Collecting and analysing data at high pile-up with ATLAS and CMS

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Detector layouts for the Phase 2 upgrades of ATLAS and CMS, designed for operation at the High-Luminosity LHC (HL-LHC) under conditions with pile-up of 140 and beyond, will be presented and discussed. The event reconstruction performance and techniques implied by these detectors and experimental conditions will be demonstrated, and possibilities for further developments will be explored. The physics reach obtainable with the upgraded detectors at HL-LHC will be shown for a selection of possible HL-LHC measurements.

1 Introduction - The High Luminosity LHC

The High Luminosity Large Hadron Collider (HL-LHC) is a planned upgrade to the Large Hadron Collider (LHC) currently in operation at CERN. Foreseen to begin operation in around 2025 following the so-called 'Phase 2' machine upgrade, it will provide $\sqrt{s} = 14$ TeV proton-proton collisions with instantaneous luminosities of between $5-7\times10^{34}$ cm^{-2}s^{-1}. This will allow integrated luminosities of $250-300$ fb^{-1} to be collected every year, resulting a total anticipated dataset of 3 ab^{-1}.

This unprecedentedly large dataset will facilitate a wide spectrum of physics analyses from precision tests of the Standard Model to New Physics searches with significantly enhanced discovery potential. However, in order to make the best use of the available data, the ATLAS and CMS collaborations must make extensive upgrades to detector systems, reconstruction algorithms, and analysis strategies to cope with the challenging experimental environment implied by the high instantaneous luminosities planned.

The experiments anticipate [1] events with an average number of 'pile-up' interactions per bunch crossing $\langle\mu\rangle = 140-200$, and the effects of the resulting high particle multiplicities on the various detector subsystems and algorithms are being thoroughly and carefully investigated using a variety of methods, and designs and optimisations made accordingly in order that the experiments will be able to identify and reconstruct physics processes of interest, maintaining or exceeding the excellent performance obtained by ATLAS and CMS up to now.

2 ATLAS Phase 2 Detector Upgrade

2.1 Inner Tracker Upgrade

As the innermost detector system of ATLAS, the Inner Tracker is the most strongly affected by the increased pile-up at HL-LHC, and so the replacement of the Inner Tracker (ITK) is one of the most crucial aspects of the Phase 2 upgrade [2]. A complete replacement of the tracking system will be undertaken; the gaseous straw-tube based Transition Radiation Tracker (TRT) will be removed due to being rendered inoperational due to the expected occupancies resulting from Phase 2 conditions, and the pixel and microstrip systems will be extended, resulting in a fully silicon based tracking detector.

From the numerous design consideration to be considered when designing a tracking system for working in high pile-up environments, among the most important are: low material budget within tracking acceptance to minimise multiple scattering and generation of secondary particles, high sensor granularity to effectively resolve nearby tracks, and sufficient number of space point measurements per track (including robustness against potential module failures) to combat combinatoric effects. Taking these and other considerations into account, a baseline tracker design was developed which meets the stated goal of maintaining or improving on current levels of performance under Phase 2 conditions, as will be discussed further in Section 4. The baseline

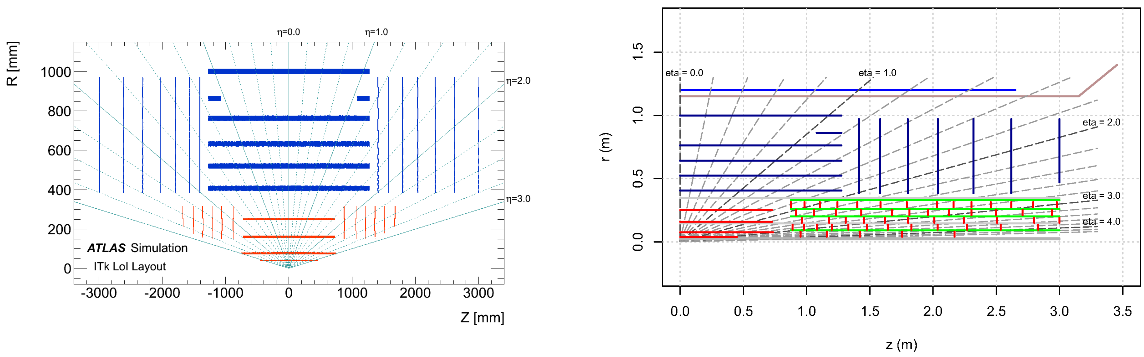

Figure 1 – Baseline ITK design for the ATLAS Phase 2 tracker upgrade (left), and a design showing a potential high-η extension (right). The right-hand figure shows only one quadrant of the detector ($z > 0$), which is symmetric around $z = 0$ and $r = 0$, while the left-hand shows both positive and negative z.

design is currently being used as a benchmark for comparison with further developments to the layout design. One particular development under serious consideration is the so-called 'high-η' extension of the pixel system, which would increase the tracking acceptance of the detector from from $|\eta| < 2.5$ to $|\eta| < 4.0$. Various possibilities for extending the tracking acceptance, as well as other possible layouts, are currently under detailed study. A possible design with high-η extension is shown in Figure 1 alongside the baseline design.

2.2 Upgrades to Other Systems

In addition to the tracker, many other ATLAS systems will undergo significant upgrades ahead of HL-LHC running.

The architecture of the ATLAS trigger system will be comprehensively updated, to move to a 2-level hardware trigger design. At Level 0, calorimeter and muon system information will be used to process events at a rate of 1 MHz and with a latency of 6 μs. Following this, Level 1 will process events at a rate of 300-400 kHz with a latency of 24 μs. Compared to the current ATLAS trigger system, the largest difference is the introduction of 'L1Track' which will bring part of the track reconstruction currently run in the HLT into Level 1. Since running tracking on full events at this stage of the trigger is not feasible, a 'Region Of Interest'-based (RoI) approach will be used, in which only specific $\eta - \phi$ segments of the detector will be processed.

Due to the increased trigger rates and radiation levels at HL-LHC, the electronics of the Tile and Liquid Argon calorimeters will need to be fully replaced. Full replacement of the Forward calorimetry may also be required, depending on the level of degradation observed in the current system in the coming years. Additionally, in the case of a 'high-η' extension, the Forward calorimetry may also be replaced with a higher granularity system to meet physics requirements. Similarly, additional Muon system chambers may be added in this case to make full use of the extended tracking acceptance.

3 CMS Phase 2 Detector Upgrade

3.1 CMS Tracker Upgrade

CMS will also perform a full replacement of their all-silicon tracking system for Phase 2, including replacing the new Pixel system introduced during the 'Phase 1' upgrade [4] around 2020. The design of the CMS baseline Phase 2 tracker [5] fulfils a similar set of requirement to those discussed in Section 2.1; high granularity, low material budget, and sufficient space points on the track. In contrast to the ATLAS design, the CMS baseline already features a pixel system with coverage up to $|\eta|$ =4, as shown in Figure 2 (left).

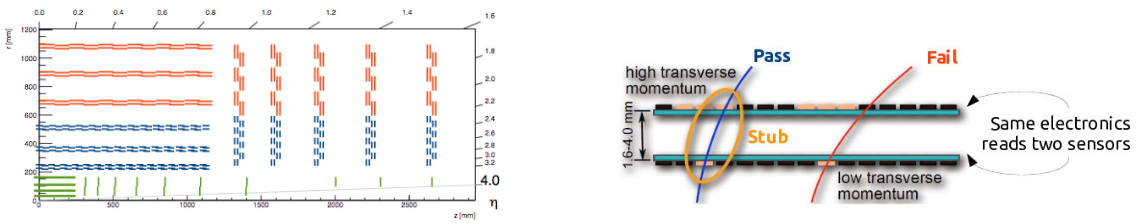

Figure 2 – The CMS basline Phase 2 tracker upgrade design (left) and an illustration of the 'stubs' used in the Silicon Self-Seeded Track Trigger concept (right)

A further significant feature of the CMS design is its use of a so-called 'Silicon Self-Seeded' approach to including track information in its hardware Level 1 trigger. By looking at the relation between pairs of hits on the two sensors of a double-sided module, high p_T track 'stubs' can be identified, as shown in Figure 2 (right). Two types of modules will be used in the 'Outer Tracker' layers according to granularity needs in the region; SS modules comprising two silicon microstrip sensors, and PS modules comprising a pixel sensors and a microstrip sensor. The performance of this system is under study, and very promising results [6] have been obtained in running Level 1 tracking using stub input, as discussed in Section 4. Two different technologies are currently under consideration for this system; FPGAs and associative memory. A latency of around 10 μs is required for processing this track information at Level 1.

3.2 Upgrades to Other Systems

Due to radiation-induced signal loss incurred prior to the Phase 2 upgrade, the CMS forward calorimeter will be replaced [7]. Two concepts are currently under consideration for the upgraded forward calorimeter system. The first is a compact Pb/LYSO Shashlik Forward electromagnetic calorimeter with a scintillator-based hadronic calorimeter. The second is a silicon/lead/copper electromagentic and silicon/brass hadronic calorimeter, with a scintillator/brass backing calorimeter to measure the energy not captured in the hadronic calorimeter.

Several upgrades are planned for the Muon system. The forward region from $1.6 < |\eta| < 2.4$ will use Resistive Plate Chambers (RPCs) and Gas Electron Multipliers (GEMs) to provide higher levels of redundancy, and cope with higher rates. GEMs will also be used to provide a 'Very Forward' extension to the muon system. This extension is planned to cover the region

$2.4 < |\eta| < 3.0$ as a baseline, but this may be extended based on the eventual design of the forward calorimetry.

4 Reconstruction Performance and Pile-up Mitigation

The expected performance of the ATLAS and CMS Phase 2 detectors under HL-LHC pile-up conditions is currently under careful study, and such studies are also being used not only to establish the performance of the layouts, but also to further optimise the detector layouts and the reconstruction techniques used. An important first step is to establish that fundamental reconstruction quantities are well behaved and well understood, such as the tracking efficiency for isolated particles in the presence of pile-up, as shown in Figure 3.

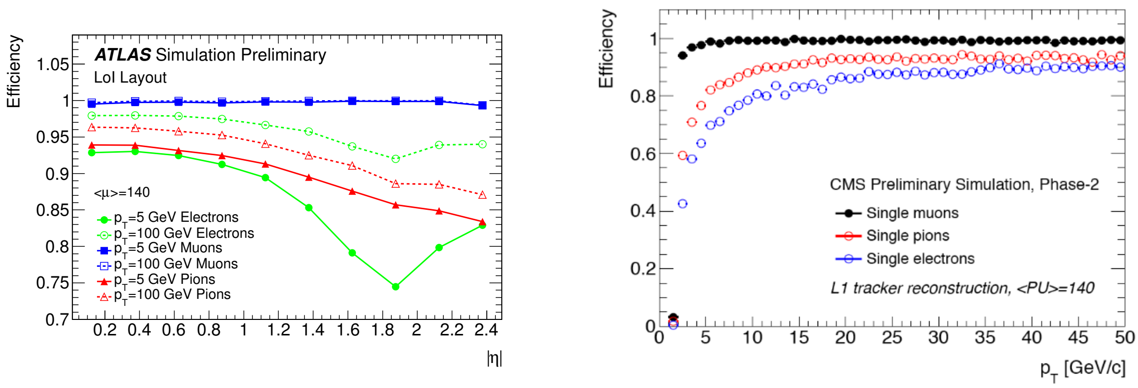

Figure 3 – Tracking efficiency for single particles with $<\mu>= 140$ for ATLAS ITK [3], as a function of η (left), and CMS Phase 2 Upgrade [6] using stub inputs, as a function of p_T (right)

Efficient and accurate reconstruction of primary vertices will be crucial for physics performance under HL-LHC conditions, and CMS have begun the process of optimising the algorithms used for vertexing for Phase 2 performance [8], as shown in Figure 4 (left), where the improved algorithm helps to recover vertex reconstruction efficiency at high pile-up. The vertexing performance achievable will depend on the precise beam spot dimensions provided by the HL-LHC machine, and ATLAS has studied the potential benefits of having a 'Long, Flat' beam spot (up to ± 15 cm in z) rather than a Gaussian beam spot with $\sigma_Z = 5$ cm (right) [9].

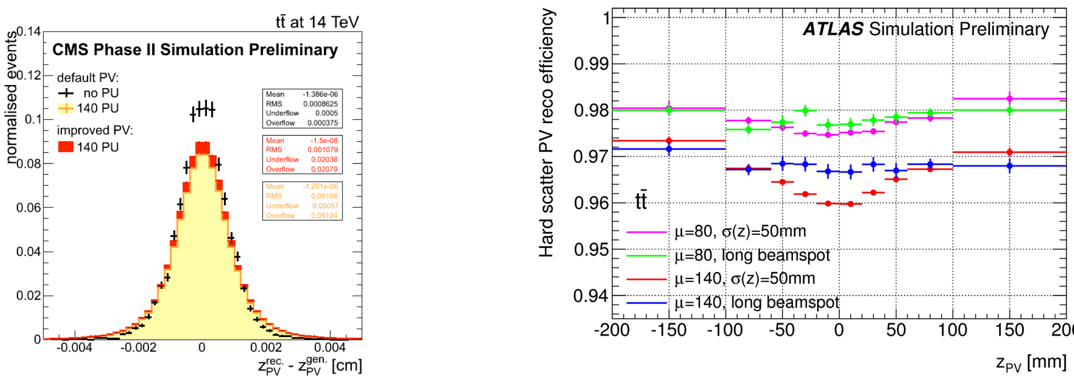

Figure 4 – CMS Primary Vertex reconstruction performance at $\mu = 0$ and $<\mu>= 140$, showing the effect of algorithmic improvements (left), and ATLAS Primary Vertex reconstruction efficiency as a function of vertex z position, for Gaussian and 'long' beamspots at $<\mu>= 80$ and $<\mu>= 140$ (right)

In addition to efficiently reconstructing physics objects, reliably identifying them will also be crucial for meeting the physics goals of the Phase 2 upgrades. Figure 5 shows the performance of b-tagging algorithms in distinguishing b-quark jets from light-quark jets, demonstrating the improved b-tagging performance of the upgraded CMS detector even under significantly higher pile-up (left), and the independence of the ATLAS b-tagging Phase 2 b-tagging performance on the beam spot profile, under the assumption that the correct primary vertex can be identified (right).

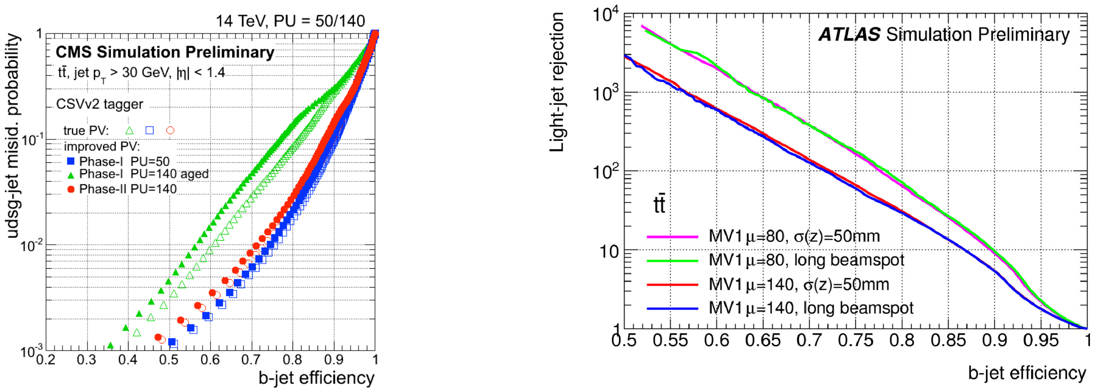

Figure 5 – Light-jet vs b-jet identification performance in simulated $t\bar{t}$ events for the CMS experiment for the Phase 1 and Phase 2 detectors under appropriate pile-up conditions, including detector aging effects and algorithmic improvements (left), and for the ATLAS Phase 2 detector with $<\mu>= 80$ and $<\mu>= 140$, with Gaussian and long beamspots, where the correct hard-scatter vertex has been selected using Monte Carlo Truth information (right)

Specific techniques are also in development for pile-up mitigation, allowing the effective discrimination of objects arising from interactions other than the hard-scatter of interest, which will be crucial for physics analyses of HL-LHC data. Pile-up jets can be effectively suppressed by application of 'Track Matching' criteria, requiring a reconstructed charged track highly compatible with the jet to be present in the event. Applying requirements on the 'Charged Fraction' (ratio of total p_T of associated tracks to the calibrated jet p_T) has also proved effective in reducing the contribution of pile-up jets within events.

Another powerful method for pile-up mitigation is the use of timing information [10], allowing significant improvements in matching photons to jets, tracks to vertices, and identification of merged jets. Effectively using such information would require improved time resolution with respect to the current detectors, with resolutions around ~ 50 ps being considered. Achieving this will require timing-specific detector elements to be included in the detectors, with a number of proposal for how to implement this under consideration [11]; among the possibilities are one or more timing layers embedded in the Electromagnetic calorimeter, a low-mass timing layer in front of the calorimeters, or a pre-shower timing layer.

5 Physics Potential of the Phase 2 Upgrades

In parallel to studies aimed at understanding and optimising detector layouts and event reconstruction, current results and assumptions for Phase 2 performance are being fed into physics analysis studies in order to establish the potential physics reach of the Phase 2 upgrades. Thanks to the huge dataset it will provide, the HL-LHC will allow ATLAS and CMS to reach unprecedented precision in measuring the properties of the Higgs Boson [12, 13], such as its couplings to other particles, particularly in the case where significantly improved theoretical uncertainties are available on the same timescale. It will also allow rare Standard Model processes, such as Higgs pair production, which offers a crucial handle for measuring the Higgs self-interaction, to be accessed [14].

The HL-LHC will also offer rich prospects in searches for Beyond the Standard Model physics, significantly increasing the discovery potential in many channels. As examples of a great many studies performed, that ATLAS has found searches for WIMP Dark Matter [15] using jets and large missing E_T can expect to have a discovery reach up to suppression scales of 2.6 TeV, and CMS has projected for $\chi_1^{\pm}\chi_2^0$ searches in the Wχ_1^0Hχ_1^0 channel with a final state of one lepton, 2 b-tagged jets and missing E_T, the mass reach ($m_{\chi_1^{\pm}} = m_{\chi_2^0}$) can be more than doubled [16].

6 Conclusions

The HL-LHC will provide huge physics potential for the ATLAS and CMS experiments, thanks to the unprecedented integrated luminosity it will provide for study. However, to make best use of this dataset the experiments will require significant upgrades. Both the ATLAS and CMS collaborations have comprehensive plans for upgrades to their detectors and reconstruction techniques, which are already projected to provide excellent performance under Phase 2 conditions. This work will be continued over the coming years to further improve the performance, resulting in an even greater physics reach to be attained.

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