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Charm-quark fragmentation fractions and production cross section at midrapidity in pp collisions at the LHC

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Abstract

Recent p_{T}-integrated cross section measurements of the ground-state charm mesons and baryons, D^0, D^+, D_s^+, Λ_c^+, and Ξ_c^0, are used to evaluate the charm fragmentation fractions and production cross section per unit of rapidity at midrapidity ($|y| < 0.5$), in pp collisions at $\sqrt{s} = 5.02$ TeV at the LHC. The latter is $\mathrm{d}\sigma^{c\bar{c}}/\mathrm{d}y|_{|y|<0.5} = 1165 \pm 44(\mathrm{stat})^{+134}_{-101}(\mathrm{syst})\ \mu\mathrm{b}$. These measurements were obtained for the first time in hadronic collisions at the LHC including the charm baryon states, recently measured by ALICE at midrapidity. The charm fragmentation fractions differ significantly from the values measured in $\mathrm{e}^+\mathrm{e}^-$ and ep collisions, providing evidence of the dependence of the parton-to-hadron fragmentation fractions on the collision system, indicating that the assumption of their universality is not supported by the measured cross sections. An increase of a factor of about 3.3 for the fragmentation fraction for the Λ_c^+ with a significance of $5\,\sigma$ between the values obtained in pp collisions and those obtained in $\mathrm{e}^+\mathrm{e}^-$ (ep) collisions is reported. The fragmentation fraction for the Ξ_c^0 was obtained for the first time in any collision system. The measured fragmentation fractions were used to update the $c\bar{c}$ cross sections per unit of rapidity at $|y| < 0.5$ at $\sqrt{s} = 2.76$ and 7 TeV, which are about 40% higher than the previously published results. The data were compared with perturbative-QCD calculations and lie at the upper edge of the theoretical bands.

*See Appendix A for the list of collaboration members

The study of heavy-flavour hadron production in proton–proton (pp) collisions provides an important test for quantum chromodynamics (QCD) calculations. The transverse-momentum (p_{T}) differential cross sections of charm mesons measured in pp collisions by the ALICE [1–5], ATLAS [6], CMS [7], and LHCb [8–10] experiments at the LHC and the STAR [11] experiment at RHIC, as well as in $\mathrm{p\overline{p}}$ collisions by the CDF [12] experiment at the Tevatron, are described within uncertainties by perturbative-QCD (pQCD) calculations having next-to-leading order (NLO) accuracy with all-order resummation of next-to-leading logarithms, such as FONLL [13–15] and NLL [16–20]. These calculations are based on the factorisation theorem, according to which the p_{T}-differential cross sections are computed as the convolution of three terms: (i) the parton distribution functions (PDFs) of the incoming (anti)protons, (ii) the partonic cross section, calculated as a perturbative series in powers of the strong coupling constant α_{s}, and (iii) the fragmentation functions which describe the transition from charm quarks into charm hadrons. The latter, in these calculations, are typically parametrised from measurements performed in $\mathrm{e^+e^-}$ or ep collisions [21], under the assumption that the hadronisation of charm quarks into charm hadrons is a universal process independent of the colliding systems. Accordingly, measurements of charm mesons were exploited in the past to derive a measurement of the charm production cross section at hadron colliders, by scaling the production cross section of the D mesons with the corresponding charm-quark fragmentation fraction, $f(\mathrm{c} \rightarrow \mathrm{D})$, taken from $\mathrm{e^+e^-}$ collisions [1, 3, 9–11, 22].

Recent measurements of charm-baryon production at midrapidity in pp collisions showed an enhancement of the $\Lambda_{\mathrm{c}}^{+}/\mathrm{D}^{0}$ [23–26] and $\Xi_{\mathrm{c}}^{+,0}/\mathrm{D}^{0}$ [27–29] ratios for $p_{\mathrm{T}} < 6-8$ GeV$/c$ with respect to the ones measured in $\mathrm{e^+e^-}$ collisions. These measurements suggest a significant difference of the fragmentation fractions of charm quarks into charm baryons in hadronic collisions at LHC energies compared to those measured in $\mathrm{e^+e^-}$ and ep collisions. These findings are similar to those obtained in the beauty sector by the CDF Collaboration at the Tevatron [30] and by the LHCb Collaboration at the LHC [31, 32].

Several models based on different assumptions, like the inclusion of hadronisation via coalescence [33, 34], or considering a set of yet-unobserved higher-mass charm-baryon states [35], or including string formation beyond the leading-colour approximation [36], have been proposed to explain the baryon enhancement. Updates of the fit to the measured fragmentation functions of $\mathrm{c} \rightarrow \Lambda_{\mathrm{c}}^{+}$ in $\mathrm{e^+e^-}$ collisions were also performed [37, 38] without improving the agreement between data and model calculations. These observations required a new approach for evaluating the charm-quark production cross section at midrapidity and the charm-quark fragmentation fractions based on the measurements of both charm mesons and baryons.

The measurements described above not only provide constraints to pQCD calculations but are also important as references for the investigation of the charm-quark interaction with the medium created in heavy-ion collisions. In particular, in the context of the heavy-ion programme at the LHC, the $\mathrm{c\overline{c}}$ production cross section per nucleon–nucleon collision is a fundamental ingredient for the determination of the amount of charmonium production by (re)generation in the quark–gluon plasma (QGP) [35, 39–41], a mechanism that is supported by J/ψ measurements in nucleus–nucleus collisions at the LHC [42, 43].

In this Letter, the charm fragmentation fractions and the charm production cross section per unit of rapidity at midrapidity ($|y| < 0.5$) in pp collisions at $\sqrt{s} = 5.02$ TeV are reported. The results were obtained by considering the contribution based on the measurement of the ground-state charm hadrons D^{0}, D^{+}, $\mathrm{D}_{\mathrm{s}}^{+}$, Λ_{c}^{+}, and Ξ_{c}^{0} by the ALICE Collaboration [5, 24, 28].

The ALICE experiment and its performance are presented in detail in [44, 45]. The main detectors used for the measurements presented here are the Inner Tracking System, the Time Projection Chamber and the Time-Of-Flight detector for vertexing, tracking, and particle identification purposes. The data from pp collisions at $\sqrt{s} = 5.02$ TeV were collected during the 2017 run with a minimum bias trigger, and correspond to an integrated luminosity L_{int}= (19.3 $\pm$ 0.4) nb^{-1} [46]. D mesons were reconstructed from their decays $\mathrm{D}^{0} \rightarrow \mathrm{K}^{-}\pi^{+}$, $\mathrm{D}^{+} \rightarrow \mathrm{K}^{-}\pi^{+}\pi^{+}$, $\mathrm{D}_{\mathrm{s}}^{+} \rightarrow \phi\pi^{+} \rightarrow \mathrm{K}^{-}\mathrm{K}^{+}\pi^{+}$, and $\mathrm{D}^{*+} \rightarrow \mathrm{D}^{0}\pi^{+}$, and charm baryons

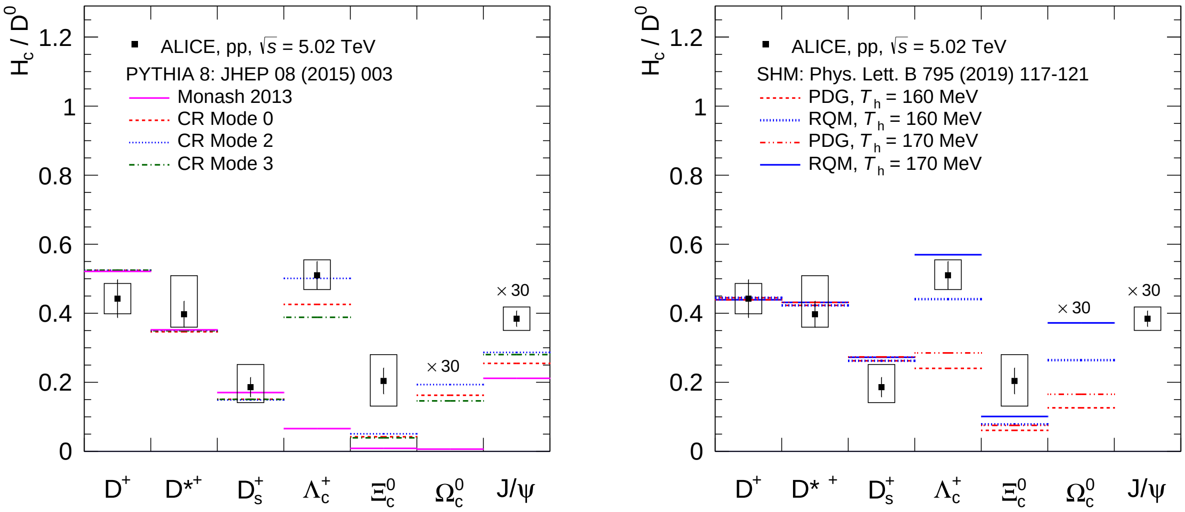

Figure 1: Transverse-momentum integrated production cross sections of the various charm meson [4, 5, 48] and baryon [24, 25, 28] species per unit of rapidity at midrapidity normalised to that of the D^0 meson measured in pp collisions at $\sqrt{s} = 5.02$ TeV. The measurements are compared with PYTHIA 8 calculations [36, 49] (left panel) and with results from a SHM [35] (right panel) (see text for details). For J/ψ the inclusive cross section was used. The $J/\psi/D^0$ ratio, as well as the model calculations for the Ω_c^0/D^0 ratio, are multiplied by a factor 30 for visibility.

from their decays $\Lambda_c^+ \to pK_S^0$, $\Lambda_c^+ \to pK^-\pi^+$, and $\Xi_c^0 \to \Xi^- e^+ \nu_e$. The charge conjugates are measured as well and the results are averaged. The cross sections of D^0 and D^+ mesons were measured down to $p_T = 0$, those of D^{*+}, D_s^+ mesons, and Λ_c^+ baryons down to $p_T = 1$ GeV/c, and those of Ξ_c^0 baryons down to $p_T = 2$ GeV/c. The extrapolated fraction of the cross section is about 30% and 55% for the hadron species measured down to $p_T = 1$ GeV/c and $p_T = 2$ GeV/c, respectively. The systematic uncertainties of the meson and baryon measurements include the following sources: (i) extraction of the raw yield; (ii) prompt fraction estimation; (iii) tracking and selection efficiency; (iv) particle identification efficiency; (v) sensitivity of the efficiencies to the hadron p_T shape generated in the simulation; (vi) p_T-extrapolation for the hadrons not measured down to $p_T = 0$. In addition, an overall normalisation systematic uncertainty induced by the branching ratios (BR) [47] and the integrated luminosity [46] were considered.

Figure 1 shows the p_T-integrated production cross sections per unit of rapidity of the various open- and hidden-charm meson (D^+, D_s^+, D^{*+}, and J/ψ) [4, 5, 48] and baryon (Λ_c^+ and Ξ_c^0) [24, 25, 28] species, obtained in pp collisions at $\sqrt{s} = 5.02$ TeV, as the average of particle and antiparticle, and normalised to the one of the D^0 meson. When computing the ratios between the different hadron species, systematic uncertainties due to tracking, the feed-down from beauty-hadron decays, the p_T-extrapolation, and the luminosity were propagated as correlated. For the Ξ_c^0 baryons, the additional contribution to the beauty feed-down systematic uncertainty due to the assumed $\Xi_b^{0,-}$-baryon production relative to that of Λ_b^+ baryons [28, 29] was considered as uncorrelated with the uncertainties related to the beauty feed-down subtraction for the other charm hadron species. In the $J/\psi/D^0$ ratio all the systematic uncertainties were propagated as uncorrelated, with the exception of the luminosity uncertainty. The treatment of the systematic uncertainties is the same also for the computation of the other quantities reported here.

In the left panel of Fig. 1 the experimental data are compared with results from the PYTHIA 8 generator, using the Monash 2013 tune [49], and tunes that implement colour reconnections (CR) beyond the leading-colour approximation [36]. In the Monash 2013 tune, the parameters governing the heavy-quark fragmentation are tuned to measurements in e^+e^- collisions. The CR tunes introduce new colour reconnection topologies, including junctions, that enhance the baryon production and, to a lesser extent, charmonia. The three considered tunes (Mode 0, 2, and 3) apply different constraints on the allowed string reconnections, taking into account causal connections of dipoles involved in a reconnection, and time dilation effects caused by relative boosts between string pieces. It is observed that for the open charm meson ratios the PYTHIA 8 generator predictions with the different tunes are fairly similar and describe the measurements within uncertainty, except for the D^+/D^0 ratio, which is overestimated by about 15%. However, this difference has a significance of only 1 standard deviation of the combined statistical and systematic uncertainties. Significant differences in the PYTHIA 8 predictions are observed when comparing them with the measured baryon-to-meson ratios. The Monash 2013 tune is observed to underestimate the Λ_c^+/D^0 and Ξ_c^0/D^0 ratios by nearly $8\,\sigma$ and $2.3\,\sigma$, respectively. It is significantly different from all the CR tunes, which provide an increase of the baryon-to-meson ratio. Mode 2 is the PYTHIA 8 tune describes the Λ_c^+/D^0 ratio, however, it still underestimates the Ξ_c^0/D^0 ratio by about $2\,\sigma$. For the $J/\psi/D^0$ ratio the CR tunes provide a better description than the Monash 2013 tune. However, all PYTHIA 8 tunes underestimate the measurement. In the simulations, as in the experimental measurement, the J/ψ cross section consists of the prompt and beauty feed-down contributions. The fraction of J/ψ from the decay of b-hadrons is about 15% for $p_T^{J/\psi} > 1.3$ GeV/c [50–52].

In the right panel of Fig. 1, the measurements are compared with two versions of a statistical hadronisation model (SHM) [35]. One is based on the charm baryon states included by the Particle Data Group (PDG) [47], while the other version includes an augmented set of charm baryon states, given by predictions of the relativistic quark model (RQM) [53]. Both versions are reported for two different hadronisation temperatures (T_h) [35]. The two T_h values of 160 MeV or 170 MeV used in the model are above the temperature of 156.5 MeV reported from a fit to the light-flavour hadron yields in central Pb–Pb collisions [54, 55]. The implementation of the two hadronisation temperatures leads only to small variations in the meson-to-meson ratios, while more significant changes are observed in the baryon sector.

The charm mesons D^0, D^+, and D_s^+ and baryons are dominantly populated by strong decays from higher-lying charm resonances. Therefore, changes due to an increased temperature on yield ratios relative to D^0 are due to subtle effects. In particular, in the meson-to-meson ratios a weak sensitivity to temperature and no change due to the added baryons is visible. For the charm baryons, even with the standard PDG spectrum, there is a stronger sensitivity to a temperature increase (dashed and dash-dotted red lines in the right panel of Fig. 1). The additional baryon states almost double the fraction of the ground-state Λ_c^+ in the system relative to the PDG scenario, when a hadronisation temperature of 170 MeV is used, and the resulting Λ_c^+/D^0 ratio becomes comparable to the ALICE measurement [24]. A similar conclusion is drawn for the production cross section of $\Sigma_c^{0,+,++}$ baryons in pp collisions at $\sqrt{s} = 13$ TeV [56]. The Ξ_c^0/D^0 ratio is observed to increase by a factor 1.3 with respect to the PDG case. With this increase of the Ξ_c^0 yield, the model calculation is compatible with the measurement within $1.2\,\sigma$. No model calculation is available for the $J/\psi/D^0$ ratio.

The $c\bar{c}$ production cross section per unit of rapidity at midrapidity ($d\sigma^{c\bar{c}}/dy|_{|y|<0.5}$) was calculated by summing the p_T-integrated cross sections of all measured ground-state charm hadrons (D^0, D^+, D_s^+, Λ_c^+, and Ξ_c^0). The contribution of the Ξ_c^0 was multiplied by a factor of two, in order to account for the contribution of the Ξ_c^+. The production cross sections of the Ξ_c^0 and Ξ_c^+ baryons were found to be compatible within experimental uncertainties in pp collisions at $\sqrt{s}$ = 13 TeV [29]. The contribution of J/ψ to the charm production cross section at midrapidity was considered negligible with respect to the other hadron species. Given the absence of measurements of Ω_c^0 baryon production at hadron colliders, an asymmetric systematic uncertainty was assigned assuming a contribution equal to the one of Ξ_c^0 considering the prediction of the Catania model [34]. This uncertainty was summed in quadrature with the other extrapolation uncertainties. Two correction factors for the different shapes of the rapidity distributions (RS) of charm hadrons and $c\bar{c}$ pairs were considered. The first factor accounts for the different rapidity distributions of charm hadrons and single charm quarks, and it was evaluated to be

Table 1: Charm-quark fragmentation fractions into charm hadrons, $f(\mathrm{c} \to \mathrm{H_c})$ determined from measurements in pp collisions at $\sqrt{s} = 5.02$ TeV. Statistical and systematic uncertainties are reported separately. To obtain the complete fragmentation of a c quark, an additional contribution equal to the one of the Ξ_c^0 should be added to account for the Ξ_c^+. The $f(\mathrm{c} \to \Lambda_c^+)$ includes the feed-down from $\Sigma_c^{0,+,++}$ baryons. The sum of the fragmentation fractions add up to unity within uncertainties, not counting here the D^{*+}, which feeds into the D^0 and D^+ mesons.

$\mathrm{H_c}$	$f(\mathrm{c} \to \mathrm{H_c})[\%]$
D^0	$39.1 \pm 1.7(\mathrm{stat})^{+2.5}_{-3.7}(\mathrm{syst})$
D^+	$17.3 \pm 1.8(\mathrm{stat})^{+1.7}_{-2.1}(\mathrm{syst})$
D_s^+	$7.3 \pm 1.0(\mathrm{stat})^{+1.9}_{-1.1}(\mathrm{syst})$
Λ_c^+	$20.4 \pm 1.3(\mathrm{stat})^{+1.6}_{-2.2}(\mathrm{syst})$
Ξ_c^0	$8.0 \pm 1.2(\mathrm{stat})^{+2.5}_{-2.4}(\mathrm{syst})$
D^{*+}	$15.5 \pm 1.2(\mathrm{stat})^{+4.1}_{-1.9}(\mathrm{syst})$

unity in the relevant rapidity range based on FONLL calculations. A 2% uncertainty on this factor was evaluated from the difference obtained with PYTHIA 8. The second correction factor was computed as the ratio $(\mathrm{d}\sigma^{\mathrm{c\bar{c}}}/\mathrm{d}y)/(\mathrm{d}\sigma^{\mathrm{c}}/\mathrm{d}y)$, which was estimated from NLO pQCD calculations (POWHEG [57]) to be 1.03. A 3% uncertainty on this factor was estimated from the difference among the values obtained by varying the factorisation and renormalisation scales independently by a factor of 2 in the POWHEG calculation and using different sets of PDFs (CT10NLO [58] and CT14NLO [59]). The resulting $\mathrm{c\bar{c}}$ cross section per unit of rapidity at midrapidity is

$$\left.\frac{\mathrm{d}\sigma^{\mathrm{c\bar{c}}}}{\mathrm{d}y}\right|^{\mathrm{pp,\ 5.02\ TeV}}_{|y|<0.5} = 1165 \pm 44(\mathrm{stat})^{+63}_{-67}(\mathrm{syst})^{+98}_{-38}(\mathrm{extr}) \pm 43(\mathrm{BR}) \pm 42(\mathrm{RS}) \pm 24(\mathrm{lumi})\ \mu\mathrm{b}. \qquad (1)$$

The reported uncertainties in Eq. 1 named (extr) and (BR) refer to extrapolation uncertainties of the charm-hadron cross sections not measured down to $p_\mathrm{T} = 0$ and to the uncertainties of the branching ratios. The extrapolated fraction of the cross section is smaller than 20%. More details on the extrapolation uncertainties are reported in [5, 25, 28].

The charm fragmentation fractions, $f(\mathrm{c} \to \mathrm{H_c})$, which represent the probabilities of a c quark to hadronise into a given charm hadron, are listed in Table 1. They were obtained by dividing the p_T-integrated cross section of each measured hadron species by the sum of the cross sections of the different ground-state charm hadron species, considering twice the contribution of the Ξ_c^0 baryon. An asymmetric uncertainty to account for the possible sizeable contribution of Ω_c^0 was added as done for the evaluation of $\mathrm{d}\sigma^{\mathrm{c\bar{c}}}/\mathrm{d}y$.

In the left panel of Fig. 2 the fractions $f(\mathrm{c} \to \mathrm{H_c})$ are compared with values derived from experimental measurements performed in $\mathrm{e^+e^-}$ collisions at LEP and B factories as well as in ep collisions [60]. The fragmentation fractions measured at midrapidity in pp collisions at the LHC are different from the ones measured in $\mathrm{e^+e^-}$ and ep collisions, confirming significant evidence that the assumption of universality (collision-system independence) of parton-to-hadron fragmentation is not valid as reported in [4, 24, 28]. The fractions $f(\mathrm{c} \to \mathrm{H_c})$ measured in $\mathrm{e^+e^-}$, including the Λ_c^+ baryon, are in agreement with a standard canonical SHM [61]. The Λ_c^+/D^0 ratio measured at midrapidity in pp and p–Pb collisions at the LHC is different from the one measured at forward rapidity by the LHCb Collaboration [8, 62] as discussed in [23, 25].

An increase of about a factor 3.3 for the fragmentation fractions for the Λ_c^+ baryons with respect to

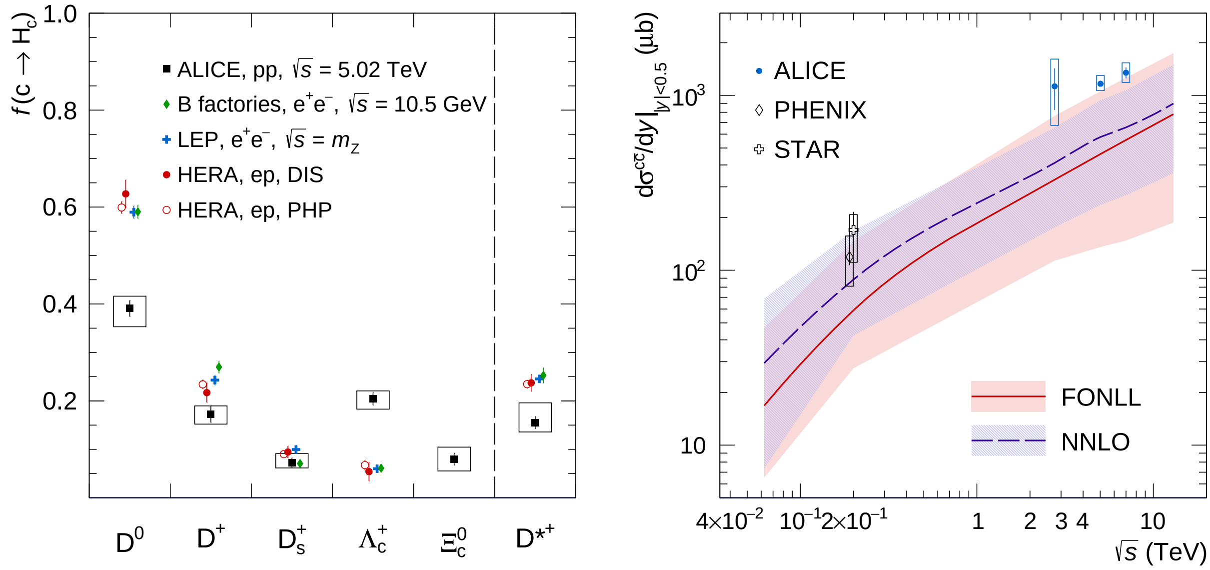

Figure 2: Left: Charm-quark fragmentation fractions into charm hadrons measured in pp collisions at $\sqrt{s}$ = 5.02 TeV in comparison with experimental measurements performed in e^+e^- collisions at LEP and at B factories, and in ep collisions at HERA [60]. The D^{*+} meson is depicted separately since its contribution is also included in the ground-state charm mesons. Right: Charm production cross section at midrapidity per unit of rapidity as a function of the collision energy. STAR [11] and PHENIX [63] results, slightly displaced in horizontal direction for better visibility, are reported. Comparisons with FONLL [13–15] (red band) and NNLO [64–66] (violet band) pQCD calculations are also shown.

e^+e^- and ep collisions, and a concomitant decrease of about a factor 1.4–1.2 for the D mesons, is observed. The significance of the difference considering the uncertainties of both measurements, is about $5\,\sigma$ for Λ_c^+ baryons. This in turn decreases the fragmentation into D^0 mesons at midrapidity by $6\,\sigma$ with respect to the measurements in e^+e^- and ep collisions. In previous measurements in e^+e^- and ep collisions no value for the Ξ_c^0 was obtained and the yield was estimated according to the assumption $f(c \rightarrow \Xi_c^+)/f(c \rightarrow \Lambda_c^+) = f(s \rightarrow \Xi^-)/f(s \rightarrow \Lambda^0) \sim 0.004$ [60]. The fraction $f(c \rightarrow \Xi_c^0)$ was measured for the first time and $f(c \rightarrow \Xi_c^0)/f(c \rightarrow \Lambda_c^+) = 0.39 \pm 0.07(\text{stat})^{+0.08}_{-0.07}(\text{syst})$ was found [28]. A first attempt to compute the fragmentation fractions in pp collisions at LHC was performed in [60] assuming universal fragmentation, since at that time the measurements of charm baryons at midrapidity were not yet available. The measurements reported here challenge that assumption.

The updated fragmentation fractions obtained for the first time taking into account the measurements of D^0, D^+, D_s^+, Λ_c^+, and Ξ_c^0 at midrapidity in pp collisions at $\sqrt{s} = 5.02$ TeV, allowed the recomputation of the charm production cross sections per unit of rapidity at midrapidity in pp collisions at $\sqrt{s} = 2.76$ and 7 TeV. The Λ_c^+/D^0 ratios measured in pp at different collision energies, as well as the Ξ_c^0/D^0 ratio, are compatible [25, 28, 56]. The charm cross sections were obtained by scaling the p_T-integrated D^0-meson cross section [1, 3] for the relative fragmentation fraction of a charm quark into a D^0 meson measured in pp collisions at $\sqrt{s} = 5.02$ TeV and applying the two correction factors for the different shapes of the rapidity distributions of charm hadrons and $c\bar{c}$ pairs. The p_T-integrated D^0-meson cross section was used because at the other energies not all charm hadrons were measured and the D^0 measurements are the most precise. The uncertainties of the fragmentation fraction (FF) were taken into account in calculating the $c\bar{c}$ production cross section as was the uncertainty introduced by the rapidity correction factors. The BR of the $D^0 \rightarrow K^-\pi^+$ decay channel was also updated, considering the latest value reported in the PDG [47].

The resulting $c\overline{c}$ cross sections per unit of rapidity at midrapidity are

$$\left.\frac{d\sigma^{c\overline{c}}}{dy}\right|_{|y|<0.5}^{\text{pp, 7 TeV}} = 1347 \pm 97(\text{stat}) \pm 104(\text{syst}) \pm 11(\text{BR}) \pm^{+142}_{-105}(\text{FF}) \pm 44(\text{RS}) \pm 47(\text{lumi})\ \mu\text{b}, \quad (2)$$

and

$$\left.\frac{d\sigma^{c\overline{c}}}{dy}\right|_{|y|<0.5}^{\text{pp, 2.76 TeV}} = 1126 \pm 303(\text{stat})^{+258}_{-429}(\text{syst})^{+397}_{-53}(\text{extr}) \pm 9(\text{BR}) \pm^{+119}_{-88}(\text{FF}) \pm 61(\text{RS}) \pm 21(\text{lumi})\ \mu\text{b} \quad (3)$$

for $\sqrt{s} = 7$ and 2.76 TeV, respectively. The updated $c\overline{c}$ cross sections at $\sqrt{s} = 2.76$ and 7 TeV are about 40% higher than the previously published results [1, 3], reflecting the differences in the fragmentation into charm baryons measured in e^+e^- and pp collisions.

In the right panel of Fig. 2, the measured $c\overline{c}$ cross sections are compared with FONLL and NNLO predictions as a function of the collision energy. The NNLO values were obtained by the authors of [64, 65] by applying to the central value of the FONLL $d\sigma^{c\overline{c}}/dy$ a K factor (NNLO/NLO) calculated with a modified version of the top++ code [66] with parameter values as in [64, 65] and using the relative scale uncertainties obtained at NNLO with top++. The $c\overline{c}$ cross sections are also compared with the STAR [11] and PHENIX [63] results measured in pp collisions at $\sqrt{s} = 200$ GeV. The STAR measurement is obtained by scaling the D^0 and D^{*+} cross sections by the charm-quark fragmentation fractions measured in e^+e^- collisions from the CLEO and BELLE experiments [60]. The PHENIX $c\overline{c}$ cross section is obtained from the measurement of the cross sections of electrons from semileptonic heavy-flavour hadron decays. Both results are compatible within uncertainties with the upper edge of the FONLL and NNLO band. The $c\overline{c}$ cross sections measured at the three LHC collision energies are higher than the upper edge of the FONLL and NNLO bands, however, compatible within approximately one standard deviation of the experimental uncertainty. The theoretical uncertainties are estimated as a convolution of the pQCD calculations obtained by varying the factorisation and renormalisation scales. The uncertainties of the PDFs and of the charm-quark mass are also included in the uncertainties of both calculations and are determined with FONLL as described in [15].

In summary, the charm production cross section per unit of rapidity at midrapidity in pp collisions at $\sqrt{s} = 5.02$ TeV was determined exploiting recent measurements of the ground-state charm hadrons, including for the first time the measured baryon states. The charm fragmentation fractions $f(c \to H_c)$ were computed for the first time in hadron collisions at the LHC using measurements of charm baryons at midrapidity, and are found to be different from those measured in e^+e^- and ep collisions. This observation indicates that the hadronisation of charm quarks into charm hadrons is not a universal process among different collision systems. The fragmentation fraction for the Ξ_c^0 baryon was measured for the first time and found to be sizeable. Finally, the charm production cross section per unit of rapidity at midrapidity, in pp collisions at $\sqrt{s} = 5.02$ TeV at the LHC was measured and lies at the upper edge of the theoretical pQCD calculations.

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References

[1] **ALICE** Collaboration, B. Abelev *et al.*, "Measurement of charm production at central rapidity in proton-proton collisions at $\sqrt{s} = 2.76$ TeV", *JHEP* **07** (2012) 191, arXiv:1205.4007 [hep-ex].

[2] **ALICE** Collaboration, B. Abelev *et al.*, "D_s^+ meson production at central rapidity in proton–proton collisions at $\sqrt{s} = 7$ TeV", *Phys. Lett. B* **718** (2012) 279, arXiv:1208.1948 [hep-ex].

[3] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of D-meson production at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **77** no. 8, (2017) 550, arXiv:1702.00766 [hep-ex].

[4] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of D^0 , D^+ , D^{*+} and D_s^+ production in pp collisions at $\sqrt{s} = 5.02$ TeV with ALICE", *Eur. Phys. J. C* **79** no. 5, (2019) 388, arXiv:1901.07979 [nucl-ex].

[5] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of beauty and charm production in pp collisions at $\sqrt{s} = 5.02$ TeV via non-prompt and prompt D mesons", arXiv:2102.13601 [nucl-ex].

[6] **ATLAS** Collaboration, G. Aad *et al.*, "Measurement of $D^{*\pm}$, $D^\pm$ and $D_s^\pm$ meson production cross sections in *pp* collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector", *Nucl. Phys. B* **907** (2016) 717–763, arXiv:1512.02913 [hep-ex].

[7] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Nuclear modification factor of D^0 mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *Phys. Lett. B* **782** (2018) 474–496, arXiv:1708.04962 [nucl-ex].

[8] **LHCb** Collaboration, R. Aaij *et al.*, "Prompt charm production in pp collisions at sqrt(s)=7 TeV", *Nucl. Phys. B* **871** (2013) 1–20, arXiv:1302.2864 [hep-ex].

[9] **LHCb** Collaboration, R. Aaij *et al.*, "Measurements of prompt charm production cross-sections in *pp* collisions at $\sqrt{s} = 13$ TeV", *JHEP* **03** (2016) 159, arXiv:1510.01707 [hep-ex]. [Erratum: JHEP 09, 013 (2016), Erratum: JHEP 05, 074 (2017)].

[10] **LHCb** Collaboration, R. Aaij *et al.*, "Measurements of prompt charm production cross-sections in pp collisions at $\sqrt{s} = 5$ TeV", *JHEP* **06** (2017) 147, arXiv:1610.02230 [hep-ex].

[11] **STAR** Collaboration, L. Adamczyk *et al.*, "Measurements of D^0 and D^* Production in $p+p$ Collisions at $\sqrt{s} = 200$ GeV", *Phys. Rev. D* **86** (2012) 072013, arXiv:1204.4244 [nucl-ex].

[12] **CDF** Collaboration, D. Acosta *et al.*, "Measurement of prompt charm meson production cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV", *Phys. Rev. Lett.* **91** (2003) 241804, arXiv:hep-ex/0307080.

[13] M. Cacciari, M. Greco, and P. Nason, "The P(T) spectrum in heavy flavor hadroproduction", *JHEP* **05** (1998) 007, arXiv:hep-ph/9803400.

[14] M. Cacciari, S. Frixione, and P. Nason, "The p(T) spectrum in heavy flavor photoproduction", *JHEP* **03** (2001) 006, arXiv:hep-ph/0102134.

[15] M. Cacciari, S. Frixione, N. Houdeau, M. L. Mangano, P. Nason, and G. Ridolfi, "Theoretical predictions for charm and bottom production at the LHC", *JHEP* **10** (2012) 137, arXiv:1205.6344 [hep-ph].

[16] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger, "Inclusive D*+- production in p anti-p collisions with massive charm quarks", *Phys. Rev. D* **71** (2005) 014018, arXiv:hep-ph/0410289.

[17] B. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger, "Inclusive Charmed-Meson Production at the CERN LHC", *Eur. Phys. J. C* **72** (2012) 2082, arXiv:1202.0439 [hep-ph].

[18] M. Benzke, M. Garzelli, B. Kniehl, G. Kramer, S. Moch, and G. Sigl, "Prompt neutrinos from atmospheric charm in the general-mass variable-flavor-number scheme", *JHEP* **12** (2017) 021, arXiv:1705.10386 [hep-ph].

[19] G. Kramer and H. Spiesberger, "Study of heavy meson production in p–Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV in the general-mass variable-flavour-number scheme", *Nucl. Phys. B* **925** (2017) 415–430, arXiv:1703.04754 [hep-ph].

[20] I. Helenius and H. Paukkunen, "Revisiting the D-meson hadroproduction in general-mass variable flavour number scheme", *JHEP* **05** (2018) 196, arXiv:1804.03557 [hep-ph].

[21] E. Braaten, K.-M. Cheung, S. Fleming, and T. C. Yuan, "Perturbative QCD fragmentation functions as a model for heavy quark fragmentation", *Phys. Rev. D* **51** (1995) 4819–4829, arXiv:hep-ph/9409316.

[22] L. Gladilin, "Fragmentation fractions of c and b quarks into charmed hadrons at LEP", *Eur. Phys. J. C* **75** no. 1, (2015) 19, arXiv:1404.3888 [hep-ex].

[23] **ALICE** Collaboration, S. Acharya *et al.*, "$\Lambda_{\rm c}^{+}$ production in pp collisions at $\sqrt{s} = 7$ TeV and in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV", *JHEP* **04** (2018) 108, arXiv:1712.09581 [nucl-ex].

[24] **ALICE** Collaboration, S. Acharya *et al.*, "$\Lambda_{\rm c}^{+}$ production and baryon-to-meson ratios in pp and p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV at the LHC", arXiv:2011.06078 [nucl-ex].

[25] **ALICE** Collaboration, S. Acharya *et al.*, "$\Lambda_{\rm c}^{+}$ production in pp and in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV", arXiv:2011.06079 [nucl-ex].

[26] **CMS** Collaboration, A. M. Sirunyan *et al.*, "Production of $\Lambda_{\rm c}^{+}$ baryons in proton-proton and lead-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV", *Phys. Lett. B* **803** (2020) 135328, arXiv:1906.03322 [hep-ex].

[27] **ALICE** Collaboration, S. Acharya *et al.*, "First measurement of $\Xi_{\rm c}^{0}$ production in pp collisions at $\sqrt{\rm s}$ = 7 TeV", *Phys. Lett. B* **781** (2018) 8–19, arXiv:1712.04242 [hep-ex].

[28] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of the production cross section of prompt $\Xi_{\rm c}^{0}$ baryons at midrapidity in pp collisions at $\sqrt{s}$ = 5.02 TeV", arXiv:2105.05616 [nucl-ex].

[29] **ALICE** Collaboration, S. Acharya *et al.*, "Measurement of the cross sections of $\Xi_{\rm c}^{0}$ and $\Xi_{\rm c}^{+}$ baryons and branching-fraction ratio BR($\Xi_{\rm c}^{0} \to \Xi^{-}{\rm e}^{+}\nu_{\rm e}$)/BR($\Xi_{\rm c}^{0} \to \Xi^{-}\pi^{+}$) in pp collisions at 13 TeV", arXiv:2105.05187 [nucl-ex].

[30] **CDF** Collaboration, T. Aaltonen *et al.*, "Measurement of Ratios of Fragmentation Fractions for Bottom Hadrons in $p\bar{p}$ Collisions at $\sqrt{s}$ = 1.96-TeV", *Phys. Rev. D* **77** (2008) 072003, arXiv:0801.4375 [hep-ex].

[31] **LHCb** Collaboration, R. Aaij *et al.*, "Measurement of b-hadron production fractions in 7 TeV pp collisions", *Phys. Rev. D* **85** (2012) 032008, arXiv:1111.2357 [hep-ex].

[32] **LHCb** Collaboration, R. Aaij *et al.*, "Measurement of b hadron fractions in 13 TeV pp collisions", *Phys. Rev. D* **100** no. 3, (2019) 031102, arXiv:1902.06794 [hep-ex].

[33] J. Song, H.-h. Li, and F.-l. Shao, "New feature of low p_T charm quark hadronization in pp collisions at $\sqrt{s} = 7$ TeV", *Eur. Phys. J. C* **78** no. 4, (2018) 344, arXiv:1801.09402 [hep-ph].

[34] V. Minissale, S. Plumari, and V. Greco, "Charm Hadrons in pp collisions at LHC energy within a Coalescence plus Fragmentation approach", arXiv:2012.12001 [hep-ph].

[35] M. He and R. Rapp, "Charm-Baryon Production in Proton-Proton Collisions", *Phys. Lett. B* **795** (2019) 117–121, arXiv:1902.08889 [nucl-th].

[36] J. R. Christiansen and P. Z. Skands, "String Formation Beyond Leading Colour", *JHEP* **08** (2015) 003, arXiv:1505.01681 [hep-ph].

[37] R. Maciuła and A. Szczurek, "Production of Λ_c baryons at the LHC within the k_T-factorization approach and independent parton fragmentation picture", *Phys. Rev. D* **98** no. 1, (2018) 014016, arXiv:1803.05807 [hep-ph].

[38] B. A. Kniehl, G. Kramer, I. Schienbein, and H. Spiesberger, "$\Lambda_c^{\pm}$ production in pp collisions with a new fragmentation function", *Phys. Rev. D* **101** no. 11, (2020) 114021, arXiv:2004.04213 [hep-ph].

[39] P. Braun-Munzinger and J. Stachel, "(Non)thermal aspects of charmonium production and a new look at J/ψ suppression", *Phys. Lett. B* **490** (2000) 196–202, arXiv:nucl-th/0007059.

[40] X. Zhao and R. Rapp, "Medium Modifications and Production of Charmonia at LHC", *Nucl. Phys. A* **859** (2011) 114–125, arXiv:1102.2194 [hep-ph].

[41] Y.-P. Liu, Z. Qu, N. Xu, and P.-F. Zhuang, "J/ψ Transverse Momentum Distribution in High Energy Nuclear Collisions at RHIC", *Phys. Lett. B* **678** (2009) 72–76, arXiv:0901.2757 [nucl-th].

[42] **ALICE** Collaboration, J. Adam *et al.*, "J/ψ suppression at forward rapidity in Pb-Pb collisions at $\sqrt{\mathbf{s_{NN}}} = \mathbf{5.02}$ TeV", *Phys. Lett. B* **766** (2017) 212–224, arXiv:1606.08197 [nucl-ex].

[43] **ALICE** Collaboration, S. Acharya *et al.*, "Centrality and transverse momentum dependence of inclusive J/ψ production at midrapidity in Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV", *Phys. Lett. B* **805** (2020) 135434, arXiv:1910.14404 [nucl-ex].

[44] **ALICE** Collaboration, K. Aamodt *et al.*, "The ALICE experiment at the CERN LHC", *JINST* **3** (2008) S08002.

[45] **ALICE** Collaboration, B. B. Abelev *et al.*, "Performance of the ALICE Experiment at the CERN LHC", *Int. J. Mod. Phys. A* **29** (2014) 1430044, arXiv:1402.4476 [nucl-ex].

[46] **ALICE** Collaboration, "ALICE 2017 luminosity determination for pp collisions at $\sqrt{s}$ = 5 TeV",. http://cds.cern.ch/record/2648933.

[47] **Particle Data Group** Collaboration, P. Zyla *et al.*, "Review of Particle Physics", *PTEP* **2020** no. 8, (2020) 083C01.

[48] **ALICE** Collaboration, S. Acharya *et al.*, "Inclusive J/ψ production at mid-rapidity in pp collisions at $\sqrt{s}$ = 5.02 TeV", *JHEP* **10** (2019) 084, arXiv:1905.07211 [nucl-ex].

[49] P. Skands, S. Carrazza, and J. Rojo, "Tuning PYTHIA 8.1: the Monash 2013 Tune", *Eur. Phys. J. C* **74** no. 8, (2014) 3024, arXiv:1404.5630 [hep-ph].

[50] **CMS** Collaboration, S. Chatrchyan *et al.*, "J/ψ and $\psi(2S)$ production in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **02** (2012) 011, arXiv:1111.1557 [hep-ex].

[51] **ATLAS** Collaboration, G. Aad *et al.*, "Measurement of the differential cross-sections of inclusive, prompt and non-prompt J/ψ production in proton-proton collisions at $\sqrt{s} = 7$ TeV", *Nucl. Phys. B* **850** (2011) 387–444, arXiv:1104.3038 [hep-ex].

[52] **ALICE** Collaboration, B. Abelev *et al.*, "Measurement of prompt J/ψ and beauty hadron production cross sections at mid-rapidity in pp collisions at $\sqrt{s} = 7$ TeV", *JHEP* **11** (2012) 065, arXiv:1205.5880 [hep-ex].

[53] D. Ebert, R. Faustov, and V. Galkin, "Spectroscopy and Regge trajectories of heavy baryons in the relativistic quark-diquark picture", *Phys. Rev. D* **84** (2011) 014025, arXiv:1105.0583 [hep-ph].

[54] A. Andronic, P. Braun-Munzinger, K. Redlich, and J. Stachel, "Decoding the phase structure of QCD via particle production at high energy", *Nature* **561** no. 7723, (2018) 321–330, arXiv:1710.09425 [nucl-th].

[55] J. Cleymans, P. M. Lo, K. Redlich, and N. Sharma, "Multiplicity dependence of (multi)strange baryons in the canonical ensemble with phase shift corrections", *Phys. Rev. C* **103** no. 1, (2021) 014904, arXiv:2009.04844 [hep-ph].

[56] **ALICE** Collaboration, "Measurement of prompt D^0, Λ_c^+, and $\Sigma_c^{0,++}(2055)$ production in pp collisions at $\sqrt{s} = 13$ TeV",. https://cds.cern.ch/record/2766124.

[57] S. Frixione, P. Nason, and G. Ridolfi, "A Positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction", *JHEP* **09** (2007) 126, arXiv:0707.3088 [hep-ph].

[58] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, and C.-P. Yuan, "New parton distributions for collider physics", *Phys. Rev. D* **82** (2010) 074024, arXiv:1007.2241 [hep-ph].

[59] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C. Yuan, "New parton distribution functions from a global analysis of quantum chromodynamics", *Phys. Rev. D* **93** no. 3, (2016) 033006, arXiv:1506.07443 [hep-ph].

[60] M. Lisovyi, A. Verbytskyi, and O. Zenaiev, "Combined analysis of charm-quark fragmentation-fraction measurements", *Eur. Phys. J. C* **76** no. 7, (2016) 397, arXiv:1509.01061 [hep-ex].

[61] A. Andronic, F. Beutler, P. Braun-Munzinger, K. Redlich, and J. Stachel, "Statistical hadronization of heavy flavor quarks in elementary collisions: Successes and failures", *Phys. Lett. B* **678** (2009) 350–354, arXiv:0904.1368 [hep-ph].

[62] **LHCb** Collaboration, R. Aaij *et al.*, "Prompt Λ_c^+ production in *p*Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV", *JHEP* **02** (2019) 102, arXiv:1809.01404 [hep-ex].

[63] **PHENIX** Collaboration, A. Adare *et al.*, "Heavy Quark Production in $p+p$ and Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}} = 200$ GeV", *Phys. Rev. C* **84** (2011) 044905, arXiv:1005.1627 [nucl-ex].

[64] D. d'Enterria and A. M. Snigirev, "Triple parton scatterings in high-energy proton-proton collisions", *Phys. Rev. Lett.* **118** no. 12, (2017) 122001, arXiv:1612.05582 [hep-ph].

[65] D. d'Enterria and A. M. Snigirev, "Triple-parton scatterings in proton–nucleus collisions at high energies", *Eur. Phys. J. C* **78** no. 5, (2018) 359, arXiv:1612.08112 [hep-ph].

[66] M. Czakon, P. Fiedler, and A. Mitov, "Total Top-Quark Pair-Production Cross Section at Hadron Colliders Through $O(\alpha_S^4)$", *Phys. Rev. Lett.* **110** (2013) 252004, arXiv:1303.6254 [hep-ph].

A The ALICE Collaboration

S. Acharya[143], D. Adamová[98], A. Adler[76], J. Adolfsson[83], G. Aglieri Rinella[35], M. Agnello[31], N. Agrawal[55], Z. Ahammed[143], S. Ahmad[16], S.U. Ahn[78], I. Ahuja[39], Z. Akbar[52], A. Akindinov[95], M. Al-Turany[110], S.N. Alam[41], D. Aleksandrov[91], B. Alessandro[61], H.M. Alfanda[7], R. Alfaro Molina[73], B. Ali[16], Y. Ali[14], A. Alici[26], N. Alizadehvandchali[127], A. Alkin[35], J. Alme[21], T. Alt[70], L. Altenkamper[21], I. Altsybeev[115], M.N. Anaam[7], C. Andrei[49], D. Andreou[93], A. Andronic[146], M. Angeletti[35], V. Anguelov[107], F. Antinori[58], P. Antonioli[55], C. Anuj[16], N. Apadula[82], L. Aphecetche[117], H. Appelshäuser[70], S. Arcelli[26], R. Arnaldi[61], I.C. Arsene[20], M. Arslandok[148,107], A. Augustinus[35], R. Averbeck[110], S. Aziz[80], M.D. Azmi[16], A. Badalà[57], Y.W. Baek[42], X. Bai[131,110], R. Bailhache[70], Y. Bailung[51], R. Bala[104], A. Balbino[31], A. Baldisseri[140], B. Balis[2], M. Ball[44], D. Banerjee[4], R. Barbera[27], L. Barioglio[108,25], M. Barlou[87], G.G. Barnaföldi[147], L.S. Barnby[97], V. Barret[137], C. Bartels[130], K. Barth[35], E. Bartsch[70], F. Baruffaldi[28], N. Bastid[137], S. Basu[83], G. Batigne[117], B. Batyunya[77], D. Bauri[50], J.L. Bazo Alba[114], I.G. Bearden[92], C. Beattie[148], I. Belikov[139], A.D.C. Bell Hechavarria[146], F. Bellini[26,35], R. Bellwied[127], S. Belokurova[115], V. Belyaev[96], G. Bencedi[71], S. Beole[25], A. Bercuci[49], Y. Berdnikov[101], A. Berdnikova[107], D. Berenyi[147], L. Bergmann[107], M.G. Besoiu[69], L. Betev[35], P.P. Bhaduri[143], A. Bhasin[104], M.A. Bhat[4], B. Bhattacharjee[43], P. Bhattacharya[23], L. Bianchi[25], N. Bianchi[53], J. Bielčík[38], J. Bielčíková[98], J. Biernat[120], A. Bilandzic[108], G. Biro[147], S. Biswas[4], J.T. Blair[121], D. Blau[91], M.B. Blidaru[110], C. Blume[70], G. Boca[29,59], F. Bock[99], A. Bogdanov[96], S. Boi[23], J. Bok[63], L. Boldizsár[147], A. Bolozdynya[96], M. Bombara[39], P.M. Bond[35], G. Bonomi[142,59], H. Borel[140], A. Borissov[84], H. Bossi[148], E. Botta[25], L. Bratrud[70], P. Braun-Munzinger[110], M. Bregant[123], M. Broz[38], G.E. Bruno[109,34], M.D. Buckland[130], D. Budnikov[111], H. Buesching[70], S. Bufalino[31], O. Bugnon[117], P. Buhler[116], Z. Buthelezi[74,134], J.B. Butt[14], S.A. Bysiak[120], D. Caffarri[93], M. Cai[28,7], H. Caines[148], A. Caliva[110], E. Calvo Villar[114], J.M.M. Camacho[122], R.S. Camacho[46], P. Camerini[24], F.D.M. Canedo[123], F. Carnesecchi[35,26], R. Caron[140], J. Castillo Castellanos[140], E.A.R. Casula[23], F. Catalano[31], C. Ceballos Sanchez[77], P. Chakraborty[50], S. Chandra[143], S. Chapeland[35], M. Chartier[130], S. Chattopadhyay[143], S. Chattopadhyay[112], A. Chauvin[23], T.G. Chavez[46], C. Cheshkov[138], B. Cheynis[138], V. Chibante Barroso[35], D.D. Chinellato[124], S. Cho[63], P. Chochula[35], P. Christakoglou[93], C.H. Christensen[92], P. Christiansen[83], T. Chujo[136], C. Cicalo[56], L. Cifarelli[26], F. Cindolo[55], M.R. Ciupek[110], G. Clai[II,55], J. Cleymans[I,126], F. Colamaria[54], J.S. Colburn[113], D. Colella[109,54,34,147], A. Collu[82], M. Colocci[35,26], M. Concas[III,61], G. Conesa Balbastre[81], Z. Conesa del Valle[80], G. Contin[24], J.G. Contreras[38], M.L. Coquet[140], T.M. Cormier[99], P. Cortese[32], M.R. Cosentino[125], F. Costa[35], S. Costanza[29,59], P. Crochet[137], E. Cuautle[71], P. Cui[7], L. Cunqueiro[99], A. Dainese[58], F.P.A. Damas[117,140], M.C. Danisch[107], A. Danu[69], I. Das[112], P. Das[89], P. Das[4], S. Das[4], S. Dash[50], S. De[89], A. De Caro[30], G. de Cataldo[54], L. De Cilladi[25], J. de Cuveland[40], A. De Falco[23], D. De Gruttola[30], N. De Marco[61], C. De Martin[24], S. De Pasquale[30], S. Deb[51], H.F. Degenhardt[123], K.R. Deja[144], L. Dello Stritto[30], S. Delsanto[25], W. Deng[7], P. Dhankher[19], D. Di Bari[34], A. Di Mauro[35], R.A. Diaz[8], T. Dietel[126], Y. Ding[138,7], R. Divià[35], D.U. Dixit[19], Ø. Djuvsland[21], U. Dmitrieva[65], J. Do[63], A. Dobrin[69], B. Dönigus[70], O. Dordic[20], A.K. Dubey[143], A. Dubla[110,93], S. Dudi[103], M. Dukhishyam[89], P. Dupieux[137], N. Dzalaiova[13], T.M. Eder[146], R.J. Ehlers[99], V.N. Eikeland[21], D. Elia[54], B. Erazmus[117], F. Ercolessi[26], F. Erhardt[102], A. Erokhin[115], M.R. Ersdal[21], B. Espagnon[80], G. Eulisse[35], D. Evans[113], S. Evdokimov[94], L. Fabbietti[108], M. Faggin[28], J. Faivre[81], F. Fan[7], A. Fantoni[53], M. Fasel[99], P. Fecchio[31], A. Feliciello[61], G. Feofilov[115], A. Fernández Téllez[46], A. Ferrero[140], A. Ferretti[25], V.J.G. Feuillard[107], J. Figiel[120], S. Filchagin[111], D. Finogeev[65], F.M. Fionda[56,21], G. Fiorenza[35,109], F. Flor[127], A.N. Flores[121], S. Foertsch[74], P. Foka[110], S. Fokin[91], E. Fragiacomo[62], E. Frajna[147], U. Fuchs[35], N. Funicello[30], C. Furget[81], A. Furs[65], J.J. Gaardhøje[92], M. Gagliardi[25], A.M. Gago[114], A. Gal[139], C.D. Galvan[122], P. Ganoti[87], C. Garabatos[110], J.R.A. Garcia[46], E. Garcia-Solis[10], K. Garg[117], C. Gargiulo[35], A. Garibli[90], K. Garner[146], P. Gasik[110], E.F. Gauger[121], A. Gautam[129], M.B. Gay Ducati[72], M. Germain[117], J. Ghosh[112], P. Ghosh[143], S.K. Ghosh[4], M. Giacalone[26], P. Gianotti[53], P. Giubellino[110,61], P. Giubilato[28], A.M.C. Glaenzer[140], P. Glässel[107], D.J.Q. Goh[85], V. Gonzalez[145], L.H. González-Trueba[73], S. Gorbunov[40], M. Gorgon[2], L. Görlich[120], S. Gotovac[36], V. Grabski[73], L.K. Graczykowski[144], L. Greiner[82], A. Grelli[64], C. Grigoras[35], V. Grigoriev[96], A. Grigoryan[I,1], S. Grigoryan[77,1], O.S. Groettvik[21], F. Grosa[35,61], J.F. Grosse-Oetringhaus[35], R. Grosso[110], G.G. Guardiano[124], R. Guernane[81], M. Guilbaud[117], K. Gulbrandsen[92], T. Gunji[135], A. Gupta[104], R. Gupta[104], S.P. Guzman[46], L. Gyulai[147], M.K. Habib[110], C. Hadjidakis[80], G. Halimoglu[70], H. Hamagaki[85], G. Hamar[147], M. Hamid[7], R. 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