Highlights from LHC Detector Upgrades

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Abstract. The High Luminosity LHC will operate at luminosities up to 7.5 times the original LHC design luminosity, and accumulate 3 times more data than originally envisioned. In order to fully exploit the physics potential of this new phase, the detectors will be significantly upgraded. Highlights of these upgrades are presented, with particular focus on new technologies.

1 Introduction

During Run 1 (2010–2012), the LHC operated at $\sqrt{s}$ = 7 and 8 TeV, the ATLAS and CMS collaborations collected about 30 fb^{-1} of good data each, and that allowed them to discover the Higgs boson. Run 2 (2015–2018) saw an increase in $\sqrt{s}$ to 13 TeV, with approximately 150 fb^{-1} of good data. This led to confirmation that many Higgs boson properties are within 20% of the Standard Model predictions and the observation of many rare processes, but no discovery of new physics yet. Run 3 (2022–2025) is now underway at $\sqrt{s}$ = 13.6 TeV, with the expectation to collect 250 fb^{-1}. Peak luminosity is now twice the design luminosity, with about 60 interactions per bunch crossing in ATLAS and CMS, which is straining the current detector capabilities.

During the HL-LHC, the accelerator is expected to deliver about 3000 fb^{-1} at $\sqrt{s}$ = 14 TeV to ATLAS and CMS, i.e. twenty times more data than has been analyzed so far. This will significantly expand the sensitivity to new physics, and should allow the experiments to observe di-Higgs production, the first direct probe of the Higgs potential, a soft Standard Model prediction (see e.g. G. Weiglein's presentation at this meeting). To get to 3000 fb^{-1}, the peak luminosity will be 7.5 times the original LHC design luminosity (typically leveled to 5 times design) and operations will last about ten years. This means the inner tracking detectors will need to withstand multi-MRad integrated doses, beyond the expected survival of the current detectors. In addition, 200 pile-up events per bunch crossing implies significantly increased complexity, which the detectors will handle by increasing granularity and adding handles (e.g. timing). To cope with this, offline algorithms will be moved upstream into the trigger system, and more data will be written to "tape". This presentation includes highlights from the upgrades planned for the four major LHC experiments: the multi-purpose ATLAS and CMS experiments, LHCb whose primary aim is flavor physics, and ALICE, which is focused on heavy ion collisions.

2 Tracking Detectors

All experiments pursue solutions for tracking detectors that increase granularity and capabilities. For ATLAS [1, 2] and CMS [3] this means going from $\mathcal{O}$(100 million) to about 5

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billion channels, including building over 10 m^2 of pixel detectors each. This requires industrialization of production and simplication of the final assembly. An example is the assembly of many modules into staves, as depicted in Figure 1 for the ATLAS silicon strip detector. The experiments will increase the pseudorapidity range covered by tracking detectors from $|\eta| \leq 2$ to $|\eta| \leq 4$ and expect to read them out at rates up to 1 MHz. Cooling will be provided by dual phase CO_2 systems to reduce the ecological impact. The CMS outer tracker will also provide high-p_T [1] track candidate stubs to the Level-1 trigger, as illustrated in Figure 2, to increase the hardware trigger rejection.

Figure 1. One of about 400 1.4 m long staves needed for the ATLAS barrel silicon strip detector. Each stave supports 28 modules.

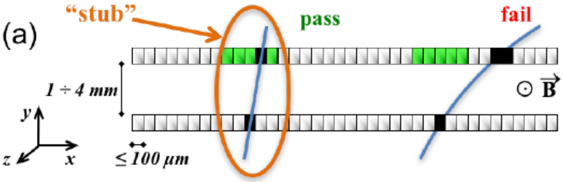

Figure 2. CMS track stub selection: correlation of signals in closely-spaced sensors enables rejection of low-p_T particles; the channels shown in green represent the selection window to define an accepted stub.

ALICE [4] and LHCb [5] plan to introduce Monolithic Active Pixels to operating experiments. These are devices that integrate sensor and readout, eliminating the need for complex bonding. ALICE's ITS3 is pushing this one step further, stitching wafer sections together to get segments up to about 25 cm long, and thinning them to 50 μm so the silicon can be bent into a cylindrical shape. This is shown in Figure 3.

3 Timing Detectors

One of the major innovations brought by the HL-LHC detector upgrades is the introduction of high-granularity silicon timing detectors, effectively leading to 4-D tracking capabilities. This is typically implemented by positioning LGAD-based sensors in front of the calorimeters. For ATLAS [6], CMS [7] and LHCb [5] the main goal is to add a handle to reject pile-up tracks, exploiting the bunch crossing "duration" of about 200 ps, but of course these detectors can also be used for particle identification at relatively low momenta (up to p_T values of about 3 GeV). The target time resolution is better than 50 ps, including the contributions from readout electronics.

4 Čerenkov Detectors

To complement the particle identification capabilities of timing detectors, Čerenkov detectors are effective at higher momenta. ALICE [8] is exploring installing at a radius of 120 cm an

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[1] p_T denotes momentum transverse to the beam direction.

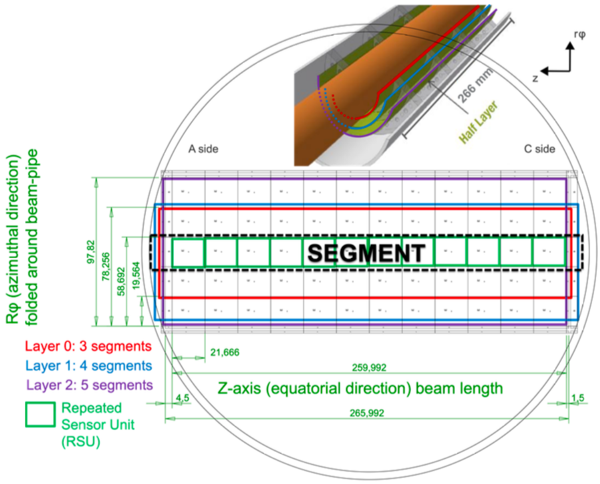

Figure 3. ALICE ITS3 CMOS wafer stitching plan and dimensions of the sensors; the illustration in the top of the figure shows the placement of the 3 lower bottom sensors bent around the beam pipe.

aerogel radiator (with a refractive index of $n = 1.03$), read out using silicon photomultipliers (SiPMs), which would give good π/K/p separation up to $p = 10$ GeV, as can be seen in Figure 4. LHCb [5] plans to reconfigure its existing Ring Imaging Čerenkov radiator with new

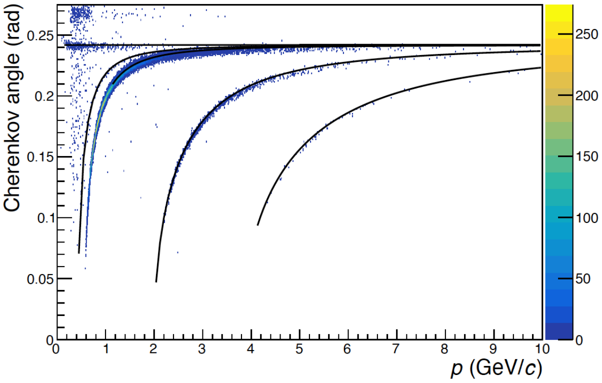

Figure 4. ALICE aerogel detector reconstructed Čerenkov angle as a function of momentum in Monte Carlo Pb–Pb events.

mirrors, and to replace the multi-anode photomultiplier tubes with SiPMs, which will allow higher rates, and, thanks to the better time resolution, help reject combinatoric background.

5 Calorimetry

Where calorimeters cannot be carried over to HL-LHC, the goal is to increase granularity and add timing capabilities, to build “5D” detectors. The light yield from CMS’ current endcap calorimeters will become insufficient, so these will be replaced with silicon-absorber (with about 1 cm^2 cells) and scintillator-absorber (4–32 cm^2) imaging calorimeters [9, 10]. ATLAS’ liquid Argon and scintillator-based calorimeters are expected to maintain their performance at HL-LHC, but the readout for all of these will be upgraded to a free-running architecture transmitting digitized waveforms sampled at 40 MHz [10, 11]. ALICE [8] is likely to use a combination of $PbWO_4$ and Pb/scintillator calorimetry. In LHCb [5] , only the innermost radii of the current calorimeters will need to be replaced, and the collaboration is exploring a spaghetti calorimeter solution using crystal fibers at the innermost radii.

6 Muon Systems

The main challenge for the muon systems will be the high rates, in particular in the forward detector regions, where they can hit MHz/cm^2 values. (ATLAS' and CMS' muon systems cover $|\eta|$ ranges up to 2.5, whereas LHCb's ranges from 16 to 260 mrad from the beamline.) Both CMS [12] and LHCb [5] are pursuing GEM-based technologies. While this is not new, the improvement is in using μ-RWELL foils, as shown in Figure 5. In testbeams, a prototype has been shown to produce a minimum ionizing particle detection efficiency of about 97% and a rate capability of about 10 MHz/cm^2.

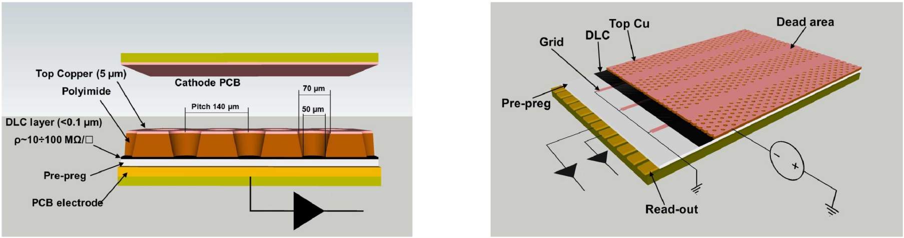

Figure 5. Layout of the μ-RWELL, with a detailed schematic of the high-rate structure.

7 Trigger and Data Acquisition Systems

In general, the approach to trigger and data acquisition systems will be to increase the bandwidth at all levels and exploit new technologies, which will enable moving algorithms upstream in the trigger architecture. The ATLAS [13] and CMS [14] hardware trigger systems will be based on ATCA blades hosting large FPGAs and many 25 Gbps links. These will have access to increased granularity (e.g. full calorimeter information), and in CMS perform track reconstruction, and the expectation is they will run machine learned algorithms, all within $O(10\ \mu s)$ latency.

The software trigger systems [13, 15] will implement algorithms very close to those used offline, implemented on heterogeneous computing farms that will exploit the relative strengths of FPGAs, GPUs and CPUs. ATLAS and CMS will increase their rate to tape from 1 kHz to 10 kHZ, which corresponds to about 4 Tbps. Even so, events in the flagship $HH \to 4b$ channel will remain difficult to trigger.

8 Closing

Construction of the High-Luminosity LHC is well underway, and this will yield a much deeper probe of the TeV scale. To fully exploit the physics potential of the luminosity increase, the detectors are undergoing a significant rebuild, including new tracking detectors, new readout electronics and trigger and data acquisition systems. The HL-LHC will mark the advent of a number of new technologies in operating experiments: MAPS pixel detectors, silicon-based timing systems with better than 50 ps resolution, and high-granularity silicon-based calorimetry. There will undoubtably be important lessons for the next generation collider detectors, whether at e^+e^-, $\mu^+\mu^-$, or pp machines.

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