

PERFORMANCE PARAMETERS – EXPERIMENTS PERSPECTIVE

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Abstract

In its physics program for the next two decades, the LHC foresees a series of upgrades to steadily increase the instantaneous luminosity of the accelerator. This paper describes the experimental challenges for the ATLAS and CMS detectors to operate and perform at increasing rates and occupancies. It focuses on the upgrades that will be implemented to maintain the physics acceptance in the trigger selection and the high efficiency and resolution in the reconstruction of the many interactions that will occur at each beam crossing.

INTRODUCTION

The upgrades of the ATLAS and CMS experiments will be accomplished in three stages during the long shutdowns foreseen for the upgrades of the LHC. In LS1, the CM energy will be increased to 13 TeV (or slightly higher), and it is expected that the bunch spacing will be reduced to 25 ns for future RUNs. It is anticipated that the peak luminosity can exceed the nominal value of 1×10^{34} Hz/cm² before LS2 and reach more than 2×10^{34} Hz/cm² after LS2. The experiment upgrades during LS1 will complete the original detector designs, consolidate operation and start to prepare for luminosities beyond the nominal value. In the period through LS2 (Phase 1) the upgrades will be completed for operation at a mean pile-up (PU) of ~ 50 proton-proton collisions per bunch crossing, with margin up to ~ 70 . In LS3 the LHC itself will be upgraded to optimize the bunch overlap at the interaction region. It is foreseen that the peak luminosity, exceeding 10^{35} Hz/cm² at the beginning of the fills, will be leveled at $\sim 5 \times 10^{34}$ Hz/cm² to control the PU. The goal for the High Luminosity LHC (Phase 2) is to deliver a further 2500 fb⁻¹ in the decade after LS3. ATLAS and CMS will need major upgrades during this shutdown to solve detector and system aging, high occupancy and radiation hardness issues, mitigate pile-up effects and enhance performance where statistics/systematics limited.

PHASE 1 UPGRADES

The phase 1 upgrades [1,2] are mainly driven by technical constraints of integration in the current detectors, in addition to the external constraints of schedule and funding. They essentially consist in: completing the original detector; increasing the readout granularity when possible without changing the detector themselves; and using new high power and large bandwidth FPGA and xTCA telecommunication standards for the data processing. These allow sufficient improvements of the

trigger selection to maintain the performance of the present detectors.

The hardware trigger in ATLAS and CMS is limited to 100 kHz and it is based on muon systems and calorimeters information. Events are selected when they contain individual or multiple particles with a momentum or energy above a threshold defining the rate allocate to each type of event. A simplified example of such a trigger menu and of the thresholds applied in CMS is presented in figure 1. For efficient selection of the interesting physics signals, the threshold must be maintained at low values. When luminosity and therefore rates increase, this can be achieved by improving the measurement precision and implementing more sophisticated selection algorithms, either at the level of individual detectors or in their combination.

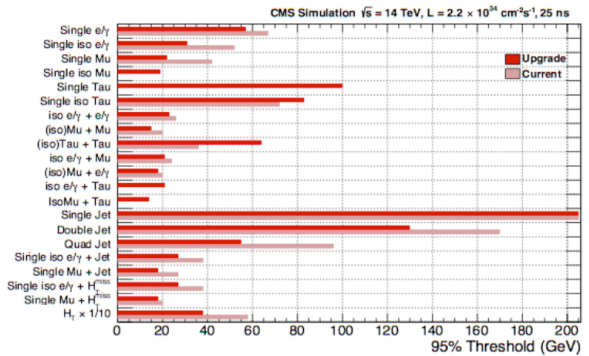
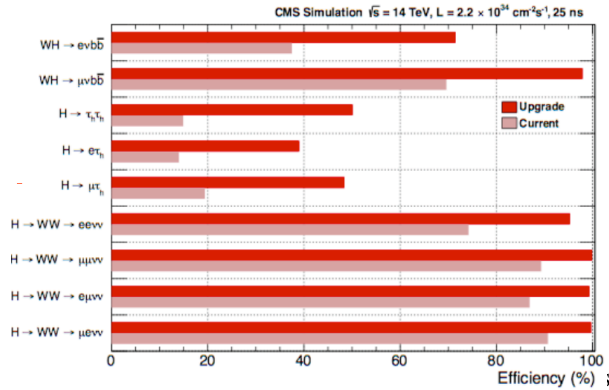


Figure 1: Example of a simplified CMS menu at 50 PU. The thresholds are adjusted to maintain the bandwidth of each trigger at similar levels for the upgraded and non-upgraded systems.

During Phase 1, the completion of the muon systems in the forward regions both in ATLAS and CMS, will allow improving the sharpness of the muon selection. Some upgrades of the calorimeter front-end and back-end electronics will allow finer granularity of the information available for the trigger. These improvements of the input data together with the additional processing power in the back-end electronics will result in better turn-on selection at the thresholds, more efficient subtraction of PU energy, better isolation of particles and identification of narrow τ -jets. New topological selection will also be introduced, based on particle masses or angular correlations. An example of the physics acceptance benefit provided by the CMS trigger upgrade is presented in figure 2.



channels with the upgraded and non-upgraded systems and for the menu presented in figure 1.

In addition to the trigger upgrades, ATLAS and CMS will upgrade their pixel detectors to measure one more space point at a lower radius of ~ 3 cm. In ATLAS this will be achieved by inserting a new long inner barrel layer, while CMS will replace the full pixel detector. These upgrades will allow improving the position precision on the origin of the charged tracks, with substantial gain in the efficiency to associate them to a primary vertex or to identify secondary vertices associated to the decay of light or heavy quarks. This is illustrated in figure 3, showing that an increase of 65% of the $ZH \rightarrow \mu\mu b\bar{b}$ signal statistics can be reached with the CMS new pixel detector.

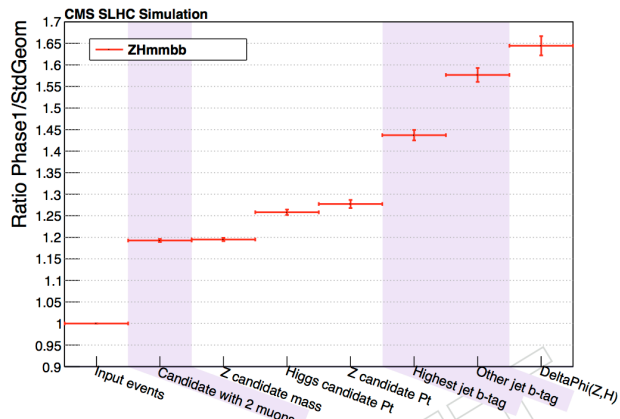


Figure 3: The ratio Phase-1 / current of events left after each selection cut at 50 PU. The cuts where the upgrade detector is expected to excel are highlighted.

PHASE 2 UPGRADES

The physics program at the HL-LHC aims at precise measurement of the Higgs couplings, as well as measurement of very low cross section processes and search and/or study of other new particles [3]. This imposes severe constraints on the detector acceptance in a

challenging PU environment, especially in the forward region of the detectors that will become extremely important. The goal for the ATLAS and CMS upgrades [4, 5] is to maintain the present performance at least up to ~ 140 PU with a capability to take data up to ~ 200 PU. While the required replacement of some systems will allow performance enhancement to cope with the highest PU, assessing the best operation point of the full experiment will need thorough investigation and major work to tune the event selection, the data reconstruction and the physics analyses.

For both ATLAS and CMS, a major upgrade will be the replacement of the tracker motivated by longevity issues and the need for a higher granularity device, also implemented in the hardware trigger event selection. To cope with the increased readout bandwidth, significant amount of the other detector front-end electronics will need replacement, also accommodating the new specifications for the trigger system. This concerns all systems in ATLAS and the DT muon chambers and the electromagnetic calorimeter in the CMS barrel. In addition, CMS will have to replace the endcap calorimeters due to longevity issues, while only the most forward part of the detector could be affected by irradiation in ATLAS.

The main features for the new silicon trackers will be a strip length divided by about a factor 4 in the outer layers, and pixels with smaller size of about $25 \times 100 \mu\text{m}^2$. Thinner sensors will be used to accommodate the large radiation doses. The assembly will be lighter than in the present detectors, significantly reducing the γ conversions and the multiple scattering of charged particles. This will ensure high reconstruction efficiency and excellent association of tracks to the proper vertices. As an example, the expected b-quark tagging performance in the future ATLAS tracker is presented in figure 4.

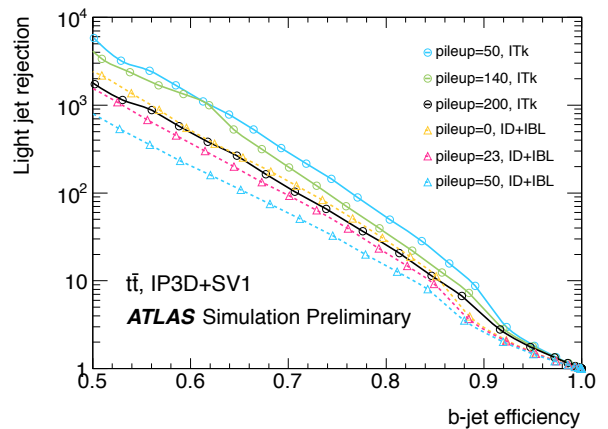


Figure 4: Performance of b-tagging with the ATLAS Phase1 (IBL) and Phase 2 (ITK) trackers.

A new feature of the future trackers could be an extension of the pixel systems in the region of pseudo-rapidity between 2.4 and 4 to cover the full range of the calorimeters. The association of charged tracks to their

energy deposits will provide PU mitigation. This has been shown to be extremely powerful to reject fakes in the identification of jets from the Vector Boson Fusion or Scattering processes that will be of major importance in the HL-LHC physics program.

The configuration of the ATLAS and CMS trackers will essentially differ in their implementation for trigger purpose. While the ATLAS detector will be read-out in regions of interest at 500 kHz, based on a calorimeter and muon first-level trigger; the CMS tracker will implement an on-detector selective read-out to provide track-trigger stubs at 40 MHz. This will be achieved measuring the bending of the tracks in the high magnetic field, over the few mm separating two sensors connected to a same read-out chip. A cut on the distance between the strip hits will allow sending only the information for tracks of

transverse momentum ≥ 2 GeV. Both in ATLAS and CMS, the hardware reconstruction of tracks in the back-end electronics could then be performed from the comparison of the hit map with a bank of patterns stored in Associative Memories. CMS is also investigating a propagation method using FPGAs. The track matching with the calorimeter and muon system objects, will provide high momentum resolution for leptons and photons, improved isolation, proper association of particles to a same vertex to reduce combinatorial background from the PU, especially in Jets, and improved total and missing transverse energy resolution. Preliminary studies indicate that the lepton trigger rates could be reduced by factors up to 10, for a given threshold (fig. 5).

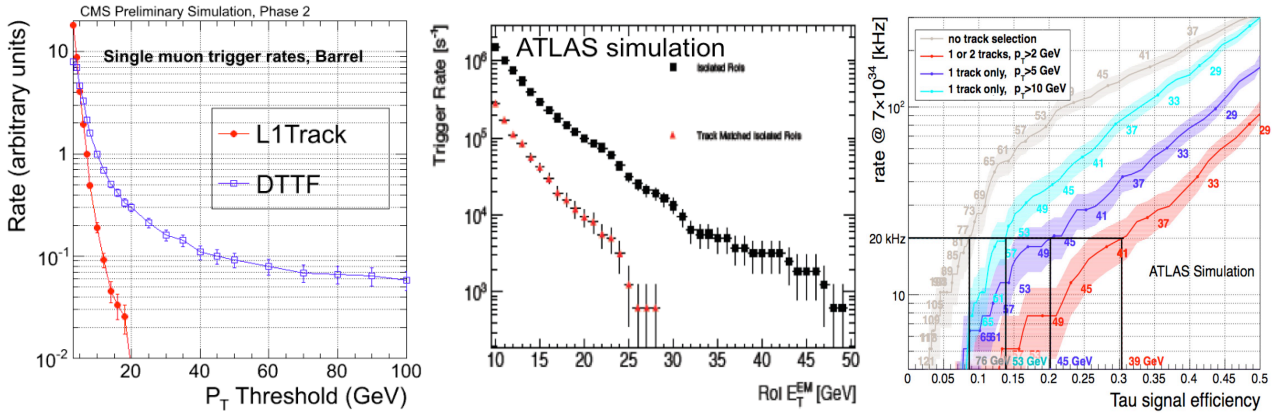


Figure 5: Single muon trigger rates in CMS with and without track matching as a function of transverse momentum threshold (left), single isolated e/γ rates in ATLAS with (red) and without (black) track information as a function of transverse energy (center), and τ signal efficiency versus rate and thresholds with and without track selection (right).

The new front-end electronics design, will also allow increasing the trigger read-out rate from the present 100 kHz up to ≥ 250 kHz in ATLAS and up to 0.5/1 MHz in CMS, depending in this latter case on the bandwidth sustainable in the pixel detector. The subsequent rise in the required computing power at the high-level trigger appears manageable within the expected progress of technologies in the timescale of the project.

As mentioned above, the potential to fully exploit the HL-LHC luminosity will be driven by the experiments performance. It has recently been shown that a new scheme of the beam crossings using a specific crab cavity configuration, could allow to lengthen the beam luminous region and to reduce the PU density. This could be a powerful mean to improve the charged tracks association to vertices to mitigate pile-up effects. However, demonstrating if it would be sufficient to allow operation at higher PU will need careful simulations and tuning of the reconstruction algorithms. Especially, the tracker

doesn't allow mitigating the effect of neutral particles PU in the calorimeters. Experiments are in the process of evaluating these effects, as well as the possibility to

mitigate the PU of neutrals through a precise time of flight measurement.

CONCLUSION

After the crucial discovery of a Higgs boson in 2012, the LHC has an extremely exciting and unique program to expand the physics reach through the next two decades. This requires major upgrades of the accelerator and of the ATLAS and CMS experiments. The first stage of these upgrades is already at construction level and studies and R&D for the High Luminosity LHC are ramping-up. Many exciting ideas are being discussed to meet the challenges of operation in the highest pile-up environment.

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