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First measurement of $\mathrm{D_{s1}(1^+)(2536)^+}$ and $\mathrm{D^*_{s2}(2^+)(2573)^+}$ production in proton–proton collisions at $\sqrt{s} = 13$ TeV at the LHC

ALICE Collaboration*

Abstract

The production yields of the orbitally excited charm-strange mesons $\mathrm{D_{s1}(1^+)(2536)^+}$ and $\mathrm{D^*_{s2}(2^+)(2573)^+}$ were measured for the first time in proton–proton (pp) collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV with the ALICE experiment at the LHC. The $\mathrm{D^+_{s1}}$ and $\mathrm{D^{*+}_{s2}}$ mesons were measured at midrapidity ($|y| < 0.5$) in minimum-bias and high-multiplicity pp collisions in the transverse-momentum interval $2 < p_{\mathrm{T}} < 24$ GeV/c. Their production yields relative to the $\mathrm{D^+_s}$ ground-state yield were found to be compatible between minimum-bias and high-multiplicity collisions, as well as with previous measurements in $\mathrm{e^{\pm}p}$ and $\mathrm{e^+e^-}$ collisions. The measured $\mathrm{D^+_{s1}/D^+_s}$ and $\mathrm{D^{*+}_{s2}/D^+_s}$ yield ratios are described by statistical hadronization models and can be used to tune the parameters governing the production of excited charm-strange hadrons in Monte Carlo generators, such as PYTHIA 8.

*See Appendix A for the list of collaboration members

The production of charm mesons with spin zero (D mesons) or one (D^* mesons) and orbital angular momentum $L = 0$ has been extensively studied in recent years in proton–proton (pp) collisions at the LHC by the ALICE [1–3], ATLAS [4], CMS [5], and LHCb [6, 7] Collaborations. The production cross sections are generally described within uncertainties by perturbative QCD calculations at next-to-leading order (NLO) with next-to-leading log resummation (e.g., FONLL [8–10] and GM-VFNS [11, 12]) via the factorization of three terms, namely the parton distribution functions (PDFs) of the incoming protons, the partonic cross section, and the fragmentation functions (FFs) describing the transition from charm quarks to the final hadrons. In these calculations, the FFs are typically parameterized from measurements in e^+e^- and $e^{\pm}p$ collisions [13] under the assumption that the hadronization of charm quarks into charm hadrons is a universal process, independent of the collision system. The relative abundances of the different D-meson species were found to be compatible with those measured in e^+e^- and $e^{\pm}p$ collisions [2, 3]. A significant discrepancy was instead observed at midrapidity for the charm baryons, whose production relative to the one of the D^0 meson turned out to be enhanced in pp collisions compared to e^+e^- and $e^{\pm}p$ collisions [14–21], implying a modification of the fragmentation fractions of charm quarks to the various charm-hadron species in pp collisions at LHC energies compared to those measured at lepton colliders at the LHC [3, 22].

The charm-meson spectroscopy has also progressed significantly in the last few decades, with also the discovery of several excited charm and charm-strange states and the determination of their properties [23–31]. However, the production yields of charm resonances were only measured at e^+e^- and $e^{\pm}p$ colliders [32–35], and no experimental result is available in hadronic collisions. The knowledge about the production yields of such states would provide important information about the hadronization of charm quarks produced in hadronic collisions, since they contribute to the ground-state charm-hadron yields via strong decays. This is, for example, the case in models based on statistical hadronization, in which the yields of the various charm-hadron species are assumed to follow the relative thermal densities and hence depend on the state mass and spin-degeneracy factor $2J + 1$, where J is the total angular momentum [36, 37]. Charm resonances are typically not included in Monte Carlo (MC) generators, such as PYTHIA 8 [38], due to the lack of knowledge about their production and decays. Moreover, the production of short-lived resonances is important to study the hadronic phase of the system created in heavy-ion collisions. In the case when a resonance has a lifetime comparable to that of the hadronic phase, suppression or regeneration of the resonance state due to interactions of its decay products with the hadron gas is observed [39–42]. A lower limit of the lifetime of the hadronic phase in central Pb–Pb collisions of about 4–7 fm$/c$ was determined via the measurement of the p_T-integrated yield ratio of the $K^*(892)^0$ resonance ($c\tau \approx 4$ fm) to $K^{\pm}$ mesons [39]. In addition, a hint of suppression was also measured in p–Pb and high-multiplicity pp collisions, suggesting the possible presence of rescattering effects and, thus, of a hadronic phase with a short but non-zero lifetime in small collision systems [40].

In this letter, the first measurement of the production yields of the orbitally excited charm-strange mesons $D_{s1}(1^+)(2536)^+$ ($c\tau \approx 214$ fm) and $D_{s2}^*(2^+)(2573)^+$ ($c\tau \approx 11.7$ fm) [43] and their charge conjugates in minimum-bias and high-multiplicity pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV is reported. In the following, D_{s1}^+ denotes $D_{s1}(1^+)(2536)^+$, and D_{s2}^{*+} stands for $D_{s2}^*(2^+)(2573)^+$. The results, which are integrated in the transverse-momentum interval $2 < p_T < 24$ GeV$/c$, are divided by the production yield of the ground state D_s^+ and compared with predictions obtained with the statistical hadronization model. The measured ratios are also used to constrain the parameters in PYTHIA 8, which regulate the production of pseudovector and tensor charm mesons, both with the the inclusion of rescattering effects in the hadronic phase or without them. Finally, the excited-to-ground state yield ratios are exploited to compute the fragmentation fractions of charm quarks into the D_{s1}^+ and D_{s2}^{*+} states. The measured values are compared to those obtained in e^+e^- collisions.

The apparatus of the ALICE experiment and its performance during the Run 2 data-taking period are described in detail in Refs. 44 and 45. The main sub-detectors, located at midrapidity ($|y| < 0.5$), employed to perform the measurements presented in this letter are: the Inner Tracking System (ITS), for tracking and vertex reconstruction; the Time Projection Chamber (TPC), for tracking and particle identification (PID); the Time-Of-Flight (TOF) detector, for particle identification. The V0 detector, composed of two arrays of scintillators located on both sides of the collision region ($-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$), is used for trigger purposes as well as to measure the event multiplicity [46]. The latter is determined from the percentile distribution of the V0M amplitude. Percentile values for higher multiplicity collisions are close to 0% and for lower ones close to 100%. In the following, the 0–0.1% V0M multiplicity class is denoted as HMV0.

The measurements reported in this letter were performed on the sample of pp collisions at $\sqrt{s} = 13$ TeV collected with the ALICE experiment from 2016 to 2018. The data were recorded using a minimum-bias trigger (MB) requiring coincident signals in both V0 scintillator arrays. Offline selection criteria were applied to remove beam-induced background events, exploiting the timing information from the V0 arrays and the correlation between the number of clusters and track segments reconstructed in the two innermost layers of the ITS. Events with pileup of collisions within the same bunch crossing, with an estimated probability ranging from 10^{-3} to 10^{-2} depending on the beam conditions, were excluded by rejecting events with more than one reconstructed primary vertex [46]. To ensure uniform pseudorapidity acceptance, only events with a primary vertex position within ± 10 cm from the nominal center of the apparatus along the beam direction were considered. Furthermore, the events satisfying the aforementioned selection criteria were required to possess at least one reconstructed track segment between the first two layers of the ITS within $|\eta| < 1$ (INEL > 0 event class).

The resulting data sample consisted of about 1.8×10^9 INEL > 0 and 0.3×10^9 HMV0 events, corresponding to integrated luminosities of about 32 nb^{-1} and 7.7 pb^{-1} [47], respectively. The multiplicity percentile measured by the V0 detector was converted into an average charged-particle multiplicity, $\langle \mathrm{d}N_{\mathrm{ch}}/\mathrm{d}\eta \rangle_{|\eta|<0.5}$, by following the prescription detailed in Ref. 46. A trigger correction was applied to account for those events that fulfill the INEL > 0 requirement but were not selected by the trigger. This correction factor $\varepsilon^{\mathrm{INEL}} = 0.920 \pm 0.003$ was estimated with a detailed Monte Carlo simulation based on the PYTHIA 8 generator [38] and the GEANT3 transport package [48]. For the HMV0 events the trigger was fully efficient and, therefore, a correction is not necessary [49].

The D_{s1}^{+} and D_{s2}^{*+} mesons and their charge conjugates were measured at midrapidity through the hadronic decay channels $D_{s1}^{+} \to D^{*+}K_S^0$ and $D_{s2}^{*+} \to D^{+}K_S^0$, whose branching ratios (BRs) are not yet measured [43]. The K_S^0 mesons were reconstructed via $K_S^0 \to \pi^+\pi^-$ decays with a BR of $(69.20 \pm 0.05)\%$ [43]. D^+ and D^{*+} mesons were reconstructed in the decay channels $D^+ \to K^-\pi^+\pi^+$ with a BR of $(9.38 \pm 0.16)\%$ [43] and $D^{*+} \to D^0(\to K^-\pi^+)\pi^+$ with a BR of $(2.67 \pm 0.03)\%$ [43], respectively. The reconstruction and selection of K_S^0-meson candidates closely followed the approaches presented in previous publications [50, 51]. Pairs of tracks with opposite charge signs, with $|\eta| < 0.8$ and satisfying the track-quality and particle-identification (PID) criteria reported in Ref. 50, were formed. Further selections based on the characteristic weak-decay topology of K_S^0 mesons were applied to reduce the combinatorial-background contribution. Similarly, D^0- and D^+-meson candidates were obtained from pairs and triplets of tracks, respectively, with the proper charge signs and $|\eta| < 0.8$. The D^{*+}-meson candidates were reconstructed by combining D^0 candidates with tracks identified as pions and having $p_{\mathrm{T}} > 50$ MeV$/c$. The signal selection exploited the reconstruction of decay-vertex topologies of D mesons displaced from the interaction vertex. A machine-learning approach based on Boosted Decision Trees (BDTs) [52, 53] was used to enhance the rejection of the combinatorial background and to separate D mesons produced directly in the charm-quark hadronization or through decays of excited charm-hadron states (prompt) from those originating from beauty-hadron decays (non-prompt). The quantities provided as input to the BDTs were based on the topological and kinematic properties of the D-meson candidates, and the PID information of their daughter tracks. The selection procedure and criteria were the same as those used in Refs. 54 and 55, for D^+ and D^{*+} mesons respectively. D_{s1}^{+}- and D_{s2}^{*+}-meson candidates were reconstructed by

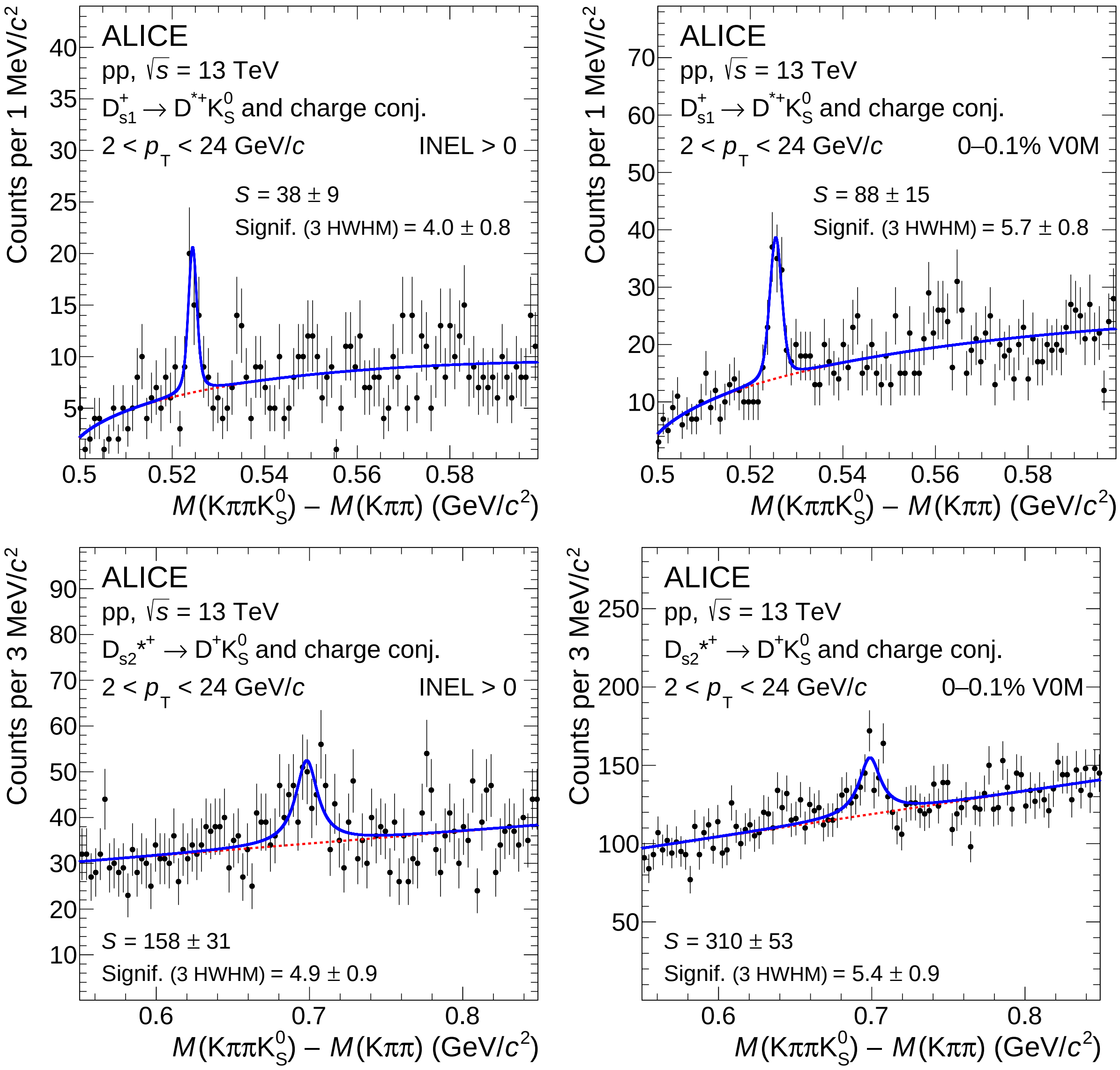

Figure 1: Invariant-mass distributions $M(\mathrm{K}\pi\pi\mathrm{K_S^0}) - M(\mathrm{K}\pi\pi)$ of $\mathrm{D_{s1}^{+}}$ (top panels) and $\mathrm{D_{s2}^{*+}}$ (bottom panels) candidates and charge conjugates in the $2 < p_{\mathrm{T}} < 24$ GeV/c interval, for the INEL > 0 and HMV0 (0–0.1% V0M) samples. The blue solid lines show the total fit functions described in the text, and the red dashed lines represent the combinatorial background. The raw-yield (S) values are reported together with their statistical uncertainties, as well as the estimated significance of the signal (Signif.).

combining $\mathrm{D^{*+}}$ and $\mathrm{D^{+}}$ mesons with $\mathrm{K_S^0}$ mesons satisfying the aforementioned selection criteria. Furthermore, only $\mathrm{D^{*+}}$, $\mathrm{D^{+}}$, and $\mathrm{K_S^0}$ mesons with a reconstructed invariant mass within a window of $\pm 3\sigma$ around the reconstructed mass value were considered, where the signal-peak width (σ) and mean for the three meson species were estimated by fitting their particle-candidate invariant-mass distributions with a Gaussian plus a function to describe the combinatorial background. No additional requirements were applied to the orbitally excited charm-strange meson candidates.

The raw yields of $\mathrm{D_{s1}^{+}}$ and $\mathrm{D_{s2}^{*+}}$ mesons were computed by integrating the signal function obtained from maximum-likelihood fits to the invariant-mass distributions $\Delta M = M(\mathrm{K}\pi\pi\mathrm{K_S^0}) - M(\mathrm{K}\pi\pi)$. The raw yields were extracted in the transverse-momentum interval $2 < p_{\mathrm{T}} < 24$ GeV$/c$ for both the INEL > 0 and HMV0 samples. The signal peak was modeled with a Voigt function, defined as the convolution of a Gaussian function and a Breit–Wigner function [56]. The widths, Γ, of the $\mathrm{D_s^{+}}$-meson resonances were fixed to their PDG values $\Gamma(D_{s1}^{+}) = (0.92 \pm 0.05)$ MeV/c^2 and $\Gamma(D_{s2}^{*+}) = (16.9 \pm 0.7)$ MeV/c^2 [43]. For the D_{s1}^{+} meson, the background was modeled with the function $a_0\sqrt{\Delta M - m(K_S^0)}\,e^{a_1[\Delta M - m(K_S^0)]}$, where $m(K_S^0)$ is the nominal rest mass of the K_S^0 meson, and a_0 and a_1 are free fit parameters. A polynomial of first order was used to describe the background in the D_{s2}^{*+}-meson fits. The invariant-mass distributions are reported in Fig. 1 together with related fit functions. A statistically reliable signal extraction is obtained for both the D_{s1}^{+} and D_{s2}^{*+} mesons for INEL > 0 and HMV0 events. The statistical significance, computed in the invariant mass region within three half-width half-maximum (HWHM) around the signal peak, ranges between 4.0 and 5.7 depending on the particle and multiplicity interval.

The corrected per-event yields times BR of prompt D_{s1}^{+} and D_{s2}^{*+} mesons at midrapidity were computed for each multiplicity class as

$$\frac{1}{N^{\mathrm{ev}}}\frac{\mathrm{d}^2N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \times \mathrm{BR} = \frac{1}{2}\frac{\varepsilon^{\mathrm{INEL}}}{N^{\mathrm{ev}}}\frac{1}{\mathrm{BR(D)} \times \mathrm{BR}(K_S^0)}\frac{f_{\mathrm{prompt}} \times N^{\mathrm{raw}}\big|_{|y|<y_{\mathrm{lab}}}}{\Delta y_{\mathrm{lab}} \times \Delta p_{\mathrm{T}} \times (\mathrm{Acc} \times \varepsilon)_{\mathrm{prompt}}}, \quad (1)$$

where N^{raw} is the raw yield, summed for particles and antiparticles, extracted in a given multiplicity class. The raw yield is divided by the prompt acceptance-times-efficiency $(\mathrm{Acc} \times \varepsilon)_{\mathrm{prompt}}$ and multiplied by the fraction of prompt D mesons in the selected sample f_{prompt} to correct for the contribution of beauty-hadron decays. It is further divided by a factor of two to obtain the charge-averaged yield, by the p_{T}-interval width Δp_{T}, and by the correction factor accounting for the rapidity coverage of reconstructed excited charm-strange mesons Δy_{lab}. The term $\mathrm{BR(D)} \times \mathrm{BR}(K_S^0)$ encompasses the normalisation for the decay-channel branching ratios of the D_s^{+}-meson resonance daughters. The factor N^{ev} denotes the number of recorded events in the INEL > 0 multiplicity class. It is corrected for the fraction of INEL > 0 events that were selected by the trigger $\varepsilon^{\mathrm{INEL}}$.

No kinematic selections were applied on the reconstructed D_{s1}^{+}- and D_{s2}^{*+}-meson candidates. Therefore the prompt acceptance-times-efficiency corrections for D^{*+}, D^{+}, and K_S^0 mesons were estimated as a function of p_{T}, y, and azimuthal angle from full MC simulations, in which pp collisions are simulated using the PYTHIA 8.243 event generator [57, 58], the generated particles are propagated through the apparatus using GEANT3 [48] reproducing the detector layout and data-taking conditions, and the reconstruction of events is performed as in real data. They were then combined, in a second step, to obtain the $(\mathrm{Acc} \times \varepsilon)_{\mathrm{prompt}}$ factor of D_{s1}^{+} and D_{s2}^{*+} mesons using a fast MC simulation based on the PYTHIA 8.243 decayer to describe the excited charm-strange meson decay kinematics. In this case, the D_{s1}^{+} and D_{s2}^{*+} mesons were sampled from the measured p_{T} distributions of D_s^{+} mesons in the same multiplicity classes taken from Ref. 49 and let decay by the PYTHIA 8 decayer. The efficiency was then computed by evaluating it as the product of the efficiencies of the daughter particles as a function of p_{T}, η, and charged-particle multiplicity estimated in number of track segments reconstructed with the first two layers of the ITS. This approach was validated by estimating the efficiency corrections of D_{s1}^{+} and D_{s2}^{*+} mesons using a full MC simulation with a limited number of generated events. The results of the two methods were in agreement within uncertainties.

The D_s^{+}-resonance prompt fraction f_{prompt} was computed from the one of D^{*+} and D^{+} mesons by accounting for the decay kinematics with an approach similar to that for the $\mathrm{Acc} \times \varepsilon$ factor. The D-meson f_{prompt} was estimated with the data-driven method introduced in Ref. 2. More details on the procedure and the obtained values can be found in Ref. 54 for D^{+} mesons and Ref. 55 for D^{*+} mesons. A correction factor of 1.93 ± 0.37 was also applied to account for the higher probability of strange quarks contained in the D_{s1}^{+} and D_{s2}^{*+} mesons to hadronise into a beauty rather than a charm hadron, as shown in Ref. 59. This factor was obtained from the measurement of prompt and non-prompt strange and non-strange D mesons in pp collisions at $\sqrt{s} = 13$ TeV [3, 59]. The resulting prompt fraction of D_{s1}^{+} (D_{s2}^{*+}) mesons is larger than 0.75 (0.85) in both the HMV0 and INEL > 0 samples.

The systematic uncertainties on the corrected yields of the measured D_{s}^{+}-meson resonances in both the INEL > 0 and HMV0 samples include the following sources: (i) extraction of the raw yield, (ii) prompt-fraction estimation, (iii) tracking and selection efficiency evaluation, (iv) sensitivity of the efficiencies to the meson p_{T} shape generated in the simulation and (v) to the description of the charged-particle multiplicity. In addition, an overall normalization systematic uncertainty due to uncertainties in the BR and the integrated luminosity was considered.

The systematic uncertainty on the raw-yield extraction was assessed by repeating the yield extraction after varying the fit configuration, in particular the fit ranges, the fit function used to describe the background, and the value of the Γ parameter by accounting for its uncertainty as reported in Ref. 43. The systematic uncertainties related to the estimation of the prompt resonance fraction in the extracted yields were computed by varying the reference value of the strange-to-non-strange D-meson ratio within the range of its uncertainties. The magnitude of these uncertainties depends on the multiplicity class and ranges between 5 and 14% for the D_{s1}^{+}, and between 4 and 7% for the D_{s2}^{*+}, respectively.

The systematic uncertainty on the track-reconstruction and selection efficiencies accounts for possible discrepancies between data and MC in the ITS–TPC prolongation, track-quality selection efficiency, description of the ALICE detector material budget, and description of the topological and PID variables exploited for the K_{S}^{0} and D-meson selection. The track-reconstruction systematic uncertainty was estimated by propagating the track-reconstruction systematic uncertainty on the single decay daughter track to the resonance considering the kinematic of the decay. The systematic on the selection efficiency was assessed by repeating the measurement of the D_{s1}^{+} and D_{s2}^{*+} corrected yields after varying the selection criteria applied to the K_{S}^{0} and D mesons. The magnitude of the systematic uncertainty related to the tracking and the BDT efficiency for both D_{s}^{+} states is of 6% and 10%, respectively.

The systematic uncertainties associated with the description of the p_{T} shape and the multiplicity of the events in the simulation were evaluated by varying the functional form employed to describe the p_{T} distribution of the generated resonances and by repeating the study employing different multiplicity weights accounting for different event-selection criteria. The assigned systematic uncertainty associated with the p_{T} shape varies between 10 and 13% depending on the multiplicity class for both the D_{s}^{+} states. The uncertainty associated with the multiplicity is less than 2% for both D_{s}^{+} states.

The ratios of the yields of the D_{s1}^{+} and D_{s2}^{*+} mesons times the relative BRs to that of the D_{s}^{+} meson as a function of the average charged-particle multiplicity $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$ at midrapidity in pp collisions at $\sqrt{s} = 13$ TeV are shown in Fig. 2. The p_{T}-differential measurements of the D_{s}^{+}-meson yields performed by the ALICE Collaboration for the INEL > 0 [3] and HMV0 [49] multiplicity classes, integrated over the p_{T} range between 2 and 24 GeV/c, were used as the denominators of the ratios. The systematic uncertainties associated with the corrected yields were treated as uncorrelated in the propagation to the ratios, except the one related to the luminosity, which was treated as fully correlated and cancels out in the ratio. The statistical and systematic uncertainties are depicted as vertical lines and empty boxes, respectively. The ratios do not show a significant dependence on $\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$.

The measurements were compared with the predictions based on the statistical hadronization model (SHM) [37] and the SHM for charm hadrons (SHMc) of the GSI–Heidelberg group [60], integrated over $p_{T} > 0$, and with the predictions from EPOS4HQ [61] in two different configurations. In the SHM and SHMc, hadron abundances are dictated by thermal weights depending on the hadron rest masses. Both the SHM and SHMc include a set of not yet observed charm-baryon states. However, unlike the SHM, SHMc assumes that charm quarks are produced in initial hard scattering processes and that the total number of (anti-)charm quarks is conserved in the collision. Computing the ratio between the excited- and ground-state charm hadron yields is beneficial for the theoretical predictions as the dependency on strangeness and charm corrections cancel out exactly. The EPOS4HQ is the heavy hadron extension of the EPOS4 generator [62]. Heavy flavor quarks, produced in hard scatterings, gluon splittings, or flavor

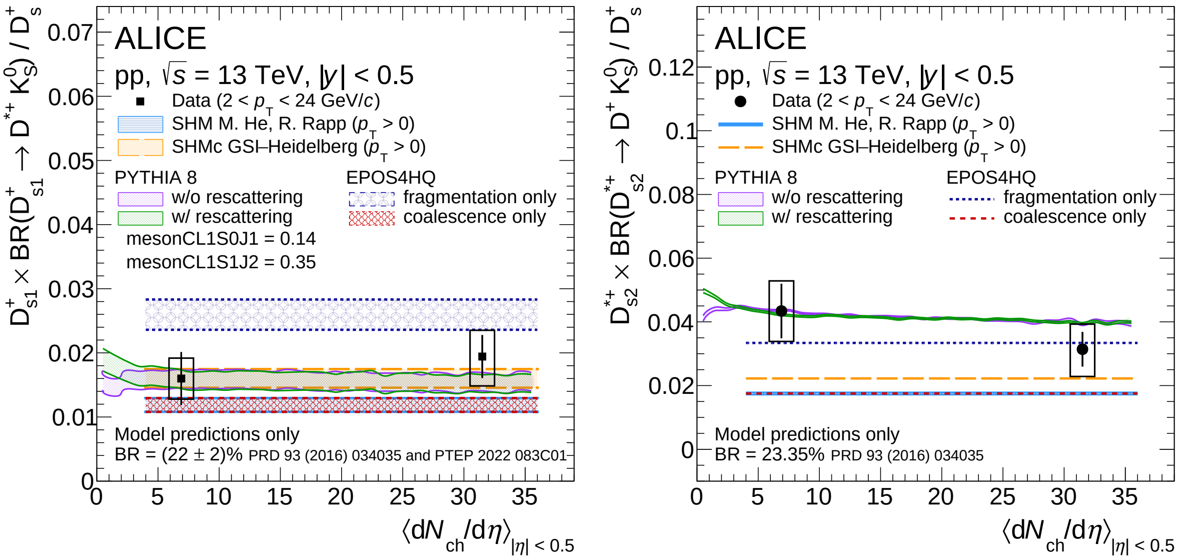

Figure 2: D_{s1}^{+}/D_{s}^{+} (left) and D_{s2}^{*+}/D_{s}^{+} (right) ratio times BR as a function of the average charged-particle multiplicity $\langle dN_{ch}/d\eta\rangle_{|\eta|<0.5}$ in pp collisions at $\sqrt{s}$ = 13 TeV at midrapidity ($|y| < 0.5$). The experimental results are compared with the theoretical predictions based on the SHM [37], the SHMc [60], PYTHIA 8 [57, 58], and EPOS4HQ [61]. The statistical and systematic uncertainties on the measured ratios are depicted as vertical lines and boxes, respectively. The theoretical uncertainty on the predicted ratios is depicted as a shaded band for the D_{s1}^{+}.

excitation, may interact with the medium constituents through elastic and inelastic processes and finally hadronise via fragmentation or coalescence. The two mechanisms are complementary and dominate at high and low momenta, respectively. The SHM, SHMc, and EPOS4HQ predictions necessitate being scaled by the BR of the analyzed hadronic decay to be fairly compared with the measurements. No measurement of these BRs is currently available, thus they were computed considering the predictions of the BR of the $D_{s1}^{+} \to D^{*}K$ and $D_{s2}^{*+} \to DK$ decays from the relativistic quark model (RQM) [63] and the ratio of the BRs between the two possible final charged states. In the case of the D_{s1}^{+}, the value reported by the PDG [43] was used with its uncertainty, while in the case of the D_{s2}^{*+} an equal contribution to $D_{s2}^{*+} \to D^{+}K^{0}$ and $D_{s2}^{*+} \to D^{0}K^{+}$ was assumed, given the very similar Q-values of the decays. The resulting values are: $BR(D_{s1}^{+} \to D^{*+}K_{S}^{0}) = (22 \pm 2)\%$ and $BR(D_{s2}^{*+} \to D^{+}K_{S}^{0}) = 23.35\%$ for the D_{s1}^{+} and D_{s2}^{*+}, respectively. The uncertainties associated with the computed BR, incorporating the uncertainties on the branching fraction provided by the PDG when available, were extended to the theoretical predictions and are depicted as shaded regions for the D_{s1}^{+}. The theoretical predictions from the SHM and the SHMc for the D_{s1}^{+}/D_{s}^{+} ratio are flat as a function of multiplicity and in good agreement with the measured ratios within 0.5 and 1.2σ at high and low multiplicity, respectively. They slightly underestimate the measured central values of the D_{s2}^{*+}/D_{s}^{+} ratio by 2σ and 1σ at low and high multiplicity, respectively. The experimental results are also compared with predictions from EPOS4HQ considering pure fragmentation or coalescence, respectively. The predicted ratios are systematically lower in the case of pure coalescence compared to pure fragmentation. A more realistic description including both the hadronization mechanisms would provide a prediction in between the ones reported in Fig. 2, therefore more in agreement with the measured ratios. The comparison with the model predictions align with what was observed for the ratio of ground-state charm mesons in pp collisions at the LHC energies [3, 22] indicating that a quantitative description of the relative production of charm meson states is successfully achieved using a statistical approach.

Orbitally excited states like the D_{s1}^{+} and D_{s2}^{*+} mesons are not considered in the PYTHIA 8 generator by default. Nevertheless, they can be included in the generation with a parameterized description of their

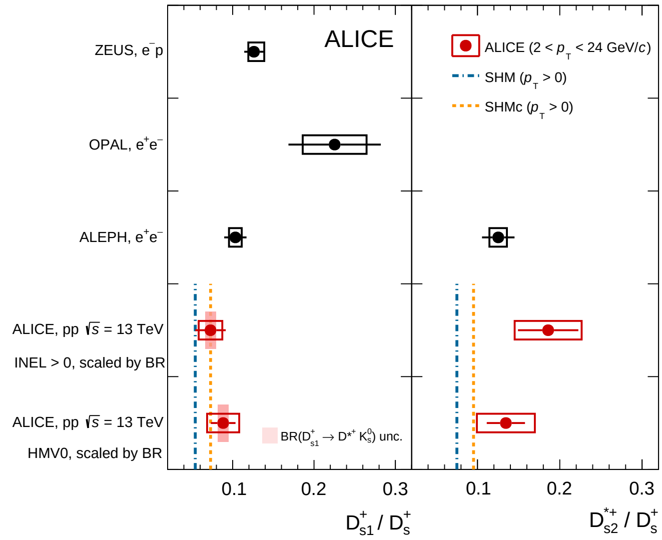

Figure 3: p_{T}-integrated yields of prompt D_{s1}^{+} (left) and D_{s2}^{*+} (right) mesons divided by the p_{T}-integrated yields of prompt D_s^{+} mesons. The measurements are compared to the ones performed at LEP [32–34, 67]. For the ALICE measurements, the results consider the BR of the decay of interest computed as described in the text considering the RQM [63] predictions and PDG information [43]. The experimental results are compared with the theoretical predictions based on the SHM [37] and the SHMc [60] models.

production and subsequent decay. The parameters regulating the production of pseudovector and tensor charm mesons (i.e. `mesonCL1S0J1` and `mesonCL1S1J2`) were tuned to minimize the χ^2 between the measured excited-to-ground state ratio in the INEL > 0 sample and the predicted one from PYTHIA 8, obtaining `mesonCL1S0J1` = 0.14 and `mesonCL1S1J2` = 0.35. In the simulation, the average charged-particle multiplicity was estimated considering the multiplicity of charged tracks at midrapidity. For the D_{s1}^{+}, the uncertainty associated with the BR relative to the considered hadronic decay channel was propagated to the PYTHIA 8 predictions as done for the thermal models and is depicted as a shaded band. In the case of the D_{s2}^{*+}/D_s^{+} ratio, the data points suggest a possible decrease with increasing $\langle dN_{\mathrm{ch}}/d\eta \rangle_{|\eta|<0.5}$, even if the values for INEL > 0 and HMV0 are compatible within uncertainties. To investigate the possible effect of the hadronic rescattering on the dependence of these ratios on $\langle dN_{\mathrm{ch}}/d\eta \rangle_{|\eta|<0.5}$, the PYTHIA 8 simulation was performed with and without enabling it [64]. The two configurations produce compatible results in the considered multiplicity range. This might be related to the fact that the lifetime of the D_{s2}^{*+} is longer than the expected duration of the hadronic phase in the collision and to the fact that the magnitude of hadronic interactions for D mesons with light hadrons is expected to be small in high-multiplicity pp collisions, as recently reported by the ALICE Collaboration [65, 66].

The ratios presented above can be compared with those from measurements of the fragmentation fractions of charm quarks into D_{s1}^{+}, D_{s2}^{*+}, and D_s^{+} mesons ($f_c \rightarrow h_c$) performed in e^+e^- and $e^{\pm}p$ collisions at LEP [32–34, 67]. Indeed, it is possible to compute the D_{s1}^{+}/D_s^{+} and D_{s2}^{*+}/D_s^{+} ratios as $(f_c \rightarrow D_{s1}^{+})/(f_c \rightarrow D_s^{+})$ and $(f_c \rightarrow D_{s2}^{*+})/(f_c \rightarrow D_s^{+})$, respectively. A direct comparison of the ratios of the fragmentation fractions with the results presented in Fig. 2 cannot be made without first accounting for the BR of the decay of the resonance. The results shown in Fig. 2 were divided by the BR computed following the procedure discussed above. Figure 3 shows a compilation of the D_{s1}^{+}/D_s^{+} and D_{s2}^{*+}/D_s^{+} ratios along with the SHM predictions in pp collisions presented above. The uncertainty associated with the BR for the D_{s1}^{+} is depicted separately as a shaded box. The ratios measured in pp collisions at the LHC and presented in this letter are consistent with those measured at LEP in e^+e^- and $e^{\pm}p$ collisions with a maximum deviation of 2.1σ for D_{s1}^{+}/D_s^{+} in the INEL > 0 sample.

In summary, the production yields of $D_{s1}(1^+)(2536)^+$ and $D_{s2}^{*}(2^+)(2573)^+$ mesons were measured for the first time at the LHC in pp collisions at $\sqrt{s} = 13$ TeV in two classes of charged-particle multiplicity. Given the absence of measurements for the BR of the considered hadronic decay channels, the results were not corrected for the relative BR. The measurements were performed at midrapidity in the $2 < p_{T} < 24$ GeV/c range, and the ratios to the analogous measurement for the D_{s}^{+} mesons scaled by the BR of the hadronic decay channel of the resonances are reported. The excited-to-ground state ratios do not show any significant dependence on the multiplicity given the current experimental uncertainty. The measurements were compared with the predictions from SHM, SHMc, and EPOS4HQ models, which quantitatively describe them.

The measured ratios were also used to tune the parameters of the PYTHIA 8 event generator governing the production of these orbitally excited states. In particular, these parameters were set to optimize the agreement between the measurements and the predictions from PYTHIA 8 at lower multiplicity. To further test the possible effects of hadronic rescattering on the excited-to-ground state ratios, the PYTHIA 8 simulation was performed including this effect or not. However, no significant difference was found between the two configurations.

Finally, a comparison was made between the D_{s1}^{+}/D_{s}^{+} and D_{s2}^{*+}/D_{s}^{+} ratios presented in this letter and the ratios of the charm-quark fragmentation fractions measured at LEP in $e^{+}e^{-}$ and $e^{\pm}p$ collisions. The results obtained at LHC and LEP are consistent within uncertainties. The extensive dataset collected during the Run 3 and 4 data-taking periods at the LHC will significantly reduce the relative uncertainties associated with these measurements, enabling a better understanding of the resonance production mechanism.

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