Physics performance with the ALICE silicon tracker

V. Manzari on behalf of the ALICE collaboration

Istituto Nazionale di Fisica Nucleare,
Bari, Italy
CERN,
Geneva, Switzerland

E-mail: vito.manzari@cern.ch

ABSTRACT: The detailed characterization of the quark gluon plasma (QGP) produced in heavy-ion collisions is the main goal of the ALICE experiment at the CERN LHC. The analysis of heavy quarks via the decays of the corresponding short-lived hadrons is among the prominent measurements to address the properties of QGP. To efficiently reconstruct these decays, the ALICE apparatus comprises a precise Inner Tracking System (ITS) made out of six layers of silicon detectors based on three different technologies, namely two layers of pixels, two of drifts and two of double-sided microstrip, listed in the order they are crossed by particles produced in the beam collision. In this paper, the contribution of the ITS to some of the main physics measurements that have been accomplished with proton and lead beams by the ALICE experiment will be discussed.

KEYWORDS: Particle tracking detectors (Solid-state detectors); Large detector systems for particle and astroparticle physics; dE/dx detectors
1 Introduction

ALICE (A Large Ion Collider Experiment) is the LHC experiment optimized for the study of high-energy collisions between lead nuclei to investigate the behaviour of QCD matter under extreme conditions of energy density and temperature. Analysis based on QCD (quantum chromodynamics) lead to a prediction of the existence of a state of deconfined quarks and gluons at energy densities above 1 GeV/fm$^3$. The transition to this state can be achieved in high-energy nuclear collisions, which allow such energy densities to be reached. Assessing the properties of the created matter requires a sound understanding of the underlying collision dynamics. For this, the heavy-ion (AA) collision studies in the new energy regime accessible at the LHC have to be complemented by proton-proton (pp) and proton-nucleus (pA) collision experiments. These control measurements, besides being interesting in themselves, are needed to separate the genuine QCD-matter signals from the cold-matter initial- and final-state effects. The physics goals of ALICE are described in detail in [1, 2], while the published results are accessible at [3].

2 The ALICE apparatus

The ALICE apparatus, shown in figure 1, has overall dimensions of $16 \times 16 \times 26 \text{m}^3$ and a total weight of $\sim 10000 \text{t}$. It was designed to cope with the particle densities expected in central Pb-Pb collisions at the LHC. The experiment has a high detector granularity, a low transverse momentum threshold $p_T \approx 0.15 \text{GeV}/c$, and good particle identification (PID) capabilities up to 20 GeV/c. The seventeen ALICE detector systems fall into three categories: central-barrel detectors, forward detectors and the MUON spectrometer. A detailed description of the ALICE apparatus can be found in [4]. The central-barrel detectors — Inner Tracking System (ITS), Time Projection Chamber (TPC), Transition Radiation Detector (TRD), Time Of Flight (TOF), Photon Spectrometer (PHOS), Electromagnetic Calorimeters (EMCal and Dcal), and High Momentum Particle Identification Detector (HMPID) — are embedded in the L3 solenoid magnet, providing a field up to $B = 0.5 \text{T}$, and address particle production at midrapidity. The forward detectors include: the preshower/gas-counter PhotonMultiplicity Detector (PMD) and the silicon Forward Multiplicity Detector (FMD),
which are dedicated to the measurement of photons and charged particles, respectively; the quartz Cherenkov detector T0 that delivers the time and the longitudinal position of the interaction; the plastic scintillator detector V0 and the Zero Degree Calorimeter (ZDC), which are mainly used for triggering and for the determination of centrality in Pb-Pb collisions. The MUON spectrometer, used to measure heavy-flavour, quarkonium and light vector meson production in the forward region, consists of a hadron absorber of $\sim 10 \lambda_{\text{int}}$, a dipole magnet of 3 Tm, five tracking stations with two pad chambers each (Muon Chambers, MCH) and two triggering stations (Muon Trigger, MTR) placed behind an additional absorber.

The Inner Tracking System (ITS) and the Time Projection Chamber (TPC) are the main charged-particle tracking detectors of ALICE. The ITS is composed of six tracking layers, two Silicon Pixel Detectors (SPD), two Silicon Drift Detectors (SDD), and two double-side Silicon Strip Detectors (SSD). In addition to tracking, SDD, SSD and TPC provide charged-particle identification via measurement of the specific ionization energy loss $dE/dx$, while the SPD contributes to the definition of the Level 0 trigger of the experiment (for a more detailed description of the SPD and its operational experience the reader is referred to [5]).

The ITS contributes to the excellent ALICE capabilities in terms of primary and secondary vertices reconstruction, tracking efficiency and momentum resolution in the proximity of the interaction vertex, standalone tracking of low momentum particles which do not reach the TPC. Therefore, the ITS plays a crucial role in the study of heavy-flavour production down to very low transverse momentum addressed by ALICE and in particular, in the physics analysis for which the knowledge of the position where the particle was generated, i.e. the primary and secondary vertices, is relevant.

---

**Figure 1.** The ALICE experiment at the CERN LHC.
3 Event reconstruction and detector performance

This section concisely describes the event reconstruction procedure in the central barrel of the ALICE apparatus and the main performance features of the ITS; for more details the reader is referred to [6]. The first step is the conversion of the detector data into “clusters”, characterized by position, signal amplitude for SDD and SSD, time and their associated errors. The clusterization is performed separately for each detector. The following step is the determination of the preliminary location of the interaction vertex using clusters in the first two ITS layers, i.e. the SPD, defined as the space point to which the maximum number of SPD tracklets (which are the lines defined by pairs of clusters, one in each SPD layer) converge. This search procedure can be accomplished online allowing a monitoring of the interaction diamond positions, whose information is propagated to the LHC; moreover, it provides the input for the following offline track and vertex reconstruction.

Subsequently, track finding and fitting in the central barrel is performed following a three stages inward-outward-inward scheme. The first inward stage starts with the track search in the outer region of the TPC, where the track density is lower. Track seeds are built using TPC clusters and the preliminary position of the interaction vertex. The seeds are propagated inward and at each step the nearest found clusters are associated to them. Only those tracks that are built from at least 20 clusters in the outer volume are propagated to the inner TPC region. The reconstructed TPC tracks, based on up to 159 clusters, are then extrapolated to the outermost ITS layer and become the seeds for track finding in the ITS. The seeds are propagated inward and are updated at each ITS layer by applying a similar procedure as in the TPC to associate ITS clusters within a proximity cut, which takes into account positions and errors. The prolonged TPC-to-ITS track candidates are sorted according to the reduced $\chi^2$ and finally only the highest quality track candidates are added to the reconstructed event. The reconstruction efficiency in the TPC sharply drops at low transverse momentum, the cutoff being around 200 MeV/$c$ for pions and 400 MeV/$c$ for protons, and is caused by energy loss and multiple scattering in the detector material. In order to recover these low momentum particles, a standalone ITS reconstruction is performed using clusters left over by the combined TPC+ITS tracking procedure. The ITS standalone algorithm enables the tracking of particles with transverse momenta down to about 80 MeV/$c$. Once the reconstruction in the ITS is complete, all tracks are extrapolated to their point of closest approach to the preliminary interaction vertex, and the outward propagation starts. The tracks are refitted by the Kalman filter in the outward direction using the clusters found at the previous stage. At each outward step, the track length integral as well as the time of flight expected for various particle species are updated for subsequent particle identification with TOF and TRD. The tracks are then propagated further for matching with signals in EMCal, PHOS, and HMPID. At the final stage of the track reconstruction, the particle identification is performed and the kinematics parameters are determined. All tracks are propagated inwards starting from the outer radius of the TPC and refitted with the previously found clusters: the track position, direction, inverse curvature and its associated covariance matrix are determined. The track reconstruction efficiency is found to be almost independent on the occupancy in the detector, even in the most central Pb-Pb collisions.

The transverse momentum resolution for TPC standalone tracks and TPC+ITS combined tracks, extracted from the track covariance matrix, is shown in the left panel of figure 2; the effect of constraining the tracks to the primary vertex is shown as well. The inverse-$p_T$ resolution is
Figure 2. The left panel shows the $p_T$ resolution for standalone TPC and ITS+TPC matched tracks with and without constraint to the vertex: the vertex constrain significantly improves the resolution of TPC standalone tracks while for ITS+TPC tracks it has basically no effect (green and blue squares overlap). The right panel shows the transverse width of the final vertex distribution (solid points), decomposed into the finite size of the luminous region $\sigma_D$ and the vertex resolution $\alpha/\sqrt{\langle dN_{ch}/d\eta \rangle}$. For comparison, the width of the preliminary (SPD) interaction vertex is shown as open points.

connected to the relative transverse momentum resolution via the relation

$$\frac{\sigma_{p_T}}{p_T} = p_T \sigma_{1/p_T}$$

From this figure one can infer that the transverse momentum resolution is dramatically improved by the ITS contribution as the TPC standalone tracks significantly benefit of the vertex constraint, while TPC+ITS combined tracks are basically not affected (green and blue open squares overlap).

Global tracks, reconstructed in TPC and ITS, are used to find the interaction vertex with a higher precision than with SPD tracklets alone. By extrapolating the tracks to the point of closest approach to the nominal beam line and removing far outliers, the approximate point of closest approach of validated tracks is determined. Then the precise vertex fit is performed using track weighting to suppress the contribution of any remaining outliers. The transverse resolution of the preliminary interaction vertices found with SPD tracklets and of the final ones, found with global tracks, are shown in the right panel of figure 2: both resolutions scale with the number of contributing tracks according to a power law. These results also show that a good vertex finding can be achieved even with a reduced number of tracks.

Once the tracks and the interaction vertex have been found in the course of event reconstruction, a search for secondary vertices from particle decays is performed. Tracks with a distance of closest approach to the interaction vertex exceeding a certain minimum value (0.5 mm in pp and 1 mm in Pb-Pb) are selected. For each unlike-sign pair of such tracks, called V0 candidate, the point of closest approach between the two tracks is calculated. An optimized set of cuts is applied to the V0 candidates to select $K^0_S$ and $\Lambda$, and facilitate the subsequent search for cascade decays. After finding V0 candidates, the search for the cascade ($\Xi^{--}$) decays is performed: V0 candidates with an invariant mass in the vicinity of the $\Lambda$ are matched with a secondary track by cutting on their mutual distance at the point of closest approach (PCA) and requesting that the latter is outside...
of a cylindrical volume of radius \( r > 0.2 \text{ cm} \) around the interaction vertex. The reconstruction of more complex secondary vertices is performed later, at the analysis stage. Similarly, for the study of heavy-flavor decays close to the interaction point, the secondary vertex is searched for by considering all unlike-sign track pairs and selecting those passing a set of topological cuts, as described in the next section.

The outer four layers of the ITS are equipped with analogue readout to provide a measurement of the ionization energy loss of particles as they pass through the detector. The measured cluster charge is normalized to the path length, which is calculated from the reconstructed track parameters to obtain a \( dE/dx \) value for each layer. For each track, the \( dE/dx \) is calculated using a truncated mean to account for the long tails in the Landau distributions. An example of the energy loss distribution as a function of the momentum both measured with the ITS standalone is shown in the left panel of figure 3: a p-K separation up to 1 GeV/\( c \) and K-\( \pi \) separation up to 450 MeV/\( c \) is achieved with the ITS standalone reconstruction. The overall charged hadron identification in ALICE is performed combining the information of a number of different subsystems, namely ITS, TPC, TOF and HMPID, to further improve the separation between particle species. The right panel of figure 3 shows the invariant yield of charged pions as a function of \( p_T \) for different centrality classes measured with three different detectors.

The impact parameter of a track is defined as the distance of closest approach of the track extrapolation to the reconstructed interaction vertex position. The measurement of the track impact parameter is crucial for the study of the physics signals characterized by the presence of a secondary vertex with a small displacement from the interaction vertex as it is the case for the detection of particles with open charm and open beauty. The impact parameter resolution is affected by the material budget, due to the multiple scattering for low \( p_T \) particles, and the intrinsic point resolution of each tracking layer.
Figure 4. Resolution of the distance of closest approach in the bending plane \((r\phi)\) between the track projection and the primary vertex for identified particles from ITS standalone tracking (left) and for all charged particles from TPC+ITS global tracking (right). The contribution from the vertex resolution is not subtracted.

Figure 4 shows the resolution on the impact parameter \(d_0\) in the bending plane \((r\phi)\) for particles tracked and identified by the ITS standalone (left panel) and the same quantity for all charged particles reconstructed in the TPC+ITS for three colliding systems and with a higher \(p_T\) reach (right panel). The contribution from the vertex resolution is not subtracted and thus one can notice an improvement of the resolution going from pp to p-Pb and Pb-Pb as consequence of the more precise vertex location due to the higher track multiplicities. From these two panels one can see that for global tracking the achieved impact parameter resolution in the bending plane is better than \(\sim 60\,\mu\text{m}\) for \(p_T > 1\,\text{GeV}/c\).

4 Physics performance

The standard analysis strategy for the extraction of charmed meson signals from the large combinatorial background due to uncorrelated tracks is based on the reconstruction and selection of secondary vertex topologies that have significant separation from the primary vertex. The \(D^0\) and \(D^+\) mesons have mean proper decay lengths \(c\tau \approx 123\) and \(312\,\mu\text{m}\), respectively, therefore, their decay secondary vertices are typically displaced by a few hundred \(\mu\text{m}\) from the primary interaction vertex. The study of \(D^0\) and \(D^+\) mesons is performed by reconstructing their hadronic decay channels \(D^0 \rightarrow K^-\pi^+\) (with branching ratio, BR, of 3.87\%) and \(D^+ \rightarrow K^-\pi^+\pi^+\) (with BR of 9.13\%), together with their charge conjugates. The identification of the charged kaons provides additional background rejection particularly in the low-momentum region. The standard analysis to filter the \(D^0\) and \(D^+\) candidates strongly rely on the ITS performance, being based on topological selection criteria. The most effective cuts to extract the relevant signals are: a secondary decay vertex having a minimum displacement from the primary vertex (100 \(\mu\text{m}\) for \(D^0\)), a maximum distance of closest approach between the secondary tracks (300 \(\mu\text{m}\) for \(D^0\)) and a minimum impact parameter of the decay tracks in the bending plane \((r\phi)\). The value of each cut is optimized for the specific signal under study. The excellent performance of ALICE in terms of heavy flavour studies, including a
detailed description of the analysis procedures, have been published in a number of papers, like for instance [7, 8].

The effectiveness of the strategy based on topological selections is illustrated in figure 5 and 6, which show the comparison between the $D^0$ signal in pp and p-Pb interactions, respectively, extracted using the topological strategy (rightmost panels) and an alternative approach based on background subtraction without topological selections, the latter does not requiring the tracking accuracy provided by the ITS. Two background subtraction methods, namely the like-sign and the event mixing, have been investigated with the aim to enhance the signal-to-noise ratio in particular at very low $p_T$, where the topological selection is less efficient to reject the background because the displacement of the secondary vertex decreases linearly with the momentum of the decaying particle.

In the like sign method, shown for the pp dataset, the combinatorial background is constructed through the invariant mass distribution of like sign $K\pi$ combinations from the same event. In the process of building $D^0$ candidates, an identified kaon is combined with an identified pion, where
one of the tracks is required to be positive and one negative. The fit to the invariant mass distribution in the first two $p_T$ bins after like-sign background subtraction is shown in the two left panels of figure 5.

In the event mixing technique, shown for the p-Pb dataset, the combinatorial background is constructed through the invariant mass of unlike sign $K\pi$ combinations from different events. To avoid mismatch due to different acceptances and to assure a similar event structure, tracks from events with similar vertex positions along the beam direction and track multiplicities are mixed. The background distribution is then subtracted from the event distribution in each $p_T$ bin. The fit to the invariant mass distribution in the first two $p_T$ bins after event mixing background subtraction is shown in the two left panels of figure 6.

Figure 7 shows the comparison of the statistical significance $S/\sqrt{S+B}$ of the $D^0$ signal in a $p_T$ range from 0 to 8 GeV/c, in pp (left) and p-Pb (right) interactions, obtained with the topology and the background subtraction analysis. The background subtraction methods are much less effective than the standard analysis as the significance is systematically lower over the full range of $p_T >$ 1 GeV/c. However, the background subtraction allows to extract the signal down to $p_T = 0$ GeV/c, which would otherwise not be possible relying on the topological analysis only.

In Pb-Pb interactions at LHC energies, the high track multiplicities, which can reach a few thousands per unit of rapidity, makes the study of heavy-flavour decays at low transverse momenta extremely challenging. Selection criteria based on the decay topology, such as the relation between the secondary and primary vertices, are mandatory to extract the signal from the huge combinatorial background. The effect of the topological cuts in Pb-Pb data is clearly illustrated in figure 8, which shows the rejection of the combinatorial background using selection criteria based on the decay topology in the $D^0 \rightarrow K^-\pi^+$ analysis. Alternative approaches attempting to reject the huge background are dramatically less effective.

5 Conclusions and outlook

The Inner Tracking System plays a key role in the study of heavy-flavour particle production, whose decays take place close to the interaction vertex. These analyses are based on topological
Figure 8. The left panel shows the invariant mass distribution of $K^-\pi^+$ pairs for $p_T > 2$ GeV/c before (symbols) and after (line) selection cuts on the relation between the secondary ($D^0$ decay) and primary vertices. The panel on the right shows the extracted $D^0$ signal in the bin $2 < p_T < 3$. The value of the $D^0$ mass and its resolution as well as the significance are shown after selection.

selection criteria, such as the distance between decay and interaction vertices, the distance of closest approach between tracks of the decay products, impact parameter in the bending plane ($r\phi$) of the decay tracks to the primary vertex as well as the particle identification over a wide momentum range. The extremely good performance of the ITS in terms of track efficiency, momentum resolution, impact parameter resolution and particle identification, contributes to the ALICE physics results, reported in a large number of published papers.

A substantial upgrade of the ITS [9, 10], consisting in the replacement of the current detector with a new one entirely based on monolithic silicon pixel sensors [11], has been approved by the CERN Research Board in March 2014. The new ITS, which will be installed during the Long Shutdown 2 of LHC will allow to access signals that are only barely accessible with the present detector, such as the $D^+_s \rightarrow K^+K^-\pi^+$ and $B \rightarrow J/\Psi(\rightarrow e^+e^-) + X$, or not at all, as charm and beauty baryons (e.g.: $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $\Lambda_b \rightarrow \Lambda_c^+\pi^-$).

References

[1] ALICE collaboration, *ALICE: physics performance report, volume I*, J. Phys. G 30 (2004) 1517.
[2] ALICE collaboration, *ALICE: physics performance report, volume II*, J. Phys. G 32 (2006) 1295.
[3] http://aliceinfo.cern.ch/ArtSubmission/publications.
[4] ALICE collaboration, *The ALICE experiment at the CERN LHC, 2008 JINST 3 S08002*.
[5] C. Cavicchioli, *Operational experience with the ALICE Pixel Detector, 2015 JINST 10 C03032*.
[6] ALICE collaboration, *Performance of the ALICE experiment at the CERN LHC, Int. J. Mod. Phys. A 29* (2014) 1430044 [arXiv:1402.4476].
[7] ALICE collaboration, *Measurement of charm production at central rapidity in proton-proton collisions at $\sqrt{s} = 7$ TeV, JHEP 01* (2012) 128 [arXiv:1111.1553].
[8] ALICE collaboration, *Suppression of high transverse momentum D mesons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV*, *JHEP* 09 (2012) 112 [arXiv:1203.2160].

[9] ALICE collaboration, *Technical design report for the upgrade of the ALICE Inner Tracking System*, *J. Phys. G* 41 (2014) 087002.

[10] M. Keil et al., *Upgrade of the ALICE Inner Tracking System*, 2015 *JINST* 10 C03012.

[11] P. Yang et al., *MAPS development for the ALICE ITS Upgrade*, 2015 *JINST* 10 C03030.