



EP Newsletter of the EP department

A word from the Deputy Head of the EP department - March 2019

Editorial

by Roger Forty

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

Welcome to the first EP newsletter of 2019. Following the completion of Run 2 at the end of last year we are now well established in the second long shutdown of the LHC, which will last for two years before beams return in 2021. This does not mean that work has eased off, as is evidenced by the wealth of interesting results that are currently being revealed at the Winter conferences. The shutdown also provides the opportunity to upgrade the experiments, each of them being a hive of activity. ALICE and LHCb are undergoing major upgrades, both concerning their detectors and the way they are readout. For LHCb in particular this is a voyage into the future, where the entire experiment will be read out at the bunch-crossing rate of 40 MHz when data taking resumes, and the trigger performed fully in software. We take this occasion to review the trigger developments of all four major LHC experiments.

Another topical issue is the update of the European Strategy for Particle Physics, an event that takes place every six or seven years, for which the main themes will be worked out during this year. The deadline for community input at the end of last year saw 160 documents submitted, outlining different views of the future of our field. In the absence of a clear statement from the Japanese government concerning the ILC, the focus of the discussions will be on which of the contenders to follow HL-LHC at the energy frontier should be supported, either CLIC or the FCC. In addition, the diversity of physics at CERN is recognized to be essential, and future proposals in this domain have been reviewed in the Physics Beyond Collider study, also as input to the strategy update. A special feature is included in this edition, giving the latest news from these various activities. Discussions at the Open Symposium in Granada in May will be crucial to drive the process forward.

You will find many more articles and interviews in this newsletter, reflecting the wide range of activity in the department, along with the introduction of new staff and fellows in EP. I wish you pleasant reading,

Roger Forty (Deputy Department Head)

ATLAS trigger system meets the challenges of Run 2

by *Stefania Xella (University of Copenhagen), Jiri Masik (University of Manchester) for the ATLAS collaboration*

 [PDF version](#)

The trigger system is an essential component of any collider experiment as it is responsible for deciding whether or not to keep an event from a given bunch-crossing interaction for later study. During Run 2 (2015 to 2018) of the Large Hadron Collider (LHC), the trigger system of the ATLAS experiment [1], shown in Figure 1, operated efficiently at instantaneous luminosities of up to $2.0 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and primarily at centre-of-mass energies, \sqrt{s} , of 13 TeV, and at higher than designed number of proton–proton interactions per bunch-crossing (pile-up).

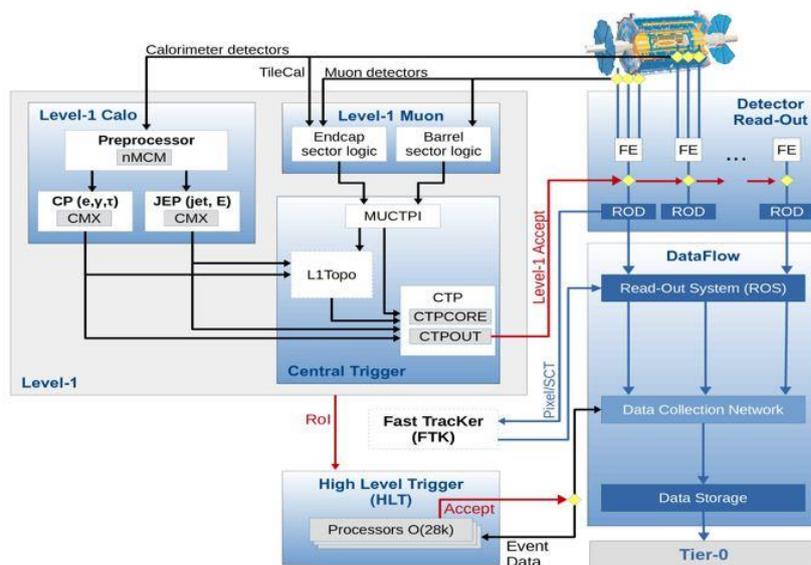


Figure 1: The ATLAS TDAQ system in Run 2 with emphasis on the components relevant for triggering (top). The L1 Topological trigger active for physics data taking since 2016 (bottom).

The ATLAS trigger system is composed of two levels: a first level trigger (L1), composed of custom made hardware, processes the input signals from the calorimeter and muon spectrometer systems

within microseconds, and reduces the rate from 40 MHz to 100 KHz; a High Level trigger (HLT) farm of commodity computers utilises high granularity signals from the calorimeter and muon spectrometer, as well as from the tracking system, and runs software algorithms to reduce within hundreds of milliseconds the output rate down to an average of 1 KHz. The HLT processes mostly data from the detector regions the L1 identified as interesting; nonetheless several triggers utilising full event information are now part of the set of trigger conditions (trigger menu) evaluated to decide whether a collision event should be kept or not.

Changes to the ATLAS trigger system for Run-2

During the first long shutdown (LS1) between LHC Run 1 and Run 2 operations, the ATLAS trigger system was improved in several parts with respect to Run-1, to withstand higher input rates and pile-up.

The L1 calorimeter was upgraded with a new FPGA-based multi-chip module (nMCM) which support the use of digital autocorrelation Finite Impulse Response (FIR) filters and the implementation of a dynamic, bunch-by-bunch pedestal correction. This allows to apply bunch-by-bunch pedestal subtraction compensating for the increased trigger rates at the beginning of a bunch train caused by the interplay of in-time and out-of-time pile-up coupled with the Liquid Argon calorimeter signal pulse shape, and linearises the L1 trigger rate as a function of the instantaneous luminosity.

In the L1 muon system, additional coincidences of muon spectrometer outer chambers in the endcap regions with Tile calorimeter or inner small wheel allowed to reduce the rate of fake muons.

A new topological trigger (L1Topo) consisting of two FPGA-based (Field- Programmable Gate Arrays) processor modules was added. The modules are programmed to perform selections based on geometric or kinematic association between trigger objects received from the L1 Calorimeter or L1 Muon systems, and allowed to keep the trigger rate under control without dramatically increasing the energy threshold requirements at L1 trigger.

The Muon-to-CTP interface (MUCPTI) and the CTP were upgraded to provide inputs to and receive inputs from L1Topo, and the CTP supports up to four independent complex dead-time settings operating simultaneously, to address various detector-specific time requirements. In addition, the number of L1 trigger selections (512) and bunch-group selections (16) were doubled compared to Run 1.

During Run-1 the HLT was split into a Level-2 and Event Filter processing step, and in Run-2 these were merged into a unique HLT step, which speeded processing data up considerably. At the HLT a two stage tracking approach was introduced to speed up track reconstruction and improve efficiency for several tau, electron, b-jet triggers. The inclusion of out-of-time pile-up corrections at HLT allowed to improve the resolution of calorimeter reconstructed objects for electron, tau, jet and b-jet triggers.

The ATLAS trigger system in Run-2 allowed the efficient and stable collection of a rich data sample for physics analyses, using different streams: a Main stream promptly reconstructed at Tier0, a B-physics and Light States stream delayed in reconstruction at Tier0 or on the grid, and a Trigger Level Analysis stream saving only trigger reconstructed data at a much higher rate than what possible for the Main stream triggers. In addition, the express stream records events at a low rate for data quality monitoring; other minor streams with physics applications, such as zero-bias and background events, are also recorded. A typical stream rate profile during a run for 2018 data taking is shown in Figure 2.

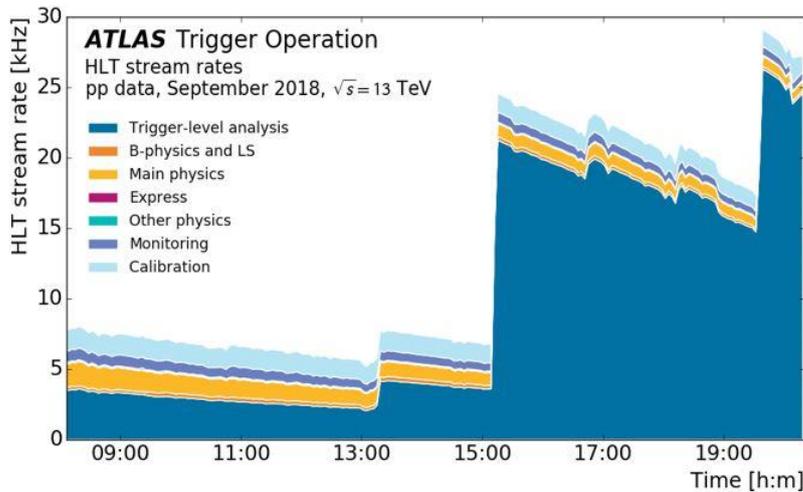


Figure 2: Trigger stream rates as a function of time in a fill taken in September 2018 with a peak luminosity of $L = 2.0 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ and a peak average number of interactions per crossing of $\langle \mu \rangle = 56$.

The ATLAS Trigger Performance

The performance of the ATLAS trigger menu is measured in data, selecting an orthogonal sample of collision events rich in the presence of di-jets, Z, W or top anti-top events, and determining the efficiency of each trigger to select offline reconstructed objects for searches or measurements. The Missing Transverse Energy trigger reconstruction based on the “pufit” method, adopted for Run-2, is shown in Figure 3. Such trigger is the key for most searches for new physics in ATLAS, both in SuperSymmetric and in Exotic models. The rate of background (left) as well as the efficiency of detecting signal (right) was extremely stable with respect to the number of pile-up interactions in Run-2, compared to Run-1, allowing very precise measurements with such triggered data.

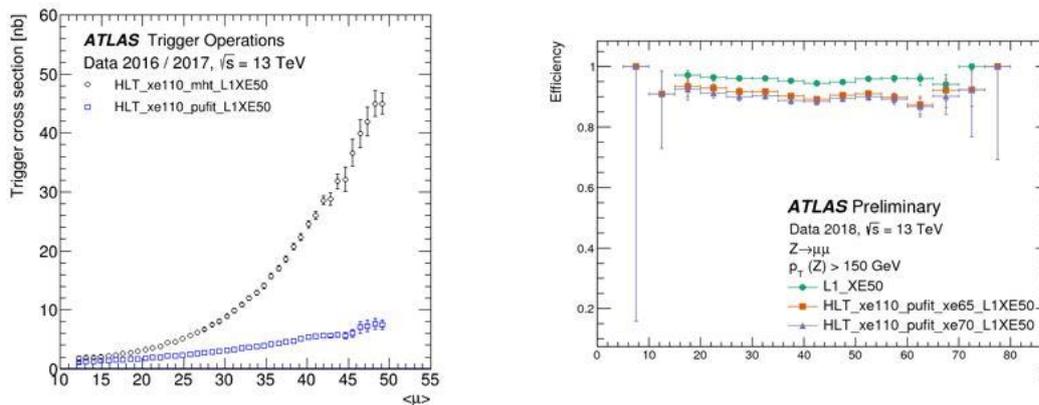


Figure 3 : Run-2 Missing Transverse Energy trigger cross section stability (left) and trigger efficiency with respect to offline reconstructed quantity (right), versus the number of pile-up interactions.

Several new physics scenarios involve hadronic final states, with one or multiple high energetic jets. During Run-2 specific calibrations including track and calorimeter information were introduced

online (Figure 4, left), as well as efficient b-tagging capabilities (Figure 4, right), to improve the efficiency for new physics.

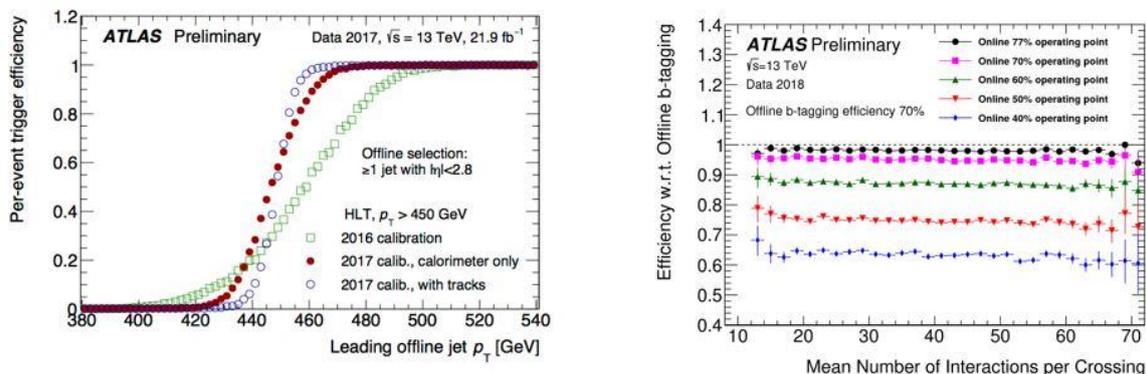


Figure 4 : Jet Trigger efficiency with respect to offline selected jets using different calibration schemes at trigger level (left); B-tagging Trigger efficiency versus number of pile-up interactions (right).

Single lepton triggers are extensively used in ATLAS. Isolation in addition to particle identification are used online to trigger on relatively low energetic leptons, useful for most analyses. Such informations are often the convolution of several input variables and therefore stability of efficiency during a run is a non trivial, albeit highly desired feature. This was achieved in Run-2, as shown in Figure 5.

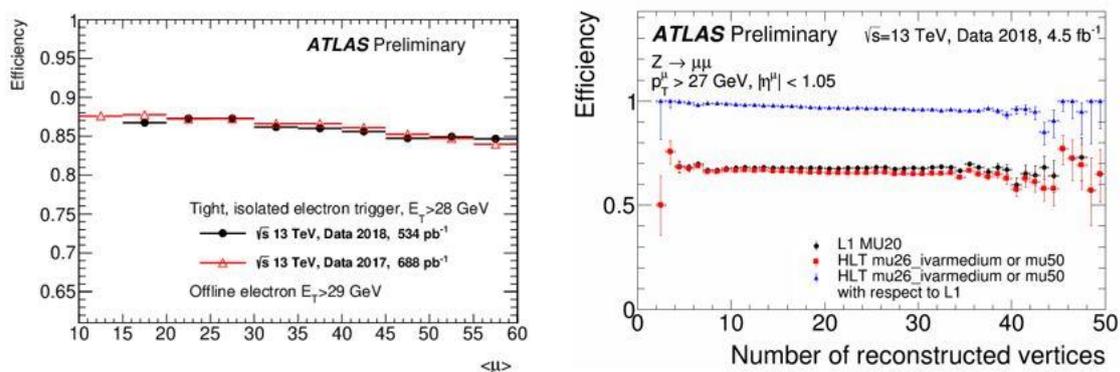


Figure 5: Trigger efficiency versus number of pile-up interactions for electron trigger (left) and muon trigger (right).

Run 3 and Beyond

The ATLAS trigger system will be upgraded in the Long Shutdown 2 (LS2) to use higher transverse and longitudinal granularity at the L1 calorimeter system, and new muon detectors in the endcap regions, namely the New Small Wheel and the new RPC station (BIS78), to reduce rates for comparable signal efficiencies at the L1 muon system. The L1Topo will also be replaced with three new boards with improved capabilities. In addition, the HLT software will undergo major changes to become multi-thread safe, and run code very similar to the offline reconstruction. These changes will be more extensive than in LS1, and will require a thorough commissioning throughout 2021.

For the HL-LHC period, the ATLAS trigger and data acquisition system will be designed to withstand higher input and output rates at L1 and HLT (1 MHz L1 and 10 kHz HLT output rate), benefiting to large extent from the L1 hardware upgrade already available in Run-3.

Further Reading:

[1] The ATLAS Collaboration, Performance of the ATLAS trigger system in 2015, Eur. Phys. J. C (2017) 77:317

ALICE trigger system: Present and Future

by *Orlando Villalobos Baillie (University of Birmingham) for the ALICE Collaboration*

 [PDF version](#)

The purpose of any trigger system is to select an event sample strongly enriched in physics processes of interest, while rejecting those not of interest, and to do so in such a way as to make efficient use of the available detectors.

The prime objective of the ALICE experiment is a comprehensive study of ultrarelativistic heavy ion interactions at LHC energies. The strong-interaction cross-section for such interactions is very large ($\sigma = 8$ barns), but, compared with what is achieved in pp collisions, the maximum luminosities available in ion-ion collisions are modest; to date, the maximum luminosity attained in Pb Pb interactions is $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$, compared with $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ at the ATLAS and CMS intersection regions in pp interactions. The physics aims of the ALICE experiment are markedly different from those of the other experiments at the CERN LHC, leading to a different approach to triggering. In addition, heavy ion interactions are characterised by very high event multiplicities. The number of charged particles produced per unit of rapidity at mid-rapidity in central collisions can reach 2000 at $\sqrt{s} = 5.02$ TeV, indicating that the total multiplicity would run to many thousands of charged particles. Measuring particle momenta and providing charged particle identification in such a high density environment is very challenging, and governs the choice of detector technologies in the experiment.

The physics signatures of interest in heavy ion collisions are either very general or very difficult to extract from background. Bulk features can be measured from essentially all events and therefore may be addressed by a Minimum Bias trigger, while other features, such as charm or beauty decays, are extremely difficult to extract at trigger level owing to the high levels of background.

Runs 1 and 2

Trigger decisions are made to meet several possible latencies in ALICE [1]. The situation for Runs 1 and 2 is shown in Table 1.

	Latency	Run1	Run2
LM	800 ns		✓
L0	1.2 μs	✓	✓
L1	6.5 μs	✓	✓
L2	100 μs	✓	✓

Table 1. Latencies for each trigger level in the ALICE trigger system, as used in Runs 1 and 2.

The LM level, introduced in Run 2, has the purpose of providing a rough minimum bias-like trigger to be used to activate (“wake-up”) the TRD electronics, which are kept switched off when not required in order to reduce heat dissipation. The “main” part of the trigger starts with L0, available since Run 1, for which most of the trigger inputs are timed.

Trigger inputs can be accepted at each of these three latencies, to a maximum of 24 (LM/L0), 20 (L1) and 6 (L2). The allowed trigger conditions are a programmable combination of ANDs of different trigger inputs, with other trigger operations (e.g. OR, negation) only possible for a subset of the inputs. The ALICE trigger takes into account the fact that some detectors read out much more quickly than others by introducing the concept of a trigger *cluster*. A trigger cluster is a group of detectors that read out together. The detectors in the forward muon spectrometer have well-matched readout characteristics and can read out much more quickly than the slowest of the central detectors. For this reason, an efficient way to manage readout is to allow the forward muon detectors to read out both separately, in a “muon cluster”, and in association with the central detectors, resulting in larger integrated luminosities for the forward muon cluster. The decision as to which cluster is to read out (whole detector or forward muon cluster) is taken dynamically, on an event-by-event basis, depending on availability of detectors. Other uses of the separate cluster concept include separating a single detector into a cluster of its own for debugging purposes.

ALICE detectors are for the most part not pipelined, reflecting the lower interaction rates at the ALICE intersection region. This implies that detectors need to employ a BUSY mechanism to protect themselves from spurious signals during readout operations. Each detector sends a maximum of two BUSY signals to the CTP (to allow for detectors with separate electronics on each side of the interaction region).

These requirements determine the characteristics of the Run1/Run 2 trigger system. The Central Trigger Processor (CTP) consists of six different board types, all implemented in 6U VME, housed in a VME crate with a custom J2 backplane for transmission of trigger signals from one board to another. A seventh board type, the Local Trigger Unit (LTU), serves as the interface between the CTP and the detectors, collecting BUSY signals from the detectors and distributing trigger signals to them. There is one LTU per detector.

The architecture of each board type is similar. The LTU, which was produced first, is at once the prototype and the most complicated board, because it also allows an emulation of the whole trigger system, generating complete trigger sequences suitable for exercising detector readout when in standalone mode, decoupled from the CTP. The board has two Field Programmable Gate Arrays (FPGAs). An Altera EPM3512, visible at the top right of the board (see fig. 1) controls the VME traffic on the J1 backplane, carrying VME commands from the VME processor for the crate to the board, including those needed to configure the firmware for the other FPGA. This is an Altera Cyclone EP1C20, and it executes the trigger logic on the board. It is situated in the centre of the board. Underneath it is a large flash memory chip where the current firmware is stored; its contents can be updated through VME. The FPGA loads this firmware at power-up. A small collection of chips at the bottom right of the board run Philips Inter Integrated Circuit (I²C) protocol to allow monitoring of voltages and temperatures on the board. These features are present on all the boards, with varying arrangements of ancillary electronics to fulfil the specific functions of each board.

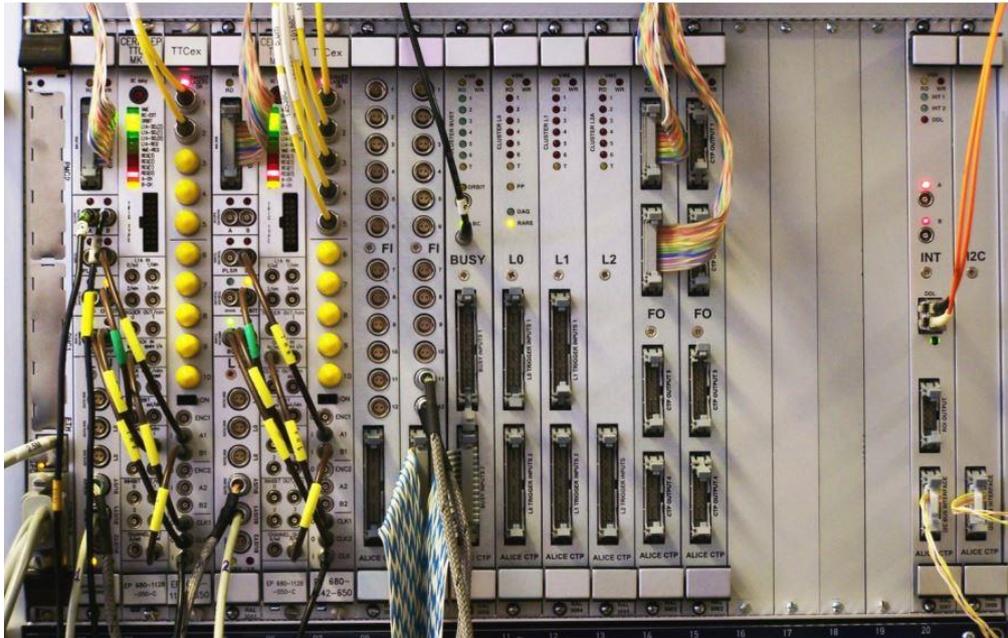


Figure 1. CTP layout for Run 1. The CTP uses six boards. Trigger inputs are sent on LVDS cables to the Fan-In boards (FI) and from there to the trigger level boards on flat cables. BUSY signals are collected and processed on the BUSY board. The L0 board is the starting point for trigger generation. The L1 and L2 boards add further trigger conditions to the trigger analysis that has been initiated. The decisions are fanned out to the detectors from the connectors on the Fan-Out boards (FO). The INT board provides trigger data for the event for trigger performance monitoring.

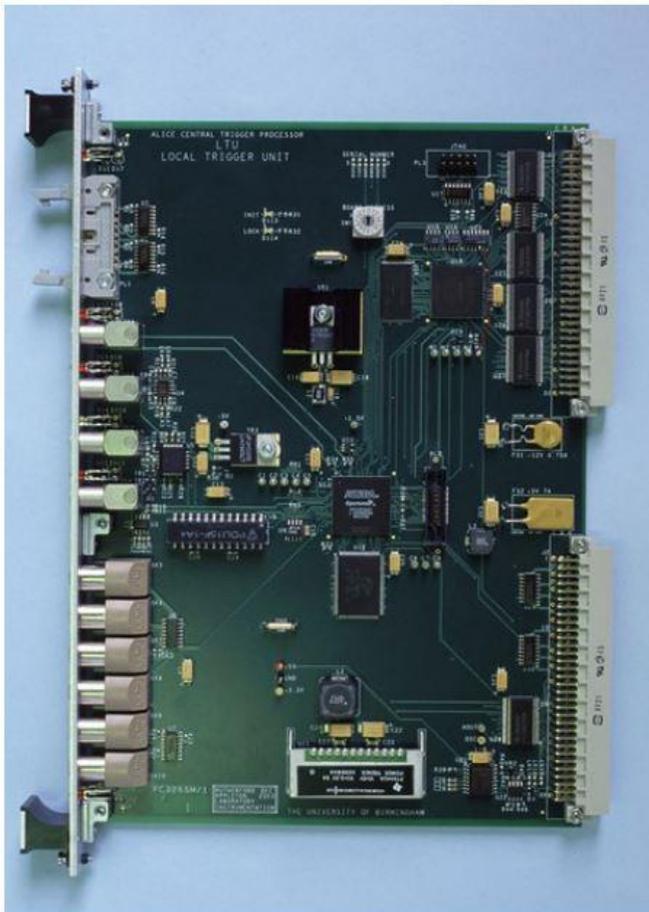


Figure 2. The Local Trigger Unit. The two FPGAs are visible at the top right and at the centre of the board. The Cyclone FPGA has a flash memory directly below it. The board is described in more detail in the text.

The trigger proved very reliable during Runs 1 and 2. Figure 2 shows the cumulative yields for different types of trigger in Run 1. The bulk of the data taken were minimum bias, and in addition triggers were taken using the forward dimuon spectrometer (“dimuon”), using the electromagnetic calorimeter to flag jets (“EMCAL jet”) and using the Transition Radiation Detector (TRD) to flag electrons with $p_T > 1 \text{ GeV}/c$.

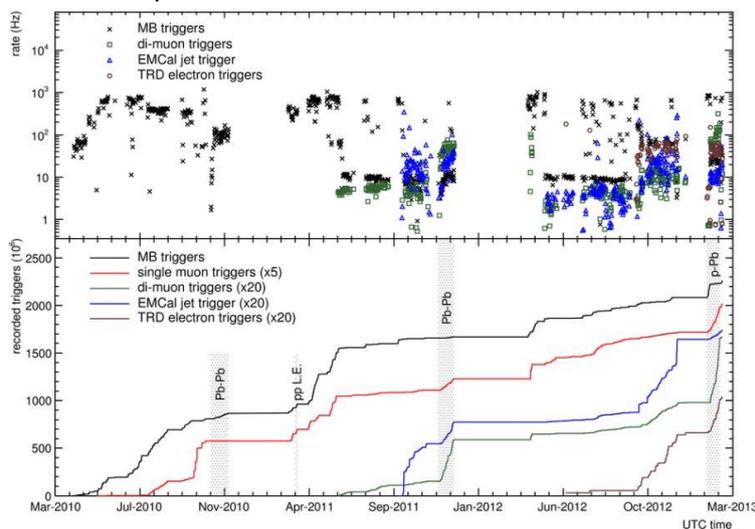


Figure 3. Trigger performance in Run 1. The integrated rates for several different trigger types are shown as a function of time. [2]

Prospects for RUN 3

In Run 3, the ALICE strategy is to focus on rare probes accessible using the ALICE strengths in particle identification and momentum reach down to very low p_T [3]. These include production of heavy quark states, heavy quarkonia, thermal photons and dileptons, the interaction of jets with the medium, and the production of exotic nuclei. Such a physics strategy does not lend itself very well to conventional trigger algorithms, as there are no trigger selections that can lead to major enrichments of the heavy flavour content of the selected sample. Enrichment can only be achieved through a full reconstruction of the decay, keeping those events, which show candidates passing a series of already specialised selections.

A few years ago, such a procedure would have been considered completely unworkable, but rapid improvements in computer performance, coupled with dramatic decreases in cost per processor unit, mean that today it is possible to assemble an array of processors (“high level trigger”) of sufficient size to have an aggregate throughput that keeps up with the data rate. In ALICE, this also means increasing the interaction rate from ~8 kHz for PbPb collisions in Runs 1 and 2 to ~50 kHz in Run 3.

Many (but not all) of the ALICE detectors will have a complete overhaul of readout electronics for Run 3, moving to a system of “continuous” readout. The TPC, in particular, lends itself to this as it naturally takes some considerable time after an interaction for all the charge from the produced tracks to drift onto the anodes (about 100 μs); with an increased interaction rate, this means the

events will mostly overlap. Nevertheless, a modification of the anode structure (to incorporate GEM readout) is necessary to avoid space charge buildup from the positive ions formed during gas amplification. The inner tracker and the muon chambers are also being re-equipped for continuous readout. In particular, the geometry of the inner tracker will be altered to provide layers closer to the interaction point, giving improved vertex resolution. The new detector will use “Alpide” monolithic silicon pixels, but will not have trigger functionality.

In this environment, the task of the trigger system is in principle simplified [4]. Detectors that have not upgraded to continuous readout require a simple Minimum Bias trigger (and all detectors, whether continuous readout or not, are required to be able to operate in triggered mode). Following the latency requirements for Runs 1 and 2, trigger inputs can arrive at 850ns, 1.2 μ s, and 6.5 μ s. However, unlike in the previous runs, each detector receives only one trigger, with a latency chosen to be suited to the detector’s readout. Detectors with continuous readout simply require a subdivision of the data stream into time intervals called *heartbeats*, to allow synchronization between different detectors.

A heartbeat has been chosen to coincide with one LHC orbit. The detectors are supposed to be dead time free, and therefore always capable of receiving fresh data. Nevertheless, situations can arise when detectors are unable to take data, and the detectors in this case report that the data for a given heartbeat are not satisfactory. These messages are collected into a *heartbeat map*, which summarizes the status of the detector (or, more specifically, those parts of it running continuous readout) for a given heartbeat. The assembly of heartbeat maps is a slower operation than the determination of the busy status of detectors; it can take several hundred microseconds to complete the whole ensemble of heartbeat statuses from all the participating detectors. Once the heartbeat map is available, the data from a given detector in that heartbeat is either kept or discarded according to programmable actions defined for different heartbeat map conditions.

Advances in FPGA technology between the time when the Run 1 and Run 3 hardware were designed have meant that the whole trigger logic can now be handled by a single FPGA, in this case a Xilinx Kintex Ultrascale (XCKU040FFVA1156) . This obviates the need for a special backplane, as all the logic is performed on one board, with a major improvement in flexibility, but makes the management of inputs to the board more challenging. The board occupies four 6U VME slots in order to allow all the connections to be made. The board is shown in fig. 4. Despite the simpler approach to the new detectors, the requirements that (i) some detectors should continue to receive triggers for each event as before and (ii) that *all* detectors, including those earmarked for continuous readout, should also be capable of conventional triggered operation, makes the board considerably more sophisticated than its predecessors. The partial replacement of the RD-12 TTC by the more powerful TTC-PON also makes the system more complicated, and more powerful.



Figure 4. Level 3 trigger board, top view. The Xilinx Kintex Ultrascale FPGA is visible (with fan) near the middle of the board.

Summary

The ALICE trigger system has served the experiment well in Runs 1 and 2, allowing a number of features designed to optimize the use of the detectors, such as dynamic partitioning and the use of “detector clusters”. In run 3 the trigger system will have a major upgrade to prepare for continuous readout, whilst retaining backward compatibility as not every detector will upgrade.

References

1. K. Aamodt et al, *The ALICE experiment at the CERN LHC*, JINST **3** (2008) S08002
2. B. Abelev et al. *Performance of the ALICE Experiment at the CERN LHC*, Int. J. Mod. Phys. **A29**(2014) 1430044
3. B. Abelev et al. *ALICE Upgrade Letter of Intent*, CERN-LHCC-2012-012
4. B. Abelev et al., *Upgrade of the Readout and Trigger System*, CERN-LHCC-2013-019

CMS Trigger: Lessons from LHC Run 2

by Alex Tapper (Imperial College London, CMS collaboration)

The CMS experiment has a two-level trigger system [1], to reduce the number of events stored from the LHC bunch crossing rate of 40 MHz to around 1 kHz. The first level (the Level-1) uses custom electronics to reduce the rate of events to 100 kHz, and the second level (the High Level Trigger), based on commodity computing hardware, provides a further reduction to 1 kHz. The Level-1 trigger takes as input coarse information from the CMS calorimeter systems and muon chambers, to reconstruct physics objects such as electrons, muons and jets, and then uses these objects, often in combination, to determine whether the event is worthy of further analysis by the Higher Level Trigger. Up to 512 conditions, making up a *menu*, are evaluated in this decision. If the event is accepted, the trigger signals this to the detector systems and the full granularity event data is sent to the High Level Trigger. The Level-1 trigger must make its

decision within 4 microseconds, as this is how long data may be stored in the detectors, waiting for the accept signal.

The High Level Trigger (HLT) runs the same multithreaded software as the CMS offline reconstruction, optimised to take its decision within an average of a few hundred milliseconds. The number of conditions evaluated in the HLT is not fixed, and in Run 2 was typically around 500, similar to the maximum of the Level-1 trigger. The HLT receives the full event data, and performs on-demand reconstruction using algorithms and calibrations as close as possible to those used offline, ensuring that the quantities used to select events are very close to the quality of those used in final analyses.

Preparations for Run 2

Preparations for Run 2 (2015-18) started while Run 1 (2010-12) was still in progress. The CMS trigger was built to accommodate the design specification of the LHC, of instantaneous luminosities of up to $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with around 20 simultaneous proton-proton interactions per bunch crossing (pile-up). After the start-up of the LHC the luminosity rose steeply and it became clear that to fully profit from the excellent performance of the LHC, the CMS trigger would need to be upgraded.

The Level-1 (L1) trigger was completely upgraded during the shutdown between Run 1 and Run 2 [2]. Everything was replaced, from the clock distribution system, all the electronics boards and fibres, right down to the databases used to store configuration data. In addition to providing improved performance, to fully benefit from the higher luminosity delivered by the LHC, the L1 trigger system was also made more robust. Legacy electronics based on the venerable VME standard were fully replaced with micro-TCA electronics, a modern telecoms standard, and state-of-the-art Field Programmable Gate Arrays were installed (see Fig. 1). Parallel galvanic links between processing components were replaced with faster (up to 10 Gb/s), more reliable and lower maintenance serial optical links. In order to not place CMS data-taking at risk from this ambitious upgrade, the decision was made to duplicate inputs to the L1 trigger from the calorimeters and a subset of the inputs from the muon chambers, to allow commissioning of the new system to proceed in parallel with reliable data-taking using the legacy trigger system.



Figure 1: An example of one of the micro-TCA processing cards developed for the Level-1 trigger upgrade for Run 2 (left) and an example of the new micro-TCA electronics, which replaced the VME standard for Run 2 (right).

The High Level Trigger is upgraded approximately annually through the addition of new computing nodes, with the latest generation of CPUs. In addition to upgrading the hardware, the CMS software is continually being improved to deliver higher performance. The increased luminosity from Run 1 to Run 2, meant the HLT was required to process events with increased pile-up, leading to longer processing times per event, and therefore requiring enhanced performance.

The main change for the HLT for Run 2 was to switch to a multithreaded version of the CMS software. This allows the analysis of multiple events concurrently within a single process, sharing non-event data while running over multiple CPU cores. This has an overall lower memory footprint, which in turn allows the HLT to run a larger number of jobs and take advantage of the Intel HyperThreading technology, to gain almost 20% higher performance. The HLT ran with up to 30 000 cores in Run 2 after the final upgrade, with an approximately equal mix of Intel Haswell, Broadwell and Skylake CPUs.

Performance and highlights

The LHC started Run 2, colliding protons at a centre-of-mass energy of 13 TeV for the first time, in 2015. The legacy L1 trigger was used for the start-up, transitioning to an intermediate upgrade using some new electronics, in particular for the heavy ion run towards the end of 2015. For this run CMS had a much improved trigger compared to Run 1, including specific heavy ion quantities such as the collision centrality. Commissioning of the full L1 upgrade with a fully parallel path for the calorimeter trigger and a slice of the muon detectors for the muon trigger was completed late in 2015. The multi-threaded software for HLT was commissioned, and CMS was ready for the LHC to turn up the luminosity!

In 2016 the fully upgraded L1 trigger became the primary trigger for CMS. Parallel running in 2015 meant that the hardware systems were fully debugged but with a multitude of new and more sophisticated algorithms, optimising and calibrating the new trigger was still a big challenge. After a somewhat rocky start to the run, successive iterations of optimisation led to smooth and efficient running, and perhaps surprisingly a very successful year in terms of uptime and data quality. The challenges for the start of the 2017 run originated with CMS detector upgrades. In particular the installation of a brand new pixel detector at the heart of CMS, which necessitated a fresh look at the track finding software to reap the benefits of an extra layer of silicon very close to the collision point. The HLT group also took the opportunity to reset the physics trigger menu. Starting from scratch and building up the physics selection anew. Problems with the new pixel detector required urgent modifications to the tracking software at HLT, to mitigate the effect of dead areas of the detector. After much hard work this was completed and despite having a larger fraction of inactive channels than expected the new pixel detector gave much improved performance.

The LHC accelerator also saw problems in 2017. The presence of air accidentally allowed inside a vacuum chamber (amusingly nicknamed *the Gruffalo*) caused problems. Interactions between the air and the proton beams led to large beam losses and subsequent beam dumps. The LHC bunch structure was changed to reduce the number of filled bunches and include more empty bunches, to mitigate the problem. The knock-on effect for ATLAS and CMS was fewer filled bunches for a given luminosity and therefore higher pile-up values. CMS ran, with the LHC levelling the instantaneous luminosity by offsetting the proton beams, at around 55 pile-up, significantly higher than had been planned for. The trigger configuration was quickly adapted to this new mode of running and smooth, if not entirely comfortable, operation was regained. The CMS trigger started to see significant effects from the expected radiation damage to parts of the CMS detector in 2017. In particular the most forward elements of the electromagnetic calorimeter, where radiation damage degraded the transparency of the lead-tungstate crystals, requiring large corrections to the response. This resulting in increased noise and large trigger rates, especially for missing energy triggers. Noise rejection thresholds were optimised for 2018, mitigating the effect on the trigger.

After the challenges of commissioning a new trigger system and adapting to LHC conditions in 2017, the final year of Run 2 in 2018 was smooth and highly successful. The long proton-proton part of the run yielded the highest luminosity yet from the LHC, peaking at just under $2.1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and delivering almost 70 fb^{-1} of data to CMS. The L1 trigger made extensive use of the new capabilities of the system, for example invariant mass calculations were used to improve efficiencies for vector-boson fusion Higgs channels and for b-physics resonances.

Figures 2 and 3 display some key performance metrics for the CMS trigger, measured in Run 2 data. Figure 2 shows the efficiency of the Level-1 single muon trigger and Fig. 3 the efficiency of the Level-1 tau trigger. Simple single object triggers, such as these, were used widely both in searches for new physics and Standard Model measurements, supplemented by more sophisticated, analysis dependent trigger conditions.

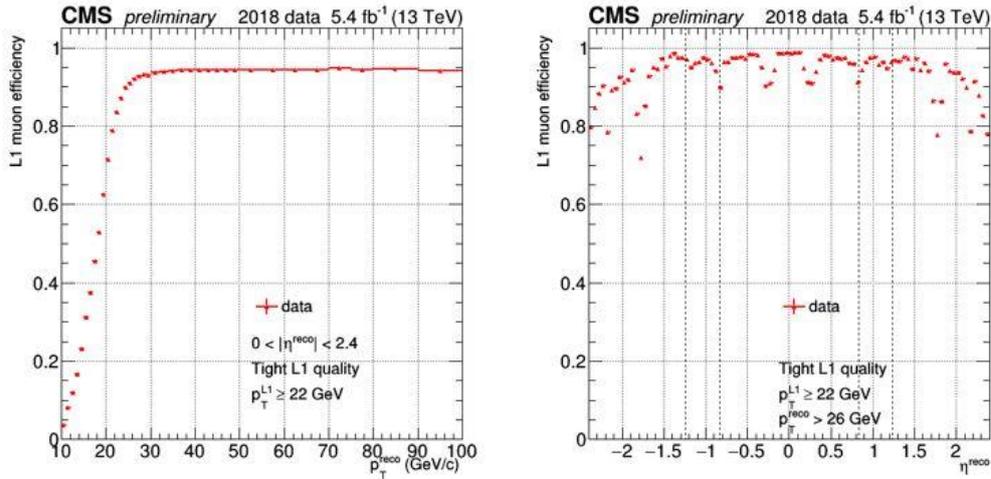


Figure 2: The efficiency of the Level-1 single muon trigger with a threshold of 22 GeV, which was a typical value in Run 2. The efficiency is presented as a function of offline muon p_T (left) and muon η (right), and was measured using the unbiased tag and probe technique in events in which a Z boson was produced and decayed to two muons.

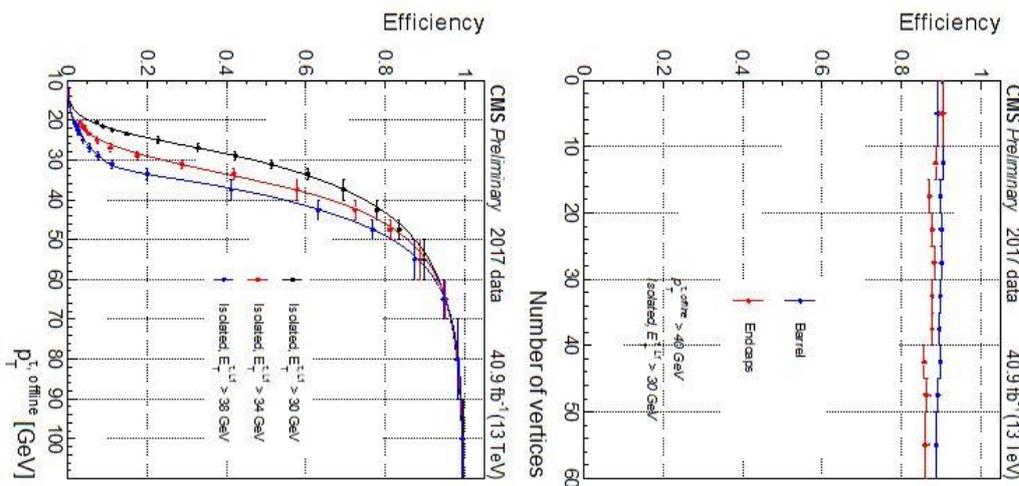


Figure 3: The efficiency of the Level-1 hadronic tau trigger with thresholds of around 30 GeV, which were typical for di-tau triggers in Run 2. The efficiency is presented as a function of offline visible hadronic tau p_T (left) and number of vertices in the event, which is highly correlated with the pile-up (right). The measurements were made using the unbiased tag and probe technique in events in which a Z boson was produced and decayed to two tau leptons.

As in the final year of Run 1 the CMS collaboration decided to “park” a large data sample, writing it to tape and only running reconstruction on it later, after the end of Run 2. Preparations were made to write a sample of unbiased b-quark decays for later analysis. Profiting from the lower pile-up and smaller event sizes at the end of LHC fills, muon triggers were adjusted to collect these events as the luminosity dropped. By the end of the 2018 proton-proton run 12 billion such events had been saved, corresponding to almost 10 billion b-quark decays (around 20 times

larger than the BaBar experiment at SLAC achieved in its lifetime). Rates of up to 50 kHz at L1 and 5.5 kHz at HLT were dedicated to collecting this dataset.

The 2018 run concluded with a highly successful Pb-Pb run, once again with dedicated triggers for the run and an expanded range of heavy ion specific quantities used in the trigger.

Prospects for Run 3 and HL-LHC

The prospects for Run 3 look very bright. Upgrades to the LHC are expected to deliver data samples of unprecedented size, enabling a wealth of novel physics measurements and searches. The CMS trigger system will undergo a modest programme of improvements towards Run 3 over the current shutdown and also prepare for the High-Luminosity LHC (HL-LHC) programme of Run 4 [3, 4]. Some developments originally intended for Run 4, look likely to be used in Run 3 already, for example Kalman Filter muon track finding in the L1 trigger, which provides a means to collect events with muons displaced far from the beamline and GPU based reconstruction at HLT, which is likely to be required for Run 4 and beyond.

Conclusion

The CMS trigger ran very successfully in LHC Run 2, taking data stably and efficiently for the varied CMS physics programme. The flexibility of the trigger system was tested in heavy ion runs and by evolving machine conditions and innovative additions to the physics programme. The lessons learnt in Run 2 are being applied to prepare for Run 3 and looking further ahead to HL-LHC.

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Trigger strategies for the LHCb experiment

by *Agnieszka Dziurda (PAN)*, *Michel De Cian (EPFL)*, *Vladimir Gligorov (CNRS)*, *Sascha Stahl (CERN)*,
Conor Fitzpatrick (CERN)

The LHCb experiment has finished a very successful data taking period in Run 2, collecting an additional 6 inverse femtobarns of proton-proton collisions. A significant modification to the Reconstruction and Trigger system of LHCb was implemented during the first LHC long shutdown period that both enhanced the physics goals of LHCb and served as a testbed for an even more ambitious upgrade prior to Run 3.

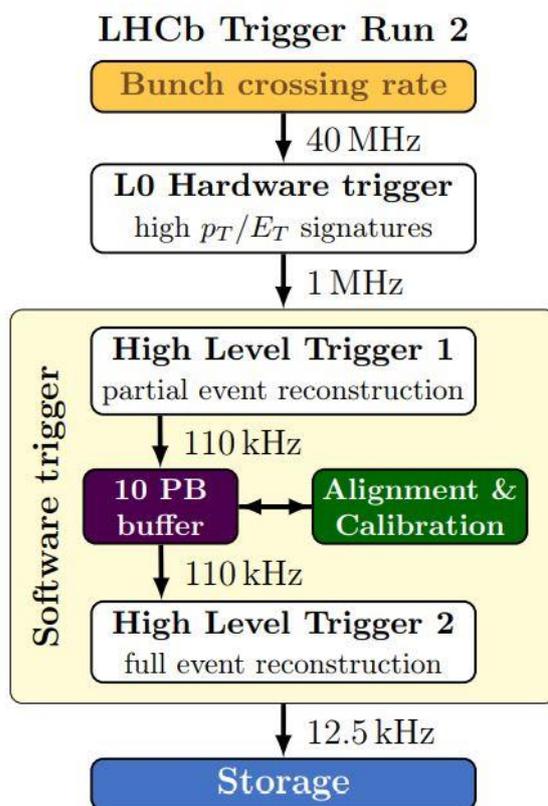


Figure 1. Overview of the LHCb trigger system

The Run 1 LHCb trigger consisted of a hardware level-0 stage that reduces the rate at which the detector is read out to 1 MHz. After this hardware stage events were processed by a two-stage higher level trigger (HLT) in software running on the Event Filter Farm, consisting of commodity servers. The first stage of the HLT performed inclusive selections on one- and two-track signatures using a subset of the information, followed by a second stage that performed more exclusive selections with access to a fast reconstruction of the entire event. After selection by the trigger, events were stored offline where they were further processed using the highest quality reconstruction taking into account subdetector specific alignments and calibrations. Although this trigger enabled the full LHCb physics programme, fuller exploitation of low-momentum charged particles at the first stage and full particle identification at the second stage would enhance the performance for c-hadron physics in particular.

For Run 2, the first and second stages of the HLT were split into separate applications and a large (~11 PB) disk buffer taking advantage of the available disk space on the event filter farm servers was

added. The combination of the disk buffer and separate software trigger stages had two significant advantages: By storing the output of HLT1 to disk, HLT2 could be run asynchronously, meaning that the event filter farm could now be used exclusively for HLT2 processing during LHC inter-fill periods and technical stops. As the LHC collides protons a little over 50% of the time including inter-fill gaps, technical stops and machine development periods, this effectively doubled the available processing resources for the trigger compared to running HLT2 synchronously.

This allowed momentum thresholds to be reduced and significantly increased the efficiency for charm physics. It also allowed alignment and calibration of the subdetectors to be performed on the output of HLT1, prior to HLT2 running: The alignment provides the best known position and orientation of the detector elements, whereas the calibration applies necessary corrections to the detector element response. In order not to impact physics measurements, the accuracy of these corrections must be significantly better than the detector resolution. Alignment and calibration quantities may vary over time for several reasons (for example pressure and temperature changes, automatic or manual movements of the detector, and as LHCb frequently switches the dipole magnet polarity), therefore these quantities need to be re-evaluated frequently.

During normal data taking in Run 2, dedicated data streams are recorded for detector alignment and calibration purposes and sent to a portion of the farm where automated procedures evaluate the current alignment and update it if necessary. Once sufficient data is collected these procedures mark the HLT1 processed data as ready for processing by HLT2. Most of the reconstruction algorithms used in Run 1 were reoptimised for Run 2 in terms of both physics performance and to reduce where possible their computing resource requirements. In addition, the Run 2 reconstruction sequence incorporated additional machine learning algorithms to reduce the number of tracks not used for analysis as early as possible in the reconstruction sequence to minimise unnecessary resource usage at later stages. The performance of the Run 2 trigger is described in [1]. When comparing the reconstruction sequences of Run 1 and 2 an overall performance gain of a factor of two in timing was obtained without any loss in performance. Thanks to these improvements and the increased available CPU time made available to HLT2 from the disk buffer the best quality, 'offline-like' Run 1 reconstruction could now be performed at HLT2.

The improved HLT reconstruction and real-time alignment and calibration removed the need for a dedicated reconstruction step offline, saving resources for simulation production and user analysis. It also allowed analysts to store only the subset of information needed for analysis rather than the full event that would be required for further reconstruction, substantially reducing the event size [2] [3]. This new paradigm greatly increases the efficiency with which signals can be selected, and allows higher rates to be saved for analysis, broadening the physics programme of the LHCb experiment.

As an example the efficiency of the HLT1 inclusive trigger lines for a subset of representative beauty- and charm-hadron decays are shown in Fig. 2.

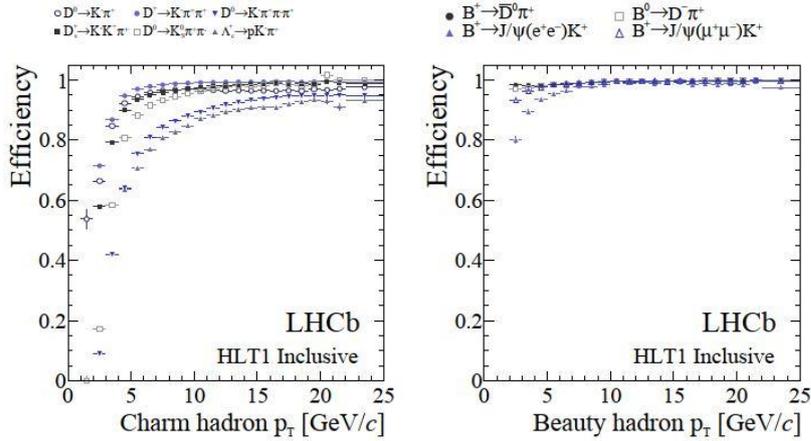


Figure 2. Efficiency of the HLT1 inclusive trigger for a subset of representative beauty (left) and charm (right) decays as a function of transverse momentum.

The Run 2 trigger and reconstruction model has been adopted as the baseline for the LHCb Upgrade, taking place over the current Long Shutdown ready to take data in Run 3. As part of this upgrade, the 1 MHz readout limitation is being removed along with the level-0 trigger, resulting in a trigger-less readout of LHCb events into a fully software trigger and reconstruction operating at the LHC bunch crossing frequency. The online alignment and calibration of LHCb data, its full reconstruction, and the subsequent use of reduced event formats together form the Real-Time Analysis paradigm.

Further Reading

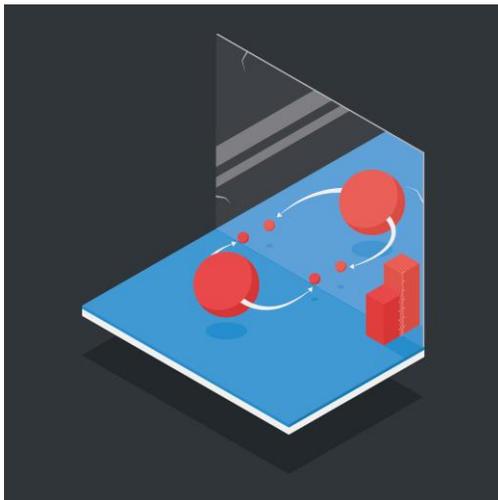
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- [3] CERN-LHCb-DP-2019-002

LHCb observes CP violation in charm

by *Patrick Koppenburg (NIKHEF)*

We live in a Universe of matter, which is a good thing but poses a problem: We know that in the Big Bang initially as much matter as antimatter was produced, and that the antimatter somehow disappeared. How this happened is one of the questions that the LHCb experiment is trying to answer.

Let us rewind. Every day's physics is left-right symmetric. You cannot for instance tell if a film of a billiards game is shown left-right reversed unless social conventions, as numbers or words, give you a clue. This is because gravity and the electromagnetic interaction are symmetric under the exchange of left and right, an operation called parity or just P. However, in 1956 Lee and Yang noted that this symmetry had never been tested in weak interactions. "Madame" Wu (as she liked to be called) then performed the experiment and indeed found that parity is violated in radioactive beta decays. Physicists had to accommodate parity violation, but would assume that the laws of physics are symmetric under the combined operation of replacing left by right and swapping the charges of all particles. This is the CP operation, where C stands for charge replacement, which is the operation of turning particles into their antiparticles. But are the physics of matter and antimatter exactly the same?



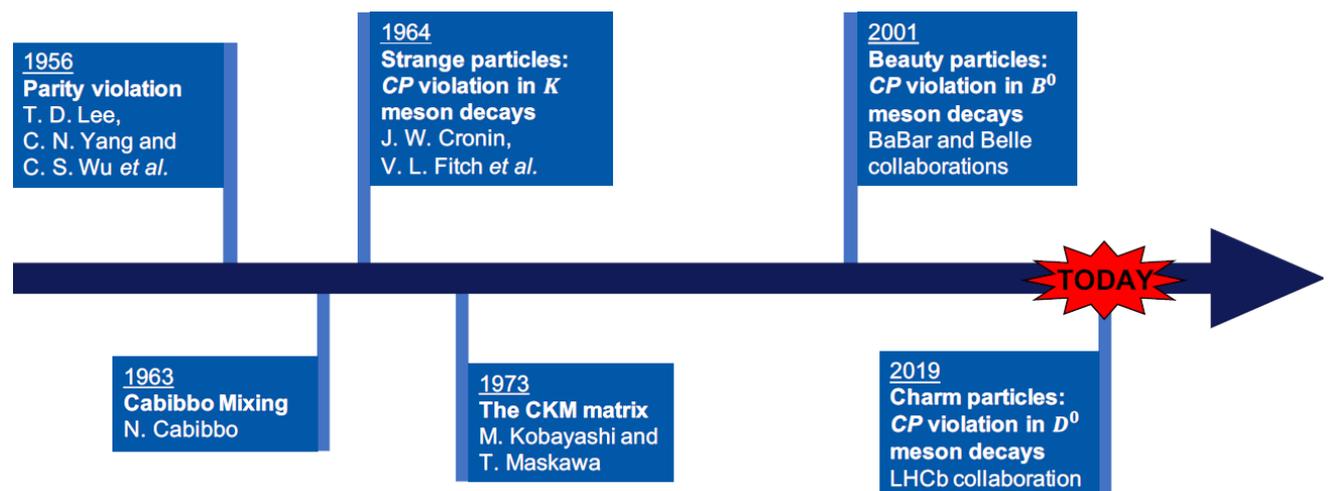
A CP-symmetry transformation swaps a particle with the mirror image of its antiparticle. The LHCb collaboration has observed a breakdown of this symmetry in the decays of the D0 meson (illustrated by the big sphere on the right) and its antimatter counterpart, the anti-D0 (big sphere on the left), into other particles (smaller spheres). The extent of the breakdown was deduced from the difference in the number of decays in each case (vertical bars, for illustration only) (Image: CERN)

In 1964 in Brookhaven, Cronin and Fitch found that the K-long meson decays to two pi mesons. That was a huge surprise! The neutral kaon system comes in two species: a short-lived K-short and a longer lived K-long, respectively decaying to two and three pi mesons. In quantum mechanical terms, these states are the two eigenstates of the CP operator, so K-long decaying to two pi mesons instead of three is a violation of CP conservation. This is actually good news, as the existence of CP violation is one of three necessary conditions listed by Sakharov to obtain a matter-dominated universe. So, problem solved? Not really.

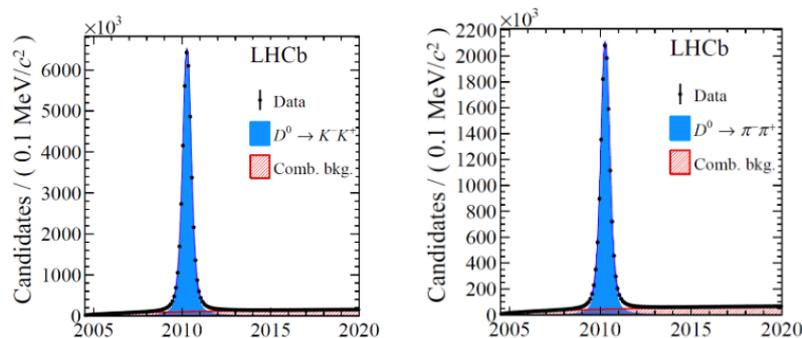
First one needs to explain how CP violation is possible at all. In 1973 Kobayashi and Maskawa implemented it as a complex phase in the quark-mixing matrix that parametrises the transitions of quarks by the weak interaction. For this to work requires the existence of at least six quarks. At the time only the up, down and strange quarks were known, so postulating three new quarks was quite audacious. The charm quark (observed in 1974) had already been conjectured, as a solution to the the GIM mechanism. The next last two would only be discovered much later: beauty in 1979 and top in 1995.

Then, the model had to be tested: two so-called B-factory experiments were built at SLAC and KEK. They observed CP violation in beauty mesons in 2001, thus confirming that the theoretical description of CP violation was correct. This however posed another problem: there is far too little CP violation to explain the universe. There must therefore be other processes that involve CP violation. CP violation in neutrinos may contribute, and the absence of CP violation in the strong interaction is also a mystery. But likely, one needs new physics with new CP-violating processes mediated by yet undiscovered particles.

Finding them is one of the goals of the LHC. The LHCb experiment exploits the enormous yields of beauty and charm hadrons to perform precision measurements in rare processes. In 2013 LHCb reported the observation of CP violation in Bs mesons and in 2016 evidence for CP violation in decays of beauty baryons. But so far nothing was found in charm.



Due to a conspiracy in the quark-mixing matrix, CP violation in charm decays is extremely suppressed. The result reported last week by LHCb required 70 million decays of D mesons to pairs of pi or K mesons, a dataset collected between 2015 and 2018. It exploits the new trigger scheme introduced for Run 2 of the LHC: after a first filtering in real time, the data is stored on disk while the full offline-quality calibration is performed. This calibration is then used in the last stage of the trigger that constructs D meson candidates. These are ready for the use by analysts without any further processing required.



The images show the so-called invariant-mass distributions used to count the number of decays that are present in the data sample. The area of each blue, bell-shaped (Gaussian) peak is proportional to the number of decays of that type recorded by the experiment. The final result, which uses essentially the full data sample collected by LHCb so far, is given by the quantity $\Delta\text{ACP}=(-0.154\pm 0.029)\%$, whose difference from zero quantifies the amount of CP violation observed. The result has a statistical significance of 5.3σ (Credits: LHCb collaboration, [arXiv:1903.08726 \[hep-ex\]](https://arxiv.org/abs/1903.08726)).

However, to achieve a precision of 10^{-4} , a trick has to be used to control systematic uncertainties. To cancel detection asymmetries, the difference in the amount of CP violation between the decays of D mesons to kaon and pion pairs is measured. Combining the new result with previous publications using 2011 and 2012 data, this difference is $(-15.4 \pm 2.9) \times 10^{-4}$, which is more than five standard deviations from zero. CP violation is thus observed in charm for the first time. Is this compatible with the Standard Model or New Physics? We do not really know yet. Calculations involving charm quarks are extremely difficult. We hope that this result will trigger more efforts into making precise predictions.

For more information, see the [LHCb website](https://lhcbblog.cern.ch/) and the [paper](#) describing the results.

[arXiv:1903.08726 \[hep-ex\]](https://arxiv.org/abs/1903.08726)

Resolving a long-standing question at ISOLDE

by *Karl Johnston (CERN)*

Among the many pioneering results that have been published at ISOLDE was the discovery of odd-even staggering in the mean-square charge radius in neutron deficient Hg isotopes in the 1970s, as part of the RADOP experiment which measured the isotopic shifts using optical spectroscopy [1], [2]. Since then, this phenomenon has been called “shape staggering” and is thought to be unprecedented elsewhere in the nuclear landscape.

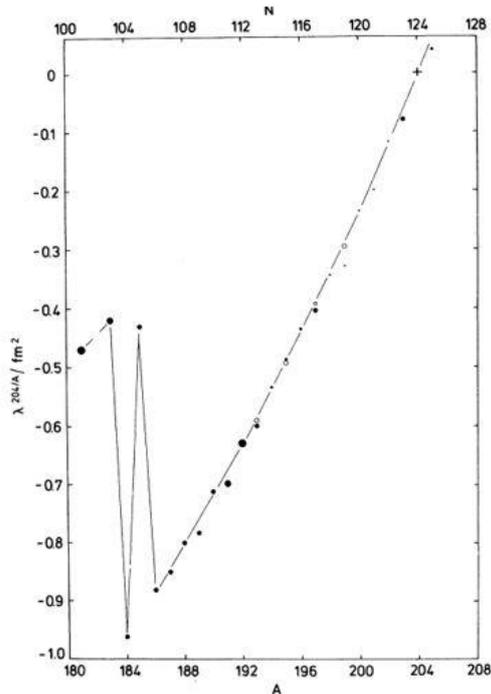


Figure 1 Example of the first observation of odd-even staggering at ISOLDE [1]

Further study revealed that this region of the nuclear chart displays a multitude of different shapes and the mercury isotopes are now known to be one of the richest regions in terms of shape coexistence. Since this discovery, numerous other studies were conducted into probing this staggering phenomena using a variety of techniques such as Coulomb Excitation, beta-decay and mass measurements. However, the theoretical basis for the staggering mechanism along with an experimental extension to ever more neutron deficient isotopes had not been attempted due to the inherent difficulties in modelling such heavy isotopes and challenges in measuring such exotic isotopes. Furthermore, measurements had only been extended down to ^{181}Hg . While the ground-state deformation has been indirectly inferred for neutron deficient mercury isotopes from in-beam recoil-decay tagging measurements, hinting towards less-deformed shapes for $A < 180$, this had not been confirmed by a direct ground-state isotope-shift measurement. The missing mean-square charge-radii data for the lighter mercury isotopes left the key question of where the shape staggering ends.

These hurdles have now been overcome at ISOLDE [3] where target and ion source developments have allowed for the production of ever more exotic isotopes, down to ^{177}Hg . Similarly, improvements in spectroscopic methods have allowed for high precision measurements of even weakly produced radioactive ions: down to rates of only a few per minute. The neutron deficient series of Hg isotopes has been characterized using an impressive combination of decay, optical and mass spectroscopies and spectrometry. Faraday cup measurements allowed for the measurement of the stable ^{196}Hg isotope – which was the reference isotope for the current study – along with other strongly produced Hg isotopes. Isomer shifts and hyperfine parameters were measured using either the ISOLDE “Windmill” setup – allowing isotopes with a production rate of only 0.1/s to be determined – and the Multi-Reflection Time of Flight spectrometer (MR-TOF) at ISOLTRAP [4]. The experimental scheme is shown in Figure 2.

Mercury isotopes were produced via spallation reactions induced by a 1.4-GeV proton beam from the PS-Booster impinging upon a molten-lead target. The neutral reaction products effused from the heated target via the transfer line. Traditionally, Hg ions can be produced using a plasma ion source, but this gives rise to strong stable contamination. In this experiment, the Hg ions were produced using the ISOLDE laser ion source *in* the plasma ion source: the so-called *VADLIS* mode. This allowed for high purity beams to be ionized which were subsequently sent to the various experimental stations. High quality Hg beams are a specialty of ISOLDE and are one of the many instances where the facility is unique worldwide.

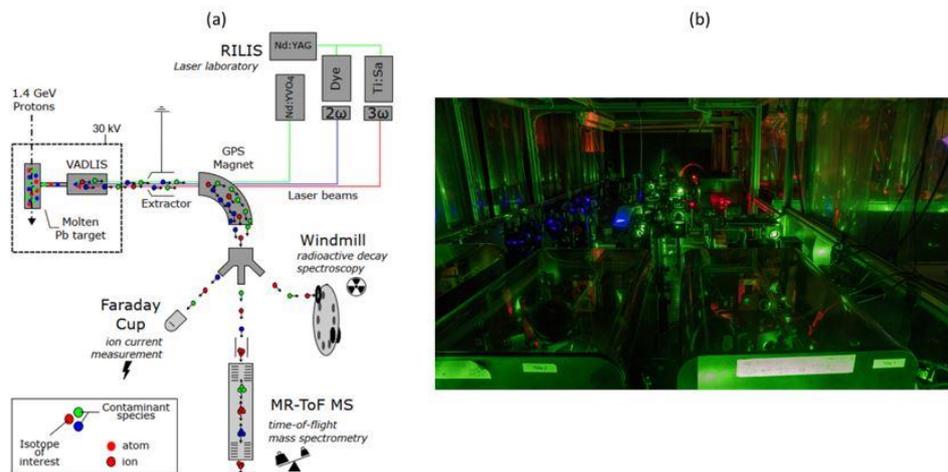


Figure 2. Overview of the various experimental techniques, which have been employed in the investigation of neutron deficient isotopes at ISOLDE (a) and the ISOLDE laser ion source (RILIS) in operation (b).

Examples of the results from the experimental campaign are shown in Figure 3. As can be clearly seen, the pronounced staggering is observed until $A=101$. Extending the measurements down to ^{177}Hg has allowed this sequence to be extended for the first time with the observation that the deformation comes to an end at ^{181}Hg . Below this, the nuclei return to a spherical shape. In addition, the measured nuclei, this finding is supported by magnetic quadrupole measurements in ^{177}Hg and ^{179}Hg . In order to understand further the mechanism that explains this unusual behavior, extensive calculations using density functional theory and large scale Monte-Carlo shell model (MCSM) were undertaken. This was the first time that such calculations were performed for such a heavy system such as Hg and were the heaviest MCSM so far. The calculations were carried out on the massively parallel K-supercomputer at RIKEN. Both the magnetic and quadrupole moments and the radii changes calculated with the MCSM agree with the experimental results to a remarkable extent. Full details of the results can be found in [4] but, in essence, the origin of the shape staggering is attributed to a subtle variation on the “usual” normal shell theory predictions for such isotopes. So-called type II shell evolution – where significant changes in nucleon occupation number produce large shifts of effective single-particle energies – is found to be responsible for the existence of near-degenerate coexistence of strongly and weakly bound deformed states, which gives rise to the observed staggering in neutron deficient Hg isotopes.

This work has highlighted not only the advances that have been made at ISOLDE in producing neutron deficient isotopes in the Hg region, but also the considerable advances in spectroscopy which have allowed these isotopes to be characterized using a host of experimental techniques. The detailed modelling using MCSM has for the first calculations of spectroscopic properties of the

heaviest isotopes yet and will surely inspire additional work in this region and on heavier isotopes. Given the improvements in computing power this will likely become the norm and fits in well with the experimental programmes at ISOLDE where – with the advent of HIE-ISOLDE – the study of such isotopes using Coulomb excitation and multi-nucleon reactions will address new areas of the nuclear chart and will benefit from this close relation to theory.

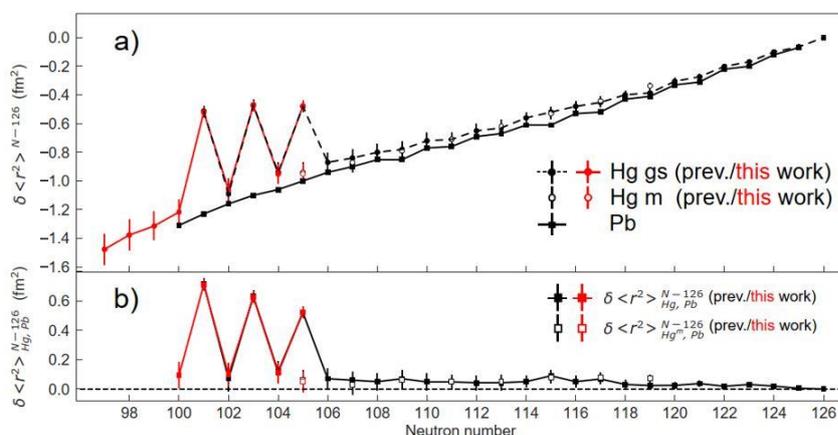


Figure 3. Measured changes in mean-square charge radius for neutron deficient Hg and Pb isotopes.

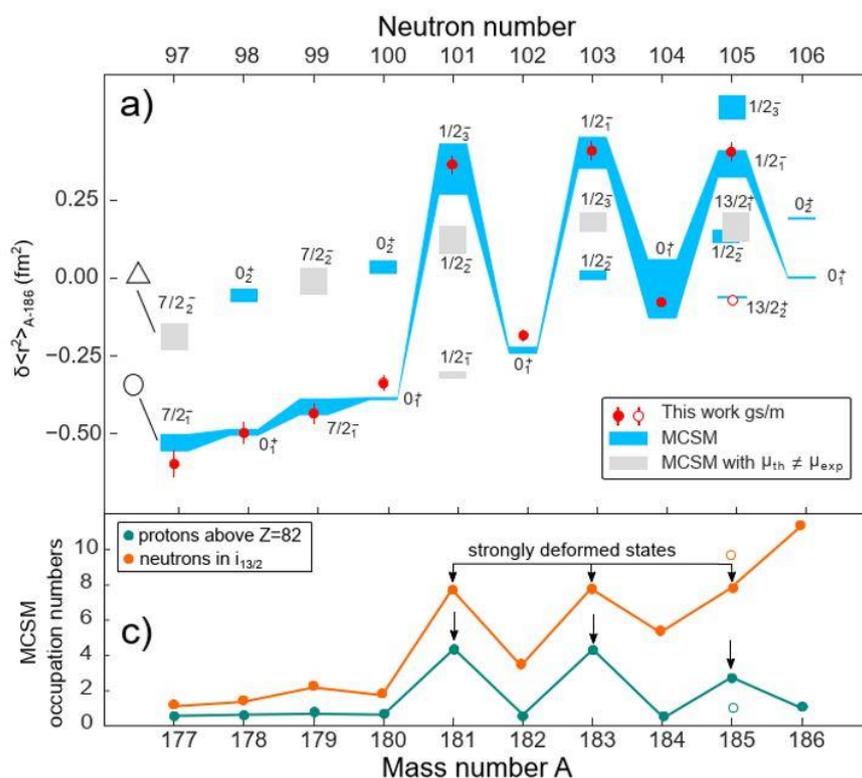


Figure 4 MCSM calculations showing remarkable agreement with experimentally measured radii.

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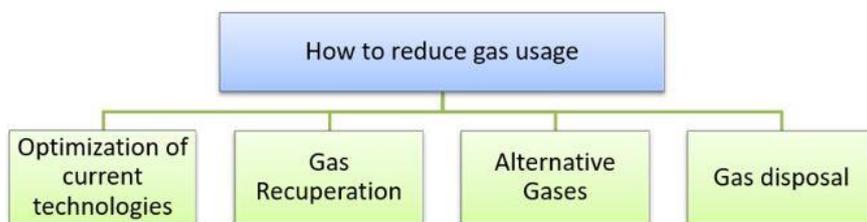
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R&D on gas usage in the LHC particle detection systems

by *R. Guida and B. Mandelli*

A wide range of gas mixtures is used for the operation of different gaseous detectors for particle physics research. Among them are gases like $C_2H_2F_4$ (R134a), CF_4 (R14), C_4F_{10} (R610) and SF_6 , which are used because they allow to achieve specific detector performance that are necessary for data taking at the LHC experiments (i.e. stability, long term performance, time resolution, rate capability, etc.). Such gases are environmentally unfriendly, as they contribute to the greenhouse effect, and currently subject to a phase down policy that started to affect the market with price increase and, in the long term, may cause a decrease in their availability.

With the idea of preparing the very long-term operation, the EP-DT Gas Team, the CERN Environmental Protection Steering board (CEPS) and the LHC experiments have elaborated a strategy based on several action lines.



Gas

consumption at the LHC experiments is already reduced by operating all particle detector systems using such gases with gas recirculation plants, i.e. systems where the return mixture from the detectors is collected, cleaned and then re-used. In addition, the first identified research line focuses the attention on the **optimization of current technologies** allowing to improve flow and pressure stability beyond original requirements to cope with new detectors needs. For example, during Run 2 the mixture recirculation rate of the RPC detector systems was limited to 85-90% due to the presence of leaks at the detector level. Despite the difficult challenge, LS2 will give a unique chance to repair as many leaks as possible and to optimize the gas systems.

The second research line is based on the development of systems able to collect the used gas mixture and to extract detector gases for their re-use. **Recuperation** systems permit to avoid venting to atmosphere the gas injected into recirculation system. Systems allowing the recuperation of different gases have been developed in the past for several detectors: CMS-CSC (CF_4), ATLAS-TGC (nC_5H_{12}), LHCb-RICH1 (C_4F_{10}) and LHCb-RICH2 (CF_4). R&D studies are now ongoing for the design of a R134a recuperation plant. Indeed, R134a represents a major contribution to the gas consumption for particle detection at CERN. During Run 2 a first test was performed with a prototype system (Figure 1) on a real LHC-RPC detector. A R134a recuperation efficiency close to 100% was achieved. Moreover, the recuperated R134a was as pure as the fresh gas. Further tests are needed to investigate the filtering capacity with respect to RPC specific impurities. The following step will be the design and construction of a module allowing storage and

re-use of the recuperated gas. In any case, this prototype has paved the way for the design of a final recuperation system for Run 3.



Figure 1: First prototype of the R134a recuperation plant successfully tested recently on the RPC detector system.

A third research line is based on the **long-term replacement of currently used gases** for the operation of gaseous detectors. An intense R&D activity is already ongoing since many years in the detector community for finding more environmentally friendly replacements in particular for R134a, SF₆ and CF₄. Hydrofluoroolefins (HFOs) compounds have been developed by industry to replace R134a as refrigerant fluid and, therefore, they are the first candidates for replacing R134a in our application. However, finding a suitable replacement for the RPC systems at the LHC experiments is particularly challenging because most of the infrastructure (i.e. high voltage systems, cables, front-end electronics) as well as the detectors themselves cannot be easily replaced. Therefore, the R&D is focused on identifying a new mixture able to reproduce the same RPC performance observed with the current R134a based mixture. Encouraging results have been obtained with a partial substitution of the R134a with HFO-1234ze and the addition of a neutral gas (for example CO₂). However, a final satisfactory solution is still far from being achieved.

For future RPC applications where, high voltage systems and detectors can be designed without specific constraints, preliminary results obtained with only HFO based mixture are also promising.

In parallel, RPC detector operation with gas recirculation system and new environmentally friendly gases is also under study at the CERN Gamma Irradiation Facility (GIF++) in presence of background radiation similar to the one expected during operation at the LHC experiments.

For cases where gases cannot be recuperated/re-used, systems for their **disposal** have been developed by industry. They are adopted when such gases after being used in the industrial process are polluted to a level for which the recuperation for re-use is not possible. Unfortunately, many of these gases are very stable compounds and therefore very difficult to dispose. Most important, abatement systems are only solving part of the problem, i.e. the gas emission. Problems like gas availability and price for detector operation are not addressed by abatement systems and these might become the challenge in the coming years due to the phase down policy for such gases.

The different strategies described above should be combined to achieve the highest possible exploitation of the gas, reducing the consumption as well as operational costs and minimizing potential problems due to availability. The challenge in using new environmentally friendly gases is coming from the fact that they behave differently with respect to R134a and therefore current detectors and front-end electronics are not optimized for their use.

Figure 2 shows how the reduction of environmentally unfriendly gas emission evolved in the recent few years as a function of the upgrades performed on the LHC gas systems (excluding the optimization already achieved during the early design phase). During LS2 a further big improvement could come from a reduction of the leak rate at detector level combined with the implementation of R134a recuperation plants.

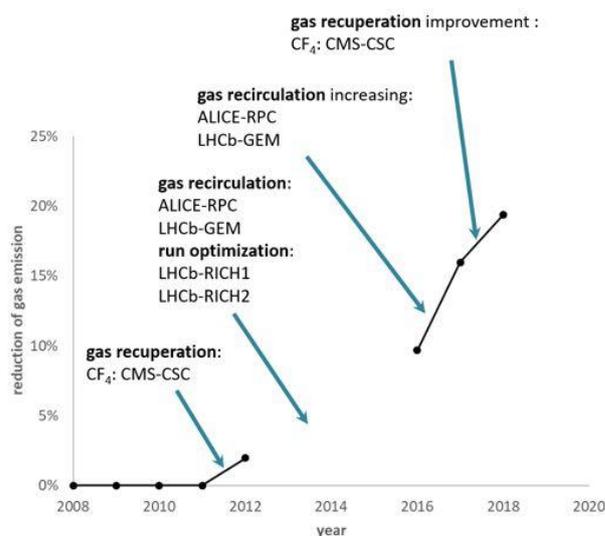


Figure 2:
Reduction of environmentally-unfriendly gas emission in the recent few years as a function of the upgrades performed on different LHC gas systems.

Further Reading

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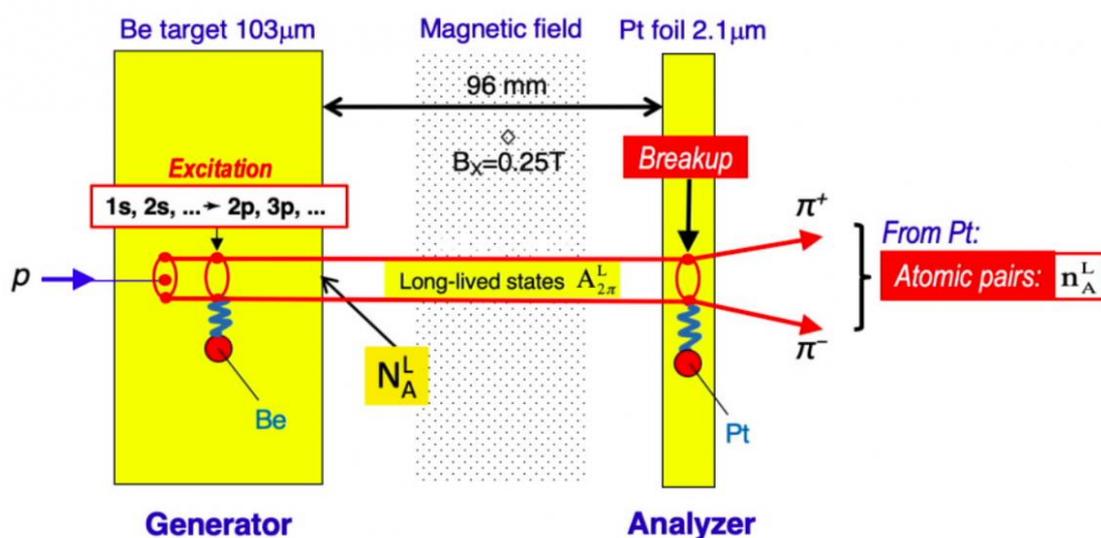
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First measurement of a long-lived meson-meson atom lifetime

by Juerg Schacher (corresponding author) on behalf of DIRAC collaboration

In addition to the ordinary atoms, abnormal or exotic atoms serve as tools to study in detail the structure of atoms and their interactions. Different exotic atoms, consisting of other building blocks than electrons, protons and neutrons, have been observed and investigated.

The DIRAC collaboration at CERN observed new kinds of exotic atoms, the "double-exotic" meson-meson atoms " $\pi^+\pi^-$ " [A] as well as " π^-K^+ " and " π^+K^- " [B]. Furthermore, DIRAC determined their extremely short lifetimes (in the ground state) of around 10^{-15} s or 1 fs [C,D]. For analysing the atomic structure of these novel bound systems, DIRAC faces the difficult challenge to measure also lifetimes of excited states. The DIRAC experiment, a magnetic double arm spectrometer, succeeded in producing long-living $\pi^+\pi^-$ atoms in a beryllium target at the CERN proton synchrotron (24 GeV) and to measure – for the first time – their lifetime of the $2p$ excited state. The generator/analyzer method of DIRAC is shown schematically in the figure. The detected lifetime of $\sim 5 \times 10^{-12}$ s (5 ps) [E] is three orders of magnitude larger than the previously measured ground state lifetime $\sim 3 \times 10^{-15}$ s (3 fs), in agreement with the corresponding QED $2p$ lifetime.



Further studies of long-living $\pi^+\pi^-$ atoms will allow to determine the *Lamb shift* of this atom, i.e. the energy differences between p and s atomic states. By this means, crucial $\pi\pi\pi$ scattering lengths can be evaluated and be compared with QCD predictions of strong interaction in the framework of Chiral Perturbation Theory and Lattice QCD.

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Upgrading the vertex detector of the LHCb experiment

by *Wouter Hulsbergen (NIKHEF) and Kazuyoshi Carvalho Akiba (NIKHEF)*

In LS2 the LHCb detector will go through a metamorphosis. To facilitate running at five times larger interaction rate than in run 2 all readout electronics will be replaced. For LHCb's vertex detector, the so-called 'vertex locator' or VELO, the upgrade is more than sophisticated electronics. To cope with the larger track density and improve track resolution the silicon strip detector — in its characteristic ρ - ϕ geometry that served so well in Run-1 and 2 — is replaced by a hybrid pixel detector. Its sensitive elements will be just over 5 mm from the LHCb beams, the closest of any vertex detector at the LHC.

To build a detector that can survive the harsh radiation environment and cope with the unprecedentedly large data rate has been a tour de force by a large international collaboration. The new VELO's 55 μm square pixel sensors are bump-bonded to the Velopix ASIC. The chip is developed by CERN and Nikhef engineers within the Medipix collaboration. The main difference with its close cousin 'Timepix' is that it can read out much more data per second.

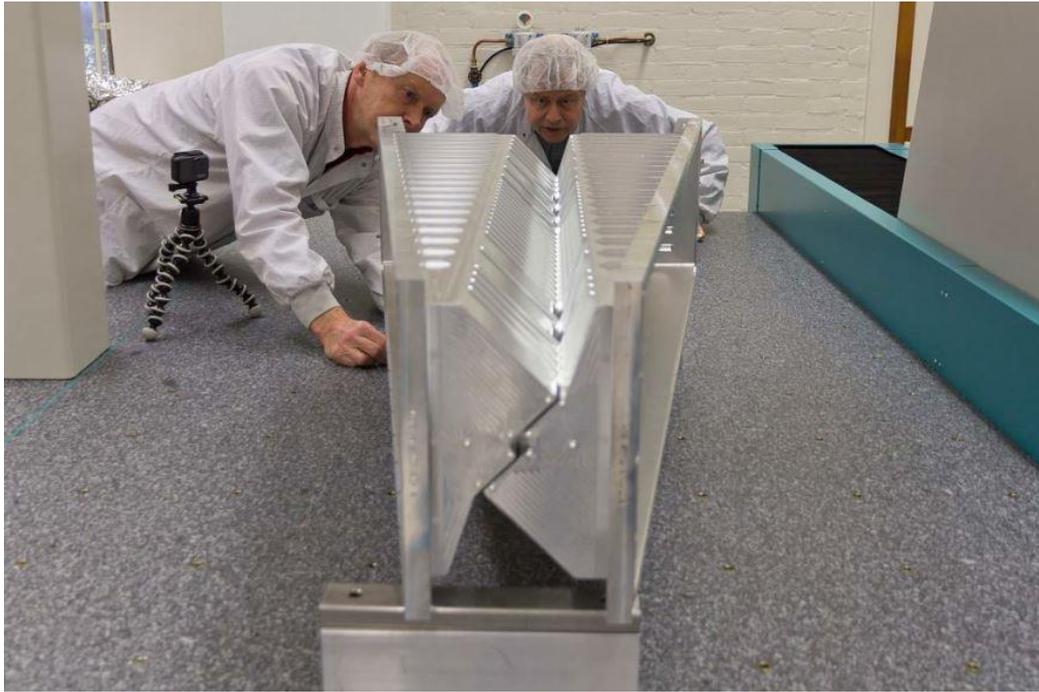
These state-of-the-art detectors are cooled by silicon micro-channel plates, a technology pioneered by NA62. Engineers and physicists from CERN and Oxford have further developed this technique to allow the use of bi-phase CO₂ as a refrigerant to cool the detectors stably down to -30 °C. The CO₂ runs through minuscule channels etched into a 0.5 mm thick plate that must withstand CO₂ pressures well above 65 bar, the boiling pressure of CO₂ at room temperature. As the plate serves also as support for the sensors and the PCBs that connect them to the control and DAQ systems, the Nikhef design of a structure that minimizes movements under large changes in temperature has been a critical step as well.



Prototype vertex locator (VELO) pixel modules were developed and tested in a beam in the North Area last year ahead of the upgrade (Image: Julien Marius Ordan/CERN).

The construction of the 52 detector modules takes place in workshops at Nikhef and the University of Manchester. Last October the first three pre-production modules were tested in a test beam at CERN (see picture). The tests have led to some small modifications in the design. Mass production in Amsterdam and Manchester will start any time now and is expected to finish by the end of the summer. Finished modules will be shipped to yet another participating partner institute, the University of Liverpool, where they will be mounted on the two detector halves that make up the final VELO.

Other critical and unique elements of the LHCb detector are the intriguingly shaped vacuum envelopes, or 'RF boxes'. (See picture). These separates the LHC vacuum from the detector volume. In the other LHC detectors the LHC beam runs through the experiment in a cylindrical beam-pipe. The beam-pipe serves as the barrier of the LHC vacuum and guides the beam mirror currents. The LHCb VELO detectors are positioned so close to the proton beams that a cylindrical beam-pipe would not give sufficient space for the LHC beams during injection. Therefore, the VELO and its beam-pipe consists of two halves that are only moved into their nominal position when stable beams are declared. The complicated shape of the foil is explained by the requirement to minimize multiple scattering and retain sufficient rigidity to withstand small pressure differences between the LHC and VELO volumes.



Berend Munneke and Tjeerd Ketel inspect the alignment of the 'left' and 'right' RF boxes at Nikhef. Once installed at CERN the LHC beam will pass through the 7 mm diameter hole in the centre. (Image: Marco Kraan /Nikhef).

The construction of the vacuum envelopes is as intriguing as their shape: They are machined out of solid blocks of aluminium. A five axis CRC machine at Nikhef carves through the 300 kg block until nothing is left but the flange and a foil that is just about 250 μm thick.

As ambitious LHCb physicists find that still too thick, technicians at CERN have developed a method to carve away another layer using ordinary chemistry: by placing the foil for a short time in a bath of NaOH, the thickness of the foil in the area that faces the beams can be reduced to a mere 150 μm .



Pierre Maurin (left) and Florent pours an etching solution into a prototype RF box in order to remove another 100 micro-meter of aluminium. The green paint protects parts of the box that should not be thinned further. (Image: Maximilien Brice /CERN).

The construction of the new Velo and RF boxes is expected to be finalized by the end of the year. Installation will be done early 2020 after which integration with the new CO2 cooling system and the rest of the detector can begin. Thanks to the upgrade of the VELO and the majority of other subsystems the LHCb detector will be ready for an ambitious physics program that starts after Long Shutdown 2 and lasts until at least 2029. The new VELO detector will start operation together with the rest of the upgraded LHCb after the LHC's Long Shutdown 2 helping to improve the experiment's physics performance while delivering readout at 40 MHz to cope with the challenges of the new operating conditions.

A report from the CLIC week

by *Rickard Ström (CERN)*



The annual Compact Linear Collider (CLIC) workshop brings together the full CLIC community, this year attracting more than 200 participants to CERN, 21-25 January. CLIC occupies a unique position in both the precision and energy frontiers, combining the benefits of electron-positron collisions with the possibility of multi-TeV collision energies. The CLIC project covers the design and parameters for a collider built and operated in three stages, from 380 GeV to 3 TeV, with a diverse physics programme spanning 30 years. CLIC uses an innovative two-beam acceleration scheme, in which high-gradient X-band accelerating structures are powered via a high-current drive beam, thereby reducing the size and cost of the accelerator complex significantly.

During the opening session, Steinar Stapnes, the CLIC project leader at CERN, reported that the key CLIC concepts such as drive beam production, operation of high-efficiency radio-frequency cavities, and other enabling technologies had all been successfully demonstrated. The afternoon session also included detailed presentations on the accelerator and detector status, and of the CLIC physics potential including key motivations for an electron-positron collider that can be extended to multi-TeV energies.

“The CLIC project offers a cost-effective and innovative technology and is ready to proceed towards construction with a Technical Design Report. Following the technology-driven timeline CLIC would realise electron-positron collisions at 380 GeV as soon as 2035,” says Stapnes.

A major focus in 2018 was the completion of a Project Implementation Plan (PiP) as well as several comprehensive Yellow Reports describing the CLIC accelerator, detector, and detailed physics studies. A central point of these documents was the finalization of a complete cost and power estimation, which for the first stage amount to around 5.9 billion CHF and 168 MW, respectively. These reports were further distilled into the two formal input documents submitted to the European Strategy for Particle Physics Update 2018 - 2020 (ESPP). Looking to the future, the workshop discussed the next important step for the CLIC project: a preparatory phase focusing on large scale tests, industrial production and detailed civil engineering aspects including siting and infrastructure. The goal is to produce a Technical Design Report (TDR), enabling the start of construction for the first CLIC stage by 2026. The CLIC project envisions first beams as early as 2035, thereby offering a competitive timescale for exploratory particle physics for the next generation of scientists.

In the CLIC detector R&D session focusing on silicon pixel technologies, several new and refined test-beam analysis and simulation results were presented. These results enabled the design of two new monolithic detector technology demonstrators targeting the challenging vertex and tracker requirements at CLIC. Final design features for both chips, as well as plans for future tests, were presented and discussed. Many of these tests will take place at the test-beam facilities of DESY in Hamburg, where the CLICdp vertex and tracker group will be welcomed for several weeks during the second planned long shutdown of CERN's accelerators in 2019/20.

The workshop heard reports on recent developments for measurements of Standard Model processes in the Higgs boson and top-quark sector as well as on the broad sensitivity for direct observation of physics beyond the Standard Model. Updates were presented on benchmark scenarios with challenging signatures such as boosted top quarks and Higgs bosons, produced at the higher-energy stages of CLIC. Further, the Higgs self-coupling, can be directly accessed at the multi-TeV collisions at CLIC through the measurement of double Higgs production. This measurement benefits from the excellent jet resolution and flavour tagging capabilities of the CLIC detector as well as the clean collision environment in electron-positron collisions. The workshop reported projections of the Higgs self-coupling, in a full simulation study, reaching a precision of about 10% (see Figure 1), an accuracy that is preserved in a global fit of the full Higgs programme of CLIC.

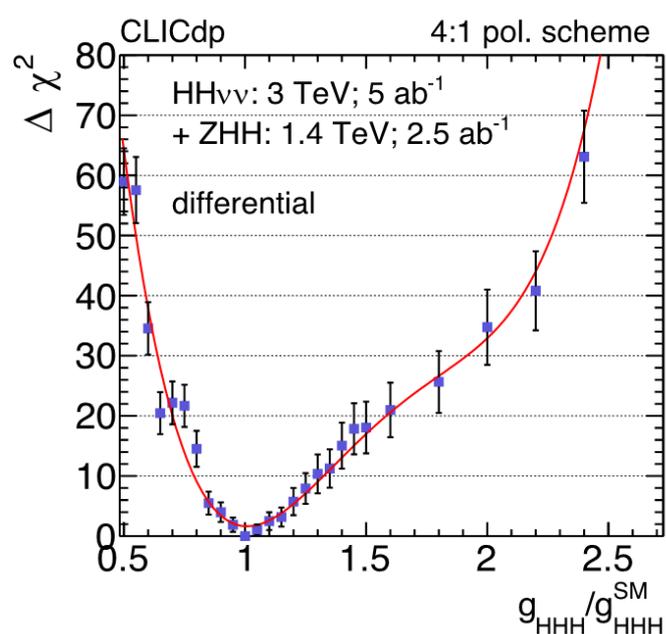


Figure 1: Sensitivity to the Higgs self-coupling using double Higgs production from the full CLIC programme. From CLICdp-Note-2018-006/arXiv:1901.05897.

The CLIC physics programme continues to attract interest from the theory community. A series of talks in a dedicated mini-workshop, joint between theorists and experimentalists, reported on the CLIC potential to extend our knowledge of physics beyond the Standard Model. New results were presented showing the CLIC potential to probe the possible composite nature of the Higgs boson at the scale of tens of TeVs (see Figure 2), to discover dark matter candidates such as the thermal Higgsino, and to study axion-like particles in a unique mass range. It was also shown how searching for neutral scalar particles will allow CLIC to explore models relating to the nature of the Electroweak Phase Transition and with non-minimal supersymmetric models addressing the Naturalness Problem. The workshop also saw discussions of first studies of stub-tracks and other long-lived particles searches, a domain in which CLIC has promising potential for future exploration.

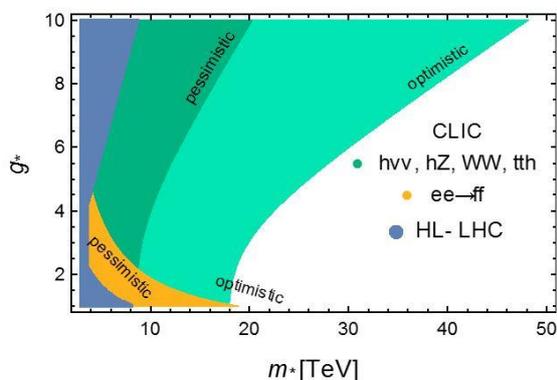


Figure 2: 5σ discovery contours for Higgs compositeness in the (m^*, g^*) plane, overlaid with the 2σ projected exclusions from HL-LHC. From CERN-2018-009-M/arXiv:1812.02093.

There is widespread support for a lepton collider that will allow for high-precision Higgs boson and top-quark physics in the post-LHC era. CLIC is a mature contender that in addition can be extended to multi-TeV collisions, providing unique sensitivity to physics beyond the Standard Model.

Further reading:

<https://clic.cern/european-strategy>

CLIC 2018 Summary Report (CERN-2018-005-M)

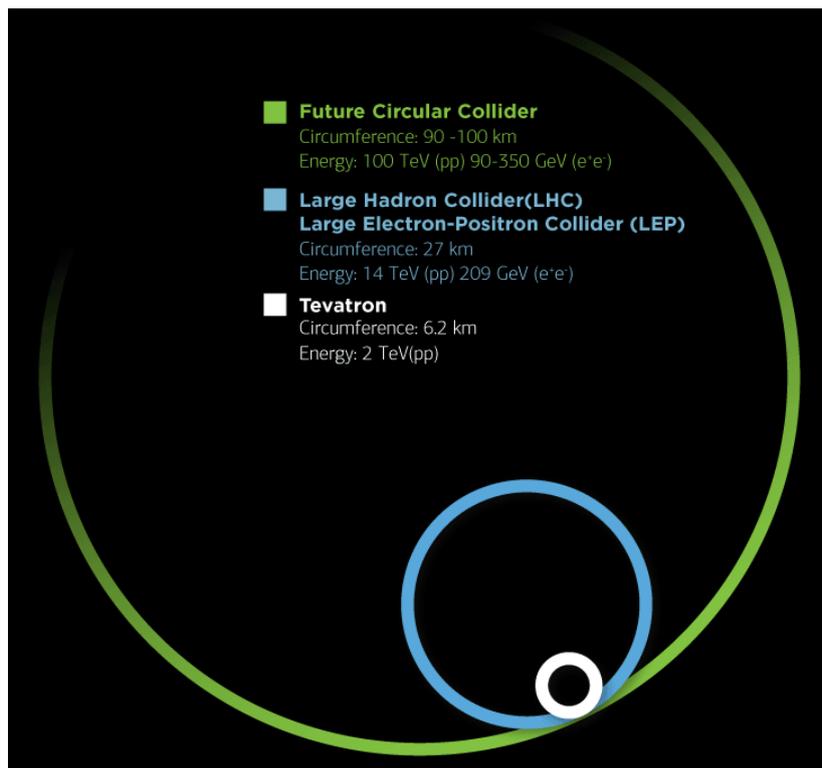
CLIC Project Implementation Plan (CERN-2018-010-M)

The CLIC Potential for New Physics (CERN-2018-009-M)

Physics at the Future Circular Collider

by *Panagiotis Charitos*

“Progress in knowledge has no price” with these words, Alain Blondel concluded the FCC Physics workshop at CERN. Over two days, the meeting reviewed the results of the FCC Conceptual Design Report and discussed a reliable implementation plan to meet the ambitious physics targets of this project.



The FCC study proposes a versatile research infrastructure that will expand in all different fronts our exploration of tiniest scales of matter and experimentally test a wide range of theories in searches for new physics. The FCC study envisages an intensity-frontier lepton collider (FCC-ee) as the first step followed by an energy-frontier hadron machine (FCC-hh) while other options include a proton-lepton (FCC-ep) interaction point and experiments at the injectors of FCC. This staged approach can offer a broad physics programme for the next 70 years representing a visionary and technically feasible answer to the challenges and questions posed by the current high-energy physics landscape.

The novel situation in particle physics calls for very broad search machines improving knowledge simultaneously in all three directions of sensitivity, precision and energy. The FCC Conceptual Design Report (CDR) demonstrates how this can be done both in a feasible and sustainable way, by taking advantage of synergies and complementarities between the successive colliders. In his opening talk, Michael Benedikt, the FCC study project leader, reviewed the key findings of the CDR and discussed the physics goals, the technological challenges for both accelerators and detectors and implementation scenarios. Key topics identified in the CDR include civil-engineering considerations about the tunnel and surface building, the FCC conductor development programme, prototyping of high-field magnet and superconducting RF cavities.

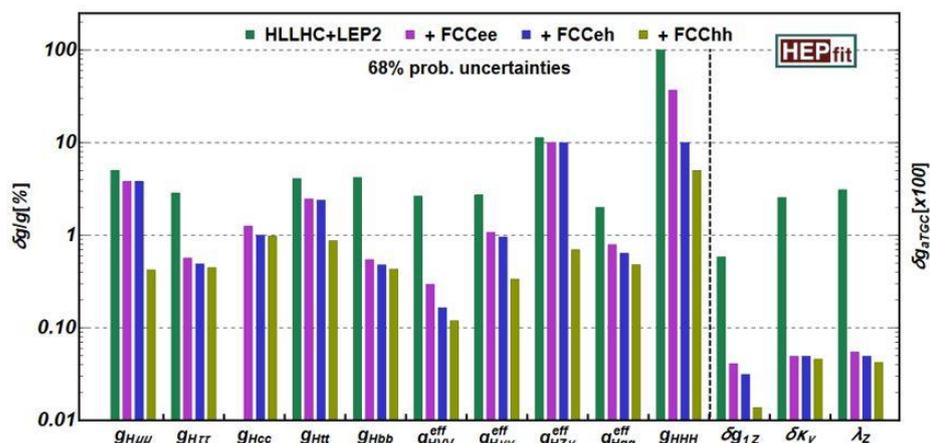
Following the Higgs discovery at the LHC physics is at a special moment of its history. On one hand, understanding the properties of the Higgs particle defines a clear goal for future collider physics. In this perspective, nothing about the Higgs boson should be taken for granted, and even seemingly naïve questions like whether the Higgs gives mass to the first and second generation of fermions or simply its total decay width, should be experimentally verified. On the other hand, a number of experimental facts and theoretical questions remain that the now completed Standard Model does not explain, which require the existence of new particles or phenomena. In his talk, Michelangelo Mangano emphasised the importance of studying in depth the dynamics that generate the potential of the Higgs boson and take a close look even at the most basic assumptions about its properties. Moreover, he discussed both the experimental observations, dark matter, baryon asymmetry and neutrino masses as well as the theoretical questions that drive future exploration in particle physics. This is an extraordinary endeavour in which particle physics progresses hand-in-hand with astrophysics, cosmology and many other sciences. Because the energy scale at which these new particles or phenomena will show up is presently largely unknown, more sensitivity, more precision and more energy are called for.

The first step of the FCC, an intensity-frontier lepton collider (FCC-ee) demonstrably has a high level of technological readiness. Construction could start by 2028 delivering the first physics beams in 2038 thus ensuring a smooth continuation at the end of the HL-LHC programme. This extremely high-luminosity collider (much higher luminosity than the linear machines!) will start its life by recording in very clean conditions more than 200,000 times the Z boson decay sample of LEP, allowing exploration of rare phenomena (symmetry violations and rare decays) with a huge step in sensitivity. Among the highlights of the FCC-ee program figures the sensitivity to new particles produced in Z decays with couplings as small as 10^{-11} those of the Standard Model (heavy neutrinos, axion-like particles etc...). With 10^8 W's, millions of Higgs bosons and top quarks following soon after, FCC-ee could perform a most comprehensive set of precision measurements probing the presence of new physics (with SM couplings) up to energies of 70 TeV. Importantly it will uniquely provide a per-mil level model-independent measurement of the Higgs boson coupling to the Z, which will serve as "fixed-candle" for further measurements of the Higgs, thus playing a similar role to LEP revealing the Standard Model's amazing predictive power that became most useful at the LHC.

The second step, that could be operational around 2060 is a >100 TeV proton collider, with 7 times the energy of the LHC and 30 times higher luminosity. This energy-frontier collider will explore an uncharted energy regime but also produce copious top, W and Higgs particles allowing to search for a complementary set of rare phenomena. The physics programme of the hadron machine is almost perfectly complementary to that of the lepton collider. One of the highlights of the FCC-hh program will be the ability to precisely (5%) measure the Higgs self-coupling, the key element of electroweak symmetry breaking to elucidate the nature of the electroweak phase transition. Finally, it will allow to test WIMPs as thermal dark matter candidates while also opening a broader perspective for dark sector searches as discussed in depth by Matthew McCullough in his talk. Another highlight of FCC-hh, using the 10 billion Higgs produced, is to be able to search for invisible Higgs decays (excellent dark matter candidates) down to a few in 10,000. Together with a heavy ion operation programme and the possibility of integrating a lepton-hadron interaction point (FCC-eh), it provides the amplest perspectives for research at the energy frontier. A duration of 25 years is projected for the subsequent operation of the FCC-hh facility to complete the currently envisaged physics programme.

The FCC integrated programme provides the most complete and model-independent studies of the Higgs boson. On one hand it will extend the range of measurable Higgs properties, its total width, and its self-coupling, allowing more incisive and model-independent determinations of its

couplings. On the other hand, the combination of superior precision and energy reach provides a framework in which indirect and direct probes of new physics complement each other, and cooperate to characterise the nature of possible discoveries. For example with FCC-ee we could measure the Higgs couplings to the Z boson with accuracy better than 0.17%, using which FCC-pp will be able to make a model-independent ttH coupling determination to <1%. Moreover, a combination of FCC-hh and FCC-ee will allow measuring the Higgs self-coupling with precision better than 5%, much higher than any other proposed collider programme.



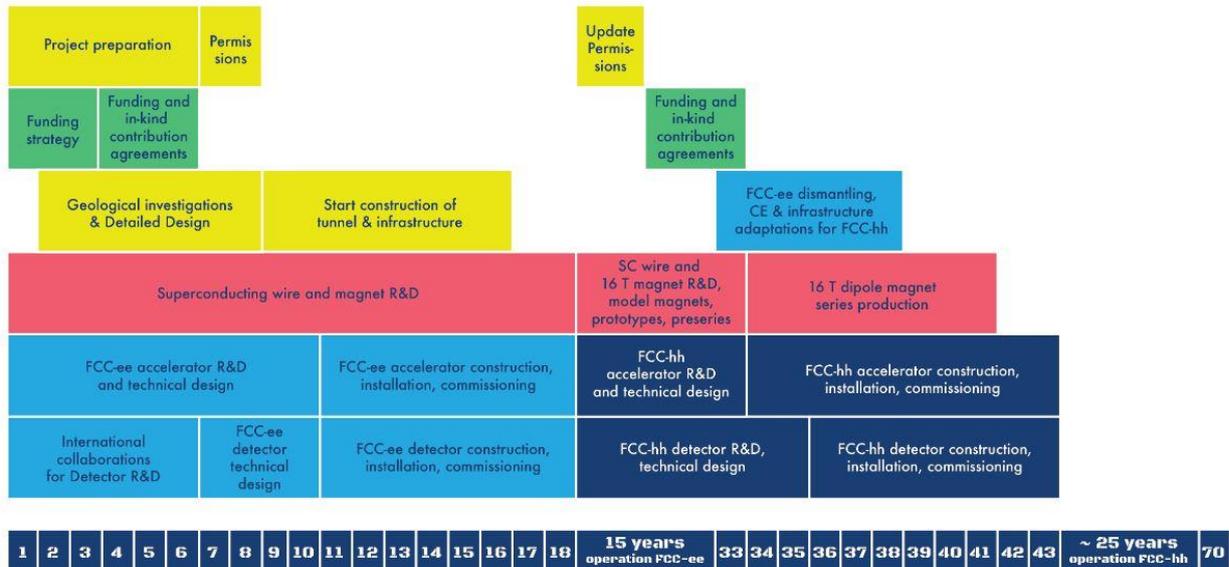
Together, FCC-ee, hh and eh can provide detailed measurements on the Higgs properties. The figure shows indicative precision in the determination of couplings to gauge bosons, quarks and leptons, as well as of the Higgs self-coupling, of its total width and of the invisible decay rate.

Patrick Janot investigated the advantage of longitudinally polarised beams in FCC-ee in Higgs couplings precision. Such polarised beams at FCC-ee would give a precision 20% better at the expense of much greater complexity and lower luminosity and thus longitudinal polarisation is not considered a worthwhile option for FCC-ee, which focuses on the high luminosity provided by the circular set-up. For comparison, that one year at the FCC-ee with two interaction points corresponds to eight years of luminosity at the ILC that has polarised beams. Moreover, the synergies between FCC (ee + hh) will offer unbeatable precision in the study of the Higgs and its interactions with other particles and allow to study in depth the properties of this unique particle.

However, this is only one of the possibilities to answer the most fundamental questions in particle physics. FCC offers a unique programme of precision measurements reducing current experimental limits and searching for deviations from the Standard Model precisions that could point to new physics. The research programme envisioned for FCC will enable searches for tiny violations of the Standard Model symmetries in the Z, W, b, τ and Higgs decays. Moreover, the complementarity of the two machines will allow direct searches for dark matter candidates and heavy neutrinos that can either couple very weakly with the SM particles or have higher masses.

Another important aspect emphasized in a number of talks is the need for further theoretical improvements in the predictions of SM phenomena at levels where higher-order contributions become significant. This stands as a huge challenge for the theoretical community to match the huge step in statistical precision with the FCC. A group of enthusiastic theorists has already started mapping the considerable work ahead.

FCC - The integrated programme



The timely implementation of a staged programme can only be ensured with an early start of the project preparatory phase. Planning now for a 70-year long programme may sound a remote goal; However as Blondel observed in the concluding talk of the conference, the first report on LEP dates back to 1976 and certainly the authors couldn't envision at that moment that 60 years later a High-Luminosity LHC would be using the same tunnel!

The impressive amount of work documented in the four volumes of the FCC CDR will inform the update of the European Strategy for Particle Physics. The discussions during the two-day workshop demonstrated that the FCC is uniquely placed among other similar designed machines as it provides the broader physics programme to attack the open problems from different fronts. Moreover, CERN's previous history in the management and completion of large-scale projects and the existing accelerator infrastructure testify to the reliability of the FCC design report. To move forward with a technical design report, additional resources will be needed and a coordinated international effort to advance the enabling technologies and optimize the machine and detector design.

The FCC project is a large and ambitious facility but the accelerators that are being considered through their synergies and complementarities offer an extraordinary tool for investigating the outstanding questions in particle physics. "The FCC offers the broadest capabilities of sensitivity, precision and high energy reach that is proposed today" notes Blondel "it sets ambitious but feasible goals for the global community resembling previous leaps in the long history of our field".

You can find more information about this event here: <https://indico.cern.ch/event/789349/timetable/>

The FCC Conceptual Design Report (CDR) is available here: fcc-cdr.web.cern.ch

Physics Beyond Colliders study reaches new milestone

by *Panagiotis Charitos*

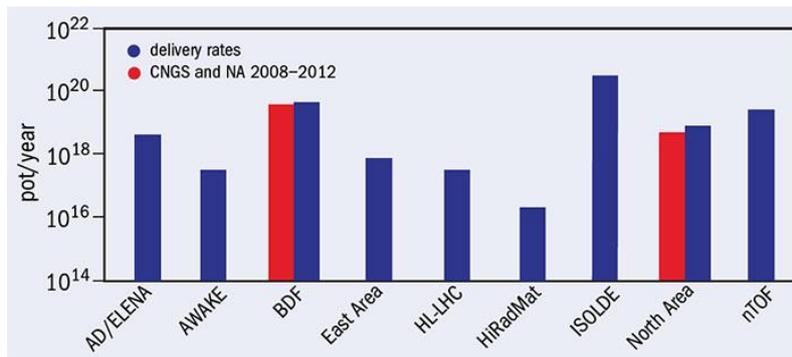


The Physics Beyond Colliders (PBC) initiative, launched in 2016, has submitted a summary report to the European Particle Physics Strategy Update (EPPSU). The projects considered under the PBC initiative will use the laboratory's existing accelerator complex to broaden the experimental quest for new physics in different ranges of interaction strengths and particle masses. The reports documents a number of opportunities and emphasizes the complementarity of the proposed experiments with searches at the LHC and other existing or planned initiatives worldwide.

Despite the tremendous progress in fundamental physics with the completion of the particle content of the Standard Model a number of questions remains unanswered while the LHC experiments test the limits of the SM description. The discovery of the Higgs boson, whilst being a tremendous success for particle physics also represents a tremendous challenge as we still need to understand how it interacts with other particles and with itself. Moreover, certain astrophysical and cosmological evidence point to the existence of physics beyond the Standard Model (BSM) though we have few clues about how this physics could look like. There are two possible reasons for that. Perhaps any new particles are heavier and thus beyond the reach of the LHC, or new physics may be weakly coupled to the Standard Model and residing in what is often called a hidden sector; the latter is also motivated by our knowledge about dark matter and dark energy that must be very weakly coupled to the Standard Model.

The Physics Beyond Collider (PBC) study is exploring how CERN's existing accelerator complex and the rich scientific infrastructure can be used for experiments that will complement the scientific programme of the LHC and possibly profit from developments for future colliders.

CERN's North Area already provides beams for dark matter and precision searches while further pushing the exploration of the strong interaction through a number of QCD based experiments. A variety of options for new experiments and their technological readiness were considered and the PBC report identifies opportunities for new experiments – and the required resources - that will cover the full range of alternatives to energy frontier direct searches.



Foreseen proton-production capabilities of the complex. (Image credit: Giovanni Rumolo)

The workhorse for high-energy fixed target experiments at CERN is the SPS. It provides a variety of beams of energies up to 400 GeV with high intensity and a high duty cycle to several different experiments in parallel. Furthermore, there is a proposal for a new SPS Beam Dump Facility (BDF) that could serve both beam dump like and fixed target experiments.

The design of BDF was developed as part of the PBC's mandate and is now ready to move on towards preparation for a technical design report. The BDF high-energy beam provides extended access to the high-mass range of the targeted region. In the first instance, exploitation is envisaged for the SHiP and TauFV experiments. The first will perform a comprehensive investigation of the hidden sector with discovery potential in the MeV-GeV range and TauFV will search for forbidden τ decays. TauFV has a leading potential for third generation lepton flavour violation decays ($\tau \rightarrow 3\mu$) thanks to the characteristics of the BDF beam.

The high-energy muon beam from the SPS could contribute to the explanation of the $(g-2)_\mu$ via the proposed MUonE experiment which could directly measure one of the terms responsible for the theoretical uncertainty. Moreover, a high-energy muon beam will make a meaningful contribution to address the proton radius puzzle as part of the COMPASS programme.

Other options for a more diverse exploitation of the SPS beams have also been considered, including the proton driven plasma wakefield acceleration of electrons to a dark matter experiment (AWAKE++); the acceleration and slow extraction of electrons to light dark matter experiments (eSPS); and the production of well-calibrated neutrinos via a muon decay ring (nuSTORM).

PBC also considered a number of experiments that will allow the precision measurements of rare decays as they can indirectly probe higher energies compared to those directly accessible at the LHC. Two such experiments are the already operational NA62 and the planned KLEVER – both focusing on kaon decays. KLEVER's motivation is to extend to neutral kaons the current NA62 measurement of ultra-rare charged kaon decays and will depend on NA62 results, the evolution of B-anomalies, and the KOTO competition in Japan. The two experiments are complementary to each other, as well as to experiments looking for B decays.

Furthermore, NA61 could measure the QCD parameters close to the expected critical regime, while upgrades to NA62 and a few months of operation in beam dump mode would explore an interesting domain of the hidden parameter space. In addition, the revival of the former DIRAC and NA60 concepts would also provide unique insights and could fit together in the underground hall currently occupied by NA62.

Coming to the LHC, fixed target studies are ongoing. LHCb is already well engaged in fixed target physics with SMOG and SMOG2. The gas storage cell approach has made significant advances beyond the pioneering LHCb SMOG program, and on the crystal front, there have been impressive results with beam, and a number of options are developed. LHCb and ALICE may focus on different

physics signals due to different acceptances, data acquisition rates and operation modes. For both experiments, the physics reach will depend strongly on the feasibility of simultaneous Fixed Target and collision operation of the LHC. For ALICE there is a possibility of dedicated Fixed Target operation during LHC proton running.

Another interesting area of research concerns long-lived particles. PBC reviewed proposals for future experiments that can search for unstable particles with lifetimes much longer than what one would expect by estimating the decay rate from the mass of the decaying particle and currently there are several reasons that can provide parametrically longer lifetimes. Collider searches for BSM phenomena motivated by the problems of the SM have largely assumed that decays of new particles occur quickly enough that they appear prompt. This expectation has impacted the design of the detectors, as well as the reconstruction and identification techniques and algorithms. However, there are several mechanisms by which particles may be metastable or even stable, with decay lengths that are significantly larger than the spatial resolution of a detector at a collider, or larger than even the scale of the entire detector. The impact of such mechanisms can be seen in the wide range of lifetimes of the particles of the SM. Thus, it is possible that BSM particles directly accessible to experimental study are long-lived, and that exploiting such signatures would discover them in collider data. Phenomenologically lifetimes greater than 10^{-8} seconds and shorter than a few minutes are particularly interesting as they are less constrained by the LHC experiments and big bang nucleosynthesis and they can be the target of specific experiments considered. Two such experiments are FASER and MATHUSLA.

The Gamma Factory has also shown successful developments in 2018 as the team injected and accelerated partially stripped ions in the LHC. The goal is to produce gamma ray beams with a break-through in intensity by up to seven orders of magnitude, at very high γ -energies up to 400 MeV, compared to the current state of art for fundamental QED measurements, vector mesons, neutrons and radioactive ions. Following the first successful results, the team is now working towards a proof-of-principle experiment in the SPS.

Moreover, the existing EDM storage ring community, based mainly in Germany (JEDI) and Korea (srEDM), joined their efforts with a fledgling CERN effort under the PBC auspices to form a loose collaboration known as CPEDM, with the aim of converging towards a common design of an EDM storage ring and beyond. Searching for new sources of CP violation is one of the most pressing tasks in fundamental physics. Electric dipole moments are one of the most sensitive probes while the proton – with its unshielded monopole charge – is considered experimentally very challenging. However, it is an interesting target as a proton ring gives the prospect to measure proton and nucleon EDMs with a sensitivity level of 10^{-29} e. cm, an attractive target at one or two orders of magnitude better precision than that of hadronic EDM experiments. Moreover, it will give the opportunity to search for oscillating EDMs that are a direct probe of dark matter consisting of axions or axion-like particles.

The projects with short term prospects at CERN (NA61, COMPASS(R_p), MUonE, NA62, NA64) have now been handed over to the SPSC Committee for detailed implementation review and recommendations.

Efforts have been made to provide some coherent leverage of CERN's technological skills base to novel experiments. Experiment synergies were explored, leading to collaboration in applied technologies – in particular, technological synergies between light-shining-through walls and QED vacuum-birefringence measurements.

Finally, some PBC projects are likely to flourish outside CERN: the IAXO axion helioscope, now in consideration at DESY; the proton EDM ring, which could be prototyped at the Jülich laboratory, also in Germany; and the REDTOP experiment devoted to η meson rare decays, for which Fermilab in the US seems better suited.

The PBC mandate has been extended until May 2020 as a support to the EPPSU process: the design of the proposed long-term facilities will continue within the PBC accelerator working groups until the strategy guidelines are known. The PBC study group will also provide any additional input the EPPSU may need. The next years will offer exciting possibilities for novel experiments exploring fundamental physics and getting a glimpse at what lies beyond our current understanding.

The documents submitted by PBC to the ESPP update are available online: <http://pbc.web.cern.ch/>

The author would like to thank Jörg Jäcke, Mike Lamont, Claude Vallée for their thoughtful comments and fruitful discussions during the preparation of this article.

Accelerating for dark discoveries

by ***Stefania Gori (UC Santa Cruz)***

Cosmological and astrophysical observations indicate that the Standard Model (SM) particles account for less than 5% of the total energy density of our Universe, while the remaining unknown 95% arises from the so-called dark energy and dark matter (DM).

The existence of dark matter has been inferred from its gravitational effects, but dark matter particles have never been directly detected, which makes their nature one of the most mysterious unanswered question in modern physics, calling for more investigations both in astrophysics and in high-energy physics.

The SM does not provide any good DM candidate. The existence of DM provides therefore strong evidence for New Physics (NP) beyond the SM. The last decade has seen tremendous progress in experimental searches for DM in the form of weakly interacting massive particles (WIMPs) with masses of $O(100 \text{ GeV})$, interacting with the SM particles through weak strength interactions. Searches include a broad range of experiments: collider experiments looking for invisible signatures, direct detection experiments searching for DM scattering in large detectors, and indirect detection experiments, seeking for DM annihilation products coming from the sky. The experimental precision has reached unprecedented levels allowing to exclude certain DM candidates from interacting significantly with the Higgs, thus putting some pressure on the WIMP paradigm.

Rather than suggesting a specific mass scale for NP, DM arguably points to a dark sector of particles not interacting through the known SM forces (electromagnetism, weak and strong interactions), and therefore only feebly-coupled to the SM. Dark sectors could be non-minimal and, similarly to the SM, contain (in addition to the DM state(s)) new force carriers, new matter fields, and new dark Higgs bosons.

In addition to the DM motivation, dark sector models are also motivated by various collider related anomalies as, for example, the $(g-2)_\mu$ anomaly, as measured at Brookhaven National Laboratory in the early 2000s, and the B-meson anomalies recently seen by the LHCb, Belle, and Babar collaborations. Furthermore, dark sectors arise in many theories proposed to address the big open questions in particle physics: the naturalness problem, the problem of the baryon-antibaryon asymmetry of the Universe, the strong CP problem, to mention some.

These new dark particles could communicate to the SM through so-called “portals”: renormalizable interactions between a particle of the dark sector and a particle of the SM sector. There exist only three portals:

- (1) the dark photon portal, thanks to which a new (generically) massive dark photon, A' , will mix with the photon and the Z-boson of the SM;
- (2) the Higgs portal, thanks to which a new dark scalar will interact with the Higgs of the SM. This portal can also induce the mixing of the dark scalar with the SM Higgs;
- (3) the neutrino portal, thanks to which a new dark fermion (a sterile neutrino) will mix with the SM neutrinos.

These portal couplings could lead to the production of the dark particles at collider-based experiments, and their subsequent decays to either known SM particles that we can track in our detectors, or other invisible dark particles that will manifest as missing energy.

In the next paragraphs we will discuss how future high-energy and high-intensity colliders can cover a unique role in unraveling the nature of DM and of the associated dark sector.

Dark sectors at high-energy colliders

The Large Hadron Collider (LHC) can produce dark particles copiously, either directly through their portal interactions (e.g. a dark photon produced from quark-antiquark fusion thanks to its mixing with the SM photon and Z-boson) or, if sufficiently light, through Higgs decays.

The direct production can be exploited both for massive (above the multi-hundred GeV scale) dark particles by the ATLAS and CMS detectors, as well as for lighter dark particles (below the Z boson mass) by ATLAS and CMS, as well as by the LHCb detector.

The Higgs boson - discovered at the LHC after a decades long hunt for the last missing piece in the SM - might play a unique role in this context. It may very well interact with many types of massive particles, including the particles of the dark sector. The tiny SM width of the Higgs, $\Gamma_h \sim 4$ MeV, combined with the ease with which the Higgs can couple to NP, make Higgs exotic decays (i.e. Higgs decays to light dark particles) a natural and often leading signature of a broad class of dark sector theories [Curtin:2013fra]. The LHC data set collected so far is already able to test exotic branching ratios as small as $\sim \text{few} \times 10^{-5}$ in the case of the cleanest decay modes (e.g. $h \rightarrow X X \rightarrow 4\mu$, where X is e.g. a dark photon or a dark scalar). The High-Luminosity (HL) stage of the LHC will have the potential to improve the bounds on some of these branching ratios by ~ 2 orders of magnitude. Even tiny branching ratios might be discovered by the HL-LHC, if realized in Nature.

Future higher energy hadron colliders can have an even broader sensitivity to dark sectors. On the one hand, thanks to the higher center of mass energy, future hadron colliders will be able to copiously produce heavier dark particles. As a figure of merit, the number of dark photons with a mass of ~ 5 TeV that can be produced at the High-Energy (HE) LHC (with a center of mass energy

of 27 TeV) with 15ab^{-1} of data will be the same as the number of ~ 2.5 TeV dark photons produced at the HL-LHC (with a center of mass energy of 14 TeV) with 3ab^{-1} of data. Correspondingly, a 100 TeV proton-proton collider with 15ab^{-1} of data would produce the same number of ~ 8 TeV dark photons.

On the other hand, higher energy hadron colliders (like the HE-LHC, or 100 TeV proton-proton colliders) can probe very weakly coupled light dark particles. These new experiments offer in fact intensity-frontier studies of the Higgs particle. In the context of Higgs exotic rare decays, they could give access to tiny Higgs branching ratios ($\sim \text{few} \times 10^{-9}$ for the 100 TeV collider) for clean decay modes. Background limited signatures can also be accessible utilizing the sizable cross section of sub-leading Higgs production modes, as the $t\bar{t}$ production.

Complementarily, high-energy lepton colliders, like the International Linear Collider (ILC), CLIC, FCC-ee, and CEPC can offer a unique reach on dark sectors thanks to their low levels of backgrounds. For example, as studied in [Liu:2016zki], CEPC, FCC-ee and ILC can robustly search for all types of Higgs exotic decays, even those that are background limited at hadron colliders, at least to the part-per-mille level of branching fractions.

Dark sectors at high-intensity collider experiments

Lower energy high-intensity collider experiments have a unique access to light dark sectors. Particularly, B-factories, fixed target experiments and neutrino experiments offer complementary opportunities for dark particles below the few GeV scale.

The BaBar experiment at the SLAC National Laboratory collided e^+e^- pairs, obtaining 530fb^{-1} of integrated luminosity at a center-of-mass energy of ~ 10.6 GeV in its ~ 10 years of run, 1999-2008. Several dark sector searches have been performed for either visible dark particles (e.g. $\mu^+\mu^-$ or e^+e^- resonances, $2\mu^+2\mu^-$ signatures) or invisible dark particles (mono-photon signature). Several of these searches set the most stringent constraints on dark particles, particularly in the mass region between few hundred MeV and a few GeV.

The next-generation B-factory experiment, Belle-II, has started colliding e^+e^- last year. This collider will collect ~ 50 times the integrated luminosity of the previous Belle experiment, as well as ~ 100 times the Babar luminosity. In addition to the larger luminosity, Belle-II has a more hermetic calorimeter and is developing targeted triggers to search for dark sectors. These unique features will warrant Belle-II an unprecedented reach for dark particles, possibly already with early data in 2019-2020.

Dark particles can also be copiously produced at electron- or proton-fixed target (beam-dump) experiments. Past experiments running in the '80s or '90s (CHARM, LSND, E137, ...) still set the most stringent constraints on several dark particles with a life time longer than a few meters and decaying visibly to SM particles. Present fixed target experiments (the HPS experiment, SeaQuest, a.o) and proposals for future experiments (NA62, SHiP, FASER, MATHUSLA, CODEX-b, a.o) will probe a plethora of additional models of visibly decaying dark sectors.

In Fig.1, we present a summary of searches for visible dark photons. Several regions of parameters are probed by past experiments (in gray), or can be probed by present/future fixed target experiments (curves at low values of the portal coupling, ϵ) as well as by Belle-II (in light red), by LHCb (in brown) and by high-energy colliders (red, orange, and green curves at high mass). Interestingly enough, past experiments were able to probe the region of parameters favored by the $(g-2)_\mu$ anomaly in this minimal dark photon model.

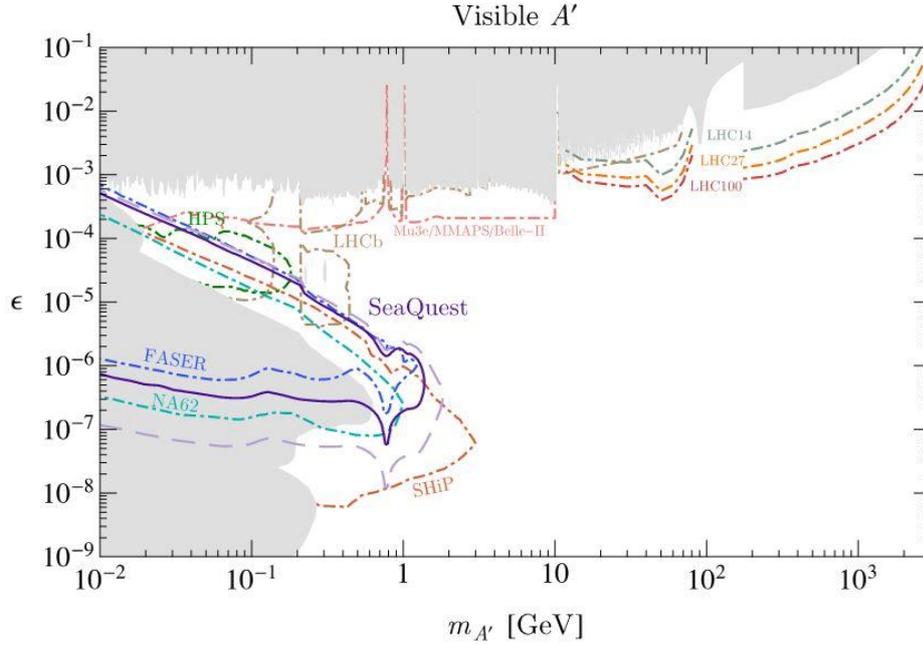


Figure 1: Reach for visible dark photons at past (in gray), at present/future fixed target experiments (curves at low values of the portal coupling, ϵ) as well as at Belle-II (in light red), at LHCb (in brown) and at high-energy colliders (red, orange, and green curves at high mass). Adapted from [Berlin:2018pwi] (we thank A. Berlin and D. Curtin for the figure).

Additionally, beam-dump and missing momentum experiments will be able to probe invisible signatures obtained from DM production and from the production of invisibly decaying dark particles: most regions of parameter space of thermal DM can be probed in the coming years by this experimental program (see [Akesson:2018vln] for the LDMX proposal).

Finally, Dark Matter particles can also be produced at present (MiniBooNE, NOvA, JSNS2, ...) and future generation (DUNE, ...) neutrino experiments thanks to their induced interaction with the proton beams of these facilities. Once produced, DM could be detected thanks to its scattering off nucleons or electrons of the neutrino detectors. Neutrino near detectors can also be used to indirectly discover dark particles through the precise measurement of rare neutrino-nucleon scattering processes. Examples are the trident processes $\nu N \rightarrow \nu N l' l$, where N is a nucleus of the detector, ν a neutrino, and l and l' two SM leptons [Altmannshofer:2014pba, Altmannshofer:2019zhy]. A possible mismatch between the measurement and the SM prediction for the cross section of these processes could hint towards the existence of beyond the SM neutrino interactions, as, for example, new force carriers that interact with neutrinos.

In conclusion, the search for dark matter and dark sectors at collider experiments is a broad and growing field that can lead to major milestones in our understanding of dark matter and beyond in the coming few years. New experiments and measurements at the high-energy and high-intensity frontiers will provide a crucial test for many well motivated theories possibly leading to new discoveries and/or a paradigm shift in the way we tackle DM questions.

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Data acquisition challenges for the ProtoDUNE-SP experiment at CERN

by *Enrico Gamberini*

The ProtoDUNE Single-Phase (SP) experiment at the Neutrino Platform at CERN ([read more](#)) is taking data after about two years of construction and commissioning. Its primary goal is to validate the design principles, construction procedures, detector technologies, and long term stability in view of DUNE (Deep Underground Neutrino Experiment) due to take data in 2025. The ProtoDUNE-SP project faced many challenges, as it represents the largest test beam as well as monolithic Liquid Argon Time Projection Chamber (LAr-TPC) yet constructed and also because of its aggressive construction and commissioning timescale. The CERN Detector Technology group has been involved in the installation and development of both the detector control system and the data acquisition system. The data acquisition system of ProtoDUNE-SP is a challenge on its own, as it requires to continuously read out data from the detector, buffer and select it and finally temporarily store it while keeping custom developments to a minimum in order to fit the tight schedule.

The ProtoDUNE-SP's TPC is composed by a central cathode plane and six Anode Plane Assemblies (APAs). These represent 4% of a DUNE Single-Phase super-module. Each APA is formed by 2560 wires and instrumented with front-end cold electronics, mounted onto the APA frames and immersed in LAr. The cold electronics continuously amplify and digitize the signals at a 2 MHz rate. Digitized data is then transmitted by Warm Interface Boards to the DAQ system via optical fibers.

The total amount of data generated by the TPC is about 440 Gbit/s and represents the main data source. This throughput exceeds the storage capabilities of the system, even considering the 20% beam duty cycle of the extracted SPS beam. Therefore the DAQ system implements a global selection system, with a baseline trigger rate of 25 Hz during the SPS spill, and compression, in order to limit the throughput to storage. The global trigger decision is a combination of signals coming from beam instrumentation, muon tagger, and photon detectors, allowing to acquire snapshots of the detector while beam particles or cosmic rays are traversing the volume of LAr.

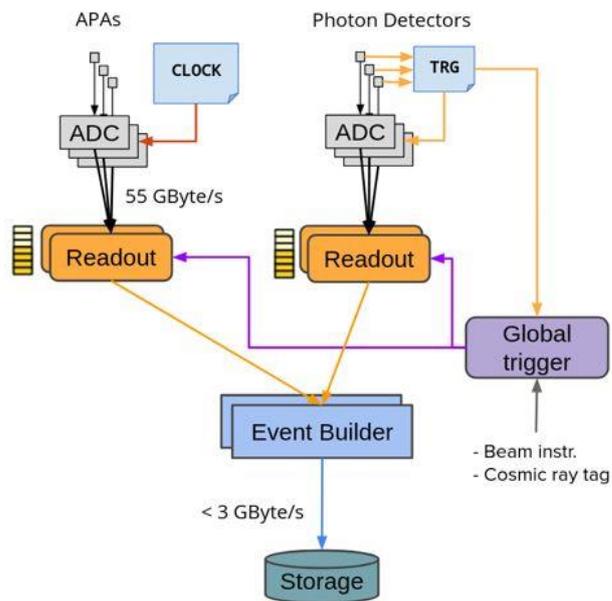


Figure 1: Block diagram illustrating the data flow in the ProtoDUNE Single-Phase data acquisition system.

Two solutions for the TPC readout have been implemented with the goal of prototyping a viable architecture for DUNE: the ATCA-based RCE and the PCIe-based FELIX.

The Reconfigurable Cluster Elements (RCE) based readout is a full meshed distributed architecture, based on networked System-On-Chip (SoC) elements on the ATCA platform, developed by the SLAC National Accelerator Laboratory. This approach focuses on early data processing, namely aggregation, formatting, compression, and buffering embedded on tightly coupled software and FPGA design. Due to the maturity of its development, it has been chosen as the baseline solution, reading 5 APAs out of the total 6.

The alternative solution proposed by the Detector Technology group uses the Front-End LInk eXchange (FELIX) system, developed within the ATLAS Collaboration at CERN. Its purpose is to support high-bandwidth readout systems needed for the High-Luminosity LHC, while moving away for custom hardware at an as early stage as possible, and instead employ commodity servers and networking devices.

This approach requires to implement custom software to handle the data, namely selecting, packing and compressing it effectively. To this end, recent technologies have been employed to offload the CPU and obtain the required throughput and performances. In particular, the Intel® QuickAssist Technology (QAT), supported in modern processors allows performing compression on a dedicated chip at a high rate. Data is beforehand reordered in CPU to maximize the compression efficiency by exploiting Advanced Vector Extensions instructions. Finally, data is transmitted between hosts through 100 Gbit/s network interfaces utilizing the Infiniband communication standard, again allowing to minimize CPU instruction for I/O.

The FELIX-based TPC readout system has been successfully employed during data taking, and it has now been chosen as baseline readout system for DUNE.



Figure 2: Racks hosting the ProtoDUNE-SP Trigger and Data Acquisition system. The system is connected to the on-detector electronics through up to 300 optical fibers. A local temporary storage of 700 TByte is also available.

After two months of data taking with beam particles between September and November 2018, ProtoDUNE-SP is now acquiring cosmic ray data and carrying out many important detector performance studies in view of DUNE.

The ongoing DAQ developments include the integration into the readout of hit finding, enabling for trigger primitive generation and self-triggering of the APA modules. Software and firmware based hit finding are being implemented in parallel and will be tested side-by-side.

Also, a novel storage technology will be tested, with the goal of offering a solution for data buffering before event building in DUNE. This R&D project, hosted by the Detector Technology group and sponsored by Intel, is being carried out in collaboration with CMS and ATLAS.

The ProtoDUNE-SP experiment at CERN validated the construction and operation of a very large LAr-TPC, from the mechanics to the cryogenic system, from the installation procedures to the detector modules construction, from the instrumentation and control to the detector electronics and data acquisition system. ProtoDUNE-SP is now playing a crucial role in the in-depth validation of all the experiment's components and offers a unique playground for prototyping and refining the appropriate solutions for DUNE.

The ProtoDUNE-SP DAQ is undergoing significant developments to transform itself towards a high availability continuous data taking system with self-triggering capabilities on the TPC data.

15th Vienna Conference on Instrumentation

by *Panagiotis Charitos*

Studying the most microscopic elements of nature rely on the parallel progress of detector concepts and associated technologies. Experimental observations and open theoretical questions point to new paths for exploration in all fronts including fixed-target, collider and astrophysical experiments that put new requirements for future detectors. The 15th Vienna Conference on Instrumentation offer the opportunity to about 300 experts from all over the world to meet and discuss ongoing R&D efforts and set future roadmaps for collaboration.



The chairperson of the 15th Vienna Conference on Instrumentation (VCI2019) and head of CERN's EP Department, Manfred Krammer, opened the conference. He reminded the audience of the first conference of this series held in 1978 under the name Vienna Wire Chamber Conference: "Enormous progress was made in these 40 years. In 1978 we discussed wire chambers as the first electronic detectors and now we have a large number of very different detector types with performances unimaginable at that time"

Following this strong tradition, the Vienna conference covered fundamental and technological issues associated with the developments and exploitation of the most advanced detector technologies as well as the value of knowledge transfer to other domains. Over five days, participants covered different topics **including sensor types, fast and efficient electronics, cooling technologies and the appropriate mechanical structures**. These are the key elements informing the design of detectors that could help us explore the energy and intensity frontiers and meet the requirements of planned and proposed facilities. Christian Joram (CERN) mentions: "Progress in experimental physics often relies on advanced and breakthroughs in instrumentation that lead to substantial gains in measurement accuracy, efficiency and speed or even open completely new approaches. The Higgs discovery and the first observation of Gravitational Waves offer two fantastic examples".

The first day started with an overview of LIGO searches for gravitational waves covering the most recent results and presenting plans for future ground-based gravitational wave detectors calling

for serious planning effort to ensure that they can be operational in the 2030s. A second plenary talk focused on the value of knowledge transfer that can maximize the impact of detector technologies and expertise in society and in particular through industry.

A number of talks presented the ongoing developments in the LHC experiments including ALICE and LHC upgrade programmes for Run3 and for the High-Luminosity LHC as well as CMS's Mip Timing Detector and ongoing R&D activities for the CLIC pixel detector. The day finished with three talks covering different aspects of Silicon Photon-Multiplier detectors. The first talk reviewed the performance of this technology and what recent developments promise for the future, the second focused on experimental advances in the time resolution of photon detection - largely motivated by high-luminosity colliders - and the final talk discussed the design of a timing counter for MEG II presenting the first successful results from a pilot run.

During the parallel sessions of the conference, a number of talks covered in depth the detector upgrade programme of the LHC experiments, including possibilities for fixed target experiments and more specialized detectors for dark matter searches, neutrino and astroparticle experiments. The diversity of the conference is reflected in the large number of contributions from proposed experiments in laboratories around the world including Belle II, Darwin, SuperNEMO, LHAASO, EUSO-SPB2, GAPS and AXEL covering a wide range of different experiments in the search for new physics.



Group photo with this year's recipients of the Young Researcher Award of the Vienna Conference on Instrumentation

The challenges lying ahead for the detector community call for up-to-date expertise. To meet them we have to attract the best talent that will form the next generation of detector experts. The organizers of VCI2019 acknowledge the importance of involving early-stage researchers in this effort and honour their work/contributions established a Young Researcher Award presented in the last day of the conference. This year's award for poster presentation was shared between Micro Christmann who worked on the optimization studies for a Beam Dump Experiment (BDX) at MESA

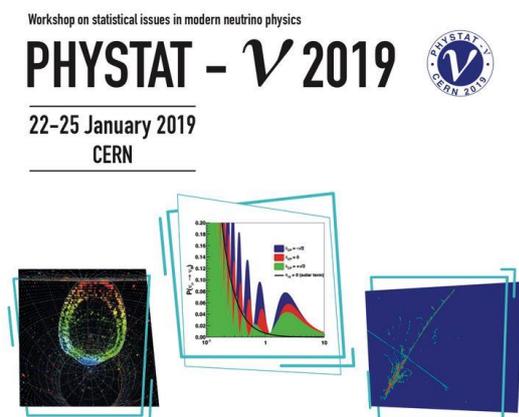
(Johannes Gutenberg University Mainz) and Jennifer Ott who presenter her work on pixel detectors on p-type MCz silicon using atomic layer deposition (ALD) grown aluminium oxide (Helsinki Institute of Physics). Aleksandra Dimitrievska (LBNL) working in the development of a large-scale prototype chip for the Phase 2 upgrade of the LHC experiments and Raffaella Donghia (LNL-INFN, Roma Tre) who contributed in the design of the MuZe CSI and SiPMS calorimeter shared the second award for the best oral presentation.

The meeting closed with a summary talk by Christian Joram, who highlighted the advances presented in the conference and emphasizing the links with CERN's EP Departments [planned R&D activities](#). Beyond innovative ideas and cross-disciplinary collaboration, development of new detector technologies call for good planning of resources and timescales and continuity. Thanks to the White Paper R&D programme that was initiated in 2006, a number of technologies and needed infrastructures were developed which led to the success of the LHC phase I and phase II upgrades. As the R&D for the LHC phase-II upgrade is ending near the end of 2020 it is timely to start preparing the future for LS3. Moreover, the CLIC and FCC studies already offer some clear ideas of the future experimental challenges and the update of the European Strategy for Particle Physics will offer more clear directions. With these targets in mind, EP's proposed R&D programme covers a wide range of topics documented in the recently [published report](#).

The high quality of the presentations and the large number of participants in VCI19 testifies to the success of the conference. It provided students and experts from across the world an opportunity to share knowledge and forge new partnerships and networks. "In the long history of the field we have seen the importance of cross-fertilization as developments for one specific experiment can catalyse progress in many fronts," says Manfred Krammer. VCI2019 gave the opportunity to display the cutting-edge work in detector technologies that can allow us to continue in the path of discovery and inspired the next generation of scientists to join this exciting field.

PHYSTAT-nu 2019 held at CERN

by *Albert De Roeck (CERN) and Davide Sgalaberna (CERN)*



Statistics is a topic that has gained increasing importance and underwent significant developments in particle physics over the past 25 years. More sophisticated methods have been developed to extract the maximum of information from the recorded data, and to make reliable predictions of the significance of measurements and observations. The community expects the experiments to perform proper statistical scrutiny on data before advancing claims of astonishing new observations. Entertaining examples, not just limited to statistics issues but situations one would prefer to avoid, have been recalled in a recent

historical review paper [1]. Neutrino experiments so far have often dealt with small event samples, that may lead to specific statistical requirements, but e.g. future long baseline and reactor experiments are expected to collect considerably larger data samples, requiring new paradigms for treating statistics questions and further reduction of the systematics.

The PHYSTAT series of Workshops [2] deals with the statistical issues that arise in analyses in High Energy Physics (and at times in Astroparticle Physics). The series started in 2000 and workshops have been organized at a semi-regular time interval. Over the recent years these workshops have been held to address the problems of specific communities such as the ones for collider and neutrino physics. In 2016 two specific workshops for neutrino physics were held, one in Japan and one in the US [3,4]. With the advent of the new CERN neutrino group in 2016 and the preparation for upcoming new experiments and upgrades, it was considered timely to have a new PHYSTAT statistics workshop on neutrinos at CERN to attract and discuss with proponents from the different communities, to review the status in the field and discuss the potentially interesting future directions.

PHYSTAT-nu 2019 [5] was organized at CERN from 22-25 January and counted about 130 registered participants. Since CERN is the home of the LHC, the venue was also convenient to attract collider experts to share their experience on statistics issues, which was an integral part of the program. Furthermore, as is a tradition for this workshop, it had a mix of physicists and statisticians that are well aware of the high energy experimental challenges. The Local Organizing Committee, composed by Olaf Behnke, Louis Lyons, Albert de Roeck and Davide Sgalaberna, was in charge of organizing the workshop and set the scientific program assisted by a scientific committee with experts from all around the World.



The workshop started with training statistics lectures, given by Louis Lyons and Glen Cowan, attended by a large audience and Jim Berger gave a very interesting talk about “Bayesian techniques”. There were excellent introductory talks on neutrino physics and statistics from Alain Blondel and Yoshi Uchida as well.

The workshop was focused on the statistical tools used in data analyses, rather than experimental details and results. Topics included were, among others, using data to extract model parameters, to referee between models, setting limits, defining discovery criteria, determination and usage of systematic uncertainties, and unfolding and machine learning for event reconstruction and classification.

Speakers and attendees from both the field of neutrino and collider physics as well as statisticians (Jim Berger, Anthony Davison, Mikael Kuusela, Chad Shafer, David van Dyk and Victor Panaretos) discussed their experience on the different statistical issues. First a taste of the tools used in

neutrino experiments (reactor, accelerator, atmospheric, solar, cosmic, global fits, etc.) was presented. The core of the workshop was composed of three main topical sessions of general interest: Systematic Uncertainties, Unfolding and Machine Learning. Each session consisted of an introductory talk given by an expert of the field, a talk reporting on the collider experience and, eventually, a talk on the experience gained by neutrino experiments. The goal was to exploit the synergy between the different communities and encourage fruitful discussions.

Talks and discussions were useful to clarify the issues faced by neutrino experiments. One fundamental challenge is the poor understanding of neutrino interactions with nuclei in the detectors. The challenges faced by the NOvA and the T2K experiments were reported: though they both rely on a near and a far detector to directly compare the un-oscillated and oscillated neutrino fluxes, a full cancellation of the systematic uncertainties is very hard, due to the different detector acceptances, possible different detector technologies, and the compositions of different neutrino interaction modes. Thus, building a total likelihood that does not rely on any model is not possible. Another major issue is given by the “unknown unknowns”. As it is hard to predict the level of understanding of neutrino interactions in 10 years from now, the future long-baseline experiments must design the near detectors very carefully, to achieve the precision required for the measurement of the neutrino CP violating phase and mass ordering. The NOvA and T2K collaborations are moving toward combining their data to improve the sensitivity to the CP violating phase and mass ordering. An analogous approach has been successfully used for ATLAS and CMS data at LHC and a detailed description of the statistical methods and tools used in the analysis was discussed at the meeting.

A common tool used to measure the neutrino-nuclei cross sections and provide data-driven inputs to the theoretical models is the Unfolding. It corrects for the kinematic observables of the final-state particles, such as muons, for effects of detector acceptance and smearing. A full session was exclusively dedicated to this topic. Usually regularization methods are used to smooth the fluctuations produced by unfolding procedures. Physicists and statisticians agreed that also unregularized results should be published.

Another hot topic was discussed during the Machine Learning session. During the last years, neutrino detectors have been developed to provide a more detailed view of the neutrino interaction event. At the same time, new “Deep Learning” techniques have been developed and are widely used in neutrino experiments. For instance, thanks to the recently available many-layer Neural Networks it becomes easier to exploit the full information provided by the detector and improve the identification of the final-state particles. An analogous approach is used in LHC to for example to discriminate beauty-quark jets from those produced by lighter quarks.

At the end of each day a session was dedicated to summarize the statistical issues tackled by the talks. The session was directed by Tom Junk, who raised all the important points for data analyses in neutrino experiments and triggered the discussion between physicists and statisticians, ranging from general problems like Bayes or Frequentism to more practical ones, like the determination of the neutrino mass ordering

David Van Dyk and Kevin McFarland gave lively summary talks and were in particular pointing out specific points to address for the neutrino physics community, in the coming years.

During the three days clearly connections between the communities were made. In general the workshop was highly appreciated by the participants and plans were made for a future follow up to resolve further outstanding statistical issues, through a future PHYSTAST-Nu meeting. An important step for current and future neutrino experiments could be setting up Statistics committee,

such as at the Tevatron and, more recently, LHC experiments. This PHYSTAT-nu workshop could be the first real step towards such a necessary and very exciting scenario.

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Can AI help us to find tracks?

by *Andreas Salzburger (CERN)*

Data science (DS) and machine learning (ML) are amongst the fastest growing sectors in science and technology, not at least due to their strong rooting in industrial and commercial applications. Global players such as Google, Facebook and Amazon have surpassed HEP in both, computing complexity and data volume. Recent advances in machine learning and artificial intelligence have made it more and more attractive to try to apply such algorithms in event reconstruction. While data analyses have been using machine learning techniques since a rather long time (and indeed very successfully), the application within the event reconstruction is less widespread, although there are certainly areas which could greatly benefit from such inclusion. One particular question is whether ML and DS can aid the pattern recognition in the high particle multiplicity environment of the HL-LHC or beyond, with the aim of lowering the computing impact of the future experiments. In particular the track reconstruction is - due to its combinatorial character - a heavily CPU intensive task.

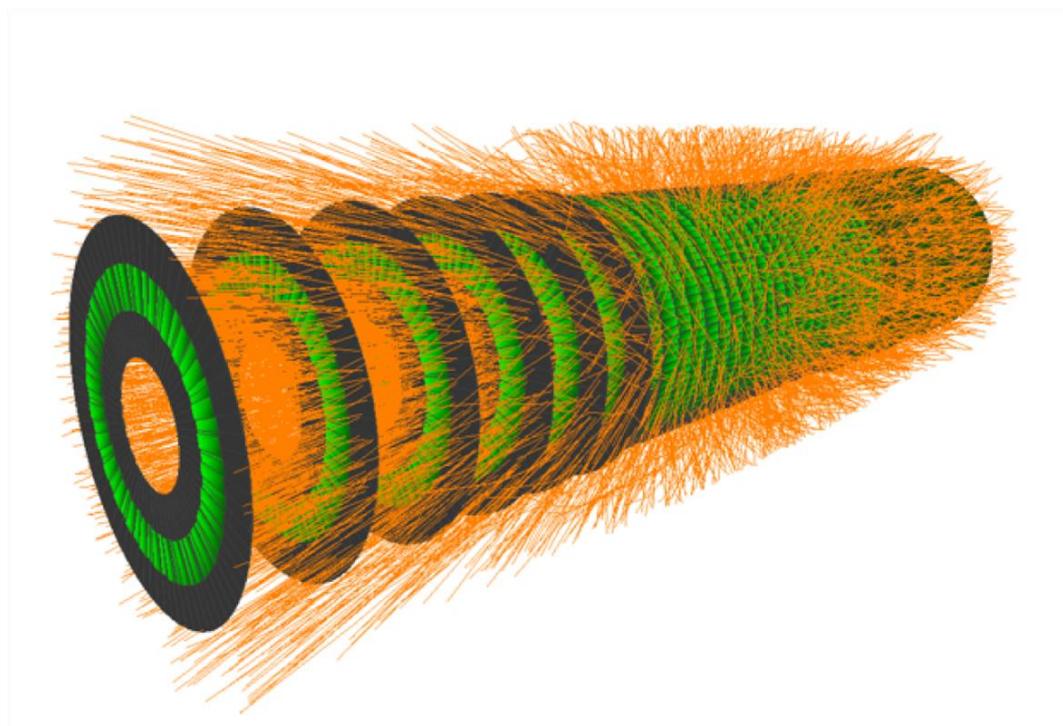


Figure 1: A detailed view of the short strip detector of the Tracking Machine Learning challenge with a simulated event with 200 pile-up interactions.

Based on the experience and the broad resonance of the Higgs Machine Learning Challenge organised in 2018, the Tracking Machine Challenge (TML) was launched in April, designed to run in two phases that focus first on accuracy (Phase 1) and then execution speed (Phase 2). The idea of such a challenge is as simple as it is compelling: a large-scale dataset is provided to the public, together with the template truth solution and a prescription of the score (or inverse cost) function. In short words, the score function attributes a positive score for each correctly assigned measurement, while penalizes wrongly assigned ones. The dataset for the challenge resembles conditions that are expected at the HL-LHC: on average 200 simulated instantaneous proton-proton collisions are overlaid with one signal event (top quark pair production), a perfect score of 1 hereby indicates that all measurements of reconstructable particles (i.e. more than four measurements are created by this particle) stemming from these collisions are correctly assigned.

The competitors are then left to find their best solution, which they have to provide for a smaller test dataset where the ground truth is removed. By uploading the solution to the challenge platform, each submission is ranked by using the truth information on the platform server. Prize money of 25 000 dollars for the winning teams and special jury prizes were provided by sponsors of the TML challenge.

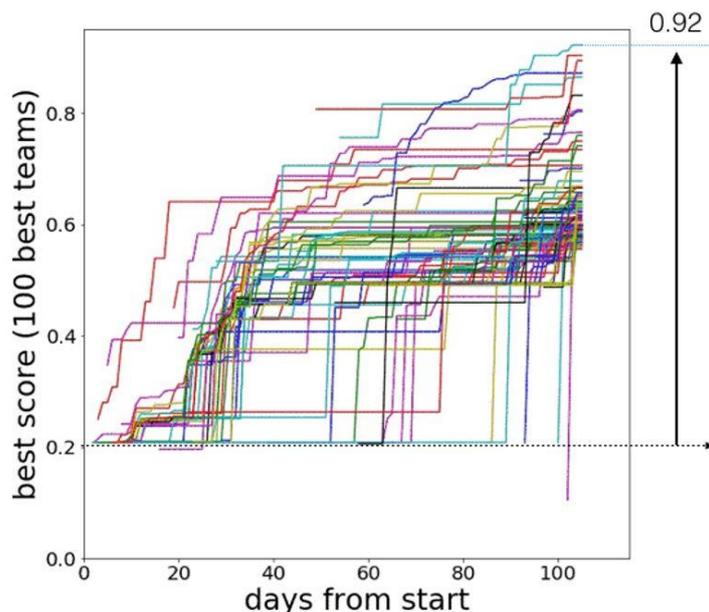


Figure 2: The evolution of score from contestants of Phase 1 during the submission phase. The starting score of 0.2 is given by the starter kit solution that implemented a simple solution built on DBScan.

In total, 656 teams from within and from outside the HEP community submitted nearly 6000 solution attempts during the submission period of Phase 1, which was hosted on the kaggle platform.

The lessons from Phase 1

The final leaderboard of Phase 1 was a mix of classical pattern recognition and ML based/inspired solutions, with both approaches reaching scores of up to 0.92. The winner,

Johan Sokrates Wind (albeit named *top quarks* in the competition), is from outside the HEP community. He performed a mixture of classical pairing/seeding followed by ML assisted pruning of the candidate and executed the task in roughly 15 seconds per event, comparable to what current HL-LHC reconstruction might take. The runner up, Pei-Lien Chou, on the other hand had a fully trained model based on deep learning, in particular the relationship of pairs of hits. The training model consisted of five hidden layers of several thousand neurons in order to accommodate the dataset and the execution time of finding a solution relied on pair building was consequently orders of magnitudes slower. All, in all, an interesting mix of classical and ML based solutions were presented and are currently being analysed.

The astonishing numbers of Phase 2

For Phase 2, the dataset has only been slightly changed: a few feature in the data set have been correct, such as a too narrow beamspot simulation in Phase 1. The reconstruction target was changed to include only particles emerging from the beam-beam interaction, secondary particles were omitted in the scoring function.

The detector setup was kept identical, although the scoring function and the mechanism was modified: as the figure of merit in Phase 2 included the throughput time as a one of the scoring parameters. This required the development of a special platform setup, which was done in cooperation with the platform host of the Phase 2, codalab [ref]. The accuracy based score of Phase-1 was augmented with a timing scoring, which was measured at submission in a controlled way: the submitters had to submit their (compiled or non-compiled) software with a dedicated API such that the in-memory dataset for the scoring events could be pushed through and both, the accuracy and speed measured at the same time in a controlled environment (2 cores with each 2 Gb memory were dedicated for each submission process). Evidently, due to the more restrictive submission pattern, but also caused by the time limit available for a submission to be successful, the number of teams submitting to Phase 2 had decreased significantly.

Phase-2 closed on March 13, 2019, with truly remarkable results. The leading submission achieves a better than a Hz throughput time for primary reconstruction of a typical HL-LHC event, while keeping an accuracy score of roughly 0.94, followed up by a very similar solution that executes only slightly slower.

RESULTS									
#	User	Entries	Date of Last Entry	score ▲	accuracy_mean ▲	accuracy_std ▲	computation time (sec) ▲	computation speed (sec/event) ▲	Duration ▲
1	sgorbuno	9	03/12/19	1.1727 (1)	0.944 (2)	0.00 (14)	28.06 (1)	0.56 (1)	64.00 (1)
2	fastrack	53	03/12/19	1.1145 (2)	0.944 (1)	0.00 (15)	55.51 (16)	1.11 (16)	91.00 (6)
3	cloudkitchen	73	03/12/19	0.9007 (3)	0.928 (3)	0.00 (13)	364.00 (18)	7.28 (18)	407.00 (8)

Figure 3: Final development result table for the Phase 2 (throughput phase) of the Tracking Machine learning challenge.

Where to go from here

The solution from Phase 1 and 2 are currently being analysed in detail, and some of them will find their ways into the experiments' software stacks. In the meantime, the TrackML dataset is being consolidated, the fast simulation augmented with a smaller scale full simulation for cross

comparison, and a reference detector and dataset prepared to be published on the CERN OpenData portal. Similarly like the NIMST data set for letter recognition, this will allow to perform future algorithmic development & performance evaluation.

Are we in the era where machines learn how to do the event reconstruction for HEP? The honest answer needs to be: not yet. But times are changing.

Investing in detector technologies

by *Panagiotis Charitos*

Detector technologies are a vital component in the exploration of the fundamental laws of nature and the search for new physics that will answer some of the questions that the Standard Model leaves unanswered. Recognizing the importance of further R&D on detector technologies that could boost their performance and allow to meet the physics challenges of new experiments, ECFA has nominated a [Detector Panel](#) – a European committee reviewing and coordinating efforts for future project. Following a broad consultation, involving different shareholders from the academia and the industry, the panel published last December its [input](#) to the update of the European Strategy for particle physics.

The report gives an overview of the status of technologies and provides a set of recommendations for future developments. Moreover, it presents the results from a recent survey conducted during summer 2018 among researchers involved in ongoing R&D activities across Europe. More than 700 respondents at different stages of their career path – from PhD students to full Professors – gave their feedback helping to collect input on various aspects (technologies, demography, organisation, etc.) from the community. With a main focus on high-energy particle physics, the survey also addressed astroparticle physics as well as neutrino and nuclear physics.

	% of replies
Astroparticle Physics	19
Neutrino Physics	17
Nuclear Physics	19
Particle Physics	72
Other branches of fundamental physics	12
Other	8
	>100

Major branches of Physics in which detector R&D is performed normalised to the number of people who responded to the survey (multiple answers possible).

Regarding the current landscape, the survey revealed that the majority of activities is dedicated to the development of vertex detectors and trackers, mostly based on semiconductors (35%) . Significant effort is also dedicated to calorimetry (15%), detectors for particle identification (14%) and timing detectors (12%) followed by other types of more specialised detectors for neutrino physics and astrophysics.

The survey also revealed a strong appreciation of the value that R&D in detector technologies has for other domains and the possible spin-offs to many daily-life applications. Among the most referred areas are medical applications (65%), dosimetry (26%), security (18) and applications for cultural heritage (10%). However, it is worrying that in only one third of the R&D cases the exploitation of

technology transfer strategy is well embedded in the programme, while the majority of respondents think that further support is needed to boost these efforts.

Activities	% normalised to number of respondents (537)
Beam tests	66
Ageing studies	21
Radiation hardness tests	44
Quality control / Quality assurance	42
Cooling	19
Services and integration	34
Software development for detector simulations	37
Software development for detector performance assessment	38
Other (<i>design, integration, production, trigger optimization, DAQ, alignment, radiopurity checks, development with industries</i>)	5
	>100

Sub-activities in which researchers are involved (multiple answers possible).

Perhaps a promising finding of the survey is the strong links established with industry in almost 50% of the R&D efforts in detector technology. In half of these cases, the collaboration was limited to the R&D phase, in 34% of the cases it refers to the mass production and full-scale industrialization of a technology. It is only in 16% of the cases that collaboration covers both the R&D and production phase and increasing this number may be a target in the future.

Regarding the funding mechanisms for this type of R&D, it seems that despite the non-negligible support from EU programmes a large portion of funding still comes from home institutes and from national funding agencies, while it is interesting to see that very few resources derive from industrial sponsors. Moreover, 77% of the respondents believe that R&D in Europe should be better coordinated among the different physics communities. In terms of other types of resources, a promising finding is the high level of satisfaction with the available infrastructure for detector R&D with about 90% of the participants confirming access to test beam infrastructures and another 90% to irradiation facilities – both important for testing new technologies and exploring novel promising ways in detector design. On the contrary there is a perceived lack of humanpower, as only 35% of the respondents think that the current level is enough to sustain future activities.

The availability of skilled professionals to join the field is linked to the need of further improving the learning and career opportunities. Although about 59% of those who responded to the survey believe that there is sufficient availability training in detector R&D the study also revealed that detector technology research is less valued compared to physics data analysis and interpretation. Moreover, an underlying assumption is that basic knowledge in electronics, mechanics and instrumentation should be better integrated in university curricula across Europe, thus better preparing students who wish to pursue a career in detector technology. Career-wise it also seems that more senior level grant support and long-term positions are needed to ensure that talented physicists and engineers decide to join R&D efforts for detectors and that future developments can profit from fresh ideas and out-of-the box thinking. Failing to attract young talent in the field of detector design could have a negative impact in fundamental research, while also depriving related industries – where detectors are key components – from future expertise.

Most promising future R&Ds	# answers (380 total)
Precision timing	210
Precise position resolution	63
Precise energy measurements	25
Radiation Hardness	29
CMOS HV-MAPS monolithic	24
High granularity imaging calorimetry	21
Artificial intelligence / Machine Learning	16
Fast (tracker) triggers (online)	16
High rate capability	14
Low power consumption in detector systems/electronics,	14
4D tracking	14

Perceived most promising future R&D topics (top-11)

Participants in the survey also acknowledged the role of recent R&D collaborations in developing networks across different detector R&D activities. RD50, RD51, RD53, CALICE and AIDA2020 are among the most successful recent examples that allowed a better coordination of resources and investments and encouraging the sharing of innovative ideas and methodologies. Further coordination through CERN or Europe's framework programme for Research and Innovation is encouraged as it would help the coordination between different design efforts, the sharing of available expertise and can catalyse developments that will attract future highly skilled professionals to the field.

Finally, the ECFA panel highlighted the need for more recognition and visibility to detector experts that also involves a changing attitude and raise of awareness within the wider particle physics community. In that sense, instrumentation schools have an important role as they can encourage/support students to make their first steps in the field. The panel proposed to help strengthening outreach/dissemination on detector technologies by working closely together with instrumentation schools and by using digital technologies to make relevant teaching material accessible to a larger audience on the Panel's web site.

The results of the ECFA Detector Panel report helped to understand the current situation and identify the strengths and weaknesses of the field. Future incentives should target on training and creating career opportunities, assessing the value of technology transfer and enhancing coordination between physics fields and technology specialisations. These are some of the areas where we need to invest to shape a successful future for the field of detector technology.