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The ALICE ITS upgrade: Pixels for quarks

by Panos Charitos

Introduction

ALICE, the heavy-ion dedicated experiment at the LHC, will soon have enhanced physics capabilities with a major upgrade of the detectors, data-taking and data-processing systems which will improve the precision of the extracted characteristics of the high density, high temperature phase of strongly interacting matter, the quark-gluon plasma (QGP), together with the exploration of new phenomena in Quantum Chromodynamics (QCD).

To perform precision measurements of the strongly interacting matter, ALICE will focus on rare probes – such as heavy flavour particles, quarkonium states, real and virtual photons, and low-mass di-leptons – as well as the study of jet quenching and exotic heavy nuclear states. Observing rare phenomena requires very large data samples, which is why ALICE is looking forward to the increased luminosity provided by the LHC in the coming years. The interaction rate of lead ions during the LHC Run 3 is foreseen to reach around 50 kHz, corresponding to an instantaneous luminosity of $6 \times 10^{27} \text{ cm}^{-2}\text{s}^{-1}$. This will enable ALICE to accumulate ten times more integrated luminosity (more than 10 nb^{-1}) and hundred times larger data sample (about 10^{11} collisions) than what has been obtained so far. In addition, the upgraded detector system will have a better efficiency for the detection of short-lived particles containing heavy flavour quarks, thanks to improved precision of the inner tracking system (ITS), a silicon tracker based on monolithic pixel sensors.

During the Long Shutdown 2 (LS2), several major upgrades are being installed in ALICE: a new inner tracking system (ITS) with a new high resolution, low-material-budget silicon tracker, which extends to the forward rapidities with the new muon forward tracker (MFT), an upgraded time projection chamber (TPC) with gas electron multiplier (GEM) detectors along with completely new faster readout, new readout electronics for the muon spectrometer, a new fast interaction trigger (FIT) detector, and an integrated online-offline (O^2) computing system to process and store the large data volume.

In this article we report on the upgrade of the ALICE Inner Tracking System (ITS): a major international R&D effort launched in 2011 that is scheduled to be installed in the ALICE cavern in June 2020.

The Upgraded ITS

The new ITS is an all-pixel silicon detector based on CMOS monolithic active pixel sensor (MAPS) covering the mid-rapidity ($|\eta| < 1.3$) region. In the MAPS technology both the sensor for charge collection and the readout circuit for digitization are hosted in the same piece of silicon instead of being bump-bonded together. The chip developed by ALICE is called ALPIDE, and uses a 180nm CMOS process provided by Tower Semiconductor. With this chip, the silicon material budget per layer is reduced by a factor of seven compared to the previous ITS. The ALPIDE chip is $15 \times 30 \text{ mm}^2$ in size containing more than half a million pixels

organized in 1024 columns and 512 rows. Its low power consumption (<40 mW/cm²) and excellent spatial resolution (~5 mm) are perfect for the inner tracker of ALICE.

The ITS consists of seven cylindrical layers of ALPIDE chips summing up a total area of 10 m² and 12.5 billion pixels. The pixel chips are installed on staves with radial distances ranging from 22 mm to 405 mm from the interaction point (IP). The beam pipe is also newly designed with a smaller radius of 18.6 mm, allowing the first detection layer to be placed closer to the IP at a radius of 22.4 mm compared to the presently 39 mm

The brand-new ITS detector will improve the impact parameter resolution by a factor of three in the transverse plane and by a factor of five along the beam axis. It will extend the tracking capabilities to much lower p_T , allowing ALICE to perform measurements of heavy-flavour hadrons with unprecedented precision and down to zero p_T . The new ITS will also enhance the readout capabilities, allowing data readout and recording at interaction rates in excess of 50 kHz, the expected Pb-Pb interaction rate at the LHC after Run 2. This increase in readout speed, together with the deployment of a new data acquisition system that will allow recording all collisions, translates to an increase by about two orders of magnitude in the collectible minimum-bias statistics compared to the present ALICE set-up.

The upgraded detector is the outcome of a well-coordinated global collaboration effort that brought together more than 30 institutes and research centres from 16 countries. Following an intense 5-year R&D programme, the successful prototyping and production of the different parts of the detector took place in 2017-2019 while the first components of the new ITS started arriving at CERN since summer 2018.

They are currently assembled and tested in Building 167 of CERN's Meyrin site, where the new ALICE ITS is taking shape, preparing for the final phase of installation and commissioning starting from mid 2020.

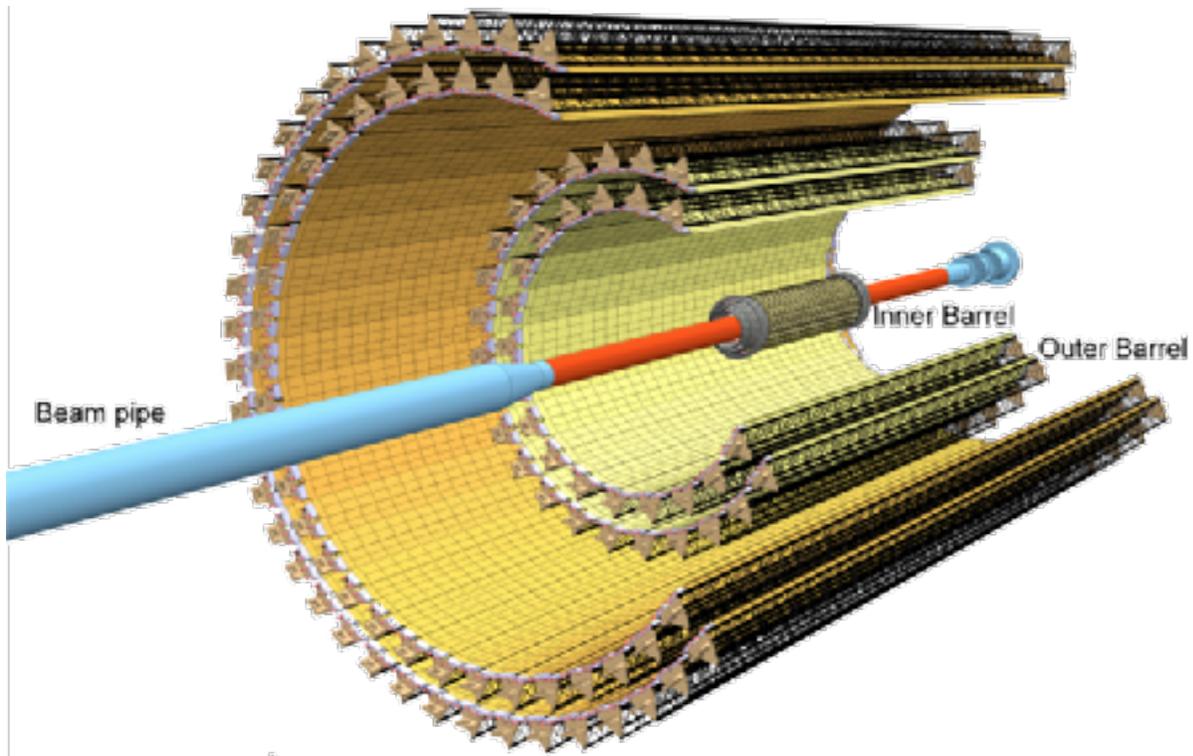


Figure 1. Picture showing the design of the new ALICE ITS and the different layers of the inner and outer barrel.

A new chip is born

The high level of vertexing and tracking performance expected from the upgraded ALICE inner tracking system (ITS) places tough demands on granularity and material thickness. To meet this challenge, ALICE has developed a new, dedicated monolithic active pixel sensor chip (MAPS), called ALPIDE, integrating both pixel sensor and read-out electronics in a single device.

This 15 x 30 mm² chip is the outcome of global collaboration. It is manufactured on a p-type substrate with a thin, high-resistivity epitaxial layer (see diagram) in a 180 nm CMOS process provided by Tower Semiconductor.

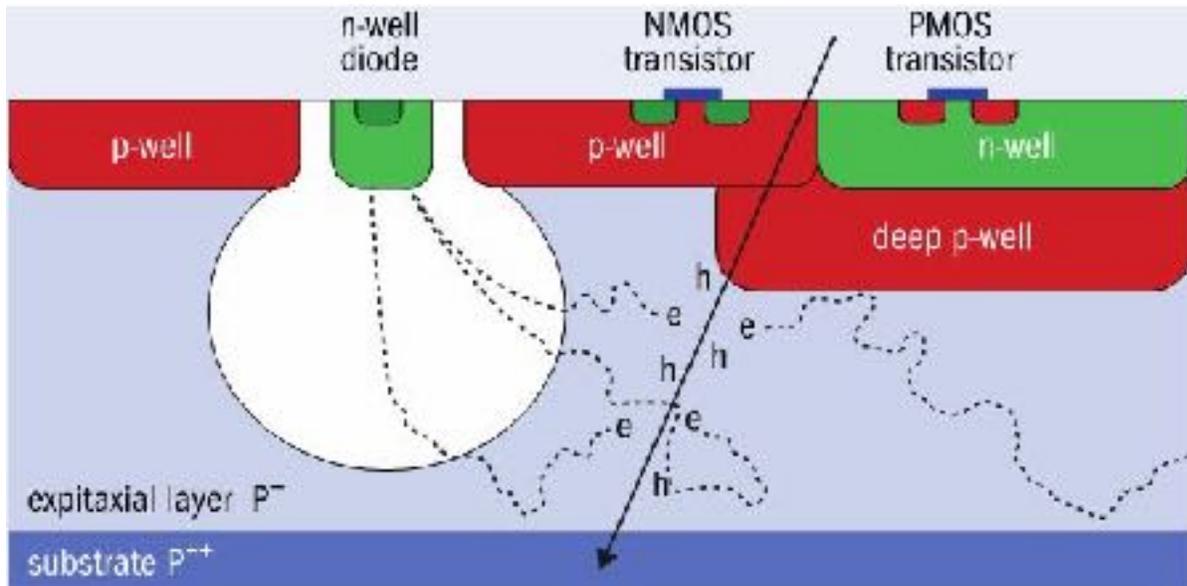


Figure 2. A schematic cross-section of CMOS pixel sensor used for the ALPIDE chip (ALICE ITS Upgrade TDR).

It includes a 512 x 1024 matrix of 29.24 x 26.88 mm² pixel cells, together with analogue biasing, control, readout and interfaces. The signal sensing element is a diode typically 100 times smaller than the pixel cell. A charged particle crossing the sensor liberates free charge-carriers in the material by ionisation. Electrons released in the epitaxial layers diffuse laterally while remaining vertically confined. When they reach the depletion volume of a sensing diode (or are released directly inside it), they are swept to the diode contact by the electric field in the depletion volume. Holes are collected by the substrate and p-wells. The diode current induced by the carrier motion in the epitaxial layer is read out by the pixel front-end. A deep p-well layer (a deep p-type implant) shields the n-wells (n-wells implants) containing PMOS transistors from the epitaxial layer and prevents them from collecting signal charge.

This allows full CMOS (NMOS and PMOS) circuits within the pixel matrix and made the ALPIDE the first CMOS MAPS chip with a sparse readout similar to hybrid pixel detectors. ALICE is currently the only LHC experiment employing MAPS technology, presenting for the first time such a large-scale application if it. This technology had previously been used by the STAR experiment at the Relativistic Heavy-Ion Collider at Brookhaven National Laboratory.

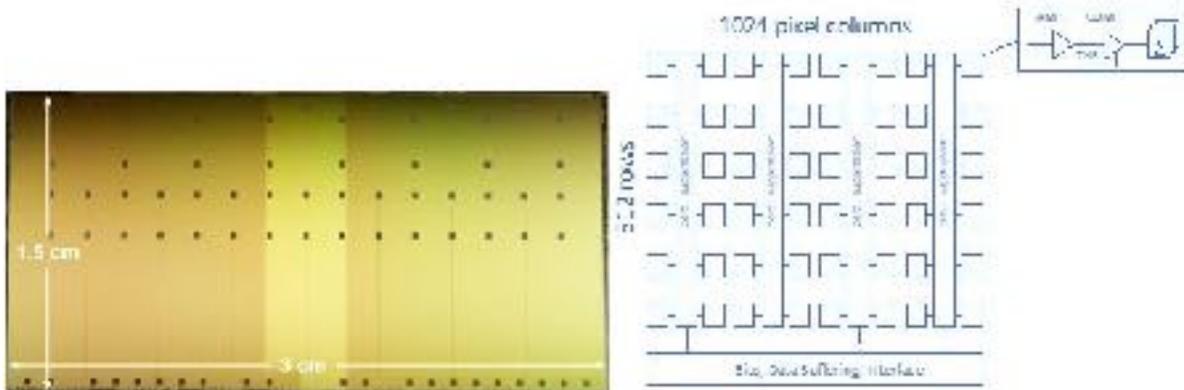


Figure 3. Picture (left) and readout architecture (right) of ALPIDE, the chip developed for the ALICE ITS upgrade.

The outstanding performance of the ALPIDE chip can be seen in the plots of Figure 4(a,b). It is the outcome of a series of prototypes used to optimize every aspect of the circuit and a continuous interplay of the chip design team and another international effort to thoroughly characterize and qualify the prototypes, eventually involving more than ten institutes around the globe and carrying out beam tests at several facilities including the CERN PS and SPS.

The design effort finished in 2016 and immediate production started allowing the timely assembly and testing of detector modules that has been completed in May 2019.

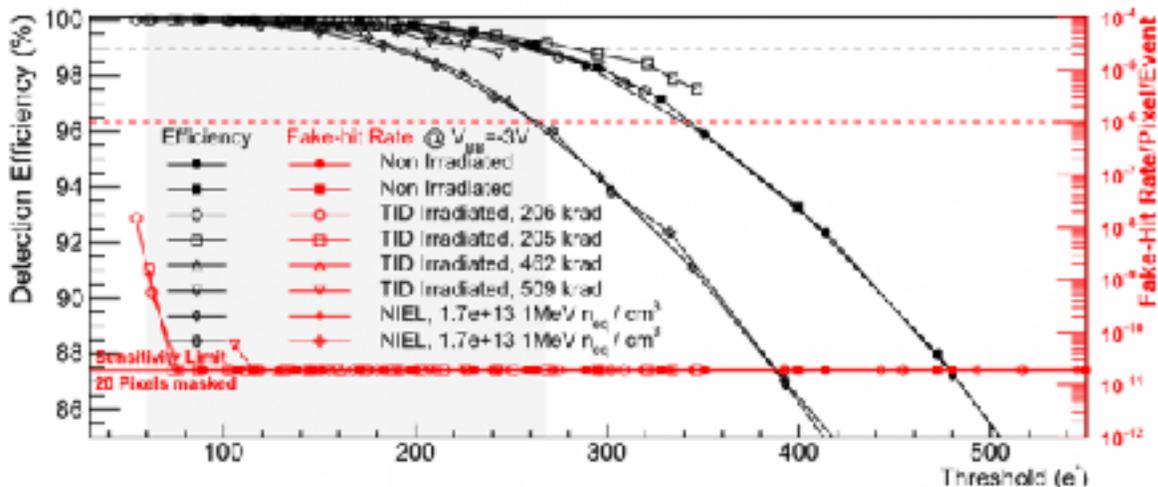


Figure 4a. The left axis shows the detection efficiency vs. threshold for several ALPIDE chips, irradiated and non-irradiated. On the right axis, the fake-hit rate is reported. Dotted lines represent the design requirements: detection efficiency larger than 99% and a fake-hit rate below 10^{-6} (/pixel/event). It can be seen that the new chip offers a very large operational margin with only 10 masked pixels (of the total of 5×10^5 pixels). The high efficiency of 99% is

retained even for a much lower fake-hit rate, compared to the design requirements, down to values of 10^{-11} (/pixel/event). The new ALPIDE chip offers very high operational margins even when the detector is radiated ten times higher compared to what is expected in the ALICE environment during the next runs of the LHC. (Nucl. Phys. A967 (2017) pp. 900-903).

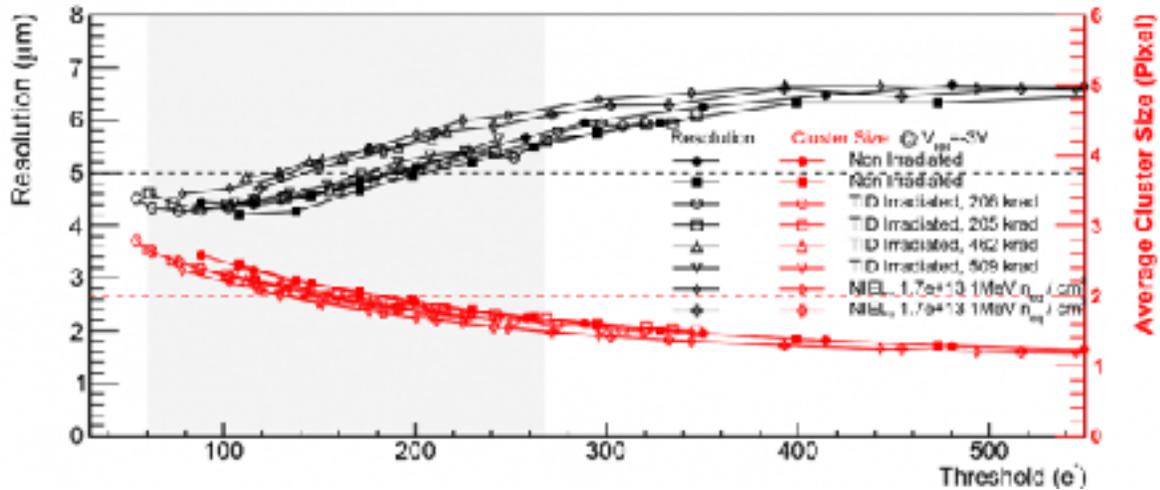


Figure 4b. The left axis shows the intrinsic spatial resolution vs. threshold for several ALPIDE chips, irradiated and non-irradiated. The right axis shows the cluster size. The plot clearly shown that a large set of operational values (and thresholds) ALPIDE offers a spatial resolution of about $5\mu\text{m}$ (Nucl. Phys. A967 (2017) pp. 900-903).

A marvel of micro-engineering

Upgrading the ITS posed a challenge for mechanical engineering. The structural support for the ALPIDE sensors should embed the cooling for the sensors, and at the same time minimize the material budget to ensure high performance. For that purpose, a new original design has been developed for the ITS stave, based on a record ultralight carbon structure with embedded micro-polyimide pipes for water-cooling at sub atmospheric pressure.

The structure is based on a thin plate, the so-called Cold Plate, obtained by an optimised lay-up of different high thermal conductive carbon plies, on which the ALPIDE sensors are glued. The Cold Plate incorporates a polyimide pipe, running along the entire stave length and back. This design enables getting the coolant inlet and outlet, at the same side of the detector that thanks to the design remains accessible.

The heat, dissipated by the ALPIDE sensors, is conducted into the cooling pipes via the carbon plate and is finally removed by the water flowing in the pipes. The polyimide pipes have been produced with very small diameters, down to 1mm, and a minimum wall thickness of $25\mu\text{m}$ for the three innermost layers.

To ensure mechanical stability the Cold Plate is stiffened by the Space Frame, a light filament wound carbon structure with a triangular cross section. This concept applies both in the staves of the three innermost layers of the Inner Barrel (IB), 290 mm in length, and the staves of the four outer layers in the Outer Barrel (OB), up to 1475 mm. The implementation of each layer is tailored based on the different geometrical and thermal constraints. Thanks to these choices, an unprecedented light weight of 1,7 gram has been achieved for the IB stave structure including the cooling pipes.

The optimization of such a non-standard production process, for so lightweight composite structures, entailed an extensive prototyping phase through which the carbon plies lay-up and co-curing process with the polyimide pipes were tuned. The final design has passed the full cycle of thermal and structural qualifications and mass production (> 300 parts) was concluded in 2018.

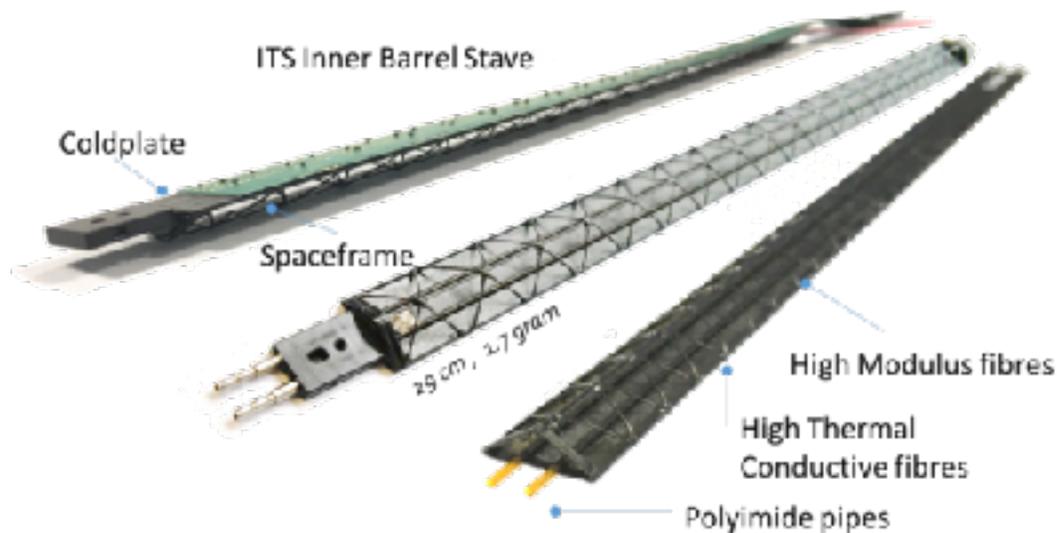


Figure 5: Inner Barrel Stave fully assembled with IB module glued on the mechanical support. The support is constituted by a high thermal conductive carbon Cold Plate with embedded polyimide cooling pipes stiffened by a carbon filament wound Spaceframe.

The staves of the Inner Barrel (IB) with a length of 290 mm are made of one module consisting of nine ALPIDE chips (see Fig.6).

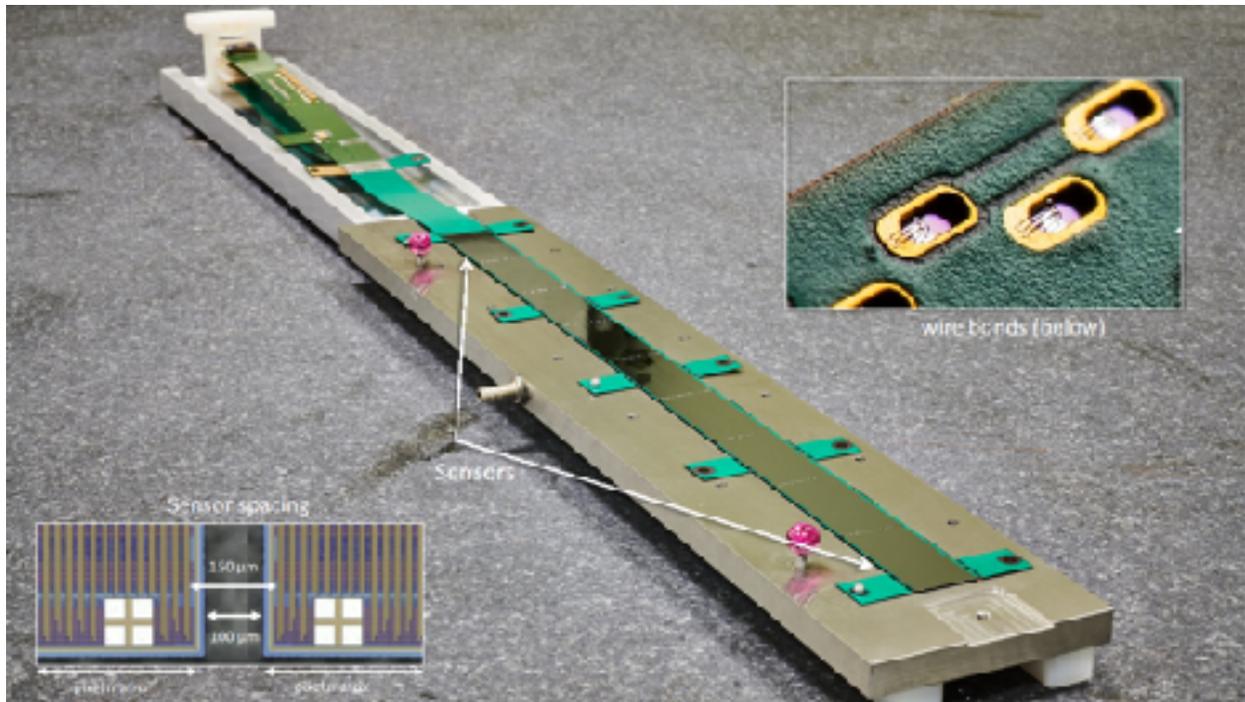


Fig 6. Photograph of an Inner Layer Module. Insets show the spacing between adjacent chips and the interconnection to the flex printed circuit board via wire bonds. (Credits: ALICE collaboration).

The OB is divided into the two middle layers and the two outer layers sharing the same design but having different length, 843 mm and 1475 mm respectively. The half-stave at the middle of the OB consist of four modules whereas the outer layer of seven.

The staves are assembled in half layers and inserted in structural barrel shells, as shown in Figure 7 for the Inner Barrel and Figures 8a and 8b for the Outer Barrel. Three Half layers will make one half of the Inner Barrel, while four half-layers will make half of the Outer Barrel.

The Design of the ITS Barrels and global mechanics was further challenged by the new detector layout, with the services connected only at one side, and by a new installation requirement, that would allow for a immediate access to the ITS during the yearly LHC winter shutdown. This requirement excludes the possibility of displacing or dismounting the surrounding detectors.

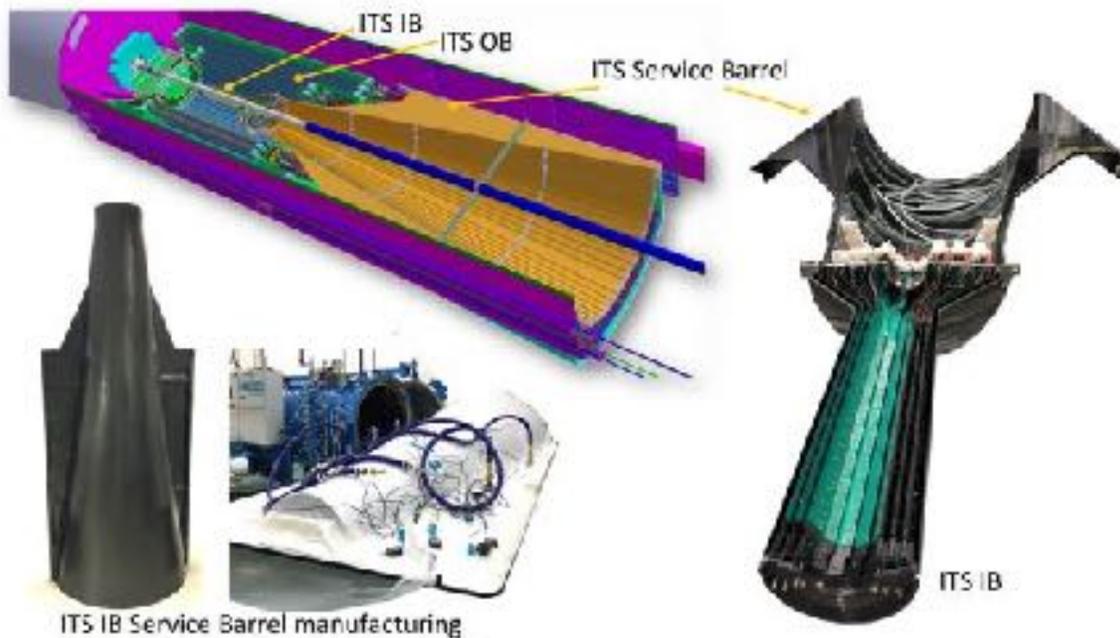


Figure 7: The three Half-Layers of the Inner Barrel are constituted by the assembly of 24 stave. The Inner Barrel keeps in position the three innermost layers of the new ITS at two millimetres from the beam pipe. The Barrels ultralight composite structure, produced at CERN, fulfil the requirement of the new ITS in term of detector layout stability and accessibility.

A new installation strategy allows for the translation of the ITS detector, in halves, by approximately 3 m along the beam pipe. During the translation, the two ITS halves progressively approaches the final position with the innermost layer at a radial distance of only 2 mm from the fragile beryllium pipe of the LHC.

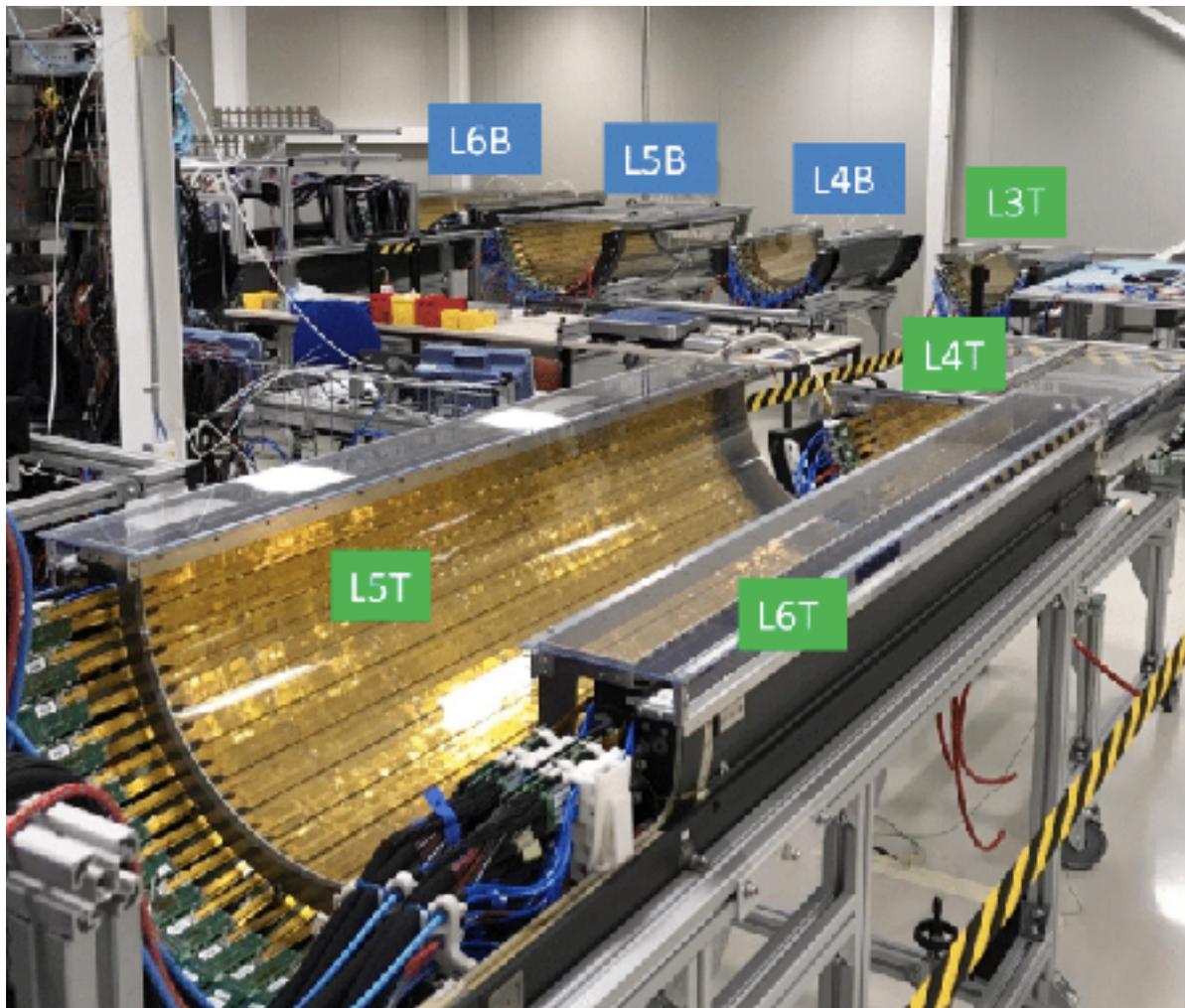


Figure 8a. Photo taken at the ITS assembly hall in Building 167 at CERN. Layers 5 and 6 for the top-half of the ITS Outer Barrel (L5T and L6T) have been assembled while Layers 4 and 3 are lining up for installation (L3T, L4T). Once assembled they will be mounted to build the full top-half barrel over the coming weeks. Moreover, in the background one can see Layers 4B, Layers 5B and Layers 4B ready for the assembly of the bottom half of the ITS outer barrel that is scheduled for October 2019.

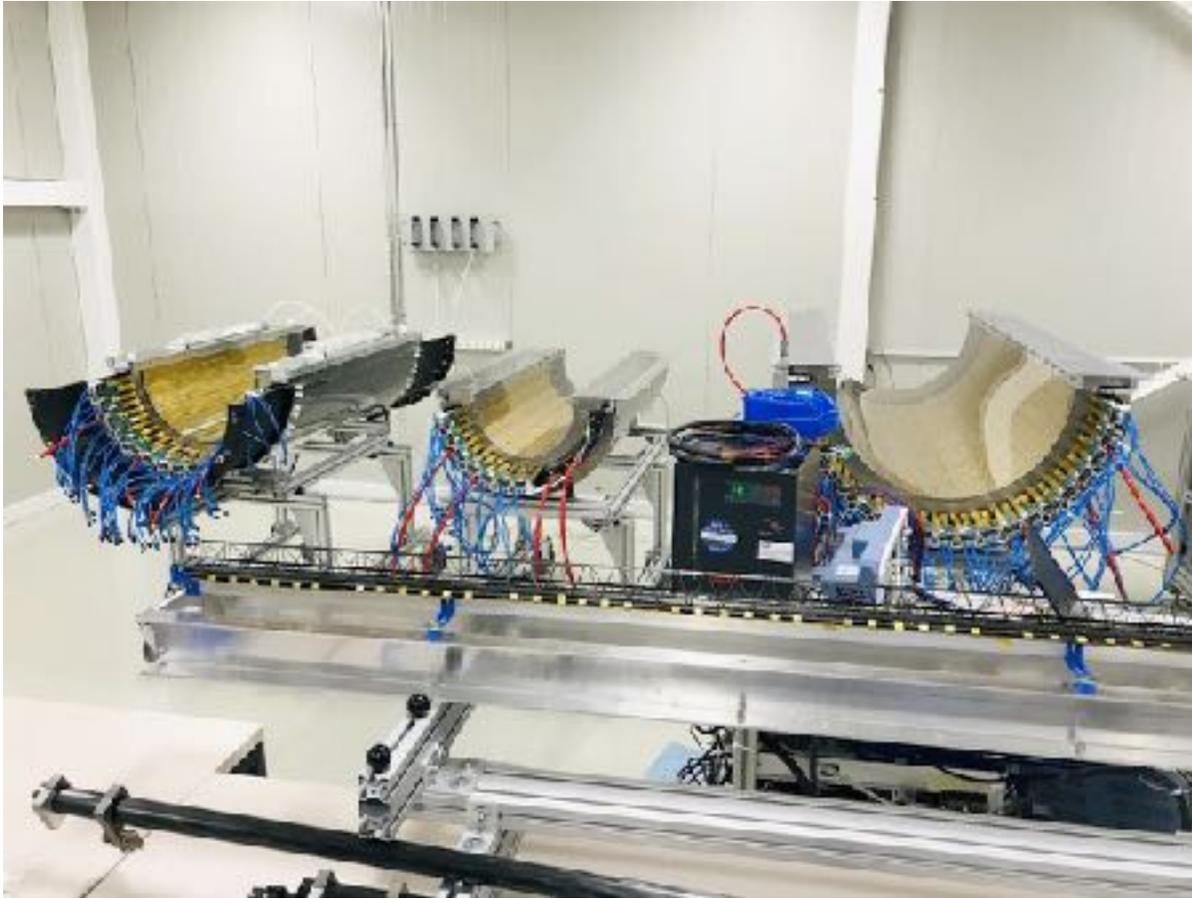


Figure 8b. The photo shows Layers 4, 3 and 5 (from right to left) that together with Layer 6 will form the half Outer Barrel of the new ITS. The different modules arrived at CERN from labs around the world – signaling a strong international effort – and are currently being assembled.

Current status

The construction of all mechanical structures was completed last year. The first fully equipped inner barrel staves were produced in 2017 and tested at realistic operational conditions in heavy-ion collisions at CERN's SPS while the stave production is expected to be completed later this September 2019. All the other main detector components (readout electronics, power distribution system, trigger, data acquisition, detector control) and services (power supplies, cooling plant) have been also produced and successfully tested.

The early availability of all services and detector components allowed to start the commissioning of the individual half-layers before they are assembled to form the two detector half-barrels (Inner and Outer) as shown in the above images. The results confirm the validity of the selected approach and the value of focused R&D on detector development.

Since last May, the collaboration has started testing the different detector components with cosmic rays simulating as close as possible the conditions of a real experiment. In a specially arranged area in Building 167 (CERN Meyrin site) teams of shifters control the various parameters of the detector and gather data that will help with the final optimization before the installation in the ALICE cavern. This activity has motivated the whole ITS collaboration to take part in this pre-commissioning phase. Owing to their strong support, plenty of test results have already been obtained that help us to understand and optimize the operational parameters of each subsystem and of the overall ITS performance. Moreover, these results allow to carefully check for any remaining issues that should be tackled before the final installation in the ALICE cavern next year.

Extremely low thermal noise vales of $<6e$ have been verified on the detector, and, together with a threshold dispersion of $\sim 20e$, allow for operation at signal-to-noise ratios of 10 and above while staying $\gg 99\%$ efficient. These performance figures of the detector, going well beyond the original design requirements, can be exemplarily seen in Figure 9 below, showing the extremely low fake-hit rate of Half-Layer 0, which drops to below 10^{-10} (/pixel/event) after masking only 42 out of the 28 million pixels; a remarkable result.

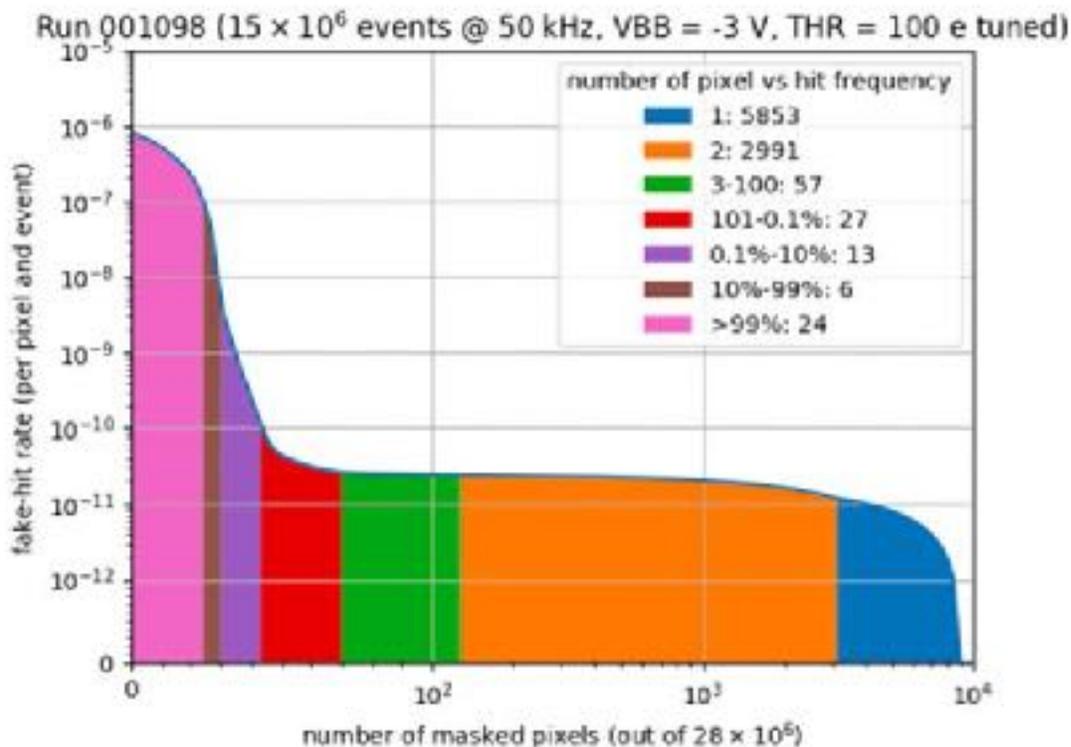


Figure 9. Fake-hit rate measured on the six staves making the Half-Layer 0. It is plotted versus the number of pixels that are masked and shows that a very small fraction of pixels is responsible for most fake hits. Different colours correspond to pixels that fire with a given

frequency. Masking of 42 pixels already lowers the fake-hit rate from 10^{-6} to 10^{-10} (/pixel/event). Pixels that fire only a few times can be partially attributed to cosmics. Note that the first division of each axis is linear, while the others are logarithmic.

The results confirm the soundness of the adopted technology, in terms of performance but also of reliability since the performance remained very stable over time.

In the past months, the team performed noise studies of the different detector elements, and also tested them using radioactive sources such as Sr-90. This method, that produces a radiography of the assembly, allows to quickly assess the correct functioning of the detector. These images contain a wealth of qualitative information, e.g. revealing the capacitors and overlapping areas of staves of the Inner Barrel (see Figure 10).

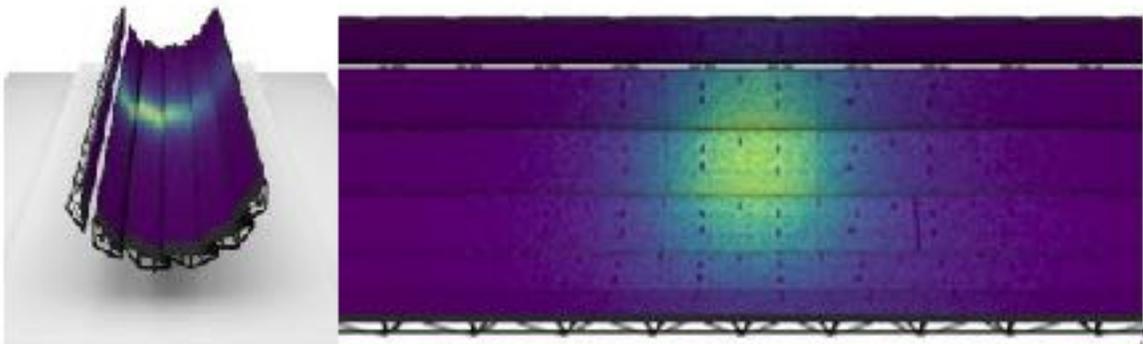


Figure 10. A Sr-90 hit map image taken with the half-layer 0 of the new ALICE ITS, projected onto the position of the chips in 3D.

Owing the overlaps of the ITS geometry, already a single half-layer has a small but non-negligible cross-section for tracks to cross three sensors and hence produce a track with three points. With this observation, the team has been collecting a large sample of cosmic particle tracks since the first half-layer has been connected to the readout at a rate of one cosmic track per minute (Figure 11 shows ~1400 of them). This data is used to verify the time alignment in readout and reconstruction of events, to verify the geometrical position of the staves, and will successively (including more detector layers) serve for the ultra-precise spatial alignment needed between the different layers of the new ITS.

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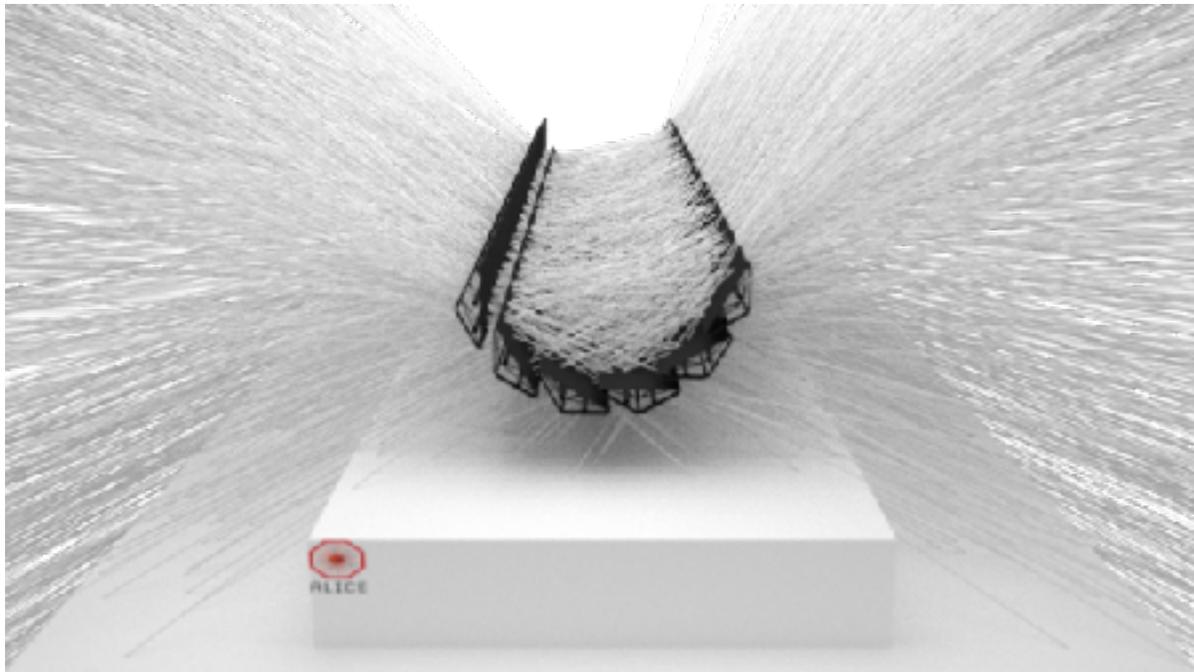


Figure 11. 3D view of the first ~1400 cosmics taken. The pictures clearly show the effect of a non-uniform (esp. angular) acceptance due to the requirement of three points on a track, while using only one detection layer.

Conclusion

Thanks to a well-structured R&D programme that attracted international collaborations and an intense period of testing and commissioning the ALICE ITS is taking shape in Building 167. The new detector is part of the upgraded ALICE which during the next runs of the LHC will provide new set of more precise measurements to meet the long-term goals of the ALICE collaboration in the study of QCD and the characterization of the Quark-Gluon Plasma.

The upgrade of the ALICE ITS will not only boost the physics capabilities of the ALICE experiment but as we discussed has advanced a number of technologies beyond the state of the art. The results of this R&D effort currently find applications both in high-energy physics (i.e. sPHENIX at RHIC, BNL and the Inner Tracking System of the MPD experiment in NICA at JINR) but also in other fields. Perhaps one of the most topical examples is medical tracking with the development of pCT detectors for application in hadron therapy. The fast monolithic pixels developed for the ITS upgrade can improve significantly the accuracy of the image with regard to the present state of the art while reducing the exposure time for patients.

An enormous amount of effort has gone into the new ITS over the past years, strengthening collaboration between CERN and institutes from around the world. The fruits of those labours can now be seen while the final installation of the detector in summer 2020 will pave the way for new discoveries that could open up a whole new field of knowledge.

NA62 experiment presents new results

NA62

SME

kaon decays

by Cristina Lazzeroni (NA62 Spokesperson, University of Birmingham)

The NA62 experiment presented the latest result on the search for the ultra-rare kaon decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ using 2017 data at the KAON2019 Conference, at the Physics in Collision Conference and during a recent CERN's EP Seminar

Kaons, the lightest elementary particles containing the strange quark, have always been a copious source of information on the fundamental interactions. Kaons played a key role in establishing the foundation of the Standard Model (SM), and kaons fixed-target experiments (NA31, NA48) at the CERN Super Proton Synchrotron (SPS) recorded the first evidence and then precisely measured direct charge-parity violation, the process ultimately responsible for the matter-antimatter asymmetry in the Universe.

Despite all its phenomenological successes, the Standard Model has some deep unsolved problems: for example, it offers no explanation for the mass hierarchy between the three fermion generations; it cannot predict the origin of matter-antimatter imbalance, nor the nature of dark matter. Extensions of the SM predict the existence of new particles or interactions, referred to as “new physics”. New physics at high-mass scales can reveal itself in dynamic effects at lower, accessible, energy like higher-order processes. When this happens, deviations from the SM predictions are observed. Higher-order processes are naturally suppressed in the SM, making them rare.

Flavour Changing Neutral Current transitions, such as $K^+ \rightarrow \pi^+ \nu \bar{\nu}$, are forbidden in the SM at the lower level (called tree level) and are sensitive to the presence of new virtual massive particles entering through higher order corrections to the leading order amplitudes, or via tree level processes mediated by new heavy gauge bosons [M. Blanke et al., EPJ C 76 (2016) no.4 182.]. They are therefore sensitive to energy scales much higher than those explored by LHC via direct searches. A precise measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio would constrain a variety of New Physics models, for example it is sensitive to lepto-quark models [G. Isidori et al., EPJ C 77 (2017) 618.], i.e. models where new particles are expected that carry both lepton and baryon quantum numbers.

A precise measurement of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay is the main goal of the NA62 experiment. This decay provides an outstanding means to search for new physics, since it is highly suppressed with a probability to occur of only about 8 out of 10^{11} kaon decays, while at the same time being precisely predicted in the Standard Model with a theory uncertainty of about 10% [A. J. Buras et al., JHEP 1411 (2014) 121.]. Because it is so precisely predicted in the SM, any small deviation from such predictions can be used to effectively confirm or constrain new physics models.

The experiment is located in CERN's North Area in the Prevezin site. The 400 GeV proton beam from the SPS impinges on a fixed beryllium target, producing a beam of hadrons. A system of collimators, magnets, and absorbers selects a monochromatic 75 GeV beam of positive particles, 6% of which are kaons. The signature of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal is simply one incoming kaon decaying to a single-detected charged-pion track. A series of subdetectors (Figure 1) provide measurements of particle momentum, energy, and identification, and veto extra activity [JINST 12 P05025 2017]. Useful K^+ decays are detected in a 65 m long decay region.

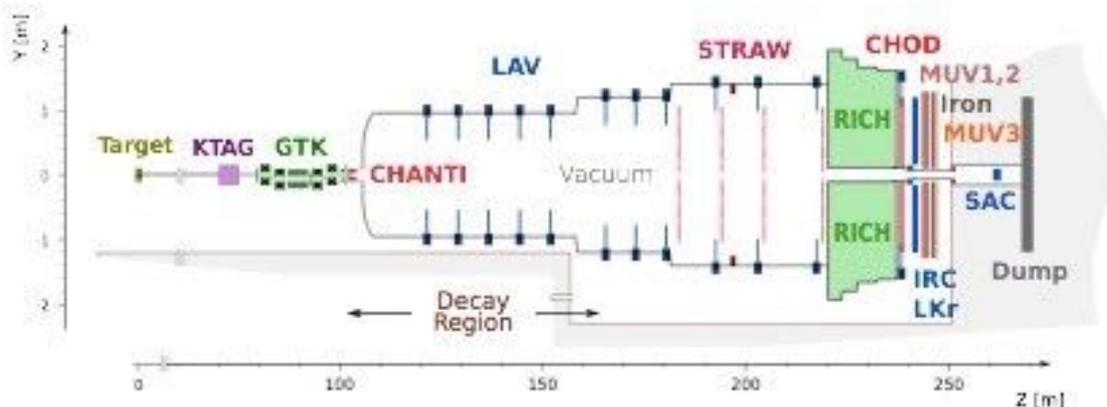


Figure 1: Schematic vertical section through the NA62 experimental setup. The main elements for the detection of the K^+ decay products are located along a 150 m long region starting 121 m downstream of the kaon production target. Useful K^+ decays are detected in a 65 m long decay region. Most detectors have an approximately cylindrical shape around the beam axis. An evacuated passage surrounding the beam trajectory allows the intense (750 MHz) flux of un-decayed beam particles to pass through without interacting with detector material before reaching the dump.

Both the incoming kaon and its decay products are measured, allowing for the signal event reconstruction and for identifying and rejecting all the other kaon decays, which is a very challenging task considering how rare the signal is. Kinematic rejection of the most abundant kaon decay modes is obtained by selecting two restricted regions (Region I and Region II, as shown in Figure 2) of the m^2_{miss} distribution defined as $(P_K - P_\pi)^2$ where P_K is the 4-

momentum of the parent particle, assumed to be a kaon and P_π is the 4-momentum of the decay particle, assumed to be a pion.

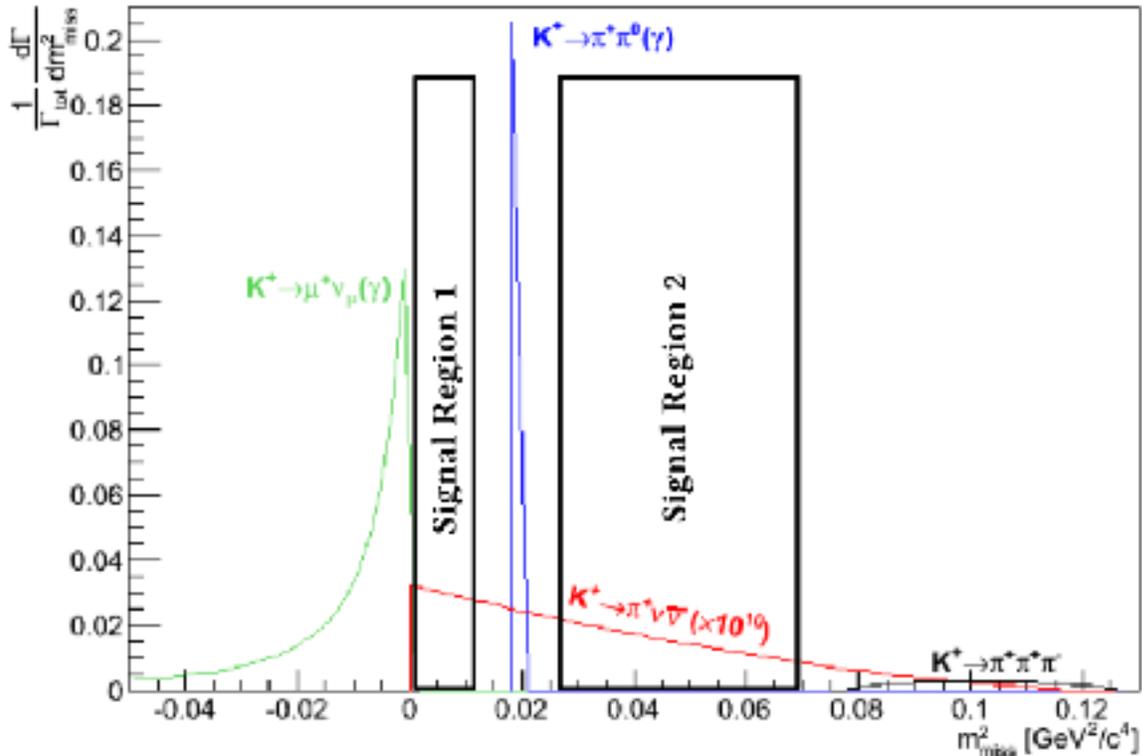


Figure 2: Distribution of missing mass squared for the signal (enhanced) and most abundant kaon decays. The two signal regions are clearly indicated as Region 1 and Region 2.

The experiment took data during 2016-2018 at increasing beam intensity. The result published last year on the 2016 data set established the experimental technique and set the first limit on the branching ratio of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ from NA62 [Phys. Lett. B 791, 156 (2019)]. The new result on 2017 data is obtained with a sample of about $2 \cdot 10^{12}$ K^+ decays. The Single Event Sensitivity (SES) is defined as the ratio of the SM $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ branching ratio over the number of expected $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ events. The SES for 2017 is 10 times better than for 2016 data and gives about 2 Standard Model events expected.

A great effort has been put in evaluating the expected background to the measurement, i.e. in identifying and quantifying the spurious events that, despite all the measures described above, might still leak into the signal region. Both data and simulation were used to this purpose. The analysis is performed “blindly”: the signal region is kept masked until the number of signal events and most importantly the number of background events are precisely evaluated, and checked using regions where the signal is negligible (so-called control regions).

The 2017 analysis included extensive checks on a variety of control regions where different types of background are enhanced, inverting or releasing specific selection criteria. Finally the expected background in the signal regions is calculated. The background sources can be divided into two categories: events due to common kaon decays happening in the decay region and escaping detection (source 1), and those due to decay happening before the decay region or due to beam particle interactions in the material and mimicking the signal (source 2). With the analysis techniques used for the 2017 data, source 1 amounts to about 0.6 events and source 2 to 0.9 events, for a total of 1.5 background events expected. At this stage in the analysis, the blind box was opened and the result revealed 2 events in Region 2 and zero events in Region 1 (Figure 3).

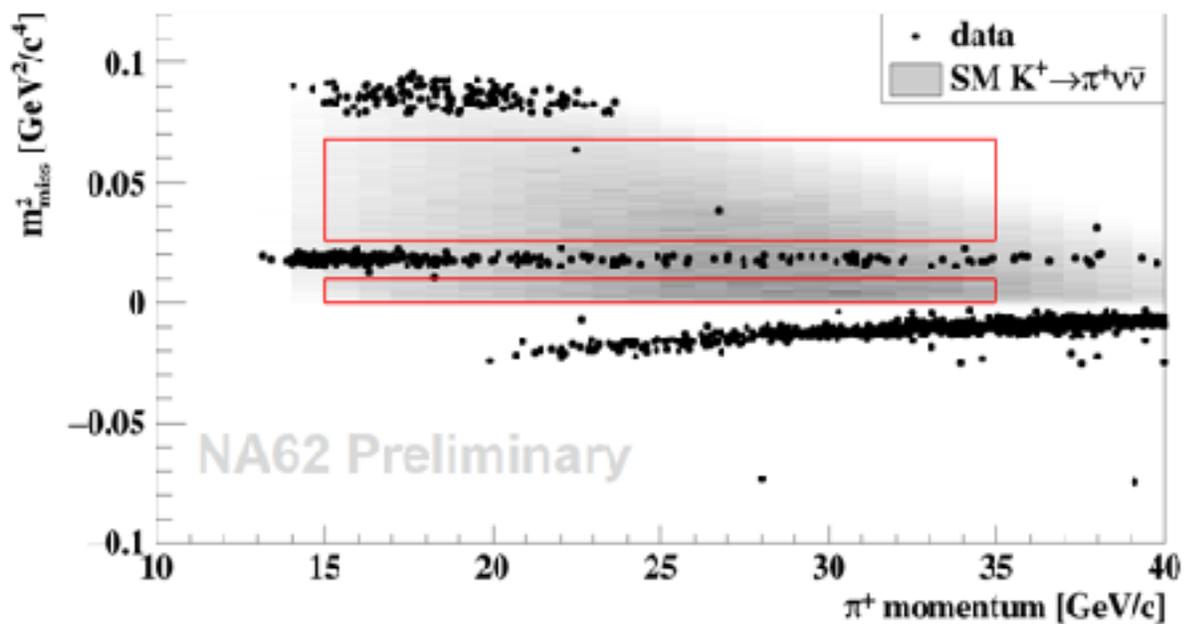


Figure 3: Distribution of missing mass squared versus pion momentum for 2017 data. The red boxes indicate the signal regions. There are two events in Region 2.

The 2017 result can be combined with the 2016 result since the analysis has been done in a totally compatible manner. The combined 2016 and 2017 result can be seen in Figure 4 as two-sided 68% band. The figure highlights the evolution of the theoretical predictions as well as the experimental measurements [Phys. Rev. D 77, 052003 (2008), Phys. Rev. D 79, 092004 (2009) for E787/E949 experiment; paper in preparation and KAON2019 Proceedings for NA62 experiment]. The observed Upper Limit at 90% confidence level is $1.85 \cdot 10^{-10}$. The result achieves a higher precision than the previous measurement, is consistent with the Standard Model and constrains already New Physics models predicting the largest enhancements. This great achievement is the result of the team effort of all the collaborating institutes, and the continuous support of CERN as hosting institution and of the financial agencies.

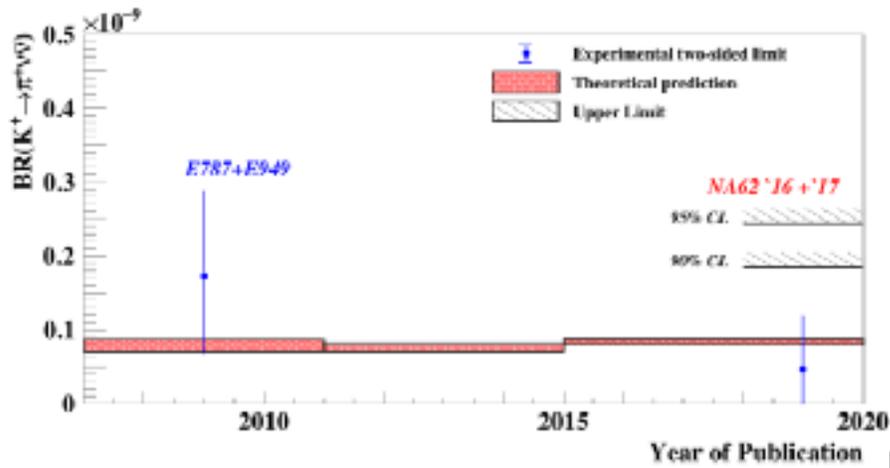
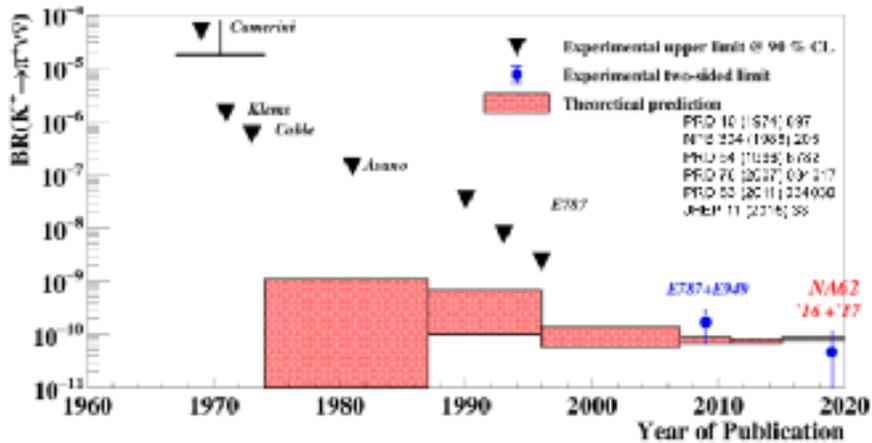


Figure 4: Historical evolution of the prediction and measurement of the branching ratio of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$.

The analysis of 2018 data, containing a sample twice as large as 2017, is in progress and the result is expected for next year. Ways to improve the signal acceptance and reduce the effect of accidental activity in the detector will be explored, as well as the use of the background shape versus the signal shape for kinematic variables.

The experiment is about to submit a beam request to CERN for data taking after the Long Shutdown 2, to complete its physics programme. There are plans to rearrange the beam setup in the GTK and achromat region to strongly suppress the background from source 2, and to take data at higher beam intensity.

LHCf sheds light on hadronic interaction models

by L. Bonechi (INFN Florence) and H. Menjo (Nagoya University)

The experience of the small LHCf collaboration, matured within the cosmic ray physics community, began in 2004 with the idea of designing a very thin detector to be installed along the LHC beam line, in such a way to cover the so called “very forward region” of the collisions. The basic purpose of such an experiment was to catch the very high energy debris emitted during collisions at small angles with respect to the interaction line, which are impossible to be measured using the large detectors surrounding the LHC interaction points. The measurement of the energy and angular spectra of these particles is an important ingredient required to enable calibrating hadronic interaction models, which are widely used for the description of the development of the so called Extensive Air Showers (EAS), particle cascades produced by extremely energetic cosmic-ray (CR) particles interacting with the atmospheric gas.

Since the first beams were circulated in the LHC ring in 2009, the LHCf apparatus, composed of two independent sampling electromagnetic calorimeters with transverse shaping capability, has been installed several times with different collision schemes, both with protons and heavy ions and at different collision energy. The two detectors were designed to measure neutral particles, mainly single photons, neutrons or neutral pions, produced at very high pseudo-rapidity $\eta > 8.4$ in p+p collisions at an energy of 14 TeV, in the centre of mass frame and in p+A collisions. Due to the characteristics of the collisions of cosmic rays happening in the Earth atmosphere, the study of the only p+p system at a single collision energy is not enough to describe completely the real processes going on at the beginning of an EAS development. In fact, the first interactions involve mainly more complex atomic nuclei, like oxygen and nitrogen. The dynamic of p+A collisions can differ in many important aspects with respect to the more simple case of p+p interactions.

A significant reduction in the cross section in proton and heavy-ion collisions with respect to p+p collisions, due to nuclear screening effects, has been found in previous measurements performed at smaller values of pseudo-rapidity and lower energy than available at the LHC; this reduction has been confirmed by LHCf itself by comparing p+p with p+Pb interactions at the LHC energy.

The measurements carried out so far by the LHCf experiment concern p+p collisions at $\sqrt{s} = 0.9, 2.76, 7$ and 13 TeV and p+Pb collisions at $\sqrt{s_{NN}} = 5$ TeV and 8 TeV. One of the LHCf detectors was then delivered and installed also at the RHIC accelerator for a further measurement to an even lower energy, performed during p+p collisions at $\sqrt{s} = 0.5$ TeV. From the point of view of cosmic rays, the energy carried by such colliding systems is equivalent to the energy of a system consisting of a proton with energy ranging from approximately 10^{14}

eV to almost 10^{17} eV, interacting with a nucleus at rest. In this way, the measurement carried out at the LHC allow covering a wide range of the cosmic ray energy spectrum, which is significant for the description of the highest energy cosmic-rays interactions with the atmosphere.

The many measurement campaigns carried out by the LHCf collaboration allowed presenting to the cosmic ray community and to the developers of hadronic interaction models many results of great interest, which represent a unique opportunity worldwide. LHCf is in fact the only existing experiment measuring particles with high energy and spatial resolutions at such high values of pseudo-rapidity and collision energy. These results allowed already a comparison of predictions by different hadronic interaction models in regions of the phase space where large discrepancies among the models still exist. Figure.1 shows as an example a comparison with model predictions of the photon and neutron energy spectra measured in different angular regions around the collision line for p+p collisions at $\sqrt{s} = 13$ TeV.

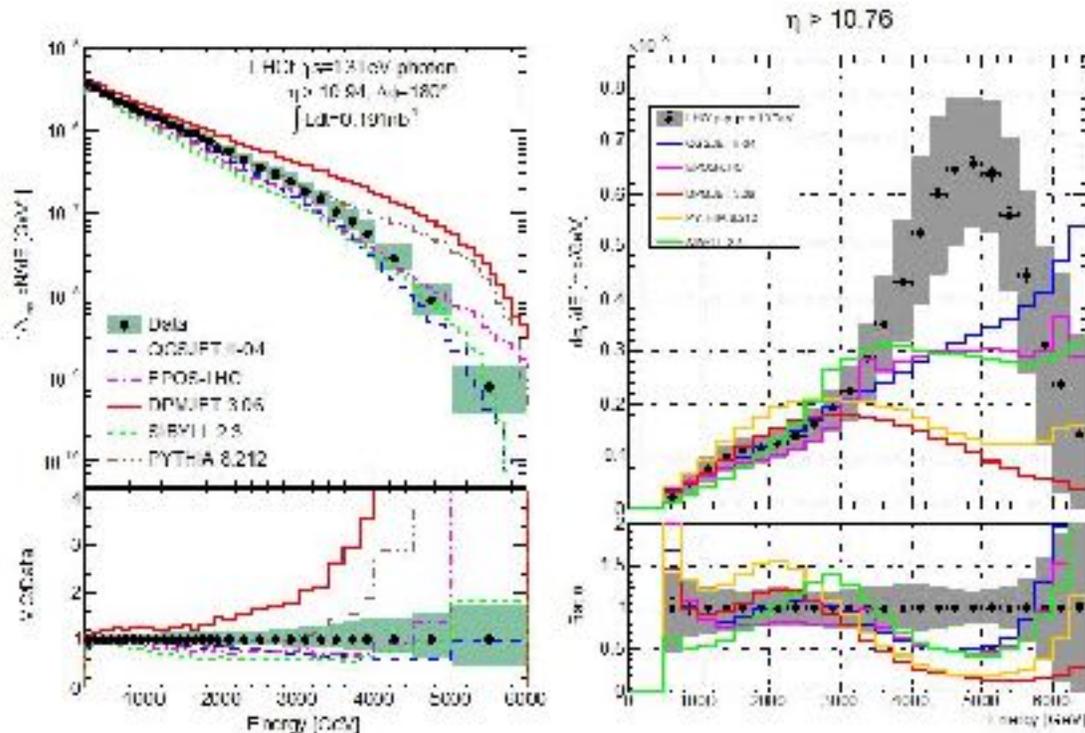


Figure 1. LHCf-measured energy spectra of forward photons (left) and neutrons (right) in p+p collisions at $\sqrt{s} = 13$ TeV.

Model developers are currently working to include the information obtained by the LHCf forward measurements in their models.

Two main points of interest for the cosmic ray community, which could be addressed at the LHC collider, are currently missing or not completely realized: a joint study of the forward

and the central pseudo-rapidity regions and the measurement of particles emitted in the central and forward regions in proton collisions with light ions. The former one, currently under development as a joint effort of the ATLAS and LHCf collaborations, was made possible thanks to the implementation of a common data taking framework implemented since 2013, which allowed collecting independent ATLAS and LHCf data sets for which the corresponding triggers can be easily identified. The latter point is now being studied by the LHC experts, after the LHCC and CERN Research Board approved the Technical Proposal presented by the LHCf collaboration for the LHC Run 3 and to support the idea of realizing collisions involving light ions.

The LHC Run 3 represents for LHCf a new opportunity to shed light on the physics of the hadronic interaction of CRs with the atmosphere, and to contribute to an improvement of the hadronic interaction models. The main reasons that led our group to submit a Technical Proposal to take part in Run 3 concern both p+p and p+O collisions.

The opportunity to take data for pp collisions at 14 TeV would allow LHCf to extend the range of energies explored during the previous operations. The LHCf group expects to improve in a significant way the physics outcome of the experimental results, thanks to the on-going hardware upgrade, to a new trigger strategy and to the joint data taking carried out with the ATLAS forward detectors. The hardware upgrade and a new trigger scheme allow us to operate at 10 times higher luminosity than in the 2015, 13 TeV proton run. Consequently we can significantly improve the collected statistics, thus opening the possibility to measure spectra of more rare neutral mesons like η and K^0 . A new combined data taking with the ATLAS central and forward detectors would open the possibility to enhance the scope of the LHCf measurements by allowing the identification of diffractive and not-diffractive collisions.

Beyond this sure improvement, the opportunity to take data in collision between protons and light ions represents a real breakthrough for the HECR physics case. There is currently a serious interest in this type of collisions, not only for the HECR field, but also in other communities. The most probable light ion collisions foreseen at LHC will use Oxygen, which is among the best possible targets for the HECR physics case. The possibility to reproduce in laboratory the first interaction responsible for the development of a real atmospheric shower, thus directly probing the high energy collisions happening in the atmosphere, will allow a significant reduction of the systematic effects that are present in the extrapolation of the LHC directly measured quantities to the widely used high energy hadronic interaction models.

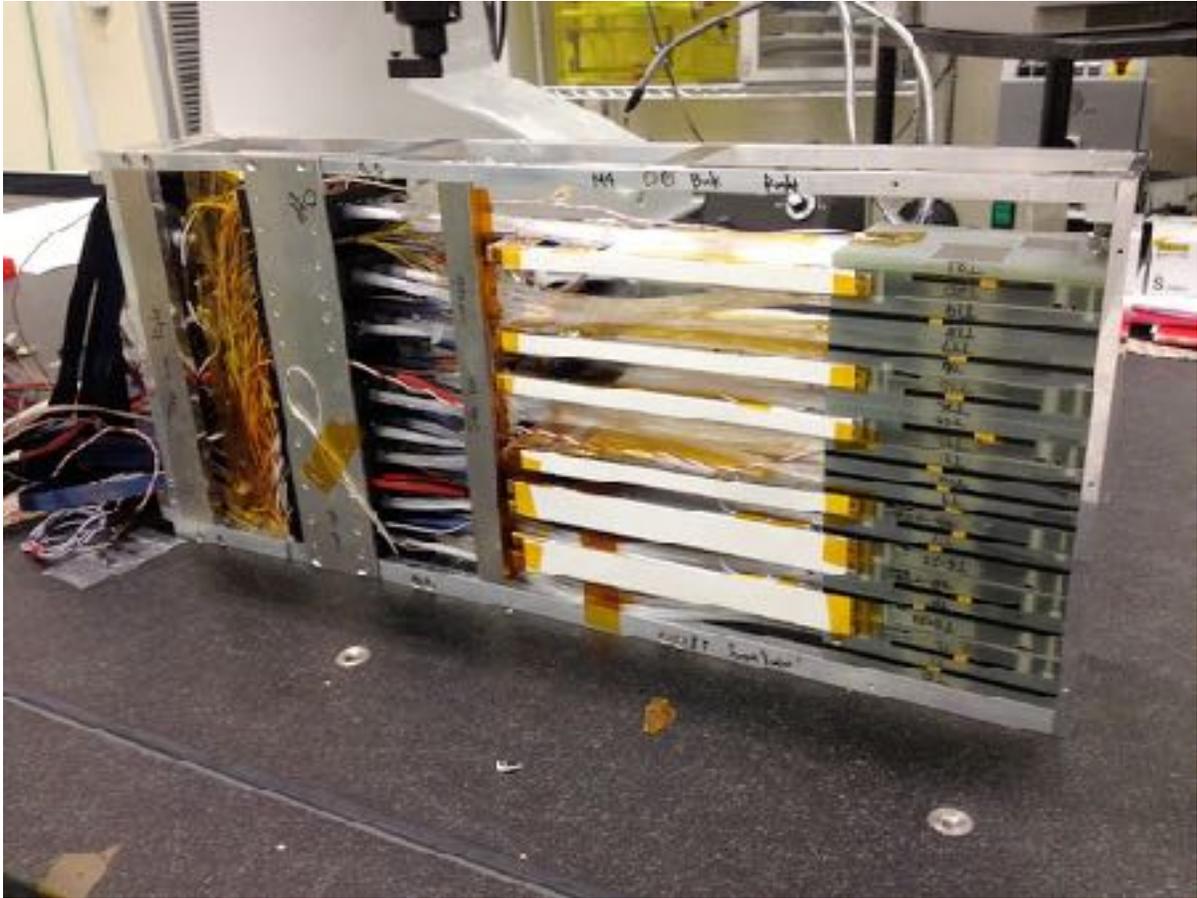


Figure 2. The image shows the LHCf Arm2 detector still open, just after the assembling of the calorimeter layers.

The photo below (Figure 3) shows the LHCf Arm2 apparatus after the installation inside the TAN structure. The readout electronics is visible on top of the TAN, while the detector lies vertically, hidden inside an instrumentation slot accessing the beam line location.



Figure 3: the Arm2 detector after the installation inside the dedicated instrumentation slot of the TAN absorber in sector LSSR1, 140 m far from the ATLAS interaction point.

Latest results from the Higgs couplings to second-generation fermions

by Panos Charitos

 [PDF version](#)

The discovery of the Higgs boson completes the Standard Model, a very successful theory describing particles of visible matter and their interactions. However, there are still big missing pieces in our fundamental understanding of matter, while certain experimental phenomena point to the existence of new physics. The LHC has opened a new chapter of detailed measurements of the Higgs interactions with all other known subatomic particles. Precise measurements of the Higgs boson properties will help elucidate the nature of the Higgs and could possibly point to new physics, manifested in the form of small deviations from the theoretical predictions of the Standard Model.

Measuring the Higgs boson decay to Standard Model particles is a daunting challenge for experimentalists. Higgs boson decays to other bosons – that led to its discovery - represent only a fraction as the Higgs boson can also decay to fermions. The decay rate depends on the square of the coupling strength, which is proportional to the fermion mass. The big difference in mass between the three generations of fermions – one of the open questions for particle physics – and particularly the small masses of the first and second generation fermions as well as the large backgrounds that mimic other processes of the Standard Model make the measurement of the Higgs boson decays to fermions one of the most challenging tasks for experimentalists. Measurements of the Higgs boson coupling to fermions can provide stringent tests of the validity of the SM.

Last year, the ATLAS and CMS collaborations announced the first measurement of the Higgs boson decay to two bottom quarks ($H \rightarrow b\bar{b}$) which accounts for about 58% of all Higgs boson decays. Moreover, both collaborations have observed the Higgs boson decaying to a τ lepton that also belongs to the third generation of fermions. These measurements were made possible thanks to the machine and detectors performance delivering a wealth of new data and to the new algorithms developed, allowing to distinguish these processes from the billions of background events. Following the measurement of Higgs boson decays to third-generation fermions, the next step is the study of the Higgs boson decays to second-generation fermions that are lighter in mass and have much lower Higgs boson decay fractions, making more complicated the identification in the detector and for the analysis. The first results of these measurements were presented during the recent EPS-HEP conference in Ghent, Belgium.

The ATLAS collaboration presented results from Higgs boson decays to a muon and antimuon pair ($H \rightarrow \mu\mu$) using the full Run 2 dataset. This includes almost twice as many Higgs boson events as the previous results from ATLAS released last year for the ICHEP conference in Seoul, Korea. As muons are lighter than τ leptons the decay of a Higgs to a

muon pair is predicted to occur 300 times less frequently than to tau-lepton pair. ATLAS detector's capabilities to identify and reconstruct muon pairs, together with the good muon momentum resolution and improved signal versus background discrimination using multivariate techniques increased the sensitivity of this analysis over that of the previous year. The resulting fit is shown in Figure 1.

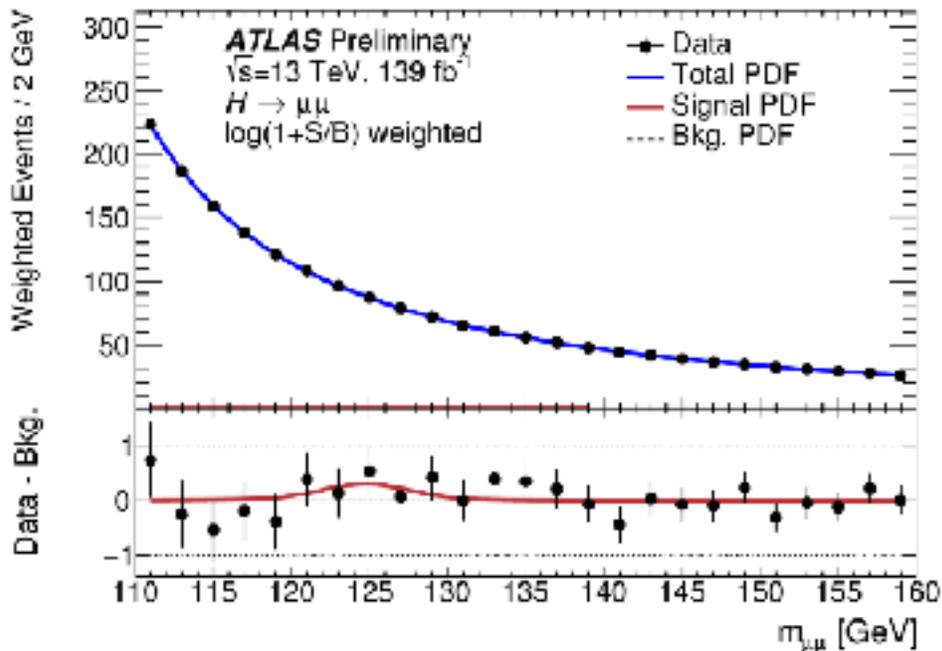


Figure 1. The muon pair invariant mass spectrum summed over all categories. Each event is weighted by $\log(1+S/B)$, where S and B are the number of signal and background events between 120 and 130 GeV of a given category determined by the simultaneous fit. The weighting visualizes the effect of the categorization on the analysis. The curves show the results of the fit. (Image: ATLAS Collaboration/CERN)

An upper limit on the Higgs boson production cross section times branching fraction to muons was set at 1.7 times the Standard Model prediction at 95% confidence level. This represents a 50% improvement compared to the previous measurement. No significant excess was observed, and further data will help improve the statistical limitations.

During the Lepton-Photon Symposium, the ATLAS Collaboration presented the first preliminary result for Higgs boson decays to electrons. Study of first generation fermions represent a daunting challenge for both the ATLAS and CMS experiments during the next runs of the LHC. According to the Standard Model this should be an extremely rare process, about 40,000 times less likely compared to the muon decays discussed before. Constraining this decay is important as any possible enhancement of this decay rate could reveal signs of new physics. Another difficulty in measuring this channel stems from the fact that the majority of electron-pair events originate from Z boson

decays ($Z \rightarrow ee$). The first results don't show any excess over the background and allowed to set an upper limit on the $H \rightarrow ee$ branching ratio of 0.036% at 95% confidence level.

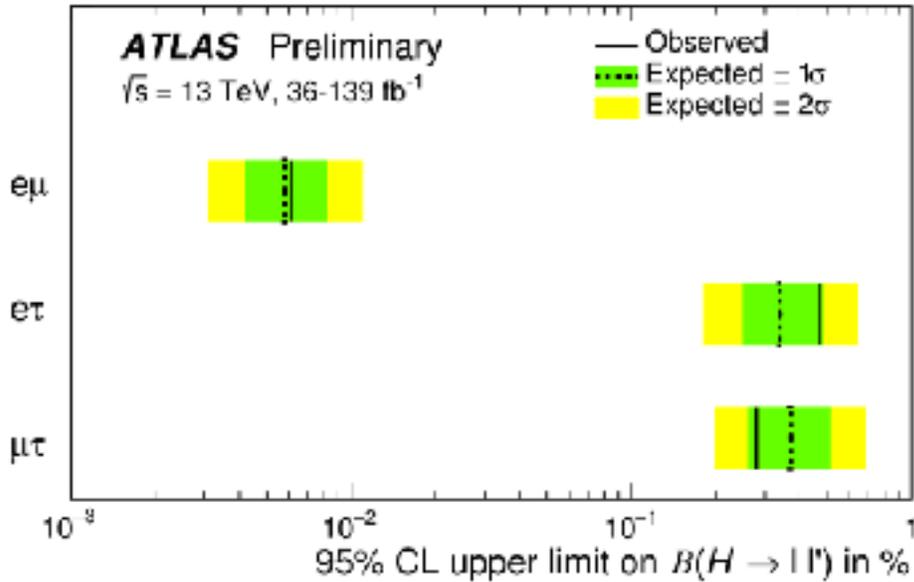


Figure 2. Summary of upper limits set on the branching ratio of the Higgs boson decaying into a pair of charged leptons of different flavour (lepton flavour violating decays), at the 95% confidence level. (Image: ATLAS Collaboration/CERN)

Finally, during the same conference ATLAS presented a search for Higgs-boson decays to an electron and a muon; a flavour-violating decay forbidden in the Standard Model. ATLAS set an upper limit of 0.006% of the $H \rightarrow e\mu$ branching ratio at 95% confidence level. These results pave the way for future results from both ATLAS and CMS collaborations that will scrutinise these channels with higher precision.

CMS has also recently presented the first result on searches for decays of Higgs bosons to a pair of charm quarks ($H \rightarrow cc$). As discussed, the coupling of the Higgs boson to any SM particle is proportional to the mass of the particle itself. Charm quarks have a mass of 1.3 GeV, about 130 times lighter compared to the third-generation top quark and three times less massive than bottom quarks. This means that the expected ratio of Higgs boson decays into charm quarks should be rather low compared to decays to bottom quarks and thus harder to observe. Moreover, the analysis becomes harder due to other events with similar backgrounds like the production of a Z boson in association with two additional charm quarks.

To search for the direct decay of the Higgs boson decaying to charm quarks, CMS looks for two different signatures: two separate charm quark jets, or for a unique "fat" jet of particles. Such a fat jet has a larger size and can contain both the charm and anti-charm quark from the Higgs boson.

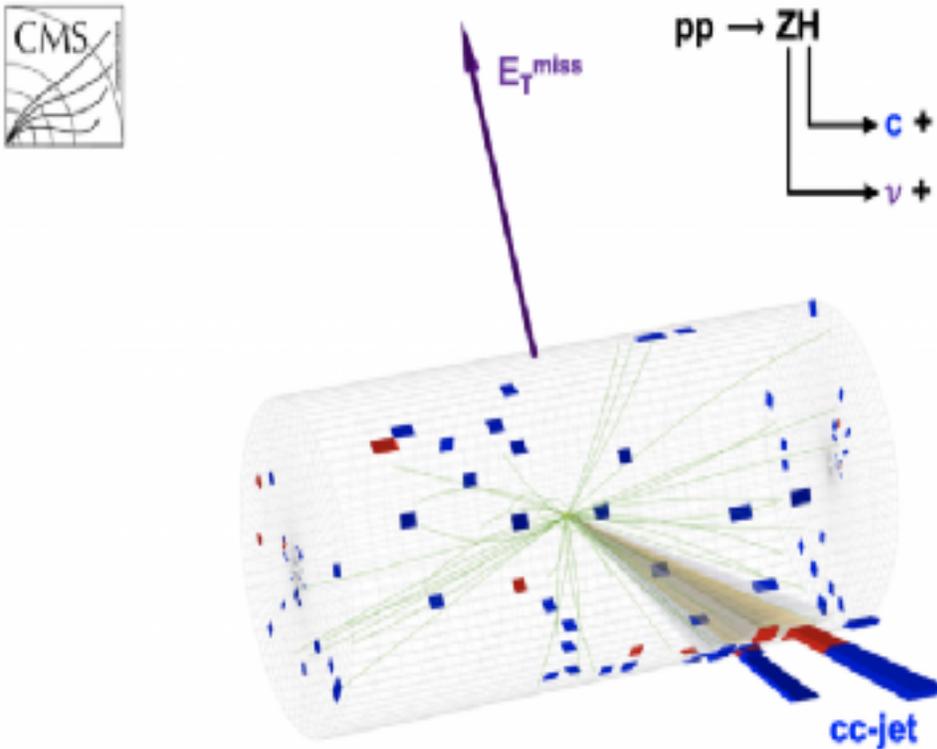


Figure 3. Representation of a collision recorded by the CMS detector that features a Z boson decays into neutrinos and a "fat" jet consistent with two charm jets, that could be from the Higgs boson. The red and blue towers represent the energy deposits in the CMS electromagnetic and hadronic calorimeter, respectively, while the green lines represent the tracks of the charged particles as reconstructed by the CMS tracker. The yellow cones identify the jets created by charm quarks. The purple arrow indicates the missing momentum in the event carried out by undetectable particles such as neutrinos.

This distinction helps to identify all the possible scenarios accurately and maximizes the analysis sensitivity. Identifying jets formed by charm quarks and isolating them from other types of jets is a huge challenge for understanding this decay channel. Eventually, to recognize the selected jets as produced by charm quarks and discard those originated from other flavour quarks, dedicated algorithms based on advanced machine learning techniques have been deployed.

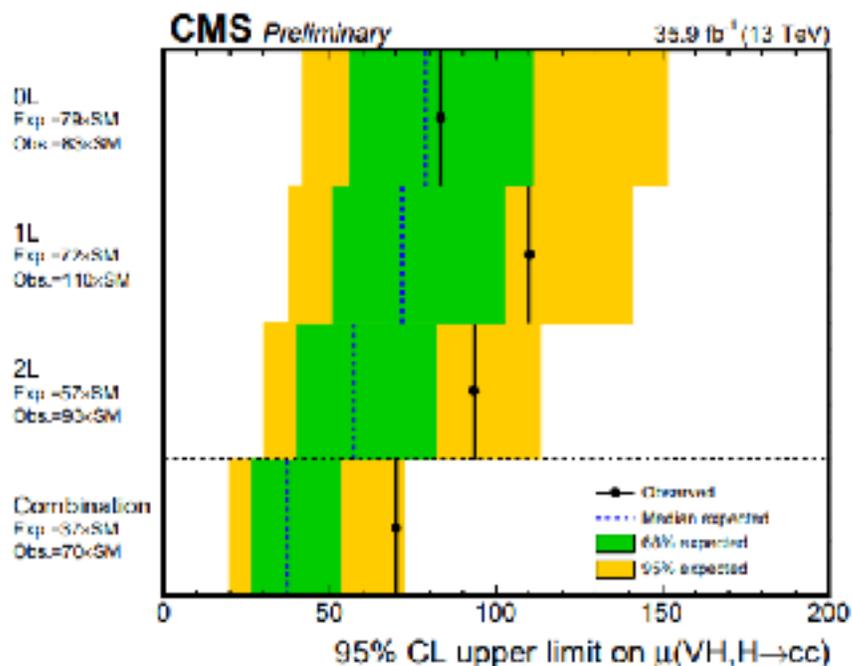


Figure 4. Upper: 95% confidence level upper limits on μ for the VH ($H \rightarrow cc$) process from the combination of the resolved-jet and merged-jet analyses in the different channels (0L, 1L, and 2L) and combined. The inner (green) band and the outer (yellow) bands indicate the regions containing 68 and 95%, respectively, of the distribution of limits expected under the background-only hypothesis.

In the case of jets from one charm quark, a Deep Neural Network is trained to identify jets of particles that originated from charm quarks using information like the direction and energy of the jet, the information relative to the charged particle tracks inside the jet and the presence of vertices found displaced with respect to the origin of the jet of particles. The output of the charm quark identification algorithm is combined with other observables in another neural network to isolate the signal from the background. In the “fat jet” topology, instead, a novel method based on a complex Deep Neural Network architecture is trained to directly distinguish Higgs bosons decaying into a pair of charm quarks from the background processes. The double-charm neural network uses similar information but also uses the internal structure of the “fat” jet and global information on the collision to do the final signal extraction.

The results from CMS set limits on the Higgs coupling to a charm quark, improving the previous analysis sensitivity to the charm decay of Higgs bosons by a factor of four. This is a significant improvement but still away from the required sensitivity for this channel if the branching ratio is the one predicted by the Standard Model. The team expects significant

further improvements in the sensitivity to the decay of the Higgs boson to charm quarks after fully exploiting the available LHC Run-2 data.

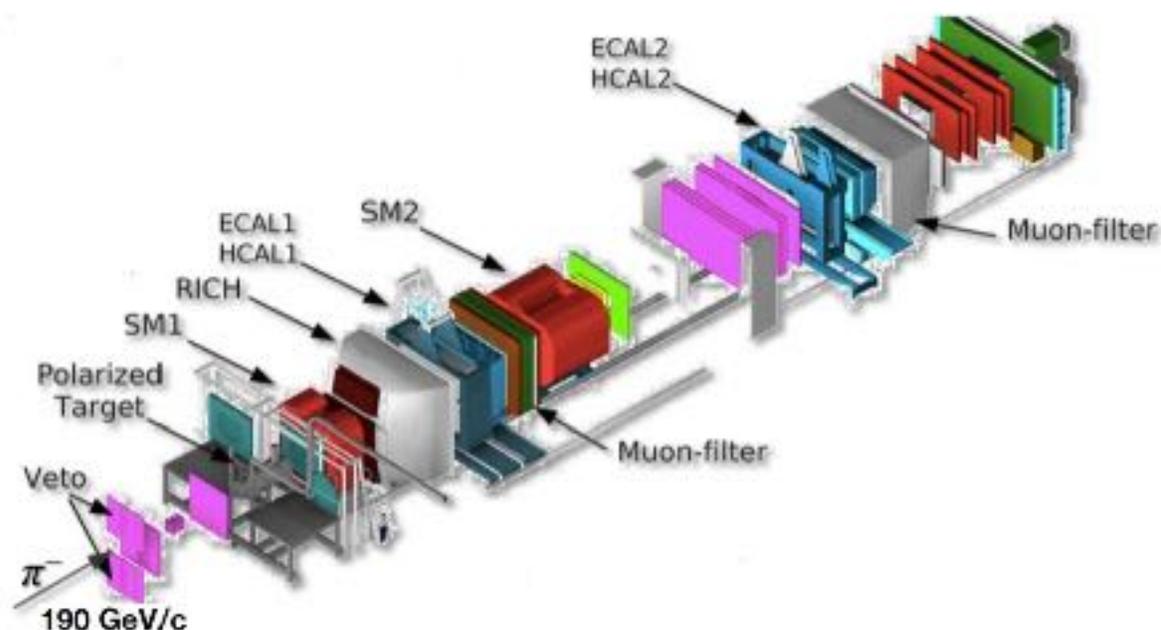
A deeper understanding of the Higgs decays to second generation fermions will require the larger datasets from the Run 3 of the LHC and the High-Luminosity LHC.

COMPASS results guiding future exploration of hadron structure in CERN's North Area.

by Oleg Denisov (INFN), Wolf-Dieter Nowak (DESY), Fulvio Tassarotto (INFN) on behalf of the COMPASS collaboration

The COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) Collaboration at CERN is the most recent one in pursuing the more than 40-years old objective to experimentally elucidate the nucleon's internal structure, in particular its spin dependence. It uses the M2 beam line of the SPS, which provides the only high-energy spin-polarized muon beam in the world. The deep-inelastic scattering process serves as a tool for studying in-depth the structure of the nucleon in terms of quarks and gluons and to investigate other phenomena like e.g. nucleon electromagnetic form factors and the strangeness content of the nucleon. Using alternatively high-energy pions or kaons delivered by the M2 beam line, a new era was opened to study exclusively produced multi-meson states, which already led to several new results in meson spectroscopy. In particular, 3-pion and $K\pi\pi$ states were studied through partial-wave analyses with unprecedented high-statistics, allowing one to identify and thoroughly analyze the properties of small signals and to search for new states.

In the last four years, the COMPASS Collaboration used their versatile two-stage open-aperture forward spectrometer in EHN2 in combination with different beam and target configurations:



Artistic view of the 60 m long COMPASS spectrometer. The two dipole magnets SM1 and SM2 are indicated in red, electromagnetic and hadron calorimeters in blue.

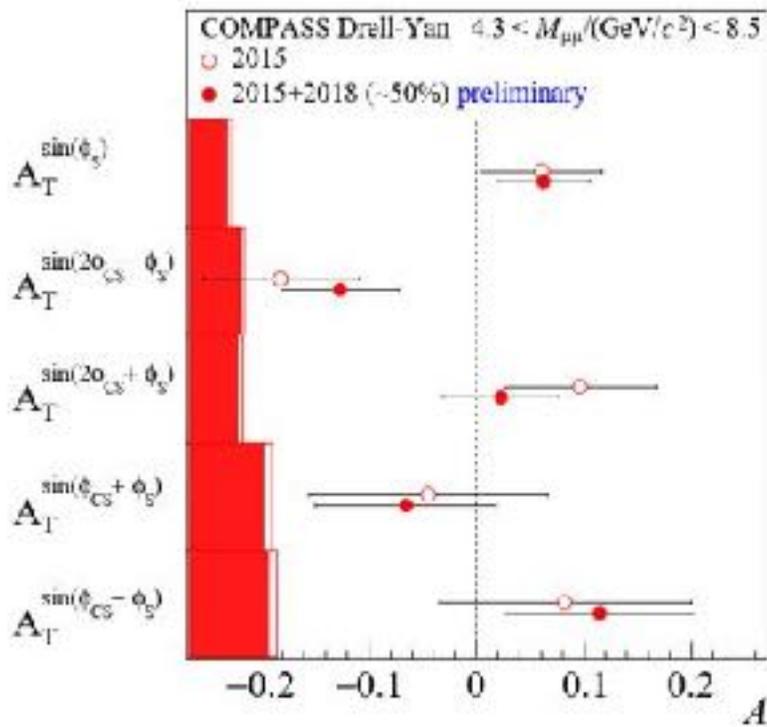
In 2015 and 2018, the Drell-Yan (DY) process was studied through pion scattering on polarised hydrogen and three types of heavy targets. In 2016 and 2017, the Deeply Virtual

Compton Scattering (DVCS) process was investigated using both charge signs of the high-energy polarised muons delivered by the M2 beam line, in conjunction with a 2.5 m-long liquid hydrogen target surrounded by a recoil-proton detector. Over these four years, the COMPASS Collaboration has produced a rich menu of results on polarised quark parton distribution functions (PDFs), Transverse-Momentum-Dependent PDFs and Generalized PDFs, as well as DIS multiplicities of pions and kaons. In addition, they published results on the production of exclusive final states using data taken earlier with a pion beam, a proton target and a recoil-proton detector. Also published were new results on the spectroscopy of standard and exotic mesons, which were obtained from data taken in earlier years.

Drell-Yan results

A key component and an unprecedented feature of the COMPASS physics programme is the study of Transverse Momentum Dependent Parton Distribution Functions (TMD PDFs) of the nucleon via the measurement of spin- (in)dependent azimuthal asymmetries in both SIDIS (semi-inclusive deep inelastic scattering) and DY processes. The first ever spin-dependent Drell-Yan measurement was performed in 2015. The measurement of the Sivers asymmetry and all other transverse spin-dependent azimuthal asymmetries was performed at a comparable hard scale in both SIDIS and DY at COMPASS. Comparing the results of these measurements offers the unique possibility to test the predicted universal and process-dependent features of TMD PDFs by using essentially the same experimental setup. The first DY results based on the 2015 data were published in Physical Review Letters in 2017. The observed Sivers asymmetry is found to be consistent with the QCD TMD-framework prediction. In order to improve the statistical precision of the result, in 2018 the COMPASS data-taking campaign was again devoted to spin-dependent DY measurements and preliminary results have been shown already (see figure below).

In parallel, further analyses have been done and are still ongoing concerning spin-independent DY azimuthal asymmetries, pion-induced DY and charmonium cross sections on nuclear targets including the so-called EMC effect, the pion valence structure, charmonium polarization and the transverse spin-dependence of azimuthal asymmetries.



TMD single-spin asymmetries measured by COMPASS in the first ever spin-dependent Drell-Yan experiment.

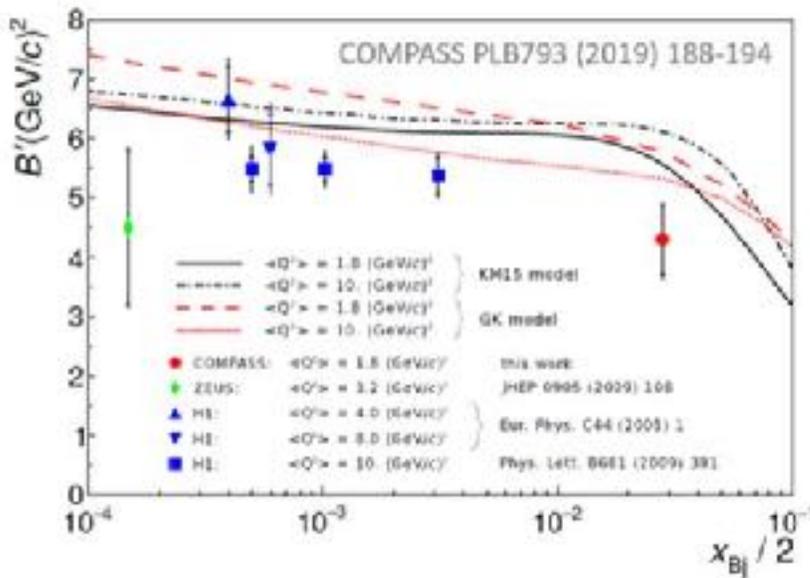
A detailed programme to access Generalised Parton Distributions

The long-lasting COMPASS effort to understand the structure of the nucleon has shifted the focus in the last years to also study Generalized Parton Distribution Functions (GPDs). They describe the correlation between transverse position and longitudinal momentum of quarks and gluons that are confined inside a hadron. This method is often referred to as (quasi-3D) nucleon tomography. GPDs are accessible through hard exclusive measurements, such as a virtual Compton scattering (DVCS) and deeply virtual meson production. These studies are performed using the world-unique high-energy (160 GeV) muon beam line at CERN's North Area, which offers beams of both charges and, correspondingly, of both (natural) polarisations.

The beam impinges on a 2.5 m long liquid hydrogen target surrounded by the CAMERA proton recoil detector to ensure the exclusivity of the reaction. The recoil proton is detected in coincidence with the scattered muon, which is emitted together with the produced photon or meson into the COMPASS forward spectrometer.

Following a successful short pilot run in 2012, data was collected in 2016 and 2017. The first result was published in PLB 793 (2019) using data from the 2012 pilot run. COMPASS

measured the slope value $B=4.3 \pm 0.7 \text{ GeV}^{-2}$ in the exponential function that describes the dependence of the average of the measured μ^+ and μ^- cross sections on the momentum transfer t . Although further analysis using the complete 2016-2017 COMPASS data is still required to improve precision, this result already nicely complements earlier ones obtained by H1 and ZEUS at HERA. As can be seen from the figure, a ‘shrinkage’ of the proton appears when the projectile probes the transverse extension of partons in the proton for increasing parton momenta, i.e. when traversing the Bjorken- x range from the gluon-dominated region over the sea-quark region to the valence-quark region.



Dependence of the average of the measured μ^+ and μ^- cross sections on Bjorken- x .

Using the same data, the production of mesons as π^0 , ρ , ω , ϕ , J/ψ is also studied. From the data of the 2012 pilot run, large transverse virtual-photon contributions for exclusive π^0 production have been observed, and the results are submitted for publication. Also, non-zero values were observed for certain spin-density matrix elements, which indicates a violation of s-channel helicity conservation in exclusive omega production that may be explained by contributions of chiral-odd GPDs.

Hadron spectroscopy, heavy states

The excitation spectrum of hadrons gives information on how the strong interaction works to keep quarks and gluons bound inside hadrons. Precise spectroscopy of hadrons provides important input to our understanding of the strong interaction in a regime where the QCD equations cannot be solved with current techniques. Lattice-QCD simulations have started very recently to reach some predictive power for excited states, so that comparisons with experiment are becoming possible.

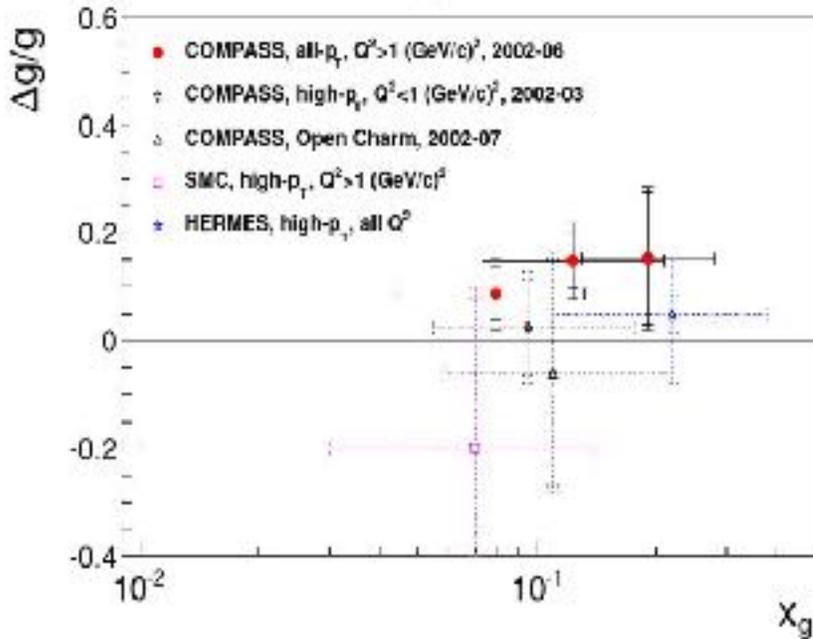
COMPASS collected data samples from peripheral (diffractive) collisions of a 190 GeV pion beam from the SPS M2 beam line with a proton target to study short-lived excited mesons consisting of up, down and strange quarks. These data allow one to study the properties of established mesons with unprecedented precision, but also open the possibility to search for new states, in particular the so-called exotic mesons (i.e. states that go beyond the simple quark-antiquark configurations of the quark model such as four-quark states or states with excited gluon fields).

By employing an analysis technique called partial-wave analysis, COMPASS disentangles the produced excited mesons in terms of their quantum numbers. As a very interesting specific result, they recently found a novel resonance-like state, the $a_1(1420)$, with surprising properties (published in [PRL 115 \(2015\) 082001](#)). In collaboration with theorists from JPAC, COMPASS data confirm the existence of the $\pi_1(1600)$, a previously disputed state, thereby solving a long-standing puzzle. This state has quantum numbers forbidden for conventional quark-antiquark states. According to QCD predictions, the $\pi_1(1600)$ could be a new form of hybrid hadronic matter: a quark-antiquark pair with an excited gluon field.

Exploiting the versatility of the M2 beam line, COMPASS also studied the production of mesons containing the heavier charm and anti-charm quarks by scattering 160 GeV and 200 GeV muons off ${}^6\text{LiD}$ and NH_3 targets. The production of the elusive $X(3872)$ meson was observed with a significance of 4.1 standard deviations, for the first time in lepton-nucleon interactions. The properties of this meson cannot be explained by the simple quark-antiquark model. The COMPASS result is complementary to the ones obtained in experiments at the LHC and at e^+e^- colliders, helping to explain this puzzle.

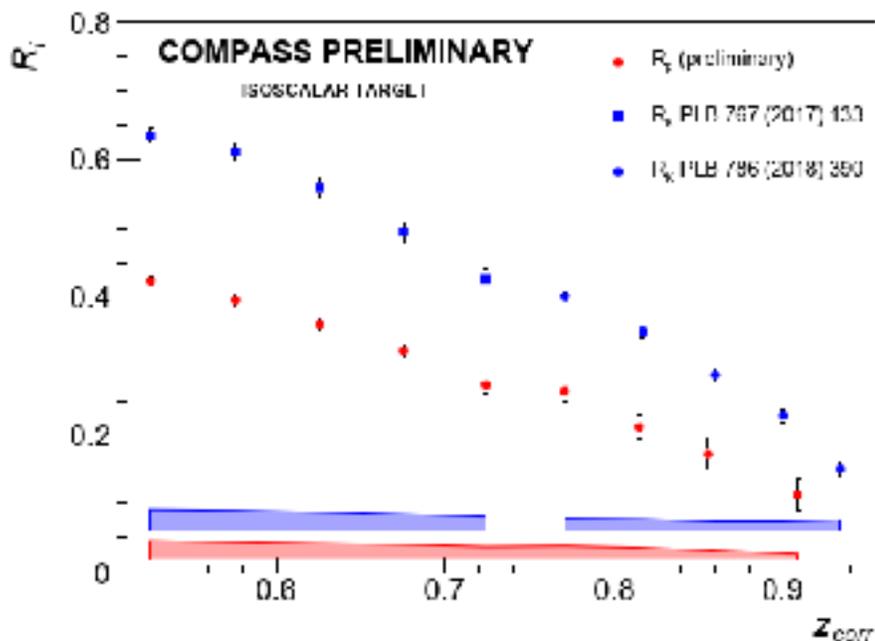
Deep Inelastic Scattering (DIS) results from longitudinally polarised muon-nucleon scattering.

The analysis of all DIS data taken with the polarised muon beam and a longitudinally polarised proton or deuteron target is finished and final results were published on the proton and deuteron spin structure functions for $Q^2 > 1 \text{ (GeV/c)}^2$. The results include a NLO pQCD analysis of polarised quark PDFs and a re-evaluation of the Bjorken sum. For the first time, a significant spin effect was observed at small values of Bjorken- x and four-momentum transfer Q^2 . In addition, a clear positive signal for the gluon contribution to the nucleon spin was measured thanks to an improved analysis of hadron production in deep inelastic scattering, see the following figure.



Results for $\Delta g/g$ in three bins of x_{gluon} compared to the world data on $\Delta g/g$ extracted in LO pQCD.

Moreover, COMPASS obtained SIDIS results using spin-independent muon-nucleon scattering. For semi-inclusive pion production, fragmentation functions were extracted and published, while for kaon production further investigations are still required at large values of z , i.e. the relative energy transfer to the produced hadron. Using an extended data set, COMPASS studied the K^- to K^+ (R_K) and antiproton-to-proton (R_p) multiplicity ratio. The comparison with pQCD calculations shows that the experimental results fall below the prediction of 0.5 for both ratios (see figure below), thereby suggesting that the applicability of factorised pQCD in DIS hadron production may need to be revisited.



Comparison of R_p and R_K , as a function of z . The expected lower limit in LO pQCD is the same for p and K at given x and Q^2 , and is about 0.5 for the data shown in the figure.

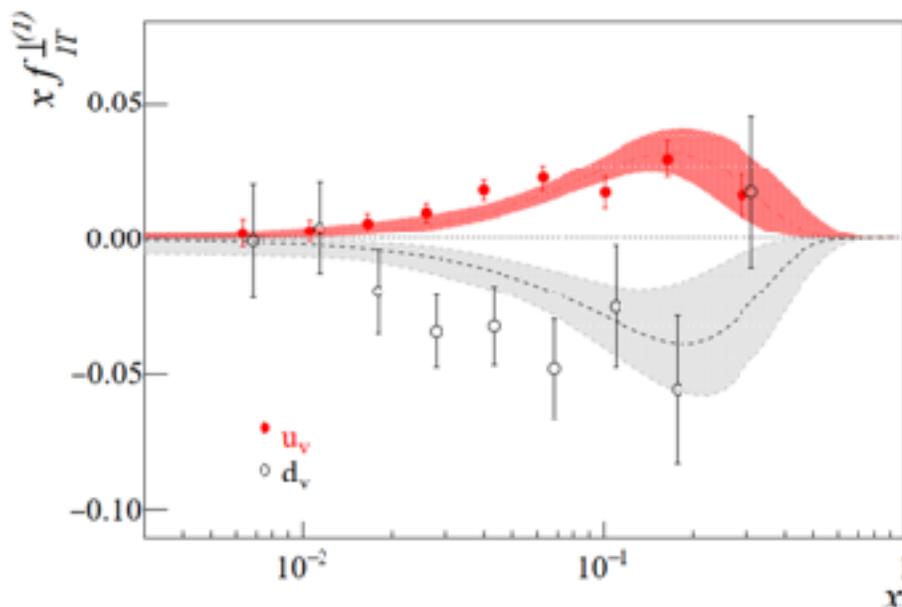
Measuring Transverse Spin Asymmetries and TMD PDFs

New results were obtained on the transverse-spin and transverse-momentum structure of the nucleon using the SIDIS data collected with the 160 GeV muon beam and transversely-polarized and unpolarised targets.

COMPASS measured Collins and Sivers asymmetries in SIDIS on proton targets that are clearly different from zero, thereby confirming the relevance of transverse-spin and transverse-momentum effects at high energy. The corresponding measurements on the deuteron provided asymmetries compatible with zero within the large statistical uncertainties. These proton and deuteron results were used in several extractions of the transversity distribution, the collinear PDFs related to the tensor charge, and the Sivers function that is presently the best studied among the TMD PDF. Indeed, the non-zero values we measured for the Sivers asymmetry in SIDIS at large x and large Q^2 constitute the solid ground to verify the change of sign of the Sivers function when comparing SIDIS to Drell-Yan.

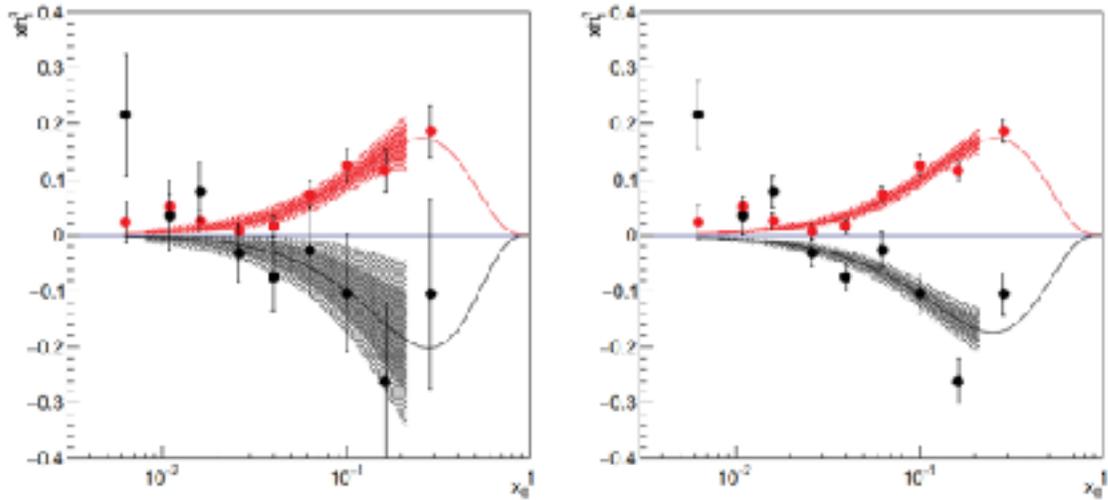
Very recently, COMPASS has extracted for the first time and published in Nucl. Phys. B 940 (2019) 34 results on the transverse-momentum-weighted Sivers asymmetry for positive and negative hadrons using the 2010 SIDIS proton data. The measurement has allowed extracting

in a direct way the first transverse moment of the Sivers function $f_{1T}^{\perp(1)}$ for the u and the d quark, shown in the figure below. The values for the u quark are different from zero, with relatively small statistical uncertainty, and in agreement with previous extractions. The large uncertainties for the d-quark PDF show the need for precise measurements of transverse-spin asymmetries on the neutron or deuteron.



Measured first moments of the Sivers functions for the u-quark (filled red points) and the d-quark (open black points), compared to a previous extraction using all the available Sivers asymmetry measurements.

More precise data are required for any analysis aiming at the extraction of transversity and TMD PDFs. This motivated COMPASS to propose a one-year measurement of transverse-spin asymmetries using a transversely polarised deuteron target. Following approval in June 2018, the data will be taken in 2021. They will balance the world statistics between deuteron and proton data and allow one to improve the knowledge on all d-quark PDFs, in particular transversity, and on the nucleon tensor charge. The results will remain unique until the eventual start of operation of the EIC, and they are complementary to the upcoming JLab12 data.



Values of $\chi \tilde{H}_T^{d,u}$ (red) and $\chi \tilde{H}_T^{d,u}$ (black), with the 68% (dark) and 90% (light) confidence bands for the present (left) and projected (right) accuracies of the deuteron data, while using all existing proton data.

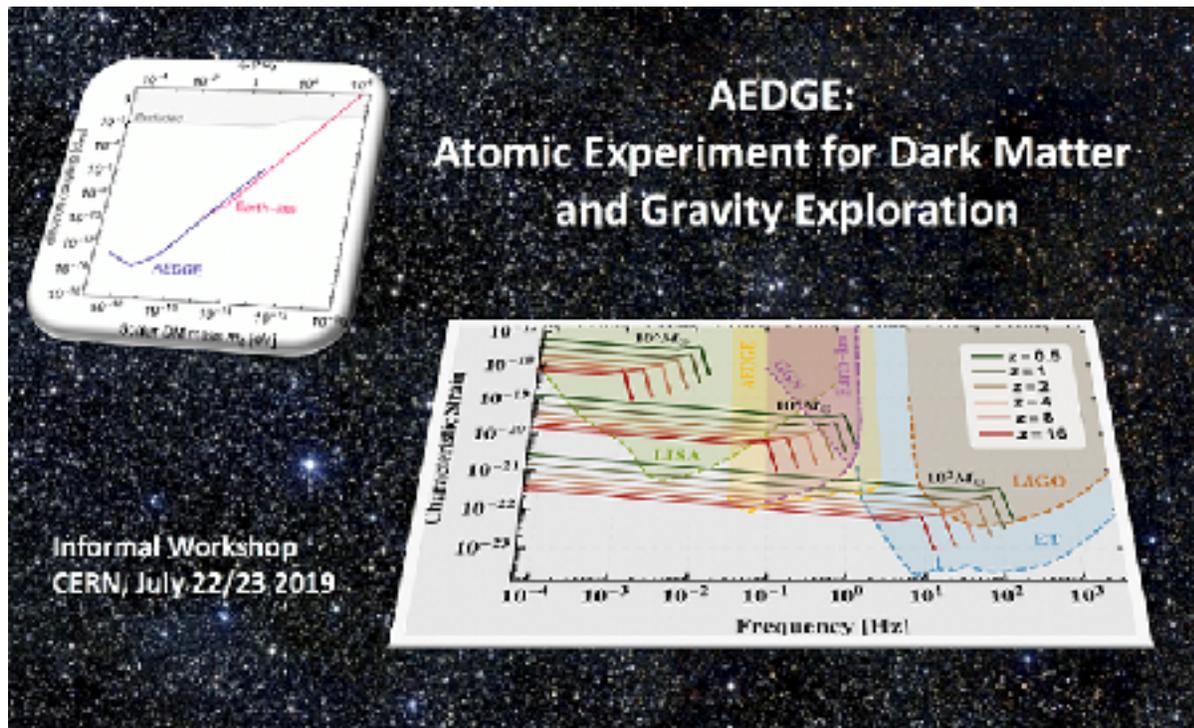
Once the 2021 data will have been analysed, COMPASS expects to reduce the uncertainties in the integral of the transversity function from 0.108 to 0.040 for the d-quark and from 0.032 to 0.019 for the u-quark. This will result in a projected uncertainty on the tensor charge of ± 0.044 , i.e. a reduction by a factor of two, as shown in the figure.

New and complementary information on the TMD structure of the nucleon comes from SIDIS measurements using unpolarised targets. In particular, information on the intrinsic transverse momentum in the nucleon can be inferred from transverse momentum distributions, and azimuthal modulations are used to access the Boer-Mulders TMD PDF. These observables were earlier measured by COMPASS using data taken with the LiD target, and they are now being extracted using the high-statistics proton data collected in 2016 and 2017 during the DVCS measurements.

Atomic Experiments for Dark Matter and Gravity Exploration

by Albert de Roeck (CERN), Panos Charitos (CERN)

A workshop on “Atomic Experiments for Dark Matter and Gravity Exploration” was held at CERN on 22nd and 23rd of July, More than 130 participants met at CERN to review the landscape of cold atom experiments for exploring dark sector physics, gravitational effects and new fundamental interactions.



The workshop offered a space to the cold atom community to meet with particle physicists and the gravitational-wave community, and review ground and space applications. Over two-days, participants discussed the physics opportunities and connections between the fundamental research areas of particle physics and gravitational physics using cold atoms as ultra-precise clocks and used as interferometers.

Cold atoms can be used as very precise clocks for searching ultra-light dark matter particles, particularly scalar particles but also pseudo-scalar axions, or more generally Axion Like Particles (ALPs), and vector dark matter, thus complementing other searches at collider and fixed-target experiments. Moreover, cold atom interferometry allows to search for mid-frequency gravitational waves thus bridging the range covered by LIGO, Virgo and the one of the future LISA mission. Searching for gravitational waves at this intermediate-frequency band should reveal signals from merging of massive black holes (between 100 and 100.000 solar masses) that power active galactic nuclei, and could further shed light on a first-order phase transition or cosmic strings that may have happened in the early universe.

The workshop shared information about long-baseline terrestrial cold-atom experiments that are already funded and under construction, such as MAGIS in the US, MIGA in France and

ZAIGA in China, as well as ideas for future terrestrial experiments such as MAGIA-advanced in Italy, AION in the UK and ELGAR in France. Dark Matter particles or the presence of new interactions/particles could change the number of clock ticks and modify the clock-ticking rate.

As an example, the UK Atom Interferometry Observatory and Network (AION) project in the UK proposes a staged series of atom interferometers with baselines of 10m, 100m, and 1km, similar to MAGIS. AION has been proposed by a consortium of particle physicists, cold atom experts and gravitational wave enthusiasts, with a strong leading role by the particle physics community. It will provide a pathway for detecting gravitational waves from the very early universe in the, as yet mostly unexplored, mid-frequency band, ranging from several milliHertz to a few Hertz. The AION Project is foreseen as a 4-stage programme: The first stage (year 1-3) the plan is to develop existing technology (Laser systems, vacuum, magnetic shielding etc.) for a 10m demonstrator and prepare for Stage 2. The Stage 1 device is proposed to be located in Oxford, with the sites for the subsequent steps awaiting more study. For more details see <http://www.hep.ph.ic.ac.uk/AION-Project/>. Stage 2 requires a vertical shaft of order 100m. Obviously CERN has several such shafts on site which could make it an attractive host lab option. Furthermore, CERN has a good cryogenic infrastructure, expert know-how on vacuum technology, laser experience and potential experimental groups that may get interested, eg. from the AD facility.

The second stage (year 3-6) builds, commissions and exploits the 100m detector and also prepares design studies for the km-scale one. The third and fourth stage (year >6) prepare the groundwork for the continuing programme with a terrestrial km-scale detector and space based detector of order 10^4 km in size.

Space facilities like CACES (China) and CAL (NASA) and sounding-rocket experiments - MAIUS (Germany) - that also use cold atoms in space and microgravity were presented during the workshop as well.

One of the goals of the meeting was the preparation of a White Paper responding to ESA's Voyage 2050 call. The White Paper focusses on the physics case for future space-based cold atom experiments names AEDGE. AEDGE is proposed as a multi-purpose facility/experiment that will enable a variety of experiments in atom optics and atom interferometry to cover a broad spectrum ranging gravitational waves astronomy to particle physics and dark matter searches. Figures 1 and 2 give the sensitivity that can be reached for the detection of light dark matter and gravitational waves as studied in the AEDGE project ([arXiv:1908.00802](https://arxiv.org/abs/1908.00802)).

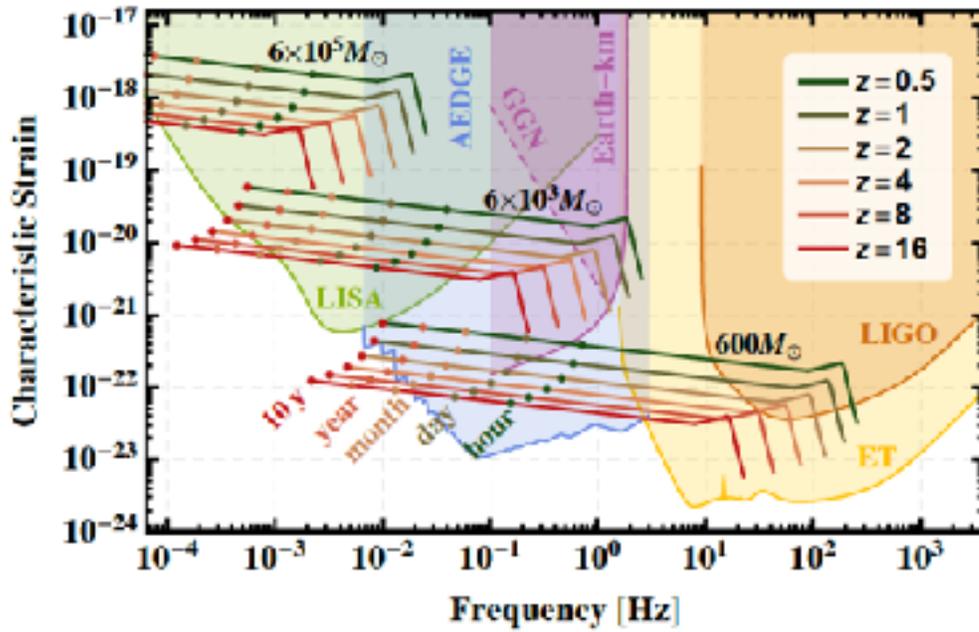


Figure 1: Comparison of the strain measurements possible with AEDGE and other experiments, showing their sensitivities to black hole mergers of differing total masses at various redshifts. An indicating also given of the time remaining before the merger. Also shown is the possible gravitational gradient noise (GGN) level for a km-scale terrestrial detector.

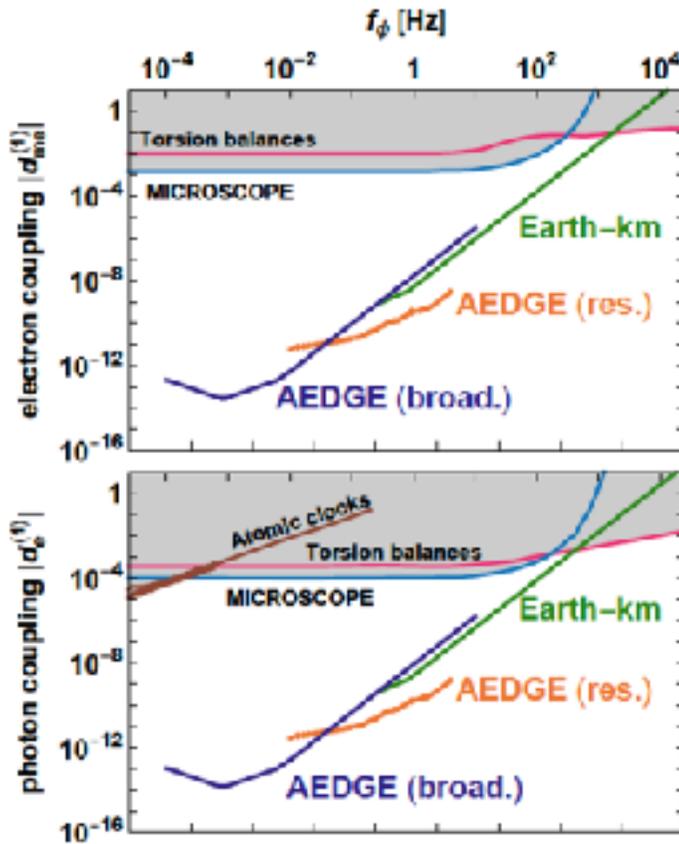


Figure 2: The sensitivities of AEDGE in broadband (purple lines) and resonant mode (orange lines) to linear scalar DM interactions with electrons (top) and photons (bottom), compared to those of a km-scale terrestrial experiment (green lines). The grey regions show parameter spaces that have been excluded by the MICROSCOPE experiment (blue lines), searches for violations of the equivalence principle with torsion balances (red lines), or by atomic clocks (brown lines).

“This effort is an excellent opportunity to bring together the different communities in Europe and to work towards a strong science case that will build the foundation for future space-based, possibly also terrestrial, projects.” said Oliver Buchmueller (Imperial College London) one of the co-organizers of the workshop.

Today Dark Matter remains one of the open and perhaps most pressing question in particle physics. AEDGE could explore different scenarios for ultra-light dark matter in the regime of m_{DM} down to 10^{-18} eV via searches for coherent effects of the oscillating DM field in the atomic cold. It could probe signals from scalar dark matter improving sensitivity of current searches while it is also promising for searches of other types of dark matter candidates.

“The use of this technology is fascinating both for the detection of gravitational waves and exploring new avenues of dark matter searches” said Albert De Roeck (CERN). “When progressing towards 100m and km-size detectors, CERN has a certainly a lot of experience to offer”.

Moreover, AEDGE can boost searches for gravitational waves. Astronomical observations in a range of different frequencies of electromagnetic waves allowed observing different structures and understanding cosmological processes in the evolution of the Universe. The same is expected to hold for gravitational waves. Probing the mid frequency band is optimal for probing collisions of black holes with masses between those detected by LIGO and super massive black holes that may be observed by LISA, as well as earlier evolution of LIGO binaries paving the way for multi-messenger astronomy.

As John Ellis (King's College London, CERN) noted in his closing remarks: "AEDGE would be a uniquely interdisciplinary space mission, harnessing cold atom technologies to address key issues in fundamental physics, astrophysics and cosmology".

More details and references can be found on <https://indico.cern.ch/event/830432/> and [arXiv:1908.00802](https://arxiv.org/abs/1908.00802)

Image notice: The image used in the front page depicts gravitational waves as emitted during a black hole merger. (Image credit: S. Ossokine, A. Buonanno, Max Planck Institute for Gravitational Physics, Simulating eXtreme Spacetimes project, D. Steinhauser, Airborne Hydro Mapping GmbH)

Nuclear Physics Meets Neutrinos

by Laura Fields (Fermilab)

Neutrino beams, such as those currently operating at Fermilab in the USA and J-PARC in Japan, are typically produced by colliding high-energy proton beams with long, thin solid targets. These collisions result in a spray of particles including short-lived hadrons such as pions or kaons. The hadrons are focused using magnetic focusing horns, which direct the hadrons into long tunnels, where they decay to neutrinos. Thick volumes of rock and shielding stop all particles except neutrinos, creating a beam of neutrinos.

Neutrinos come in three flavors known as electron, muon and tau neutrinos. After a neutrino of one flavor is created, it can “oscillate” into a different flavor, with the probability of oscillation depending on the neutrino’s energy and distance traveled. These neutrino oscillations were the first discovery of physics beyond the Standard Model and were the subject of the Nobel Prize in 2015.

Modern neutrino experiments such as NOvA and T2K are studying neutrino oscillations in fine detail in order to understand whether there may be more unknown physics at play, and whether a phenomenon known as CP violation occurs in neutrino oscillations. CP violation would allow neutrinos and antineutrinos to oscillate differently, and could be a critical part of the answer to a big question not explained by the Standard Model: why our universe appears to be made out of mostly matter rather than equal parts matter and anti-matter.

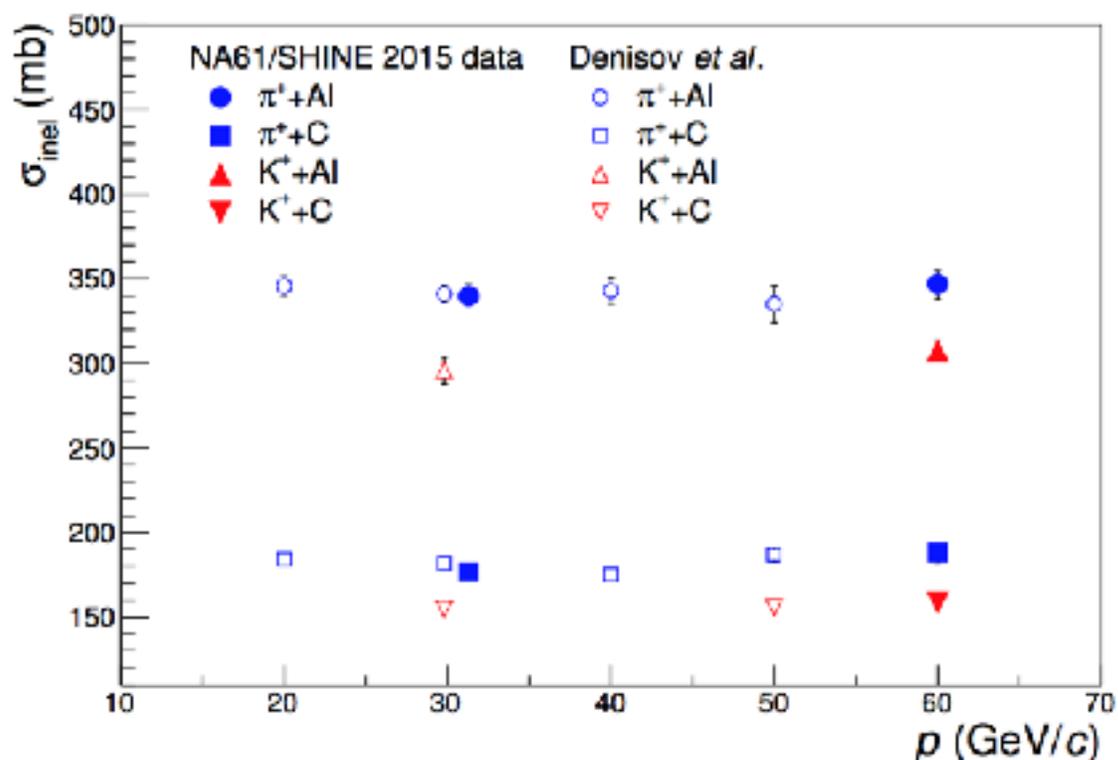


Fig 1. NA61 Measurements of the pion and kaon inelastic scattering cross sections on Aluminum and Carbon, as a function of incident particle momentum, compared with previous measurements by Denisov et al.

Neutrino oscillations are studied by generating neutrino beams consisting mainly of one flavor of neutrino physics and then studying that beam after it has traveled a long distance. Because neutrino oscillations vary with neutrino energy, it is very important to have a precise prediction of the number of neutrinos in the beam before oscillation and their energy spectrum (often called the “neutrino flux”). Estimating the neutrino flux is difficult because neutrinos are neutral particles that interact very rarely and can’t be measured or controlled like most particle beams. To measure neutrino flux, experiments instead have to measure the number of hadrons that were produced and focused before decaying to neutrinos. These measurements can’t be made in neutrino beams themselves because of the extremely high intensities (more than 10^{13} protons per second!) necessary to produce neutrino beams.

That’s where the NA61/SHINE experiment comes in. With its large-acceptance Time Projection Chambers, NA61/SHINE is able to make very precise measurements of the interactions that happen in neutrino beams. Over the past several years, NA61/SHINE has executed a program of measurements aimed at improving neutrino flux predictions in Fermilab’s neutrino beams (including the currently operating NuMI and planned LBNF beams). Fig. 1 shows recent measurements of pion and kaon inelastic interaction cross sections in carbon and aluminum thin targets.

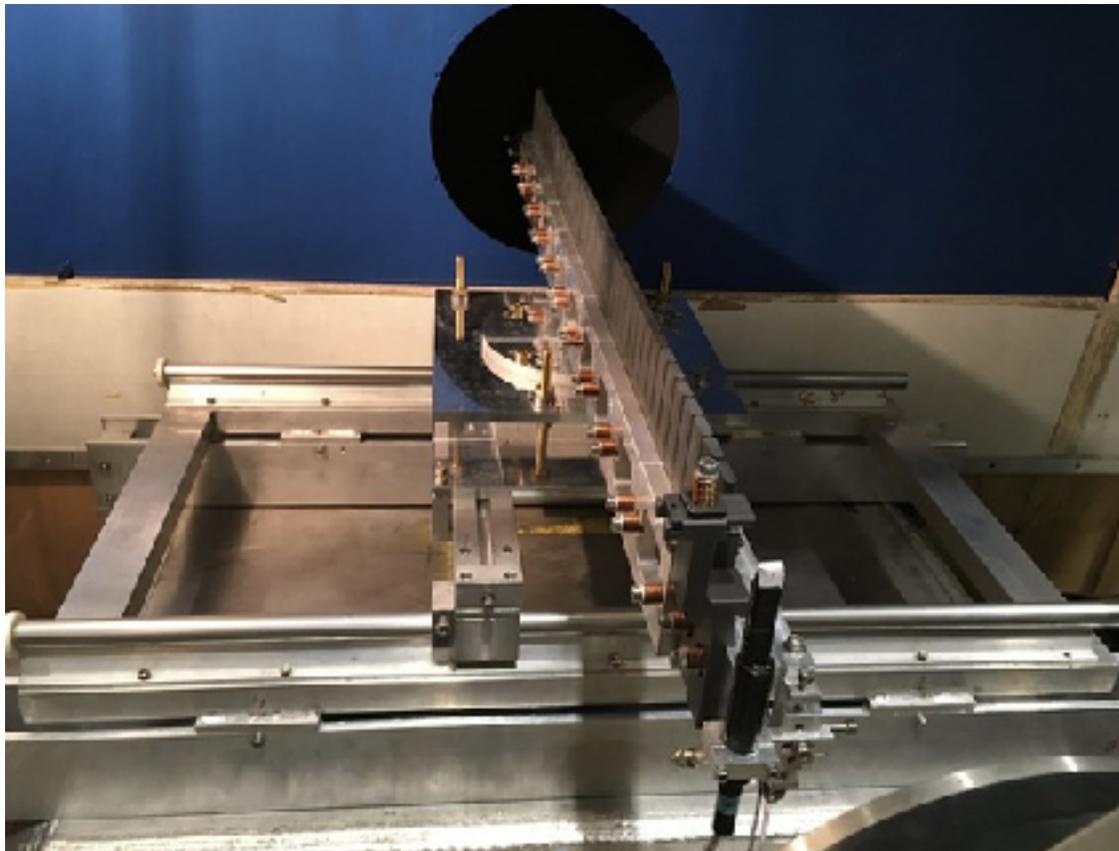


Fig. 2: A NuMI beam target installed in the NA61 experiment. Photo: Eric Zimmerman, University of Colorado.

Measuring individual interactions using thin targets contributes significantly to our understanding of neutrino fluxes, but even better is directly measuring hadrons produced using replicas of the actual neutrino beam targets. NA61/SHINE is also able to do that. In 2018, the collaboration took data on a replica of the NuMI beam target that will be used by experiments in the NuMI beam, including NOvA and MINERvA. Fig. 2 shows the NuMI target installed in NA61/SHINE. The resulting data set is currently being calibrated and analyzed.

Looking into the future, the NA61/SHINE neutrino program will focus on measurements needed by the next generation of neutrino oscillation experiments, including DUNE and T2HK. For example, the collaboration is considering upgraded tracking systems that will enhance the hadron production measurements using replica LBNF/DUNE targets (which will be much longer than currently-operating targets) to enable these experiments to produce high-precision neutrino physics.

ATLAS NSW Upgrade: preparing installation and commission of its first sector

ATLAS

New Small Wheel

LS2

by Panos Charitos (CERN), Members of the ATLAS NSW upgrade team

 [PDF version](#)

The New Small Wheel (NSW) Upgrade is the most complex and challenging Phase-1 Upgrade project of ATLAS. As all the other upgrade projects for the LHC experiments, the goal is to meet the challenges of the High-Luminosity LHC era and to cope with the unprecedented levels of pile up and background rates.



As discussed in a previous EP Newsletter (*A New Small Wheel for ATLAS is taking Shape, December 2018*), the two New Small Wheels will replace the innermost stations of the ATLAS Endcap Muon Spectrometer. While the basic geometry is the same for the two detectors (each consisting of 16 pie-shaped sectors), pretty much nothing else will remain the same: Monitored Drift Tube (MDT), Cathode Strip (CSC) and Thin Gap (TGC) Chambers will be replaced by the novel Micromegas (Micro-mesh gaseous structures) detector technology, in combination with small strip Thin Gap chambers (sTGC). Moreover, the number of detection planes will increase from 4 (in the present CSC region) or 8 (in the MDTs) to 16.

Both Micromegas and sTGC will provide precision tracking and triggering functionality, introducing a high level of redundancy and the means for sophisticated internal consistency checking. In addition, the NSW electronics, which consists of more than 8000 on-detector frontend, readout and trigger boards, uses a novel ASIC, the so called VMM chip custom developed for the upgrade and providing amplifier, shaper, discriminator, charge measurement as well peak detection and timing functionality. More than 50000 VMM chips will be installed in the system, to cover the approximately 2 million readout channels of the MM and sTGC chambers.

During the last eight months, chamber construction has advanced significantly in all production sites: Chile, China, Canada, Israel and Russia for the sTGC, and Germany, France, Italy, Greece and Russia for the Micromegas. Most of the chambers needed to complete the first of the NSWs, have already been built, albeit not yet all delivered to CERN. For the

Micromegas in particular, the team found an instable HV behaviour in some of the chambers chambers and thus performed a number of dedicated tests holding the chambers at the development laboratories. In the past months, substantial progress has been made to efficiently tackle these issues and progress with the building of the detectors; especially in cases that the origin of this instability was due to low resistivity at local spots in some of the Micromegas readout boards. On the electronics side, all but one of the electronics components and cards have successfully passed the Production Readiness Review and today most of the ASICs and several of the electronics cards are in production.

Activities at CERN ramped up drastically in the last months, and are now in full swing in buildings 899 (BB5), 180 and 191. A full NSW sector consists of two sTGC wedges and a Micromegas double wedge; for the first such sector, both parts are currently assembled and prepared for testing

In building BB5, the first micromegas chambers have arrived and double-checked for gas tightness as well as their HV behavior. Following these tests a fraction of the chambers is sent to the dedicated Gamma Irradiation Facility GIF++ in CERN's North Area, and further tested under different irradiation levels to ensure their quality and their ultimate performance. Upon successfully passing these tests, chambers are assembled into what is called a double wedge; the "Micromegas part" of each of the 16 detector sectors.

Literally hundreds of cables must be pre-installed in the Micromegas support structure. They are carefully routed to avoid breaching the stringent geometrical envelopes imposed by the very limited space for the installation of the NSW. Finally, the double wedge is equipped with its electronics, and undergoes a full readout test and a few days of data taking with cosmic rays.

The sTGC chambers have also arrived in building 180. They undergo similar reception tests, like the Micromegas, to spot any faults that may have incurred during the transport procedure. All sTGCs are also checked at the GIF++ facility under high irradiation rates. Following these steps, each of the three chambers is assembled into the sTGC wedge. Wedge assemble is done by placing the sTGC chambers on a granite table, aligning them with great precision against a reference jigging, and then gluing a fiberglass support frame on top of them.

Once the operation is done on one side, the "half wedge" is rotated and the support frame glued to the other side. After this step, the wedge be handled without special vacuum tooling. Services are installed, and each wedge is then again tested for several weeks with the nominal gas mixture at full high voltage. Once electronics cards are available front end boards are installed and the cabling is finished.



Figure 1. Mechanical assembly of a sector. The sTGC wedges are visible on the outside, while the Micromegas double wedge is sandwiched in between them.



Figure 2. A Micromegas double wedge, for a small sector, with all its electronics installed and under cosmic ray validation in BB5

Finally in building 191, the mechanical support structures for the NSWs have been completed. For the A-side one, a major effort went into pre-installing the many cables, fibers, cooling and gas pipes and was successfully completed in May 2019. The structure is now ready for receiving the different detector sectors. The commissioning team took over and equipped building 191 with a gas and cooling system to supply the NSW during tests; they installed the required power supplies, readout and HV allowing to operate up to 2 sectors simultaneously.



Figure 3: The two News Small Wheel structures, ready and waiting for the first detector sector to be installed.

A significant challenge for the team is to establish a smooth procedure for ensuring that a sector works properly, including the trigger path and thus guarantee a smooth operation. Several different approaches will be used, internal pulsing for the VMMs using pre-defined hits patterns, and verifying that they are reconstructed as trigger segments, localized scintillators triggered by cosmic rays and checking that the triggered muons are equally seen in both the MM and sTGC chambers and a full auto-trigger mode for the Micromegas.



Figure 4. The first completed Micromegas large sector double wedge. Large sectors can be installed only when all small sectors are in place. They will be stored therefore for the moment.



Figure 5. sTGC_wedges: Several assembled sTGC wedges during their rHV and longterm gas test in building 180.

The NSW team plans to install the first sector in the next weeks. The results from these tests and the experience gained from its installation will be used for a system review planned for November. At that point, an assessment shall also happen on whether NSW-A will be ready for the planned installation in August next year; Regarding the NSW side C, ATLAS the team aims to install it during the next LHC year-end-technical stop that is scheduled to take place after the first year of Run-3 data taking.

Stay tuned for more developments...

An interview with Nobel Laureate Adam Riess

Interviews

by Panos Charitos

 [PDF version](#)

An interview with Nobel Laureate Adam Riess (Professor of Astronomy and Physics at the Johns Hopkins University) who was jointly awarded the 2011 Nobel Prize for Physics, with

Saul Perlmutter and Brian P. Schmidt, for discovering the accelerated expansion of the Universe. The acceleration of the universe is a startling result that completely changed modern physics revealing that the majority of the universe's mass-energy was of a completely unknown nature. Nima Arkani-Hamed was right to characterize the Discovery of the Higgs and the discovery of the Accelerated expansion of the Universe as the two most dramatic moments in the physics of the 21st century.

We discuss with Riess about his previous work on using Type Ia supernovae to measure the expansion rate of the universe, the steps that lead to this discovery and the role that particle physics could play in interpreting this result. Finally, we ask him about the Hubble constant tension – a topic where he is actively involved – and whether this signals a new era for modern cosmology.



1) What was the path that led you to choose astronomy as a career – were you interested in science from a young age?

As a kid I was fascinated by the big questions about what is out there and for how long our universe existed. These are questions that one could either ask in a religious context or a scientific context and the latter appealed to me.

As a graduate student I was fascinated to learn that the universe is expanding and that we could quantitatively measure this expansion and determine its age. So after my junior year in high school, I spent a month at New Jersey Governor's school of science where I took my first course on Einstein's theory of special relativity. When Jim Supplee started explaining the concepts of space contraction and time dilation I knew that this is what I wanted to follow and I continued in MIT's physics class in 1988 and then to Harvard for my PhD with Bob Kirshner and William Press.

2) Could you tell us a few words about "the discovery of the accelerating expansion of the universe through observations of distant supernovae." for which you won the Nobel Prize in Physics in 2011?

Today we are able to make very precise measurements of the expansion rate of the universe by measuring the distances and redshifts of supernova explosions of Type Ia. The shift in a supernova's spectrum due to the expansion of space gives its redshift (z) and the relation between redshift and distance is used to determine the expansion rate of the universe. Supernovae with greater redshifts, lying at greater distances, reveal the past expansion rate as their light was emitted at an epoch when the universe was younger.

Supernovae Type Ia were the suitable candidate for these measurements as you need objects that are very luminous (thus can be observed even when they are very far) and highly uniform (so that intrinsic scatter doesn't blur the signal). Supernovae Type Ia are the most luminous of the common supernova types, peaking at 4 billion solar luminosities, and thus allowing us to look at extreme large distances. However things can get confused as some are intrinsically more luminous than others requiring careful analysis to precisely estimate their distances. Moreover, variations in the amount of dust along the line of sight further complicates these measurements. Part of the success that led to this discovery, comes from the development of instruments and methods to tackle these issues and to increase the precision of these measurements, particularly by developing new algorithms and also from the use of large format CCDs.

Measuring with accuracy the distance and redshift of Supernovae of Type Ia was the goal of a campaign that we launched 1994. Furthermore, by measuring these quantities for objects that lie even further away we can infer how fast the universe expands at a certain time in the past, perhaps even billions years ago. By comparing the expansion rates at two different epochs of the universe we can estimate the expansion rate of the universe and how it changes over time.

3) What was the first result?

We made this comparison in 1998, using a sample of 15 SNIa, and to our surprise we found that instead of decreasing the expansion rate was speeding up. In other words, the expansion of the universe is accelerating. The result was enabled through our use of a set of 34 nearby SNe (17 supernovae from the Calan/Tololo Survey that both teams used, another 17 from my thesis and my Snapshot paper).

4) What was the original motivation for these measurements?

We wanted to measure the expected deceleration of the universe at larger scales. The hope was to find evidence for some kind of extra matter that theorists predicted might be

out there. Back in the 1990s the assumption was that we live in a dense universe, governed by baryonic and dark matter but astronomers could only observe 30% of the expected matter. Therefore we looked at larger scales to measure the deceleration rate due to gravity as this could give us a hint about the universe's total mass. But instead of decelerating we found that the universe was expanding at an accelerating rate.

Knowing how the expansion decelerated we can predict the amount of mass the universe must have. The higher the mass of the universe the more gravity should pull against its expansion leading to a deceleration of the expansion rate. But what we measured was stunning! The only way to match the measured change in the expansion rate was to allow for some type of "negative" mass. Since there is no such thing as negative mass the result could be interpreted if the universe instead of decelerating is speeding up its expansion.



5) What was the first reactions from your colleagues when the result was announced?

That our result was wrong (laughs). There were understandably different reactions but the fact that two independent teams [the Supernova Cosmology Project and the High-Z Supernova Search Team] were measuring an accelerating expansion rate and the independent confirmation from measurements of the Cosmic Microwave Background made it clear that the universe is accelerating.

We reviewed all possible sources of errors including the presence of some unknown astrophysical process but these were ultimately ruled out. I should add that our previous work in analysing and removing the effects of interstellar dust was also

helpful in this respect. Barring a series of unrelated mistakes, we were looking at a new feature of the universe.

There were other puzzles at that time in cosmology that the idea of an accelerating universe could also solve. The so-called “age crisis”, as many stars were looking older than the age of the universe, was one of them. This meant that either the stellar ages are too high or that there is something wrong with the age of the universe and its expansion. This discrepancy could be resolved taking into account an accelerated expansion and a new value for the Hubble constant. So everything fit together.

6) How this seemingly odd result can be interpreted?

The result reminded us of the cosmological constant that Einstein famously introduced in 1917 to get a static universe though it is clear that we are dealing with something new.

One idea is that the cosmological constant can be linked to the vacuum energy but we know that vacuum energy can't be the final answer. If one sums the contributions from the presumed quantum states in the universe it gets to be an enormous number for the expansion rate; about 120 times higher than what is actually occurring. This acceleration rate is so high that it would have ripped apart galaxies, stars, and planets, before anything formed. So the fact that we observe structures in the universe - and that we exist - tells us that that calculation is grossly inaccurate.

Today we are trying to measure more precisely this expansion rate. This accelerating expansion can be due to what we broadly refer to as dark energy, that is strong enough to push the entire universe but its source and its physics remain unknown. It is an ongoing area of research.

7) By which other methods we try to measure the rate of this expansion?

Today there is a vast range of approaches, using both space and ground experiments, for measuring the acceleration rate of the universe. A lot of work is ongoing to identify more SN Type Ia and measure their distances and redshifts with higher precision.

Other groups are also looking to baryonic acoustic oscillations that would provide a standard “ruler” for measuring cosmological distances in the universe. Imagine a super dense region in the primordial plasma of the universe that gravitationally attracts matter. At a certain point the heat created by the interaction of this matter with photons could create a large amount of outward pressure. The gravity pulling inwards and the heat pressure pushing outwards create oscillations, analogous to sound waves, that are used

to measure the cosmic distance scale and probe the expansion history of the universe. These sound waves lead to the acoustic oscillations seen in CMB anisotropies, but also leave a faint imprint in the clustering of galaxies and matter today.

There are also proposals for using weak gravitational lensing that is extremely sensitive to the parameters describing dark energy as well as the shape and history of the universe. Teams are also looking to red-shift space distortions due to the peculiar velocities of galaxies that can tell us something about the expansion of the universe.

All in all, today we have a variety of tools to understand the nature of dark energy and we hope to be able to learn something new in the next few years.

8) What's the improvement in precision that you aim to gain from future surveys?

The hope is to be able to measure the Equation of State of Dark Energy with 1% precision and the changes of the Equation of State over time with about 10% precision. Achieving this precision will offer a better understanding of whether dark energy is the cosmological constant or perhaps some form of energy temporarily stored in a scalar field that could possibly change over time.

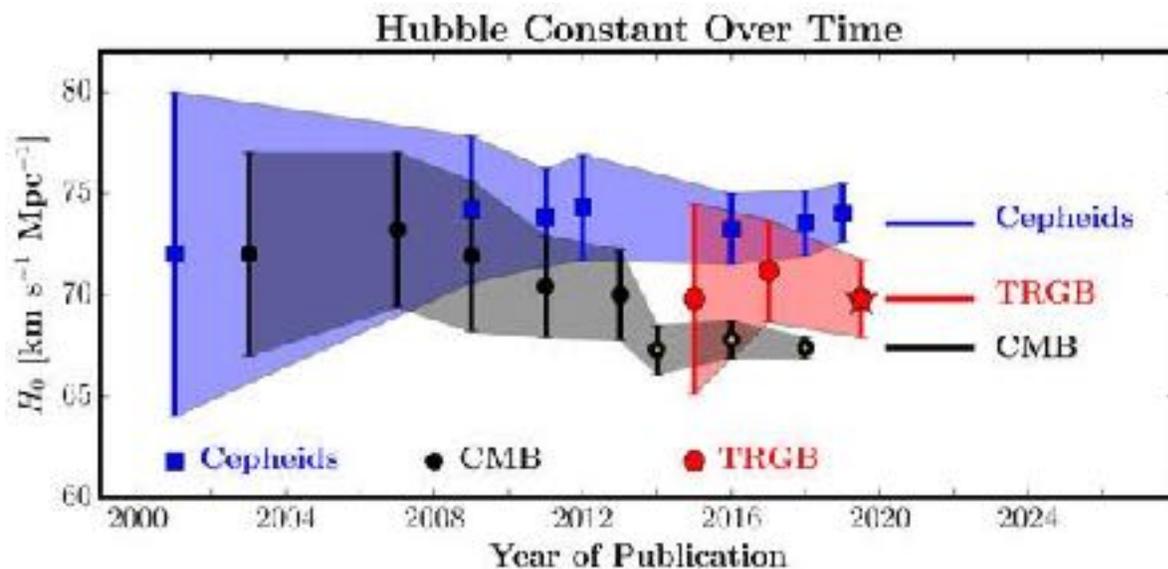
9) Is this one of the topics you are currently involved?

Yes, among other things! I am also working on improving the precision of the measurements of the Hubble constant which characterizes the present state and expansion rate of our universe. Refined measurements of H_0 could also point to potential discrepancies in the cosmological model.

10) What do we mean by referring to the so-called Hubble constant tension?

The problem is that even when we account for dark energy (factoring in any uncertainties we are aware) we get a discrepancy of about 9% when we compare the predicted expansion rate of the universe based on Cosmic Microwave Background data using the Λ CDM model with the present expansion. The uncertainty in this measurement has now gone below 2% leading to a significance of more than 5σ . New observations by the SH0ES program would likely reduce the overall error on H_0 to 1.5%. Moreover, the fact that this result is supported by many independent measurements testifies to its validity.

There is something more profound in the disagreement of these two measurements. One measures how fast the universe is expanding today while the other is based on the physics of the early universe - taking into account a specific model - and measuring how fast it should be expanding. If these values don't agree, we may be missing something in our cosmological model that connects the two epochs in the history of our universe. A new feature in the dark sector of the Universe appears in my view increasingly necessary to explain the present difference between the two values.



The value of the current expansion rate of the universe, also called the Hubble constant, appears to depend on how it's measured. Observations of the early universe give lower values (gray) than those measured using nearby objects (blue). Studies of red giant stars are giving a value of the Hubble constant that's right in the middle (red). Freedman et al. / Astrophysical Journal.

11) When did the seriousness of the H0 discrepancy become clear?

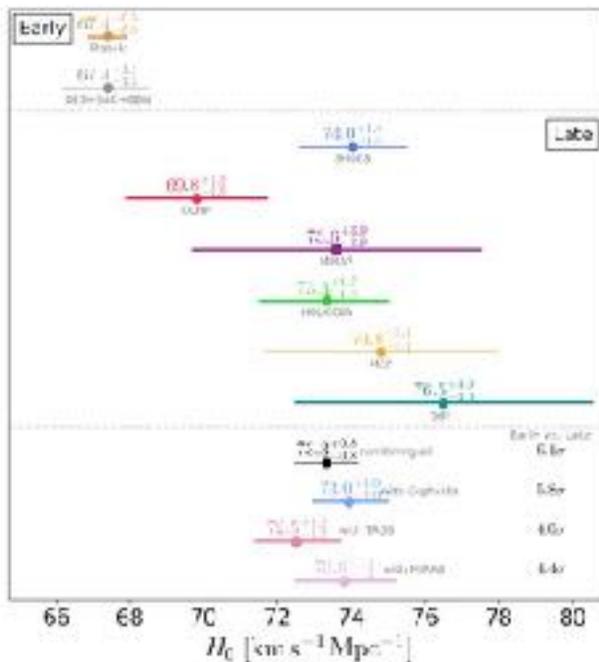
It is hard to pinpoint a date but I would say it was between the publication of first results from Planck in 2013 and the publication of our 2016 paper that measured the Hubble constant to 3% that it became clear there was a discrepancy.

Since then, the tension has been growing and that's why it is difficult to define one day for everyone. Various people were convinced along this way as new data came in while there are people who are still not convinced and perhaps never could be.

11) How can this discrepancy be interpreted?

The standard cosmological model (Λ CDM) is more or less the right model that we use to extrapolate the evolution from the Big Bang to the present cosmos. A model with six free parameters that covers a time length of about 13 billion years. This model is based on certain assumptions, that the space in the early universe is flat, that there are three neutrinos, that dark matter is very uninteresting, that the dark energy is similar to the cosmological constant and that there is no more complex physics.

So one, or perhaps a combination, of the above mentioned things can be wrong. Knowing the original content of the Universe and the physics we should be able to measure how the Universe was expanding in the past and what should be its present expansion rate. The fact that there is a discrepancy means that we don't have the right understanding.



The past decade or so has seen dozens of measurements of the Hubble constant, using sources near (in the box labeled "Late") and far (in the box labeled "Early"). There seems to be a discrepancy depending on whether the measurements are based on the early universe or the present-day universe, as seen in the box labeled "Early vs. Late," though the amount of discrepancy depends on which sources are used. Recent measurements by Freedman and colleagues are labeled "CCHP." Vivien Bonvin / HOLICOW Team

12) Do you have colleagues who are still not convinced about this result?

It is interesting that you ask that as I just came back from a conference in Santa Barbara, California, where this exact question was raised. Almost everybody voted that this was a problem but there were few hands raised expressing alternative ideas. So it seems that this is a serious issue that we have to tackle.

In my view, this diversity of opinions is a healthy sign for science. We shouldn't all think and proceed in the same way. To progress in science we should take into account alternative viewpoints and continuously reassess the evidence we have without taking anything for granted.

13) You've said that the discrepancy "could not plausibly occur by chance". What, then, could be its source?

One idea is an episode of dark energy increasing expansion before recombination, another idea is a new relativistic particle and there have been other ideas like a more complicated form of Dark Matter with unexpected characteristics. It is an interesting and exciting time to explore this question.

We think that the phenomenon that we call inflation is similar to what we call Dark Energy and it is possible that there was another episode in the history of the universe just after the Big Bang and before inflation. There are theories predicting that a form of "early dark energy" becomes significant just before the recombination epoch giving a boost to the Universe that matches our current observations.

Another option is the presence of dark radiation; a term that could account for a new type of neutrino or for another relativistic particle present in the early history of the Universe and important to define its evolution. The presence of dark radiation would change the estimate of the expansion rate before the recombination period and is also a way to address the Hubble constant problem. Future measurement could tell us if other predictions of this theory are correct or not.

14) Does particle physics have a complementary role to play compared to other experiments? Both in terms of research goals but also on other features like big collaborations.

Oh definitely. Both collider and astrophysics experiments could potentially reveal either a property of dark matter or a new relativistic particle or something that will change the cosmological calculations and solve some of the open questions. Particle physics is related to early universe physics and of course it plays a role.

In my view there is a certain overlap concerning the contributions of these fields in understanding the physics of the early universe, a lot of cross-talk and blurring of the lines and that's healthy for deepening our understanding of nature.

Moreover science today is done in really large teams, which means that you have a larger pool of ideas and possible solutions to problems coming in. This poses a challenge as you need to have people coming from a very wide range of backgrounds, cultures, upbringing, education because you really need a broader set of ideas for a scientific collaboration to succeed.

15) Has receiving the Nobel Prize at such a relatively early age being a blessing or a curse?

It has been a great honour. You can choose whether you want to do science or not as long as this choice is available. So certainly the Nobel is not a curse. You just have to recognize the freedom of choices that you have.

16) You had mentioned that we live in an exciting period as we can quantitatively answer many questions that were previously left for the Rabbi or the Priest. I am wondering which are the questions today left for the Rabbi?

I think you could still ask them whether there was a sort of creator who made this universe for us to discover these wonders and ask questions about what existed before the Big Bang. These are areas that we presently have limited ability to answer with science. Of course this can change at any moment. Science doesn't have a scale or a particular area where it can or can't work. Curiosity drives us to explore different scales of nature for evidence that could help us understand the universe.

17) Which are the future challenges for your research?

Our team is continuing trying to refine the measurements we have been taking while this is a growing community. Hopefully, if you come back in a couple of years we will have more answers to your questions.

Discussing synergies between particle physics, astrophysics and nuclear physics

by Caterina Doglioni (Lund University)

 [PDF version](#)

One overarching objective of science is to further our understanding of the universe, from its early stages to its current state and future evolution. This depends on gaining insight on the universe's most macroscopic components, for example galaxies and stars, as well as describing its smallest components, namely elementary particles and nuclei and their interactions. It is clear that this endeavor requires combined expertise from the fields of astroparticle physics, particle physics and nuclear physics.

A number of the contributions and discussions at the recent Granada meeting for the update of the [European Strategy of Particle Physics](#), as well as the contribution at the EPS-HEP ECFA Open Session summarized in this newsletter, highlighted a growing wish for closer collaboration between ECFA and the astrophysics (APPEC) and nuclear physics (NuPECC) communities.

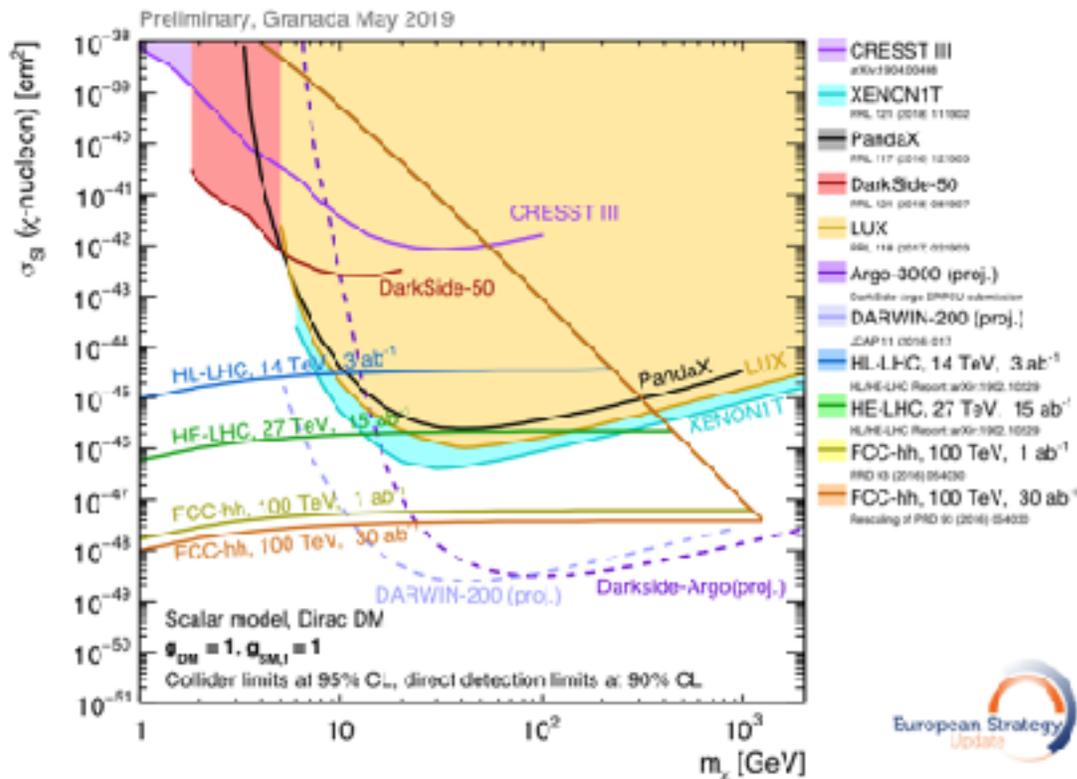
Many physics problems where synergies between particle physics, astrophysics and nuclear physics are required are discussed in the APPEC and NuPECC strategy documents (see links at the bottom of this piece). Among those, this contribution focused on the challenge of elucidating the nature of 27% of the matter-energy content of the universe, commonly called "dark matter". Pursuing these scientific goals also requires mastering challenges related to instrumentation (e.g. beams and detectors), data acquisition, selection and analysis, and making data and results available to the broader science communities. Joint work and recognition of these "foundation" topics, also covered in detail in the contributions by C. Biscari, A. Cattai and G. A. Stewart in the ECFA newsletter [1], will help all communities grow towards their individual and common scientific goals. This contribution presented one of the many common challenges faced by particle physics and astrophysics: the necessity of dealing with large, sometimes heterogeneous datasets and derive insight from them in short periods of time.

New physics discoveries and dark matter

The Large Hadron Collider has yielded the discovery of a new particle, the Higgs boson. Precision measurements and fits of other quantities in the Standard Model of Particle Physics guided a search lasting decades after the conception of the Higgs mechanism. With the European Strategy Update, the particle physics community is currently deciding what are the best tools to employ to test the Standard Model: "how/where to look next for new physics" is a relevant question in this process, given that hints coming from the Standard Model itself

are not as telling as in the case of the Higgs boson. For this reason, research directions for physics beyond the Standard Model can be found in open problems in astrophysics that need a systematic exploration, for example the determination of the nature of dark matter.

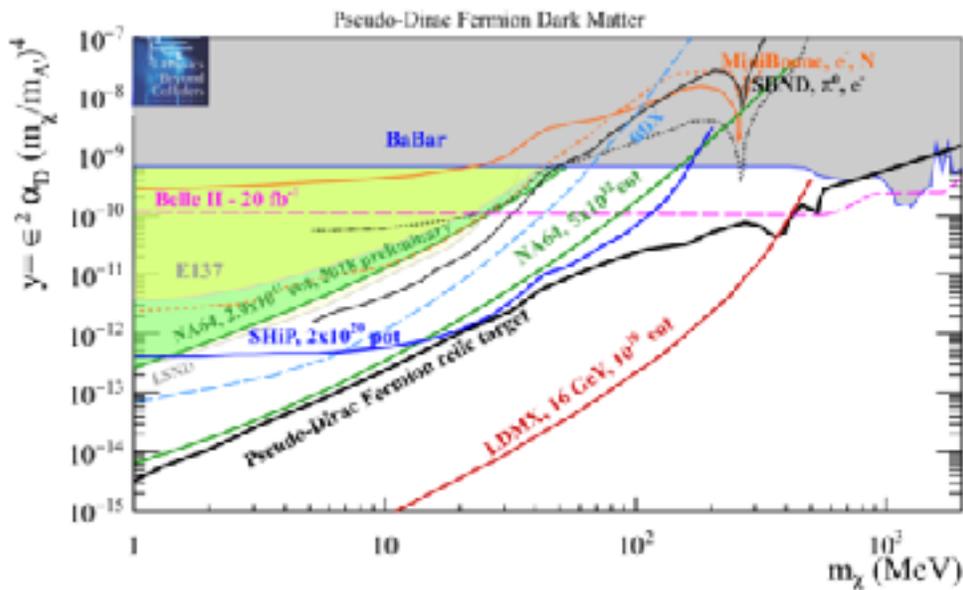
One of the many explanations for this dark matter is that it is composed by new massive particles that interact only weakly with ordinary matter particles, or Weakly Interacting Massive Particles (WIMPs). These new particles can be produced at colliders, as well as detected by direct and indirect detection astrophysics experiments in space and underground (see [2] and links for a summary). By producing new particles in the lab, colliders are well placed to understand the nature of these particle's interactions with ordinary matter. The necessary confirmation that these new particles have also a cosmological origin comes from complementary observations in direct and indirect detection experiments.



Comparison of sensitivities of future collider and direct detection experiments within a simplified model scenario of a WIMP where the interaction between Standard Model quarks and the dark matter is mediated by a new scalar particle. If DM is composed by particles within this model with a mass between 10 GeV and 1 TeV, future colliders and direct detection experiment can confirm each other's discoveries in the next decades. Taken from C. Doglioni's talk in the EPPSU meeting in Granada [3], to appear in the EPPSU Briefing Book.

The WIMP scenario shown in Figure 1 in the previous paragraph represents only a very simple benchmark in the landscape of theories on the nature of dark matter. Many other

compelling explanations exist: for example the WIMP can be identified with the lightest, stable and invisible particle included in many supersymmetric models that also answer other outstanding questions of the Standard Model. Alternatives to the WIMP paradigm also exist, for example models where the dark matter particle is much lighter and has a mass below the GeV. In these cases, searches at collider and direct detection experiments are complementary to searches at other planned dedicated accelerator experiments (e.g. beam dump experiments such as SHIP [3], NA64 [4], and LDMX [5] among others), as well as underground experiments using novel sensor technologies (e.g. SENSEI [6] and DAMIC [7]).



Comparison of sensitivities of future collider and non-collider experiments for a model of light dark matter being produced via a new dark boson, showing the complementarity between different kinds of experiments in different ranges of dark matter particle mass and couplings with the dark boson. Taken from R. Poettgen's talk in the EPPSU meeting in Granada [9], to appear in the EPPSU Briefing Book.

Axions (and axion-like particles) [10] also may be connected to solutions of the dark matter problem, being the DM particle candidate themselves or the mediators of the SM-DM interaction. Synergies between many different experiments and theoretical frameworks is evident in the case of those particles. Depending on the mass range and coupling of those particles, a discovery of such particles may occur at the high-luminosity LHC, at lepton colliders (e.g. Belle II [11]) or at high-precision experiments that search for these particles directly (e.g. IAXO [12] and ADMX [13]), or measure fundamental constants sensitive to fifth forces. Interaction between the members of these different experimental communities, as well as with theory and astrophysics, are needed to shape the future search program of these complementary experiments.

In general, connecting results and potential discoveries from different experiments within a coherent framework requires both particle and astroparticle physics theory involvement. This

effort has been started by the [LHC Dark Matter Working Group](#), where the Astroparticle community wishes to be further involved (see [14]). A parallel effort for non-WIMP, non-collider dark matter and dark sector searches is ongoing within the [Physics Beyond Colliders Working Group](#).

A connection to nuclear physics in these and other (e.g. beam dump) dark matter experiments is needed to fully understand instrumental and beam backgrounds, as well as simulation. Particle and astroparticle experiments searching for dark matter also benefit from cross-talk in terms of instrumentation (e.g. sensors and cryogenics) and interpretation of results.

“Data firehoses” and shared solutions in high energy physics and astrophysics

Another example of a common challenge for different fields is the ever-increasing volume of data available to different fields of research. Examples of current “data firehoses” are the LHC, especially in light of the planned high-luminosity upgrade, and upcoming astrophysics surveys such as [LSST](#) and [SKA](#) to name but two. Similar challenges in data acquisition and recording are present in neutrino physics experiments, in the case of their supernova detection data streams. In all these cases, a fast and close-to-real-time analysis of the data is necessary, so that events of interest can be recorded or investigated further in a timely and cost-effective way, and common real-time analysis solutions are being investigated and deployed by multiple experiments.

Another point of contact is when software solutions are shared across fields, for example in the case of gravitational waves and high energy physics with the CernVM software appliance [15] and the RUCIO distributed data management system that is in use by LHC experiments and will be adopted by neutrino experiments as well [16].

Collaborative efforts

A number of platforms and fora exist at CERN and in Europe to facilitate cross-talk among different communities. In addition to the already-mentioned Dark Matter Working Group, there are (just to name a few) the recently inaugurated European Center for [Astroparticle Physics currently hosted by CERN](#), the European Science Cluster for Astronomy & Particle physics [ESFRI research infrastructures project](#), the [HEP Software Foundation](#) to facilitate cooperation and common effort in software and computing, as well as the very successful [CERN neutrino platform](#).

Conclusions

The examples brought forward in this EPS-HEP contribution are only a very limited subset of how the particle, astroparticle and nuclear physics communities can be answering challenging scientific questions together. Other topics where synergies exist mentioned during the session were axion-like particles [10], the theory and experimental efforts bridging

the gap between nuclear and high energy physics [17], and the opportunities offered by astrophysics experiments (e.g. Auger) spanning a much higher and complementary energy regime with respect to nuclear and particle physics experiments.

Since detector technologies are often common to different communities, the CERN expertise stemming from the current world-leading collider program can be reused. Moreover, data collection and analysis benefit from becoming faster, more efficient and more open: using versatile computing strategies and tools to solve diverse problems encourages common expertise that lasts beyond a single experiment.

In conclusion, there is the common wish that the European Strategy process will facilitate closer collaboration between the particle, astroparticle and nuclear physics communities, in a context where the design of detectors, data acquisition systems and computing are an integral part in our quest to understand the universe.

References

- [1] <https://cds.cern.ch/record/2688156/files/ECFA-Newsletter-3-Summer2019-final.pdf>
- [2] <https://atlas.cern/updates/atlas-feature/dark-matter>
- [3] C. Doglioni's talk at EPPSU Granada <https://indico.cern.ch/event/808335/contributions/3373983/>
- [4] <https://ship.web.cern.ch/ship/>
- [5] <https://na64.web.cern.ch>
- [6] <https://confluence.slac.stanford.edu/display/MME/Light+Dark+Matter+Experiment>
- [7] <http://news.fnal.gov/2017/09/hunt-light-dark-matter/>
- [8] <https://damic.uchicago.edu>
- [9] <https://indico.cern.ch/event/808335/contributions/3374018/> (R. Poettgen's talk at EPPSU Granada).
- [10] <https://ep-news.web.cern.ch/content/axion-particle-searches-lhc> and I. Irastorza's talk at EPS-HEP: <https://indico.cern.ch/event/577856/contributions/3396833/>
- [11] <https://www.belle2.org>
- [12] <https://cerncourier.com/a/iixo-the-international-axion-observatory/>
- [13] <https://depts.washington.edu/admx/>
- [14] <https://www.appec.org/news/eppsu-and-the-synergy-of-astroparticle-and-particle-physics>
- [15] <http://ep-news.web.cern.ch/content/cernvm-2019-workshop>

[16] <https://home.cern/news/news/computing/managing-scientific-data-exascale-rucio>

[17] J. Fiete's talk at EPS-HEP: <https://indico.cern.ch/event/577856/contributions/3396853/>

More information on astroparticle and nuclear physics strategies at the following websites:

- APPEC: <https://www.appec.org>,

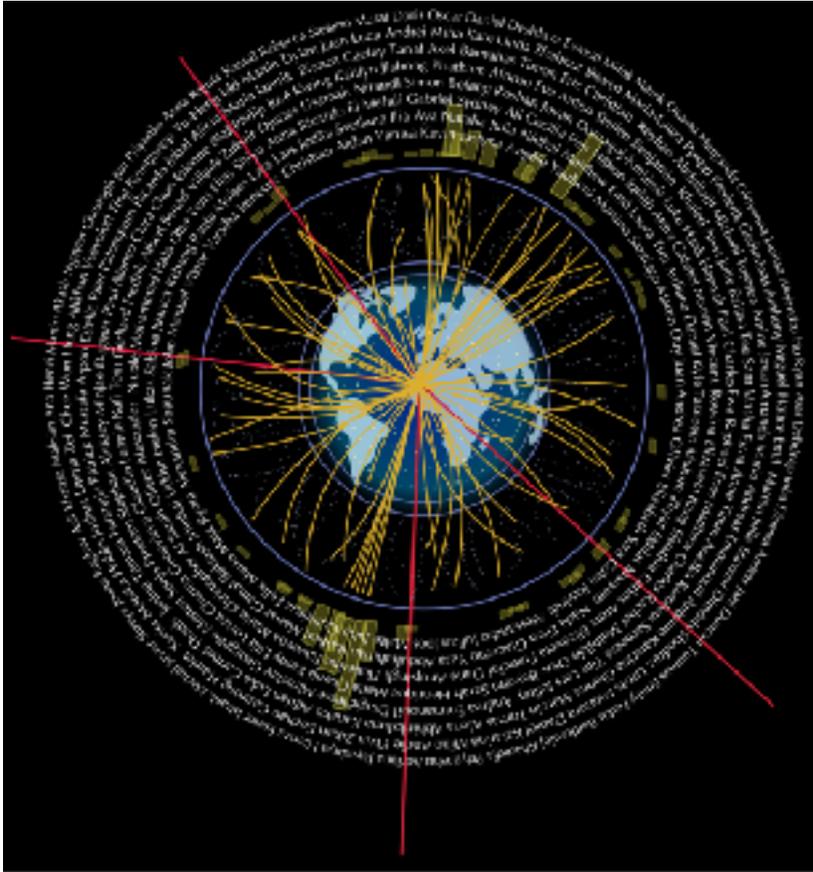
- NuPECC: <http://www.nupecc.org>

Summer students 2019: A Supercalifragilisticexpialidocious experience

CERN Summer Students

by Panos Charitos

 [PDF version](#)



Established in 1962, by CERN's former Director General Victor Weisskopf, the laboratory's summer students programme welcomed more than 300 undergraduates from all over the world to get a hands-on experience of CERN's diverse activities.

From physics research to software development and from R&D in novel technologies to knowledge transfer, summer students broaden their horizons in the inspiring international environment of CERN. Over the years, the summer student programme has flourished and this summer almost 300 students from

92 countries arrived at CERN. During the programme, they have the opportunity to attend a series of lectures from world-renowned experts on a wide range of topics reflecting the laboratory's mission. Moreover, they work on a special project under the guidance and supervision of more senior researcher. Their results are presented in a number of occasions including dedicated workshops and a Summer Student poster session.

The Member State Summer Student Programme is organized by CERN's HR team, while the Non-Member State component offers the opportunity to students from other countries to be part of this unique experience. The steadily increasing number of applications reflects the attractiveness of the programme worldwide. It should be noted that the development of the NMS Summer Students Programme is today an important part of CERN's policy to promote greater global integration in the field of particle physics and accelerator technologies.

Being a summer student at CERN is not only about research experience and hard training in high-energy physics. It is also an exercise in openness and diversity. Over an intense training period that lasts from 8 to 13 weeks, students learn to appreciate different perspectives, values and ideas which are key elements for progressing in science but also in building a more open society. During their time at CERN, students have the chance to interact and make new friendships; Getting to grips with diversity and inclusion is a life-changing experience and a journey of personal development.



It's really hard to summarize the experiences that CERN's summer students programme offers to its participants in an article and this is why following past year's tradition we have developed an [interactive map](#). Among them you can read about [Arpon Paul's](#) unexpected encounters, [Eissa](#)

[Alnasrallah's](#) big questions, [Ardiana's Journey to CERN](#), [Abdullatif Rashdan's](#) unforgettable experience, [Daniel Prelipcean's](#) vision for open science, [Kyungseop Yoon's](#) account of the analogy between HEP and classical music, [Laura Bruce's](#) journey to the land of the immeasurable and [Piter Paye Mamami's](#) Supercalifragilisticoespialidoso experience.

Though few weeks seems like a short time, CERN's summer student programme is a transformative experience, equipping students for the rest of their academic and professional life. Take this opportunity and apply for next year's summer student programme: <https://home.cern/summer-student-programme>

Baby MIND prepares for first physics run with WAGASCI at T2K

by Etam Noah (University of Geneva)

 [PDF version](#)

Extracting ever more precise information from long-baseline neutrino oscillation experiments calls for a better understanding of neutrino production and neutrino interactions with their target detectors, through experimental programmes dedicated to neutrino cross-section measurements and validation of neutrino interaction models. The challenge is in the extrapolation from interaction rates at the near detectors to predictions for observed events at the far detector as a function of neutrino oscillation parameters. To address this challenge, the general approach is to reduce the associated systematic errors from flux, detector and neutrino interaction model uncertainties.

The T2K WAGASCI experiment aims at measuring neutrino cross-sections in water (the target material of the Super-Kamiokande far detector) and hydrocarbon (CH) around 1 GeV. It is part of an extensive program of cross-section measurements at the near detector hall by the T2K collaboration that includes the existing ND280 near detector, and an upgrade to the ND280 due online in 2022.

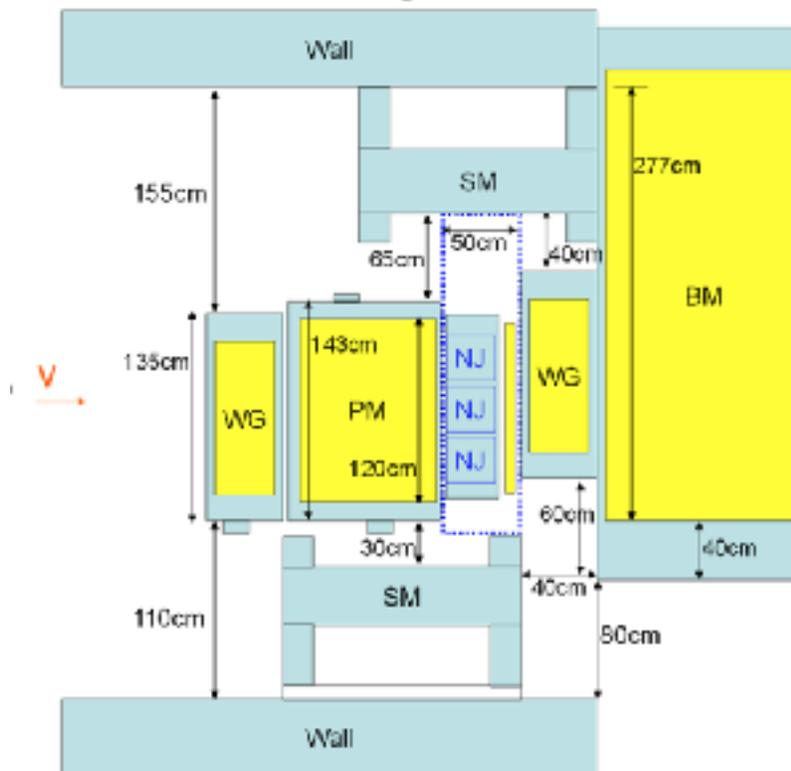


Figure 1. The WAGASCI experiment detector layout: WG=WAGASCI, PM=Proton Module, NJ=Ninja, SM=Side muon range detector, BM=Baby MIND.

The Baby MIND detector was designed, assembled and tested at CERN as part of the Neutrino Platform NP05 project (link [here](#)). It will track muons produced when neutrinos interact with detector materials through the dominant Charged Current Quasi Elastic (CCQE) neutrino-nucleon interactions, measuring their momentum and identifying their charge with high efficiency in the momentum range 0.4 to 5 GeV/c. The charge ID capabilities are especially important to reject background events, which arise from the beam itself. The muon neutrinos of interest are produced from the decay of positive pions. Each such decay also produces a positive muon. It is the decay of these secondary muons that generates the unwanted backgrounds, electron neutrinos and muon anti-neutrinos. By changing the polarity of the magnetic horns that focus the pions before decay, it is possible to obtain a muon anti-neutrino beam from negative pions. The fraction of unwanted background events from secondary muon neutrinos can be as large as 30% in this beam mode.

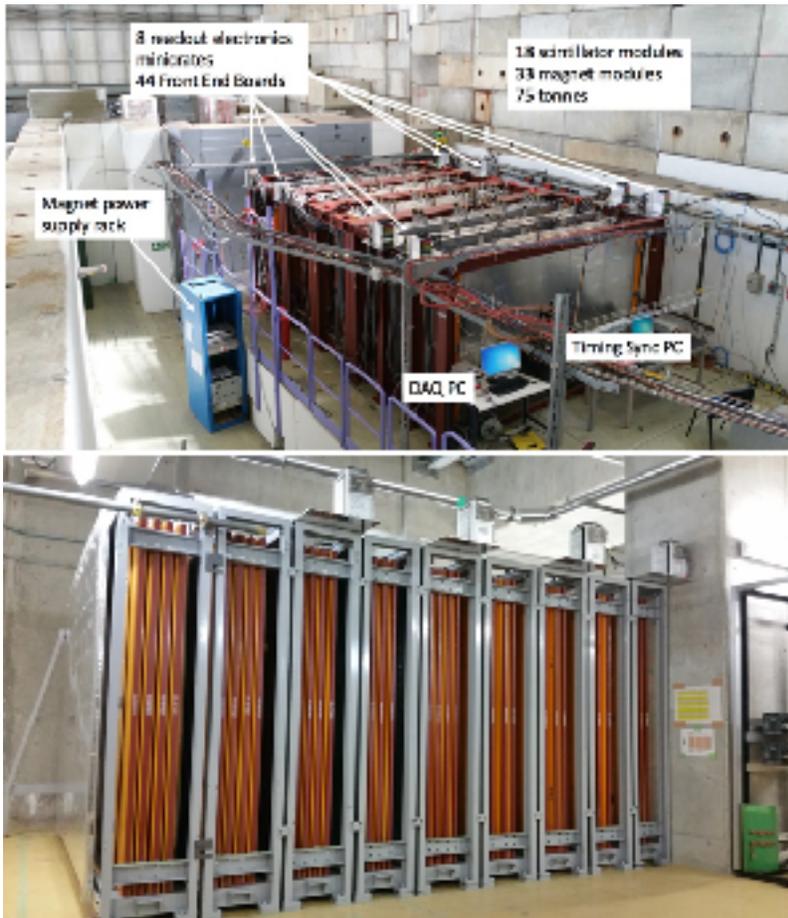


Figure 2. Baby MIND at CERN (top) during beam tests at the PS experimental hall in 2017 and at J-PARC (bottom) at the end of the 2-week installation phase in 2018.

The main CERN hardware contribution is the design and construction of the warm magnet system, a novel system proposed by the EP-ADO group. The 33 ARMCO steel magnet modules each with their own air-cooled aluminium coils, mark a departure from the more traditional layout with a coil around a large monolithic steel block. The design offers the advantage of very uniform magnetic field lines across the detector volume that are fully contained within the magnet steel resulting in moderate 10 kW power consumption for 1.5 T. Compactness and modularity are further advantages as the 2 tonne magnet modules can be handled independently for transport and installation.

Baby MIND was installed at J-PARC over a 2-week period in 2018. The magnet and scintillator module assemblies were lowered into the experiment pit from the surface of the Neutrino Monitor (NM) building through a restricted shaft access opening one at a time. They were then transported at the pit floor level from the shaft area to their intended positions in support structures hosting 3 or 4 modules. Handling operations were delicate, having to comply at all times with very stringent earthquake safety directives at J-PARC, which is hosted within a Japanese Atomic Energy Agency (JAEA) campus. Commissioning of Baby MIND at J-PARC was then carried out to check the detector was fully functional after transport and re-assembly, and confirmed good synchronisation of the readout electronics with the T2K beam.

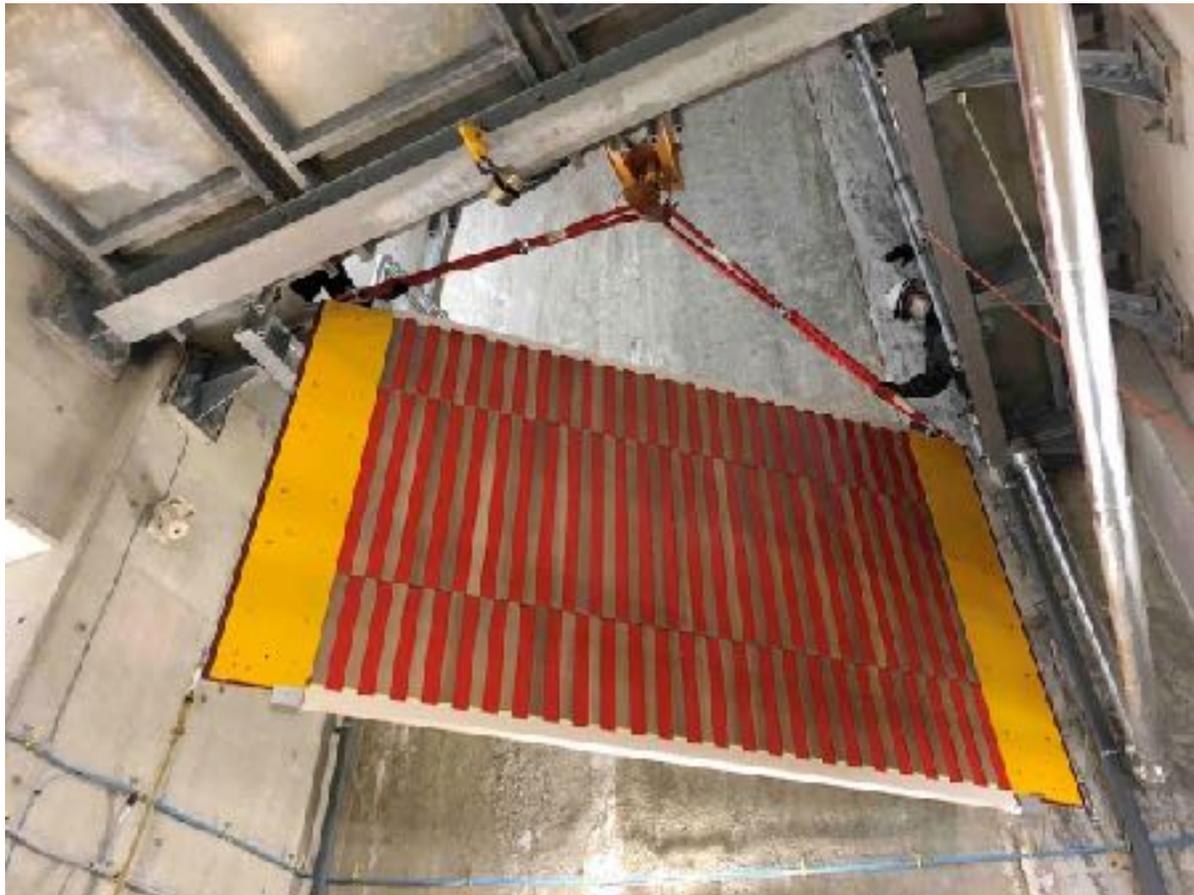


Figure 3. A magnet module being lowered into the pit at J-PARC.



Figure 4. View from the surface floor of the Neutrino Monitoring (NM) building at J-PARC showing the lowering of a Baby MIND magnet and scintillator module assembly down the shaft to the pit (B2) floor, past the ND280 detector which is enclosed in the CERN-donated UA1 magnet.

The WAGASCI experiment will operate two main neutrino target types, the fully active plastic scintillator Proton Module, and the WAGASCI detector modules. The latter consist of a 3D grid-like lattice of rectangular cuboids with active plastic scintillator walls and passive water-filled inner volumes. A very high water to scintillator ratio (4:1) is obtained in this way. This high ratio, combined with the 4 Pi tracking capabilities and low detection threshold for protons and pions open up a range of possibilities for cross-section measurements in water.

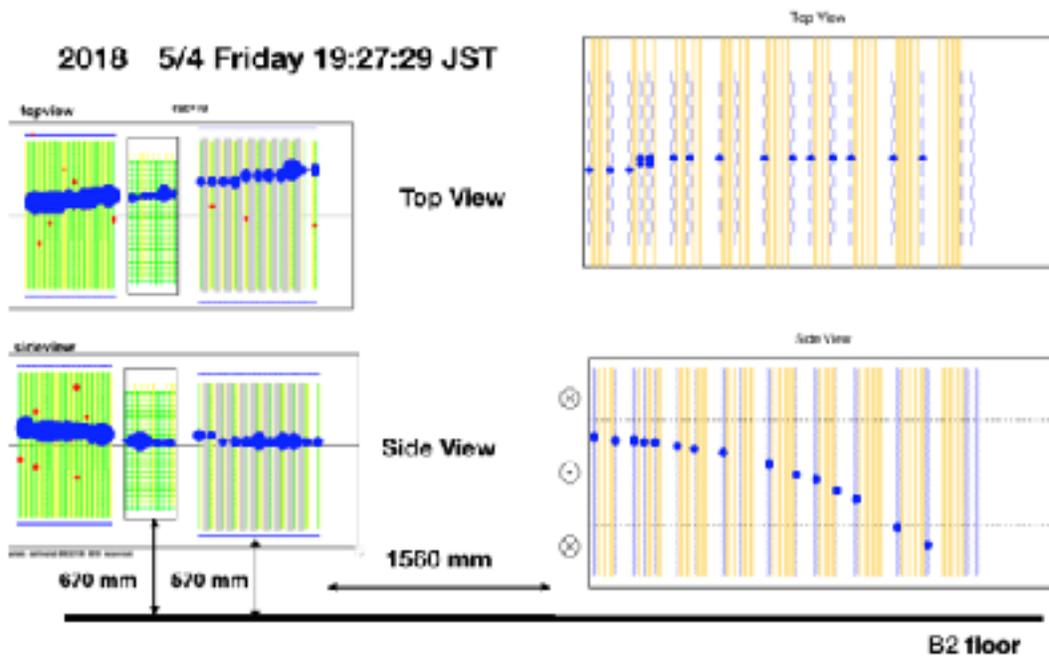


Figure 5. Event display obtained during the Baby MIND commissioning run in 2018: neutrino interaction upstream of Baby MIND with the resulting muon incident on Baby MIND from the left.

WAGASCI is located at an off-axis angle of 1.5 degrees, different to the 2.5 degrees off-axis angle of the T2K ND280 and Super-K detectors which are 280 m and 295 km from the neutrino source respectively. Placing the detector "off-axis" with respect to the primary proton beam axis narrows the neutrino beam spectrum and lowers its peak. By subtracting fluxes at ND280 and WAGASCI, even narrower "pseudo-monochromatic" beams can be obtained, from 0.2 to 0.9 GeV and from 0.6 to 2 GeV. This method will be studied through the measurement of flux-integrated cross-sections at these two fluxes.

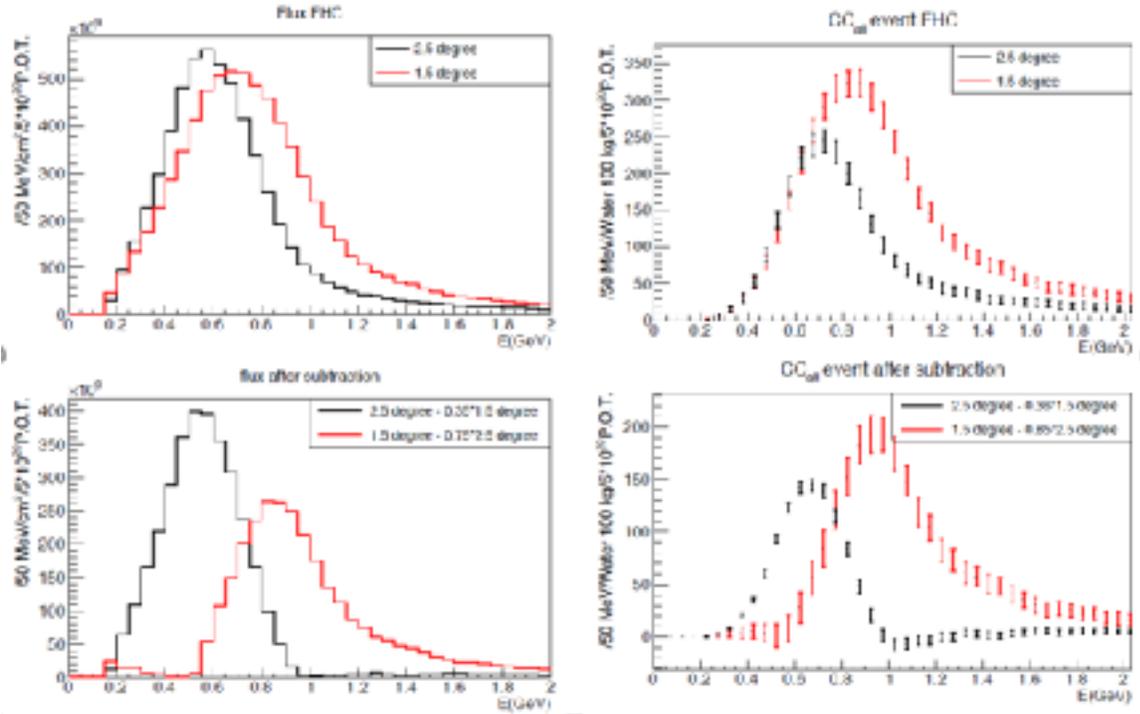


Figure 6. Energy spectra obtained by using different off-axis angle fluxes. The top two plots show the energy distribution of the fluxes (left) and neutrino interactions (right) for ND280 (2.5 degrees off-axis) and WAGASCI (1.5 degrees off-axis). The bottom plots show the spectra obtained by subtraction of ND280 and WAGASCI fluxes.

The WAGASCI concept has already produced two of the most precise measurements of neutrino interaction cross-sections in water at 0.9 GeV and 1.5 GeV mean neutrino energies. With the complete WAGASCI setup that now includes Baby MIND with its ability to tell the charge of the outgoing muon, and the side MRDs that extend the range of angles over which muons can be observed, we can look forward to a wide program of cross-section measurements on H₂O, CH and Fe including absolute cross-sections, cross-section ratios, inclusive and exclusive double-differential cross-sections.

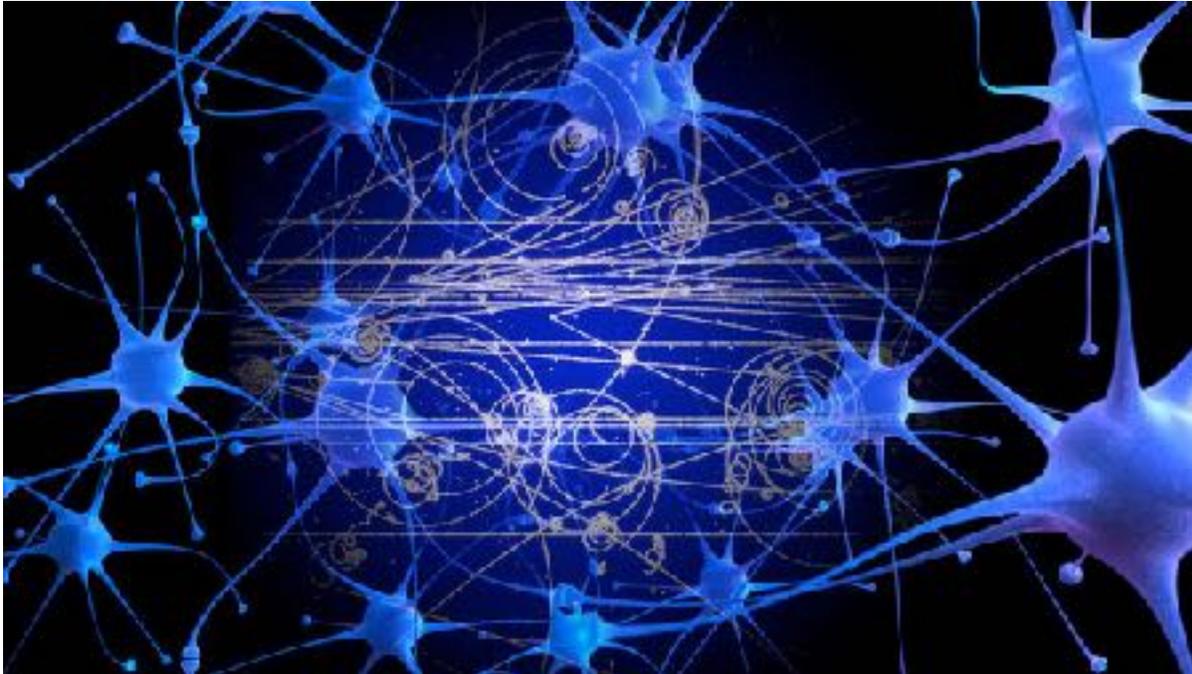
by Sandro Marchioro (CERN, ESE group)

 [PDF version](#)

I have spent a considerable amount of my time as Master student in Physics in the late 70's performing a fairly prosaic function that nevertheless required the presence of humans (physics professors, trained technicians and of course students): scanning thousands of BEBC pictures with (occasional) neutrino events, a task that today would simply be called "pattern recognition".

The task consisted in looking more or less simultaneously at several images showing the inside of the BEBC chamber where charged particles had deposited a very volatile and ethereal image of their own passage under the form of tracks made of tiny gas bubbles that could be photographed with some stereo cameras. A good event coming from a neutrino interaction had to have the collision point generated within a fiducial volume well inside the BEBC cylinder. Computers in the '70s were already sufficiently powerful that once a potential good track was pointed out to them, its precise geometry could be calculated without too much trouble. But the very fact of recognising such tracks as seen from a set of stereo cameras was still only in the realm of human pattern recognition. Instructions for human scanners were reasonably simple and easy to perform: search for a vertex within the fiducial volume with so and so many out-coming tracks with more or less this bending: if found, use a sort of primitive mouse device to select certain points on the tracks in all available projections (this was the tricky part), and ask the computer to work-out if such hypothesis was consistent with having chosen the right tracks in all projections, and finally - if everything went well — let the computer calculate the kinematic for the event. Repeat.

The first week of such task was very exciting, red LEDs flashing in the computer room, a smooth and regular noise coming from the stepping-motors used to move the huge rolls of high resolution film, even air-conditioning was available, and surely my human nature made me dream that on those pictures I could possibly make some great discovery; nevertheless, after several thousand pictures a day, drudgery came up fast and my brain started wondering in some other direction.



Without the shadow of a doubt today this function could be performed by a computer appropriately programmed to execute one of the many “machine learning”, “neural network” or “artificial intelligence” (pick one) algorithms that are promising to change the way machines interact with sensors and actuators in so many application fields. Today millions of images of far greater complexity than those simple BEBC pictures are analysed daily in real time for all sort of purposes using CPUs, GPUs or other high power Vector or Tensor Units, all trying to imitate in a more or less “brain inspired” way what we humans can perform with such apparent ease.

A huge design community with expertise between computer science and electronics is currently working at moving some of the algorithms (or parts thereof) used in such applications to more energy efficient hardware. After all, we humans spend continuously of the order of just 10W to see, recognise, analyse, store, elaborate, interpret and correlate images and their implications, but our best machines are still orders of magnitudes away from such performances and the opportunities for improvements are huge.

While people carefully avoid the use of the two words “artificial intelligence”, what they are trying to achieve is precisely to imitate - at least at some levels - the synthesis capability of the human brain by recognising and predicting behaviours from information rich in details but also of redundancy and noise. Surely the definition of true “intelligence” is sufficiently vague that philosophical discussions on the matter will continue for years to come, but even a fairly primitive self-driving car system - in my humble opinion - is far more intelligent than what I was doing during (part of) my Master thesis.

Many modern machine learning algorithms run on computers with almost infinite digital precision, but researchers have quickly realised that many algorithms are very undemanding in terms of precision (exactly like the we can recognise a face after years of ageing of within a very noisy, discoloured or partial image). This suggests that certain features could be computed through the more imprecise but potentially much lower power “analog” circuits without loss of accuracy on the final result.

The development of algorithms cannot be decoupled from the development of suitable architectures. Essentially all modern computers are built around the separation of processing and (several levels of) memory storage, while processing is so embedded in the operation of the human brain that nobody has yet been able to separate the two components within it. This hints that while suitable for initial explorations, standard computers or even fancy tensorial units may in the long term not be the best tools to integrate widely diffused machine learning. In-memory-processing may be the way to go, and many academic and commercial researchers are looking into new materials, circuits and architectures to implement such ideas with many impressive results as those shown at recent conferences and workshops on these subjects.

A recent [seminar](#), organized by CERN’s EP department, of Prof. Boris Murmann (Stanford University EE Department) illustrated some of these advances, with particular emphasis on work aimed at a drastic optimization of the power consumption of such machines. He showed how analog and digital circuit and system design have to proceed hand-in-hand to make such future systems efficient. In the present state of relatively shallow theoretical understanding of the fundamental mathematics underlying the behavior of these machines, mixing people with different backgrounds and expertise and attack problems from different angles is also very important.

Boundaries between analog and digital may indeed become fuzzy, but does it really matter if at the end the algorithm works?

Scientists in High Energy Physics have historically been early and visionary adopters of many advanced technologies: they have been willing to bet their career on new materials (for instance silicon sensors long before commercial imagers came of age), advanced technologies (for instance deep sub-micron well before the space and military communities) or even architectures (up to the mid-80s people in HEP were literally making their own computers). They have also been courageous enough to build machines and experiments of unprecedented size and complexities for scientific purposes, and also have not hesitated to conceive experiments to collect unheard-of quantities of data. It is therefore very reasonable to predict that the process of looking at and interpreting data will soon have to be complemented by the adoption of new techniques coming from the machine-learning community and that future experiments will be enthusiastic adopters of such techniques.

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