Measurements of charm quark production and hadronization at CMS

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Abstract. The study of charm quark hadrons is an important probe into the hadronization of heavy quarks. More specifically, we present results on the production of Λ_c baryon, the nuclear modification factors (R_{AA}), and the Λ_c/D^0 yield ratios at $\sqrt{s_{NN}} = 5.02$ TeV in proton-proton (**pp**) collisions and in different centrality regions in lead-lead (**PbPb**) collisions, using data recorded with the CMS detector in 2017 and 2018, respectively. The reported R_{AA} for Λ_c provides useful information regarding the energy loss mechanism and the hadronization processes of charm quark in the quark-gluon plasma. The transverse momentum (p_T) dependence of the R_{AA} is similar to that of other charm and beauty hadrons but with its minimum shifted towards higher p_T. Comparing the Λ_c/D^0 production ratio in pp and **PbPb** collisions suggests that coalescence as a hadronization process is not significant for $p_T > 10$ GeV/c. The ratio becomes comparable to the measurements in e^+e^- collisions for $p_T > 30$ GeV/c. We also present results of the Λ_c baryon and D^0 meson production and their ratios in proton-lead (**pPb**) collisions at $\sqrt{s_{NN}} = 8.16$ TeV as a function of p_T and final-state multiplicity using the data recorded by the CMS experiment in 2016. We do not observe significant multiplicity dependence for the baryon over meson ratio for charm hadrons. Based on a previous study, the difference between the results from charm quarks and those from light quarks suggests coalescence processes for heavy quarks do not increase further with multiplicity, unlike light quarks.

1 Introduction

The quark gluon plasma (QGP), a state with deconfined quarks and gluons, is produced in heavy ion collisions at high energies [1–3]. Since the charm quarks are formed at the early stages of collision due to their large rest mass, they follow the medium evolution and provide insights into different methods of hadronization in the QGP. In the presence of QGP, we expect the coalescence process of hadronization to be more favorable and enhance the production of baryons. We study this effect by measuring the baryon-to-meson ratio for charmed hadrons. The energy loss of charm quarks traveling through the QGP is also interesting since quarks can lose energy via radiation or interactions with the medium [4]. We measure the nuclear modification factor (R_{AA}) to study the suppression of the charm hadrons that are produced in large systems (like PbPb collisions) compared to smaller systems (like pp collisions).

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In this contribution, we report on the measurements of promptly produced Λ_c^+ baryon production at the center-of-mass energy per nucleon, $\sqrt{s_{_{NN}}}$ = 5.02 TeV in pp and PbPb collisions collected by the CMS detector in 2017 and 2018, respectively [5, 6]. We present the cross section of Λ_c^+ in pp collisions and the yields in PbPb collisions, scaled by the mean nuclear overlap function ($\langle T_{AA} \rangle$) as a function of Λ_c^+ transverse momentum (p_T) along with the ratio of Λ_c^+ to D^0 production in pp and PbPb collisions and the R_{AA} vs p_T. We also present the results for Λ_c^+ and D^0 productions in pPb collisions at $\sqrt{s_{_{NN}}}$ = 8.16 TeV, collected in 2016 [7]. The multiplicity dependence of Λ_c^+ and D^0 production yields in pPb collisions is presented.

2 Data sets and analysis details

These analyses use pp, PbPb and pPb collision data at collected with integrated luminosities of 252 nb^{-1}, 0.607 nb^{-1} and 97.8 nb^{-1} respectively. The prompt Λ_c^+ baryons are reconstructed in the central rapidity region ($|y| < 1$) decaying via strong interaction $\Lambda_c^+ \to pK^-\pi^+$ ($\Lambda_c^- \to \bar{p}K^+\pi^-$) for pp and PbPb collisions. Due to the absence of particle identification, the particles are reconstructed using all possible combinations of the decay tracks. A gradient-boosted decision tree (BDTG) algorithm from TMVA package is applied to reduce the combinatorial background. For pPb collisions, the Λ_c^+ baryons are reconstructed using the decay channel $\Lambda_c^+ \to K_S^0 p$ and the K_S^0 meson is reconstructed using the decay channel $K_S^0 \to \pi^+\pi^-$. A Multilayer Perceptron (MLP) from the TMVA package is used in the training to suppress the combinatorial background. The D^0 is reconstructed via the decay channel $D^0 \to K^-\pi^+$, and BDTG training is used to improve the signal extraction.

3 Results

The prompt Λ_c^+ cross section in pp collisions at $\sqrt{s_{_{NN}}}$ = 5.02 TeV from Ref. [6] is shown in Fig. 1 (left). The model predictions from PYTHIA8 with color reconnection mode 2 [14] and GM-VFNS models [15, 16] are also shown in the plot. The lower panel shows the ratio of the data to the model calculations, and we observe that the ratio tends to 1 as we approach higher p_T values. For $p_T < 10$ GeV/c, the models are systematically lower than the data, suggesting a possible breakdown of the universality of charm quark fragmentation.

The $\langle T_{AA} \rangle$ scaled yield of prompt Λ_c^+ in PbPb collisions at $\sqrt{s_{_{NN}}}$ = 5.02 TeV from Ref. [6] is shown in Fig. 1 (middle). For $p_T > 10$ GeV/c, the $\langle T_{AA} \rangle$ scaled yields of Λ_c^+ in PbPb are systematically lower than the Λ_c^+ cross section in pp collisions. We see the suppression is more for central (0-10%) than for peripheral (50-90%) PbPb collisions, as expected due to the energy loss of charm quark in the QGP medium. The effects of centrality on the suppression of Λ_c^+ production can also be observed in Fig. 1 (right), showing the R_{AA} for prompt Λ_c^+ in PbPb collisions. The R_{AA} also follows a trend decreasing from low p_T up to $p_T \approx 14$ GeV/c and then increases with higher p_T similar to other heavy flavor hadrons.

The ratio of prompt Λ_c^+ to prompt D^0 in pp and PbPb collisions is shown in Fig. 2. In the left panel, calculations based on the Catania model [8] (labeled PLB821 (2021) 136622), including both fragmentation and coalescence and the TAMU model [9] (labeled PLB795 (2019) 117), including excited charmed baryons beyond the PDG are compared to the ratio in pp collisions and both explain the data reasonably for $p_T < 12$ GeV/c. The PYTHIA8 model with CR2 is consistent with the data at $p_T < 10$ GeV/c and systematically below the data for the p_T region 10–30 GeV/c. In the right panel of Fig. 2, the ratio in PbPb collisions is shown for centrality classes 0–10 and 0–90%. Since the results are consistent with pp results for $p_T > 10$ GeV/c, suggesting that coalescence does not play a significant role in the

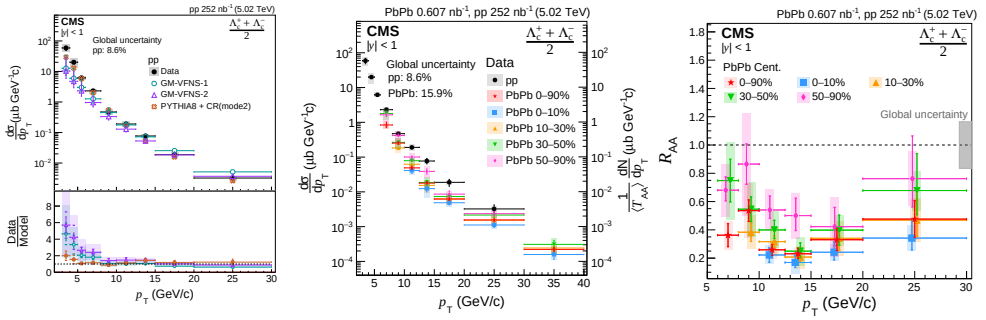

Figure 1. The p_{T}-differential cross sections for prompt Λ_{c}^{+} production in pp collisions is shown in the left figure along with model calculations from GM-VFNS and PYTHIA8. The lower panel shows the ratios of the data to the model calculations. The middle figure shows the results for pp and PbPb collisions for five centrality classes. The figure on the right shows the R_{AA} for these centrality classes in PbPb collisions. The bars and bands show the statistical and systematic uncertainties, respectively. These figures are taken from Ref. [6]

hadronization of Λ_{c}^{+} in this higher p_{T} region. The model calculation for PbPb collisions in the 0–20% centrality [10] class (labeled PRL124 (2020) 042301) is consistent with the data in the 0–10% centrality class in p_{T} region 10–12.5 GeV/c.

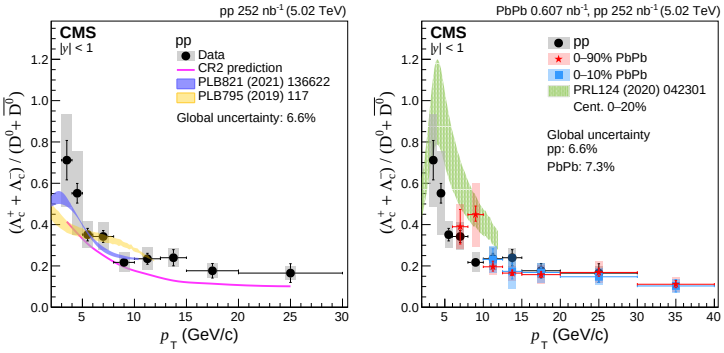

Figure 2. The $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$ ratio is shown in these plots. The left plot shows the results in pp collisions (circles) and the model calculations based on Catania and TAMU models. The right plot shows the ratios in PbPb collisions in 2 centrality classes and a model calculation based on the TAMU model for central events (0–20%). These figures are taken from Ref. [6]

The p_{T} spectra for both Λ_{c}^{+} and D^{0} in pPb collisions are measured for different multiplicity regions (determined based on the number of offline selected tracks, $N_{\mathrm{trk}}^{\mathrm{offline}}$), and we observe an increase in the Λ_{c}^{+} and D^{0} production with multiplicity. The baryon-to-meson ratio versus $N_{\mathrm{trk}}^{\mathrm{offline}}$is shown in the right panel of Fig. 3 in pPb collisions. The ratio of Λ_{c}^{+} to D^{0} is compared to that of Λ to $\mathrm{K}_{\mathrm{S}}^{0}$, and there is no indication of $N_{\mathrm{trk}}^{\mathrm{offline}}$dependence for the charmed hadrons in the p_{T} region 3–5 GeV/c, in contrast to the lighter hadrons. This suggests that the coalescence process might saturate faster for charmed quarks with multiplicity. In the left panel of Fig. 3, the baryon-to-meson ratio is shown with p_{T} for the low- and high-$N_{\mathrm{trk}}^{\mathrm{offline}}$regions. The ratios slightly decrease with increasing p_{T} and are consistent with the pp and PbPb (0–90% centrality) results in the overlapping p_{T} region of 4–10 GeV/c.

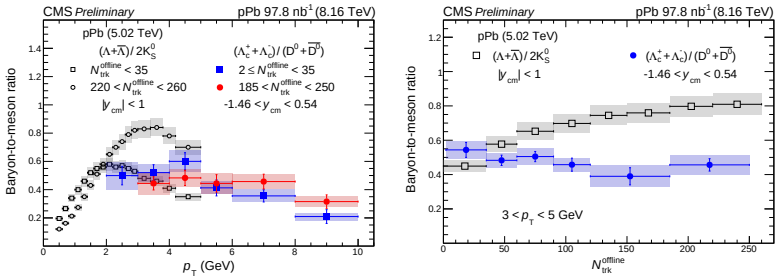

Figure 3. The ratio of Λ_c^+ baryon to D^0 meson production in pPb collisions for two different multiplicity regions are shown in the left plot, along with the ratio of Λ to (two times) K_S^0 meson production at $\sqrt{s_{NN}}$ =5.02 TeV from Ref. [12]. The plot on the right shows the ratio vs multiplicity ($N_{trk}^{offline}$). These figures are taken from Ref. [7]

4 Summary

We see no significant multiplicity dependence of the Λ_c^+/D^0 ratio in pPb collisions, suggesting early saturation of charm quark coalescence with multiplicity. Also, the Λ_c^+ production is significantly suppressed in PbPb collisions compared to pp collisions, implying the loss of charm quark energy in the medium. The observed cross section of Λ_c^+ in pp collisions is significantly higher than predicted by the GM-VFNS models (tuned to e^+e^- collision data). This suggests a possible breakdown of the universality of the charm quark fragmentation function. For the higher transverse momentum (p_T) region ($p_T > 10\,GeV/c$), the Λ_c^+/D^0 ratios for pp and PbPb collisions are consistent with each other, suggesting that coalescence might not play a significant role in charm quark hadronization. The ratios also approach the Λ_c^+/D^0 ratio in e^+e^- collision with increasing p_T.

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