EP Newsletter of the EP department

FASER joins the exploration for new physics

FASER

PBC

long-lived particles

*by **Jamie Boyd (CERN)***

PDF version

On March 5th the CERN Research Board approved the ForwArd Search ExpeRiment (FASER), for installation at the LHC during Long Shutdown 2. FASER is an experiment designed to broaden the search for new physics at the LHC, by looking for light, weakly- interacting new particles that could be produced in the LHC collisions in the extreme forward direction.

The idea for such an experiment was proposed by J. L. Feng, I. Galon, F. Kling, and S. Trojanowski, theorists at the University of Irvine, California in a paper released in the summer of 2017 [1]. In 2018 they started to work with experimentalists, forming a collaboration to realise this idea in an experiment at the LHC. By the summer 2017 the project had attracted funding from the Heising-Simons foundation and the Simons foundation, two private foundations from the US, allowing the experiment to rapidly progress through the review by the LHCC, with a letter of intent [2] submitted in July 2018, followed by a Technical Proposal [2] submitted in November 2018. Following successful review, and further scrutiny from the LHC Machine Committee and the LS2 Committee the experiment was formally approved in March 2019.

The basic idea of FASER is based on the fact that a huge number of standard model particles, such as pions, are produced in the LHC collisions, predominantly very closely aligned around the colliding beam axis. New physics particles that can be very rarely produced in the decay of such pions, could then be detected in a very small detector with an active area of only 20cm across, when placed 500m from the collision point. In fact 2% of π^0's produced in the LHC collisions (with E>10 GeV) are produced in this angular region, which covers only $2^{-6\%}$ of the solid angle.

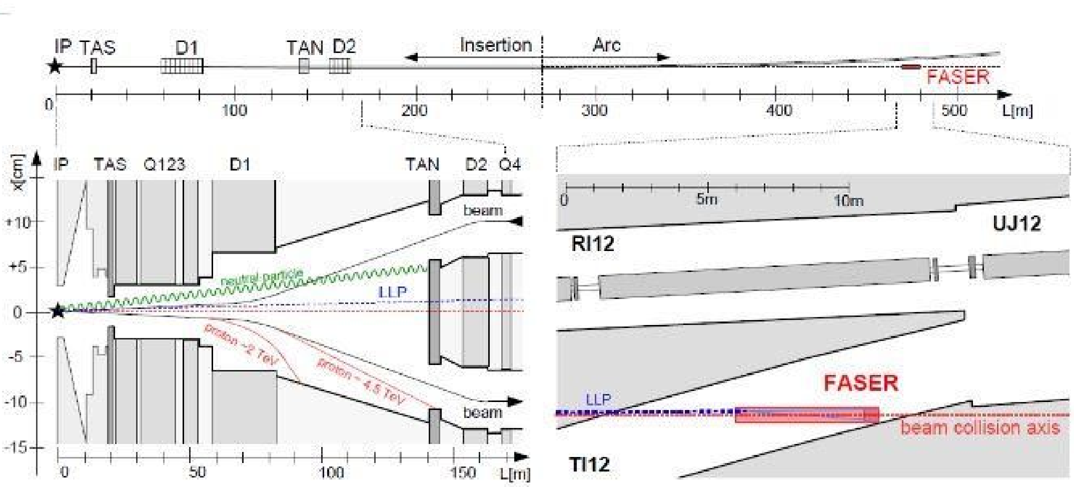


Fig 1: (Top) A schematic of the LHC in the region up to 500m from the ATLAS collision point (shown at the left hand side). The bottom right panel shows the location where FASER will be installed aligned with the beam collision axis in the TI12 tunnel.

A particular target is the 'dark photon', which can act as a mediator particle for light dark matter, and is discussed in more detail in Ref [4]. For a dark photon with a mass of 100 MeV and a coupling to SM particles of eps=10^{-5}, these would only produced once in about 10^{10} π^0 decays.

However in Run-3 of the LHC an expected 10^15 pi0s will be produced in the angular region corresponding to the FASER detector, meaning ~10^5 dark photons could be produced pointing towards FASER. The large energy of these pi0s mean that the dark photon is likely to travel long distances before it decays, and a few 100s of these 100,000 dark photons could decay inside the FASER detector.

Amazingly, it turns out that there already exists an ideal location for the FASER detector to be placed, so that it can be aligned directly on the collision axis. This is an unused service tunnel that joins the LHC 480m from the ATLAS collision point, called TI12. In the past this tunnel was used to inject leptons from the SPS into the LEP collider, but it is no longer used. Figure 1 shows a sketch of the LHC tunnel for 500m on one side of ATLAS, showing the location where FASER will be installed in TI12. With just a small amount of digging in this tunnel, a 5.5m-long detector can be situated on the collision axis, allowing good sensitivity to dark photons and other light weakly interacting new particles, in unexplored, and theoretically well motivated, regions of parameter space.

The extremely fast turn around for FASER, from an idea in a paper, to an approved experiment was made possible by support from the CERN Physics Beyond Colliders study group, which provided resources for running background simulations, measuring backgrounds, mapping out the collision axis in TI12, and studying the infrastructure work that needs be done for FASER to be installed and operated. In addition, the FASER detector will re-use spare modules from the ATLAS silicon micro-strip tracker (SCT), and from the LHCb electromagnetic calorimeter, allowing it to skip the design and construction phase for these new detectors, and saving both time and money.

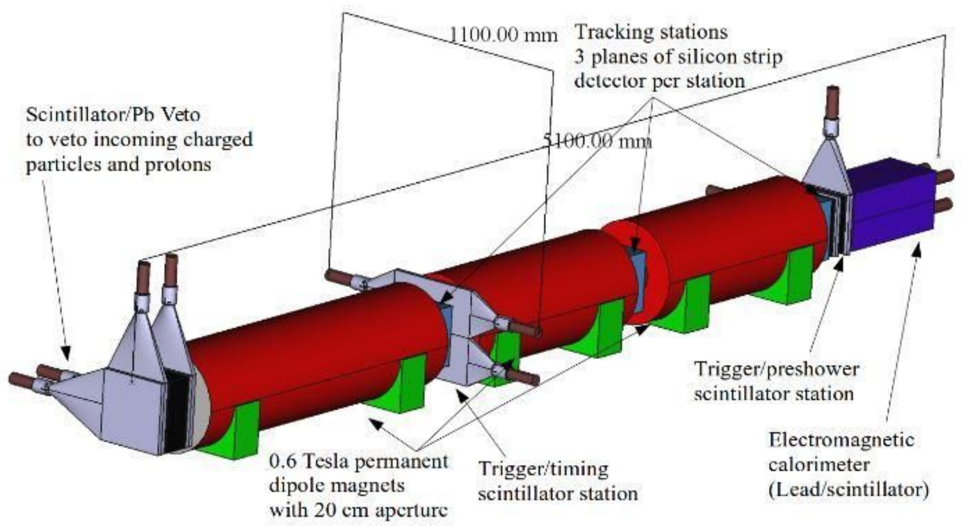


Fig 2: A schematic of the FASER detector. Showing the scintillators (grey), magnets (red), tracking stations (blue), and electromagnetic calorimeter (purple). Particles from the ATLAS collisions enter from the left hand side. The first magnet represents the decay volume for the dark photons.

A sketch of the detector is shown in Figure 2. At the entrance there are a number of scintillator planes, which will be used to ensure charged particles are not entering the detector when searching for the signal topology. This is followed by a 1.5m-long decay volume, enclosed in a 0.6T dipole magnet. Following this there is a spectrometer to measure the trajectories of charged particles produced in dark photon decays inside the decay volume. The spectrometer is made up of two 1m-long dipole magnets (also with 0.6T), with tracking stations, positioned at the start, middle and end of the spectrometer. Each tracking station is made up of three layers of double-sided silicon strip SCT modules. At the end of the detector the electromagnetic calorimeter allows to measure the electromagnetic energy in the event, and to distinguish between decays to electrons or photons, compared to muons or hadrons. The expected physics sensitivity of FASER across dark photon parameter space is shown in Figure 3 and the reach has been estimated in many potential new physics models [4].

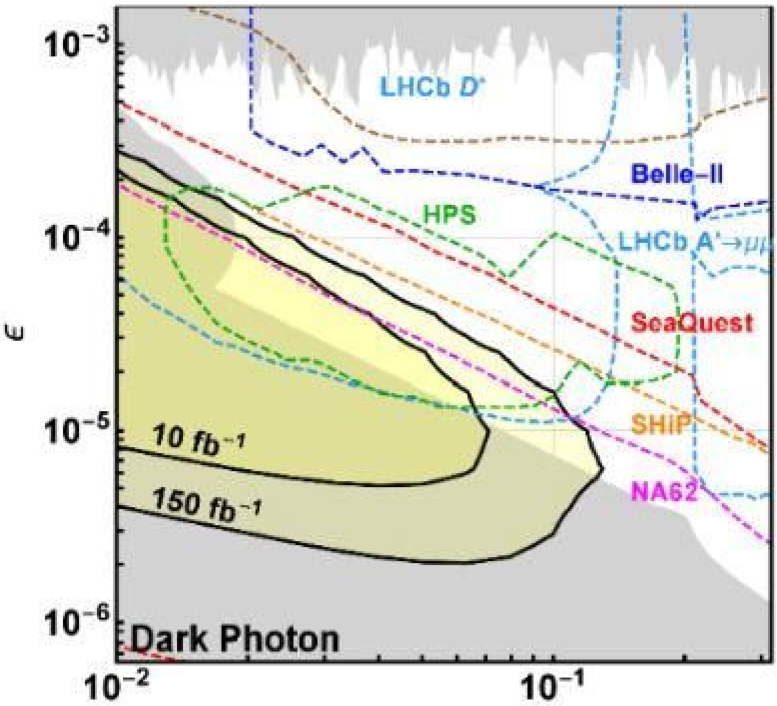


Fig 3: The expected exclusion limit in dark photon parameter space for 10/fb (expected in 2021) and 150/fb (expected during the full LHC Run-3) of data at the LHC. Projected limits from proposed future experiments are also shown.

There is an ambitious timeline to build, test and install the detector into TI12 before summer 2020, when the LHC machine in that sector will be cooled down. The schedule foresees to have the individual systems ready by the end of 2019, and then for combined commissioning on the surface during the first part of 2020. The magnets, which are being built by the CERN magnet group, are expected to become available in the first quarter of 2020. The Collaboration currently consists of 38 researches from 16 institutes in 8 countries, and includes CERN fellows, and staff, working part time on FASER. Given the tight timeline, and small collaboration, it represents a nice opportunity for young researchers to get involved in construction and commissioning in a short timescale compared to hardware projects on the big LHC experiments.

As well as searching for weakly interacting light new physics particles FASER may be able to make neutrino measurements, based on the huge flux of high energy neutrinos that are produced in the LHC collisions and traverse the detector location. Studies are ongoing to see what measurements may be possible.

Despite the fact that FASER is not up and running yet, there are already ideas for a potential upgrade, which would see a bigger detector, installed in the same location. Such a detector (with a transverse radius of 1m compared to 10cm) would have sensitivity to new physics particles produced in heavy meson decays (such as B-decays), which are produced more spread out around the beam axis.

However, given the tight timeline the team are currently focussing on getting FASER installed and working in LS2. They are looking forward to increasing the ability to search for new physics with the LHC, in a complementary way to the bigger LHC experiments.

Further Reading

[1] - J. L. Feng, I. Galon, F. Kling, and S. Trojanowski ,Phys. Rev. D 97, 035001 (2018) hep-ph:1708.09389

[2] – FASER Collaboration, “Letter of Intent for FASER: ForwArd Search ExpeRiment at the LHC”, arXiv:1811.10243

[3] - FASER Collaboration, “Technical Proposal for FASER: ForwArd Search ExpeRiment at the LHC”, arXiv:1812.09139

[4] - https://ep-news.web.cern.ch/content/lifetime-frontier

[5] - FASER Collaboration, “FASER's Physics Reach for Long-Lived Particles”, arXiv:1811.12522

Physics from neutrino near detectors: opening a new window for BSM searches

With the advent of a new generation of neutrino experiments which leverage high-intensity neutrino beams for precision measurements, it is timely to explore the opportunity that these experiments offer for searches of beyond the standard model (BSM) physics. The realm of BSM physics has been mostly sought at high-energy regimes at colliders, such as the LHC at CERN. Therefore, the exploration at neutrino experiments will enable complementary measurements at the energy regimes that balance that of the LHC. This, furthermore, is totally in concert with recent ideas for high-intensity beams for fixed target and beam-dump experiments world-wide, e.g., those at CERN [1].

A key feature of the long and short baseline neutrino facilities that prepare for a new generation of neutrino physics experiments is the use of advanced detector technologies. Decisive measurements are expected from the short baseline experiments on the sterile-like neutrino phenomena at the SBL program at FNAL. These experiments are by definition located close to the neutrino source, within a few hundred meters, and the driving technology choice is liquid Argon TPCs. At the same time, long baseline experiments consist of a concise near detector within a few hundred meters of the neutrino source, followed by a very large far detector, at a distance of hundreds or even a thousand kilometres away.

Neutrino beams are generated from a very intense high-energy proton drive beam with an energy typically in the range of 10 to 100 GeV, dumped on a dense target. This produces a secondary beam consisting mostly of pions and kaons, and these mesons decay to dominantly yield a muon and a neutrino. The neutrinos will pass through the absorber before continuing their way to the experiments. The near detector's main task is to measure the un-oscillated neutrino flux, used to gauge for the observation of the neutrino interactions at the far detector. The need for more precise measurements in a near detector that allow controlling the systematic uncertainties on oscillation measurements has been demonstrated over the last years. As a result, the planned near detectors have become very sophisticated precision particle detectors, providing full acceptance and many capabilities than just monitoring the flux or providing the much needed neutrino-nucleus interaction measurements. This awareness has led recently to a number of workshops and discussions reported here.

In essence, the neutrino beam facility and near-by detectors can be considered as (non-optimized) beam dump experiments. Therefore, we have taken a closer look at the potential they offer in searches for new weakly coupled low mass long-lived particles, such as heavy neutral leptons (HNLs), low mass dark matter, dark photons and so on. Many of these search scenarios were recently also the focus of the Physics Beyond Collider study at CERN [1].

One year ago a small kick-off workshop was organized at CERN called "Near detector physics at neutrino experiments" (18-22 June) [2] with only about 20 key participants, but a clear picture and strong interest emerged from that meeting. They offer a large discovery potential, explored in depth, in searches for light exotic mediators, light dark matter, MeV range neutrinos and HNLs, the sensitivity to new physics of trident event production, and to non-standard neutrino interactions, as well as potentially very interesting classical Standard Model type of measurements. HNLs are a very popular extensions of the Standard Model aiming to explain baryon asymmetry in the Universe, neutrino masses, and dark matter and it should be noted that they are one of the main targets of the SHiP proposal at CERN, see [3].

New physics can be probed with near detectors via the following processes (See Fig 1.). Neutrinos created as described above could mix with new, perhaps right handed heavy neutrinos, if kinematically allowed. Hence some of these neutrinos may turn into HNLs that can potentially live long and decay in the near detector. BSM particles like dark photons can be produced directly in the decays of the produced light mesons and may decay in the near detector. Other new light particles than could be produced in the beam dump are for example light dark matter and milli-charged particles. The latter are foreseen in the case of a dark sector that has its own QED which kinematically mixes with the Standard Model QED. Such stable light BSM particles can interact in the near detectors via elastic or inelastic scattering processes with the target electrons and nucleons.

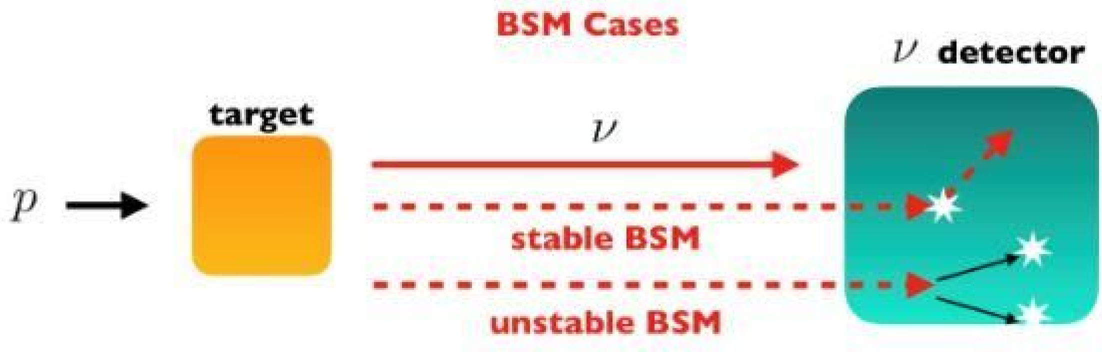


Figure1: Schematic view for BSM physics opportunities with neutrino near detectors

New generator tools - such as MadDump- are being developed as well, which should facilitate experimental groups to perform such studies. In all, this first workshop was just the tip of the iceberg, showing there was a significant potential for such searches at near detectors in neutrino beamlines. This led to a larger and more open workshop organized at FNAL called "Physics opportunities in the Near DUNE detector hall (December 3-7)" [4], gathering about 80 participants. New topics were discussed in detail, such as the exciting sensitivity to light dark matter in the DUNE near detector, new ideas and sensitivity tests for discovering milli-charged particles specifically in Liquid Argon TPCs (Fig. 2), sensitivity to scalars with B-L charge that can lead to several interesting phenomena: new decays, beam-strahlung, dark matter, etc. Moreover, precision Standard Model measurements in neutrino scattering are part of the rich slew of physics topics offered by the near detector capabilities, such as measurement of sin2 θW and electroweak physics, strange sea and charm production, measurement of strange sea contribution to the nucleon spin ∆s, and more.

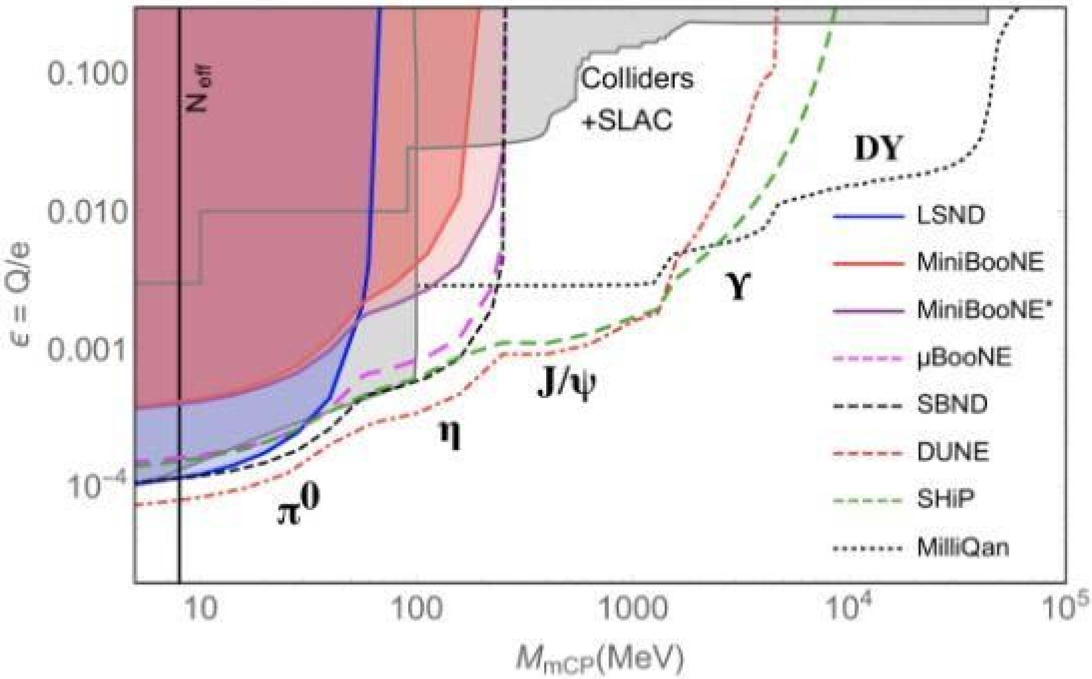


Figure2: An example of BSM physics reach with different present and future possible experiments for the search of milli-charge particles related to a dark QED model. The reach is shown as function of the fractional charge and particle mass. [5]

Finally, the community interested in searching for new physics with present and particularly future accelerator-based neutrino experiments, gathered together for a 2 day topical working meeting in Arlington, Texas on “New Opportunities at the next Generation Neutrino Experiments” (April 12-13). The purpose was in particular to prepare a first white paper. About 45 authors have compiled a paper that will be published on the arXiv in the next weeks.

The next-generation neutrino experiments definitely offer new opportunities, and a systematics mapping of the sensitivities for searches for new physics scenarios is a next goal. Obviously, the presently designed near detectors have not been optimized for such a program but are driven by the requirements of the core neutrino oscillation program. Modest detector additions, e.g., adding precision timing detectors, could strongly enhance the capabilities. Compared to the beam facility proposed for CERN in the North Hall, eg for the DUNE detector we expect to get more protons on target (1-2E21 POT/year) but the beam energy is considerably lower and the position of the detector is more than 500 meters from the dump. Hence eg for HNL searches the near detector will focus more towards smaller masses, up to 2 GeV or so. There will be certainly an interesting complementarity among the different search experiments in the low mass region, all expected to start around 2027!

Further reading

[1] arXiv:1901.09966
[2] https://indico.cern.ch/event/721473/
[3] EP newsletter: https://ep-news.web.cern.ch/content/hunting-right-handed-neutrinos-new-g...
[4] https://indico.fnal.gov/event/18430/
[5] arXiv:1806.03310

The GEMs of CMS

by ***Archana Sharma (Project Manager CMS Muon GEM Upgrade, CERN)***

PDF version

To prepare for the higher collision energy and luminosity of the subsequent running period of the LHC significant improvements are ongoing in the CMS detector. One of the planned upgrades is the installation of large-area GEM detectors in the forward muon region. Following an extensive R&D program since 2009, Triple GEM (Gas Electron CMS GEM Upgrade Multiplier) chambers have been developed as the optimal solution for three detector stations of the CMS Endcap. GEM technology has been successfully used in the past years in high-energy experiments including STAR, TOTEM and LHCb. The CMS GEM Upgrade project represents the next major step in the evolution GEM detector systems, both in terms of detector size and quantity, from a small number of medium-sized detectors to a large number of large-sized detectors. The sensitive area covered by GEMs in these three upgrades would be ~ 350m^2, totaling around 720 detector modules and about 1000m^2 of GEM foils.

The GEM detector can operate in the high-rate environments of Run 3 and HL-LHC and provide precise tracking thereby improving muon momentum resolution. This is done by exploiting the measurement of the bending angle of muons that emerge at an angle of around 10° relative to the beam axis. The adopted triple-GEM technology consists of a stack of three GEM foils interspersed at a distance of few mm enveloped in an argon carbon dioxide gas mixture delimited by drift and readout electrodes. The GEM foils are made of a metal-clad polymer with a thickness of 50 μm, chemically etched with millions of holes, typically 50 to 100 per mm.

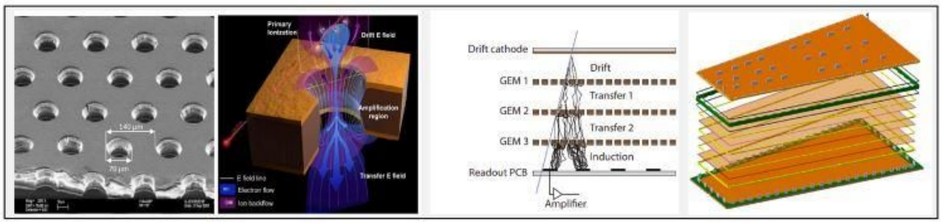


Figure 1. (a): Scanning Electron Microscope (SEM) picture of a GEM foil (left). and schematic view of the electric field lines (b): Principle of operation of a generic triple-GEM chamber and definition of drift, transfer, and signal induction gaps. Stack of three foils arranged in tandem for sharing maximum operational gain within the drift and readout electrodes separated by mechanical frames.

When muons pass through a GEM detector, gas molecules within the detector are ionized and release electrons. These electrons drift towards the holes where they experience the very intense electric field inside the holes thereby acquiring enough kinetic energy to produce secondary ionization in the gas. This produces an electron avalanche process, which induces an electrical signal of the readout strips as shown in Figure 1. With three foils in tandem the multiplication process is shared, thereby improving stability against any possible discharges in the detector.
To meet the requirements of the CMS experiment, an early Phase 2 upgrade with 144 one-meter GEM detectors have been produced and are scheduled to be installed in the CMS endcap during 2019-20. Given the large number of detectors and the complexity of this technology, a very comprehensive and stringent quality control process has been established to ensure good performance and timely production of all the components.

A 5-year R&D programme resulted in five generations of prototype detectors that were built and tested between 2010-2014. Thanks to the knowhow and technical experience accumulated, the R&D programmes demonstrated that large-area GEM foils can be reliably manufactured and that using these foils for building triple-GEM detectors can satisfy the required performance. For CMS, an innovative technique of stretching foils to build detectors without glue was elaborated and validated over several versions of prototypes. The details of these approaches is documented in a technical design report submitted and subsequently approved by CMS and LHCC : CERN-LHCC-2015-012.

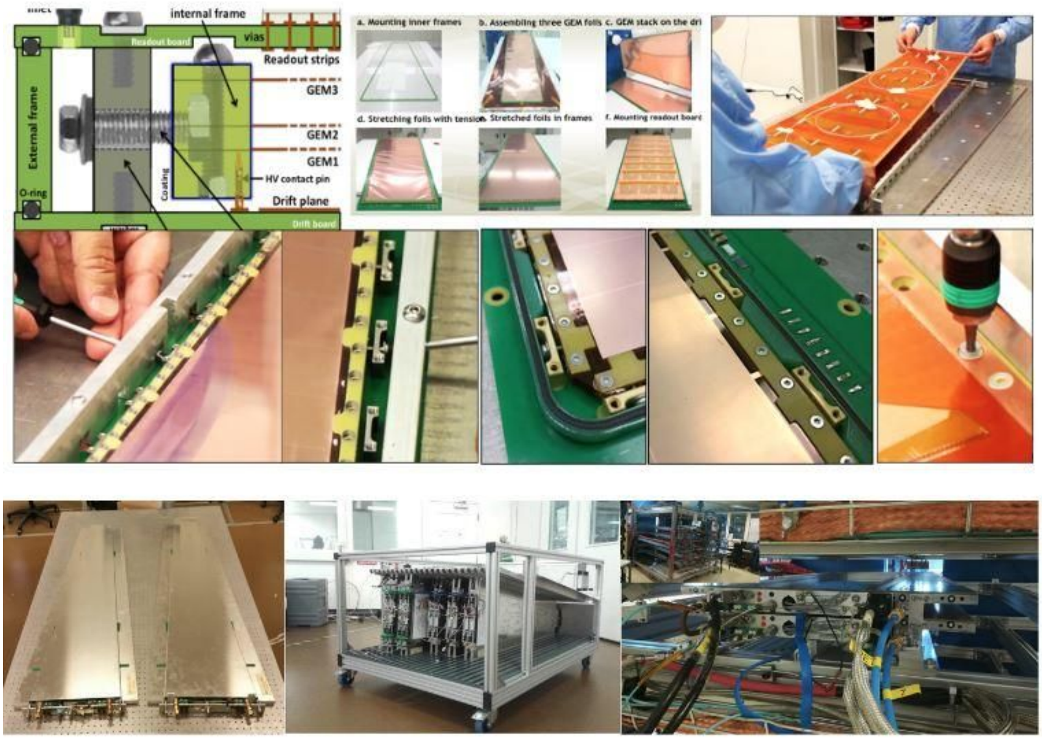


Figure 2. Top: Main steps of the GE1/1 chamber construction after several iterations 2010-2015. Bottom Left: Final chambers after closing. Middle: 10 chambers ready to go for installation for Slice Test in CMS (2015-2017). Right: Cosmic tests before final installation.

Once the procedures of construction, assembly and validation tests with rigorous quality control procedures had been established several production sites from all over the world participated in the production. Extensive training workshops were held at CERN in the CMS GEM laboratory to train all the teams at the respective production and satellite sites. Apart from CERN the production sites include Gent in Belgium with Aachen in Germany, INFN Bari and LNF Frascati in Italy, Florida Institute of Technology in the USA, Bhabha Atomic Research Centre (BARC), Panjab and Delhi Universities, and Saha Institute of Nuclear Physics in India, and National Centre for Physics in Pakistan. The flow of detector components from and to the production sites was streamlined and well documented in a Database. Once the detectors were complete at the sites, they were sent to CERN for final certification. In a period of about two years 144 chambers were completed and are all at CERN presently undergoing the last stages of the quality control chain. An interesting observation is that the uniformity of all these detectors has been measured to within 15% as specified and expected at the technical design. Kudos to the meticulous work of all the production site managers and their teams.

Fig.3 : Left: LHC Event display with the Slice test GEM detectors. Middle: Production sites validated from all over the world. Bottom: 144 chambers ready for final validation with cosmic tests before installation in CMS.

Ten chambers were assembled in the final configuration and installed in CMS during a year end technical top in 2016, as a "demonstrator slice test". The exercise served extremely useful in terms of all the feedback that has been injected towards the final installation and commissioning. An event display is shown in Fig. 3. In the CMS GEM lab attention is fully focused on the final integration of the electronics and validation of the performance of the detectors. The technical coordination team is working towards the installation of the first station GE11 imminently. "We need to install the chambers, but also the associated infrastructure, such as the gas, electricity and cooling distribution systems," explains Michele Bianco. "We also plan to install the infrastructure required for the 288 future chambers that will be installed during the 2021-2022 technical stop. Then, during Long Shutdown 3 (between 2024 and 2026), 216 more modules will be added." A first full prototype with four working modules has been, tested and trial installed in CMS to prepare for this massive operation as shown in Fig. 4.

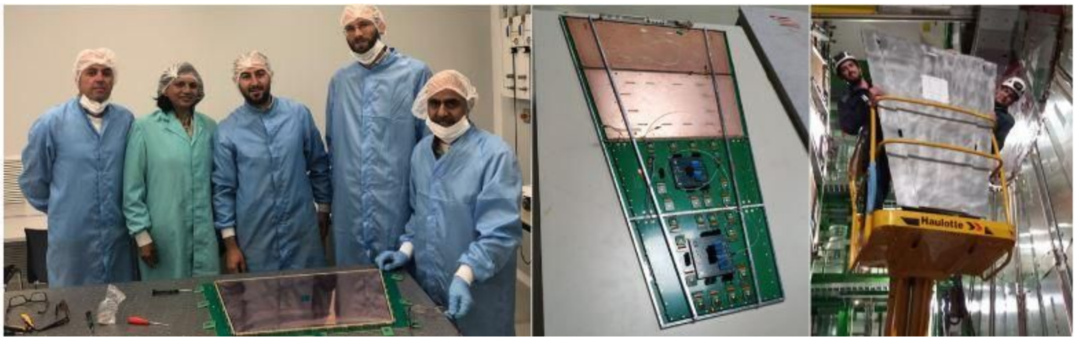


Fig. 4: Left: Preparation towards the second station of GEMs in CMS- single module. Middle: A complete GE21 Detector. Right: Installation exercise for GE21.

The installation of GE1/1 is an important milestone for the full CMS collaboration since it represents the first full Phase II Upgrade detector, with a completely new detector technology for CMS", says Anna Colaleo, CMS Muon System Manager. Thanks to the vibrant and committed global collaborative R&D effort of the nearly 40 Institutions, the first leg of this upgrade namely GE11 is currently on schedule and will be installed and commissioned in LS2 and pave the way for the next two stations.

HIE-ISOLDE: a unique window into the nucleus

by ***Karl Johnston (CERN)***

PDF version

With the recent completion of the second phase of HIE-ISOLDE, CERN's ISOLDE facility has a machine capable of answering long-unanswered questions about the nature of the nucleus. The installation of 4 cryomodules in 2018 allowed for the acceleration of radioactive isotopes up to 7.4 MeV/u for A/q = 4.5. This new accelerator, in combination with ISOLDE's expertise for producing radioisotopes, allows for the re-acceleration of the widest variety of radioactive isotopes worldwide.

The ISOLDE community is now beginning to take advantage of these new opportunities offered at HIE-ISOLDE to peer into the nucleus with a fresh eye. The first two papers from HIE-ISOLDE experiments have recently been published and highlight its potential in two different experiments, both employing the Miniball gamma detector array which can be seen in figure 1.

Figure 1: The Miniball array, used for all the measurements described in this article.

The first results arose from IS551, which reported on the Coulomb excitation of the very neutron-rich ^{132}Sn, an isotope with 50 protons and 82 neutrons [1]. This nucleus has been long identified as a doubly-magic nucleus, but never directly proved to be so. Of the 3200 known nuclei, only 10 possess the properties of being doubly magic: displaying increased stability compared to their neighbouring isotopes due to the perfect filling of proton and neutron shells within the nucleus (similar to the electrons filling atomic shells, making the noble gasses the most stable and least reactive of all elements). The importance of studying ^{132}Sn extends beyond nuclear structure: it is also at a critical path in the r-process, which governs the astrophysical process for the production of elements heavier than iron in the universe. The production path around ^{132}Sn is not fully understood; the precise study of this nucleus is therefore also crucial for nuclear astrophysics. The recent results have shown beyond any doubt that it is indeed doubly-magic.

The experiment employed a novel production technique for the radioactive isotope, using a molecular form of Sn – in the form of $^{132}Sn^{34}S$. This allowed the experiment to obtain a purer beam of ^{132}Sn, because the unwanted isobaric ^{132}Cs does not form such molecules, and therefore is not present after the mass separation of a mass 166 beam. The molecule was subsequently broken up in the low energy part of the HIE-ISOLDE accelerator before the 132Sn beam was re-accelerated to an energy of 5.45MeV/u and directed onto a ^{206}Pb target in the vacuum chamber inside the Miniball arry. This reaction excited the nucleons in the 132Sn nuclei to higher-energy states. These collective excitations, which have low chances of occurring, decayed with emission of gamma-ray photons, which MINIBALL detected. By analysing the number of gamma-ray photons detected, the authors measured the strengths of these excitations with an order of magnitude higher precision that before, thanks to the reaction being more probably at these higher beam energies. From these transition strengths, they found more pronounced excitations in ^{132}Sn compared to those of its nuclear neighbours. This was as predicted by theory and is a crucial feature of doubly magic nuclei. It thus confirms the doubly magic nature of ^{132}Sn. An example spectrum is shown in figure two, where the key gamma rays are indicated.

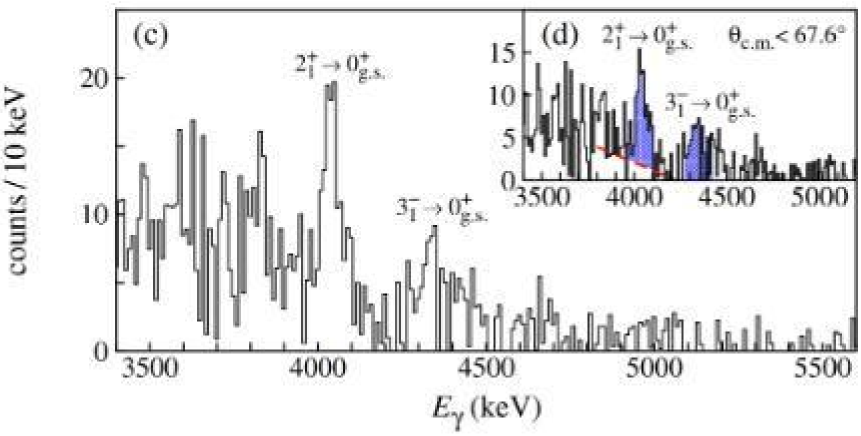


Figure 2: Two Gamma rays from the coulomb excitation of ^{132}Sn (a) indicating the ^{132}Sn 2_1^+ -> $0_{g.s}^+$ and 3^-_1 -> $0_{g.s}^+$ transitions and (b) same as for (a) but with the restriction of scattering angles ensuring pure electromagnetic excitation [1].

The second paper reports on the Coulomb excitation of even Rn isotopes and is from experiment IS552. Nuclei are known to take on many forms and their shape is dependent on the underlying nuclear structure. E.g. doubly-magic nuclei like ^{132}Sn are spherical, but others cn be prolate (rugby-ball-like) shaped or oblate (pancake-like) deformed. An additional category are nuclei which lack the reflection symmetry of the rugby-ball-like or pancake-like nuclei; these nuclei can take an octupole (pear-like) shape. Nuclei with such an asymmetric static pear-like shape have attracted considerable interest for their role in the search for permanent electric dipole moments (EDMs), as such a moment is expected to be amplified in octupole deformed nuclei. Ra and Rn nuclei have been identified as suitable candidates in the search for EDMs and, when the isotope possesses a static octupole shape, the nuclear Schiff moment due to a non-zero EDM, could be enhanced by a factor of 100-1000. The identification of pear-shaped nuclei is already a specialism of ISOLDE: the observation by Gaffney et al [2] of static octupole deformation in the isotopes of ^{224}Ra and ^{226}Ra was a milestone measurement a few years ago. Now, a new paper builds on this work, and reports on the first spectroscopy of the excited states of even Rn isotopes: ^{224}Rn and ^{226}Rn [3].

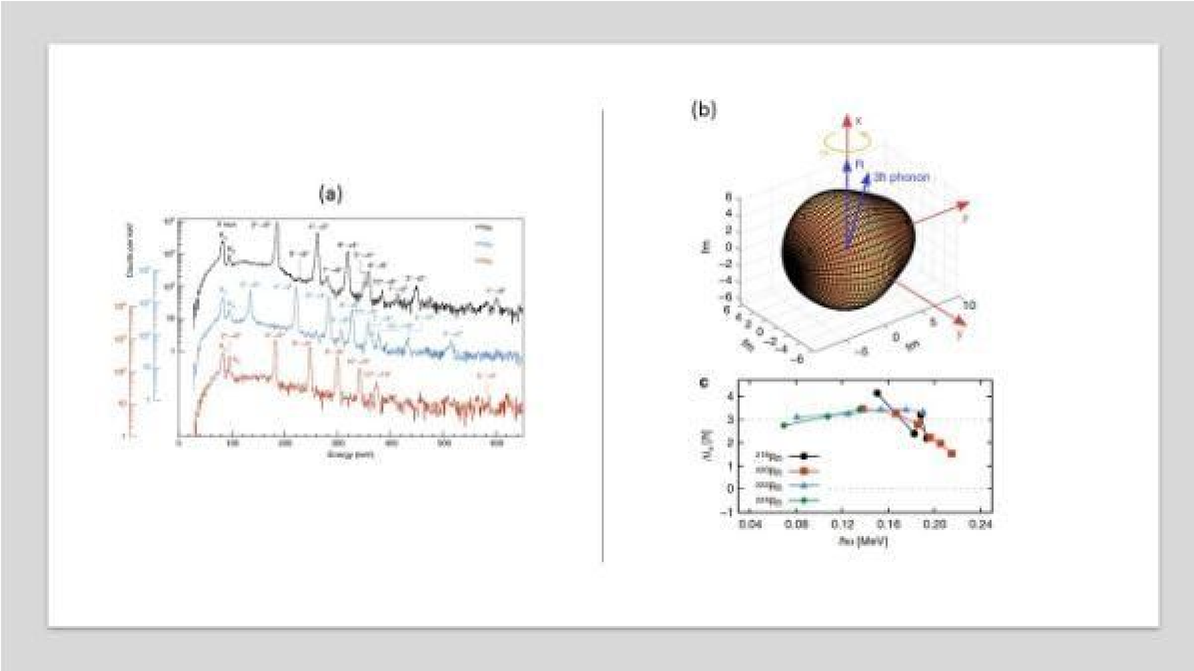


Figure 3: (a) Gamma spectrum from the even Rn isotopes measured at HIE-ISOLDE. (b) Cartoon of phonon coupling in octupole deformed nuclei and the difference in aligned spin for negative- and positive-parity states in $^{218-224}$Rn. The dashed line at Δix=0 is the expected value for isotopes possessing static-octupole deformation, indicating that the investigated Rn nuclei do not possess this property.

Rn beams were produced by irradiating a ThC target coupled to a cold plasma ion source. The ions were reaccelerated to 5.08MeV/u and directed towards a target of ^{120}Sn. The re-acceleration – and indeed production – of such heavy ions is unique to ISOLDE worldwide and is among the many aspects where ISOLDE continues to lead the field for radioactive ion beam facilities. A typical spectrum is shown in figure 3 showing the rich gamma spectrum under consideration. Unlike other isotopes – such as ^{224}Ra, which display static octupole deformation [2] – the Rn isotopes do not display this property. Thus, these isotopes are less sensitive for searches for an EDM, contrary to earlier claims.

HIE-ISOLDE has already shown with these first two results the impact which this new accelerator will have, not only in nuclear physics, but beyond. A rich bounty of results is expected from other experiments which have had the opportunity to run before LS2 including the ISOLDE solenoidal spectrometer and the versatile scattering chamber. The first experiments undertaking transfer studies at the high energies offered by HIE-ISOLDE are still being analysed and the user community is eagerly awaiting the restart of the machine after LS2 when it can be exploited to its full potential.

References:

[1] D. Rosiak *et al.* Phys. Rev. Lett. **121**, 252501

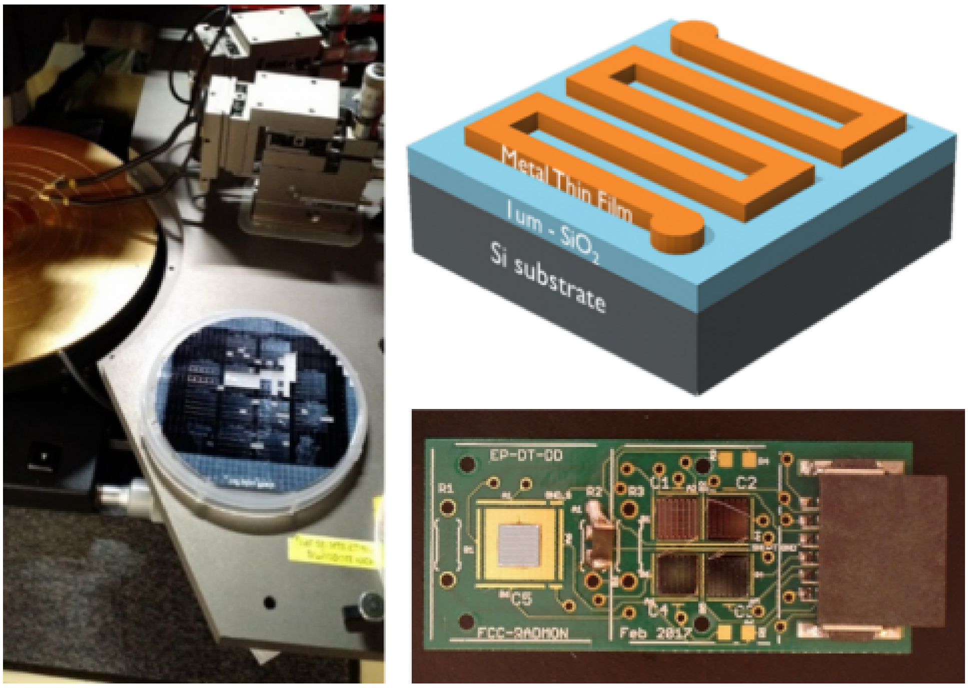
[2] Gaffney, L. P. *et al.* Studies of pear-shaped nuclei using accelerated radioactive beams. Nature **497**, 199–204 (2013).

[3] P. Butler *et al* The observation of vibrating pear-shapes in radon nuclei *Nature Communications* **10**, Article number: 2473 (2019)

DT group: A year in review

by ***Panos Charitos***

PDF version



In the beginning of June, the EP-DT group has published its Annual Report summarizing its yearly activities and offering an overview of major achievements and future collaborative plans.

The Detector Technologies (DT) group comprises expertise in many key domains for advanced detector systems and engages in several detector projects both for LHC and non-LHC experiments. Moreover, it operates services for detector operation and infrastructures for research & development open to all CERN users around the world. The DT group is also involved in R&D for future experiments.

Burkhard Schmidt, DT group leader, notes: “The 2018 annual report reflects the high motivation of the group. The work is carried out in close collaboration with teams from CERN experiments who value DT’s contributions. In the same spirit, we are eagerly looking forward to a strong participation in the strategic R&D for future experimental efforts.”

One of the core activities of the group has been the participation to the upgrades of ALICE and LHCb sub-detector systems scheduled for LS2. For ALICE, the upgrade programme includes a new beampipe with a smaller diameter, a new Inner Tracking System (ITS), a vertex tracker for forward muons (MFT), the upgrade of the Time Projection Chamber (TPC) with GEM detectors, the upgrade of the forward trigger detectors and the upgrade of the online and offline system. DT is involved in the upgrade of the new ITS. For LHCb, the upgrade includes a new VELO detector and the installation of a Scintillating Fiber tracker replacing the current Outer Tracker (based on gas straw tubes) and Inner Tracker (Silicon micro-strips). Finally, DT contributes to these upgrades and the ones for the LHCb upstream tracker, RICH detector and muon system.

In 2018, the DT group continued playing an important role in the ATLAS Phase II Upgrade. The DT efforts focus on the mechanical integration of the Outer Layers for the new Pixel Detector. For the CMS Tracker's Phase II upgrade, as well scheduled for installation during LHC LS3 in 2025, the DT group collaborates with the CMS team in the development and construction of the Outer Tracker as well as in the CMS High Granularity Calorimeter (HGCAL). Group members are also actively involved in the operation and upgrade of non-LHC experiments including CLOUD and NA62, and provide technical support to ISOLDE.
In 2018, the group was heavily involved in the preparation of a new strategic R&D programme on experimental technologies, launched by the CERN EP department. The programme builds on CERN's current expertise and covers the domains of detectors, electronics and software together with intimately connected systems such as mechanics, cooling and experimental magnets. These efforts are also reflected in the group's contribution to design plans for post-LHC colliders.

Finally, 2018 show a number of facilities offering sophisticated equipment for the development of new detector technologies. The CERN Gamma Irradiation Facility (GIF++) offers a unique place for detector R&D tests where a strong gamma source and a muon particle beam are simultaneously available. Moreover the proton irradiation facility (IRRAD) at the PS East Area concluded successfully the first run of this facility which is operational since the LS1 with more than 2500 samples irradiated. During 2018, the proposal for the extension of the GIF++ and the IRRAD technical areas was accepted. The year 2019 will be dedicated to the thorough maintenance and upgrade of the various irradiation systems. IRRAD is also part of the AIDA-2020 Transnational Access (TA) to irradiation facilities program that provides funding for external users to perform their irradiation tests at CERN and as of today 18 projects and 76 users have been given access to test their components under conditions that are as close as possible to real applications.

In 2018, new equipment was also installed in a number of other labs among which Thin-Film Lab, the Bond Lab, the Solid State Detector Lab and the Quality Assurance and Reliability Lab. A milestone for the DT group was also the installation of the Micropattern Technologies workshop in the new building 107. This development will allow to continue with the mass production of Micro Pattern Gas Detectors (GEM and MircoMegas) under much improved conditions and according to the high standards requested by the experiments.

The 2018 Annual Report can be found HERE.

Exploring dark sector with NA64: First results from the combined analysis of 2016-2018 runs

NA64

by ***Sergei Gninenko (Russian Academy of Sciences), Paolo Crivelli (ETH Zurich)***

PDF version

Searches for dark matter (DM) particles, an essential experimental goal for particle physics, are entering in an interesting stage. Despite the strong astrophysical evidence for dark matter, little is still known about the origin and dynamics of this substance of our Universe.

The significant efforts on both direct and indirect searches at the LHC and other dedicated experiments around the world has ruled out many DM models, but have not yet yielded unambiguous DM signals. Perhaps, the main difficulty that hinders progress, keeping the mystery around DM, is that it can only be studied through its gravitational interaction with ordinary matter. Therefore, the idea of introducing a new way of interaction between dark and visible matter, in addition to gravity, opens a rather exciting path for exploration.

Several theoretical models motivate the extension of the SM by introducing the concept of dark sectors consisting of a set of particles and fields which is similar to that of the SM, but transform under new gauge symmetries and do not interact with the SM. In analogy with QED, for which the massless photon mediate the force between charged particles, there could be a dark QED with a so-called dark photon that mediates a force between dark particles. Such a dark photon (A') could have a mass $m_{A'} \lesssim 1$ GeV and it could couple to the SM through the kinetic mixing with the ordinary photon parameterized by the mixing strength ε.

In the presence of light dark matter particles, with masses < $m_{A'}$, the dark photon could predominantly decay invisibly into those particles. Models introducing such invisible A' decays offer new intriguing possibilities to explain hints on astrophysical signals of dark matter. They assume the existence of a dark photon with a mass in the sub-GeV region and a coupling strength to ordinary photons in the range of $\varepsilon \simeq 10^{-5}$-$10^{-3}$.

This assumption has motivated a wide range of ideas and proposals that were widely discussed during the Physics Beyond Colliders annual workshop at CERN. Proposals include ideas for dark forces and other portals between the visible and dark sectors which might be probed at low energy, high-precision experiments at CERN's SPS.

One of the experiments that attracted noticeable attention during the PBC meeting was NA64. It was designed for a broad search for dark sector physics by looking for missing energy events using the active beam dump approach. NA64 was approved in 2016 and its primary goal was to search for invisible decays of dark photons, covering a large part of the parameter space for exploring the observed muon g-2 anomaly.

The basic idea is the following, if dark photons (A') exist they can be produced via the kinetic mixing with bremsstrahlung photons through the reaction $e^-Z \rightarrow e^-ZA'$ of high-energy electrons scattering off nuclei (Z) from an active target. This will be followed immediately by the decay of $A' \rightarrow \chi\ \chi$ into dark matter particles χ. The χ would penetrate a hermetic detector located downstream the target without interacting and would carry away a fraction of the beam energy. Therefore, observing an excess of events with large missing energy above small backgrounds would signal the presence of dark photons. Moreover, to ensure that any excess is due to the 100 GeV electrons, the emitted synchrotron radiation from the beam is used to tag each electron individually and beyond any doubt.

The technique of observing missing energy in the products of high-energy interactions currently being explored by NA64 on an electron beam was put forward during the Physics Beyond Colliders kick-off workshop in 2016. This approach complements classical beam dump experiments and provides much better sensitivity for a specific parameter space. In the case of beam dump experiments, the products of dark photon decays (i.e. other dark sector particles) could penetrate the dump and have observable interactions in a far detector.

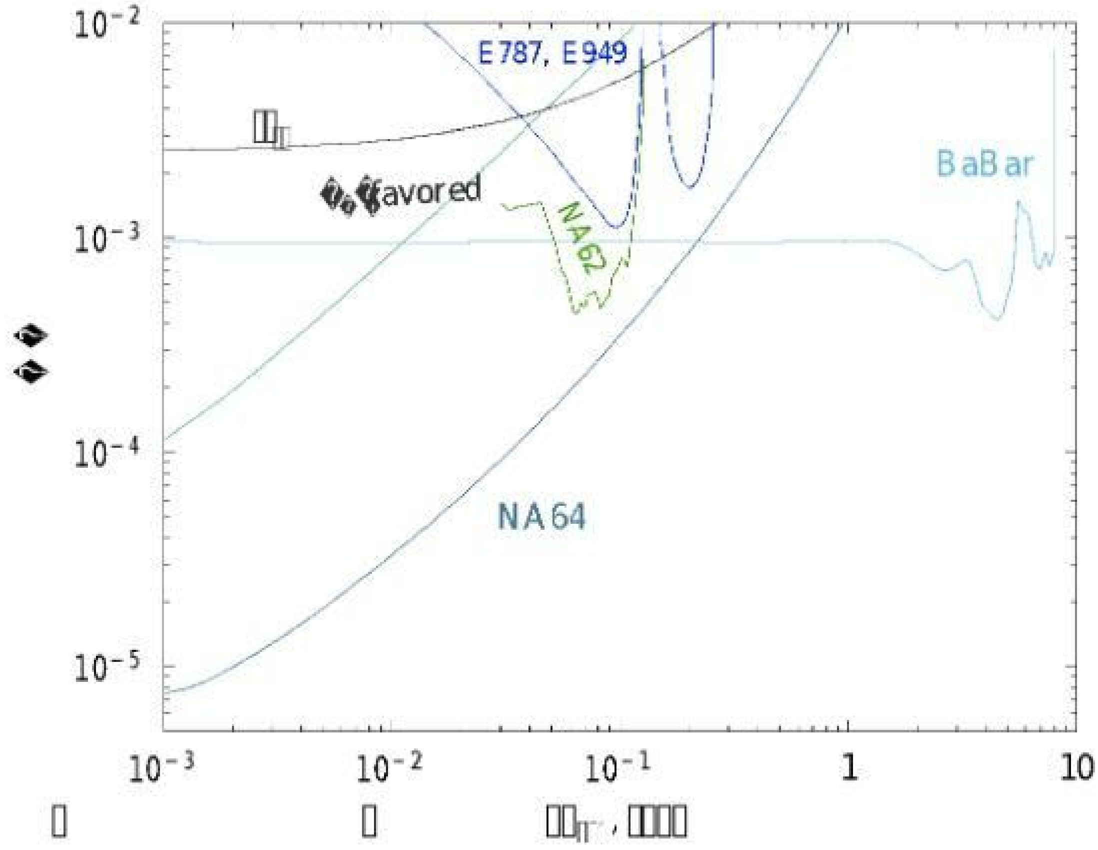


Figure 1. Na64 limits on the γ - A' mixing from the combined 2016-2018 runs.

A64 began operation in July 2016 for a period of two weeks and completed its physics programme with a six-week run in 2018. The July results were published in Phys. Rev.

Lett. (2017) and exclude values of the dark photon (A′) coupling that would make dark photons relative for explaining the muon g-2 anomaly. While not ruling out the existence of dark photons, these results serve as an important demonstration of the feasibility of the NA64 approach and give guidance for the further upgrade of the detector. Significantly more data accumulated in 2017-2018 with improved apparatus allowed to search for A´s as a mediator of dark matter production in invisible decay mode and other invisible decays of dark-sector particles. The combined NA64 bounds from 2016-2018 runs on the γ - A' mixing are shown in Fig. 1, while new limits on the parameter Y are shown in Fig. 2. This variable characterizes the cross section for the DM <-> SM annihilation and is convenient for comparison of results from other experiments, also shown in Fig. 2. The black curves calculated for the scalar, Majorana and Pseudo-Dirac DM relic abundance represents the Y parameter space, which is an explicit target for NA64.

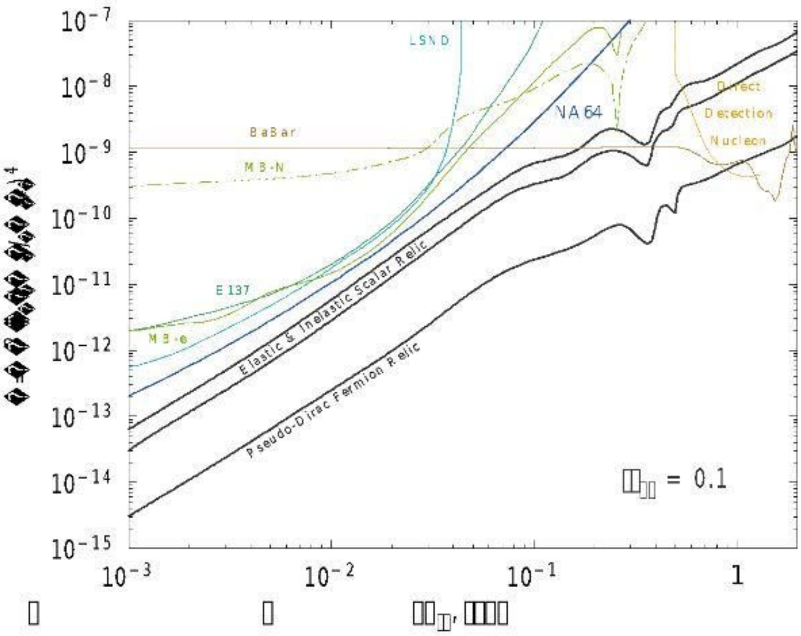


Figure 2. Na64 constraints on sub-GeV DM from the combined 2016-2018 runs.

One can see that NA64 provides the best stringent constraints on both variables, ε and Y, for the A' and DM masses in the sub-GeV regime. Thus, demonstrating the power of the active beam dump approach for the dark matter search compared to the classical beam dump experiment such as LSND, E137, and MiniBooNE. The further goal of NA64 is to accumulate up to $\sim 10^{13}$ electrons on target (EOT) after LS2 in order to probe the remaining DM parameter space shown in Fig. 2.

The search for dark photons is one of many approaches for trying to detect dark matter. Today we have a rapidly growing variety of models suggesting new particles weakly coupled to lepton and/or quarks solving the DM and other problems in particle physics. In order to strengthen experiment operating in such unusual situation, we thought of NA64 as of a new type of experiment able to provide a quick response in testing these models.

For example, in 2016 the experiment of Krasznahorkay et al. in ATOMKI has reported observation of a 6.8 σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the $^8Be^*$ exited state nuclear transitions to its ground state accompanied by an emission of an e^+e^- via internal pair creation. It has been shown that this anomaly can be interpreted as an emission of a new gauge boson (X) followed by its prompt decay X → e^+e^- and provide a particle physics explanations of the anomaly that is consistent with all existing constraints based on the assumption that its coupling to electrons is in the range of $2\times10^{-4} < \varepsilon < 1.4\times10^{-3}$ and mass m_X = 16.7 MeV. The models predict relatively large charged lepton couplings $\varepsilon_e \simeq 0.001$ that can also resolve the muon g-2 anomaly.

In 2017-18 after a detector reconfiguration NA64 has a physics runs to obtain data for searching for the X and A′ → e^+e^- decays with 100-150 GeV electrons at the H4 line in CERN's North Area. The preliminary combined results excluded the significant part of the X boson parameter space are shown in Fig. 3 and SPSC recommended the continuation of A′ and X searches with data from the 2021 run.

Another example is related to the muon $(g\text{-}2)_\mu$ anomaly, which is under more accurate study by the currently running experiment E989 at FNAL. While the A′ explanation of the muon g-2 anomaly has been ruled out by NA64 and BaBar, there is still one remaining interesting explanation provided by the $L_\mu - L_\tau$ model.

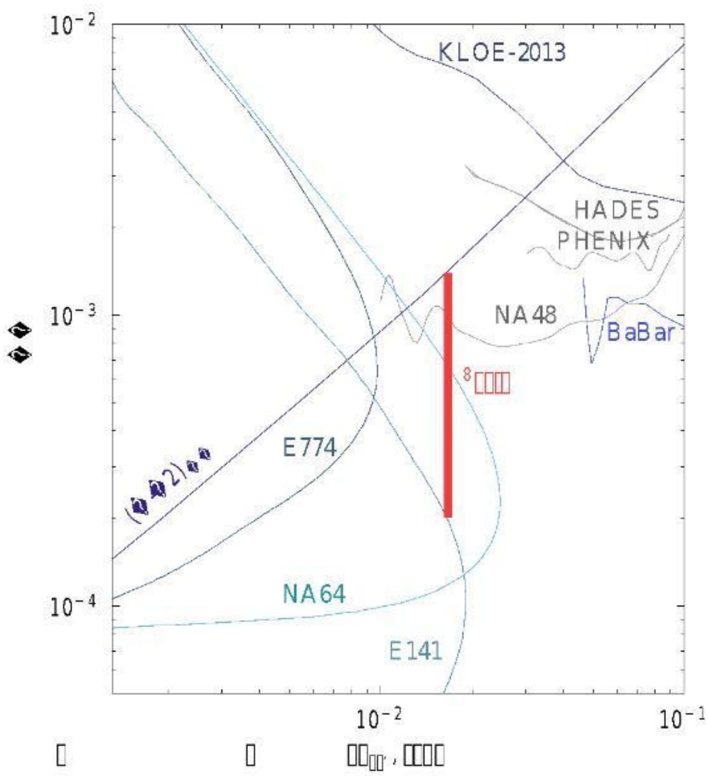


Figure 3. Na64 preliminary combined results from the 2017-2018 runs on the search for the 16.7 X boson from the 8Be anomaly and A′ -> e+e− decays of dark photons.

In this model the $(g\text{-}2)_\mu$ discrepancy is explained by the possible existence of a new leptophobic sub-GeV Z′ boson, which is weakly coupled predominantly to the second and third lepton generation leptons. The surprising fact is that the SM extension which includes such Z′ is still renormalizable and no new fermions are required. In addition, the invisible dark Z´ boson could serve as a portal between the visible and dark sectors offer new intriguing possibilities to explain hints on dark matter.

These results motivated the NA64 Collaboration to propose a new experiment called NA64$_\mu$ aiming to search for Z´ with the M2 muon beam at the SPS. Interestingly, NA64$_\mu$ could also probe the dark photon (A´) invisible decay similar to NA64 running in the electron mode (NA64$_e$). The combined NA64$_e$ and NA64$_\mu$ results with ~10^{13} EOT and a few 10^{13} MOT, respectively, will allow to cover almost fully the parameter space of the most interesting sub-GeV DM models shown in Fig. 2 . This makes NA64e and NA64$_\mu$ extremely complementary to each other and greatly increases the exploratory power of sub-GeV DM searches with CERN's SPS.

Further Reading

NA64 Collaboration, Phys.Rev.Lett. 118 (2017), 011802
NA64 Collaboration, Phys.Rev.Lett. 120 (2018), 231802
NA64 Collaboration, Phys.Rev. D97 (2018), 072002
NA64 Collaboration, CERN-SPSC-2018-024 / SPSC-P-348-ADD-3, 13/10/2018

The Higgs boson as a probe for new physics

Higgs
ATLAS
CMS

*by **Toyoko Orimoto (Northeastern University)***

PDF version

The discovery of the Higgs boson has ushered in a new era of exploration at the Large Hadron Collider (LHC). Persistent tensions in the Standard Model (SM) of particle physics compel us to seek out physics beyond the SM (BSM) at the TeV scale, and the Higgs boson provides us with a potential portal to new physics. A number of BSM models have been proposed as a solution to these existing tensions. For example, new, massive particles may couple to the SM Higgs boson, producing exotic decays of the SM Higgs boson or enhancements to the production of the SM Higgs boson.

Since the Higgs boson discovery, there has been a significant campaign by the ATLAS and CMS collaborations to measure all aspects of the newly discovered particle. The mass of the Higgs boson was not predicted by the SM, but it has been measured by the ATLAS and CMS collaborations to be 125 ± 0.21 (stat) ± 0.11 (syst) GeV. Given its mass, all production cross sections, couplings to other SM particles, and decay rates of the Higgs boson are predicted by the SM. In addition, the SM Higgs boson is expected to be a scalar particle (spin-0 and even parity) with no electric charge, arising from a single Higgs doublet. Nearly all measurements thus far have confirmed that the particle is indeed the Higgs boson predicted by the SM. Figure 1 shows the measurements of the Higgs boson production and decay rates in a variety of channels from the ATLAS detector, which have mostly been measured to be SM-Higgs-boson-like. Nonetheless, as can be seen in Figure 2, the latest constraints on the decay of the Higgs boson to invisible particles, in addition to other measurements, still leave room for significant BSM effects.

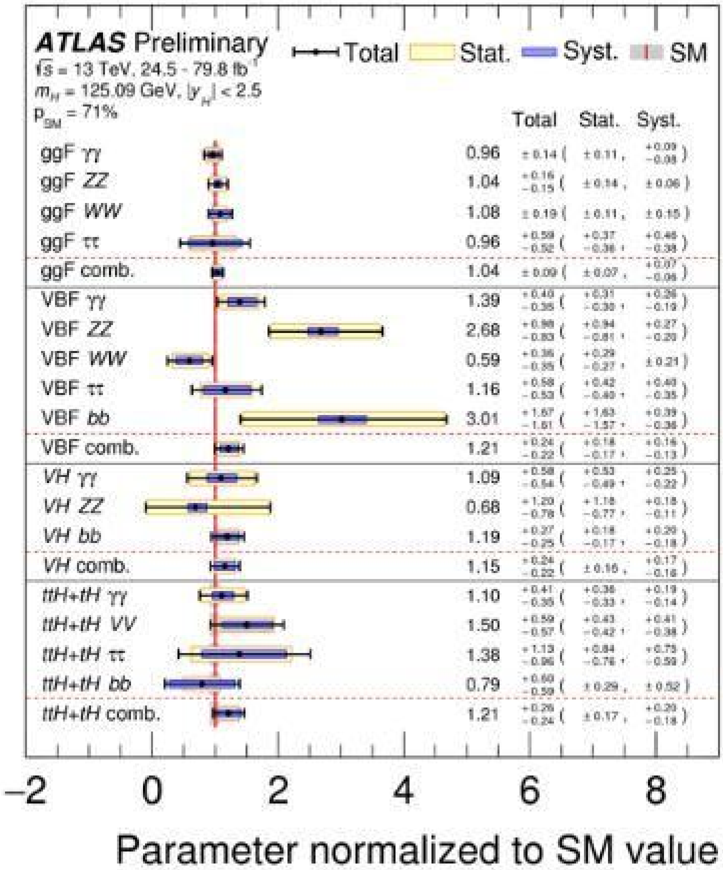


Figure 1: Best fit values of the cross section times branching fraction for the Higgs boson, from the ATLAS collaboration. The gluon fusion (ggF), vector boson fusion (VBF), associated production (VH, ttH, tH) mechanisms are included, in various decay modes. The values are obtained from a simultaneous fit to all channels. https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2019-005/

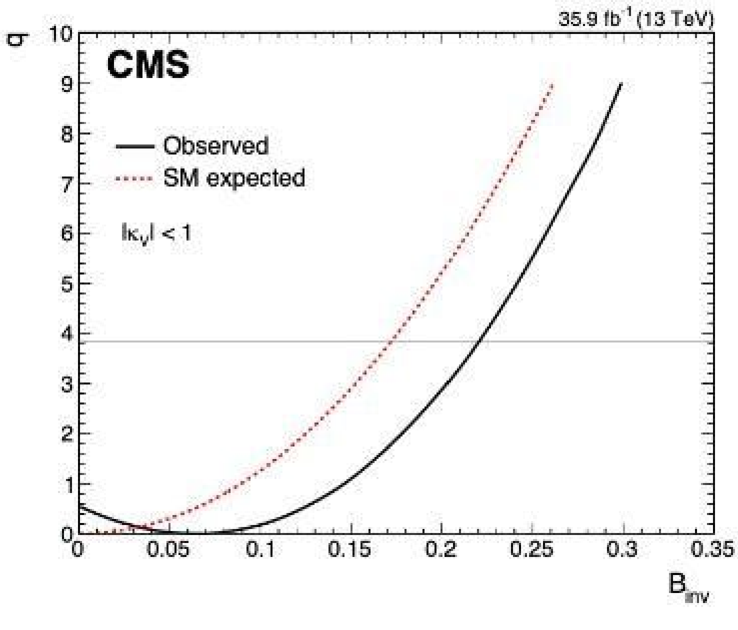


Figure 2: Constraints on the branching fraction of the Higgs boson decaying to invisible particles, as a function of test statistic q, from the CMS collaboration. http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-031/index.html

The BSM models probed by studies of the Higgs boson can generally be classified in three categories: additional BSM Higgs bosons, exotic or rare decays of the SM Higgs boson, and exotic production of the SM Higgs. In the first category, some BSM models, such as supersymmetry (SUSY), extend the Higgs sector to include additional Higgs doublets or triplets. The additional Higgs bosons arising from these added doublets or triplets may be more (or less) massive than the SM Higgs boson, or can be electrically charged, unlike the SM Higgs boson. For example, the minimal supersymmetric SM (MSSM) is a two-Higgs-doublet-model (2HDM), predicting five total Higgs bosons. In particular, in the MSSM, the SM Higgs boson (h) is joined by an additional CP-even Higgs (H), a CP-odd pseudoscalar Higgs (A), and two charged Higgses (H).

If a 2HDM exists, then the couplings of the SM Higgs boson to SM particles may be modified. We can thus derive indirect constraints on 2HDMs from measurements of the SM Higgs boson properties. For example, Figure 3 depicts constraints on 2HDMs arising from the precision Higgs measurements mentioned earlier. The limits are shown in terms of the mixing angles in the MSSM (α, β) and the mass of the additional pseudoscalar Higgs (m_A), which are typical ways to parametrize the MSSM.

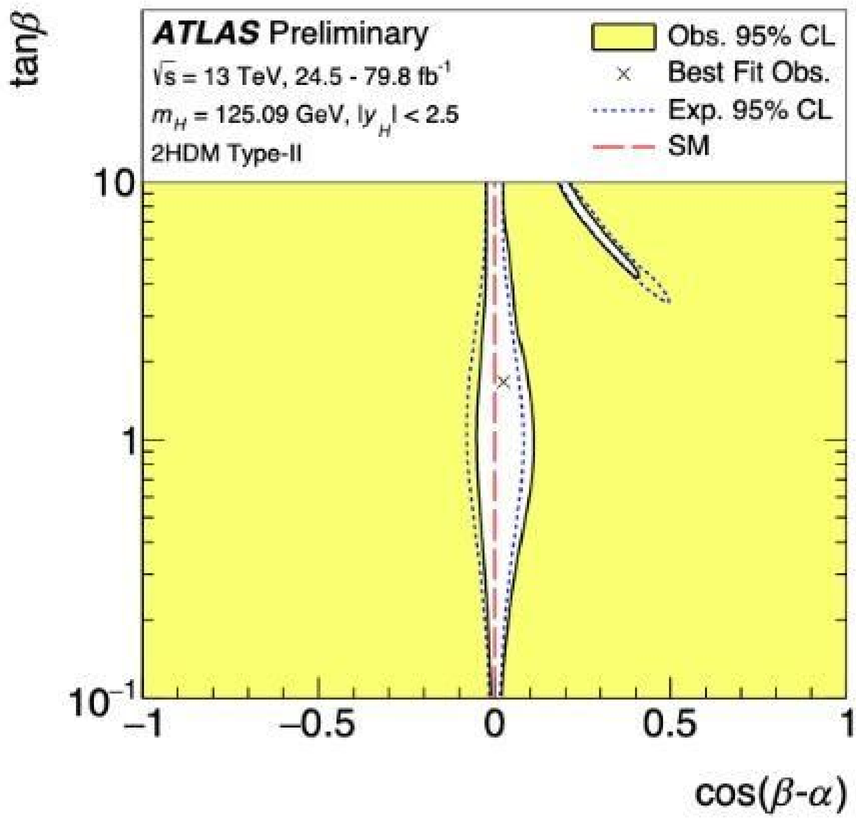


Figure 3: Regions of the (cos(β - α), tan β) plane excluded by fits to the measured rates of Higgs boson production and decays, from the ATLAS collaboration. The alignment limit at cos(β - α) = 0, in which all Higgs boson couplings take their SM values, is indicated by the dashed red line. https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2019-005/

We also search directly for additional Higgs bosons, such as the potentially heavy Higgs bosons predicted by the MSSM (H, A). A variety of decay channels are used for such searches, including heavy Higgs boson decays to fermions (A/H → ττ, μμ, bb, tt), vector bosons (A/H → WW, ZZ, γγ), and Higgs boson + vector boson (H → AZ; A → Zh). For instance, Figure 4 depicts the regions of the [mA, tanβ] plane which have been excluded by direct searches for heavy Higgs bosons by the ATLAS collaboration in the “habeus” MSSM (hMSSM) model. Figure 4 also shows the stringent indirect constraints (hashed region) arising from the aforementioned precision measurements of the SM Higgs boson.

In addition to neutral, heavy Higgses, searches for charged, heavy Higges have been pursued. The predominant production and decay mechanisms depend on the mass of the H^+. For example, for higher masses, H^+ → tb is the dominant decay mode, while H^+ → τν accesses the full mass range. Figure 5 shows a summary of the charged Higgs results from the CMS collaboration, in terms of constraints on tan β and mH^+. The complementarity between the H^+ → tb and H^+ → τν results, as well as between the direct searches and the indirect constraints (in hashed red), is evident.

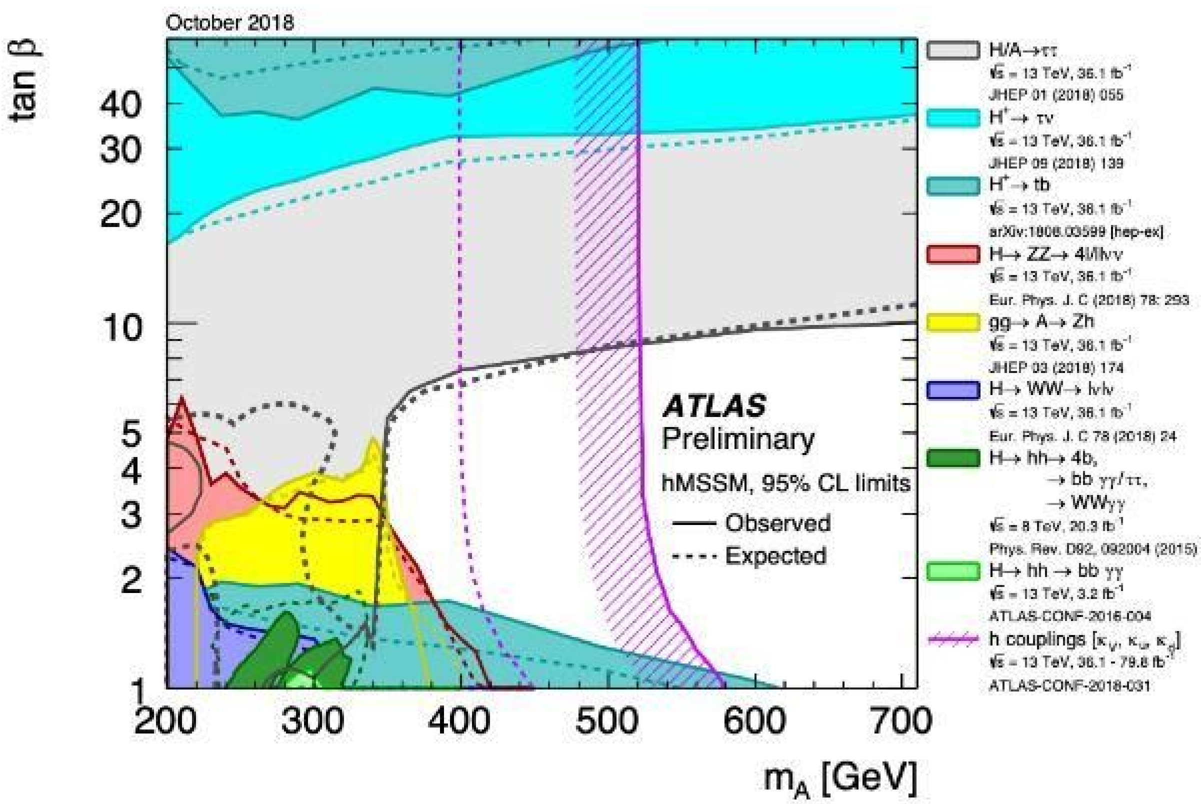


Figure 4: Regions of the [m_A, tanβ] plane excluded in the hMSSM model via direct searches for heavy Higgs bosons from the ATLAS collaboration (solid fill). Overlaid are the constraints from the measured rates of observed Higgs boson production and decays (hashed fill).
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CombinedSummaryPlots/HIGGS/

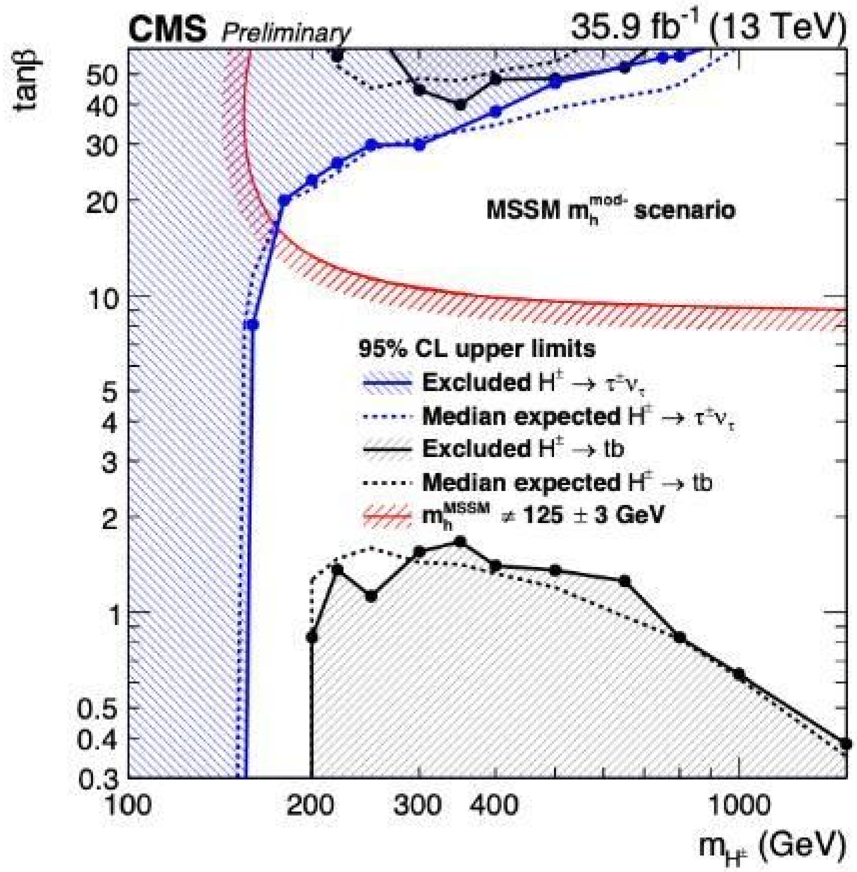


Figure 5: Observed limits (solid points) from the CMS charged Higgs searches, interpreted as a 95% confidence level exclusion region (hatched area) in the MSSM (mH, tanβ) parameter space, compared to the expected limit assuming only standard model processes (dashed line). The region below the red line is excluded assuming that the observed neutral Higgs boson is the light CP-even 2HDM Higgs boson with a mass of 125±3
GeV. http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/HIG-18-004/index.html

New physics may also manifest itself by affecting the decays of the SM Higgs boson. BSM physics can enhance rare decays, such as Higgs boson decays to quarkonia (h → J/ψ J/ψ, YY, J/ψ γ, etc), or induce flavor-changing neutral current decays (t → hq). The SM Higgs boson itself may also be decay to new BSM particles.

As mentioned earlier, measurements of the SM Higgs boson still leave room for such exotic decays.For instance, the next-to-minimal supersymmetric SM (NMSSM) adds a singlet to the MSSM, thus resulting in two more Higgs bosons. The lightest, pseudoscalar Higgs boson (a) in this scenario can be very light (on the order of ~GeV) and thus may have escaped detection. The SM Higgs boson in this case can decay into pairs of these light pseudoscalar particles, which subsequently decay into pairs of SM particles (such as bb, ττ, μμ, γγ). In the case that the pseudoscalar is very low mass (< 10 GeV), the final state particles may be highly boosted, presenting a challenge for particle identification. Figure 6 shows a summary of searches for such decays (h → aa → XXYY) from the CMS collaboration, in terms of the upper limits on the branching fraction as a function of the pseudoscalar mass (m_a).

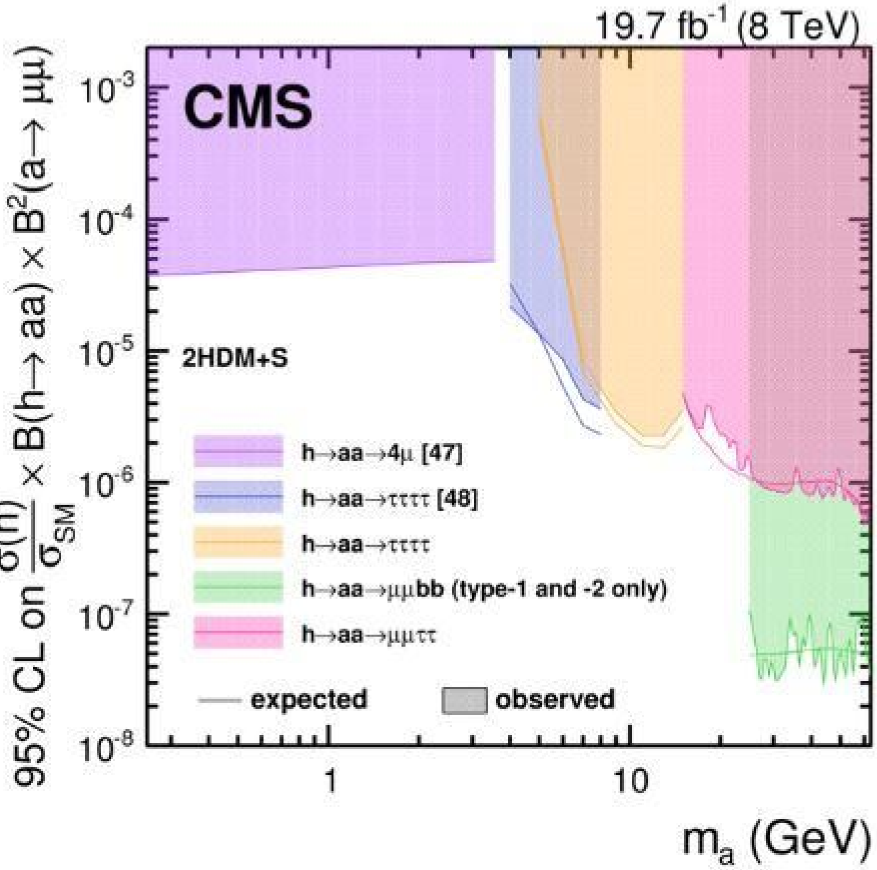


Figure 6: Upper limits on the cross section times branching ratio for SM Higgs boson decays to light pseudoscalars (h → aa → XXYY), normalized to the SM Higgs boson cross section.

Moreover, the SM Higgs boson may be undergoing "invisible" decays to new particles, such as dark matter (DM) candidate particles, which escape detection in the ATLAS and CMS detectors. The SM branching ratio for invisible Higgs boson decays is very small, about 0.12% for Higgs boson decays to two Z bosons, which then decay to neutrinos. Since the Higgs boson is decaying to undetectable particles, an additional handle is required to select these events. As such, the Higgs boson production mechanisms which are considered include: vector boson fusion, in which the Higgs boson is produced with two forward jets; associated production with a W or Z boson (in which the leptons from the W or Z boson decay are used to identify the event); associated production with a final-state or initial-state radiation jet recoiling against the Higgs boson; associated production with a top quark pair.

In the absence of any signal, these invisible Higgs search results can be translated into upper limits on the cross-section for DM - nucleon interactions as a function of the DM candidate particle mass. Figure 7 depicts a summary plot from the CMS collaboration for the 90% confidence level upper limits combining all search channels. This figure also highlights the complementarity between the results from the LHC and those from DM direct detection experiments, especially in the low mass region.

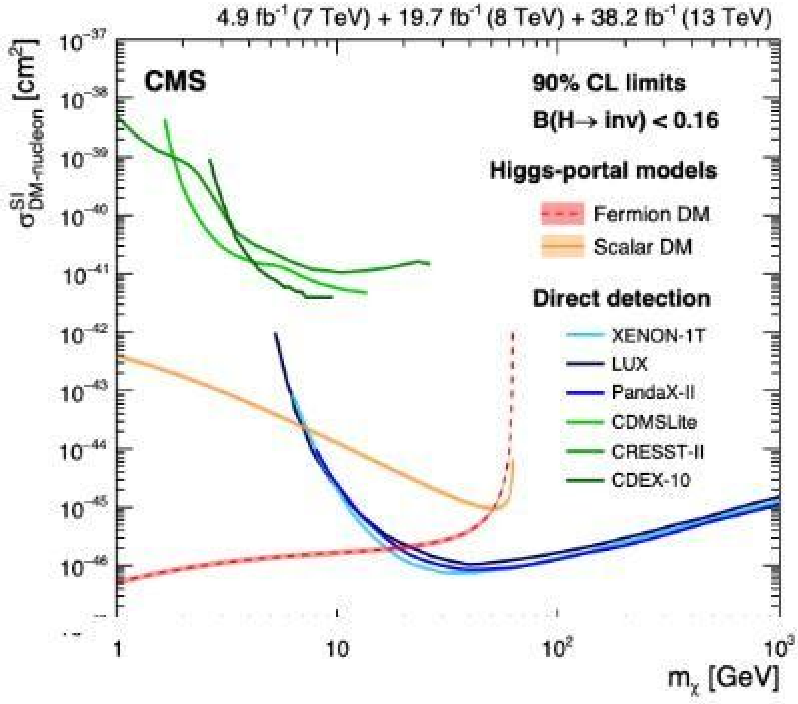


Figure 7: 90% CL upper limits on the spin-independent DM-nucleon scattering cross section in Higgs-portal models, assuming a scalar (solid orange) or fermion (dashed red) DM candidate. Limits are computed as a function of m_x and are compared to those from direct detection experiments. http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-023/index.html

In addition to affecting its decays, BSM physics may alter the production of SM Higgs bosons at the LHC. Akin to the invisible Higgs searches that were just described, the SM Higgs boson may be produced with undetectable particles, such as DM candidate particles. The detector signature would be a SM Higgs boson (eg, decaying as h → bb, γγ) produced with missing transverse energy, and as such, these studies are often called “mono-Higgs” searches. Figure 8 shows the constraints from the ATLAS mono-Higgs searches on m_a and m_A, in the framework of a 2HDM+a model.

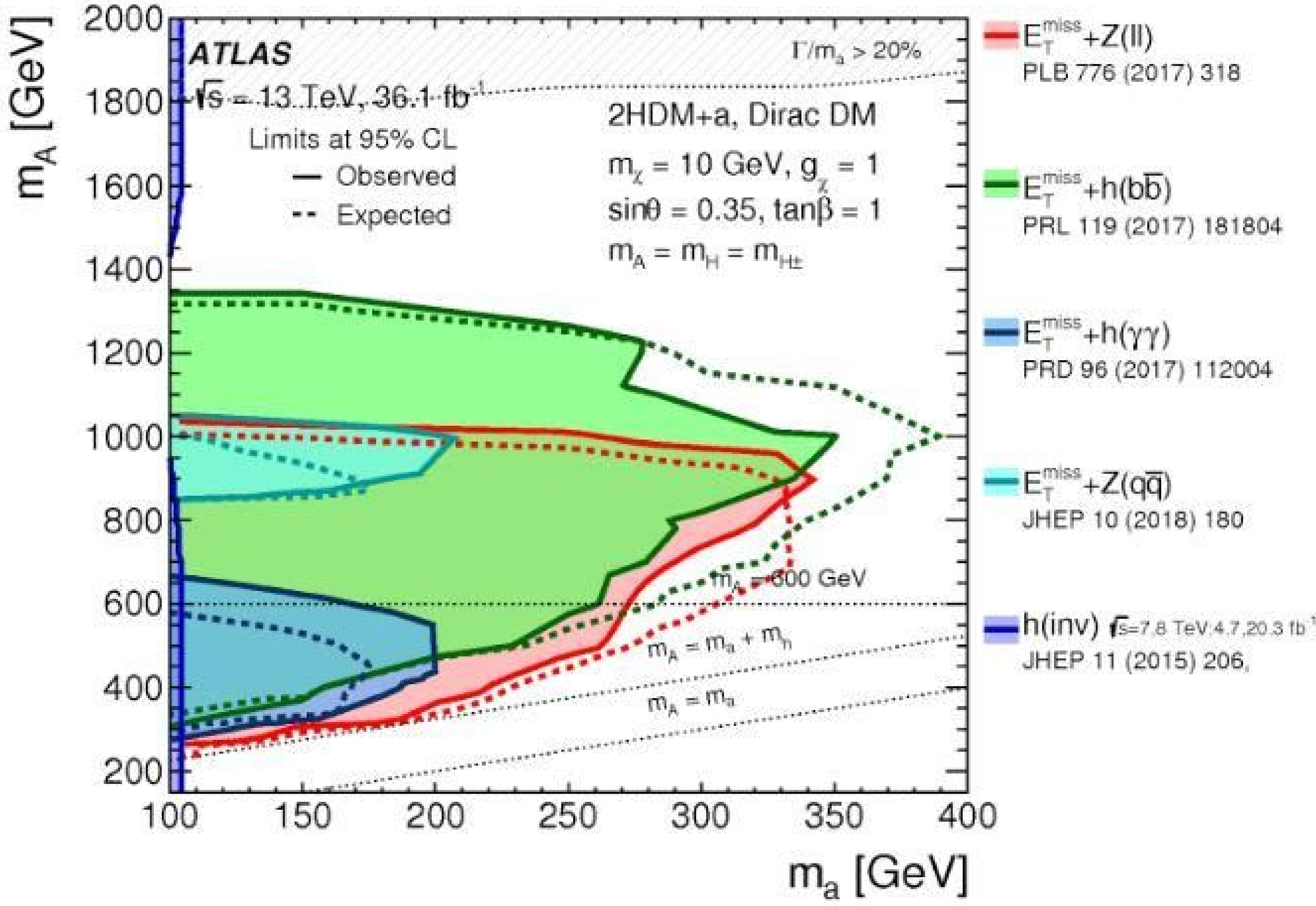


Figure 8: Regions in the (m_a, m_A) plane excluded by data at 95% CL by the ATLAS mono-object searches and invisible Higgs analyses, in a 2HDM+a model. The dashed grey regions at the top of the figure indicate the region where the width of any of the Higgs bosons exceeds 20% of its mass.https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2017-32/

Lastly, the measurement of di-Higgs production (HH) is an important probe of the Higgs boson self-coupling. HH events are predicted by the SM, but are loop-induced and have a very low expected cross section. However, the HH process can be enhanced by BSM physics, in both resonant and nonresonant mechanisms. In the resonant case, HH may be produced through the decay of a massive resonance, such as a spin-2 graviton or a spin-0 radion, which are predicted in models of warped extra spatial dimensions. In the nonresonant case, the HH process may be enhanced through new particles traversing the loops of the HH diagrams. The two Higgs bosons are sought in the typical SM Higgs boson decay channels (eg, bb, γγ, ττ, VV), with the different channels exhibiting varying levels of sensitivity as a function of the resonance mass. Figure 9 shows the 95% confidence level upper limits on the cross-section times branching ratio for producing a graviton, as a function of the graviton mass, combining several analyses from the CMS collaboration. Potential nonresonant enhancements are typically encapsulated in terms of several parameters, such as $\kappa_\lambda$which measures deviations of the Higgs boson tri-linear self coupling (in the SM, κ_λ = 1). Figure 10 shows the ATLAS Runs 1 and 2 combined constraint on κ_λ as a profile likelihood scan, combining several HH channels. Although the SM HH process is not expected to be observed at the LHC, in the absence of BSM enhancements, SM HH will be a benchmark channel for the high-luminosity upgrade of the LHC (HL-LHC).

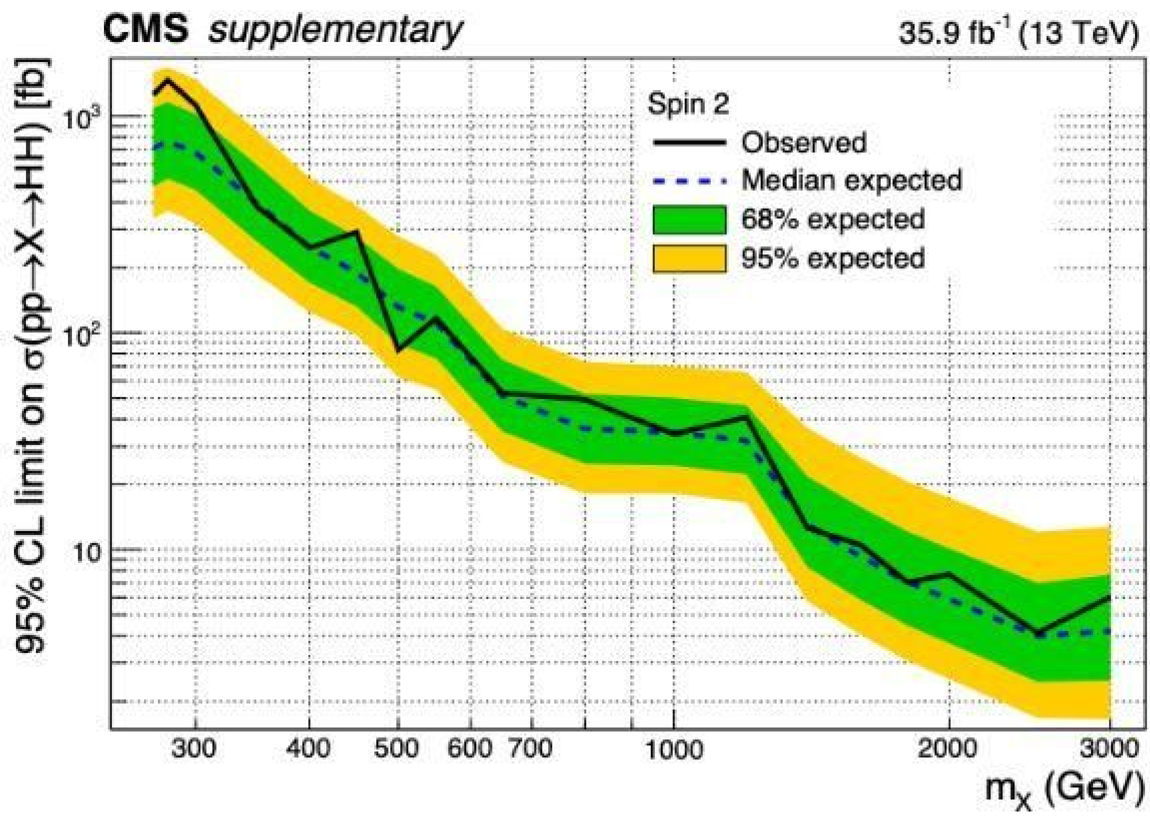


Figure 9: 95% confidence level exclusion limits on the production of a narrow, spin-2 resonance decaying into a pair of Higgs bosons, from the CMS collaboration. http://cms-results.web.cern.ch/cms-results/public-results/publications/HIG-17-030/index.html

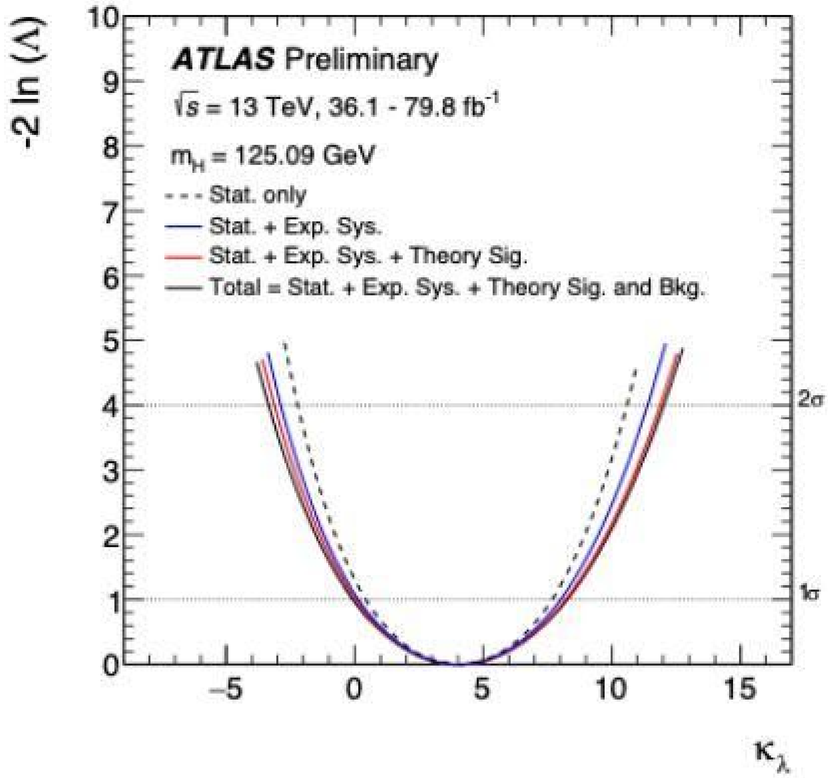


Figure 10: Profile likelihood scan, in terms of -2 lnΛ(κ_λ), performed as a function of κλ on data from the ATLAS collaboration. The dotted horizontal lines show the ±1σ and ±2σ uncertainties on κ_λ.
https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PUBNOTES/ATL-PHYS-PUB-2019-009/

The discovery of the Higgs boson has presented us with exciting new paths for resolving the remaining mysteries of the SM. The Higgs boson has opened a door to new explorations of BSM physics at the LHC, through indirect constraints arising from precision measurements of the SM Higgs boson, as well as direct searches for new phenomena. This article has touched upon just a few of those studies, including searches for additional Higgs bosons and interactions of the SM Higgs boson with DM candidate particles. Moreover, the data provided by the upcoming Run 3 of the LHC and the HL-LHC will further aid our exploration of new physics using the Higgs boson.

Studying the Higgs at future colliders

*by **Panos Charitos***

PDF version

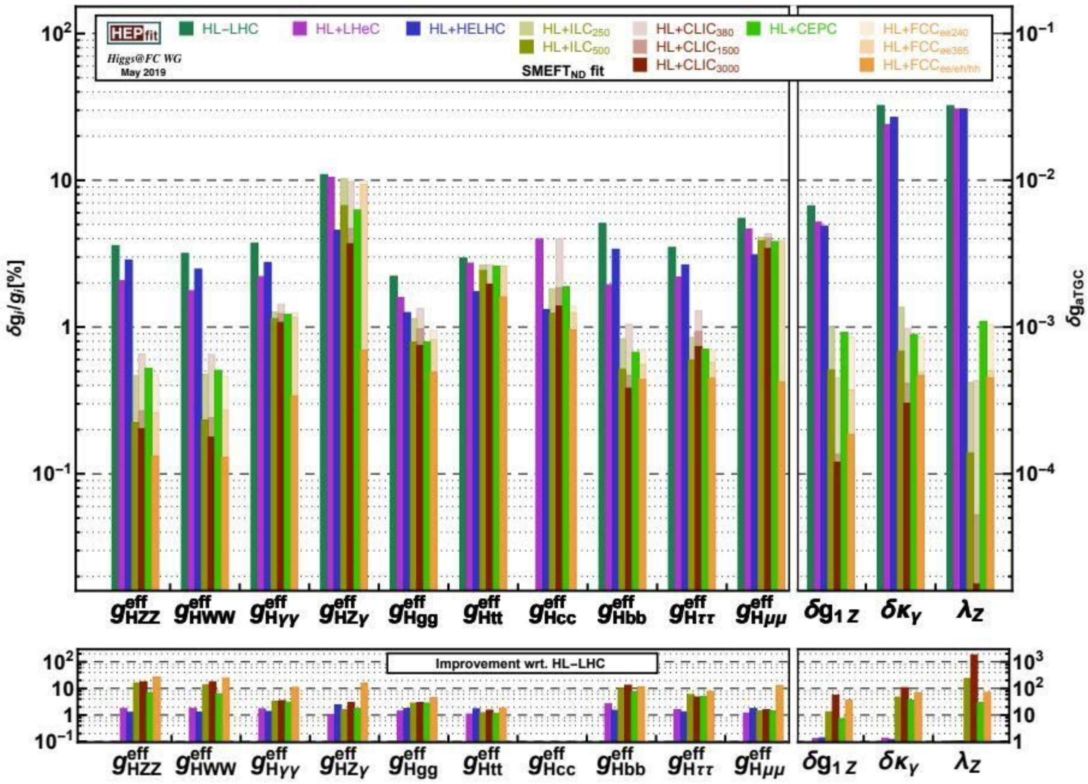
The LHC offers a very detailed knowledge of how the Standard Model particles interact, but we know that this knowledge is incomplete. A number of experimental data and theoretical motivations point to the existence of new physics beyond the description of the Standard Model. The recently discovered Higgs boson crowned a success of the SM and calls for further studies on this newly observed sector. In that context, the study of the Higgs boson and how it couples with the known particles of the Standard Model sets a clear, albeit ambitious, challenge for the experimental programme of any post-LHC machine.

To address the opportunities offered by proposed future colliders, the European Strategy for Particle Physics has formed a group to study in details the projected performance and possible searches. Following an intense period of work, during which they reviewed the design studies for these future machines, the group prepared a comprehensive report that largely informed discussions during the recent EPPSU meeting in Granada. Comparing possible measurements and searches linked to the Higgs boson at the different environment offered by circular and linear colliders has not been a trivial task. Things get more complicated as one has to take into account different theoretical considerations that enter these calculations and the projected performance for these machines.

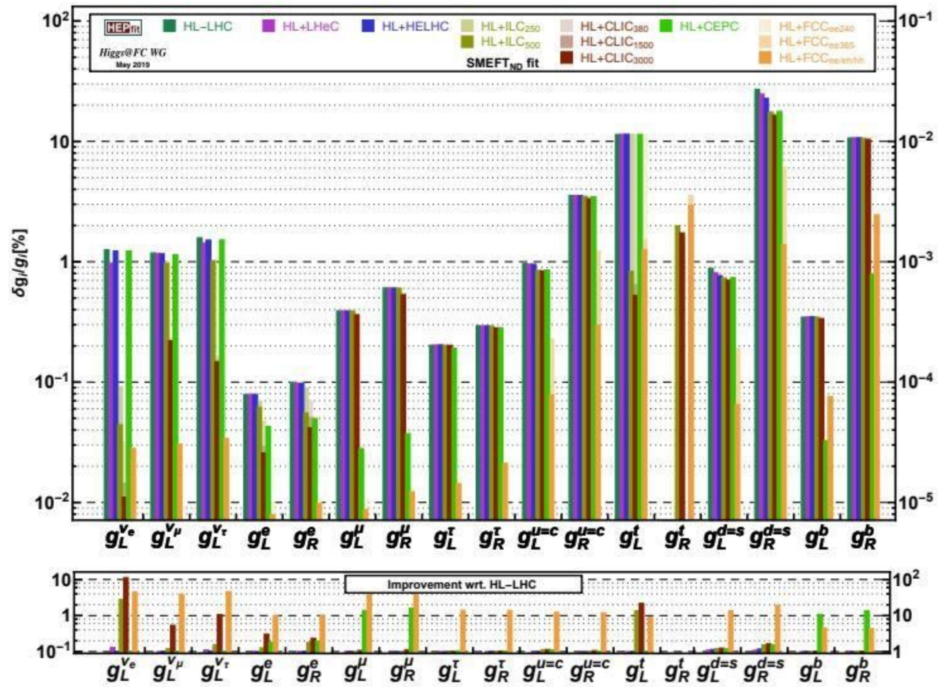
A key aspect of the experimental programme of a post-LHC collider includes precision studies of Higgs couplings, self-couplings and its total width as well as the study of rare decays. Since these couplings are well defined in the framework of the Standard Model, small deviations could be a sign of new physics. However, in the absence of knowledge of the form that new physics can have we need to parametrize our ignorance in terms of continuous deformations of the Higgs boson couplings. Different assumptions allow to capture different classes of new physics dynamics which was one of the challenges faced in producing this report. Two other topics discussed in the report are the significant progress expected in future colliders include the sensitivity to new high-scale physics through loop corrections as well as very sensitive searches for CP violating effects.

The calculations are combined with the expected reach of the HL-LHC programme. To understand the potential of future machines both the κ-framework and EFT analysis are taken into account.The first offers a convenient exploration tool without requiring further computations than those included in the SM and can capture the dominant effects of well motivated new physics scenarios on a set of on-shell Higgs observables. However, the validity of this approach is limited if you want to put Higgs measurements in perspective and compare them to processes with different particle multiplicities or combined with measurements at different energy scales. This is where, the EFT proves to be a more powerful tool. First of all, it allows to exploit polarisation- and angular-dependent observables to which κ-analysis remains blind. Moreover, EFT probes the Higgs in the extreme kinematical regions relevant for colliders operating far above the weak scale, exploring the tails of kinematical distributions. In addition, EFT offers a consistent framework where predictions can be systematically improved via the inclusion of both higher loop corrections in the SM couplings and corrections from new physics can be encoded in operators of even higher dimensions. The report presents detailed comparisons basedon these two frameworks and the current design parameters of the proposed future colliders. The primary goal is to allow a clear and coherent comparison that can guide decisions for the future of the field.

Another crucial experimental challenge is the measurement of Higgs couplings with other known particles of the Standard Model. A future lepton collider could push precision measurements closer to the 1% threshold where a number of new physics theories can be studied. In that respected the proposed High-Energy upgrade of the LHC (HE-LHC) seems to offer small improvements compared to the planned High-Luminosity LHC (HL-LHC) which will boost the precision measurement of these couplings.



Sensitivity at 68% probability to deviations in the different effective Higgs couplings and aTGC from a global fit to the projections available at each future collider project. Results obtained within the SMEFT framework in the benchmark SMEFTND.



Sensitivity at 68% probability to deviations in the different EW couplings from a global fit to the projections available at each future collider project. Results obtained within the SMEFT framework in the benchmark SMEFTND. See the original report (Fig.4, p.22) for details and the discussion therein.

Regarding the study of Higgs couplings to vector bosons, both CEPC and FCC-ee would be able to measure the effective H→ ZZ coupling with a precision of ~ 0.3%. Following a 15 years programme at 365 GeV, the FCC-ee can bring the H→ ZZ coupling down to ~ 0.2% thanks to the unprecedented luminosities of circular colliders. In the case of ILC, operating at 250 GeV a precision of ~ 0.4−0.5% can be achieved while to reach the same precision as FCC-ee would require to double its energy up to 500 GeV and about 22 years of operation. CLIC could also offer a two-per mille accuracy of the Higgs couplings to vector bosons about a 23-year programme profiting also from its upgradability to higher energies up to 1.5 TeV.

Turning now to the Higgs couplings to fermions, a similar pattern of improvements is observed for couplings to bottom quark and τ lepton. The top quark Yukawa is not directly accessible for lepton colliders running below the ttH threshold that can be accessed with the high-energy runs of the lepton machines. ILC at 500 GeV can reach a precision ~ 6-7% that can be brought to 3% by pushing the energy to 550 GeV and a similar projection exists for CLIC operating at 1.5 TeV. It should be noted though that a possible future 100 TeV proton collider (FCC-hh) coupled with precise measurements of the Z to top/antitop coupling at FCC-ee could bring the precision for this measurement down to 1%. The report notes that a number of Higgs couplings, mainly those associated to rare decays, remain statistically limited above the 1% threshold and only the combination with a high-luminosity proton machine could bring all the main Higgs couplings below 1%.

It should be noted that a precise measurement of the mass of the Higgs boson is needed also needed to improve the accuracy of these measurements. Future accelerators are expected to substantially improve the precision of the Higgs mass measurement. It is important to combine precise measurements of the Higgs couplings with equally precise

measurements of the Higgs mass, to the level of 10 MeV which is possible at 240/250 GeV lepton colliders. Moreover, in the SM, the width of a 125 GeV H boson is predicted to be around 4 MeV, i.e. three orders of magnitude smaller than that of the weak bosons and of the top quark. It is therefore very challenging to measure it directly. All methods considered so far at colliders are in fact indirect and model dependent to various degrees. Three methods have been proposed at the LHC, and are considered for future hadron colliders while lepton colliders could also provide complementary results allowing to extract the total width of the Higgs boson with a mild model dependence (based on the measurements of the inclusive cross section of the ZH process).
Another top priority for future colliders is the measurement of the Higgs potential. This would allow to search for sizeable departures from the SM form and understand the role of the Higgs field in the spontaneous breaking of the electroweak symmetry and consequently the generation of the masses of all the Standard Model particles. Unfortunately the measurement of the Higgs potential depends on a number of theoretical considerations that are extensively discussed in the report. A robust analysis requires to be able to disentangle a variation due to a modified Higgs self-interaction from variations due other deformations of the Standard Model which proves to be a daunting challenge. Several of the proposed post-LHC colliders will reach a sensitivity of order 20%, thus establishing the existence of the self-interaction at 5σ. Even more remarkable, CLIC3000 can reach a sensitivity of 10% and FCChh bring it down to 5%, where one could start probing the size of the quantum corrections to the Higgs potential directly.

Another interesting topic concerns the Higgs boson rare decays as they can provide access to Higgs couplings which are expected to be small and thus have not yet been directly probed. For example, if we observe an enhanced rate in processes that are predicted to be rare in the SM this could be a signal of new physics at play. The ability of future colliders to explore these rare decays depends mainly on the number of Higgs bosons produced and the available statistics. Another way in which new physics could manifest in the study of rare decays is through peculiar signatures of final states. Finally, the Higgs boson could also decay to invisible particles that could be good Dark Matter candidates. The proposed lepton colliders improve the sensitivity by about a factor 10 compared to HL-LHC while a 100 TeV energy-frontier machine improves it by another order of magnitude and will probe values below that of the SM. In that front, high-energy hadron colliders are more sensitive and will allow direct searches for DM candidates.

Furthermore, searching for non-zero CP-odd components in the interaction of the Higgs with the other SM particles could shed light to the strong CP problem, offering the missing additional sources for CP violation to explain the apparent imbalance between matter and antimatter. Searches for this extra source of CP violation focus on ttH at hadron colliders and on ttH and tH final states at lepton colliders, respectively. For example, by studying distributions in ttH, the HL-LHC will be able to exclude a CP-odd Higgs at 95%CL with about 200 fb−1 of integrated luminosity. CLIC 1.5 TeV foresees to measure the mixing angle for the top quark, αt ttH‾ to better than 15◦ while FCC-ee offers a precision of 1.9% on α_t. The most promising direct probe of CP violation in fermionic Higgs decays is the τ+τ− decay channel that benefits from a relatively large branching fraction. Accessing the CP violating phase requires a measurement of the linear polarisations of both τ leptons and the azimuthal angle between them.

In conclusion the report details a wealth of useful data, comparing different types of searches around the Higgs in future colliders. It places the Higgs measurements in perspective with other new physics studies at future colliders while offering a comprehensive overview of precision studies of the Higgs boson as a guaranteed deliverable of any future collider facility. The dedicated effort to make this comparison has been acknowledged during the Granada meeting and this document will inform the final drafting session setting the priorities for the next post-LHC collider.

Read the full report: https://arxiv.org/pdf/1905.03764.pdf

Silicon photonics for high-energy physics experiments

by ***Andrea Kraxner (CERN), Jan Troska (CERN)***

PDF version

Optical links have become ubiquitous in High Energy Physics (HEP) experiments to transport data generated from the particle detectors and other control points along the accelerator to the processing electronics. So far, links based on both single-mode Edge Emitting Lasers (EELs) [1] and multi-mode Vertical Cavity Surface Emitting Lasers (VCSELs) [2] are in us. The drawback of these laser diode-based technologies is their degradation due to displacement damage from particle fluence [3]. With the ever-higher radiation levels and the increasing data volumes, alternatives have to be investigated. In the innermost detector regions the challenge is not only to withstand the high radiation levels but also to satisfy the space restraints which make highly integrated links necessary. Silicon Photonics seems to be a quite promising candidate addressing all those points and is currently being investigated for its applicability for use in optical links in future HEP experiments.

Silicon photonics is a highly integrated platform where all photonic components like photodetectors, modulators, lasers and the electronics are grown or implemented on the same piece of silicon. Silicon On Insulator (SOI) wafers in combination with well-established CMOS processes are used for the production. The compatibility with CMOS electronics opens the door to highly integrate the optical links within the detector system. In order to achieve this goal it has to be made sure that optical links based on silicon photonics can perform in and withstand the harsh conditions of the HEP experiments and at the same time can satisfy the challenges of low power consumption and high data rates.

In a first step, the radiation resistance of the building blocks of a silicon photonics optical link, which are modulators, photodiodes and waveguides have been investigated. While we found that all tested devices are very resistant against displacement damage, modulators unfortunately show a strong degradation due to ionizing radiation [4]. A silicon photonics test chip was designed by us (Figure 1), including different passive structures as well as modulator and photodiode structures [5]. Numerous irradiation tests and simulations have been performed to better understand the effects and to overcome the degradation due to total ionizing dose. We showed that it is possible to increase the radiation resistance by design [6] and that an additional increase can be achieved when the devices are operated at low temperatures [7].

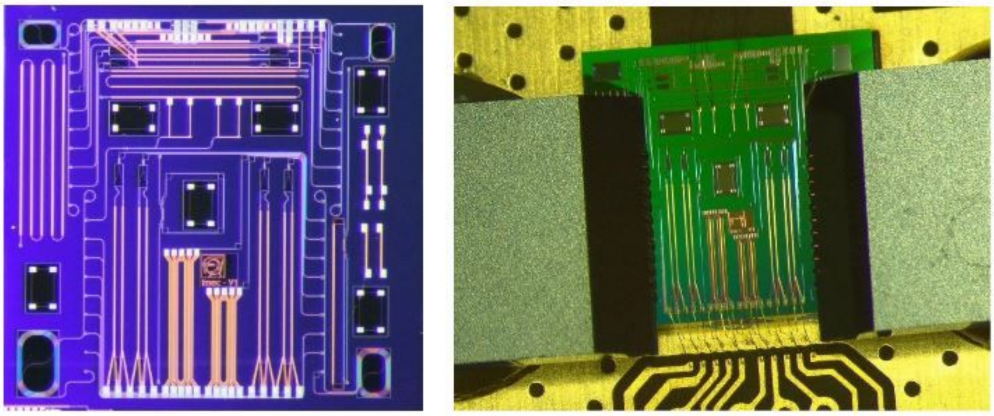


Figure 1: Silicon Photonics test chip designed by the Opto team of the EP-ESE-BE section. Bare chip (left) and including electrical and optical assembly (right).

Throughout the investigations, we found a very efficient annealing effect of the irradiated modulators, applying a forward bias [7]. This leads to a full recovery after irradiation, which was proven by re-irradiation tests. But also, we showed that a high enough current for a sufficient time period prevents the radiation induced degradation already during irradiation [8]. As the standard operation of these modulators (depletion type modulator) is in reverse bias it is not possible to anneal the devices during their operation but in phases where the operation of the HEP experiments is paused eg. during shut-downs, technical stops or interfills the annealing could be performed.

In this first technology evaluation period the focus was mainly on so called Mach-Zehnder Modulators. While these devices come with many advantages such as stability towards manufacturing errors, temperature and wavelength drift as well as already very well proven systems based on MZMs they also come with some drawbacks. First of all a rather large size (more than 1 mm) is necessary to reach the desired efficiency and this comes hand in hand with quite high biasing voltages and high optical losses. All of this leads to a high power consumption. One alternative could be the so-called Ring Modulator [9], which gains more and more attention in the silicon photonics community. Due to the smaller size (negligible optical loss) and higher tuning efficiency, the power consumption can be reduced. The only disadvantage is the high sensitivity to temperature and manufacturing variations, which makes a control loop including a local heater necessary. However, this also brings some positive effect. The possibility of tuning the resonant frequency combined with their small size, ring modulators are very attractive for use in multi-channel systems like wavelength division multiplexing (WDM) [10].

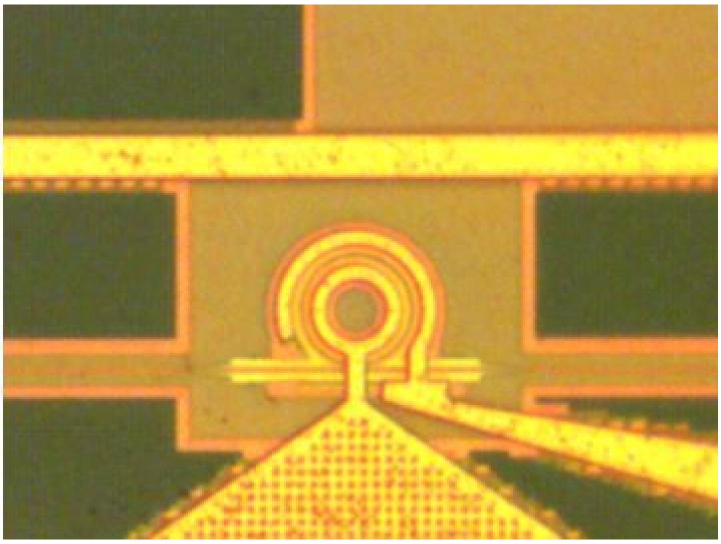


Figure 2: Microscope image of a Ring Modulator.

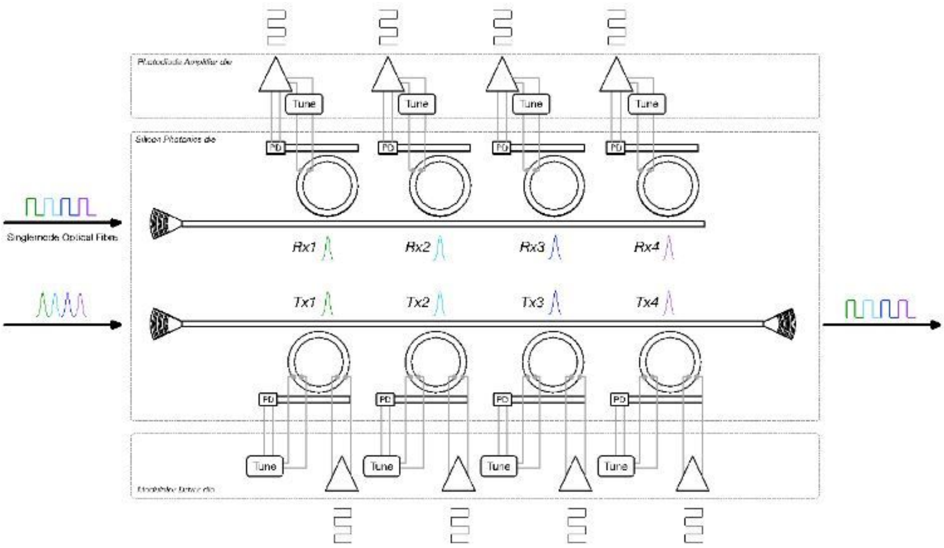


Figure 3: Schematic of a ring modulator WDM transceiver. Ring resonators with different and tuneable resonator wavelengths are located along horizontally drawn bus waveguides.

Taking into account the advantages and following the trend in the community we started to investigate this structure more intensively. In Figure 2 a microscope image of the ring modulator investigated by us is shown. The radius of this structure is 7.5µm. As the same modulation mechanisms as in the MZMs are used we can assume the same behavior with radiation which we could already prove by measurements. In our most recent activities, we are designing a new test chip to further investigate the suitability of ring modulators for HEP experiments and test first transmitter and receiver system designs based on WDM (schematic of the system in Figure 3).

Further Reading:

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ENUBET: a beam for the precision era of neutrino physics

by ***Francesco Terranova (INFN)***

PDF version

Even if neutrino oscillations were discovered more than 20 years ago, our knowledge of mixing, flavor oscillation and CP violation in the neutrino sector is still far from the precision achieved for quarks. CP violation in the quark sector was established in 1964 and the CKM matrix is measured at sub-percent level both for light and heavy flavors. On the contrary, CP violation in neutrinos is not established, yet, and unitary tests of the neutrino counterpart of the CKM matrix (the Pontecorvo-Maki-NakagawaSakata – PMNS – matrix) have not even started. All in all, flavor physics in neutrinos is a discipline still in its infancy but such a gap comes as no surprise: the neutrino cross sections are the faintest among elementary fermions and the experimental study of flavor physics for the neutrinos remains a major challenge in particle physics.

Accelerator neutrino beams are the workhorse of precision neutrino physics: they produce high intensity beams of muon-neutrinos and play a role similar to b-factories in quark physics. Unlike bfactories, however, the luminosity of these facilities, i.e. the neutrino flux at source, are known with a very limited precision - typically at the level of 10%. Such limitation impacts in a direct manner on all neutrino cross section measurements which, in turn, are determined at the 10% level or worse. At the time of the discovery of neutrino oscillations, a 10% precision in the knowledge of standard model cross sections was a tolerable nuisance but nowadays it is a hindrance that jeopardizes the physics reach of the next generation neutrino facilities, including DUNE and Hyper-Kamiokande. A breakthrough in cross section physics require a neutrino source with a unprecedented control of the flux, energy and flavor. The design of such a source is the main aim of NP06/ENUBET, one of the most ambitious R&D carried on in the framework of the CERN Neutrino Platform.

The ENUBET Collaboration together with particle and accelerator physicists at CERN is developing the technology of "monitored neutrino beams", i.e. neutrino beams where the flux of the neutrinos at source is measured at single particle level. The flux is measured in the most direct manner: detecting the charged lepton that is produced together with the neutrino after the decay of the parent meson. In general, neutrino beams are produced by the decay in flight of pions and kaons along a decay tunnel located after a target and a system of magnetic lenses (“horns”). The ENUBET “narrow band beam” is a moderate intensity muon-neutrino beam with a fully instrumented decay tunnel. The tunnel instrumentation of ENUBET monitors the production of electron neutrinos detecting the positrons produced by the K+® e + p 0 ne decays of the kaons. ENUBET is therefore a fully controlled electron neutrino source. Similarly, beam diagnostics monitor the decay of the pions after a transfer line with a narrow momentum acceptance: it results in a high precision muon neutrino source where the energy of the neutrino is known within 10%.

The challenges of ENUBET are first of all the challenges that the LHC has to face, namely handling huge particle rates in a high radiation environment: the decay tunnel of a 100 kW power fixed target experiment. This is the reason why ENUBET resorts to technologies originally developed for collider experiments and is so closely connected to CERN. The ENUBET Collaboration has been established in 2016 and funded by the European Research Council through the 2015 Consolidator Grant Programme (PI: A. Longhin). Since 2016, the technology of monitored neutrino beams has progressed enormously in all fields: the design of the proton extraction scheme, the focusing and transfer line and the instrumentation of the decay tunnel. The final goal of NP06/ENUBET is to build a full-fledged segment of the decay tunnel and test it in realistic conditions at the Renovated East Experimental Area of the PS. The run of the “ENUBET demonstrator” will be a major step toward the validation of the monitored neutrino beam concept. The CERN Neutrino Platform is providing the ideal environment for this R&D to progress, while at this time there is no commitment for a future neutrino beam at CERN.

Even if several challenges have still to be overcome, results achieved so far have really exceeded our expectations. In summer 2018, the ENUBET Collaboration demonstrated that an intensity sufficient for high precision cross section measurement could be reached with a purely static focusing system. A static system dilutes the particle flow in the wall of the tunnel by more than an order of magnitude so that secondary leptons could be not only be monitored but also time-tagged on a particle-by-particle basis if the timing system reaches a precision of 100 ps. Timing at such level of precision is routine work at the LHC but would represent a landmark in experimental neutrino physics: the neutrinos observed at the neutrino detector could be uniquely associated with the lepton and the other decay product of the kaon on an event-by-event basis. Such a facility has been envisaged in the 60s and is customarily called a “tagged neutrino beam”.

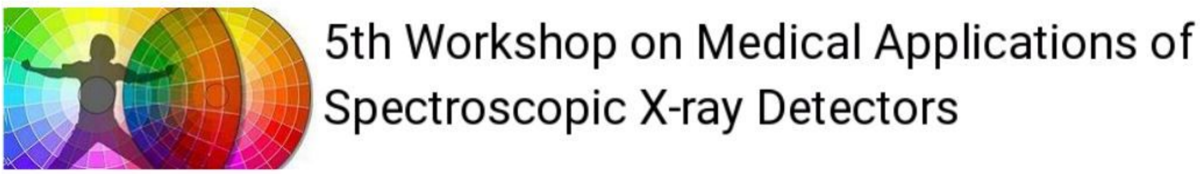
Tagged neutrino beams are the holy grail of accelerator neutrino physics because each neutrinos is flavor tagged by the corresponding lepton at source on an event by event basis. As noted by B. Pontecorvo in 1979, “the possibility of using tagged-neutrino beams in high-energy experiments must have occurred to many people” but in 2019 this possibility is still well beyond current technologies. Time tagging of neutrinos with the associated lepton in the decay tunnel has defeated all attempts performed in the 80s because the technological challenges were insurmountable at that time and still remain at the frontier of experimental physics. In a neutrino beam, 1013 pions or kaons must be produced in a 50 m decay tunnel in order to observe a 1 GeV neutrino in a 500 ton detector. Their decay products must be recorded by the front-end electronics, time tagged and associated with the neutrino event at the detector. The ENUBET static focusing neutrino beam combined with the gigantic technology leaps on particle detection, timing, data acquisition and analysis fostered by collider experiments bring Pontecorvo's dream-facility well within reach.

In the next years, NP06/ENUBET will bring monitored beams to a level of readiness suitable for a Conceptual Design Report, which will ground a new generation of cross section experiments. These experiments will run in parallel to the high intensity long-baseline facilities as DUNE and HyperKamiokande providing the precision and knowledge of Standard Model interactions that currently limit their physics reach. They will also perform exquisite tests of physics beyond the Standard Model in the neutrino sector due to the unprecedented level of control of the source. Last but not least, they will serve a wide and vibrant community of neutrino physicists investigating neutrino scattering and cross sections. Their detectors (the liquid argon TPC of ProtoDUNE's, the near detectors for T2K-II), are under development in the framework of the CERN Neutrino Platform: a programme that makes CERN a focus for European involvement in precision neutrino physics for the decade to come.

Colour X-rays for Medicine: The 2019 specXray workshop

*by **Panos Charitos***

PDF version



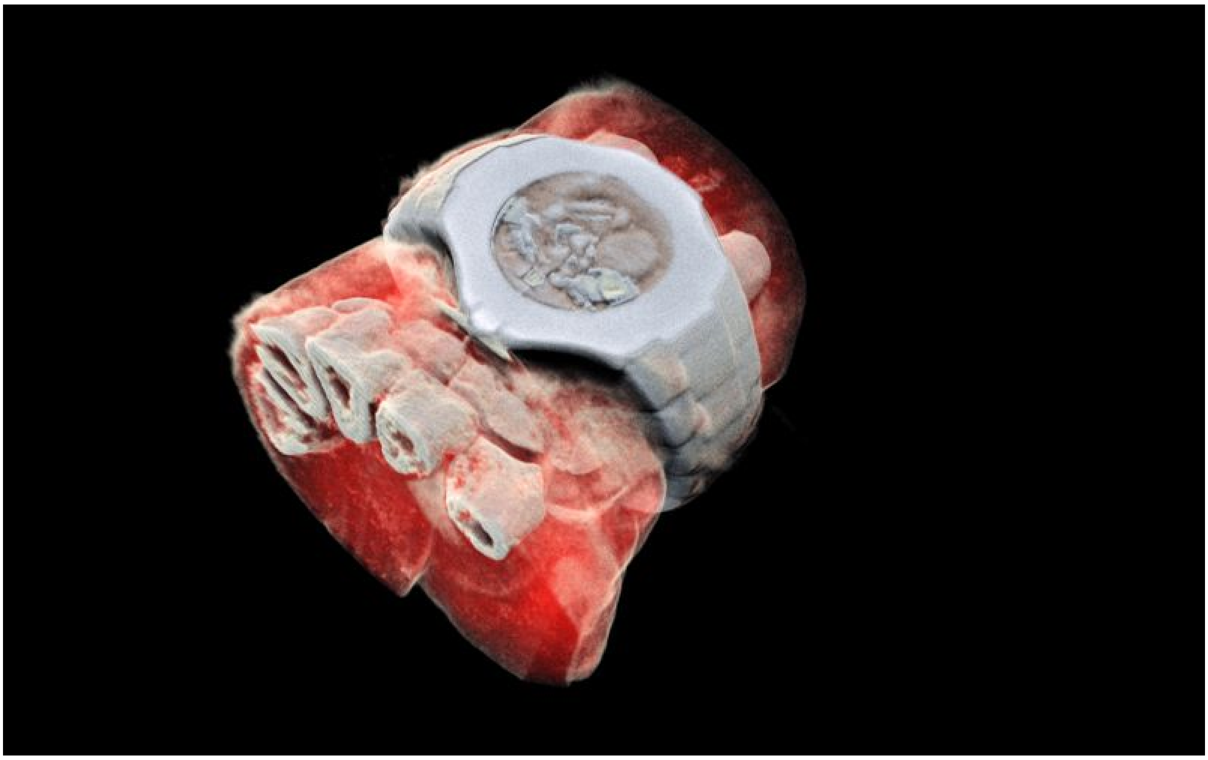
The fifth workshop on Medical Applications of Spectroscopic X-ray Detectors (specXray) took place at CERN from 13 to 17th of May. Since its establishment in 2011, the workshop has brought together specialists from different but related fields focusing on how best to advance effort and understanding in the new imaging modality of spectroscopic X-ray imaging. The 120 participants comprised clinicians, radiologists, biologists, tracer developers, imaging system specialists and detector and ASIC developers.

All of the major medical radiology equipment suppliers were represented along with researchers from many of the major medical schools. Prof Anthony Butler from the University of Canterbury (New Zealand) in the closing summary of the conference noted: "Since the first meeting, scepticism about the benefits of such an approach (and the associated technical challenges) has gradually given way to an acceptance that the approach has great potential, offering new avenues in diagnostic imaging."

Indeed, since the discovery of the x-rays by Röntgen in 1895, there is a continuing interplay between physics and medicine boosting both imagining and treatment techniques. More specifically, in the case of medical imaging, technological advancements for particle detectors have fuelled new developments in medical imaging.

A number of image metrics, presented by clinicians during the workshop together with practical case studies carried out using prototype clinical systems have shown that spectroscopic photon counting gives better image quality at reduced dose. Moreover, studies have shown that multiple contrast agents can be distinguished leading to potential applications in functional X-ray imaging.

Perhaps it should be noted that last year, scientists in New Zealand applied the spectroscopic imaging technique to perform the first-ever 3-D, colour X-ray on a living human using a Medipix3-based system, promising to revolutionize the field of medical diagnostics. The latest results were presented by Butler and first clinical trials are underway.



A 3D image of a wrist with a watch showing part of the finger bones in white and soft tissue in red. (Image: MARS Bioimaging Ltd)

The mood of the meeting was rather positive with most participants convinced that spectroscopic X-ray imaging will find its place in clinical practice in the coming years. “This is what happens when you bring people with good ideas together to form a community” noted Stephan Kappler, a member of the Scientific committee. With more than 300,000,000

CT scans being performed annually around the world the potential impact for the spectroscopic X-ray imaging modality is huge.

Workshop webpage: http://specxray.web.cern.ch/specxray/

You can find more information about the Detector Seminar: https://indico.cern.ch/event/819651/

CernVM 2019 Workshop

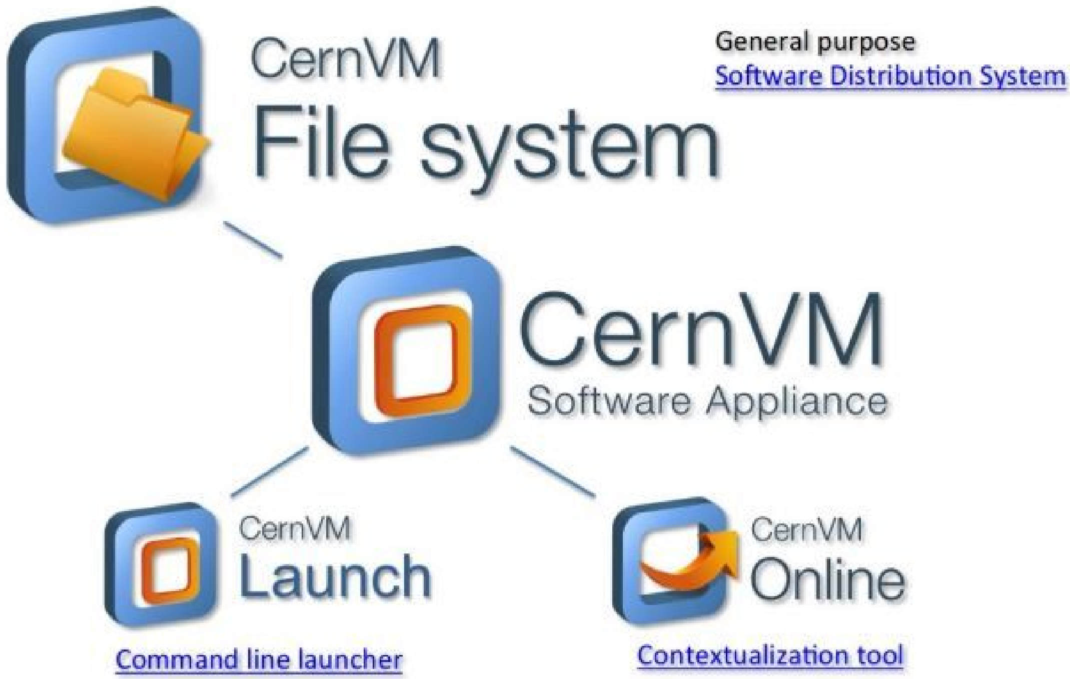
by ***Jakob Blomer (CERN)***

PDF version

From 3rd June to 5th June, the 2019 CernVM Workshop took place. As about every 18 months, the CernVM workshop brings together software developers from EP-SFT, computing experts from the LHC experiments, WLCG system operators, and invited speakers from the IT industry. More than 40 participants discussed the state and future directions of the CernVM File System (CernVM-FS) and the CernVM Virtual Appliance. Frédéric Hemmer, head of CERN's IT department, kindly provided the workshop welcome note, which underlines CernVM's strong collaboration between EP-SFT and IT-SM.

Started as a four years R&D project in 2008, the CernVM software ecosystem became a mission critical component for the LHC experiments. It takes care, at LHC scale, of delivering our scientific applications and platforms to the worldwide distributed computing infrastructure and has since been adopted across HEP and beyond, such as by the LIGO and EUCLID collaborations.

For the future development, three themes emerged during the workshop. First, the need for seamless integration of the CernVM-FS technology with industry container ecosystems - a topic already raised in previous events and workshops - was confirmed, with a focus on the technologies Kubernetes, Docker, and Singularity. HEP users will need the application isolation and orchestration capabilities offered by industry standard tools combined with the efficient distribution capabilities of CernVM-FS to effectively deploy complex containerized applications. Second, various previous efforts on accessing supercomputers at HPC centers beared fruit. Targeted developments made it possible to access scientific software on many HPC systems. Thereby the CernVM specific part in harnessing supercomputers is getting under control, in what generally remains a challenging task on many other fronts. Third, there is a continuous need for faster and more convenient ways to publish data in CernVM-FS. This is most acute for the software development teams that currently prepare the experiment frameworks for run 3 upgrades and HL-LHC.



In order to get a fresh look onto the technology landscape, the CernVM workshop has a tradition of inviting speakers from industry and academia on hot computing topics. This year, we were glad to hear from Harris Hancock, software engineer at the U.S. CDN provider Cloudflare, on the state of the art in edge computing and serverless computing. Dorian Krause, head of the HPC systems division at the Jülich Supercomputing Centre, presented the roadmap of future supercomputing hardware. Michel Bauer from the U.S. start-up Sylabs gave insights into the Singularity container engine and sketched out a path for integrating CernVM-FS technology. Jesse Williamson, software developer with the Ubuntu creator Canonical and former CernVM-FS contributor, provided a critical review of application areas for Ceph-FS and CernVM-FS. Prof. Douglas Thain from the University of Notre Dame (Indiana) shared his research on building and managing scalable scientific applications. From the Linux technology company Red Hat, Giuseppe Scrivano completed the technology outlook session with the latest developments on overlay file systems and Linux kernel container mechanics.

Group photo of the invited speakers of the CernVM workshop during their visit to the CMS experiment at P5.

All the invited speakers where given a guided tour to the CMS experiment, and several stayed at CERN for the entire week for further discussions with LHC computing experts. The CernVM team is very grateful to all participants for the very valuable contributions and the fruitful workshop atmosphere! The provided feedback is now due for incorporation in the medium-term development plan.

Exploring dark sector with NA64: First results from the combined analysis of 2016-2018 runs

by ***Sergei Gninenko (Russian Academy of Sciences), Paolo Crivelli (ETH Zurich)***

PDF version

Searches for dark matter (DM) particles, an essential experimental goal for particle physics, are entering in an interesting stage. Despite the strong astrophysical evidence for dark matter, little is still known about the origin and dynamics of this substance of our Universe.

The significant efforts on both direct and indirect searches at the LHC and other dedicated experiments around the world has ruled out many DM models, but have not yet yielded unambiguous DM signals. Perhaps, the main difficulty that hinders progress, keeping the mystery around DM, is that it can only be studied through its gravitational interaction with ordinary matter. Therefore, the idea of introducing a new way of interaction between dark and visible matter, in addition to gravity, opens a rather exciting path for exploration.

Several theoretical models motivate the extension of the SM by introducing the concept of dark sectors consisting of a set of particles and fields which is similar to that of the SM, but transform under new gauge symmetries and do not interact with the SM. In analogy with QED, for which the massless photon mediate the force between charged particles, there could be a dark QED with a so-called dark photon that mediates a force between dark particles. Such a dark photon (A') could have a mass $m_{A'} \lesssim 1$ GeV and it could couple to the SM through the kinetic mixing with the ordinary photon parameterized by the mixing strength ε.

In the presence of light dark matter particles, with masses < $m_{A'}$, the dark photon could predominantly decay invisibly into those particles. Models introducing such invisible A' decays offer new intriguing possibilities to explain hints on astrophysical signals of dark matter. They assume the existence of a dark photon with a mass in the sub-GeV region and a coupling strength to ordinary photons in the range of $\varepsilon \simeq 10^{-5}$-$10^{-3}$.

This assumption has motivated a wide range of ideas and proposals that were widely discussed during the Physics Beyond Colliders annual workshop at CERN. Proposals include ideas for dark forces and other portals between the visible and dark sectors which might be probed at low energy, high-precision experiments at CERN's SPS.

One of the experiments that attracted noticeable attention during the PBC meeting was NA64. It was designed for a broad search for dark sector physics by looking for missing energy events using the active beam dump approach. NA64 was approved in 2016 and its primary goal was to search for invisible decays of dark photons, covering a large part of the parameter space for exploring the observed muon g-2 anomaly.

The basic idea is the following, if dark photons (A') exist they can be produced via the kinetic mixing with bremsstrahlung photons through the reaction $e^-Z \rightarrow e^-ZA'$ of high-energy electrons scattering off nuclei (Z) from an active target. This will be followed immediately by the decay of $A' \rightarrow \chi \ \chi$ into dark matter particles χ. The χ would penetrate a hermetic detector located downstream the target without interacting and would carry away a fraction of the beam energy. Therefore, observing an excess of events with large missing energy above small backgrounds would signal the presence of dark photons. Moreover, to ensure that any excess is due to the 100 GeV electrons, the emitted synchrotron radiation from the beam is used to tag each electron individually and beyond any doubt.

The technique of observing missing energy in the products of high-energy interactions currently being explored by NA64 on an electron beam was put forward during the Physics Beyond Colliders kick-off workshop in 2016. This approach complements classical beam dump experiments and provides much better sensitivity for a specific parameter space. In the case of beam dump experiments, the products of dark photon decays (i.e. other dark sector particles) could penetrate the dump and have observable interactions in a far detector.

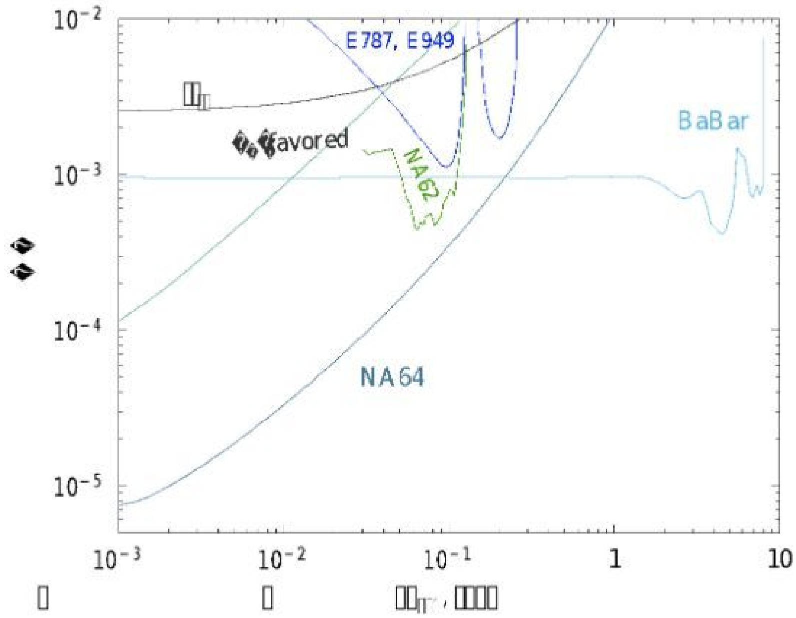


Figure 1. Na64 limits on the γ - A' mixing from the combined 2016-2018 runs.

A64 began operation in July 2016 for a period of two weeks and completed its physics programme with a six-week run in 2018. The July results were published in Phys. Rev. Lett. (2017) and exclude values of the dark photon (A′) coupling that would make dark photons relative for explaining the muon g-2 anomaly. While not ruling out the existence of dark photons, these results serve as an important demonstration of the feasibility of the NA64 approach and give guidance for the further upgrade of the detector. Significantly more data accumulated in 2017-2018 with improved apparatus allowed to search for A´s as a mediator of dark matter production in invisible decay mode and other invisible decays of dark-sector particles. The combined NA64 bounds from 2016-2018 runs on the γ - A' mixing are shown in Fig. 1, while new limits on the parameter Y are shown in Fig. 2. This variable characterizes the cross section for the DM <-> SM annihilation and is convenient for comparison of results from other experiments, also shown in Fig. 2. The black curves calculated for the scalar, Majorana and Pseudo-Dirac DM relic abundance represents the Y parameter space, which is an explicit target for NA64.

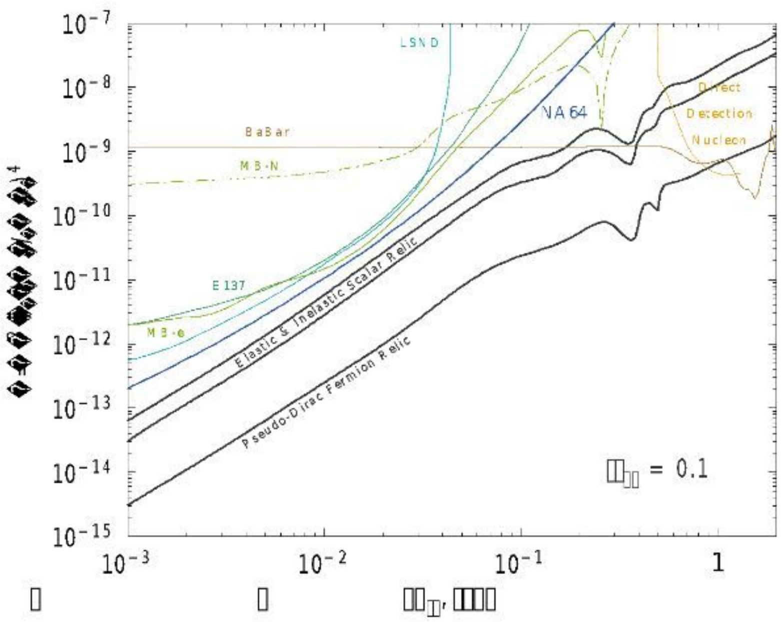


Figure 2. Na64 constraints on sub-GeV DM from the combined 2016-2018 runs.

One can see that NA64 provides the best stringent constraints on both variables, ε and Y, for the A' and DM masses in the sub-GeV regime. Thus, demonstrating the power of the active beam dump approach for the dark matter search compared to the classical beam dump experiment such as LSND, E137, and MiniBooNE. The further goal of NA64 is to accumulate up to $\sim 10^{13}$ electrons on target (EOT) after LS2 in order to probe the remaining DM parameter space shown in Fig. 2.

The search for dark photons is one of many approaches for trying to detect dark matter. Today we have a rapidly growing variety of models suggesting new particles weakly coupled to lepton and/or quarks solving the DM and other problems in particle physics. In order to strengthen experiment operating in such unusual situation, we thought of NA64 as of a new type of experiment able to provide a quick response in testing these models.

For example, in 2016 the experiment of Krasznahorkay et al. in ATOMKI has reported observation of a 6.8 σ excess of events in the invariant mass distributions of e^+e^- pairs produced in the $^8Be^*$ exited state nuclear transitions to its ground state accompanied by an emission of an e^+e^- via internal pair creation. It has been shown that this anomaly can be interpreted as an emission of a new gauge boson (X) followed by its prompt decay $X \rightarrow e^+e^-$ and provide a particle physics explanations of the anomaly that is consistent with all existing constraints based on the assumption that its coupling to electrons is in the range of $2\times10^{-4} < \varepsilon < 1.4\times10^{-3}$ and mass $m_X = 16.7$ MeV. The models predict relatively large charged lepton couplings $\varepsilon_e \simeq 0.001$ that can also resolve the muon g-2 anomaly.

In 2017-18 after a detector reconfiguration NA64 has a physics runs to obtain data for searching for the X and A′ → e^+e^- decays with 100-150 GeV electrons at the H4 line in CERN's North Area. The preliminary combined results excluded the significant part of the X boson parameter space are shown in Fig. 3 and SPSC recommended the continuation of A′ and X searches with data from the 2021 run.

Another example is related to the muon $(g\text{-}2)_\mu$ anomaly, which is under more accurate study by the currently running experiment E989 at FNAL. While the A′ explanation of the muon g-2 anomaly has been ruled out by NA64 and BaBar, there is still one remaining interesting explanation provided by the $L_\mu - L_T$ model.

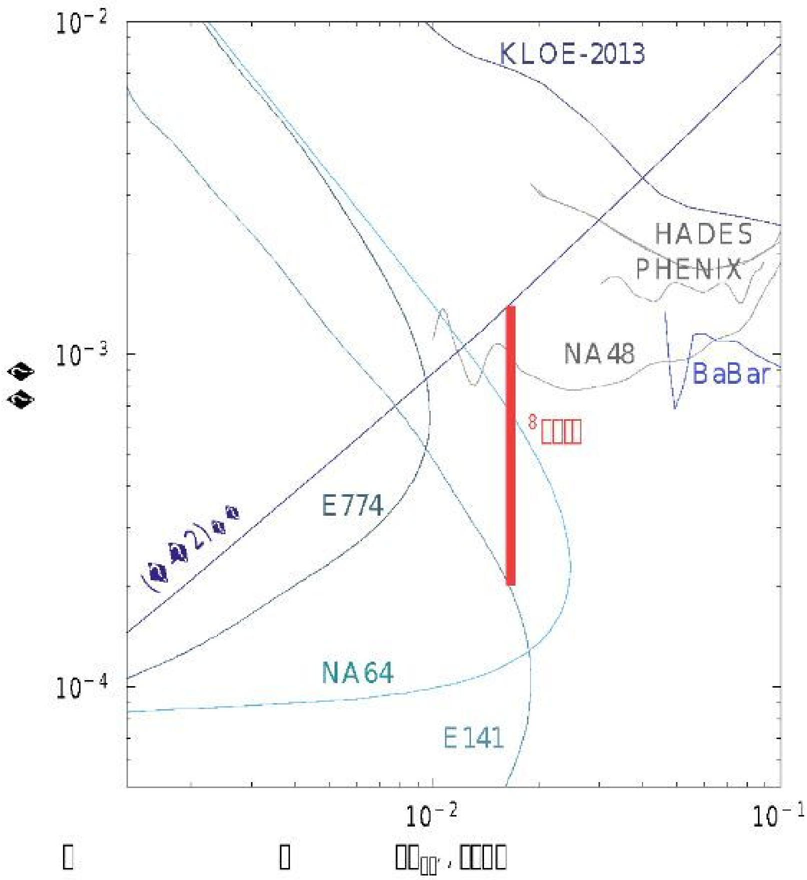


Figure 3. Na64 preliminary combined results from the 2017-2018 runs on the search for the 16.7 X boson from the 8Be anomaly and A′ -> e+e− decays of dark photons.

In this model the $(g\text{-}2)_\mu$ discrepancy is explained by the possible existence of a new leptophobic sub-GeV Z′ boson, which is weakly coupled predominantly to the second and third lepton generation leptons. The surprising fact is that the SM extension which includes such Z′ is still renormalizable and no new fermions are required. In addition, the invisible dark Z´ boson could serve as a portal between the visible and dark sectors offer new intriguing possibilities to explain hints on dark matter.

These results motivated the NA64 Collaboration to propose a new experiment called $NA64_{\mu}$ aiming to search for Z´ with the M2 muon beam at the SPS. Interestingly, $NA64_{\mu}$ could also probe the dark photon (A´) invisible decay similar to NA64 running in the electron mode ($NA64_{e}$). The combined $NA64_{e}$ and $NA64_{\mu}$ results with ~10^{13} EOT and a few 10^{13} MOT, respectively, will allow to cover almost fully the parameter space of the most interesting sub-GeV DM models shown in Fig. 2 . This makes NA64e and $NA64_{\mu}$ extremely complementary to each other and greatly increases the exploratory power of sub-GeV DM searches with CERN's SPS.

Further Reading

NA64 Collaboration, Phys.Rev.Lett. 118 (2017), 011802

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COMPASS++/AMBER: A new QCD facility at CERN's SPS M2 beam line

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PDF version

The COMPASS++/AMBER Collaboration proposes to establish a "New QCD facility at the M2 beam line of the CERN SPS". Such an unrivalled installation would make the experimental hall EHN2 the site for a great variety of measurements to address fundamental issues of strong interactions. The proposed measurements cover a wide range in the squared four-momentum transfer Q^2: at lowest values of Q^2 we want to determine the proton charge radius through elastic muon-proton scattering, at intermediate Q^2 we want to perform spectroscopy of mesons and baryons by using dedicated meson beams, and at high Q^2 we plan to study the structure of mesons and baryons via the Drell-Yan process. In our Letter of Intent (LoI) [1], which was recently submitted to the SPSC, we have described physics goals, sensitivity reach and competitiveness for such a future general-purpose fixed-target facility at CERN.

In phase-1, starting in the year 2022, we plan to perform three experiments making use of the existing M2 beam line that provides muons as well as pions and protons: (1) an accurate measurement of the electric form factor G_E of the proton at small values of the squared four-momentum transfer Q^2 to extract the proton charge radius, using the high energy muon beam (2) a study of the pion-induced Drell-Yan process to better determine the poorly known parton distribution functions (PDFs) of the pion and study nuclear PDFs; (3) a determination of the antiproton production cross section by scattering high energy protons on proton and helium-4 targets. A better knowledge of this cross section will improve the accuracy in interpretating the existing results from indirect Dark Matter Searches, as those obtained by the AMS-02 [2] experiment on the International Space Station. A proposal comprising all presently available details on these three measurements was recently submitted to the SPSC [3]. Brief summaries are given below in sections 2 to 4.

Beyond LS3, we propose to upgrade the M2 beam line by installing an RF-separation stage that will provide high-intensity and high-energy beams of charged kaons with a high level of purity. Such an upgrade is presently under study by CERN EN-EA in the framework of the Physics-beyond-Colliders Initiative. Once realised, it would make the CERN SPS M2 beam line unique in the world for many years to come. A brief summary is given below in sect. 5.

With RF-separated kaons, the virgin field of high-precision strange-meson spectroscopy becomes accessible, a first measurement of the kaon polarisability can be performed using the Primakoff process and measurements of the Drell-Yan process will allow access to the presently practically unknown quark-gluon structure of kaons. A variety of further measurements is proposed in the LoI, using RF-separated kaons or antiprotons in conjunction with various experiment-specific installations in the target region, including spectroscopy with low-energy antiprotons, spin-dependent Deeply Virtual Compton Scattering and Deeply Virtual Meson production, meson induced prompt-photon production, etc.

Novel instrumentation using modern detector architecture will be constructed and installed in the experimental hall EHN2, where the upgraded multi-purpose two-stage magnetic spectrometer will serve as experimental backbone of the new facility. Upgrades will be designed to serve for as many individual experiments as possible and installed along the lifetime of the facility according to actual needs and availabilities. As an example, we describe below the planned triggerless data acquisition system (see sect. 6).

The full project is expected to stretch across the next 10 to 15 years. As it continues to attract physicists world-wide, the physics scope of the facility should remain open for future exciting ideas, using either (RF-separated) hadron beams or the muon beam. Proposals for further measurements, based upon ideas already discussed in the LoI or possible new ones, will be submitted in due time.

Proton charge-radius measurement using muon-proton elastic scattering

In spite of many years of intense activity, the proton-radius puzzle remains unsolved up to now. An eventual explanation of this mismatch requires four key measurements: elastic lepton scattering and finite-size effects in atomic levels, in both cases using electrons and muons. In contrast to the atomic spectroscopy approaches, scattering experiments do not determine the proton radius directly, but by measuring the Q^2-dependence of the electric form factor over an extended range and then extrapolating the form factor linearly towards $Q^2 = 0$. Results are available for three types of experiments, but not yet for muon-proton scattering. To date, a discrepancy as large as 5 standard deviations exists between the two most recent precision measurements: $r^{rms}_{CREMA} = 0.841 \pm 0.001$ fm from line-splitting measurements in laser spectroscopy of muonic hydrogen and $r^{rms}_{MAMI} = 0.879 \pm 0.008$ fm from elastic electron-proton scattering.

The proposed measurement aims at a precision determination of the electric mean-square charge radius of the proton. This approach constitutes the “missing element” in the above mentioned fourfold variety of approaches to solve the proton radius puzzle. The Q^2-dependence of the cross section in high energy muon-proton elastic scattering will be measured over the range $0.001 < Q^2/(\mathrm{GeV}^2/c^2) < 0.04$ in order to constrain its Q^2-slope near zero. The sensitivity of this measurement is illustrated in Fig. 1. The projected statistical accuracy on the proton radius is 0.01 fm or better with a considerably smaller systematic uncertainty. Using high-energy muons instead of electrons is highly advantageous, as several experimental systematic effects and also theoretical (radiative) corrections are considerably smaller.

The accuracy to be reached by the proposed muon-proton scattering experiment is expected to be comparable to that obtained in electron-proton scattering at MAMI. Comparing the results on the proton charge radius from these two complementary measurements performed with very similar techniques will allow to probe interpretations of the proton radius mismatch to be caused by lepton flavour effects.

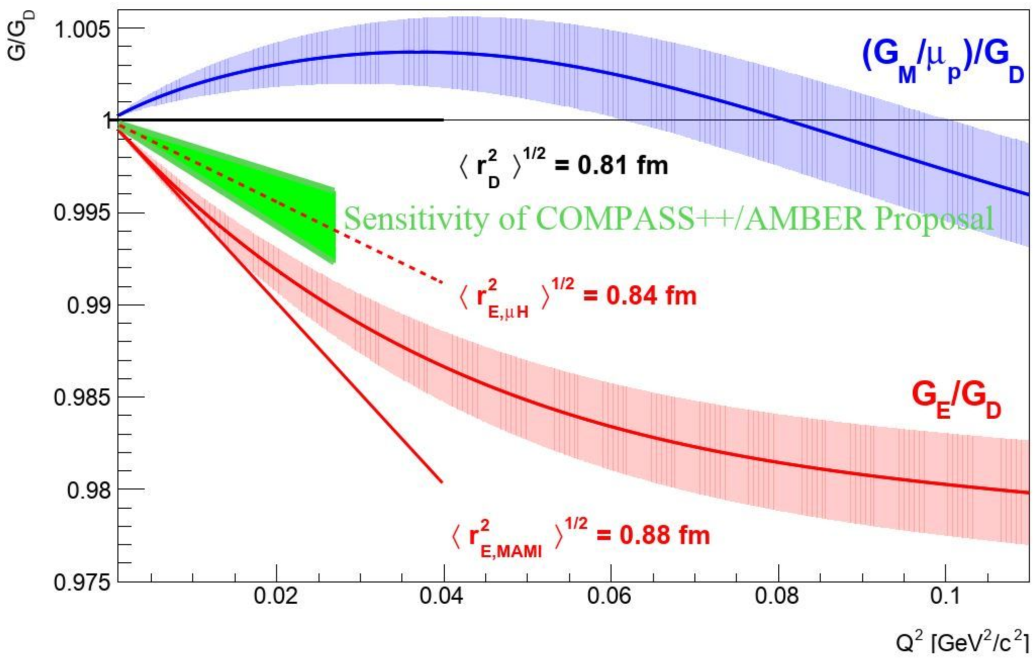

Figure 1: The ratio between the electric form factor of the proton and its dipole formula. The sensitivity of the proposed COMPASS++/AMBER measurement is shown as a band around the line corresponding to a proton charge radius of 0.84 fm.

The measurement will employ a time-projection chamber filled with pure hydrogen up to pressures of 20 bar, which serves at the same time as a target and as detector gas. The high-pressure (up to 20 bars) hydrogen TPC (see Fig. 2) will be built for the proton-radius measurement following a design similar to that used for the electron-proton scattering experiment in Mainz. The main difference is the length of the active target region: the Mainz version has one 400 mm long drift cell, the new COMPASS++/AMBER TPC will have either two or four drift cells of 400 mm. The TPC will operate in ionisation- chamber mode, i.e. with no gas amplification. It will accurately measure the recoil-proton energy, the recoil-proton angle and the coordinate of the interaction point along the beam direction.

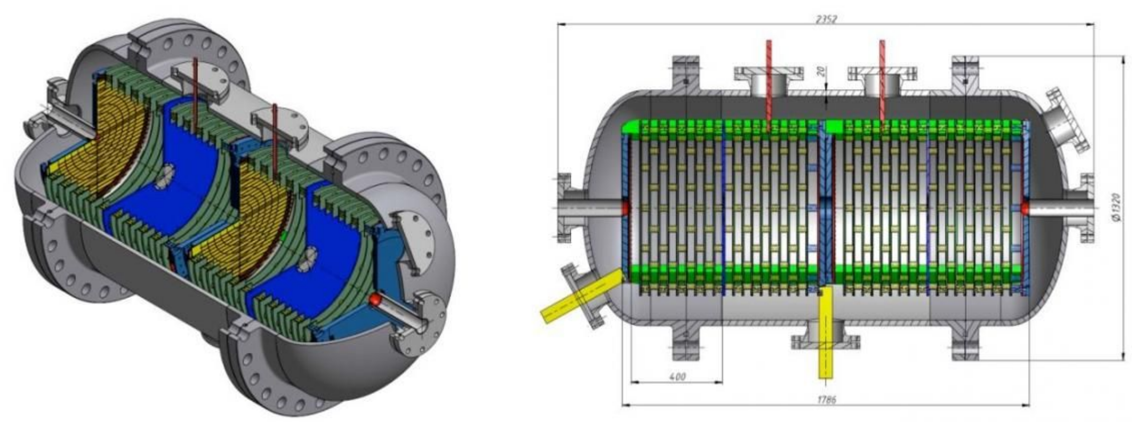

Figure 2: Engineering design for the four-cell hydrogen TPC

Drell-Yan and J/ψ production using the conventional M2 hadron beam

The experimental determination of the meson structure remains a long-awaited and critical input to theoretical efforts that seek to explain the emergence of massive composite hadrons, including the large mass difference between pion and proton. A major step forward in the determination of the nearly unknown pion and kaon parton distribution functions is the main objective of the planned measurements, which will also provide benchmarks for testing recent predictions of non-perturbative QCD calculations performed on the lattice or in the framework of the Dyson-Schwinger equations. At medium and large values of Bjorken-x, a quantitative comparison between the pion and the kaon valence-quark distributions will become possible. At smaller values of Bjorken-x, improved knowledge on the onset of sea-quark and gluon distributions in the meson will help in explaining the differences between the gluon contents of pions, kaons and nucleons, and shed light on the mechanism that generates the hadron masses.

In order to determine the shape of the sea-quark distribution in the pion and better constrain the region of phase space in the Bjorken-x variable corresponding to corresponding to $x_\pi > 0.1$, data will be collected with pion beams of positive and negative charge impinging on a light isoscalar target. Figure 3 shows accuracy estimates for the ratio $\Sigma_{sea}/\Sigma_{val}$ as a function of x_π, in the dimuon mass range $4.0 < M_{\mu\mu/}(GeV/c^2) < 8.5$, which will be accessible with a good mass resolution thanks to new vertex detectors. The curves labelled SMRS represent the predictions for three possible contributions of the sea quarks to the pion momentum, ranging from 10% to 20%. The three different assumptions for the pion sea yield increasingly different predictions for x_π values below 0.5.

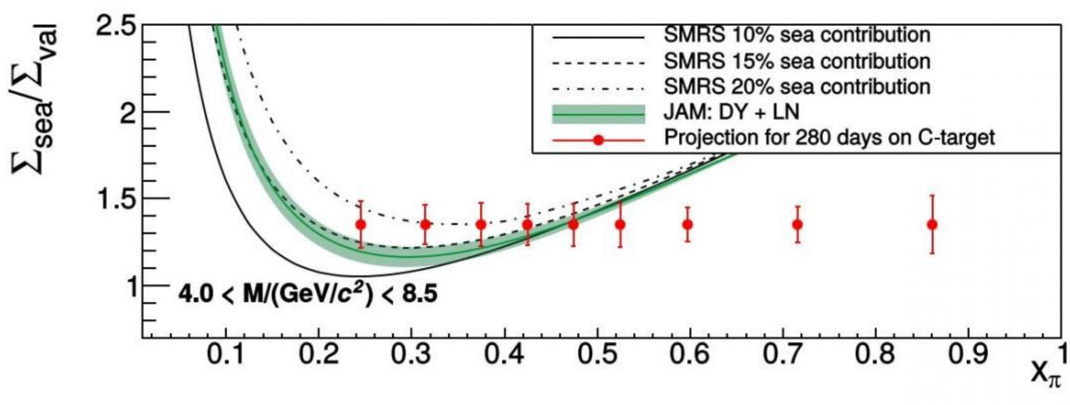

Figure 3: The ratio $\Sigma_{sea}/\Sigma_{val}$ as a function of x_π, for three different sea-quark distributions (10%,15% and 20%). The shown statistical accuracy is expected when using the foreseen COMPASS++/AMBER data-taking conditions.

Furthermore, an analysis that simultaneously accounts for the differential cross section and for the degree of polarization of the produced charmonia resonances is expected to provide stringent experimental constraints on their production mechanisms. Hence J/ψ production provides an alternative access to both quark and gluon distributions in the incoming meson. In parallel to meson-structure measurements, the availability of heavier nuclear targets in the setup will allow the study of cold nuclear effects such as nuclear PDFs and parton energy loss.

Measurement of proton-induced antiproton production cross sections

The purpose of this experiment is the measurement of the antiproton production cross sections in proton-proton and proton-^{4}He scattering for projectile energies from several ten to a few hundred GeV. In combination with similar measurements by LHCb in the TeV range, the COMPASS++/AMBER measurements will provide a fundamental data set that is expected to allow for a significantly higher accuracy of the predicted natural flux of antiprotons in the galactic cosmic rays. This is of great importance as the indirect detection of dark matter (DM) is based on the search for products of DM annihilation or decay, which are expected to appear as distortions in the spectra of rare cosmic ray components like positrons, antiprotons, or even antideuterons. The new data set will thus substantially improve the sensitivity of existing (and future) very accurate AMS antiproton flux measurements to DM signals, which is presently limited by the poor knowledge of the antiproton production cross sections.

In order to be able to profit from the AMS-02 high-precision data, a similar accuracy has to be achieved in the computation of the antiproton source term for all the production channels. Figure 4 reports the extrapolated AMS relative uncertainty on the antiproton/proton ratio. The collection of new data using a proton beam with energies ranging between 60 and 280 GeV in conjunction with a ^{4}He (or H) target would allow to extensively characterise the antiproton production spectrum. This is a key point to derive and/or constrain antiproton production models, which in turn may lead to a further decrease in the overall uncertainty on the antiproton production cross section.

The existing M2 hadron beam line with its momentum range between 20 and 280 GeV/c is an ideal place to perform this measurement. The double-differential antiproton production cross section will be measured using the spectrometer in EHN2 equipped with liquid-hydrogen or liquid-helium targets and using the antiproton-identification capabilities of the RICH detector. Measuring for several beam momenta the cross section in 20 bins each for antiproton momentum and pseudorapidity, a 1% statistical uncertainty will be reached for the cross section with an anticipated point-to-point systematic uncertainty of less than 5%.

RF-separated beams

A study of a possible enrichment of desired particle species in the M2 beam has been launched by EN-EA in the context of the Physics Beyond Colliders Initiative.

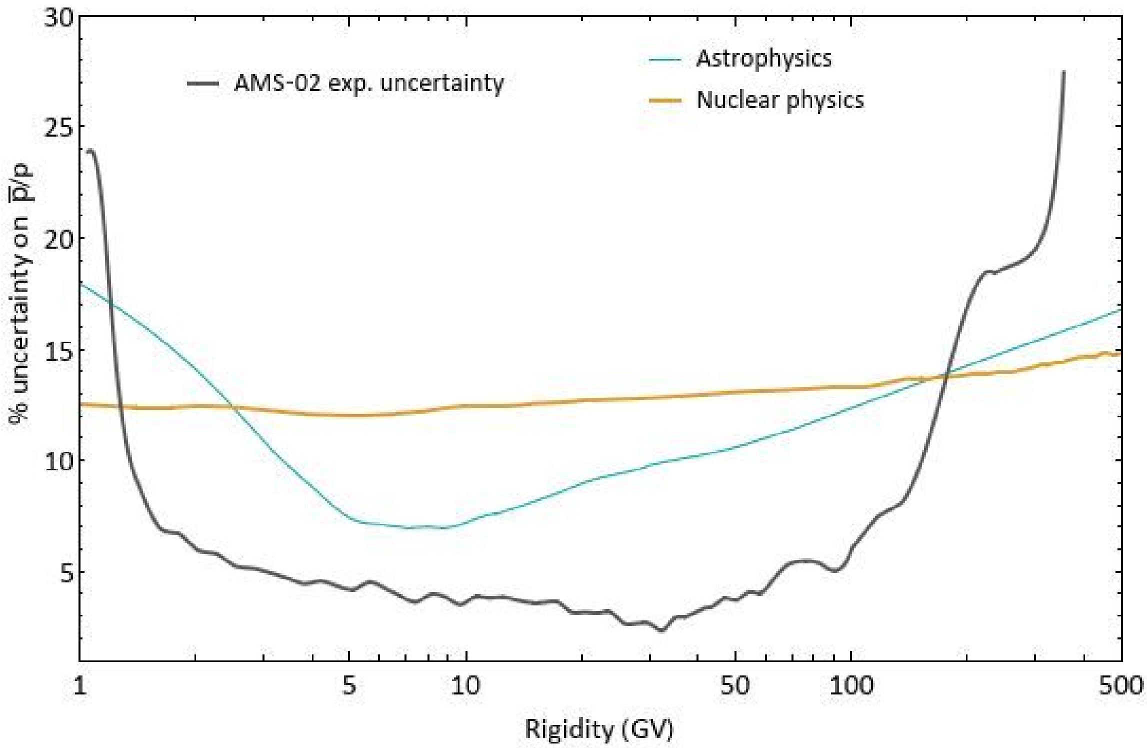

Figure 4: Relative uncertainty afflicting the prediction for the p̅/p ratio, shown in dependence on the rigidity p/Ze (expressed in GigaVolt). In light blue the up-to-date astrophysical uncertainty (based on AMS-02 data analysis), in dark yellow the mean of the nuclear physics uncertainties. In black for comparison the AMS-02 measurement uncertainties as reported in [2]

While alternative techniques can be employed for particles at lower energies, the method of RF-separation is the only effective way to provide the desired high-purity kaon and antiproton beams in the M2 beam line. The method of RF-separation was first employed at CERN in the 1960s based on ideas of Panofsky and Schnell and it is based on exploiting the different velocities of particle species in a beam with defined momentum. As displayed in Fig. 5, two dipole RF cavities (RF_1 + RF_2) with frequency f are implemented at a given distance L. The transverse kick of RF_1 is either amplified or compensated by RF_2 depending on the phase difference that is given by the difference of velocities of the various particle species. For two species i (i = 1, 2) with masses m_i and velocities β_i, this quantity reads $\Delta\Phi = 2\pi(Lf/c)(\beta_1^{-1} - \beta_2^{-1})$. In the limit of large momenta, ΔΦ can also be expressed as a mass difference between the two species at the beam momentum p.

For kaons as wanted particles, the phase difference could be chosen at $\Delta\Phi_{\pi p} = 2\pi$, which results in $\Delta\Phi_{\pi K} = 94^{\circ}$. This means that the kick for both protons and pions would be compensated by

RF2 and they would be absorbed in the beam stopper. The kaons would receive a close-to-maximum transverse kick and mostly go around the stopper. For antiproton beams, the phase difference could be chosen at $\Delta\Phi_{\pi p^{-}} = \pi$, which results in $\Delta\Phi_{p^{-}K} = 133^{\circ}$ and $\Delta\Phi_{p^{-}e} = 184^{\circ}$. In this case, the antiprotons would receive an acceptable deflection while electrons and pions are dumped effectively.

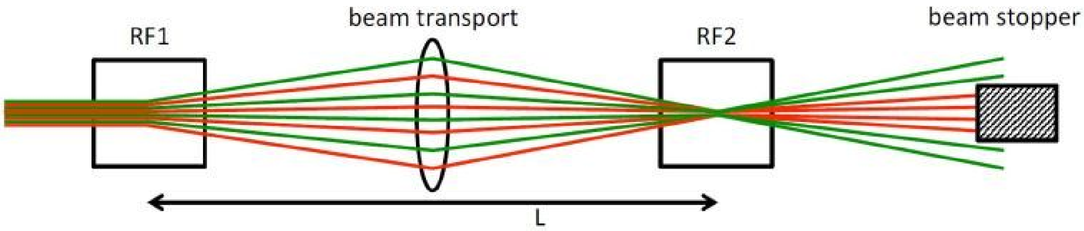

Figure 5: Panofsky-Schnell method for RF-separated beams. The unwanted particles (red) are stopped by a beam stopper while the wanted particles (green) receive a net deflection by the combination of the RF_1 and RF_2 dipole RF cavities out of the central axis, which is sufficient to go around the stopper.

In the current optics, the two FODO sections of the M2 beam have been kept unchanged, which has the benefit of keeping the possibility to change back to the muon beam configuration at a rather moderate cost and within a shorter time compared to a complete change of all M2 beam line elements. Depending on evolving requirements and further optimisation, the option to go back to muon beams could be checked in more detail.

The ”triggerless” DAQ

The development of a data acquisition system for the COMPASS++/AMBER experiment is challenged by diverse requirements imposed by the wide physics program and difference in detector’s compositions, and the requirement of high precision measurements i.e. high statistics and high beam rates. These requirements can be met as the rapid development of technology allows for a transition from the classical trigger based data acquisition to a continuous read-out scheme, in which detector subsystems deliver continuous time-stamped data streams for real-time processing in later stages of the DAQ (e.g. High Level Triggering / Feature extraction) and dead time free storage of the whole data stream.

The development of the Compass DAQ in the past led to a new design, where most of the traditional computers were substituted with FPGAs. This new iFDAQ was introduced for the COMPASS run in 2014 and successive further development has led to a very stable and modular DAQ system, which was successfully used in the last years of the Compass II data taking. For the design of the new data acquisition system it is proposed to adopt a rather far-looking approach to allow the use in a wide range of physics cases and needs in the Compass++/AMBER framework. The logical step is to go to a continuous data acquisition with a digital trigger system, which is tightly integrated in the iFDAQ framework. (Fig. 6).

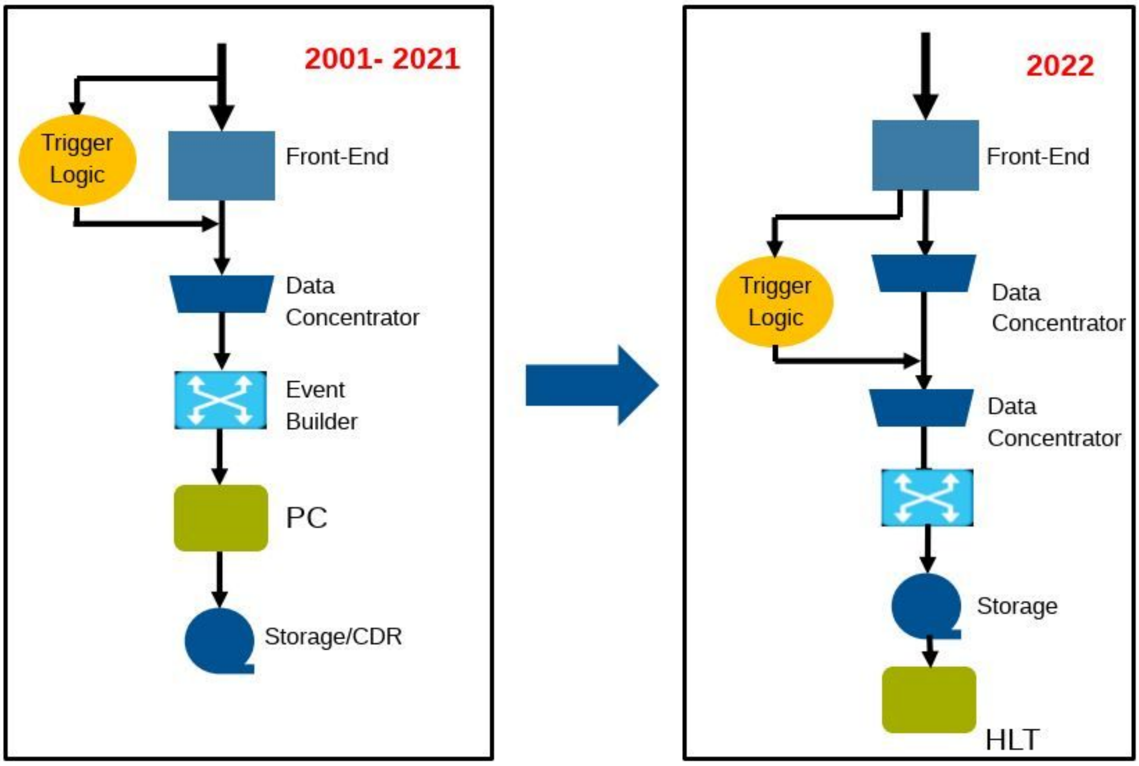

Figure 6: Evolution of iFDAQ.

For this approach all detectors have to be equipped with front-end electronics, which is able to digitize the analog signals of the detectors in real time, perform zero suppression, and stream the data continuously to the next DAQ level. After the front-ends, the data is split into two data streams. Each detector sends a data-stream to the DAQ, where it is buffered until the trigger decision is made. The front-ends of the detectors, which participate in the trigger decision, have a second data stream that is sent to the digital trigger processor and is used to make the selection of data that is later stored to disk.

The trigger processor is a multi stage FPGA unit where the first stage corrects the data with calibrations and builds time correlated event candidates. These so-called "Events of Interest" are then further processed in several stages to work out the trigger decision, according to the different physics programs. The output of the hardware trigger is broadcasted via the Time and Control System to all DAQ modules where the corresponding data are extracted and sent to the hardware event builder, then distributed between online computers and stored on local disks. The DAQ can run in two modes, i.e. the complete not-triggered mode where everything is directly written to disk and the triggered mode where sophisticated trigger algorithms are used to reduce the outgoing bandwidth to 20 Gbit/s, which is the maximum sustained bandwidth to the central data storage at the moment. The mode of operation and the needed reduction factor depend on the physics program and covers a wide range. The modularity of the DAQ enables us to scale the system according to the different requirements.

Future Reading

[1] B. Adams et al., Letter of Intent: a "New QCD facility at the M2 beam line of the CERN SPS" (COMPASS++/AMBER), ArXiv:1808.00848, Tech. rep., CERN- SPSC-2019-003 (SPSC-I-250).

[2] M. Aguilar et al., "Antiproton Flux, Antiproton-to-Proton Flux Ratio, and Properties of Elementary Particle Fluxes in Primary Cosmic Rays Measured with the Alpha Magnetic Spectrometer on the International Space Station" Phys. Rev. Lett. 117 (2016) 091103

[3] B. Adams et al., The COMPASS++/AMBER Collaboration, "Proposal for Measurements at the M2 beam line of the CERN SPS, Phase-1: 2022-2024", CERN-SPSC-2019022, SPSC-P-360, June 5, 2019.

MUonE experiment plans to shed light to the muon anomalous magnetic moment

MUonE

by ***Clara Matteuzzi (INFN), Luca Trentadue (University of Parma)***

PDF version

The long-standing discrepancy between the experimental value and the Standard Model (SM) prediction of the anomalous magnetic moment of the muon, a_μ remains one of fundamental parameters in Quantum Field Theory that still lacks an explanation. The discrepancy could be due to the presence of new physics, or to a lack of precision in the determination of the expected SM value or perhaps to a lack of precision in experimental measurements.

Presently, the most accurate experimental value of the muon anomaly a_μ, has been measured by the BNL E821 experiment with an uncertainty of 0.54 parts per million and disagrees with the most accurate theoretical predictions at more than a 3.5σ level (it can reach 4σ depending on certain underlying theoretical assumptions). The new results expected from the next-generation of (g-2) experiments at Fermilab (USA) and J-PARC (Japan) will reach the impressive precision of 0.14 parts per million.

These extremely precise results will open the possibility of testing with unprecedented precision the internal consistency of the SM at the level of quantum loop corrections. The uncertainty on the leading order hadronic (HLO) contribution to a_μ, a_μ^{HLO}, dominates the SM value prediction and remains the main limitation of this formidable test of the SM. The MUonE collaboration proposes the use of a new method to measure these contributions. This method could further boost experimental sensitivity and shed light to one of the most prominent discrepancies in particle physics.

The MUonE proposal builds on CERN's previous tradition and aims at providing a completely new and independent experimental measurement and determination of the hadronic contributions to the muon anomalous magnetic moment, allowing a direct comparison, and therefore a validation, of the theoretical expectations.

Currently, the determination of HLO contributions is based on the measurement of the total hadronic cross-section in the electron-positron annihilation process at lepton$^-$ colliders in the time-like region (see [1]). The newly proposed method is based on a completely different approach, and, instead of considering the electron-positron annihilation cross-section, it uses a scattering process of muons on atomic electrons, to measure directly the HLO hadronic vacuum polarization [2].

According to this approach the quantity a_μ^{HLO} can be extracted by comparing the measurement of the muon-electron elastic scattering μ-e →μ-e differential cross-section as a function of the momentum transfer *t* in the space-like region, with the theoretical predictions calculated with an adequate precision. To achieve a meaningful measurement, a strong collaboration between experimental and theoretical communities is needed.

The proposed experiment needs a high energy muon beam, covering a region in momentum transfer up to and beyond the value of t = -0.108 Gev^2 , including the region where the hadronic corrections mostly affect the cross-section. (see [2]). The muon beam energy of 150 GeV, available at the beam line M2 at CERN will allow to collect data covering ~87% of the cross-section curve (Fig. 1) whose integration allows to calculate a_μ^{HLO}. The remaining part of the integral (~13%), cannot be reached directly but can be determined by using time-like data and perturbative QCD, or eventually lattice QCD results.

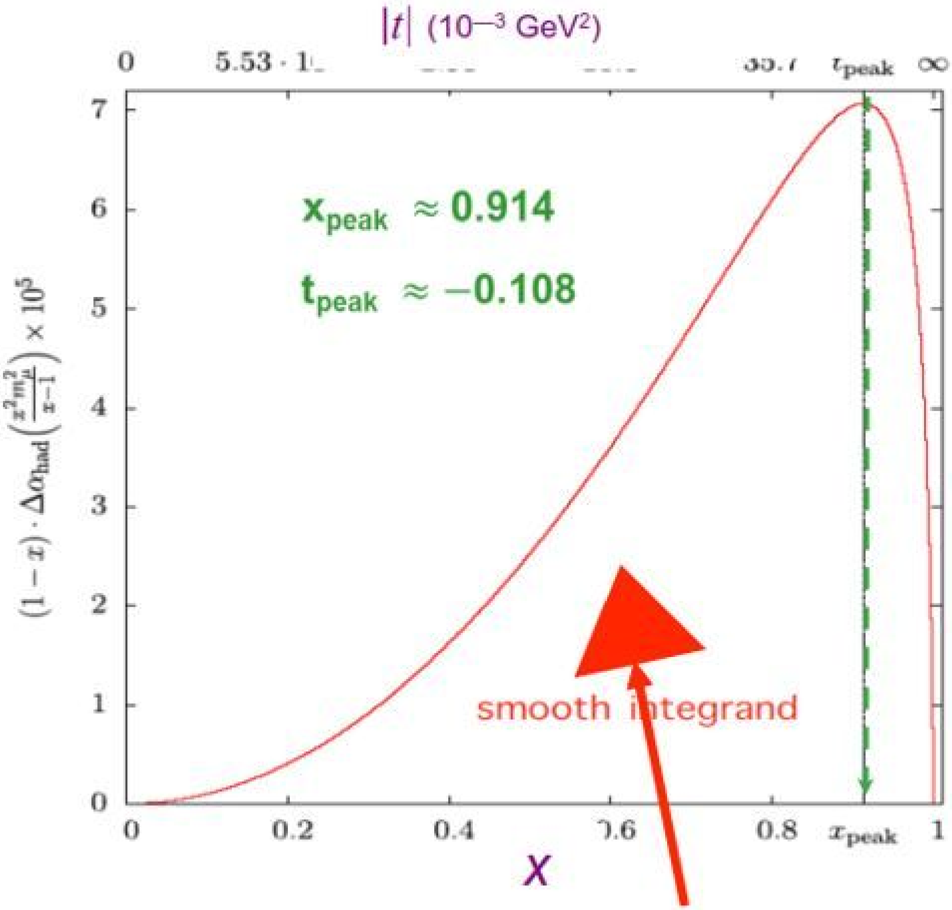

Figure 1. shows the integrand that MUonE plans to measure as discussed in the text.

With a muon beam with an average flux of the order of 10^7 μ's/s as the one present in the CERN North Area complex, a statistical accuracy of the order of 0.3% on a_μ could be reached with few years of data taking. Therefore, the challenge of the proposed measurement is the control of the systematics, both on the theoretical and experimental side, at a comparable level of accuracy.

On the theory side there is an intense research program as part of this project, including important efforts by the lattice QCD community. Calculations are under way to improve the evaluation of the leading order contribution to a_μ, due to the hadronic vacuum polarization corrections to the one-loop diagram, as well as the next-to-leading (NLO) hadronic ones. Very recently, also the next-to-next-to-leading (NNLO) hadronic corrections have been addressed, by computing the insertions of hadronic vacuum polarization diagrams and estimating the hadronic light-by-light contributions.

Moreover, the collaboration has proposed a design for the MUonE detector; a modular system, made up of 40 identical stations, each consisting of a 15 mm thick layer of Be (or ~1.0 mm C) followed by three silicon tracking layers, covering a lever arm of about a meter. The detector is sketched in Fig. 2. The transversal size is small, 10x10 cm, but it is enough to contain the kinematics of an elastic event, due to its large boost. The configuration must provide an angular resolution for the outcoming directions of the muon and electron of better than 0.02 mrad. The tracker will be the heart of the MUonE detector, and the measurement will be based on the two outgoing angles, of muon and electron, and their kinematical correlation.

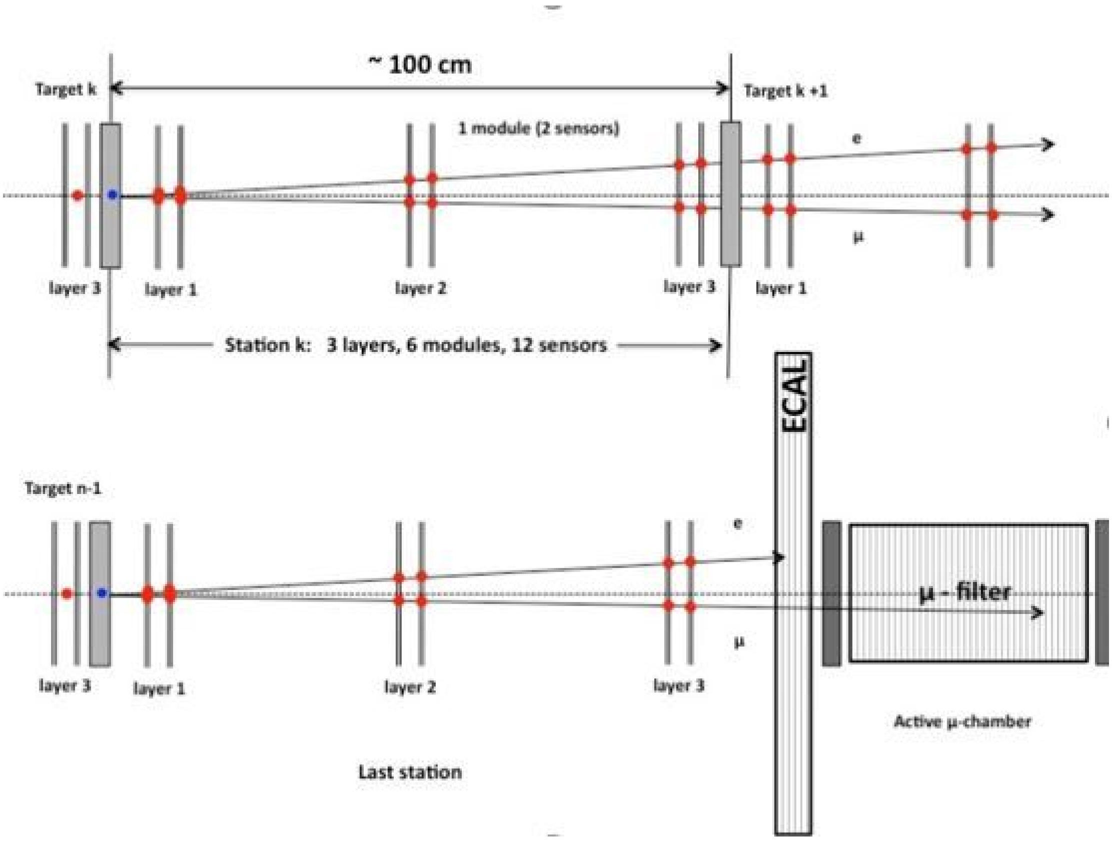

Figure 2. Drawing of the detector of the proposed MUonE experiment.

The design of the detector and a trigger that can address the systematic uncertainties is one of the main challenges for MUonE. The silicon sensors, the electronics and the DAQ architecture are inspired from the CMS tracker upgrade-II project, which has agreed to provide to the MUonE collaboration the necessary 40 stations of the final detector.

Two beam tests took place in 2017 (in H8 line) and in 2018 (downstream the COMPASS detector). In 2017 the aim was to test how precisely one can model the multiple scattering of electrons towards the low energy range. The data taken in 2018, running with muons, aim at studying elastic scattering events and their kinematical correlation. If approved, the experiment should run during the Run 3 period. You can read more details in [3].

Further Reading

[1] F. Jegerlehner, Acta Phys.Polon. B49 (2018), arXiv:1804.07409; EPJ Web Conf. 166 (2018) 00022, arXiv:1705.00263.

[2] G. Abbiendi, C.M. Carloni Calame, U. Marconi, C. Matteuzzi, G. Montagna, O. Nicrosini, M. Passera, F. Piccinini, R. Tenchini, L. Trentadue, G. Venanzoni, Eur. Phys. J. C 77 (2017) no.3, 139

[3] Letter of Intent: the MUonE project