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Constraining hadronization mechanisms with Λ_c^+/D^0 production ratios in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

ALICE Collaboration*

Abstract

The production of prompt Λ_c^+ baryons at midrapidity ($|y| < 0.5$) was measured in central (0–10%) and mid-central (30–50%) Pb–Pb collisions at the center-of-mass energy per nucleon–nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV with the ALICE detector. The Λ_c^+ production yield, the Λ_c^+/D^0 production ratio, and the Λ_c^+ nuclear modification factor R_{AA} are reported. The results are more precise and more differential in transverse momentum (p_T) and centrality with respect to previous measurements. The Λ_c^+/D^0 ratio, which is enhanced with respect to the pp measurement for $4 < p_T < 8$ GeV/c, is described by theoretical calculations that model the charm-quark transport in the quark–gluon plasma and include hadronization via both coalescence and fragmentation mechanisms.

*See Appendix A for the list of collaboration members

Heavy-ion collisions at LHC energies produce a phase of strongly-interacting matter, known as the quark–gluon plasma (QGP), in which quarks and gluons are deconfined [1]. The existing measurements indicate that the QGP behaves as a strongly-coupled low-viscosity liquid-like system [2]. Heavy quarks, produced at the start of the collision, experience the full evolution of the system and constitute a unique probe of the QGP properties [3]. The hadronization of heavy quarks into open heavy-flavor hadrons is expected to be influenced by the presence of a deconfined medium: theoretical calculations that include modified hadronization via quark coalescence or via a resonance recombination approach [4–8] predict a significant enhancement of the Λ_c^+/D^0 yield ratio in heavy-ion collisions compared to the expected ratio in pp collisions. In addition, the collective radial expansion of the system determines a flow-velocity profile common to all thermalized particles, that could increase the Λ_c^+/D^0 ratio at intermediate transverse momentum (p_T) [7–9]. The study of such a potential enhancement requires a good understanding of Λ_c^+ production in smaller collision systems, which showed surprising features at LHC energies. The production of Λ_c^+ baryons at the LHC was measured by the ALICE Collaboration in pp collisions at $\sqrt{s} = 5.02$, 7, and 13 TeV [10–13] and at 5.02 TeV [14] and 7 TeV [15] by the CMS and LHCb Collaboration, respectively. At midrapidity, the ALICE and CMS results show a significant enhancement in the Λ_c^+/D^0 yield ratio (up to a factor 3–5 for $p_T < 8$ GeV/c) compared to e^+e^- and e^-p measurements [16–21] and QCD-inspired theoretical predictions [22–25] where charm fragmentation is tuned on e^+e^- and e^-p measurements [26, 27]. Models that include color reconnection beyond the leading-color approximation [28] or hadron production via coalescence [29] as well as models that are based on statistical hadronization including feed-down from yet-unmeasured charm-baryon states [30] are on the contrary able to describe the Λ_c^+/D^0 ratio at midrapidity.

A recent measurement performed by ALICE in intervals of charged-particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV [31] showed that in a hadronic collision, even at relatively small multiplicities, charm-quark hadronization proceeds differently than in e^+e^- collisions. The p_T-dependence of the Λ_c^+/D^0 ratio evolves with multiplicity and the maximum of the ratio increases for the higher multiplicity intervals. Whether the p_T-differential Λ_c^+/D^0 ratio keeps evolving with multiplicity up to the typical multiplicities of Pb–Pb collisions, and whether an overall p_T-integrated enhancement of Λ_c^+ production relative to the D^0 one is present at higher multiplicities is an open question, fundamental to the understanding of charm-quark hadronization.

The Λ_c^+ production in nucleus–nucleus collisions was measured for the first time at the LHC by ALICE in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the 0–80% centrality interval for $6 < p_T < 12$ GeV/c [32]. The Λ_c^+/D^0 ratio was found to be close to unity, larger than the corresponding ratio measured in pp collisions, and well described by calculations including hadronization via coalescence mechanisms [7, 8]. The Λ_c^+/D^0 ratio measured in the interval $3 < p_T < 6$ GeV/c by the STAR Collaboration in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [33] increases towards more central collisions and is also described by model calculations including hadronization via coalescence [5, 7, 8, 34–36]. The CMS measurement in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV [14], performed in the interval $10 < p_T < 20$ GeV/c, is consistent with the pp result within uncertainties, suggesting that modified hadronization due to the presence of a deconfined medium has no significant effect in this p_T range.

In this letter, the measurement of the p_T-differential production yields of prompt Λ_c^+ baryons in central (0–10%) and mid-central (30–50%) collisions using the 2018 Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV are reported down to low (1 GeV/c) p_T. The results are more precise and more differential in p_T and centrality with respect to previous measurements. The Λ_c^+/D^0 yield ratios and the nuclear modification factor R_{AA}, which is defined as the ratio of the production yield in Pb–Pb collisions and the cross section in pp collisions scaled by the average nuclear overlap function (proportional to the number of nucleon–nucleon collisions), are reported as function of p_T and compared with theoretical predictions. The p_T-integrated Λ_c^+ production yield and Λ_c^+/D^0 ratio, extrapolated to $p_T = 0$, are also presented for the first time in Pb–Pb collisions.

The ALICE apparatus is described in detail in [37, 38]. The data were collected using triggers (as detailed in [39]) based on the signal amplitude in the V0 detectors [40], which are also used for the centrality determination [41]. Events were further selected offline using selection criteria defined in [39]. The number of events in the centrality classes 0–10% and 30–50% considered for this analysis is about 100×10^6 and 85×10^6, respectively, corresponding to a luminosity of $(130.5 \pm 0.5)\ \mu b^{-1}$ and $(55.5 \pm 0.2)\ \mu b^{-1}$ [42]. The Monte Carlo (MC) simulations utilized in this analysis are produced using the HIJING 1.36 [43] and PYTHIA 8.243 [44] (Monash tune [22]) event generators and the GEANT3 transport package [45], as described in the supplemental material [46].

The Λ_c^+ baryon and its charge conjugate were reconstructed by exploiting the topology of the hadronic decay channel $\Lambda_c^+ \to pK_S^0 \to p\pi^+\pi^-$ (branching ratio $BR = 1.10 \pm 0.06\%$) [27]. Charged-particle tracks used to define the Λ_c^+ candidates are reconstructed using the Inner Tracking System (ITS) [47] and the Time Projection Chamber (TPC) [48], located in a solenoid magnet that provides a 0.5 T field parallel to the beam direction. The $\Lambda_c^+ \to pK_S^0$ candidates combine a proton-candidate track with a K_S^0-meson candidate, reconstructed in the $K_S^0 \to \pi^+\pi^-$ decay channel. Only proton (pion) tracks with $|\eta| < 0.8$ and $p_T > 0.4$ (0.1) GeV/c were considered for the analysis. The selection of tracks with $|\eta| < 0.8$ limits the Λ_c^+ acceptance in rapidity. For this reason a fiducial acceptance selection was applied on the rapidity of the Λ_c^+ candidates, $|y_{lab}| < y_{fid}(p_T)$, where y_{fid} increases from 0.6 to 0.8 in $1 < p_T < 5$ GeV/c, and $y_{fid} = 0.8$ for $p_T > 5$ GeV/c.

The Λ_c^+-candidate selection was performed using multivariate techniques based on the Boosted Decision Tree (BDT) algorithm provided by the XGBoost package [49]. The selection criteria considered in the optimization included both topological [10] and particle identification (PID) variables. The PID was performed using the specific ionization energy loss dE/dx in the TPC gas and the time of flight from the interaction point to the Time-Of-Flight (TOF) detector [50, 51]. The BDT training was performed considering as signal candidates prompt (not coming from beauty-hadron decays) Λ_c^+ decays from MC simulations [46]. Background candidates were taken from the sidebands of the invariant mass distribution in data. The yields of Λ_c^+ baryons were extracted in each p_T interval via binned maximum-likelihood fits to the candidate invariant mass distributions. The fitting function consisted of a Gaussian term to estimate the signal and a second-, third-, or fourth-order polynomial function (depending on p_T) to estimate the background. To improve the fit stability, the width of the Gaussian was fixed in each p_T interval to the values obtained from simulations. The raw-yield extraction is challenging, especially at low p_T with signal-to-background ratios below one per mille and statistical significances varying between 3 and 6 [46].

The corrected yields of prompt Λ_c^+ baryons were obtained in each centrality interval as

$$\left.\frac{dN^{\Lambda_c^+}}{dp_T}\right|_{|y|<0.5} = \frac{f_{prompt} \times \frac{1}{2} \left. N_{raw}^{\Lambda_c^\pm}\right|_{|y|<y_{fid}}}{\Delta p_T \times c_{\Delta y} \times (A \times \varepsilon)_{prompt} \times BR \times N_{ev}}. \quad (1)$$

The raw yield values $N_{raw}^{\Lambda_c^\pm}$, extracted in a given p_T interval of width Δp_T, were divided by a factor two and multiplied by the prompt fraction f_{prompt} to obtain the charge-averaged yields of prompt Λ_c^+. Furthermore, they were divided by $c_{\Delta y} \times (A \times \varepsilon)$, enclosing the rapidity coverage and the acceptance-times-efficiency, by the BR of the decay channel, and by the number of analyzed events N_{ev}.

The $(A \times \varepsilon)$ correction was determined from MC simulations [46], using samples not employed in the BDT training. The generated p_T spectrum used to calculate the efficiencies was reweighted to reproduce the shape obtained from the D^0 measurement [39] multiplied by Λ_c^+/D^0 calculations from the TAMU model [8] in 0–10% and 30–50% Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The $(A \times \varepsilon)$ increases from 1% (3%) at low p_T to about 12% (16%) at high p_T for central (mid-central) collisions.

The f_{prompt} fraction was estimated as described in [10, 32]. In particular, the beauty-quark produc-

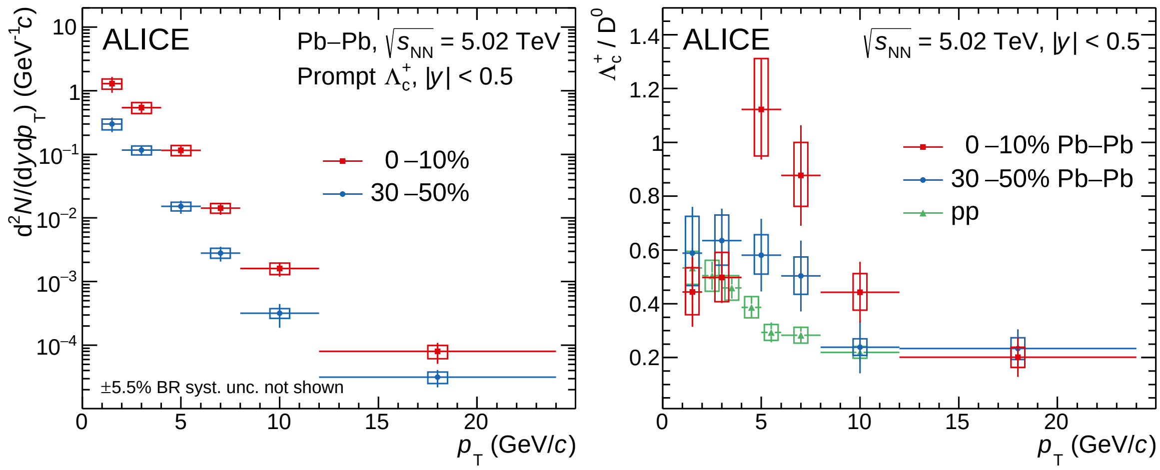

Figure 1: Left: p_T-differential production yields of prompt Λ_c^+ in central (0–10%) and mid-central (30–50%) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Right: Λ_c^+/D^0 ratio in central and mid-central Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with the results obtained from pp collisions [10, 11].

tion cross section was estimated with FONLL calculations [52, 53], the fraction of beauty quarks that fragment into Λ_b^0 was estimated from the $\Lambda_b^0/(B^0 + B^+)$ ratio measured by LHCb in pp collisions at $\sqrt{s} = 13$ TeV [54], and the $\Lambda_b^0 \to \Lambda_c^+ + X$ decay kinematics taken from PYTHIA 8. Since no measurements of beauty-baryon production in nucleus–nucleus collisions are available, the central hypothesis of the ratio $R_{AA}^{non-prompt}/R_{AA}^{prompt}$ was considered to be equal to 2 for Λ_c^+ as predicted by the "Catania" theoretical calculation [6]. The resulting f_{prompt} fraction was found to be about 0.97 at low p_T and about 0.81 at high p_T.

The systematic uncertainties of the Λ_c^+ corrected yields include contributions from the raw-yield extraction (from 7% to 15% depending on p_T and centrality), the tracking efficiency (from 8% to 12%), the Λ_c^+ selection efficiency (from 7% to 8%), the MC generated p_T spectra (smaller than 8%), the statistical uncertainty of the efficiency (1% at low p_T and 4% at high p_T), and the subtraction of feed-down Λ_c^+ baryons from b-hadron decays which includes contributions from the theoretical beauty-quark cross section (from 2% to 10%) and from the $R_{AA}^{non-prompt}$ assumption (from 2% to 12%). As detailed in [46], all uncertainties were estimated with similar procedures as those introduced in [10, 32, 39]. Furthermore, a global systematic uncertainty due to the centrality interval definition (2% for mid-central, negligible for central) [39] and the branching ratio (5.5%) [27] was assigned. For the R_{AA}, the uncertainty of the pp normalization uncertainty [10] and of the average nuclear overlap function [42] are included in the global normalization uncertainty. The propagation of the systematic uncertainties to the Λ_c^+/D^0 ratio and to the R_{AA} are presented in the supplemental material [46].

The p_T-differential production yields of prompt Λ_c^+ baryons are shown in Fig. 1 (left panel). The statistical and total systematic uncertainties are shown as error bars and boxes, respectively, for all figures. In the right panel of Fig. 1, the ratio between the production yields of Λ_c^+ baryons and D^0 mesons, measured in the same centrality intervals [39], are presented and compared with the pp measurement at the same collision energy [10, 11]. The ratios increase from pp to mid-central and central Pb–Pb collisions for $4 < p_T < 8$ GeV/c with a significance of 2.0σ and 3.7σ, respectively. This enhancement is qualitatively similar to what is observed for the p/π [55] and Λ/K_S^0 [56] ratios. The central and mid-central Λ_c^+/D^0 ratios in $12 < p_T < 24$ GeV/c are compatible with the measurement by CMS in 0–100% Pb–Pb collisions in the similar $p_T > 10$ GeV/c region [14]. For $p_T > 4$ GeV/c, the ratio measured in central collisions resembles in magnitude and p_T trend the one reported by STAR in $2.5 < p_T < 8$ GeV/c in 10–80% Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV [33].

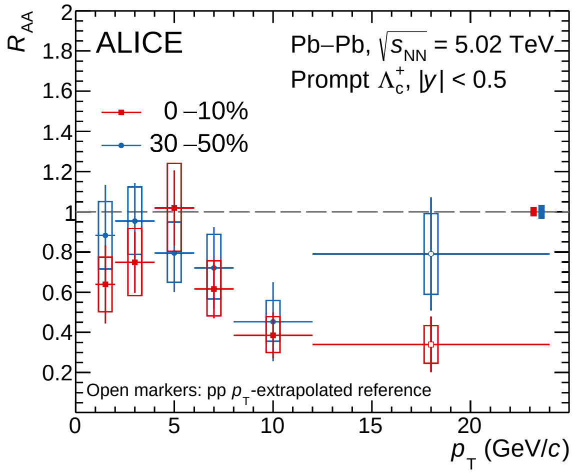

Figure 2: The nuclear modification factor of prompt Λ_c^+ as a function of p_T in central (0–10%) and mid-central (30–50%) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The normalization uncertainties are shown as boxes around unity.

The nuclear modification factor R_{AA} of prompt Λ_c^+ is presented in Fig. 2, for which the p_T-differential cross section in pp collisions at $\sqrt{s} = 5.02$ TeV from [10] was used as reference. This cross section was extrapolated to $12 < p_T < 24$ GeV/c exploiting the Λ_c^+ and D^0 measurements at $\sqrt{s} = 5.02$ and 13 TeV [13, 57], assuming no $\sqrt{s}$ dependence for the Λ_c^+/D^0 ratio as observed within uncertainties for the full measured p_T range [13]. For $p_T < 6$ GeV/c, the R_{AA} is found to be compatible with unity, within uncertainties, for both central and mid-central collisions, while a suppression due to the charm-quark energy loss in the QGP is observed for higher p_T. Comparisons with predictions of different theoretical models [7–9] and with D mesons [39, 58] are provided in [46].

Figure 3 compares the p_T-differential Λ_c^+/D^0 ratios shown in Fig. 1 with different theoretical predictions: Catania [7], TAMU [8], and the GSI–Heidelberg statistical hadronization model (SHMc) [9]. The predictions of Catania and TAMU for pp collisions [29, 30] are also compared with the existing measurement in pp collisions [10, 11]. The Catania model [7] assumes that a QGP is formed in both pp and Pb–Pb collisions. In Pb–Pb collisions heavy-quark transport is implemented via the Boltzmann equation, and in both pp and Pb–Pb collisions hadronization occurs either via coalescence, implemented through the Wigner formalism, or via fragmentation in case the quarks do not undergo coalescence. The TAMU model [8] describes charm-quark transport in an expanding medium with the Langevin equation and hadronization proceeds primarily via coalescence, implemented with a Resonance Recombination Model (RRM) [59]. Left-over charm quarks not undergoing coalescence are hadronized via fragmentation. In pp collisions, the charm-hadron abundances are instead determined with a statistical hadronization approach [30]. In both collision systems the underlying charm-baryon spectrum includes yet-unobserved excited states [27] predicted by the Relativistic Quark Model (RQM) [60] and lattice QCD [30]. Finally, for the SHMc predictions [9] the charm-hadron p_T spectra are modeled within a core-corona approach. The core contribution represents the central region of the colliding nuclei where charm quarks achieve local thermal equilibrium in a hydrodynamically expanding QGP. The charm-hadron spectra in the corona contribution are, instead, parameterized from measurements in pp collisions. The p_T-spectra modification due to resonance decays is computed using the FastReso package [61].

The SHMc describes the Λ_c^+/D^0 ratio in mid-central collisions, but underpredicts the ratio in $4 < p_T < 8$ GeV/c in central collisions. The prediction of the Catania model in central collisions overestimates (underestimates) the Λ_c^+/D^0 ratio at low (intermediate) p_T. The TAMU predictions reproduce the magnitude and shape of the Λ_c^+/D^0 ratios. While both coalescence model calculations are able to describe the Λ_c^+/D^0 ratio in Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV in the 10–80% centrality interval [33], the TAMU

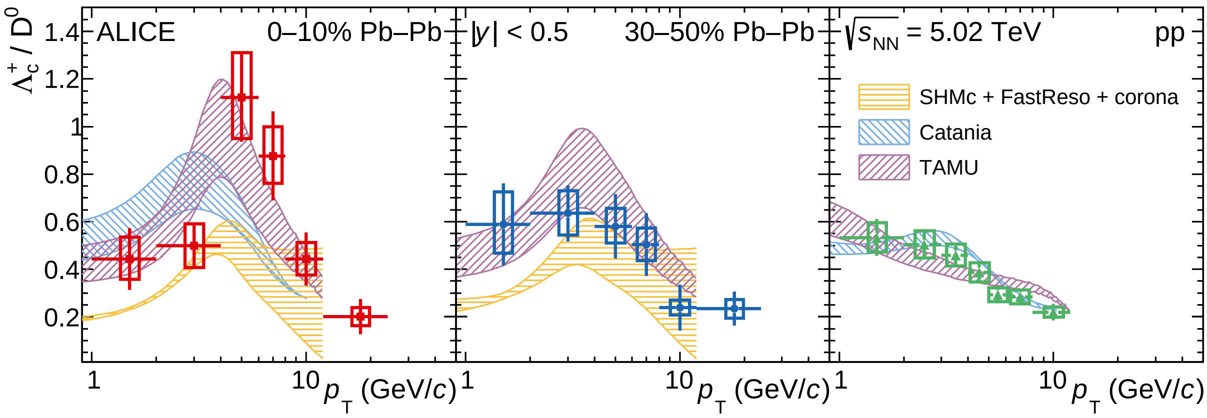

Figure 3: The Λ_c^+/D^0 yield ratio as a function of p_T in 0–10% (left) and 30–50% (middle) Pb–Pb and pp (right) collisions at $\sqrt{s_{NN}} = 5.02$ TeV compared with predictions of different theoretical calculations [7–9, 29, 30, 61].

model reproduces significantly better the data in central Pb–Pb collisions. The Catania and TAMU predictions also describe both the magnitude and p_T shape of the measured Λ_c^+/D^0 ratio in pp collisions.

The Λ_c^+ production yield for $p_T > 0$ was estimated by summing up the p_T-differential yields, extrapolating the Λ_c^+/D^0 ratio down to $p_T = 0$, and exploiting the measurement of the D^0 yield in the interval $0 < p_T < 1$ GeV/c [39]. The p_T-differential Λ_c^+/D^0 ratio was interpolated using the shape predicted by TAMU [8], Catania [7] (not available for 30–50%), SHMc [9], and blast-wave [62] calculations, leaving the normalization as a free parameter. The shape from TAMU was chosen for the central value based on the χ^2/ndf values, while the difference between the obtained yields was considered in the systematic uncertainty due to the extrapolation. The results for the prompt Λ_c^+ production yields per unit of rapidity in $|y| < 0.5$ are $dN/dy = 3.28 \pm 0.42\,(\text{stat}) \pm 0.44\,(\text{syst}) \pm 0.16\,(\text{BR})\,^{+0.46}_{-0.29}\,(\text{extr})$ for central collisions and $dN/dy = 0.70 \pm 0.09\,(\text{stat}) \pm 0.09\,(\text{syst}) \pm 0.04\,(\text{BR})\,^{+0.07}_{-0.05}\,(\text{extr})$ for mid-central collisions, where the visible yield is about 81% of the total for both centrality classes. The SHMc [9] predicts lower values, $dN/dy = 1.55 \pm 0.23$ and $dN/dy = 0.316 \pm 0.036$, respectively. Finally, the measured Λ_c^+/D^0 ratios, obtained dividing the p_T-integrated Λ_c^+ and D^0 yields [39], are $0.48^{+0.13}_{-0.12}$ in the 0–10% and $0.55^{+0.14}_{-0.13}$ in the 30–50% centrality classes, taking into account the correlation between the measured and extrapolated uncertainties [46]. These results are compatible with the result in pp collisions [10] within one standard deviation of the combined uncertainties. This may suggest that the charm hadronization and Λ_c^+ production do not differ significantly in Pb–Pb and pp collisions, and the observed baryon enhancement at intermediate p_T is predominantly caused by a different modification of the hadron spectra due to interactions in the hadronic phase. An alternative explanation is that charm hadronization is indeed modified in Pb–Pb collisions, but the different kinematic distributions of light and charm quarks at hadronization time in pp and Pb–Pb collisions modulate the amplitude and p_T dependence of the Λ_c^+/D^0 ratio producing a marginal effect on the p_T-integrated yield ratio. The uncertainty of the p_T-integrated yield is still relatively large, and more precise measurements at low p_T will help to further discriminate between charm-baryon formation scenarios.

In summary, the measurement of the production yield of Λ_c^+ baryons, the Λ_c^+/D^0 yield ratio, and the R_{AA} in central (0–10%) and mid-central (30–50%) Pb–Pb collisions at a center-of-mass energy per nucleon pair $\sqrt{s_{NN}} = 5.02$ TeV were presented. The ratios increase from pp to central Pb–Pb collisions for $4 < p_T < 8$ GeV/c with a significance of 3.7σ. The measurements are described by theoretical calculations that include both coalescence and fragmentation processes when describing the hadronization of heavy flavors in the QGP. The upgraded ALICE detector for the LHC Runs 3 and 4 will increase the integrated luminosity by a factor of about 50 and the tracking precision by a factor 3–6, meaning future measurements of Λ_c^+-baryon production will allow for stronger constraints on the heavy-quark hadronization mechanisms in heavy-ion collisions [63].

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Krizkova Gajdosova[37], M. Kroesen[105], M. Krüger[68], D.M. Krupova[37], E. Kryshen[99], M. Krzewicki[39], V. Kučera[34], C. Kuhn[138], P.G. Kuijer[91], T. Kumaoka[134], D. Kumar[142], L. Kumar[101], N. Kumar[101], S. Kundu[34], P. Kurashvili[86], A. Kurepin[63], A.B. Kurepin[63], A. Kuryakin[109], S. Kushpil[96], J. Kvapil[111], M.J. Kweon[61], J.Y. Kwon[61], Y. Kwon[148], S.L. La Pointe[39], P. La Rocca[26], Y.S. Lai[80], A. Lakrathok[116], M. Lamanna[34], R. Langoy[130], P. Larionov[34,52], E. Laudi[34], L. Lautner[34,106], R. Lavicka[114,37], T. Lazareva[113], R. Lea[141,23,58], J. Lehrbach[39], R.C. Lemmon[95], I. León Monzón[120], E.D. Lesser[19], M. Lettrich[34,106], P. Lévai[146], X. Li[11], X.L. Li[7], J. Lien[130], R. Lietava[111], B. Lim[17], S.H. Lim[17], V. Lindenstruth[39], A. Lindner[48], C. Lippmann[108], A. Liu[19], D.H. Liu[7], J. Liu[128], I.M. Lofnes[21], V. Loginov[94], C. Loizides[97], P. Loncar[35], J.A. Lopez[105], X. Lopez[136], E. López Torres[8], J.R. Luhder[145], M. Lunardon[27], G. Luparello[60], Y.G. Ma[40], A. Maevskaya[63], M. Mager[34], T. Mahmoud[43], A. Maire[138], M. Malaev[99], N.M. Malik[102], Q.W. Malik[20], S.K. Malik[102], L. Malinina[IV,75], D. Mal'Kevich[93], D. Mallick[87], N. Mallick[50], G. Mandaglio[32,56], V. Manko[89], F. Manso[136], V. Manzari[53], Y. Mao[7], G.V. Margagliotti[23], A. Margotti[54], A. Marín[108], C. Markert[119], M. Marquard[68], N.A. Martin[105], P. Martinengo[34], J.L. Martinez[125], M.I. Martínez[45], G. Martínez García[115], S. Masciocchi[108], M. Masera[24], A. Masoni[55], L. Massacrier[78], A. Mastroserio[140,53], A.M. Mathis[106], O. Matonoha[81], P.F.T. Matuoka[121], A. Matyja[118], C. Mayer[118], A.L. Mazuecos[34], F. Mazzaschi[24], M. Mazzilli[34], J.E. Mdhluli[132], A.F. Mechler[68], Y. Melikyan[63], A. Menchaca-Rocha[71], E. Meninno[114,29], A.S. Menon[125], M. Meres[13], S. Mhlanga[124,72], Y. Miake[134], L. Micheletti[59], L.C. Migliorin[137], D.L. Mihaylov[106], K. Mikhaylov[75,93], A.N. Mishra[146], D. Miśkowiec[108], A. Modak[4], A.P. Mohanty[62], B. Mohanty[87], M. Mohisin Khan[V,16], M.A. Molander[44], Z. Moravcova[90], C. Mordasini[106], D.A. Moreira De Godoy[145], I. Morozov[63], A. Morsch[34], T. Mrnjavac[34], V. Muccifora[52], E. Mudnic[35], D. Mühlheim[145], S. Muhuri[142], J.D. Mulligan[80], A. Mulliri[22], M.G. Munhoz[121], R.H. Munzer[68], H. Murakami[133], S. Murray[124], L. Musa[34], J. Musinsky[64], J.W. Myrcha[143], B. Naik[132], R. Nair[86], B.K. Nandi[49], R. Nania[54], E. Nappi[53], A.F. Nassirpour[81], A. Nath[105], C. Nattrass[131], A. Neagu[20], A. Negru[135], L. Nellen[69], S.V. Nesbo[36], G. Neskovic[39], D. Nesterov[113], B.S. Nielsen[90], E.G. Nielsen[90], S. Nikolaev[89], S. Nikulin[89], V. Nikulin[99], F. Noferini[54], S. Noh[12], P. Nomokonov[75], J. Norman[128], N. Novitzky[134], P. Nowakowski[143], A. Nyanin[89], J. Nystrand[21], M. Ogino[83], A. Ohlson[81], V.A. Okorokov[94], J. Oleniacz[143], A.C. Oliveira Da Silva[131], M.H. Oliver[147], A. Onnerstad[126], C. Oppedisano[59], A. Ortiz Velasquez[69], T. Osako[46], A. Oskarsson[81], J. Otwinowski[118], M. Oya[46], K. Oyama[83], Y. Pachmayer[105], S. Padhan[49], D. Pagano[141,58], G. Paić[69], A. Palasciano[53], J. Pan[144], S. Panebianco[139], J. Park[61], J.E. Parkkila[126], S.P. Pathak[125], R.N. Patra[102,34], B. Paul[22], H. Pei[7], T. Peitzmann[62], X. Peng[7], L.G. Pereira[70], H. Pereira Da Costa[139], D. Peresunko[89,82], G.M. Perez[8], S. Perrin[139], Y. Pestov[5], V. Petráček[37], M. Petrovici[48], R.P. Pezzi[115,70], S. Piano[60], M. Pikna[13], P. Pillot[115], O. Pinazza[54,34], L. Pinsky[125], C. Pinto[26], S. Pisano[52], M. Płoskoń[80], M. Planinic[100], F. Pliquett[68], M.G. Poghosyan[97], B. Polichtchouk[92], S. Politano[30], N. Poljak[100], A. Pop[48], S. Porteboeuf-Houssais[136], J. Porter[80], V. Pozdniakov[75], S.K. Prasad[4], R. Preghenella[54], F. Prino[59], C.A. Pruneau[144], I. Pshenichnov[63], M. Puccio[34], S. Qiu[91], L. Quaglia[24], R.E. Quishpe[125], S. Ragoni[111], A. Rakotozafindrabe[139], L. Ramello[31], F. Rami[138], S.A.R. Ramirez[45], A.G.T. Ramos[33], T.A. Rancien[79], R. Raniwala[103], S. Raniwala[103], S.S. Räsänen[44], R. Rath[50], I. Ravasenga[91], K.F. Read[97,131], A.R. Redelbach[39], K. Redlich[VI,86], A. Rehman[21], P. Reichelt[68], F. Reidt[34], H.A. Reme-ness[36], Z. Rescakova[38], K. Reygers[105], A. Riabov[99], V. Riabov[99], T. Richert[81], M. Richter[20], W. Riegler[34], F. Riggi[26], C. Ristea[67], M. Rodríguez Cahuantzi[45], K. Røed[20], R. Rogalev[92], E. Rogochaya[75], T.S. Rogoschinski[68], D. Rohr[34], D. Röhrich[21], P.F. Rojas[45], S. Rojas Torres[37], P.S. Rokita[143], F. Ronchetti[52], A. Rosano[32,56], E.D. Rosas[69], A. Rossi[57], A. Roy[50], P. Roy[110], S. Roy[49], N. Rubini[25], O.V. Rueda[81], D. Ruggiano[143], R. Rui[23], B. Rumyantsev[75], P.G. Russek[2], R. Russo[91], A. Rustamov[88], E. Ryabinkin[89], Y. Ryabov[99], A. Rybicki[118], H. Rytkonen[126], W. Rzesa[143], O.A.M. Saarimaki[44], R. Sadek[115], S. Sadovsky[92], J. Saetre[21], K. Šafařík[37], S.K. Saha[142], S. Saha[87], B. Sahoo[49], P. Sahoo[49], R. Sahoo[50], S. Sahoo[65], D. Sahu[50], P.K. Sahu[65], J. Saini[142], S. Sakai[134], M.P. Salvan[108], S. Sambyal[102], T.B. Saramela[121], D. Sarkar[144], N. Sarkar[142], P. Sarma[42], V.M. Sarti[106], M.H.P. Sas[147], J. Schambach[97], H.S. Scheid[68], C. Schiaua[48], R. Schicker[105], A. Schmah[105], C. Schmidt[108], H.R. Schmidt[104], M.O. Schmidt[34,105], M. Schmidt[104], N.V. Schmidt[97,68], A.R. Schmier[131], R. Schotter[138], J. Schukraft[34], K. Schwarz[108], K. Schweda[108], G. Scioli[25], E. Scomparin[59], J.E. Seger[15], Y. Sekiguchi[133], D. Sekihata[133], I. Selyuzhenkov[108,94], S. Senyukov[138], J.J. Seo[61], D. Serebryakov[63], L. Šerkšnytė[106], A. Sevcenco[67], T.J. Shaba[72], A. Shabanov[63], A. Shabetai[115], R. Shahoyan[34], W. Shaikh[110], A. Shangaraev[92], A. Sharma[101], H. Sharma[118], M. Sharma[102], N. Sharma[101], S. Sharma[102], U. Sharma[102], A. Shatat[78], O. Sheibani[125], K. Shigaki[46], M. Shimomura[84], S. Shirinkin[93], Q. Shou[40], Y. Sibiriak[89], S. Siddhanta[55], T. Siemiarczuk[86], T.F. Silva[121], D. Silvermyr[81], T. Simantathammakul[116], G. Simonetti[34], B. Singh[106], R. Singh[87], R. Singh[102], R. Singh[50], V.K. Singh[142], V. Singhal[142], T. Sinha[110], B. Sitar[13], M. Sitta[31], T.B. Skaali[20], G. Skorodumovs[105], M. Slupecki[44], N. Smirnov[147], R.J.M. Snellings[62], C. Soncco[112], J. Song[125], A. Songmoolnak[116], F. Soramel[27], S. Sorensen[131], I. Sputowska[118], J. Stachel[105], I. Stan[67], P.J. Steffanic[131], S.F. Stiefelmaier[105], D. Stocco[115], I. Storehaug[20], M.M. Storetvedt[36], P. Stratmann[145], S. Strazzi[25], C.P. Stylianidis[91], A.A.P. Suaide[121], C. Suire[78], M. Sukhanov[63], M. Suljic[34], R. Sultanov[93], V. Sumberia[102], S. Sumowidagdo[51], S. Swain[65], A. Szabo[13], I. Szarka[13], U. Tabassam[14], S.F. Taghavi[106], G. Taillepied[108,136], J. Takahashi[122], G.J. Tambave[21], S. Tang[136,7], Z. Tang[129], J.D. Tapia Takaki[VII,127], N. Tapus[135], M.G. Tarzila[48], A. Tauro[34], G. Tejeda Muñoz[45], A. Telesca[34], L. Terlizzi[24], C. Terrevoli[125], G. Tersimonov[3], S. Thakur[142], D. Thomas[119], R. Tieulent[137], A. Tikhonov[63], A.R. Timmins[125], M. Tkacik[117], A. Toia[68], N. Topilskaya[63], M. Toppi[52], F. Torales-Acosta[19], T. Tork[78], A. Trifiró[32,56], A.S. Triolo[32], S. Tripathy[54,69], T. Tripathy[49], S. Trogolo[34,27], V. Trubnikov[3], W.H. Trzaska[126], T.P. Trzcinski[143], A. Tumkin[109], R. Turrisi[57], T.S. Tveter[20], K. Ullaland[21], A. Uras[137], M. Urioni[58,141], G.L. Usai[22], M. Vala[38], N. Valle[28], S. Vallero[59], L.V.R. van Doremalen[62], M. van Leeuwen[91], P. Vande Vyvre[34], D. Varga[146], Z. Varga[146], M. Varga-Kofarago[146], M. Vasileiou[85], A. Vasiliev[89], O. Vázquez Doce[52,106], V. Vechernin[113],

A. Velure[21], E. Vercellin[24], S. Vergara Limón[45], L. Vermunt[62], R. Vértesi[146], M. Verweij[62], L. Vickovic[35], Z. Vilakazi[132], O. Villalobos Baillie[111], G. Vino[53], A. Vinogradov[89], T. Virgili[29], V. Vislavicius[90], A. Vodopyanov[75], B. Volkel[34,105], M.A. Völkl[105], K. Voloshin[93], S.A. Voloshin[144], G. Volpe[33], B. von Haller[34], I. Vorobyev[106], N. Vozniuk[63], J. Vrláková[38], B. Wagner[21], C. Wang[40], D. Wang[40], M. Weber[114], R.J.G.V. Weelden[91], A. Wegrzynek[34], S.C. Wenzel[34], J.P. Wessels[145], S.L. Weyhmiller[147], J. Wiechula[68], J. Wikne[20], G. Wilk[86], J. Wilkinson[108], G.A. Willems[145], B. Windelband[105], M. Winn[139], W.E. Witt[131], J.R. Wright[119], W. Wu[40], Y. Wu[129], R. Xu[7], A.K. Yadav[142], S. Yalcin[77], Y. Yamaguchi[46], K. Yamakawa[46], S. Yang[21], S. Yano[46], Z. Yin[7], I.-K. Yoo[17], J.H. Yoon[61], S. Yuan[21], A. Yuncu[105], V. Zaccolo[23], C. Zampolli[34], H.J.C. Zanoli[62], F. Zanone[105], N. Zardoshti[34], A. Zarochentsev[113], P. Závada[66], N. Zaviyalov[109], M. Zhalov[99], B. Zhang[7], S. Zhang[40], X. Zhang[7], Y. Zhang[129], V. Zherebchevskii[113], Y. Zhi[11], N. Zhigareva[93], D. Zhou[7], Y. Zhou[90], J. Zhu[108,7], Y. Zhu[7], G. Zinovjev[I,3], N. Zurlo[141,58]

Affiliation Notes

[I] Deceased
[II] Also at: Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA), Bologna, Italy
[III] Also at: Dipartimento DET del Politecnico di Torino, Turin, Italy
[IV] Also at: M.V. Lomonosov Moscow State University, D.V. Skobeltsyn Institute of Nuclear, Physics, Moscow, Russia
[V] Also at: Department of Applied Physics, Aligarh Muslim University, Aligarh, India
[VI] Also at: Institute of Theoretical Physics, University of Wroclaw, Poland
[VII] Also at: University of Kansas, Lawrence, Kansas, United States

Collaboration Institutes

[1] A.I. Alikhanyan National Science Laboratory (Yerevan Physics Institute) Foundation, Yerevan, Armenia
[2] AGH University of Science and Technology, Cracow, Poland
[3] Bogolyubov Institute for Theoretical Physics, National Academy of Sciences of Ukraine, Kiev, Ukraine
[4] Bose Institute, Department of Physics and Centre for Astroparticle Physics and Space Science (CAPSS), Kolkata, India
[5] Budker Institute for Nuclear Physics, Novosibirsk, Russia
[6] California Polytechnic State University, San Luis Obispo, California, United States
[7] Central China Normal University, Wuhan, China
[8] Centro de Aplicaciones Tecnológicas y Desarrollo Nuclear (CEADEN), Havana, Cuba
[9] Centro de Investigación y de Estudios Avanzados (CINVESTAV), Mexico City and Mérida, Mexico
[10] Chicago State University, Chicago, Illinois, United States
[11] China Institute of Atomic Energy, Beijing, China
[12] Chungbuk National University, Cheongju, Republic of Korea
[13] Comenius University Bratislava, Faculty of Mathematics, Physics and Informatics, Bratislava, Slovakia
[14] COMSATS University Islamabad, Islamabad, Pakistan
[15] Creighton University, Omaha, Nebraska, United States
[16] Department of Physics, Aligarh Muslim University, Aligarh, India
[17] Department of Physics, Pusan National University, Pusan, Republic of Korea

[18] Department of Physics, Sejong University, Seoul, Republic of Korea
[19] Department of Physics, University of California, Berkeley, California, United States
[20] Department of Physics, University of Oslo, Oslo, Norway
[21] Department of Physics and Technology, University of Bergen, Bergen, Norway
[22] Dipartimento di Fisica dell'Università and Sezione INFN, Cagliari, Italy
[23] Dipartimento di Fisica dell'Università and Sezione INFN, Trieste, Italy
[24] Dipartimento di Fisica dell'Università and Sezione INFN, Turin, Italy
[25] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Bologna, Italy
[26] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Catania, Italy
[27] Dipartimento di Fisica e Astronomia dell'Università and Sezione INFN, Padova, Italy
[28] Dipartimento di Fisica e Nucleare e Teorica, Università di Pavia, Pavia, Italy
[29] Dipartimento di Fisica 'E.R. Caianiello' dell'Università and Gruppo Collegato INFN, Salerno, Italy
[30] Dipartimento DISAT del Politecnico and Sezione INFN, Turin, Italy
[31] Dipartimento di Scienze e Innovazione Tecnologica dell'Università del Piemonte Orientale and INFN Sezione di Torino, Alessandria, Italy
[32] Dipartimento di Scienze MIFT, Università di Messina, Messina, Italy
[33] Dipartimento Interateneo di Fisica 'M. Merlin' and Sezione INFN, Bari, Italy
[34] European Organization for Nuclear Research (CERN), Geneva, Switzerland
[35] Faculty of Electrical Engineering, Mechanical Engineering and Naval Architecture, University of Split, Split, Croatia
[36] Faculty of Engineering and Science, Western Norway University of Applied Sciences, Bergen, Norway
[37] Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Prague, Czech Republic
[38] Faculty of Science, P.J. Šafárik University, Košice, Slovakia
[39] Frankfurt Institute for Advanced Studies, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[40] Fudan University, Shanghai, China
[41] Gangneung-Wonju National University, Gangneung, Republic of Korea
[42] Gauhati University, Department of Physics, Guwahati, India
[43] Helmholtz-Institut für Strahlen- und Kernphysik, Rheinische Friedrich-Wilhelms-Universität Bonn, Bonn, Germany
[44] Helsinki Institute of Physics (HIP), Helsinki, Finland
[45] High Energy Physics Group, Universidad Autónoma de Puebla, Puebla, Mexico
[46] Hiroshima University, Hiroshima, Japan
[47] Hochschule Worms, Zentrum für Technologietransfer und Telekommunikation (ZTT), Worms, Germany
[48] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
[49] Indian Institute of Technology Bombay (IIT), Mumbai, India
[50] Indian Institute of Technology Indore, Indore, India
[51] Indonesian Institute of Sciences, Jakarta, Indonesia
[52] INFN, Laboratori Nazionali di Frascati, Frascati, Italy
[53] INFN, Sezione di Bari, Bari, Italy
[54] INFN, Sezione di Bologna, Bologna, Italy
[55] INFN, Sezione di Cagliari, Cagliari, Italy
[56] INFN, Sezione di Catania, Catania, Italy
[57] INFN, Sezione di Padova, Padova, Italy
[58] INFN, Sezione di Pavia, Pavia, Italy
[59] INFN, Sezione di Torino, Turin, Italy
[60] INFN, Sezione di Trieste, Trieste, Italy

[61] Inha University, Incheon, Republic of Korea
[62] Institute for Gravitational and Subatomic Physics (GRASP), Utrecht University/Nikhef, Utrecht, Netherlands
[63] Institute for Nuclear Research, Academy of Sciences, Moscow, Russia
[64] Institute of Experimental Physics, Slovak Academy of Sciences, Košice, Slovakia
[65] Institute of Physics, Homi Bhabha National Institute, Bhubaneswar, India
[66] Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic
[67] Institute of Space Science (ISS), Bucharest, Romania
[68] Institut für Kernphysik, Johann Wolfgang Goethe-Universität Frankfurt, Frankfurt, Germany
[69] Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Mexico City, Mexico
[70] Instituto de Física, Universidade Federal do Rio Grande do Sul (UFRGS), Porto Alegre, Brazil
[71] Instituto de Física, Universidad Nacional Autónoma de México, Mexico City, Mexico
[72] iThemba LABS, National Research Foundation, Somerset West, South Africa
[73] Jeonbuk National University, Jeonju, Republic of Korea
[74] Johann-Wolfgang-Goethe Universität Frankfurt Institut für Informatik, Fachbereich Informatik und Mathematik, Frankfurt, Germany
[75] Joint Institute for Nuclear Research (JINR), Dubna, Russia
[76] Korea Institute of Science and Technology Information, Daejeon, Republic of Korea
[77] KTO Karatay University, Konya, Turkey
[78] Laboratoire de Physique des 2 Infinis, Irène Joliot-Curie, Orsay, France
[79] Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS-IN2P3, Grenoble, France
[80] Lawrence Berkeley National Laboratory, Berkeley, California, United States
[81] Lund University Department of Physics, Division of Particle Physics, Lund, Sweden
[82] Moscow Institute for Physics and Technology, Moscow, Russia
[83] Nagasaki Institute of Applied Science, Nagasaki, Japan
[84] Nara Women's University (NWU), Nara, Japan
[85] National and Kapodistrian University of Athens, School of Science, Department of Physics , Athens, Greece
[86] National Centre for Nuclear Research, Warsaw, Poland
[87] National Institute of Science Education and Research, Homi Bhabha National Institute, Jatni, India
[88] National Nuclear Research Center, Baku, Azerbaijan
[89] National Research Centre Kurchatov Institute, Moscow, Russia
[90] Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
[91] Nikhef, National institute for subatomic physics, Amsterdam, Netherlands
[92] NRC Kurchatov Institute IHEP, Protvino, Russia
[93] NRC «Kurchatov»Institute - ITEP, Moscow, Russia
[94] NRNU Moscow Engineering Physics Institute, Moscow, Russia
[95] Nuclear Physics Group, STFC Daresbury Laboratory, Daresbury, United Kingdom
[96] Nuclear Physics Institute of the Czech Academy of Sciences, Řež u Prahy, Czech Republic
[97] Oak Ridge National Laboratory, Oak Ridge, Tennessee, United States
[98] Ohio State University, Columbus, Ohio, United States
[99] Petersburg Nuclear Physics Institute, Gatchina, Russia
[100] Physics department, Faculty of science, University of Zagreb, Zagreb, Croatia
[101] Physics Department, Panjab University, Chandigarh, India
[102] Physics Department, University of Jammu, Jammu, India
[103] Physics Department, University of Rajasthan, Jaipur, India
[104] Physikalisches Institut, Eberhard-Karls-Universität Tübingen, Tübingen, Germany
[105] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
[106] Physik Department, Technische Universität München, Munich, Germany

[107] Politecnico di Bari and Sezione INFN, Bari, Italy
[108] Research Division and ExtreMe Matter Institute EMMI, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[109] Russian Federal Nuclear Center (VNIIEF), Sarov, Russia
[110] Saha Institute of Nuclear Physics, Homi Bhabha National Institute, Kolkata, India
[111] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[112] Sección Física, Departamento de Ciencias, Pontificia Universidad Católica del Perú, Lima, Peru
[113] St. Petersburg State University, St. Petersburg, Russia
[114] Stefan Meyer Institut für Subatomare Physik (SMI), Vienna, Austria
[115] SUBATECH, IMT Atlantique, Université de Nantes, CNRS-IN2P3, Nantes, France
[116] Suranaree University of Technology, Nakhon Ratchasima, Thailand
[117] Technical University of Košice, Košice, Slovakia
[118] The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Cracow, Poland
[119] The University of Texas at Austin, Austin, Texas, United States
[120] Universidad Autónoma de Sinaloa, Culiacán, Mexico
[121] Universidade de São Paulo (USP), São Paulo, Brazil
[122] Universidade Estadual de Campinas (UNICAMP), Campinas, Brazil
[123] Universidade Federal do ABC, Santo Andre, Brazil
[124] University of Cape Town, Cape Town, South Africa
[125] University of Houston, Houston, Texas, United States
[126] University of Jyväskylä, Jyväskylä, Finland
[127] University of Kansas, Lawrence, Kansas, United States
[128] University of Liverpool, Liverpool, United Kingdom
[129] University of Science and Technology of China, Hefei, China
[130] University of South-Eastern Norway, Tonsberg, Norway
[131] University of Tennessee, Knoxville, Tennessee, United States
[132] University of the Witwatersrand, Johannesburg, South Africa
[133] University of Tokyo, Tokyo, Japan
[134] University of Tsukuba, Tsukuba, Japan
[135] University Politehnica of Bucharest, Bucharest, Romania
[136] Université Clermont Auvergne, CNRS/IN2P3, LPC, Clermont-Ferrand, France
[137] Université de Lyon, CNRS/IN2P3, Institut de Physique des 2 Infinis de Lyon, Lyon, France
[138] Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France, Strasbourg, France
[139] Université Paris-Saclay Centre d'Etudes de Saclay (CEA), IRFU, Départment de Physique Nucléaire (DPhN), Saclay, France
[140] Università degli Studi di Foggia, Foggia, Italy
[141] Università di Brescia, Brescia, Italy
[142] Variable Energy Cyclotron Centre, Homi Bhabha National Institute, Kolkata, India
[143] Warsaw University of Technology, Warsaw, Poland
[144] Wayne State University, Detroit, Michigan, United States
[145] Westfälische Wilhelms-Universität Münster, Institut für Kernphysik, Münster, Germany
[146] Wigner Research Centre for Physics, Budapest, Hungary
[147] Yale University, New Haven, Connecticut, United States
[148] Yonsei University, Seoul, Republic of Korea

B Supplemental material

B.1 Monte Carlo simulations

The Monte Carlo (MC) simulations utilized in the analysis for the Boosted Decision Tree (BDT) training and the acceptance-times-efficiency correction were obtained using the HIJING 1.36 event generator [43] to simulate Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. In each simulated event, Λ_c^+ signals were added by injecting $c\overline{c}$ or $b\overline{b}$ pairs generated with the PYTHIA 8.243 event generator [44] with the Monash tune [22]. The Λ_c^+ baryons were forced to decay into the hadronic decay channel of interest, $\Lambda_c^+ \to pK_S^0 \to p\pi^+\pi^-$. All generated particles were transported through the ALICE detector using the GEANT3 package [45]. The conditions of all the ALICE detectors in terms of active channels, gain, noise level, and alignment, and their evolution with time during the data taking, were taken into account in the simulations.

B.2 Invariant mass spectra

The yields of Λ_c^+ baryons were obtained via binned maximum-likelihood fits to the candidate invariant mass distributions. The fitting function was composed of a Gaussian term to estimate the signal and a second-, third-, or fourth-order polynomial function (depending on the p_T interval) to estimate the background. Examples of the invariant mass distributions from which the Λ_c^+ raw yields are extracted are reported in Fig. B.1. The spectra together with the result of the fits in $1 < p_T < 2$ GeV/c and $4 < p_T < 6$ GeV/c for central (0–10%) and $2 < p_T < 4$ GeV/c and $8 < p_T < 12$ GeV/c for mid-central (30–50%) Pb–Pb collisions are shown.

B.3 Systematic uncertainties

The systematic uncertainty of the raw-yield extraction (ranging from 7% to 15%) was estimated by repeating the invariant mass fits varying the lower and upper limits of the fit range, the bin width, the functional form of the background fit function, and considering the Gaussian width as free parameter in the fit. The procedure to estimate the systematic uncertainty of the track-reconstruction efficiency (from 8% to 12%) includes variations of the track-quality selection criteria and studies of the matching efficiency of ITS clusters to tracks reconstructed in the TPC, as described in detail in [32]. The systematic uncertainty of the Λ_c^+ selection efficiency (from 7% to 8%) was estimated by repeating the analysis with different selections on the BDT output, resulting in up to 50% lower and 20–50% higher efficiency values. An additional contribution derives from the p_T spectra of Λ_c^+ generated in the simulation (at maximum 8%), which was estimated by using the Λ_c^+/D^0 predictions of the Catania model [7] and the SHMc [9] instead of the TAMU prediction [8] in the p_T-shape reweighting procedure. Finally, the systematic uncertainty of the feed-down subtraction was estimated by varying the FONLL parameters and the function describing the Λ_b^0 fragmentation fraction as described in [10] (from 2% to 10%), as well as varying the hypothesis on $R_{AA}^{non-prompt}$ (from 2% to 12%). For the latter, an interval $1/3 < R_{AA}^{non-prompt}/R_{AA}^{prompt} < 3$ was considered, wider with respect to that used for non-strange D mesons [39] to cover possible yet unmeasured differences between the modification of charm- and beauty-baryon production in Pb–Pb collisions with respect to the one in pp collisions.

The sources of systematic uncertainty considered in this analysis are assumed to be uncorrelated among each other and the total systematic uncertainty in each p_T and centrality interval is calculated as the quadratic sum of the estimated values. For the Λ_c^+/D^0 ratio, the Λ_c^+ and D^0 uncertainties were considered as uncorrelated except for the tracking efficiency and the feed-down contribution, which partially cancel in the ratio, and the systematic uncertainty of the centrality interval definition, which fully cancels. For the R_{AA}, the pp and Pb–Pb uncertainties were considered as uncorrelated except for the branching ratio uncertainty (due to the different considered decay modes in the pp measurement) and the feed-down contribution, which both partially cancel out. Finally, in case of the p_T-integrated Λ_c^+/D^0 ratio, there is a correlation between the extrapolation uncertainty of the Λ_c^+ baryon and the measured uncertainties of

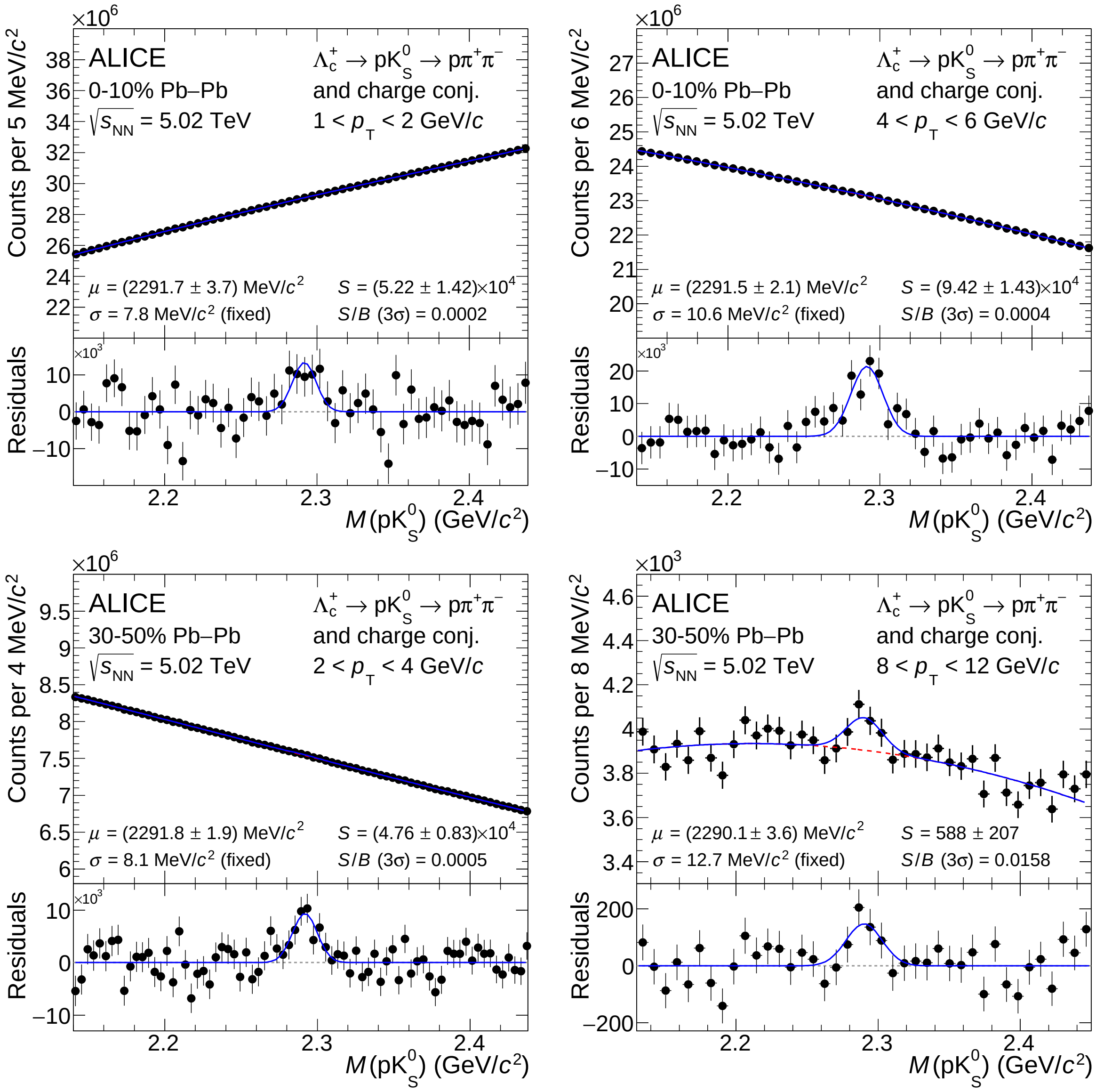

Figure B.1: Invariant mass (M) distributions of $\Lambda_c^+ \to pK^0_S \to p\pi^+\pi^-$ candidates and charge conjugates in different p_T intervals in central (0–10%; top) and mid-central (30–50%; bottom) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The blue solid lines show the total fit functions and the red dashed lines are the combinatorial-background terms. The values of the mean (μ) and the width (σ) of the signal peak are reported together with the signal counts (S) and the signal-over-background ratio (S/B) in the mass interval $(\mu - 3\sigma, \mu + 3\sigma)$.

the Λ_c^+ and D^0 hadrons. To treat this correlation, the extrapolation uncertainty is divided into a correlated part (estimated as the extrapolation uncertainty due to the interpolation procedure when considering only the shape predicted by TAMU) and an uncorrelated part (the total extrapolation uncertainty subtracting the correlated part) with respect to the measured uncertainties. The uncorrelated part is summed in quadrature with the measured uncertainties, while the correlated part is added linearly.

B.4 Nuclear modification factor

Figure B.2 shows the nuclear modification factor R_{AA} of prompt Λ_c^+ baryons in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared with the R_{AA} of prompt D_s^+ mesons [58] and the average R_{AA} of prompt D^0, D^+, and D^{*+} mesons [39], in the 0–10% and 30–50% centrality intervals. The suppression of all

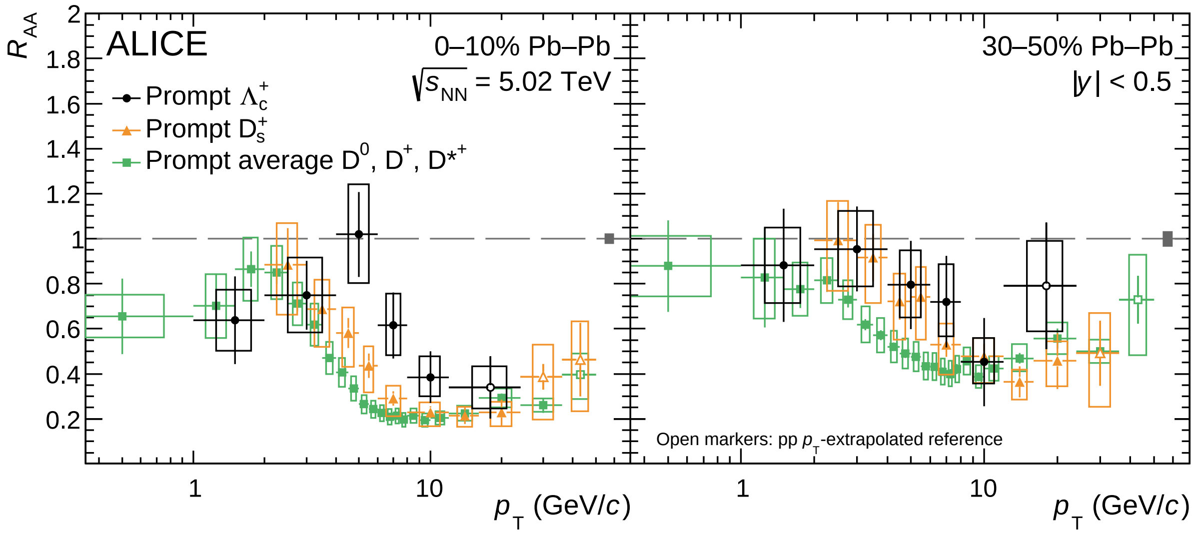

Figure B.2: Nuclear modification factor R_{AA} of prompt Λ_c^+ baryons in central (0–10%; left) and mid-central (30–50%; right) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared with the R_{AA} of prompt D_s^+ [58] and the average of prompt non-strange D mesons [39]. The statistical and total systematic uncertainties are shown as error bars and boxes, respectively. The normalization uncertainties are shown as boxes around unity.

charm-hadron species from $p_T \gtrsim 3$ GeV/c is understood as being primarily due to the interaction of charm quarks with the quark–gluon plasma, modifying its momentum spectra. In central collisions in the region $4 < p_T < 8$ GeV/c, there is a hint of a hierarchy $R_{AA}(D) < R_{AA}(D_s^+) < R_{AA}(\Lambda_c^+)$, indicating that the suppression of Λ_c^+ baryons is less than that of strange D_s^+ mesons, which is in turn less than that of non-strange D mesons in this p_T region. In mid-central collisions, this hierarchy is less pronounced. Along with the enhanced Λ_c^+/D^0 ratio in central collisions, this hierarchy would give further indications that hadronization occurs also via coalescence, which is expected to increase the probability of charm quarks hadronizing to D mesons with strange quarks and Λ_c^+ baryons with respect to non-strange charm mesons. However, more precise measurements are needed before confirming such a hierarchy.

Figure B.3 shows the R_{AA} of prompt Λ_c^+ baryons compared with theoretical models, namely the Catania model [7] implementing hadronization via quark coalescence and fragmentation, TAMU [8], which implements coalescence via a resonance recombination method, and the SHMc [9], which uses statistical hadronization with a core–corona approach. The TAMU model provides a good description of the R_{AA}, over the whole p_T range, in both central and mid-central collisions. The Catania model describes the data in both central and mid-central collisions for $p_T > 2$ GeV/c, however for $p_T < 2$ GeV/c the model predicts an R_{AA} higher than unity which is disfavored by data. The SHMc model instead significantly underestimates the Λ_c^+ R_{AA} over the whole p_T range. As already noted by the authors of [9], this suggests that the corona description could be further optimized.

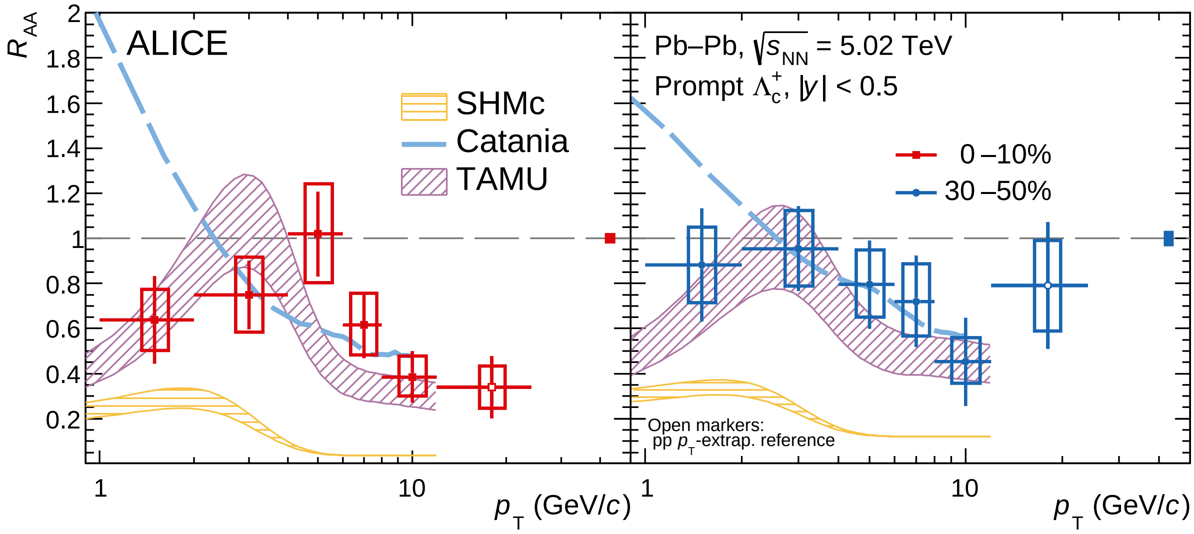

Figure B.3: Nuclear modification factor R_{AA} of prompt Λ_c^+ baryons in central (0–10%; left) and mid-central (30–50%; right) Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, compared with model predictions. When estimated, the model uncertainty is shown as a shaded band.