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Study of charm hadronization via Λ_c and D_s production in pp and PbPb collisions with the CMS experiment

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Because of their large masses, the interactions of heavy quarks with the quark-gluon plasma (QGP) may be different from those of light quarks and hence can provide essential inputs in understanding the QGP. With strange quark yields being enhanced in the presence of a QGP, the production of D_s^+ is expected to be enhanced if recombination plays an important role in the hadronization process. Furthermore, studies of the lightest charm baryon, Λ_c^+, can provide further information to charm quark hadronization. Models involving quark coalescence predict a large enhancement of Λ_c^+ production in PbPb collisions compared to pp collisions. The Λ_c^+ and D_s production in both pp and PbPb collisions at a nucleon-nucleon center-of-mass energy of 5.02 TeV have been measured in the CMS experiment. Results of Λ_c^+ and D_s differential cross-sections, and the ratios of these two yields over those for D^0 in pp and PbPb collisions are presented.

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1. Introduction

Heavy quarks are good probes of the Quark-Gluon Plasma (QGP) because they are created at the earliest stage of the heavy-ion (AA) collision and they follow the whole evolution of the system [1]. They are also convenient for perturbative calculations and therefore make a good connection between theoretical predictions and experimental results. Their energy loss mechanism is expected to be different from that of light quarks [2] and hence can provide important inputs for studying the properties of the medium. The heavy quarks could also play an important role in understanding the fragmentation processes. It has been found that for up, down, and strange quarks, the baryon-to-meson ratio is enhanced in AA collisions with respect to that in the proton-proton (pp) collisions [3] due to coalescence and there is an indication that the charm quark could exhibit a similar behavior. In this paper, the p_{T}-differential analysis of the production of inclusive Λ_c^+ baryons ad prompt D_s^+ mesons in pp and lead-lead (PbPb) collisions will be presented as well as comparison with corresponding D^0 results.

The charm hadronization has been studied already at the LHC [4–7] with a discrepancy reported between ALICE and LHCb, although the measurements were done in different rapidity regions. ALICE results also show a larger Λ_c^+/D^0 cross-section ratio in PbPb than in pp collisions and also a larger nuclear modification factor of strange than non-strange D mesons [8]. However, the uncertainties of these results are still too large to draw a definite conclusion.

2. Analysis details

This analysis is performed using pp and PbPb collision data at the center of mass energy per nucleon pair of 5.02 TeV, collected by the CMS detector [11] during the year 2015 and 2017 respectively. The total integrated luminosity for pp (PbPb) data is $27.4\mathrm{pb}^{-1}$ ($539\ \mu\mathrm{b}^{-1}$).

The Λ_c^+ baryons are reconstructed via the hadronic decay channel $\Lambda_c^+ \to \mathrm{pK}^-\pi^+$ and for D_s^+ the corresponding decay channel $D_s^+ \to \phi\pi^+ \to \mathrm{K}^+\mathrm{K}^-\pi^+$ was used. There was no particle identification and all possible mass assignments of three charged tracks, with net charge of +1, are taken into account. It was found that the incorrect mass assignment for the Λ_c^+ reconstruction produces a broad distribution in the invariant mass and is indistinguishable from the combinatorial background. For the D_s^+, the invariant mass of $\mathrm{K}^+\mathrm{K}^-$ pairs is required to be within 9 MeV/c^2 of the nominal ϕ mass (1.0195 GeV/c^2) [9]. This condition makes incorrect mass assignments of charged tracks negligible. Particle candidates are reconstructed within the rapidity range $|y| < 1$ and background is further reduced by using multivariate methods [10].

The signal yield in each p_{T} interval is extracted with an unbinned maximum-likelihood fit to the invariant mass distributions. For the signal shape modeling the sum of two Gaussian functions is used, with the same mean but different widths, with the parameters fixed based on the Monte Carlo simulation sample. In the case of the Λ_c^+ baryon reconstruction, the background is modeled with a third-order Chebyshev polynomial, while in the case of the D_s^+ a second-order Chebyshev polynomial was found to be sufficient.

Another difference in the two reconstructions comes from the additional contribution to the D_s^+ signal from different decay channels with the same final states, for example $D_s^+ \to f_0\pi^+ \to \mathrm{K}^+\mathrm{K}^-\pi^+$. To estimate this fraction a fit to the $\mathrm{K}^+\mathrm{K}^-$ pair invariant mass distribution is performed. Finally, the non-prompt ratio of the D_s^+ cross-section is estimated by the measured non-prompt D^0 result [12] multiplied by the total cross section ratio of D_s^+ to D^0.

3. Results

Figure 1 shows the p_T-differential cross section of inclusive Λ_c^+ baryon production in pp as well as the comparison with various models. The shape of the p_T distribution is well predicted by PYTHIA 8 Tune CUETPM81, but the experimental values are systematically higher. A calculation with PYTHIA 8 with the color reconnection (CR) [13] mechanism is consistent with data. Predictions from the GM-VFNS model [15], which are based on perturbative QCD calculations and include only prompt Λ_c^+ [15], are significantly below data for $p_\mathrm{T} < 10$ GeV/c.

The pp results are also compared with T_AA-scaled yields in PbPb collisions for $p_\mathrm{T} < 10$ GeV/c in three centrality classes. Lower values of the Λ_c^+ cross section in PbPb with respect to pp, as well as centrality dependence, suggest enhanced suppression in the PbPb collisions, although a definite conclusion cannot be made due to large uncertainties.

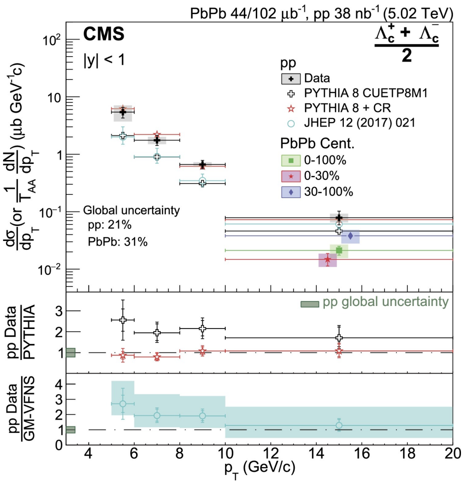

Figure 1: The p_T-differential cross section of inclusive Λ_c^+ in pp and PbPb collisions [18]. In addition comparisons with PYTHIA 8 Tune CUETP8M1 and PYTHIA 8 + CR [13], and GM-VFNS [15] models are also shown.

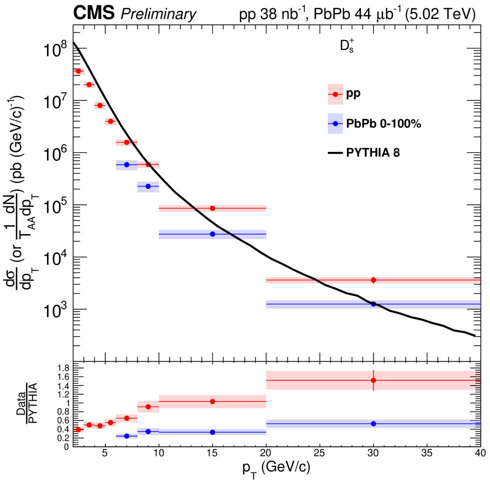

Figure 2: The p_T-differential cross section of prompt D_s^+ in pp and PbPb collisions [19]. Points represent experimental data and the line predictions from PYTHIA8 Tune CUETP8M1 model.

Figure 2 shows the p_T-differential cross section of inclusive D_s^+ production in pp and PbPb collisions. These results are compared with PYTHIA 8 Tune CUETPM81 showing the disagreement in p_T distributions. At low p_T, the D_s^+ cross section is overestimated by PYTHIA calculations, while at high p_T the PYTHIA calculations are smaller than the measured data.

The inclusive Λ_c^+ over prompt D^0 production ratio in pp collisions as a function of p_T and in PbPb collisions for $10 < p_\mathrm{T} < 20$ GeV/c in the centrality range 0–100% is presented on the Fig. 3. The PbPb measurement is consistent with the pp result. This may suggest that there is no significant contribution from the coalescence process in the measured kinematic range. The production ratio in pp collisions is about three times larger in magnitude compared to the calculation from PYTHIA 8 Tune CUETP8M1, while calculations using a color reconnection model are again consistent with pp data.

The experimental results are also compared with two models that give predictions for the prompt Λ_c^+/D^0 production ratio. The Catania [16] model includes both coalescence and fragmentation in pp collisions and predicts a stronger dependence on transverse momentum. Another approach is the TAMU model [17], based on the statistical hadronization with extra excited charm baryon states not listed in the current PDG review [14]. The prediction of this model provides a reasonable description of the data for $p_T < 10$ GeV/c.

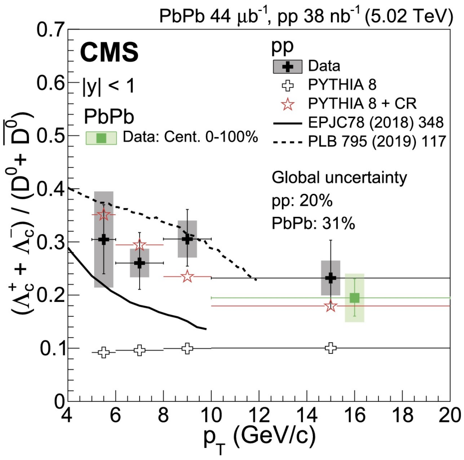

Figure 3: The inclusive Λ_c^+ over prompt D^0 production ratio in pp collisions as a function of p_T and in PbPb collisions is shown [18] and compared with theoretical predictions of PYTHIA Tune TUETP8M1, PYTHIA 8 + CR [13], Catania [16], and TAMU [17] model.

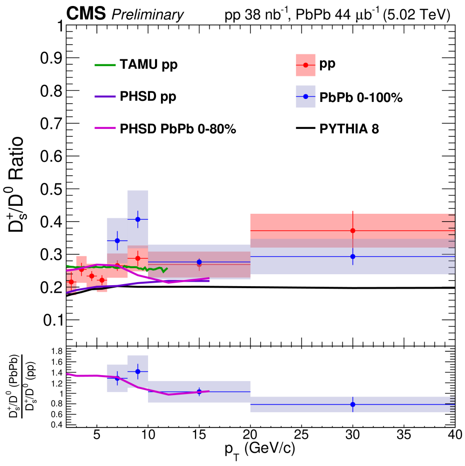

Figure 4: The ratios of prompt D_s^+/D^0 production as a function of transverse momentum in pp and PbPb collisions are shown [19] and compared with the predictions of PYTHIA 8 Tune CUETP8M1, TAMU [17], and PHSD [20, 21] models in the top panel. Double ratio of prompt D_s^+/D^0 in PbPb over pp is presented in the lower panel.

The ratios of prompt D_s^+/D^0 production as a function of transverse momentum in pp and PbPb collisions are shown in the Fig. 4. Again, the magnitude of the ratios is underpredicted by PYTHIA 8 Tune CUETP8M1. Good agreement between TAMU [17] model and measured D_s^+/D^0 in pp collisions, together with Λ_c^+/D^0 data comparison, could be a sign of existence of an excited charm baryon state. PHSD [20, 21], a microscopic transport model which includes the production through coalescence in PbPb collisions, is similar to PYTHIA in terms of pp collision prediction, but reproduces the observed double ratio of D_s^+/D^0 in pp and PbPb collisions.

4. Summary

The CMS measurements of inclusive Λ_c^+ and prompt D_s^+ production are presented and also compared with D^0 results. No significant coalescence of Λ_c^+ in $10 < p_T < 20$ GeV/c was apparent. The PYTHIA 8 model with color reconnection gives a good description of Λ_c^+ production in pp collisions. A reasonable description of both Λ_c^+ and D_s^+ with the TAMU model could be a sign of the existence of extra excited charm baryon states.

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