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# Tracking, particle flow and muon performance at CMS and ATLAS

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A review of recent results and developments for the tracking, muon and particle flow performance of the CMS and ATLAS experiments is presented.

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## 1. Introduction

A precise and reliable reconstruction and identification of tracks and muons is of paramount importance for the success of the physics program of the CMS [1, 2] and ATLAS [3, 4] experiments. The high luminosity of the LHC, up to $2 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$ in existing datasets and up to $7 \cdot 10^{34}$ cm$^{-2}$s$^{-1}$ foreseen for the High Luminosity LHC (HL-LHC) program, represents one of the main challenges. The data collected in Run-2 of the LHC, the first data collected during the ongoing Run-3 and simulations for conditions expected at the HL-LHC are used to assess the performance of the reconstruction of tracks and muons and to develop new techniques more resilient to high luminosity levels. This includes also the development of Particle Flow (PFlow) techniques, which combine information from the various subdetectors of the experiments to provide a global reconstruction of events, with an optimized assignment of detector signals to physics objects.
These proceeedings provide an overview on recent results and developments for the performance of the tracking, muon and particle flow reconstruction of the ATLAS and CMS experiments.

## 2. Tracking performance

Tracks are reconstructed in the ATLAS and CMS experiments using information from their inner tracking systems, with detector hits used as track seeds, applying then a variety of pattern recognition techniques to create track candidates, proceeding with a track fit, followed by a final track selection. The high occupancy of detector hits due to the pileup is one of the main challenges of this reconstruction, which is extremely demanding from a computational point of view.
Results obtained on Run-3 data from the two collaborations show excellent performance of the tracking systems. Ref. [5] shows efficiencies above 99% and in very good agreement with expectations for the offline track reconstruction in ATLAS. Ref. [6] presents trigger-level track performance for CMS, with efficiencies of about 80% obtained with respect to offline reconstruction.
One important area of development for the experiments is towards possible signature of new physics resulting in long-lived particles, producing displaced tracks, which present a more challenging reconstruction due to the removal of the $pp$ interaction vertex constraint. CMS presents in Ref. [7] a calibration of the fake rate for displaced tracks performed using $K_s^0 \to \pi^\pm\pi^\mp$ decays, finding good agreement with expectations. In Ref. [8] a performance study on displaced track reconstruction efficiency and fake rate (see Figure 1) on ATLAS Run-2 data is discussed. For Run-3 ATLAS underwent a major overhaul of the track and muon reconstruction [9], with an improved rejection of fake tracks and muons at early stage of the reconstruction and the implementation of multi-threading, resulting in a speed improvement of a factor 2-4 of the algorithms, freeing the resources for a full inclusion of displaced tracks in the standard ATLAS reconstruction.
For HL-LHC a pileup of up to 200 $pp$ collisions per event is expected. ATLAS presents in Ref. [10] studies on the expected performance of the new full-silicon tracker to be installed for the HL-LHC, showing a significantly improved resilience against pileup of the track reconstruction for the new detector compared to the present one. CMS shows in Ref. [11] that tracking performance at trigger level can be significantly improved in high pileup conditions by usage of dedicated algorithms and of heterogeneous computing exploiting parallelization on GPUs, as shown in Figure 1. Both collaborations are also exploring Machine Learning (ML) techniques for track reconstruction in dense

environments. This is discussed in Ref. [12], where CMS presents a new algorithm with improved efficiency and reduced computational footprint for track reconstruction within highly energetic jets, based on a Convolutional Neural Network algorithm. In Ref. [13] ATLAS presents a proof of concept study of a pattern recognition algorithm based on a Graph Neural Network algorithm.

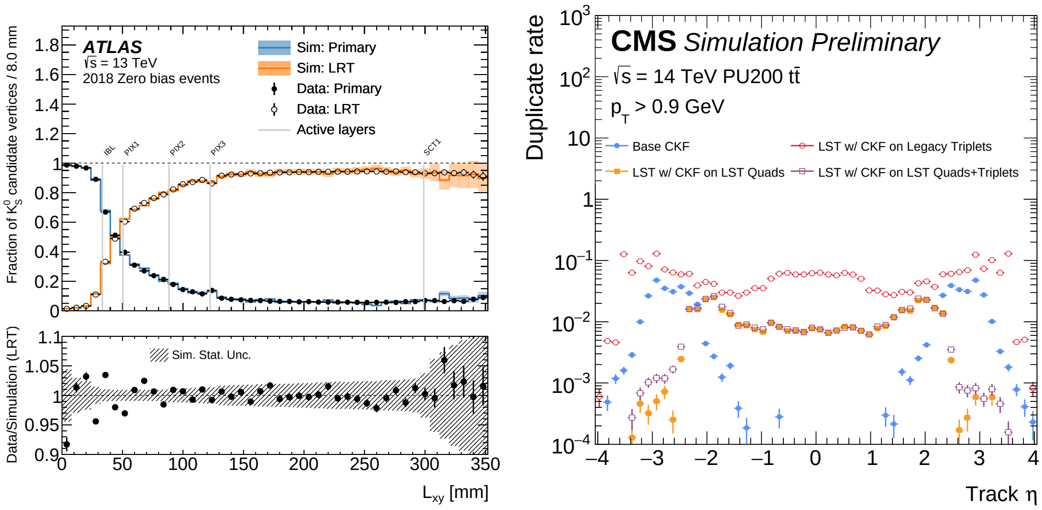


**Figure 1:** (Left) calibration of the ATLAS reconstruction of $K^0_s \to \pi^{\pm}\pi^{\mp}$ vertices using Run-2 data for the standard (blue) and displaced (orange) track reconstruction strategies [8]. (Right) duplicate rate of the CMS trigger-level track reconstruction expected at the HL-LHC for the baseline Combinatorial Kalman Filter reconstruction (CKF) and for different configurations of the new Line Segment Tracking algorithm (LST), designed for heterogeneous computing resources [11]; a proper combination of the different techniques in different regions of the detector will provide the optimal performance.

## 3. Muon performance

Muon reconstruction is performed using separately the inner tracking and muon spectrometer systems, after which in most cases a combined track is produced, with alternative strategies used to recover efficiencies at low momentum or in regions of the detectors with reduced acceptance. Calorimeter information is usually included in the reconstruction. Muon candidates are then selected applying Working Points (WPs) corresponding to sets of quality cuts. Isolation criteria are applied to select prompt muons by cutting on energy deposits and/or tracks around the muon. The momentum measurement can combine information from various subdetectors in different ways, and both experiments have a variety of stratiegies dedicated to different use cases. The calibration of muon performance in data is usually performed using di-muon decays of resonances ($J/\Psi$, $\Upsilon$, $Z$). CMS released sets of detailed studies for Run-3 in Ref. [14, 15] for muon reconstruction, identification and isolation performance, evaluated for WPs optimised for different use cases. The calibration of a WP dedicated to highly energetic muons has been performed using a sample of Drell-Yan events for transverse momenta up to 1 TeV. The efficiency of the CMS muon trigger as measured in $Z \to \mu\mu$ events collected in Run-3, as a function of muon kinematics and pileup levels, is presented in Ref. [16], proving stable performance during data taking and a relatively small dependency of

trigger performance on pileup.
Ref. [17] presents a sets of efficiency and momentum calibration studies for the ATLAS experiment using Run-3 data (see Figure 2). Performance are found to be in good agreement with expectations, in particular for 2023 data which fully includes the new detectors installed in the forward region of the spectrometer for Run-3, after the commissioning performed in 2022. A more dedicated study on the performance of the newly installed detectors is presented in Ref. [18]. A set of preliminary results have been presented by ATLAS also for the alignment of the muon detector using a special dataset collected with the toroidal magnet turned off in 2023 [19].
A further area of development is the application of ML techniques for muon identification and isolation. In Ref. [20] CMS presents a random forest algorithm designed to reject muons from light hadron decays or misreconstructed tracks, and a classifier based on a boosted decision tree aiming at selecting isolated muons, e.g from $W, Z$ boson decays. Both algorithms outperform cut-based WPs and are calibrated in data, with good agreement with predictions. ATLAS presents in Ref. [21] a preliminary study for an algorithm based on a multi-task transformer architecture designed to select isolated muons, showing also in this case better performance than cut-based approaches.

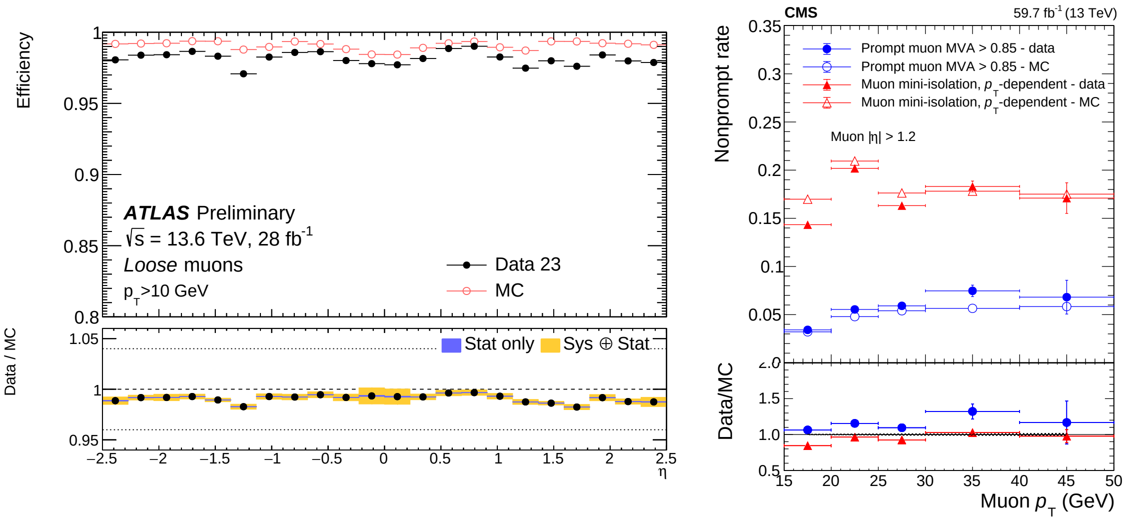


**Figure 2:** (Left) efficiency measured in $Z \rightarrow \mu\mu$ events on data collected in 2023 by the ATLAS experiment [17] ; the efficiency is very high and at per-cent level agreement with predictions; this is particularly interesting in the $|\eta| > 1.3$ region, where the muon spectrometer was upgraded with new detectors, that were commissioned during 2022. (Right) efficiencies measured on the background of non-prompt muons for a cut-based (red) and multivariate (MVA, blue) algorithm on data collected in Run-2 by the CMS collaboration [20]; the background can be significantly better rejected by the MVA algorithm.

## 4. Particle flow performance

PFlow algorithms aim at a global event reconstruction by unambiguously assigning signals in all subdetectors to individual particles: electrons, muons, neutral hadrons, charged hadrons and so on. In ATLAS at the moment PFlow algorithms are mostly used for jet reconstruction and for lepton isolation [22], while CMS makes a more extensive usage of PFlow techniques, with a full global event reconstruction [23]. Development of PFlow techniques clearly can benefit from

ML, which can optimize usage of a large number of information and properly evaluate correlations among observables. An example is presented by ATLAS in Ref. [24], which studies different ML architectures for distinguishing and properly calibrating charged pion deposits in calorimeters from those associated with neutral pions (see Figure 3). CMS presents in Ref. [25] an approach based on graph neural networks for the global event reconstruction, also aiming at optimization of performance on heterogeneous computing resources, exploiting parallelization on GPUs. An optimal usage of computing resources and the usage of GPUs can significantly improve performance, in particular for trigger algorithms. In Ref. [26] CMS presents a study for PFlow reconstruction at trigger level using a heterogeneous computing architecture, which shows significant improvements with respect to fully CPU-based architectures (see Figure 3).
PFlow techniques are expected to be more and more widely used by the ATLAS and CMS collaborations, and they will be able to exploit also the detectors upgrade for the HL-LHC program, that will involve installation of several subdetectors providing precise timing information, in order to more efficiently reject pileup contributions to events. These upgrades will allow for significant improvements in PFlow techniques.

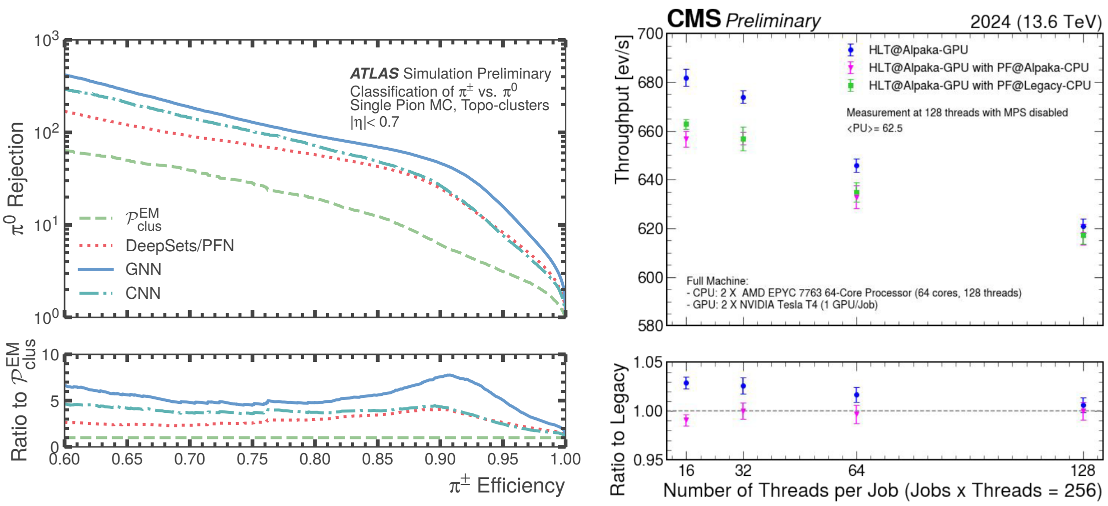


**Figure 3:** (Left) comparison of different ML architectures on simulation for the separation of charged pions energy deposits from those of neutral pions in ATLAS calorimeters [24]. (Right) comparison of the throughput of trigger-level PFlow reconstruction for CPU-based (green, pink) and GPU-based (blue) architectures as a function of the number of threads per job [26].

## 5. Conclusion

Recent results from the CMS and ATLAS collaborations in the context of tracking, muon and PFlow performance have been reviewed. Measurements show very good performance on the ongoing Run-3 data taking campaign. Work is in progress in many areas to improve reconstruction performance, in particular in view of the HL-LHC campaign. A wider usage of ML techniques, an optimized usage of computing resources, exploring parallelization on GPUs in heterogeneous architectures, and more global approaches to event reconstruction with PFlow techniques to fully exploit the detectors, will allow for significantly improving the reconstruction performance on existing and future datasets for the two experiments.

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