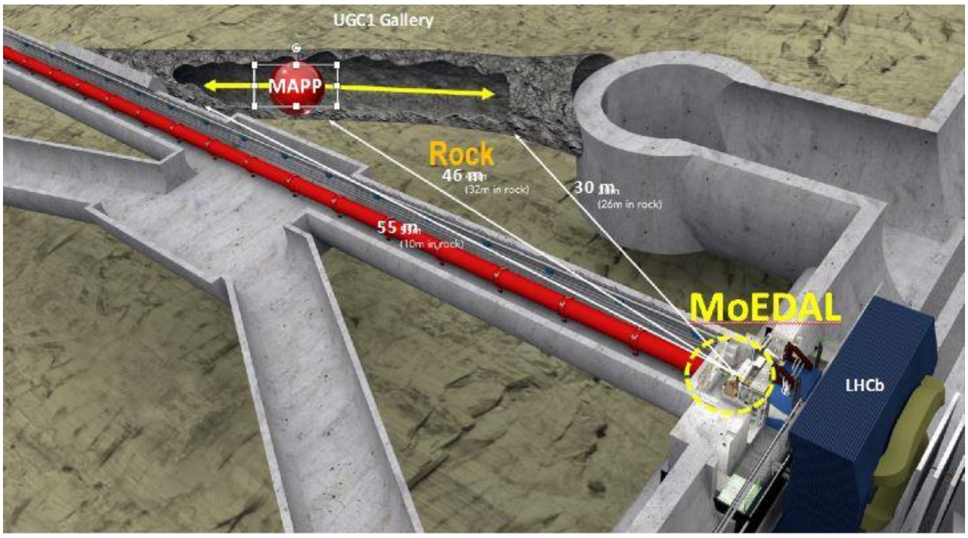


Figure 4. The MoEDAL MAPP sub-detector deployed in the UGC1 gallery in the vicinity of IP8.

The aim of the MAPP sub-detector is to extend the discovery reach of the MoEDAL experiment to include mini-charged particles and new long-lived neutral particles. We feel this is in keeping with MoEDAL's philosophy of expanding the physics reach of the LHC, in scenarios where the GPDs have significantly reduced sensitivity. We envisage that the full MAPP detector, will be comprised of two sections each of 100 (10 cm x 10 cm x 120 cm) scintillator bars readout out at each end by Photomultiplier Tubes (PMTs) forming a "double-decker" sandwich with three ToF hodoscope planes as the "bread", as shown if Figure 5 (left). The purpose of the 2.4 m total length of scintillator is to enhance the signal with fractional charge as low as 0.001*e*, where *e* is the electron charge. The function of the decay zone in front of MAPP is to enhance its ability to detect decays in flight. A photograph of the 1/10th size prototype of the first compartment of the proposed MAPP detector, deployed in the UGC1 gallery, is shown in Figure 5 (right).

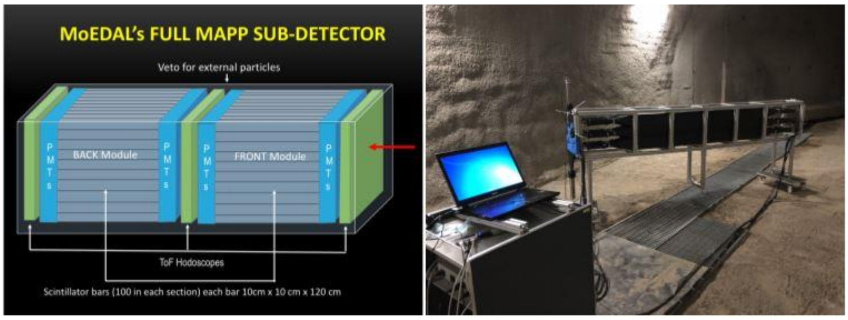


Figure 5. (Left) A sketch of the proposed MAPP sub-detector. (Right) A photograph of the MAPP prototype deployed in the UGC1 gallery.

The MoEDAL Collaboration is now preparing a request to take data during LHC's Run-3, to pursue the search for highly ionizing messengers of physics beyond the Standard Model to 14 TeV, using the 30 fb^{-1} of luminosity that is expected to be available at IP8 over that period. During the LHCs imminent shutdown (LS2) we will also complete the analysis of all of the data we took during Run-2, with the full detector. Additionally, we will utilize this respite in LHC running to deploy and test the new MAPP sub-detector the purpose of which will be to search for fractionally charged particles and new long-lived neutrals. Paradoxically, the LS2 shutdown will mark an exciting period of intense activity for MoEDAL, the LHC's newest experiment.

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ProtoDUNE sees first particle tracks

Introduction

The CERN Neutrino Platform was installed in 2014 following the recommendation of the European Strategy Group for CERN to engage in the worldwide experimental neutrino program. The platform engaged from the start in the future Deep Underground Neutrino Experiment (DUNE) in the US, which plans for its far detector the construction of four large liquid argon Time Projection Chambers (LArTPCs), each having a volume of 17 kton.

In 2015 two ProtoDUNE experiments were proposed to the CERN SPSC, one based on the single phase (SP) and one the dual phase (DP) LArTPC technology. The SP prototype was approved at CERN as experiment NP-04. ProtoDUNE-SP, a crucial part of the DUNE effort towards the construction of the full detector, is a significant experiment in its own right. With a total liquid argon mass of 0.77 kton, it represents the largest monolithic single-phase LArTPC detector built to date. It is housed in the extension to the EHN1 hall in the North Area, where the CERN Neutrino Platform has provided a new dedicated charged-particle test beamline. The ProtoDUNE-SP schedule was very tight from the start, in order to be able to make use of beam data before the start of LHC LS2 shutdown at the end of this year.

ProtoDUNE-SP prototypes the designs of most of the single-phase DUNE far detector module (DUNE-SP) components at a 1:1 scale, with an extrapolation of about 1:20 in total LAr mass for the final detector. The construction started roughly two years ago (only!) by installing the large structures for the cryostat. The first key components, namely the anode wire planes, started to arrive at the end of 2017. The ProtoDUNE-SP detector has six of these modules in total, which are each 6 metres high and 2.5 metres wide.

The construction and operation of ProtoDUNE-SP serves to validate the novel membrane cryostat technology and associated cryogenics, and the networking and computing infrastructure that will handle the data and simulated data sets. A charged-particle beam test will enable critical calibration measurements necessary for precise calorimetry. It will also enable the collection of invaluable data sets for optimizing the event reconstruction algorithms – i.e., for finding interaction vertices and for particle identification – and ultimately for quantifying and reducing systematic uncertainties for the DUNE far detector. These measurements are expected to significantly improve the overall physics reach of the DUNE experiment.

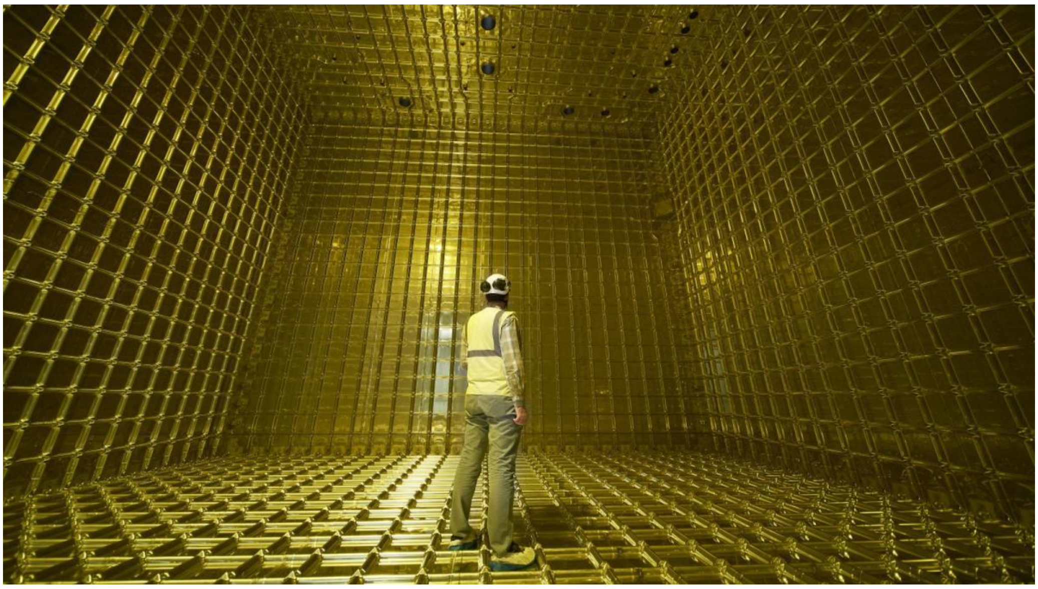

Figure 1: Inside of the ProtoDUNE detector cryostat.

Data taking and monitoring

The detector filling started on August 8th and finished on September 13th. The liquid argon purification started on September 18th and continued until the end of the test-beam on November 12th. After the first purification run, the electron lifetime exceeded by far the nominal configuration of 3 ms. The high voltage (HV) was ramped up to -180kV at the cathode on September 21st. The detector operated stably and without major issues for most of the test-beam period. With more than 4 million triggers collected in the 0.3 - 7 GeV/c momentum region, ProtoDUNE-SP acquired a large sample of pions, protons, electrons and kaons for energy resolution studies and cross-section measurements on argon. A few million cosmic-ray tracks were also collected for calibration studies.

During beam operation, the data quality was continuously monitored using online and semi-offline monitor tools. While the online monitor (OM) tools provide validation plots a few minutes after the data is recorded, the semi-offline data quality monitors (DQM) run a light reconstruction on a small fraction (~1%) of the data recorded. OM and DQM are supplementary data quality tools confirming that the few weeks of test-beam data collected are of good quality. Cosmic-ray muons are used to estimate the electron lifetime and the signal-to-noise ratio (Figures 2a and 2b). The increase in electron lifetime and to signal-to-noise ratio is visible in these plots.

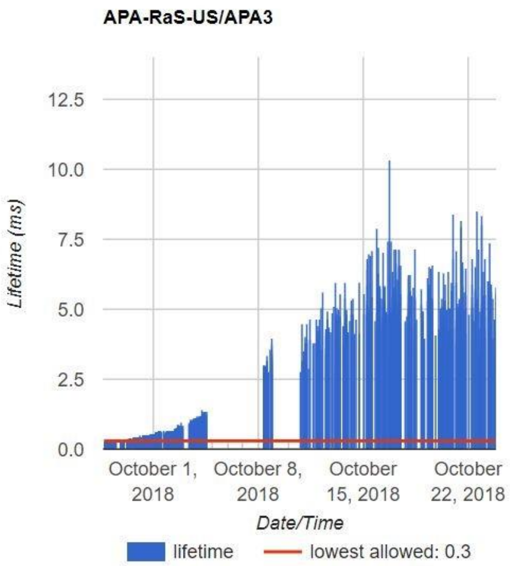

Figure 2a: Electron lifetime estimated from the semi-offline data quality monitors using cosmic-ray muons (left)

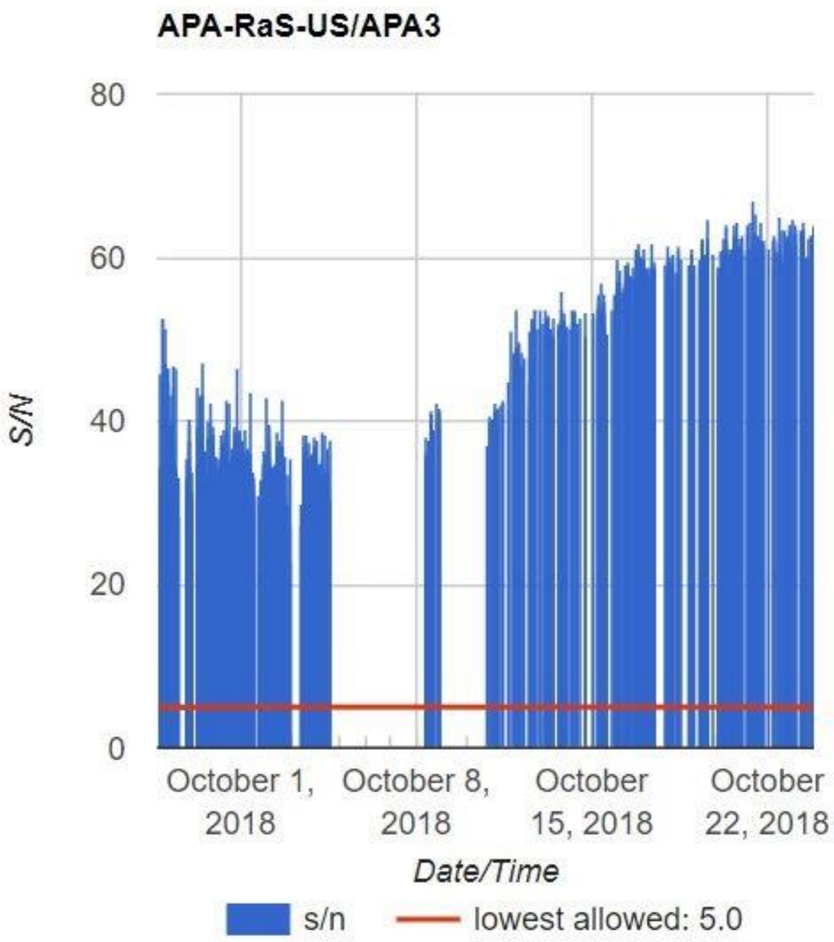

Figure 2b: Signal-to-noise ratio estimated from the semi-offline data quality monitors using cosmic-ray muons (right).

Calibration and reconstruction

The ProtoDUNE-SP TPC has three independent readout planes consisting of a number of parallel wires. Signals found on the wires are reconstructed into hits that are then matched in time across the three wire planes. The hits are clustered and reconstructed as objects representing a primary particle and the hierarchy of daughter particles. This hierarchy consists of a number of track and shower objects that describe the full interaction of the primary particle.

The event reconstruction software has performed very well out-of-the-box since the detector was turned on. Soon after the high voltage was starting to ramp the first small track segments were reconstructed even with low purity of the liquid argon. As the purity increased and the high voltage was stable at -180 kV test beam interactions were fully reconstructed in three dimensions (see Fig. 3).

Work is now on-going to calibrate the detector from the low-level waveforms up to the correction of the space-charge effect, which is the distortion of the electric field due to a build-up of argon ions in the TPC. Dedicated runs are being taken now that the beam data taking has finished to calibrate the readout electronics, and ProtoDUNE-SP will continue to collect cosmic-ray data.

Development of the physics analyses, including the primary physics goal to measure the charged pion interaction cross-section on argon nuclei, is underway and relies on the underlying calibration and reconstruction studies.

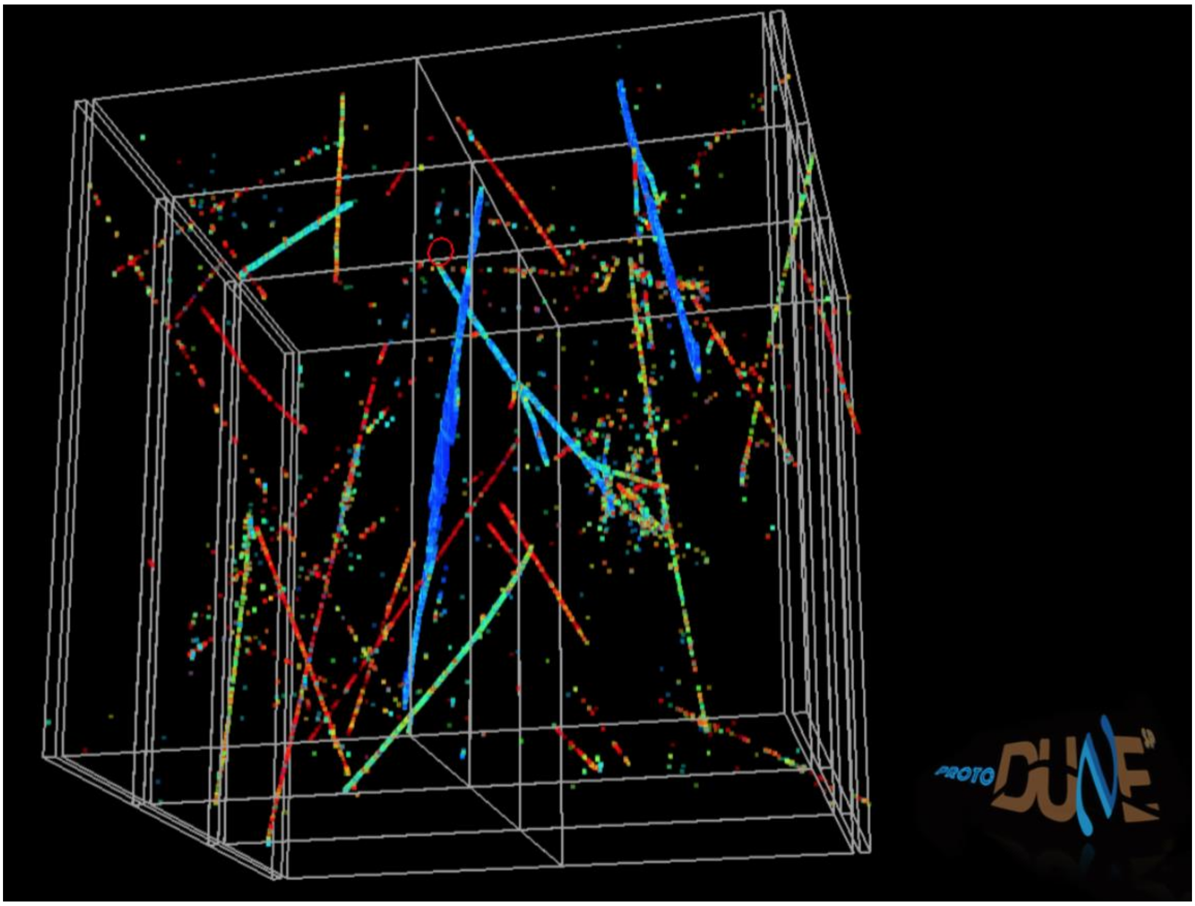

Figure 3: A reconstructed test-beam π^+ (entering the TPC from the red circle) interacting inside ProtoDUNE-SP with a number of coincident cosmic ray muons.

Conclusions

The ProtoDUNE-SP detector was built and commissioned in a record time, and was found to function amazingly well after switch-on, during the last few months. This is a major step forward for the planning of the DUNE far detector. Valuable lessons were learned in assembly, commissioning and operation of these detectors. Excellent data on hadron-argon scattering has been collected in the last few months.

The present plan is to continue to operate the detectors during the next two years with cosmic rays, to establish among others the long-term stability. Plans are being discussed for a possible life after the LS2 with beam. Finally, we also look forward to the ProtoDUNE-DP switching on early in 2019.

A bright year for the EP-DT irradiation facilities

DT
by by Federico Ravotti and Martin R. Jaekel (EP-DT)
PDF version

The CERN proton irradiation facility (IRRAD – www.cern.ch/ps-irrad) at the PS East Area and the new gamma irradiation facility (GIF++ - www.cern.ch/gif-irrad) at the SPS North Area have been designed and built during LS1 to cope with the increasing need for irradiation experiments of the EP experimental community, working for the High-Luminosity upgrade of the LHC and beyond. Both these new facilities are the natural upgrade of historical services of the EP department that, since the 90's, were exploiting the proton beam at the PS and the SPS muon beam (in the former West Area) for studying the radiation hardness of materials and semiconductor devices and to test particle detector prototypes including tracker, calorimeter elements and muon chambers.

The IRRAD facility, operated by a team in EP-DT, is nowadays part of a more complex infrastructure in the PS East Area divided in two separated facilities operating in parallel and sharing the same high-energy proton beam (24 GeV/c) extracted to the T8 beam-line. While in IRRAD, irradiations are performed with the primary protons, in CHARM (located downstream IRRAD and operated by the EN department) a mixed-particle radiation field is generated by a thick target, thus reproducing the radiation environment of the LHC tunnel and the typical shielded areas of the CERN accelerator complex.

IRRAD reached the LS2 after four full consecutive years of operation since 2015. During one year, more than 200 days of beam-time are available for irradiation experiments in IRRAD. As shown in the Figure (LEFT), for about the same beam-time, the number of irradiated samples constantly increased reaching a peak around 800 samples/year during these last two runs before the LS2 (2017-2018). Using the new software application "IRRAD Data Manager", developed within the AIDA-2020 project (www.cern.ch/irrad-data-manager), about 1000 samples belonging to 81 different irradiation experiments were initially registered in 2018 by the 92 users of the facility. The final number of irradiated objects takes into account the final samples availability, the daily operational constraints (as the maximum interaction length allowed in the facility, etc.) and a fair distribution of the beam-time among the users. As in 2017, this exceptional performance was possible also thanks to the excellent availability and quality of the irradiation beam provided by the BE-OP team that, also in this last run before LS2, reached the level of $5\text{x}10^{17}$ protons delivered to IRRAD.

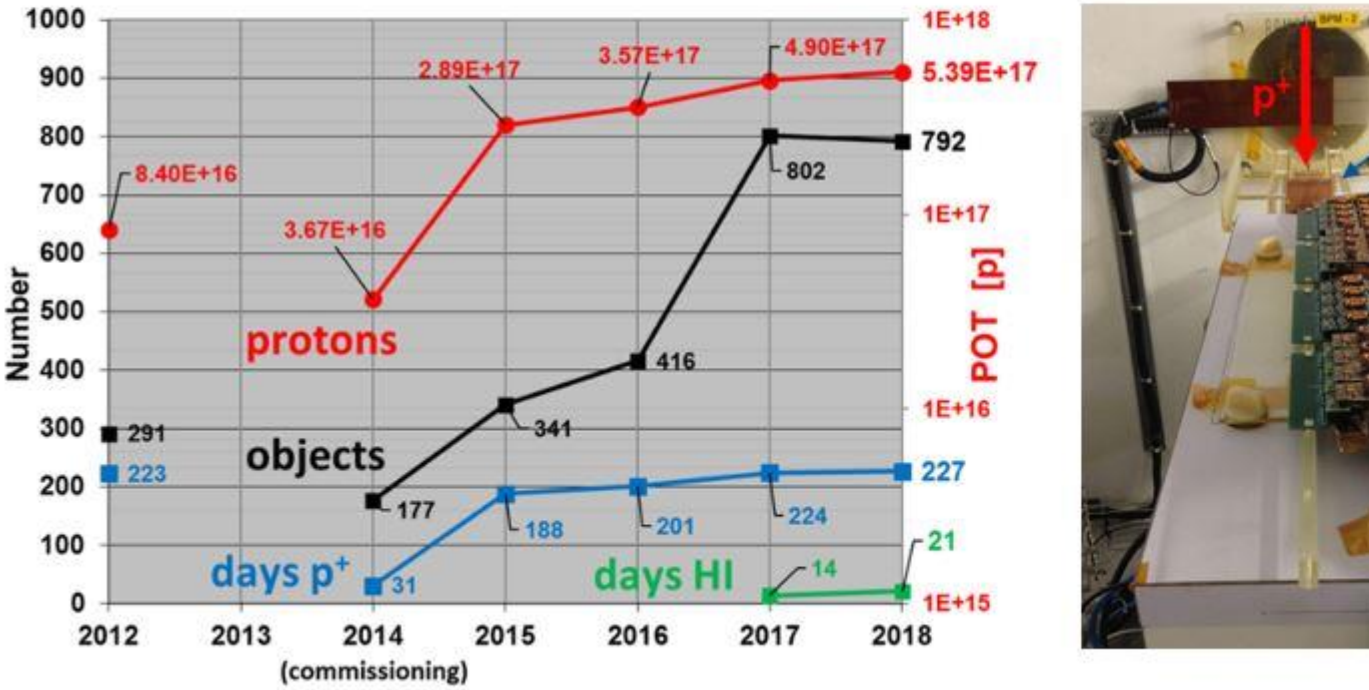

Fig. 1. – Left: Statistics for the IRRAD facility during its first run (2014-2018). The number of irradiated objects and days of proton and Heavy Ion (HI) beam time (left vertical axis), as well as the total number of protons delivered to IRRAD (right vertical axis), are plotted for the last 7-years of operation. Right: Irradiation of the FEAST2 DC/DC converters during 2018. The secondary particle field generated by the thin copper target (visible upstream in the picture) impinges on the samples irradiated at room temperature located on the top and inside the thermal box (visible in the foreground) where a temperature of -25°C and low RH are maintained.

About 30% of the irradiated samples in 2018 were belonging to the R&D collaborations, mainly RD50 and RD53, as well as belonging to common development and R&D projects for future accelerators (FCC). Another 50% of samples came from the LHC experimental collaborations. This includes the ATLAS, CMS, LHCb and TOTEM experiment. The final 20% were samples for radiation hardness studies belonging to LHC equipment groups in the EN and TE department (electrical distribution, magnets, vacuum, cryogenics, etc.) as well as to the CERN safety unit (HSE). During 2018, a special experiment also took place in IRRAD and required to setup a “thin” copper target to locally generate a stray secondary particle field. These special irradiation conditions, setup for the very first time in IRRAD, enabled the testing of the FEAST2 DC/DC converters developed by the EP-ESE group in different environmental conditions (see Figure 1 – right).

Finally, the last 3 weeks of the run 2018 were again dedicated to the development and characterization of an ^{82}Pb Heavy-Ion (HI) beam on T8. Several dosimetric measurements were performed with the main goal to provide a beam for Single Event Effect (SEE) studies in electronic components for space application, as well as to evaluate the possibility to propose, after LS2, the East Area facility as a test-bench for the experimental collaborations involved in HI physics.

The IRRAD team in EP-DT is now preparing the work for LS2 where several maintenance interventions are planned in order to mitigate the radiation-induced damage on the various irradiation equipment of the facility. Moreover, an extension of the IRRAD technical area (used for the storage, handling and characterization of the irradiated samples) is also foreseen in the framework of the ongoing East Area renovation project.

The GIF^{++}was constructed as a joint project between the CERN engineering and physics departments and commissioned in late 2014, replacing the original Gamma Irradiation Facility in the West Area that had lost access to a muon beam in 2004. Especially designed for testing gas based muon detectors for the upgrade program of the LHC experiments, GIF^{++} is a unique place where high energy charged particle beams, mainly muons with momenta up to 100 GeV/c, are combined with a 14 TBq ^{137}Cs source (as of 2014), roughly 30 times the photon intensity of the previous facility. The 100 m^2 irradiation bunker has two independent irradiation zones – both equipped with an angular correction filters and an absorption filter system - making it possible to simultaneously test several real size detectors, up to several m^2, as well as a broad range of smaller prototype detectors and electronic components. The facility is equipped with a central control system to record all relevant environmental parameters, beam parameters, filter settings, as well as to redirect interlocks on gas mixtures qualities supplied to the detectors. A wide range of readily available gases can be used by connecting to the gas panels distributed throughout the facility.

Since 2015, the facility users are coordinated by EP-DT. The facility operates in two main modes: throughout the year, the gamma irradiation is available - only interrupted by short maintenance periods – and work concentrates on ageing studies and radiation hardness of components. The absorption filters (and distance from the source) are used to control the level of radiation and therefore the acceleration factor for the ageing studies. During 6-9 weeks per year, the facility also receives the muon beam from the T2 target and work concentrates on performance tests of the muon detectors under varying background condition. In this second mode, the gamma field intensity is tuned to simulate the radiation background these chambers will experience in their final positions inside the LHC experiment during HL-LHC conditions.

Typically, the facility hosts up to 20 detector setups per year requiring muon beam, in addition to several setups requesting gamma irradiation only. Due to the size of the setups, a maximum of 9-11 setups along the beamline in total can be fitted inside the irradiation bunker, distributed along the two fields as shown in Fig.2. While the majority of installed systems come from the LHC experiments, GIF^{++} regularly hosts setups from other departments (e.g. Beam-Loss Monitors for BE) or different research facilities (e.g. muon detectors for CBM/FAIR). Over the last years, the search for new environmentally friendly gas mixtures and the test of gas recycling systems also became a mayor field of research at GIF^{++}.

Fig.2 – GIF^{++} irradiation bunker during October Muon beam time 2018. Up to 11 different setups – often composed of multiple chambers – could be hosted along the muon beam, while several other experiments could continue to use only the irradiator.

In contrast to other CERN irradiation facilities, the GIF^{++} irradiator will be fully operational during LS2 - as much as the ongoing consolidation works in EHN1 will permit it. The work load will even intensify in the coming two years, with 4 major mass-production campaigns announced, while the majority of long-term ageing tests will continue. The tests for the ATLAS and ALICE muon detectors have already started in 2018, both requiring frequent access to the irradiation bunker to exchanges chambers.

Due to the success of the facility and its increasing user base, the GIF^{++} is constantly overbooked, with the space inside the bunker being one of the main limitations. Thanks to the financial support from all four LHC experiments as well as the EP and EN departments, the bunker will be significantly extended in the upstream direction during LS2, adding more than 40 m^2 of irradiation area. The design of the extension has been finalised, with work expected to start in mid-2019 and lasting for 4 weeks. The increased distance from the source (+ 9 m) will allow to place low-intensity irradiation tests further away, removing the need for high absorption filters and increasing the photon intensity for other long-term setups running in parallel. This will ease the space constraints during the mass production campaigns, and will be a big step in optimising the usage of the muon beam during the LHC - Run 3 with better access to the individual setups and the possibility to host an even increased number of detectors for HL-LHC studies and beyond.

The IRRAD and GIF++ facilities are also part of the AIDA-2020 Transnational Access to irradiation facilities program that provides funding for external users to perform their irradiation tests at CERN. While IRRAD will resume operation only after the LS2, GIF++

will continue to be operational (for gamma irradiations only and compatibly with the upgrade works detailed above) and some Transnational Access funds remain available for the facility users. More details are available here: http://aida2020.web.cern.ch/content/how-apply-transnational-access

The EP-DT Irradiation Facilities team: J. Bronuzzi, B. Gkotse, M. Glaser, G. Gorine, M. Jaekel, I. Mateu, G. Pezzullo and F. Ravotti

A New Small Wheel for ATLAS is taking shape

by Aimilios Koulouris (ATLAS, NTUA), Panos Charitos (CERN)

In order to fully exploit the HL-LHC luminosities, the innermost stations, the so called Small Wheels (SW), of the ATLAS Muon Spectrometer need to be replaced, by two new detector assemblies called New Small Wheels (NSW). This upgrade is schedule to take place in LS2 (at least for sides A based on the current schedule). This sets one of the largest challenges for the phase 1 upgrade project of the ATLAS Muon System to be installed during the LHC long shutdown in 2019/20.

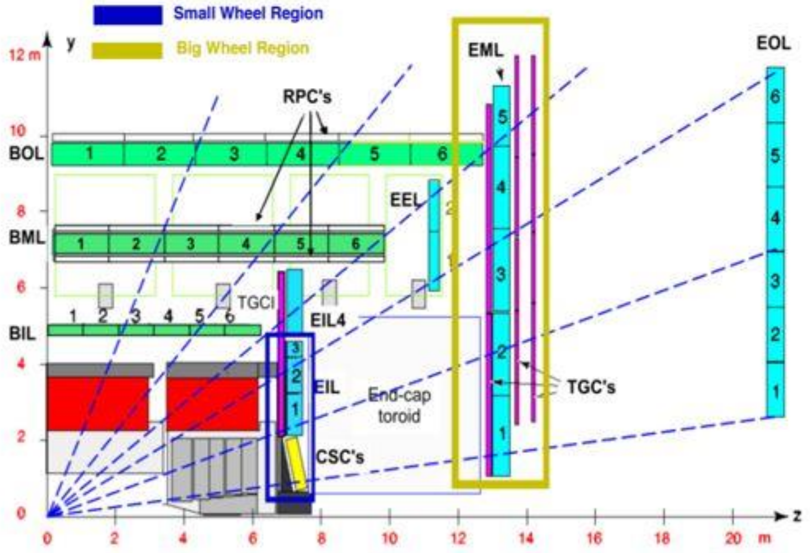

Figure 1: A z-y view of 1/4 of the ATLAS detector. The blue boxes indicate the end-cap Monitored Drift Tube chambers and the yellow box in the Small Wheel area the Cathode Strip Chambers (CSC). Green boxes are barrel MDT chambers. Trigger chambers, Resistive Plate Chambers (RPC) and Thin Gap Chambers (TGC) are indicated by the outlined white and magenta boxes. This is a cut-out of the muon spectrometer at the large sectors, hence the names "End-cap Inner Large" (EIL), "End-cap Middle Large" (EML) and "End-cap Outer Large" (EOL). The detector regions of the Small Wheel and Big Wheel are also outlined.

The New Small Wheel (NSW) will have to operate in a high background radiation region (counting rates up to 15 kHz/cm2) while reconstructing muon tracks with high precision as well as furnishing information for the Level-1 trigger. A very clear indication of the origin of the triggered muon is necessary and will be provided by the NSW. These performance criteria are demanding. In particular, the precision reconstruction of tracks for offline analysis requires a spatial resolution of about 100 µm, and the Level-1 trigger track segments have to be reconstructed online with an angular resolution of approximately 1 mrad.

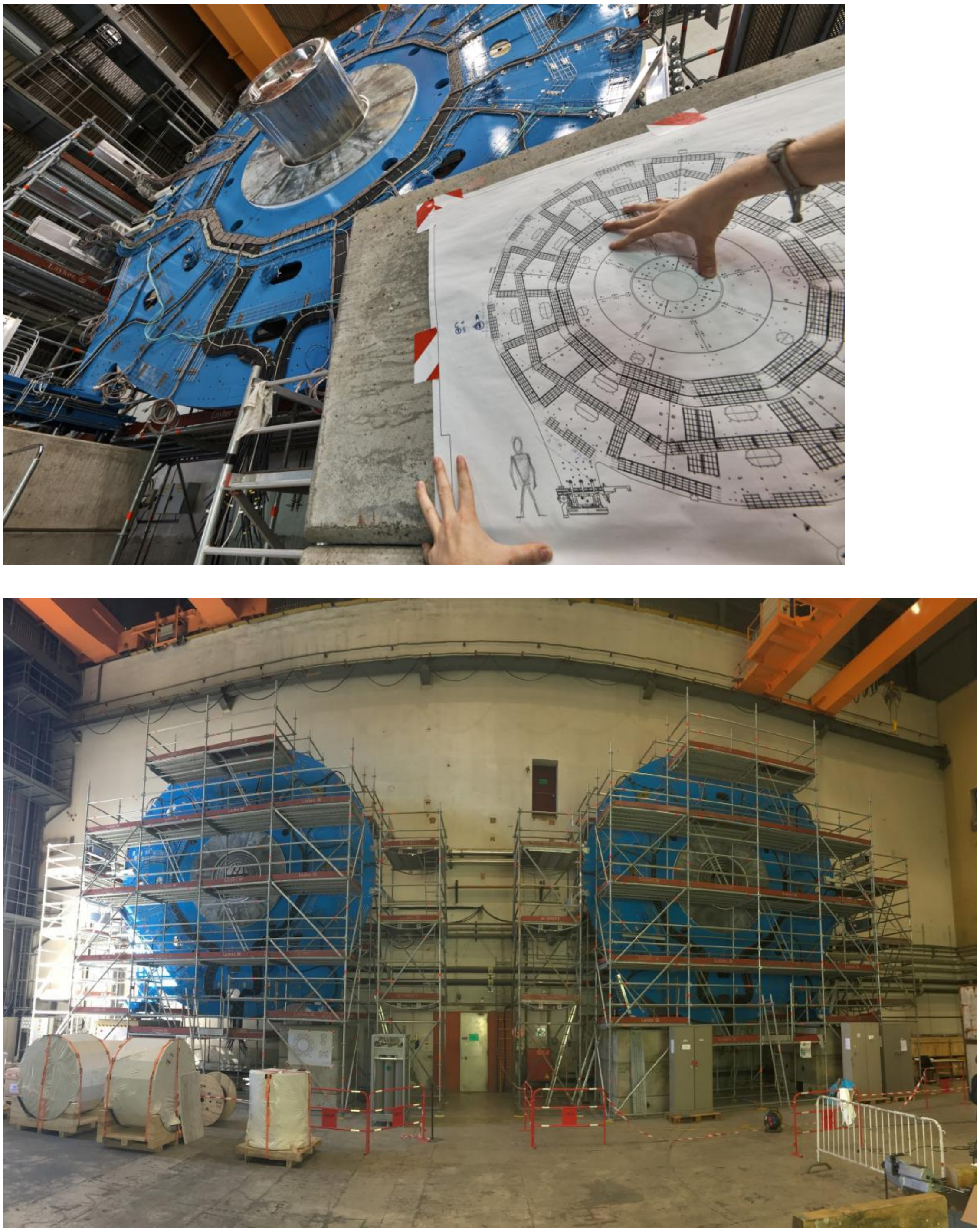

Figure 2: Two views of the shielding disk (NJD) which will support the chambers, in b191, shown with and without scaffolding, and with services routed around its periphery.

The ATLAS NSW has two detector technologies, Micromegas (MM) and small strip Thin Gap Chambers (sTGC), which both provide tracking and triggering capability, and thus a very high level of redundancy. The small strip pitch, 0.5mm for the MM and approx. 3.5mm for sTGC provide exceptional tracking precision capabilities up to very high background rates.

Such a precision is crucial to maintain the current ATLAS muon momentum resolution in the high background environment of the upgraded LHC. In addition, sTGC have excellent timing resolution and can provide bunch crossing identification, while both sTGC and MM chambers can, at the same time, confirm the existence of track segments found by the muon end-cap middle station (Big Wheels) online.

A unique challenge for the Micromegas build for ATLAS upgrade is the larger dimension compared to other experiments and previously built such detectors. The realization of the ATLAS NSW requires the production of large size MM with a surface of about 3 m^2, The design and the construction procedures for the NSW Micromegas are the result of detailed studies for each single element which comprises the chamber with extensive prototyping and tests, taking into account different mechanical simulation models. The detectors have trapezoidal shape and are arranged in quadruplets, with 4 layers each, in order to provide four independent points; the readout planes are disposed in a "back-to-back" configuration onto two stiffening panels with an aluminum honeycomb internal structure. Two readout planes are equipped with strips parallel to the bases of the trapezoid for the measurement of the precision coordinate while on the other two the strips are alternatively inclined to provide the second coordinate.

During an intense R&D phase, in collaboration with EP's D&T group, small and medium size single layer prototypes have been constructed. In 2013 two large working prototypes with a single readout layer have been built at CERN laboratories in order to prove the ability to construct large size MM with the adequate mechanical precision. An important step in the prototype developed of the MM was the construction in spring 2014 of the first quadruplet with dimensions of 1.2 x 0.5 m2 in a configuration very close to the final one chosen for the NSW. In order to demonstrate the performance characteristics of the MM technology and also to optimize the design and operational characteristics of the detector, several prototypes have been tested with high energy particle beams. The studies included testing of chambers of various sizes with different characteristics in different beam environments. Lessons learned during the production of this prototype have been used in the design of the final modules and are essential for establishing the procedures of construction and assembly.

In the previous month, the New Small Wheel structures have taken shape in building 191, with both mechanics and services installation well advanced. All parts of the so called new JD, the shielding disk made of iron have been received. The JD serves as the support for the New Small Wheel detectors, but also for shielding the end-cap muon chambers from hadrons. Following that, the structure spokes also arrived over the summer, taking their place on the new JD, one by one. They will serve as support for the assembled detectors. Meanwhile, the services team is installing numerous cables and pipes on the disk, in a very confined space. Only a few millimetres can be used between the disk and the chambers for the cables on one side. Only a few millimetres can be used between the disk and the calorimeter on the other side. Having to work from an elevating platform makes it even more challenging. Of course, inside every spoke, there is an alignment bar, equipped with cameras, establishing contact with each other, soon to be looking between and onto the detectors, in order to mark the real positions of each chamber with sub-millimeter precision.

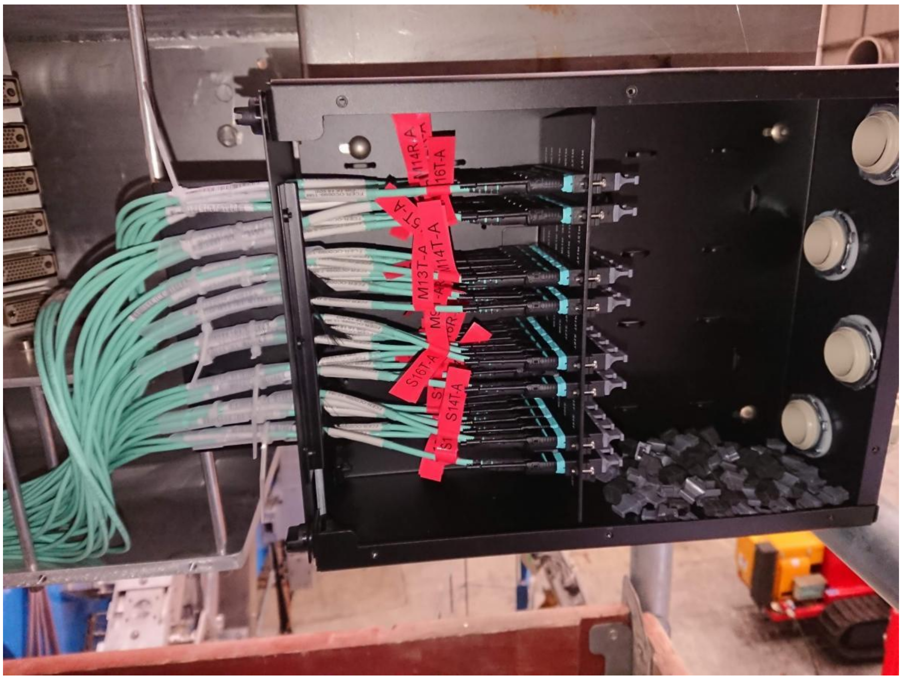

Figure 3: A fiber connection panel at the edge of the wheels.

In building 180, sTGC chambers are prepared, following several steps that include alignment on a flat granite table, glueing a frame on both sides to create a wedge. Once a wedge is in hands, the adapter boards, Faraday cages, cables, pipes, cables trays and the rest of front-end electronics are mounted. All procedures and tools have been defined and are available and ready for accepting chambers as they arrive.

Figure 4: Three sTGC quadruplets assembled in a wedge, with alignment fibers routed on the surface

A bit further in the countryside, in building 899 (BB5), the integration site for the Micromegas chambers lies. Similar to the sTGC, the chambers arriving will be positioned and aligned, to be assembled into wedges, on a common middle support. On a daily basis, cables arrive to be assembled with connectors, and tested; piping cut to length, cleaned and protected until installation; gas leak and high voltage test stations are employed for quality control. The ensemble is completed with a cosmics test stand, to be used as a final quality check before shipping the Micromegas to building 191 for assembling with the sTGC.

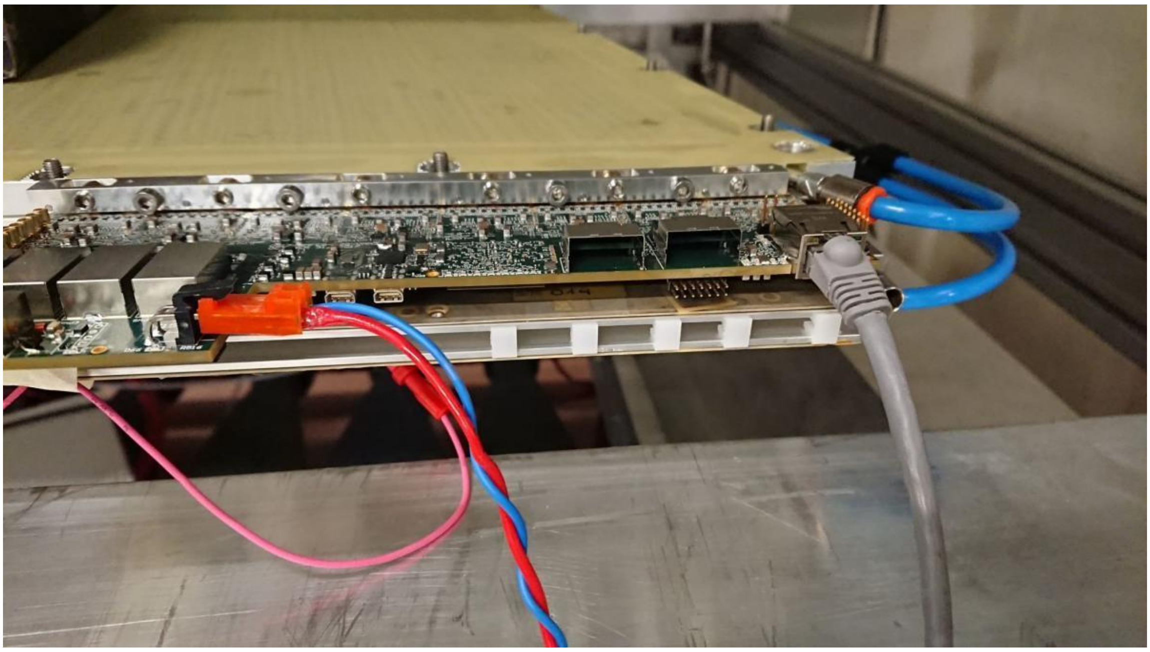

Figure 5: A Micromegas test Front-end board mounted on the chamber

Back to the Meyrin site, a slice of the New Small Wheel electronics is developed, as a base to establish all connections and interfaces between the boards, and further develop the system. The New Small Wheel custom ASICs are in their final stages. The front-end read-out chip, VMM, went through its Production Readiness Review in October of 2018 after the final improvements with version 3a, while the rest of companion chips (ROC, TDS, ART) have already been produced in quantity and are undergoing packaging. The corresponding front-end boards are also closing in on their own production. The Micromegas one (version 319) is equipped with the final ASICs and currently undergoes some final checks with respect to grounding and noise. The sTGC one (version 2.3) is on a similar path.

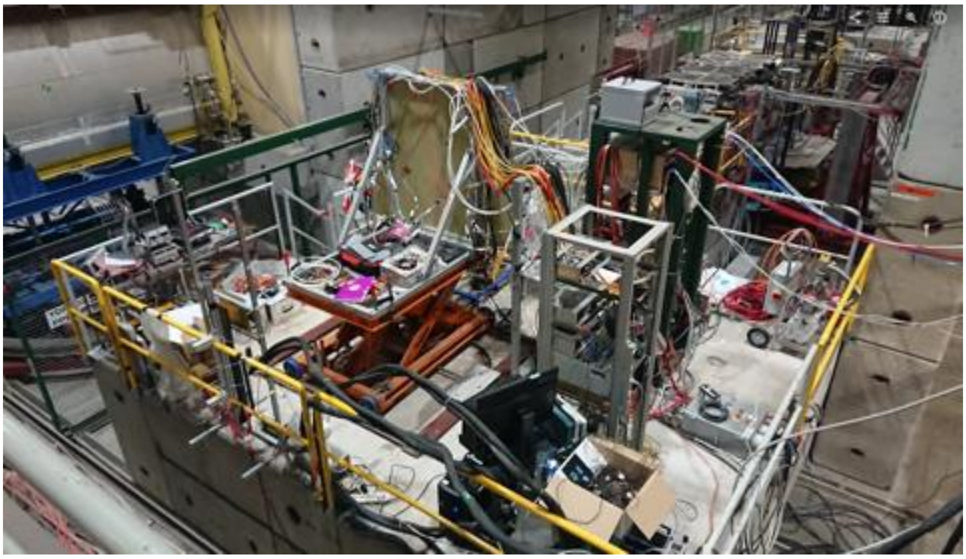

Figure 6: The SM2 module 1 at CERN's North Area, tested under beam.

A lot of activity is ongoing also in the Prevessin side. The teams are testing chambers either with the SPS extraction line hadron beams, or at the Gamma Irradiation Facility (GIF), located in the same building. Over the summer, a Micromegas module (type SM2) was tested at the H8 area, in order to study performance under different rates and different gases, to further understand the micro-TPC reconstruction used for inclined tracks, and to define a safe high voltage working point for the chambers. The sTGC also carefully studied trigger performance and chamber efficiency on their chamber (type QL1), but also tested in GIF their tracking capabilities with the high uncorrelated background rate (type QS3).

At the construction sites, in Italy, Germany, Russia/Greece and France, for the Micromegas, and Chile, Canada, Israel, Russia and China, for the sTGC, the construction and assembly of chambers is happening. The Micromegas community has been tackling HV stability issues in the beginning of the year. Over the summer, a production module equipped with near final electronics was tested in the North Area, to define the right operating point, while trying to maintain good resolution and efficiency, while the effect of a lower working point in ATLAS performance was evaluated with Monte Carlo.

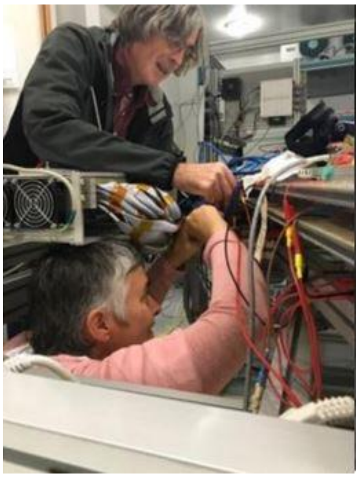

Figure 7: Physicists working in Saclay to connect a Micromegas module (left) and the proud team in Thessaloniki, Greece, ready to ship drift panels to Dubna for assembly (right).

In parallel, further studies on the mesh choice, and looking into optimising the gas choice, were carried out. A great effort, leading to a combined review of panel cleaning and operating procedures, as well as long term stability. This resulted in resuming production of series chambers during this Fall. And so, both technologies having entered series production, while all infrastructure is revving, all procedures and schedules are optimised to accommodate to the Long Shutdown planning.

The first New Small Wheel is scheduled to enter the ATLAS cavern in Spring of 2020. A lot of progress has been achieved, with many important milestones ahead; the fruits of labor from a strong collaboration.

Note: The authors would like to warmly thank Stephanie Zimmermann, project leader of the ATLAS NSW upgrade, for her thoughtful comments on this article.

Colliders join the hunt for dark energy

The birth of a new science

The beginning of the twentieth century was marked by two of the greatest scientific discoveries: quantum mechanics and the theory of relativity, which became the driving forces behind an array of new scientific breakthroughs and technological leaps. Quantum mechanics led to the invention of transistors and the computer revolution. The theory of relativity completely transformed our way of thinking about space, time and gravity but also gave birth to a new scientific field: that of cosmology.

In 1917, Einstein took the first step towards developing modern cosmology by deriving an exact solution of his equations that described the observable universe in its entirety. This was the first cosmological model, which contained the famous constant Λ, the so-called "cosmological constant", which he introduced in order to make the universe static, in accordance with the dominant cosmological belief of the time. A few years later, in 1929, Edwin Hubble observed that the local neighborhood of the universe is expanding, which led Einstein to quickly abandon his model, calling the cosmological constant the "biggest blunder" of his life. Little did he know that half a century later, his biggest blunder would lead to an unexpected discovery and a Nobel prize.

The "Big Bang" and the cosmological standard model

After the first cosmological model by Einstein, several prominent physicists turned to the study of the early universe and proposed their own models, the most famous being the Friedmann-Lemaître-Robertson-Walker model (FLRW). The FLRW model was first proposed by Soviet physicist Alexander Friedmann who found a solution of the Einstein equations that described a homogeneous and isotropic universe. The solution went unnoticed for several years, until the Belgian physicist Georges Lemaître arrived at the same conclusion, realising that the FLRW model could describe an expanding universe, which when traced back in time would appear to originate from a single point, later known as the "Big Bang".

At those times "the study of the early universe was widely regarded as not the sort of thing to which a respectable scientist would devote his time", as Weinberg wrote. The situation changed completely with the discovery of the Cosmic Microwave Background radiation (CMB) in 1964 by Arno Penzias and Robert Wilson, which gave observational evidence that the observable universe is isotropic and evolved from a state of higher density.

More astronomical observations and the detailed measurement of CMB by space missions like COBE, WMAP and Planck established the so-called standard model of cosmology. This model uses the Einstein equations to describe the evolution of space-time (FLRW metric), which is governed by the matter content of the universe. Different types of matter can lead to a different evolution, e.g. relativistic matter like photons and neutrinos leads to a quickly decelerated expansion, non-relativistic matter like baryons or dark matter leads to a more slowly decelerated expansion. There is yet another form of matter, which acts like a negative pressure leading to an accelerated expansion of space-time. The latter is known as "dark energy" (DE). Einstein's cosmological constant is a specific form of DE, which is constant in time and leads to an exponentially accelerated expansion.

An unexpected observation

In the 1990s cosmologists had several observations at hand, with which they could get the first detailed view of the cosmos: they knew that dark matter had to be present in galaxies together with baryonic matter and the first CMB data by COBE allowed to estimate the matter content of the universe. In the late 1990s we knew that the universe is governed by baryonic and dark matter and it appears to be flat, so two teams, the Supernova Cosmology Project and the High-Z Supernova Search Team, set out to measure the rate at which the expansion was slowing down due to gravity.

Much to everyone's surprise they found out that the expansion was not slowing down but accelerating! This discovery was awarded the Nobel prize in 2011. The accelerated expansion implied the existence of a new type of matter, DE which counteracts the effect of gravity at cosmological scales, pushing the universe to expand. The simplest explanation for DE is Einstein's cosmological constant, which can be identified with the vacuum energy density. The problem with this is that the predicted energy density differs from the observed one by more than 50 orders of magnitude, probably the most embarrassing disagreement between theory and experiment in the history of science!

Apart from the cosmological constant there is a vast landscape of theories that can explain the accelerating expansion, ranging from theories with new fundamental fields beyond the Standard Model (SM) to modifications of general relativity. Despite the plethora of alternative models there is no leading candidate among them and several questions about the nature of DE still remain open: we don't know whether it's due to a new particle or a modification of gravity, whether it's constant or dynamic and whether it interacts with other fundamental particles or not. Therefore, DE constitutes one of the biggest mysteries in particle physics and cosmology.

Searching for dark energy

Dark energy affects the expansion of space-time and is therefore imprinted on several observables that we can access with today's instruments, such as CMB, the growth rate of large structures like galaxies, gravitational lensing etc. More recently gravitational waves have been added to this list.

Collider experiments offer an alternative approach, whereby DE could be produced in collisions of SM particles and directly detected. This approach features several advantages. First of all, it is believed that DE should couple to SM fields in order to screen additional gravitational forces which are predicted to exist at small scales but not been observed [1]. Coupling to SM fields means that DE could be produced and directly detected at colliders. Moreover, it has been argued that cosmological observations alone might be unable to distinguish models with new fields from modified gravity and particle physics experiments might be able to alleviate this problem, known as "dark degeneracy" [2]. Finally, in order to understand the nature of DE several experiments offering different insights will be needed. Collider experiments access different parts of the parameter space and could investigate the microscopic nature of DE if discovered, thereby providing complementary information to the cosmological probes mentioned above.

The first collider search for dark energy

Searches for dark energy had not been performed until recently at colliders, due to the lack of models describing the interaction between DE and SM particles. A concrete model was recently proposed in a recent paper by Philippe Brax, Clare Burrage, Christoph Englert, and Michael Spannowsky [3] thus paving the way towards the first collider search for DE ***(see also a previous EP article HERE)***.

This model extends the Standard Model Lagrangian with a set of higher dimension operators which encode the different couplings between DE and SM particles. These operators are suppressed by a characteristic energy scale, which is not determined theoretically, but can be constrained experimentally. The experimental goal is precisely to pinpoint the characteristic energy scales associated with the different DE-SM couplings.

Two representative operators predict that DE couples preferentially to either very massive particles like the top quark, a coupling known as "conformal", or to final states with high momentum transfers, like final states involving high energy jets, a coupling known as "disformal". In a big class of these operators the DE particle cannot decay inside the detector, therefore leaving a missing energy signature. Two of the smoking gun signals for the detection of DE are therefore the production of a pair of top-antitop quarks or the production of high energy jets, associated with high missing energy.

Such signatures are similar to the ones expected by the production of top squarks, where the missing energy would be due to the neutralinos from the top squark decays or from the production of standard model particles in association with dark matter particles, which also leave a missing energy signature in the detector. The ATLAS collaboration therefore re-interpreted the result of recent searches for stop quarks [5] and dark matter produced in association with jets [6], setting the most stringent limits on the DE model [4], as shown in the figure below.

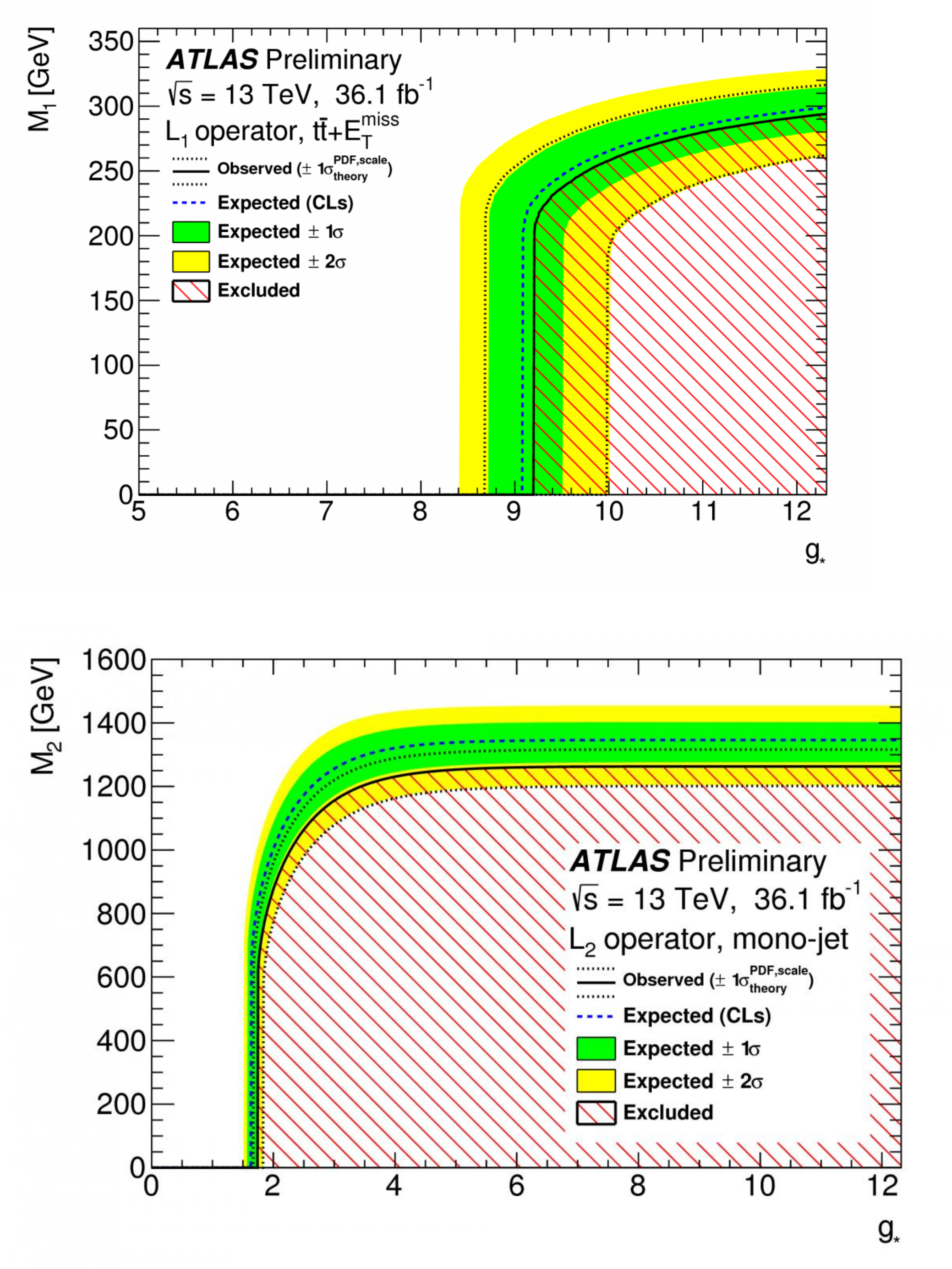

Figure: Limits on the energy scale of the interaction between DE and SM particles (M) as a function of the DE-SM coupling (g_*), from the search in events with top quarks and missing energy (lop) and the mono-jet search (bottom).

The search for DE has revealed that the characteristic energy scale must be higher than approximately 300 GeV for the conformal coupling and 1.2 TeV for the disformal coupling.

The limits on the disformal coupling are several order of magnitudes higher than the limits obtained from other laboratory experiments and cosmological probes, proving that colliders can provide crucial information for understanding the nature of DE.

What lies ahead

With the first search for dark energy, ATLAS became the first experiment to probe all forms of matter in the observable universe, demonstrating the versatility of collider experiments and opening a new avenue of interdisciplinary research, which lies at the interface of particle physics and cosmology.

The search for DE at colliders is only at the beginning and a lot of work remains to be done by both theorists and experimentalists. More experimental signatures and more types of coupling between DE and SM matter have to be explored and more optimal search strategies could eventually be developed.

All in all, colliders offer an alternative way of searching for DE that will help together with cosmological observations and other laboratory experiments to further our understanding of one of the biggest mysteries of our time.

Further reading

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[2] Kunz PRD 80 (2009) 123001 Kunz, Sapone PRL 98 (2007) 121301

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[5] ATLAS collaboration, JHEP **12** (2017) 085

[6] ATLAS collaboration, JHEP **01** (2018) 126

Interview with Claudia de Rham

by Spyros Argyropoulos (University of Iowa), Panos Charitos (CERN)
PDF version

For one week in November, Geneva hosted the 18th edition of the annual Wright Colloquium. This year's theme was "Gravity" The Universal Attraction" and gathered researchers and thinkers to present their research and share some of the questions that intrigue them while showing off the most fascinating data that could help us understand this so fundamental and yet elusive force.

Professor Claudia de Rham discussed about "The Dark Side of the Universe". A faculty member at Imperial College London, de Rham grapples with some of the most fundamental questions at the intersection of gravity, cosmology and particle physics. In her talk, she invited the audience on a journey to the outskirts of the observable Universe in a

quest to understand the behaviour of gravitation and how it is linked with the so-called Dark Energy.

We met de Rham before her talk and discussed about the nature of gravity, her work on massive gravity and possible observables coming from gravitational waves. How can a new theory of gravity help us tackle the dark-energy content and what can be learned from collider experiments? These are some of the questions that you can read in this interview. Finally, we discuss with Claudia about the importance of presenting research results to a general audience and the need for a paradigm-shift in science communication.

What motivated you to become a cosmologist?

As a child, I enjoyed staring at the starry sky! In fact, like perhaps many kids, I was dreaming off becoming an astronaut. Later, as an undergraduate student, I had the opportunity to do an internship in NASA's Jet Propulsion Laboratory. My project was to study the correlation between the magnetic and gravitational fields of Mars and involved a lot of data analysis. This helped me to realise that I was interested in more fundamental questions. Questions related to the first principles and basic laws that describe our universe. This is when I have decided to focus on theoretical physics.

In that sense, cosmology has been the obvious choice since it offers the opportunity to explore nature at its most fundamental level while keeping a sort of "connection" with the sky! Through cosmology we try to answer the most fundamental questions about our own existence and the origins of the universe.

What do you see today as the main challenges for cosmology?

A key challenge comes with the new observational data allowing to look much further and at different epochs of our Universe. More data means also more effort to interpret them, thus calling for theoretical developments.

Moreover, when designing new missions we also need to think the type of data needed to verify our theories or understand where to search next. From a theoretical perspective, I think that there is still a lot of work needed on the foundations of theoretical cosmology. Pioneers, like Steven Hawking, Roger Penrose, Steven Weinberg, Tom Kibble formulated the basis of our current understanding back in the 1960s and set the framework for further theoretical and experimental exploration. They were amazing in communicating their ideas to a larger group of people creating a whole new community. This is their legacy. The community that inherited their ideas is today the main driving force of our field.

You have recently received the Blavatnik award for your work in massive gravity. What's the key concept behind this idea?

Massive gravity is exactly what you think when you hear these two words! Some of the particle carriers of forces in the Standard Model have a mass, like the W and Z bosons that carry the electroweak force. Today we believe that the photon is massless though there are some theoretical ideas that it could also have a mass and certain constraints have been placed on its value.

Massive gravity introduces a similar concept for the graviton - or any spin-2 particle - that is the carrier of the gravitational force. Today, we believe that like photons, such particles, if they exist, are massless. The theory of massive gravity though suggests that they have a certain mass and succeeds to introduce it without violating other theoretical or experimental constraints.

The possibility of a massive graviton is not something new. In fact throughout the 20th century there were efforts to incorporate this in GR but a number of issues arised. These problems are similar to what happens when you give a mass to the photon; as soon it gets mass it can't travel anymore at the speed of light while excitations along its travel path introduce an extra degree of freedom in the electromagnetic field.

Similarly, adding mass to the carrier of the gravitational force would add additional polarizations in the gravitational waves as they travel in spacetime. This effect was understood already in the 30s when Wolfgang Pauli and Markus Fierz developed a theory of a massive spin-2 field propagating on a flat spacetime background. Moreover, it was later understood that giving a mass to the graviton adds extra degrees of freedom that makes the theory very unstable. Massive gravity comes with a so-called "ghost"; an instability that cannot be controlled and to which every particle would decay very rapidly. This of course can't be the case and for decades people thought that a massive graviton - any spin 2 particle that carries gravity - is excluded.

This was also our mindset and within the community we were exploring different complementary options. I started playing with a specific model and during cosmo 2008 at CERN I realized that Gregory Gabadadze had come up with precisely the same model. We started discussing and that's how we started our collaboration!

We knew that our model was not fully consistent and required further completion. For example, we could see that it violated the existing no-go theorems for massive gravity, which indicated that there could actually be a loophole behind these long standing arguments against massive gravity. To solve that we started exploring the maths behind the theorem (or performing a more careful constraint analysis) and soon discovered how the no-go theorems could in fact be evaded and how to allow the graviton to have a mass. So together with Gabadadze and Andrew Tolley we developed a fully consistent theory of massive gravity accommodating a massive graviton.

It will most probably not be the final description of what is going on but it certainly provides a framework with which we can explore alternative theories of gravity, at least at the largest cosmological scales.

Which challenges does the theory of massive gravity address?

This boils down to the so-called cosmological constant problem. The cosmological constant, that is linked to the energy of the vacuum, seems a very natural candidate for dark energy. Therefore, you may ask why not to keep only that as a simple and elegant solution to the dark energy problem and assume that the vacuum energy is responsible for the observed expansion of the universe?

Well, then you confront the real problem because if you try to calculate how much each particle contributes to the vacuum energy with the known laws of particle physics, you end up with a very large number which is 120 orders of magnitude higher than what we observe. This is perhaps a strong statement as it assumes that there are particles contributing to the vacuum energy all the way up to the Planck scale (or it assumes a cutoff of the order of the Planck scale). In my view this is not necessarily the case. However, even restricting ourselves to known particles, like the recently discovered Higgs boson, with a mass of 125 GeV, would give us a discrepancy of 56-57 orders of magnitude with observations. That's the cosmological constant problem.

The motivation for massive gravity is to get the best of both worlds: you say that the vacuum energy is responsible for the observed acceleration and because the graviton is massive, the contribution of vacuum energy to the acceleration of the universe is much smaller than what general relativity predicts.

An attractive property of massive gravity is that while the graviton mass is extremely small compared to all other particles of the standard model, it remains small even when you include effect of quantum corrections, so it is technically natural. In GR the graviton is massless and of course we know that a mass will not be generated by quantum correction. This is forbidden by local symmetries. As soon as we give the graviton a mass, it of course receives quantum corrections, however in the case of massive gravity, the radiative corrections to the mass are themselves proportional to the mass. This is a little more subtle than t'Hooft naturalness argument for global symmetries (since the symmetries recovered in the massless limit are local), but it is a technical naturalness quality that we able to show. This is in contrast to the cosmological constant which is unstable under quantum corrections, the cosmological constant receives radiate corrections which are unrelated to its actual value.

What experimental ways are there to test massive gravity?

Perhaps one of the most cleanest ways is through observations of gravitational waves. If the graviton is massive, the gravitational waves would have a modified dispersion relation: high-frequency waves will travel faster compared to low-frequency ones. So with the LIGO observations and from the absence of such a modification of the dispersion relation one can put a limit on the graviton's mass, which has to be smaller than 10^{-21} eV. This seems very small but we are thinking more of a cosmological mass for the graviton which has to be around 10^{-32}-10^{-33} eV; still ten orders of magnitude below what we get from LIGO.

The other set of constraints come from the fact that we can have an additional channel of radiation because you don't have just the two polarizations but you have additional excitations. So systems of objects spinning around each other (like neutron stars) could lose energy more rapidly as they emit in more channels. We have some constraints from binary pulsars that have been observed over years and we have a good control of how much energy is lost over a certain period of time which puts another bound on the mass of the graviton though not so strong (again about 10^{-20} eV). There are also tests that offer better bounds but are more model dependent.

Is a massive graviton compatible with a quantum theory of gravity?

Massive gravity is a low-energy modification of gravity and doesn't answer the question what the fundamental theory of gravity at high energy is and how gravity is quantized. One might think that massive gravity is just a theory at low energy while there should be another one at high-energy scales and these two things know little about each other. This is roughly correct at first sight but we can actually do much better than that ! Integrating out heavier degrees of freedom has consequences at what you see at lower energies and conversely if you think about it from a low-energy effective field theory perspective, the type of operators you have would lead to a particular class of UV completions. So even though we don't know what the UV completion of massive gravity is, we impose a lot of constraints to make sure that it could enjoy a meaningful UV completion.

There are alternative models that attempt to explain dark energy by introducing new fields. Do you think that our understanding of dark energy will involve only a modification of gravity or also of the standard model of particle physics?

There is a fundamental question concerning what you really try to modify. If you think about modifying the gravitational degrees of freedom, the standard polarisations of the graviton, at large distances it would effectively be like giving a mass to the graviton. There are alternative ways to modify gravity by introducing by hand additional degrees of freedom. These don't affect directly how the graviton behaves but can give you additional degrees of freedom that may or may not be linked to gravity.

In my view, If you start adding additional scalars or vectors in their own right then this is in the framework of dark energy. You have gravity and additional degrees of freedom that you add by hand and may or may not couple with gravity in a minimal way and may slightly modify the properties of gravity like the propagation of gravitational waves, but this modification is not intrinsic to gravity itself.

A lot of alternative models introduce additional fields, scalars, vectors etc, but they don't tackle the cosmological constant problem. They put the cosmological constant to zero and then try to explain dark energy. In many models of gravity that rely on additional fields to explain dark energy, the tuning present in the mass or coupling of these extra fields is typically as large as the cosmological constant tuning. So you haven't solved the cosmological constant problem in the first place and you introduce a new parameter that is not natural; a new naturalness issue in that sense.

There are few models that try to introduce additional fields to tackle the cosmological constant

problem itself but not many. We know from Weinberg's no-go theorem that within the context of GR, any standard type of field introduced to explain dark energy or address the cosmological constant problem typically has a similar type of tuning involved.

Do you think that it is important to communicate our scientific efforts?

Fundamentally what we do interests and excites the public that wants to learn more about our research. As scientists we have this culture of exchange and sharing. Communicating to the public sometimes also helps to put things on a more concrete basis.

Of course there are different levels of what we share. I have pages of calculations that probably I will not share with the public. You share the work that is more polished and represents the story.

Moreover, the news on the discovery of gravitational waves or the Higgs boson in a way may give a biased impression to the public. Of course it is important to share these discoveries that also offer the opportunity to reach a wider audience and discuss about our research, however the public often thinks that a new discovery is a complete package; a happy-ending for the scientific community.

I think we shouldn't be afraid to crack open our research and also emphasize the number of things we don't understand. This is actually the reason we continue to do fundamental research. When the Higgs boson was discovered many people ask: "now what?", "why do we need to continue with particle physics?". This was the case with the announcement of the gravitational wave detection, generating big headlines like "Einstein was right". But this is not at all the point of scientific research. It makes it sound as if it is the end of the story, while in reality every discovery is the beginning of a new era. We don't do research to prove if someone was right or wrong. We do research to learn from it and move forward and this is an important point that we should include in our communication efforts. We are all explorers and the public loves taking part in this exploration.

Meeting the challenges of tracking detector mechanics

by Panos Charitos

Designing detectors to meet the physics requirements of future high-energy experiments calls for a strong R&D program on new detector-systems. This includes sensors technologies, fast and efficient electronics, mechanics and cooling techniques that could cope with the environment offered in high-energy and high-intensity colliders planned for the post-LHC era. An important role in future R&D programs for the innermost vertex and tracking detectors is played by the mechanics that will have to cope with a wide range of competing requirements.

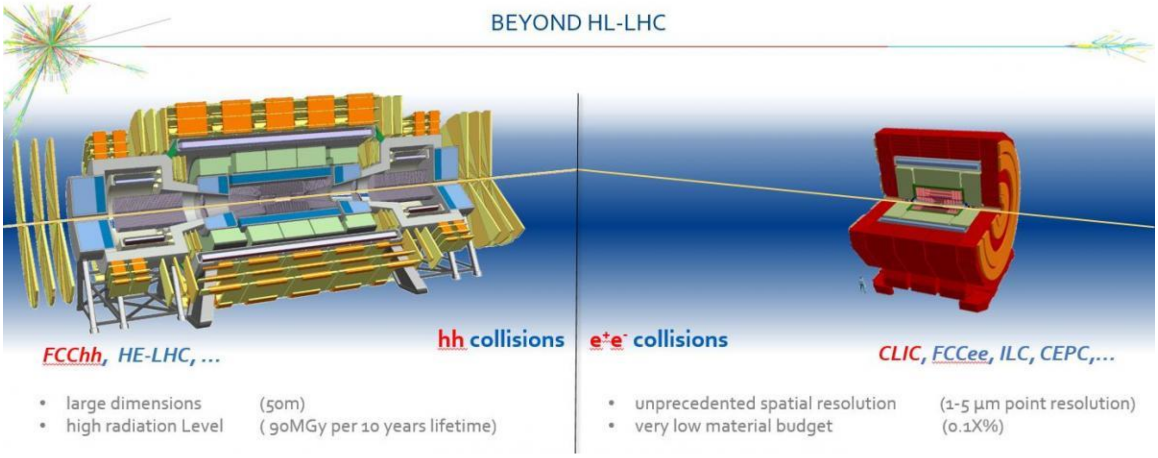


Figure 1: Future detector mechanics has to cope with large range of demanding requirements.

In an inspiring talk during a recent DT seminar, Corrado Gargiulo, discussed the challenges posed by future tracking detector mechanics at the High Luminosity upgrade of the LHC and future post-LHC colliders. In his presentation he discussed the planned upgrades for the silicon trackers of the four LHC experiments in the upcoming long shutdown periods. During LS2, LHCb plans to upgrade the VELO detector using Hybrid Pixel Sensor and ALICE will upgrade the Inner Tracking System using Monolithic Active Pixel Sensors. Further down the road, in LS3, CMS and ATLAS experiments plan major upgrades of their trackers including a combination of pixel and strips sensors for the inner and outer layers.

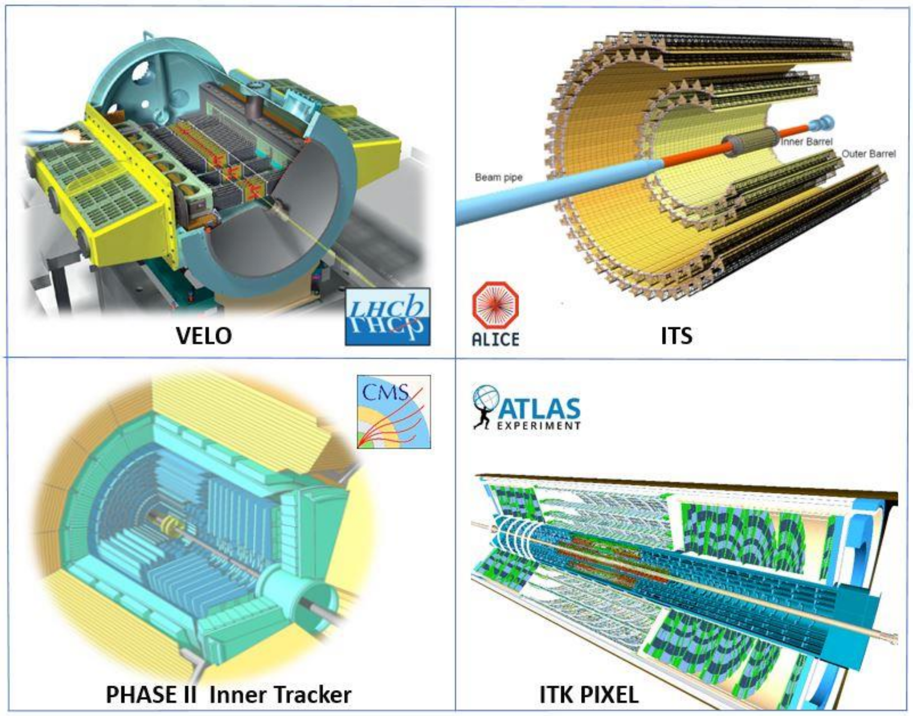


Figure 2: The upgrades of the tracking systems of the LHC Experiments at LS2 (ALICE and LHCb) and LS3 (ATLAS and CMS)

Corrado then projected the discussion into future, bridging and comparing design requirements from the upcoming LHC trackers upgrades to future detectors beyond the HL-LHC, and more specifically anticipating possible design directions for the mechanics. While the full exploitation of the potential of the HL-LHC is the clear top priority for the next 15 years, a number of studies for a major post-LHC project at CERN are being pursued: CLIC, FCC-hh, FCC-ee; complemented by advanced design studies of an International Linear Collider. Looking forward to the European strategy prioritizing the next big projects in the field, the wide range of future detectors can been grouped in hadron collider detectors and lepton collider detectors, in an attempt to address common requirements for mechanics and cooling. While the first will propose exceptionally large dimensions and extremely high radiation levels, the second will require unprecedented spatial resolution and thus extremely low material budget to avoid the emission of secondary particles as background, and high stability.

In the lepton collider experiments therefore the clear challenge for the mechanics will be to hold in position the next generation sensors with extraordinarily low material, while providing high stiffness and stability, with a target of <0.1% X_0, for the Vertex detector innermost layer to compare with the limit of about 0.3% that will be reached in the LHC next upgrades. A future silicon pixel tracker, which excludes from the detector acceptance all services and mechanical support structures would represent an ideal design.

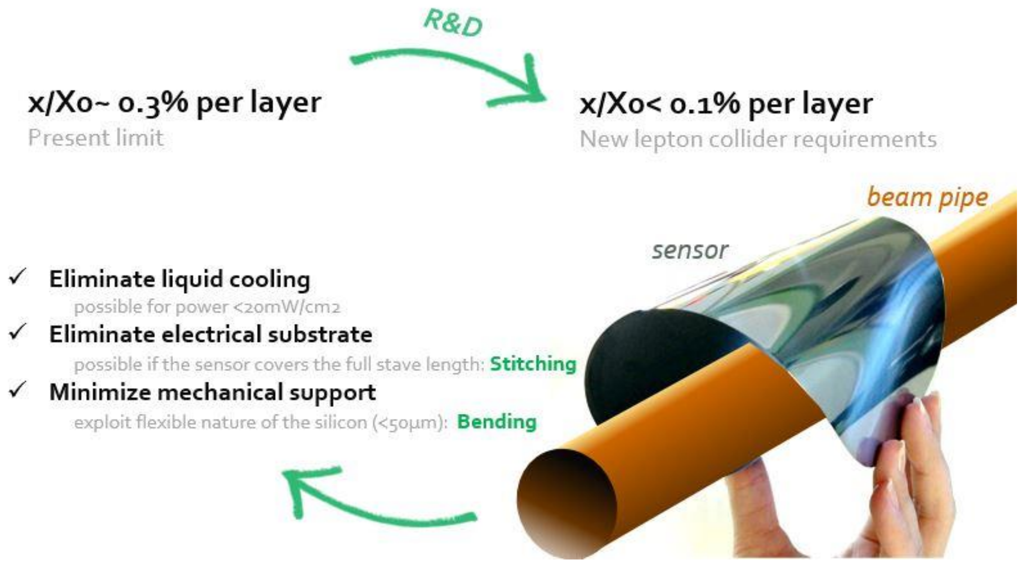


Figure 3: future vertex detectors aim to unprecedented minimum material budget which call for R&D on new sensor technologies and cooling solutions.

To eliminate the material in front of the sensor, new technologies, (like stitching) are pursued, capable to produce large area silicon sensors (from present few square cm to few hundred square cm). This would allow to cover most of the detection area with few sensors, confining the electrical interconnection to the sensors edge, outside the acceptance area. In addition the reduction of sensor thickness to few tens of microns will potentially allow for its direct bending to the final layer radius. Such layout would allow for removing power and data cable from the active area, minimizing mechanics and removing piping, where cooling solutions based on gas flow would be adopted.

At the other extreme, the harsh radiation environment in the future hadron collider experiments (ex. 90 MGy in 10 years lifetime for FCC-hh with $5x10^{17}$ 1MeV neq/cm^2), will impose severe constraints on the material used for the mechanics, while at the same time driving the cooling design.

Embedded liquid cooling systems in the mechanical substrates at the back of the sensors will allow at the same time to efficiently remove the dissipated heat and bring the sensors at lower and lower temperature, such to extend service life and limit leakage current in the new high radiation environment of hadron experiments.

Corrado also mentioned that for the cooling microchannel substrate, the microfabrication processes, either based on silicon microfabrication or carbon composite microvascular approaches, will need to be fully exploited and new additive manufacturing technologies (3D printing) and materials will be investigated. At the same time the needs to reach temperatures below -40°C will go beyond the limit of the present cooling solutions; new coolants will have to be studied and tested. As a long term prospective, the use of more environmental friendly cooling fluid will drive the research like Hydro Fluoro Olefeins (HFOs) and Fuoroketons (FK) that are now progressively substituting in the industry Hydrofluorocarbon (HFC) and Perfluorocarbons (PFC).

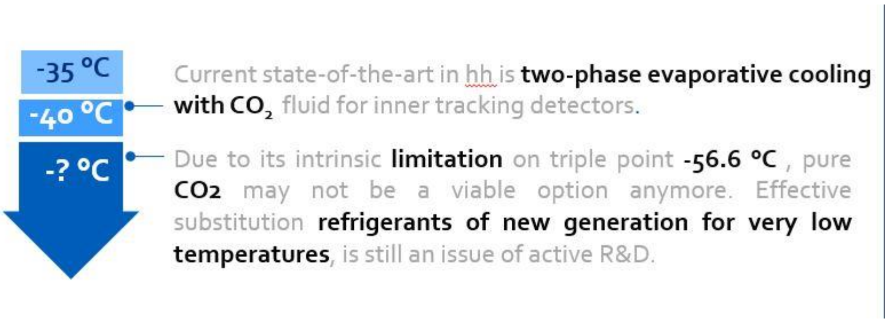


Figure 4: New detectors cooling requirements in high radiation environment will require the identification of new coolants and development of new system to reach lower temperatures.

Moreover, for covering large surfaces (e.g. the FCC-hh tracker length is 32 m to be compared to CMS/ATLAS length about 6 m) further research will push for cooling technologies that can be scaled to large areas without joints (heat pipes, passive thermal interface) which will provide reworkability and also increase the reliability of these systems. In general the minimization of the service connections, both hydraulic and electrical, and of the interfaces to the external world, should be pursued to minimize installation work. The risk of an increased integration should then be mitigated by automated assembly procedures and quality control.

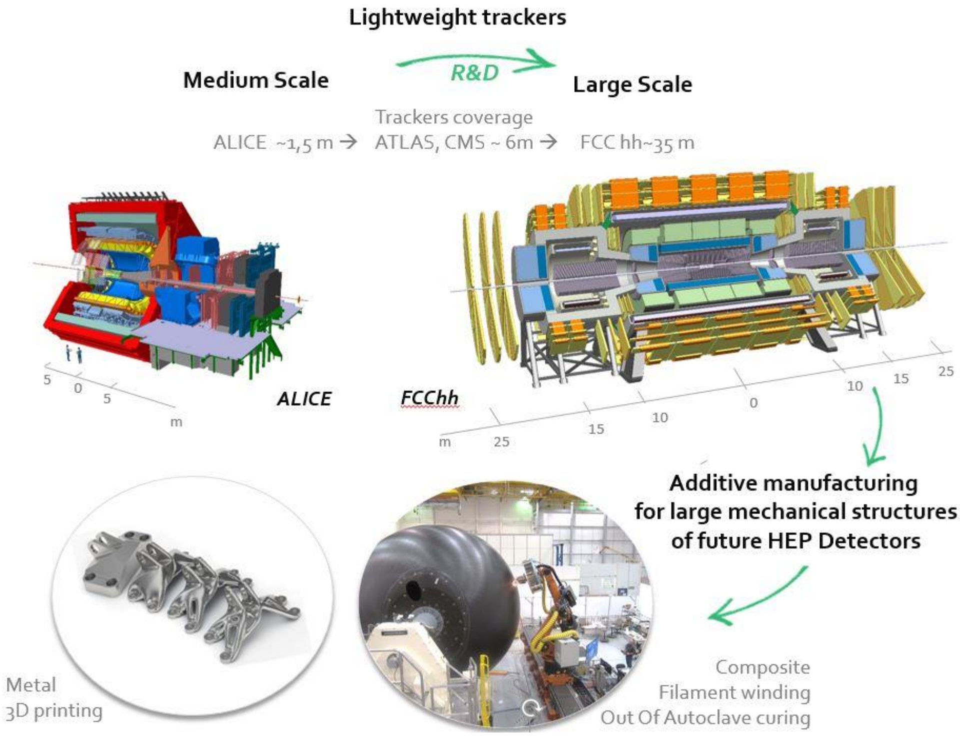


Figure 5: Large scale dimensions of future trackers will require more automated and cheap processes.

Finally, Corrado pointed out that beyond the challenges, for the mechanics and cooling, to guarantee the next generation tracker performances, the new radiation levels in the hadron experiments will affect the future operational scenarios with an impact on the design of the detectors in terms of remote access and maintenance.

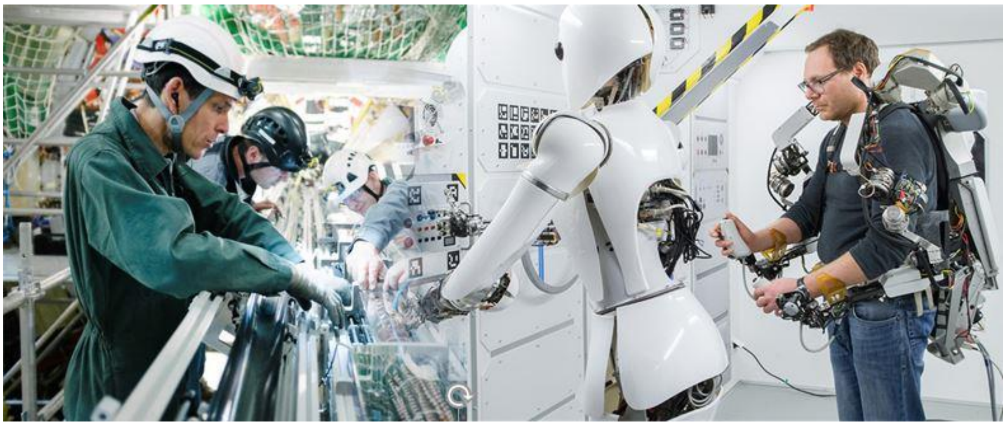


Figure 6: Designing Detectors that can be maintained by robots using appropriate and easily accessible interfaces such to decrease personnel exposures to hazards.

New detectors must be designed to be easily inspected and possibly maintained by robots so as to decrease personnel exposure to hazards. A completely new concept for detector connectivity, accesses and interfaces enabling use of automated systems/robots must be foreseen at the very first phase of detector design as it will influence the definition of the future experiment segmentation and layout.

INSIGHTS: A new network of statistics for HEP and beyond

Following the success of the AMVA4NewPhysics network, a new 4-year Innovative Training Network funded by the Horizon 2020 program of the European Commission will develop new statistical methods and boost the use of machine learning (ML) to solve some of the most challenging problems in particle physics and society. The ITN, named “INSIGHTS”, is led by Glen Cowan, a professor at Royal Holloway University London, a member of the ATLAS collaboration, and a long-time expert of statistics techniques for data analysis, whose textbook on the topic is highly appreciated by the high-energy physics community. But speaking of books, one could not forget to mention that two other PIs of the network (Prof. Luca Lista, Univ. Naples, and Dr. Olaf Behnke, DESY) also authored successful textbooks in statistics for data analysis! That should clarify that the network has a really high training potential in this area.

The unprecedented amount of data at the Exa-Byte scale to be collected by the CERN experiments during the HL-LHC phase will require novel approaches to train and use ML models. Furthermore, the energy-frontier colliders currently in the process of being designed put even higher challenges in designing new statistics tools that will allow to disentangle and identify new physics in the foreseen high levels of background. Indeed, advanced statistical methods have proven to be key elements of recent advances in the field. INSIGHTS will enable significant further progress with particular emphasis on multivariate analysis, parametric modelling and Bayesian computation. Yet the development of modern state-of-the art ML methods and techniques will naturally lend itself to be also applied to problems in unrelated areas of research, of interest of climate science, internet data mining, and a number of applications in industry, following the tradition of high-energy physics

INSIGHTS follows the thread dug by AMVA4NewPhysics in pursuing and extending the above goals. It brings together a network of 11 beneficiaries (Royal Holloway London, Univ. Oslo, Max Planck Institute Munich, NIKHEF, INFN, KPMG, Univ. Naples, Univ. Lund, CERN, Pangea Formazione, Univ. Edimburgh) plus several partners from research centres, universities and the industry. 12 early-stage researchers (ESR) will join the ATLAS and CMS collaborations, digging deep in the datasets recently acquired by the experiments, or work on the development of ML tools for non-HEP applications. The INSIGHTS network has the principal aim of providing them with advanced training in statistical methods and ML. Most of them will earn a Ph.D. in particle physics at the end of their 3-year involvement in the ITN; all will become highly-employable experts in data science.

More information on the INSIGHTS program is provided at the network web site,https://www.insights-itn.eu/ . From there, you may also get acquainted with the 12 ESRs and follow their blogging activities, which are just starting, following the steps of the 10 ESRs of AMVA4NewPhysics at https://amva4newphysics.wordpress.com.

HL-LHC computational challenge for ATLAS and CMS experiments

by Tommaso Boccali (INFN and CERN) Davide Costanzo (Sheffield U and CERN)

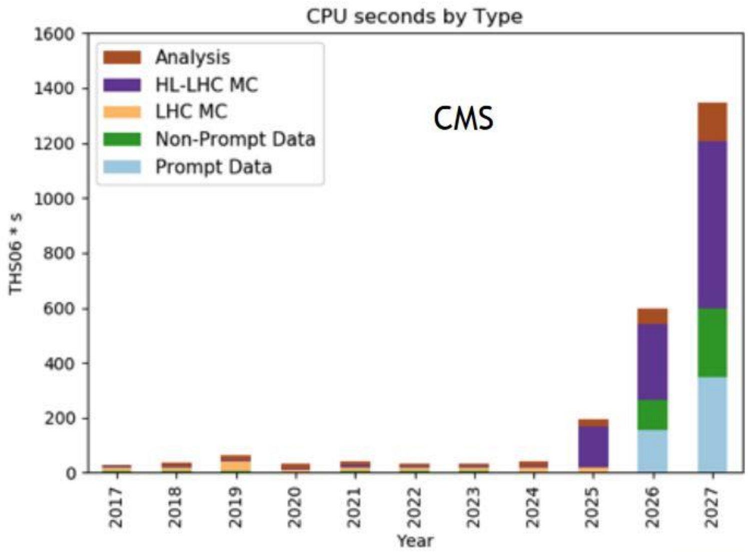
The two general purpose LHC Experiments, ATLAS [1] and CMS [2], are going to be confronted with challenging experimental conditions at the High Luminosity LHC Run (HL-LHC), starting in 2026. In particular, computing systems will have to cope with greatly increased data samples and data acquisition and processing rates.

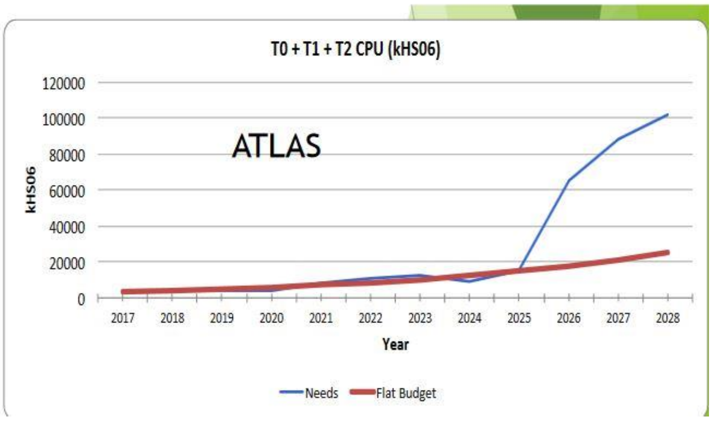
While the collision centre-of-mass energy of 14 TeV is not going to change with respect to the previous run, the instantaneous luminosities, and thus the event complexity at each bunch crossing, are going to increase substantially. For every bunch crossing, about 200 low-energy collisions are expected to accompany the hard process selected by the experiments’ trigger systems. This has to be compared with the Run-2 average number of 35 collisions.

The increased event complexity by ~6x (from 35 to 200) is not the only source of additional computing load. ATLAS and CMS will install by 2026 new detectors with extended performance, with increased channel count and in general more complex to reconstruct. On top of that, the two experiments are planning to expand the trigger rate from the current 1 kHz, possibly up to 10 kHz, meaning that every second up to 10,000 events can be written on to disk.

The need for computing resources generally scales differently with the resource type. Storage (disks, tapes) scale roughly linearly with event complexity and trigger rate; by the above estimates, 2027 needs should be roughly x5 (event complexity) to x10 (trigger rates) larger than for 2018. Processing needs scale more than linearly, due to the combinatorial behavior of most time-consuming algorithms like tracking and clustering; in the same conditions, CPU needs will scale as much as 100x with respect to 2018 needs.

Of course we expect that technology advancements in the fields of processors and storage will help closing the gap. Recent estimates [3], though, tell us that in the period 2018-2027 a maximum improvement of a factor 5 or 6 is expected. Back-of-the-envelope estimates say that the annual cost of computing for ATLAS and CMS could increase by a factor between 10 and 20 at the HL-LHC. Such an increase in funding is not feasible, hence the experiments have launched extensive R&D programmes in order to find solutions for a viable HL-LHC computing.





The differences between the two experiments estimates are mostly due different R&D paths but a common underlying message is that further R&D is needed to meet the challenges of HL-LHC.

Current directions include the utilization of GPGPUs, FPGAs and other state of the art computing technologies in order to lower the cost of processing, and optimized models and infrastructures for a cheaper storage solution.

The mainstream path towards a viable HL-LHC computing for ATLAS and CMS does not currently include options that could benefit from Quantum Computing / Quantum Technologies. Though the technology is promising in the long run, it seems too early to base our model on its availability at large scale.

There are at least two aspects in Quantum Technologies that can be relevant to HEP Experiments, in the medium-long time range: the utilization of Quantum Simulators and the so-called Quantum Supremacy for computing.

Simulators are quantum systems which, at least locally, reproduce the behavior of other quantum systems, in a controlled environment. Already now simple systems have been demonstrated[4], and it is not unrealistic to think that with theory and technological evolution, systems of interest for HEP like QED, QCD, or the full Standard Model can be deployed on a quantum system setup.

Quantum supremacy is the ability of quantum computers to surpass in performance any classical system; it is due to the exponential scaling of quantum systems with the number of qubits N, which at large N cannot be matched by any non-quantum system. It is largely theoretical at the moment, given the systems commercially available.

Following a workshop held at CERN on November 5th and 6th[5] it became clear that the technological and evolution the Quantum Computing is in an exponential phase. Today machines with tens of qubits are commercially available via Cloud interfaces. At the same time, user friendly programming toolkits have been made available to test Quantum Algorithms on real machines or software emulators; at least four of them were presented at the workshop. They are generally based on Python, and already integrated with the main Data Analysis frameworks used in High Energy Physics, like Numpy, TensorFlow and Scikit-learn. A typical class of problems considered ideal for Quantum computing is when in presence of combinatorial algorithms, like the reconstruction and identification of tracks and clusters; an example at the former has been given at the workshop.

Given the involvement of major players in the IT technology, like Google, IBM, D-wave, Intel, Microsoft and many more, it is not possible to exclude a major technological breakthrough on a shorter than expected time scale. The experiments are suggested to perform R&D activities on quantum technologies, in order to gain understanding and experience on such novel systems. This has already started in some cases, as the presentations at the workshop show, but the level of commitment needs to be increased and coordinated within the experiment managements.

In this phase, it is essential that researchers are guided and helped by experts in the field, and are able to access quantum machines and emulators via preferential paths. We therefore welcome the initiative CERN/OpenLab has started, and hope we will be able to contribute to a closer interaction between High Energy Physics and Quantum Computing research fields.

Further reading:

[1] https://atlas.cern/

[2] https://cms.cern/

[3] https://twiki.cern.ch/twiki/bin/view/Main/TechMarketPerf

[4] https://journals.aps.org/prx/abstract/10.1103/PhysRevX.6.011023

[5] https://indico.cern.ch/event/719844/timetable/