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Supplemental material for "Observation of a multiplicity dependence in the $p_{\rm T}$-differential charm baryon-to-meson ratios in proton–proton collisions at $\sqrt{s} = 13$ TeV"

ALICE Collaboration*

Abstract

The following public note presents supplemental figures for the paper "Observation of a multiplicity dependence in the $p_{\rm T}$-differential charm baryon-to-meson ratios in proton–proton collisions at $\sqrt{s} = 13$ TeV " [1]. The production of prompt $\rm D^0$, $\rm D_s^+$, and Λ_c^+ hadrons, and their ratios, $\rm D_s^+/D^0$ and $\Lambda_c^+/\rm D^0$, are measured in proton–proton collisions at $\sqrt{s} = 13$ TeV at midrapidity ($|y| < 0.5$) with the ALICE detector at the LHC. The measurements are performed as a function of the candidate transverse momentum ($p_{\rm T}$), in intervals of charged-particle multiplicity. This note presents $\rm D^0$, $\rm D_s^+$, and Λ_c^+ invariant-mass spectra and acceptance-times-efficiency distributions in different $p_{\rm T}$ and multiplicity intervals. The $p_{\rm T}$-differential yield in multiplicity intervals estimated at mid- and forward rapidity are also shown. Finally, the charm-hadron $p_{\rm T}$-integrated yields in the visible $p_{\rm T}$ range and those extrapolated to $p_{\rm T} > 0$ are reported, as well as the $\rm D_s^+/D^0$ and $\Lambda_c^+/\rm D^0$ yield ratios as a function of charged-particle multiplicity, together with comparison with different PYTHIA predictions.

*See Appendix A for the list of collaboration members

1 Invariant-mass and acceptance-times-efficiency distributions

The study presented in Ref. [1] obtains the charm-hadron raw yields (including both particles and antiparticles) from binned maximum-likelihood fits to the invariant-mass distributions of D^0, D_s^+, and Λ_c^+ candidates. Figure 1 shows a few examples of the invariant-mass spectra together with the results of the fits for D^0, D_s^+, $\Lambda_c^+ \to pK^-\pi^+$, and $\Lambda_c^+ \to pK_S^0$ candidates in different transverse momentum (p_T) intervals and multiplicity event classes evaluated with the multiplicity estimator at midrapidity (N_{trkl}). More details on the fitting procedure are provided in Ref. [1–3].

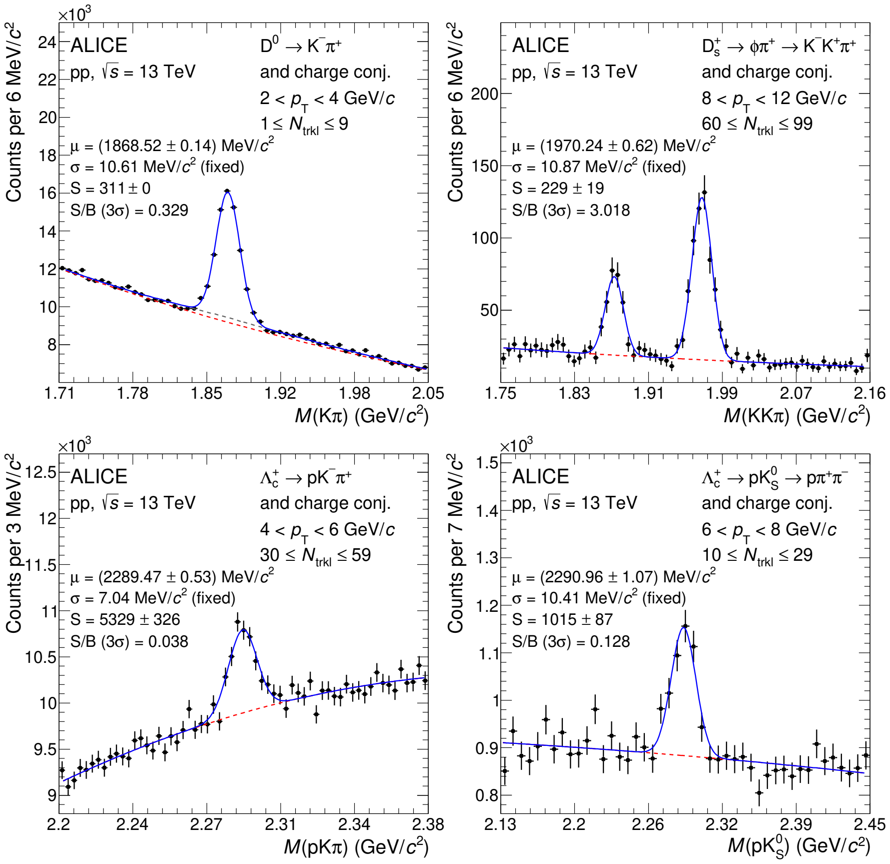

Figure 1: Invariant-mass (M) distributions of D^0, D_s^+, $\Lambda_c^+ \to pK^-\pi^+$, and $\Lambda_c^+ \to pK_S^0$ candidates and charge conjugates in different p_T and multiplicity intervals evaluated at midrapidity. The blue solid lines show the total fit functions and the red dashed lines are the combinatorial-background terms. For the D^0 fit, the grey dashed line represents the combinatorial background with the contribution of the reflections, as explained in Ref. [1]. 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-to-background ratio (S/B) in the mass interval ($\mu - 3\sigma, \mu + 3\sigma$). Only the statistical uncertainties from the fit are reported.

The acceptance-times-efficiency distributions for the different charm hadrons are determined from simulations in each multiplicity event class (see Ref. [1] for details). In Fig. 2 the distributions as a function of p_T for prompt D^0, D_s^+, $\Lambda_c^+ \to pK^-\pi^+$, and $\Lambda_c^+ \to pK_S^0$ hadrons within the fiducial acceptance region are reported for the N_{trkl} multiplicity estimator.

2 Transverse-momentum-differential spectra

Figure 3 reports the p_T-differential spectra of D^0, D_s^+, and Λ_c^+ hadrons for the INEL > 0 class and the three multiplicity classes selected using the multiplicity estimator at forward rapidity (p_{V0M}) defined

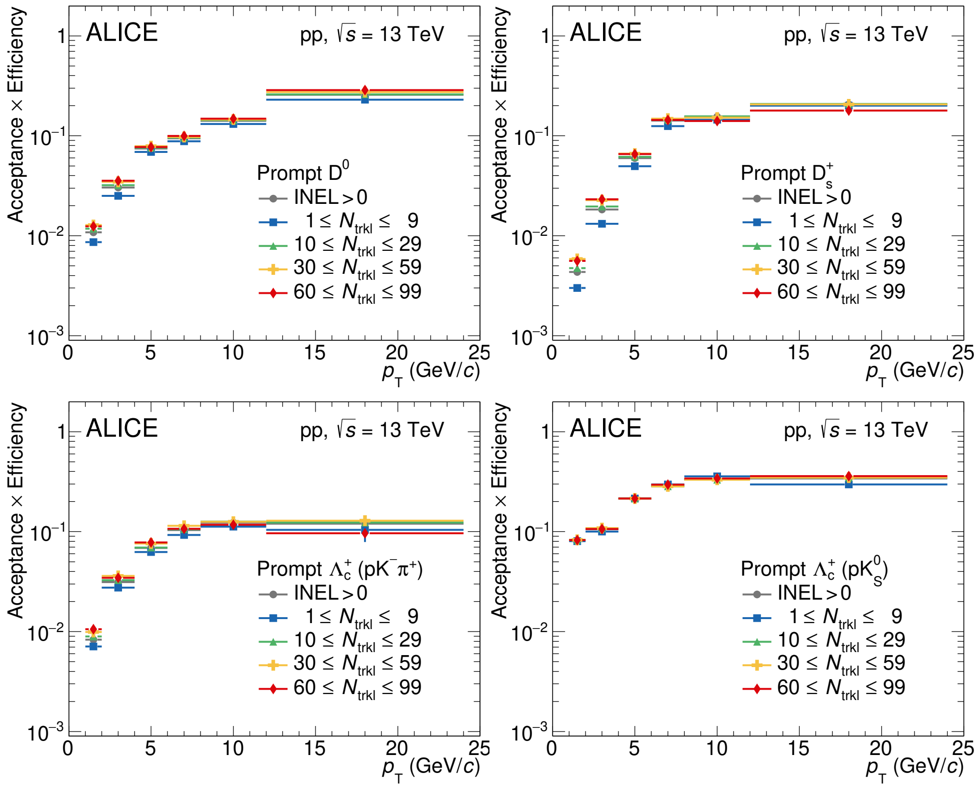

Figure 2: Acceptance-times-efficiency for prompt D^0, D_s^+, $\Lambda_c^+ \to pK^-\pi^+$, and $\Lambda_c^+ \to pK_S^0$ hadrons, as a function of p_T for the multiplicity intervals evaluated at midrapidity.

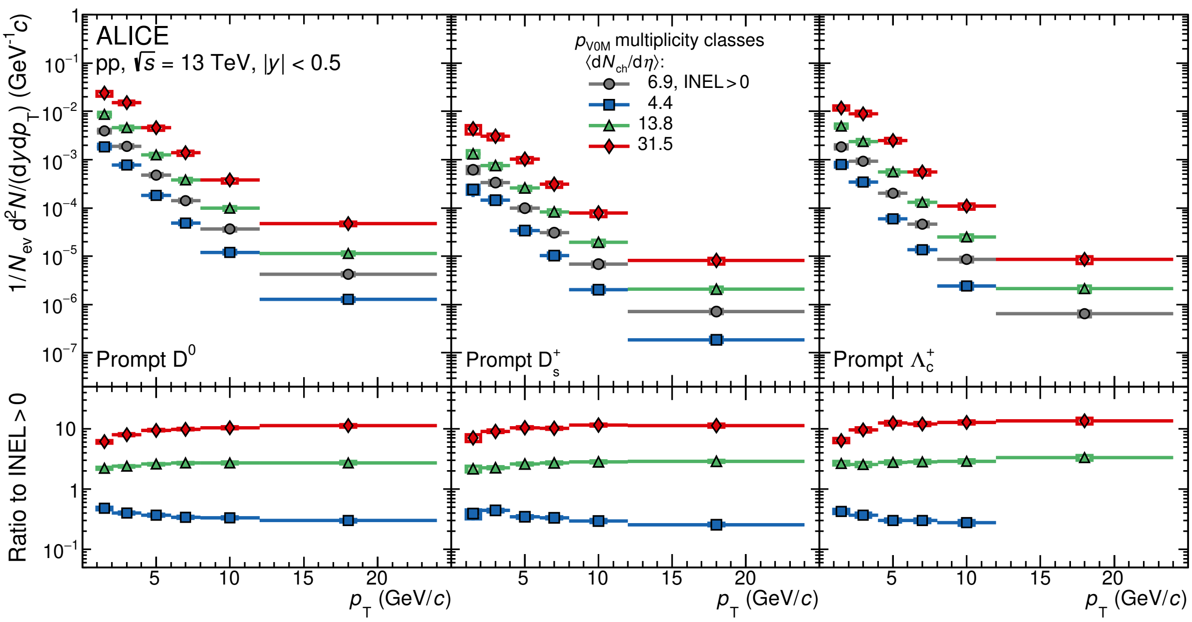

Figure 3: Transverse-momentum spectra of D^0, D_s^+, and Λ_c^+ hadrons measured in pp collisions at $\sqrt{s} = 13$ TeV at midrapidity, for different multiplicity classes selected with the p_{V0M} estimator at forward rapidity. The corresponding ratios to INEL > 0 are shown in the bottom panels.

in Ref. [1]. The bottom panels present the ratios to the INEL > 0 class. The p_T spectra for the N_{trkl}

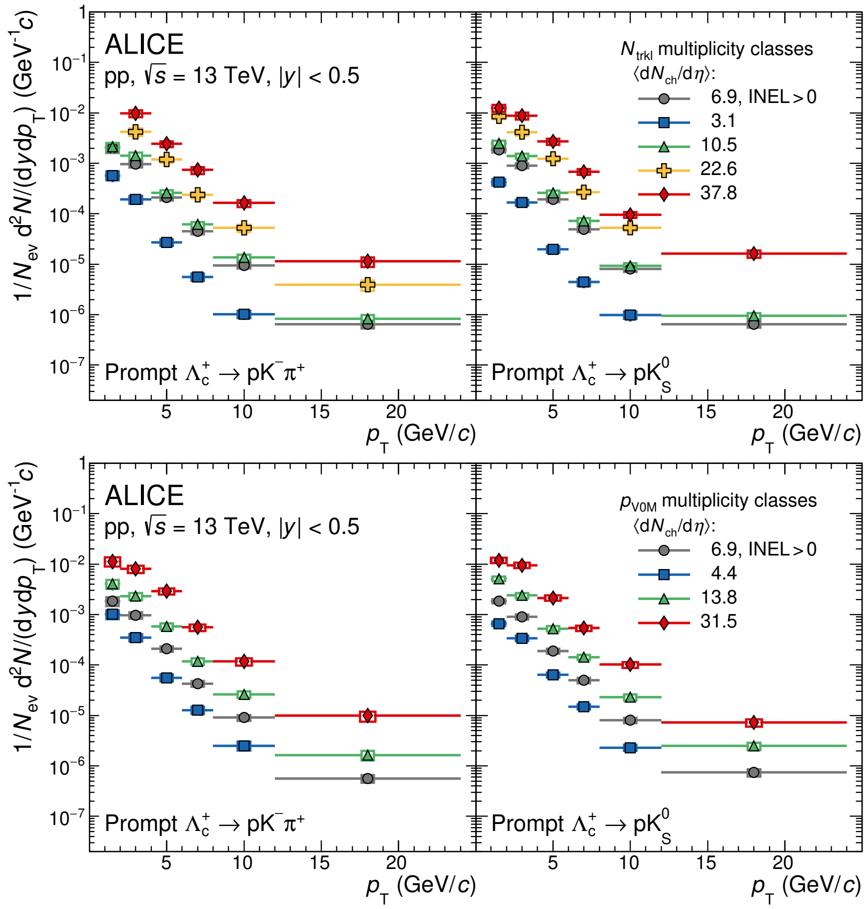

Figure 4: The $p_{\rm T}$-differential spectra of $\Lambda_c^+ \rightarrow pK^-\pi^+$ (left panel) and $\Lambda_c^+ \rightarrow pK^0_S$ (right panel) baryons measured in pp collisions at $\sqrt{s} = 13$ TeV at midrapidity, in different multiplicity event classes selected using the multiplicity estimators at midrapidity (top) and forward rapidity (bottom).

estimator, as well as the strategy regarding the uncertainties on the ratio to the INEL > 0 class, are provided in Ref. [1].

The $p_{\rm T}$-differential spectra of the prompt Λ_c^+ baryon in pp collisions at $\sqrt{s} = 13$ TeV, as reported in Ref. [1] and Fig. 3, were derived from a weighted average of the two decay channels $\Lambda_c^+ \rightarrow pK^-\pi^+$ and $\Lambda_c^+ \rightarrow pK^0_S$, to obtain a more precise measurement. In Fig. 4, the spectra are shown for both of these Λ_c^+ decay channels in the different event-multiplicity classes measured with the $N_{\rm trkl}$ and $p_{\rm V0M}$ multiplicity estimators. The measurements in the two decay channels agree, for all the $p_{\rm T}$ and multiplicity intervals, within the statistical and uncorrelated systematic uncertainties, justifying the averaging used for the study in Ref. [1].

3 Transverse-momentum-integrated yields and hadron ratios

The $p_{\rm T}$-integrated yields of the D^0, D_s^+, and Λ_c^+ hadrons were computed by integrating the $p_{\rm T}$-differential spectra in the corresponding measured range and extrapolating them down to $p_{\rm T} = 0$ in each multiplicity interval, using the strategy as described in Ref. [1]. The extrapolation factor for $p_{\rm T} > 24$ GeV/c was estimated and found to be negligible. The integrated yields in the visible $p_{\rm T}$ range are reported in Table 1 for the three hadrons in the INEL > 0 class and the four multiplicity intervals estimated with the $N_{\rm trkl}$ estimator. In Table 2 the $p_{\rm T}$-integrated yields extrapolated to the full $p_{\rm T}$ range, together with the extrapolation factor, are reported. Figure 5 shows the $p_{\rm T}$-integrated yields in the visible and full $p_{\rm T}$ range as a

Table 1: The p_T-integrated yields for the D^0, D_s^+, and Λ_c^+ hadrons in the visible p_T range for the INEL > 0 class and the four multiplicity intervals estimated at midrapidity with the N_{trkl} estimator.

Hadron	$\langle dN_{ch}/d\eta \rangle$	Kin. range (GeV/c)	$1/N_{ev} \cdot dN/dy\|_{\|y\|<0.5}^{\text{visible}\,p_T}$ ($\times 10^3$)
D^0	6.9 (INEL > 0)	$1 < p_T < 24$	9.15 ± 0.21 (stat.) $^{+0.71}_{-0.75}$ (syst.)
	3.1	$1 < p_T < 24$	2.50 ± 0.10 (stat.) $^{+0.29}_{-0.23}$ (syst.)
	10.5	$1 < p_T < 24$	13.69 ± 0.30 (stat.) $^{+1.13}_{-1.18}$ (syst.)
	22.6	$1 < p_T < 24$	34.71 ± 1.41 (stat.) $^{+2.66}_{-3.69}$ (syst.)
	37.8	$1 < p_T < 24$	79.58 ± 2.84 (stat.) $^{+6.93}_{-11.9}$ (syst.)
D_s^+	6.9 (INEL > 0)	$1 < p_T < 24$	1.55 ± 0.11 (stat.) $^{+0.18}_{-0.19}$ (syst.)
	3.1	$2 < p_T < 24$	0.24 ± 0.02 (stat.) $^{+0.04}_{-0.03}$ (syst.)
	10.5	$1 < p_T < 24$	2.37 ± 0.19 (stat.) $^{+0.30}_{-0.30}$ (syst.)
	22.6	$2 < p_T < 24$	4.17 ± 0.21 (stat.) $^{+0.45}_{-0.58}$ (syst.)
	37.8	$2 < p_T < 24$	9.31 ± 0.36 (stat.) $^{+1.11}_{-1.71}$ (syst.)
Λ_c^+	6.9 (INEL > 0)	$1 < p_T < 24$	4.28 ± 0.18 (stat.) $^{+0.39}_{-0.40}$ (syst.)
	3.1	$1 < p_T < 12$	0.90 ± 0.08 (stat.) $^{+0.11}_{-0.11}$ (syst.)
	10.5	$1 < p_T < 24$	5.98 ± 0.33 (stat.) $^{+0.57}_{-0.58}$ (syst.)
	22.6	$1 < p_T < 24$	19.98 ± 1.80 (stat.) $^{+2.05}_{-2.11}$ (syst.)
	37.8	$1 < p_T < 24$	38.36 ± 3.25 (stat.) $^{+4.21}_{-4.51}$ (syst.)

Table 2: D^0, D_s^+, and Λ_c^+ p_T-integrated yields extrapolated in the full p_T range for INEL > 0 and different multiplicity intervals at midrapidity. Extrapolation factors are also reported.

Hadron	$\langle dN_{ch}/d\eta \rangle$	Extrap. factor	$1/N_{ev} \cdot dN/dy\|_{\|y\|<0.5}^{p_T>0}$ ($\times 10^3$)
D^0	6.9 (INEL > 0)	$1.27^{+0.04}_{-0.03}$	11.67 ± 0.26 (stat.) $^{+0.91}_{-0.96}$ (syst.) $^{+0.28}_{-0.32}$ (extr.)
	3.1	$1.45^{+0.00}_{-0.14}$	3.61 ± 0.14 (stat.) $^{+0.42}_{-0.34}$ (syst.) $^{+0.02}_{-0.33}$ (extr.)
	10.5	$1.28^{+0.02}_{-0.01}$	17.53 ± 0.38 (stat.) $^{+1.45}_{-1.51}$ (syst.) $^{+0.31}_{-0.13}$ (extr.)
	22.6	$1.19^{+0.07}_{-0.03}$	41.39 ± 1.68 (stat.) $^{+3.17}_{-4.40}$ (syst.) $^{+2.21}_{-1.17}$ (extr.)
	37.8	$1.14^{+0.11}_{-0.00}$	91.04 ± 3.25 (stat.) $^{+7.93}_{-13.6}$ (syst.) $^{+8.72}_{-0.13}$ (extr.)
D_s^+	6.9 (INEL > 0)	$1.24^{+0.02}_{-0.08}$	1.92 ± 0.13 (stat.) $^{+0.22}_{-0.23}$ (syst.) $^{+0.03}_{-0.13}$ (extr.)
	3.1	$2.53^{+0.24}_{-0.03}$	0.60 ± 0.04 (stat.) $^{+0.10}_{-0.09}$ (syst.) $^{+0.06}_{-0.01}$ (extr.)
	10.5	$1.24^{+0.03}_{-0.05}$	2.95 ± 0.23 (stat.) $^{+0.37}_{-0.38}$ (syst.) $^{+0.07}_{-0.12}$ (extr.)
	22.6	$1.65^{+0.20}_{-0.00}$	6.88 ± 0.34 (stat.) $^{+0.75}_{-0.96}$ (syst.) $^{+0.83}_{-0.00}$ (extr.)
	37.8	$1.49^{+0.26}_{-0.07}$	13.83 ± 0.53 (stat.) $^{+1.66}_{-2.54}$ (syst.) $^{+2.45}_{-0.65}$ (extr.)
Λ_c^+	6.9 (INEL > 0)	$1.34^{+0.02}_{-0.10}$	5.72 ± 0.24 (stat.) $^{+0.52}_{-0.53}$ (syst.) $^{+0.08}_{-0.40}$ (extr.)
	3.1	$1.63^{+0.00}_{-0.34}$	1.47 ± 0.13 (stat.) $^{+0.18}_{-0.18}$ (syst.) $^{+0.00}_{-0.31}$ (extr.)
	10.5	$1.38^{+0.01}_{-0.18}$	8.26 ± 0.46 (stat.) $^{+0.79}_{-0.80}$ (syst.) $^{+0.08}_{-1.06}$ (extr.)
	22.6	$1.25^{+0.02}_{-0.06}$	24.88 ± 2.24 (stat.) $^{+2.55}_{-2.63}$ (syst.) $^{+0.57}_{-1.20}$ (extr.)
	37.8	$1.18^{+0.04}_{-0.05}$	45.22 ± 3.83 (stat.) $^{+4.97}_{-5.31}$ (syst.) $^{+1.76}_{-1.93}$ (extr.)

function of $\langle dN_{ch}/d\eta \rangle$.

Finally, the p_T-integrated D_s^+/D^0 and Λ_c^+/D^0 yield ratios in the visible p_T range are reported in Fig. 6 as a function of $\langle dN_{ch}/d\eta \rangle$. In Fig. 7, the p_T-integrated yield ratios for $p_T > 0$ (left) and for $4 < p_T < 6$ GeV/c

are shown for Λ_c^+/D^0 (upper panels) and D_s^+/D^0 (lower panels), as a function of $\langle dN_{ch}/d\eta \rangle$. Both the Λ_c^+/D^0 and the D_s^+/D^0 yield ratios do not show strong signs of increase with multiplicity. The results are compared with PYTHIA predictions [4, 5] evaluated in the corresponding p_T intervals. As discussed in Ref. [1], the Λ_c^+/D^0 measurements disfavour the Monash prediction in the whole multiplicity range. They also tend to be significantly below the CR-BLC Mode 2 for the highest multiplicity interval, for both the p_T-integrated and the $4 < p_T < 6$ GeV/c measurements. By contrast, the D_s^+/D^0 yield ratios are in agreement with the four considered tunes of the PYTHIA event generator within uncertainties. The p_T-integrated yield ratios measured as a function of charged-particle multiplicity, and the yield ratios computed in $4 < p_T < 6$ GeV/c are in agreement within uncertainties, for both Λ_c^+/D^0 and D_s^+/D^0 measurements.

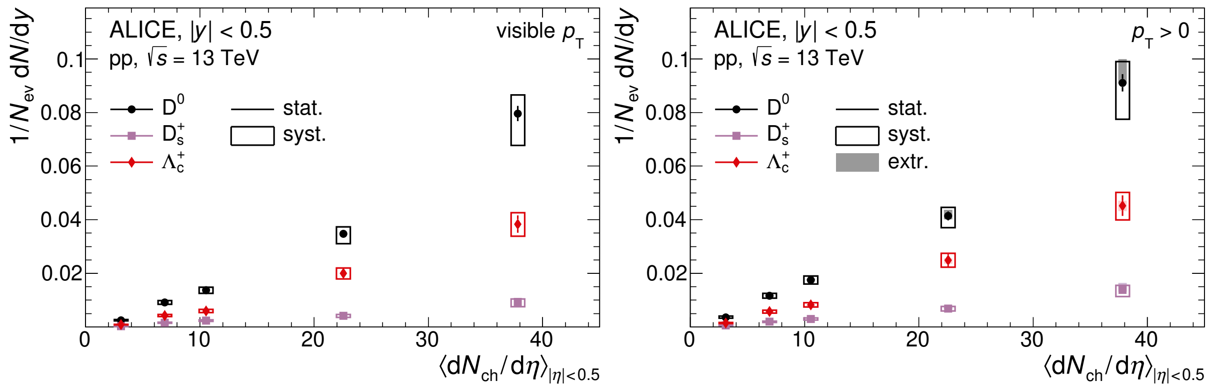

Figure 5: The p_T-integrated yields for D^0, D_s^+, and Λ_c^+ hadrons in the visible p_T range (left) and $p_T > 0$ (right) as a function of charged-particle multiplicity in pp collisions at $\sqrt{s} = 13$ TeV. Statistical and systematic uncertainties are shown by error bars and empty boxes, respectively. The shaded boxes in the right panel represent the uncertainties on the extrapolation procedure.

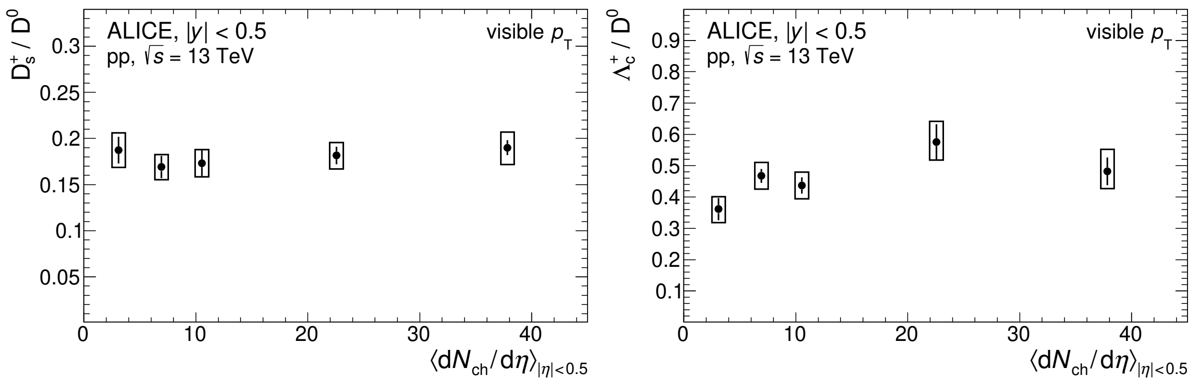

Figure 6: The D_s^+/D^0 and Λ_c^+/D^0 p_T-integrated yield ratios in the visible p_T range, as a function of $\langle dN_{ch}/d\eta \rangle$, in pp collisions at $\sqrt{s} = 13$ TeV.

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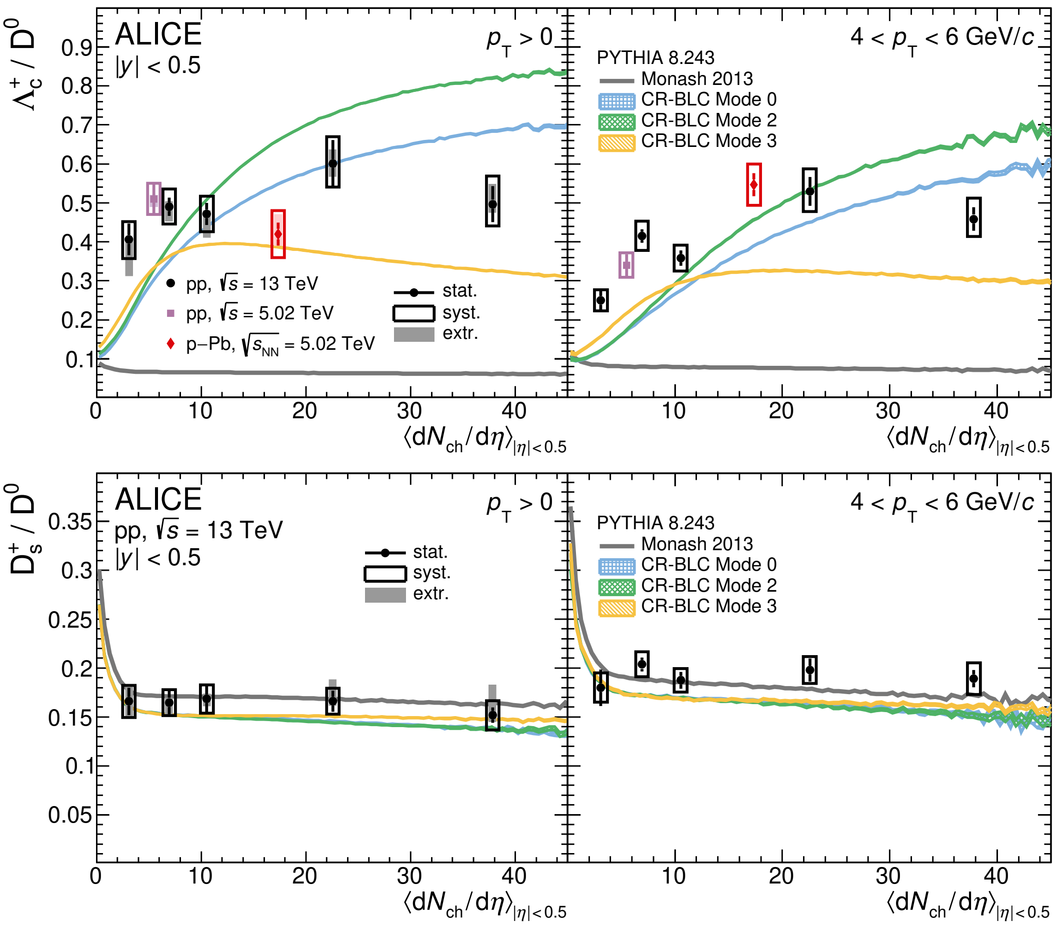

Figure 7: The p_{T}-integrated Λ_c^+/D^0 (top) and $\mathrm{D}_s^+/\mathrm{D}^0$ (bottom) yield ratios extrapolated for $p_{\mathrm{T}} > 0$ (left panel) and for the $4 < p_{\mathrm{T}} < 6$ GeV/c interval (right panel). Statistical and systematic uncertainties are shown by error bars and empty boxes, respectively, while the shaded boxes represent the extrapolation uncertainties. The corresponding PYTHIA predictions [4, 5] are also shown.

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S. Acharya[142], D. Adamová[96], A. Adler[74], J. Adolfsson[81], G. Aglieri Rinella[34], M. Agnello[30], N. Agrawal[54], Z. Ahammed[142], S. Ahmad[16], S.U. Ahn[76], I. Ahuja[38], Z. Akbar[51], A. Akindinov[93], M. Al-Turany[108], S.N. Alam[16], D. Aleksandrov[89], B. Alessandro[59], H.M. Alfanda[7], R. Alfaro Molina[71], B. Ali[16], Y. Ali[14], A. Alici[25], N. Alizadehvandchali[125], A. Alkin[34], J. Alme[21], G. Alocco[55], T. Alt[68], I. Altsybeev[113], M.N. Anaam[7], C. Andrei[48], D. Andreou[91], A. Andronic[145], V. Anguelov[105], F. Antinori[57], P. Antonioli[54], C. Anuj[16], N. Apadula[80], L. Aphecetche[115], H. Appelshäuser[68], S. Arcelli[25], R. Arnaldi[59], I.C. Arsene[20], M. Arslandok[147], A. Augustinus[34], R. Averbeck[108], S. Aziz[78], M.D. Azmi[16], A. Badalà[56], Y.W. Baek[41], X. Bai[129,108], R. Bailhache[68], Y. Bailung[50], R. Bala[102], A. Balbino[30], A. Baldisseri[139], B. Balis[2], D. Banerjee[4], Z. Banoo[102], R. Barbera[26], L. Barioglio[106], M. 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Cicalo[55], L. Cifarelli[25], F. Cindolo[54], M.R. Ciupek[108], G. Clai[II,54], J. Cleymans[I,124], F. Colamaria[53], J.S. Colburn[111], D. Colella[53,107,33], A. Collu[80], M. Colocci[34], M. Concas[III,59], G. Conesa Balbastre[79], Z. Conesa del Valle[78], G. Contin[23], J.G. Contreras[37], M.L. Coquet[139], T.M. Cormier[97], P. Cortese[31], M.R. Cosentino[123], F. Costa[34], S. Costanza[28,58], P. Crochet[136], R. Cruz-Torres[80], E. Cuautle[69], P. Cui[7], L. Cunqueiro[97], A. Dainese[57], M.C. Danisch[105], A. Danu[67], P. Das[87], P. Das[4], S. Das[4], S. Dash[49], A. De Caro[29], G. de Cataldo[53], L. De Cilladi[24], J. de Cuveland[39], A. De Falco[22], D. De Gruttola[29], N. De Marco[59], C. De Martin[23], S. De Pasquale[29], S. Deb[50], H.F. Degenhardt[121], K.R. Deja[143], R. Del Grande[106], L. Dello Stritto[29], W. Deng[7], P. Dhankher[19], D. Di Bari[33], A. Di Mauro[34], R.A. Diaz[8], T. Dietel[124], Y. Ding[137,7], R. Divià[34], D.U. Dixit[19], Ø. Djuvsland[21], U. Dmitrieva[63], J. Do[61], A. Dobrin[67], B. Dönigus[68], A.K. Dubey[142], A. Dubla[108,91], S. Dudi[101], P. Dupieux[136], N. Dzalaiova[13], T.M. Eder[145], R.J. Ehlers[97], V.N. Eikeland[21], F. Eisenhut[68], D. Elia[53], B. Erazmus[115], F. Ercolessi[25], F. Erhardt[100], A. Erokhin[113], M.R. Ersdal[21], B. Espagnon[78], G. Eulisse[34], D. Evans[111], S. Evdokimov[92], L. Fabbietti[106], M. Faggin[27], J. Faivre[79], F. Fan[7], W. Fan[80], A. Fantoni[52], M. Fasel[97], P. Fecchio[30], A. Feliciello[59], G. Feofilov[113], A. Fernández Téllez[45], A. Ferrero[139], A. Ferretti[24], V.J.G. Feuillard[105], J. Figiel[118], V. Filova[37], D. Finogeev[63], F.M. Fionda[55], G. Fiorenza[34], F. Flor[125], A.N. Flores[119], S. Foertsch[72], S. Fokin[89], E. Fragiacomo[60], E. Frajna[146], A. Francisco[136], U. Fuchs[34], N. Funicello[29], C. Furget[79], A. Furs[63], J.J. Gaardhøje[90], M. Gagliardi[24], A.M. Gago[112], A. Gal[138], C.D. Galvan[120], P. Ganoti[85], C. Garabatos[108], J.R.A. Garcia[45], E. Garcia-Solis[10], K. Garg[115], C. Gargiulo[34], A. Garibli[88], K. Garner[145], P. Gasik[108], E.F. Gauger[119], A. Gautam[127], M.B. Gay Ducati[70], M. Germain[115], P. Ghosh[142], S.K. Ghosh[4], M. Giacalone[25], P. Gianotti[52], P. Giubellino[108,59], P. Giubilato[27], A.M.C. Glaenzer[139], P. Glässel[105], E. Glimos[131], D.J.Q. Goh[83], V. Gonzalez[144], L.H. González-Trueba[71], S. Gorbunov[39], M. Gorgon[2], L. Görlich[118], S. Gotovac[35], V. Grabski[71], L.K. Graczykowski[143], L. Greiner[80], A. Grelli[62], C. Grigoras[34], V. Grigoriev[94], S. Grigoryan[75,1], F. Grosa[34,59], J.F. Grosse-Oetringhaus[34], R. Grosso[108], D. Grund[37], G.G. Guardiano[122], R. Guernane[79], M. Guilbaud[115], K. Gulbrandsen[90], T. Gunji[133], W. Guo[7], A. Gupta[102], R. Gupta[102], S.P. Guzman[45], L. Gyulai[146], M.K. Habib[108], C. Hadjidakis[78], H. Hamagaki[83], M. Hamid[7], R. Hannigan[119], M.R. Haque[143], A. Harlenderova[108], J.W. Harris[147], A. Harton[10], J.A. Hasenbichler[34], H. Hassan[97], D. Hatzifotiadou[54], P. Hauer[43], L.B. Havener[147], S.T. Heckel[106], E. Hellbär[108], H. Helstrup[36], T. Herman[37], E.G. Hernandez[45], G. Herrera Corral[9], F. Herrmann[145], K.F. Hetland[36], H. Hillemanns[34], C. Hills[128], B. Hippolyte[138], B. Hofman[62], B. Hohlweger[91], J. Honermann[145], G.H. Hong[148], D. Horak[37], S. Hornung[108], A. Horzyk[2], R. Hosokawa[15], Y. Hou[7], P. Hristov[34], C. Hughes[131], P. Huhn[68], L.M. Huhta[126], C.V. Hulse[78], T.J. Humanic[98], H. Hushnud[110], L.A. Husova[145],

A. Hutson[125], J.P. Iddon[34,128], R. Ilkaev[109], H. Ilyas[14], M. Inaba[134], G.M. Innocenti[34], M. Ippolitov[89], A. Isakov[96], T. Isidori[127], M.S. Islam[110], M. Ivanov[108], V. Ivanov[99], V. Izucheev[92], M. Jablonski[2], B. Jacak[80], N. Jacazio[34], P.M. Jacobs[80], S. Jadlovska[117], J. Jadlovsky[117], S. Jaelani[62], C. Jahnke[122,121], M.J. Jakubowska[143], A. Jalotra[102], M.A. Janik[143], T. Janson[74], M. Jercic[100], O. Jevons[111], A.A.P. Jimenez[69], F. Jonas[97,145], P.G. Jones[111], J.M. Jowett [34,108], J. Jung[68], M. Jung[68], A. Junique[34], A. Jusko[111], M.J. Kabus[143], J. Kaewjai[116], P. Kalinak[64], A.S. Kalteyer[108], A. Kalweit[34], V. Kaplin[94], A. Karasu Uysal[77], D. Karatovic[100], O. Karavichev[63], T. Karavicheva[63], P. Karczmarczyk[143], E. Karpechev[63], V. Kashyap[87], A. Kazantsev[89], U. Kebschull[74], R. Keidel[47], D.L.D. Keijdener[62], M. Keil[34], B. Ketzer[43], Z. Khabanova[91], A.M. Khan[7], S. Khan[16], A. Khanzadeev[99], Y. Kharlov[92,82], A. Khatun[16], A. Khuntia[118], B. Kileng[36], B. Kim[17,61], C. Kim[17], D.J. Kim[126], E.J. Kim[73], J. Kim[148], J.S. Kim[41], J. Kim[105], J. Kim[73], M. Kim[105], S. Kim[18], T. Kim[148], S. Kirsch[68], I. Kisel[39], S. Kiselev[93], A. Kisiel[143], J.P. Kitowski[2], J.L. Klay[6], J. Klein[34], S. Klein[80], C. Klein-Bösing[145], M. Kleiner[68], T. Klemenz[106], A. Kluge[34], A.G. Knospe[125], C. Kobdaj[116], T. Kollegger[108], A. Kondratyev[75], N. Kondratyeva[94], E. Kondratyuk[92], J. Konig[68], S.A. Konigstorfer[106], P.J. Konopka[34], G. Kornakov[143], S.D. Koryciak[2], A. Kotliarov[96], O. Kovalenko[86], V. Kovalenko[113], M. Kowalski[118], I. Králik[64], A. Kravčáková[38], L. Kreis[108], M. Krivda[111,64], F. Krizek[96], K. 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. 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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], V. Samsonov[I,99,94], 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[136], J. Takahashi[122], G.J. Tambave[21], S. Tang[136,7], Z. Tang[129], J.D. Tapia Takaki[VII,127], 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], 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], 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], 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