EP Newsletter of the EP department

A word from the Head of the EP department - December 2019

*by **Manfred Krammer***

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

Another year turns to its end. It was the first year of the Long Shutdown 2 with all the accelerators stopped at CERN. This didn’t mean that we were idling in EP. On the contrary, enormous work was done by the experiments to maintain and upgrade their detectors and in the case of ALICE and LHCb a major exchange of several large detector subsystems is taking place. Physics analyses were of course also continuing and the production of new physics results remains on a very high level.

In this edition of the EP newsletter you will find again many interesting articles from all across the department. Apart from the articles giving some insights in ongoing upgrade work of the LHC experiments you will also find news from the large number of smaller experiments at CERN, e.g. in this edition from ISOLDE, BASE and CAST. These smaller experiments are often in the shadow of the big ones, although they are equally challenging and produce very interesting unique physics results. I suggest to take same time to read about their progress.

Exciting things happened not only underground but also above our heads. AMS on the International Space Station is a recognised experiment at CERN. The detector was assembled at CERN and the mission control centre is at CERN Prevessin. A few weeks ago spectacular space walks were conducted to repair the cooling system of this particle physics experiment in space. You will find the full story in this newsletter, with exciting pictures and why and how one of our top engineers in EP was involved.

Winter is here and as the weather gets colder, make yourself comfortable over the Xmas break and read these and other stories.

Let me finish this editorial by wishing you and your families Happy Holidays and a Peaceful and Successful New Year!

Manfred Krammer

EP Department Head

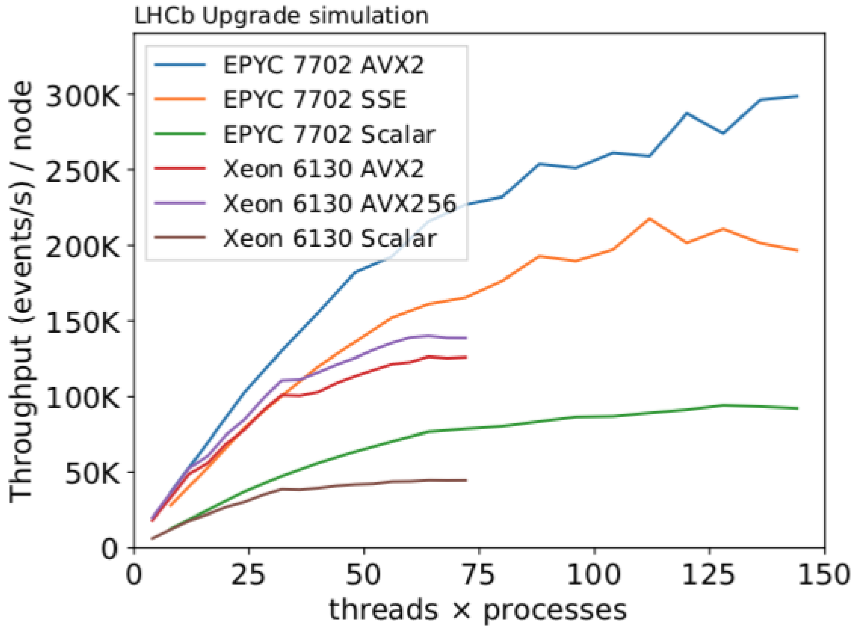
Upgrading the LHCb trigger system

by ***Dorothea vom Bruch (LPNHE/CNRS), Vladimir Vava Gligorov (LPNHE/CNRS) , Alex Pearce (CERN), Sascha Stahl (CERN)***

The LHCb experiment is undergoing a significant upgrade during LS2 in order to allow it to run at a five times higher instantaneous luminosity in LHC Run 3. In order to deal with the corresponding increase in pileup per bunch crossing, most of the LHCb subdetectors are being upgraded to improve their granularity, including a complete replacement of the tracking system, the installation of a new pixel vertex detector and a complete overhaul of the fron-end electronics to allow to read out data at 40 MHz rate. The upgrade of the LHCb trigger is one of the greatest data challenges attempted in HEP. At the heart of this upgrade lie the LHCb's DAQ and trigger system, which will allow the entire detector to be read out at 40 MHz and reconstructed in real time in software using commodity processors for the first time. Reading out and processing 40 Tb/s in real time, the upgraded LHCb DAQ has a comparable readout rate as the full ATLAS and CMS HL-LHC detectors. Although LHCb's software was incrementally optimized throughout Run 1 and 2, it was clear that such an incremental approach would not scale towards Run 3. For this reason the collaboration has since 2015 engaged in a full rewrite of its reconstruction and selection software to enable it to take advantage of modern highly parallel processing architectures.

A real-time detector reconstruction is necessary because LHCb is optimized to study, with high precision, relatively light but abundantly produced particles like beauty and charm hadrons, whose signal rates in the LHCb detector will exceed 1 MHz in the upgrade/next run(s) of the LHC. This abundance of signal has two consequences. First of all, because the signal particles are light, it is not enough to look at calorimeter or muon information in the first trigger level. Instead, LHCb must reconstruct tracks and combine momentum and decay vertex information to select the most interesting 0.5–1 MHz of events for further processing. Secondly, LHCb must then perform a full offline reconstruction of these selected events in the second trigger stage, using a real-time alignment and calibration of the detector. This in turn allows LHCb to select signals with high purity and discard in real time most of the detector information not associated to these signals; a process called “real-time analysis” which was first deployed at the LHCb experiment as a proof-of-concept in Run 2.

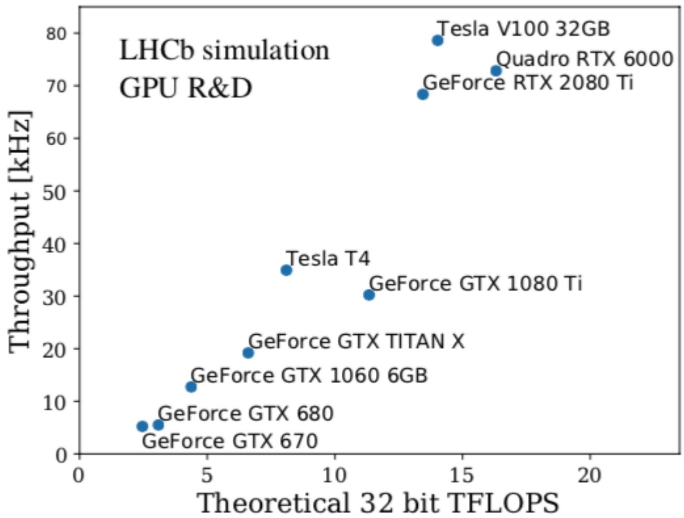
Compared to Run 2, the upgrade software trigger will have to cope with a five times higher instantaneous luminosity and a thirty times higher read-out rate. It became clear early on in the design process that using the available computing resources in the same fashion as in Run 2 will not scale with the same factors. Modern computing architectures get their processing power from an increased amount of compute cores where several threads process the data in parallel (thread-level parallelism), and an increased amount of instruction-level parallelism where the same instruction operates on multiple data simultaneously (Single Instruction, Multiple Data). It was therefore necessary to redesign LHCb’s software framework and scalar algorithms to efficiently utilise such highly parallel architectures.



A common problem with highly parallel computing is the interference of threads. This can manifest itself in two threads blocking each other as they need the same resources, or in one thread undesirably changing the state of another. To avoid these problems LHCb has implemented a simple but effective model: every algorithm must explicitly define all its inputs and outputs, and the algorithm must not have any “state” or memory of whether it was executed before. The requirement that algorithms are stateless makes sure that running the same algorithm on multiple events in parallel does not lead to interference. While thread-level parallelism is handled by the underlying software framework (“Gaudi”), exploiting instruction-level parallelism is specific to individual algorithms and has to be done manually by the developer to be most effective. Existing algorithms are often not suited to this process of vectorization. Because the optimal approach can depend on the specific computing architecture, it is interesting to perform R&D in parallel for different architectures. Putting these concepts together in the reconstruction software has led to a near-linear scaling with the number of physical cores, shown in Figure 1, which is the theoretical best case. This demonstrates that, unlike the Run 2 code, LHCb’s upgrade software can efficiently exploit modern x86 computing architectures.

Alongside optimizing its x86 software, LHCb has since around 2013 also been exploring the highly parallel architecture of graphics processing units (GPUs). The key concepts of multi-threaded many-core x86 programming apply similarly to the GPU architecture, which enabled cross-platform development. In particular, algorithms are designed by data flow in the two cases and the Structure of Arrays (SoA) data layout is ideal whether for access by x86 vector instructions or by GPUs threads. Furthermore, the parallelization levels within one event were explored concurrently for vectorized x86 and GPU algorithms. For example, the reconstruction of tracks in the vertex detector benefited greatly from an exchange of improvements found in the optimal GPU and CPU implementations []. Compared to the x86 architecture, GPUs have a limited amount of memory available (on the order of tens of GB), however because the raw event size at LHCb is about 100 kB this still allows thousands of events to be processed in parallel and does not limit the system. Similarly, the I/O performance of the 3rd generation PCIe bus (16 GB/s) used by current state-of-the-art GPUs was already sufficient to satisfy LHCb's Run 3 requirements. The 4th generation cards coming onto the market now provide significant margin on top of what is needed.

The main tasks of the upgrade first-level trigger are charged particle reconstruction in LHCb's three tracking detectors, muon identification, primary and secondary vertex reconstruction and inclusive selections which reduce the event rate by a factor of between 30 and 60. Because the first level trigger consists of a relatively small number of algorithms that are inherently highly parallelizable, LHCb was able to implement complete and viable first-level triggers on both x86 and GPU architectures. In both cases a few hundred modern CPU servers or consumer GPU cards are sufficient to process the incoming 40 Tb/s data stream and reduce the data rate for subsequent alignment, calibration and processing by the full LHCb reconstruction. Figure 2 shows the throughput for the first trigger stage on various GPU models as a function of their theoretical 32-bit FLOPs performance. Analogously to the earlier CPU plot, this linear behaviour shows an optimal exploitation of the underlying architecture.



Advancing the software while at the same time teaching people these changes and integrating new developers into the team is a challenging process. LHCb has invested a great deal of effort into this since Run 1, with a gradually increased focus on providing documentation, as well as organising dedicated training sessions called [“Starterkits”] for newcomers. In addition, LHCb organizes several times per year so-called hackathons. People of all levels of experience, from total beginners to the core developers, get together to work on the software. Here we use the facilities provided by the IdeaSquare at CERN to create a collaborative and welcoming environment. Discussions in the Red Bus or in the kitchen while having lunch together are always fruitful, and the physical distance of the IdeaSquare from the main Meyrin site protects participants from distractions. The hackathons successfully serve two purposes. First, people brainstorm over solutions to difficult problems and new developments are seeded by these ideas. Second, newcomers learn to work with the software and profit from the direct support of more advanced collaborators. Often the age plays no role, PhD students help post-docs and vice versa.

The successful rewrite of LHCb's software enables our real-time analysis model introduced in Run 2 to continue into the upgrade. In this model, publication-quality analysis is performed in the trigger itself. For the majority of LHCb's physics programme this means [] fully selecting the signal candidate in real-time, and permanently throwing away detector information not associated with this candidate. Such exclusive trigger selections bring inherent improvements in signal efficiency in comparison to relying on inclusive triggers, because a greater number of signal candidates can be recorded for the same available storage space. However, capturing the full breadth of the broad LHCb physics programme means a large number of selections must be implemented. In Run 2, the final trigger stage defined around 600 individual selections. In Run 3, a comprehensive exploitation of the real-time analysis model will result in around 2000 selections running in the trigger simultaneously. These lines must be written by physics analysts, who do not necessarily know the details of the trigger but understand best the tradeoffs in signal efficiency and systematics involved in trigger selections.

Writing such selections involves piecing together individual algorithms into a complete trigger *configuration*. The selected/designed framework used to define this configuration is just as critical to the trigger as the high-performance reconstruction algorithms. It ensures that configurations are reproducible, well tested, that selections do not interfere with each other, and that physics analysts can intuitively understand what the trigger does. Providing an intuitive configuration framework is key in helping physicists go from ideas to implementation in as little time as possible. For this reason, a significant and coordinated effort has gone into a complete redesign of this framework for Run 3. Inspired by the earlier Starterkits, the framework has been documented from the ground up, providing even the least experienced LHCb members with an accessible entrance point. Physics analysis working groups have responded positively and started the effort of writing Run 3 trigger selections in earnest, with over 100 lines already in place. This teamwork will be crucial to ensure the smoothest possible commissioning and startup during Run 3.

The rewrite of LHCb's software, which has gone hand-in-hand with the modernization of its development model, has involved more than 100 physicists and computer scientists over a period of five years. And these efforts are paying off: not only has the reconstruction become many factors faster and uses factors less memory, greatly reducing the cost of the Run 3 processing, but the collaboration even has the luxury of choosing between a first-level trigger implemented on CPUs or GPUs. This effort will also serve as an excellent template for the even bigger challenges of the future LHCb upgrades, which have the ambition of processing over 400 Tb/s of detector in real-time. In this context, the lessons learned by LHCb in cross-architecture development will be particularly relevant to leave the collaboration maximum flexibility to react to future and often unpredictable trends in commercial processing hardware.

Complex series of spacewalks to fix AMS detector

by ***Panos Charitos***

PDF version

The AMS-02 experiment was designed and developed by an international team led by MIT physicist Samuel Ting and assembled at CERN starting in 2003. Perched atop the International Space Station's S3 truss segment, AMS-02 has been hunting for cosmic particles that have traveled from the furthest reaches of the universe. It was originally meant to run for three years without the need for any intervention by the inhabitants of the ISS.

The detector consists of a series of components that record the identity, trajectory and momentum of subatomic particles zipping around the cosmos. Just as visible light allows astronomers to study distant stars and galaxies, these particles—cosmic rays—enable physicists to study the far reaches of the universe. AMS-02 also allows physicists to search for evidence of dark matter, an elusive material that has so far been observed only through its gravitational pull on visible matter.

The AMS-02 experiment was launched to the ISS aboard the Space Shuttle Endeavour's STS-134 mission in May 2011.The experiment was originally designed to run through 2014 and has already survived more than twice that long. During this lifetime, it has collected data from more than 148 billion cosmic rays. The observation of anti-nuclei heavier than antiprotons in cosmic rays would have far-reaching consequences as they might originate from either segregated primordial antimatter or from the annihilation of dark matter particles. Thus, the search for these particles addresses two of the most fundamental questions in modern physics: the baryon to anti-baryon asymmetry in the universe as well as the existence and nature of dark matter, which is assumed to account for about 85% of the matter in the universe and for about a quarter of its total energy density.

While the rest of the detector is still in excellent shape, the pumps for the internal cooling system of the tracking detector have not been functioning properly which motivated the need for an upgrade. Specifically, three of the instrument’s four cooling pumps have failed, they were never meant to be repaired or replaced, which should mean that the AMS-02 would soon be switched off, and retire from its marathon particle-hunting mission. However, the scientific community profiting and learning so much from AMS-02 data was not ready for that.

Therefore, they start planning a repair over the course of several spacewalks. This would allow AMS-02 to continue collecting data through 2030 and continue searching for new physics in a complementary fashion with data from underground and collider experiments. Over four years the AMS-02 team worked at the development and construction of a new pump system to replace the existing one, while the team of astronauts trained at NASA’s Johnson Space Center to perform four spacewalks, each lasting more than six hours. Their training involved a variety of ways to simulate repairs including a large swimming pool called the Neutral Buoyancy Lab (NBL), a suspension harness called the Active Response Gravity Offload System (ARGOS), and virtual reality applications.

Because the AMS-02 detector was not designed to be repaired in space, the CERN-AMS project engineer, Corrado Gargiulo of the EP department, and the NASA team in charge of the operations had to identify the best location for the intervention and carefully design a process that would allow to remove a bulky debris shield, and cut through the stainless-steel cooling pipes without creating safety risks for the crew of the ISS. Treating with objects that have sharp edges in space and having to work around such an area is very challenging. Part of the solution was to develop a set of roughly 25 specialized space tools to be used and stored in the ISS. This mission is considered to be one of the most challenging spacewalks since work to repair the Hubble Space Telescope.

Finally last month, on November 15th, Luca Parmitano, the Italian astronaut from ESA, and his spacewalking partner, NASA astronaut Andrew Morgan, went for their first Extra Vehicular Activity, EVA1. Jessica Meir and Christina Koch, NASA astronauts, supported the duo from inside the Station. They operated the Canadarm2 robotic arm, with Luca fixed at its extremity through his spacesuit boots; they positioned and kept Luca at the exact AMS-02 work sites, on top of the Station's S3 Truss structure, between a pair of solar arrays and radiators. Andrew arrived in the proximity of Luca moving along the ISS Truss, and secured to different ISS handrails. The two astronauts managed to remove the debris shield, necessary to gain access to the main work site (Fig1). Given the size of the shield, the best option was to jettison it, something rarely done - as they couldn’t take it back inside the ISS.

Figure 1: Preparing to remove the AMS-02 detector debris shield and gain access to the main working site.

After EVA1, on November 22nd at around 13:05 CET, Luca and Drew went out again, for the second EVA. The depressurization of the AMS cooling system and the following cuts of the eight stainless steel lines were accomplished through an exceptional successful sequence of operations. The old cooling box with the failed pumps was, in this way, isolated and the cut lines ready for the connection to the new pump system.

Figure 2. During a spacewalk earlier this month, Luka Parmitano carried out of the ISS the box with the new pumps to be installed in AMS-02 (Credit: NASA).

On the 2nd of December, Luca carried out the large box with the new pumps (Fig 2) and, with Drew, started the most critical spacewalk, EVA3. The new box was fixed to AMS-02, then the power and data connectors were mated such to allow CERN-AMS Payload Operations Control Center team to establish the communication and control. Luca and Andrew spent the next hours connecting one after the other the eight tubes to the new pumps, through specifically designed hydraulic connectors.

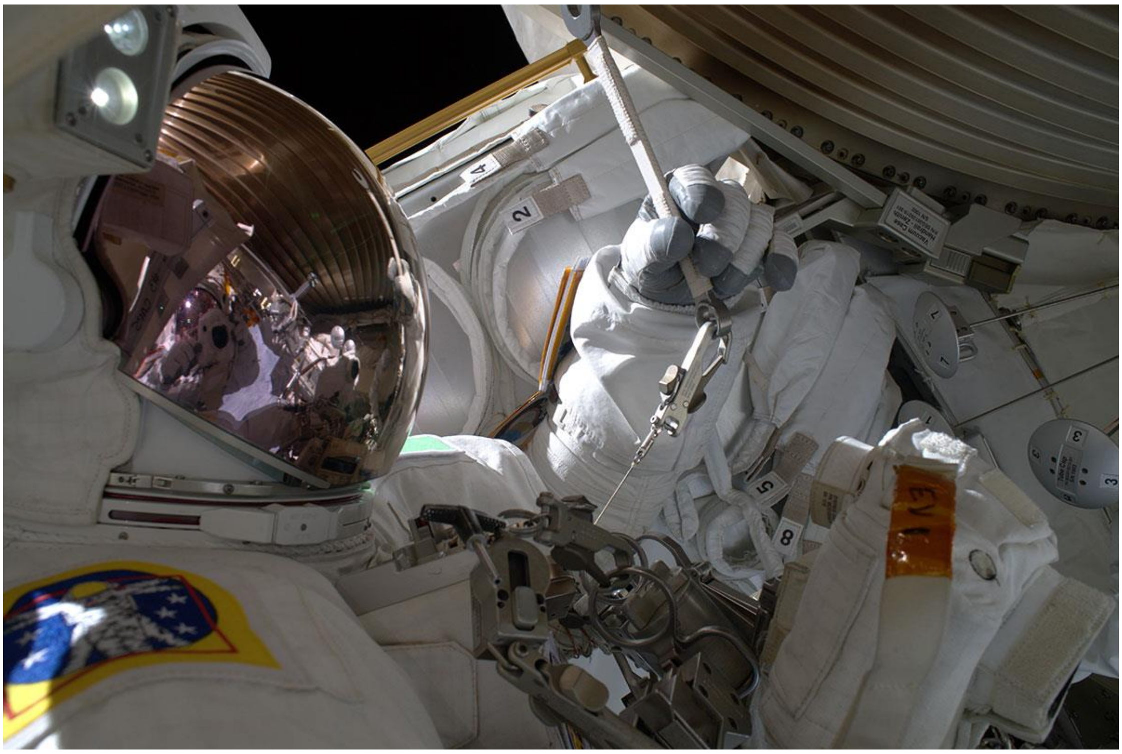


Figure 3. The long process to swage (connect) the tubes is completed using a specially designed 7/8" wrench. (via @Luca Parmitano Twitter account, Credit: NASA).

Such a repair in outer space, that would have been a complex intervention on ground, has been a unique and extraordinary challenge. The difficulties have been overcome by the astronauts' skills supported in real time by experts from the Mission Control Center in Houston, including Corrado, after extensive training and planning on the ground based on the through documentation collected while assembling AMS-02 at CERN. Luca and Drew refer to the diagrams prepared by Corrado as "pure magic".

A final spacewalk is planned in January to check for leaks, and arrange thermal insulation to replace the jettisoned debris shield.

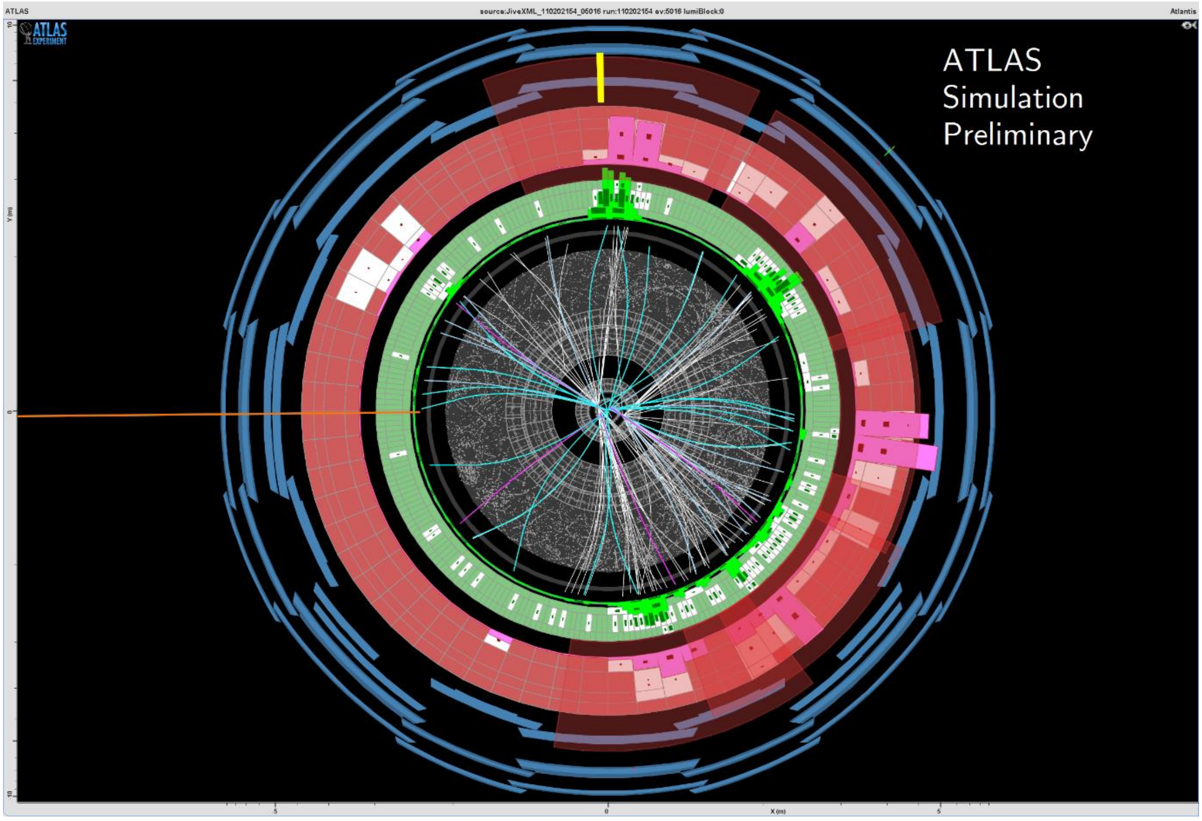
Many challenges have been tackled leading up to and during these spacewalks. When the upcoming EVA is successfully completed, it will allow AMS-02 to continue to hunt for particles to deepen, challenge and potentially change the understanding of our universe for years to come.

The author would like to thank Mike Capell and Corrado Gargiulo for their fruitful comments and suggestions.

Note: The first photo in the article shows a spectacular view from above, through @AstroDrewMorgan 's lens while flying over the Caribbean (Credit: NASA)

Exploring the Lifetime Frontier at the LHC and Beyond

*by **James Beacham (ATLAS Experiment, CERN)***



By any reasonable measure, the first ten years of the LHC have been an unmitigated success. But are we exploring everywhere in our data? The overwhelming majority of the searches for particles beyond the Standard Model (BSM) conducted at ATLAS and CMS, for example, assume that the new particle — such as a new force-carrier like a Z', a squark or gluino from supersymmetric models, a quantum black hole, an exotic cousin of the Higgs boson — after being produced in the proton-proton collision, lives for such a short amount of time that it decays to detectable Standard Model (SM) particles essentially immediately, or "promptly".

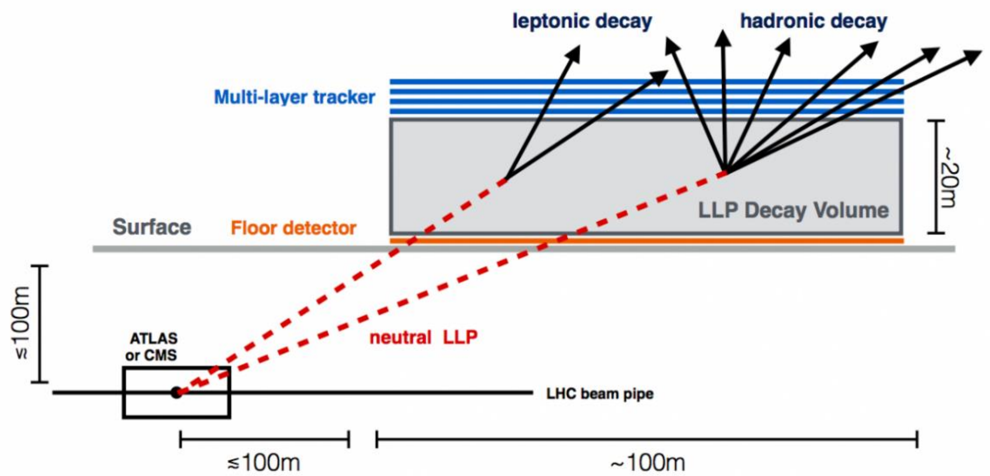
But is this a good universal assumption? What if the new BSM particle lives long enough to drift millimeters, centimeters, or even meters into our detectors before decaying?

At first glance, this might seem baroque, but the SM contains particles that span an enormous range of lifetimes, from the Z boson (which lives for about 10^-25 seconds) to B-hadrons (~picoseconds) the muon (2.2 µs) to the electron (stable). Treating the lifetime of the BSM particle as a free parameter, instead, results in detector signatures very different from those resulting from promptly decaying particles. Unless dedicated triggering strategies are used and special searches are conducted (and indeed new dedicated detectors are built), these long-lived particles (LLPs) could escape our grasp and remain undiscovered.

Searches for LLPs have been conducted from the beginning of the LHC's research program (and previously at Tevatron and LEP), but until about 2016 they had always been considered fringe or exotic-exotic rather than a core component of our research. It was under this set of circumstances that, in early 2016, a few of us independent researchers from ATLAS, CMS, LHCb, and the theory and phenomenology communities formed the LHC LLP Community initiative, dedicated to answering one question: How do we best ensure that we don't miss LLP discoveries for the remainder of the LHC research program and beyond?

After the success of our first mini-workshop in 2016 — and continuing the tradition defined by prior workshops such as "LHC Searches for Long-Lived BSM Particles: Theory Meets Experiment", at the University of Massachusetts, Amherst, in November of 2015, and "Experimental Challenges for the LHC Run II", at the Kavli Institute for Theoretical Physics in May of 2016 — our efforts have grown into an ongoing platform for new ideas, discussion, and brainstorming. The main activities of this initative so far have been a major community white paper, made public in March of 2019, and two workshops a year, the most recent of which was held from 25-27 November 2019, at Ghent University in Belgium, titled, "Searching for long-lived particles at the LHC: Sixth Workshop of the LHC LLP Community".

This flurry of cross-experiment and theory-meets-experiment collaborative activity has nicely tracked an explosion in experimental activity. Not only have the ATLAS, CMS, and LHCb collaborations continued to publish a growing number of BSM LLP searches, multiple separate and dedicated detectors outside of — but still using the collision points inside of — the central experiments have been built or proposed. The first of these was the MoEDAL experiment, which has been running near the LHCb detector since 2015 and searches for LLPs like monopoles.
The FASER experiment — recently fully funded, approved, and to be installed in 2020 — will be a detector apparatus several meters long and about 20 cm by 20 cm wide, positioned 480 m away from the ATLAS experiment near the LHC tunnel to catch any LLPs (like dark photons) that are produced in the middle of the ATLAS detector and travel very close to the beamline but outside of the detector volume. Likewise, the CODEX-b experiment is proposed to be installed near LHCb and the MilliQan experiment (with a working prototype already installed) near CMS. And the MATHUSLA experiment proposal takes this concept to the extreme, designed to be an open-air chamber, 200 m by 200 m by 20 m, instrumented with layers of resistive plate chambers, positioned on the earth's surface above CMS, resulting in an experiment optimally sensitive to ultra-long-lived particles not possible to be detected by any of the other schemes. Similarly, a recent proposal to instrument the service caverns above ATLAS or CMS, called ANUBIS, would be nicely complementary to the existing suite of proposals, and a far-future proposal — for Run 5 in the High-Luminosity era of the LHC — called AL3X would modify the existing experimental setup of the ALICE detector, installing a large amount of shielding near the collision point to reduce backgrounds to negligible, creating an excellent LLP detector.

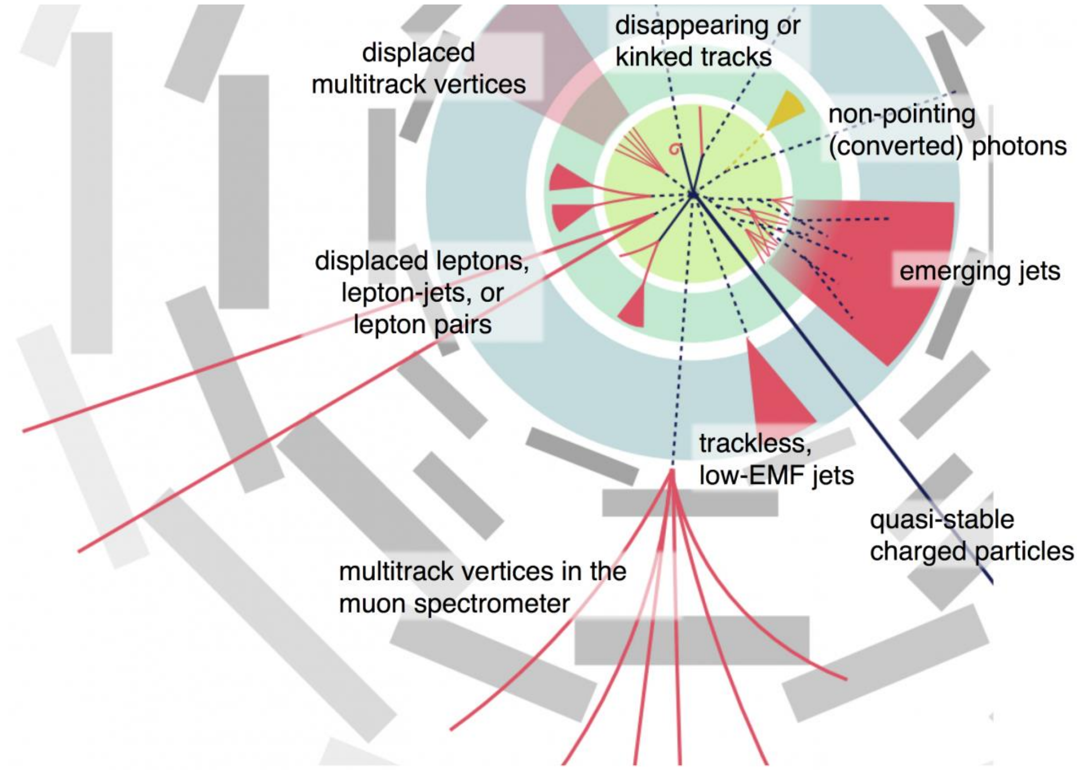


Schematic of the proposed MATHUSLA detector (Source: https://arxiv.org/abs/1901.04040)

By nature, such searches are exploratory and experimental. They're inspired not by any particular theoretical motivation but by our desire to ensure that we don't miss new discoveries based upon quite universal ideas from particle physics and quantum field theory themselves that may give rise to uncovered or undercovered detector signatures. A new particle may be neutral or charged, may have higher or lower mass, may decay in some set of ways to SM particles, and, yes, may have a lifetime that is long compared to the vast majority of prompt searches. These assumptions are generic. The benefits of employing this mindset — mapping out detector signature space rather than theory model — are many, not least of which is that it makes it straightforward for theorists to compare our results to those from other experiments in the context of very simple classes of theoretical models that could help us understand the biggest open questions of physics.

Dark photons could appear in ATLAS, CMS, or LHCb as LLPs, and these dark photons could be similar to those searched for in non-LHC experiments like NA62, Belle 2, APEX, HPS, etc. — and could explain why dark matter is so elusive and point toward a means of discovering it. Heavy neutral leptons could also appear as LLPs, and if they were found at the LHC such a finding could potentially be corroborated by planned experiments like SHiP, DUNE, NA62, and others — and could help explain why SM neutrinos have such small masses and potentially explain the matter-antimatter asymmetry of our universe.

Similar connections exist between multiple other LLP signatures and burning open questions of physics. The exploration of these connections is the task of initiatives like the Physics Beyond Colliders project and the upcoming workshop on feebly-interacting particles, FIPs 2020, in May of next year, that will bring together members of collider, accelerator, neutrino, axion / ALP, dark matter direct and indirect detection communities as well as theorists and phenomenologists to compare and contrast discovery capabilities for very feebly-coupled particles — including LLPs — among multiple experiments. Such collaborative, community-based projects to understand deeply how theoretical considerations relate to experimental capabilities for LLPs and FIPs are a natural continuation of already existing fundamental work. The MATHUSLA physics case document contains a comprehensive collection of the vast array of theoretical frameworks within which LLPs naturally arise. And the Physics Beyond Colliders BSM document contains a similarly comprehensive exploration of the various experiments around the world, existing and proposed, of projections as to their potential to make discoveries in the context of several different classes of theoretical models, or portals.



A schematic showing the variety of possible Long-lived particles signatures (Credits: Heather Russell from the LLP White Paper).

This connection to the theory and phenomenology communities is vital, but the single most important aspect of contemporary particle physics is that theory no longer solely guides us. As experimental particle physicists our duty is to map our detector signature space, not theoretical model space. The future is experimental. This was the organizing principle of the LHC LLP Community white paper. It's a comprehensive document — a combination review paper; set of recommendations for simplified models, triggers, and searches to be conducted; accounting of open discovery possibilities; record of accumulated knowledge; and speculation for the future — that serves as the definitive guide to LLP searches at the LHC. It also contains a unique chapter on dark showers, a relatively unexplored theoretical idea that postulates that the dark sector — undiscovered BSM particles related to dark matter that don't interact with regular matter very much, if at all — could be structured more like our SM quantum chromodynamics (QCD), but with couplings and parameters potentially very different from ours. This dark QCD could give rise to completely wild and unexplored detector signatures, and will present a wonderful set of challenges and opportunities in the future. This framing — that theory models should more generically inform experimental searches in the context of uncovered detector signatures — is a good example of the organizing principle of the white paper.

This is also the organizing principle of the LHC LLP Community workshops, like the one in Ghent in November 2019. Several dozen researchers traveled from around the world to discuss LLP signatures, new results from experiments, possible triggers for LHC Run 3 and the HL-LHC, ways to look for LLPs in astrophysics and cosmology, and, yes, new theoretical ideas for LLPs that, crucially, would give rise to searches or detector signatures that we are currently not covering or that are challenging or impossible to perform with existing experimental methods. This emphasis on stretching our detectors and analysis techniques to their limits in the search for LLPs has also driven one of the most recent initiatives with the LHC LLP Community, exploring machine learning (ML) techniques.

This was a core component of the Ghent workshop, as well, where, in addition to several new independent studies of ML methods applied to LLP searches, there was much progress in utilizing CMS Open Data — 300 TB of CMS data released to the world at large several years ago — to create a community training set for LLP searches, to enable multiple researchers within and outside of the CMS experiment to make progress on this front. This work will be a focus of next year's workshops, currently planned to be held at CERN and in Japan.

The particle physics community is embracing its duty to fully explore the lifetime frontier. This extends to future high-energy collider projects, as well. Several studies have already been performed to investigate the potential to discover LLPs — and to ensure that LLPs as discovery modes are not overlooked — at proposed machines such as the Future Circular Collider (FCC) at CERN, the Circular Electron-Positron Collider (CEPC) in China, and linear colliders like CLIC (CERN) and the ILC (Japan), but many more studies are needed. Mapping the lifetime frontier is a work in progress.

Finding the Higgs boson in the CLOUD

by ***Clemens Lange (CMS, CERN)***

PDF version

It's hard to believe that it has already been more than seven years since the discovery of the Higgs boson. Since then, numerous papers have been published by the ATLAS and CMS collaborations measuring the long-awaited particle's properties in detail. Have you ever wondered whether one could repeat one of the analyses that led to the discovery? The CMS software (CMSSW) release and the corresponding analysis code that were used at that time are based on the Scientific Linux CERN 6 distribution, whose latest release dates back to April 2017. There are only a few publicly accessible machines left that still run this Linux version, and soon none will be available anymore. Does this mean that this groundbreaking achievement will not be reproducible?

Fortunately, the answer is "no". There are still ways to re-run the Higgs boson analyses, and even better, these methods are faster and more robust than the original analyses ever were. This was demonstrated last spring at a conference called KubeCon + CloudNativeCon Europe 2019, and more recently during the CHEP 2019 conference, thanks to a collaborative effort between ATLAS and CMS experiments and our colleagues from CERN's IT department. But let's take a moment to discuss the steps that led to this result.

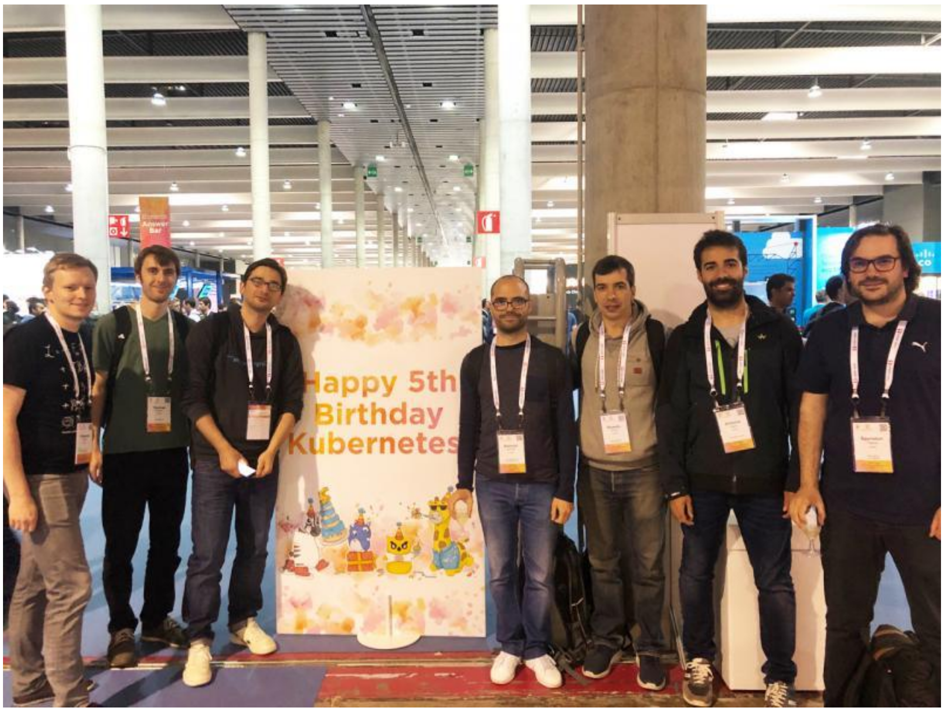
The key to making this possible are so-called software containers. These containers can include anything from a simple web server to a software framework that runs e.g. a machine learning training job. In the case of a physics analysis, such as the Higgs search mentioned above, they contain the needed Linux distribution, the CMSSW release, an extract of the database including the data-taking conditions, as well as the compiled analysis code. A big advantage of software containers in general is that they largely isolate the software from the host system, making their execution not only safer, but also allowing for more uniform operation. All required software, libraries and configuration files are bundled in the container so that they can easily be copied and executed on other platforms. In addition, this enables full reproducibility, as for instance desired by the data preservation efforts of the LHC experiments. The only "input" needed for the execution are the actual data sets.

While most analysts in high energy physics (HEP) do not yet use containers in their daily work, they are becoming more and more common. The CMS collaboration has been using a dedicated set of software containers since a while for the data set production system, and if you are a member of the ATLAS collaboration, you can even submit jobs to the Worldwide LHC Computing Grid to be executed using your own software containers. The HTCondor-based batch system at CERN also supports the execution of containers (see their documentation).

Furthermore, when it comes to machine learning, the software stack is often much more recent than what is available on LXPLUS. There are clear advantages if you can build a container on your computer or using CERN's GitLab installation (see example), and then work in the same environment on any machine. This also facilitates executing the containers in remote data centres, which is often referred to as cloud computing.

Over the last couple of years, containers have become the de-facto standard way of operating in the tech industry. This is largely due to a software called Docker, a set of tools initially released in 2013, which significantly simplified the creation and execution of containers on Linux servers. About a year later, a container-orchestration system called Kubernetes was announced. This platform automates the deployment, scaling, and management of containers, and has widely been adopted in industry.

Recent innovations in these areas are discussed at the KubeCon + CloudNative conference that focuses on the use of Kubernetes and the future of "cloud native computing". KubeCon + CloudNativeCon is one of the largest open source software conferences in the world. The 2019 edition in Europe had about 7,700 participants, and more than 12,000 attended the most recent version that was held in North America.

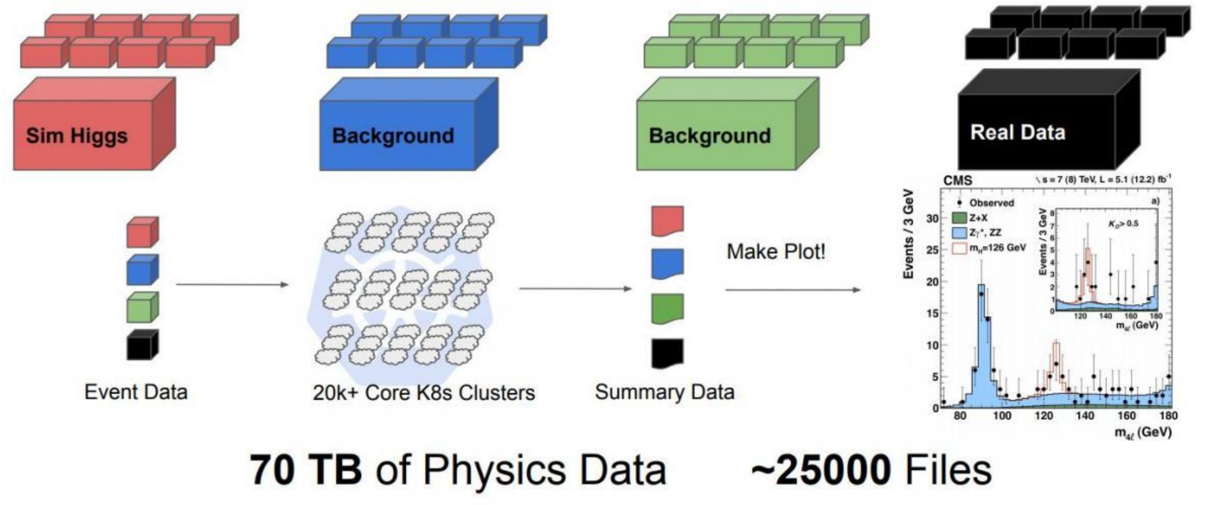


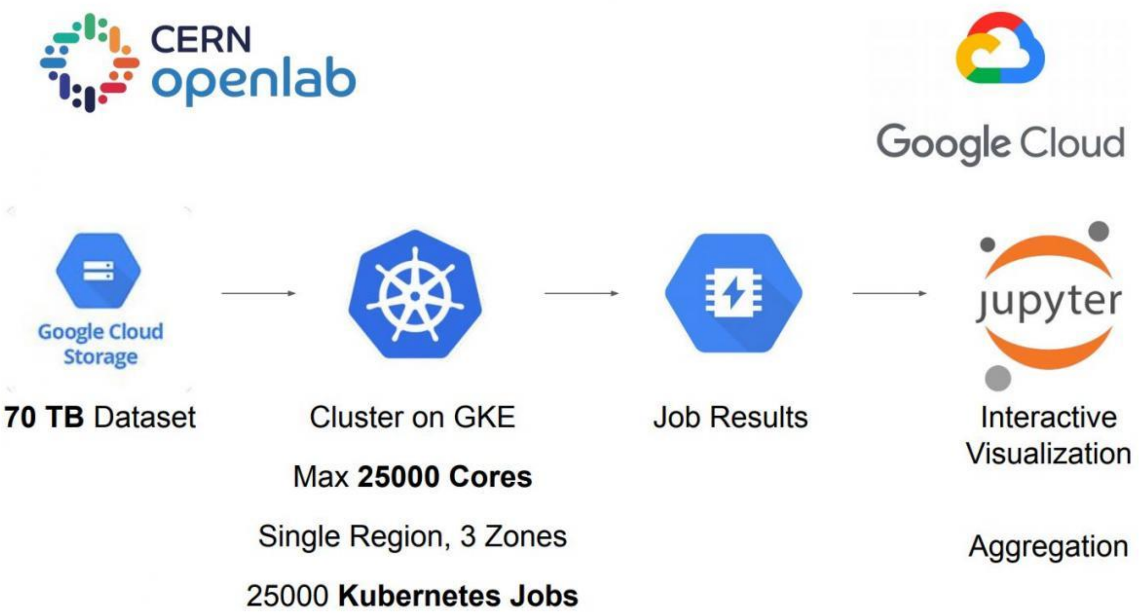
The CERN group at Kubecon Europe 2019, celebrating the 5th birthday of Kubernetes (left to right): Clemens Lange, Thomas Hartland, Lukas Heinrich, Belmiro Moreira, Ricardo Rocha, Antonio Nappi, and Spyridon Trigazis.

With container-related tools available, the question that remains is whether they can realistically be used in a physics analysis. For KubeCon Europe 2019 that took place in May 2019 in Barcelona, Spain, I had joined forces with a few colleagues from CERN (Ricardo Rocha, Thomas Hartland, both IT Department, and Lukas Heinrich, EP Department) to demonstrate that by orchestrating software containers and using the practically unlimited computing resources available in public clouds, a physics analysis that would typically require several hours to days can be performed within minutes.

In order to be able to engage with the predominantly tech crowd at this conference, we had to come up with something special. Not everyone might be interested in a HEP analysis, but the Higgs boson has so far intrigued almost everyone. What better to do than show everyone the Higgs boson mass peak emerge from the data? Luckily, the CMS Open Data project makes this possible! Although the actual analysis code used for the Higgs analyses is not publicly available, the CMS Open Data team provides several analysis examples. One of them is a simplified analysis of the Higgs boson decaying to four leptons via two Z bosons. The reconstruction of this final state is relatively easy—it's just adding up the four-vectors of the four identified final state leptons to yield the Higgs boson mass. However, the challenge is processing the huge amounts of data: about 70

Terabytes of data spread across 25,000 files, which correspond to 50% of the 2011 and 2012 data sets plus the corresponding simulation samples that were openly available at that time. Thanks to a collaboration with Google through the CERN Openlab, we were given credits so that we could scale to 25,000 CPU cores, allowing us to process one file per core, 25,000 jobs running in parallel.





The figures show how the rediscovery of the H ➜ ZZ ➜ 4 leptons channel would look like in a cloud native approach (top) and how the use of standard tools facilitates the transition from traditional HEP infrastructure to the cloud (taken from Lukas Heinrich's and Ricardo Rocha's presentation during CHEP 2019).

Another significant advantage of cloud computing is that you only pay for what you use: it turns out that with only around 1,000 CHF of cloud computing fees one can repeat our demonstration, i.e. process all relevant simulation and collision data sets from 2011 and 2012 in the cloud. This could for instance be used to write out the data into a lighter format, containing only the information required for further analysis and thus allowing to use public cloud services for performing an analysis.

Following the original ideas and after developing some tools, we were invited to give a keynote presentation, representing CERN in front of a huge audience. We were very much relieved that the demonstration worked! The Higgs boson mass peak showed up within a few minutes after starting the jobs and the audience cheered! You can watch the video recording on YouTube. It was a great experience being part of such an endeavour. Also, everyone I talked to was excited to learn about CERN and our work.

As an experimental physicist at CERN, could you do the same? In principle, yes! There were a couple of tricks that we had to play to be able to process the data as quickly as possible, such as copying the files to faster hard disks and streaming the results into an in-memory database instead of storing them on disk, but this is only really an issue when processing Terabytes of data in seconds. In your daily work, you are usually able to run several hundred jobs in parallel using the batch system or the grid. If you put your analysis code into a container, and e.g. store that container in CERN's GitLab container registry, you will furthermore have a self-contained backup of your analysis that is guaranteed to run for many years. Your analysis will be fully reproducible, and reusing it e.g. for a re-interpretation in the future will be straight-forward. Building the containers for your analysis code is actually easier when working in a HEP environment, since you can mount the experimental software such as CMSSW via the CernVM file system (CVMFS) that is available on LXPLUS/LXBATCH and most grid sites. Only when using the public cloud, the full CMSSW release needs to be added into the software container.

There are further implications in using this containerisation approach that strongly align with the principles of Open Science. Once the data are publicly accessible, anyone can repeat and reuse the analysis. The big step forward here is that one does not need the grid or a batch farm such as the ones available only to HEP experimentalists, but can orchestrate the software containers using Kubernetes on a public cloud service. Anyone could rediscover the Higgs boson!

The author would like to thank Ricardo Rocha, Lukas Heinrich, and Thomas Hartland for the excellent collaboration

CMS Open data in use

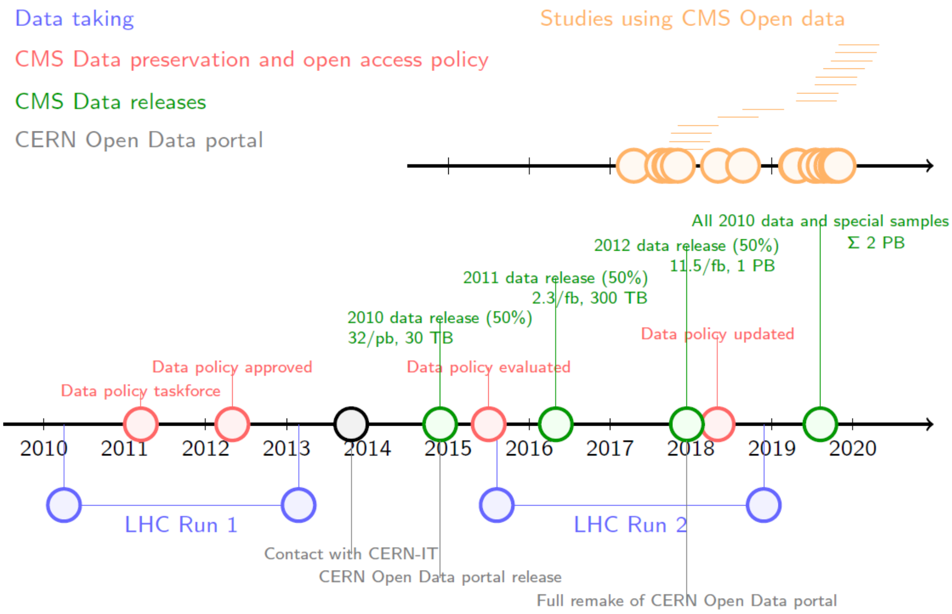
by ***Kati Lassila-Perini (Helsinki Institute of Physics)***

"[...] The release of data could create a community of users which may be nurtured through regular events organized by CMS.[...]"

This is a phrase in the CMS data preservation, re-use and open access policy, which was first approved seven and a half years ago. Now five years after the first release through CERN Open Data portal, and after three other successful releases, the latest of them last July, and with half of the CMS Run1 data available in the public domain it is a good moment to reflect on the interest and outcome that these data have generated.

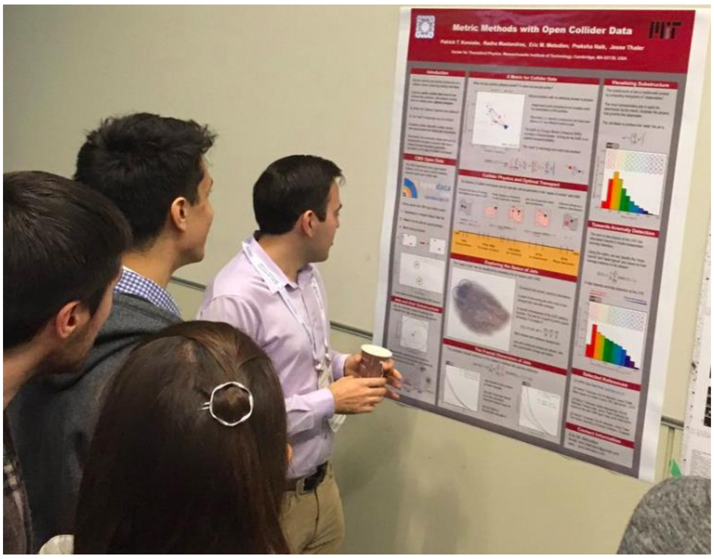
The first publications using CMS Open data started to appear two years after the first release. It was with great excitement and pleasure that CMS physicists learnt about the first study ever done on public collider data: Exposing the QCD Splitting Function with CMS Open Data by Prof. Jesse Thaler and his group in MIT. Even more so as we, in the small CMS Data preservation and open access group, were very much aware that the instructions and documentation on the data usage were far from complete, a fact which was and still is reflected in the subtitle "Nice! But how do I analyse these data?" in our getting started instructions. We were and we are truly impressed by the work done by CMS open data users to understand the complex data and inherent complications due to their experimental nature.

Making data public does not make them any easier to analyse than they are for the members of the collaboration. We all know what it takes for a newcomer to get thoroughly familiar with experimental data: it usually takes a PhD. The first studies based on CMS Open data, however, have shown that using these data and getting new results based on them is possible if the analysis group is as dedicated to the work as analysis groups within the experiment are. Prof. Matthew Strassler nicely captures this in a recent post The Importance and Challenges of "Open Data" at the Large Hadron Collider. Providing open data, on the one hand, and making studies based on them, on the other hand, is expensive in personnel and time, but its value is clear: "[...]There is no guarantee, for instance, that any machine superseding the LHC will be built during my lifetime; it is a minimum of 20 and perhaps 40 years away. In all that time, the LHC's data will be the state of the art in proton-proton collider physics, so it ought to be stored so that experts can use it 25 years from now. The price for making that possible has to be paid."



Since those first publications, the number of studies using CMS public datasets has been steadily growing, as shown in the graphics above. We can track them through citations to DOIs with which all datasets on CERN Open Data portal are delivered. The topics range from physics searches to analysis method testing and algorithm development. Real experimental data in real-life quantities can also be used to demonstrate the computing challenges as described by Clemens Lange in this issue of the newsletter [LINK]. Furthermore, CMS Open data has been used in benchmarking ROOT, the tool, which has a foremost role in the analysis of any experimental particle physics data, as recently shown by Stefan Wunsch in a CHEP contribution. The CMS Open data comes with example work flows and these have been useful test cases for new services for analysis reproducibility such as ReANA.

The main worry often associated with the release of open data is the possibility that external users would get "wrong" results raising the need for additional work by the collaboration to correct them. This has not happened in these five years that open data have been available. Furthermore, authors of studies fully adhere to the open science paradigm and commonly share their code and derived data as done in the recent note Exploring the Space of Jets with CMS Open Data so that their expertise gained by using open data can be put into practice in the experiment.



Eric Metodiev from MIT showing the new methods developed by using CMS Open data in NeurIPS 2019 workshop on Machine Learning and the Physical Sciences in Vancouver, Canada

These studies and the questions we receive from the CMS Open data users are a great motivation for us to constantly improve our archival. Many missing features, necessary for full scientific usage of these data, have been brought to our attention through the support mail of the open data portal. These vary from technical questions when getting started with the virtual image in which the analysis can be done to details of the data selection and physics object reconstruction. Working on these reported issues, we have been able to add features to the portal records and improve the documentation. Frequently asked questions - and their solutions - have been added to the troubleshooting guide. In addition, external users have spotted missing files and mistakes, which we have been able to recover and correct in time.

An Open Data tutorial was held last August for the participants of CERN's International Teachers Programme. The tutorial was coordinated by Kati Lassila-Perini and two summer trainees, Linda Hemmann and Juha -Matti Teuho from Helsinki's Institute of Physics (Credits: Jeff Wiener).

We have a long to-do list to work through to provide a self-contained set of instructions for research use of CMS Open data. Recently, we asked CMS Open data users to provide their feedback that would help us set a priority list for improvements. Top of this list is to provide a complete enough analysis example, which walks the newcomer through different steps in the analysis of experimental data thus complementing the already existing examples. We have set that as a goal to reach before the first workshop for users of CMS open data, planned for summer 2020 at the LPC in Fermilab, to which we are looking forward with great excitement. As Jesse Thaler and Matthew Strassler put it in their note to the editor in Nature Physics, this exchange is a vital part of testing of CMS Open data archival: "[...] scientists can stress test archival methods; any deficiencies are easier to fix now than later".

Besides their scientific use, CMS Open data are in wide use in education and outreach. Having the detailed analysis object data files on the portal together with simplified samples in csv format and an example code to produce such format, makes it straight-forward for anyone to use them in any educational context, from schools to university physics courses. In addition to already available simplified dataset, for example with double-lepton spectrum or the ready-made root files needed for the final plotting in the Higgs to four lepton analysis, anyone can easily produce a simplified dataset specific to a learning goal or context. A collection of Jupyter notebooks for handy use directly in a browser in SWAN for CERN users or in Binder free for anyone is available in a repository. A quick start to CMS open data is provided, as well as a notebook illustrating the Higgs to four lepton analysis. We warmly welcome further contributions to this collection in different languages.

To foster communication with the open data users, the CERN Open data portal team has now opened a discussion forum in https://opendata-forum.cern.ch/. We welcome all open data users to this forum and we hope it becomes a place for exchange of information not only between the users and the support team but also among the user community.

Many new efforts are ongoing in the domain of preserving data and analysis knowledge as reviewed in a recent workshop. LHC experiments are all profiting from common tools and services, which are now being developed at CERN. Different approaches such as reinterpreting searches based on preserved data products in ATLAS as detailed by Lukas Heinrich in his article about RECAST published in this newsletter, are all aiming at maximizing exploitation of LHC data.

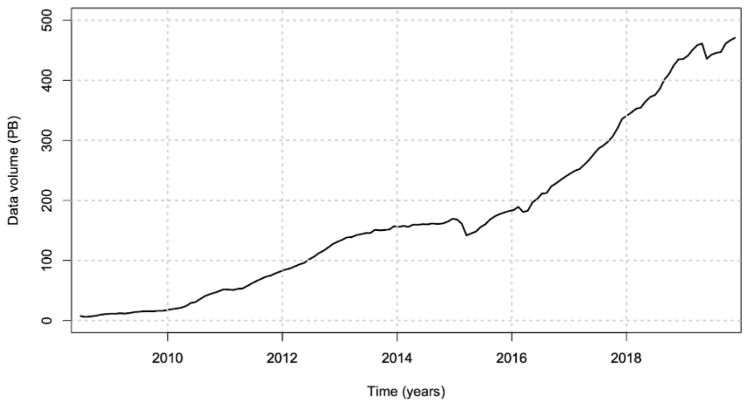
The discussion has now started how to sustainably fund these efforts. For open data, the CMS experiment has lead the way, and we as data providers, the CERN Open Data portal team as a service provider, and the CMS Open data users have shown beyond any doubt that open science with preserved LHC data is possible. As summarized in the note to Nature Science by Thaler and Strassler: The public collider data complements the overall LHC research effort and full publication of the LHC experiments' data is in the best interest of particle physics.

Scientific data management with Rucio

by ***Martin Barisits (CERN), Mario Lassnig (CERN)***

Today's scientific experiments are manifold and diverse in their objectives, size, and workflows. However, one commonality uniting most, if not all, scientific experiments is the creation and analysis of data. Managing these scientific datasets is becoming an increasingly complex and complicated challenge. We have evolved from storing data in single devices, to using storage infrastructures filling entire data-centers, up to today where we are storing the data in numerous geographically dispersed data warehouses, interconnected by massive high-bandwidth networks. But this path is just at the beginning. With the ever-increasing data volume needs of future experiments, such as the high-luminosity upgrade of the LHC, neutrino experiments such as DUNE, or upcoming astro-physics instruments like LSST or SKA, the need for efficient and cost-effective scientific data management has never been greater.

One prominent solution to tackle these challenges is the scientific data management system Rucio. Named after the reliable donkey of the famous Don Quixote novel, Rucio is an open-source software framework that provides scientific collaborations with the functionality to organize, manage, monitor, and access their distributed data at scale. It was designed based on more than ten years of experience with the distributed data management system DQ2 of the ATLAS experiment. While at the beginning the software was principally designed and developed by and for the ATLAS collaboration, it was understood very early that there is a clear need for data management in the big science landscape at large, as well as the potential of a community-driven data management solution. Consequently, Rucio was changed to the Apache open-source license and became a community-driven software project. Rucio was originally put into production for ATLAS in December 2014, following several years of development, integration, and migration effort. Soon after, the Xenon1T and AMS experiments expressed their interest in Rucio and after a thorough evaluation, it was put into production as the principal data management system for both experiments.



ATLAS data volume managed by Rucio

The core motivation of Rucio is to shield the user from the complexity of the distributed infrastructure environments and to facilitate data access in a convenient and efficient way. Since the actual infrastructure is usually heterogeneous and involving technologies from different manufacturers and even commercial cloud providers, Rucio allows to present the data to the user in a federated way, effectively hiding these complications. This gives experiments and organizations the needed flexibility in choosing the technologies best fitting their use cases, given financial constraints. One of the pillars of Rucio is its ability to express data placement and lifetime requirements in a convenient rule-based language. This enables organizations to express their computing models and dataflows with policies that are continuously monitored and automatically enforced on the data. The system design follows the FAIR data principles, thus all data is Findable via a rich set of metadata, Accessible using standardized protocols, Interoperable using qualified references, and Re-Usable. The entire software stack is designed in a horizontally scalable way, allowing organizations to easily scale their deployment over time with increasing data requirements. Major system components, such as storage interaction protocols, interfaces to transfer systems or authentication mechanisms are designed in a pluggable way, allowing communities to expand the software to their needs. Furthermore, Rucio is compatible with numerous database systems to avoid vendor lock-in.

The first Rucio Community Workshop was hosted at CERN in 2018. This two-day workshop marked the kick-off of Rucio as a wider community project and brought together experts from ten scientific experiments to discuss data management needs and the evolution of the Rucio software stack. Since then a second workshop was hosted in 2019 by the University of Oslo and a third workshop is currently being prepared for 2020 at Fermilab near Chicago. The Rucio community has grown to over 30 organizations using, evaluating, and participating in the development of Rucio. In 2018, the decision by the CMS collaboration to adopt Rucio for Run-3 marked a breakthrough for the community project. Other communities evaluating or deploying Rucio, to name a few, include the neutrino experiments DUNE and IceCube, the Belle II experiment, the gravitational wave experiments LIGO & Virgo as well as communities in the astro-physics domain, such as SKA, LSST, or EISCAT_3D. Even communities outside of physics, e.g., the EUXDAT project in the agricultural data domain are investigating Rucio.

2nd Rucio Community Workshop, 28 Feb - 1 Mar 2019, University of Oslo, Norway

Being an open-source software, Rucio is becoming an integrated part of the Open Science initiative. Current developments are aimed to integrate the system into Open Data and Open Access platforms such as zenodo. The long term strategy of Rucio focuses on the scalability of the system in the era of high luminosity LHC and to prepare the system for an area where massive data producing experiments from different sciences share common resources, such as research networks and storage systems. The integration of new infrastructures, especially High Performance computers, is a major objective in the development roadmap since this enables the utilization of these resources across the entire Rucio community. Another objective is extending the support for metadata with the integration of external data stores. Rucio is a central component for the implementation of novel data lake concepts that offer storage workflows to further optimize the data access patterns even across sites and to reduce storage costs.

Rucio started as a data management solution for the ATLAS experiment. It turned since into a community driven open source initiative in which large scientific communities within HEP and beyond strive to tackle the big data challenges of the next generation experiments in a common development project.

Further reading:

Rucio Website - https://rucio.cern.ch
“Rucio: Scientific Data Management” in Computing and Software for Big Science (Springer) - https://link.springer.com/article/10.1007/s41781-019-0026-3

RECAST: A framework for reinterpreting physics searches at the LHC

*by **Lukas Heinrich (ATLAS, CERN)***

On 22 of December 2015 a SpaceX rocket launched towards space delivering satellites to low Earth orbit and then, instead of being lost to the depths of the ocean, the rocket's first stage -- the most expensive component of a rocket -- returned back to earth landing at Cape Canaveral. It was the first time ever such a landing has been achieved, heralding the start of a new era of reusable rockets and more affordable access to space. Since then, the process has been streamlined and rocket landing and reuse has almost become routine. In high energy physics, the ATLAS experiment is pursuing an analogous program, RECAST, in order to make some of its most precious assets -- the data analysis pipelines -- reusable and easily deployable. The program will allow to analyze the ATLAS experiment's dataset more comprehensively and to study previously uncovered physics models.

At the core of the scientific method lies the interplay between theory and experiment: the formulation of a hypothesis and the testing of said hypothesis through experimentation. Here, high energy physics finds itself in a peculiar situation: After the discovery of the Higgs boson in 2012, the Standard Model of Particle Physics is now completed. However, despite its many successes the Standard Model cannot account for many phenomena we observe, such as the existence of Dark Matter, the matter-antimatter asymmetry or the origin of neutrino masses to just name a few. Over the last decades, many new theories have been proposed to explain these phenomena, but they can often only be tested using the data of the few experiments of the Large Hadron Collider.

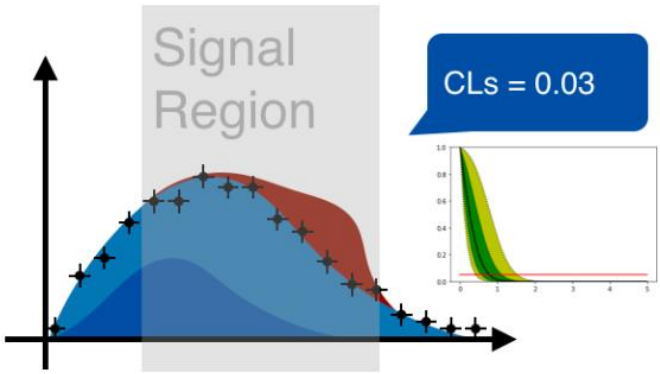
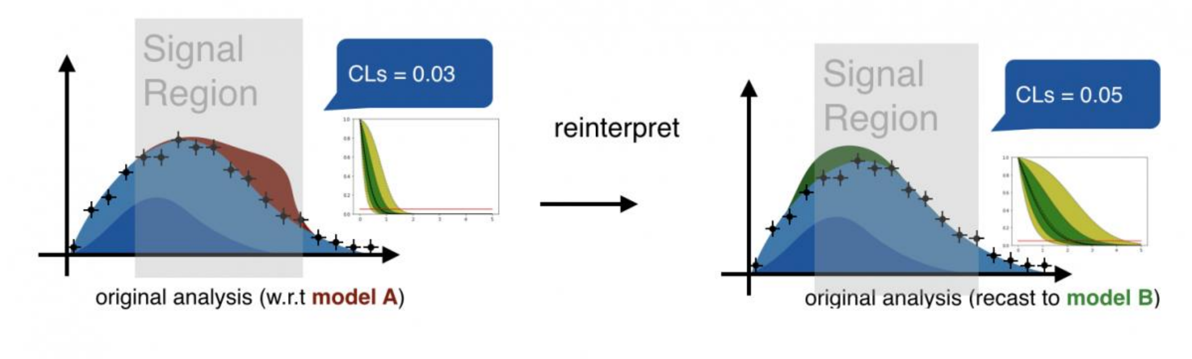


Figure 1: Sketch of an analysis. For a given corner of the dataset, the Standard Model backgrounds are estimated (blue areas) as well as a possible contribution from new physics phenomena. Here, the data (black markers) is sufficiently well described by the Standard Model contributions, and thus the new physics hypothesis is ruled out.

Testing a theory involves a careful measurement of the collisions in a particular corner of the dataset. The analysis teams must calculate precisely how many events would be expected from background Standard Model processes in that "corner" and similarly how many events one would expect from the particular theory of new physics one is interested in. With these calculations in hand, analysts can look at the actual observed data and perform a statistical analysis in order to decide whether the particular theory is favored by the data or rather excluded in favor of the

Standard Model (see Figure 1). In the end such an analysis is defined by a complex software-based analysis pipeline. Most of the work in developing such a pipeline is in carving out the corner in the dataset that holds the most information about the studied theory as well as making the precise Standard Model calculations: if you want to discover new physics, you first need to understand your backgrounds!



Given the effort needed for creating such a pipeline from scratch to study a given theory in detail, the first question one should ask before considering a new theory is: “is it already excluded by what we know from past experiments?” This is especially important given the large range of possible theories of new physics. Here one can employ a powerful method: reinterpretation.

Reinterpretation exploits the fact that a theory’s effects can materialize in a corner of the dataset that was already analyzed with respect to a different theory. If this is the case, most of the work is already done: the data slice and the code to analyze are well-defined, even the Standard Model backgrounds are already estimated! The only remaining task is to calculate estimate the effect of the new theory and perform the statistical analysis to decide whether it’s viable in the face of the observed data or not (see Figure 2).

Software Preservation - Workflows and the Container Revolution

This is where software preservation comes in: to calculate the expected effects of the new theory in the data region studied by an existing analysis, the analysis pipeline must be re-activated to make the necessary calculations on the new input theory. That means the software making up the pipeline must be preserved in a reusable way -- much like the rocket boosters are recovered to be reused later.

In order to preserve software for later (re-)use, it’s not enough to simply archive its code. Almost all scientific software builds on top of other software, so in order to have functional code one not only has to preserve the code itself but also all of its dependencies. This might sound daunting, but with the rise of cloud computing new possibilities are emerging: The concept of Linux Containers, popularized through the open source project Docker defines an easily shareable, executable and self-contained format to package and archive entire software environments. This technology is increasingly used not only in cloud computing but also in software-heavy science domains such as bioinformatics and high-energy physics. Thanks to centrally supported infrastructure developed within the ATLAS experiment and CERN, analysis teams can now easily preserve their analysis code in this format, such that it can be used for reinterpretation purposes.

However, software preservation alone is not enough: one also has to also preserve the knowledge of exactly how to use it in order to be able to extract new science out of the old code. Here, workflow languages, such as CWL, yadage and others, help describe not only the how to achieve individual tasks, such as selecting interesting events, using the preserved software, but also provide -- just like a recipe -- the exact ordering in which the various tasks of an analysis must be carried out.

RECAST

The RECAST (Request Efficiency Computation for Alternative Signal Theories) project combines the scientific motivation for a rich reinterpretation programme at the LHC with the technical capabilities afforded by workflow languages and preservable software environments. The major search groups within the ATLAS collaboration now require new analyses to be preserved using these new tools such that when a new model of physics is proposed by theorists, the collaboration can re-use these archived analyses to derive a first assessment through reinterpretation. The preserved analyses are also expected to be used in a wave of summary studies planned once the data analyses of the second run of the LHC are finalized. For example, a global analysis of a large class of supersymmetric models, referred to as the phenomenological MSSM, allows a detailed assessment of the state of supersymmetry beyond the narrower scope of individual models.

Hunting the Dark Higgs

In Summer 2019, the first fruits of this new type of analysis preservation have been reaped. A group of theorists had proposed a novel way through which dark matter could be produced together, or in association with, a new type of Higgs boson, the “dark Higgs”. The authors note that this new production mode is similar to the association production of dark matter and the Standard Model Higgs boson. In both cases the experimental signature consists of high energy jets from the decay products of the (dark) Higgs and missing energy carried away by the dark matter particles that leave no trace in the detector.

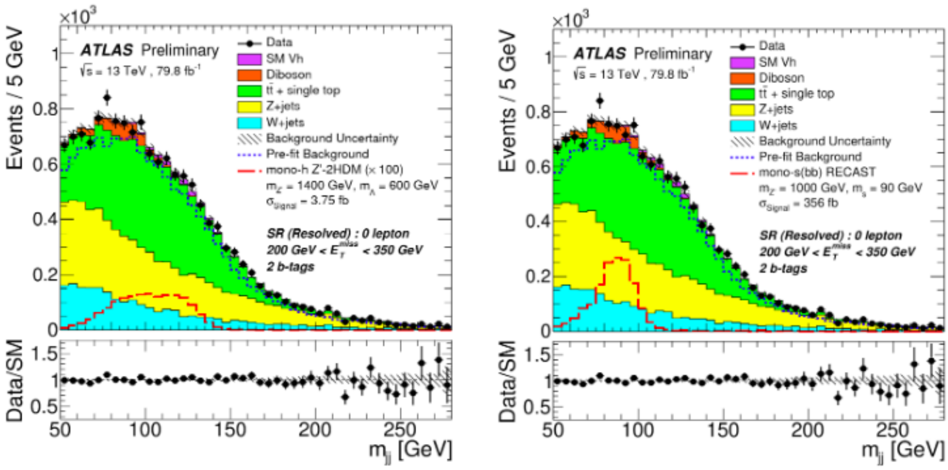


Figure 3: Reinterpretation in Action. Left: The result of the original analysis. The observed data is shown as black markers, while the filled colored histograms are Standard Model backgrounds. The original signal is shown as a dashed histogram. Right: The reinterpreted analysis. Data and Backgrounds remain unchanged, but a new signal component is now being considered.

While there was no dedicated search yet for this new model, the more standard case of associated dark matter production with a Standard Model Higgs had indeed already been searched for in the ATLAS data. The existing analysis was designed in a general enough way to also be sensitive to the dark-Higgs scenario and the analysis pipeline had been archived with the new cloud-computing technologies. Thus a reinterpretation of the existing analysis in the context of the dark-Higgs scenario was possible and even though the analysis was not optimized for the dark-Higgs scenario, the data slice studied by the analysis was informative enough to rule out a range of dark Higgs mass values as seen in Figure 4.

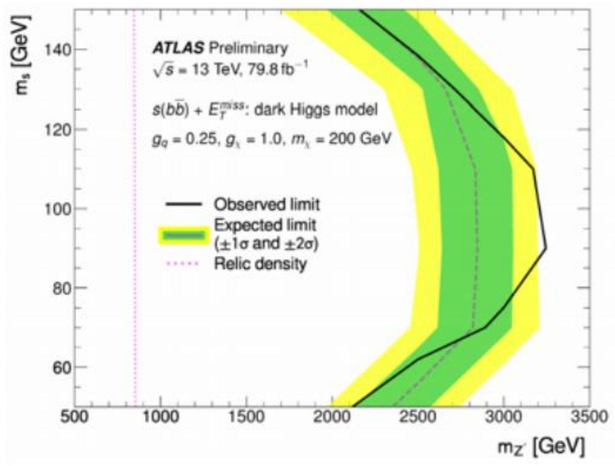


Figure 4: Mass values for the resonance and dark-higgs mass. The values to the left of the black contour could be ruled out through the reinterpretation of an analysis studying dark matter production in association with a Standard Model Higgs boson.

A new bridge between Theory and Experiment

The first result obtained through RECAST is hopefully only the beginning of a new avenue through which experimentalists and theorists can exchange their findings. As with the first landed booster of SpaceX, this first attempt produced a lot of insights not only about the physics at hand but, crucially, also about the process of publishing reinterpretation results in general. As we gain more experience, we hope to streamline the process, so that publishing RECAST results becomes as routine as booster landings have become.

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Finding the best candidates for atomic EDM searches

by ***Peter Butler, Liam Gaffney, Joonas Konki (University of Liverpool)***

The search for hints of new physics Beyond the Standard Model (BSM) calls for a combination of experimental strategies including both direct searches but also a number of very high-precision measurements of certain quantities looking for deviations that could be interpreted in the framework of BSM physics. As experimental techniques advance, sophisticated devices allow for ultra-precise measurements that can probe higher scales where new physics may be at play.

Searches for the permanent electric dipole moments (EDMs) of molecules, atoms, nucleons and nuclei provide powerful probes of charge-parity (CP) violation both within and beyond the Standard Model. The minimal SUSY extension of the SM (MSSM) already contains many possible CP-violating phases, even in its minimally flavour-violating (MFV) version while the maximally CP-violating MFV version, the MCPMFV model has six CP-violating phases, to which may be added the QCD vacuum phase θ_{QCD}. Some CP-violating phases may manifest themselves at the TeV scale and be accessible to contemporary collider experiments, e.g. at the LHC. However, baryogenesis could equally well be achieved via CP-violating phases appearing at higher energy scales, and EDMs have the potential to probe beyond the TeV scale, in particular because the Standard Model Kobayashi–Maskawa predictions for EDMs are quite small. At present the best experimental limits for EDMs of diamagnetic systems are for the neutron and for ^{199}Hg, while the best limits for paramagnetic systems are for HfF+ and for ThO. These limits have placed severe constraints on CP-violating parameters in models extending the SM.

Diamagnetic atoms with octupole-deformed (pear-shaped) nuclei are very important in the search for EDMs, because odd-A nuclei having this reflection-asymmetric shape will have an enhanced nuclear Schiff moment (the r^2-weighted electric dipole charge distribution in a nucleus) that induces the atomic EDM. The enhancement arises from the presence of the large octupole collectivity and the occurrence of nearly degenerate parity doublets in pear-shaped nuclei – two states of the same spin but opposite parity, one of which is the ground state. For such nuclei the sensitivity of the

EDM measurement to CP violation over non-octupole-enhanced systems such as ^{199}Hg can be improved by a factor of 100–1,000.

The number of observed cases where the octupole correlations are strong enough to induce a static pear-shape is small. Strong evidence for this type of deformation comes from the observation of a particular behaviour of the energy levels for the rotating quantum system and from an enhancement in the electric octupole moment. So far there are only two cases, ^{224}Ra and ^{226}Ra for which both experimental signatures have been observed. The presence of a parity doublet of 55keV at the ground state of ^{225}Ra makes this nucleus therefore a good choice for EDM searches, and a programme to look for EDMs in this atomic system is well underway at the Argonne National Laboratory. In contrast to the radium isotopes, much less is known about the behaviour of radon (Rn) nuclei, also proposed as candidates for atomic EDM searches on account of possible enhancement of their Schiff moments.

Therefore the team studied the low-lying quantum states in ^{224}Rn and ^{226}Rn by accelerating beams of these radioactive nuclei to understand their potential for EDM searches capable of probing new physics.

Recent ISOLDE results

In order to determine the shape of nuclei, the rotational model can be used to connect the intrinsic deformation, which is not directly observable, to the electric charge moments that arise from the non-spherical charge distribution. Twenty five years ago Coulomb excitation was applied to the detailed measurements of the octupole shape of ^{148}Nd in the Z ~ 56, N ~ 88 region and of ^{226}Ra in the Z ~ 88 and N ~134 region, but measurements of other nuclei in the latter mass region have had to wait for the development of accelerated beams of heavy radioactive nuclei. This was realised in 2010 when ^{224}Ra beams were accelerated for the first time and ^{220}Rn beams accelerated in 2011. The collaboration published the results on the octupole characteristics of the latter two nuclei in 2013. These ISOLDE measurements and the new measurements discussed here all used the Miniball detector array to detect g-rays following the Coulomb excitation of the radioactive beam by the target, usually a thin foil of an enriched (stable) isotope of Ni or Sn. Miniball is an array of 24 high-purity germanium detectors, each with six-fold segmentation and arranged in eight triple-clusters. The scattered projectiles and target recoils were detected in a highly segmented silicon detector, defining the kinematics of the two-body reaction and enabling the energy of the Doppler corrected g-rays to be measured precisely.

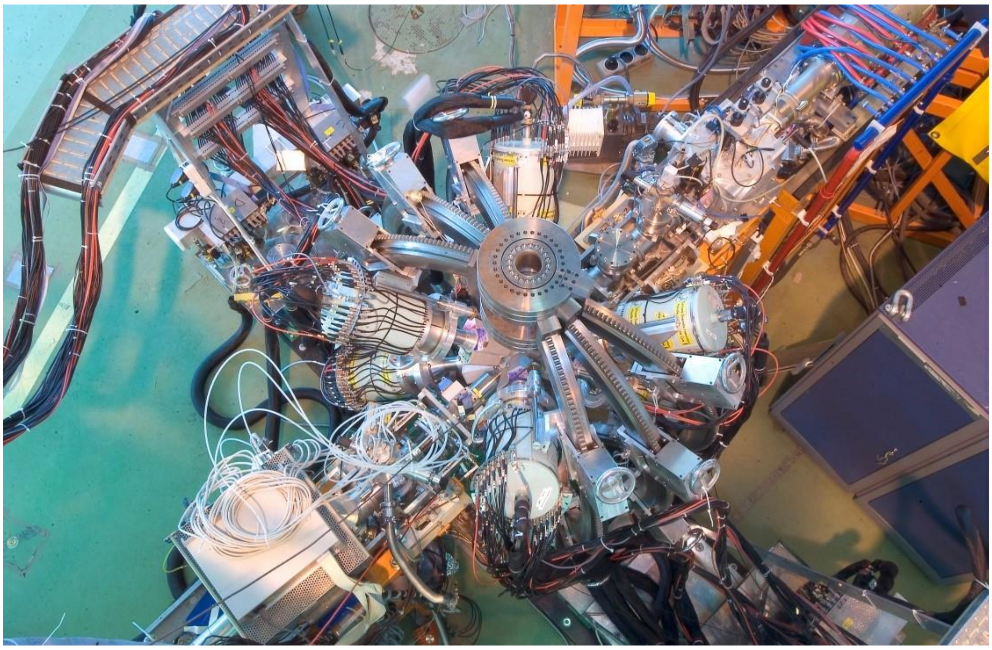


Figure 1: The Miniball spectrometer in the ISOLDE experimental hall.

In the new measurements ISOLDE produced ^{224}Rn (Z = 86, N = 138) and ^{226}Rn (Z = 86, N = 140) ions by bombarding a thick thorium carbide target with ~10^{13} protons s^{-1} at 1.4 GeV from the CERN PS Booster. The ions were accelerated in HIE-ISOLDE to an energy of 5.08 MeV per nucleon and bombarded secondary targets of ^{120}Sn. By looking at time-ordered coincident relationships between pairs of g-rays, their decay sequence and the energies and spins of excited states in ^{224,226}Rn were determined for the first time. To verify the identification technique, the team used another isotope of radon, ^{222}Rn that was accelerated to 4.23 MeV/u. The results from these measurements are shown in the figure. Here Di_x (figure c) is calculated by subtracting from the value of spin for each negative parity state an interpolated, smoothed value for the positive parity spin at the same value of rotational frequency w. For a nucleus with stable octupole deformation the value of Di_x is expected to be zero. For octupole-vibrational nuclei in which the negative-parity states arise from the coupling of an octupole phonon to the positive-parity states, the value of Di_x can approach three if the phonon becomes aligned with the rotational axis. This appears to be the case for all radon isotopes.

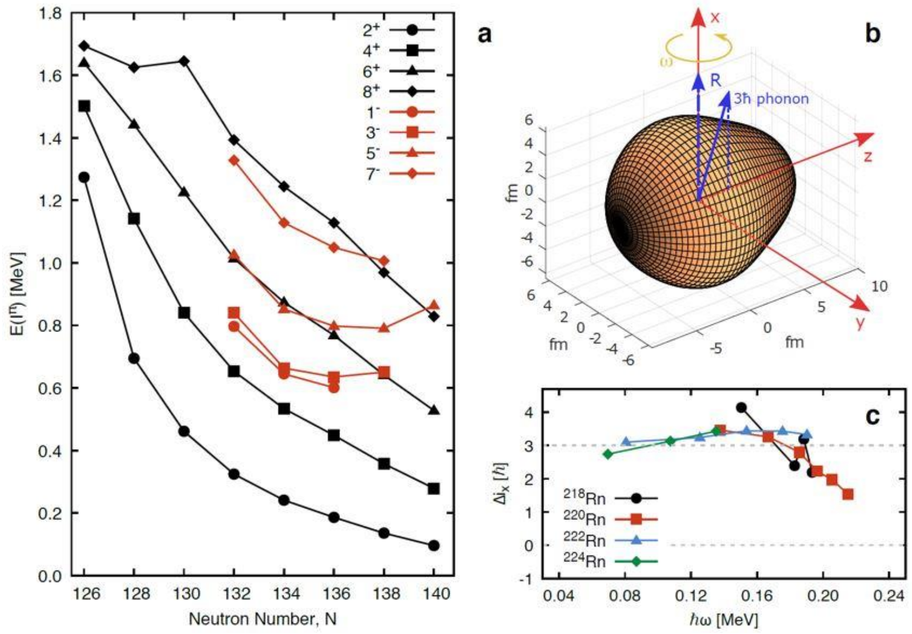


Figure 2: (a) Systematics of the energies for different spins of low-lying positive-parity (black) and negative-parity states (red) in radon isotopes; (b) cartoon illustrating how the octupole phonon vector aligns with the rotation (R) vector (which is orthogonal to the rotating body's symmetry axis) so that I=R+3 and; (c) difference in aligned spin for negative- and positive-parity states in $^{218\text{-}224}$Rn).

The observation of octupole-vibrational bands in the even-even radon isotopes is consistent with several theoretical calculations, which predict that only nuclei with Z > 86 have stable octupole deformation. The study concluded that there are no isotopes of radon that have static octupole deformation, so that any parity doublets in the odd-mass neighbours will not be closely spaced in energy. Therefore radon atoms provide less favourable conditions for the enhancement of a measurable atomic EDM. The next steps will be to attempt to measure the properties of the excited quantum states in odd-A radon isotopes directly populated by β-decay, by taking advantage of contamination-free astatine beams that will be available after LS2. In addition, the collaboration is currently analysing data that will determine the electric octupole strength in ^{222,224}Rn, necessary to determine the Schiff moment in these nuclei vital for any future EDM measurement.

Further Reading:

P. Butler, L.P. Gaffney, M. Zielinska., "Observation of vibrating pear-shapes in radon nuclei' (doi: 10.1038/s41467-019-10494-5): https://www.nature.com/articles/s41467-019-10494-5

Precision timing upgrade of the CMS detector

by ***Joel Butler (Fermilab), Keti Kaadze (University of Kansas), Tommaso Tabarelli (CERN) & Panos Charitos (CERN),***

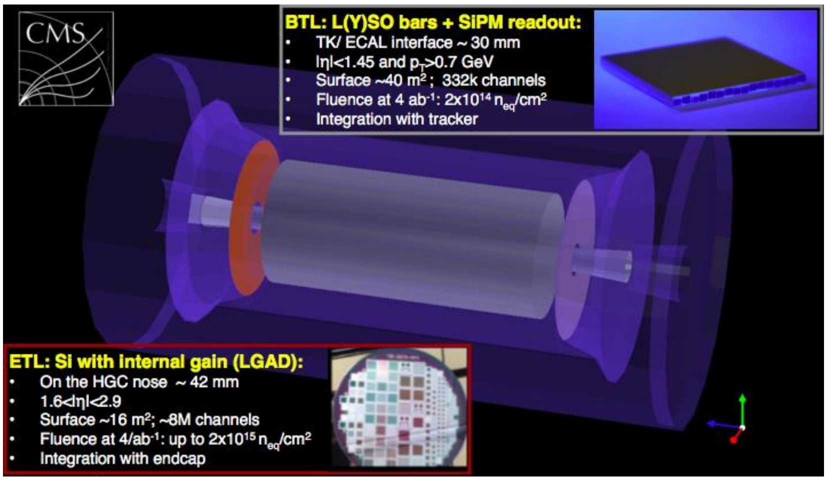
Soon after 2027, the LHC will enter the high luminosity era, known as HL-LHC. It will begin operations at a stable luminosity of 5.0×10^{34} cm^{-2} s^{-1}, resulting in much higher collision rates than currently achievable, but with a pileup of 140 collisions during a bunch crossing. In an ultimate scenario, it will operate at 7.5×10^{34} cm^{-2} s^{-1} luminosity with 200 pileup collisions per bunch crossing. The CMS detector must be upgraded to maintain its excellent performance in terms of efficiency, resolution, and background rejection for all final state particles and physical quantities at these higher rates, increased pileup, and much higher integrated radiation doses. Maintaining the detector's performance in the demanding conditions of the HL-LHC is crucial to extend the direct search for physics Beyond the Standard Model (BSM) and the program of precision measurements to look for deviations from the predictions of the standard model (SM).

In the current LHC conditions, with pileup of 40-50, charged particles from pileup can be effectively excluded using tracking. Specifically, the current pileup mitigation strategy is to remove charged tracks inconsistent with the vertex of interest, usually the one with the highest activity or transverse momentum. However, the contamination of charged particles from pileup scales with pileup density, increasing to >1 vertex/mm, while the increase in the spatial overlap of tracks and energy deposits from these extra collisions will degrade the identification and the reconstruction efficiency for the interesting one. The first step of the response to high pileup is to improve the CMS Tracker by providing smaller detection elements (silicon pixels and strips) resulting in improved spatial resolution so that charged tracks can be assigned to the correct vertices. Even then, however, some significant level of misassignment of tracks to vertices persists.

Another challenge for CMS is to assign neutral showers to the correct vertex and accurately measure their energy in the face of very high pileup. Showers, from neutral particles, e.g. γ and neutrons, are recorded through the energy they deposit in the calorimeters, which in CMS do not have directional information and cannot be associated with specific vertices, confusing the interpretation of the events. Energy from pileup interactions must be removed with special statistical inference techniques, which still suffer from some contamination from neutral energy from other collisions in the bunch.

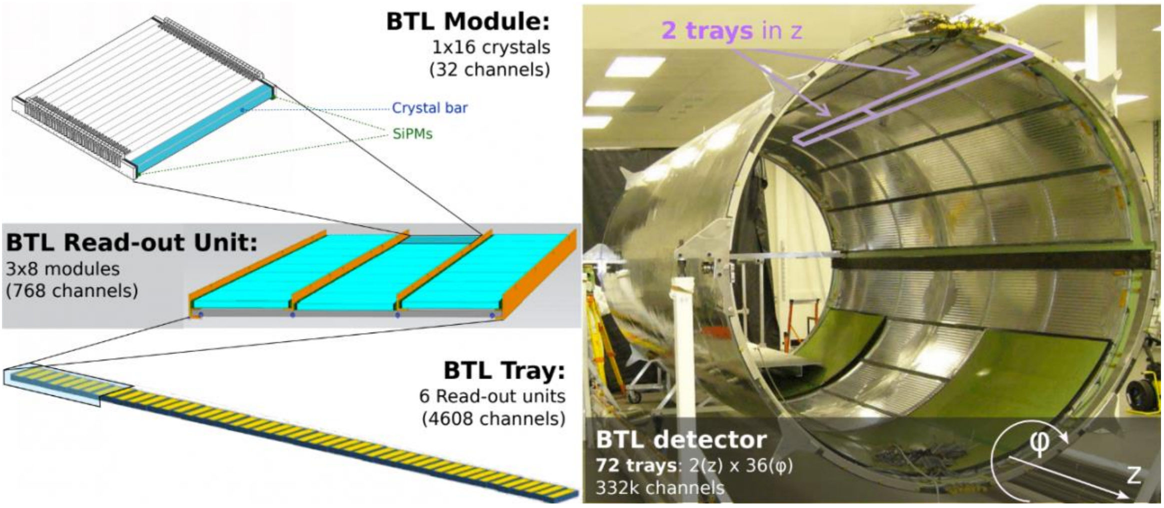
CMS plans to further reduce the effects of pileup by the use of precision timing using the fact that the individual collisions within a bunch crossing are not simultaneous, but instead occur at slightly different times. The proton bunches travelling at the LHC –nearly at the speed of light- still need about a nanosecond to fully pass through each other. This results in a time distribution with an RMS of 180-200 picoseconds, approximately independent of where along the collision axis the interaction occurs. It is this time difference that CMS will exploit to provide additional capability to correctly associate tracks and showers to vertices. Further upgrades, in addition to the new Tracker, are needed: a new dedicated detector, the MIP timing detector (MTD), for precision timing of minimum ionizing particles (MIPs); and electronics upgrades to enhance the timing capabilities of all the calorimeters. The first of these upgrades is the subject of the remainder of this article.

The MTD is a hermetic detector that will surround the entire Outer Tracker and will measure the time-of-arrival of each charged particle. The time resolution is expected to be ~35 ps on all charged tracks at the beginning of the HL-LHC. By the end of HL-LHC operations, after the detector has experienced about 3000 fb^{-1} of collisions, the resolution will be degraded by approximately a factor of two. The proposed design and adopted technologies must meet a number of different technical requirements including radiation and magnetic field tolerance, low deadtime, high granularity (low occupancy), low cost per unit area, and must be far along in their R&D programs to allow us to meet the schedule requirements of the upgrade. Five technologies were investigated and studied in dedicated beam tests and radiation exposures. Crystal scintillators read out with silicon photomultipliers (SiPMs) were chosen to instrument the barrel region of CMS and Low-Gain-Avalanche-Detectors (LGADs), silicon sensors with internal gain in the neighborhood of 10-30, emerged as the best technology for the endcap timing layers. A simplified layout of the MTD is shown in the following image.



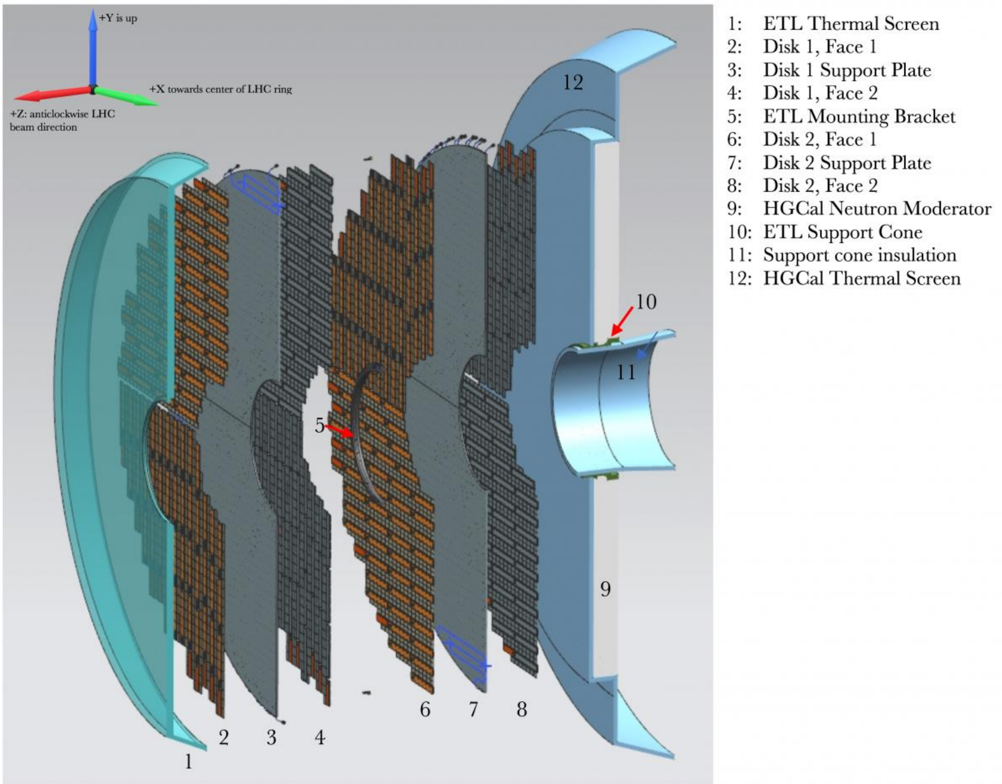
A schematic view of the GEANT geometry of the timing layers implemented in the CMS software for simulation studies comprising a barrel layer (grey cylinder), at the interface between the tracker and the ECAL, and two silicon endcap (orange and light violet discs) timing layers in front of the endcap calorimeter.

The Barrel Timing Layer (BTL) will cover the pseudorapidity region up to $|\eta| = 1.48$ with a total active surface of about 40 m^2. The fundamental detection cell is based on a very small bars LYSO:Ce crystals of 57 mm length, and transverse dimensions of 3 mm width. The crystals' radial thickness vary from 3.7 mm ($|\eta| < 0.7$) to 2.4 mm ($|\eta| > 1.1$), to equalize the slant depth crossed by all particles starting from the interaction point. Each bar is read out by two SiPMs, one on each end, with cross-sectional areas matched to the faces of the bars. They are located at the outer edge of the Outer Tracker support cylinder about 1.1 m from the beams over a length of about 5 m. Groups of 16 bars (32 SiPMs) are read out by a custom ASIC. The average of the time from the two SiPMs gives the time-of-arrival of the charged particle independent of its position along the 57 mm of the bar and the time difference gives an approximate distance along the bar. There are approximately 166,000 bars. The good timing resolution of ~30 ps of the design has been already demonstrated in tests of small prototypes consisting of crystals read out with SiPMs both at CERN and Fermilab. Moreover they were also proven to be radiation tolerant up to a neutron equivalent fluence of 3×10^{14} cm^{-2} when cooled to below −30 °C.



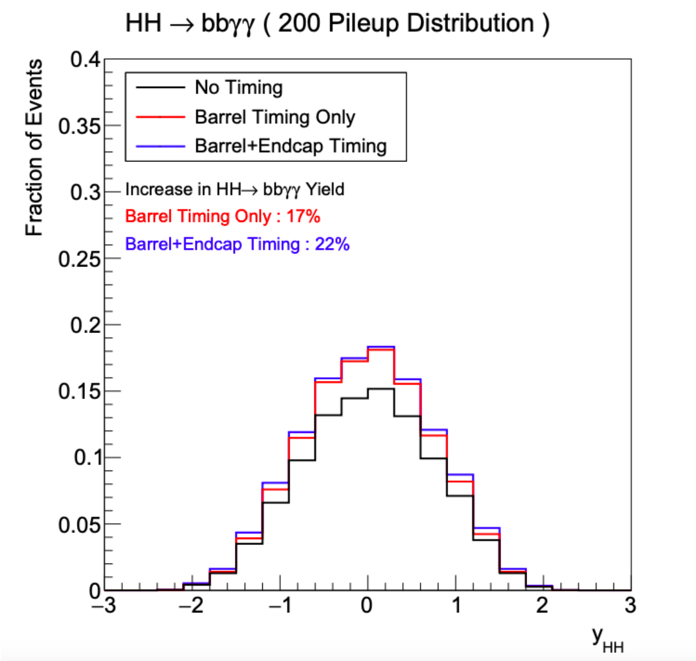
Overview of the BTL showing the hierarchical arrangement of the various components, bars, modules, Readout Units, and trays, inside the Tracker support tube.

The MTD system is closed by the Endcap Timing Layer (ETL) which has disks at each end of the barrel. There are two disks on each end, providing two timing measurements per track. Low-Gain-Avalanche-Diodes (LGADs) provide high time resolution over the pseudorapidity range from about $|\eta| = 1.6$ to $|\eta| = 2.9$. The LGADs consist of 1.3 x 1.3 mm^2 pads of silicon. A 16 x 16 array of pads is read out by a custom ASIC which measures the arrival time of particles at each pad and the energy deposited in it. The total area of all four disks is about 15 m^2 and there are nearly 9 million pads in total. The need to choose a different technology than for the barrel is imposed by the radiation tolerance limitations. Ongoing studies of the radiation tolerance of LGADs indicate a promising performance of about 30 (50) ps at fluences of 3×10^{15} cm^{-2} corresponding to $|\eta| = 3.0$, at the beginning (end) of the HL-LHC operation. The same technology is also proposed for a fast-timing layer under consideration for the very forward region ($2.4 < |\eta| < 4.8$) of the ATLAS experiment. The ETL will be installed in a thermally isolated volume on the nose of the Endcap ECAL, positioned about 3 m from the interaction point. The disks have a radius of 1.2 m and are split vertically in a “clam-shell” arrangement, allowing then to be extracted from the detector without even removing the beam pipe.



Cross-sectional view of the endcap timing layer along the beam axis. The interaction point is to the left of the image. Shown are two ETL disks populated with modules on both faces, along with the support structure. The grey sections are the active areas of the modules with LGAD sensors. Each orange bar represents a service hybrid.

The CMS physics programme at the HL-LHC targets a wide range of studies, including precise measurements of the Higgs boson properties and direct BSM searches. All these studies will benefit from the improved efficiency for isolated objects. A very crucial measurement to be performed is the di-Higgs production, which will provide a direct measurement of the Higgs self-coupling. In this case, precision timing could increase the signal yields for constant background in HH→ bbγγ by 22% while similar improvements are predicted for other Higgs boson signatures, ranging from 15–20% in the case of HH→ 4b to 20–26% for H→ 4μ.



Impact on signal efficiency for HH → bbγγ for no-timing, barrel only timing, and barrel plus endcap timing scenarios. The quantity yHH is the rapidity of the di-Higgs system.

Moreover, the sensitivity to searches for new physics depends on measuring the missing transverse energy (E_{missT}). In that sense, tails are equally important for tracking resolution and the proposed detector could achieve a nominal |Δz| < 1 mm window providing very high efficiency in isolation sums. The gain in the E_{missT} resolution with track timing leads to a reduction of ~ 40% in the tail of the distribution above 130 GeV, which approximately offsets the performance degradation for SUSY searches because of the higher pileup.

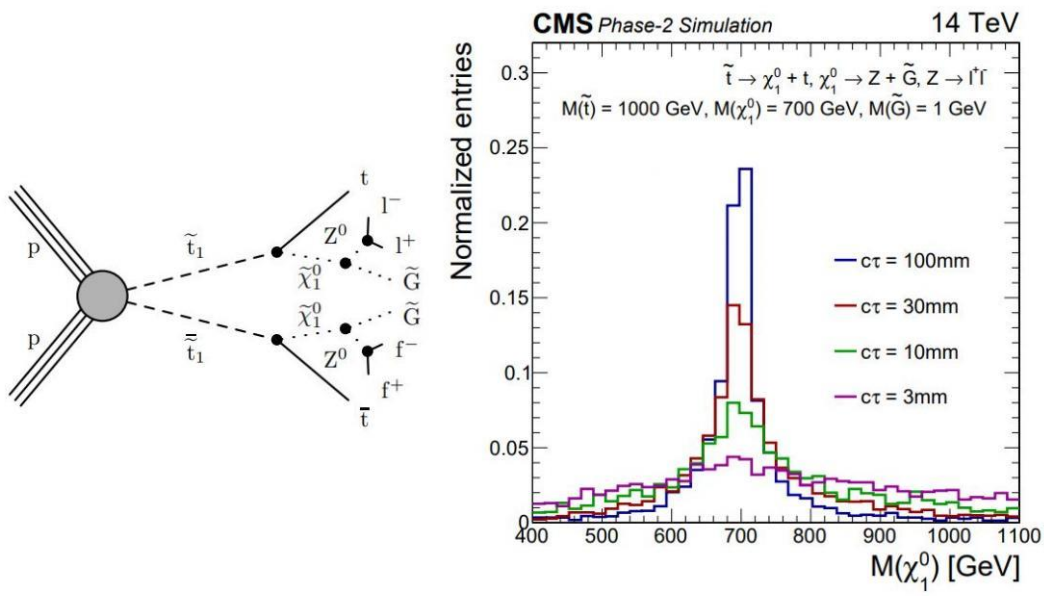


Diagram for top-squark pair production and decay (left), η and mass distribution for a 700 GeV neutralino with three different lifetimes reconstructed from the kinematic closure of the secondary vertex using time information with 30 ps resolution (right).

In addition, the improved track-time reconstruction opens whole new capabilities that allow CMS to look for phenomena that are outside the capability of the current detector. These include searches for neutral long lived particles (LLPs), postulated in many extensions of the SM. Heavy particles that travel a distance in the tracking volume and then decay into lighter standard model particles produce very delayed signals in the MTD. Time-of-flight between the collision vertex and the MTD can also be used to identify charged hadrons, such as pions, kaons, or protons, at relatively low transverse momentum of a few GeV/c, typical of most particles produced in Heavy Ion collisions, providing new opportunities to study those collisions as well.

Thus, the capabilities offered by the MTD, combined with other planned CMS upgrades will contribute to improvements in many physics analyses during the HL-LHC and deepen our understanding of the validity of the SM and the physics of the ElectroWeak sector, enable searches for new LLPs and enhance our knowledge of the collisions of Heavy Ions. A detailed technical design report for the MTD was submitted earlier this year and approved recently by the CERN Research Board.

Further Reading:

[1] A MIP Timing Detector for the CMS Phase-2 Upgrade, Technical Design Report, CMS Collaboration

BASE probes antimatter - dark matter interaction

by ***Panagiotis Charitos***

PDF version

In a recent paper, the BASE collaboration presented results from a direct search for interactions of antimatter with dark matter and placed direct constraints on the interaction of ultralight axion-like particles (dark-matter candidates) with antiprotons. Their analysis constrained the value of the axion–antiproton interaction parameter in the range of 0.1 to 0.6 GeV for axion mass in the range of 2×10^{-23} to 4×10^{-17} eV.

The authors present also astrophysical limits on the axion-antiproton interaction up to a mass of 0.01 eV by considering a hypothetical axion emission from antiprotons in supernova SN1987A, which represents the current best limit from such kinds of observations. The new laboratory result reported by BASE improves the sensitivity for ultra-light axion-like particles compared to the limits from astrophysical observations by about a factor of 100 000. The same analysis also sets limits on six combinations of previously unconstrained Lorentz- and CPT-violating terms of a model, which discusses effects of CPT-and Lorentz-violating coefficients on the standard model, recognized as the non-minimal standard model extension.

It is the first time that antimatter is used as an antenna to probe the existence of new particles like the hypothesized axion (see https://ep-news.web.cern.ch/content/rise-axions). In 1977, Robert Peccei and Helen Quinn developed a theory introducing a new field that could resolve the "strong CP problem" - the fact why CP violation is not observed in strong interactions. The proposed mechanism, in turn, led to the invention of CP-axions and, more general, axion-like particles, which are excellent dark matter candidates.

Many experiments around the world have launched extensive DM axion searches to cover the relevant parameter space. Existing theoretical underpinnings of the axion do not predict a value for the axion mass. Cosmological considerations indicate that if the axion is the source of the cold dark matter in the universe, it should have a mass in the range of about 1–25 μeV⁄c^2 - about 10^{15} times smaller than the masses of weakly interacting massive particles (WIMPs). With such a small mass, in our Solar System, trillions of axions per cubic centimeter are required to account for the observed dark matter density. However, the interactions of axions with ordinary matter and photons are expected to be so feeble that their detection requires extremely sensitive techniques. So far, intense axion searches have not given any hints for the existence of this particle while the variety of experimental approaches has allowed to exclude certain parts of the parameter space leaving though still a lot of room for future experimental searches. The lack of experimental evidence inspired the BASE collaboration to come up with the approach to search for axions within a certain mass range by probing possible axion-effects on antimatter. Using a single antiproton in a Penning trap, the BASE team searched for possible modulations in the frequency at which the spin of the antiproton precesses, as illustrated in Fig. 1. Such modulations would hypothetically be imposed by oscillating axions, which couple to the antiproton spin.

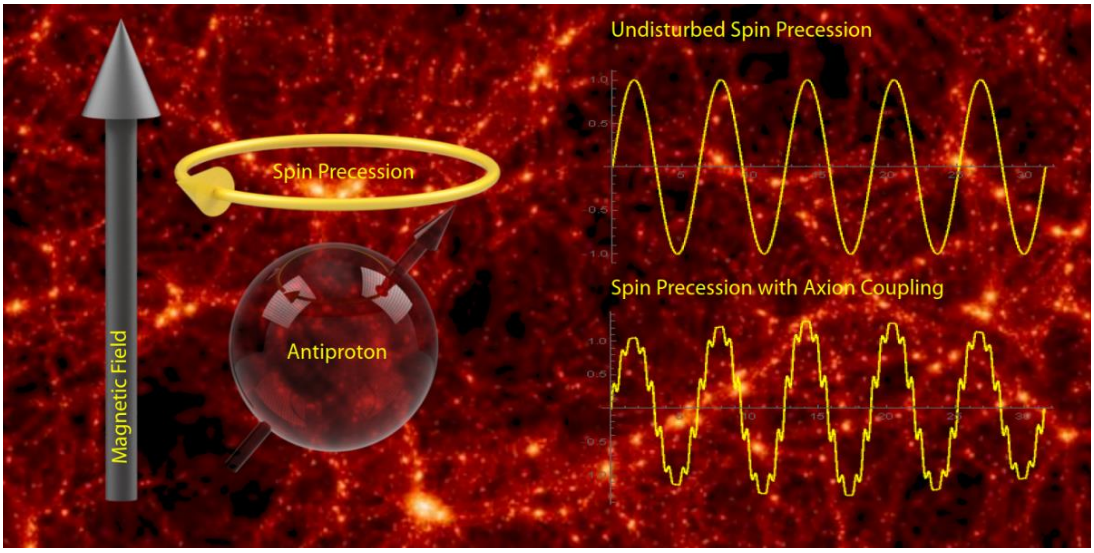


Figure 1. Illustration of the detection principle. The antiproton precesses in the magnetic field of the Penning trap magnet, a time series signal would lead to a signal as shown upper right. The axion coupling would modulate this signal to a shape as shown lower left. BASE was analyzing their magnetic moment data set for such modulations. The non-detection of such signals enabled BASE to set first constraints on axion/antiproton coupling.

To record data-sets which enable such studies, BASE stores single antiprotons in ultra-stable, high-precision Penning traps. In the strong magnetic field of the trap the antiprotons oscillate at characteristic frequencies, the spin precesses at the Larmor frequency ν_L, while the particle oscillates in parallel in the superconducting magnet at a complex trajectory, from which the cyclotron frequency ν_c is obtained. Measuring the Larmor-to-cyclotron frequency ratio ν_L/ν_c almost a thousand times over the course of about three months, BASE determined the time-averaged frequency of the antiproton's precession ν_L of around 80 MHz with an uncertainty of 120 mHz. From this measurement, the BASE scientists were able to improve their previous best measurement of the antiproton magnetic moment by more than a factor of 350. By looking for periodic variations in the time-sequence of this extended experimental data-set, the BASE team was now able to set first direct laboratory limits on axion–antiproton interactions, as shown in Fig. 2. For the interpretation of the results BASE teamed up with Dima Budker and Yevgeny Stadnik, scientists from the PRISMA+ Cluster at the University of Mainz, which have great expertise in dark matter research.

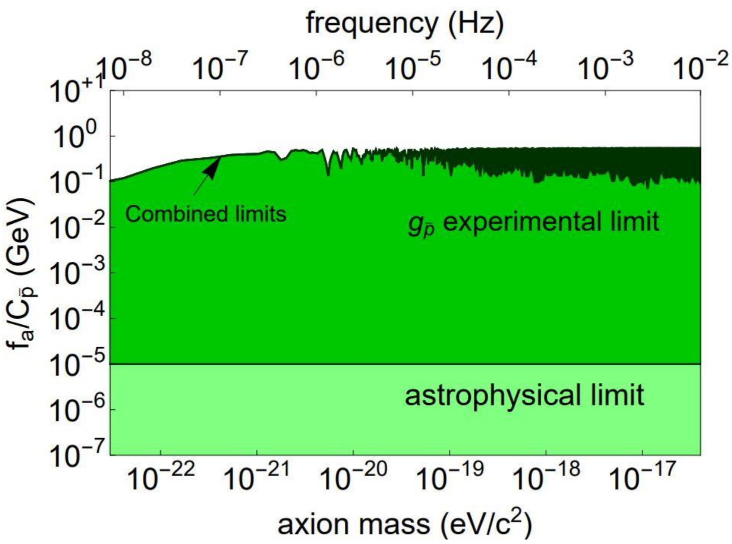


Figure 2. Constraining axion–antiproton interactions. Recently BASE published experimental limits on the coupling between axion dark matter and antiprotons. These bounds are expressed in terms of an axion–antiproton interaction parameter and vary with the axion mass or the frequency of the axion (Credits: BASE Collaboration).

Currently BASE is gearing up the experiment to enable measurements of the antiproton magnetic moment at a precision level of at least 150 parts in a trillion. It is moreover planned to implement experiment schemes which allow for higher sampling rates and longer data-acquisition campaigns. A comparable analysis of these future results would increase the mass-bandwidth and improve the antiproton/axion interaction limits by at least a factor of 10.

The author would like to thank Christian Smorra and Stefan Ulmer for their invaluable help in preparing this article.

Further Reading: https://www.nature.com/articles/s41586-019-1727-9

The NNLO frontier

by ***C. G. Papadopoulos (NCSR-Demokritos)***

The potential of a post-LHC collider to explore for hints of new physics relies on technological advancements but also on theoretical developments that will allow very accurate background determinations. With a concensus growing for a lepton collider offering a wide range of precision Higgs and electroweak measurements it is important to consider the required theoretical improvements. First, and foremost there is a clear need to increase the accuracy of automated computations of inclusive quantities from the first order next-to-leading order (NLO) to the next-to-next-to-learing order (NNLO). As stated in the Physics Briefing Book of the EPPSU: "Fully automated NLO tools are now available and the next challenge is to upgrade them to the NNLO level". The article discusses recent progresses and the challenges lying ahead to progress in parallel with advancements in the accelerator and experimental frontier.

The quest to understand the constituents and forces of Nature, from the shortest accessible distances to processes at astrophysical scales, has led physicists to build the Standard Model of particle physics, now celebrating its jubilee. It has a long record of success in quantitatively describing all experimental results and precisely predicting a wide variety of new phenomena.

High-energy particle colliders have been extremely powerful and successful tools, furnishing copious data that have yielded discoveries of new particles and precision measurements of fundamental interaction parameters. The energy frontier is currently at the CERN's Large Hadron Collider (LHC), which today hosts the most important infrastructure in particle physics not only in Europe but worldwide. The celebrated 2012 discovery of the Higgs boson was made there by the scientific teams of the two general-purpose detectors, ATLAS and CMS. The LHC has just come to the end of its second run. With the end of this run, the current era of broad searches is drawing to a close.

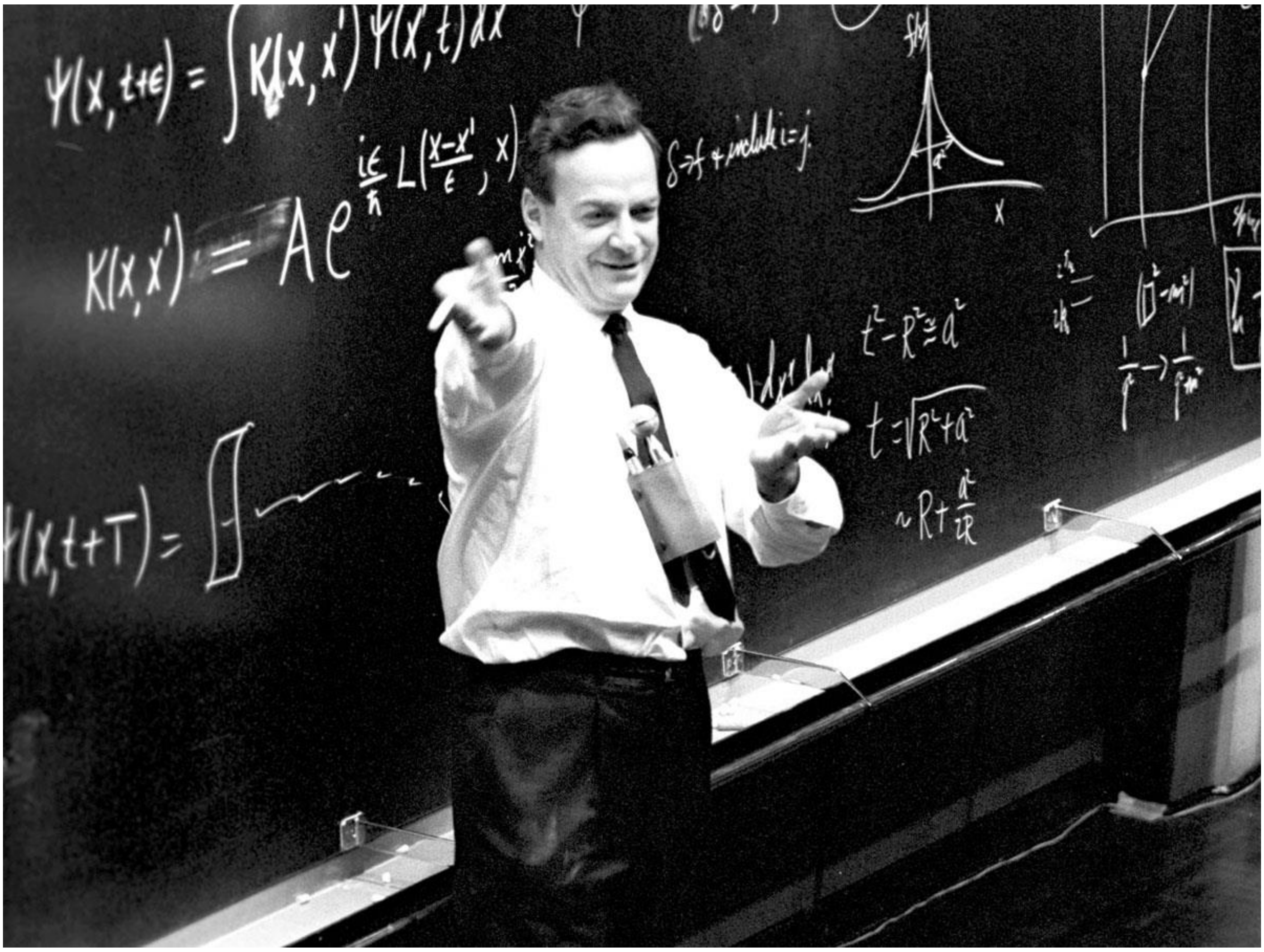
A new era of precision measurements is dawning with Run 3 and the subsequent High Luminosity LHC Run. Precision measurements will require precise theoretical predictions if the scientific community is to fully exploit the machine's potential, as well as the work of its thousands of experienced experimenters, early-stage researchers, and technicians. A new effort to produce theoretical predictions at the level of precision needed for upcoming data is thus most timely. This effort will also lay the groundwork for a theoretical program to accompany not only LHC experiments through their planned schedule over the next decade and a half but also the long-run scientific program of the high-energy physics community, as for instance the Future Circular Collider (FCC) project.

The theoretical prediction of observable distributions can be carried out within the well-understood framework of perturbative QCD [1]. The core ingredients are scattering probabilities, i.e. cross sections and differential distributions. They can be determined by taking into account (i.e. integrating and summing) all possible configurations of allowed final states, and all configurations of the gluon and quark beams which the protons are effectively providing. Quantum fluctuations give rise to 'virtual' corrections to these scattering probabilities. Moreover, states that differ by additional massless particles — such as a photon in quantum electrodynamics or a gluon in QCD — of too low energy or too nearby in angle, are indistinguishable from each other. We need to integrate therefore over all such contributions as part of the 'real emission' corrections. This integral, done naively, yields an infinite result, because the probability of finding such low-energy particles grows inversely with the decreasing energy (and likewise for the angle). These infinities are called infrared divergences. The divergences must be isolated and regulated. They can then be integrated, and the potentially divergent parts cancel against those arising from 'virtual' contributions. The remaining terms are finite and can be evaluated numerically.

It is necessary to stress that the first three orders of the expansion in the coupling constants, most importantly in the strong coupling, are especially relevant in the analysis of physical observables. Indeed, the leading order (LO) provides a rough estimate only, where neither the normalization (for instance the total fiducial cross section) nor the estimation of the theoretical uncertainty are reliable, due to the strong dependence on the unphysical renormalization and factorization scales. The next-to-leading order (NLO) provides a meaningful normalization, but it is only at the next-to-next-to-leading order (NNLO) that a reliable estimate of the precision of the theory predictions as well can be achieved. Besides, for many processes, the corrections turn out to be so large, that even higher loop calculations (NNNLO) are required [2].

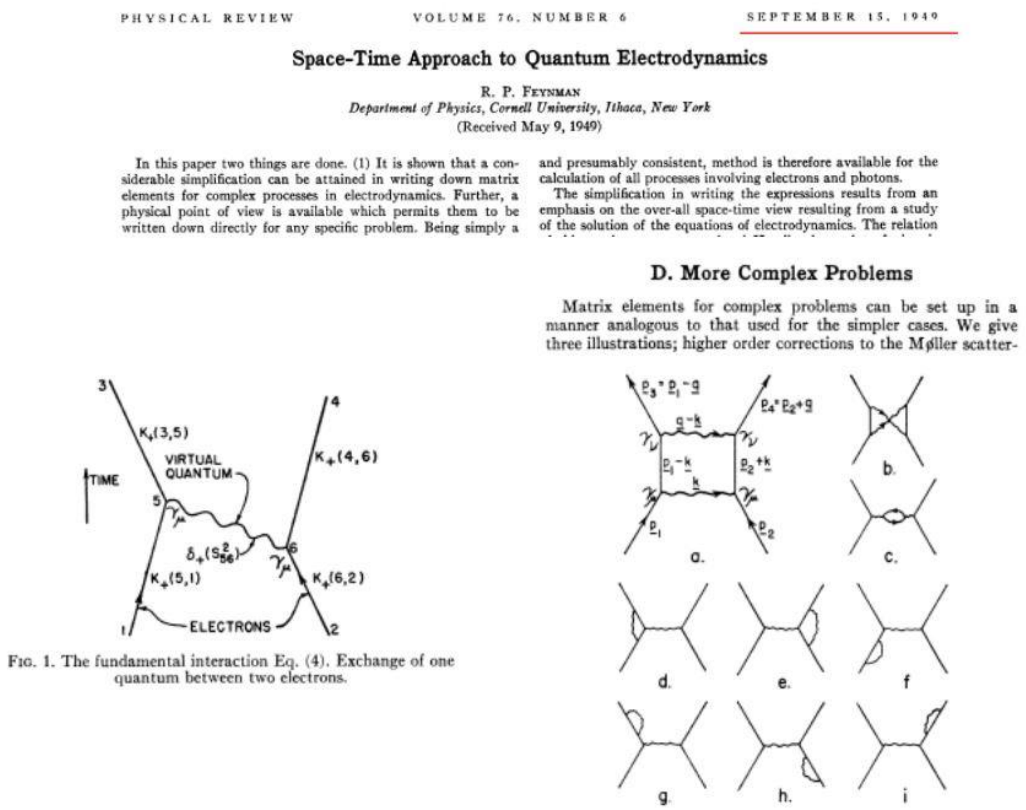
At the first quantitative order in the perturbative expansion, the next-to-leading order (NLO), several approaches to the 'real emission' corrections have been developed, tested, and well understood [3]. As far as the 'virtual' corrections to the scattering amplitudes are concerned, our understanding has been impressively evolved over the last fifteen years. Thanks to the reduction of one-loop amplitudes to a set of Master Integrals (a minimal set of Feynman Integrals that form a basis of them [4]), either using unitarity methods [5] or an integrand-level approach [6], the way one-loop calculations are preformed has drastically changed, resulting in many fully automated numerical tools [7-11] (for a review on the topic see [12]), making the next-to-leading order (NLO) approximation the default precision for theoretical predictions at the LHC.

It is almost seventy years from the time Feynman Integrals were first introduced [13] and forty-five years since the dimensional regularisation [14] set up the framework for an efficient use of loop integrals in computing scattering matrix elements, and still the frontier of multi-scale multi-loop integral calculations (maximal both in number of scales and number of loops) is determined by the planar five-point two-loop massless integrals [15-16], recently computed. The reason for this slow pace is to be traced back to our unsatisfactory understanding of the structure of Feynman integrals and of the scattering amplitudes in general, and it is not just a matter of computing resources.



Richard Feynman in September 1949 published its two papers introducing the use the so-called Feynman diagrams greatly reducing the amount of computationsl involved in calcuating a rate or cross-section of a physics process. (Credits: CERN).

Adding a new ‘next’ (NLO, NNLO, etc.) in the perturbative series is not just a technicality, but we are, unfortunately, entering a new unexplored territory, where new concepts and approaches have to be invented. We have therefore no other alternative but to explore the next ‘next’ order, with the aim at the ‘practical’ side, to provide more advanced theoretical predictions that will match the foreseen experimental precision, and at the ‘theoretical’ side, to unveil the structure of scattering amplitudes.


PHYSICAL REVIEW VOLUME 76, NUMBER 6 SEPTEMBER 15, 1949

Space-Time Approach to Quantum Electrodynamics

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(Received May 9, 1949)

In this paper two things are done. (1) It is shown that a considerable simplification can be attained in writing down matrix elements for complex processes in electrodynamics. Further, a physical point of view is available which permits them to be written down directly for any specific problem. Being simply a and presumably consistent, method is therefore available for the calculation of all processes involving electrons and photons.

The simplification in writing the expressions results from an emphasis on the over-all space-time view resulting from a study of the solution of the equations of electrodynamics. The relation

D. More Complex Problems

Matrix elements for complex problems can be set up in a manner analogous to that used for the simpler cases. We give three illustrations; higher order corrections to the Møller scatter-

FIG. 1. The fundamental interaction Eq. (4). Exchange of one quantum between two electrons.

The first published Feynman diagram (right) shows the classic case of two electrons exchanging a virtual photon. Such diagrams are essential in particle physics, as they represent terms in the equations, as well as illustrating particle interactions schematically.

Calculations of multi-loop integrals have a long history. Contrary to the one-loop case, where Master Integrals have been known for a long time ago [17], a complete library of Master Integrals at two loops (or even beyond) is still missing. The overall most successful method to calculate multi-loop Feynman integrals is based on expressing them in terms of an integral representation over the so-called Feynman or Schwinger parameters. In fact, the introduction of the sector decomposition method [18-19], resulted in a powerful computational framework for their numerical evaluation [20]. Nevertheless, the most successful method to obtain analytic expressions and numerical estimates of multi-scale multi-loop Feynman Integrals is, for the time being, the differential equations approach [21]. With the introduction of the canonical form of the differential equations [22], a major step towards the understanding of the mathematical structure (multiple polylogarithms) of Feynman Integrals and subsequently of the scattering amplitudes has been achieved.

This paved the road for the computation of practically all two-loop QCD virtual amplitudes with massless internal states. Two-loop amplitude calculations with massive internal/external states [23] (relevant for instance to the top-pair production and to the mixed QCD and electroweak corrections) are also available and new mathematical structures (elliptic polylogarithms) have been developed in order to obtain analytic insight [24] of certain Feynman Integrals. At the same time, the calculation of ‘real emission’ corrections at the next-to-next-to-leading order, NNLO, which relies on the single– and doubly–unresolved parton contributions, seems to approach a certain state of maturity. The past few years we have seen remarkable developments in the understanding and the treatment of infrared singularities in NNLO computations, and a range of methods based on different physical ideas have been successfully developed and applied [25-33]. It is fair to say that, with the achieved completion of the vast majority of 2 → 2 scattering processes calculations, we have witnessed the start of the NNLO revolution.

Nevertheless, in order to reach the same level of understanding as in the NLO case, much more needs to be done. The current frontier of NNLO calculations is as always split in two directions. In the frontier of 'real emission' corrections, we seek to improve and automate the current computational tools and algorithms, with the aim to extent our NNLO calculations beyond the 2 → 2 barrier. On the other hand, with respect to the two-loop amplitudes, significant progress has been seen over the last couple of years. Two-loop amplitude reduction for 2 --> 3 processes is now well developed [34-36], even for massive external states [37]. Analytic expressions for the previously unknown two-loop five-point Master Integrals have also been obtained [15-16]. It is hoped that in the near future, not only theoretical predictions for 2 → 3 processes, as for instance three-jet, H+2jets or V+2jets production will be available, but also the groundwork for the extension and automation for arbitrary 2 → n processes will be established, marking the maturity era of the NNLO revolution.

The developments and challenges described in this article call for further theoretical research, in order to promote our understanding of the makings of the Standard Model of particles physics and unveil, by comparing with the experimental measurements, the boundaries where new physics may lie.

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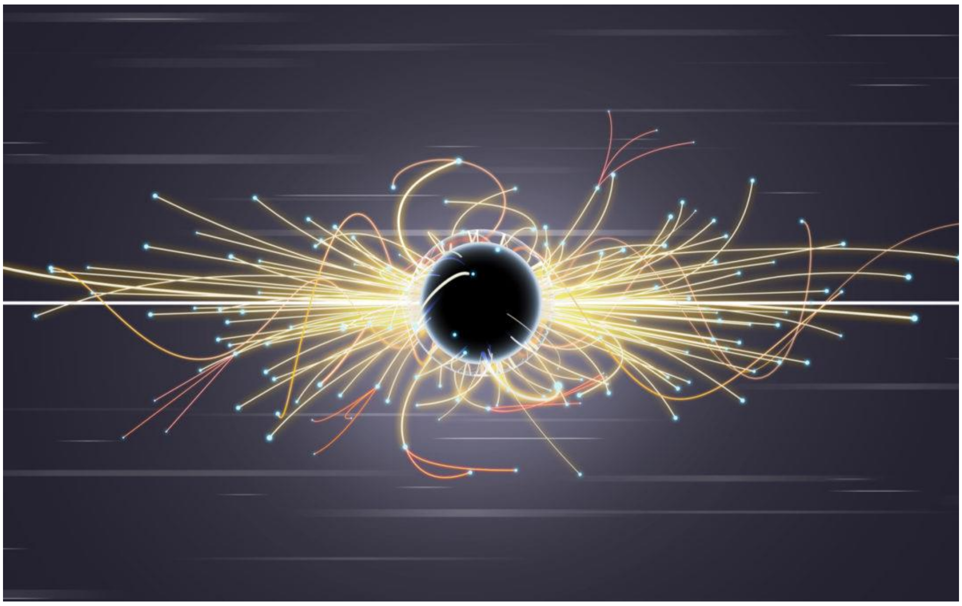
Image note: In 1972, the 1st Europhysics Conference on Neutrinos (Neutrino'72) was held in this town, gathering several major physicists among whom Richard Feynman. A memorial tree was planted for that occasion by Feynman in the Tagore Promenade, which is still standing today among many other trees by famous poets, politicians and scientists (Credits:https://indico.ific.uv.es/event/3356/page/58-venue).

Shaping the future of particle physics

by ***Panagiotis Charitos***

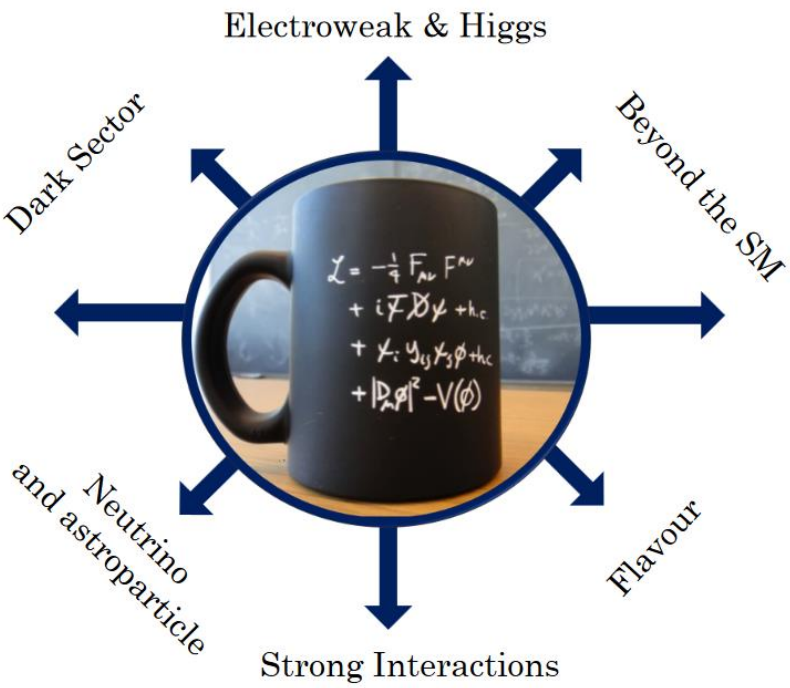
The ongoing update of the European Strategy for Particle Physics aims to identify the potential opportunities and challenges of the proposed research programme through an inclusive and evidence-driven process. Discussions focus on the parameter space that can be explored and how future searches could guide theoretical developments along with synergies on required R&D lines in detector development, accelerator technology, computing and other vital tools to progress in fundamental physics. Given the exploratory role of any post-LHC machine the question of synergies with other fields including astroparticle physics as well as cosmology and the gravitational wave community emerges. Finally, the strategy faces new challenges given the complexity of the proposed next-generation colliders and the interest of China and Japan to host a post-LHC collider. The different challenges are detailed in the Physics Briefing book that was published by the Physics Planning Group last October. The goal is to offer a coherent framework for understanding the possibilities offered by the proposed machines along with their complementarity with non-collider searches. This will inform future discussions during the drafting session scheduled for January 2020.



One of the top priorities remains the full exploitation of the LHC results and the high-luminosity (HL-LHC) upgrade of the machine, which remain key priorities for the global particle physics community. The outstanding performance of the LHC, confirms the CERN's Council decision in December 1991 meeting that the LHC was the "right machine for the advancement of the subject and the future of CERN". The ongoing upgrades of the LHC experiments will allow to measure the couplings of the Higgs boson to SM bosons and third-generation fermions at the percent level. This task calls for significant improvements in theory as discussed in this issue. Moreover, upgrades of LHCb, ATLAS and CMS will offer enhanced B-physics capabilities complementing searches of Belle II and of the high-transverse momentum programme. Similarly during dedicated heavy-ion runs the LHC experiments will continue exploring the nature of QCD and the physics describing the formation of hadrons. Furthermore, results from the LHC complement those of fixed-target, underground and astroparticle experiments allowing to test a significant part of the parameter space where new physics can lie.

Physics questions after the LHC

Results from the LHC and previous colliders have helped us to establish the Standard Model (SM) as the successful description of fundamental particles and their interactions. However, today we are still confronted with many unresolved puzzles - both experimentally and theoretically - that can be tackled only with a bold experimental programme based on substantial technological advances. This is why the next scientific tool should give us the broadest possible research programme allowing a smooth continuation after the completion of the LHC programme around 2040. Proposed future colliders can explore new physics extensively, up to multi-TeV scales, through direct and indirect searches. Lepton colliders like CLIC and FCC-ee tend to perform well in indirect searches in spite of the substantially lower centre-of-mass energy while hadron colliders like the proposed FCC-hh have a better reach for direct searches of new states, while profiting from its complementarity with FCC-ee in the FCC integrated programme.



Following the discovery of the Higgs boson a number of research areas call for a diverse experimental programme along with theoretical developments (Image courtesy of Prof. Jorgen D' Hondt, from the **105th Plenary ECFA meeting - CERN*).***

One of the main experimental challenges for next-generation particle colliders is to scrutinize the properties of the Higgs and delve into the physics of the electroweak sector. The remarkable self-consistency of the SM depends on the values of the coupling constants. Thus the collected inputs prioritize a lepton collider as the next project since it would serve as a Higgs factory. This would allow to study the Higgs interactions with all other known particles of the Standard Model but also with itself. New physics, it is argued, would influence the values of the Higgs couplings to the fundamental constituents of matter and interactions, and could be detected provided they are measured with very high precision to be sensitive to the relevant energy scales.

Future colliders could also probe the whether the Higgs is accompanied by other related spinless particles or not and whether it is a more composite rather than a fundamental particle (for an in-depth discussion see a previous EP article: https://ep-news.web.cern.ch/content/higgs-boson-probe-new-physics). In addition, high-energy colliders like the proposed FCC-hh will contribute in a complementary way to the Higgs, the electroweak precision and the flavour programmes where LHC experiments have made important contributions. One example is the study of rare Higgs decays (e.g. $H \rightarrow \mu\mu$, $\nu\nu$, $Z\gamma$) profiting from the high luminosity, while they will greatly improve precision measurements of the Higgs self-couplings compared to lepton machines and allow to measure the full Higgs potential.

Moreover, future colliders reaching energies of 100 TeV will be able to address the nature of the electroweak phase transition that took place in the early Universe. While the phase transition is a high-temperature phenomenon that cannot be recreated experimentally, precision measurements of Higgs properties— in particular of the triple-Higgs self-coupling—will give us decisive elements to reconstruct the dynamics that occurred when the Universe changed its vacuum state. According to the SM, the Higgs mechanism took place as a smooth crossover when the Universe cooled down to temperatures below 160 GeV, but the transition could be very different due to new physics. Testing the nature of the electroweak phase transition is an important task for future colliders that will considerably expand our knowledge about the early history of the Universe. Measuring a first order transition would open the door to the exciting prospect of explaining the cosmic baryon asymmetry with weak-scale physics or of observing with next-generation gravitational interferometers the primordial gravitational waves produced by the abrupt transition at that epoch.

A second main research line in particle physics is the study of strong interactions. Though the creation of QGP as an almost perfect liquid has been experimentally established, studies of heavy-ion collisions at the LHC (by the dedicated heavy-ion ALICE experiment as well as by the other LHC experiments) and at RHIC (Brookhaven) have been a constant source of surprises. Open questions include the mechanism for the transition from QCD to long-distance phenomena and the characterisation of the collective behaviour emerging under extreme conditions similar to those that existed just fractions of a second after the Big Bang. Experimental measurements are needed to understand the behavior of strong interactions in the non-perturbative regime where theoretical calculations become very demanding. Furthermore, the observation of collective effects opened a new area of studies for the heavy-ion community. A high-energy AA/pA/pp research programme offered at a circular collider would be unique to Europe and would lead to a profound understanding of hot and dense QCD matter. The lower-energy research programme of QCD matter at the SPS at CERN, is complementary to other emerging facilities worldwide in the US (BES at BNL), in Germany (FAIR), in Russia (NICA at JINR) or in Japan (J-PARC), and brings valuable contributions in the exploration of the QCD phase diagram

Flavour physics is another regime where future experiments will shed light, allowing to study new pathways to searching for new physics. The document identified that “Experimental hints for deviations from SM predictions in flavour processes are one of our best hopes to direct research towards the right energy scale where new physics may lurk”. From both the experimental and the theory side, a novel synergy between the searches for flavour violating decays and for feebly interacting and dark particles is emerging. The next generation of flavour physics experiments, will inaugurate a completely new realm of sensitivity using many different observables available in future experiments. We do not know which approach will discover evidence of New Physics first, the highly sensitive search for deviations from SM predictions in precision flavour physics or direct observation of new particles. Input from both will be needed to understand the physics that lies beyond the Standard Model. In the mid-term future much can be gained from the possible upgrade of the LHCb experiment for the HL-LHC in addition to the hope that the pending question of lepton number universality will be fully resolved with more data. On the longer term, the Tera-Z option of the FCC-ee also offers an attractive program of exploring flavour physics with high precision.

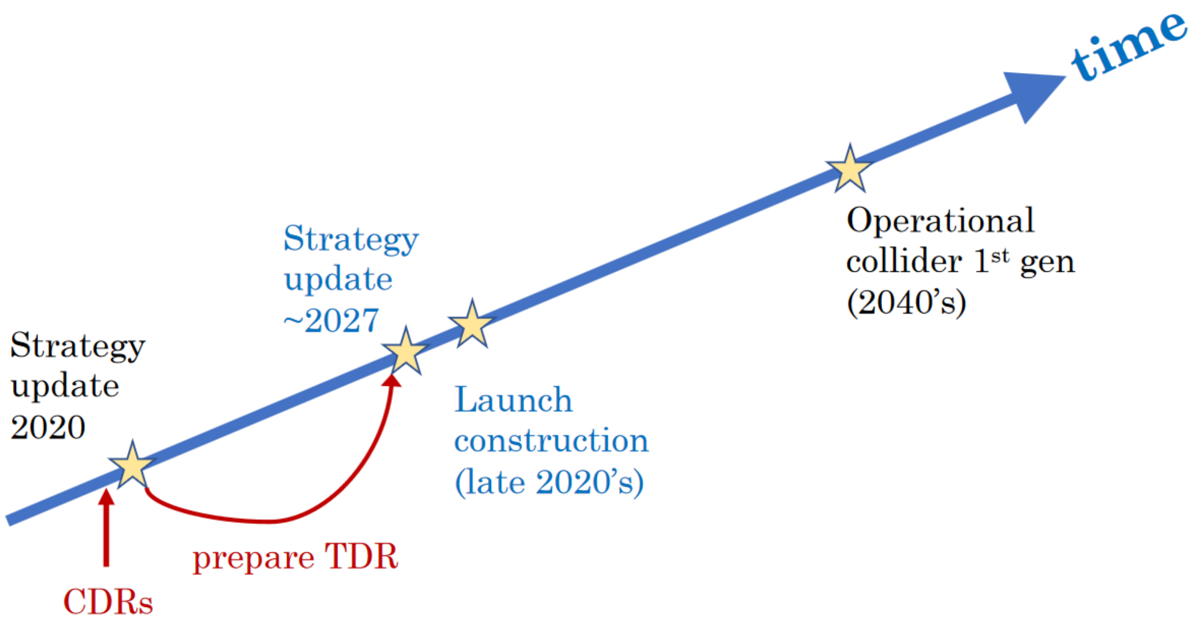
Another experimental goal for a post-LHC machine is the search for Dark Matter candidate particles. Historically direct-detection DM experiments have been dominated by WIMP searches. However taken into account the limits from multiple overlapping direct detection experiments, there is a paradigm shift focusing on a broader set of particles that could be anything from as light as 10^{-22} eV to as heavy as primordial black holes of tens of solar masses. In particular, the search for ultralight DM particles like the axion and axion-like particles has gained significant momentum. The study of the Higgs (given its unique characteristics) and sterile neutrinos, or the recently proposed long-lived particles (LLPs) are also promising candidates to shed light on the dark matter mystery. Future colliders (ILC/ CLIC, FCC-ee/hh/eh) have an excellent potential to explore models of thermal DM in the GeV to 10TeV mass range complementing other experimental searches based on accelerators, solar haloscopes or light shining-through-wall experiments. Discussing DM searches we also have to consider the comlementarity of future collider searches with those from other approaches including dedicated underground experiments but also by large astroparticle detectors like H.E.S.S., Antares or IceCube, and in the near future the CTA observatory expected to start operations in 2022. Therefore while updating the EPPSU one has to consider the opportunity for Europe to play a leading role in DM searches using CERN's accelerator complex and the potential of a post-LHC collider but also by contributing to the axion research programme in other laboratories.

The physics briefing book includes a discussion on neutrino physics given the surging interest from the global community and facilities planned both in the US and Japan as well as astrophysics and underground experiments targeting the study of this particle. Neutrino masses offer today one of the strongest experimental signs for the existence of new physics beyond the Standard Model. Therefore, we need to continue exploring the neutrino sector with accelerator, reactor, solar and atmospheric neutrino experiments. CERN's Neutrino Platform (NP) brings together as of today about 90 European institutions to support and participate in detector R&D and construction for neutrino facilities. EP department has also launched in 2016, the neutrino group, to coordinate activities within the department and ensure that Europe will continue playing a vital role in the mid-term future. Furthermore, the physics briefing book suggests/explores a range of alternative approaches not limited to colliders, but complemented by beam-dump, fixed-target and other experiments. Feebly-interacting and long-lived particles are two recent examples demonstrating how the experimental community can come up with new ideas as a healthy response to the LHC results.

Finally, discussing about very precise measurements poses a clear need for better independent determination of the proton structure to feed theoretical calculations. This motivates the proposed programme based on fixed target experiments and on dedicated ep machines has been proposed in Europe, in the US and in China. The high-energy end of the proposed facilities at CERN such as the LHeC and/or FCC-eh have in addition the potential to complement the programme of BSM physics discussed above.

The future demands diversity

The way forward involves challenges that cannot be addressed without constant progress in advancing accelerator science, designing better detectors, and developing proper computer infrastructures. The Physics Briefing book emphasizes the need to retain a strong focus on instrumentation R&D and develop an environment that stimulates innovation, with the primary goal of addressing the well-defined technological challenges of future experimental programmes. Technology innovation emerges from synergies within the fields of physics as well as with industry and any future research infrastructure will act as hub for co-innovation between academia and industry. The continued R&D on solid-state sensors has led to the possibility to add timing detectors to LHC experiments upgrades - an improvement that was not originally foreseen - enabling better pile-up rejection while paves the way for using these technologies for medical purposes and other applications beyond HEP.



Typical path for a successful decision requires to consider the physics questions that we target, compare the physics opportunities offered by the different experimental approaches along with the performance of the proposed research infrastrcutrues, select a scenario and plan early the next steps. (Image from Prof. Jorgen D' Hondt's presentation during the 105th ECFA plenary meeting at CERN).

The goal for next year is to turn the results documented in the Physics Briefing Book into a coherent strategy that will enable Europe to continue leading in the field of particle physics and will guide CERN - as a truly international laboratory - into the future. The European Strategy for Particle Physics revision will conclude in May 2020, and will hopefully identify a concrete vision for the future of the field. The outcome of the strategy will guide the complex preparatory efforts for a post-LHC collider and allow to establish the required level of co-operation at European and international level. The realisation of any future project relies not only on the experimentalists, currently involved in the LHC experiments and elsewhere, but also on the strong support of the theory community and, last but not least, new advances in technologies, computing software and infrastructure.

First SWAN workshop at CERN

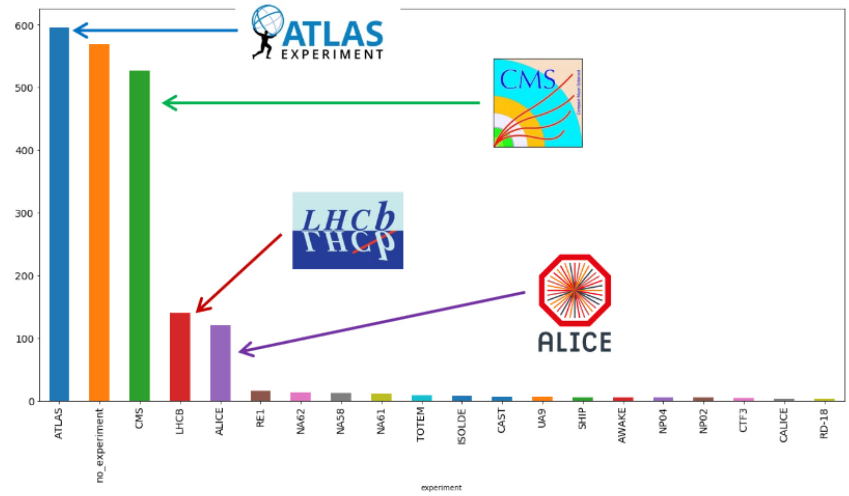
by ***Enric Tejedor Saavedra (CERN)***

The first SWAN and Jupyter Notebooks Users' Workshop was held last October at CERN. SWAN (Service for Wab based ANalysis) is a platform enabling users to perform interactive data analysis on the Cloud. The goal ot he meeting was to offer a space where users could openly share their experience and gather feedback for develpments that could improve the service to serve future needs.

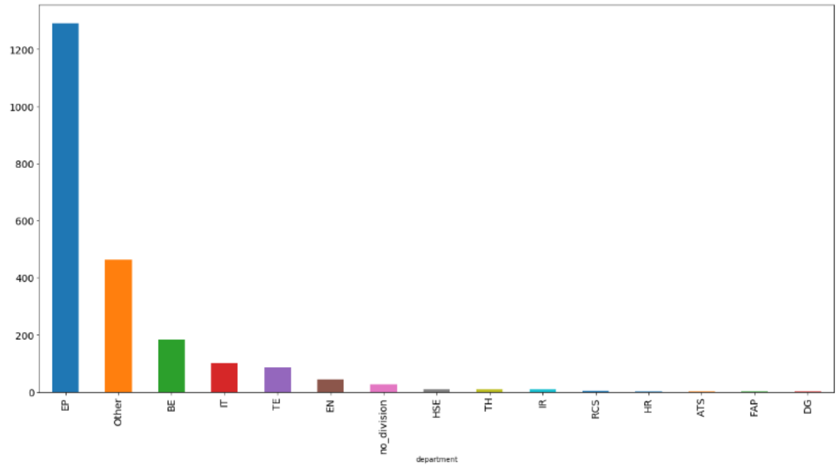
The workshop was divided in two sessions, one in the morning and another one in the afternoon. The morning session started with a few presentations from the SWAN team, which gave an overview of the service and introduced the new features that are foreseen for the service, for example the migration of the interface to JupyterLab, the possibility to offload computations to GPUs from SWAN; moreover, the ScienceBox software package was presented as a way to easily deploy private SWAN instances on premises. After that, a block of presentations from the experiments followed, which explained how they use SWAN to do their analyses, mainly from Python. They highlighted SWAN features such as the integration with CERNBox and EOS for persistent storage and the ready-to-use software provided by CVMFS.

Furthermore, they brought up two main topics: first, the fact that SWAN users could benefit from collaborative notebooks, that is, being able to share notebooks with your colleagues that everyone can edit, even concurrently; second, the possible need to increase the memory provided by a SWAN session, in order to support use cases that load big datasets into memory. On the other hand, some presenters showed their efforts in configuring experiment software, in particular for ALICE and CMS, on top of the LCG releases, and it was discussed how to make such process work more smoothly. Finally, the morning session also included a presentation that showed the experience of an Australian company, AARNet, that is running its own instance of SWAN for more than 3700 users.

In the afternoon session, the Beams and the Technology departments explained how they are using SWAN to query and analyse LHC log data, either by connecting to a database directly from a notebook or, as done in the NXCALS project, by offloading computations to Spark clusters from SWAN. Moreover, the TE colleagues also explained how SWAN is used to generate superconducting magnet files and how it helps in the LHC Signal Monitoring Project, with features such as rapid prototyping, easy sharing of notebooks, plug-and-play style of working and better reproducibility; they also stated that GPUs could be an asset for them and would speedup some of their workflows. The IT department and the HSE unit were also represented with talks about using SWAN to analyse tape server logs and in the area of operational radiation protection, respectively. Finally, a block of presentations on SWAN for education and outreach highlighted the value of SWAN for hosting tutorials and courses and for accessing open data, and they advocated for having an open instance of SWAN for education, which would need to be accessible with lightweight accounts..



Users by Experiment



Users by Department

Plots showing the number of SWAN users per experiment (top) and per CERN's Department (bottom). The two plots were presented during the workshop by Diogo Castro (see HERE).

In summary, the SWAN Users' Workshop was a great opportunity to bring together the SWAN user community and the SWAN team, get to know each other, exchange impressions about the service and discuss how it should evolve. Learning about how SWAN is used and what needs to be improved was crucial for the SWAN team to provide a better service to the users. This was only the first edition of the workshop, but more will come to keep in touch with the community.

CAST: from Solar to Dark Matter Axions searches

*by **Marios Maroudas (University of Patras), Yannis Semertzidis (Center for Axion and Precision Physics Research, IBS)***

CERN's Axion Solar telescope (CAST) has been running since 2003 searching for the axion: a hypothetical particle introduced in 1978 as a consequence of the Peccei-Quinn mechanism aiming to solve the strong CP problem, i.e why is the neutron electric dipole moment limit some ten orders of magnitude smaller than expected from QCD. CAST's detection technique is based on the inverse Primakoff effect, dictating that inside a strong electric or magnetic field an axion can couple to a virtual photon producing a detectable photon. During its operation, CAST has progressively put world-class limits on the axion-photon coupling for a wide range of axion masses. The latest result published in 2017 in Nature Physics, sets an upper limit on the axion-photon coupling strength of $g_{a\gamma\gamma} < 0.66 \times 10^{-10}$ GeV^{-1} (95% CL) for all axions with masses below 0.02 eV.

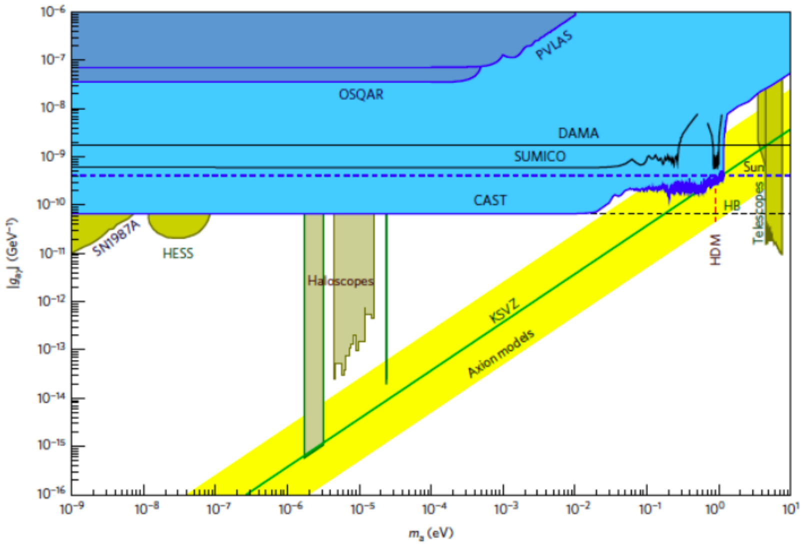


Figure 1a. The latest solar axion exclusion plot.

Figure 1b: CAST experiment and close up photo of the twin bores of the CASt magnet where the RADES and CAST-CAPP RF cavities are installed.

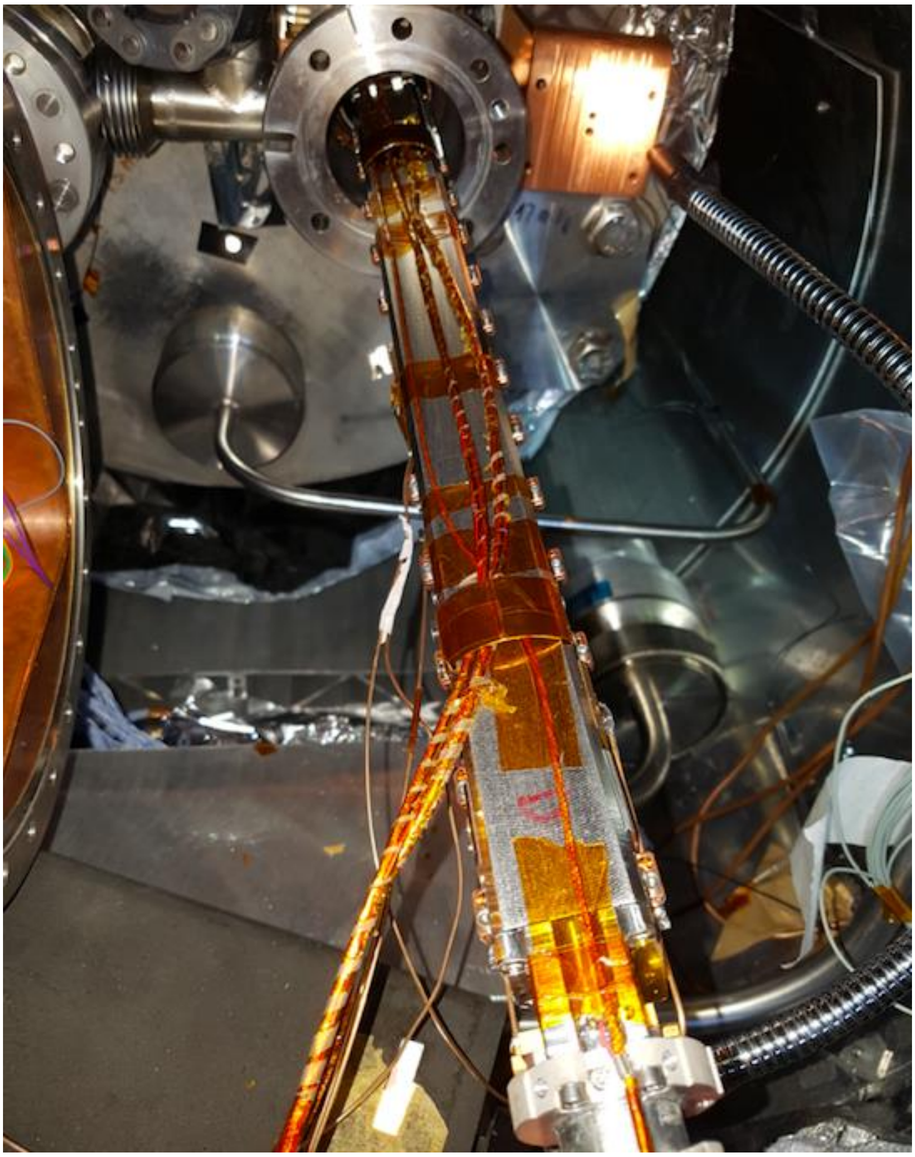


Figure 1c. Installation of CAST-CAPP RF cavities on one of the two bores of CAST magnet

In addition to offering a solution to the strong CP problem, axions in the mass range around 1 - 100 μeV are also good cold dark matter candidates, as they are non-baryonic and can be produced in sufficient abundance during the Big Bang. Given that the dark matter density within our Milky Way halo is expected to be ρ_A=0.45 GeV/cm^3, dark matter axions would have a local number density of the order of 10^{14} / cm^3 but remaining nearly undetectable due to their very feeble coupling.

Today, the most promising experiments for detecting dark matter axions are still the so-called "*Axion Haloscopes*", based on the Sikivie haloscope technique, which have the potential to detect them around the μeV mass region. Haloscopes consist of high-Q microwave cavities immersed in a strong magnetic field. The axion-to-photon conversion rate in a region of space where a strong magnetic field is present, is further enhanced if the outgoing photon, is detected in a microwave cavity resonating to the frequency of the axion mass. The operation of such RF cavities involves the appropriate choice of available electromagnetic modes, and, as the axion mass is unknown, a tuning mechanism for adjusting the resonant frequencies and thus covering a wide range of axion masses is indispensable.

The CAST superconducting magnet provides a dipole magnetic field of 9T, and has a twin-bore geometry (length, diameter) into which the rectangular design of the cavities used for dark matter axion searches has to fit. The on-resonance axion conversion efficiency in a microwave cavity, and thus its ability to search for dark matter axions, increases with the magnetic field squared (**B**^{2}), the cavity quality factor **Q** (the ratio of the cavity stored-energy to its power loss per cycle), the volume **V** of the cavity, and the so-called geometry factor **C** determined by the direction of the external magnetic dield and the cavity mode, with the dependence is given by the following formula where ρ_A stands for the axion field density and m_A the axion mass:

$$P \approx g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 \cdot Q \cdot V \cdot C$$

Searches for Dark Matter axions

Early this autumn the CAST team successfully completed the installation and commissioning of two varieties of cavities, the RADES and CAST-CAPP sub-detectors, one in each bore of the CAST dipole magnet, making CAST the only experiment at CERN looking for the direct detection of dark matter axions. RADES consists of a 1m long “alternating irises” stainless-steel cavity able to search for dark matter axions around 34 μeV. On the other hand, the CAST-CAPP sub-detector, whose latest results are presented here, consists of four tunable stainless-steel cavities 25mm x 23mm x 390mm electroplated with 30μm of copper. The most crucial element of CAST-CAPP, its delicate tuning mechanism, consists of 2 parallel sapphire plates activated by a piezoelectric motor through a locomotive mechanism delivering a tuning resolution of better than 100 Hz
in stable conditions (Figure 2). The current maximum tuning range is of the order of 400 MHz corresponding to axions masses between 21-23 μeV.

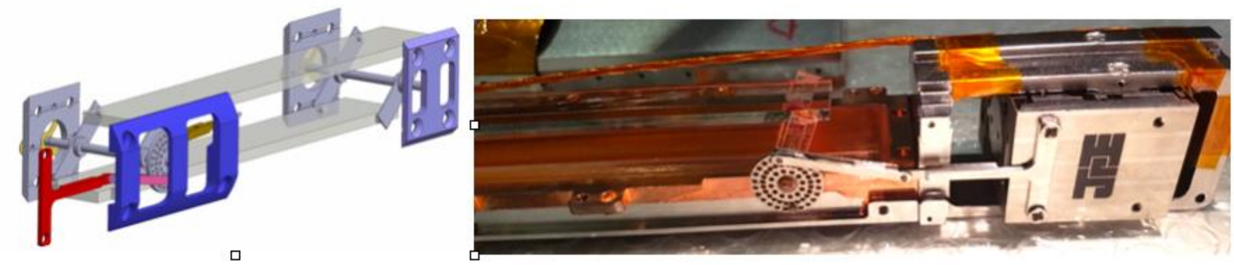


Figure 2: The tuning mechanism of CAST-CAPP detector (left) and the stepper motor providing the movement through the locomotive mechanism (right).

Furthermore, since CAST’s sensitivity increases with the cavity volume, in order to increase the effective volume, the “phase-matching” technique has been applied. The concept is to get simultaneous read-outs from several frequency-matched cavities and then combine them coherently. This improves the signal-to-noise ratio linearly with the number of cavities. This technically challenging concept has also been achieved with CAST-CAPP for three coherent cavities in data-taking conditions (Figure 3).

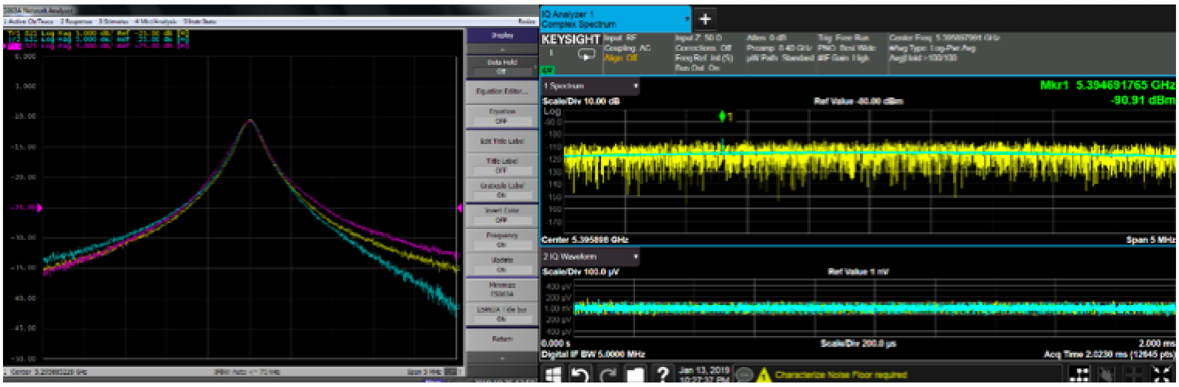


Figure 3: **Three phase-matched cavities of CAST-CAPP (left) and a presentation of complex spectrum mode of a spectrum analyzer during data-taking with a calibration peak (right).**

In addition to searches for conventional axions, CAST-CAPP introduced for the first time in axion dark matter research, the “fast resonant scanning technique”. Thanks to the fast scanning mechanism CAST-CAPP detector is also sensitive to dark matter axion tidal or cosmological streams as well as to theoretically motivated axion mini-clusters. A quite wide axion mass range can be already scanned within a time period of a few hours to eventually take advantage of streaming dark matter towards the Earth. The axion flux enhancement due to gravitational focusing by the Sun can be up to 10^8 and in the ideal case as high as 10^{11} (Figure 4). Apparently, the faster the scanning the shorter axion bursts can be detected. The current maximum scanning speed of CAST-CAPP is 5 MHz/ 30 sec and therefore it's full tuning range of 400 MHz can be covered with one hour.

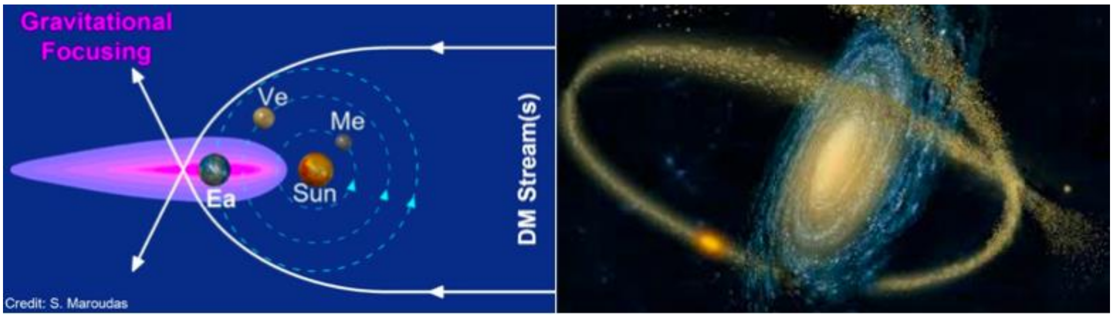


Figure 4: Schematic view of the flow of a putative slow-moving stream being gravitationally focused by the Sun towards the Earth.

At the same time, an alternative wideband scanning technique has been established for the first time, which is based on an out of resonance scanning, abandoning the resonance enhancement factor Q . This could be more than compensated by a temporally large axion flux enhancement. The minimum scanning period for this technique is 10 min for the maximum 300 MHz usable range and is currently done automatically for several hours.

During the latest 2019 data taking run (12/09 - 01/12) a total of 280 MHz frequency range with 200 kHz steps has been scanned with the “fast scanning” method with a total data acquisition time of using all four cavities. Moreover, using the phase-matching technique with three of the cavities, we successfully covered a frequency range of 64 MHz using steps of 200 kHz over a total data acquisition time of 18.4 d. With the present performance and a total of 26.5 d of data analyzed CAST-CAPP has excluded DM halo axions in the parameter space above the reference KSVZ line (Figure 5). If during these measurements there was an axion stream or axion cluster (in this frequency range) with a density enhancement of 10^3 passing by, we would have seen it.

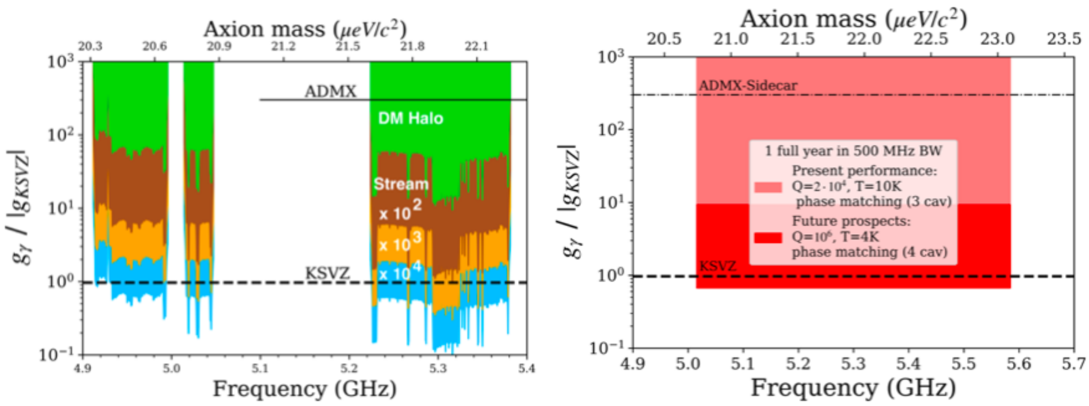


Figure 5: Exclusion plot assuming galactic halo dark matter axions (green) and with enhancement due to streaming (other colours) (left). Perspectives for future longtime measurements assuming present and improved cavity performance (right).

Conclusion

These first successful runs have demonstrated the discovery potential of CAST as an axion dark matter antenna. We are now ready for continued stable running, aiming to cover a bigger frequency range and at the same time increase the sensitivity as the acquisition time will be bigger. Possible upgrades could include an enhancement of the piezoelectric motors for faster tuning in a broader frequency range with less heat dissipation, minimization of the heat dissipation of the cryogenic amplifiers through different bias conditions and better cooling of the cavities, and a fully automatic and user independent DAQ system and storage. Ongoing R&D in IBS/CAPP-Korea could increase the cavity's Q-factor up to 10^6 (almost a factor of 100), by transforming them into superconducting ones using YBCO tape on their inner surface. CAST is ready to extend its sensitive axion searches, if the current run is extended into 2020.

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Optical Data Transmission for LHC Experiment Phase-2 Upgrades

by ***Jan Troska (CERN)***

Optical Readout and Control Systems have become ubiquitous with the LHC-era of Particle Physics Experiments, with each generation of detector upgrades bringing a need to transfer ever-greater amounts of data. Just like in our everyday lives where we now take for granted the ability to watch movies on our mobile phones, so the particle physicist takes for granted the availability of technology to allow the collection of more and more data that can be analysed to detect the faintest of signals. Each generation of experiment challenges us developers to conceive faster, smaller, and more radiation tolerant opto-electronic systems.

The Versatile Link Plus (VL^+) project has developed an optical data transmission system capable of transferring up to 10 Gb/s of data to and from the innermost detectors that must sustain the highest radiation levels during operation of the HL-LHC. These optical links will be deployed in all of the so-called Phase-2 Upgrades that the LHC experiments are preparing in order to exploit the physics potential of the increased luminosity that the HL-LHC will provide. The VL^+ project is a collaboration between CERN, Fermilab, Southern Methodist University, and the University of Oxford. Our team within the EP-ESE group is responsible for the development of the optical transceiver that converts the electrical data produced by the detectors to optical signals that can be transmitted over 50-100 m of optical fibre to the shielded underground control rooms for further processing. The optical transceiver module ($VTRx^+$), shown in the photograph below, is a miniaturised object measuring only 10 mm x 20 mm and is below 2.5 mm in height. It is light enough to be placed throughout the future pixel and tracker detectors of ATLAS and CMS. Radiation tolerance is also a key parameter for any component for future use inside the HL-LHC detectors and this has been designed into the components and assembly of the $VTRx^+$.

VTRx+ optical transceiver module (Credits: CERN)

The $VTRx^+$ module contains four optical transmitters: Vertical Cavity Surface Emitting Lasers (VCSELs) that convert electrical inputs, driven by a custom-designed laser driver ASIC, to modulated light. The $VTRx^+$ module also contains one optical receiver: a photodiode and custom transimpedance amplifier (TIA) to turn the optical input into an electrical signal for the control of the detector. The completed module with its optical fibre pigtail is able to operate in the intense magnetic- and radiation fields that will be encountered in the HL-LHC experiments. The strongest magnetic field present in the HL-LHC detectors is the 4T field of the CMS Solenoid, which sets the tolerance limit for the $VTRx^+$ module. The radiation levels used to qualify the $VTRx^+$ module are 1 MGy of ionising dose, 10^{15} neutrons/cm^2 and 10^{15} hadrons/cm^2. Over twenty years of studying the effect of radiation from different particle species and energies on optoelectronic components allow us to confidently simulate the radiation field in the HL-LHC detectors using a single radiation source. Thus one radiation test to a total fluence of $3x10^{15}$ 20 MeV neutrons/cm^2 available at the Cyclotron facility of the Université Catholique de Louvain-la-Neuve in Belgium is enough to qualify the modules and components, which greatly simplifies the problem.

An extensive multi-year development programme has allowed us to both select suitable components and refine the module design to meet the requirements. We have evaluated VCSELs and photodiodes from multiple vendors in the framework of a CERN Market Survey that has culminated in the recent signature of contracts worth a little over 1 MCHF. Careful evaluation of device performance was necessary including environmental testing over the full specification range from -35 to +60 °C, as well as multiple radiation tests. The VCSEL and photodiode production samples for final validation of their radiation tolerance are scheduled for delivery in the first Quarter of 2020 together with the first large batches of these components. We must validate every VCSEL and photodiode production wafer because these are commercial parts that offer no guarantee of tolerance to our harsh environment and we must eliminate the very small probability that minor process improvements at the manufacturer lead to changes in the excellent radiation tolerance that we have observed over many years of testing.

The ASIC chipset used in the VTRx+ consists of a quad channel VCSEL driver and a single channel transimpedance amplifier (TIA) for the photodiode signals. Both designs have been made in standard CMOS processes using special design techniques to increase the overall radiation tolerance of the circuits. The driver has just passed its final design review and has been submitted for fabrication in a 65 nm process, while the TIA has already been produced in a 130 nm process and is currently undergoing wafer-level testing.

The VTRx+ module design has passed through ten iterations to evaluate different configurations of electrical- and optical connection, in particular the method for attaching the optical fibre. This careful evaluation has allowed us to settle on an extremely thin (2.5 mm) module that fits the space constraints of our most challenging detector applications. The final thickness of the VTRx+ is to be compared to the typical thickness of 10 mm of our previous generation of optical transceiver module that is currently being deployed in the ALICE, ATLAS, CMS, and LHCb Phase-1 upgrades. A very important step in the VTRx+ project was the decision taken late last year to pursue the production of a CERN module design over the purchasing of a commercial design. This decision will lead to significant cost savings to the experiments while maintaining the high performance of the module.

We have just completed the assembly of the first large batch of a little over 350 prototype VTRx+ modules following an extensive survey of companies to find those capable of handing the very tight assembly tolerances (+/- 5 µm) required to achieve good performance. The CERN-designed modules were produced by a German industrial partner, one of the very few European companies identified during our survey. While this first large batch of prototypes was produced in Germany, their fibre pigtails were attached at CERN where we also carried out the testing. This allowed us to trial and refine our test methods and setups in preparation for transferring them to the industrial partner for the series production. Although we had produced tens of prototypes at a time while iterating on the design, this was also the first time we had significant statistics from testing to validate our 90-95% yield target for the final assembly of around 60k modules that will begin in 2020. Although we were just shy of our target for this batch, discussions with the industrial partner have identified some easy to implement process improvements that we are confident will allow us to reach our yield target in production. The modules have now been distributed to end users in ATLAS and CMS for inclusion in system level tests.

The VTRx+ module production will start in the first half of 2020. A first pre-series will be produced in order to fine-tune the assembly and testing process at the manufacturer. We will then carry out the full qualification of the modules before giving the green light to start the series production of approximately 60000 modules at the end of 2020. It promises to be another busy year!

AMVA4NewPhysics legacy in searches for new physics

by ***Anna Stakia (CMS, CERN)***

A couple of months ago, the four-year life cycle of AMVA4NewPhysics, a Horizon2020-funded Marie Skłodowska-Curie Innovative Training Network (ITN), in which CERN participated as one of the member institutions, was completed. With the ultimate objective of searching ways which would improve the measurement and search sensitivity of the ATLAS and CMS experiments at the LHC, AMVA4NewPhysics, under the scientific coordination of Dr. Tommaso Dorigo (INFN, Padova), focused on the study of advanced Multivariate analysis methods for High Energy Physics. Embracing the individual and collaborative work of its members, in the direction of broadening the base of research and enhancing its innovation, AMVA4NewPhysics achieved the set goal, leading the development and optimisation of several promising Machine Learning (ML) tools for use by the HEP experiments, while meeting and advancing the key principles that distinguish a Marie Skłodowska-Curie programme.

The work performed within AMVA4NewPhysics, parts of which have been publicly presented in conferences, workshops and seminars by its members, may be viewed as consisting of four main pillars: (1) customization and optimization of advanced Statistical Learning (SL) tools for the precise measurement of the properties of the Higgs boson, (2) development of new SL algorithms towards achieving higher sensitivity in physics analyses of targeted and global New Physics searches, (3) improvement of the Matrix Element Method through the addition of new tools that extend its applications, as in the Higgs measurements, and (4) development of new SL algorithms for use by the HEP analyses, from modeling methods to anomaly detection methods in model-independent searches.

One of the main studies conducted within the first work package is the application of Machine Learning techniques in the signal versus background classification problem for the decay channel [1-2]. This study was inspired by the 2014 'Higgs Boson ML Challenge' <https://www.kaggle.com/c/higgs-boson>, a benchmark competition on the comparison of the applicability of different ML approaches to HEP datasets. In this study, many tests were made towards assessing the extent to which alternative and recent ML techniques may improve the performance of the then winning solution. In the Neural Networks used for the tests, several modifications are considered, for example in the activation function and learning rate choice, and in the use of ensembling and data augmentation. The proposed solution is eventually found to demonstrate an important improvement over the competition's winning one, in terms of not only the performance measurement, but also the training and inference time, as well as the hardware required.

Another significant result, connected with the content of the second work package, is the application of Deep Neural Networks to the implementation of multiclass classification for the heavy flavour tagging at the CMS experiment. The identification of jets originating from b and c quarks plays a crucial role in the sensitivity of the physics analyses performing New Physics searches or any precision studies. The suggested taggers DeepCSV, DeepFlavour and DeepJet [3-8], three versions of a common generic approach, significantly outperform the standard identifiers in CMS in all transverse momentum regions, offering a notable gain in the b/c jet efficiency versus the corresponding misidentification probability for the different origins of jets. More input variables describing the jet constituents, deeper Neural Network processing the information, and a NN model that exploits the jet structure as it being an image, constitute the key components of the evolution and the differences among the aforementioned, currently recommended in CMS, tagger versions.

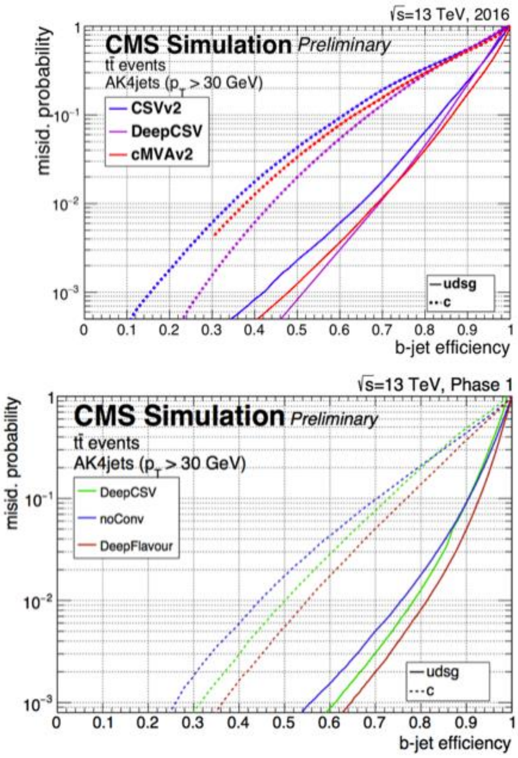

Figure shows b-jet efficiency vs. misidentification probability for c-jets, and uds- and gluon-jets of simulated events, requiring a minimal transverse momentum of 30 GeV. Left: Comparison between DeepCSV and CSVv2, cMVAv2 [4]. Right: Comparison between DeepFlavour and DeepCSV, noConv (a DeepFlavour approach with no convolutional layers) [5]

A third indicative example of the rich scientific outcome of the AMVA4NewPhysics ITN lies in the domain of the Matrix Element Method (MEM) applications. MEM appears as the alternative to the ML techniques used on the LHC datasets to discover the data structure and compare it with theory; it proposes starting from theory to evaluate the experimental events probabilities and then measure the related compatibility with the experimental data. Despite the fact that no NN training is required in this case, the intrinsic complexity of this method in terms of the numerical integration that is needed raises other computing time restrictions. However, the suggested MoMEMta software package [9-12], via the parametrisation of the phase space it performs and the consequent change of integration variables, and along with additional technical features, provides a fast, modular and user-friendly way to tackle these MEM problems, manifesting its functionality in several use-cases, as in the Higgs measurements.

Photo with several of the ESRs, while attending the statistical lecture of Prof. Gilles Louppe, organised by AMVA4NewPhysics, during the Network's Workshop in Athens in June 2018:

Moving to the fourth research pillar of this ITN, a number of multivariate algorithms were developed for analysis tasks in Higgs physics and new particle searches. In particular, Inverse Bagging, a novel model-independent method for New Physics searches, has been proposed [13-15]. As the related data may be divided into two categories, simulated (labelled) and experimental (unlabelled), a semi-supervised anomaly detection problem arises. Besides performing hypothesis testing, this method proceeds to multiple data sampling, which can eventually provide classification of observations into signal- and background-like; the information from the individual anomalous properties of the observations, and the observation scores that are eventually obtained through the multiple sampling iterations, can finally lead to deducing how likely an observation has been generated by a signal. Several tests of this method have been done, as well as comparisons with different methods. Inverse Bagging demonstrates a generally satisfying performance, and therefore has the potential of becoming a promising tool for use in the anomaly detection problems

The material corresponding to the entire work performed within this ITN, including the aforementioned studies, along with the results obtained, has been submitted in the form of several dedicated documents that are available on the AMVA4NewPhysics website <https://amva4newphysics.wordpress.com>, here <https://amva4newphysics.wordpress.com/deliverables>.

All this outcome was made possible within -and thanks to- a Network that would manifest a strong diversity aspect; AMVA4NewPhysicsed

In summary, AMVA4NewPhysics delivered important advancements in Multivariate Analysis and Machine Learning tools for High Energy Physics at the LHC, and in so doing produced an ideal training environment for PhD students. The ESRs were provided not only with an extensive expertise to use while in their PhD studies, but also with the appropriate skill set to subsequently continue conducting key ML research both for HEP experiments and for other applications. Indeed, several of the fellows have already obtained their title and continue related research, holding attractive occupations in academia and outside of it.

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*AMVA4NewPhysics members in **bold**

Shining more light on the onset of deconfinement

*by **Maciej P. Lewicki and Ludwik Turko (University of Wrocław) on behalf of the NA61/SHINE Collaboration***

"It was easier to know it than to explain why I know it." said Sherlock.*

- A Study in Scarlet, Sir Arthur Conan Doyle 1886

NA61/SHINE has recently completed data acquisition for its original programme on strong interactions. The Collaboration has gathered a rich data on collisions of ions in a two-dimensional scan: varying the beam energy and the sizes of colliding nuclei. Most recent analysis of hadron production in $^{40}Ar+^{45}Sc$ and $^{7}Be+^{9}Be$ interactions deliver some puzzling results, that none of the current theoretical models can reproduce.

The NA61/SHINE experiment at CERN

NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) [1] is a multi-purpose experiment studying hadron production in hadron-proton, hadron-nucleus and nucleus-nucleus collisions at the SPS [2]. The programme on strong interactions includes the study of the properties of the onset of deconfinement [2] and the search for the critical point of strongly interacting matter [3]. Additionally two large projects of reference measurements are ongoing on requests of neutrino and cosmic ray physics.

The new results highlighted here, obtained in the framework of the strong interaction programme, concern transverse mass spectra and mean multiplicities of the most abundant charged hadrons (π^-, π^+, $K^-$and K^+) produced in central collisions of intermediate size ions, $^{7}Be+^{9}Be$ [4] and $^{40}Ar+^{45}Sc$ [5], in the beam momentum range of 19A–150A GeV/c ($\sqrt{s_{NN}}$ = 5.12–16.83 GeV). The particle identification was performed using data on mean energy loss (dE/dx) measured by four large volume TPCs, which was supplemented by the measurement of time of flight (tof) in a region where dE/dx distribution for various particle species overlap (low momenta $p \leq 7$Gev/c). This yields results in a large acceptance — NA61/SHINE measures particles down to zero transverse momentum in almost complete forward hemisphere. Consequently mean multiplicities of hadrons produced in whole phase-space can be extracted. These are very important traits of fixed-target experiments.

A proper selection of most central events presents a unique experimental challenge, especially so in case of collisions of small ions. While proton-proton interactions can be classified as elastic or inelastic and central collisions of very large ions of lead can be in some sense distinguished based on the multiplicity of produced particles, neither method is well suited for "intermediate" systems like Be+Be or Ar+Sc. Moreover, the latter method may lead to a bias, as particle multiplicity depends on physics of interest. A procedure devised by NA61/SHINE relies on the measurement of forward energy EF of collision spectators in a modular calorimeter called Projectile Spectator Detector. The most central collisions deposit the smallest energy EF. This allows for a precise, reproducible and, what is crucial, unbiased selection of central events. Measurement of forward energy of projectile spectators is yet another trait reserved for fixed-target experiments.

Small and large systems

The comparative study of collisions of protons and heavy ions offer an incredibly rich source of information about the collective behavior of strongly interacting matter. It enables us to reach beyond elementary interactions and ask more involved questions: what are the phases of strongly interacting matter? How do the transitions between these phases happen? After almost 50 years of measurements of hadron production at broad range of collisions energies and countless theoretical attempts of explanation of quarks and gluons interplay we have some answers, but as it is usually the case in physics — even more questions.

In the early 2000's the discovery of the new, deconfined state of strongly interacting matter created in high energy collisions was announced by CERN and RHIC. Just a couple years later, in 2004, the NA49 Experiment identified the energy at which the deconfinement phase-transition takes place. The Collaboration published the measurements of Pb+Pb interactions, showing rapid changes of collision energy dependence of basic hadron production properties, among them: the step (a plateau in the inverse slope parameter in transverse momentum distribution of pions) and the so-called horn (a sharp peak in K^+/π^+ ratio) that could serve as strangeness/entropy proxy.
These signatures were in agreement with the first model implementing deconfinement in heavy-ion collisions, the Statistical Model of Early Stage [11]. Moreover, they both appeared at the same collision energy (see: Pb+Pb and Au+Au data in Figs. 1 and 2). NA49's results were therefore interpreted as an evidence of the onset of deconfinement — an energy at which the matter created at the early stage of the collision appears in the form of quark-gluon plasma.

Phase structure of hadronic matter becomes more and more involved correspondingly to progresses in theoretical understanding of the subject and collecting more and more experimental data. While the largest experimentally available now energies at LHC and RHIC colliders seem to provide data related to the crossover region between quark-gluon plasma and hadron gas then the SPS fixed-target NA61/SHINE experiment is particularly suited to explore the hypothetical first-order phase transition line with the critical point included.

The phases of QCD matter depend on two primary parameters: temperature T and baryo-chemical potential μB. With changing the energy of the collision we can traverse the phase-diagram in a particular direction — increasing collision energies results in smaller μB and larger T. In order to study a broader domain of the QCD phase-diagram we also vary the sizes of colliding nuclei. Hence with the NA61/SHINE's unique two-dimensional scan in collision energy and system size we seek the signatures of the onset of deconfinement, aiming to pinpoint the location of the phase-transition line.

Intermediate size ions

So what do we learn from the new NA61/SHINE's data on Be+Be and Ar+Sc reactions? Let us focus on the most prominent signature of the onset of deconfinement — the "horn". The phase transition seems apparent in the characteristic, non-monotonic behavior of the kaon over pion ratio in central heavy ion collisions (see: Pb+Pb and Au+Au in Fig. 1). In case of intermediate size systems however, no such vivid structure is present. Nevertheless, two interesting features demand attention. Firstly, a clear distinction between two data sets is visible — p+p and Be+Be results cluster around similar values, while Pb+Pb, Au+Au and Ar+Sc show much higher $K+/\pi+$ ratios. Secondly, although Ar+Sc is clearly separated from small systems its energy dependence does not resemble the sharp peak seen in heavy-ion reactions [14]. No theoretical description can reproduce this behavior — neither statistical [11, 12] nor dynamical models [13].

Complementary to the above, Fig. 2 displays the energy dependence of the inverse slope T, fitted to the transverse mass spectra of charged kaons (K+ and K−). In central heavy ion collisions we see a characteristic step-like behavior. Under assumption that the parameter T can be treated as a vague analogy of temperature, it can be considered as a strong interactions analogy of the ice-water phase-transition. Once again we notice the proximity of p+p and Be+Be measurements. Similarly T obtained for Ar+Sc collisions is higher, but not as high as for heavy lead nuclei.

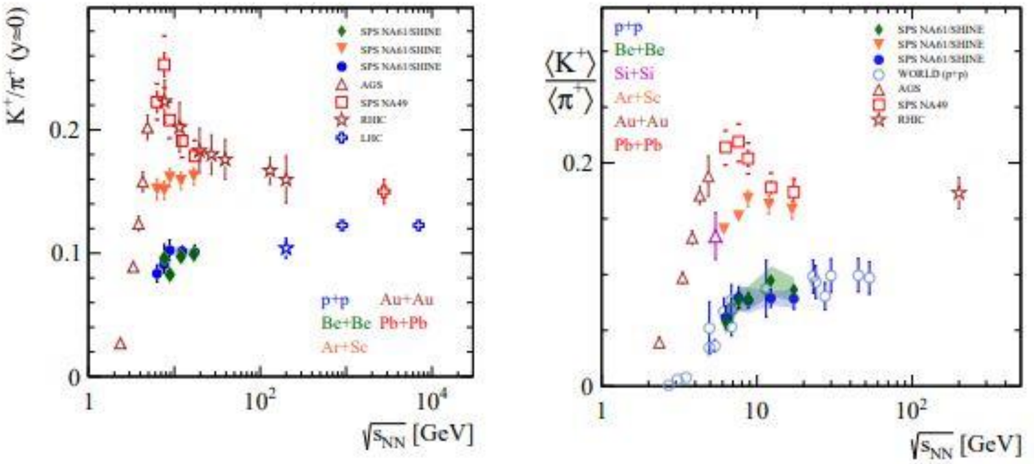

Figure 1: Measurements of ratio of K^+/π^+ in mid-rapidity (left plot) and in whole phase space "4π" (on the right) in dependence on collision energy $\sqrt{s_{NN}}$. Very pronounced differences between data on p+p (blue) and Pb+Pb (red) were identified as a signature of the onset of deconfinement. New data on intermediate size systems: Be+Be (green) and Ar+Sc (orange) were recently measured by NA61/SHINE.

So what do we learn from the new data on Be+Be and Ar+Sc reactions? Let us focus on one of the suggested signature of the onset of deconfinement — the "horn". The phase transition seems apparent in the characteristic, non-monotonic behavior of the kaon over pion ratio in central heavy ion collisions (see: Pb+Pb and Au+Au in fig. 1). In case of intermediate size systems however, no such vivid structure is present. Nevertheless, two interesting features demand attention. Firstly, a clear distinction between two sets is visible — p+p and Be+Be data points cluster around similar values, while Pb+Pb, Au+Au and Ar+Sc show much higher K^+/π^+ ratios. Secondly, although Ar+Sc is clearly separated from small systems its energy dependence does not resemble the sharp peak seen in heavy-ion reactions [8]. No theoretical description can reproduce this behavior — neither statistical [5, 6] nor dynamical models [7].

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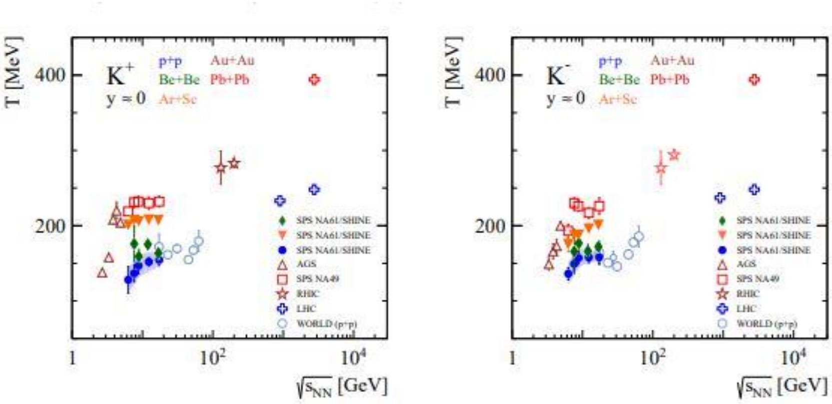

Figure 2: Collision energy dependence of inverse slope parameter T measured in transverse momentum spectra of charged kaons K^+ and K^-. Note a plateau visible in measurements of Pb+Pb at $\sqrt{s_{NN}} \approx 10$GeV/c – also a signature of the onset of deconfinement. Similar structure is also visible for smaller systems: Be+Be and Ar+Sc.

Onset of fireball

The observed rapid change of hadron production properties that starts when moving from Be+Be to Ar+Sc collisions hints a beginning of the creation of large clusters of strongly interacting matter — the so-called onset of fireball [16]. The similarities of p+p and Be+Be systems suggests that interactions of these systems could form small non-equilibrium clusters via binary collisions of nucleons, exactly like in the Wounded Nucleon Model [15]. On the other hand properties of Pb+Pb collisions are pretty well described by statistical and hydrodynamical models, which assume creation of collectively evolving fireball. Results on Ar+Sc collisions are clearly closer to the Pb+Pb ones than to p+p and Be+Be measurements. Summarizing, we could distinguish four domains of collision dynamics, split by the two critical phenomena: the onset of deconfinement and the onset of fireball, as seen in Fig. 3. The onset of decon-finement from confined matter to quark-gluon plasma is well established in the fireball region at high masses of the colliding nuclei, while its presence in the small cluster regime is still an open question — an incredibly interesting question, certainly deserving a separate study.

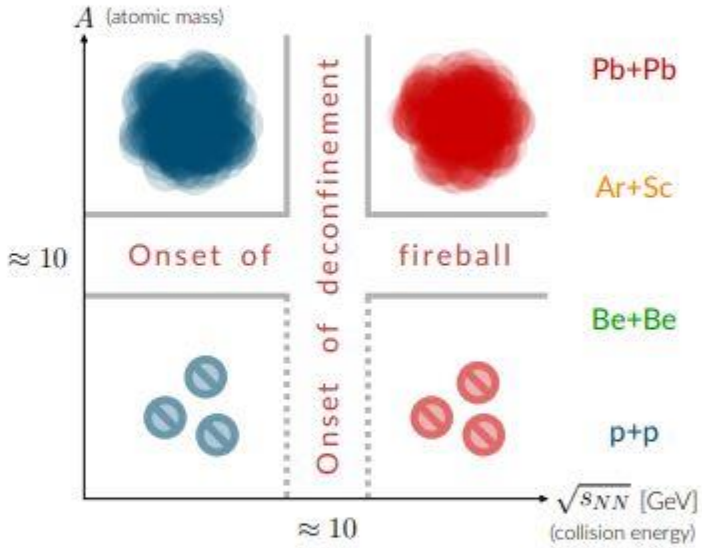

Figure 3: The diagram shows hypothesized four domains that can be assigned to collisions in the SPS energy range. On top of the onset of deconfinement, there is an onset of fireball – beginning of creation of large clusters with increasing system size. It is still unclear how to interpret the transition to higher energies in case of small systems.

Extension beyond 2020

The quest for understanding the phases of strongly interacting matter continues and many unanswered questions remain [17]. In the following we briefly present the next steps of NA61/SHINE.

The second stage of the NA61 experiment, starting after the Long Shutdown 2 (LS2) would include measurements of charm hadron production in Pb+Pb collisions. The main objective is to obtain the first data on mean number of charm-anticharm pairs produced in the full phase space in heavy ion collisions. To highlight the need of such measurements let us note that the theoretical predictions concerning $\langle c\bar{c} \rangle$ production at top SPS energy differ by about two orders of magnitude [18]. Further new results would give us new insights on the collision energy and centrality dependence. These data will help to answer the long-standing questions about the mechanism of open charm production, the relation between the onset of deconfinement and open charm production, and the behaviour of J/ψ in quark-gluon plasma.

NA61/SHINE is the only experiment which could conduct such measurements in the near future. Together with other heavy ion experiments it creates a full-tone physical picture of QCD in dense medium.

***Quote reminded by J. R. Pelaez [4]**

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