EP Newsletter of the EP department

Welcome to the autumn issue of the EP newsletter!

It has been a busy and exciting summer with a wealth of new results presented by the LHC experiments at international conferences. The first observation of Higgs boson coupling with top and bottom quarks reported by both ATLAS and CMS is yet another remarkable confirmation of the Standard Model of particle physics, but also marks an important step forward in our understanding of the origin of mass. While benefiting from the exceptional performance of the LHC, these latest results utilised new improved analysis techniques and machine learning algorithms - about which you read in our previous issue.

Progress in particle physics often relies on breakthroughs in instrumentation. This is one of the motivations for the new R&D initiative of the EP department on new Detector Technologies. After the very successful workshop in March this year (reported on in the spring issue), the definition of the programme is now in its final phase. Eight working group have converged over the summer on the selection of the most relevant technologies in the fields of detectors, experimental magnets, electronics and software. The results of this intense process - detailed work plans and resource estimates - will be presented to the community in a public event on the 25th of September.

Two related efforts, covered in this issue, concern the design of the VELOpix chip for LHCb and new readout chips for the CMS detector to cope with the challenges of HL-LHC. You can also read about the ROOT user's workshop discussing the challenges and future shape of this comprehensive analysis software framework, to meet the requirements of the particle and nuclear physics community. As has now become a tradition, we have also prepared an interactive world map reflecting the diversity of cultures, regions and topics that characterise the CERN summer students' programme.

Finally, this edition features a special focus on axion searches and CERN's active role in this field. Theorised in the '70s by Wilczek and Weinberg, the axion could solve the strong CP problem while certain classes could also account for dark matter. We talked to the key protagonists, Helen Quinn, Roberto Peccei and Pierre Sikivie, and present the different approaches followed by experiments at CERN to search for this elusive particle.

I hope that you will enjoy reading the new issue.

Christian Joram,

A glimpse on CERN's 2018 summer students programme.

Summer Students Programme
Member States
Non-member states
by ***Panos Charitos***

PDF version

This year CERN welcomed more than 250 students from all over the world as part of its summer student's programme (Credits: Julien Ordan, CERN)

Each summer CERN welcomes undergraduate students from all over the world to pursue research projects in physics or related science and technical disciplines.

During an intense programme that lasts from 8 to 13 weeks, students have the chance to develop their own scientific projects and immerse in immerse in certain aspects of frontier research. In addition to their work as members of an experimental team, students are offered a series of introductory lectures on a variety of topics: from particle physics to accelerator technologies. The variety of topics offers a deeper understanding of the mission of the laboratory and its ongoing R&D programmes.

Moreover, summer students have the chance to visit various sites around CERN, including experimental and accelerator areas, and get a hands-on experience in CERN workshops. Like previous years, they had the chance to present their work in a dedicated poster session in CERN's main building. Like every year, the organizers had prepared a rich and diverse programme of activities in order to offer the students an unforgettable experience.

A group photo in front of CERN's R2 restaurant (Credits: Anna Mestvirishvilli @CERN).

CERN's summer students programme offer a multidisciplinary and multicultural environment that not only provide valuable skills to participants but also inspires them to think about a scientific career. It demonstrates that CERN is not only a centre of scientific excellence but also a place that trains the scientists and innovators of tomorrow. After all, many former Summer Sudents have gone on to bright careers in science and they have often facilitated scientific collaborations between CERN and their countries!

Being part of CERN's summer student programme is a once-in-a-lifetime opportunity to make valuable and long-lasting contacts with fellow researchers from all over the world. More than 250 students from 50 countries travel to CERN every summer becoming part of a big and diverse mosaic of cultures.

Among them you can meet in this issue: **Kathryn Coldham** from the UK who worked on the High-Granularity calorimeter for CMS, **Ann Njeri** from Kenya joining the team the develops a new GEM facility, **Diyaselis Delgado López** from the Caribbean island of Puerto Rico involved in data analysis for CMS, **Paul Richard Stein** working on simulations for the performance of the electromagnetic calorimeter for a future collider and **Sabrina Milagros Zacarias** working for the RD50 collaboration.

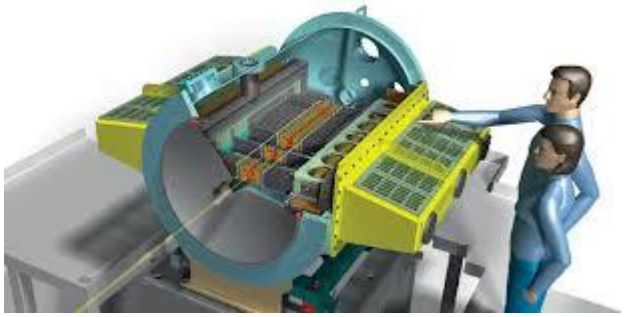
Explore an **interactive map** and travel around the world with their stories*.

The author would like to warmly thank Mrs. Despoina Driva (HR - Member States Summer student programme) and Mrs. Eszter Badinova (IR - NMS Summer Students Programme) for their help in the preparation of this article.

VeloPix, a new hybrid pixel readout ASIC for the LHCb upgrade.

*by **Paula Collins, Jan Buytaert***

The LHCb-VELO group, which is composed of several institutes from the UK, Spain, Netherlands, Russia, Brazil and CERN are constructing an upgraded version of the VErtex LOcator (VELO) to be installed and commissioned during the long shutdown LS2 in 2019/2020. Unlike the currently operating strip detector, which enters its final year of very successful operation and has truly performed beyond expectation, it will be a pixel based detector made of nearly 41 million small square (55um x 55um) sensing elements. This change is mandated by the requirement to perform pattern recognition at 40 MHz in a full software trigger and to cope with a five-fold increase in luminosity. The new pixel detector will also approach the LHC colliding beams by an unprecedented 5 mm.



To design a new readout ASIC called VeloPix, LHCb has benefited enormously from the vast experience of the Medipix/Timepix design team of the CERN and Nikhef micro-electronics groups. The development of the “Timepix3” ASIC, in which LHCb has actively participated, already demonstrated several of the new concepts required for the final VeloPix. Because space inside a pixel is very limited and one wants to add as much functionality as possible, a new approach with so-called logic super-pixel groups has been implemented, where pixels share common functionality such as time tagging, hit buffering and readout control. Furthermore, a new data driven readout was introduced, which means that as soon as a pixel was hit by a particle, a small data packet would be created and flow off chip without any further traffic control. For VeloPix a major challenge remained, namely a further ten- fold increase in total data rate while limiting the power consumption. This issue was addressed by implementing four multi-gigabit/sec serial outputs on the ASIC, providing a sustained output rate of nearly 20 Gigabit/s. The complete detector consists of 624 ASICs delivering a sustained data rate of nearly 2 Terabit/s over 1020 optical links to an online computing farm. Further adding to the complexity of this ASIC is the very high radiation environment and vacuum in which it will operate.

A first ASIC was submitted for fabrication in 2016 and extensively tested in the past months. Some errors, such as single event latch-up, appeared unexpectedly and were interpreted as a consequence of a recent change of ASIC manufacturer. Also, excessive clock jitter degraded significantly the quality of the serial data transmission.

A new fabrication, which successfully addressed these issues, was launched in 2017 and all silicon wafers have successfully been tested in a wafer probe station. The dies are now being thinned and bump bonded to the sensors. The construction of the detector modules will start this summer, in time for completion and installation of the full detector in a year from now.

Developing new electronics for the CMS tracking system.

by ***Panos Charitos. Kostas Kloukinas***

The High Luminosity Large Hadron Collider (HL-LHC) entails a substantial upgrade of the CMS tracking system, to cope with much more demanding requirements and to implement additional functionalities. One of the main challenges for the experiments is the increased number of pile up events which for an instantaneous luminosity of $5\times 10^{34} cm^{-2} s^{-1}$ corresponds to more than 100 pileup events per bunch crossing at an operating frequency of 40MHz. Thus, good spatial and time resolution become increasingly important in order to distinguish between different primary events. In addition, a higher number of jets is posing an extra challenge for the HL-LHC upgrade of the CMS detector.

The event filtering at Level-1 becomes substantially more challenging at HL-LHC, not only because the rate of events passing a given selection scales with the instantaneous luminosity, but also because the performance of selection algorithms degrades with increasing pile-up. Selection of good events at the first trigger level need to be enhanced by the Tracker information, ensuring the rejection of tracks with low momentum.

The CMS tracker is required to provide prompt information of particles with high transverse momentum reducing “on-line” the amount of data that will be transmitted to the back-end. The main novelty is the capability of tracking charged particles with a transverse momentum (p_T) higher than a certain threshold (nominally 2 GeV/c) at each bunch crossing (i.e. every 25 ns). These particles are not interesting for the Level-1 reconstruction and rejecting them with pT threshold of 1–2 GeV/c reduces the bandwidth requirements by at least one order of magnitude.

The capability of reconstructing physics events during the High Luminosity phase of the LHC together with the requirement of reducing the detector material budget makes the design of this new particle tracking system a hard engineering challenge. On the one hand, introducing the “intelligence” to select interesting information at front-end level requires very complex and power hungry readout electronics. On the other hand, minimizing the amount of interactions of the incoming particles with the detector material makes necessary the reduction of the cooling system material, the power supply cables and consequently of the power consumption. Moreover, the new detector is required to have improved radiation tolerance to withstand radiation levels up to $10^{16} n_{eq} cm^{-2}$.

As **Kostas Kloukinas (CERN),** explains: “The Outer Tracker modules must recognize particles with low transverse momentum (p_T) and provide selected information for the Level-1 trigger at each bunch crossing while at the same time store locally the full information and transmit it out only upon a positive L1 trigger decision. To achieve this function, we exploit the bending effect of the particle trajectory inside the 3.8 T magnetic field of the CMS detector as a function of the particles p_T. The concept consists of correlating signals in two closely-spaced sensors where the distance between the hits is correlated with the particle *pT* , allowing the *pT* discrimination to be made. A pair of hits that fulfils the selection cut is called a “stub”, and its coordinates are sent out for the Level-1 processing. This process is similar to building a vector of these high-momentum particles the so-called “stub”. The requirement to identify a particle’s stub together with the limited power and material budget drive the development of the Outer Tracker modules.

Figure 1 depicts the construction of a novel detector module consisting of one Pixel sensor and one Strip forming the so-called Pixel-Strip (PS) module. The correlation of the coordinates

measured by the two sensors in the *x–y* plane enables the *pT* discrimination, while the segmentation of the pixelated sensor along the *z* direction (R direction in end-cap configuration), provides a precision coordinate that contributes to the required *z*0 resolution for the reconstructed track.

The PS module to operate requires high-speed real time interconnects between the readout ASICs of the new chip. SSAs are bump-bonded on the electronics hybrid while the MPAs are bump-bonded on the sensor and wire-bonded to the electronics hybrid as shown in Figure 2.

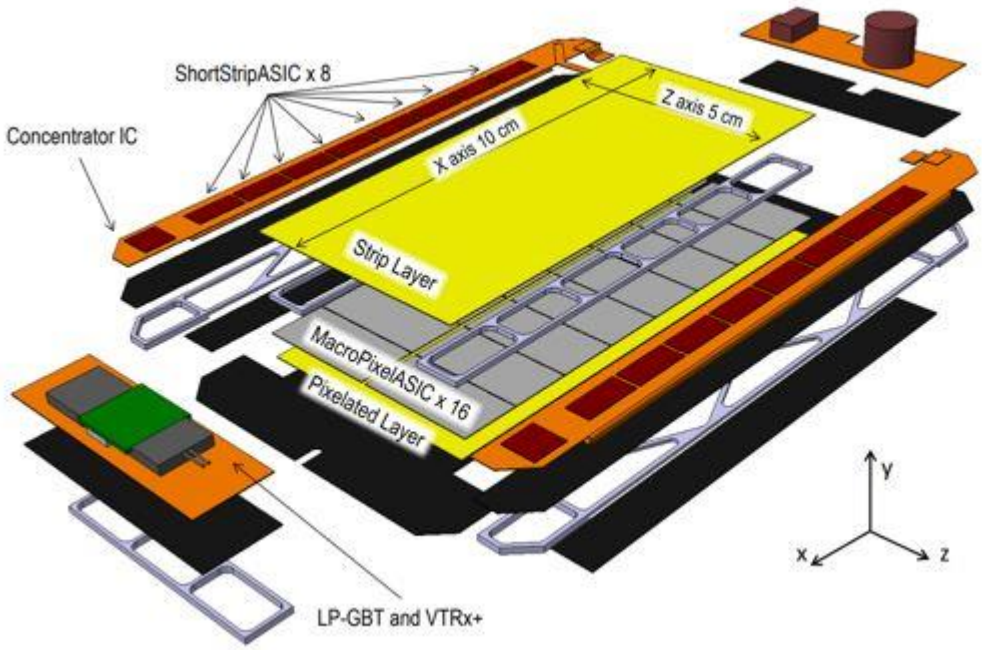


Figure 1: Pixel-Strip (PS) module exploded view. The stack consists of (bottom to top) a cooling plate (black), a pixel sensor (yellow), a layer of 16 MPAs (grey), two Al-CF sensor spacers (ligth blue), 2 FrontEnd hybrids (orange) housing the SSA (red) and the Concentrator IC (red), 2 service hybrids (orange) housing the optical link (green) and the DCDC converters (brown) and a short-strip detector (yellow).

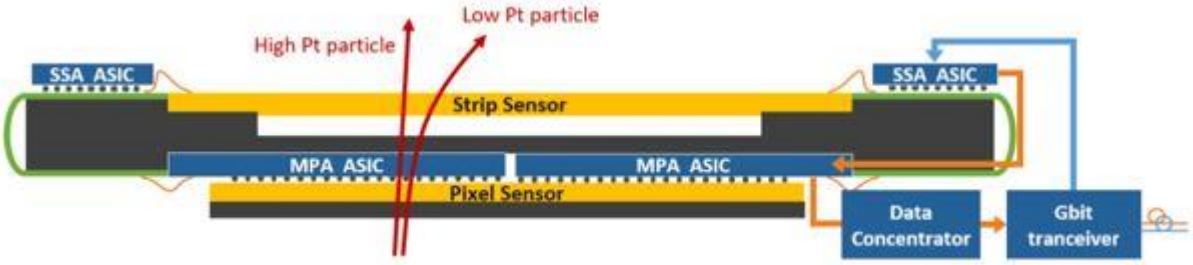


Figure 2: Cross-section of the Pixel-Strip (PS) module.

ELECTRONICS

The new design adopts a double layer sensor architecture in order to provide a fast on-detector identification of high transverse momentum tracks for the Level-1 trigger while rejecting local signals. For this purpose, the innermost part of the outer tracker is based on a combination of a pixelated sensor with a short strip sensor, the so-called Pixel-Strip module (PS). The new module can be placed with different orientations in the outer CMS tracker: in the barrel layers, the beam is

parallel to the z-axis of the module, while in the end cap layers, it is parallel to the y-axis of the module and in both configurations the x-axis stays on the r-phi plane. Along the x-axis, the dimensions of the strips and pixels length is 100 µm, while along the z-axis it is 2.5 cm for the strips and 1.5 mm for the pixels.

The complex logic and the large storage capabilities required by the design would suggest to move to a very down-scaled technology in order to reduce the power consumption. Commercially available CMOS technologies include deep sub-micron nodes down to 28 nm, but going to deep downscaled technologies would ensure an even lower power consumption, but it would strongly increase the prototyping cost, require a new campaign for radiation possibly causing unnecessary delays in the project.

Besides functionalities, the other specifications which drive the design are the physical constraints. The pixel segmentation is constrained by the granularity requirements of the upgrade, while the ASIC size is limited by the requirement of planarity for the module assembly.

The new chip consists of two strip sensors (1920 strips per module) and a Macro-Pixel sensor with more than 30.720 pixel channels as shown in Figure.1. The readout of these sensors is carried out by distinct ASICs, the Strip Sensor ASIC (SSA), for the strip layer, and the Macro Pixel ASIC (MPA) for the pixel layer.

The event reconstruction performances are influenced by the amount of material in the tracker fiducial volume introducing a limit in the material allowed for the cooling and the power distribution. This leads to the very challenging power density requirement of < 90 mW/cm^2 and to a total power consumption requirement of 250 mW per MPA-SSA couple.

The Short-Strip sensor readout ASIC (SSA)

Since the PS-module strip sensor is composed by 1920 strips disposed in two columns, 16 SSAs per module are necessary for the readout operation.

As **Alessandro Caratelli (CERN)** explains: the SSA ASIC comprises a low-noise (ENC < 800 *e*−) front-end followed by double-threshold dis- crimination circuits to detect and distinguish normal incidence particles from highly ionizing particles (HIPs). Particle hits are sorted in clusters which are filtered using a programmable thresh- old aperture to reduce bandwidth and data processing. Encoded clusters are transmitted at the bunch-crossing frequency of 40 *MHz* to the MPA ASIC for correlation with hits from the pixel detector layer thus allowing the on-detector rejection of non-interesting events with consequent data reduction by factor ≈ 20. Full sensor particle hits are also stored in the on-chip radiation tolerant SRAM for a period of up to 12.8 µ*s* and are being transmitted to the MPA readout path upon a level-1 (L1) trigger command. L1 trigger rates up to 1 *MHz* and up to 16 consecutive triggers can be accommodated without loss of triggered events.
Low-power and radiation hardening design techniques have been employed to fulfill the very tight power consumption requirement of 50 *mW* per chip and the capability to resist up to an integrated ionizing dose of 200 *Mrad*.

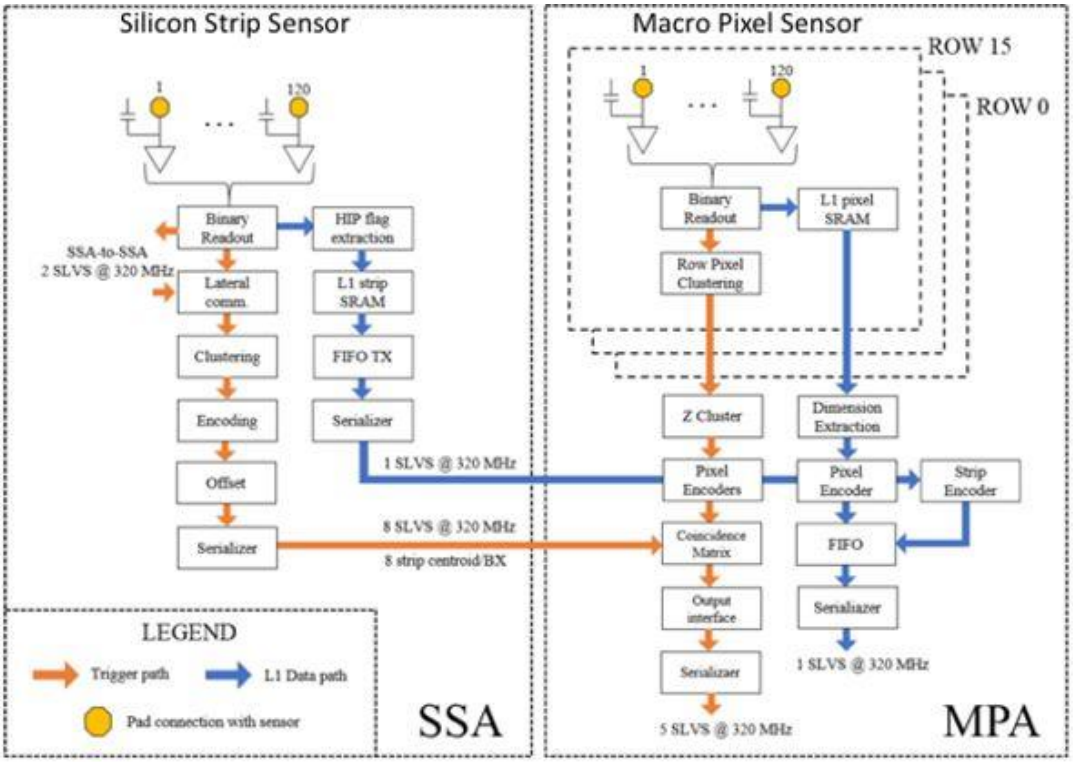


Figure. 3 SSA-MPA chipset.

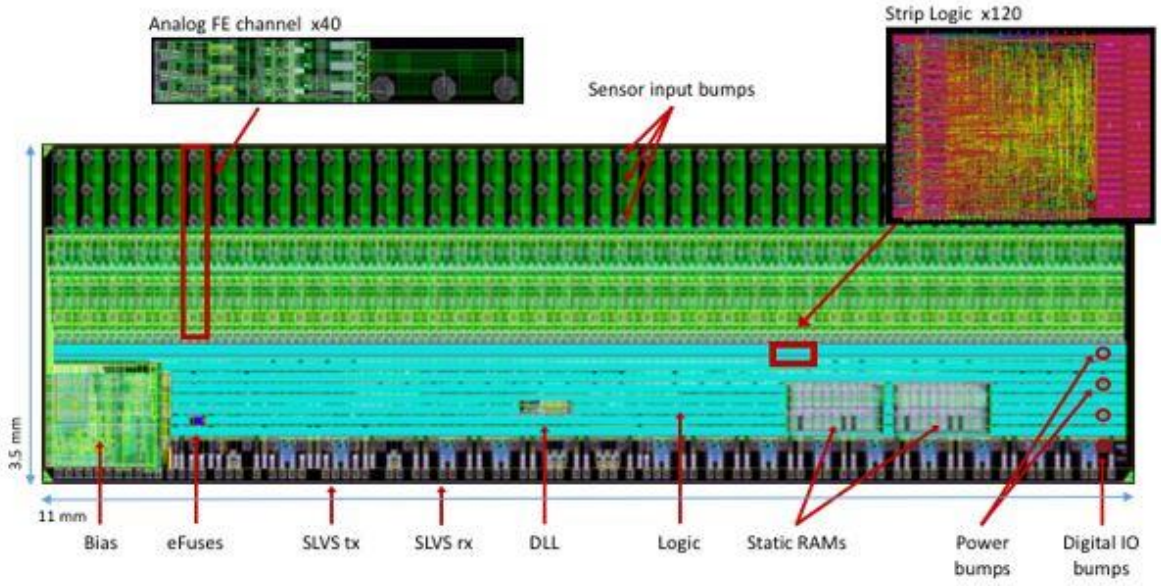
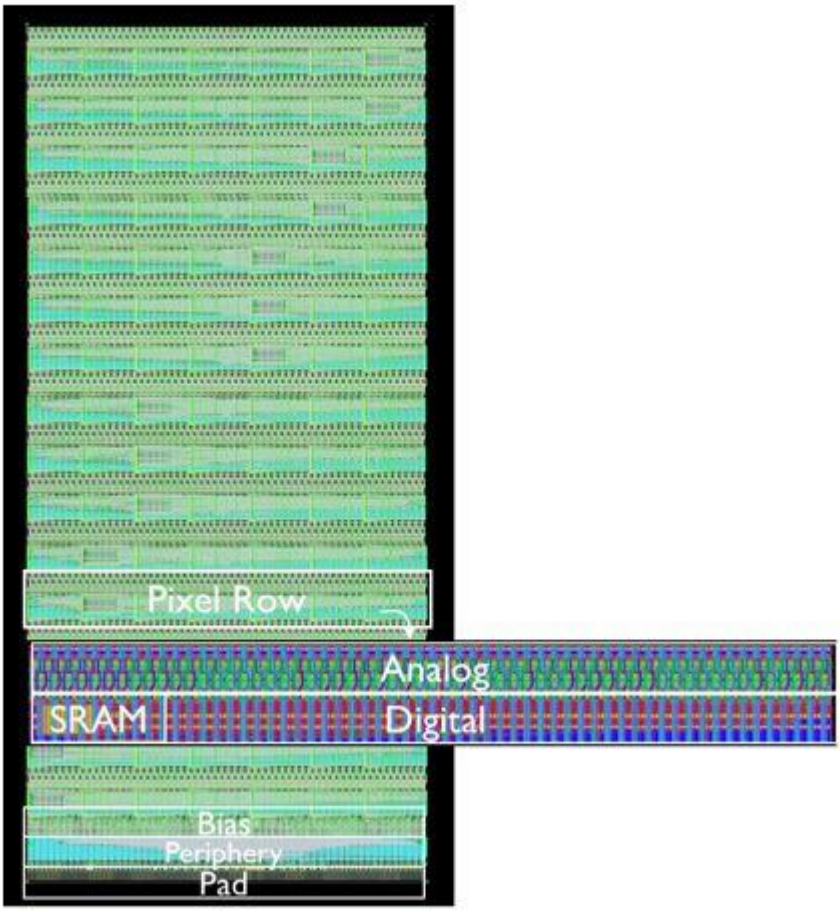


Figure 4 Layout of the SSA prototype.

Macro Pixel sensor readout ASIC (MPA)

The large size of the pixelated sensor requires the use of 16 MPA ASICs for reading out a single sensor. The pixel segmentation is constrained by the granularity requirements of the upgrade, while the ASIC size is limited by the requirement of planarity for the module assembly. Consequently, given a pixel of 100 µm x 1446 µm, the pixel array per MPA contains 16 rows and 120 columns. With these dimensions, the large size of the pixel sensor requires the use of 16 MPAs for reading out a single sensor.

As **Davide Ceresa (CERN)** explains: The MPA features a binary readout that works continuously at the 40 MHz bunch crossing rate. The binary data are processed in parallel through two readout paths: L1 data and “stub” finding readout paths. The L1 data readout path stores the binary image of the pixel sensor in radiation tolerant memories for the L1 Latency and transmits them if requested by an L1 trigger signal. The L1 data are zero-suppressed and contain also the L1 strip data from the SSA. The “stub” finding readout path continuously applies zero suppression to the pixel binary data and combines them with the strip binary data from the SSA to compute the particle’s transverse momentum. The generated “stubs” are transmitted synchronously to the trigger system. The top-level architecture of the MPA is shown in Figure 3.



Perhaps, one of the most challenging constraint of the MPA development is the limited power budget available to carry out the complex functions. Given also the large area of the chip, another non-negligible contribution to the power consumption is the bunch-crossing synchronous on-chip data transport of the hits. To contain the power consumption within the permitted limit, the design team implemented several low power techniques. Limiting the transport of data along the long axis (11mm) of the chip and performing the hit finding operation at the pixel row level allows to reduce power consumption. Similarly, the L1 data pipeline memories are located at the row level instead of the periphery of the ASIC and a memory gating technique, has been developed to limit the power consumption exploiting the low hit occupancy in the outer part of the CMS Tracker. The pixel array readout logic must operate synchronously to the bunch crossing 40MHz clock. The electrical activity of a conventional clock distribution network consists of the 40% of the total power consumption. To mitigate this problem, a special clock distribution technique is employed using a mixed approach of a clock-trunk along the long axis of the chip and clock-tree buffers along the pixel rows. Multi-Supply Voltage technique was also used to operate the most power hungry digital

core logic at a reduced power supply voltage. Since the power consumption is proportional to the square of the power supply voltage

Silicon prototypes

The use of advanced semiconductor technologies entails very important prototype engineering costs. The prototyping cost of the MPA and SSA ASICs on a 64nm CMOS process is in the region of a million US dollars. Therefore, first silicon success is primordial in containing the development costs. To achieve this goal, the designs need to be fully verified for error-free functionality and as well as for compliance with the manufacturer's design rules. The extensive use of specialized state-of-the-art Electronic Design Automation (EDA) tools is crucial in the design process. It can be said that the amount of the verification effort for the MPA SSA ASICs was equal if not higher than the design development efforts.

The first full size prototypes of the MPA and SSA ASICs, integrating all functionalities for in system operation, were submitted for fabrication in September 2017. Both designs were prototyped on a common fabrication run known in industry as MPW (Multi-Project Wafer) run in order to minimize fabrication costs. Silicon wafer prototypes were received at CERN two months later. Figure 6 shows a silicon wafer with MPA and SSA ASICs mounted on a 300 mm wafer probe station at CERN waiting to be electrically tested. This wafer probe station is a newly acquired equipment, hosted in the EP-ESE/ME group which is indispensable in order to test the large (300mm) wafers.

A custom test-bench was developed to facilitate the functional testing and performance characterization of the MPA and SSA ASICs at wafer level as well as individually diced form. Figure 7 shows the MPA-SSA teste-bench system while Figure 8 shows diced parts mounted on their corresponding PCB carrier boards.

The electrical characterization has proven the functionalities of the full front-end analog chain and a first version of the Stub Finding logic. Radiation tests have shown the functionalities of the design up to doses higher than 300 Mrad. In addition, the demonstrator helped the team to short out several technical aspects related to the Module Assembly.

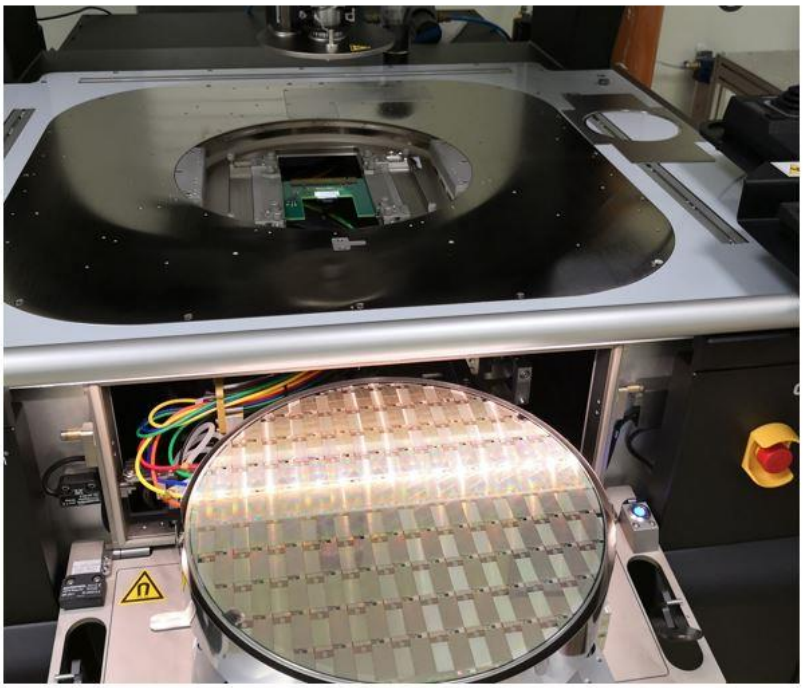


Figure 6. Silicon wafers with MPA & SSA prototype ASICs mounted on a 300mm wafer prober at CERN.

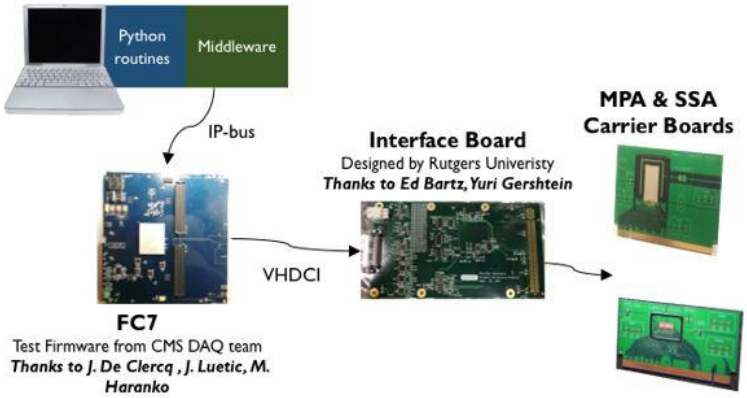


Figure 7. MPA-SSA prototype test bench system at CERN.

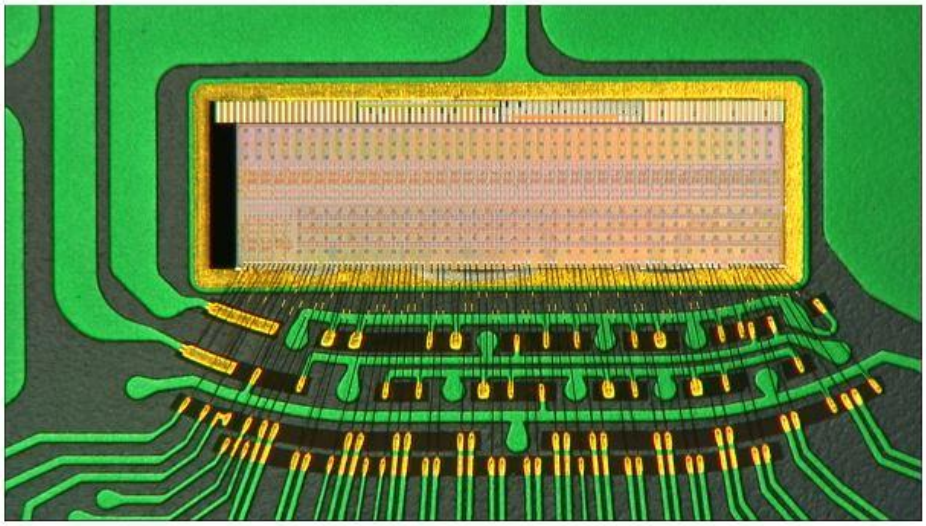


Figure 8. SSA ASIC full size Silicon prototype mounted on test carrier PCB (physical die size dimensions: 11 mm x 3.5 mm).

Both ASIC prototypes were exhaustively tested and their functionality was compared with the expected results from the simulations. Their analog performance was evaluated and found to be well within the requirements for operation with the PS-module sensors. The prototypes were also irradiated using an X-ray facility at CERN to prove their radiation tolerance up to a Total Ionizing Dose of 200MRad; the dose which is expected to receive during their operation in the CMS Outer Tracker environment.

verall, the first prototypes demonstrated the performance of the analog front-end and the functionality of the digital logic. The success of the MPA and the SSA prototypes is a very important step for the construction of the CMS Outer Tracker PS-modules and proves the feasibility of an intelligent particle tracking system in hybrid pixel detector with the given power budget.

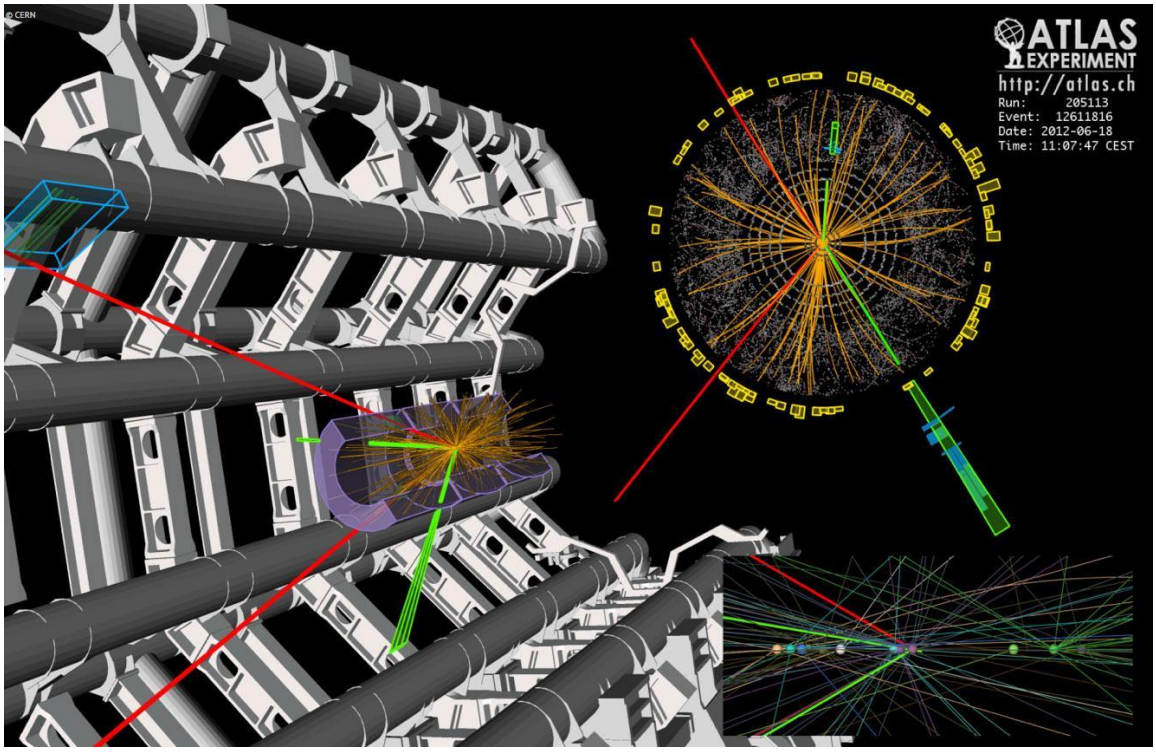
This is the first time that data coming from the tracker will be used in the L1 trigger decision at the LHC experiment. By adopting this strategy, the experiment could reduce the volume of transmitted data by an order of magnitude and consequently simplify some of the track finding algorithms. This novel concept requires the front-end electronics to include the intelligence for discriminating

particles based on their transverse momentum as well as the employment if low power techniques and high speed interconnects.

Successful tests of the first full-functionality prototypes have provided important knowledge about the operation of the ASICs with sensors and characterizations with radioactive source and test beam campaigns.

ATLAS presents a strategy for a general search of new physics.

*by **Panos Charitos***



One of the main goals of the Large Hadron Collider is to look for signals beyond the Standard Model (the other major goal has already been fulfilled with the discovery of the Higgs boson). To this day scientists are still lacking clues. Could it be that signals for new physics are still hiding in the LHC data out of sight of the SUSY and Exotics searches performed to date? Did we really look at all relevant places?

Adopting a more generic strategy allows searches for physics beyond the Standard Model without making assumptions on what such new physics signals might look like and that consequently minimise the probability of missing evidence of new physics. In other words, we can get a more “direct” look to the data in searching for hints of new physics that could answer some of the outstanding questions in particle physics. By adopting this approach, physicists hope to find hints of new physics that may be hiding in the data harvested from the current LHC runs.

In a recent paper, a team of ATLAS researchers, presented a strategy that the ATLAS collaboration can adopt in generically searching for systematic and (quasi-)model independent deviations from the SM predictions. “This is the first LHC strategy for a model-independent analysis to search for physics beyond the Standard Model (BSM) in a structured, global and automated way.” says

Sascha Caron, an ATLAS physicist from NIKHEF and Radboud University and a member of the analysis group. The goal is to identify phase-space regions where significant deviations from the SM predictions call for further detailed analysis; contrary to previous efforts that aimed to exhaustively measure the level of these deviations. According to Marina Rotaru, physicist at IFIN-HH and analysis team member: “The main advantage of this procedure is that it allows a large number of phase-space regions to be tested with the available resources, thereby minimizing the possibility of missing a signal for new physics”.

It is not the first time that a similar approach is applied in high-energy physics. Previously, general search studies applied/used to analyse data by the H1 collaboration at HERA and by the D0 and CDF collaborations at Tevatron. Today, the data from these experiments have been well analysed and understood, they can serve to better tune a general strategy approach for the LHC experiments. “With no indication for physics beyond the Standard Model such an approach will ensure that deviations in the LHC datasets are not overlooked” says Simone Amoroso, physicist at DESY and co-author of the study.

Searches for new physics at the LHC are based on testing (BSM) models and looking for deviations through many specific data sets or applying global fits searching for inconsistencies with the SM predictions. “Rather than letting theoretical models guide our searches, we make minimal assumptions and let the data tell us where we have to focus our next search efforts”, says Jeroen Schouwenberg, a physicist from NIKHEF and co-author of this study.

This is not a trivial exercise! It requires a very good understanding of all Standard Model processes as well as the development of sophisticated tools for the statistical analysis; learning from what was applied in previous experiments. “To understand the complexity of the problem consider that in the current paper we have 704 final states (Fig.1) as a result of considering electrons, muons, b-tagged jets, non-b-tagged jets, photos and missing transverse momentum. We then break each final state down further as a function of an observable that better allows the detection of for instance a new particle (Fig.2). By doing that we end up with more than 300,000 different data selections that are being tested.” explained Jeroen.

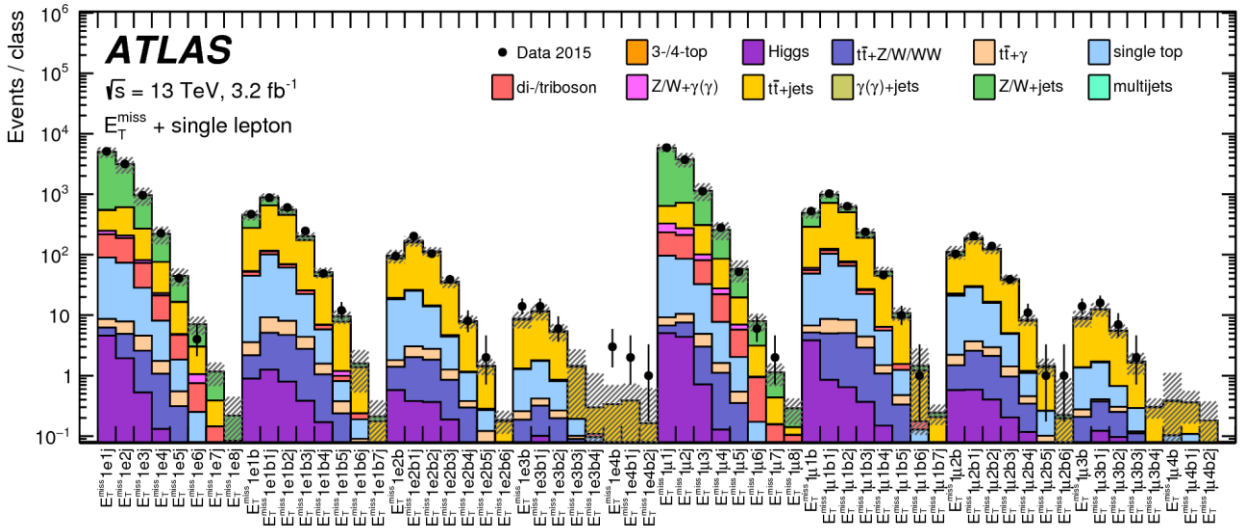


Fig.1:The number of events in data, and for the different SM background predictions considered, for classes with large ETmiss, one lepton and (b-)jets (no photons). The classes are labelled according to the multiplicity and type (e, μ, γ, j, b,

ETmiss) of the reconstructed objects for the given event class. The hatched bands indicate the total uncertainty of the SM prediction.

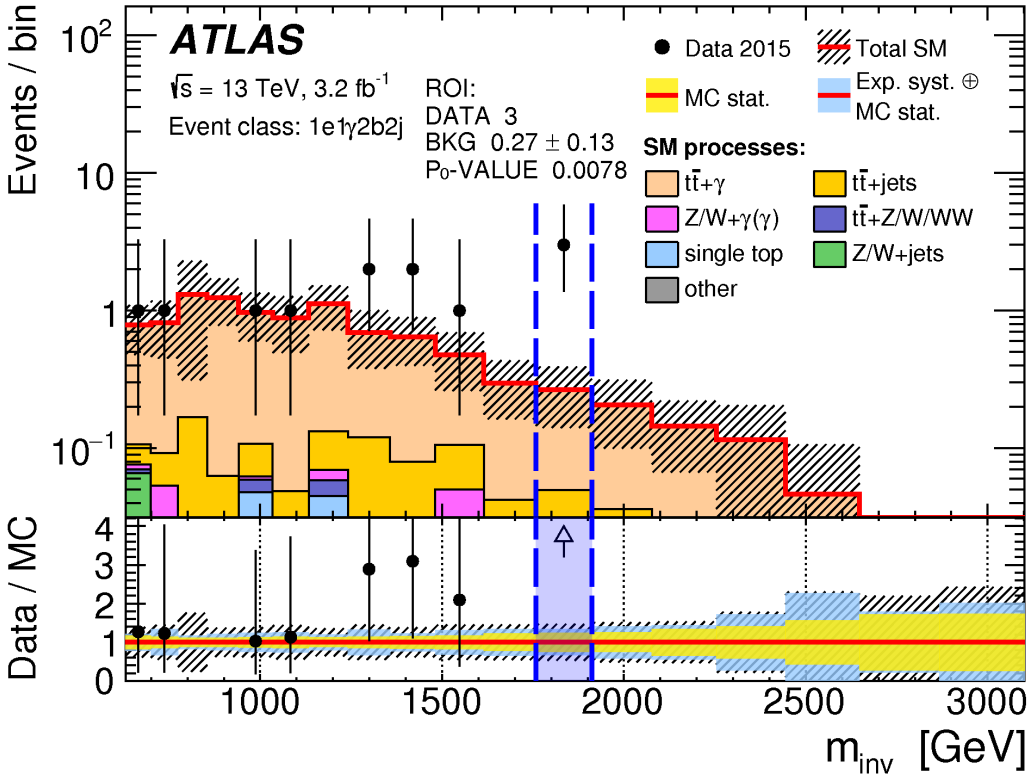


Fig.2: An upward fluctuation in the m_{inv} distribution of the 1e 1γ 2b 2j channel. (d) A downward fluctuation in the m_{eff} distribution of the 6j channel. (e) A downward fluctuation in the m_{inv}distribution of the E_T^{miss} 2μ 1j channel. (f) An upward fluctuation in the m_{eff} distribution of the E_T^{miss} 3j channel. The hatched band includes all systematic and statistical uncertainties from MC simulations. In the ratio plots the inner solid uncertainty band shows the statistical uncertainty from MC simulations, the middle solid band includes the experimental systematic uncertainty, and the hatched band includes the theoretical systematic uncertainty.

In this strategy, high-pT events are selected and classified into different (exclusive) categories, labelled with the multiplicity of final-state objects. Typically, the analysis uses objects that are also used to characterize hadron collisions (i.e. electrons, muons, taus, jets, photons) while more complicated objects can be included. These final-state categories are then automatically analysed for deviations from the SM prediction in several BSM-sensitive distributions using an algorithm that locates the region of largest excess or deficit. It should be noted that the relevant SM processes are simulated with Monte Carlo event generators which is one of the points that can be further improved by adopting a better background model for future implementations. Moreover, sensitivity tests for specific signal models are performed to understand the effectiveness of this approach for the LHC experiments and specifically for ATLAS.

Through a detailed analysis that lasted over two years, the team demonstrated that the new analysis could find unexpected signals for new physics, thanks to the larger phase-space regions probed that otherwise could remain uninvestigated. The method would trigger a more detailed analysis for areas where there is a deviation from the Standard Model. Moreover, this method is sensitive to smaller excesses that can occur when combining two or three independent data selections. The probability of a deviation occurring in any of the final states can be determined with pseudo-experiments, thus allowing a global interpretation of the probability of finding a new deviation with an experiment like ATLAS.

The strategy so far has been applied to the data collected by the ATLAS experiment during 2015, corresponding to 3.2 fb^{-1} at 13 TeV. Sensitivity studies with various benchmarks ($t\bar{t}$ + γ, W Z, gluino, and Z' production) have shown that the strategy could discover signals for new physics without an a priori knowledge of the existence of the processes. "With the new approach a gluino with a mass of 1.1 TeV could be discovered with a dataset of 10 fb^{-1} without any a priori assumption of the model, decay chain, cross- section or branching ratio and using a definition of significance which takes into account the many regions of the general search" explains Caron. This can be compared with a dedicated optimized search for gluinos in ATLAS which would discover gluinos up to 1.35 TeV with this dataset, but assuming that ATLAS would only look for this particular model (i.e. using a local definition of significance).

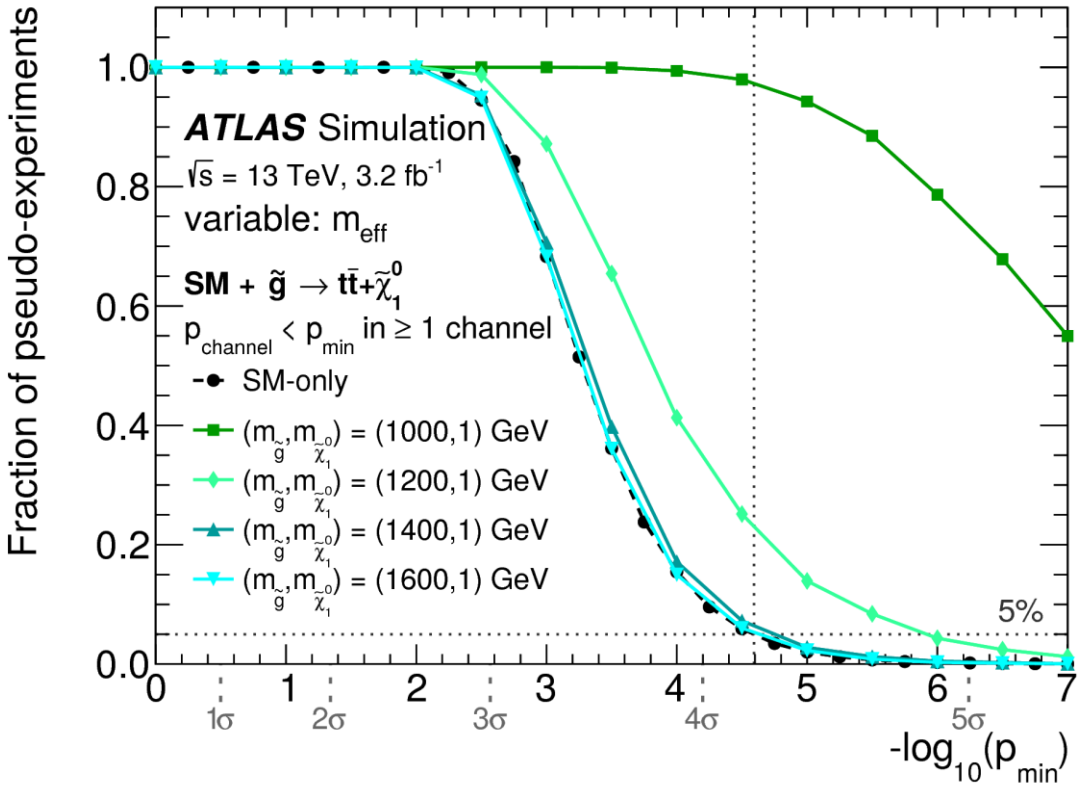


Fig. 3: The fraction of pseudo-experiments in which a deviation is found with a pchannel-value smaller than a given pmin. Distributions are shown for pseudo-experiments generated from the SM expectation (circular markers), and after injecting signals of (a) inclusive Z' decays or (b) gluino pairs with $g \rightarrow t\bar{t}\chi_1^0$ decays and various masses. The line corresponding to the injection of a Z' boson with a mass of 4 TeV and a gluino with a mass of 1600 GeV overlap with the line obtained from the SM-only pseudo-experiments due to the small signal cross-section.

A general strategy, could significantly help current searches for BSM physics and offers a fresh way to analyse current data from the LHC. It is true that since this strategy covers a very wide parameter space without narrowing it down to optimize for a specific class of BSM signals, it achieves a lower sensitivity compared to current dedicated searches and it does not provide any limits on BSM models. Further improvement of the method lies in the development of better algorithms – sensitive also to different types of signals – as well as identifying better observables.

The first results of the new strategy were published in July. There was no significant deviation found and it didn't call for a dedicated analysis using data-derived signal regions. However, this new approach proves to be useful in searching for signals of unknown particles and interactions in

the subsequent Run 2 datasets, especial when combined with Machine Learning techniques. Who knows, maybe the next signal of new physics is will be found by an algorithm!

Read the full paper here: https://arxiv.org/pdf/1807.07447.pdf

Mapping the CMS inner tracking system with unprecedented precision.

by ***Phil Baringer, Maxime Gouzevitch and Anna Kropivnitskaya***

In an experiment like CMS, it is important to know where all the detector material is. For example, in order to properly simulate the detector response, you need to know not only where the sensors are, but also the locations of the inactive material. Suppose you are searching for a long-lived particle that decays inside your detector. A significant background to your search would come from particles interacting with the material that they pass through, resulting in electron bremsstrahlung, photon conversions, or nuclear interactions (NIs) that could create a pattern of tracks that resembles your particle's decay signature. Material also affects your ability to precisely reconstruct particle trajectories because of multiple scattering and energy loss and it is important to model this properly.

Precise survey measurements are made of the positions of detector components at the time of installation, but these positions might change with time. Gravity can cause structures to sag. Variations in temperature, air pressure, and the magnetic field can cause components to move. So it is important to re-measure the positions of detector components during operation. Sensor positions can be determined using various alignment procedures, but these procedures don't work for inactive elements such as the beam pipe or support structures.

The CMS Collaboration's 800th paper describes a technique for measuring the positions of inactive elements using NIs ("Measurement of the structure of the inner tracking detector of the CMS experiment using nuclear interactions," arXiv:1807.03289 [physics.ins-det]). Photon conversions can also be used to track the positions of inactive material, but because the opening angle between the electron and positron produced in the conversion is so narrow, the location of the point where the conversion occurred cannot be precisely determined along the direction of the original photon. (It is well determined perpendicular to the photon direction.) When a hadron undergoes a nuclear interaction with material in the detector several particles can emerge with larger scattering angles. The location where the interaction occurred is referred to as the NI vertex. The position resolution for reconstructed NI vertices is typically less than a millimeter. By reconstructing a large number of NI vertices in a detector element, the element's position can be determined with a precision on the order of 100 microns. This equals or exceeds the precision of the original survey measurements.

The measurements described in the paper focused on the inner detector where the density of reconstructed NI vertices is the highest. The innermost of the CMS subdetectors is the pixel tracker. The barrel portion of the pixel detector (BPIX) and its inner shield are composed of two semi-circular halves. Figure 1 shows a photograph of one of the halves of the BPIX detector prior to installation. The BPIX detector support rails are located on the outer edge of the BPIX detector, and hold its layers in place. The pixel detector support tube encloses the BPIX detector and the

support rails. The pixel detectors are installed around the beam pipe, and an accurate measurement of the beam pipe position is also important.

Figure 1: (left) Photograph of one half of the BPIX detector showing longitudinal support, three layers, and inner shield. (right) Photograph showing an end of the BPIX detector while standing on the installation cassette. Optical targets, indicated by the numbers 2001, 2002, and 2003, are used to locate the BPIX detector within the CMS cavern. Photographs by Antje Behrens, CERN.

The data reported in the paper were recorded from proton-proton collisions at a center-of-mass energy of 13 TeV in 2015. The data set used in this analysis yielded 5.40 million events with at least one NI vertex. These NI's produced an image of the inner CMS detector that is shown in Fig. 2. If a "photograph" is an image made from photons, then we can call our image made from hadrons a "hadrograph." The ``hadrograph" shows the density of NI vertices projected onto the x-y plane (the plane perpendicular to the proton beam direction) in the barrel region ($|z| < 25$ cm). The beam pipe, the BPIX detector with its support, and the first layer of the barrel strip tracking detector can be seen in the image.

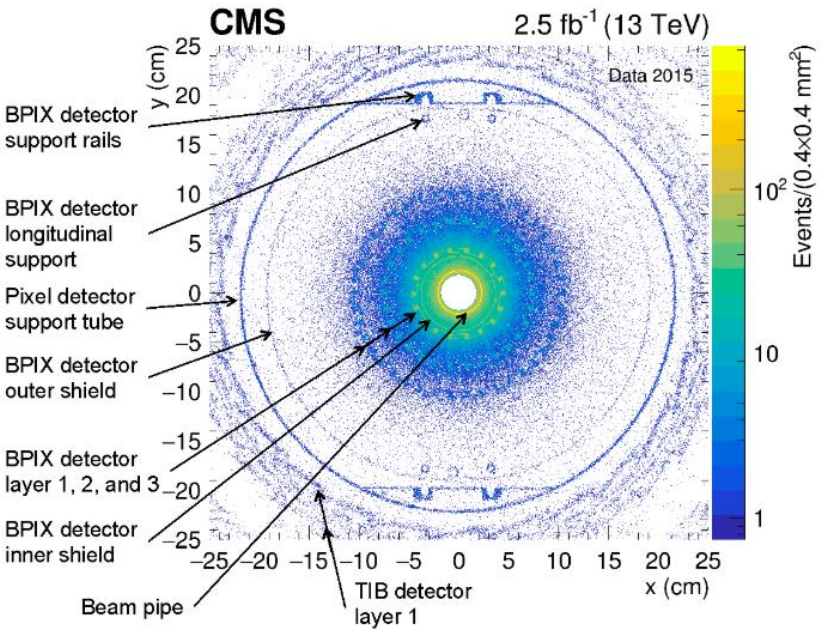


Figure 2: Hadrography of the tracker detector in the *x-y* plane in the barrel region (|z| < 25 cm). The density of NI vertices is indicated by the color scale. The signatures of the beam pipe, the BPIX detector with its support, and the first layer of the TIB detector can be observed above the background of misreconstructed NIs.

To determine the positions of the inactive detector elements, we modeled the elements using geometrical shapes, and fit those shapes to a background-subtracted NI vertex position distribution. All the inactive elements we considered, except for the support rails, have a cylindrical geometry with their axes being collinear to the beam axis. We could thus perform our position fits in the x-y plane using shapes such as a circle (for the beam pipe), a half-circle (for the BPIX detector inner shield), or an ellipse (for the pixel detector support tube). Background came from tracks forming fake vertices due to randomly occurring spatial overlaps.

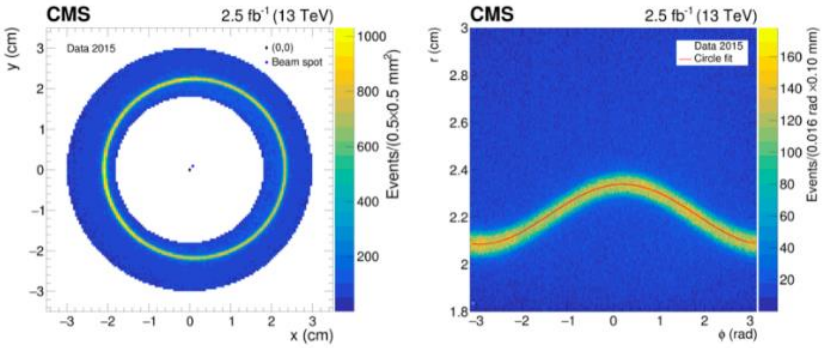


Figure 3: The beam pipe region at the barrel part (|z| < 25 cm) for the *x-y* plane (left) and the *r-*ϕ coordinates (right) are shown. The density of NI vertices is indicated by the color scale. The red line shows the fitted circle in the *r-*ϕ coordinates. The blue point in the center of the *r-*ϕ plane corresponds to the average beam spot position of x_{bs} = 0.8 mm and y_{bs} = 0.9 mm in 2015.

In Fig. 3, we show the data used to measure the position of the beam pipe along with the fit (red curve). In Fig. 4, we show the data and fit for the BPIX inner shield. These figures show the density of NI vertices in the relevant regions. In the left plot the data are projected onto the x-y plane, while

the right plot shows the r-φ coordinates with the fit. If the beam pipe or BPIX inner shield were centered at (0, 0) in the CMS coordinate system, the fit in the r-φ plane would look like a simple horizontal line. The sinusoidal distributions in the right-hand plots indicate that the centers are shifted away from the origin by about a millimeter.

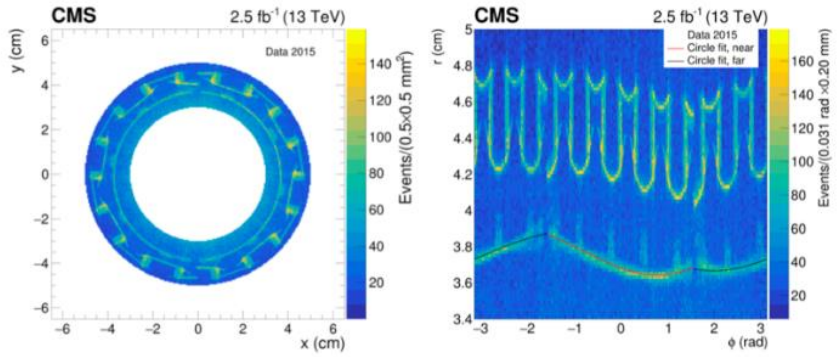


Figure 4: The BPIX detector inner shield at the barrel part (|z| < 25 cm) for the *x*-*y* plane (left) and the *r*-)coordinates (right) are shown. The density of NI vertices is indicated by the color scale. The red and black lines at around r = 3.8 cm show the fitted half-circles on the far and near sides, respectively for *r*-)coordinates. Modules in the first BPIX detector layer are visible at larger radius. The small bumps that can be seen around the shield correspond to cables connected to the first BPIX detector layer.

Table 1 summarizes the results from the fits. The values of the parameters are tabulated for the fits to the beam pipe with a circle, the BPIX detector inner shield with two half-circles, and the pixel detector support tube with an ellipse.

Only systematic uncertainties are provided, since the statistical uncertainties are negligible (below 10 μm). Not listed in the table is the fit to the BPIX detector support rails, which were observed to be 3 mm below the CMS center.

CMS has been using NI hadrography for some time. It was used in 2010 to "weigh" the CMS tracker by relating the density of NI vertices to the flux of particles and the local density of the material. By comparing this density in data with the detector simulation it was shown that the tracker material was well modeled. (http://cds.cern.ch/record/1279138?ln=en). Hadrography was again used in 2011 to determine whether the magnetic field caused deformations of the beam pipe. A special run with the field set to 2 Tesla was compared with normal runs at 4 Tesla. No deformation above 300 microns was observed.

Object	R (cm)	x_0 (mm)	y_0 (mm)
Beam pipe	2.211 ± 0.003	1.24 ± 0.03	0.27 ± 0.03
BPIX detector inner shield, far	3.774 ± 0.017	0.44 ± 0.17	-0.98 ± 0.17
BPIX detector inner shield, near	3.774 ± 0.017	-0.93 ± 0.17	-0.91 ± 0.17
Pixel detector support tube	R_x: 21.703 ± 0.007	-0.75 ± 0.07	-3.15 ± 0.07
	R_y: 21.803 ± 0.007		

Table 1: Results of the fit to the beam pipe with a circle, the BPIX detector inner shield with two half-circles, and the pixel detector support tube with an ellipse. Only systematic uncertainties are provided, since the statistical uncertainties are negligible.

In Spring 2017, an upgraded pixel detector was installed. Since the innermost layer of the 2017 upgraded pixel detector is closer to the beam pipe than the original detector was, we needed to have precise measurements of the mechanical clearances. To prepare for this upgrade, a special

narrow section of the beam pipe was inserted in 2013-2014. The radius of this beam pipe was 2.2 cm and the position of the first layer of the pixel detector as was close as 2.6 cm. In 2015, hadrography was used to conclude that the sagging due to gravity of the beam pipe was negligible compared to the allowed clearances.

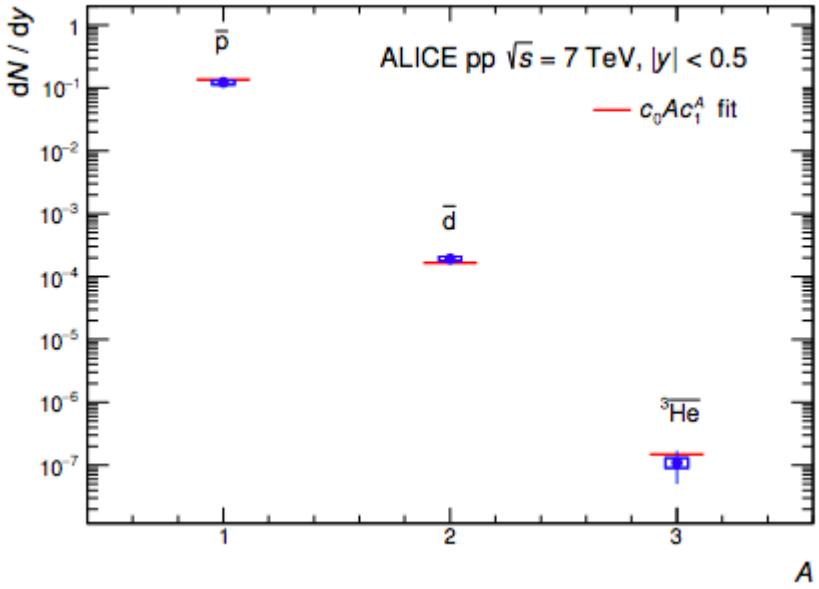
Nuclear interactions have a bad reputation because they can degrade the quality of the reconstruction of charged and neutral hadrons. But we have seen that they can be useful too. NI vertices can be used to produce a high-precision map of the material inside the tracker. Our NI material mapping provided important information for the design of the new pixel detector's support system and helped to establish reliable installation procedures. We were able to map structures with a precision that is better than the typical installation tolerances and compatible with previous survey measurements.

Anti-nuclei in the cosmos and at the LHC.

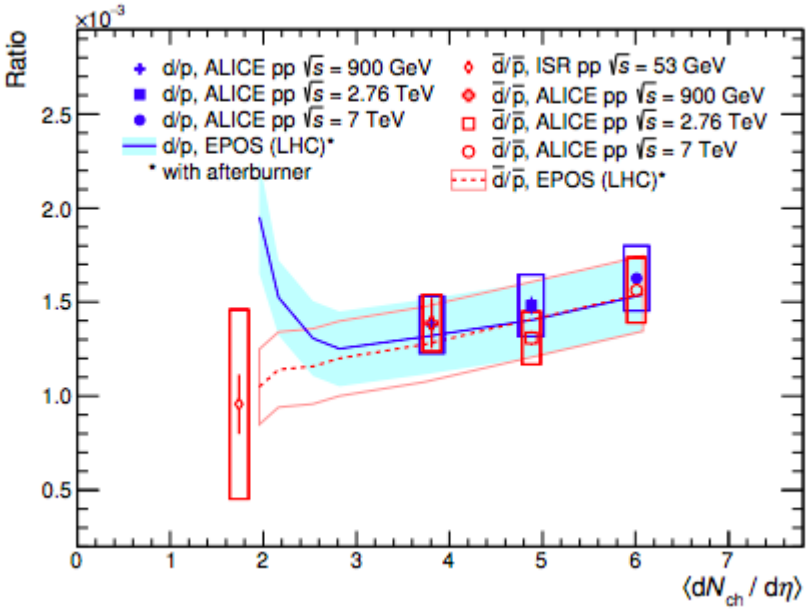
*by **A, Kalweit (CERN)***

The ALICE collaboration has recently released several measurements on the production of anti-deuterons and anti-3He in proton-proton and Pb-Pb collisions at LHC energies. These results are not only interesting for the study of the hot QCD medium produced in heavy- ion collisions, but they also provide crucial input for astrophysicists to understand the nature and origin of the anti-nuclei candidates which have been recorded by the AMS collaboration. Given the enormous challenges of identifying rare particles with a space-borne detector, the AMS collaboration is still clarifying if their observed events are of true nature or the result of misidentification. Nevertheless, the potential interpretation of the observed results is already ongoing.

The observation of anti-nuclei heavier than anti-protons in cosmic rays would have far reaching consequences as they might originate from either segregated primordial anti-matter or from the annihilation of dark matter particles. Thus, the search for these particles addresses two of the most fundamental questions in modern physics: the baryon to anti-baryon asymmetry in the universe as well as the existence and nature of dark matter, which is assumed to account for about 85% of the matter in the universe and to about a quarter of its total energy density.



Integrated yields (dN/dy) of anti-protons, anti-deuterons and 3He nuclei as a function of the number of anti-nucleons in inelastic pp collisions at √ s = 7 TeV.



Integrated deuteron-to-proton (d/p) and anti-deuteron-to-anti-proton (d/p) ratios in inelastic pp collisions as a function of the average charged particle multiplicity for different center-of-mass energies. The average d/p ratio in AA collisions lies two times above the highest value in pp collisions (not shown). Dashed and solid lines represent the expected values from EPOS (LHC) with afterburner and the bands their uncertainties.

However, also high energetic collisions of cosmic rays can produce anti-nuclei. These secondary anti-nuclei correspond to the background in the searches for anti-nuclei from primordial or dark matter origin. It was long believed that the production rates of these secondary anti-nuclei are so low, that already the observation of a single anti-3He nucleus (a bound state of two anti-protons and one anti-neutron) would be indicative of new physics. For the estimation of these

background rates, the LHC data becomes crucial as it allows to study the production of light anti-nuclei in the laboratory. As a matter of fact, while the anti-3He nucleus was discovered in the 1970s in proton-Ion collisions, its production in proton-proton collisions was first measured by the ALICE collaboration. Several theory groups are now addressing quantitatively the question how many anti-nuclei from secondary anti-nuclei are expected in space-borne experiments based on the recent LHC data. This turns the previously very qualitative estimates into quantitative studies.

One of the most striking observations in the ALICE data is the fact that the yield of anti-nuclei drops by a factor between 1000 (proton-proton collisions) and 330 (Pb-Pb collisions) for each additional anti-nucleon. In Pb-Pb collisions, this so-called penalty factor was measured up to the anti-alpha (anti-4He) and in proton-proton collisions up to anti-3He. It is therefore very striking that the AMS collaboration lately reported that in the same data sample two potential candidates of anti-4He were found and six potential candidates of anti-3He. Such a ratio would correspond to a much smaller penalty factor. This lead theorists to speculations which even consider the existence of anti-stars containing anti-4He.

The study of anti- and hyper-nuclei, including the measurement of anti-4He in pp collisions, will also be a major part of the ALICE physics program in LHC Run 3 & 4. The expected large integrated luminosities and the upgraded ALICE detector in this data taking campaign are ideal for the study of these rare objects.

Further reading:

https://arxiv.org/abs/1808.08961
http://arxiv.org/abs/arXiv:1704.05431
http://arxiv.org/abs/arXiv:1709.08522

LHCb experiment helping space-based experiments.

*by **Panagiotis Charitos***

The study of antiprotons in cosmic rays is an exciting field of research today. Cosmic ray antiprotons are believed to be produced when the high-energetic particles interact with the interstellar gas forming secondary particles. Such collisions are expected to produce a certain limited number of antiprotons, thus offering an explanation for the small fraction of antiprotons (about one per 10,000 protons) observed in cosmic rays outside of the Earth's atmosphere.

In addition to secondary antiprotons there are possible sources of primary antiprotons; those most often discussed are products of dark matter particle annihilation and evaporation of primordial black holes. Among the favorite dark matter candidates are the so-called WIMPs that in pairs can annihilate into known particles and antiparticles, making it possible to infer WIMPs in the Galactic halo by the products of their annihilation. Detailed measurement of antiprotons in CRs could help solving one of the biggest puzzles in modern physics, the nature of dark matter.

Predicting the flux of secondary Cosmic Ray antiprotons poses two significant challenges. The first is related to uncertainties related to the cosmic-ray galactic diffusion and propagation mechanisms while the second is related to the poor knowledge of the production cross- section for antiprotons, that consequently limits theoretical calculations. In the past years, new space missions like the AMS-02 and PAMELA experiments have significantly improved the precision of the antiproton flux measurement, extending it to antiproton energies up to 500 GeV. By precisely measuring other nuclei which are believed to be secondary, in particular the Boron flux compared to the Carbon one, they could also provide a calibration for models accounting for the propagation of cosmic rays, thus addressing the first uncertainty. By precisely measuring other nuclei which are believed to be secondary, in particular the Boron flux compared to that of Carbon, they provided a calibration for models accounting for the propagation of cosmic rays. Recently, the LHCb experiment at CERN contributed to the second missing piece by presenting new direct experimental measurements of the antiprotons production cross section.

The LHCb experiment measured for the first time the antiproton production in pHe collisions, which are responsible for the production of about 40% of the secondary antiprotons, hydrogen and helium nuclei being the main components of both the primary cosmic rays and the interstellar medium. The result has been submitted to Physical Review Letters and was presented in August during TeVPA 2018. The energy scale, $\sqrt{s_{NN}}$ = 110 GeV, and the measured range of the antiproton kinematic spectrum are crucial for interpreting the precise p cosmic ray measurements from the PAMELA and AMS-02 experiments by improving the precision of secondary antiproton cosmic ray flux prediction.

The first detections of antiprotons in CRs were reported almost 35 years ago by Bogomolov et al. (1979) and Golden et al. (1979), both reporting an excess with a factor of ∼3 above expectations. The excess was later shown to be due to some poorly understood background. However, these measurements stimulated an intensive discussion about the possibility to observe primary antiprotons produced in exotic processes.

The recent high-precision measurements of CRs, however, have changed the landscape dramatically. PAMELA has measured the antiproton-to-proton flux ratio from 1 to 100 GeV and more recently AMS-02 extended this measurement up to 500 GeV. Both experiments, found that there might be a slight excess of the antiproton flux above a few tens of GeV energies compared with the expected flux of secondary antiprotons, which could be explained by a Dark Matter model without constraints from other observations such as γ-rays. One of the caveats of this study remains the uncertainty on production cross- section of antiprotons.

Therefore, a substantial improvement of our understanding about secondary and primary CR antiprotons calls for substantial improvement of the antiproton production cross-section. LHCb results fill in an area for which until today there had been no data. The experiment is well suited for this type of measurement thanks to its forward geometry and its System for Measuring Overlap with Gas (SMOG). Their combination endows LHCb with a fixed-target like geometry allowing to use the powerful LHC beams. Thanks to SMOG, a small amount of noble gases can be injected in the LHC beam pipe around the LHCb collision region, thus allowing to perform fixed-target

collisions using the LHCb beams. Possible targets currently include He, Ne, and Ar gases, while other gas species, notably hydrogen, could be used in the future.

The data for this study were collected in May 2016, from proton beams with an energy of 6.5 TeV hitting helium nuclei at rest (√ sNN = 110 GeV). Using the excellent tracking and particle identification capabilities LHCb count antiprotons in bins of momentum and transverse momentum, with momentum ranging from 12 to 110 GeV/c.

The results for this study are shown in Fig. 1, and represent the production cross- section for antiprotons promptly produced in the collisions. These results should decrease the uncertainties on the computation of the antiproton flux, allowing to improve the interpretation of measurements from cosmic-ray experiments.

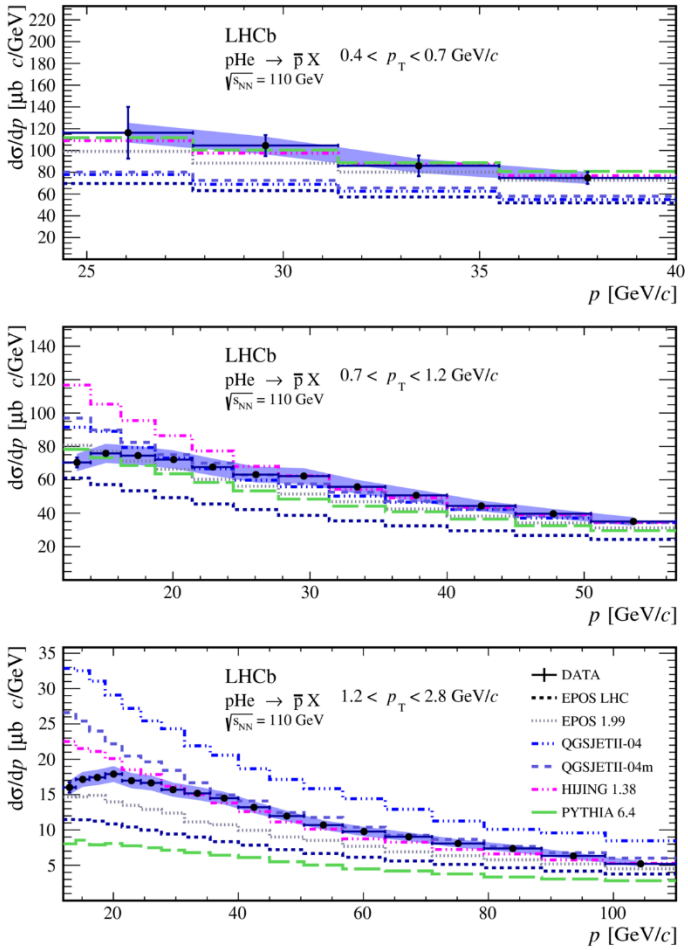


Figure 1: **Antiproton production cross-section as a function of momentum, integrated over various pTpT regions. The data points are compared with predictions from theoretical models. The uncertainties on the data points are uncorrelated only, while the shaded area indicates the correlated uncertainty.**

The measurement was made possible thanks to a novel method developed by LHC physicists to deal with a possible large systematic effect, stemming from the difficulty in estimating the luminosity. Since the density of the gas target is not precisely known, the luminosity was determined from the yield of events where an atomic electron from the target is scattered elastically by the proton beam into the detector acceptance. "These events are hidden within the much more abundant background from hadronic collisions with helium nuclei, but have a distinctive signature:

an electron identified in the detector with the right kinematic properties, and nothing else. This allowed to select a high-purity sample of events due to proton-elastic scattering, whose cross-section is very well known, so that the density of atomic electrons could be computed", explains Giacomo Graziani from INFN, one of the key investigators in this analysis.

The result is the first in a programme exploiting the fixed-target configuration of LHCb, which will provide unique measurements of interest for nuclear and cosmic rays physics at the relatively unexplored scale of $\sqrt{s_{NN}} \sim 100$ GeV. These measurements could deepen our understanding of how cosmic rays interact both at the interstellar medium and in the atmosphere, thanks to the possibility of using neon gas a target, while nitrogen and oxygen could also be possible in the future. “Physics in the fixed target configuration with LHCb was not originally foreseen, and is a stunning demonstration of the vitality of our collaboration and of the great flexibility of our detector and data taking systems." comments Giovanni Passaleva, spokesperson of the LHCb collaboration. "This is only the beginning for the fixed target physics program, which is expected to deliver more results of interest to cosmic ray physics, and also to heavy ion physics. We are also in the process of developing further this program in the future by improving the target system."

It should be noted that a thorough and systematic measurement of the antiproton cross- sections over a wide energy range is extremely important and through different process will shed more light on understanding some of the cosmic puzzles. LHCb could scan the beam energy from 0.9 to 7 TeV, offering results of the antiproton production cross- sections over a wide energy range. Moreover, the measurement is extended to lower energies by another CERN experiment, NA61 that recently provided precise measurements from pp collisions. The LHCb team also plans to extend the study to antiprotons produced by anti-hyperon decays, expected to account for 20-30% of the production. LHCb can cleanly select decays of anti-Λ baryons, and also measure inclusively detached antiprotons from both anti-Λ and anti-Σ^{+}.

“The LHCb Collaboration has been amazingly reactive to our requirements on cross- section data on helium target. They have arrived with the first data ever. Their measurement paves the road to more precise predictions, permitting us a better understanding of the origin of antimatter in our Galaxy and of possible contributions from cosmological relic particles” says Fiorenza Donato, professor of theoretical physics at Turin University and one of the main instigators of this kind of measurements.

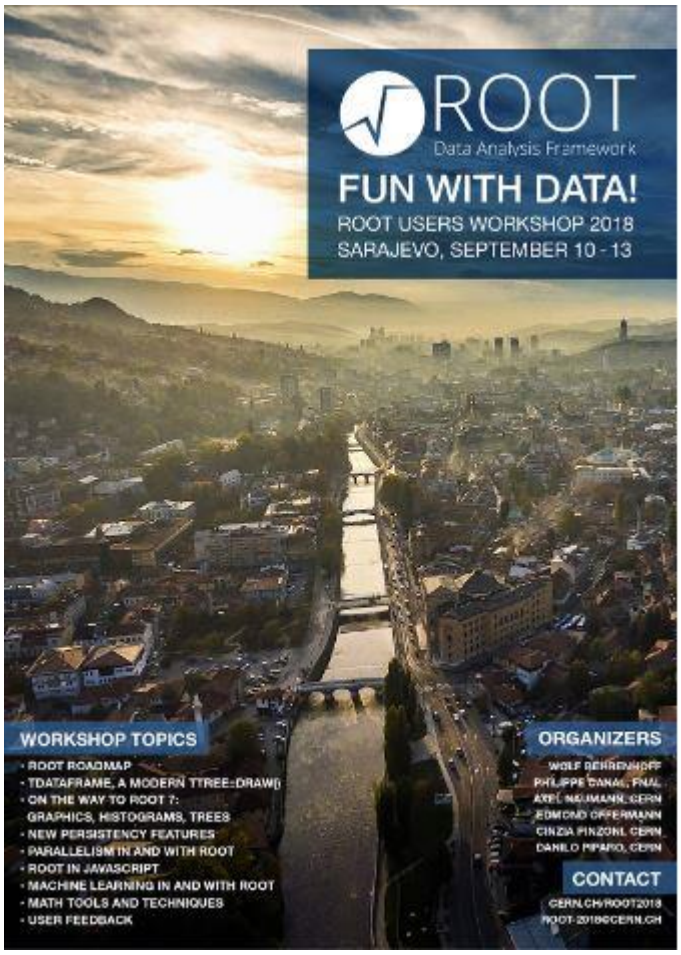
Accurate measurements of the cross sections would allow more information to be extracted from the now rather precise CR measurements and affect the way we interpret current evidences for primary antiprotons signaling exotic processes. Current results reflect the complementarity of CERN’s research programme, and will contribute to our understanding of the origin of cosmic rays; the mysterious messengers of our Universe.

Read more: https://arxiv.org/abs/1808.06127
and in a presentation by Giacomo Graziani during TeVPA '18:

https://indico.desy.de/indico/event/18204/session/19/contribution/390

ROOT 10th workshop: Fun with Data.

*by **Danilo Piparo for the ROOT team***



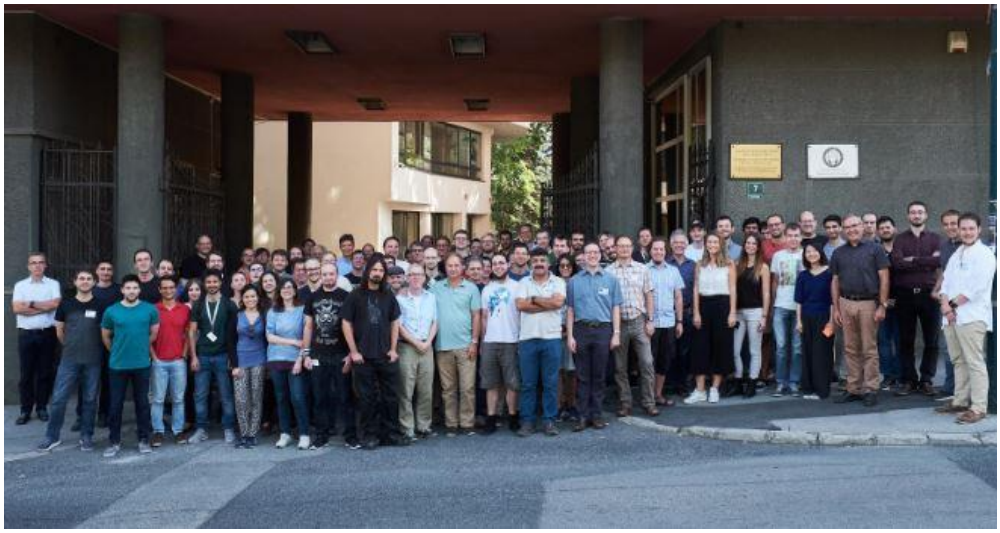
ROOT is a modular software toolkit mainly developed in the SFT group and is made for processing, analysing and visualising scientific data. It also allows to read and write data: presently, LHC experiments alone produced about 1 Exabyte (one million Terabytes!) of data stored on disks and tapes in ROOT file format.

Thousands of HEP physicists use ROOT daily to produce scientific results: for us, the ROOT team, this is a big responsibility especially considering the unprecedented challenges Run III and HL-LHC pose to the field of scientific computation. Luckily we can rely on a very lively community of users. Their contribution is so useful for us that, periodically, a ROOT Users' Workshop is organised. This event has the objective of gathering together the ROOT community to collect criticism, praise, suggestions and complaints. It is a unique occasion to shape the future of the ROOT project, together, users and developers.

The 10th ROOT Users Workshop took place in Sarajevo, at the Academy of Science and Arts, from the 10th to 13th September. Easily reachable from Geneva, the city of Sarajevo is a fantastic location: an exceptional setting made even better by the well known Balkan hospitality. The workshop was also an unprecedented opportunity to involve Bosnia and Herzegovina in the activities of CERN. More than one hundred people attended, also from the local university, making the event a real success: a 30% increment with respect to the previous workshop organised in 2015. The participants came from Europe and America, bringing about different levels of expertise:

students, about a third of the audience, analysis physicists, framework developers, software experts and ROOT enthusiasts.

The workshop featured 69 high quality contributions as well as hours of engaging discussions, during the officially scheduled sessions but also during breaks, lunches, dinners, social events or walks around the city. Companies also participated to the event with three invited contributions. Peter Müßig (SAP) presented OpenUI5, the open source core of the SAP javascript framework used to build enterprise-grade web user interfaces that will be used for ROOT's GUI. Chandler Carruth (Google) discussed ways to make large-scale software projects written in C++, the main language for number crunching code in HEP, simpler, faster and safer. Sylvain Corlay (Quantstack) showed novel ways to tackle numerical analysis with multi-dimensional array expressions. These industry speakers enjoyed the workshop, too, and plan to come to CERN in the future to extend the collaboration.



ROOT Users' Workshop 2018 attendees at the Academy of Science and Arts of Bosnia and Herzegovina.

Indeed ROOT's renovation was the main theme of the workshop. ROOT started to be the cornerstone of virtually all HENP software stacks about two decades ago. Presently, the toolkit, in order to be at the bleeding edge of software technology, is undergoing an intense upgrade program of its key components: this huge effort represents really exciting times for physicists and software developers. ROOT's users appreciated the effort to make ROOT easier to use, faster on modern computer architectures and ultimately more modern with the sole objective of reducing the time interval between data delivery and presentation of plots to illustrate results.

In particular the spotlight was on the modernisation of the I/O subsystem, crucial for the future Physics Programme of the LHC, the parallelisation of ROOT, a prerequisite to face the analysis of Run III and HL-LHC datasets, as well as the new graphics, statistical and multivariate tools and interface to the Python language: all elements of prime importance for the everyday work of physicists.

Participants' feedback on the workshop was enthusiastic. The setting was wonderful and the local logistics flawless. The atmosphere has always been positive, criticism was constructive and extremely useful for the ROOT team. The whole team would like to thank the participating physicists and computer scientists during the workshop: we sincerely appreciated your active engagement! We are eagerly looking forward to organising the next ROOT workshop!

We would like to thank Edmond Offermann and the EP department for making this event possible with their contributions.

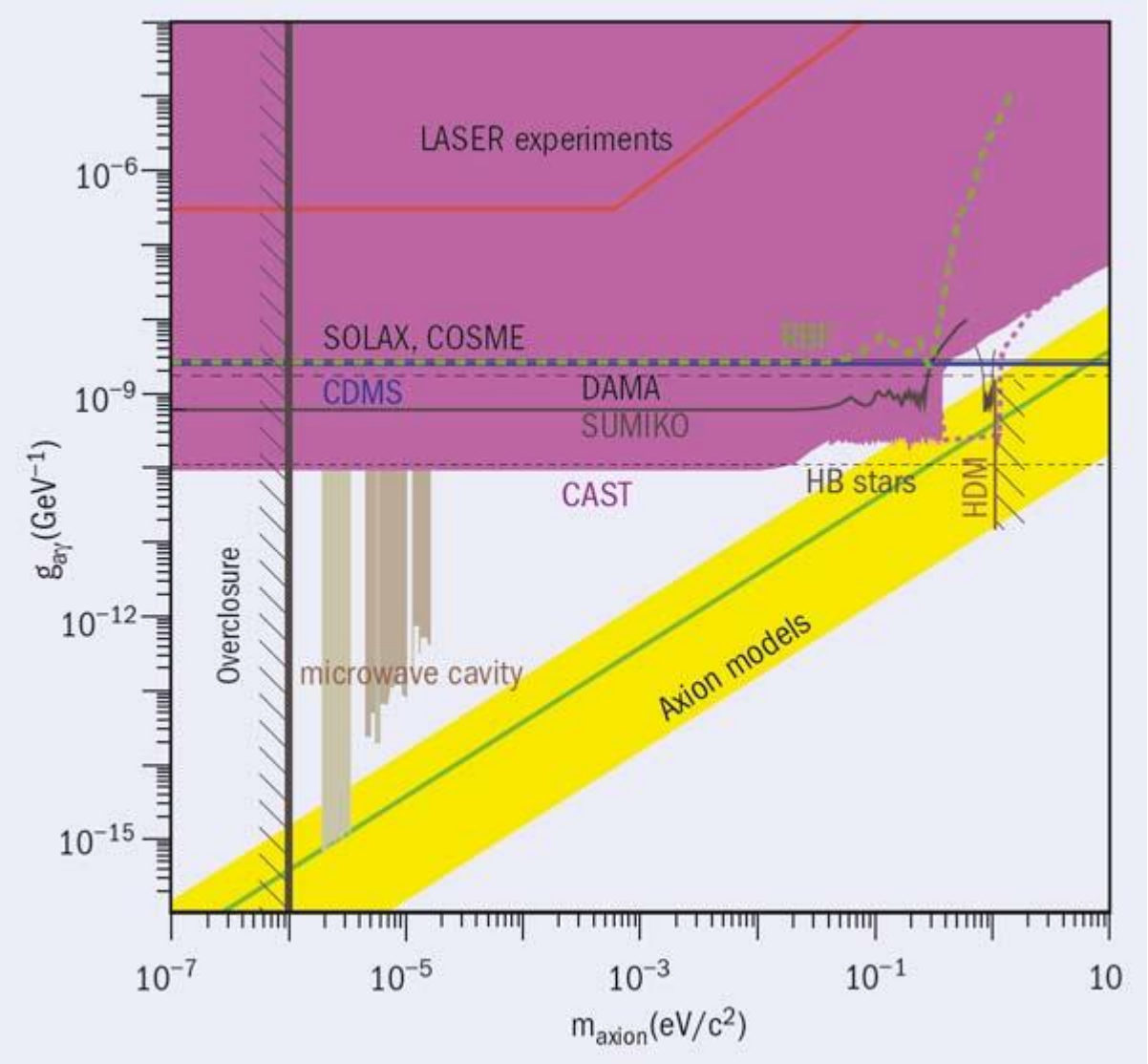
Searching for axions: old and new ideas.

by ***Panagiotis Charitos***

PDF version

QCD, the theory of strong interactions allows the violation of CP symmetry that would result in a non-zero value for the neutron electric dipole moment. Current measurements constrain the neutron EDM to be one trillionth of the size predicted by QCD (because of CP violation). This means that the strength of this interaction (parameterized as an angle θ) has to be fine-tuned to an extremely small value of less than 10^{-10} rad. This constitutes a fine-tuning problem that challenged theoretical physics back in the '70s.

The axion, or more specifically a new field that could be responsible for the small values of θ, was introduced to solve this problem. In 1977, Robert Peccei and Helen Quinn developed a theory which promoted the angle θ from a fixed parameter to a field that has an additional chiral symmetry. In analogy to the Higgs mechanism, the spontaneous breaking of this symmetry gives rise to a new field which was later called the axion field. The axion was identified by Weinberg and Wilczek as the pseudo Nambu-Goldstone (pNG) boson of the new spontaneously broken global symmetry that Peccei and Quinn had postulated. Adding the axion field in the QCD Lagrangian can solve the neutron EDM problem. In this issue, Peccei and Quinn recall the interesting developments that led to the formulation of the Peccei-Quinn mechanism and reflect on future searches for axions and physics beyond the Standard Model.



Axion–photon coupling versus the rest mass of QCD-inspired axions, showing the limits achieved by the helioscopes RBF, Sumico and CAST in the context of axion searches in general. It also shows astrophysically and cosmologically derived conclusions from HB stars and the hot dark matter (HDM) limit (Imace Credit: CERN Courier).

Recently, interest in axion searches has heightened as axions of a specific mass range are good candidates of cold dark matter. Many experiments around the world have launched extensive DM axion searches to cover the relevant parameter space. Evidence for cold dark matter was first obtained from considering the rotation curves of outer objects in galaxies, which reveal that the average galactic mass not only consists of dust and gases, but also and for its most part of a nonluminous halo of unknown composition that doesn't emit nor absorb light at any significant level. The majority of the dark matter observed has the form of Cold Dark Matter, which means that this exotic component was nonrelativistic at the time of galaxy formation, thus pointing to searches for non-relativistic axions.

Existing theoretical underpinnings of the axion do not predict a value for the axion mass. Cosmological considerations indicate that if the axion is the source of the cold dark matter in the universe, it should have a mass in the range of about 1–25 μeV/c^2 - about 10^{15} times smaller than the WIMP's. With such a small mass, we would expect tens of trillions of axions per cubic

centimeter in our Solar System to account for the observed dark matter density. However, the interactions of axions with ordinary matter and photons are expected to be so feeble - they could fly through the whole Universe even if it was made out of bricks - that their detection requires extremely sensitive techniques.

Axions that could solve both the strong CP and DM problem, should have very specific mass ranges (very light) and be copiously produced. The phenomenology of axions and Axion-like particles is determined by their low mass and very weak interactions and they could affect stellar evolution and cosmology in a similar way to thermal neutrinos. The produced axions are non-relativistic particles and their contribution to the dark matter density scales as $\Omega_{axion} \sim m^{-7/6}_a$. This scaling unambiguously implies that the axion mass must be fine-tuned $m_a = 10^{-5}$ eV to saturate the DM density today while larger axion mass will contribute very little to Ω_{DM}. Much lighter axions would overclose the universe, and therefore $m_a \approx 1$ μeV may be taken as a strong lower limit on the axion mass. Moreover, stellar evolution also places strict limits on the upper mass of axions. Axions with masses larger than $\sim$ 16 meV would have quenched the neutrino pulse observed from SN1987a, thus bounding the axion mass from above.

In this issue, we interview Pierre Sikivie, who first came up with ideas on how to detect this seemingly invisible particle. The technique relies on the fact that the axion strongly couples to the photon when travelling inside a magnetic field. This permits the conversion of an axion or ALP into a single real photon in an external electromagnetic field, i.e. the so-called Primakoff effect, as well as the inverse process. Axions can be also produced as a result of the Primakoff effect in a stellar plasma at high temperature and in that case we have ultra-relativistic axions. Axions travelling through a magnetic field can convert to photons and the probability of this transformation depends on the intensity of the magnetic field.

This fact motivated the searches of axions with dedicated resonating (RF) cavities. The power of this method depends on the axion mass, its coupling constant to photons, their local density as well as on the volume, the form factor and the loaded quality factor of the cavity. The key idea is that one the axions will fly through the cavity, where it will interact with its magnetic field and convert to a photon of a specific wavelength. For the conversion to take place, the frequency of the cavity must equal the mass of the axion resulting in an extremely monochromatic signal. The search is performed by tuning the cavity in small overlapping steps and the expected signal power is extraordinarily tiny.

Deriving from Sikivie's ideas comes two other devices: the axion helioscope that could detect the copious flux of axions emitted from the Sun and the axion haloscope to detect axions from the hypothetical dark matter galactic halo. Sikivie's proposal demonstrated that we can use natural sources of axions which are extremely efficient, like the Sun or even relic axions from the Big Bang. Because of the extremely large fluxes of natural axions, helioscopes and haloscopes are typically much more sensitive to axions and ALPs than their purely laboratory competitors, although their luminosities are also subject to larger uncertainties, especially in the case of dark matter axions.

CERN's diverse experimental programme include searches for axions and ALPs with a number of different experimental technologies. In this special issue we present results of direct searches at the LHC through proton and heavy-ion collisions as well as in-depth report from the dedicated haloscope (CAST) with its proposed upgrade and a discussion of the most recent OSQAR results. During the last two decades, the efforts and size of the community have been steadily growing but the few last years have witnessed a real blossoming of ideas. Many new groups have entered the

field, new exciting detection concepts have been proposed and several demonstrative small-scale setups have been commissioned.

Experimental searches for solar and dark matter axions.

*by **Igor Garzia Irastorza, Panos Charitos***

Detection of solar axions

If axions exist, they would be produced in large quantities in the solar interior. Photons from the solar plasma would convert into axions in the Coulomb fields of charged particles via the Primakoff axion-photon conversion. Once produced, axions get out of the star unimpeded and travel to the Earth, offering a great opportunity for direct detection in terrestrial axion helioscopes.

The emission of axions by the Sun is a robust prediction of axion theory. The Primakoff solar axion flux depends only on the axion-photon coupling, a generic property of axion models. The energy distribution of solar axions (1 to 10 keV approx.) reflects the photon energies at the solar core and thus is entirely determined by well-known solar physics. It is independent on the value of the axion mass (as long as it is below ~keV). If the axion couples to electrons, additional axion production channels may become relevant. But the Primakoff component can be considered as a guaranteed minimum whose search allows, at the least, to place a robust bound on the axion-photon coupling over a wide range of mass values. Solar axions offers a detection strategy that does not rely on cosmological (e.g, the axion being the dark matter) assumptions, and thus is highly complementary to dark matter axion searches.

The axion helioscope concept was proposed by Pierre Sikivie more than 30 years ago. It invokes the conversion of the solar axions back to photons in a strong laboratory magnet. The resulting photons are x-rays that can be detected behind the magnet when it is pointing to the Sun. This has

been the strategy followed by the CERN Axion Solar Telescope (CAST) using a decommissioned LHC test magnet that provides a 9 T field inside the two 10 m long, 5 cm diameter, magnet bores. CAST magnet is placed over a platform that allows to move it to track the Sun during 3 hours per day. CAST performance has mostly relied on the availability of this first-class magnet. However, CAST has introduced new elements beyond the conventional helioscope concept, like the focusing the x-rays to increase signal-to-noise ratio, or the use of low background techniques (radiopurity, shielding, offline discrimination) for the detectors. During more than a decade of operation, CAST has put progressively stronger limits on the axion-photon coupling across a wide range of axion masses, in particular being the first helioscope probing relevant QCD axion models of sub-eV mass. The latest of these results, published last year in Nature Physics, sets an upper bound on the axion-photon coupling of 0.66 x 10-10 GeV-10 (see Figure 1). This value competes with the strongest bound coming from astrophysics. Advancing beyond this state-of-the-art is now highly motivated, not only because it would mean to venture into regions of parameter space allowed by astrophysics, but also because a number of astrophysical observations seem to hint at precisely this range of parameters. CAST has also searched for solar axions produced via the axion-electron coupling, although the very stringent astrophysical bound on this coupling remains so far unchallenged by experiments.

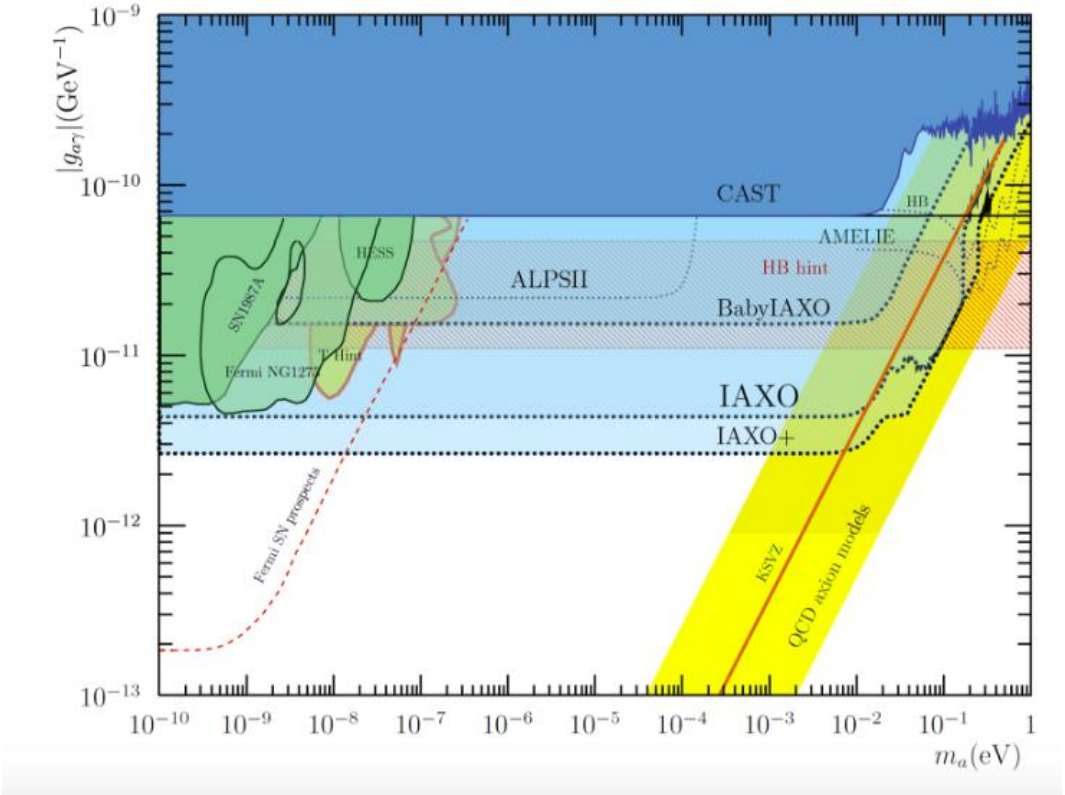


Figure 1 - *Parameter space of the axion and ALPs with the region currently excluded by CAST (blue). Semi-transparent blue regions are sensitivity projection of BabyIAXO and IAXO (both nominal and the upgraded IAXO+). The BabyIAXO prospects are estimated very conservatively using the minimal configuration for the magnet and detectors, and 1 year of data, without considering a possible gas phase. The IAXO+ line represents an extra factor 10 in figure-of-merit with respect the nominal IAXO parameters. Also shown are the sensitivity prospects of the ALPS-II experiment, and various regions related with the Universe transparency to high energy photons. The yellow band correspond to the standard place for QCD axion models.*

To substantially improve the current CAST bounds and go deeper into unexplored axion parameter space requires a completely new infrastructure, like the one proposed by the International Axion Observatory (IAXO). IAXO is a next generation axion helioscope aiming at a better signal-to-noise ratio compared to CAST. This means a sensitivity to the axion-photon coupling more than one order of magnitude beyond the CAST bound, deep into unexplored ALP space and in particular probing QCD axion models down to the meV scale (see Figure 1). For axions coupling with electrons, IAXO will be able to be sensitive to values beyond current astrophysical bounds for the first time for any experiment, and directly test the range of values that are hinted if the anomalous cooling observed in white stars is due to axions.

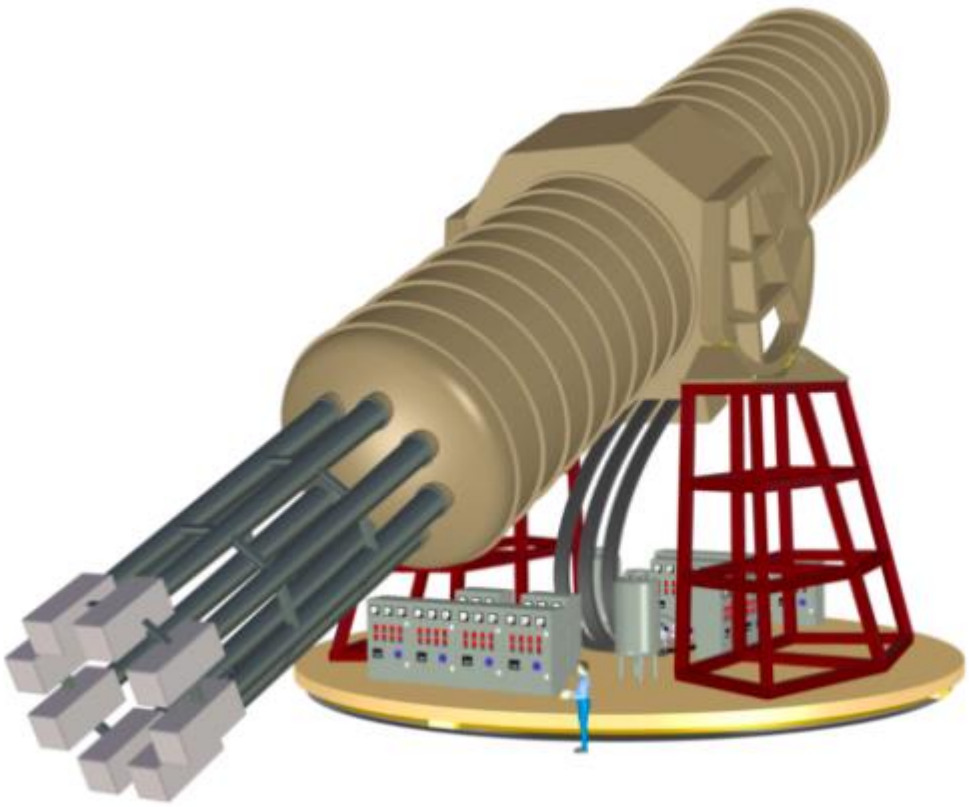


Figure 2.- *Conceptual design of IAXO in its baseline configuration. Shown are the magnet cryostat, the eight telescope+detector systems, the service units and the inclination system and rotating platform.*

This is only possible by building a new dedicated large-scale magnet, designed maximizing the helioscope figure of merit. The IAXO magnet, shown in Figure 2, will be a superconducting magnet following a large multi-bore toroidal configuration, to efficiently produce an intense magnetic field over a large volume. The design is inspired by the ATLAS barrel and end-cap toroids, the largest superconducting toroids ever built and presently in operation at CERN. Indeed the experience of CERN in the design, construction and operation of large superconducting magnets is crucial for the project.

IAXO will also make extensive use of novel detection concepts pioneered at a small scale in CAST, like x-ray focusing and low background detectors. The former relies on the fact that, at grazing incident angles, it is possible to make x-ray mirrors with high reflectivity. True-imaging optics are

possible employing two conic-shaped mirrors, a design principle that is being used in x-ray astronomy for nearly 50 years to build x-ray telescopes. This class of optics -commonly referred to as Wolter-I optics- allows “nesting” or placing concentric, co-focal x-ray mirrors inside one another to achieve high throughput, a principle much like a Russian nesting doll. IAXO envisions optics similar to those used on NASA’s NuSTAR (3-79 keV), an x-ray astrophysics satellite currently in orbit, but optimized for the solar axion spectrum energies. The NuSTAR telescopes consist of multiple mirror pieces that have been thermally-formed or “slumped” to match the desired shape and covered with a multilayer coating to enhance the reflections of x-rays. The coatings consist of alternating layers of a reflector material like platinum and a spacer material like carbon with a thickness of a few to a few tens of atoms per layer and will be optimized for the IAXO’s axion search. Each of the eight magnet bores will be equipped with such optics.

At the focal plane in each of the optics, IAXO will have low-background x-ray detectors. Several technologies are under consideration, but the most developed one are small gaseous chambers read by pixelised microbulk Micromegas planes. These detectors have been extensively developed in the recent years in the context of rare event experiments, and in CAST in particular. They involve low-background techniques typically developed in underground laboratories, like the use of radiopure detector components, appropriate shielding, and the use of offline discrimination algorithms, but adapted to the particularities of operation at surface. Micromegas detectors have proven to be largely amenable to these developments, due to the relative simplicity of their design (for a highly pixelised detector, and correspondingly high number of readout channels). The core of these detectors, the microbulk readout, is of special interest as it is manufactured out of raw foils made of kapton and copper, two materials known to be very radiopure. Alternative or additional x-ray detection technologies are also considered for IAXO, like GridPix detectors, Magnetic Metallic Calorimeters, Transition Edge Sensors, or Silicon Drift Detectors. All of them show promise to outperform the baseline Micromegas detectors in aspects like energy threshold or resolution, of interest e.g. to search for solar axions via the axion-electron coupling (and featuring both lower energies that the standard Primakoff ones, as well as monochromatic peaks in the spectrum).

Although both x-ray focusing and low background techniques were exploited since an early phase of the CAST experiment, only in the most recent data taking run were both combined in the same detection system. Figure 3 shows the “IAXO pathfinder” system that took data in one CAST bore in 2014-15 and that enabled the latest result of the experiment above mentioned. It was so dubbed because it includes 1) the first purpose-built x-ray optics for axions, implementing (at a much lower scale) the same technique proposed for IAXO, and 2) the most advanced shielded Micromegas x-ray detector so far, placed at the focal point. The system registered a record background level of an average of 0.003 counts/hour (i.e. an average of one count in the signal region during 6 months of operation of CAST). Figure 4 shows and explains some representative data plots from this detector system.

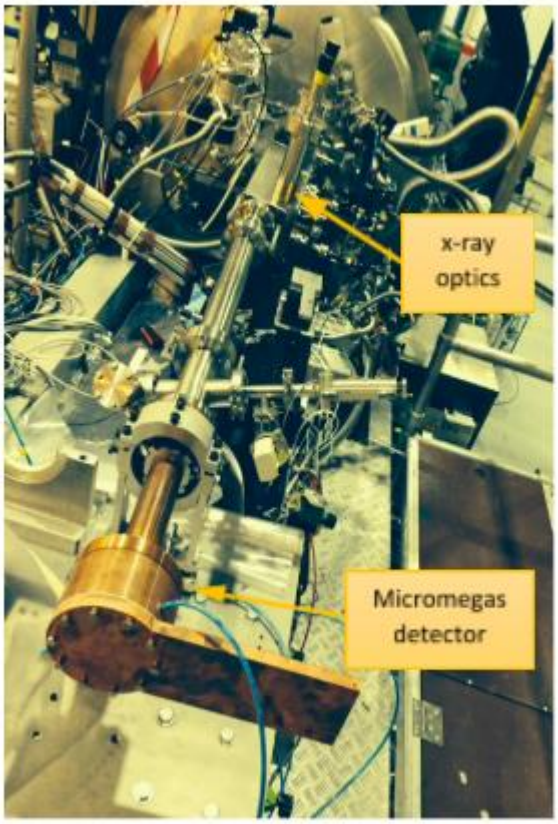


Figure 3 - *Picture of the IAXO pathfinder system (with the detector shielding removed) as installed in one of the magnet bores of CAST, and composed of an x-ray optics and a Micromegas detector placed at the focal spot of the optics.*

IAXO is currently in the technical design phase. Important recent milestones include the formalization of the international collaboration last year, currently encompassing 17 institutions from all over the world, including CERN and DESY, the latter likely to host the experiment. The project received good recommendation from the CERN SPSC in an early stage and is now is being reviewed as part of the Physics Beyond Colliders (PBC) Study. As mentioned above, CERN unique experience in magnet technologies is very important for the experiment. Effective CERN support in this regard is already being materialized in the magnet design efforts, in particular via the PBC technology subgroup. The collaboration is now working to realize BabyIAXO, an intermediate-scale version of the full experiment, that will serve to prototype (and potentially improve) all subsystems of the experiment and mitigate risks for the full infrastructure, but at the same time will operate as a fully-fledged axion helioscope. BabyIAXO magnet will feature one bore, and therefore one detection system, but of representative dimensions of the full IAXO systems. As shown in Figure 1, BabyIAXO will enjoy relevant physics case in itself, already with potential for discovery. It is expected that it could be built in 2-3 years and bring the solar axion community into physics production relatively early, while preparing the ground for the full IAXO. The fact that BabyIAXO has attracted ERC funding in this year's call is a proof of the excitement of these prospects and adds credibility to the near term plans of the project.

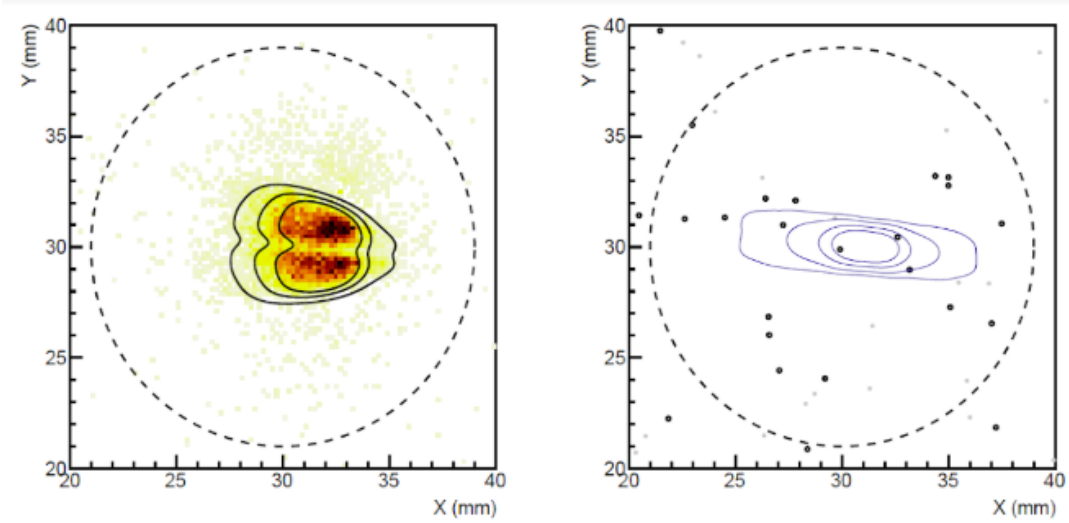


Figure 4.- *2D hitmaps of the Micromegas detector of the IAXO pathfinder system at CAST, durign a calibration run (left) and the integrated 6.5 months data run in axion-sensitive "sun tracking" conditions (right). The calibration is performed with an X-ray source placed ~12 m away (at the other side of the magnet). The contours in the calibration run represent the 95%, 85% and 68% signal-encircling regions from ray-trace simulations, taking into account the source size and distance. In the sun tracking plot, grey dots represent events that pass all detector cuts but that are in coincidence with the muon vetoes, and therefore rejected. Black dots represent final counts. Closed contours indicate the 99%, 95%, 85% and 68% signal-encircling regions out of detailed ray-trace simulations of the telescope plus spatial resolution of the detector. The large dashed circle represents the region of detector exposed to daily energy calibration.*

Detection of dark matter axions

If our galactic dark matter halo is made of axions, we would be embedded in an "axion sea" of huge number density. These axions are non-relativistic and with velocities much smaller that their mass, so they are best viewed as a scalar classical field oscillating with a fixed frequency equal to the axion mass. Despite the feeble interaction these axions can be detected exploiting coherence effects. The conventional axion haloscope concept proposed by Sikivie, invokes the conversion of these axions into photons inside a magnet and their resonant detection in a microwave cavity. The signal power is proportional to the quality factor Q of the cavity, although this amplification works only in a narrow relative frequency window of 1/Q around the axion mass. Given that the axion mass is unknown, these experiments must allow tuning the resonant frequency over a range as wide as possible. Data taking with haloscopes thus entails scanning very thin mass-slices of parameter space.

The ADMX experiment at the U. of Washington is the most advanced implementation of this concept. After more than 25 years of R&D, ADMX has proven that the concept can realistically achieve sensitivity to QCD axions in the few μeV mass ballpark. If the axion mass is in the μeV range and the DM is made mostly of axions, ADMX will find it in the coming years. However, there is a strong motivation to perform axion DM searches at higher masses too. Applying the haloscope technique at higher masses is challenging, because higher frequencies imply lower cavity volumes and correspondingly lower signals. This drop in sensitivity may be compensated with improvements in other experimental parameters (higher magnetic field, lower noise, higher quality factors,…), like the recent results from the HAYSTAC collaboration at 24 μeV shows. But going to even larger masses will probably require other approaches. During the last years, several ideas

have been proposed and many new groups are starting R&D and prototyping work to tackle this challenge. An appealing approach is to somehow equip a large detection volume with a high-frequency resonant structure, in other words, to decouple resonant frequency (and axion mass) from cavity volume. Two possible ways to implement this strategy are currently being tested at CAST at CERN.

After the completion of the original solar axion program of CAST in 2015, the collaboration turned its physics goal to the search for solar chameleons and DM axions. The latter is represented by two subprojects, CAST-CAPP and RADES, both aiming at using the CAST magnet to develop effective high-mass axion haloscopes.

The Relic Axion Detector Exploratory Setup (RADES) aims at developing long-aspect-ratio cavities (that can fit in the CAST dipole) by physically appending many smaller rectangular cavities, interconnected with irises, in what resembles a RF filter structure. The precise geometry of the cavity can be optimized to obtain maximal coupling to the axion field for a given resonant mode, or alternatively to simultaneously share it among several modes at different frequencies, which opens interesting possibilities. This approach allows to (in principle, arbitrarily) enlarge the volume of the overall cavity but keeping a high resonant frequency, which is determined by the size of the unit cavity. The need for external phase matching is avoided, as it is guaranteed by design, and the concept offers a much better control of mode crowding. The concept has been successfully proven with small scale fixed-frequency 8.4 GHz (about 35 μeV) of only 5 unit-cavities shown in Figure x, that has been already tested inside the CAST magnet. The next steps include the implementation of a mechanism of frequency tuning, and the construction of prototypes with progressively larger number of unit-cavities. Effectively filling the whole bore of the CAST magnet with such structure should provide relevant sensitivity to QCD DM axions in the mentioned mass value.

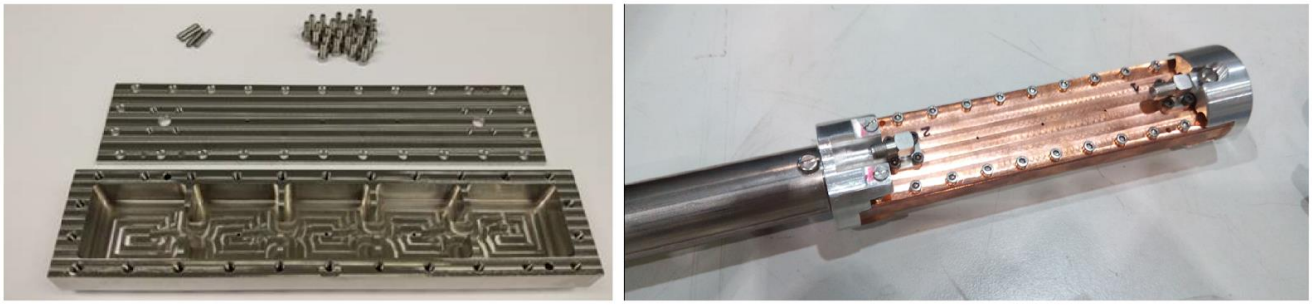
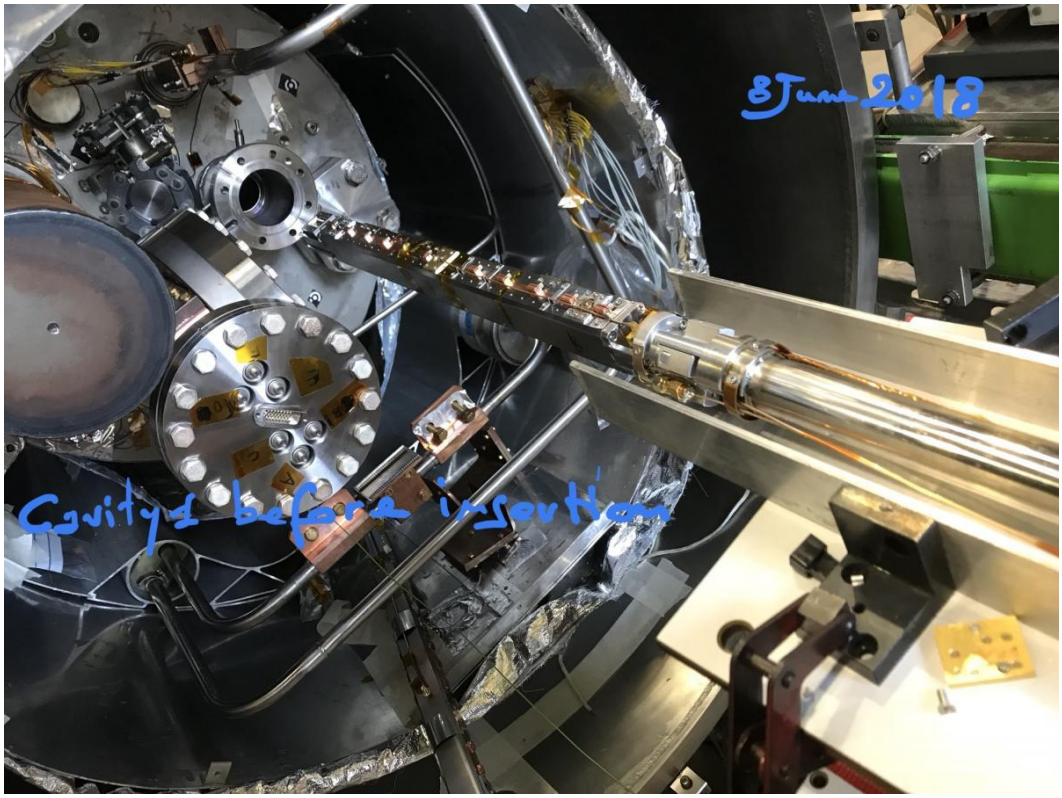


Figure 5 - First RADES prototype. Left: Cavity body in stainless steel before coating and assembly. Right: copper-coated cavity mounted onto the stick used to insert it inside the CAST magnet.

The installation of the CAST-CAPP/IBS was also completed earlier this summer. These cavities were developed in strong collaboration with the CAPP centre in Korea, following the centre's international expertise in axion searches. CAST-CAPP/IBS Detector project is a haloscope search for axion DM with rectangular cavities inserted in the bores of the CAST dipole magnet.



The on-resonance cavity power resulting from an axion signal would be ~ 10^{-23} W, assuming a coupling constant $g_{a\gamma\gamma}$ of 10^{-14} GeV^{-1} . If we require a signal-to noise ratio of 4, the time required to measure this power level at a given resonant frequency (axion mass) falls in the order of 10 days, for a system temperature of 3.8 K resulting from adding the magnet operating temperature, 1.8 K, to a commercial amplifier noise temperature of 2 K. If the experiment operates at lower temperatures of, 1.8 K, we should expect to achieve the same signal to noise ratio in less time. The sensitivity would scale accordingly, further demonstrating the good potential of this setup for axion DM search in a region of the parameter space, $g_{a\gamma\gamma}$ vs. axion mass, where no data currently exist. In the case of CAST-CAPP/IBS, their sensitivity could reach into the QCD axion parameter space over the unexplored region of (2–3)×10^{-5} eV axion mass range, provided that phase-matching of multiple cavities is possible.

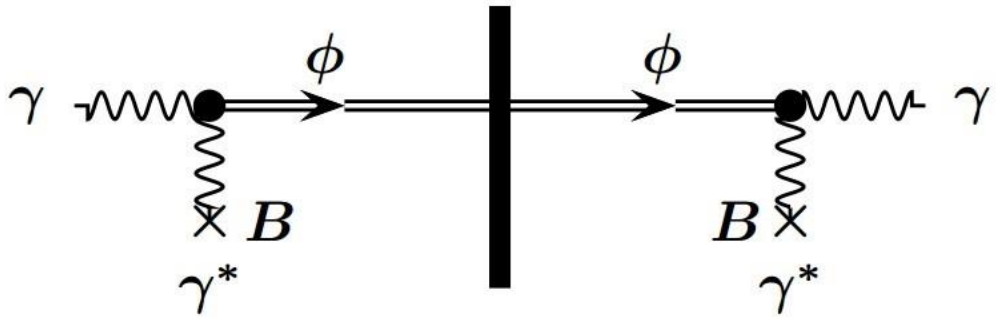
Following preliminary cavity engineering models, the first fully tunable cavities were produced in Korea and installed in CAST this summer. The first results are expected in the next weeks allowing to understand the behaviour of these cavities before exploiting their full potential.

OSQAR experiment at CERN

Two distinct OSQAR experiments at CERN, namely SQAR-LSW and OSQAR-VMB look mostly for ALPS through studies of optical properties of the quantum vacuum permeated by a strong magnetic field. There are based on an extensive use of spare LHC dipoles providing a magnetic field of 9 T over 14.3 m. OSQAR experiments are complementary to CAST.

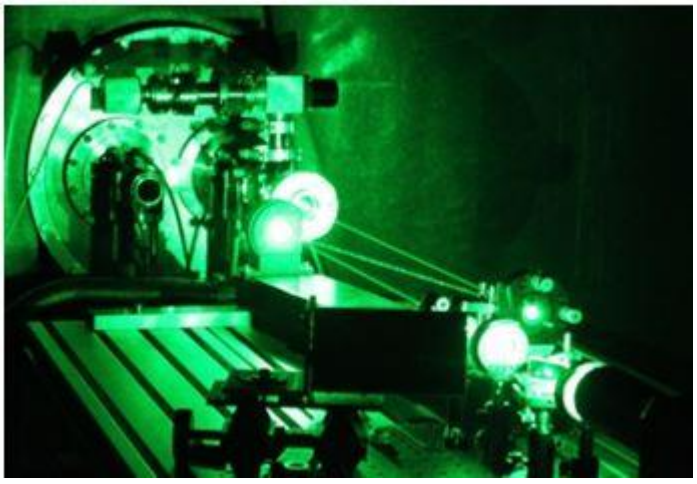
OSQAR experiment shines the laser into a vacuum chamber containing a barrier that stops photons but lets axions pass through. If they glimpse light on the other side of the barrier, the researchers deduce that axions have travelled through the barrier, and turned back into detectable photons on the other side. Physicists know this type of experiment colloquially as "light shining through a wall". The stronger the electromagnetic field, the greater the chance of an axion occurring. This makes the especially powerful LHC magnets ideal for the OSQAR experiment.

The OSQAR-LSW experiment aims to detect ALPs from the light shining through wall experimental scheme shown in Fig. 2. This type of experiment can be split in three main parts, one for the photon to axion conversion in strong magnetic field, a second one for the absorption of non-converted photons and the last part for the photon regeneration and detection.



Principle of a LSW experiment within two vacuum chambers permeated by a strong transverse magnetic field and separated by an optical absorber.

The basic ingredient concerns the production of ALPs from a polarised laser beam in the background of a strong magnetic field through the Primakoff process γ γ* --> A. If ALPs are produced, they propagate freely along the same direction as the laser beam, cross the wall due their low coupling strength to matter before entering in the regeneration chamber located on the opposite side of the experiment. All photons not converted into ALPs in the first part of the experiment are absorbed by the wall inserted in between. A second external magnetic field applied within the regeneration area, allows the ALP to be reconverted into a photon via the inverse process A γ* --> γ before being subsequently detected.



The OSQAR experiment in operation with the 20 W laser beam aligned within the second aperture of the LHC dipole (OSQAR-CHASE run, 21 July 2017).

First results excluded a large part of the parameter space over a specific range of possible masses for the axion-like particles. A number of possibilities for upgrading OSQAR-LSW is being discussed under the Physics Beyond Collider working group.

Axion-like particle searches at the LHC.

by ***Andrea Thamm, Tom Melia, Panos Charitos***

The Standard Model (SM) of Particle Physics is plagued by some longstanding conceptual and practical questions, and we have to go beyond the Standard Model to address them. A guiding principle of the Standard Model is that we should expect to see all processes which are consistent with its symmetries. However, measurements of the (lack of an) electric dipole moment of the neutron imply a parameter to be as small as 1 part in 10,000,000,000. This tiny number is very unlikely to occur by accident, but the Standard Model provides no explanation. As this small parameter occurs only in quantum chromodynamics (QCD), this question is usually referred to as the strong CP problem.

The strong CP problem could be resolved by the presence of a hypothetical new particle, the QCD axion, which is related to a more complex theoretical model governed by the Peccei-Quinn symmetry. These QCD axions acquire their mass from coupling to the QCD condensate and have tight relations between their mass and coupling strengths to SM particles. Removing this relation between mass and coupling strengths motivates the axion-like particle (ALP). Axion-like particles are hypothetical light pseudo-Nambu Goldstone bosons which do not necessarily address the strong CP problem and appear in the spontaneous breaking of a global symmetry. ALPs can interact with all particles of the SM. Their masses and coupling strengths are theoretically free parameters and can span many orders of magnitude. In certain regions of parameter space ALPs can be non-thermal candidates for Dark Matter or, in other regions where they decay, mediators to a dark sector. For large symmetry breaking scales, the ALP can be a harbinger of a new physics sector at such high energy scales that would otherwise be experimentally inaccessible.

Depending on the ALP mass and its couplings to SM particles, the search strategy varies greatly. For masses below twice the electron mass, the ALP can only decay into photons and the corresponding decay rate scales like the third power of the ALP mass. Thus, light ALPs are usually long-lived and travel long distances before decaying. Experiments looking for long-lived ALPs coming from the sun and other distant objects are thus most suited. E.g. energy loss of stars through radiation of ALPs is constrained by the ratio of red giants to younger stars of the so-called horizontal branch (HB). Another strong constraint arises from the measurement of the length of the neutrino burst from Supernova SN1987a, which would have been shorter in the presence of an energy loss from ALP emission as well as from the non-observation of a photon burst from SN1987a due to the decay of emitted ALPs. In addition, a set of cosmological constraints from the modification to big-bang nucleosynthesis, distortions of the cosmic microwave background and extragalactic background light measurements exclude a large region of this parameter space and are sensitive to very small ALP-photon couplings. For subGeV ALPs, beam-dump searches are sensitive to ALPs radiated off photons, which are exchanged between the incoming beam and the target nuclei (Primakoff effect) and decay back to photons outside the target. The proposed ShiP experiment would probe significant parts of the ALP parameter space in the mass range between 1 MeV and 1 GeV, but also ongoing searches at NA62 might be sensitive to such ALPs Dobrich (2015). For ALPs with MeV to hundreds of GeV scale masses, collider experiments become relevant. If the ALP is long-lived, it would leave a missing energy signature in the detector, and BaBar, CLEO, LEP, the Tevatron and the LHC have searched for these signals. ALPs with larger masses and/or larger couplings become short lived and can decay inside the detector. This opens up exciting new possibilities for searches at the LHC and future colliders. Depending on its mass,

the ALP could decay into two photons, leptons or jets. ALP couplings to other SM particles are generally less constrained than the ALP-photon coupling.

ALPs searches at the LHC

At the LHC, ALPs can be produced resonantly in the process pp → a, or they can be produced in exotic decays of the Z- or Higgs boson. The relevant processes would be Z → γa, h → Za or h → aa. Once produced, the ALP can then either be long lived and escape the detector as missing energy, or it can decay inside the detector. Long-lived or invisibly decaying ALPs at the LHC have been explored recently in (Mimasu,2014 and Brivio,2017). Projections for missing energy signatures, such as pp → aW(γ), pp → ajj(γ), pp → ha and pp → tta with stable ALPs or invisible ALP decays have been considered in Brivio (2017). For short-lived ALPs, ATLAS and CMS can reconstruct its decay products. The only decay mode for light ALPs is into two photons. For ALP masses larger than twice the electron mass, the decay into two electrons opens up. Similarly, for masses larger than twice the muon or tau mass, ALP decays into two muons or taus are possible. ALP masses larger than three times the pion mass are required for hadronic decays into two jets to be kinematically allowed. All these decay modes can be searched for at the LHC. The left panel of Figure 1 shows a summary of current constraints in the plane ALP mass vs ALP-photon coupling. The coloured regions show the different experimental constraints mentioned above. Collider constraints, in particular, exist for large ALP-photon couplings. The blue area shows bounds from LEP looking for e+e- → Z → γa → 3γ. Decays of on shell Zbosons at the LHC have been discussed Bauer(2017), Mimasu (2014), Jaeckel (2015) and Brivio (2017) and are shown in orange. The purple region is excluded by Tevatron searches for pp → 3γ.

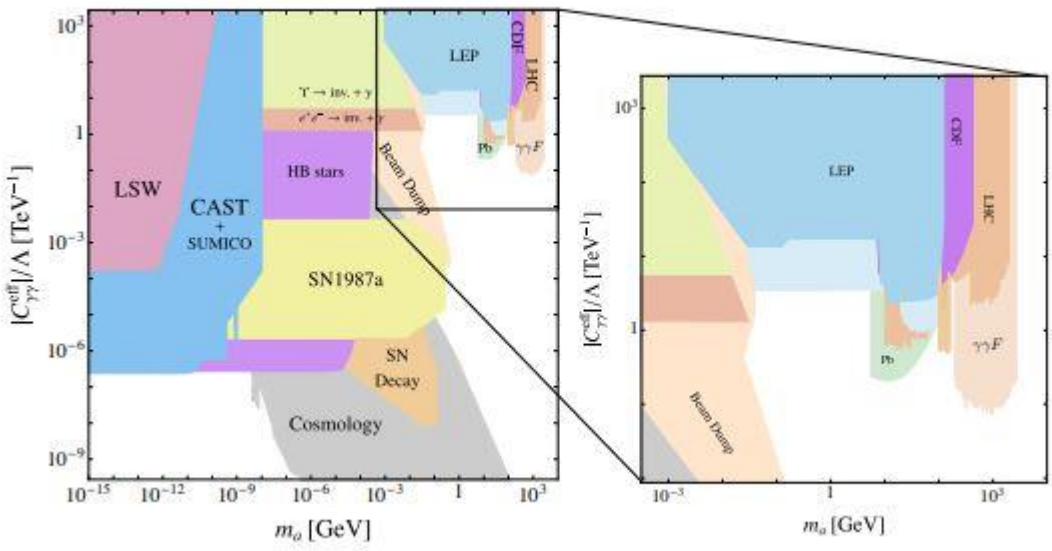


Figure 1. Constraints on the ALP mass and ALP-photon coupling derived from various experiments. Right: Enlarged display of the constraints from collider searches: LEP (light blue and blue), CDF (purple), LHC from associated production and Z decays (orange), LHC from photon fusion (light orange), and from heavy-ion collisions at the LHC (green). Plot taken from Bauer (2018).

Exotic decays of Z- or Higgs bosons can be powerful channels to search for axion-like particles. The light green region in Figure 2 shows the expected LHC reach in the channel h → Za → Zγγ with 300 fb-1 integrated luminosity. We see the complementarity to previously excluded regions in

parameter space. This is the case because ALPs in the light green region are short-lived enough to decay inside the detector. Projections for h → aa and Z → γa are similar.

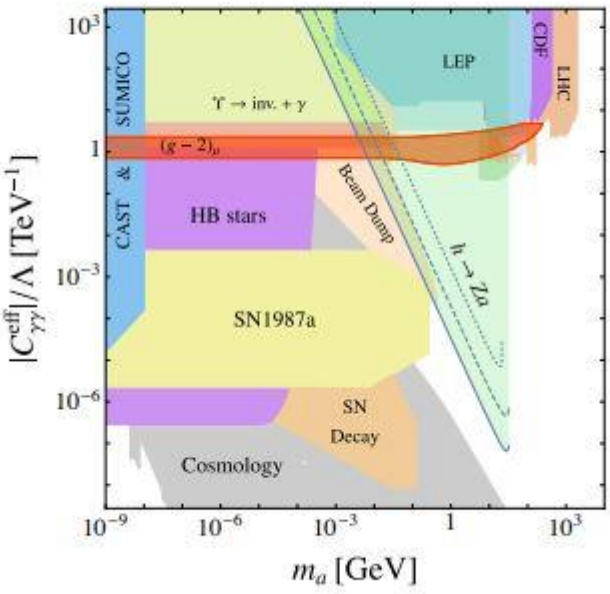


Figure 2. Constraints on the ALP mass and ALP-photon coupling along with the parameter regions that can be probed in the decay h → Za → Zγγ in LHC Run-2 with 300 fb-1 of integrated luminosity (light green region). Plot taken from Bauer (2017).

These projected bounds for exotic Higgs decays include an intrinsic assumption on the ALPHiggs coupling. Studies on resonant production, pp → a → γγ, avoid these assumptions since the ALP coupling to gluons and to photons is related in many explicit models. Figure 3 shows current and expected bounds in this process. See Mariotti (2017) for more details on this process.

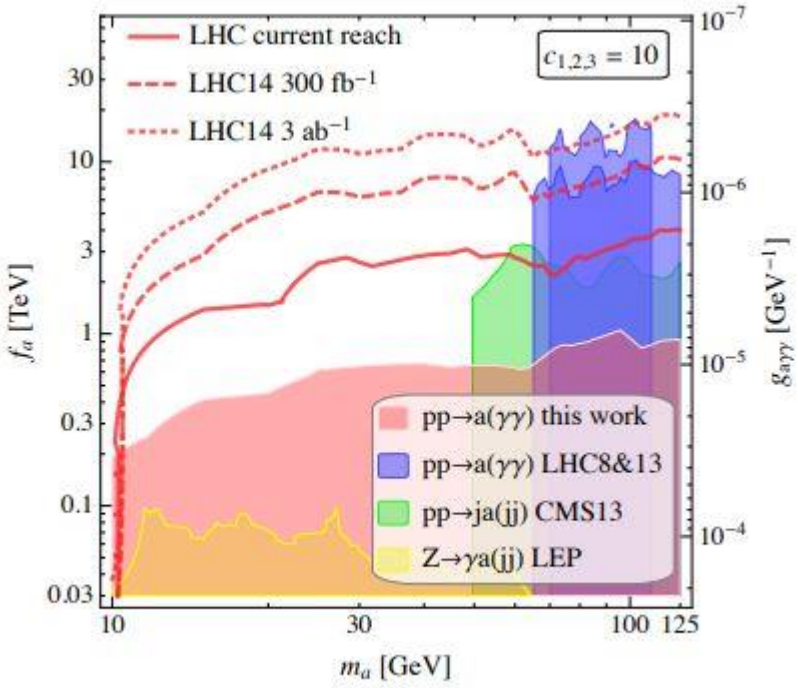


Figure 3: Shaded regions show constraints from existing collider searches at LEP Adriani (1992) and the CMS (2015, 2017), Sirunyan (2017), and from the bound derived in Mariotti (2017). Lines: projected LHC sensitivities at 8 and 14 TeV. Plot taken from Marriotti (2017).

ALPs searches in heavy-ion collisions

Ultra-peripheral heavy ion collisions at the LHC present a unique environment to search for ALPs that couple to electromagnetism, owing to a large Z^4 (Z=82 for lead) enhancement to the cross section, and low backgrounds [1]. In fact, the strongest limits on ALPs in the mass range 10 GeV < m_a < 100 GeV can be obtained by recasting an ATLAS analysis [2] using the 480 microbarn^{-1} Pb-Pb data set.

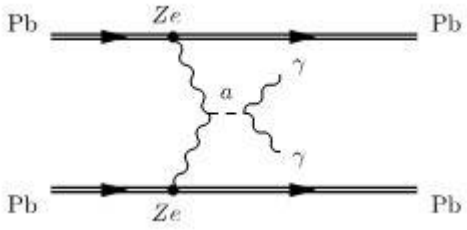
Ultra-peripheral collisions are characterized by an impact parameter that is much larger than the radius of the ion, and very little breakup of the ions (leading to extremely low activity in the detector). ALPs can be produced via photon-photon fusion, where the initial photon flux is high owing to the strong electric field of the ions; decay back into photons provides a `bump-hunt' channel with low background – see Fig. 1. Dominant backgrounds in this channel are standard model light-by-light scattering [3], and electrons faking photons; both backgrounds become negligible for $m_{\gamma\gamma}$ >=20GeV.

A recent ATLAS measurement of light-by-light scattering [2] provides an m_gammagamma spectrum in the region 6-30 GeV that can be used to derive a limit on parameter Lambda in the ALP Lagrangian.

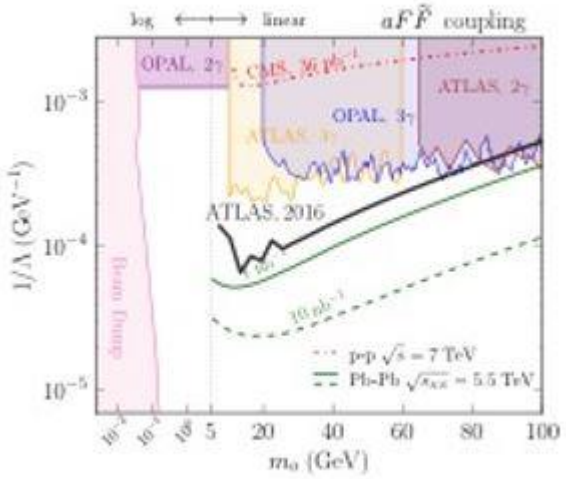
The results of this recasting were presented in [4], following the treatment proposed in [1]. They are shown here in Fig. 2, along with projected sensitivities for 1 nb^{-1} and 10 nb^{-1} of lead-lead

collision data. The limit is set up to 100 GeV, under the assumption that ATLAS sees no events in bins greater than m_gammagamma >30 GeV.
It is an interesting aspect of ALP physics that lead-lead collisions at the LHC can provide more competitive limits than proton-proton collisions, which usually dominate searches for beyond-the-standard model physics.

Figures: Taken directly from [4]



ALP production via photon-photon fusion in ultra-peripheral lead-lead collisions, with subsequent decay into two photons.



Caption: 95% exclusion limits on the parameter Lambda in eq. (1), as a function of ALP mass. Figure taken from Ref.[4], and using ATLAS results on light-by-light scattering [2]. Exclusion limits are also shown from other LHC searches (ATLAS 2 and 3 photon), LEP 2 (OPAL 2 and 3 photon) and beam dump experiments (for details see Ref. [1]). Projections assuming 1 nb^{-1} and 10 nb^{-1}luminosity of Pb-Pb collisions are are shown in green.

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OSQAR experiment sheds light on a hidden sector of CERN's scientific heritage

*by **Pierre Pugnat on the behalf of the OSQAR collaboration***

Particle physics is not only confined to the high energy frontier. There are unexplored territories at ultra-low energies, of sub-eV to eV, which are also very promising, such as for example in dark matter (DM) searches. The emblematic particle of this physics is the axion, a pseudo-scalar particle predicted independently in 1978 by S. Weinberg [1] and F. Wilczek [2], to solve the fundamental problem of the apparent non-violation of the CP symmetry by the strong interaction (QCD) from the breaking of the Peccei and Quinn symmetry [3].

Standard axion with coupling at the electroweak scale, i.e. with a mass in the keV range, has been excluded after extensive searches in collider experiments. This has led the scientific community to consider the case of "almost" invisible axion, i.e. with a mass and coupling to other particles extremely weak. If the axion mass is in the range 10^{-6} to 10^{-2} eV, this particle could also be responsible for the DM of our universe and constitutes one of the rare non-supersymmetric candidates. On the other hand, various ultra-light and weakly interacting scalar and pseudo-scalar particles are naturally present in string theory without the need of solving the strong CP problem. This new family of particles has coined the name of WISPs for Weakly Interacting Slim Particles in complement to the WIMPs standing for Weakly Interacting Massive Particles. P. Sikivie showed in 1983 [4] that the invisible axion as well as axion like particles (ALPs), a subfamily of WISPs, could be detected via a chiral anomaly that modifies Maxwell's equations.
In this context, the two distinct OSQAR experiments at CERN (Fig.1), namely the OSQAR-LSW and OSQAR-VMB look mostly for ALPS through studies of optical properties of the quantum vacuum permeated by a strong magnetic field [5].More recently OSQAR has been extended with OSQAR-CHASE [6] in the search of chameleons, a special type of particle that could account for dark matter. The above mentioned experiments are based on an extensive use of spare LHC dipoles providing a magnetic field of 9 T over 14.3 m. OSQAR experiments are complementary to CAST [7], originally an helioscope searching axion and ALPs, which might be produced by the sun. It has been recently converted into haloscope to scrutinise the DM wind of our galactic halo crossing the Earth.

The title of this letter highlights the hidden sector of CERN's scientific heritage since the first proposal to test the QED by measuring the vacuum magnetic birefringence was actually born at CERN in 1979 [8] with some very preliminary tests done in the early '80s. In addition, the possibility to detect nearly massless, spin-zero particles on light propagation in a magnetic field was first theoretically investigated at CERN in 1986 [9].

Fig.1: The OSQAR experiment at CERN installed in the SM18 hall with the laser protective area installed in front of a spare LHC dipole.

OSQAR-Light Shine through walls

The OSQAR-LSW experiment aims to detect ALPs from the light shining through wall experimental scheme [10] shown in Fig. 2. This type of experiment can be split in three main parts, one for the photon to axion conversion in strong magnetic field, a second one for the absorption of non-converted photons and the last part for the photon regeneration and detection.

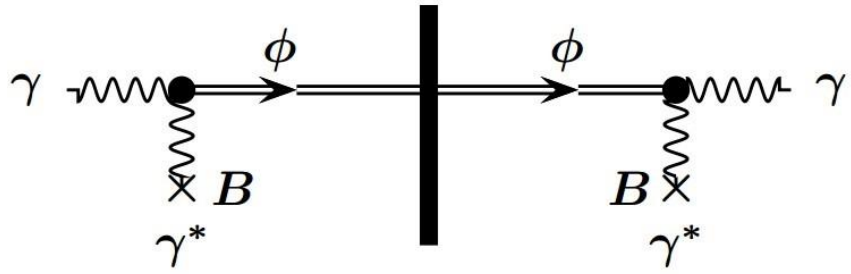

Fig. 2: Principle of a LSW experiment within two vacuum chambers permeated by a strong transverse magnetic field and separated by an optical absorber.

The basic ingredient concerns the production of ALPs from a polarised laser beam in the background of a strong magnetic field through the Primakoff process γ γ* --> *A*. If ALPs are produced, they propagate freely along the same direction as the laser beam, cross the wall due their low coupling strength to matter before entering in the regeneration chamber located on the opposite side of the experiment. All photons not converted into ALPs in the first part of the experiment are absorbed by the wall inserted in between. A second external magnetic field applied

within the regeneration area, allows the ALP to be reconverted into a photon via the inverse process $A\ \gamma^* \rightarrow \gamma$ before being subsequently detected.

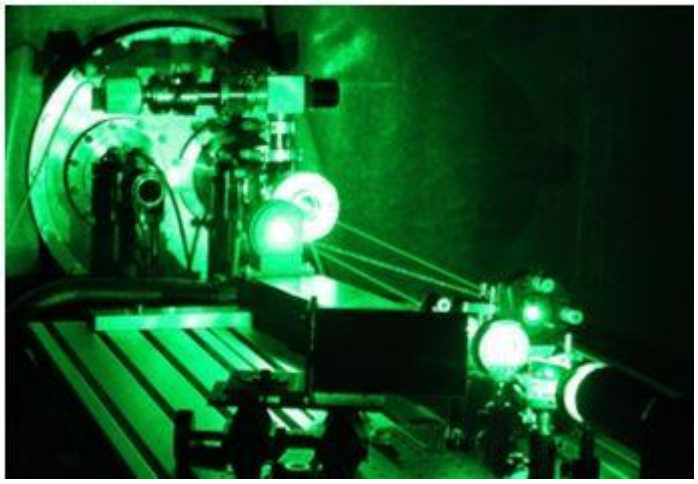

Fig. 3: The OSQAR experiment in operation with the 20 W laser beam aligned within the second aperture of the LHC dipole (OSQAR-CHASE run, 21 July 2017).

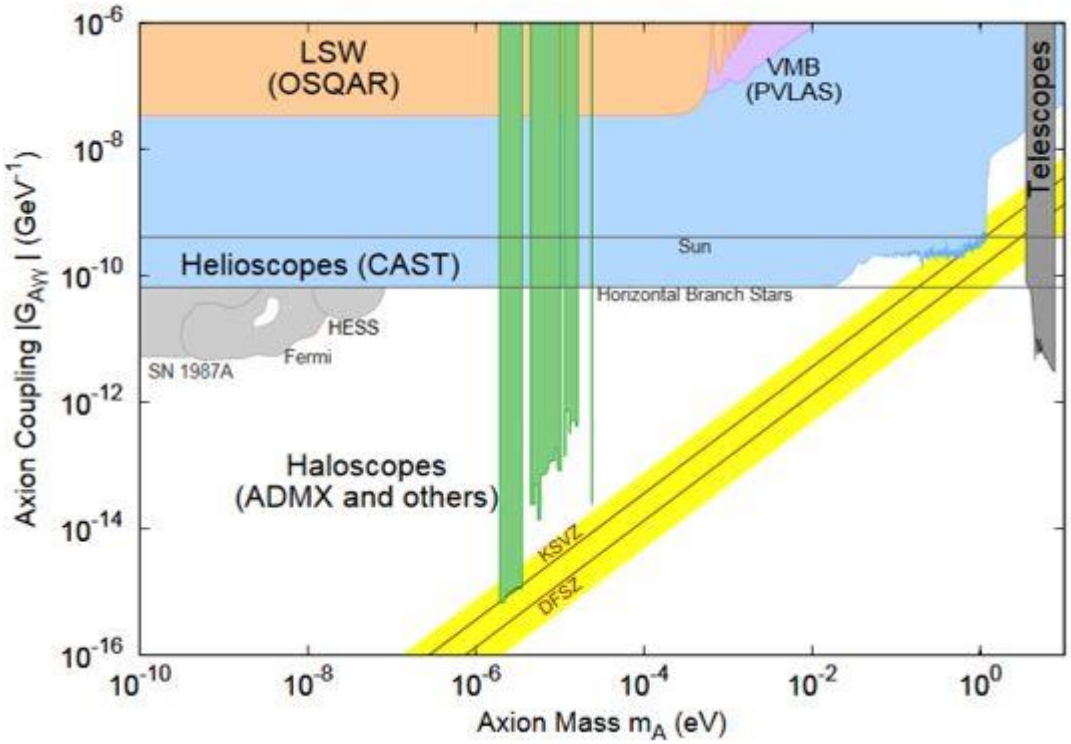

Fig. 4: Exclusion plots for axion and axion-like particles as a function of the axion mass and the di-photon coupling constant (extracted from [12]). QCD axions are constrained within the yellow band by the two theoretical models KSVZ and DFSZ. Haloscopes are today the most sensitive experiments to detect QCD Axion from the inverse Primakoff effect assuming they are the main component of dark matter of our galactic halos. The CAST helioscope is sensitive to QCD axion in the eV range and ALPs produced within the sun independently on whether such particles are component or not of dark matter. LSW experiments such as OSQAR are today the less sensitive and their performance must be improved. They are the only ones requiring no additional hypothesis "of anthropic type" to be analyzed. The exclusion limit obtained by PVLAS from VMB measurement without reaching the QED prediction, is more sensitive at higher axion mass than OSQAR because of the shorter length of the magnets used.

The OSQAR-LSW experiment is installed in the SM18 hall at CERN (Fig. 1). For the last experimental run, a 20 W CW laser beam has been aligned within one of the apertures of two spare LHC dipoles (Fig. 3) to interact with magnetic field. For the detection of the regenerated photons, state-of-the-art CCD has been used and the sensitivity after data analysis of Bayesian type reached 0.64 mHz at 95 % confidence level [11]. Thanks to the performance of the LHC dipoles, which were pushed to 9 T, *i.e.* close to their ultimate field limit, the last results obtained by OSQAR-LSW are the most sensitive to date for this type of experiment (Fig. 4). Other statistical data analysis methods are being developed to further improve the sensitivity. They are based on Wiener matched filtering technics and are very similar to the ones used in the analyses of Virgo and Ligo data.
The sensitivity of an LSW experiment expressed by the di-photon coupling constant $G\alpha_{\gamma\gamma}$, varies as $(BL)^{-1}$ with B the magnetic field and L the magnetic length, which are the dominant factors. A number of possibilities for upgrading OSQAR-LSW is being discussed within the Technology working group of the PBC (Physics Beyond Colliders) before addressing the proposal to the SPSC. They involve using spare LHC dipoles that could provide a large magnetic field integral - a key component in axion searches - on a length of about 120 m. The details of this proposal, OSWAR-LSW^{+} and the challenges of implementing this scheme are discussed in the PCB committee.

OSQAR-CHASE

Following the pioneering work of the GammeV experiment at Fermilab [13], OSQAR-CHASE is looking for a magneto-phosphorescent or afterglow signal of the vacuum permeated by a transverse magnetic field [6]. The key ingredient is still the di-photon chameleon coupling, assuming this time they can interact strongly with matter. When chameleons attempt to penetrate materials, such as walls and windows of the vacuum chamber, their effective mass grows sharply and they reflect. Therefore, chameleons with energy less than the effective mass in the material will be completely reflected by this material, allowing them to be trapped inside the vacuum chamber during the charging phase of the experiment, via the Primakoff effect. Chameleons produced in the vacuum chamber will be confined until they are being regenerated into photons in the magnetic field from the inverse Primakoff process, which emerge as an exponential decaying afterglow signal once the original laser photon source is turned off. The analysis of the 2017 OSQAR-CHASE run performed with a single LHC dipole is in progress and an improvement of the latest results obtained by the GammeV collaboration is expected.

OSQAR-VMB

Since its prediction in 1936 by Heisenberg and Weisskopf in the early development of the Quantum Electrodynamic (QED), the measurement of the Vacuum Magnetic Birefringence (VMB) is still one of the most difficult challenges in optical metrology. According to QED, the vacuum permeated by a transverse magnetic field is an active medium able to change the polarization of light from linear to elliptical.

The “n-1” anomaly to be measured is of the order 10^{-22}, which corresponds to the relative difference of the vacuum refractive indices in a magnetic field of 9.5 T. The measurement of the QED-VMB is in the same line as the measurements of the anomalous magnetic moment of the muon performed in the early years of CERN [14]. Contributions to the VMB could also arise from new light scalar/pseudoscalar particles like axions that couple to photons and this would manifest itself as a sizeable deviation from the pure QED prediction [9]. Because of the numerous critical issues to be solved, OSQAR-VMB is still in its preparatory phase at CERN and in collaborating institutes [15]. The perspective discussed within the PBC technology working group is to bring together the OSQAR collaboration with PVLAS one, whose experiment is located at the Department of Physics and INFN section of Ferrara in Italy, and which is currently testing a new optical scheme [16].

A fully dedicated experiment at CERN for measuring for the first time the QED-VMB, possibly up to the term in α^3 with α being the fine-structure constant, profiting from the unique opportunity of using state-of-the-art superconducting accelerator magnets and related infrastructures.

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CERN – HEP Software Foundation participates in Google's Summer of Code 2018.

by ***Panos Charitos***

PDF version

Google Summer of Code (GSoC) allows students to contribute to development of open-source projects, mentored by participating organizations. CERN-SFT participates in GSoC since 2011. In 2017, the programme expanded to involve the whole high-energy physics community, in particular by creating a GSoC umbrella organization that included not only CERN but also many other institutions worldwide. The umbrella was given the name of CERN-HSF (CERN HEP Software Foundation), thus bringing together common international efforts in high-energy physics software and computing.

This year, CERN participated in GSoC, helping the community of developers working for HEP to find new contributors and to produce even more code! Like in previous years, students are involved in projects strongly linked to some of the main open source packages developed by the SFT group, namely: ROOT, CVMFS, Geant4 and GeantV. A total of 29 projects were granted by Google to CERN-HSF (the highest number ever), 12 of which have been mainly supervised by SFT members. On the other hand, 64 mentors coming from 25 different organizations have contributed to the success of GSoC at CERN-HSF in 2018.

In the last six months, students worked closely with their mentors developing their projects. During this time, experts from CERN had the opportunity to evaluate student's ideas and skills and further refine some of these projects. From 23 April to 14 May, following the initial selection process, the community bonding period took place. The students had the chance to interact with their mentors and with fellow coders and exchange ideas in an informal and creative setup, which made them become familiar with their projects and prepare them for their development tasks.

Following the community bonding period, the GSoC coding period officially started since the mid of May and lasted until the beginning of September. During this phase, students worked on the tasks that they had in their project plan with the guidance of the mentors. Finally, on 14 August, students submitted the final result of their projects.

The topics of the projects covered multiple areas, including machine learning, distributed computing, storage systems, parallelization, data analysis, simulation, linear algebra, job monitoring and package management. The work of all the students was high quality and provided useful features for their corresponding projects; for example, a student achieved very good results

with the parallelization of convolutional neural networks on GPUs, and another one developed a library to make it transparent for the user to distribute data analysis with Spark.

The remarkable success of these projects, as well as the previous successful participation of SFT in GSoC, the organizers are eagerly looking forward to the final work of the GSoCers.

For more information and a list of projects visit:

http://hepsoftwarefoundation.org/activities/gsoc.htm

AXIONS

Roberto Peccei

A world renowned theoretical physicist working in the interface between astroparticle physics and cosmology. He is probably best known for his work on strong CP violation. Together with Helen Quinn, Peccei suggested a mechanism to address the strong CP problem, a major blemish of the Standard Model of particle physics- namely its failure to explain why the fundamental laws of physics in the strong interactions look the same if you run time backwards.

Peccei and Quinn received in 2013 the prestigious Sakurai Prize for Theoretical physics "for the proposal of the elegant mechanism to resolve the famous problem of strong-CP violation which, in turn, led to the invention of axions, a subject of intense experimental and theoretical investigation for more than three decades."

Born in Italy, in 1942 Peccei decided very early that he wanted to become a physicist. "I was always fascinated by the big scientific questions about the Universe. However, my desire to study physics came from a science prize that I won in high school. The prize included a book on atomic energy that I found fascinating. That's when I decided that I wanted to become a physicist."

Following his father advice, he applied to the MIT's department of Physics and got accepted. He obtained his B.S. in 1962 and completed his PhD in 1969 writing a thesis on "The chiral dynamic method and its applications in high energy physics". At MIT is where he first met Steven Weinberg, who later with Frank Wilczek noted that the Peccei-Quinn mechanism implied the existence of axions.

"In the mid 60-s things were rather complicated in particle physics and it was not always easy to choose the right path to follow. One of the hottest topics in fundamental physics then was the resurgence of field theory. I got interested in effective Lagrangians and I worked during my PhD on effective Lagrangians for threshold π-N scattering. "

Following his PhD, Peccei became a post-doctoral fellow at the University of Washington in Seattle and after that was offered a position as Assistant Professor at Stanford. "This is where I first met Helen Quinn, who was a visiting Professor from Harvard University. We both had similar interests related to the existence of instantons in the strong interactions and soon we started working together. One of the first things that we tried to understand was how instantons lead to fermion number violation.

During that time, Steven Weinberg was also visiting Stanford and liked to discuss physics during lunchtime. Quinn and Peccei often had lunch with him and enjoyed the chance to discuss their research with him. "Weinberg brought up the so-called θ problem in strong interactions. Why no CP violation was measured by the experiments? Could this θ be a parameter that goes to zero values". Peccei and Quinn were stimulated by Weinberg to think about this problem, partly because he continuously was asking them whether they had a solution to this conundrum!

"At some point, we realized that we could naturally arrive at a zero value for theta by introducing a new symmetry", that is today known as the Peccei-Quinn symmetry. "You can use this symmetry to turn theta from a constant parameter to a dynamical one and thus explain the lack of any CP violation in strong interactions".

The strong CP problem can be solved essentially three ways: assume some unconventional dynamics or a spontaneously broken CP symmetry or a third approach is to introduce an additional chiral symmetry. This is the path pursued by Peccei and Quinn. Peccei notes

Introducing an additional chiral symmetry to the Standard Model is a very natural solution for the strong CP problem since this chiral symmetry, effectively, rotates the θ parameter away to zero. This symmetry is spontaneously broken and introducing it to the theory essentially replaces the static CP-violating θ angle with a dynamical CP-conserving field. As a spontaneously broken symmetry, there is always an associated pseudo-Goldstone boson and its field is the so-called axion field. Peccei says: "We were very excited to having solved the strong CP problem that we didn't delve in the consequences of this symmetry. Weinberg and Wilczek, independently, understood that the Peccei-Quinn symmetry implies the existence of a new particle. Both of them were generous to give us credit for the PQ symmetry idea!"

The axion is the resulting Nambu–Goldstone boson and its field, a, can be redefined to absorb the parameter θ. While initially massless, non-perturbative effects, which make QCD θ dependent, result in a potential for the axion. This potential causes the axion to acquire a mass and relax to the CP conserving minimum, solving the strong CP problem. Furthermore, as there are no degrees of freedom available for the axion in the Standard Model, new fields must be added to realize the PQ solution.

Originally, the axion was thought to be very light, with a mass inversely proportional to the the EW scale. "The idea was that the scale breaking of the PQ symmetry is the same as the scale of weak interactions. That meant that axions should have a mass in the MeV or sub-MeV range and originally many people thought that axions should be closely related to the Higgs particle. In addition, the axion field could be very important for the development of the early Universe and axions should have been abundantly produced during the earliest moments of the Big Bang"

"The original model was long ago ruled out by experiment but one can assume that the PQ symmetry breaks at much larger energy scales which consequently means that axions should be much lighter". Indeed, more recently, attention turned to much smaller values of the axion mass (and in consequence feebler couplings), which are not excluded by experiments. Axions of this sort arise very naturally in models that unify the interactions of the Standard Model and can be very good candidates for dark matter due to the fact that they still carry mass while interacting very weakly with the rest of our Universe. "This part revived a lot of interest for research in this field and I find exciting the fact that currently there are so many axion experiments going on".

Following his work on formulating the PQ symmetry, Peccei was involved in many different models that incorporated this symmetry. "What is clear to me is that the best solution of

Today, Fermi scale axions have been ruled out, but invisible axions models like the so-called, KSVZ and DFSZ models, are still viable. Axion oscillations toward its minimun could account for the dark matter in the Universe. "This is an exciting possibility. No totally compelling invisible axion models exist, and there are no strong arguments to believe that the symmetry breaking scale takes precisely the value needed for axions to be the dark matter in the Universe. Nevertheless, it is encouraging that experimentalists are actively searching for signals of invisible axions."

As for the future, Peccei thinks that we should continue exploring the energy frontier and intensity frontiers aiming for higher energies up to 100 TeV. "Of course it is more speculative to argue for a higher-energy machine now, compared to the LHC for which the Higgs was a very strong motivation. However, looking at the history of the field this is the way forward. Going to higher energies or higher precision could reveal some discrepancies that can provide hints for the new physics to answer the open questions that leaves the Standard Model incomplete". He continues "understanding what stabilizes the Higgs mass to such a low scale, preventing it from going up to the Planck scale, or exploring the nature of dark matter are two of the biggest challenges for the next machine. There are many guesses but we need more experimental evidence".

Peccei believes that to understand the universe we need to explore different frontiers, both in astronomy and in particle physics. "You really have to look at a broader gamut of disciplines. I think four centuries ago, if you wanted to understand the universe, you did need to invent the telescope that looked at the universe. Now, you need many more tool. You are trying to bring all the people that have tools that will help us understand the universe together. I think that that is the mission, perhaps a bit broad but is the right mission."

Finally, Peccei notes the importance of collaboration for advancing in fundamental physics. "I see young people working very much in the same style as we used it. You look at a problem, you attack it in various ways, and together with your colleagues, you postulate and comment on new ideas. That kind of interaction still exists and is vital for our field". As to his advice to young physicists: "Be persistent, patient and follow the physics. This is what I always did. Although I worked on the strong CP problem while at Stanford I didn't

Two pictures to frame my career, the first is my 1961 passport photo from when I arrived in the US, and the second is me and my Franklin Award sponsor Larry Gladney (who is also a physicist) at the award ceremony.

Photo credit for that picture should be to Dan Burke Photography.

Helen Quinn

A professor emerita at the Department of Energy's SLAC National Accelerator Laboratory and Stanford University, received the 2018 Benjamin Franklin Medal in Physics last April for her accomplishments in the field of particle physics.

As a student, Quinn says, she grew up in an environment that encouraged curiosity about how things work and about identifying connections between different parts of our world. She recalls her math teacher saying "Helen, you could be a mathematician because are so lazy; you will never solve a problem the hard way, but always have to find a better way". "I am not sure if she wanted to praise me but somehow I felt that she supported my tendency to want to understand mathematics at a deeper level, which was critical to my later career."

Quinn started her undergraduate studies in the University of Melbourne. With some financial support from the Australian Weather Bureau, she registered to study meteorology. "If my family hadn't decided to move to the US, I would have become a meteorologist! In 1962 we all moved to Palo Alto and I was accepted at Stanford. I quickly started looking in different courses of study that would allow me to get my degree and decided to study physics. This was partly thanks to Jerry Pine, now a Professor in Caltech. He gave me the flexibility to attend different classes and decide where I wanted to place myself in a way that I could complete the degree."

Quinn's interest in particle physics began at Stanford in 1963, after completing her undergraduate education in physics. "My advisor encouraged me to move on and apply for a graduate programme but said 'Many graduate schools are reluctant to accept women because they get married and they do not finish. But I don't think we need to worry about that with you.' This left me thinking 'Is he telling me I'm never going to get married or trying to encourage me?'". Stanford, however, did accept her as a graduate student.

"I was lucky to be there at the time when the Stanford Linear Accelerator Center was being built." SLAC was the world's longest linear accelerator and promised unprecedented explorations of the subatomic world. "Really, the beginning of my interest was the fact that particle physics was bubbling at that time at Stanford, and that's where I got hooked on it." Quinn thinks that an important element in any scientist's career is the opportunity to meet inspiring colleagues and interact with teams working at the forefront of research. Enthusiasm for a problem seems to be contagious, she says.

After graduating from Stanford, Quinn pursued research at the German research center DESY and at Harvard University. During her graduate studies in Stanford, she met and married Dan Quinn, then a student of experimental particle physics. They applied together for postdoctoral positions at DESY and were both accepted. Two years later, her husband was offered an Assistant Professor position at Tufts University. "I thought, well if there is a city in the country where I could also find an academic position, it is Boston! But I did not find a job that year. I thought about becoming a high-school teacher and registered for some education courses in Tufts, which included practice teaching in a local high school. Perhaps this is when I began my preparation for my later work in science education!" Eventually, Quinn decided to continue with her research in particle physics, first as a visitor and later with a position at Harvard. She collaborated with theorist Steven Weinberg and Howard Georgi to publish a paper on "Hierarchy of Interactions in Unified Gauge Theories" that introduced a general formalism for understanding how the strong, weak and electromagnetic fundamental interactions merge at very high-energy scales. This paper is one of

Quinn made her next move by taking a leave of absence from Harvard. "In 1976, we moved back to California because my husband was changing his career from physics to decision analysis and that's where he found a job. I used my Sloan fellowship to visit Stanford for a year, then began looking for a job around Stanford. SLAC could offer me only a temporary research position, so from an Associate Professor at Harvard I found myself again as a post-doc at SLAC" until the following year, when Quinn became a member of the SLAC permanent scientific staff.

During the year at Stanford, she worked with Roberto Peccei on another highly recognized contribution, now called Peccei-Quinn Symmetry. "The question behind our work was: how come the CP violation in weak interactions doesn't infect strong interactions? What is the mechanism that protects strong interactions from this violation?" CP is a symmetry between the laws of physics for matter and those for antimatter. It is known to be violated by weak interactions, but experimental upper limits on the electric dipole moment of the neutron put very tight limits on any strong interaction CP violation. In the strong interaction theory, such effects can enter; the parameter that defines their size is called theta.

"We started exploring this problem by thinking about cosmology! If quarks had zero masses — which we assume is the case for quarks in the early Universe— then one could tune away any theta parameter by redefinitions of quark field phases. Roberto and I prepared the first draft of a paper based on this idea, but it was completely wrong! We talked to Steven Weinberg, who was then visiting Stanford and he made a comment that helped me recognize that, by tuning away the theta parameter, you change the phase of various Yukawa couplings. Although the Yukawa couplings are also invisible in the high energy situation of the early Universe, they are the places where CP violation is hiding until quarks get their masses. So we did not tell Steve our wrong idea and went off to think some more.

We now understood that the solution was linked to the Yukawa couplings. "I saw that we needed to add a symmetry to arrange them so that the effective value of theta after the quarks get their masses would be zero, no matter what it was in the high energy situation. The trick is that the symmetry links the phase of the quark mass matrix to the theta parameter, so that the combination, which is quantity that matters for CP violation, is naturally zero once the Universe cools enough that the quark masses appear. To allow the symmetry, the theory added additional Higgs-type scalar particles to the Standard Model."

Weinberg and, separately, Wilzeck immediately saw that the Peccei-Quinn theory suggests the existence of a very light but yet-to-be-found particle, called the axion. Quinn remembers that "Roberto and I were so excited to have solved the original problem that we decided to quickly move forward to publish our idea with the simplest possible example model. This was only a toy model. We did not think it was realistic so we did not further explore its phenomenology. We were just using it to illustrate how the symmetry worked to solve the CP problem (laughs). "So we did not notice that the model also illustrated another general principle, according to which there should be a light scalar particle associated with the symmetry. This is the axion! In fact, Weinberg, before publishing his paper, called me and asked me, 'Did you notice...', and I paused for ten second before replying, 'Of course this is a consequence of our theory, but no, we had not noticed it'".

The first Peccei-Quinn model was soon ruled out by experimental tests. Versions that have more additional Higgs fields add more parameters and give the flexibility to evade those experimental limits. Following a suggestion from Pierre Sikivie, experiments are now searching for axions as a possible explanation of dark matter. Observing them, or any other additional scalar particles would be very interesting. Today, the term axion is used for any very light scalar particle with relatively little interaction with anything else, though it does interact with photons. Other axion searches probe for these particles in parameter regions that would not work for dark matter.

Quinn notes that even if searches for DM axions exclude that possibility, this won't rule out the Peccei-Quinn theory. "It simply rules out that axions are the dark matter in our Universe. You know, it is very hard to exclude a theory that predicts something that is very hard to detect".

Quinn reminisces at the changed state of particle theory, saying "I started before we had any of the current theory and now is a very different time. We had the Fermi four-fermion theory for weak interactions, which we knew didn't work beyond leading order, but we were not too worried because that was good enough to make estimates. There really was no calculable theory for strong interactions. Those were considered to be mediated by rho and pi mesons". She adds: "We also had Current Algebra and Regge theory that were useful, and still apply, but are incomplete. At the same time, there was Jeff Chew's bootstrap model claiming that no particle is elementary. Particle physics seemed very confused."

Helen Quinn

The early 1970s brought big changes when the pieces of the Standard Model were pulled together. At that time she was a high school teacher and Joel Primack, a junior fellow at Harvard and a good friend of Quinn invited her to visit theorists at Harvard University, and the conversation led her to return to research "At that moment, a piece of work had just appeared that was really fundamental to the development of the Standard Model. In 1971 Gerard 't Hooft and Martinus Veltman published a new method for calculating in gauge theories, which underlie the Standard Model. Their paper allowed many physicists to revisit Weinberg's paper "A Model of Leptons" that is a key piece of the Standard Model today. Although it was published in 1967, it had very few citations before 1971 because no one knew how to make calculations beyond the leading order."

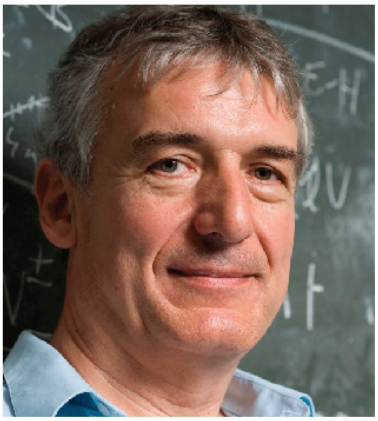
Together with Tom Appelquist, Primack and Quinn set to work to apply the 't Hooft and Veltman approach. "Before the Standard Model, there was a problem with weak interaction theory. You could do the first-order calculation, but the next order (the one-loop calculation) was infinite. So the old theory was not well-defined nor stable. We did the first finite one-loop calculation of weak interactions (muon decay) using the new theory. In that paper we also mentioned that the strong theory needed to be a vector-like theory so as not to disturb the good results. I remember how pleased Steve Weinberg was with our result."

Over the next few years, developments extended Weinberg's lepton model to quarks and the charm quark was predicted and discovered. Parallel developments built the QCD theory of the strong interactions of quarks, also a gauge theory. By 1976, John Iliopoulos in a talk in the Lepton-Proton conference could put all the pieces of the Standard Model together. "It was a great period and a stimulating intellectual environment. During my years at Harvard, Steven Weinberg was there, as well as Appelquist, Georgi, Glashow, DeRujula and others. David Politzer was a graduate student."

However, Quinn is less optimistic about the modern picture of particle physics which is very different compared to the 1960s. "Currently we have an incredibly good theory up to a certain scale and indirect evidence that there must be something more, possibly at very much higher scales. It is extremely hard to probe those scales. We can speculate and build very nice theories but we have little evidence to test them. It may be that we will not get access to an energy scale that can give us evidence to distinguish among all the speculations and reveal more of nature's reality. We have gone from having lots of unexplained data but little successful theory in the 1960s to having a very successful theory and little data that points the way to go beyond it today."

Following her retirement in 2010, Quinn has focussed on science education. She chaired the National Research Council committee that produced "A Framework for K-12 Science Education," an influential report that served as the basis for the 2013 Next Generation Science Standards. Essentially, in the US, standards are the basis on which the States build assessments, and thus they're a set of guideposts for teachers and curriculum developers about what to teach. "Over 30 states in the US have now adopted standards based on the Framework and it has also had major influence internationally. However, by their nature, standards are bits and pieces of knowledge. It really helps to have a broader picture, such as that given by the Framework to express the vision for science education; the guideposts alone are not enough."

Science education remains her primary focus. Quinn finds the work rewarding and significant, albeit in a more pragmatic way than developing new particle physics theories, as it can impact many more people. "We are aiming not only to educate physicists and other scientists for tomorrow but also to make science and scientific thinking available to everyone. Everyone needs to make decisions for themselves or their community and to be able to look for evidence to support or refute the information they are given as they are confronted with complex questions. Science education, done right, gives us the knowledge and capacity to think through such decisions in a different way." She adds: "I want every citizen to have that capability because that can affect the future in ways that are constructive and positive. I want citizens who can look at a problem in their community and think like a scientist about the part of the problem that is science. I also want high school and college graduates equipped with capabilities that employers want, whether they come from well-educated families or not. Science education has an important part to play in making this a reality."



A Q&A with

Pierre Sikivie

Which are the key process through which axions were produced in the early Universe?

Axions are produced in the early universe in two different populations, which we may call "hot" and "cold". The hot axions are thermally produced in the primordial plasma as are most other particles, including photons and neutrinos. Hot axions have a temperature of order a couple degrees Kelvin today.

Like standard model neutrinos, they move too fast to gather in galactic halos. For this reason, hot axions are not a good candidate for the dark matter that is observed in galactic halos and in clusters of galaxies. Like relic standard model neutrinos, they are a form of "hot dark matter". I do not know of a good way to detect hot axions in the laboratory and as far as I know, there is no good way to detect relic standard model neutrinos either.

The cold axions are produced in a process of "vacuum realignment", pointed out in 1982 by a number of authors. This process is specific to light very weakly coupled Bose fields, such as axions or axion-like particles. The key point is that when the axion mass effectively turns on during the QCD phase transition (at a temperature of order 1 GeV, and a time of order 10-7 seconds after the Big Bang) the axion field is not initially at the minimum of its effective potential. It begins to oscillate then.

These oscillations do not dissipate because axions are very weakly coupled. The energy density in the oscillations is a form of cold dark matter. Cold axions are very cold, much colder than the other cold dark matter candidates. A number of credible methods have been proposed to detect cold dark matter axions that surround us because we are in the halo of the Milky Way galaxy. The cavity haloscope is one of those methods.

Why axions are good dark matter candidates? Can they co-exist with other possible candidates for dark mater (i.e. sterile neutrinos, susy particles, etc)?

A good dark matter candidate should have the following basic properties:

a) the particle must be stable, i.e. its lifetime must be much longer than the present age of the universe

b) it must be neutral and sufficiently weakly interacting that its evolution in the early universe is in first approximation determined solely by its gravitational interactions. In particular, it cannot be baryonic (ordinary atoms and molecules).

Pierre Sikivie

Axions have all the required properties, but in addition they solve the Strong CP Problem of the Standard Model of elementary particles. In fact, they were first proposed as a solution of the Strong CP Problem. The fact that they are a good dark matter candidate came as a bonus.

Axions, weakly interacting massive particles (WIMPs) including SUSY particles, and sterile neutrinos all have the basic properties required of a good dark matter candidate.

Finally, we think today that the dark matter could be a mixture of things. My collaborators and I have argued on the basis of the phenomenology of caustic rings of dark matter in galactic halos that at least some of the dark matter (more than 30%) is axions or axion-like particles.

Which were the key developments that lead to the development of the axion haloscope and the axion helioscope?

I am happy to recount how the axion haloscope (to detect dark matter axions) and the axion helioscope (to detect solar axions) were invented.

Back in the early 80s, it was thought that the Strong CP Problem may be solved by an axion which is very light and very weakly interacting, the so-called "invisible axion". I became a junior faculty member at the University of Florida around that time. My first teaching assignment was graduate level electromagnetism and as you may guess, I did many problems in J.D. Jackson's famous book on the subject.

I graciously agreed to spend a month at Harvard in the summer of 1983. On my way there, in a spirit of preparation, I read a preprint by Sidney Coleman, called "The magnetic monopole fifty years later". At the end of his review, Coleman raises an interesting question. It may be phrased as follows: when a magnetic monopole traverses an axionic domain wall, it acquires electric charge due to an effect that Edward Witten had pointed out. Where does this electric charge come from?

While at Harvard (in Jefferson lab), I thought about this and realized that the question can be answered by considering the generalization of Maxwell's equations that describes the axion field along with the electromagnetic field. The generalization is now usually referred to as "Axion Electrodynamics". Using these equations, I saw that when a monopole

The techniques of Jackson's book were proving to be very useful in thinking about these effects. While I was at it, I thought I might calculate the event rates in hypothetical experiments that would test the invisible axion hypothesis by some electromagnetic means. I confirmed at first the common wisdom that such experiments would be very difficult, impossible really. The event rates are too low! One of the more attractive ideas that emerged was to convert axions to photons in a magnetic field. The trouble was that one had to produce the axions first. One might produce the axions by the inverse process of photon to axion conversion in a magnetic field but the overall rate for both production and detection was too small to yield a feasible experiment. I was thinking that the axions might be produced in a nuclear reactor, or even a nuclear explosion, when it occurred to me that the solar interior is a huge reactor. It is very powerful, nearby, yet also shielded from us. It produces a reliable flux of axions on Earth, much larger than anything that could be made in the laboratory, and completely free of charge. Thus was born the idea of CAST-type experiments: convert solar axions to x-rays in a laboratory magnetic field. I called it the "axion helioscope" because it would allow one to look inside the Sun if one had a signal.

The "axion haloscope" is similar but here one attempts to detect axions that are already in the laboratory as dark matter. It also uses the conversion of axions to photons in a magnetic field, but in this case the photons are microwave radiation. Because the dark matter axions are non-relativistic it is helpful to have an electromagnetic cavity to capture the photons. The conversion is resonant if the cavity is tuned to the axion mass.

Which is currently the experimental status in Dark Matter axion searches?

The most mature approach to dark matter axion detection is the technique involving a cavity immersed in a strong magnetic field, the original axion haloscope. A couple of months ago the ADMX experiment at the University of Washington in Seattle, which uses this method, announced that it reached sensitivity to detect dark matter axions in even the most weakly coupled case. The cavity approach is also being pursued at Yale University, at the Center for Axion and Precision Physics in Daejeon, Korea, and at the University of Western Australia. Now that sufficient sensitivity has been achieved, the challenge is to extend the search to the widest possible range of axion masses. The cavity approach is most feasible in the approximate axion mass range 0.3 to 30 micro-eV. A key research and development challenge is to develop cavities or cavity arrays that have high resonant frequency but also high effective volume for coupling to dark matter axions.

To go to higher frequencies, variations have been proposed which involve making the magnetic field inhomogeneous on small length scales (such as the ORPHEUS wire array) or engineering the cavity modes using parallel dielectric plates (MADMAX). Axion absorption in atomic transitions has also been proposed to reach higher axion masses. To reach lower masses, the cavity may be replaced by a LC circuit (e.g. ABRACADABRA). To reach even lower masses, nuclear magnetic resonance methods have been proposed (CASPER).

How was your original suggestion for an axion haloscope originally perceived by your peers?

It was well received and there was no controversy. Yet compared to WIMP searches, axion searches have been very slow to develop. I think this is mainly due to the fact that the axion searches require expertise in a variety of areas which are not part of traditional particle physics. Let me illustrate this with the cavity experiment. It is motivated by particle physics and cosmology, but searches for dark matter in the form of a wave when most particle physicists are used to thinking about particles.

(We are taught about waves in school but quasi-forget about waves when drawing Feynman diagrams or when building particle detectors.) The fact that cold axions are not thermally produced may also be a psychological difficulty. Most importantly, the cavity experiment uses a variety of technologies - microwave engineering, ultra-low noise receivers in a high magnetic field environment, cryogenics - which are not typically used by high energy physicists and which had to be specially developed. It is fair to say that the physicists who develop and carry out axion dark matter searches are very courageous!

In parallel to earth-based experiments, do we expect more limits to come from astrophysical observations?

Indeed, axions may play interesting roles in astronomical observations. Many cosmologists suggest that axion-like particles cause the universe to be more transparent to high energy gamma radiation than expected, and that they are responsable for a faster than expected cooling of white dwarfs. It was shown six years ago that axion dark matter cools baryons. The recent observation by the EDGES collaboration of a lower baryon temperature at cosmic dawn than expected under "standard" assumptions may be new evidence that the dark matter is axions, at least in part.

When constraints from early negative particle physics searches and from astrophysics are taken into account, the production and detection rates of axions in standard collider experiments are generally found to be too low for meaningful searches to be carried out. However, particle beams may be used in novel ways. Gianni Carugno and I worked on a scheme to use ion beams to detect dark matter axions by the transitions the axions may cause between the atomic levels of the ions in the beam. Unfortunately, the scheme requires at least 109 particles in the beam and this is far more than what is currently achievable.

Do you have an advice for young researchers now entering the field of dark matter/axion searches?

I remember reading somewhere Feynman's advice to young scientists aspiring to great discoveries. He said: "You have to develop your own tools". It would be hard for me to improve on that short sentence.

Conclude

CERN's diverse experimental programme include searches for axions and ALPs with a number of different experimental technologies. In this special issue we present results of direct searches at the LHC through proton and heavy-ion collisions as well as in-depth report from the dedicated haloscope (CAST) with its foreseen upgrade and finally the light-through wall OSQAR experiment.

AXIONS