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Measurements of $D^+_s$ production in pp, p–Pb and Pb–Pb collisions with ALICE at the LHC

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Abstract. ALICE has measured $D^+_s$ production at mid-rapidity in pp ($\sqrt{s}=7$ TeV), p–Pb ($\sqrt{s_{NN}}=5.02$ TeV) and Pb–Pb ($\sqrt{s_{NN}}=2.76$ TeV) collisions, through the hadronic decay channel $D^+_s \rightarrow \phi \pi^+ \rightarrow K^+ K^- \pi^+$. The study of the $D^+_s$-meson production could reveal important details about charm-quark hadronisation in the Quark-Gluon Plasma (QGP). The measured $D^+_s$ yields in pp and p–Pb collisions and the nuclear modification factors for central and semi-central Pb–Pb collisions will be shown here as a function of transverse momentum.

1. Introduction

Heavy quarks (charm and beauty) are excellent tools to study the properties of the hot and dense medium created in high-energy heavy-ion collisions. Charm and beauty quarks are produced in high-momentum transfer parton scatterings. Therefore, their production cross-section can be calculated using perturbative QCD (pQCD). Such processes occur, in Pb–Pb collisions, at the early stage of the reaction and on timescales shorter than the QGP formation time [1]. Heavy quarks hence experience the entire evolution of the fireball, interacting with its constituents via both elastic and inelastic processes, exchanging energy and momentum with the expanding medium [1, 2].

Evidence for heavy-quark energy loss is provided by the measurement of the nuclear modification factor $R_{AA}$, defined as the ratio of the yield measured in nucleus–nucleus collisions and the cross-section in pp interactions scaled by the average nuclear overlap function for a given centrality class. If no medium effects are present, one expects $R_{AA} = 1$. A value of $R_{AA}$ that differs from unity implies modifications of the production of D(B) mesons relative to pp collisions, that can be induced by initial or final-state effects. In particular, the observed suppression of D mesons at high $p_T$ with respect to the binary-scaled pp yield is described in terms of in-medium energy loss of charm quarks [3].

A significant fraction of charm quarks could undergo hadronisation via in-medium coalescence at intermediate and low momentum [4]. Furthermore, an enhancement of strangeness production with respect to pp collisions was long suggested as a possible signal of QGP formation [5]. Strange and multistrange hadron enhancement was observed from SPS to LHC energy, showing a dependence on the strangeness content of the particles and also on the collision centrality [6, 7, 8]. In this scenario, the measurement of $D^+_s$ production would provide knowledge on charm-quark hadronisation inside the medium. The possibility of coalescence of charm quarks with the medium constituents, together with the possible strangeness enhancement, should lead to a
larger relative abundance of D_s mesons compared to non-strange D mesons when going from pp to Pb–Pb collisions [10].

2. Reconstruction of D^+_s mesons in ALICE

D^+_s mesons and their charge conjugates are reconstructed at mid rapidity (|y| < 0.8) in their decay channel \( D^+_s \rightarrow \phi\pi^+ \rightarrow K^+ K^-\pi^+ \), with a branching ratio of \( (2.24 \pm 0.10)\% \) and a mean proper decay length of \( (150 \pm 2) \mu m \) [11]. The analysis strategy is based on the reconstruction of three-prong decay topologies with a secondary vertex separated from the interaction vertex. The large combinatorial background is reduced by applying a selection based on the decay topology together with a selection on the invariant mass of the reconstructed \( \phi \) meson. To separate secondary and primary vertices, excellent vertex and impact parameter resolutions are mandatory. These are provided by the Inner Tracking System (ITS), a six-layer silicon detector covering the pseudorapidity interval \( |\eta| < 0.9 \) [12]. In the same pseudorapidity region, track reconstruction is performed using the ITS together with the Time Projection Chamber (TPC). Finally, particle identification is provided in \( |\eta| < 0.9 \) by the TPC via specific energy-loss measurements and by the Time-Of-Flight (TOF) detector. They provide K/\( \pi \) separation up to a transverse momentum \( p_T \sim 2.5 \text{ GeV}/c \). A track is considered compatible with the kaon or pion hypothesis if both its dE/dx and time-of-flight are within 3\( \sigma \) from the expected values. Tracks without a TOF signal (mostly at low momentum) are identified using only the TPC information and requiring a 2\( \sigma \) compatibility with the expected dE/dx.

The raw \( D^+_s \)-meson yield was corrected to obtain the production yields of prompt mesons (i.e. not coming from weak decays of B mesons) [13]. A correction was also applied for the acceptance and selection efficiency of prompt \( D^+_s \) mesons. The measurements presented here refer to prompt \( D^+_s \) only, as they were computed as the average of particles and antiparticles under the assumption that the production cross section is the same for \( D^+_s \) and \( D^-_s \).
3. Results

3.1. pp collisions at \( \sqrt{s} = 7 \) TeV

D\(_{s}^{+}\) production in pp collisions was measured from a data sample of \(3 \times 10^6\) events, corresponding to an integrated luminosity \(L_{\text{int}} = 4.8 \, \text{nb}^{-1}\). The result in pp collisions provides a test for pQCD calculations at LHC energies, as well as a reference for p–Pb and Pb–Pb measurements. The production cross section of prompt D\(_{s}^{+}\) mesons in four transverse momentum intervals in the range \(2 < p_T < 12\) GeV/c is shown in Fig. 1 [13]. The error bars represent the statistical uncertainties, the systematic uncertainties are shown as empty boxes. The measurement is well described within uncertainties by a pQCD next-to-leading order GM-VFNS calculation [14]. It is also compatible with the \(k_T\)-factorization model at LO [15], that uses unintegrated gluon distributions in the proton.

3.2. p–Pb collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV

The data sample of p–Pb collisions consists of \(97.3 \times 10^6\) events (\(L_{\text{int}} = 48.6 \, \mu \text{b}^{-1}\)). Measurements with this colliding system are necessary to assess the role of possible cold nuclear matter effects in the modification of heavy-flavour production with respect to pp collisions. They are therefore crucial for the interpretation of the results in Pb–Pb collisions where a hot and dense medium is created. Figure 2 shows the \(p_T\)-differential cross section of prompt D\(_{s}^{+}\)-meson production in the range \(2 < p_T < 12\) GeV/c [16]. Data in p–Pb collisions (black points) are compared to the reference obtained by scaling the measured cross section in pp collisions at \(\sqrt{s} = 7\) TeV to \(\sqrt{s} = 5.02\) TeV (blue points) and multiplying it by the number of nucleons in the lead nucleus. The two cross sections are compatible within uncertainties. The \(R_{pPb}\) obtained as the ratio of these cross sections is compatible with unity within uncertainties. This result indicates that cold nuclear matter effects are small in the measured \(p_T\) range.

3.3. Pb–Pb collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV

Two different centrality classes were analysed, namely the 7.5% most central collisions (\(16 \times 10^6\) events, \(L_{\text{int}} = 21.5 \, \mu \text{b}^{-1}\)) and the semi-central collisions in the 20–50% class (\(13.5 \times 10^6\) events, \(L_{\text{int}} = 5.9 \, \mu \text{b}^{-1}\)). The \(R_{AA}\) of D\(_{s}^{+}\) mesons as a function of \(p_T\) is shown in Fig. 3, in three \(p_T\) intervals from 4 to 12 GeV/c for the most central events, and in two \(p_T\) intervals from 6 to 12 GeV/c for semi-central events. A significant suppression of the D\(_{s}^{+}\)-meson yield by a factor about three in Pb–Pb collisions relative to the binary-scaled pp cross section is observed in the highest \(p_T\) interval (\(8 < p_T < 12\) GeV/c) for the most central events. This suppression is due to in-medium energy loss as \(R_{pPb}\) in this \(p_T\) range is compatible with unity. A hint for a smaller suppression is found for the more peripheral events at the same \(p_T\), although the values are consistent within uncertainties. The comparison of \(R_{AA}\) of D\(_{s}^{+}\) in the 0–7.5% centrality class with the average nuclear modification factor of D\(_{0}\), D\(_{+}\) and D\(_{+}^{*}\) mesons measured in the same centrality class is presented in Fig. 4. The central values of the D\(_{s}^{+}\) \(R_{AA}\) are larger than those of non-strange D mesons in the intervals \(4 < p_T < 6\) and \(6 < p_T < 8\) GeV/c, but compatible within uncertainties. To conclude about the predicted enhancement of the D\(_{s}^{+}\) yield relative to non-strange D mesons in heavy-ion collisions and about the centrality dependence of D\(_{s}^{+}\) \(R_{AA}\), uncertainties need to be reduced.

In Fig. 4 the results are also compared to predictions of the TAMU model [17], which currently is the only one that provides quantitative calculations for the \(p_T\)-differential D\(_{s}^{+}\) nuclear modification factor. In this model the interactions of charm quarks with the medium constituents are described via elastic collisions. The hadronisation of charm quarks into non-strange D and D\(_{s}\) mesons is performed via recombination with thermalized light and strange quarks, respectively. The \(R_{AA}\) of D\(_{s}\) is hence predicted to be higher relative to non-strange D mesons. The theoretical calculation results can describe the measurements within uncertainties.
4. Conclusions

We have measured $D_s^+$ production in pp, p–Pb and Pb–Pb collisions. The measurement of the $p_T$-differential cross section in pp collisions is described by pQCD calculations at LHC energies. The results for the 7.5% most central events in Pb–Pb collisions indicate a suppression ($R_{AA} \sim 0.3$) of the production of $D_s^+$ mesons at high $p_T$ ($8 < p_T < 12$ GeV/$c$) with respect to the reference obtained from the binary-scaled pp yields. The observed suppression is compatible with that of non-strange D mesons and can be described by models including charm quark in-medium energy loss. At lower momenta ($4 < p_T < 8$ GeV/$c$), where the relative abundance of strange and non-strange D mesons could be influenced by charm quark recombination in the medium, the values of the $D_s^+$-meson nuclear modification factor are larger than those of non-strange D mesons, although compatible within uncertainties.

The larger data samples that will be collected during Run 2 at the LHC will allow us to substantially reduce the measurement uncertainties and to provide further constraints to models.

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