Feasibility study for the detection of $D^0 \to K^- \pi^+$ decays in Pb–Pb collisions at LHC with ALICE

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Abstract

The ALICE experiment at the CERN LHC collider is devoted to the study of heavy-ion collisions at a centre of mass energy of 5.5 TeV per nucleon. The study of open charm production in nucleus–nucleus collisions at the LHC allows investigation of the mechanisms of heavy quark production and energy loss in the hot and dense medium formed in the early stage of the collision. In addition, the open charm production cross section is the natural normalization for the study of $J/\psi$ production. The reconstruction of exclusive hadronic decays of charm particles is the only way to obtain a direct measurement of their transverse momentum distribution. We present the results of a feasibility study for the detection of $D^0 \to K^- \pi^+$ decays in Pb–Pb collisions with ALICE.

1. The ALICE experiment

ALICE (a large ion collider experiment) \cite{1} is an experiment in preparation at the large hadron collider (LHC) optimized for the study of heavy-ion collisions at a centre of mass energy of 5.5 TeV per nucleon. The aim of the experiment is to study the behaviour of nuclear matter at high densities and temperatures. In these conditions a transition to a phase where the quarks and gluons are deconfined and the chiral symmetry is restored (quark gluon plasma (QGP)) is expected.

Figure 1 shows the layout of the ALICE experiment. The detector consists of two main components: the central barrel and the forward muon spectrometer. The coverage of the central detectors allows the tracking of particles emitted on a pseudorapidity range $|\eta| < 0.9$ over the full azimuth. These detectors are embedded in a large magnet which provides a weak solenoidal field of $0.5 \text{T}$. The muon spectrometer covers the pseudorapidity range $2.4 < \eta < 4$. We define here the ALICE global reference frame, which has the $z$ axis parallel to the beam line, and the $x$ and $y$ axes in the transverse plane.

The study reported here involves the following central barrel detectors: the inner tracking system (ITS), the time projection chamber (TPC) and the time of flight (TOF). These
detectors provide tracking and particle identification capabilities in the pseudorapidity range $-0.9 < \eta < 0.9$.

A major technical challenge is imposed by the large number of particles produced in the collision of lead ions. There is a considerable spread in the predictions of the charged particle rapidity density in Pb–Pb collisions at the LHC. The largest value predicted corresponds to 8000 charged particles per unit of rapidity for central Pb–Pb collisions. However, the extrapolation of the recent RHIC results to LHC energies favours multiplicities lower by about a factor of 3 [2]. This physics analysis has been performed assuming $dN_{ch}/dy = 6000$.

2. Physics motivation

The charm production cross section at LHC energies in nucleon–nucleon collisions has been calculated at next-to-leading order (NLO) [3, 4]. The study of open charm production in heavy-ion collisions at the LHC, and the comparison with the production in $pp$ and $p–A$ interactions, is one of the issues addressed by ALICE since it allows investigation of the mechanisms of heavy quark production in the hot and dense medium formed in the early stage of the collision.

If a QGP phase is formed, secondary parton scattering in the hot and dense partonic system produced may provide an additional source of charm quarks [5, 6]. This QGP-induced production has been predicted to be even more important than the direct $c\bar{c}$ production (e.g. [6] predicts an enhancement by more than one order of magnitude with respect to the case where no QGP is formed). In such a scenario, the number of charm quarks produced would strongly depend on the initial temperature of the plasma and on its lifetime and it would therefore give information on the early phase of the collision. At lower energies there are indications of a
possible enhanced production of charm quarks in Pb–Pb collisions at SPS energy from the dimuon spectrum measured by NA50 [7].

The formation of the plasma would not only modify the total production cross section, but it would also change the kinematical properties of the produced heavy quarks. The interaction of the charm quarks with the plasma will reduce their momenta because of the elastic collisions with the partons of the medium and because of the radiative losses (see, e.g., [8] and references therein). The process of energy loss obviously would not change the number of charm quarks produced but it would lead to a considerable modification in the final kinematical distributions of the $D$ mesons into which the quarks hadronize; in particular, their transverse momentum ($p_T = \sqrt{p_x^2 + p_y^2}$) would be reduced. However, an effective reduction in the observed heavy quark yield can be expected because of the finite $p_T$ cut-off. In this respect, the capability of the detector to measure the transverse momentum distribution of the charm mesons down to $p_T$ as low as possible is crucial, in order to minimize the errors due to the extrapolation to $p_T = 0$. The reconstruction of the exclusive hadronic decays of $D^0$ and $D^\pm$ is the only way to obtain a direct measurement of their $p_T$ distribution. In the following, it will be shown that ALICE will be able to measure $D^0$ decays in central Pb–Pb collisions down to $p_T$ as low as 1 GeV/c.

The measurement of the cross section for open charm production is also essential as a reference to measure a possible suppression of charmonium production due to the transition to a deconfined phase. At the SPS charm quarks are produced essentially via quark–antiquark annihilation ($q\bar{q} \rightarrow c\bar{c}$). The dilepton continuum produced in Drell–Yan processes ($q\bar{q} \rightarrow \ell^+\ell^-$) was used as a normalization for the $J/\psi$ production (NA50 experiment). However, at LHC energies heavy quarks are mainly produced through gluon fusion processes ($gg \rightarrow Q\bar{Q}$) and the Drell–Yan process does not provide an adequate reference. A direct measurement of the open charm yield would then provide a natural normalization for $J/\psi$ production.

3. Detection strategy

The states $D^0$ and $D^\pm$ (and antiparticles) of the lowest charm hadron multiplet can decay only through weak processes and have lifetimes of the order of the picosecond ($c\tau = (123.7 \pm 0.8) \, \mu m$ for the $D^0$ and $c\tau = (315.3 \pm 3.9) \, \mu m$ for the $D^\pm$ [9]). Therefore, the distance between the interaction point (primary vertex) and their decay point (secondary vertex) is measurable. The selection of a suitable decay channel, which involves only charged particle products, allows the direct identification of the charm states by computing the invariant mass of fully reconstructed topologies originating from secondary vertices.

The capability of the detector to separate the secondary vertex from the interaction point is determined by the resolution in the impact parameter, the impact parameter being the distance of closest approach of a particle trajectory to the primary vertex. The decay products of a charm particle have typical impact parameters of the order of 100 $\mu$m.

In this analysis, we follow the general lines for the detection strategy of open charm in the hadronic channels defined in the ALICE ITS Technical Design Report [10].

We consider as a benchmark the process $D^0 \rightarrow K^-\pi^+$ (and $\bar{D}^0 \rightarrow K^+\pi^-$); the fraction of $D^0$ mesons which decay in $K^-\pi^+$ is ($3.83 \pm 0.09$)% [9].

The impact parameter resolution depends mainly on the thickness and radius of the beam pipe and on the position, spatial resolution and material thickness of the inner detector layers. The beam pipe, which is built of beryllium, has a thickness of 0.8 mm and a radius of 3 cm. The inner tracking system [10] of ALICE is composed of two layers of silicon pixel detectors.
Figure 2. Schematic view of the detectors employed in this analysis.

Table 1. Parameters of the six detector layers in the ITS.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Type</th>
<th>( r ) (cm)</th>
<th>Thickness (% of ( X_0 ))</th>
<th>Spatial precision ( r \psi \times z ) (( \mu m^2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pixel</td>
<td>4</td>
<td>1.24</td>
<td>12 \times 120</td>
</tr>
<tr>
<td>2</td>
<td>Pixel</td>
<td>7</td>
<td>1.24</td>
<td>12 \times 120</td>
</tr>
<tr>
<td>3</td>
<td>Drift</td>
<td>14.9</td>
<td>0.94</td>
<td>38 \times 28</td>
</tr>
<tr>
<td>4</td>
<td>Drift</td>
<td>23.8</td>
<td>0.95</td>
<td>38 \times 28</td>
</tr>
<tr>
<td>5</td>
<td>Strip</td>
<td>39.1</td>
<td>0.91</td>
<td>20 \times 830</td>
</tr>
<tr>
<td>6</td>
<td>Strip</td>
<td>43.6</td>
<td>0.87</td>
<td>20 \times 830</td>
</tr>
</tbody>
</table>

(SP), two layers of silicon drift detectors (SDD) and two layers of silicon strip detectors (SSD). Their positions, thicknesses and spatial resolutions are reported in table 1. The two most important detectors for the measurement of the impact parameter are the two layers of silicon pixels. In the \( p_T \) range of interest for the decay products of charm particles, they allow a resolution of about 60 \( \mu m \) for the impact parameter projection in the bending plane to be achieved (figure 5). This precision is necessary in order to suppress the large combinatorial background by selecting a few charm decay tracks from a large number of primary vertex tracks, thus enabling us to restrict the study to decay topologies well separated from the primary vertex.

In addition to the ITS, the other ALICE detectors which will be employed for the detection of hadronic charm are the time projection chamber \cite{11} (tracking and momentum measurements) and the time of flight \cite{12} (particle identification) (also the transition radiation detector \cite{13} will give useful information on the tracking, but for the moment it is not included in this simulation). A schematic view of the detectors employed in this analysis is shown in figure 2.

4. Simulation and reconstruction

4.1. Charm production cross section at LHC

The cross sections for the production of \( c \bar{c} \) pairs in \( pp \) collisions at LHC energies (5.5 and 14 TeV) have been calculated using a program by Mangano et al \cite{14} and two sets of NLO
parton distribution functions (PDFs)—MRST and CTEQ5M1—which take into account small $x_B$ Bjørken HERA results [15, 16]. The calculations use $m_c = 1.2$ GeV for the $c$ quark mass and $\mu_F = \mu_R = 2m_c$ for the factorization and renormalization scales. Results are reported in table 2. The difference due to the choice of the parton distribution functions is $\sim 15–20\%$.

The extrapolation to Pb–Pb collisions at $\sqrt{s} = 5.5$ TeV is done as follows. In nucleus–nucleus collisions ($A–B$) the cross section for hard processes, averaged over all impact parameters, is parametrized as

$$\sigma_{AB}^{\text{hard}} = \alpha \sigma_{pp}^{\text{hard}}(A) \sigma_{pp}^{\text{hard}}(B)$$

where $\alpha = 1$ if no nuclear effects are taken into account. The only nuclear effect we consider is the shadowing, which is accounted for by using the EKS98 parametrization [18] to correct the PDFs. Therefore, in the following we will use $\alpha = 1$.

The cross section as a function of the impact parameter $b$ can be written as

$$d\sigma_{AB}^{\text{hard}}(b) = \sigma_{pp}^{\text{hard}}(A) T_{AB}(b) d^2 b$$

where $T_{AB}(b)$ is the total thickness function of the two nuclei at impact parameter $b$, computed according to the Glauber model [17]. We have assumed a centrality selection corresponding to $5\%$ of the total inelastic cross section. This corresponds to a cut on the impact parameter: $b < 3.5$ fm. We use for the $c\bar{c}$ production rate the average of the values obtained using the MRST and the CTEQ5M1 PDFs:

$$N_{c\bar{c}}^{Pb–Pb}(5\%\sigma_{tot}) = 115.$$  

The transverse momentum and rapidity distributions for the generated charm quarks and antiquarks, as well as the hadronization ‘branching ratios’ in charm mesons and baryons, were obtained from the event generator PYTHIA6 [19]. We have tuned the parameters of PYTHIA in order to reproduce as well as possible the NLO predictions for the kinematical distributions of the bare quarks [14]. The PDFs used are the CTEQ4L, modified to account for the nuclear shadowing; we verified that the results obtained with these PDFs lie in between the ones obtained with the CTEQ5 and MRST for all relevant kinematical quantities.

In table 3, we report the yields and $dN/dy$ at $y = 0$ for $D^0 + \bar{D}^0$, $D^+ + D^-$, using a charm yield of $N^{c\bar{c}}$/event = 115.

### 4.2. Background and signal generation

The background and the signal of open charm mesons have been generated and analysed separately.

The background to the charm signal is mainly given by combinations of primary tracks which undergo scatterings in the material of the beam pipe and of the innermost detector.
Figure 3. Transverse momentum distributions for pions (left) and kaons (right) from background (dashed line) and signal (solid line). The histograms are normalized to the same integral.

layer and appear as large impact parameter tracks. Other background sources are given by tracks with large impact parameter coming from the decay of hyperons and $K^0_S$ tracks from undetected charm decays and from $\bar{p}$ and $\bar{n}$ annihilations in the beam pipe and in the innermost SPD layer.

The background events were generated using the HIJING [20] event generator (which includes nuclear shadowing and quenching effects). The collision impact parameter $b$ has been sampled from the physical distribution $dN/db \propto b$ and the condition $b < 2$ fm has been applied in order to generate central collisions. The obtained charged particle rapidity density is $dN_{ch}/dy \simeq 6000$, at midrapidity. Our background sample consists of $4 \times 10^5$ such events.

The signal was generated using PYTHIA, as described in the previous section. Many $D^0/\bar{D}^0$ mesons, with decay forced in a charged $K, \pi$ pair, were superimposed in one single event. The number of $D^0$ per event has been chosen in order to have the same track multiplicity as in a central HIJING event. In this way, the $D^0$ decay products are reconstructed with the same efficiency as if they were produced in a central Pb–Pb collision. It has been verified that the different momentum and impact parameter distributions of these ‘signal events’ with respect to central HIJING events does not affect the reconstruction efficiency significantly, as can be seen in figure 7.

A total of 1000 such ‘signal events’ were generated. Using our present rate estimate, such a number of $D^0$ will be produced in $\simeq 6.1 \times 10^5$ central Pb–Pb events: slightly more than one week of Pb–Pb running at the LHC. All the results presented here are scaled to $10^7$ central Pb–Pb events.

For both signal and background events, the $z$ position of the primary vertex has been sampled from a Gaussian distribution ($\sigma = 5.3$ cm) with a cut at $\pm 1 \sigma$. This corresponds to the expected width of the fiducial interaction region. We assumed that the beam is centred at (0, 0) in the $(x, y)$ plane.

In figure 3, we plot the generated $p_T$ distributions for background pions and kaons, compared with the corresponding distributions for $D^0$ decay products.

3 The impact parameter range used for the generation of the background events is $b < 2$ fm, while it was $b < 3.5$ fm for the estimate of the charm production rate. This choice is due to technical reasons; however, it is a conservative one, since $b < 2$ fm gives a larger multiplicity for background tracks than $b < 3.5$ fm.
4.3. Simulation of the apparatus and track reconstruction

The simulation has been done within the ALICE object-oriented simulation framework, AliRoot [21]. In this simulation the value of the magnetic field is 0.4 T. Previous simulations used a lower magnetic field of 0.2 T [22].

The combinatorial background for charm detection in hadronic decay channels is very large (e.g. for \( D^0 \rightarrow K^-\pi^+ \) we have \( \frac{S}{B} \sim 10^{-6} \) in the mass range \( M_{D^0} \pm 3\sigma \), before selections); therefore to extract the charm signal with good significance one has to apply cuts selective enough to reduce the background by six to seven orders of magnitude. As a consequence, a large number of events are required in the analysis. This makes the simulation of the whole ALICE detector very demanding in terms of CPU time and disk space. Therefore, we have used a simplified version of the simulation (‘fast’ simulation). Each particle is transported through the apparatus; however, the track is followed only up to the entrance of the TPC, where its position and momentum on the first pad row are stored. The reconstructed track parameters at the entrance of the TPC are then estimated from the generated quantities at the first pad row using a parametrized response of the TPC tracking. This parametrization describes accurately the resolutions in the track parameters, their correlations and the tracking efficiency in the TPC as obtained from the TPC standard reconstruction algorithm (based on the Kalman filter method [23]); the covariance matrix of the track is also parametrized. The requirements in computing time and disk space are in this way reduced by about a factor of 35, because the TPC is not included in the detailed detector simulation. Using this approach, however, the tracking efficiency is underestimated since about 12% of the tracks traverse the dead area between the first pad rows of two adjacent TPC sectors. These tracks may still be reconstructed if they enter the TPC at a larger radius, but they are lost from the point of view of the parametrization since they lack the information on the generated track parameters stored in the first TPC pad row.

For the beam pipe and the ITS detectors, which are instrumental in determining the impact parameter of the tracks and the position of the secondary vertex, the crucial quantities to extract the charm signal, we use a detailed description. The transport of the charged particles in the materials, performed by the \textsc{geant3} [24] package, takes into account the complete theory of multiple Coulomb scattering. Pattern recognition and track fitting in the ITS are performed, exactly as in the complete simulation, using the standard Kalman filter algorithm, which uses the TPC tracks as seeds for the tracking in the ITS.

As shown in figure 4, the resolutions in transverse momentum and impact parameter after the reconstruction in the ITS do not change if we use the parameterized response of the TPC.

In order to contain the CPU time and storage space within reasonable limits, the position resolution of the ITS detectors has been parametrized. The comparison between the fast and the detailed ITS responses is shown in figure 5 for the impact parameter resolution.

The \( z \) position of the primary vertex has been estimated for each event using a method based on the correlation of the points in the two pixel layers as described in [25, 26]. The obtained resolution is \( \sigma_z \simeq 5.5 \mu m \) for \( dN_{ch}/dy \simeq 6000 \). In the bending plane the spread is given by the Pb beam transverse size (\( \sigma_x = \sigma_y \simeq 15 \mu m \)).

The reconstruction in the ITS has been performed in three steps:

- at first the tracks are found using a strong constraint on the primary vertex position. This constraint is important to maximize the tracking efficiency;
- these tracks are then re-fitted releasing the vertex constraint in order not to bias the determination of the impact parameter; clusters associated with reconstructed tracks are removed;
• a second pass of track finding is done without any vertex constraint to search for tracks originating from decays far from the primary vertex (mainly hyperons and $K^0_S$ decays).

The tracks considered in this analysis are required to have at least 5 ITS points associated with them, including the points from both pixel layers. This allows increasing the statistics without deteriorating the impact parameter resolution. As shown in figure 6, tracks with 6 ITS points and tracks which miss at most one SDD or SSD layer have essentially the same impact parameter resolution.

We have estimated a loss of $\sim 10\%$ of the tracks due to the dead channels in the ITS. We did not correct for this effect since it roughly compensates the efficiency loss due to the incorrect treatment of the TPC dead regions.
Figure 6. Impact parameter resolution for primary pions with points on each ITS layer and for those missing at most one SDD or SSD layer (both SPD layers required).

Figure 7. ITS tracking efficiency, defined as the ratio between the number of tracks reconstructed in the ITS with respect to the number of tracks reconstructed in the TPC, as a function of $p_T$ for central HIJING events and for ‘signal events’ containing only $D^0/\bar{D^0}$, decaying in $K\pi$, with the same track multiplicity as a central HIJING event.

The reconstruction has been done exactly in the same way for the background and signal. Figure 7 demonstrates that the tracking efficiency in the ITS for the ‘signal events’ is the same as for the background events.

4.4. Particle identification

In the momentum range of interest for charm analysis the particle identification capability is determined mainly by the TOF detector. The association of the particle type to a track (tagging) is determined by applying cuts on time of flight and momentum. The values of these cuts determine the identification efficiency and the contamination of the sample.
The identification efficiency for a particle type $i$ is defined as the ratio of the number of tracks of type $i$ correctly tagged as $i$ to the total number of tracks of type $i$; the contamination is defined as the ratio of the number of tracks incorrectly tagged as $i$ to the total number of tracks tagged as $i$. The optimal level of contamination and efficiency depends on the specific physics case under study.

We divide our set of reconstructed tracks into four samples: those identified as pions ($\pi_{\text{tag}}$), as kaons ($K_{\text{tag}}$), as protons ($p_{\text{tag}}$) and non-identified ($?_{\text{tag}}$). A $D^0 \rightarrow K^-\pi^+$ decay for which both the pion and the kaon tracks have been detected corresponds to a pair of tracks of opposite charges ($-$, $+$). According to their PID, the pair can fall in one of the following samples:

- **Sample A** ($K_{\text{tag}}, \pi_{\text{tag}}$) + ($K_{\text{tag}}, ?_{\text{tag}}$): the kaon is identified while the other track can be identified as pion or non-identified;
- **Sample B** ($?_{\text{tag}}, \pi_{\text{tag}}$): only the positive track is identified as pion;
- **Sample C** ($?_{\text{tag}}, ?_{\text{tag}}$): both tracks were not identified; in this sample each pair is counted twice, once as a $D^0$ candidate and once as a $\bar{D}^0$ candidate.
- **Sample D**: All other combinations, such as e.g. ($\pi_{\text{tag}}, \pi_{\text{tag}}$). These pairs are rejected.

Since in the signal the ratio $K/\pi$ is 1, while in the background it is very small ($\sim 0.1$), the definition of the kaon tag should favour a high efficiency with respect to the request for having a very pure kaon sample. On the other hand, we must require quite a pure sample of pions since every kaon identified as a pion contributes to the ($\pi_{\text{tag}}, \pi_{\text{tag}}$) sample, resulting in a loss of the signal.

Following these guidelines the PID tags have been defined in the following way:

- any track not matched with a single-fired TOF pad$^4$ is tagged as $?_{\text{tag}}$;
- tracks matched with a single-fired TOF pad are tagged according to the graphical cuts shown in figure 8; if a track falls outside all graphical cuts it is tagged as $?_{\text{tag}}$.

$^4$ The TOF detector is divided into 'pads', each one with an area of $\sim 3 \times 3$ cm$^2$. A pad is 'single fired' if it has only one hit on it [12].
In this way, for every particle type, we can compute the probabilities to be tagged as pion, kaon, proton or non-identified. These probabilities are shown in figure 9 as a function of the total momentum. The three samples A, B and C are populated with $D^0$ candidates according to these probabilities both for the signal and for the background.

### 5. Analysis and results

In table 4, we present the signal-to-background ratios for the three samples in the invariant mass range $|M(K,\pi) - M_{D^0}| < 3\sigma$, before any geometrical or kinematical selection. Due to the small fraction of kaons in the background, sample A (kaon identification required) shows the highest $S/B$ ratio ($\sim 2 \times 10^{-5}$). However, figure 9 (central panel) shows that the identification probability decreases rapidly for kaons with momentum larger than 1.5 GeV/c; therefore, for $D^0$ momenta larger than $\sim 2$–3 GeV/c, the fraction of signal that populates sample A becomes marginal. For this reason, we consider as our standard sample the sum of the three samples A, B and C (called ‘total’ in table 4); this corresponds to the rejection of $(\pi_{tag},\pi_{tag})$ and $(K_{tag},K_{tag})$ pairs. In the low $p_T$ region, it will be eventually convenient to restrict the PID selection to sample A only.

Several selection cuts are applied in order to increase the $S/B$ ratio to the level needed to extract the signal. Their definition is presented in the following paragraphs.

Figure 10 shows a sketch of the $D^0 \rightarrow K^- \pi^+$ decay. For each $D^0$ candidate we compute the position of the decay vertex; this is done with a minimization of the distance in space between the two helices representing the particle trajectories. Pairs for which the distance of closest approach ($dca$) between the tracks is larger than $dca_{\text{max}}$ (\approx 300 \mu m) are rejected.

Since the transverse momentum distributions for the signal are harder than those for the background, it is convenient to apply a cut on the minimum $p_T$ for $K$ and $\pi$ ($p_T > 200$ MeV/c).
The momentum of the $D^0$ candidate is calculated as the sum of the momenta of the kaon and of the pion at the position of closest approach between the two tracks. In the reference frame of the decaying $D^0$, we define $\theta^*$ as the angle between the pion momentum and the $D^0$ line of flight (see the sketch in figure 11). As shown in figure 11 (right), the background accumulates at $\cos \theta^* = \pm 1$. The distribution for the signal is not uniform due to the other cuts applied, in particular the cut on the minimum $p_T$ of the pion and of the kaon. The slight asymmetry reflects the different mass of the kaon and the pion. Only pairs with $|\cos \theta^*| < \cosh_{\text{max}} (\approx 0.6)$ are kept.

With these cuts the signal-to-background ratio improves by a factor of $\sim 100$. In order to improve beyond this, the most effective selection to extract the $D^0$ mesons out of the large combinatorial background is based on the impact parameter and on the requirement that the reconstructed $D^0$ points back to the primary vertex.

We will consider only the impact parameter projection on the bending plane since it is measured much more precisely than that along the $z$ direction. In the bending plane, the impact parameter is defined as the distance of closest approach of the track to the primary vertex (as discussed above, the position of the primary vertex is estimated with a resolution of $\approx 15 \mu m$ in the bending plane). The impact parameter distribution is shown in figure 12 for the various sources of background. It can be seen that for very large impact parameters ($d_0 > 500 \mu m$) the dominant background comes from the decay of hyperons and $K^0_S$. Indeed, we have found that an upper cut on $d_0$ gives an efficient rejection of this background contribution.

The projection of the tracks on the bending plane allows us to define a sign for the impact parameter. This sign is positive or negative according to the position of the track.
projection with respect to the primary vertex (the orientation is given by the direction of the track momentum). The tracks of opposite charge originating from a $D^0$ decaying far from the primary vertex will then have impact parameters of opposite signs and large in absolute value. This is illustrated in figure 10. A very appropriate variable for selection is the product of the two transverse projections of the impact parameters. For true decays this quantity should tend to be negative and large in absolute value. In figure 13 we plot the distribution of the product of impact parameters for the signal and background, normalized to the same number of entries. This cut improves the $S/B$ ratio by a factor of $\approx 10$.

The condition for the $D^0$ to point back to the primary vertex is imposed by a cut on the angle between the momentum vector of the $D^0$ candidate and the line connecting the primary and the secondary vertices (pointing angle $\theta_{\text{pointing}}$). The cosine of $\theta_{\text{pointing}}$ peaks at +1 for the signal, and is almost uniformly distributed for the background, as shown in figure 14.
Figure 14. Cosine of the pointing angle for signal and background combinations. The two distributions are normalized to the same number of entries.

Table 5. Final value of the cuts in the different $p_T$ bins.

<table>
<thead>
<tr>
<th>Cut name</th>
<th>$1 &lt; p_T &lt; 2\text{ GeV}/c$</th>
<th>$2 &lt; p_T &lt; 3\text{ GeV}/c$</th>
<th>$3 &lt; p_T &lt; 5\text{ GeV}/c$</th>
<th>$p_T &gt; 5\text{ GeV}/c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance of closest approach ($d_{ca}$)</td>
<td>$d_{ca} &lt; 400\text{ \mu m}$</td>
<td>$d_{ca} &lt; 300\text{ \mu m}$</td>
<td>$d_{ca} &lt; 300\text{ \mu m}$</td>
<td>$d_{ca} &lt; 300\text{ \mu m}$</td>
</tr>
<tr>
<td>Pion min. $p_T$</td>
<td>$</td>
<td>\cos \theta^*</td>
<td>&lt; 0.6$</td>
<td>$</td>
</tr>
<tr>
<td>Kaon min. $p_T$</td>
<td>$p_T(K) &gt; 800\text{ MeV}/c$</td>
<td>$p_T(K) &gt; 800\text{ MeV}/c$</td>
<td>$p_T(K) &gt; 800\text{ MeV}/c$</td>
<td>$p_T(K) &gt; 800\text{ MeV}/c$</td>
</tr>
<tr>
<td>$\Delta M =</td>
<td>M(K\pi) - M_{\rho\rho}</td>
<td>$</td>
<td>$</td>
<td>\Delta M</td>
</tr>
<tr>
<td>Pion max. impact parameter</td>
<td>$d_{0}^\pi &lt; 700\text{ \mu m}$</td>
<td>$d_{0}^\pi &lt; 500\text{ \mu m}$</td>
<td>$d_{0}^\pi &lt; 500\text{ \mu m}$</td>
<td>$d_{0}^\pi &lt; 500\text{ \mu m}$</td>
</tr>
<tr>
<td>Kaon max. impact parameter</td>
<td>$d_{0}^K &lt; 700\text{ \mu m}$</td>
<td>$d_{0}^K &lt; 500\text{ \mu m}$</td>
<td>$d_{0}^K &lt; 500\text{ \mu m}$</td>
<td>$d_{0}^K &lt; 500\text{ \mu m}$</td>
</tr>
<tr>
<td>$\prod_{d_{0}} = d_0^\pi \times d_0^K$</td>
<td>$\prod_{d_{0}} &lt; -60000\text{ \mu m}^2$</td>
<td>$\prod_{d_{0}} &lt; -40000\text{ \mu m}^2$</td>
<td>$\prod_{d_{0}} &lt; -30000\text{ \mu m}^2$</td>
<td>$\prod_{d_{0}} &lt; -20000\text{ \mu m}^2$</td>
</tr>
<tr>
<td>Pointing angle $\cos \theta_p$</td>
<td>$\cos \theta_p &gt; 0.95$</td>
<td>$\cos \theta_p &gt; 0.98$</td>
<td>$\cos \theta_p &gt; 0.98$</td>
<td>$\cos \theta_p &gt; 0.98$</td>
</tr>
</tbody>
</table>

Table 6. Final values of $S/B$ and $S/\sqrt{S+B}$ for $10^7$ Pb–Pb events.

<table>
<thead>
<tr>
<th>Sample</th>
<th>$S$/event</th>
<th>$B$/event</th>
<th>$S/B$</th>
<th>$S/\sqrt{S+B}$ ($10^7$ events)</th>
<th>$\sigma_S/S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>$4.4 \times 10^{-4}$</td>
<td>$1.4 \times 10^{-3}$</td>
<td>32%</td>
<td>33</td>
<td>4%</td>
</tr>
<tr>
<td>B</td>
<td>$4.3 \times 10^{-4}$</td>
<td>$5.2 \times 10^{-3}$</td>
<td>8%</td>
<td>8</td>
<td>18%</td>
</tr>
<tr>
<td>C</td>
<td>$4.6 \times 10^{-4}$</td>
<td>$5.0 \times 10^{-3}$</td>
<td>9%</td>
<td>9</td>
<td>16%</td>
</tr>
<tr>
<td>Total</td>
<td>$1.3 \times 10^{-3}$</td>
<td>$1.16 \times 10^{-2}$</td>
<td>11%</td>
<td>37</td>
<td>4%</td>
</tr>
</tbody>
</table>

Demanding to have $\cos \theta_{\text{pointing}} > 0.98$ would also give, by itself, a background rejection of one order of magnitude.

A much larger rejection factor can be obtained by combining these two cuts. In fact, if the secondary vertex is well separated from the primary one, the impact parameters are large and the pointing angle is small, since the $D^0$ flight direction is measured with a better
resolution. Therefore, the two variables are strongly correlated in the signal, while this correlation is absent in the background. This can be seen in figure 15, which shows the bidimensional plot of $\cos \theta_{\text{pointing}}$ versus the product of impact parameters. The improvement in the signal-to-background ratio obtained by applying the combined cut is about a factor of $10^3$.

Every cut has been studied in order to maximize the statistical significance $S/\sqrt{S+B}$, calculated for $10^7$ central Pb–Pb events. Also, the optimization of the cuts has been done separately for the following bins in the $p_T$ of the $D^0$: $1 < p_T < 2$ GeV/$c$, $2 < p_T < 3$ GeV/$c$, $3 < p_T < 5$ GeV/$c$, $p_T > 5$ GeV/$c$. The optimization procedure consists in varying one cut at a time while the others are kept constant and selecting the value of the cut which maximizes the significance. As an example of the cut-tuning procedure, figure 16 shows the tuning of the $d_0(K) \times d_0(\pi)$ cut for the different $p_T$ bins. The significance is plotted as a function of the value of the cut. For higher momenta the maximum of the significance is found at higher values of the cut, since the impact parameter resolution improves as the $p_T$ increases.

In table 5 the final values of the cuts are reported.

Figure 17 shows the invariant mass distribution for the sum of samples A, B and C after selection, corresponding to $10^7$ events. The $D^0$ invariant mass resolution is 12 MeV (with a 0.4 T magnetic field).
Figure 16. Tuning of the $d_0(K) \times d_0(\pi)$ cut for the different $p_T(D^0)$ bins. The arrows mark the values chosen for the cut.

Figure 17. $K\pi$ invariant mass distribution for $10^7$ events. The same distribution after background subtraction is shown in the inset.

In table 6 the values for $S$/event, $B$/event and $S/B$, in the invariant mass range $|M(K, \pi) - M_{D^0}| < 1\sigma$, are presented. The cuts applied so far, including also the $\pm 1\sigma$ cut on the invariant mass, select 1% of the signal and reduce the background by a factor of $4 \times 10^{-7}$. In the same table, we also report the significance $S/\sqrt{S+B}$ for $10^7$ Pb–Pb events.
and the relative error $\sigma_S/S$ on the estimation of the number $S$ of detected $D^0$ mesons. The relative error depends on the method of background subtraction; we estimated that it will amount to about $\sqrt{S + 2B}/S$. 

Figure 18. $K\pi$ invariant mass distribution in the bin $1 < p_T < 2\text{GeV}/c$ for the sample of candidates with kaon identified (10$^7$ events).

Figure 19. $p_T$ distribution for the signal (solid line) and for the background (dashed line) after selection (left); the normalization corresponds to one central Pb–Pb event. Corresponding significance for 10$^7$ events as a function of $p_T$ (right). The marker shows the significance obtained in the bin $1 < p_T < 2\text{GeV}/c$ requiring the identification of the kaon.
Table 7. $S/B$ and $S/\sqrt{S+B}$ as from this analysis ($dN_{ch}/dy = 6000$) and scaled for a lower multiplicity ($dN_{ch}/dy = 3000$).

<table>
<thead>
<tr>
<th>$dN_{ch}/dy$</th>
<th>$S/B$</th>
<th>$S/\sqrt{S+B}$ (10$^7$ events)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>11%</td>
<td>37</td>
</tr>
<tr>
<td>3000</td>
<td>44%</td>
<td>74</td>
</tr>
</tbody>
</table>

Considering the sum of three samples A, B and C, the significance integrated over all $p_T$ is 37. Figure 19 shows the $p_T$ distribution of the signal and of the background absolutely normalized and the significance as a function of $p_T$. With $10^7$ events we will have a significance larger than 10 up to about 10 GeV/c of $p_T$. For $p_T > 4$ GeV/c, the ratio $S/B$ increases but the significance decreases due to the decrease in the signal statistics. The bin $1 < p_T < 2$ GeV/c has a significance of about 8. However, since at low $p_T$ the kaon identification efficiency is still quite large, considering candidates with the kaon identified (sample A) gives a significance of 12 in this $p_T$ bin (as shown by the marker in the right panel of figure 19). Figure 18 shows the invariant mass distribution for this sample; even for this low $p_T$ bin, the signal is well visible over the background.

With the choice of parameters we have used for the generation of the signal, the fraction of the transverse momentum distribution for which we have sensitivity ($p_T > 1$ GeV/c) corresponds to about 65% of the total $D^0$ production cross section, at midrapidity.

The present analysis assumes a charged particle rapidity density of $dN_{ch}/dy = 6000$ for the underlying events. The most recent results [2] from the RHIC collider at BNL indicate as a more realistic value $dN_{ch}/dy = 3000$, or even lower. If the multiplicity density $dN_{ch}/dy$ decreases, the number of background pairs decreases as $(dN_{ch}/dy)^2$. Therefore, $S/B$ is proportional to $(dN_{ch}/dy)^{-2}$. The significance is proportional to $(dN_{ch}/dy)^{-1}$ if $S \ll B$, so that $S/\sqrt{S+B} \simeq S/\sqrt{B}$. This condition holds for our $p_T$-integrated significance, since we have $S \simeq B/10$; for the $p_T$-dependent significance such a scaling can be applied only up to $p_T \simeq 3$ GeV/c, as for larger transverse momenta the significance is dominated by the statistics of the signal. In Table 7 we just scale the $p_T$-integrated results, according to the proportionalities mentioned above, to a case of lower multiplicity (the $cc$ production rate is not rescaled because it is not clear how it will be correlated with the total multiplicity and because we have used the average of the values given by the different PDFs, which is already a conservative estimate). In addition, with a lower multiplicity the tracking efficiency will improve and a further improvement can be expected from a refinement of the cuts.

6. Conclusions

A feasibility study for the detection of $D^0$ mesons in the $K^-\pi^+$ decay channel in Pb–Pb collisions at the LHC has been presented. The detection strategy is based on the invariant mass analysis of fully reconstructed topologies that originated in displaced secondary decay vertices. This strategy exploits the excellent capabilities of the ALICE detector in track reconstruction (time projection chamber and inner tracking system), secondary vertex identification (inner tracking system with silicon pixel detectors) and particle identification (time of flight). All the expected background sources have been included. The signal selection has been studied as a function of $p_T$. With a sample of $10^7$ central Pb–Pb collisions, $D^0$ mesons can be selected with a statistical significance larger than 10 up to $p_T \simeq 10$ GeV/c. The lower $p_T$ limit is 1 GeV/c.
Besides the $D^0$, there are other particles with open charm that could, in principle, be fully reconstructed via their hadronic decays. Among them, $D^- \rightarrow K^- \pi^+ \pi^-$ and $D^{*+} \rightarrow D^0 \pi^+$ look promising and their detection should be feasible with ALICE.

Acknowledgments

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References

[1] ALICE Technical Proposal CERN/LHCC 95-71