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First study of the two-body scattering involving charm hadrons

ALICE Collaboration*

Abstract

This Letter presents the first measurement of the interaction between charm hadrons and nucleons. The two-particle momentum correlations of $\mathrm{pD^-}$ and $\mathrm{\overline{p}D^+}$ pairs are measured by the ALICE Collaboration in high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV. The data are compatible with the Coulomb-only interaction hypothesis within $(1.1\text{–}1.5)\sigma$. Considering an attractive nucleon(N)$\mathrm{\overline{D}}$ strong interaction, in contrast to most model predictions which suggest an overall repulsive interaction, slightly improves the level of agreement. This measurement allows for the first time an estimation of the 68% confidence level interval for the isospin I = 0 inverse scattering length of the $\mathrm{N\overline{D}}$ state $f^{-1}_{0,\,\mathrm{I=0}} \in [-0.4, 0.9]$ fm^{-1}, assuming negligible interaction for the isospin I = 1 channel.

*See Appendix A for the list of collaboration members

The study of the residual strong interaction among hadrons is a very active field within nuclear physics. This interaction can lead to the formation of bound states, such as nuclei, or molecular states as, for example, the $\Lambda(1405)$, which is considered as being generated from the attractive forces in the nucleon(N)$\overline{\mathrm{K}}$-$\Sigma\pi$ channels [1–4]. One of the most fervent discussions in this context is nowadays revolving around systems involving charm mesons (D, D*). Studies of their interaction are motivated by the observation of several new states with hidden charm and/or beauty (so-called XYZ states) [5–9], as well as with open charm such as the $\mathrm{T_{cc}}^{+}$ [10, 11], and also of pentaquark states like $\mathrm{P_c}(4380)$ and $\mathrm{P_c}(4450)$ [12, 13]. These exotic hadrons can be described as compact multiquark states in the context of the constituent-quark model [14], but are also considered as natural candidates for loosely bound molecular states [5, 6]. For example, the structure of the $\chi_{c1}(3872)$ (formerly X(3872)) has been interpreted as a $\overline{\mathrm{D}}\mathrm{D}^{*}$/$\mathrm{D}\overline{\mathrm{D}}^{*}$ molecular state or as a tetraquark [15]. Currently, definite conclusions are difficult to draw because of the lack of any direct experimental information on the $\mathrm{D}\overline{\mathrm{D}}^{*}$ strong interaction. Strong support for the molecular nature of the $\Lambda(1405)$ came not least from low-energy $\mathrm{N}\overline{\mathrm{K}}$ scattering data and information on the $\mathrm{p}\overline{\mathrm{K}}$ scattering length from kaonic hydrogen atoms [16–19]. Hence, a determination of the scattering parameters of systems involving D and/or D* mesons are pivotal to advance in the interpretation of the many observed states. The first step in this direction is the investigation of the interaction between the p(uud)$\mathrm{D}^{-}(\overline{\mathrm{c}}\mathrm{d})$ pair and its charge conjugate. This interaction does not couple to the lower energy meson-baryon channels since no $\mathrm{q}\overline{\mathrm{q}}$ annihilation can occur. A measurement of it is also an essential reference for the study of the in-medium D- and D*-meson properties. Similarly to kaons and antikaons, it is theoretically predicted that possible modifications of the charm-meson spectral function at large baryonic densities can be connected to a decrease of the chiral condensate, thus providing sensitivity to chiral-symmetry restoration [20].

So far, the topic of the strong interaction between hadrons containing charm quarks was addressed only from a theoretical point of view [21–24] by employing different effective models anchored to the successful description of other baryon–meson final states, such as the $\mathrm{N}\overline{\mathrm{K}}$ and NK systems, while data are missing. Scattering experiments [25] and systematic studies of stable and unstable nuclei [26], accompanied by sophisticated calculations achieved within effective field theories [27, 28], allowed us to reach a solid comprehension of the interaction among nucleons. When extending these studies to interactions including strange hadrons, the average properties of the interactions of some strange nucleon–hadron combinations (p$\mathrm{K}^{\pm}$ [29–31], pΛ, and pΣ^{0} [32–34]) could be gauged with the help of scattering data and measurements of kaonic atoms [35]. The study of Λ hypernuclei [36] led to the extraction of an average attractive potential. The situation has drastically changed in recent years, thanks to the novel employment of the femtoscopy technique [37] in pp and p–Pb collisions at the LHC applied to almost all combinations of protons and strange hadrons [38]. The ALICE Collaboration could precisely study the following interactions: pp, p$\mathrm{K}^{\pm}$, pΛ, p$\overline{\Lambda}$, pΣ^{0}, $\Lambda\Lambda$, $\Lambda\overline{\Lambda}$, p$\Xi^{-}$, p$\Omega^{-}$ and pϕ [38–46]. Since conventional scattering experiments cannot be performed with D mesons and charm nuclei [47] have not been discovered yet (searches for charm nuclear states are included in the scientific program of the Japan Proton Accelerator Research Complex [48]), the femtoscopy technique can be employed to study the ND and $\mathrm{N}\overline{\mathrm{D}}$ interactions. In this Letter, the first measurement of the strong interaction between a D^{-} meson and a proton is reported. This pioneering analysis employs D^{-} instead of the more abundantly produced $\overline{\mathrm{D}}^{0}$ mesons because of the smaller contribution from decays of excited charm states and the possibility to separate particles and antiparticles without ambiguity.

The analysis was performed using a sample of high-multiplicity pp collisions at $\sqrt{s} = 13$ TeV collected by ALICE [49, 50] during the LHC Run 2 (2016–2018). The main detectors used for this analysis are the Inner Tracking System (ITS) [51], the Time Projection Chamber (TPC) [52] and the Time-Of-Flight (TOF) detector [53]. The events were recorded with a high-multiplicity trigger relying on the measured signal amplitudes in the V0 detector, which consists of two scintillator arrays covering the pseudorapidity intervals $-3.7 < \eta < -1.7$ and $2.8 < \eta < 5.1$ [54]. The collected data sample corresponds to the 0.17% highest-multiplicity events out of all inelastic collisions with at least one charged particle in the pseudorapidity range $|\eta| < 1$ (INEL > 0). Events were further selected offline in order to remove machine-induced backgrounds [50]. The events were required to have a reconstructed collision vertex located within ± 10 cm from the center of the detector along the beam-line direction to maintain a uniform acceptance. Events with multiple primary vertices, reconstructed from track segments measured with the two innermost ITS layers, were rejected. The remaining undetected pileup is of the order of 1% and therefore negligible in the analysis. After these selections, the analyzed data sample consists of about 10^9 events. The Monte Carlo (MC) samples used in this analysis consist of pp collisions simulated using the PYTHIA 8.243 event generator [55, 56] with the Monash-13 tune [57] and GEANT3 [58] for the propagation of the generated particles through the detector.

The proton candidates are selected according to the methods described in [38]. Charged-particle tracks reconstructed with the TPC are required to have transverse momentum $0.5 < p_{\rm T} < 4.05$ GeV$/c$ and pseudorapidity $|\eta| < 0.8$. Particle identification (PID) is conducted by measuring the specific energy loss and the time of flight with the TPC and TOF detectors, respectively. The selection is based on the deviation n_σ between the measured value and the one expected for protons, normalized by the detector resolution σ. For proton candidates with a momentum $p < 0.75$ GeV/c, only the TPC is used by requiring $|n_\sigma^{\rm TPC}| < 3$, while for larger momenta the PID information of TPC and TOF are combined. With these selection criteria, the purity of the proton sample averaged over $p_{\rm T}$ is 98% [38]. The contribution of secondary protons originating from weak decays or interactions with the detector material is assessed by using MC template fits to the measured distribution of the distance of closest approach of the track to the primary vertex. The estimated average fraction of primary protons is 86% [38].

The $\rm D^{\pm}$ mesons are reconstructed via their hadronic decay channel $\rm D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$, having a branching ratio BR $= (9.38 \pm 0.15)\%$ [59]. D-meson candidates are defined combining triplets of tracks reconstructed in the TPC and ITS detectors with the proper charge signs, $|\eta| < 0.8$, $p_{\rm T} > 0.3$ GeV$/c$, and a minimum of two (out of six) hits in the ITS, with at least one in either of the two innermost layers to ensure a good pointing resolution. To reduce the large combinatorial background and the contribution of $\rm D^{\pm}$ mesons originating from beauty-hadron decays (non-prompt), a machine-learning multi-class classification algorithm based on Boosted Decision Trees (BDT) provided by the XGBOOST library [60, 61] is employed. The variables utilized for the candidate selection in the BDT are based on the displaced decay-vertex topology, exploiting the mean proper decay length of $\rm D^{\pm}$ mesons of $c\tau \approx 312$ μm [59], and on the PID of charged pions and kaons. Before that, a preselection of the $\rm D^{\pm}$ candidates by requiring a 3σ compatibility either with the TPC or the TOF expected signals of the daughter tracks is applied. Signal samples of prompt (originating from charm-quark hadronization or decays of excited charm states) and non-prompt $\rm D^{\pm}$ mesons for the BDT training are obtained from MC simulations. The background samples are obtained from the sidebands of the candidate invariant mass distributions in data. The BDT outputs are related to the candidate probability to be a prompt or non-prompt D meson, or combinatorial background. D-meson candidates are selected in the $p_{\rm T}$ interval between 1 and 10 GeV$/c$ by requiring a high probability to be a prompt $\rm D^{\pm}$ meson and a low probability to be a combinatorial-background candidate.

A selection on the candidate invariant mass ($M(\rm K\pi\pi)$) is applied to obtain a high-purity sample of $\rm D^{\pm}$ mesons. To this end, the $M(\rm K\pi\pi)$ distribution of $\rm D^{\pm}$ candidates is fitted in intervals of $p_{\rm T}$ with a Gaussian function for the signal and an exponential term for the background. The width of the signal peak $\sigma_{\rm D^{\pm}}$ increases from 6 to 10 MeV$/c^2$ with increasing $p_{\rm T}$. Only candidates with $M(\rm K\pi\pi)$ within $2\,\sigma_{\rm D^{\pm}}$ from the invariant mass peak mean ($M_{\rm D^{\pm}}$) are considered for the $\rm pD^{-}$ correlations, leading to a purity that is $(61.7 \pm 0.9({\rm stat}) \pm 0.7({\rm syst}))\%$ on average. The systematic uncertainty is evaluated by repeating the invariant mass fits, varying the background fit function and the invariant mass upper and lower limits.

The fraction of $\rm D^{\pm}$ mesons originating from beauty-hadron decays, $f_{\rm non\text{-}prompt}$, is obtained by sampling the raw yield at different values of the BDT-output score related to the probability of being a non-prompt $\rm D^{\pm}$ meson. Details about the procedure can be found in [62]. The $f_{\rm non\text{-}prompt}$ factor is estimated to

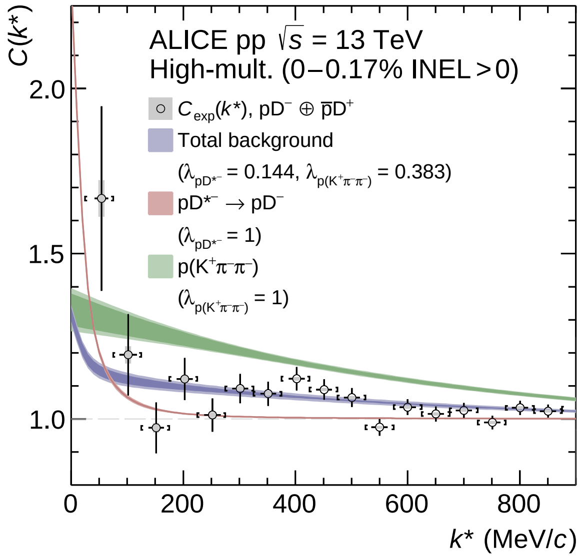

Figure 1: Experimental pD^- correlation function (black symbols) together with the contribution from $p(K^+\pi^-\pi^-)$ (green band) and pD^{*-} (red band), and the total background model (purple band). The $p(K^+\pi^-\pi^-)$ and pD^{*-} contributions are not scaled by the respective λ parameter. Statistical (bars) and systematic uncertainties (boxes) are shown separately. The width of the dark (light) shaded bands depicts the statistical (total) uncertainty of the parametrized background contributions.

be $(7.7 \pm 0.5(\mathrm{stat}) \pm 0.2(\mathrm{syst}))\%$. The systematic uncertainty is evaluated by repeating the procedure with different sets of selection criteria, varying the fitting parameters in the raw-yield extraction, and by weighting the multiplicity distribution in the MC sample used for the efficiency computation in order to reproduce the one in data. Differently from the component originating from beauty-hadron weak decays, $D^{\pm}$ mesons originating from excited charm-meson strong decays cannot be experimentally resolved from promptly produced $D^{\pm}$ mesons due to their short lifetime. The two largest sources are the $D^{*\pm} \rightarrow D^{\pm}\pi^0$ and $D^{*\pm} \rightarrow D^{\pm}\gamma$ decays, having $\mathrm{BR} = (30.7 \pm 0.5)\%$ and $\mathrm{BR} = (1.6 \pm 0.4)\%$ [59], respectively. Their contribution is estimated from the production cross sections of D^+ and D^{*+} mesons measured in pp collisions at $\sqrt{s} = 5.02$ TeV [62, 63] and employing the PYTHIA 8 decayer for the description of the $D^{*\pm} \rightarrow D^{\pm}X$ decay kinematics. The fraction of $D^{\pm}$ mesons in $1 < p_{\mathrm{T}} < 10$ GeV$/c$ originating from $D^{*\pm}$ decays is estimated to be $(27.6 \pm 1.3(\mathrm{stat}) \pm 2.4(\mathrm{syst}))\%$.

The proton and D^- candidates are then combined and their relative momentum k^* is evaluated as $k^* = \frac{1}{2} \times |\boldsymbol{p}^*_{\mathrm{p}} - \boldsymbol{p}^*_{\mathrm{D}}|$, where $\boldsymbol{p}^*_{\mathrm{p,D}}$ are the momenta of the two particles in the pair rest frame. The k^* distribution of pD^- pairs, $N_{\mathrm{same}}(k^*)$, is then divided by the one obtained combining proton and D^- candidates from different events, $N_{\mathrm{mixed}}(k^*)$, to compute the two-particle momentum correlation function, which is defined as $C_{\mathrm{exp}}(k^*) = \mathcal{N} \times N_{\mathrm{same}}(k^*)/N_{\mathrm{mixed}}(k^*)$ [64]. The normalization constant $\mathcal{N}$ is obtained from $k^* \in [1500, 2000]$ MeV$/c$ where the correlation function is independent of k^* [65]. Since the correlation functions for pD^- and $\overline{p}D^+$ are consistent with each other within statistical uncertainties, they are combined and in the following pD^- will represent $pD^- \oplus \overline{p}D^+$. The resulting correlation function $C_{\mathrm{exp}}(k^*)$ is displayed in Fig. 1. The data are compatible with unity for $k^* > 500$ MeV$/c$, while they show a possible hint of an increase for lower k^* values. In total 200 pD^- and 221 $\overline{p}D^+$ pairs contribute to $N_{\mathrm{same}}(k^*)$ in the region of $k^* < 200$ MeV$/c$, where model calculations [21–24] predict a deviation from unity. The systematic uncertainties of $C_{\mathrm{exp}}(k^*)$ are assessed by simultaneously varying the proton and D^- selection criteria.

The measured two-particle momentum correlation function can be related to the source function and the two-particle wave function via the Koonin–Pratt equation $C(k^*) = \int \mathrm{d}^3r^* S(r^*) |\Psi(k^*, r^*)|^2$ [64], where $S(r^*)$ is the source function, $\Psi(k^*,r^*)$ is the two-particle wave function, and r^* refers to the relative distance between the two particles. The source function for the pD$^-$ pairs is estimated by employing the hypothesis of a common source for all hadrons in high-multiplicity pp collisions at the LHC when correcting for strong decays of extremely short-lived resonances ($c\tau \lesssim 10$ fm) feeding into the particle pairs [66]. The strong decays feeding into protons are included in the source of pD$^-$ pairs. In contrast, both beauty-hadron and D$^{*\pm}$ decays occur at larger distances than the typical range for the strong interaction [59]. This implies that the correlation function for D$^-$ mesons originating from these decays will only carry the imprint of the interaction of the parent particle with the proton without impacting the size of the emitting source. The core source determined in [66] features a dependence on the transverse mass $m_{\rm T}$ of the particle pair, which is attributed to a collective expansion of the system [64, 67–69]. The participation in this collective expansion is typically studied via the measurement of the second harmonic coefficient v_2 of the Fourier decomposition of the azimuthal distribution of the produced particle momenta [70, 71]. In high-multiplicity pp collisions, the CMS Collaboration reported comparable values of v_2 for light-flavor and prompt-charm hadrons [72]. Hence, the core source of pD$^-$ pairs with $k^* < 200$ MeV$/c$ is estimated by parameterizing the measured $m_{\rm T}$ dependence of the source radius extracted from pp correlations in [66] and evaluating it at the $\langle m_{\rm T}\rangle = 2.7$ GeV$/c^2$ of the pD$^-$ pairs. Since the production mechanism of charm mesons might not be identical to that of light-flavor baryons, the emission of the pp and pD$^-$ pairs is studied by simulating pp events with PYTHIA 8.301 [56] and computing their relative distance in the pair rest frame, r^*, considering only D$^-$ mesons originating directly from charm-quark hadronization. These studies indicate that the core source of pD$^-$ at the pertinent $\langle m_{\rm T}\rangle$ is smaller by about 25% compared to that of pp pairs. This is included in the systematic uncertainty of the source radius. The resulting overall source is parametrized by a Gaussian profile characterized by an effective radius $R_{\rm eff} = 0.89^{+0.08}_{-0.22}$ fm.

The correlation function due to the genuine pD$^-$ interaction can be extracted from the measured $C_{\rm exp}(k^*)$ by estimating and subtracting the contributions of D$^-$ mesons originating from beauty-hadron and D^{*-} decays, protons originating from strange-hadron decays, as well as misidentified protons and combinatorial-background D-meson candidates. Hence, the experimental correlation function is decomposed as

$$C_{\rm exp}(k^*) = \lambda_{\rm pD^-} \times C_{\rm pD^-}(k^*) + \lambda_{\rm p(K^+\pi^-\pi^-)} \times C_{\rm p(K^+\pi^-\pi^-)}(k^*) + \lambda_{\rm pD^{*-}} \times C_{\rm pD^{*-}}(k^*) + \lambda_{\rm flat} \times C_{\rm flat}. \quad (1)$$

The combinatorial ($\rm K^+\pi^-\pi^-$) background below the D$^-$ peak and the final-state interaction among protons and D$^-$ from D^{*-} decays play a significant role. All other contributions are assumed to be $C(k^*) \sim 1$ and are therefore included in the $C_{\rm flat}$ contribution. The relative weights, λ_i, are evaluated considering the contributions to D$^-$ candidates described above and following the procedure explained in [38] for the protons. They are about 33.9% for $C_{\rm pD^-}(k^*)$ and 38.8%, 14.4%, and 13.4% for the p($\rm K^+\pi^-\pi^-$), pD^{*-}, and flat contributions, respectively.

The correlation function $C_{\rm p(K^+\pi^-\pi^-)}$ is extracted from the sidebands of the D$^-$ candidates, chosen as $[M_{\rm D^-}(p_{\rm T}) - 200\,{\rm MeV}/c,\ M_{\rm D^-}(p_{\rm T}) - 5\times\sigma_{\rm D^-}(p_{\rm T})]$ and $[M_{\rm D^-}(p_{\rm T}) + 5\times\sigma_{\rm D^-}(p_{\rm T}),\ M_{\rm D^-}(p_{\rm T}) + 200\,{\rm MeV}/c]$ for the left and right sidebands, respectively. The contamination from $\rm D^{*-} \to \overline{D}^0\pi^- \to K^+\pi^-\pi^-$ decays in the right sideband is suppressed by a $2.5\sigma_{\rm D^{*-}}$ rejection around the mean value of the D^{*-} invariant mass peak. The resulting correlation function is parametrized by a third-order polynomial in $k^* \in [0,\ 1.5]$ GeV$/c$ and is displayed by the green curve in Fig. 1. The observed behavior is determined by meson–meson and baryon–meson mini-jets and residual two-body interactions among the quadruplet, as previously observed [41, 45].

The residual pD^{*-} correlation function is computed employing the Koonin–Pratt formalism using the CATS framework [73] to obtain a two-particle wave function $\Psi(k^*,r^*)$ considering only the Coulomb interaction and assuming that the source radius is the same as for pD$^-$ pairs. The obtained pD^{*-} correlation function is transformed to the momentum basis of the pD$^-$ relative momentum by considering the kinematics of the $\rm D^{*-} \to D^-X$ decay [74]. The resulting correlation function is shown in Fig. 1 as a

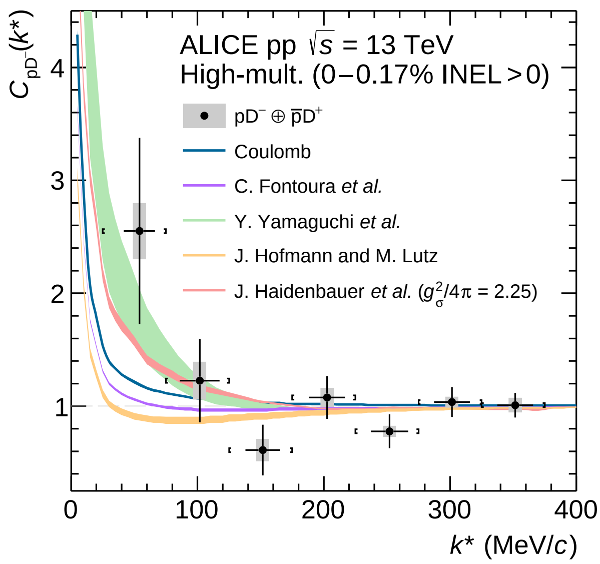

Figure 2: Genuine pD^- correlation function compared with different theoretical models (see text for details). The null hypothesis is represented by the curve corresponding to the Coulomb interaction only.

red band. The purple band in Fig. 1 represents the total background that includes all contributions with their corresponding weights. Finally, the genuine pD^- correlation function is obtained by solving Eq. 1 for $C_{pD^-}(k^*)$ and is shown in Fig. 2. The possible enhancement at low k^* could be attributed to an overall attractive genuine pD^- final-state interaction.

The systematic uncertainties of the genuine pD^- correlation function, $C_{pD^-}(k^*)$, include (i) the uncertainties of $C_{exp}(k^*)$, (ii) the uncertainties of the λ_i weights, and (iii) the uncertainties related to the parametrization of the background sources. In particular, the systematic uncertainties of $C_{p(K^+\pi^-\pi^-)}(k^*)$ are estimated by varying the proton and D^--candidate selection criteria and the range of the fit of the $C(k^*)$ parametrized from the invariant mass sidebands. The uncertainties of the λ_i weights are derived from the systematic uncertainties on the D^- purity and $f_{\text{non-prompt}}$ reported above. The systematic uncertainty of $C_{pD^{*-}}(k^*)$ is due to the uncertainty on the emitting source. The overall relative systematic uncertainty on $C_{pD^-}(k^*)$ resulting from the different sources is of 10% in the lowest k^* interval.

The resulting genuine $C_{pD^-}(k^*)$ correlation function can be employed to study the pD^- strong interaction that is characterized by two isospin configurations and is coupled to the $n\overline{D}^0$ channel. First of all, in order to assess the effect of the strong interaction on the correlation function, only the Coulomb interaction is considered. The corresponding correlation function is obtained using CATS [73]. Secondly, various theoretical approaches to describe the strong interaction are benchmarked, including meson exchange (Haidenbauer et al. [21]), meson exchange based on heavy quark symmetry (Yamaguchi et al. [24]), an SU(4) contact interaction (Hoffmann and Lutz [22]), and a chiral quark model (Fontoura et al. [23]). The relative wave functions for the model [21] are provided directly, while for the models from [22–24] they are evaluated by employing a Gaussian potential whose strength is adjusted to describe the corresponding published $I = 0$ and $I = 1$ scattering lengths listed in Table 1. The pD^- correlation function is computed within the Koonin–Pratt formalism, taking into account explicitly the coupling between the pD^- and $n\overline{D}^0$ channels [75] and including the Coulomb interaction [76]. The finite experimental momentum resolution is considered in the modeling of the correlation functions [38].

The outcome of these models is compared in Fig. 2 with the measured genuine pD^- correlation function. The degree of consistency between data and models is obtained from the p-value computed in the range $k^* < 200$ MeV$/c$. It is expressed by the number of standard deviations n_σ reported in Table 1, where the n_σ range accounts, at one standard deviation level, for the total uncertainties of the data points and the

Table 1: Scattering parameters of the different theoretical models for the N$\overline{\mathrm{D}}$ interaction [21–24] and degree of consistency with the experimental data. Negative scattering parameters correspond to either a repulsive interaction or to an attractive interaction with the presence of a bound state [24]. Positive scattering parameters correspond to an attractive interaction.

Model	f_0 (I = 0)	f_0 (I = 1)	n_σ
Coulomb			(1.1–1.5)
Haidenbauer et al. [21]			
$- g_\sigma^2/4\pi = 1$	0.14	−0.28	(1.2–1.5)
$- g_\sigma^2/4\pi = 2.25$	0.67	0.04	(0.8–1.3)
Hofmann and Lutz [22]	−0.16	−0.26	(1.3–1.6)
Yamaguchi et al. [24]	−4.38	−0.07	(0.6–1.1)
Fontoura et al. [23]	0.16	−0.25	(1.1–1.5)

models. The data are compatible with the Coulomb-only hypothesis within $(1.1–1.5)\sigma$. Nevertheless, the level of agreement slightly improves in case of the model by Yamaguchi et al. as reported in Table 1, where the n_σ values are summarized together with the scattering lengths f_0. Here, the high-energy physics convention on the scattering-length sign is adopted: a negative value corresponds to either a repulsive interaction or to an attractive one with presence of a bound state, while a positive value corresponds to an attractive interaction. Most notably, this is the only model in the literature that does not predict a repulsive N$\overline{\mathrm{D}}$ interaction and, in addition, it foresees the formation of a N$\overline{\mathrm{D}}$ bound state with a mass of 2804 MeV$/c^2$ in the I = 0 channel. For the model by Haidenbauer et al., a better agreement with the data can be achieved by fine-tuning the effective scalar coupling constant g_σ [21]. As demonstrated in Table 1, when increasing the coupling constant to $g_\sigma^2/4\pi = 2.25$ the overall degree of consistency with the data is improved. This also implies a change of the interaction, from repulsive to attractive.

Finally, the scattering parameters can be constrained by comparing the data with the outcome of calculations carried out varying the strength of the potential and the source radius. In this case the interaction potential is parametrized by a Gaussian-type functional form with the range of ρ-meson exchange. In this estimation, it is assumed that the interaction in the I = 1 channel is negligible for simplicity. The

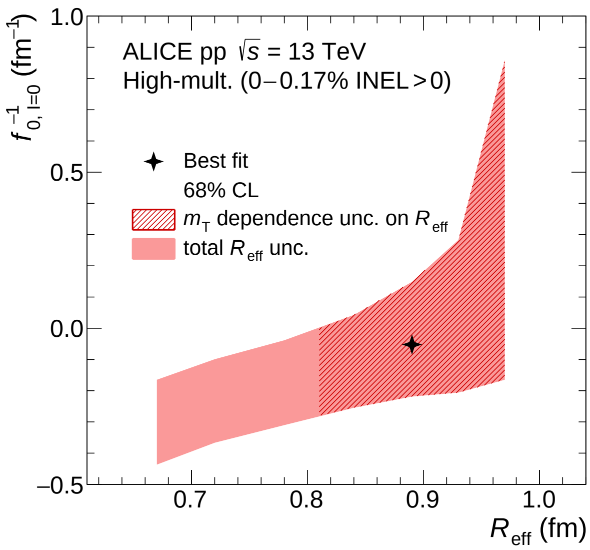

Figure 3: Regions of 68% confidence intervals for the inverse scattering length $f^{-1}_{0,\,\mathrm{I}=0}$ as a function of the source radius varied within one standard deviation considering only the m_T dependence on R_eff and the total uncertainty (see text for details) under the assumption of negligible interaction for I = 1. The most probable value is reported by the star symbol.

data are found to be consistent with a potential strength of $V_{\mathrm{I}=0} \in [-1450, -1050]$ MeV within 1σ. This corresponds to an inverse scattering-length interval of $f_{0,\,\mathrm{I}=0}^{-1} \in [-0.4, 0.9]$ fm^{-1}. Since the determined potential strength is always attractive, the positive values of the scattering length imply an attractive interaction without bound states, while the negative values are consistent with the presence of a $\mathrm{N\overline{D}}$ bound state. Figure 3 shows the confidence interval as a function of the source radius varied within 1σ of its uncertainty. The dashed interval corresponds to the radius uncertainty due to only the m_{T} dependence while the full-shaded interval shows the total radius uncertainty. Given that most models predict a repulsive I = 1 interaction, in reality the I = 0 interaction might have to be even more attractive. The herewith presented limits provide valuable guidance for further theoretical studies advancing the understanding of the strong interaction in the charm sector.

In conclusion, this Letter presents the first measurement of correlation functions involving charm hadrons, which allows access to the strong interaction between a proton and a charm meson. The genuine pD^{-} correlation function reflects the pattern of an overall attractive interaction. The data are compatible within $(1.1\text{–}1.5)\sigma$ with the correlation function obtained from the hypothesis of a Coulomb-only interaction. The degree of consistency improves when considering, in addition, state-of-the-art models that predict an attractive strong $\mathrm{N\overline{D}}$ interaction with or without a bound state. Finally, assuming no interaction for the I = 1 channel, the scattering length of the $\mathrm{N\overline{D}}$ system in the isospin I = 0 channel is obtained as $f_{0,\,\mathrm{I}=0}^{-1} \in [-0.4, 0.9]$ fm^{-1}. This exploratory study paves the way for precision studies of the strong interactions involving charm hadrons, facilitated by about one order of magnitude larger pp data samples expected to be collected in the next years during the LHC Runs 3 and 4 [77].

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B Supplemental material

B.1 $D^{\pm}$ signal and non-prompt fraction evaluation

The invariant mass distribution ($M(\mathrm{K}\pi\pi)$) of $D^{\pm}$ candidates is fitted in p_{T} intervals of 1 GeV width in the range $1 < p_{\mathrm{T}} < 10$ GeV/c with a Gaussian function for the signal and an exponential term for the combinatorial background in order to determine the $M(\mathrm{K}\pi\pi)$ interval for the selection of $D^{\pm}$ candidates to pair with the protons and the corresponding purity. The left panel of Fig. B.1 shows the $M(\mathrm{K}\pi\pi)$ distribution for $D^{\pm}$ with $2 < p_{\mathrm{T}} < 3$ GeV/c. The solid green curve represents the total fit function, and the gray dotted curve represents the combinatorial background. The two vertical lines correspond to the invariant mass window $|M(\mathrm{K}\pi\pi)| < 2\sigma_{\mathrm{D}^{\pm}}$, where $\sigma_{\mathrm{D}^{\pm}}$ is the width of the Gaussian function used to describe the signal, used to select $D^{\pm}$-meson candidates to be paired with proton candidates. The contributions of $D^{\pm}$ mesons originating directly from charm-quark hadronization or from decays of excited charm-hadron states (prompt), and from beauty-hadron decays (non-prompt) depicted in the figure with the red and blue distributions, are obtained with a data-driven method. The yields of prompt and non-prompt $D^{\pm}$ mesons can be extracted by solving a system of equations that relate each raw yield Y_i to the corrected yields of prompt (N_{prompt}) and non-prompt ($N_{\text{non-prompt}}$) $D^{\pm}$ mesons via the acceptance-times-efficiency factors for prompt ($(\mathrm{Acc}\times\varepsilon)_i^{\text{non-prompt}}$) and non-prompt ($(\mathrm{Acc}\times\varepsilon)_i^{\text{prompt}}$) $D^{\pm}$ mesons as follows

$$\begin{pmatrix} (\mathrm{Acc}\times\varepsilon)_1^{\mathrm{prompt}} & (\mathrm{Acc}\times\varepsilon)_1^{\text{non-prompt}} \\ \vdots & \vdots \\ (\mathrm{Acc}\times\varepsilon)_{\mathrm{n}}^{\mathrm{prompt}} & (\mathrm{Acc}\times\varepsilon)_{\mathrm{n}}^{\text{non-prompt}} \end{pmatrix} \times \begin{pmatrix} N_{\mathrm{prompt}} \\ N_{\text{non-prompt}} \end{pmatrix} - \begin{pmatrix} Y_1 \\ \vdots \\ Y_{\mathrm{n}} \end{pmatrix} = \begin{pmatrix} \delta_1 \\ \vdots \\ \delta_{\mathrm{n}} \end{pmatrix}. \tag{B.1}$$

The δ_i factors represent a residuum that accounts for the equations not holding exactly due to the uncertainty of Y_i, $(\mathrm{Acc}\times\varepsilon)_i^{\text{non-prompt}}$, and $(\mathrm{Acc}\times\varepsilon)_i^{\text{prompt}}$. Each equation is obtained sampling the raw yield at different values of the Boosted Decision Tree (BDT) output related to the candidate probability of being a non-prompt $D^{\pm}$ meson, as explained in [62]. The system of equations can be solved via a χ^2 minimization, which leads to the determination of N_{prompt} and $N_{\text{non-prompt}}$. These can then be used to compute the fraction of non-prompt $D^{\pm}$ mesons $f^{j}_{\text{non-prompt}}$

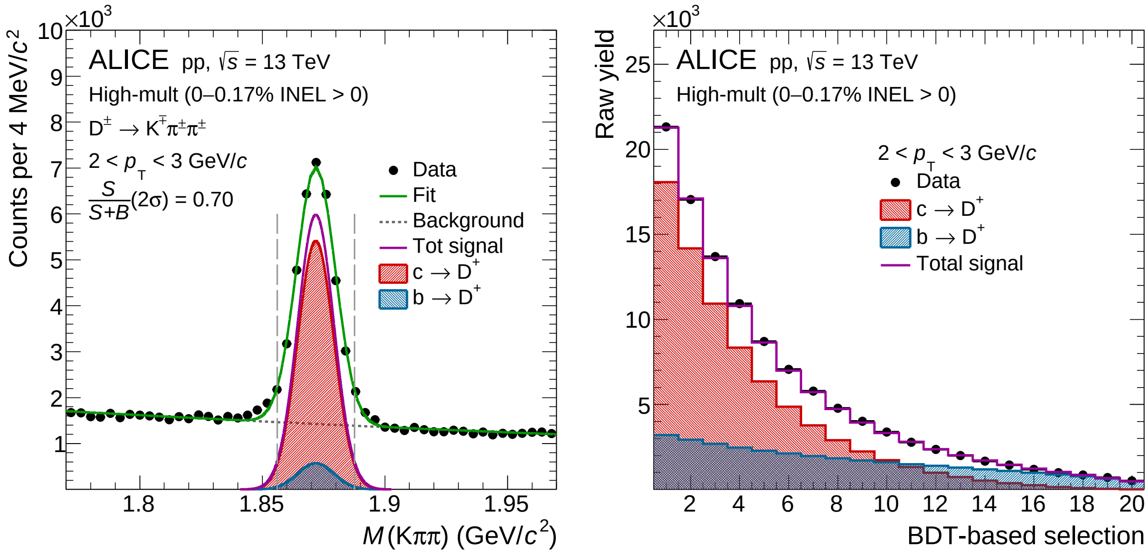

Figure B.1: Left: invariant mass distributions of $D^{\pm}$ candidates in the $2 < p_{\mathrm{T}} < 3$ GeV/c interval. The green solid line shows the total fit function and the gray dotted line the combinatorial background. The contributions of $D^{\pm}$ mesons originating from charm hadronisation and beauty-hadron decays are obtained with the method relying on the definition of different selection criteria, as explained in the text. Right: example of raw-yield distribution as a function of the BDT-based selection employed in the procedure adopted for the determination of the fraction of $D^{\pm}$ originating from beauty-hadron decays for the $2 < p_{\mathrm{T}} < 3$ GeV/c interval.

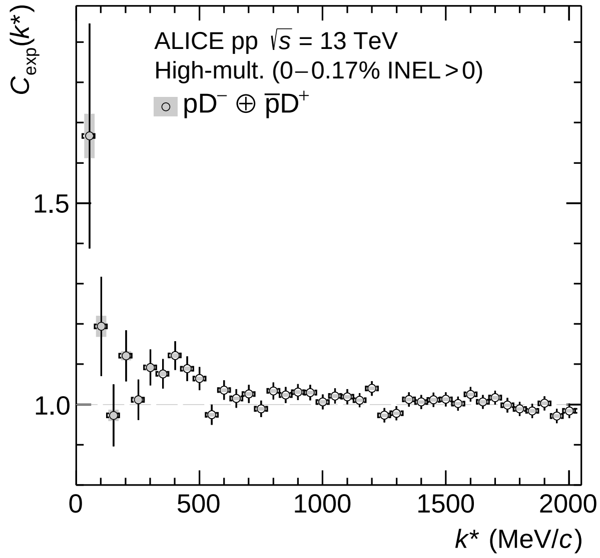

Figure B.2: Experimental pD^- correlation function in the range $0 < k^* < 2$ GeV/c. Statistical (bars) and systematic uncertainties (shaded boxes) are shown separately. The open boxes represent the bin width.

for a given selection j,

$$f^{j}_{\text{non-prompt}} = \frac{(\mathrm{Acc}\times\varepsilon)^{\text{non-prompt}}_{j} \times N_{\text{non-prompt}}}{(\mathrm{Acc}\times\varepsilon)^{\text{non-prompt}}_{j} \times N_{\text{non-prompt}} + (\mathrm{Acc}\times\varepsilon)^{\text{prompt}}_{j} \times N_{\text{prompt}}}. \quad \text{(B.2)}$$

The right panel of Fig. B.1 shows an example of a raw-yield distribution as a function of the BDT-based selection used in the minimization procedure for $\mathrm{D}^{\pm}$ mesons with $2 < p_{\mathrm{T}} < 3$ GeV/c. The leftmost data point of the distribution represents the raw yield corresponding to the loosest selection on the BDT output related to the candidate probability of being a non-prompt $\mathrm{D}^{\pm}$ meson, while the rightmost one corresponds to the strictest selection, which is expected to preferentially select non-prompt $\mathrm{D}^{\pm}$ mesons. The prompt and non-prompt components, obtained for each BDT-based selection from the procedure, are represented by the red and blue filled histograms, respectively, while their sum is reported by the magenta histogram.

B.2 Experimental correlation function

The experimental correlation function $C_{\mathrm{exp}}(k^*)$ is obtained by combining protons and D^- candidates and computing their relative momentum $k^* = \frac{1}{2} \times |\boldsymbol{p}^*_{\mathrm{p}} - \boldsymbol{p}^*_{\mathrm{D}}|$, where $\boldsymbol{p}^*_{\mathrm{p,D}}$ are the momenta of the two particles in their rest frame. In particular, it is computed as $C_{\mathrm{exp}}(k^*) = \mathscr{N} \times N_{\mathrm{same}}(k^*)/N_{\mathrm{mixed}}(k^*)$ [64], where $N_{\mathrm{same}}(k^*)$ is the number of proton and D^- candidates in the same event with relative momentum k^*, while $N_{\mathrm{mixed}}(k^*)$ is obtained by considering protons and D^- candidates from different events. $\mathscr{N}$ is a normalization factor obtained by requiring $C_{\mathrm{exp}}(k^*)$ to be at unity in $k^* \in [1500, 2000]$ MeV/c. Figure B.2 shows $C_{\mathrm{exp}}(k^*)$ in an extended k^* range. In the interval $1500 < k^* < 2000$ MeV/c the correlation function is independent of k^*, as expected since in this region of k^* the pairs of particles are not affected by any interaction.

B.3 Evaluation of interaction-potential and scattering-length confidence interval

The strong interaction between a proton and a D^- meson is characterized by two isospin configurations and is coupled to the $\mathrm{n}\overline{\mathrm{D}}^0$ channel. In order to extract some information about the strength of the interaction potential and the scattering length, the interaction is modeled by a Gaussian potential with an interaction range given by ρ meson exchanges. Due to the limited statistical precision of the data, the potential of the isospin state $I = 1$ component is neglected. Finally, the correlation function $C_{\mathrm{pD}^-}(k^*)$ is computed including the Coulomb interaction and the coupled channel. This procedure is repeated for different values of the interaction potential for the $I = 0$ channel ($V_{I=0}$). For all the correlation functions corresponding to the different interaction potentials, the agreement with the data is obtained by computing the χ^2 using a bootstrap procedure. Both the statistical and systematic uncertainties

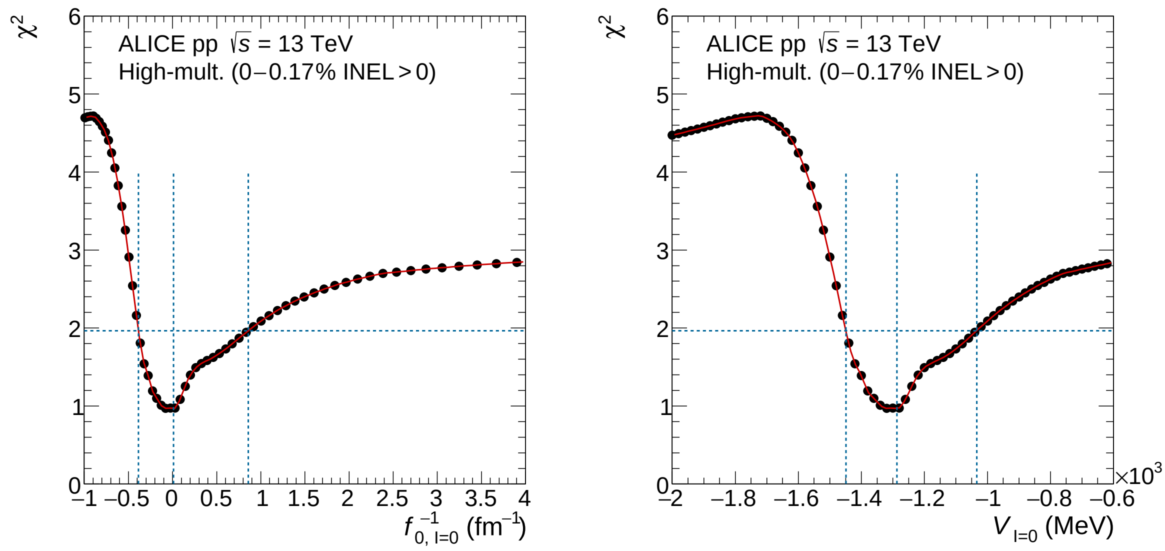

Figure B.3: χ^2 distributions obtained by comparing the measured $C_{\mathrm{pD}^-}(k^*)$ with the correlation function calculated with an interaction modeled by a Gaussian potential with an interaction range given by ρ-meson exchanges as a function of the inverse scattering length (left panel) and the interaction potential (right panel) for $I = 0$. The blue dotted lines represent the value of $f^{-1}_{0,\,I=0}$ and $V_{I=0}$ for which the χ^2 is minimum and for the $1\,\sigma$ confidence interval.

of the data are considered in the bootstrap procedure, as well as the uncertainty on the emitting source radius (R_{eff}) in the computed $C_{\mathrm{pD}^-}(k^*)$, which is varied within 1σ of its uncertainty. The resulting overall χ^2 distributions are shown in Fig. B.3 as a function of of $f^{-1}_{0,\,I=0}$ and $V_{I=0}$ in the left and right panels, respectively. The data are found to be consistent with a potential strength of $V_{\mathrm{I=0}} \in [-1450, -1050]$ MeV within 1σ. This corresponds to an inverse scattering-length interval of $f^{-1}_{0,\,\mathrm{I=0}} \in [-0.4, 0.9]$ fm^{-1}. The same procedure was repeated for fixed values of R_{eff} in order to obtain the 1σ confidence interval as a function of the emitting source radius.