

# ATLAS observes Higgs boson produced in association with top quarks

ATLAS  
Higgs  
top quark

The ATLAS collaboration presented the first evidence of “ttH production”, a rare process where a pair of top quarks emits a Higgs boson. Observing this process would provide new insight into the Higgs mechanism and allow for new studies of how unknown physics might (or might not) change the behaviour of this fundamental particle.

The top quark and the Higgs boson are the most massive particles in the Standard Model. As the Higgs boson interacts stronger with heavier particles, the interaction between the top quark and the Higgs boson (known as the “top quark Yukawa coupling”) is expected to be large. Although we can indirectly infer information on the Higgs-to-top interaction from other Higgs boson measurements, a direct measurement of this interaction’s size is important to confirm the indirect results. This can be obtained by observing and measuring ttH events.

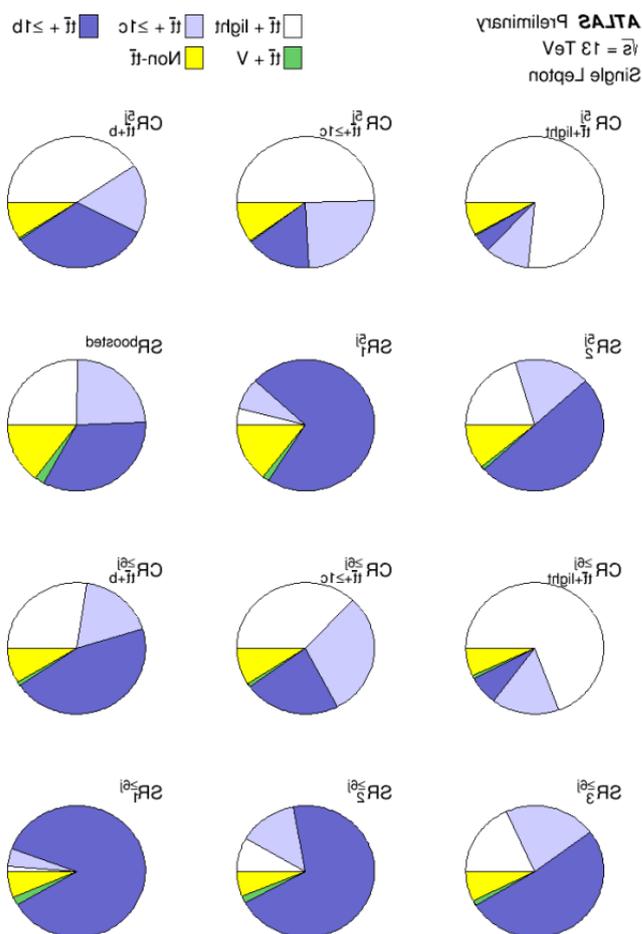


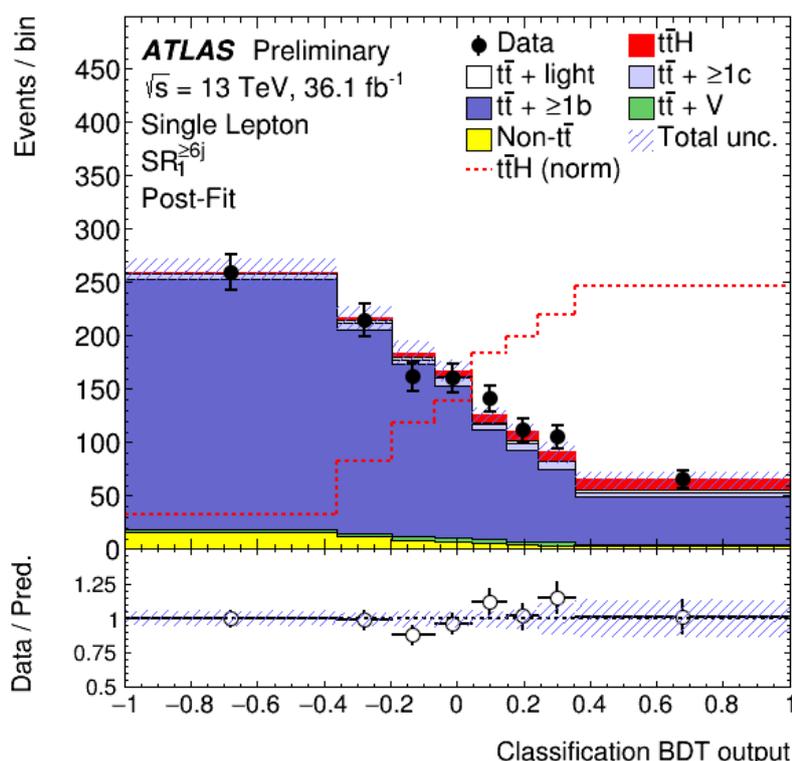
Figure 1: Fractional contributions of the various backgrounds to the total background prediction in each region of the ttH(H→bb) analysis for events with exactly one electron or muon. (Image: ATLAS Collaboration/CERN)

The low production rate – or cross section – of  $t\bar{t}H$  (only 1% of the total Higgs boson rate) makes it especially difficult to measure. The number and complexity of ways in which the Higgs boson and top quarks can decay add to the difficulty. Using the 13 TeV dataset collected in 2015 and 2016, ATLAS performed several searches targeting different Higgs boson decay modes. By combining these results, ATLAS has found statistically significant evidence for  $t\bar{t}H$  production.

### A couple of beauties: exploring the $t\bar{t}H$ ( $H \rightarrow b\bar{b}$ ) channel

As over half of Higgs bosons decay to a pair of bottom quarks ( $H \rightarrow b\bar{b}$ ), the  $t\bar{t}H$  ( $H \rightarrow b\bar{b}$ ) decay channel offers the largest statistical sample of  $t\bar{t}H$  events. However, its signal is very difficult to extract, as top quarks are frequently produced in association with a pair of bottom quarks not originating from a Higgs boson, making the signal difficult to distinguish from this background.

The analysis relies on the identification of b-jets (jets resulting from the hadronization of bottom quarks) and complex multivariate analysis techniques to reconstruct the events and determine whether candidates are more likely to arise from  $t\bar{t}H$  production or from the large background. Events with one or two opposite-sign charged leptons (electron or muon) are categorized into 19 regions as a function of the number of jets and b-jets, and the quality of the b-jet identification. All these regions are statistically combined.



**Figure 2: Comparison between data and prediction for the Boosted Decision Tree discriminant in the most sensitive region of the  $t\bar{t}H$  ( $H \rightarrow b\bar{b}$ ) channel with a single electron or muon. The red dotted line depicts the  $t\bar{t}H$  signal shape (not to scale). (Image: ATLAS Collaboration/CERN).**

In the most sensitive regions, ATLAS uses a machine learning algorithm (“Boosted Decision Tree”) trained on simulated events to better discriminate the  $t\bar{t}H$  signal from the background. Less signal-sensitive regions are useful to reduce the large background uncertainties. The background content in each region with exactly one lepton is shown in Figure 1. The most sensitive region contains

events with exactly one electron or muon, six jets and four b-jets of the best quality (corresponding to a probability to correctly identify a real b-jet of 60%). The Boosted Decision Tree output for this region is shown in Figure 2, where data and prediction are compared.

### Multiple leptons: searching for $t\bar{t}H$ in $H \rightarrow WW$ and $H \rightarrow \tau\tau$ events

The probability of the Higgs boson decaying to a pair of W bosons or a pair of tau leptons is smaller (22% and 6%, respectively), however the background in these decays is also much smaller and easier to estimate. These decays are detected in searches for events with either a pair of same-sign charged leptons, or three or more charged leptons. Seven analyses were performed in total, each targeting a different combination of possible leptons in the final state. Figure 3 shows the expected and observed number of events in each channel in their respective initial selections, as well as additional selections that were used to confirm the background modelling.

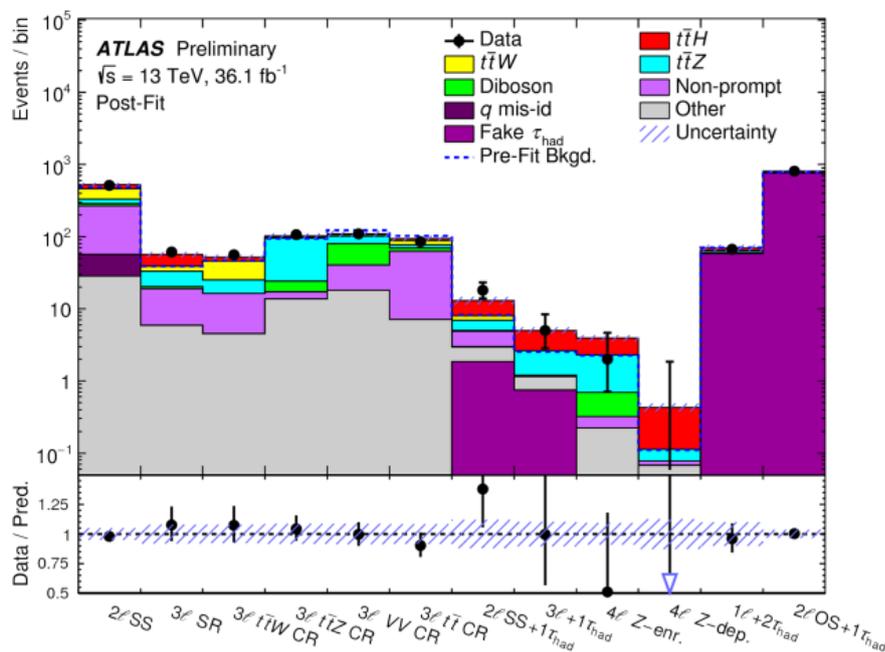
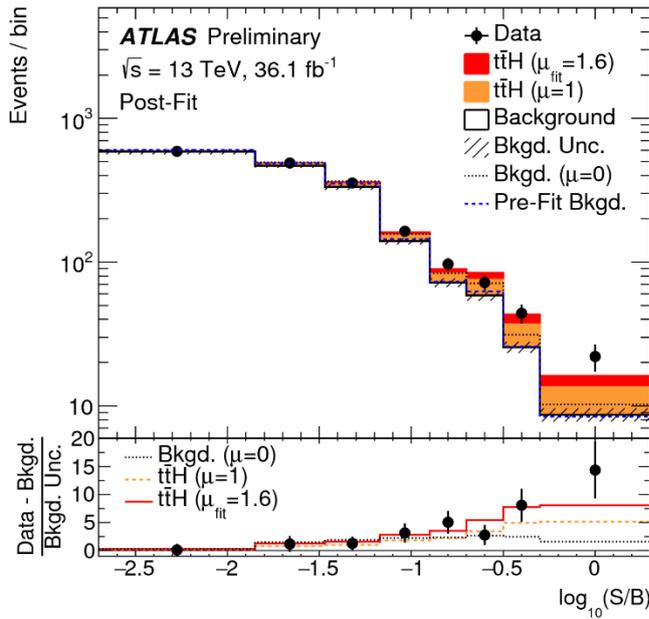


Figure 3: Comparison of prediction to data after the fit in the eight signal and four control regions of the  $t\bar{t}H$  multi-lepton analysis. (Image: ATLAS Collaboration/CERN)

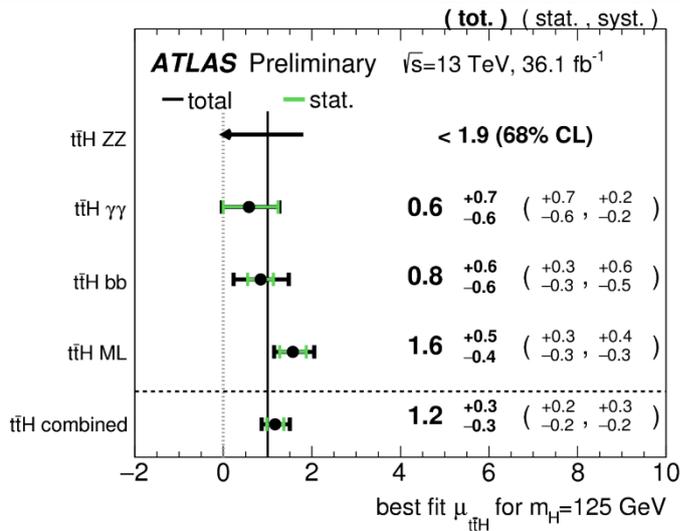


**Figure 4: Event yields as a function of  $\log(S/B)$  for data, background and a Higgs boson signal with  $m(H) = 125$  GeV. The final-discriminant bins in all signal regions of the  $t\bar{t}H$  multi-lepton analysis are combined into bins of  $\log(S/B)$ , where  $S$  is the expected signal yield and  $B$  the fitted background yield. (Image: ATLAS Collaboration/CERN)**

A major challenge for multi-lepton analyses is distinguishing leptons produced in the decay of a  $W$  boson (itself coming from a top quark or a Higgs boson) from those produced by the decay of lighter particles containing  $b$ -quarks. The latter, so-called “non-prompt” leptons, are plentiful in top quark decays. However, as they are typically associated with additional nearby particles, the same techniques used to identify jets arising from  $b$ -quarks can be used to identify non-prompt leptons. This allowed ATLAS to significantly reduce the non-prompt lepton background compared to earlier analyses.

Another complication is that several important background decays in multi-lepton searches – in particular, top quark pair production with an additional  $Z$  or  $W$  boson – are themselves quite rare and thus not yet fully understood. As such, the new ATLAS analyses were designed to minimize the impact of these backgrounds and to permit an in-situ check of compatibility with the theoretical predictions.

In Figure 4, the various histogram bins used in the combined fit of all the multi-lepton analyses have been unrolled according to the increasing expected signal-over-background ratio, with the most background-like bins on the left and the most signal-like ones on the right. An excess of data over the expected background is clearly visible in the high signal-over-background bins on the right. This excess corresponds to 4.1 standard deviations.



**Figure 5: Summary of the measurements of the ttH signal strength from individual analyses and the combined result. The best-fit values of the signal strength  $\mu_{ttH}$  for the individual analyses are extracted independently, and systematic uncertainty nuisance parameters are only correlated for the combination. As no events are observed in the  $H \rightarrow ZZ^* \rightarrow 4l$  analysis, a 68% C.L. upper limit on  $\mu_{ttH}$  is reported. (Image: ATLAS Collaboration/CERN)**  
**Rare decays: ttH in diphoton and ZZ channels**

A Higgs boson can also decay to a pair of photons or to a pair of Z bosons, which then decay to a pair of leptons (leading to a four-lepton final state). These decays are quite rare, but enjoy very small and well-controlled backgrounds. Studies in these channels were combined with the new  $H \rightarrow bb$  and multi-lepton channels described above.

### Combining evidence

ATLAS statistically combined all of these analyses to observe an excess with a significance of 4.2 standard deviations, for an excess of 3.8 standard deviations expected in the Standard Model. This is the first evidence of the ttH process occurring at ATLAS. Figure 5 summarizes the ratio of observed-to-expected ttH signal rate (or “signal strength”) in each of the channels described above, as well as in the combination. A cross-section of  $590 +160 -150$  fb is measured, in good agreement with the Standard Model prediction of  $507 +35 -50$  fb. This measurement, when combined with other Higgs boson production studies, will add more detail to our understanding of the Higgs boson.

## RADECS 2017 comes to Geneva

ESE

by *Francis Anghinolfi (EP-ESE)*

RADECS([link is external](#)) (RADIation Effects on Components and Systems) is the yearly European conference gathering world-class scientists in the field of radiation effects in electronics devices and systems. This year the conference has been organised by the partnership between CERN and CNES, the French Space Agency, and has taken place on October 2<sup>nd</sup> to 6<sup>th</sup> at the International Conference Centre of Geneva (CICG).



***Opening session of RADECS 2017 that was hosted this year in Geneva. (Image Credits: CERN)***

Following a long tradition, the one-week long event is opened by a full day dedicated to a short course, followed by three and half days of technical sessions – including a rich poster session and a radiation effects data workshop mainly focusing on the presentation of results from irradiation experiments of commercial electronics components. The topics discussed during the technical sessions include radiation environments, irradiation facilities, hardness assurance procedures, hardening-by-design approaches, as well as basic radiation mechanisms at the atomic level for both material and electronics components. Modelling or radiation effects are of course also covered, and this year a session dedicated to Application-Specific Integrated Circuits (ASICs) as well as round-table discussions on selected topics were also included for the first time.

CERN being the host of this edition, a large number of researchers from our community could participate in the conference and benefit of the rich amount of information presented in the technical session. This increased representation also translated in an excellent visibility of the work that the High Energy Physics community is accomplishing in the field: oral and poster presentations related to this work were abundant. This allowed to comparing both the radiation requirements and the qualification approaches of our community with typical specifications and procedures used in other domains where radiation tolerance is required.

The conference has been organized jointly by teams of the EN, EP and IPT-KT departments. The EP participation has been especially visible during the “short course” day entitled “From Space to

Ground and below” that had the ambition of summarising and comparing the radiation environments and working practices in Space, Avionics, Terrestrial and High-Energy Physics applications. The course, targeted for both beginners and confirmed professionals in the field, started with a comparison of the radiation environments (G. Santin, ESA) and was followed by lectures on selected topics: total ionizing dose effects in MOS devices (D. Fleetwood, Vanderbilt University), dosimetry techniques and radiation test facilities (F. Ravotti, CERN EP), displacement damage in optoelectronic devices (C. Virmondois, CNES), displacement damage in silicon detectors (M. Moll, CERN EP). To close the day, qualification procedures and best practices for the selection of electronics components for Space (A. Carvalho, Airbus Space Equipment) and for the LHC accelerator and experiments (S. Uznanski, CERN EN) were presented. A record number of more than 300 professionals participated to the course.



**Group photo from RADECS 2017 (Image Credits: CERN)**

A strong industrial exhibition, with 50 booths, prepared in collaboration with CERN's IPT-KT department that supported the event, triggered fruitful interactions between researchers and the industrial representatives. In addition, a networking evening entitled “Swiss Space Night” was organised at the Swiss Tech Conference Center of EPFL with the keynote speeches of Mauro Augelli (CNES/CADMOS), and of the Swiss astronaut Claude Nicollier.

Attracting students has received a special attention, with dedicated social events, the RADSAGA (RADIATION and Reliability Challenges for Electronics used in Space, Aviation, Ground and Accelerators) training event in parallel to the conference, and a dedicated sponsorship for helping students to participate.

Including participants in the short course, the technical sessions and also the industrial exhibitors, this year's RADECS attracted more than 670 participants, coming from 25 countries. This record

number of attendees for the RADECS conference testifies for the large interest of the radiation effects community in CERN's activities. Together with the excellent venue at the CIGG, the successful introduction of new themes in the technical session, and the rich social program for both attendees and their companions, this made the RADECS 2017 an outstanding edition of the conference.

## Implications of LHCb measurements and future prospects

LHCb

by *Monica Pepe-Altarelli (LHCb collaboration)*

A record number of over three hundred physicists from the LHCb collaboration and the theory community got together on 8-10 November at CERN for the seventh edition of the workshop on the “[Implications of LHCb measurements and future prospects](#)”. The very accurate results obtained by LHCb in a broad range of topics have made a large impact on the flavour physics landscape and have implications on classes of extensions of the Standard Model (SM), bearing in mind the interplay with the results of searches for on-shell production of new particles at ATLAS and CMS.



This series of joint LHCb–theory workshops is aiming at facilitating informal discussions between LHCb experimentalists and theorists, leading to a fruitful, mutual exchange of information. The format has proved to be very successful. This year, the attendance was record-breaking, so that the meeting venue had to be moved from the usual “Filtration Plant” to the more spacious Main Auditorium.

The workshop was organized in four streams covering “Mixing and CP violation in beauty and charm”, “Semileptonic decays, rare decays, and tests of lepton flavour universality”, “Electroweak physics, heavy flavour production, implications for PDFs, and exotic searches” and “QCD spectroscopy and exotic hadrons”.

Each stream was introduced by an experimental overview presenting the current status and prospects. This was followed by a series of theoretical presentations typically covering the latest, state-of-the-art calculations, or suggesting interesting observables or analysis methods to test new theoretical ideas.

Examples of recent results that have attracted a lot of interest and were extensively discussed include spectroscopy of conventional and exotic hadrons, as the emergence of exotic states, such as four-quark and five-quark hadrons, has provided new challenges for QCD. Measurements of CP-violating observables in  $B_{(s)}$  meson decays are used to determine the angles of the Unitarity Triangle and hence probe for manifestations of New Physics (NP) beyond the Cabibbo-Kobayashi-Maskawa SM paradigm. Unfortunately, the data present an overwhelming agreement with the SM, thus placing severe constraints on NP scenarios. The good news is that the majority of these measurements are statistically limited, with theoretical uncertainties on the interpretation of the physical observables much smaller than the attainable experimental precision, even at the end of the LHCb Phase I upgrade. This was extensively discussed by Greig Cowan, from the University of Edinburgh, in the keynote session, in which he presented challenges and ideas for opportunities in flavour physics and beyond, in the HL-LHC era.

A significant part of the workshop was devoted to the discussion of a few exciting and intriguing anomalies in the b-quark sector, when performing tests of Lepton Flavour Universality (LFU). These anomalies can naturally be grouped into two categories, according to the underlying quark-level transition:

- those arising in  $b \rightarrow s l^+ l^-$  flavour-changing neutral-currents at one-loop level, when measuring  $B^0 \rightarrow K^+ l^- l^-$ , or  $B^+ \rightarrow K^+ l^+ l^-$ , with  $l = e$  or  $\mu$ ;
- those arising in  $b \rightarrow c l \nu$  charged-currents at tree level, when measuring  $B^0 \rightarrow D^+ l^- \nu$ , or  $B^+ \rightarrow J/\psi l \nu$ , with  $l = \tau$  or a light lepton ( $\mu$  or  $e$ ).

As discussed by Gino Isidori, from the University of Zurich, in his keynote speech, taken together these anomalies represent the largest coherent set of possible NP effects in the present data. He described a well-motivated model with NP coupled mainly to the third generation of quarks and leptons that describes both charged- and neutral- current anomalies while being consistent with the absence of deviations from the SM so far observed in other low- and high- $p_T$  observables.

It is certainly too early to draw any definite conclusions. In fact, it should be pointed out that so far not a single LFU measurement exhibits a deviation with respect to the SM above the  $3\sigma$  level. However, what is particularly interesting, is that these anomalies challenge the LFU assumption, which we have taken for granted for many years. Furthermore, these measurements have been performed so far with Run-1 data only. Updates with Run-2 data are under way and should allow LHCb to rule out the possibility of weird statistical fluctuations. LHCb's results are interesting and make searches for these and other similar processes well worth pursuing.

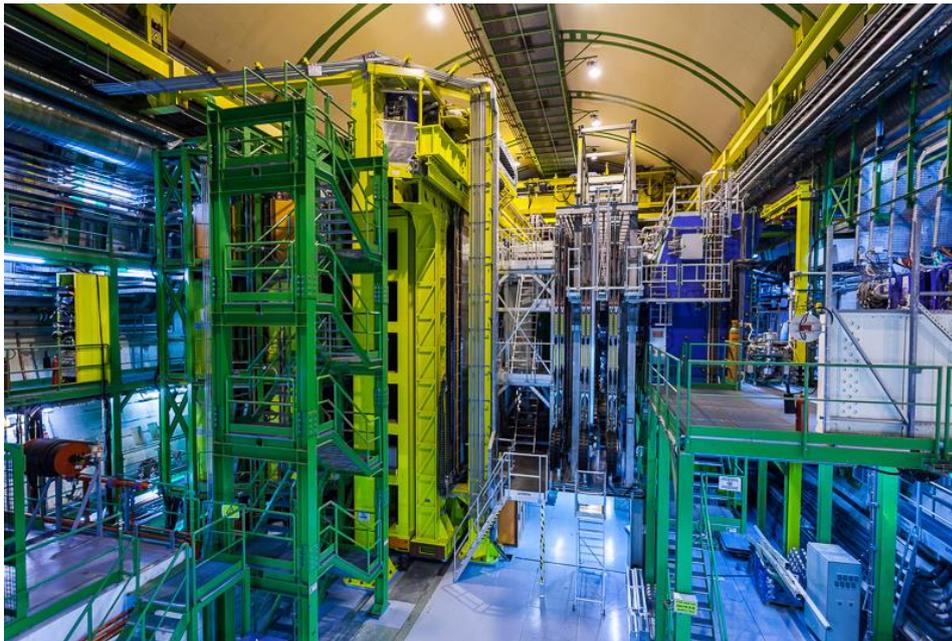
## LHCb prepares for the major upgrade in LS2

LHCb

by *Rolf Lindner and Eric Thomas*

Following the excellent performance of the LHC machine and after a very successful year for LHCb with a recorded luminosity of  $1.7 \text{ fb}^{-1}$  over the year 2017 LHCb goes now into the Years-End-Technical-Stop YETS.

The experiment has taken data very efficiently with a detector operating smoothly over the entire period. However most of the detectors will require maintenance and small repair work. This is particularly true for the Muon system which will be opened for the first time since two years. Nine MWPC chambers (out of 1368), randomly distributed inside the detector, will be replaced. Three of them were recently manufactured in collaborating institutes on purpose. Similarly 2-3 GEM detectors (out of 24) will be exchanged by new ones. The other large detectors (HCAL, ECAL, Outer Tracker) will also be opened to work on some PMTs, fix the electronics, and improve grounding. A few HPDs of RICH 2 will also be replaced toward the end of the Technical Stop. Emphasis will be set as well on the detector services, mainly the detector cooling and gas systems on which an extensive maintenance is scheduled.



Concerning the safety systems, service and tests are planned for the Alarm Level 3 equipment and the Detector Safety System, including upgrade of CPU firmware.

A major work at point 8 will be the exchange of the lift for the LHC machine. Although this work will actually not be in the experimental cavern, the personnel working on the LHC machine sector in the vicinity of LHC8 will have to pass through the LHCb experiment. Preparation for this passage have been concluded and means for a safe passing of the cavern will be put in place before the Christmas Closure of CERN.

As the LHCb detector is in good shape and the repair and maintenance work is certainly manageable in the coming month, the LHCb collaboration will concentrate on the preparation for the massive upgrade of the experiment in the long shut-down 2019/20. First cooling transfer lines

for the future Vertex Locator and Upstream Tracker were already installed in collaboration with the groups EP-DT and EN-CV, and final tests will take place over the next weeks, including the installation of the junction box that distributes the coolant close to the detector.

Preparation towards the new data centre at point 8 are progressing well. Very recently and with the great support by IPT, the contract for the data centre modules have been signed and the delivery of the first module is scheduled for autumn 2018. In close collaboration with the SMB and EN department, studies for the infrastructure are pursued intensively, as they have to be in place in summer next year.

With the LHC Run 3, Data from all detector Front-End electronics will be sent continuously at 40 MHz over optical fibres to 500 Readout boards into the data centre, 350m away from the detector at the surface, where they will be processed in the PC-Farm. Here, another milestone has been successfully achieved. The Readout boards, called TELL40, have been designed, prototyped and tested, ready for the production. The tendering process has been completed and the company for the board assembly will be selected soon.

Production of the upgraded detector has started in many collaborating institutes and the assembly areas at the experimental site are ready to accept the different sub-system parts for being put together. Modules for the SciFi Tracker have arrived last summer already. Transport and handling tools for the new systems have been design and the first ones are already constructed. To easy the dismantling, transport and storage of existing detector parts, special structures were developed and the construction of these is schedule for the first months of next year. In order to ensure a fast dismantling of the obsolete detector and service systems in LS2, storage areas will have to be erected close to the experimental hall. Negotiations with all stakeholders at LHC8 are completed and areas for a new temporary construction have been defined.

Finally, it should be noted that for every activity in LS2, Work Package Procedures are being established, including all safety aspects. These documents are crucial for a smooth process of the dismantling and installation at the experimental site and will be finalized during a comprehensive LHCb installation review in May 2018.

In less than one year the Long Shutdown 2 will start and the experimental cavern will be open for two years then. Although there are still some critical hurdles to be overcome and the schedule is very tight, the LHCb collaboration is excited as this moment approaches quickly. But before that, the experiment will prepare for another successful year of data taking.

## A special Xenon run for NA61

SME

LHC

by *Panos Charitos*



Earlier in October, the Large Hadron Collider had a special run of colliding xenon nuclei; a new flavour compared to the standard proton and lead collisions foreseen in the LHC experimental programme.

Xenon is a noble gas, present in miniscule quantities in the atmosphere. Its atoms consist of 54 protons and between 70 and 82 neutrons, depending on the isotope. The  $^{129}\text{Xe}$  collisions in the LHC are therefore similar to the lead-lead [collisions\(link is external\)](#) that are regularly carried out at the LHC. In that sense collisions between protons look significantly less busy, with fewer particles produced compared to the heavy-ion environment. However, this new run may lead to some surprising discoveries. After all this has been the case in the past when asymmetric proton-lead collisions shown unexpected collective behaviour.

The request for this unusual client of the LHC came from the NA61/SHINE experiment the as part of its reach programme on the physics of strong interactions. The xenon ions were injected into the pre-accelerators of the LHC to allow the NA61/SHINE experiment to study in detail the phase transition to a new state of matter where quarks and gluons travel free for very short distances forming the so-called quark-gluon plasma.

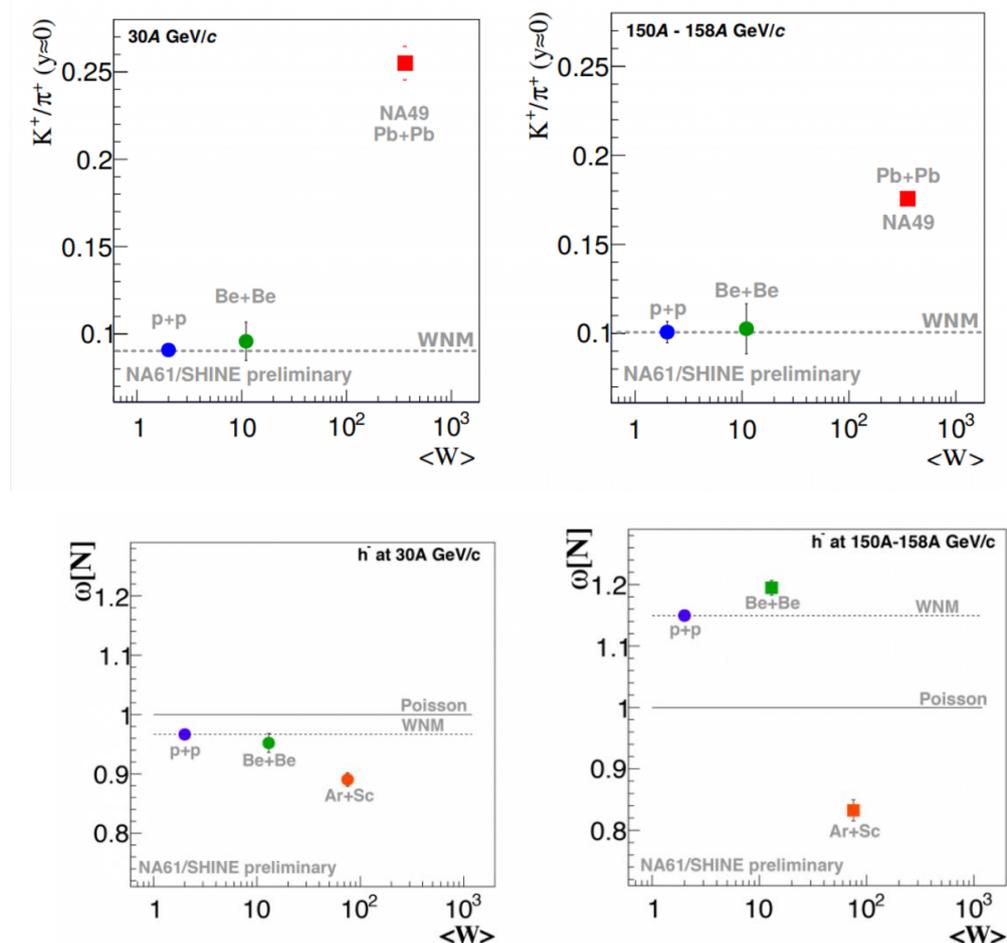
In 2009, NA61/SHINE has launched an ambitious programme measuring proton-proton, proton-nucleus and nucleus-nucleus collisions in an attempt to scope out the threshold for actually producing this primordial state of matter and discover the critical point of strongly interacting matter. This is performed by a two-dimensional scan of the phase diagram, by measuring particle spectra and fluctuations as a function of collision energy and system size.

For eight weeks, the SPS will supply xenon ions to the [NA61/SHINE](#) experiment allowing physicists to gather more data and carefully map the onset of deconfinement. The Xe+La results will be compared with previous data from p+p, Be+Be, Ar+Sc and Pb+Pb collisions, as well as with NA49 Pb+Pb results. As Marek Gazdzicki, spokesperson of NA61 explains: "With the NA61/SHINE ion program we plan, for the first time in history, to perform a full 2D scan with system size and energy. The new data complement what we got from previous runs since 2009 and will allow to cover a broad range of the phase diagram offering valuable experimental results".

In analyzing the data, researchers are looking for a characteristic "horn" and "step" in collisions of light and medium size nuclei. They try to understand whether these signatures of the onset of this

new phase of matter previously observed for Pb+Pb/Au+Au depend on the system size. Secondly, they are searching for the critical point. An increase of the critical point signal, the so-called hill of fluctuations, is expected for systems freezing-out near the critical point. Therefore non-monotonic dependence of the CP signal on control parameters (energy and size of colliding nuclei) will help physicists to locate the critical point.

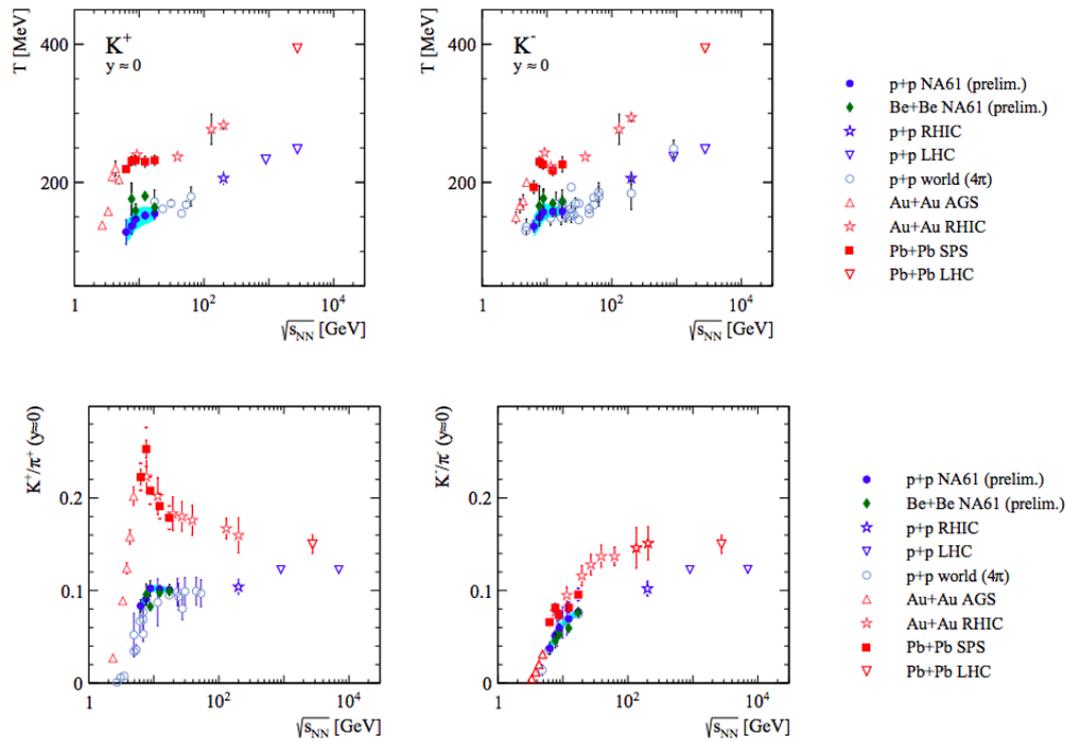
Figure 1 shows example plots on the system size dependence of the ratio of  $K^+$  and  $\pi^+$  yields at mid-rapidity and of the scaled variance of multiplicity distributions,  $\omega[N]$ . The dashed line shows prediction of Wounded Nucleon Model. Be+Be results were found to be very close to p+p independently of collision energy while there is a jump between light (p+p, Be+Be) and intermediate/heavy (Ar+Sc, Pb+Pb) systems.



It is important to recall that the  $K^+/\pi^+$  ratio in proton-proton collisions is lower than all predictions from statistical models while in lead-lead it is in better agreement with predictions for large volume systems. Furthermore, both in p+p and Be+Be collisions at high beam momenta, multiplicity fluctuations turn out to be higher than those predicted by statistical models. However, they are close to their predicted values for large volume systems in central Ar+Sc and Pb+Pb collisions. Thus, the observed rapid change of hadron production properties that emerges as we move from Be+Be to Ar+Sc collisions can be interpreted as the beginning of creation of large clusters of strongly interacting matter. This phenomenon is often referred as the onset of fireball. The

extension of the present study and the inclusion of data from Xe+La collisions observed with NA61 will further extend knowledge of this phenomenon.

Furthermore, hadron production properties in heavy ion collisions are found to change rapidly with increasing collision energy in the low SPS energy domain,  $\sqrt{s_{NN}} \approx 10$  GeV. The NA61/SHINE results shown in Figs. 2 indicate that this is also the case in inelastic p+p interactions and probably also in Be+Be collisions. The phenomenon is labelled as the onset of deconfinement and interpreted as the beginning of creation of quark-gluon plasma with the increase of collision energies.



Thus, the two-dimensional scan conducted by NA61/SHINE by varying collision energy and nuclear mass number of colliding nuclei indicates four domains of hadron production properties separated by two thresholds: the onset of deconfinement and the onset of fireball. The sketch presented in the figure below illustrates the general concepts and the above conclusions.



**Two-dimensional scan conducted by NA61/SHINE by varying collision energy and nuclear mass number of colliding nuclei indicates four domains of hadron production properties separated by two thresholds: the onset of deconfinement and the onset of fireball.**

With increasing nuclear mass number, the density of clusters in the transverse plane increases. Thus, the probability to form large clusters by overlapping many elementary clusters may rapidly increase with  $A$ , the behaviour typical for percolation models. However, this approach does not explain the equilibrium properties of large clusters.

Within the AdS/CFT correspondence creation of strongly interacting matter (system of strongly interacting particles in equilibrium) is dual to the formation of a (black hole) horizon and trapping some amount of information from the distant observer. It was found that the formation of the trapping surface takes place when critical values of model parameters are reached. This may serve as a possible explanation of the onset of the fireball phenomenon - only starting from a sufficiently large nuclear mass number the formation of the trapping surface in  $A+A$  collisions is possible. If this is the case then this is then observed as the onset of fireball. Further analysis of data will tell us if this is true or part of a larger picture.

You can also read here a [report \(link is external\)](#) from the four LHC experiments.

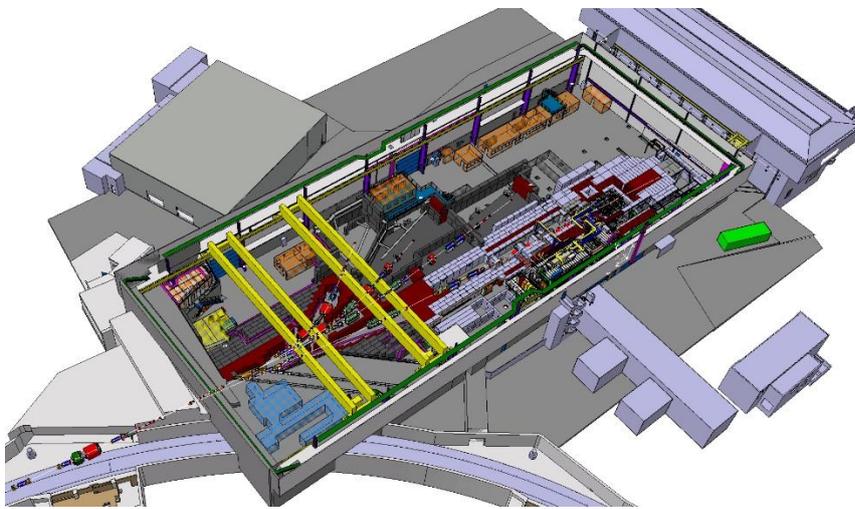
## 2017: an exceptional year for the EP-DT proton irradiation facility

### IRRAD

DT

by *Federico Ravotti (EP-DT)*

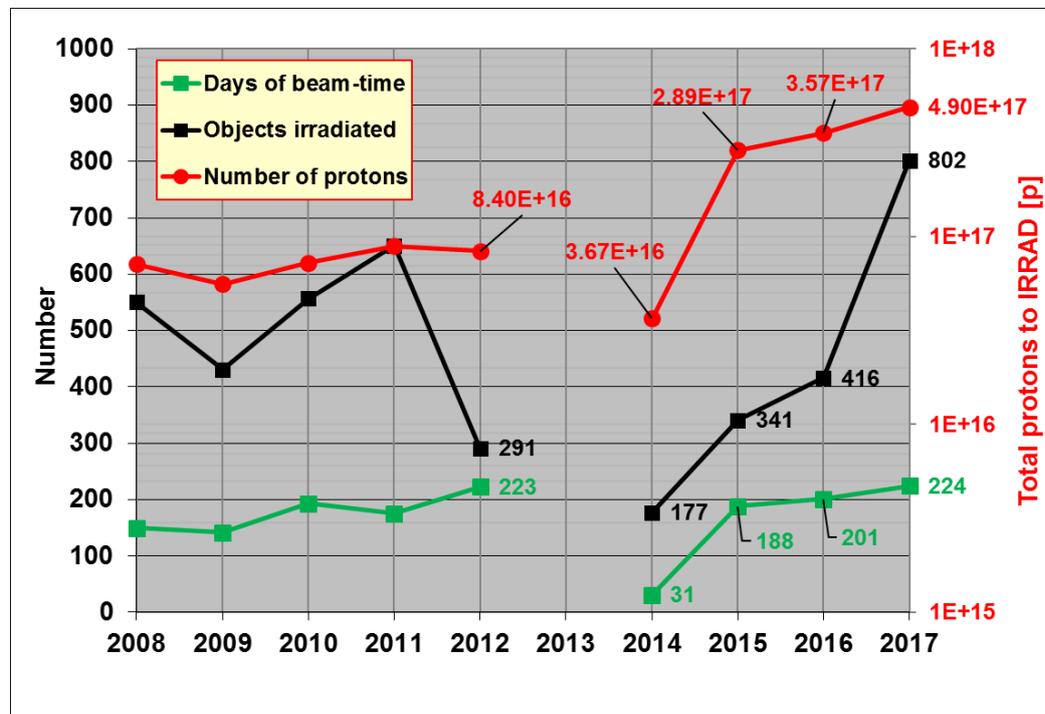
The CERN proton irradiation facility (IRRAD) at the PS East Area has been designed and built during LS1 to cope with the increasing need for irradiation experiments of the EP experimental community, working for the High-Luminosity upgrade of the LHC and beyond. This new facility is the natural upgrade of a historical service in the experimental physics department that, since the early 90's, exploit the high intensity proton beam of the CERN PS for studying the radiation hardness of materials and semiconductor devices (see also: <https://ep-news.web.cern.ch/content/new-proton-mixed-field-irradiation-facility-cern-ps-1>).



The IRRAD facility, operated by the PH-DT group, is nowadays part of a more complex infrastructure in the PS East Area available after the LS1. The new PS facility is divided in two separated irradiation areas operating in parallel and sharing the same high-energy proton beam (24 GeV/c) extracted from the PS to the T8 beam-line. The IRRAD facility is located upstream of the mixed-field facility (CHARM). While in IRRAD, irradiation experiments are performed with the primary protons, in CHARM a mixed-particle radiation field is used after being generated by a 50 cm thick copper or aluminium target. The CHARM facility, operated by the EN department, is optimized to reproduce the radiation environment of the LHC tunnel and the typical shielded areas of the CERN accelerator complex. Moreover, since 2016, the East Area facility hosts also a measurement location which makes parasitic use of the radiation field emerging from the CHARM target to perform characterization studies of the shielding properties of various materials. This facility (called CERN Shielding Benchmark Facility or CSFB) is used by the CERN Radiation Protection group and benefits of one week of dedicated beam-time per year.

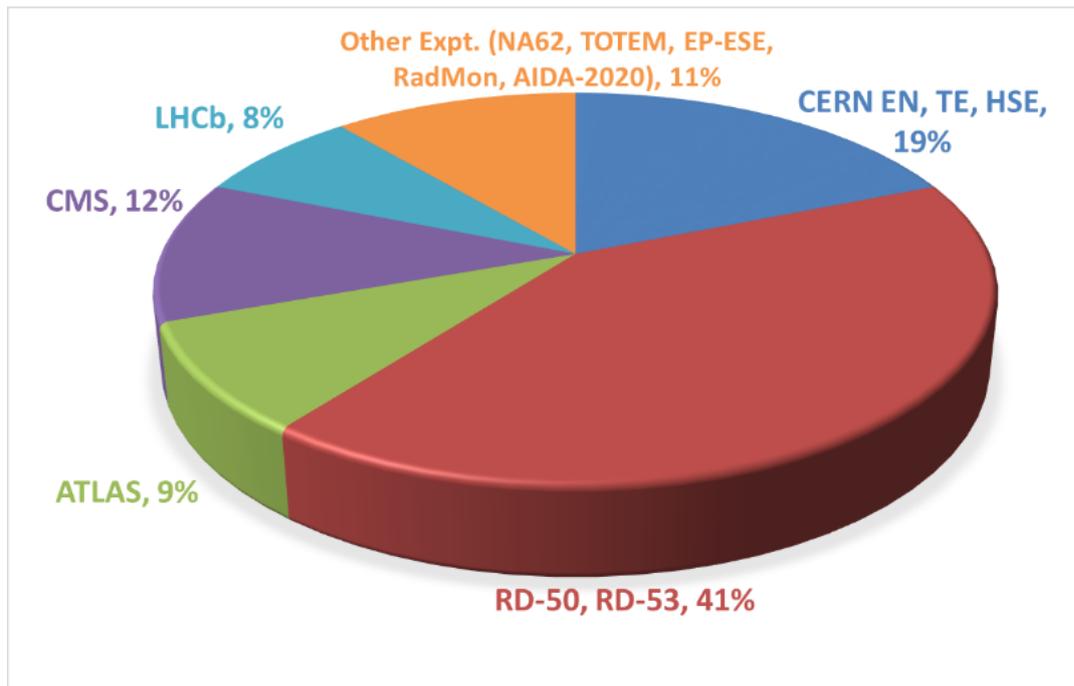
After a short run of one month in 2014, IRRAD has been operational for three full consecutive years since 2015. In a calendar year, about 200 days of beam-time are available for irradiation experiments in IRRAD. As shown in Figure 1, the number of irradiated samples constantly increased year after year since the new facility began its operation after LS1. More in detail, the run 2017 for the users of IRRAD started at the end of April and ended on 3rd of December 2017. During these 32-weeks of operation, more than 800 objects, belonging to 33 users of 19 different

institutes from 12 countries, have been exposed to the proton beam. This large number of samples (about 50% more than in the previous run 2016) represents a record for the new facility. This exceptional performance was possible also thanks to the excellent availability of the PS accelerator and the high-quality of the irradiation beam provided by the BE-OP team at the CCC which nowadays steadily approach the design limit of  $5 \times 10^{11}$  particles per proton spill delivered to IRRAD.



**Fig.1 – Statistics for the IRRAD facility before and after LS1 (2012-2014). The number of irradiated objects and days of beam time (left vertical axis), as well as the total number of protons delivered to IRRAD (right vertical axis), are plotted for the last 9-years of operation.**

Details on the users of the facility and the number of irradiated objects per experiment, for the year 2017, are given in Figure 2. About 40% of them are solid-state detector test-samples belonging to the R&D collaborations, mainly RD50 ([www.cern.ch/rd50](http://www.cern.ch/rd50)) for which the IRRAD facility was originally developed in the late 90's. Another 40% of samples comes for the LHC and other CERN experimental collaborations such NA62. This includes the ATLAS, CMS, LHCb and TOTEM experiments that are now evaluating the new detector technologies for the Phase II and future upgrades of their tracking and calorimeter detectors, as well as samples from common development projects performed within the CERN microelectronics group (EP-ESE) and R&D projects for future accelerators (FCC). The final 20% is constituted of material samples for radiation hardness studies belonging to LHC equipment groups in the EN and TE department (electrical distribution, magnets, etc.) as well as to the CERN safety unit (HSE).



**Fig.2 –Origin of the objects (more than 800 in total) exposed to the proton beam in IRRAD during 2017.**

Although the proton run is now concluded, before the YETS 2017/2018, the first two weeks of December 2017 are now dedicated to the development and commissioning of a heavy-ions beam on T8. This has the main goal to provide a beam for Single Event Effect (SEE) studies in electronic components for space application in CHARM; however, it will be made available in the end of 2018 (with Pb-ions) also to the users of IRRAD.

The IRRAD team in EP-DT is looking forward to the irradiation run 2018, the last one before the LS2. The detailed program for 2018, as well as all information about how to request beam-time and register samples for proton irradiation will become available at this URL: [www.cern.ch/ps-irradduring](http://www.cern.ch/ps-irradduring) February next year. So far, users from ATLAS, CMS, the CERN vacuum group (TE) and target group (STI) express their interest and requested beam-time in IRRAD, confirming the key role of this test infrastructure for the CERN experimental and accelerator communities.

The IRRAD facility is also part of the AIDA2020 Transnational Access to irradiation facilities program that provides funding for external users to perform their irradiation tests at CERN. More details are available here: <http://aida2020.web.cern.ch/content/how-apply-transnational-access>

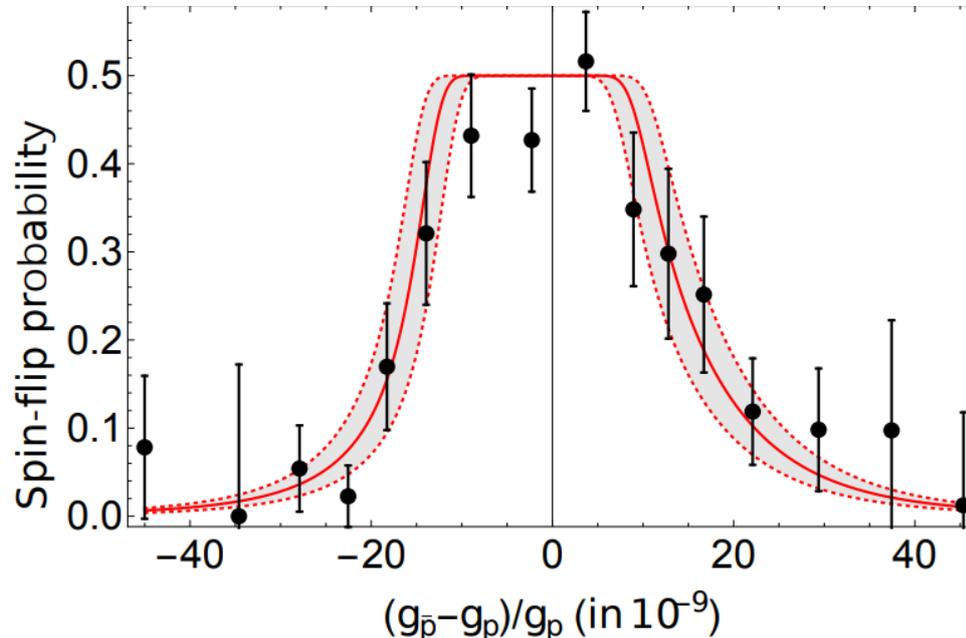
**The EP-DT Irradiation Facilities team:** B. Gkotse, M. Glaser, G. Gorine, M. Jaekel, I. Mateu, G. Pezzullo and F. Ravotti

## Another milestone for the BASE collaboration

by *Christian Smorra on behalf of the BASE collaboration*

In a recent publication in the Nature magazine, the BASE collaboration reports on the first high-precision measurement of the antiproton magnetic moment with parts per billion uncertainty (see <https://www.nature.com/articles/nature24048>(link is external)). The antiproton magnetic moment is now determined with 350-fold improved precision to be  $-2.792\,847\,344\,1(42)$  times the nuclear magneton. Two single antiprotons confined separately in a multi Penning trap system with extremely high vacuum have been questioned in a novel measurement scheme to unveil this number with nine significant digits.

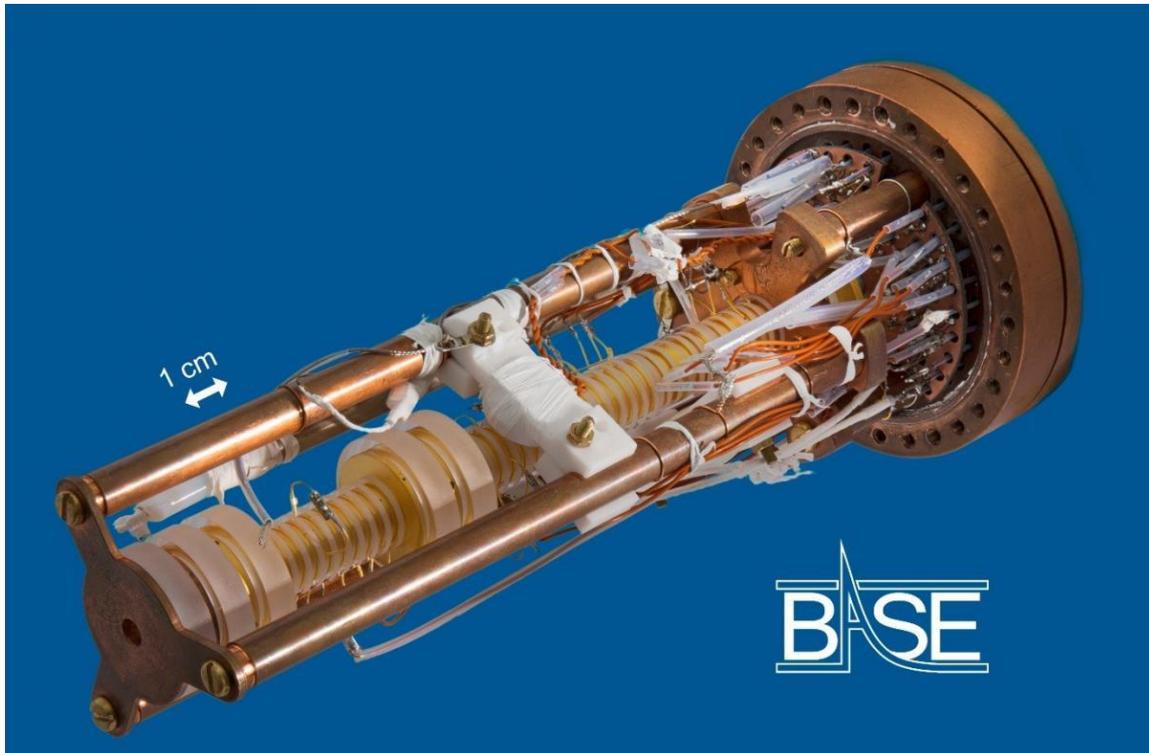
The BASE collaboration set their sails in 2013 in the Antiproton Decelerator (AD) to compare the fundamental properties of protons and antiprotons with highest precision. The team around Stefan Ulmer, spokesperson of the BASE collaboration, has made comparisons of the proton and antiproton charge-to-mass ratios, set lower limits on the antiproton lifetime, and reported including the recent study two record values for the antiproton magnetic moment. Such measurements challenge an important symmetry in the Standard Model of particle physics: The combined charge, parity and time-reversal (CPT) invariance. This symmetry is imbedded into the quantum field theories of the Standard Model and requires protons and antiprotons to have the same fundamental properties. Masses, lifetimes, charges and magnetic moments must be identical, but the latter two have opposite signs. Any observed deviation in their fundamental properties would hint to yet uncovered interactions that would act differently on protons and antiprotons, such as those described by the Standard Model Extension or CPT-odd dimension-five operators.



**g-factor resonance:** spin-flip probability as a function of the irradiated frequency ratio. The red line is the result of a direct likelihood estimation of  $g_p$  and  $\Omega_R$ . The grey area indicates the 68% error band. The black data points are binned averages of the measured  $P_{SF}(f)$  displayed with error bars corresponding to 1 standard deviation.

To make these high-precision studies, the BASE team operates a multi Penning trap system placed in a cryogenic vacuum chamber inside the bore of a superconducting magnet with 1.9 T field strength. The electrode system provides four harmonic Penning trap configurations and is

shown in Fig 1. One of them is the reservoir trap, which serves as interface between the AD and the single-particle precision Penning traps. Antiprotons injected from the AD, and in the future from ELENA, are confined and cooled in this trap to temperatures of a few Kelvin. A potential tweezer method allows pulling out single antiprotons from the reservoir, and using them for precision experiments. In this way, the BASE team operated their experiment for 405 days from a single shot of antiprotons.



**Fig. 1: The assembly of the BASE Penning trap system. The trap stack consists of gold-plated electrodes made from oxygen-free copper, which are spaced by sapphire rings. The electrodes form four harmonic field configurations. One of them, the analysis trap, has a ferromagnetic ring electrode to provide the strong magnetic bottle ( $B_2 = 30\text{T/m}^2$ ) for the spin state identification (Photo: Stefan Sellner, RIKEN).**

The magnetic moment measurement requires to measure two frequencies of the trapped antiprotons, the Larmor frequency, which is the precession frequency of the antiproton's spin around the magnetic field lines and the cyclotron frequency, the revolution frequency in the magnetic field. The cyclotron frequency is non-destructively measured by detecting tiny image currents of a few fA induced by the antiproton's motion in the trap electrodes. This is an established technique, which has also been used for the determination of atomic masses in high-precision mass spectrometers, such as the antiproton  $q/m$  spectrometer operated by the TRAP collaboration at LEAR, or MPIK's PENTATRAP mass spectrometer.

The major challenge is the measurement of the Larmor frequency, which is not directly accessible by image currents. One possibility is to induce spin transitions between the two Zeeman levels of the antiproton's spin in the magnetic field and observing that the spin orientation changes. But how can you observe the orientation of a single nuclear spin?

Nobel laureate H. G. Dehmelt invented a technique, which he called the continuous Stern-Gerlach effect. It allows making quantum non-demolition measurements of the spin state of a trapped charged particle. This technique has been successfully applied to make the most precise measurements of the electron and positron magnetic moments; the most precise values for these

quantities have been obtained at Harvard University and the University of Washington, respectively. To this end, an inhomogeneous magnetic field is superimposed to the Penning trap, and the curvature term  $B_2$  of the magnetic field in units  $T/m^2$  couples the magnetic moment of the particle to its axial oscillation. In a homogeneous magnetic field, the axial motion is a harmonic oscillation generated by electric field preventing the particle from moving along the magnetic field lines. The result from adding the magnetic bottle  $B_2$ , is that the particle changes its axial frequency when a spin transition occurs.

The application of this technique to the antiproton comes with a major challenge. The frequency shift caused by a spin transition is proportional to the factor magnetic moment over mass  $m/m$ , which is more than one million times smaller for the antiproton compared to the electron. To compensate this, the BASE team uses a magnetic bottle at the technical limit  $B_2=300\,000\text{ T/m}^2$  to couple the antiproton's spin magnetic moment to its axial oscillation. Even in this strong inhomogeneous magnetic field, a spin flip changes the axial frequency of about 700 kHz only by 180 mHz. The strong magnetic bottle complicates the experiment since frequency measurements exhibit also line broadening due to the dependence of the magnetic field on the antiproton's motional amplitudes. This has been the major limitation in the measurements reported by the ATRAP collaboration in 2013 and also in the BASE measurement reported earlier this year.

The so-called double Penning trap technique for magnetic moments overcomes these limitations. In this scheme, the two frequencies are measured in a homogeneous trap, the precision trap, and the trap with the magnetic bottle, the analysis trap, is only used to identify the spin state before and after spin transitions are driven in the precision trap. This measurement scheme has been conventionally applied with one particle used for the measurement of both frequencies.

The BASE team developed in their newest measurement a scheme, which separates the two frequency measurements onto two particles: a cyclotron antiproton to calibrate the magnetic field, and a Larmor antiproton for the spin transition spectroscopy. The two antiprotons are placed alternately in the precision trap, and the magnetic field is interrogated by the cyclotron antiproton before and after driving a spin transition of the Larmor antiproton in the same magnetic field. This novel scheme allows to keep the Larmor antiproton at a radial temperature below 0.2 K during the whole measurement procedure, whereas the cyclotron antiproton is heated by each magnetic field measurement to a temperature of about 350 K.

Spin transitions in the analysis trap can only be observed at temperatures below 0.2 K, because spurious voltage noise of about  $10\text{ pV/Hz}^{1/2}$  destabilizes the axial frequency due to mode coupling in the magnetic bottle. The transition rate in the radial modes becomes only small enough to identify individual spin transitions for ultra-cold particles below the 0.2 K threshold. The re-cooling of the radial modes after the cyclotron frequency measurement has been limiting the statistical uncertainty in past measurement. The new accelerated two-particle measurement scheme allowed to accumulate more statistics and is therefore about a factor of 2 more precise than the double trap measurement of the proton magnetic moment in 2014, which was carried out in the BASE-Mainz experiment.

The reported measurement reveals that protons and antiprotons have the same magnetic moments up to nine digits of precision. CPT-odd interactions in the baryon sector, which would manifest in a measured difference in the magnetic moments, have been excluded with an energy resolution of  $10^{-24}\text{ GeV}$ . The BASE collaboration continues to improve their methods to make even more precise tests of CPT invariance in the future and probe for effects of beyond Standard Model physics with an even higher energy resolution.

# Searching for leptoquarks at the LHC

by *Panos Charitos*

Last month, Admir Greljo (University of Mainz) and Abdollah Mohammad (Kansas State University, US) during the Collider Cross Talk, gave a comprehensive overview of the theoretical and experimental aspects in leptoquarks searches.

Leptoquarks are hypothetical particles that can turn quarks into leptons and vice versa and they can be either scalar (spin-zero) or vector (spin-one) particles. Moreover, they participate both in QCD and electroweak interactions in addition to the direct quark-lepton coupling as they have both a color and an electroweak charge.

Recently there has been some renewed interest in leptoquarks. The reason is that these particles seem well equipped to address some of the hottest topic in the search for new physics that lie beyond the Standard Model. Moreover, recent hints of lepton universality violation in semileptonic B-meson decays strengthened the interest in leptoquarks.

As Admir Greljo explains: "Leptoquarks are quite common in models beyond the Standard Model. Such particles typically arise as composite resonances of a hypothetical new strong dynamics at the TeV scale. They help us to address the electroweak scale stabilization problem (the smallness of the Higgs boson mass) in a natural way". He adds: "Another paradigm predicting leptoquarks is a model of quark-lepton unification strongly motivated by the charge quantization as well as hinted gauge coupling unification. Thirdly, supersymmetry with the R-parity violation is a motivated theoretical framework predicting leptoquarks."

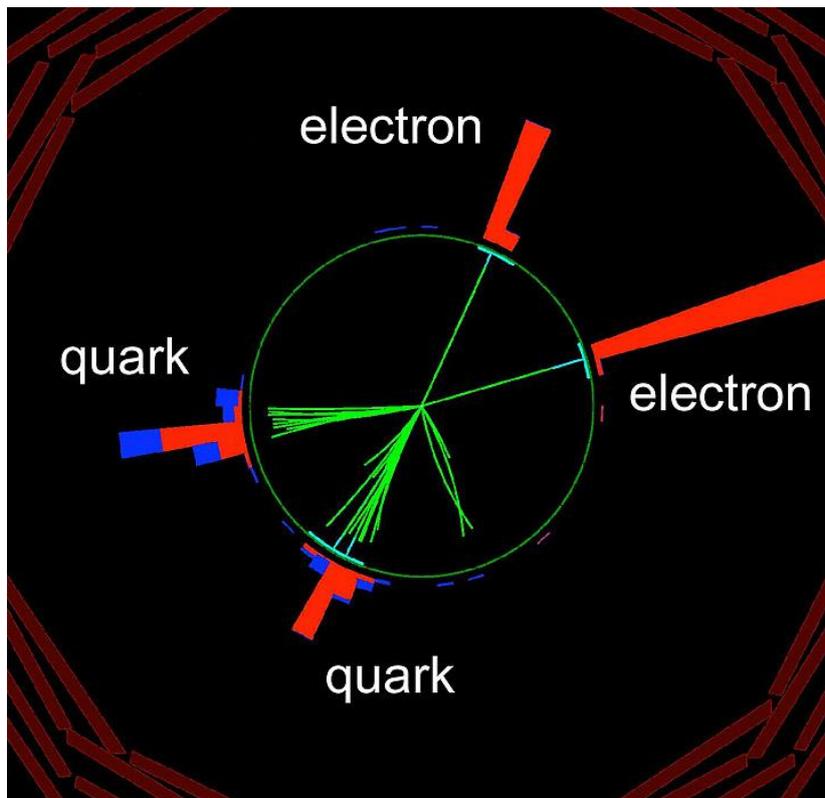
In fact there is a wide range of possible quantum numbers for leptoquarks which however can be restricted both by theoretical assumptions and results from current experimental searches. Greljo notes: "The leptoquark zoo contains only a handful of distinct particles which, however, exhibit a very rich phenomenology (see for example [here\(link is external\)](#)). If they exist, they could leave a footprint in precisely measured low-energy observables such as flavour transitions and electroweak tests, but also lead to a spectacular signature in the ATLAS and CMS detectors."

In fact, direct limits come from their production cross sections at colliders, while indirect limits are calculated from the bounds on the leptoquark-induced four-fermion interactions, which are observed in low-energy experiments. LEP, Tevatron and LHC experiments search for pair production of the leptoquark states.

At the LHC, there are two main leptoquark production mechanisms at play. Firstly, leptoquarks are copiously produced in pairs via strong interactions followed by the prompt decay to leptons and jets. "This is indeed a conventional assumption in most experimental searches" says Greljo. After creation, a leptoquark would split almost immediately into a quark and a lepton and could be identified by looking for their decay products. Quarks, since they can't exist isolated, quickly create many quark-antiquark pairs and form a "jet" of particles that can be identified by the large energy deposition in the calorimeter. The lepton can be an electron, muon, tau or a neutrino. An electron is identified by the presence of an isolated track in a tracking chamber and energy deposition in the electromagnetic portion of a calorimeter. Neutrinos are identified by "missing" energy since they escape the detector, carrying energy away.

Another important mechanism at the LHC, is the production of a single leptoquark in association with a lepton due to the direct quark-lepton coupling. Greljo says: "The later process is an important complementary perspective which is not yet fully exploited by the experimental collaborations.

Finally, it should be noted that leptoquarks can lead to non-resonant effects in the high energy tails of the dilepton invariant mass”.

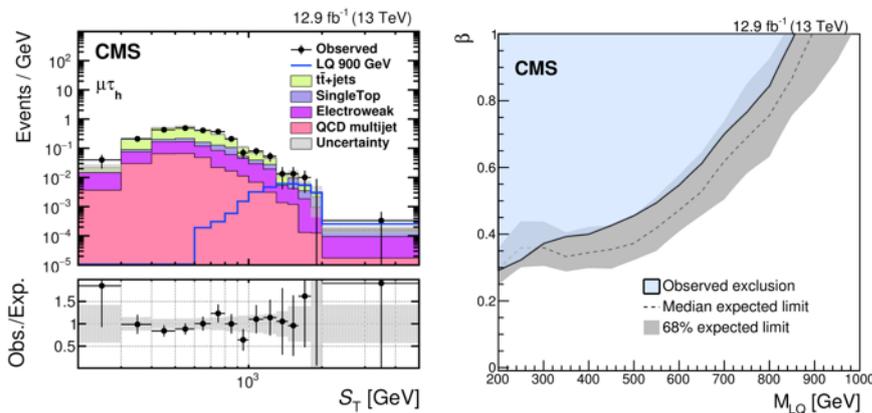


**Particle collisions that look like this are used to search for leptoquarks. This figure is specifically for (electron + up/down quark) type collisions. (Image credits: Fermilab Today).**

There have been extensive searches for leptoquarks both by ATLAS and CMS experiments. These searches include all three generation leptoquarks using both 8 TeV and 13 TeV data. Nonetheless, so far there is no smoking gun for the existence of the leptoquarks.

The most recent results from CMS experiment on the pair production of the third generation scalar leptoquarks in the events with two taus and two b-jets, exclude leptoquarks with masses below 850 GeV at 95% confidence level using 12.9 fb<sup>-1</sup> of 13 TeV data. The scalar sum of the transverse momenta of the two tau leptons (which one decays to a muon or an electron and the other decays to hadrons), two jets and missing transverse energy, denoted by ST, is used as the final observable.

To obtain the limit on the product of the cross section and branching ratio of leptoquarks to a lepton and a quark, the ST distribution of all standard model backgrounds plus signal hypothesis is compared to that of data. Data shows agreement with the background-only hypothesis which excludes the presence of a signal. In the following plot (left) the ST distribution is shown for the semileptonic decay of the tau into a muon. Similar plot exists for the electron channel as well. The 95% confidence level has obtained by combining both channels. The limit depends on the branching fraction of the third-generation leptoquark to a tau lepton and b quark, and is usually denoted by  $\beta$ . The observed and expected exclusion limit in terms of the  $\beta$  is depicted in the right plot.



Similar analysis has been performed on the third generation leptoquarks where both tau leptons decay hadronically using  $2.3 \text{ fb}^{-1}$  of 13 TeV data. For the case of  $\beta = 1$ , the observed exclusion limit is set to about 740 GeV. Exploring the LQ in the first and second generations using  $2.6 \text{ fb}^{-1}$ , also reveals no indication of the signal and the limits are set on the product of cross section and branching ratio of the LQ which is equivalent to 1130 and 1165 GeV, respectively.

CMS has also explored leptoquarks in other final states (i.e. top plus taus) and through different production mechanism such as single produced leptoquark. ATLAS has also conducted several searches for both pair-produced and singly-produced leptoquarks in different generations, all leading to set a limit in the lack of presence of a signal on top of the standard model background. However, since the last public results, LHC has provided much more integrated luminosity and both CMS and ATLAS experiments are analysing the entire 2016 and possibly 2017 data to shed light on the existence of leptoquarks with the largest dataset we had ever.

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This “Cross Collider” talk showed that the physics of Leptoquarks is a very rich and mature subject and at the same time, a rapidly evolving field on both experimental and theoretical fronts. It is only through the collective effort of the whole community that we will be able to make progress in the quest for new physics.

# Searching for leptoquarks at the LHC

ATLAS

CMS

LHCb

TH

by **Panos Charitos**

 [PDF version](#)

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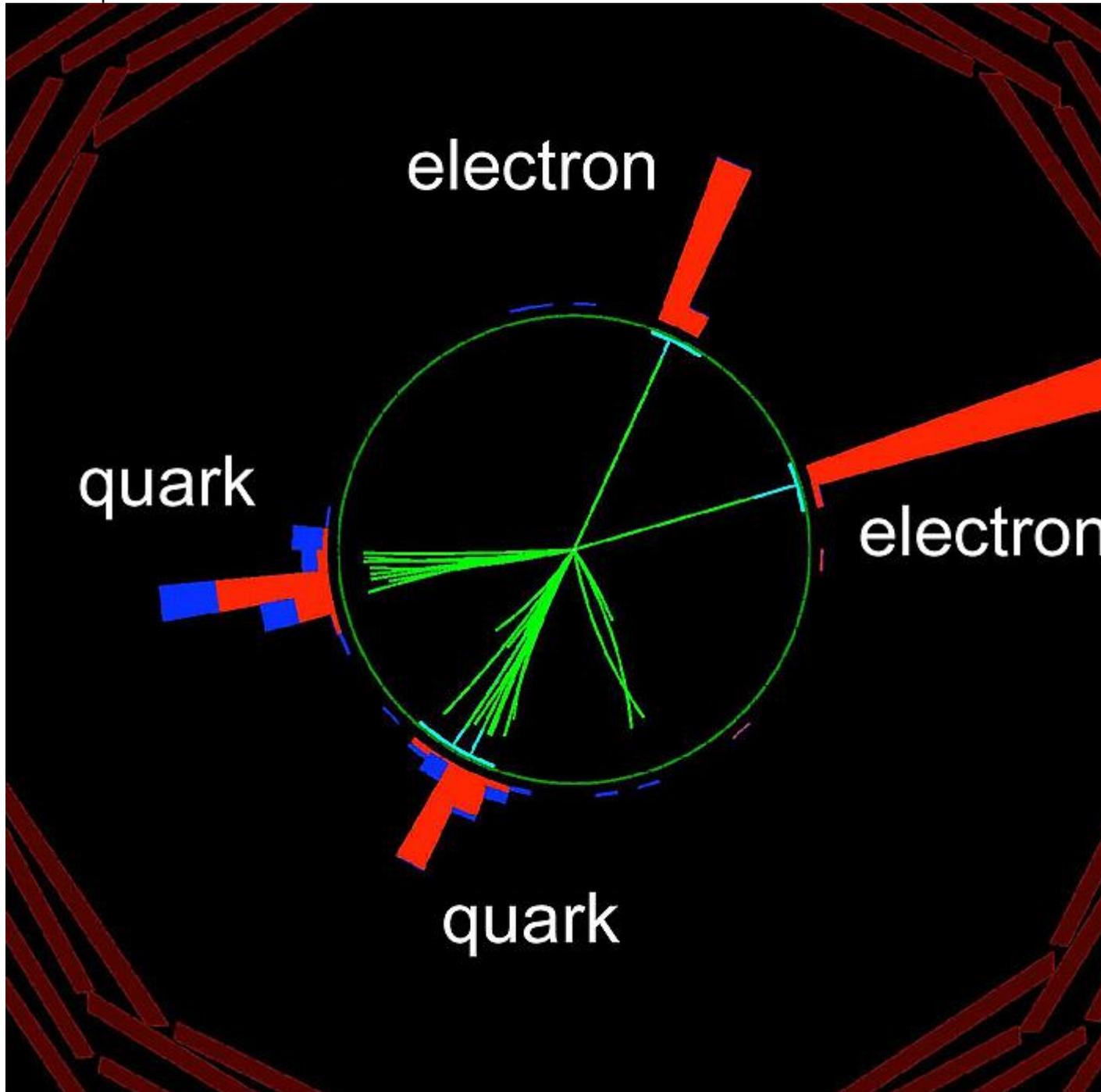
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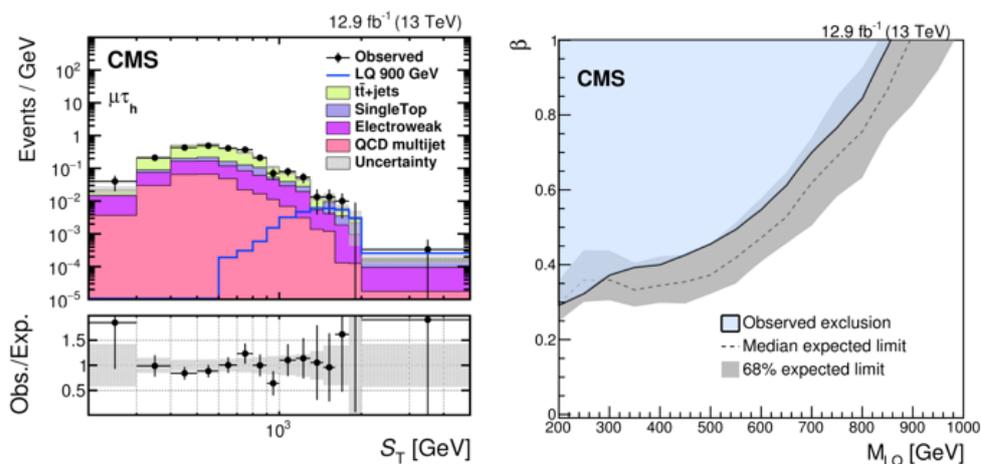


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## **Designing Utopia – An Ultralow Picoammeter**

by *Evgenia Voulgari (ESE)*

There are various applications where the output of a sensor is a low current. In some cases like in ionizing radiation measurements, device characterization, leakage current measurements and biosensing instrumentation, the current that has to be measured can be as low as few femtoamperes. However, designing a measuring digitizer for the femtoampere range is not a trivial task.

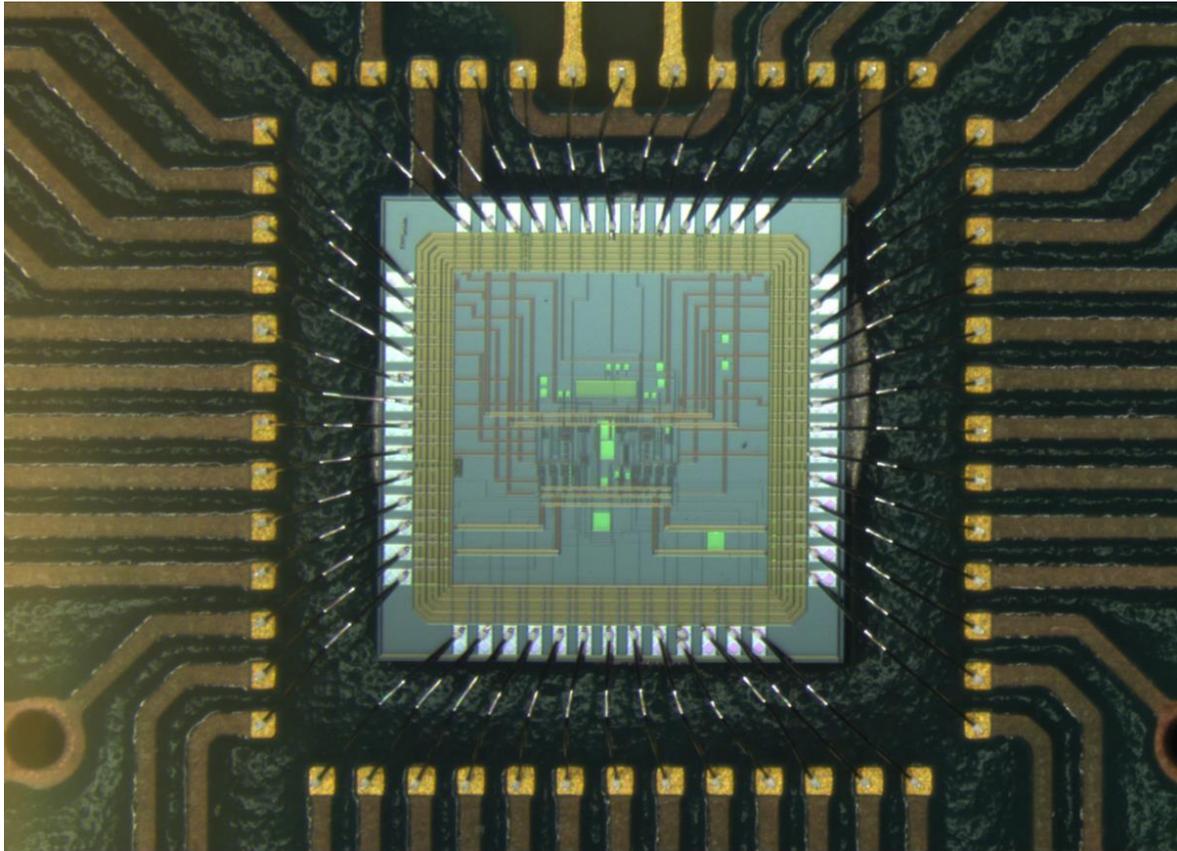
One could ask what is the smallest current that can be accurately measured using a readout front-end circuit ? To answer this question we should start from the leakage current of a minimum size MOS transistor in a standard CMOS process. The net leakage current for example in AMS 0.35  $\mu\text{m}$  technology can be in the order of hundreds of femtoamperes.

The radiation monitors that are used at CERN for radiation monitoring are based on ionization chambers whose output current spans over more than 9 decades starting from 1 fA and extending to 5  $\mu\text{A}$ . The required resolution is also 1 fA that is equal to a flow of about 6250 electrons/second.

So measuring a current that is equal to 1 femtoampere is challenging especially because of the main limitation, the leakage currents that are injected into the circuit’s input from various sources. But this is not the only constraint since measuring over such a wide dynamic range requires high speed so that the system can react to a current up to 5  $\mu\text{A}$ : 5000 million times bigger.

We named this ASIC Utopia, for two main reasons. Firstly because we designed an Ultra-low Picoammeter, but mainly inspired by the demanding requirements. Measuring currents down to 1 femtoampere set a big challenge. The final measurements and the characterization of the first demonstrator, the Utopia 1 ASIC, proved that Utopia turned to reality.

Based on the architecture of a current to frequency converter that has been used in the past for front-ends for radiation monitoring, we designed a demonstrator with four channels that differ slightly in order to isolate, measure and evaluate the different sources of leakage currents. The net leakage was related to the input switches, the ESD protection diodes, the adjacent pins voltage, the PCB and finally the cable and the connector.



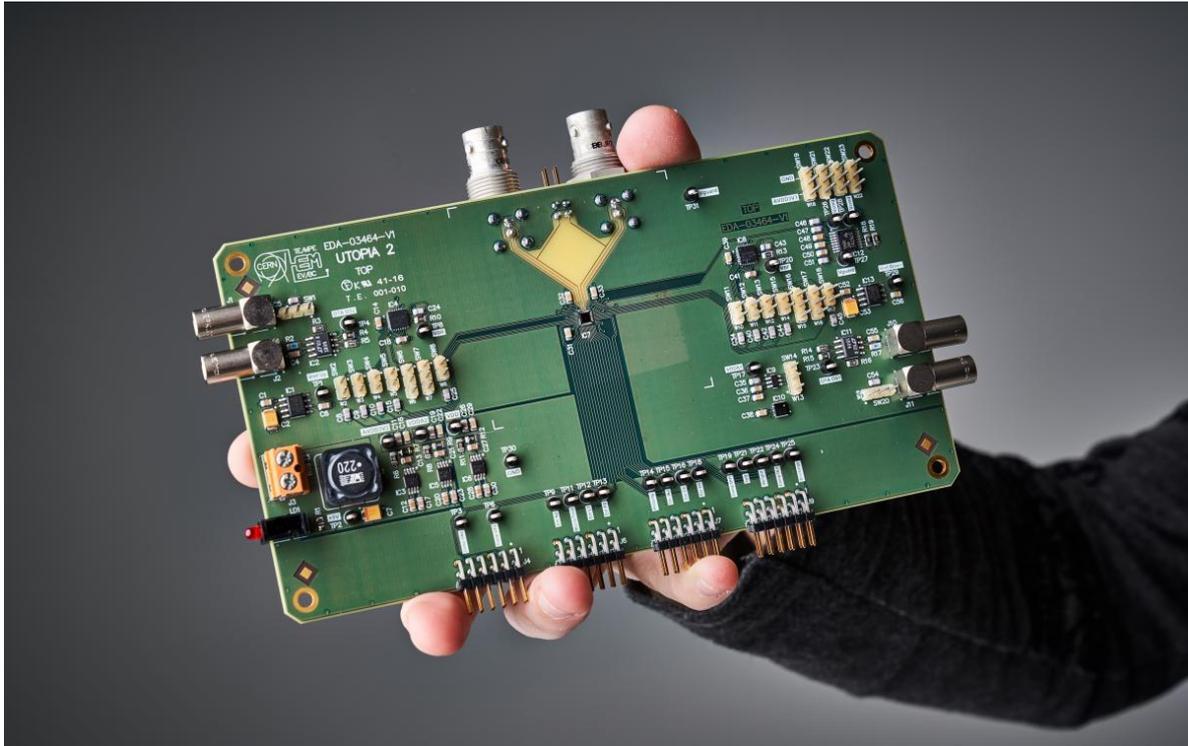
**Figure 1: Microscopic picture of the Utopia 2 ASIC that is designed in AMS 0.35  $\mu\text{m}$  technology and has a die size of 2.75 mm x 2.75 mm.**

Circuit techniques that can decrease the subthreshold leakage current were used along with methods to minimize the extrinsic leakage current sources in system level. After the characterization of the ASIC, the dominant source of leakage current proved to be that of the electrostatic discharge protection. This also has a strong temperature dependence doubling every 8 °C.

In order to overcome this problem, the Utopia 2 ASIC was designed using an active leakage current compensation scheme. A dummy channel that replicates the input structures of the measuring channel and is designed matched to it, can subtract the leakage current from the measuring channel's input. This scheme provides a leakage current-free measuring channel that digitizes the current that is related to the incident radiation.

After solving the femtoampere current obstacle, the ASIC had to measure current up to 5 microamperes. The speed of the OTA was increased and an automatically selected second range was introduced in order to be able to cover the wide measurement range.

This state of the art ASIC, was characterized at METAS, the Swiss Federal Institute of Metrology, where measurements down to 1 femtoampere took place.



**Figure 2: The Utopia 2 PCB that was used to characterize the Utopia 2 ASIC.**

This work is the outcome of the collaboration between the EP-ESE group, the HSE-RP group and the Electronics LAB (ELAB) of EPFL. The chip was designed and tested in order to be used from the Radiation Protection group of CERN for the new radiation monitoring system.

More information about the Utopia 2 ASIC can be found in the doctoral thesis: [A nine decade femtoampere current to frequency converter](#)

# Deep learning and the quest for new physics at the LHC

by *Panos Charitos*

With massive amounts of computational power, machines can now recognize objects and translate speech in real time. Deep-learning software attempts to mimic the activity in layers of neurons in the neocortex, the wrinkly 80 percent of the brain where thinking occurs. The software learns, in a very real sense, to recognize patterns in digital representations of sounds, images while it can also be used to analyse the data collected by the detectors of the LHC experiments.

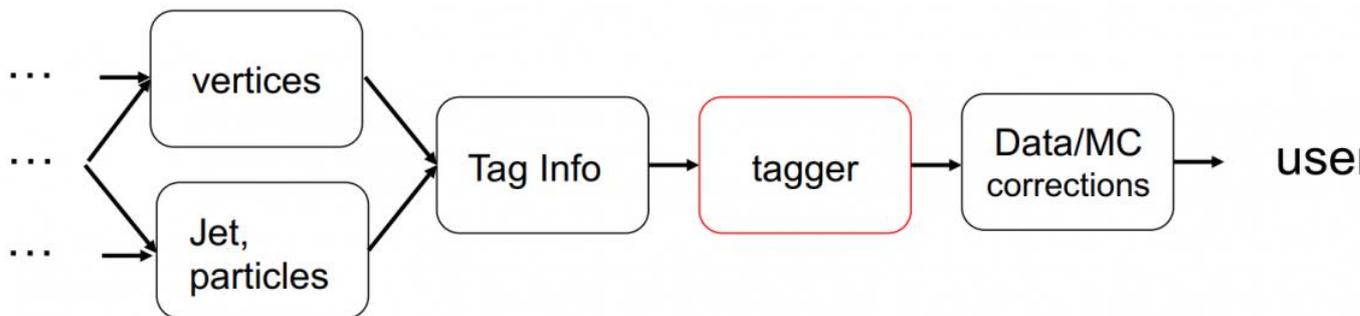
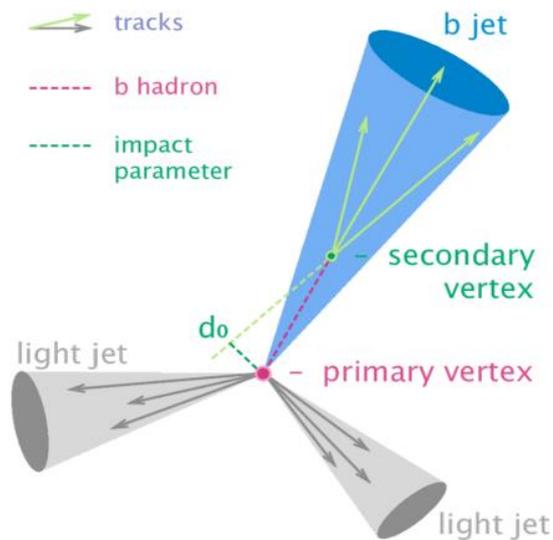
The current Deep Learning hype is that given enough data and enough training time, it will be able to learn on its own. Could it also be the case that in the future it helps us to graph new ideas and concepts in high-energy physics? This may be an exaggeration of what the state-of-the-art is capable of doing for now and far from the actual practice of deep learning. However, it is true that Deep Learning over the past few years given rise to a massive collection of ideas and techniques that were previously either unknown or known to be untenable.

A key property of any particle is how often it decays into other particles. The ATLAS and CMS experiments at the LHC search for new particles and processes using head-on collisions of protons of extraordinarily high energy. Searches for rare processes and short-living particles are challenges by the required statistics and the noisy background that could hide signals of new physics. This challenges puts a need to explore how advanced machine-learning methods could apply to improve the analysis of data recorded by the experiments.

Presently the experiments select interesting events - at the level of the so-called High-Level Triggering - by reconstructing the trajectory of each particle using the raw data from the silicon layers of the inner tracker. Raw data from the detector are processed to obtain hit clusters, which are formed by nearby silicon pixels which have an electrical current value greater than zero. The cluster shape depends both on the particle, on its trajectory and on the module that has been hit. In that sense, track reconstruction by its nature is a combinatorial problem that requires great computational resources.

It is implemented as an iterative algorithm where each iteration apply five steps. In the seed generation track seed are created from hits in the internal layers of the detector based on a set of parameters. The seeds found in the first step are used for the track finding, which looks for other hits in the outer layers. After all the hits have been associated to the track the track fitting determines the parameters of the trajectory. The last step of the iteration is track selection, which is necessary because the previous steps could generate fake tracks. This steps looks for signals that denotes fake particles, like a large number of missing hits. Note that missing hits could be caused by different reason, like broken pixels or a region not covered by sensors. The previous steps are repeated in an iterative fashion, each time with different parameters for the seeding phase. Using this method it is possible to search for easy tracks first, eliminate from the successive searches the hits associated with the found tracks, and look for the more difficult tracks in the successive steps with a less dense environment.

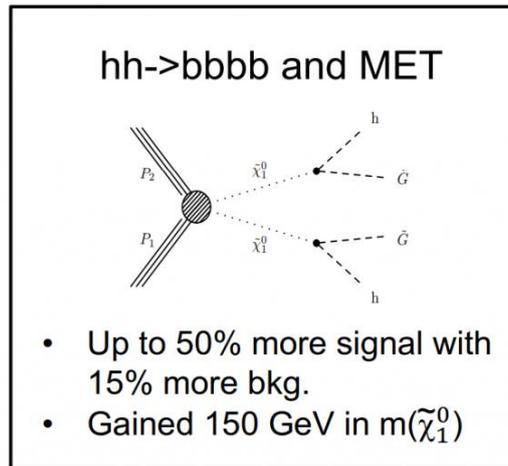
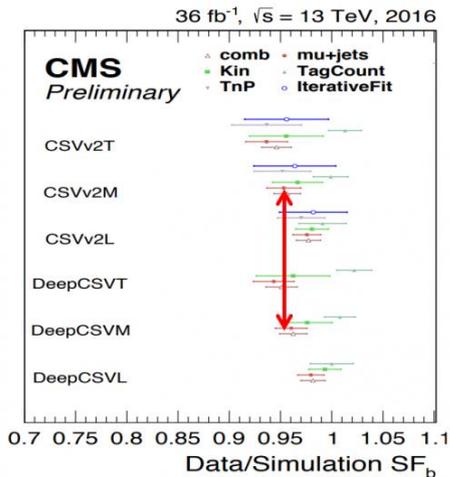
As perhaps you can imagine, the main problem of this approach is the huge number of fake tracks generated during the seed generation and track finding. One of the most challenging and interesting applications of machine learning techniques is the study of jets originating from heavy flavour quarks (b/c "tagging"). Studying the particle tracks from these jets is crucial in searches for new physics at the LHC as well as the precise measurement of Standard Model processes. Starting with improved b-jet tagging techniques the method can also be applied in jets containing W, Z or top particles.



**The reconstruction chain in jet tagging; the task is to identify the particles coming in a jet like (i.e. b-quarks as in the image above). Image credit: M. Stoye.**

Markus Stoye, is leading this effort within the CMS collaboration. Already during his PhD in the University of Hamburg, he familiarized with the application of statistical and numerical techniques in high-energy physics and specifically in the alignment of the CMS tracker during which they had to ensure that 16.000 silicon sensors would be aligned with the detector. In the last 18 months he decided to apply deep learning techniques to tackle the challenges of studying the jets of particles produced at the LHC. The new generation of b tagging algorithms have shown incredible performance compared to previous b-taggers. Stoye explains: “A variety of b tagging algorithms has been developed at CMS to select b-quark jets based on variables such as the impact parameters of the charged-particle tracks, the properties of reconstructed decay vertices, and the presence or absence of a lepton.”

After an initial training period during which he familiarized himself with the concepts and available tools he decided to start building a group within the CMS collaboration and together with a small team they worked to implement the neural network techniques for b-tagging. Following the first successful results of the CMS tagger, that demonstrated significant improvement compared to previous taggers, the team grew and today there are about ten people working to push further deep learning techniques in the analysis of CMS data.



**The right plot shows a comparison between the scale factors measured by different methods in  $t\bar{t}$  events (Kin, TagCount, TnP, IterativeFit), the combined scale factors obtained from the muon enriched sample (mu+jets), and the combined scale factors obtained from  $t\bar{t}$  and muon enriched samples (comb). Further information: [here](#).**

They currently design a neural network architecture that can do simultaneously the formerly independent steps that are followed in the analysis of jets, e.g. variable design per particle and track selection. Stoye explains: "The input to the deep learning algorithm are the constituents of the jet, all its particles and secondary vertices. These adds up to about 1000 features and if you use a general dense deep neural network you might have 10.000.000 to minimize in your optimization and in the customized structure is only 250.000 as based on some assumptions - correct in the physics sense - you can reduce the complexity". In contrast to other algorithms, the new approach uses properties of all charged and neutral particle-flow candidates, as well as of secondary vertices within the jet, without a b-tagging specific preselection. "The neural network consists of multiple 1x1 convolutional layers for each input collection, their output is given to recurrent layers, followed by several densely connected layers. So far, in our simulations, this algorithm outperforms the other taggers significantly, in particular for high-pt jets, which could lead to improved sensitivity in searches for new physics with high energetic b jets in the final state."

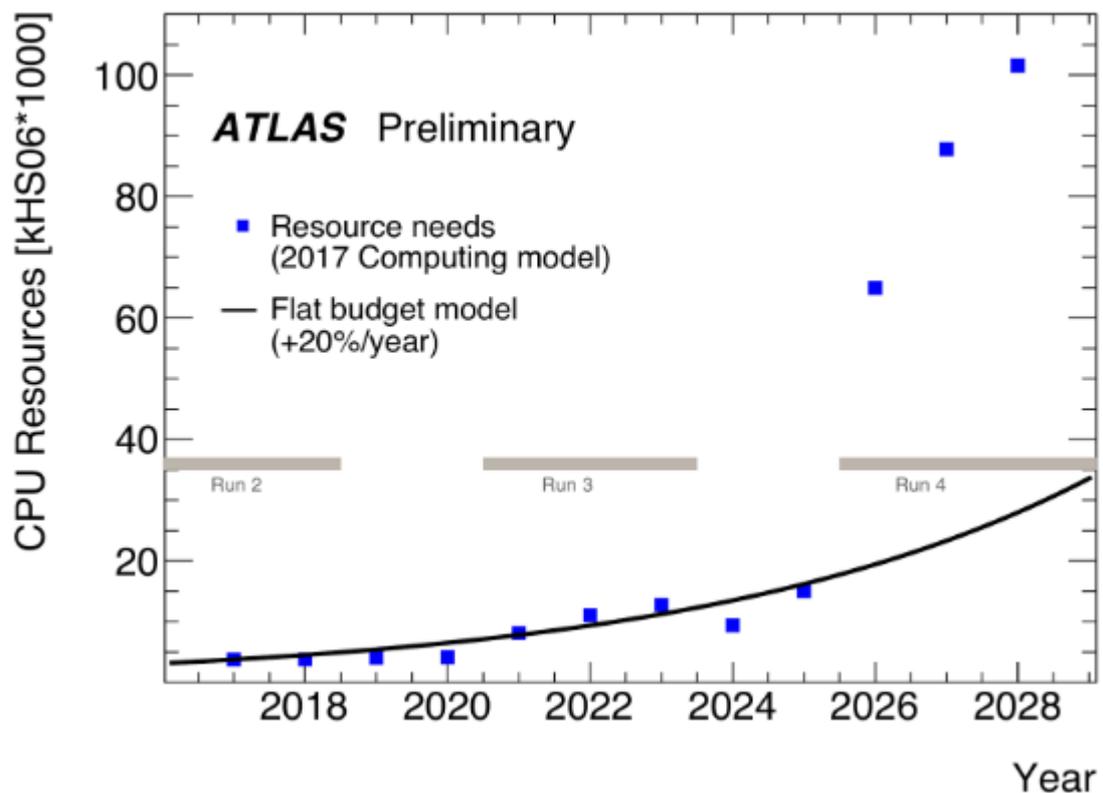
"In this process one has to understand both the available architectures as well as the physics problems. We input pretty complete information about the particles to the algorithm and gradually the neural network starts becomes able to figure out itself what is most important for the analysis." and continues: "We know that we have better tagging following the copious efforts of the past nine months. Thanks to the neural network technique there is an acceleration in the way we improve on these fields compared to the past though this is not to undermine all past efforts and the way in which they pushed our understanding."

As a next step, the team plans to develop ways to reduce systematic uncertainties. Stoye explains: "Presently there are different approaches on that within data science and this is an aspect that I am presently focusing. This is a major branch of research in data science in general and is called domain adaptation while it will be a major step in developing new techniques".

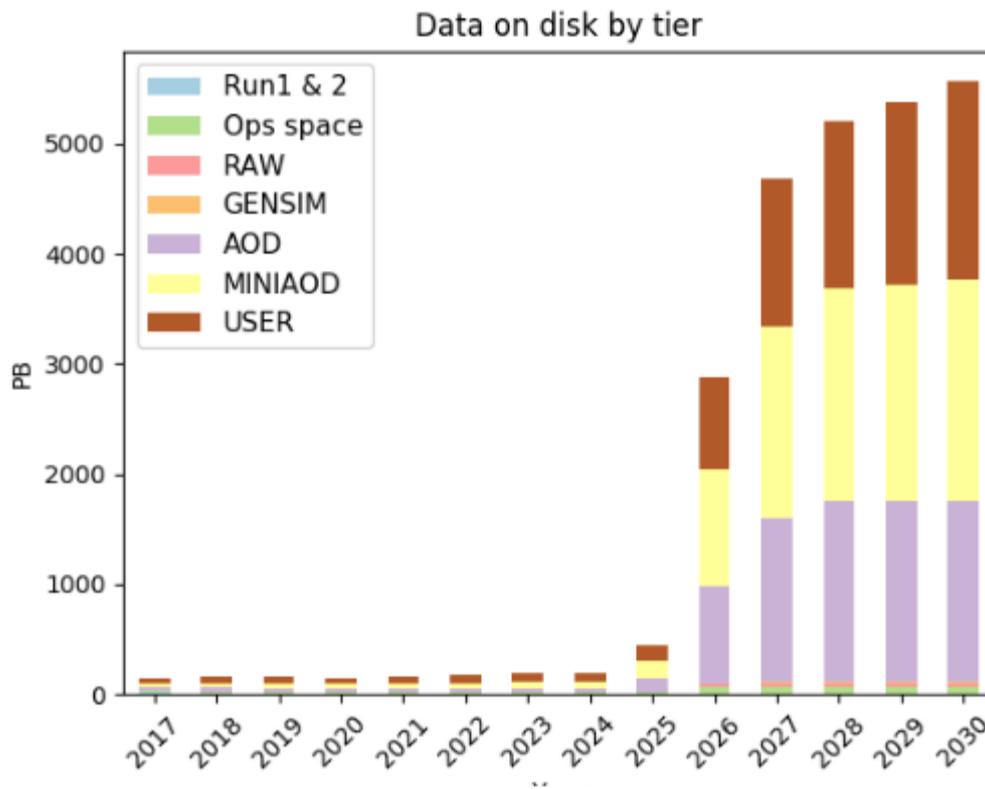
## The HEP Software Foundation Community White Paper looks forward to the HL-LHC

by *Graeme Stewart, EP-SFT*

The High Luminosity LHC programme not only pushes the frontiers of accelerator and detector technology, but it also brings enormous challenges to the software and computing that is used to turn high luminosity data into physics. The scale of the problem is huge - the total LHC dataset is already almost 1 exabyte and some 30 times more data than the LHC has currently produced will be collected by ATLAS and CMS in the future. Extrapolating today's solutions a decade into the future leaves experiments short by at least an order of magnitude in storage and computing, if one assumes Moore's Law and more or less constant operational budgets. At the same time, the nature of computing hardware (processors, storage, networks) is evolving, with radically new paradigms that will require significant re-engineering to exploit.



***ATLAS Estimated CPU resources (in kHS06) needed for the years 2018 to 2028 for both data and simulation processing. The blue points are estimates based on the current software performance estimates and using the ATLAS computing model parameters from 2017. The solid line shows the amount of resources expected to be available if a flat funding scenario is assumed, which implies an increase of 20% per year, based on the current technology trends.***



***CMS estimated disk space required into the HL-LHC era, using the current computing model with parameters projected out for the next 12 years.***

In anticipation of these challenges the [HEP Software Foundation\(link is external\)](#) (HSF) was founded in 2014 to encourage common approaches to the problems we face. The HSF was then charged by WLCG to produce a Community White Paper Roadmap (CWP) for HEP that anticipates the “software upgrade” that is needed to run in parallel with the detector hardware upgrades planned for the HL-LHC. As well as improving the performance of our software for modern architectures we wanted to explore new approaches that would extend our physics reach and ways to improve the sustainability of our software in the coming decades. Although there was a HL-LHC focus we looked at the problems from the perspective of the whole HEP program, including the Linear Collider, the Intensity Frontier, Belle II, and the FCC.

The CWP initiative kicked off with a workshop in San Diego that brought together more than 100 software and computing experts for 2.5 days of plenary and topical discussions. From the ideas seeded here many working groups were formed that in the following six months organised their own workshops and events to marshal ideas and engage with experts outside of our field. A final workshop at LAPP in Annecy in June 2017 started to conclude the process with working groups presenting their work and plans. While groups finalised their work over the next few months, producing papers that will be uploaded to arXiv, an editorial board was assembled that encompassed a broad cross section of software and computing experts. The Editorial Board took charge of summarising the work of each of the working groups and producing the [final CWP Roadmap\(link is external\)](#). A first draft was released in October, followed by a second draft in November and the final version of the Roadmap is being prepared now. Almost every aspect of HEP software and computing is presented in 13 sections. In each section the challenges are

discussed, current practice described, and an R&D programme is presented that describes the work that is required in the coming years.



***The HSF final CWP workshop in Annecy gathered almost 100 experts from HEP software and computing***

Simulation remains a critical part of our programme, with improvements to physics event generators needed to effectively use next-to-next-to-leading order event generation for the processes studied at the HL-LHC, where the massive volume of data reduces experimental uncertainties well below those from theoretical predictions in many cases. Improved physics models for detector simulation need to be developed for high precision work at the LHC and for the neutrino programme. Adapting Geant4 for effective use on modern CPUs and GPUs is another part of the R&D programme, as well as developing common toolkits to help with Fast Simulation. The shift to new computing architectures is equally important for our software triggers and event reconstruction code, where the pile-up at high luminosity makes charged particle tracking within a reasonable computing budget a key challenge to face. Doing more and more in software triggers, as being developed by ALICE and LHCb for Run 3, will help control the data volumes and enable analysis to happen directly from initial reconstruction. The development of Machine Learning techniques appropriate to our field should also lead to advances that improve both simulation and reconstruction performance and reduce costs. These techniques are also under investigation for analysis, where they already find many applications in Run 2. Taking techniques from outside our field offers great promise, as many data science tools look to have applications in HEP. The data science domain tends to tackle analysis problems on dedicated cluster resources, a version of which could replace the many expensive cycles of data skimming and thinning that are employed today.

This restructuring of resources at facilities is a key area to develop in order to evolve our WLCG computing site resources and also to incorporate commercial and scientific clouds into the pool available for HEP computing. In some regions HPCs will also play a major role for us in the future, but are not suitable for current HEP workflows. More effective use of the network and more consolidated storage resources, into a 'data lake' configuration will help deliver data to compute resources more effectively than is done today. Our workload management systems and software frameworks will need to evolve to this new heterogeneous landscape.

The challenges we face are wide ranging and hard and they require new investment in the critical areas and a commitment to solving problems in common. We will have to train a new generation of physicists with updated computing skills and help the career paths of our specialists. 'Business as usual' will not solve these problems nor will hardware come to our rescue.

The CWP Roadmap has already been very widely endorsed by the community, but we want as many people as possible in HEP software and computing to support it, which you can still do [here\(link is external\)](#) or by sending an email to [hsf-cwp-ghost-writers@googlegroups.com](mailto:hsf-cwp-ghost-writers@googlegroups.com)(link

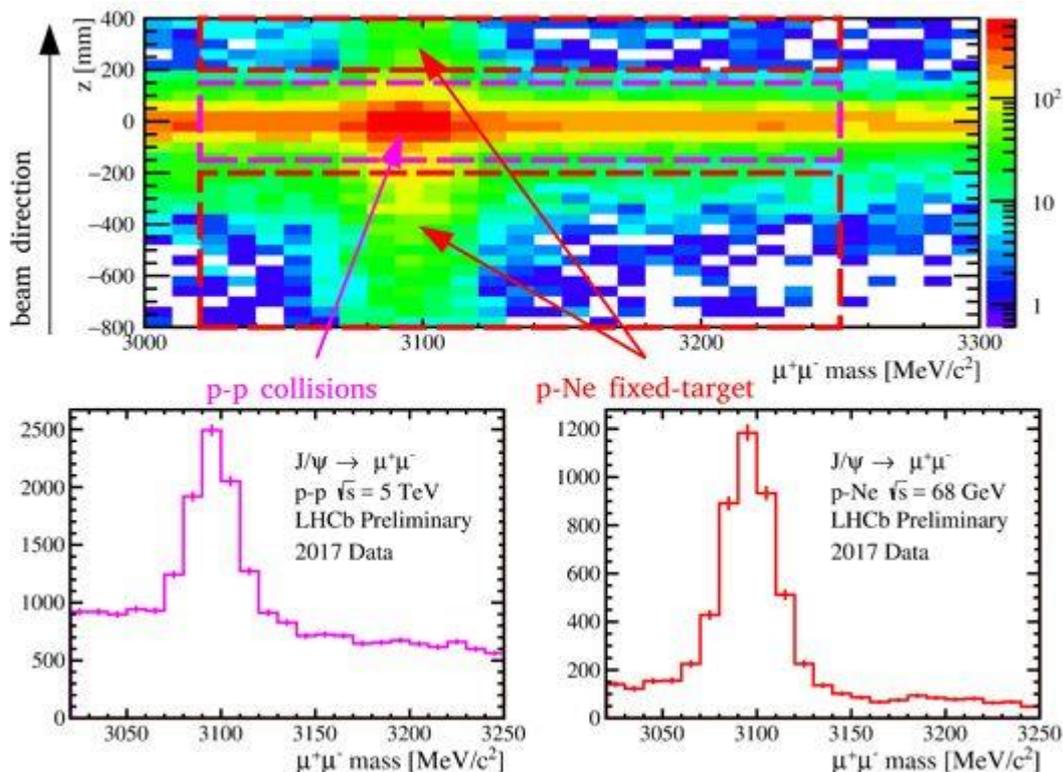
sends e-mail). The next step after defining the roadmap is to start to walk along the road; the joint [WLCG/HSF workshop](#) in Naples in March 2018 will start to put into practice the plans we have laid out.

## “Grand Unification” of data taking for the LHCb experiment

### LHCb

The 2017 data taking period for LHCb ended at the end of November. Towards the end of the 2017 run at the centre-of-mass energy of 13 TeV, the LHC provided collisions at a reduced energy of 5 TeV to produce reference data for proton-lead and lead-lead collisions taken earlier in Run 2. Besides the scientific interest of proton-proton (p-p) physics at 5 TeV for the LHCb heavy-ion programme, the experiment has been taking at the same time a parallel stream of data from fixed-target collisions with another world record in high energy physics.

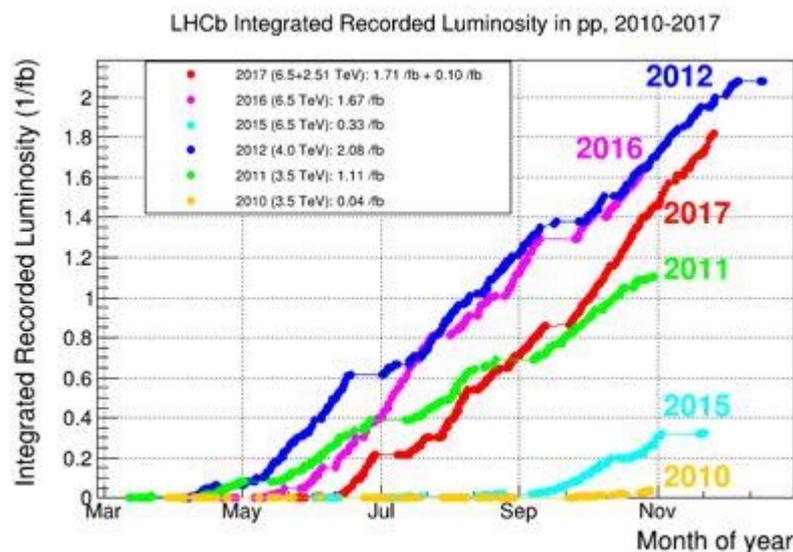
There have been typically 1836 bunches of protons circulating in each LHC ring, out of which 1094 collided inside the LHCb detector. LHCb physicists decided to use additional non-colliding bunches to accumulate the largest sample of proton-neon data in a fixed-target configuration. The LHCb experiment has the unique ability of injecting gas, neon in this case, into the interaction region and therefore study processes that would otherwise be inaccessible. This gas-injection system was originally designed to help LHCb measure the brightness of the accelerator's beams, but is now being used for dedicated physics measurements. This kind of operation is called by physicists a “fixed-target” mode in contrast to the standard “collider” mode used at the LHC, as in this case the LHC protons are colliding with stationary neon nuclei.



It has been the first time ever that an experiment has collected data in the collider and fixed-target modes simultaneously. LHCb physicists showed that it is possible to reconstruct both sets of data

in parallel, align the detector elements and track particle trajectories correctly. A real challenge has been to develop an online event selection (trigger) system handling efficiently both data taking conditions. The live images (left) obtained by the data acquisition computer programs show reconstructed  $\mu^+\mu^-$  invariant mass spectra. The  $J/\psi$ -meson peaks are clearly visible in the two different operational modes. The two-dimensional plot shows the z coordinate (along the proton beam direction) of the origin of the  $\mu^+\mu^-$  pair. A strong accumulation around  $z=0$  indicates the p-p collision point. The pink-dashed rectangle highlights the regions where p-p collision events were selected. The two other (red-dashed) rectangles show the region where only p-Ne collisions take place.

LHCb continues to revolutionise data acquisition and analysis techniques. Already two years ago the concepts of “online” and “offline” analysis were unified. The calibration and alignment process takes place now automatically online and stored data are immediately available offline for physics analysis. This time the collider and fixed-target modes of operation have been unified into the same data acquisition framework. In particle physics, a grand-unified theory is one in which at very high energies the electromagnetic, weak and strong interactions unify as a single force. Today LHCb physicists have succeeded to unify very different concepts of data taking and analysis.



The 2017 data taking period has been very successful, because of the excellent performances of both the LHC and the LHCb experiment itself. The image shows the growth of integrated luminosity during different years of LHC operation. The 2017 integrated luminosity is higher than that collected in 2016. The overall Run 2 luminosity (2015-2017),  $3.7 \text{ fb}^{-1}$ , is already higher than that recorded in Run 1 ( $3 \text{ fb}^{-1}$ , 2010-2012).

A traditional end-of-year shutdown period, so-called Year End Technical Stop (YETS), is starting now. It will be used for maintenance and improvements to the LHC and its detectors. LHCb plans to exploit this period to perform maintenance work on many sub-detectors. It is planned that protons will start to circulate again in the LHC rings at the beginning of April 2018 and that the first p-p collisions for physics will take place in early May, marking the beginning of the last year of Run 2. The two-year Long Shutdown 2 will then start in December 2018, and during this period the LHCb detector will face its first major upgrade, which will allow the experiment to take data at much higher rate.

## Scintillation light at the end of the tunnel

by *Lukas Gruber (EP-DT)*

The LHC Long Shutdown 2 (LS2) is approaching in giant steps and with it the date for the installation of the [LHCb upgrade detectors](#) (EPnews, May 16 2014, A. Schopper). A large SciFi tracker [will replace the current downstream trackers](#) (EPnews, Nov 6 2014, C. Joram). SciFi stands for scintillating fibre and means that the fibres will produce tiny light flashes when they are traversed by charged particles like electrons, pions or kaons. The new tracker will use more than 10'000 km of scintillating plastic fibre to cover an area of about 340 m<sup>2</sup> making it the largest SciFi tracker ever built. The fibres have a diameter of only 0.25 mm, enabling a detector resolution of better than 0.1 mm.

After being fabricated in Japan, the fibres spend most of their early life on travelling! First to CERN, where they undergo extensive quality checks, then to four winding centres located in Germany, Switzerland and Russia to be packed in 6-layer fibre mats, before meeting again either in Heidelberg or Amsterdam to form fibre modules and finally back at CERN for detector assembly.

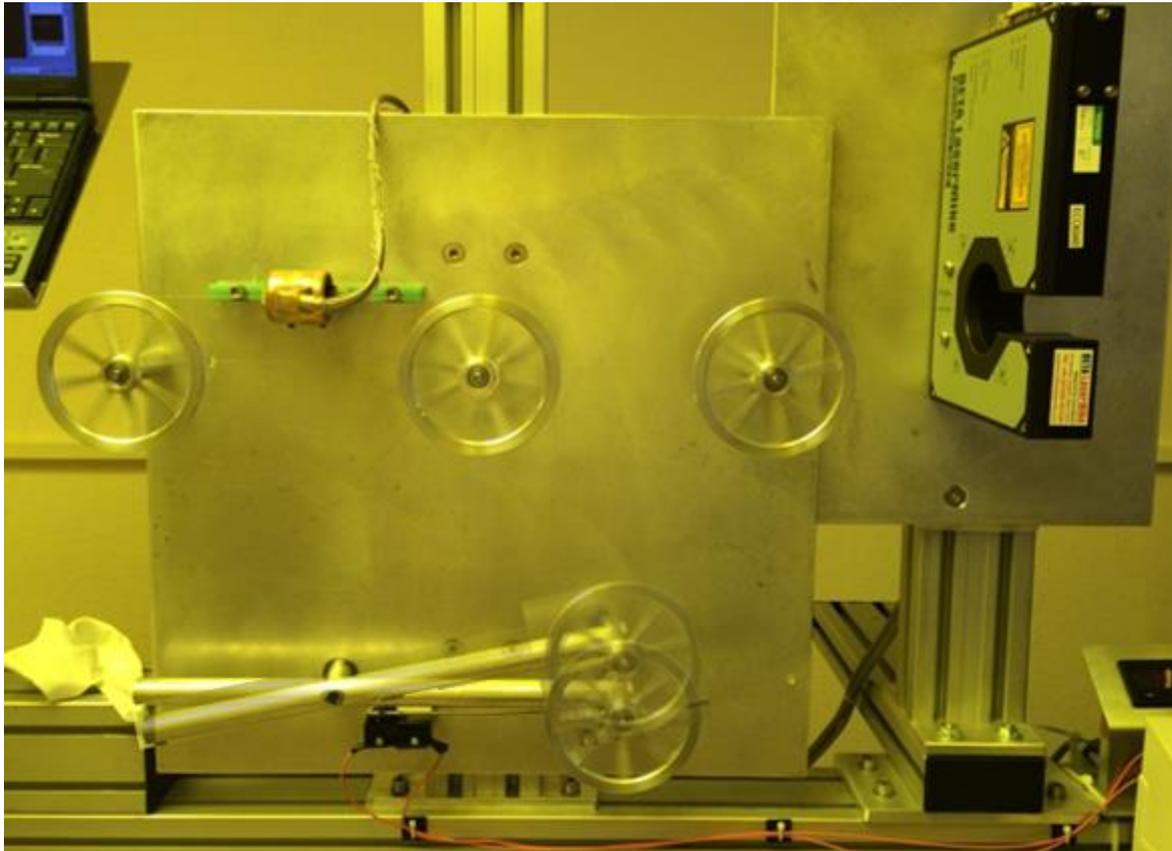


***The SciFi scanning team behind the 6 meter long fibre scanning machine set-up at CERN. From left to right: Robert Kristic, Christian Joram, Biplab Dey, Lukas Gruber.***

At present, the fibre quality assurance (QA) of the fibres at CERN is nearing completion. Three quarters of the 1'200 fibre mats have been wound and the first 20 modules have arrived at CERN (Bulletin reference, Issue No. 34-36/2017). After that, the fibres will be installed 100 meters underground, this will be the most sparkling part of their life as part of LHCb.

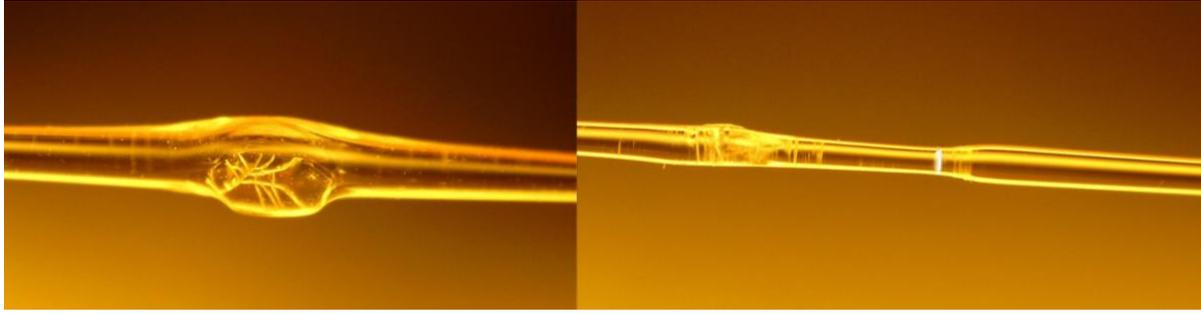
Within the last few years CERN's main responsibility within the SciFi project was the R&D and QA of the scintillating fibres for SciFi, which started with the selection of the suitable fibre model and culminated in testing 11'000 km of fibre between May 2016 and December 2017. If it was in one piece, this fibre would be longer than the flight distance between the production site in Japan and

CERN or one quarter of the earth circumference. To allow for reasonable packaging and shipping the fibres are delivered on about 900 individual spools, each about 12.5 km in length,



***Bump removing section of the fibre scanner. If the fibre diameter exceeds 0.35 mm the fibre gets stuck in the hot tool, the rotatable arm moves up, stops the machine and slowly pulls the fibre through the conical tool with a tension of 100 cN (g).***

Over the last 20 months the SciFi fibre team received 24 of these spools, i.e. 300 km of fibre, every two weeks. More than 1'500 fibre samples were evaluated to determine parameters like optical attenuation length, light yield and resilience against X-ray radiation and ensure that the delivered material fulfils the requirements. In addition, a fibre scanner was developed and built at CERN to precisely measure the fibre diameter and simultaneously monitor the surface quality. It is operated from 7 a.m. to 7 p.m. on workdays since almost two years without major interruptions to enable scanning of 11'000 km of fibre until end of 2017. A special feature of the machine is the possibility to shrink diameter excesses ("bumps") larger than 0.35 mm that would potentially cause distortions in the 6-layer pattern of fibre mats. The simple but effective method is based on pulling the fibre through a conical tool which is heated to 100°C. Such bumps appear on average once every 1.5 km such that in total about 7'200 noticeable bumps were detected, out of which 90% could be handled successfully by the machine, whereas the rest had to be cut out manually. The ability to remove most defects "on the go" drastically simplified the life of the technicians at the four winding centres.



***Diameter defect before (left) and after (right) shrinking.***



***Gluing of two fibre end pieces after cutting out a large diameter defect.***

Already in spring next year, the first fibre modules together with photodetectors, front-end electronics, cooling and other services will be mounted in LHCb's new assembly hall (B3852) on a 7 m high C-shaped frame, representing one twelfth of the complete SciFi tracker. These operations are very labour intense and we count at least 12 months before all 12 C-frames can be installed in their final position in the LHCb underground cavern. If everything goes to plan, our fibres will start to twinkle in 2020 and measure precise particle tracks in LHCb.

## **A successful heavy-ion campaign for ALICE**

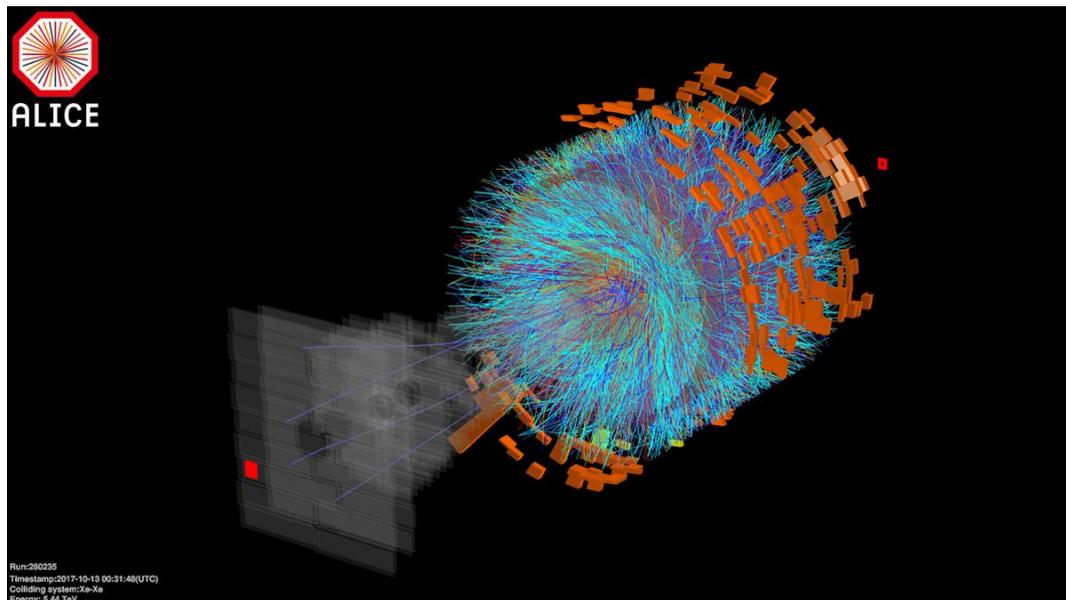
ALICE

by *Virginia Greco (ALICE Collaboration)*

 [PDF version](#)

The LHC has just ended its 2017 operation and the experiments have already started their plan of intervention for the end-of-year break. The last two weeks of data taking have been particularly important for ALICE, since a special run dedicated to our experiment took place. Proton-proton collisions with a centre-of-mass energy of 5TeV were delivered to allow ALICE to take data that will be used as a reference for the measurements performed in Pb-Pb and p-Pb systems at identical energy. The objective was to take 870 million minimum bias events. As it had been computed, in order to accomplish this result 160 hours of data taking were needed, to which the

time for the setup of the accelerator and the normal intervals between fills were summed. Altogether, this accounts for 11 days of run, which had been granted to ALICE.



Even though the goal set was quite ambitious, it was not only reached, but even exceeded. The LHC exhibited really good performance, the setup time was shorter than expected and our experiment run with very high efficiency (about 97%). Thanks to shorter setting up time and intervals between fills, ALICE could take data for 180 hours, over which it recorded 986 million minimum bias events (more than 100 million extra events), and the run could even be stopped one day in advance.

In parallel to minimum bias events, triggered data were also taken with requirements on the muon and calorimeter detectors. Reaching good statistics for this kind of events was particularly challenging, since the interaction rate was set low (50 KHz in average) to have high quality minimum bias data.

This excellent special run concluded the very successful data-taking campaign of 2017. ALICE collected data of pp collisions at 13 TeV in the centre of mass over various months, storing 866 million minimum bias events in nominal conditions and 145 million ones with a lower solenoid magnetic field (0.2 T instead of 0.5 T). A reduced magnetic field allows detecting, and thus studying, particles of low transversal momentum – which are less curved and thus cross the detector instead of spiraling over.

A good amount of high multiplicity events, triggered with the silicon pixel inner tracker, was also gathered, as well as data samples taken with other specific trigger requirements on the calorimeters, gammas, jets, muons, coincidence muons-calorimetres, and diffractive events.

In October, ALICE had also the possibility to collect data of xenon-xenon interactions, exceptionally delivered to the LHC experiments along a 6-hour run. During this fill, 1.7 million events were recorded, which are now being analyzed and the results discussed in the internal physics meetings.

At the moment, two months of technical stop and minor interventions on the instrumentation lies ahead, while the commissioning and then the physics data taking will be retrieved in March 2018.

## A portable gas system for particle detectors.

DT

[gas systems](#)

by **Panos Charitos**

 [PDF version](#)

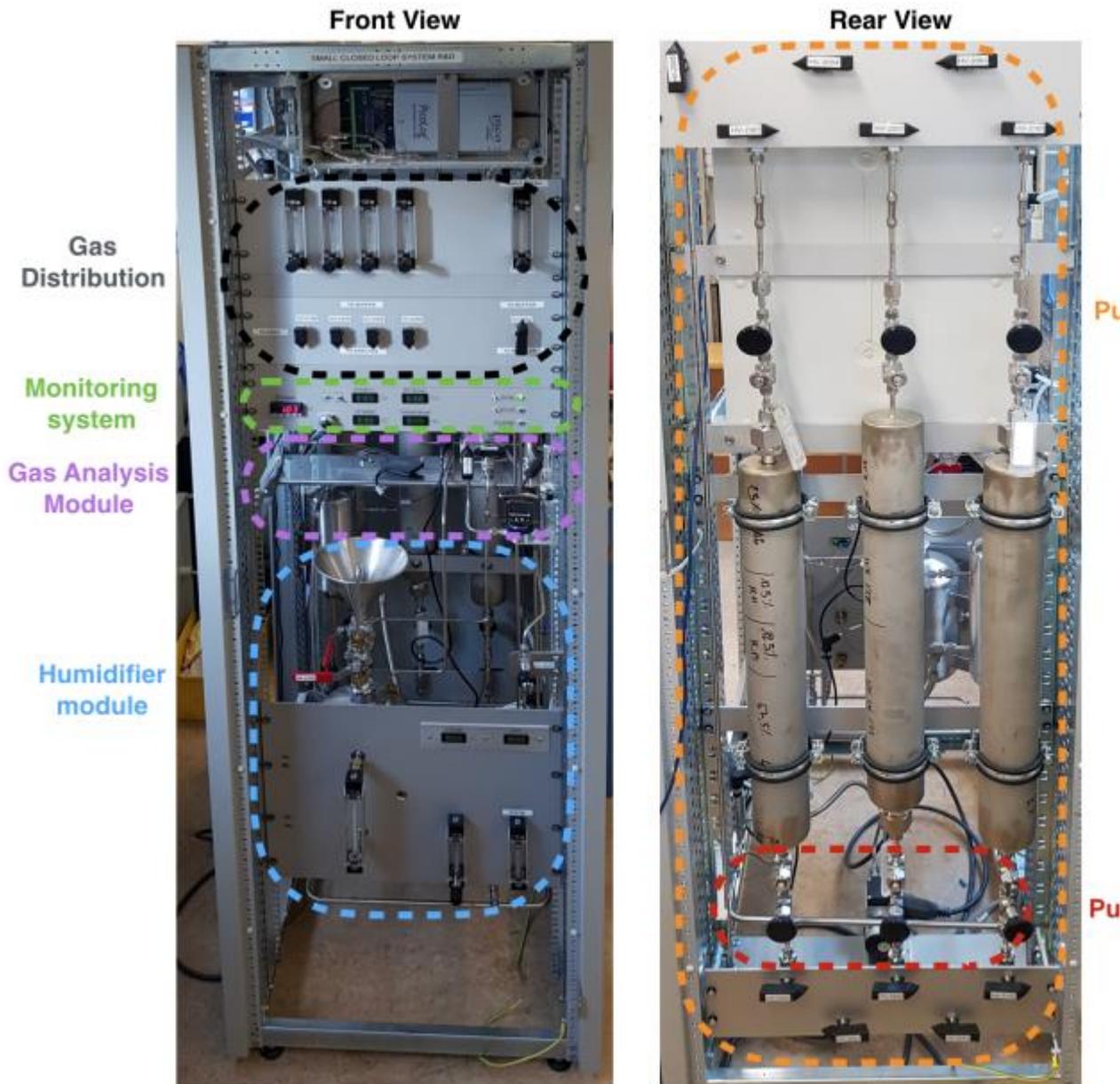
Today, about 30 gas systems are used to deliver the right gas mixture to the corresponding gaseous detectors at the LHC experiments. The detector gas mixture is the sensitive medium where the charge multiplication produces the signal that is then recorded and analysed. The correct and stable gas mixture composition is therefore the key ingredient for an efficient and reliable operation of the LHC experiments.

Gas systems of the LHC experiments are the result of a strong collaborative effort between CERN's Gas Systems Team (nowadays part of CERN/EP-DT-FS) that designed and build the gas systems and the CERN/BE and CERN/EN departments that develop software controls and provide the primary gas supply, respectively. The operational experience over the last years has demonstrated an impressive reliability level: greater than 99.95% corresponding to less than 1.5 hours of down-time per year (power-cuts and external problem excluded).

The reduction of any emissions and operational costs can be achieved by recirculating the gas mixtures used in the detectors. Especially the control of greenhouse gas (GHG) emission is an important subject for the operation of the current experiments but also for the design of future particle detectors as new regulations will put more stringent limits while may also result at higher costs.

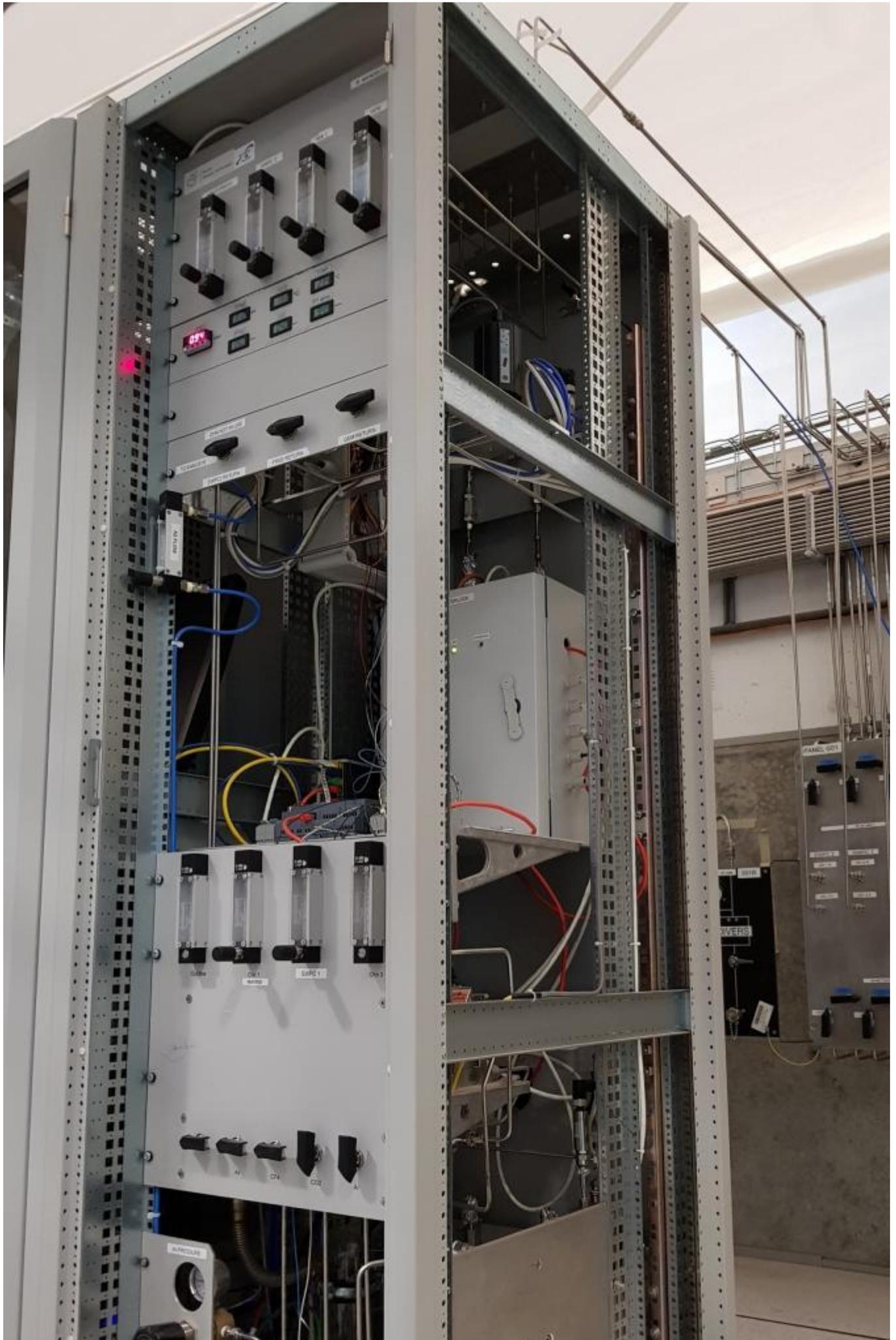
Nowadays R&D activities with gaseous detectors are ramping up as part of the LHC detector upgrade programs, as for example long-term detector tests, detector quality assurance before installation in the experiments, test-beam and laboratories tests. To minimise the emissions coming from these activities, the EP-DT Gas Systems team has developed a compact and flexible gas recirculation unit, which is about ten times less expensive than a standard LHC gas recirculation system. The main features of this gas recirculation unit are its flexibility and its user-friendly operation: it can be easily adapted for all types of gases and detectors as well as for specific requirements (recirculation fraction, low/high flow rates, detector working pressure, gas cleaning agents, etc.).

To address different user requirements, the unit follows a modular design and is divided in several logic modules. Two recirculation units are operational since more than two years for two different set-ups: CMS Cathode Strip Chamber test at GIF++ and gas recirculation development for Gas Electron Multiplier.. The first few years of operation have confirmed an extremely high reliability and stability of the two recirculation systems, which work in different conditions (recirculation flow, pressure, etc.) and with different detector types. Based on the development of this recirculation unit, the CERN Gas Systems team developed also the gas recirculation plant for the LHCb GEM detector, which is running stable since 2016 and allowed a 90% reduction of the CF4 consumption.



**Figure 1: Front and rear view of the gas recirculation unit. The different logic modules are highlighted.**

The principle of operation of this portable unit is based on a pump ensuring the gas circulation and extraction from the detector. Through several settings the users can choose the gas recirculation rate as well as the detector pressure, the gas flows ensuring the right mixture for the detector. A gas analysis module is installed after the distribution module allowing to analyse the gas exiting the detectors or coming from the purifier module. Though it allows to use different types of gas analysers the primary choice has been the use of H<sub>2</sub>O and O<sub>2</sub>.



Finally, monitoring is based on several electronic and software tools. Since one of the goal of the development of the new gas recirculation unit was the cost-effectiveness, it was decided to not have any remote control though a higher-level of automation is possible by upgrading the user interface.

The choice of instruments and materials has been done considering the experience of the LHC gas systems, the quality-price relation and the availability on the market. This year a new unit has been installed at the Gamma Irradiation Facility for the ATLAS and CMS Resistive Plate Chamber (RPC) R&D and it will allow a significant reduction of GHG emissions coming from the use of C<sub>2</sub>H<sub>2</sub>F<sub>4</sub> and SF<sub>6</sub>. More units are currently under construction for different detectors technologies that will be tested on a long-term basis in laboratories, beam-tests or irradiation facilities.

*The author would like to thank Beatrice Mandelli and Roberto Guida (EP-DT) for the invaluable contributions and comments.*

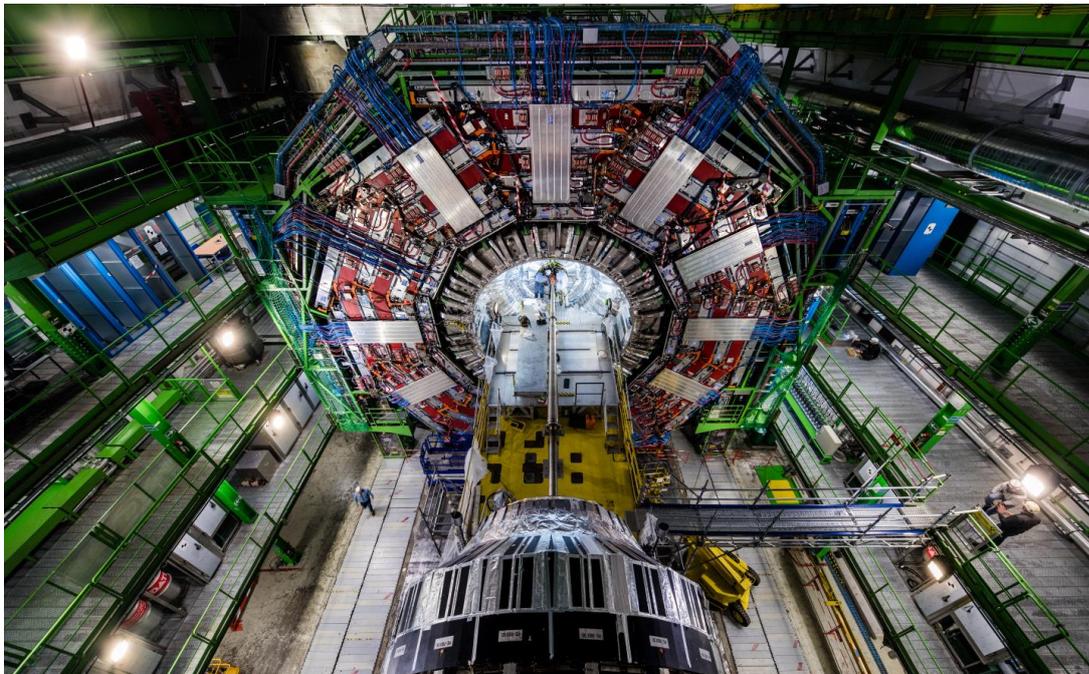
You can read the full paper published in Jinst (IOP): [here\(link is external\)](#).

## New paradigms for the CMS Phase-2 Upgrades

CMS

by **Austin Ball and Didier Claude Contardo (CMS)**

The CMS Phase-2 Upgrade projects will replace or improve detector systems to provide the necessary physics performance under the challenging conditions of high luminosity at the HL-LHC. Installation of the upgraded detector systems starts in LS2 and is planned to be completed in LS3, presently scheduled for 2024 to mid-2026.



A major experimental requirement for the upgrades will be to distinguish the hard proton collisions among the hundreds of softer collisions that will pileup in each beam crossing. The new systems

will therefore need high resolution to separate the trajectories and energy deposits of particles produced in these different collisions and then to associate them to their correct origin.

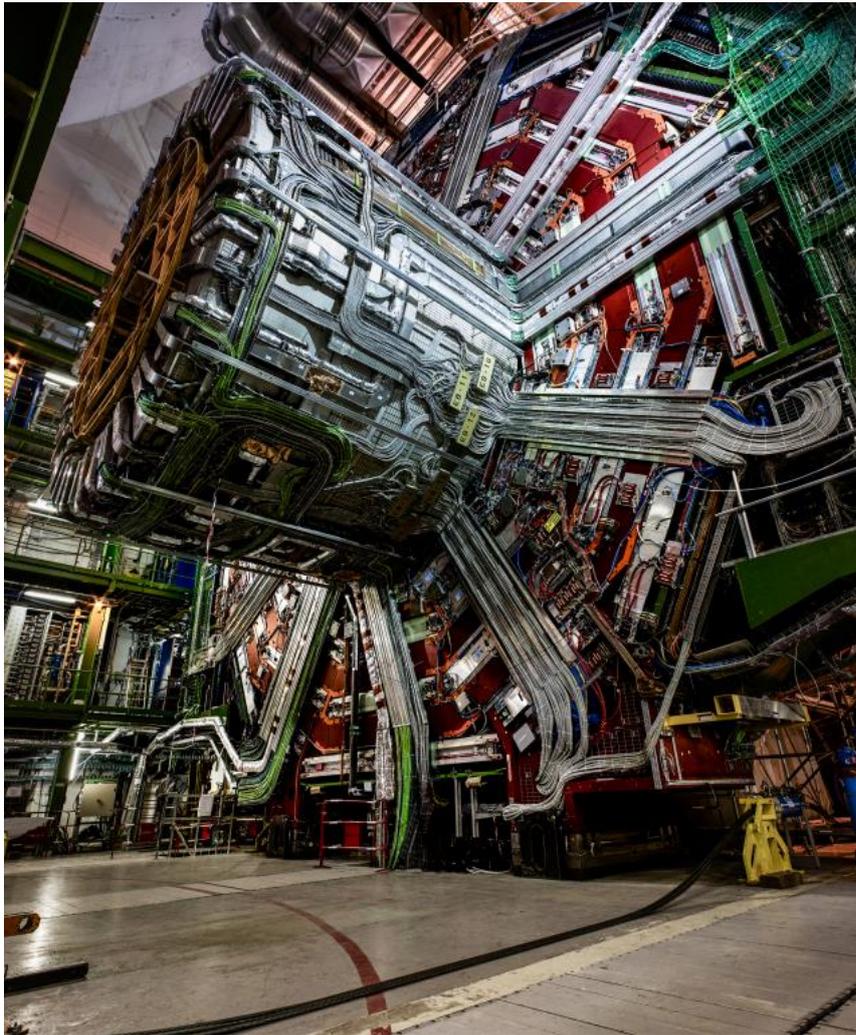
The new CMS Silicon-Tracker will play a crucial role in this process, with a substantial increase in the number of channels and an improved spatial resolution. A special design of the outer part of the detector, exploiting the high magnetic field of the experiment, will also enable the usage of track elements in the event selection at the 40 MHz beam crossing frequency. This unique feature, along with the opportunities offered by improvements in FPGA processing power and bandwidth, will allow more sophisticated trigger algorithms to be deployed. These will enable current physics acceptance to be maintained at the highest HL-LHC luminosity. The Pixel detector at the heart of the tracking system will extend into the forward regions, which will greatly enhance the performance for major signals of the HL-LHC physics program, such as Vector Boson Fusion processes and the searches for new physics with missing energy.



The new Endcap Calorimeter will be the first large-scale deployment of an innovative technology in a particle physics experiment. The interleaved detector layers within the absorber structure will feature a high granularity electromagnetic section based on 28 layers of silicon sensors with pad segmentation, and a hadronic section of 24 layers using the same technology in its innermost layers, with a less segmented scintillator tile section at higher radius. The high granularity of this system will allow measurement of the 3D topology of energy deposits in particle showers induced by incident electrons, photons and hadrons, as well as precise time-stamping of neutral particles down to low transverse momentum.

Knowing the time of flight (ToF) of minimum ionizing particles from their identified spatial origin will be a powerful means of resolving collisions that occur close together in space during the bunch crossings, but at different times (within the total spread of  $\approx 190$  ps). To exploit this technique, CMS proposes an additional hermetic detector (MIP Timing Detector - MTD) with a timing precision of  $\approx 30$  ps. A conceptual design has been developed using small LYSO crystals with SiPM readout in the barrel region and a new generation of specialized silicon detectors, the Low Gain Avalanche Diodes, in the endcap region (where radiation tolerance is more demanding). Studies, which also exploit the new timing abilities of the upgraded Barrel and Endcap Calorimeters for neutral particle showers, show that the MTD can significantly enhance the performance for reconstructing physics objects associated with hard collisions, leading to a substantially improved significance reach for all physics channels. Additionally, the MTD will provide a new means to execute and extend the searches for long lived particles (LLP) now considered in several theory models. Muon system

upgrades will provide new trigger capabilities for these LLPs and an enhanced acceptance in the forward regions that will benefit several physics channels.



Recently, CMS has submitted documentation, describing the major upgrade projects, for review by the LHCC and UCG CERN committees. Technical Design Reports for the Tracking System, Barrel Calorimeters, Muon Systems and Endcap Calorimeter include extensive simulation studies to demonstrate the physics performance, describe the baseline design and any remaining technical developments, and present the project schedule and cost. The tracker TDR has already been approved by the CERN Research Board in November. The Trigger and DAQ upgrades require shorter production times, and the corresponding TDRs will be submitted in 2020-2021, based on up-to-date technical solutions. In interim documents, the baseline design for the architecture of these two systems, along with updated cost projections and institute contributions were summarized for the LHCC and the projects were endorsed to proceed toward TDRs. The MTD was only recently introduced by CMS in the Phase-2 upgrade scope. It is described in a Technical Proposal submitted to the LHCC and, if agreed, a TDR will be prepared for submission in late 2018.

To conclude, the CMS upgrade projects are making good technical progress, and the reviews of technical documentation and resources are proceeding as planned. The funding model is under development, and the final agreements about funding and about construction responsibilities will follow the project approvals that are essential milestones of this year and the early part of 2018.

## First positrons for GBAR

PS

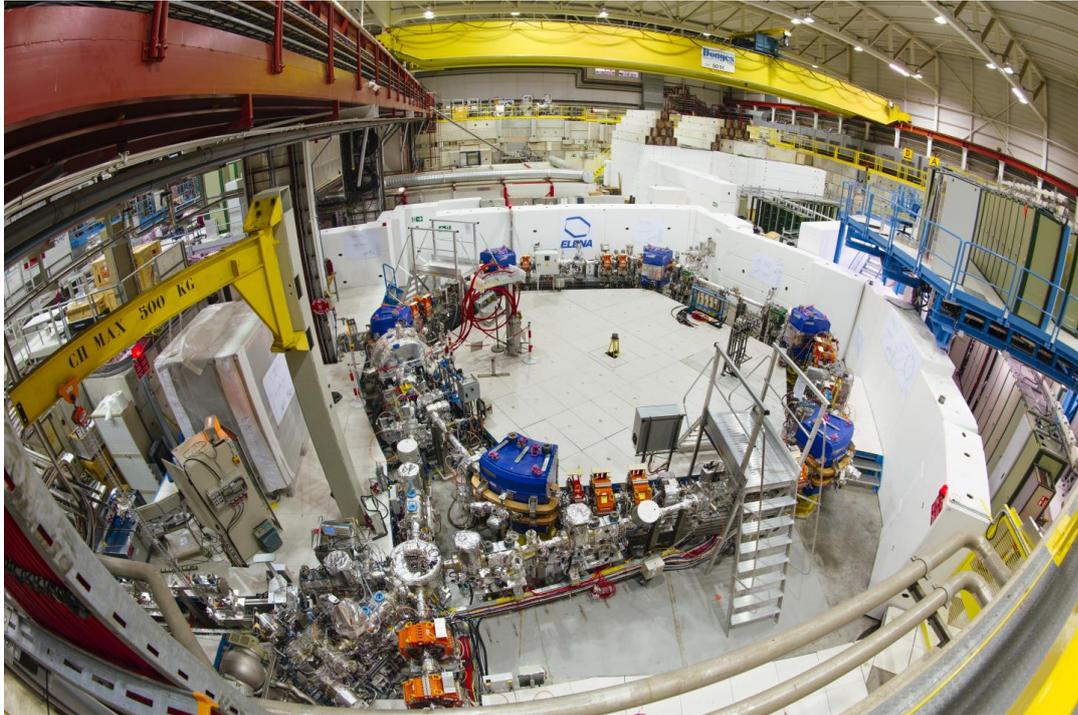
AD

SME

ELENA

GBAR

by *Patrice Perez*



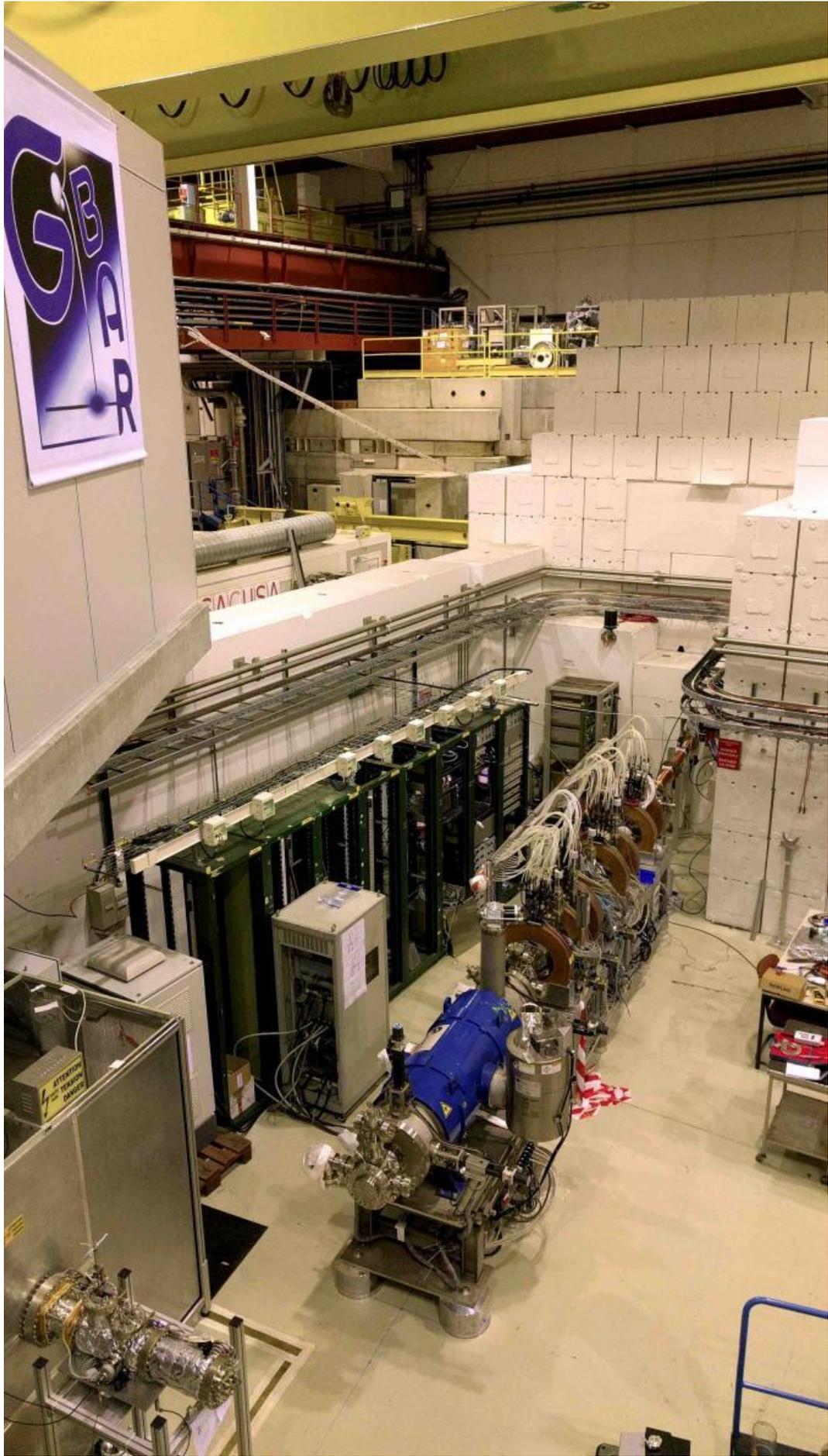
At the CERN Antimatter Factory, antihydrogen atoms are produced routinely by merging antiprotons and positrons. In order to control this process, it is necessary to reduce the energy of those particles, i.e. decelerate them to the lowest possible energies. The antiprotons are generated by interactions of protons coming from the PS (Proton Synchrotron([link is external](#))) with a metallic target. They are further decelerated in the AD (Antiproton Decelerator([link is external](#))) to 5.3 MeV, to be followed by another deceleration step with ELENA (Extra Low Energy Antiproton), which is a new deceleration ring being commissioned to reach 100 keV. The positrons are usually obtained from the decay of  $^{22}\text{Na}$  radioactive sources of high intensity. The GBAR experiment however requires a much higher positron intensity to produce not only antihydrogen atoms but also anti ions. This will be performed in a chain of two charge exchange reactions:



where Ps stands for positronium the bound pair of an electron and a positron. The required amount of positronium, hence of positrons, is of the order of  $10^{10}$  per antiproton pulse.

The radioactive sources are limited in size in order to obtain a narrow beam and also in thickness since positrons could interact within the source itself. The half-life of those sources is 2.6 years. There is only one provider. Experiments dealing with slow positrons use also nuclear research

reactors such as in Munich or Delft, or electron accelerators as was the case at Livermore. These would not fit in the AD hall though. We thus studied the possibility to use a small electron linear accelerator. There, positrons are produced by pair creation in the interaction of the electron beam with a high Z and dense target. The production rate increases with the energy of the electron beam. However, activation of the environment becomes huge when the energy of the beam exceeds 10 MeV and would prevent interventions by researchers. The positron rate is then lower at such energy compared to the energy of the accelerators used for particle physics. This can be compensated by a high intensity of the electron beam and is typically what is done with particle irradiators. We used a 5 MeV linac at CEA-Saclay in France to demonstrate successfully this scheme, obtaining a flux of  $3 \times 10^6$  slow  $e^+$ /s, i.e. already similar to the strongest radioactive sources.



***Figure 1 GBAR positron beam line coming out of the radiation shield in the AD hall. The line is being equipped with Penning-Malmberg traps for accumulation of the positrons before interaction with the antiprotons.***

The **GBAR linac**[\(link is external\)](#) was built at the NCBJ laboratory in Swierk (Poland). Its first version was transported to CERN this year and is being commissioned at an energy of 9 MeV. The repetition rate can be varied between 1 and 300 Hz with a pulse length of 3  $\mu$ s. The electron beam hits a tungsten target where gamma rays and positrons are produced with an average energy of the order of 1 MeV. The large amount of gamma rays and electrons requires an important radiation shield made of concrete and iron. It was made at CERN with refurbished LEP yokes and normal blocks totaling a mass of 1400 tons. The energy of the positrons is reduced to a few eV when they interact in a moderator made of tungsten meshes. Such low energy positrons, also called slow positrons, can then be easily transported to the experimental zone located outside the radiation shield that hosts the linac. At this point in the commissioning period, the electron intensity and energy is kept well below the regime foreseen for the experiment. However, we already could measure the positron flux at values that would reach  $10^8$  e<sup>+</sup>/s when extrapolated to the final energy and intensity. Caution must be met in such linear extrapolation since we do not know the true extrapolation curve. Indeed several effects can change the extrapolation such as heating of the moderator and creation of defects with irradiation. Answers are due in March 2018 with the final version of the linac to be installed then.