Open charm meson analysis in proton-proton collisions at the LHC with ALICE

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Abstract. The extremely high energies that will be reached with the Large Hadron Collider (LHC) at CERN will allow studying the production of open charm with high statistics in both proton-proton and Pb-Pb collisions. The study of open charm (D) mesons in Pb-Pb collisions will be a powerful tool to investigate the production of heavy flavours and their interaction with the medium produced in such collisions (QGP). Heavy flavour yields will provide also a normalization for quarkonia production. We will present a general overview of the ALICE collaboration heavy flavour program, then we will focus on the analysis and reconstruction strategies developed for the study of the charmed (D) mesons by the ALICE collaboration for proton-proton collisions, with special emphasis on the charged D mesons. Finally, some expected results obtained with MonteCarlo production will be shown.

1. Introduction
At the Large Hadron Collider (LHC) at CERN energies as high as $\sqrt{s_{NN}} = 5.5$ TeV for Pb-Pb collisions and $\sqrt{s_{NN}} = 14$ TeV for proton-proton collisions will be reached, opening up a new domain for the study of strongly interacting matter in conditions of high temperature (3 to 5 times higher than the critical temperature) and high energy density (15 to 60 GeV/fm\textsuperscript{3}). QCD calculations\textsuperscript{[1]} at high temperature and high energy density predict in such conditions the formation of a deconfined state of matter, called Quark-Gluon Plasma. In the study of the properties of the produced (deconfined) state, heavy quarks play a crucial role. Heavy quarks and hard partons, abundantly produced at LHC energies in the initial hard scattering processes, are sensitive probes of the medium formed in the collisions as they may lose energy by gluon radiation while propagating through the medium itself.

At LHC energy, charm and beauty will be abundantly produced. The cross-sections at LHC are expected to increase by about a factor of 10 for charm and 100 for beauty with respect to RHIC. The baseline production cross-section of $Q\overline{Q}$ pairs for ALICE simulation studies has been calculated in the framework of collinear factorization and pQCD\textsuperscript{[2]}, including the nuclear modification of the parton distribution functions (PDFs)\textsuperscript{[3]}. The expected $c\overline{c}$ and $b\overline{b}$ production yields for pp collisions at the maximum energy available at the LHC ($\sqrt{s_{NN}} = 14$ TeV) are 0.16 and 0.0072, respectively\textsuperscript{[4]}. For the 5 \text% most central Pb-Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV, the expected yields are 115 and 4.6 respectively, but it has to be noted that these predictions have large uncertainties, of about a factor 2 to 3, depending on the choice of the quark masses and QCD scales.

\textsuperscript{1} For the ALICE collaboration
# Meson Decay channel

| Meson | Decay channel | $c\tau$ | BR  |
|-------|---------------|---------|-----|
| $D^0$ | $D^0 \rightarrow K^- \pi^+$ | 122.9$\mu$m | (3.91 ± 0.05)% |
| $D^0$ | $D^0 \rightarrow K\pi\pi\pi$ | 122.9$\mu$m | (8.14 ± 0.20)% |
| $D^+$ | $D^+ \rightarrow K^-\pi^+\pi^+$ | 311.8$\mu$m | (9.2 ± 0.25)% |
| $D_s^+$ | $D_s^+ \rightarrow K^+\pi^-\pi^+$ | 149.9$\mu$m | (5.50 ± 0.28)% |
| $D^{++}$ | $D^{++} \rightarrow D^0\pi^+$ | | (61.9 ± 2.9)% |

Table 1. Golden Channels for the reconstruction of open charm mesons[5]

2. The ALICE experiment at the LHC

The ALICE experiment, described in detail in[6], has very good performances for heavy flavour measurements[7]. Experimentally, the two key elements for a rich heavy-flavour program are: good tracking/vertexing and good particle identification. In ALICE, Particle tracking relies on the six concentric layers of high resolution silicon detectors of the Inner Tracking System (ITS)$^2$, a large volume of time projection chamber (TPC)$^3$, and a high granularity transition-radiation detector (TRD). The ALICE detection strategy for charm and beauty hadrons relies on resolving secondary detached vertices reconstructed from tracks with large impact parameters ($d_0$)$^4$. The precision on impact parameter measurement is mainly provided by the two innermost ITS layers (SPD) in the bending plane ($r\phi$) and the two intermediate ITS layer (SDD) for $z$-coordinate. A resolution $\sigma_{d0}$ better than 60$\mu$m in the bending plane is achieved for tracks with $p_T > 1.5$ GeV/c. Particle identification is performed, in the central rapidity region, over the full azimuth by a dE/dx measurement in the tracking detectors (TPC and ITS), via time of flight measurement using Time of Flight detector (TOF) and transition radiation measurement in the Transition Radiation Detector (TRD). Muons are identified in the Forward Muon Spectrometer in the pseudorapidity range $-4 < \eta < -2.5$

3. Open Charm measurement

Open charm meson will be measured through their hadronic decays in fully reconstructed topologies. The strategy to reduce the large combinatorial background is based on the selection of displaced-vertex topologies, i.e. large separation between the primary and the secondary vertex, good alignment between the reconstructed D meson momentum and the flight line, large impact parameter. The golden channels that will be studied are listed in table 1.

After the reconstruction, an invariant mass analysis is used to extract the raw signal yield, and then corrections for the detector acceptance, for selection efficiency and reconstruction efficiency are applied.

$D^0$ reconstruction

The most promising channel for the study of $D^0$[7, 8] is the channel $D^0 \rightarrow K^-\pi^+$, although also the 4-prongs decay $D^0 \rightarrow K\pi\pi\pi$ will be studied. The selection strategy is based on the application of 2 different cuts: the product of the impact parameter of the two tracks ($d_0^{K} \times d_0^{\pi}$)

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$^2$ Two innermost layers equipped with silicon pixel (SPD) plus two middle layers of silicon drift detectors (SDD), and two outermost layers of silicon strip detectors (SSD)

$^3$ see J. Alme et al, Nucl. Instr. Meth. A (in print), arXiv:1001.1950

$^4$ the impact parameter being the distance of closest approach of a particle trajectory to the primary vertex
and the cosinus of the pointing angle\(^5\) of the reconstructed \(D^0\) meson. Figure 1 shows a sketch of this decay topology. The goal of this selection is to increase the significance (the ratio \(\frac{S}{\sqrt{S+B}}\), where \(S\) is the signal and \(B\) the background). The effect of this cuts on the significance is shown in figure 2. As shown in Figure 3, the statistical error on \(D^0\) is expected to be smaller than 20% after the first year of data taking at 14 TeV\(^{10}\).

\(^5\) If the reconstructed particle is a real D meson, then \(\cos \theta_{\text{point}} \approx 1\), being \(\theta_{\text{point}}\) the angle between the momentum of the reconstructed particle and the flight line towards the primary vertex.
$D^+$ reconstruction

The $D^+$ meson will be reconstructed in the channel $D^+ \to K^- \pi^+ \pi^+$[9]. With respect to the decay $D^0 \to K^- \pi^+$ this topology is affected by higher combinatorial background. On the other hand, as shown in table 1, the branching ratio of this decay is higher and the $D^+$ has longer life time ($c\tau \sim 310 \mu m$). Thus we can use a cut on the distance between primary and secondary vertex to remove combinatorial background. Triplets with the correct charge sign combination will be built, then the main cuts for a selection strategy to separate the signal from the huge combinatorial background for the $D^+$ are therefore the distance between the primary and secondary vertices and the cosine of the pointing angle of the reconstructed meson. To perform this selection, an extremely good vertexing resolution, both on the primary and secondary vertex must be reached. The expected performance on vertex resolution of ALICE is shown in figure 5. Figure 4 shows the expected statistical error after 1 year of data taking. The significance for the $D^+$ is shown in figure 6 for both pp and Pb-Pb collisions.

Figure 4. Relative statistical error for $D^+$ after 1 year of data taking in pp (14 TeV) collisions and Pb-Pb (5.5 ATev) collisions

Figure 5. Resolution on the $D^+$ decay vertex

Figure 6. $D^+$ significance after 1 year of data taking in pp (14 TeV) collisions and Pb-Pb (5.5 ATev) collisions
$D^*$ and $D_s$ reconstruction

$D_s$ reconstruction is very challenging, as the yield of $D_s$ against the huge combinatorial background is low. But $D_s$ is likely to decay in a final state $K^- K^+\pi^+$ through an intermediate resonant states, so the analysis can take advantage from this to separate signal from background. The analysis will be performed in the channel $D_s \rightarrow \phi \pi^+ \rightarrow K^- K^+\pi^+$, where simulations show[11] that reconstruction of $D_s$ is feasible, even without PID, for reconstructed $p_T$ as low as 3-4 GeV/c.

$D^{*+}$ has a large branching ratio ($\sim 67\%$) for the channel $D^{*+} \rightarrow D^0 \pi_{soft}^+ \rightarrow K^- \pi^+\pi_{soft}^+$. The analysis technique is based on the reconstruction of the $D^0$ and on the finding of a suitable $\pi$ track of low momentum ($\pi_{soft}$). An estimation of the significance for the $D^*$ after one year of data taking is provided in figure 7.

![Figure 7. $D^*$ significance after 1 year of data taking in pp (14 TeV) collisions, ($\sim 10^9$ events). Solid: PID performed with both TPC and ITS, dotted: ITS only.](image)

4. Energy Loss

![Figure 8. Nuclear modification factor for $D^+$ meson, 1 year of data taking, energy loss calculation from[12]](image)

![Figure 9. Nuclear modification factor for $B$ meson, 1 year of data taking, energy loss calculation from[12]](image)

Parton energy loss is expected to depend strongly on the properties of the medium (gluon density, volume) and of the probe (colour charge, mass) travelling through it. Charm and beauty
quarks are expected to be qualitatively different probes with respect to light partons, as their energy loss is reduced due to mass effects. In figures 8 and 9 is shown the expected measure of the nuclear modification factor after 1 year of data taking for the $D^+$ and the electrons coming from $B$ decay. The ratio $R_{DH}(Pt) = \frac{R_{AA}^D(Pt)}{R_{AA}^h(Pt)}$ shown in figure 10 is an interesting probes of the colour charge dependence of the energy loss, as light hadrons mainly come from gluons, carrying a stronger colour charge. Also, the ratio $R_{BD}(Pt) = \frac{R_{AA}^B(Pt)}{R_{AA}^D(Pt)}$ (figure 11) is a probe of the mass dependence of the energy loss, as $B$ and $D$ come from objects with the same colour charge but different mass.

**Figure 10.** Heavy-to-light ratio, 1 year of data taking, energy loss calculation from[12]

**Figure 11.** $R_{BD}$, 1 year of data taking, energy loss calculation from[12]

5. Charm Flow

Flow, and especially the elliptic flow[13, 14], is an important probe which can provide information about the thermalization of the medium (QGP) produced in a non-central high energy collision. If thermalization is achieved, then collective behaviour should appear. Heavy flavour, due to their higher mass, are less likely to thermalize. Thus, the measurement of the flow of heavy flavours is interesting to study the properties of the QGP.

In figures 12 and 13 is shown the expected measurement of the elliptic flow of $D^+$ mesons for $2 \times 10^7$ Pb-Pb events for two different cases: minimum bias trigger (in the left panel) and semi-peripherical trigger (in the right panel) in the two extreme conditions of no charm flow (meaning that charm doesn’t thermalize in the medium) and of charm flowing in the same way as light partons. Statistical error bars are strongly reduced when we move from minimum bias to semi-peripherical ($6 < b < 9$ fm) events, thus $v_2(p_T)$ should be measurable down to $p_T \sim 1 GeV/c$.

6. Conclusions

With its excellent tracking, vertexing and particle identification capabilities, ALICE has very promising perspectives for the studies of heavy flavour production. It has been shown there is good feasibility of reconstruction of $D$ and $B$ mesons with a good significance in one year of data taking at nominal luminosity. This will allow to measure with good precision the energy loss and the azimuthal anisotropy of those particles.

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Figure 12. Expected $D^+$ elliptic flow after $2 \times 10^7$ Pb-Pb minimum bias events. Solid: $v_2^D = v_2^q$, dotted: $v_2^D = 0$

Figure 13. Expected $D^+$ elliptic flow after $2 \times 10^7$ Pb-Pb semi-peripheral events ($6 < b < 9$ fm). Solid: $v_2^D = v_2^q$, dotted: $v_2^D = 0$

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