Published by IOP Publishing for Sissa Medialab

Received: *October 6, 2023*
Revised: *November 21, 2023*
Accepted: *December 29, 2023*
Published: *February 1, 2024*

24TH International Workshop on Radiation Imaging Detectors
Oslo, Norway
25–29 June 2023

First results of the upgraded ALICE Inner Tracking System in LHC Run 3

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Abstract: Major upgrades of the ALICE experiment at CERN were completed during the LHC Long Shutdown 2 (2019–2021). The ALICE detector is currently taking data and has been doing so from the start of the third period of operation of the LHC (Run 3) on July 5th, 2022. One key part of these upgrades is the new Inner Tracking System (ITS2), a full silicon-pixel vertexing and tracking detector constructed entirely with CMOS monolithic active pixel sensors (ALPIDE). The ITS2 consists of three inner layers (50 µm thick sensors) and four outer layers (100 µm thick sensors) covering $10\,\mathrm{m}^2$ and containing 12.5 billion pixels with a pixel pitch of $27\,\mu\mathrm{m} \times 29\,\mu\mathrm{m}$. It offers a significant improvement in impact-parameter resolution and tracking efficiency, thanks to the increased granularity, the very low material budget ($0.35\%\ X_0$/layer in the inner barrel) as well as a smaller beam pipe radius. The ITS2 was successfully installed in the ALICE experiment in May 2021, followed by a period of comprehensive on-site commissioning, before starting data taking in July 2022. In this paper, the detector construction and commissioning will be introduced briefly. The performance results from the first phase of proton-proton collisions recorded to date in LHC Run 3 will be discussed in detail, which include detector calibration, long-term evolution of the ALPIDE sensor threshold and noise, and the first measurement of the impact parameter.

Keywords: Large detector systems for particle and astroparticle physics; Large detector-systems performance; Particle tracking detectors (Solid-state detectors); Performance of High Energy Physics Detectors

https://doi.org/10.1088/1748-0221/19/02/C02002

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1 Introduction

ALICE [1] (A Large Ion Collider Experiment) is a versatile detector designed for heavy-ion physics studies at the Large Hadron Collider (LHC). Its primary objective is to investigate the properties of the quark–gluon plasma and strongly interacting matter at extreme energy densities by analyzing collisions involving nucleus–nucleus, proton–proton, and proton–nucleus.

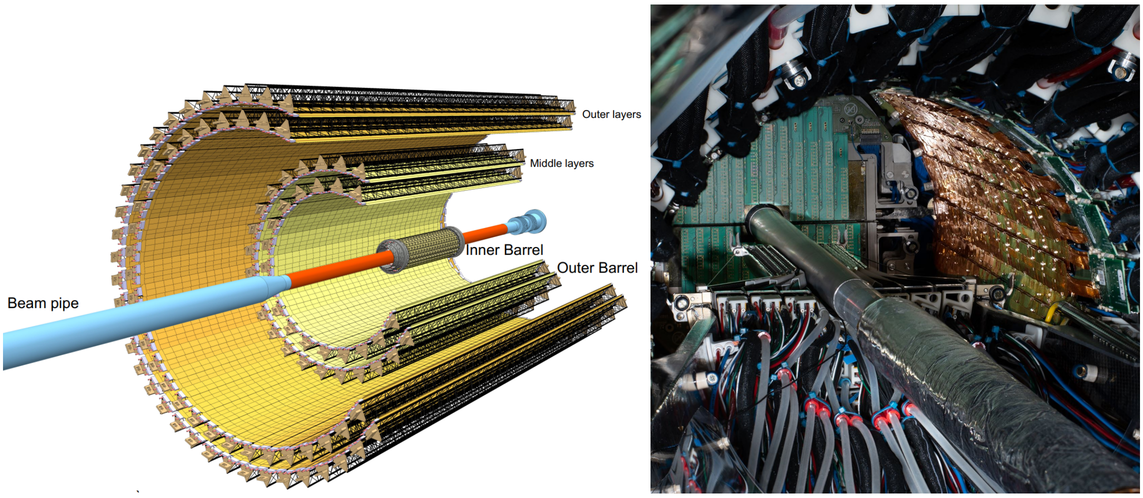
The ALICE is dedicated to reconstructing tracks with a high multiplicity in central Pb–Pb collisions and providing particle identification over a wide transverse momentum range. Fruitful research outcomes have been attained based on the data acquired in the LHC Run 1 and 2 [2]. Major upgrades [3, 4] of the ALICE were completed during the LHC Long Shutdown 2 (2019–2021) to extend its physics capabilities with a significant improvement in tracking precision and efficiency at low transverse momentum.

The new Inner Tracking System, called ITS2, is one of the key upgrades during the Long Shutdown 2, offering a significant improvement in impact parameter resolution and tracking efficiency. Details regarding the detector's design, construction, and commissioning can be found in section 2. The detector calibration and performance results in the first phase of LHC Run 3 are discussed in section 3 and 4, respectively.

2 ITS upgrade and commissioning

The ITS2 [5] is a cylindrical silicon pixel detector consisting of 7 layers as depicted in figure 1(a). The detector is divided into two main sections: the inner barrel (IB), which comprises the three innermost layers, and the outer barrel (OB), organized into two sets of double layers: middle layers and outer layers.

The ITS2 is based on the Monolithic Active Pixel Sensor (MAPS) technology and the pixel sensor is known as ALice PIxel DEtector (ALPIDE) [6] covering about 10 m^2 area. The ALPIDE sensor was fabricated with a TowerJazz 180 nm CMOS technology for imaging sensors with a high-resistivity of 1 $\mathrm{k\Omega \cdot cm}$ p-type epitaxial layer over a p-type substrate. The sensor dimension measures approximately 1.5 cm × 3 cm, and it is comprised of a total of 512×1024 pixels with a pixel pitch of 27 μm and 29 μm along the row and column direction providing an impressive spatial resolution of approximately 5 μm × 5 μm. The readout of frame data from the matrix is zero-suppressed and this is accomplished by using an array of circuits known as priority encoders. The data can be read out in serial with



(a) ITS2 layout (b) Detector install

Figure 1. ITS2 layout and detector installation. (a) IB: 3 inner layers. OB: 2 middle layers and 2 outer layers. (b) OB and half-IB were installed in the ALICE experiment.

differential signaling up to 1.2 Gbps. The data transmission uses 8b/10b encoding, which results in a maximum data throughput of 960 Mbps. It has demonstrated a radiation tolerance of 500 kRad (190% of the lifetime dose, including a combined fluence that is 3.2 times the lifetime fluence) for total ionizing dose and 1.7×10^{13} $1\,\text{MeV}/n_{\text{eq}}$ (1 MeV neutron equivalent fluence) for non-ionizing energy loss, corresponding to ten times the fluence expected over the full detector lifetime. The sensors are glued onto an aluminum-based flexible printed circuit to form a Hybrid Integrated Circuit (HIC). The HICs are then glued onto a carbon cold plate and a space frame to complete a stave. Thanks to the thinner pixel sensor design (50 µm for IB and 100 µm) and lightweight mechanical supports, ITS2 achieves a notable reduction in material budget, especially in the inner barrel (IB), decreasing its contribution to the total radiation length from 1.14% X_0 to 0.36% X_0, where X_0 denotes the radiation length. The geometrical parameters of the ITS2 are listed in table 1, which are optimized to achieve the best performance in terms of pointing resolution, and tracking efficiency in Pb–Pb collisions.

Table 1. ITS2 geometrical parameters.

Layer Number	Radius (mm)	Stave length (mm)	Number of staves	Number of HICs per stave	Number of chips per HIC	Total number of chips
0	23	271	12	1	9	108
1	31	271	16	1	9	144
2	39	271	20	1	9	180
3	196	844	24	8	14	2688
4	245	844	30	8	14	3360
5	344	1478	42	14	14	8232
6	393	1478	48	14	14	9408

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The detector construction was successfully completed in 2019. The commissioning of ITS2 primarily consists of two main stages: the initial on-surface commissioning conducted in a dedicated cleanroom at CERN and the subsequent on-site commissioning within the ALICE experiment. The on-surface commissioning phase commenced in July 2019 and successfully concluded in December 2020. Following this, the detector was relocated and installed within the ALICE experiment in May 2021. The final commissioning of the detector, in coordination with other detectors in the ALICE experiment, was carried out during the period from July 2021 to June 2022. The long-term stability of the detector, detector fake-hit rate, charge threshold uniformity, detection efficiency, and pre-alignment were validated during the commissioning phases [7] by means of powering tests, fake-hit rate and threshold scans, dedicated cosmic-ray runs, and the LHC pilot pp collisions at a center-of-mass energy of $\sqrt{s} = 900\,\text{GeV}$.

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3 Detector calibration

The calibration of the ITS2 involves two main procedures: pixel charge threshold tuning and noisy pixel masking. These calibration steps are crucial to ensure the uniformity of the detector response and the tracking efficiency during physics data collection.

The threshold value of each ALPIDE sensor can be adjusted globally by tuning two on-chip Digital-to-Analog Converters (DACs). A test pulse ranging around the target threshold is injected into the pixel matrix to tune the DAC values and to find out the DAC settings which adjust the threshold to match the target value. After this threshold tuning, the threshold scans involving about 2% pixels per chip lasting about 5 minutes are carried out to monitor and confirm the threshold distribution across the entire detector during the LHC beam dump periods. The threshold scan with full pixel matrix can be performed during longer no-beam time, such as LHC technical stops. The threshold distribution for all the 24120 sensors of ITS2 after tuning to 100 electrons is shown in figure 2. One can see that the pixel charge threshold for all the sensors is well tuned to the target value of 100 electrons. The equivalent noise charge measured from the threshold scan is about 5 electrons, which is consistent with the result obtained during the detector production phase. The variations of the average threshold for each detector layer as a function of time in shown in figure 3. In the first phase of Run 3, a very good pixel threshold stability is observed, with variations below 10 electrons as shown in the plot.

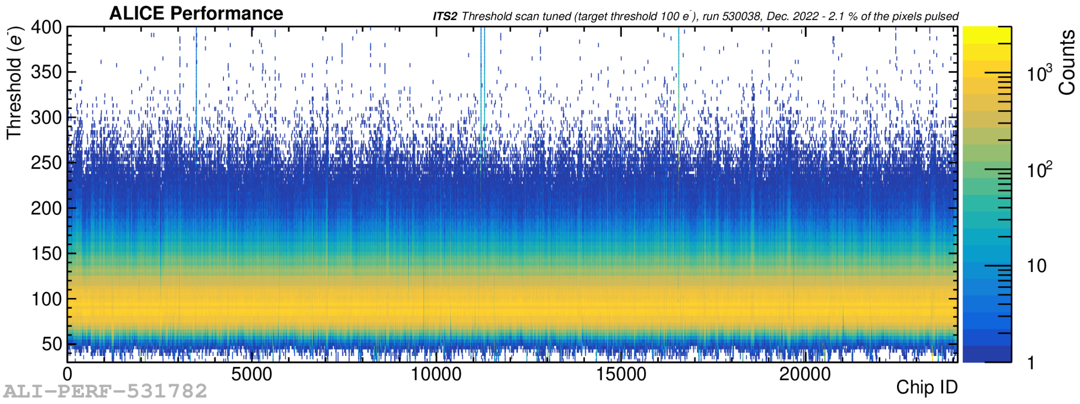

Figure 2. ITS2 threshold distributions of 2% pixels for each chip after tuning to a target value of 100 electrons.

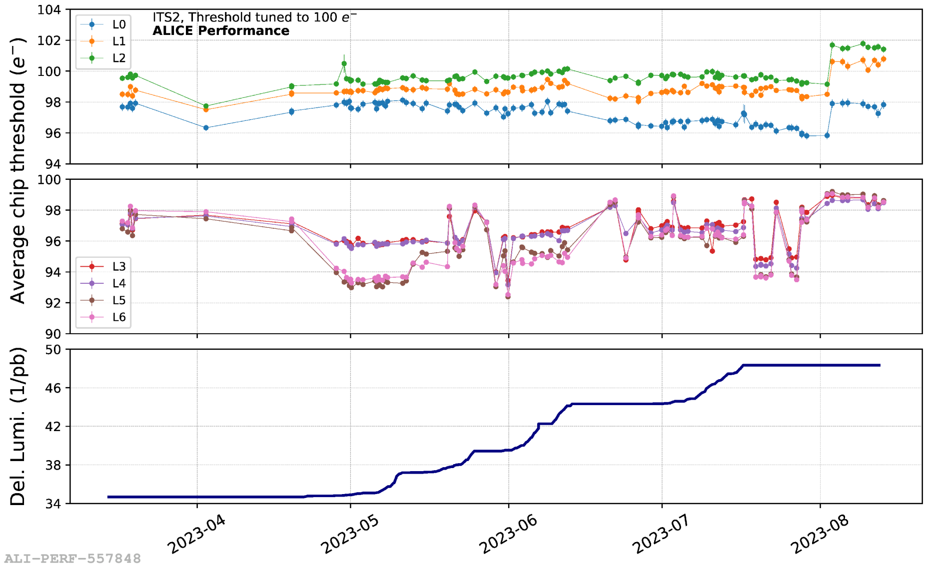

Figure 3. Threshold stability. Top figure: the three layers for IB. Middle figure: the four layers for OB. Bottom figure: delivered luminosity. The variations in late May and July on OB, and in early August on the whole detector were due to slightly optimized power supply voltages to the ALPIDE sensors.

A dedicated noise calibration scan aiming to spot and mask noisy pixels is then carried out after a successful pixel threshold calibration. The pixels with an occupancy greater than 10^{-2} and 10^{-6} hits/event for IB and OB, respectively, are flagged as noisy and masked in data taking. The looser criterion for IB is set in order to fully exploit the detector in terms of detection efficiency while the readout bandwidth and reconstruction load are affordable. The fraction of masked pixels for each stave is shown in figure 4. Only a few tens of pixels per chip are masked at the nominal threshold of 100 electrons resulting in a fake-hit rate (FHR) of about 10^{-8} hits/event/pixel, which is well below the required value of 10^{-6} hits/event/pixel. The sensor FHR and the number of noisy pixels are continuously monitored through dedicated cosmic-ray runs in the absence of beam activity in the LHC. The average FHR for each detector layer as a function of time measured in 2022 is shown in figure 5. There are no obvious variations in the FHR and noisy pixel addresses with accumulated

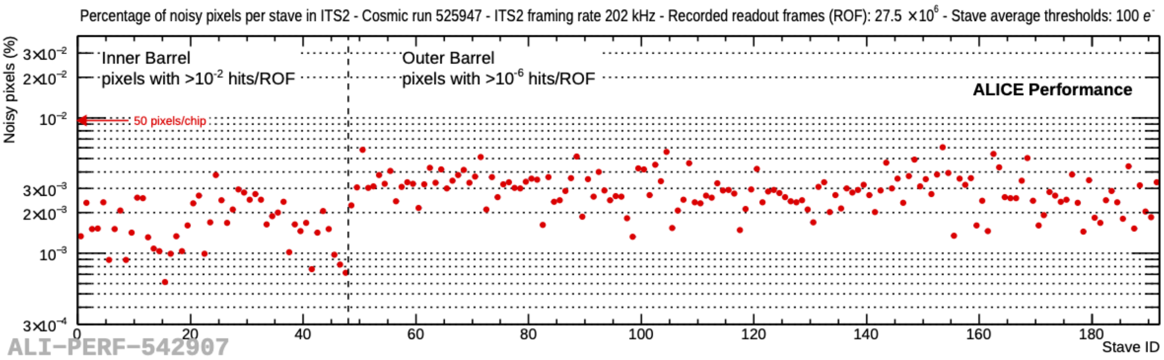

Figure 4. Fraction of masked pixels when the threshold is tuned to 100 electrons. Only a few tens of pixels are masked for each stave, about 0.015% in total.

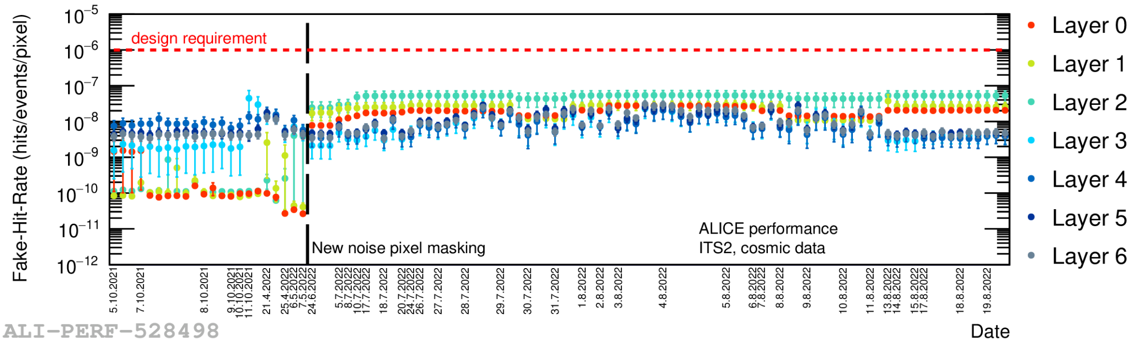

Figure 5. Average FHR for each layer as a function of time in 2022. Very stable FHR over time across the whole detector and extremely low noise level after masking the noisy pixels.

radiation exposure so far in Run 3. Consequently, the detector can be operated with the static noisy pixel masks in place, without requiring detector recalibration during a run.

4 Detector performance

The LHC Run 3 officially started with the first proton physics fill on July 5th, 2022. Since the beginning of Run 3, the ITS2 has been actively collecting physics data, maintaining nominal continuous readout rates of 202 kHz for pp collisions at $\sqrt{s}$ = 13.6 TeV with a 650 kHz inelastic interaction rate (INEL) in 2022 and 2023, and 45 kHz for the Pb–Pb pilot beam test at a center-of-mass energy per nucleon pairs of $\sqrt{s_{NN}}$ = 5.36 TeV with a very low interaction rate of about 40 Hz in November 2022. Apart from the production pp physics data taking at 650 kHz INEL, the detector was tested up to 5 MHz INEL to stress the detector readout system and consolidate the data processing chain in preparation for the first heavy-ion run in the Run 3 scheduled to be started in September 2023.

Comprehensive investigations have been conducted on the detector's FHR, noisy pixel, pixel charge threshold, and alignment in both the detector commissioning, as described in section 2 and 3, and physics data-taking phases to achieve the best performance of the detector. The detector data quality and performance are monitored in real-time relying on the synchronous quality control (QC) software modules [8], and studied carefully in the asynchronous data reconstruction. Throughout the first phase of Run 3, the detector's performance parameters, such as cluster occupancy, cluster size, impact parameter, and tracking efficiency, have been continually studied.

The pixel cluster occupancy and size were studied based on the data taken with pp collisions at $\sqrt{s}$ = 13.6 TeV in 2022. The average cluster occupancy, namely the number of fired clusters per readout frame, and its variation with different interaction rates (IRs) and the comparison with Monte Carlo (MC) simulation can be seen in figure 6. The average cluster occupancy ranges from 0.1 to 10 depending on the position with respect to the interaction point and the pseudo-rapidity, η. The occupancy is strongly dependent on the IR and agrees with the MC simulation result. The average cluster size and the dependence of IRs are shown in figure 7. The average size is between 3 and 8 and shows a very strong correlation with η. The dependence on IRs is much less significant compared with cluster occupancy. The modest correlation between cluster size and IR can be attributed to the observation that at lower interaction rates, noise hits become similar in number to the actual physics hits, thus leading to a reduction in cluster size as a result. The same trend can be reproduced in

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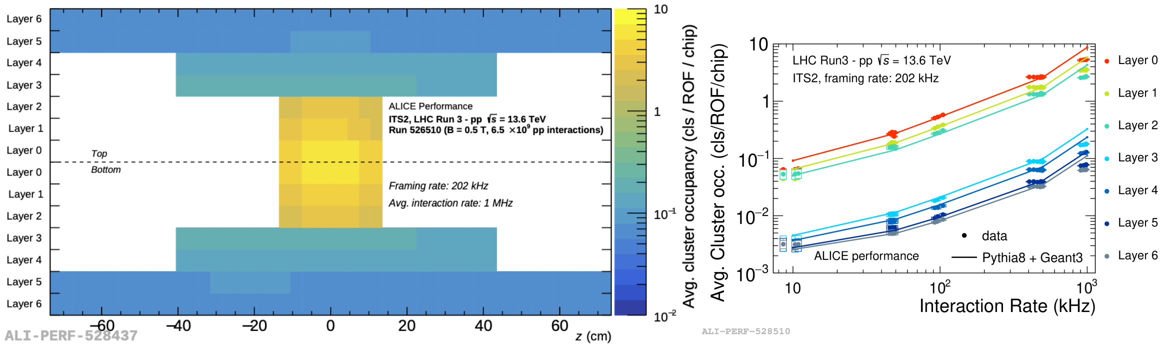
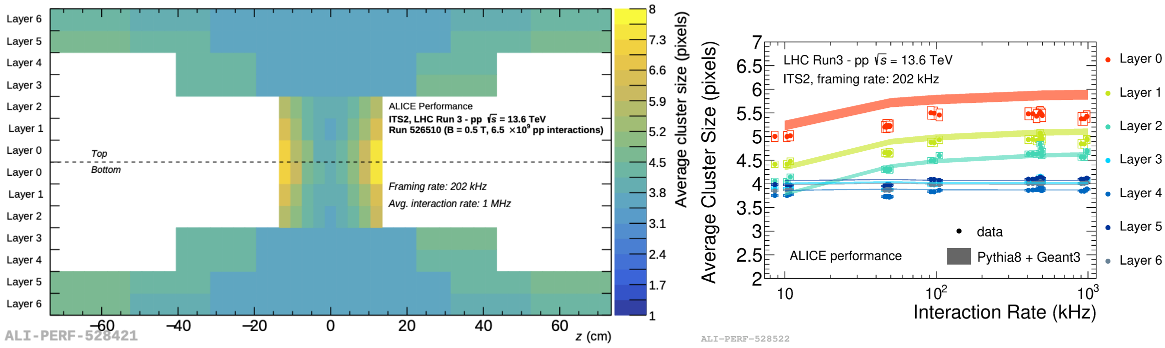


(a) Cluster occupancy

(b) Cluster occupancy as a function of IR

Figure 6. Cluster occupancy. (a) The average cluster occupancy for each chip (HIC) on IB (OB) in pp collisions at $\sqrt{s}$ = 13.6 TeV with an IR at 1 MHz (equivalent to 1.4 MHz INEL). (b) The measured cluster occupancy and MC simulation based on Pythia8 and Geant3 as a function of the IR.



(a) Cluster size

(b) Cluster size as a function of IR

Figure 7. Cluster size. (a) The average cluster size for each chip (HIC) on IB (OB) in pp collisions at $\sqrt{s}$ = 13.6 TeV with an IR at 1 MHz (equivalent to 1.4 MHz INEL). (b) The measured cluster size and MC simulation based on Pythia8 and Geant3 as a function of the IR.

MC simulations. There is a small discrepancy between the measured cluster size and the simulation results, which can be mainly explained by taking into account that only an average value per barrel is considered instead of a single-chip one when estimating the noise in the simulation.

Another key parameter to evaluate the detector performance is the tracks impact parameter. The impact parameter of a track is determined as the closest distance between the track's extrapolated path and the position of the reconstructed interaction vertex. Accurate measurement of the track's impact parameter holds significant importance in the analysis of physics signals, particularly when dealing with scenarios featuring a secondary vertex located in close proximity to the interaction vertex. The impact parameter resolution is influenced by the material budget, primarily due to multiple scattering effects on low p_{T} particles, as well as the intrinsic pointing resolution of the pixel sensor. The impact parameter of the reconstructed global tracks, i.e., tracks matched with the tracklets reconstructed from the Time-Projection Chamber (TPC), is shown in figure 8. Compared with results from Run 2, there is a 2.5 times improvement in $r\phi$ plane, which is already close to the expected value. The remaining discrepancy of about 20% from MC simulation is attributed to the non-optimal TPC space-charge distortions and the residual misalignment.

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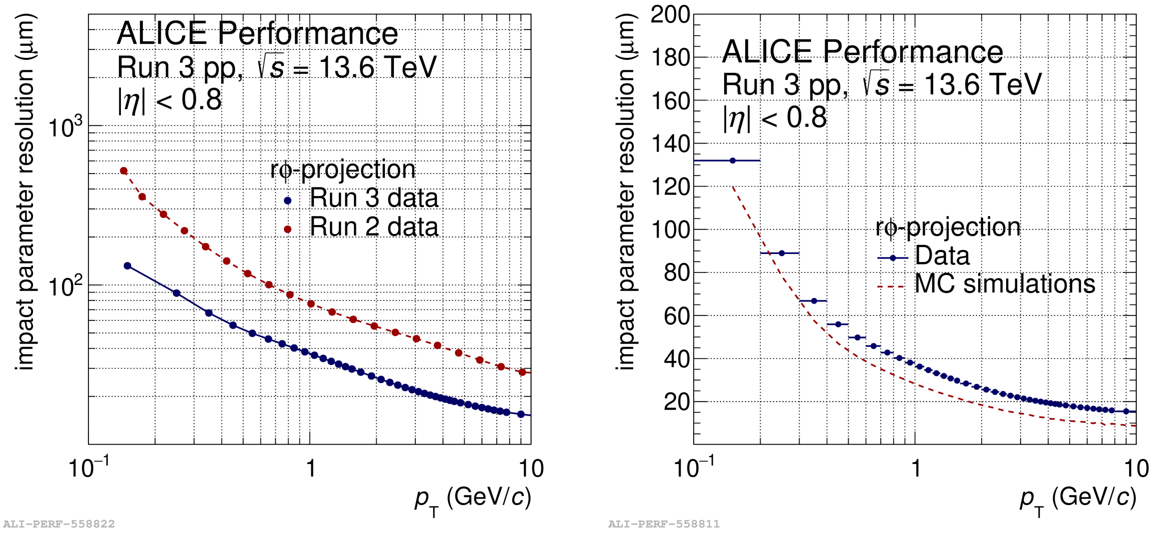

(a) Comparison between Run 2 and Run 3

(b) Comparison between Run 3 and MC simulation

Figure 8. Impact parameter in $r\phi$ plane in pp collisions at $\sqrt{s}$ = 13.6 TeV based on ITS-TPC global tracks requiring at least 1 hit in 3 innermost ITS layers.

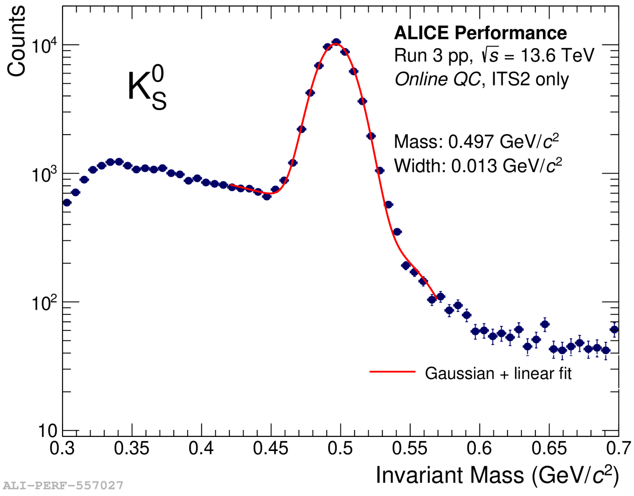

Figure 9. Invariant mass distribution of K^0_s reconstructed with ITS2-standalone tracks in pp collisions at $\sqrt{s}$ = 13.6 TeV.

During physics data taking in Run 3, the invariant mass for a set of typical particles can be extracted with the synchronous QC task based on ITS2-standalone tracks, which allows a fast check for physics performance. In figure 9, the invariant mass distribution with a prominent peak of K^0_s is shown. Thorough studies have been conducted during the asynchronous reconstructions to further improve its precision.

The tracking efficiency is also under investigation with properly implemented MC simulation. Additionally, a potential particle identification capability on the ALPIDE sensor is being tested by looking into the cluster size and extracting the time over threshold information with low interaction pp collisions. This serves as a valuable demonstration for the development of next-generation MAPS-based detectors.

5 Summary

The new MAPS-based Inner Tracking System, known as ITS2, has been designed and constructed with the primary goal of enhancing the ALICE tracking capabilities, in particular at low transverse momentum. The on-surface commissioning including full description of the detector running conditions, detector installation in the ALICE experiment, and the global commissioning alongside other ALICE detectors were successfully carried out between 2019 and 2022. The detector underwent a thorough validation prior to the beginning of the LHC Run 3. The detector has been operated smoothly with a very satisfactory low noise level and stable pixel threshold, and showing excellent performance during the pp collisions. The data taking was also successful in the low interaction rate test with Pb–Pb collisions in November 2022 and the ITS2 stands ready for the first physics data taking session with Pb–Pb collisions scheduled for October 2023.

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