PROCEEDINGS OF SCIENCE

Run 3 performance of new hardware in ALICE

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ALICE (A Large Ion Collider Experiment), an experiment optimized for the study of heavy-ion physics at the Large Hadron Collider (LHC), has delivered a wealth of important physics results during Runs 1 and 2 of the LHC. In order to profit from LHC luminosity increases and advancements in detector technology, the ALICE experiment underwent a major upgrade during LHC Long Shutdown 2 (2019–2022). This includes a comprehensive upgrade to the core detectors and a new event processing infrastructure with a redesigned online–offline software framework. These improvements enable the recording of Pb–Pb collisions at interaction rates of up to 50 kHz with a continuous readout.

ALICE has been operational and collecting data since the start of LHC Run 3 on July 5$^{\text{th}}$, 2022. In this paper, the ALICE upgrade during the Long Shutdown 2 will be described briefly. Preliminary performance results of the upgraded detectors from the first phase of proton–proton and Pb–Pb collisions in the LHC Run 3 will be discussed in detail.

The Eleventh Annual Conference on Large Hadron Collider Physics (LHCP2023)
22-26 May 2023
Belgrade, Serbia

[*] Speaker

https://pos.sissa.it/

PoS(LHCP2023)052

1. Introduction

ALICE [1] is a general-purpose detector with a focus on heavy-ion physics at the LHC, aiming to explore the physics of quark–gluon plasma and the behavior of strongly interacting matter under exceptionally high energy densities through various collision processes involving nuclei and protons.

ALICE is designed to reconstruct tracks in the high signal density environment produced in central Pb–Pb collisions and to identify charged particles across a wide range of transverse momenta. The data gathered during LHC Run 1 and 2 have yielded valuable scientific results [1]. The main physics objectives, detailed in [2], require an increase in the available data sample for measurements of signals with small signal over background ratios, as well as a significant improvement of vertexing and tracking capabilities at low transverse momentum. Following the LHC Long Shutdown 2 (LS2), ALICE is required to operate at an instantaneous luminosity of 6×10^{27} cm^{-2}s^{-1}, corresponding to a minimum-bias interaction rate for Pb–Pb collisions of approximately 50 kHz. This rate significantly exceeds the detector's operational specifications during Run 1 and 2. Substantial upgrades [3] to ALICE were made during LS2, which have broadened its physics capabilities, particularly improving tracking precision and efficiency at low transverse momentum. Details regarding the upgrades can be found in Section 2. The performance results for the upgraded detector are discussed in Section 3.

2. Upgrades during LS2

The upgrades to the ALICE experiment encompass a range of new and improved components. A new beam pipe with a smaller radius was installed to allow the placement of tracking detectors closer to the collision point. Most of the ALICE detectors have been modified to support continuous readout, while the few detector systems not upgraded for continuous readout employ a minimum-bias trigger to initiate readouts. Consequently, the Central Trigger System [4] was upgraded to support both continuous and triggered readout modes, catering to different detectors. The Fast Interaction Trigger (FIT) [5] detectors were upgraded to enhance the triggering capabilities. The FIT is capable of precisely measuring collision times, determining global collision parameters, such as centrality and event plane for heavy-ion collisions, providing vetoes for ultra-peripheral, electromagnetic and diffractive interactions, and luminosity monitoring. A high-resolution, low-material Inner Tracking System, called ITS2 [6], was constructed based on the monolithic active pixel sensor technology, with a pixel sensor known as the ALice PIxel DEtector (ALPIDE) [7]. This offers a significant improvement in tracking precision and efficiency at low transverse momentum. A new Muon Forward Tracker (MFT) [8], utilizing the same pixel sensors as ITS2, was installed to enhance the vertexing capabilities of the existing muon spectrometer. The readout technology of the Time Projection Chamber (TPC) [9] was updated from multi-wire proportional chamber to the more advanced gas electron multiplier (GEM) detectors. This transition facilitated continuous readout, accommodating an interaction rate of 50 kHz in Pb–Pb collisions with an acceptable pile-up rate.

Significant enhancements were made to the online–offline (O^2) [10] computing infrastructure. The O^2 system consists of two main distributed computing clusters: the First Level Processors (FLPs) and the Event Processing Nodes (EPNs). The FLPs are designed to handle the high data throughput directly from detectors and provide a first level of data compression. The EPNs receive data from the FLPs and perform extensive data compression, detector calibration and event

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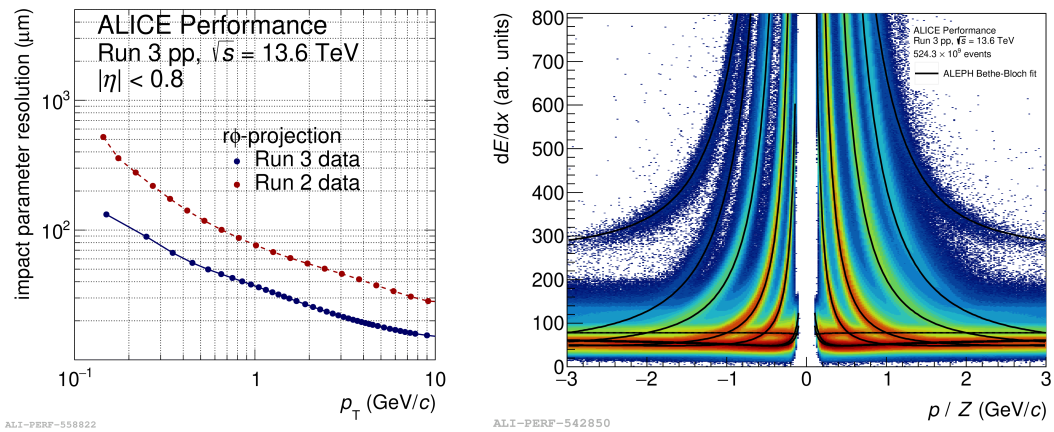
reconstruction through the use of graphics processing units. The initial data rates in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.36 TeV with an interaction rate of 47 kHz were successfully reduced from 3.4 TB/s to 770 GB/s on the FLPs and subsequently further compressed to 170 GB/s following the synchronous event reconstruction process on the EPNs.

3. Performance of the upgraded detectors

Since the beginning of Run 3, the ALICE detectors have been actively collecting physics data in pp collisions at $\sqrt{s}$ = 13.6 TeV mostly with a 650 kHz inelastic interaction rate and in Pb–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.36 TeV with a peak interaction rate of 47 kHz. In the first two years of Run 3, the total collected data amounted to 29 pb^{-1} for pp and 1.5 nb^{-1} for Pb–Pb collisions.

The FIT detectors employ a combination of timing, charge, and vertex positioning criteria to effectively discriminate against background noise when they monitor the luminosity and generate the minimum-bias trigger signal. Specifically, the FT0, a component of the FIT system, has exhibited a time resolution of 9 ps for Pb–Pb collisions and 18 ps for pp collisions. The FT0 vertex position also shows a good correlation with the primary vertex reconstructed by the central tracking detectors. Improvements in FIT performance are expected through updated calibrations and improved reconstruction algorithms.



(a) Impact parameter resolution **(b)** dE/dx measured with the TPC

Figure 1: Impact parameter resolution and PID in pp collisions at $\sqrt{s}$ = 13.6 TeV. (a) Impact parameter resolution in $r\phi$ plane based on ITS–TPC global tracks. (b) PID in TPC with 524.3 billion events. The bands corresponding to individual particle species have been fitted to a Bethe–Bloch parametrization.

The ITS2 is a key component for collision vertexing and tracking and has been operational since the beginning of Run 3. It consists of 24120 ALPIDE sensors with a total of 12.6 billion pixels. The calibration of such a complex system is therefore challenging. Initially, the pixel charge threshold is tuned to the targeted value of 100 electrons. This is followed by a dedicated noisy pixel masking. As a result, the detector achieves a very uniform threshold distribution and shows an extremely low fake detection rate of about 10^{-8} hits/event/pixel. A comparable performance is also observed in the MFT with respect to the threshold adjustment and the number of noisy

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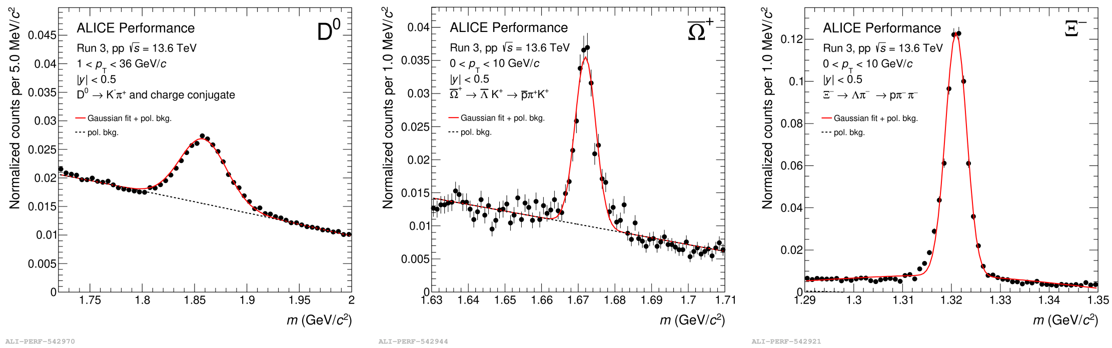
pixels. The impact parameter resolution of the reconstructed global tracks in pp collisions, i.e., ITS standalone tracks matched with tracks reconstructed in the TPC, is shown in Fig. 1a. There is a factor-2.5 improvement in the $r\phi$ plane compared to the Run 2 result, which is already close to the expected value. The remaining discrepancy of about 20% between data and Monte Carlo simulation is attributed to the use of unoptimized corrections of spatial distortions in the TPC and the residual misalignment.

The TPC is the main detector for tracking and charged-particle identification (PID) in ALICE. To enhance its capabilities, a specific configuration of the GEM stacks was adopted to minimize ion backflow to under 1% and a sophisticated calibration approach was developed to preserve its intrinsic tracking performance. Figure 1b shows the observed specific energy loss ($\mathrm{d}E/\mathrm{d}x$) as a function of the particle momentum per unit charge in TPC, illustrating the distinct separation among various particle types.

By analyzing data from pp interactions, the invariant mass of a selection of typical particles has been successfully reconstructed. The peaks for D^0, $\overline{\Omega}^+$ and Ξ^- are prominent, as shown in Fig. 2, indicating that the performance of the detectors is robust. A significant improvement in the invariant-mass resolution is expected with further optimizations of the reconstruction processes and updated TPC calibrations.



(a) D^0 (b) $\overline{\Omega}^+$ (c) Ξ^-

Figure 2: Invariant mass distributions for D^0, $\overline{\Omega}^+$ and Ξ^-.

4. Summary

Major upgrades to ALICE were successfully completed during LHC LS2, leading to enhanced performance in LHC Run 3. Improvements in detectors and O^2 infrastructure have enabled continuous readout, as wel as refinements in track reconstruction, vertexing, and PID, yielding unprecedented data sample after the first two years of operation in Run 3. Preliminary results from Run 3 show promising reconstruction performance, and further enhancements are expected with optimized track reconstruction processes and updated detector calibrations.

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