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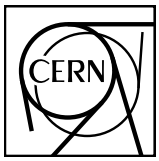

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Observation of enhanced double parton scattering in proton-lead collisions at $\sqrt{s_{\rm NN}} = 8.16\,\text{TeV}$

LHCb collaboration[†]

Abstract

A study of prompt charm-hadron pair production in proton-lead collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV is performed using data corresponding to an integrated luminosity of about $30\,\text{nb}^{-1}$, collected with the LHCb experiment. Production cross-sections for different pairs of charm hadrons are measured and kinematic correlations between the two charm hadrons are investigated. This is the first measurement of associated production of two charm hadrons in proton-lead collisions. The results confirm the predicted enhancement of double parton scattering in heavy-ion collisions.

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At high energy hadron colliders, particles are produced in fundamental collisions of internal partons in the beam projectiles. The underlying parton densities are described by parton distribution functions (PDFs). The associated production of multiple heavy-flavor hadrons can be generated from a single parton scattering (SPS) or multiple parton scatterings. The latter is necessary for the successful description of large charged-track multiplicities and event-activity-dependent heavy-flavor production [1–4]. In a simple model, assuming that the PDFs of two partons in the same projectile are independent, the associated production cross-section of final-state particles A and B from two separate partonic interactions, *i.e.* a double parton scattering (DPS) process, is related to the inclusive production cross-section of A and B, σ^A and σ^B, as [5–14],

$$\sigma^{AB}_{\rm DPS} = \frac{1}{1+\delta_{AB}}\frac{\sigma^A\sigma^B}{\sigma_{\rm eff}}. \tag{1}$$

Here, $\delta_{AB} = 1$ if A and B are identical and is zero otherwise, and $\sigma_{\rm eff}$ is the so-called effective cross-section. The parameter $\sigma_{\rm eff}$ is related to the collision geometry and is expected to be independent of the final state [15–17].

The production of two open charm hadrons, D_1D_2, and $J/\psi D$ meson pairs is of particular interest in the study of SPS and DPS processes. In this Letter, D and $D_{1,2}$ refer to either a D^0, D^+ or D_s^+ meson and the inclusion of charge conjugate states is implied. Both like-sign (LS) and opposite-sign (OS) open charm hadron pairs are considered. In an LS pair the two hadrons have the same charm-quark flavor, while in an OS pair they have opposite charm flavors. Opposite-sign pairs can be produced from a $c\overline{c}$ pair via SPS, thus the kinematics of the two hadrons are correlated. This correlation may be modified in heavy-ion data compared to proton-proton (pp) collisions, due to nuclear matter effects [18–25]. The OS correlation is predicted to be sensitive to the properties of the hot medium formed in ultra-relativistic heavy nucleus-nucleus collisions [26–36].

The two hadrons in an LS pair produced in a DPS process are expected to be uncorrelated. Studies of LS pair production and correlation in different environments help to test the universality of the parameter $\sigma_{\rm eff}$ and gain insight into the underlying parton correlations. The ratio of DPS to SPS cross-sections in proton-lead (p-Pb) collisions is estimated to be about three times larger than in pp collisions [10, 37–43]. Since DPS production involves two parton pairs, it is very sensitive to the nuclear PDF (nPDF), including its possible dependence on the position inside the Pb nucleus [44].

Production of OS charm and beauty pairs has been studied in fully reconstructed decays [45–49] and using partially reconstructed decays [50–57], and the hadron and anti-hadron are found to be correlated; in particular, the azimuthal angle, $\Delta\phi$, between the two hadron directions projected to the plane transverse to the beam line favors values close to $\Delta\phi = 0$ or π. Production of LS charm pairs, double quarkonium and multiple jets at the Tevatron and the LHC revealed evidence of DPS signals [49, 58–66]. The effective cross-section is measured to be in the range of 10 to 20 mb for most final states, however, a value as low as 5 mb is extracted using double quarkonium production [67–69]. More measurements are required to resolve this puzzle.

This Letter presents the first measurement of charm pair production in p-Pb collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\rm NN}} = 8.16\,\text{TeV}$. The data were collected with the LHCb experiment at a low interaction rate in two distinct beam configurations. In the pPb configuration, particles produced in the direction of the proton beam are analysed, while in the Pbp configuration particles are analysed in the Pb beam direction. The pPb

(Pbp) data correspond to an integrated luminosity of $12.2 \pm 0.3\,\text{nb}^{-1}$ ($18.6 \pm 0.5\,\text{nb}^{-1}$). The detector coordinate system is defined to have the z-axis aligned with the proton beam direction. In the following, particle rapidities (y) are defined in the nucleon-nucleon rest frame.

The LHCb detector is a single-arm forward spectrometer described in detail in Refs. [70, 71]. The online event selection is performed by a trigger, which consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. Charm hadrons ($H_c \equiv D^0, D^+, D_s^+, J/\psi$) are reconstructed online via the decays $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^-K^+\pi^+$ and $J/\psi \to \mu^+\mu^-$. The data samples are selected by the hardware trigger based on the calorimeter activity for D candidates and based on the muon system for J/ψ candidates. Candidate pairs are formed by D^0D^0, $D^0\overline{D}^0$ and $D^+D^\pm$ combinations (same species), and $D^0D^\pm$, $D^0D_s^\pm$, $D^+D_s^\pm$ and $J/\psi D^{0,+}$ combinations (different species). Other charm pairs are not considered due to their limited yield in the data. The tracks used to reconstruct the D mesons are required to be positively identified as kaons or pions and must be separated from every primary p-Pb collision vertex (PV). These tracks are also required to have transverse momentum $p_\text{T} > 250\,\text{MeV}/c$ and at least one track must have $p_\text{T} > 500\,\text{MeV}/c$ ($p_\text{T} > 1000\,\text{MeV}/c$) for D^0 (D^+, D_s^+) final states. The tracks are required to form a vertex of good quality that is separated from every PV. The reconstructed D mesons are required to be consistent with originating from a PV, which favors prompt production over mesons from beauty-hadron decays (denoted as charm-from-b). The two muons used to reconstruct J/ψ candidates are required to have $p_\text{T} > 500\,\text{MeV}/c$ and form a good-quality vertex.

In the offline selection, kaons and pions are required to have momentum $p > 3\,\text{GeV}/c$, and muons to have $p > 6\,\text{GeV}/c$, $p_\text{T} > 750\,\text{MeV}/c$ and be positively identified by using information from all subdetectors [72, 73]. The K^-K^+ invariant mass from the $D_s^+ \to K^-K^+\pi^+$ decay is required to be within $\pm 20\,\text{MeV}/c^2$ of the known $\phi(1020)$ mass [74]. A kinematic fit is performed on each charm hadron and on the pair, constraining them to originate from a PV. Requirements on the fit qualities strongly reduce charm-from-b contributions but retain more than 99% of prompt pairs.

Results are obtained in a charm-hadron kinematic region $p_\text{T}(H_c) < 12\,\text{GeV}/c$ and $1.7 < y(H_c) < 3.7$ ($-4.7 < y(H_c) < -2.7$) for pPb (Pbp) data. For D^+ and D_s^+ mesons the requirement $p_\text{T}(H_c) > 2\,\text{GeV}/c$ is applied due to extremely small yields at lower p_T. Total cross-sections of D^0D^0, $D^0\overline{D}^0$ and $J/\psi D^0$ pair production are also evaluated in the full LHCb rapidity acceptance, $1.5 < y(H_c) < 4$ ($-5 < y(H_c) < -2.5$) for pPb (Pbp) data, in order to compare with single charm production [75, 76].

The cross-section for a charm pair is calculated as $\sigma = N^\text{corr}/(\mathcal{L} \times \mathcal{B}_1 \times \mathcal{B}_2)$, where $\mathcal{L}$ is the integrated luminosity, and N^corr is the signal yield after efficiency correction and the subtraction of charm-from-b background. The branching fractions of the two charm-hadron decays, $\mathcal{B}_{1,2}$, are taken from Ref. [74] for the D^0, D^+, J/ψ decays, and $\mathcal{B}(D_s^+ \to (K^+K^-)_\phi\pi^+) = (2.24 \pm 0.13)\%$ from Refs. [77, 78]. The raw signal yield is determined from an unbinned maximum likelihood fit to the distribution of the invariant masses, m_1 and m_2, of the two charm hadrons. The two-dimensional probability densities comprise four components: signal-signal, background-background, signal-background and background-signal for the first-second charm hadron in a pair. The background is mainly from random combinations of tracks. The signal component for each charm hadron is described by the sum of a Gaussian and a Crystal Ball function (CB) [79]

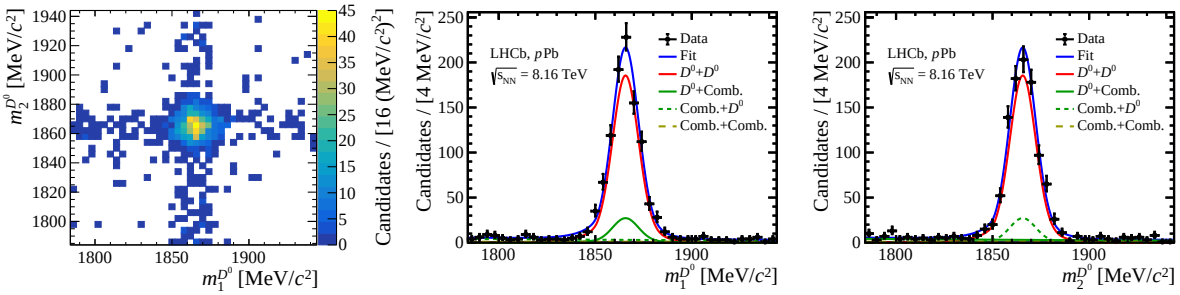

Figure 1: (Left) Two-dimensional invariant-mass distributions of (m_1, m_2) for D^0D^0 pairs and the projections on (middle) m_1 and (right) m_2 with the fit results superimposed. Shown in the projection plots are (points with bars) pPb data, (solid blue) the total fit and its four components.

and the background component by an exponential function. The distribution for pairs of same-species hadrons is constructed to be independent of the ordering of m_1 and m_2. As an example, the (m_1, m_2) distribution for D^0D^0 candidates and its projection on m_1 and m_2 are are shown in Fig. 1 for pPb data, with the fit projections overlaid. More distributions are shown in the Supplemental Material. The raw signal yield is between 100 and 4000 for all hadron pairs considered.

The total detection efficiency for each individual charm hadron is evaluated from simulated signal decays, properly corrected using control samples of p-Pb collisions. These control samples are used to calibrate track finding and particle identification (PID) efficiencies [80]. In the simulation, minimum-bias p-Pb collisions are produced using the EPOS generator [81] according to beam configurations of the data. Charm hadrons are generated in pp collisions at $\sqrt{s} = 8.16\,\text{TeV}$ using PYTHIA8 [82,83] and are embedded into EPOS minimum-bias events. Particle decays are described by EVTGEN [84], while the particle interaction with the detector, and its response, are implemented using the GEANT4 toolkit [85] as described in Ref. [86]. The track finding efficiency in data and simulation is studied with a tag-and-probe method using $J/\psi \to \mu^+\mu^-$ decays [87]. Similarly, the PID efficiency is measured using large control samples of $D^0 \to K^-\pi^+$ and $J/\psi \to \mu^+\mu^-$ decays for K^-, π^+ and μ^- tracks, in bins of track momentum and pseudorapidity (p, η). The average charged-track multiplicity in OS data is similar to the one in the control samples, while for LS data it is about 13% higher, which is consistent with a larger contribution of multiple parton scattering in LS data [1–4]. The corresponding difference in detector occupancy results in different detection efficiencies in LS and OS data, which is evaluated in control samples. Efficiencies from control samples are combined with simulation to obtain the efficiency for each charm hadron as a function of $p_{\rm T}$ and y, $\epsilon(p_{\rm T}, y)$, which is used to determine the efficiency corrected signal yield $\sum_i \frac{w^i}{\epsilon_1(p_{\rm T}^i, y^i)\epsilon_2(p_{\rm T}^i, y^i)}$. Here w^i is the signal *sPlot* weight [88] used to remove the contribution of background and is obtained from the fit to the invariant-mass distribution, and $\epsilon_{1,2}(p_{\rm T}^i, y^i)$ is the efficiency for the first and second hadron in the i^{th} candidate pair in data. The signal yield is then corrected for the charm-from-b contamination, which is estimated to be less than 1% for open charm pairs and $(4 \pm 2)\%$ ($(3.0 \pm 1.5)\%$) for $J/\psi D$ pairs in pPb (Pbp) data.

Several sources of systematic uncertainties are investigated. The variation of the signal yield is studied with fits to the invariant-mass distribution using a different signal

or background model. A maximum relative variation of 2% is obtained on the signal yield. The dominant systematic uncertainty arises from the limited control sample size to determine the track finding efficiency, which is on average about 5% (10%) per track in pPb (Pbp) data. An uncertainty of 2% per hadron track is introduced to account for the loss of particles due to interactions with the detector material. Due to the small sample size and the choice of (p, η) binning for each track, the PID efficiencies obtained from control samples introduce an uncertainty of less than 1% on the total efficiency of each charm hadron. Other contributions include the uncertainty on the total efficiency due to the size of the simulation sample, the uncertainty on the charm decay branching fractions, the uncertainty on the luminosity measurements and on the charm-from-b fraction. These uncertainties are propagated to the cross-section measurements.

Total cross-sections are determined for all charm pairs. Results are detailed in the Supplemental Material. For LS open charm pairs, the measurements are in good agreement with theoretical calculations including both SPS and DPS production [42]. The $J/\psi D^0$ cross-section is found to be generally higher than SPS production, calculated using the weighted EPPS16 nPDF [89–92].

Prompt single charm cross-sections in pPb data were measured to be smaller than those of Pbp data [76, 93], which is explained by modifications of the nPDF. The same effect would result in even stronger suppression of DPS production in pPb compared to Pbp data due to the participation of two pairs of partons. For charm pairs, the cross-section ratio between pPb and Pbp data, the forward-backward ratio ($R_{\rm FB}$), is determined for $2.7 < |y(H_c)| < 3.7, p_{\rm T}(H_c) > 2\,{\rm GeV}/c$, to be $0.40 \pm 0.05 \pm 0.10$ ($0.61 \pm 0.04 \pm 0.12$) averaged over LS (OS) open charm pairs, and is $0.26 \pm 0.06 \pm 0.04$ for $J/\psi D$ pairs. Here and in the following, the first uncertainty is statistical and the second is systematic. The results indicate reduced production in pPb compared to Pbp data for both LS and OS pairs. The $R_{\rm FB}$ of OS production is compatible with that of prompt D^0 mesons [76, 93], while that of LS production is smaller. The ratio between the $R_{\rm FB}$ of LS and OS production, $0.66 \pm 0.09 \pm 0.03$, is in good agreement with the $R_{\rm FB}$ of OS data and the $R_{\rm FB}$ of prompt D^0 production. The measurements favor the interpretation of LS production via DPS.

The LS over OS cross-section ratio, $R^{D_1D_2} \equiv \sigma^{D_1D_2}/\sigma^{D_1\bar{D}_2}$, is determined for all studied D_1D_2 pairs under the $p_{\rm T}(D) > 2\,{\rm GeV}/c$ requirement, giving an average value of $0.308 \pm 0.015 \pm 0.010$ and $0.391 \pm 0.019 \pm 0.025$ for pPb and Pbp data respectively. The measurements agree with the calculations in Ref. [42] of $0.57^{+0.16}_{-0.41}$ (pPb) and $0.52^{+0.17}_{-0.38}$ (Pbp), and are significantly larger than that in pp collisions where $R^{D^0D^0} = 0.109 \pm 0.008$ [49], indicating an enhancement of LS pair production over OS pairs in p-Pb collisions. The differential results as a function of $y(H_c)$ is shown in the Supplemental Material.

The correlations of kinematics between the two charm hadrons in a pair are investigated from the distributions of the two-charm invariant mass (m_{DD}) and their relative azimuthal angle $\Delta\phi$. The differential cross-section for each variable is normalized by the total cross-section, such that the largest systematic uncertainty, the one from the track finding efficiency, almost completely cancels. As examples, in Fig. 2, the m_{DD} distribution is shown for D^0D^0 and $D^0\overline{D}^0$ pairs without any requirement on $p_{\rm T}(D)$. The difference between D^0D^0 and $D^0\overline{D}^0$ pairs is determined to be more than three (two) standard deviations in pPb (Pbp) data, studied using a χ^2 test. For both D^0D^0 and $D^0\overline{D}^0$ pairs, the m_{DD} distribution is compatible between pPb and Pbp data. The $D^0\overline{D}^0$ pair shows a similar m_{DD} distribution to that of the Pythia8 simulation, in which the fraction of inclusive charm production that contains more than one charm pair within the LHCb

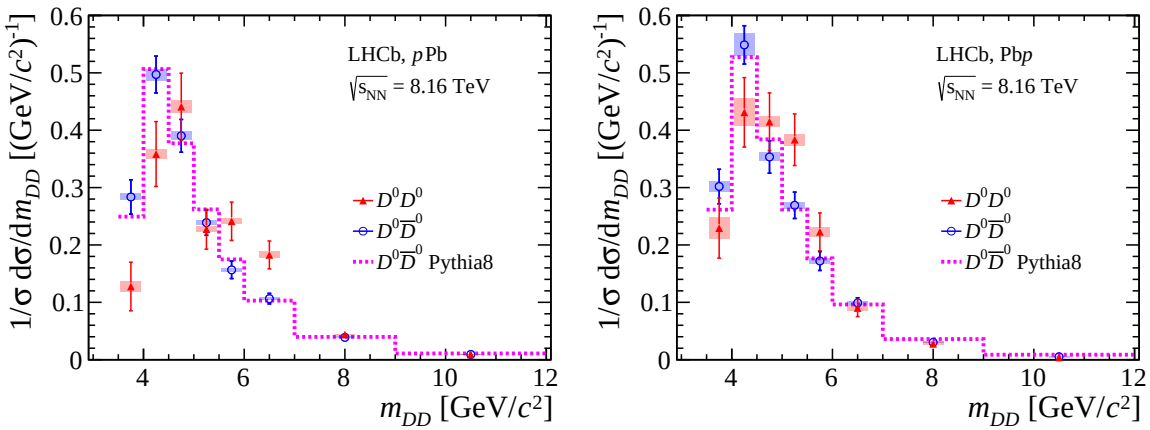

Figure 2: Two-charm hadron invariant-mass distribution of (red) D^0D^0 and (blue) $D^0\overline{D}^0$ pairs in (left) pPb, (right) Pbp data and (magenta dashed line) PYTHIA8 simulation. Vertical bars (filled box) are statistical (systematic) uncertainties.

acceptance is about 7%.

The $\Delta\phi$ distribution is shown in Fig. 3 for D^0D^0 and $D^0\overline{D}^0$ pairs with and without the requirement $p_{\rm T}(D^0) > 2\,{\rm GeV}/c$. Without this condition, the $\Delta\phi$ distribution is almost uniform for both LS and OS pairs, similar to that in PYTHIA8 simulation. However, with the $p_{\rm T}(D^0) > 2\,{\rm GeV}/c$ requirement, the $D^0\overline{D}^0$ pair favors values $\Delta\phi \sim 0$, while that of D^0D^0 pairs is still compatible with being flat, and both show inconsistency with the PYTHIA8 simulation. In general, the behaviour that m_{DD} distribution in D^0D^0 pairs peaks at higher values compared to that of $D^0\overline{D}^0$ pairs and the flat D^0D^0 $\Delta\phi$ distribution are qualitatively consistent with a large DPS contribution in LS pair production. Distributions of the pair transverse momentum and the two-charm relative rapidity are found to be compatible in OS data, LS data and the PYTHIA8 simulation.

The effective cross-section $\sigma_{{\rm eff},\,p{\rm Pb}}$ is calculated according to Eq. 1 using the D^0D^0 and $J/\psi D^0$ cross-sections [6], assuming solely DPS production, where the prompt J/ψ and D^0 production are evaluated from LHCb measurements [75, 76]. The results are displayed in Table 1 with a typical value of order 1 b. The $\sigma_{{\rm eff},\,p{\rm Pb}}$ measurement is about a factor of three smaller than the one obtained by the scaling the $\sigma_{{\rm eff},\,pp}$ result [78] by the Pb nucleus mass number 208, under the assumption that there is no nuclear modification for DPS production, which is shown in Table 1 as pp extrapolation. The result confirms the expectation that DPS production in p-Pb collisions is enhanced by a factor of three [10, 37–42]. The $\sigma_{{\rm eff},\,p{\rm Pb}}$ value measured using $J/\psi D^0$ production is smaller than that observed in D^0D^0 production, as measured in pp data [78], which could be due

Table 1: The effective cross-section $\sigma_{{\rm eff},\,p{\rm Pb}}$ (in b) measured using $J/\psi D^0$ and D^0D^0 pair production in p-Pb data and the extrapolated values from pp data [78].

Pairs	$-5 < y(H_c) < -2.5$	$1.5 < y(H_c) < 4$	pp extrapolation
D^0D^0	$0.99 \pm 0.09 \pm 0.09$	$1.41 \pm 0.11 \pm 0.10$	4.3 ± 0.5
$J/\psi D^0$	$0.64 \pm 0.10 \pm 0.06$	$0.92 \pm 0.22 \pm 0.06$	3.1 ± 0.3

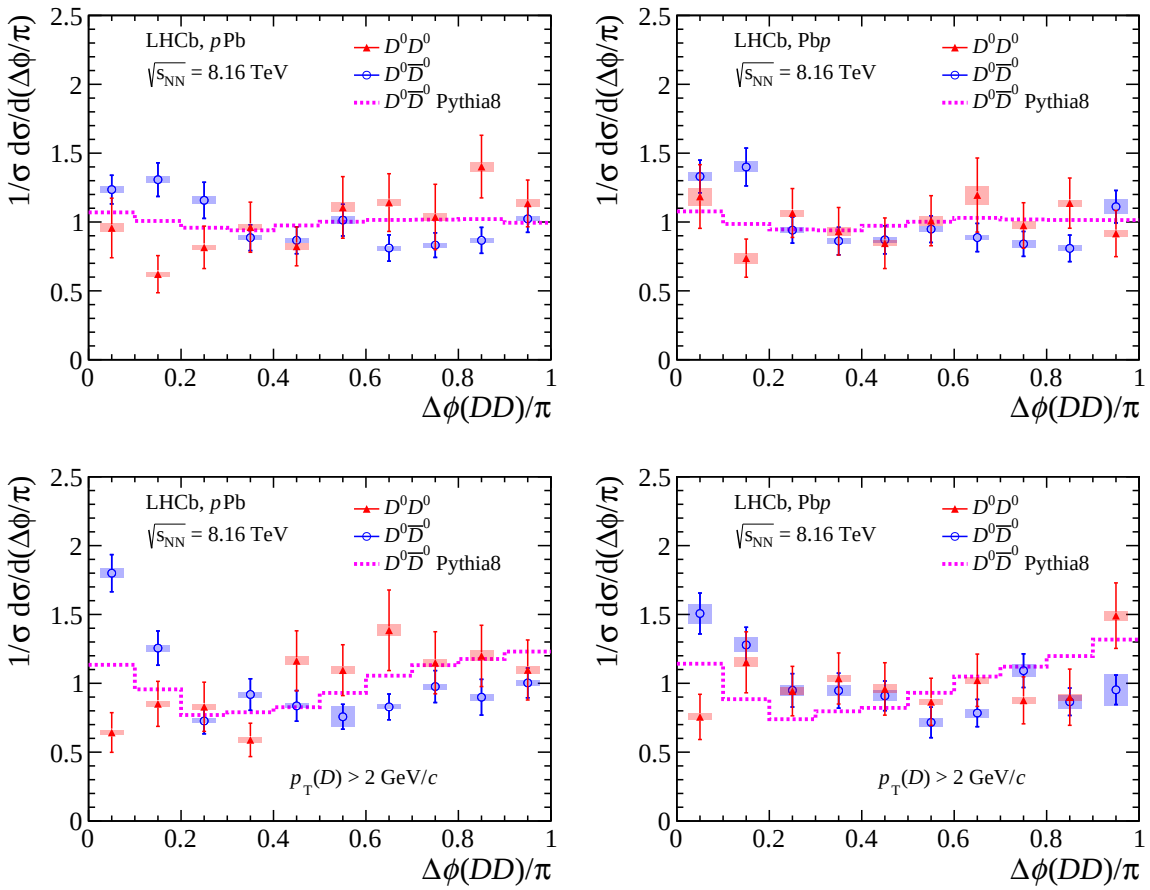

Figure 3: The $\Delta\phi$ distribution for (red) D^0D^0 and (blue) $D^0\overline{D}^0$ pairs in (left) pPb, (right) Pbp data and the (magenta dashed line) PYTHIA8 simulation, (bottom) with and (top) without the $p_{\rm T}(D^0) > 2\,{\rm GeV}/c$ requirement. Vertical bars (filled box) are statistical (systematic) uncertainties.

to SPS contamination [94] or DPS enhancement in $J/\psi D^0$ production. The pPb data shows a higher $\sigma_{{\rm eff},p{\rm Pb}}$ value compared to Pbp data, suggesting a different level of DPS enhancement when comparing pPb and Pbp data.

The nuclear modification factor, $R \equiv \frac{\sigma_{p{\rm Pb}}}{208\sigma_{pp}}$, is measured for $J/\psi D^0$ and D^0D^0 pairs with $R^{H_cH_c'} = R^{H_c} \times R^{H_c'} \times \frac{208\sigma_{{\rm eff},pp}}{\sigma_{{\rm eff},p{\rm Pb}}}$, where $\sigma_{p{\rm Pb}}$ and σ_{pp} are the cross-sections of charm pairs in p-Pb and pp collisions, respectively. Assuming variations of R and $\sigma_{{\rm eff},pp}$ as a function of collision energy are small for $p_{\rm T}$-integrated production, using measurements of $\sigma_{{\rm eff},pp}$ [49], $R^{J/\psi}$ [75] and R^{D^0} [93], $R^{D^0D^0} = 1.3 \pm 0.2$ (4.2 ± 0.8) and $R^{J/\psi D^0} = 1.5 \pm 0.5$ (4.6 ± 1.3) for pPb (Pbp) data are obtained, where the uncertainties are the total. The results are about a factor of three larger compared to that of single J/ψ or D^0 hadron production [75, 93].

To summarise, the production of LS and OS open charm hadron pairs as well as $J/\psi D$ pairs are studied in p-Pb collisions at $\sqrt{s_{\rm NN}} = 8.16\,{\rm TeV}$ using fully reconstructed decays. The cross-section ratio between LS and OS pairs is found to be a factor of three higher than that in pp data. The forward-backward ratio of OS pairs is compatible with

single charm production, while a smaller value is found for LS pairs. Distributions of the two-charm invariant mass and relative azimuthal angle show a difference between LS and OS pairs, and the LS pairs exhibit a flat relative azimuthal angle distribution independent of charm hadron $p_{\rm T}$. The measured effective cross-sections of $J/\psi D^0$ and D^0D^0 pairs are significantly different from values scaled from pp collisions assuming no nuclear modification. The effective cross-section and nuclear modification factor for $J/\psi D^0$ and D^0D^0 are in general compatible with the expected enhancement factor of three for DPS production. The findings indicate the first direct observation of enhanced double parton scattering for charm production in p-Pb data. The $\sigma_{\rm eff,\,pPb}$ result is different between pPb and Pbp data and between $J/\psi D^0$ and D^0D^0 pairs may suggest additional effects not considered yet, which deserve further investigation using future LHCb data samples.

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Supplemental Material

Invariant mass distributions and fit projections

The invariant mass distributions and the fit projections are shown in Fig. 4 for D^0D^0 pairs in Pbp data, and in Figs. 5 and 6 for $D^0\overline{D}^0$ and $J/\psi D^0$ pairs in both pPb and Pbp data.

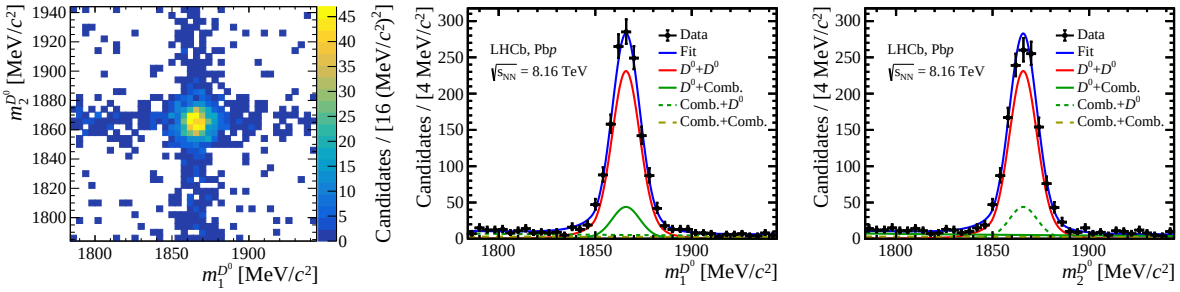

Figure 4: (Left) Two-dimensional invariant-mass distributions of (m_1, m_2) for D^0D^0 pairs and the projections on (middle) m_1 and (right) m_2 with the fit results superimposed. Shown in the projection plots are (points with error bars) Pbp data, (solid blue) the total fit and the four fit components.

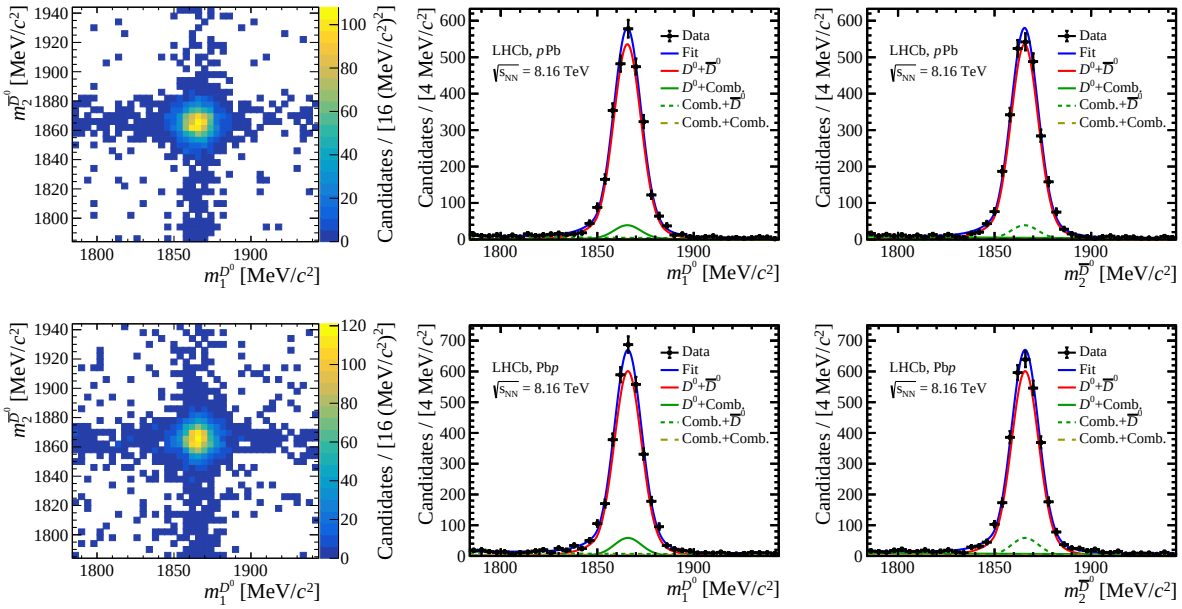

Figure 5: (Left) Two-dimensional invariant-mass distributions of (m_1, m_2) for $D^0\overline{D}^0$ pairs and the projections on (middle) m_1 and (right) m_2 with the fit results superimposed. Shown in the projection plots are (points with error bars) data data, (solid blue) the total fit and the four fit components. The plots in the top (bottom) row correspond to pPb (Pbp) data.

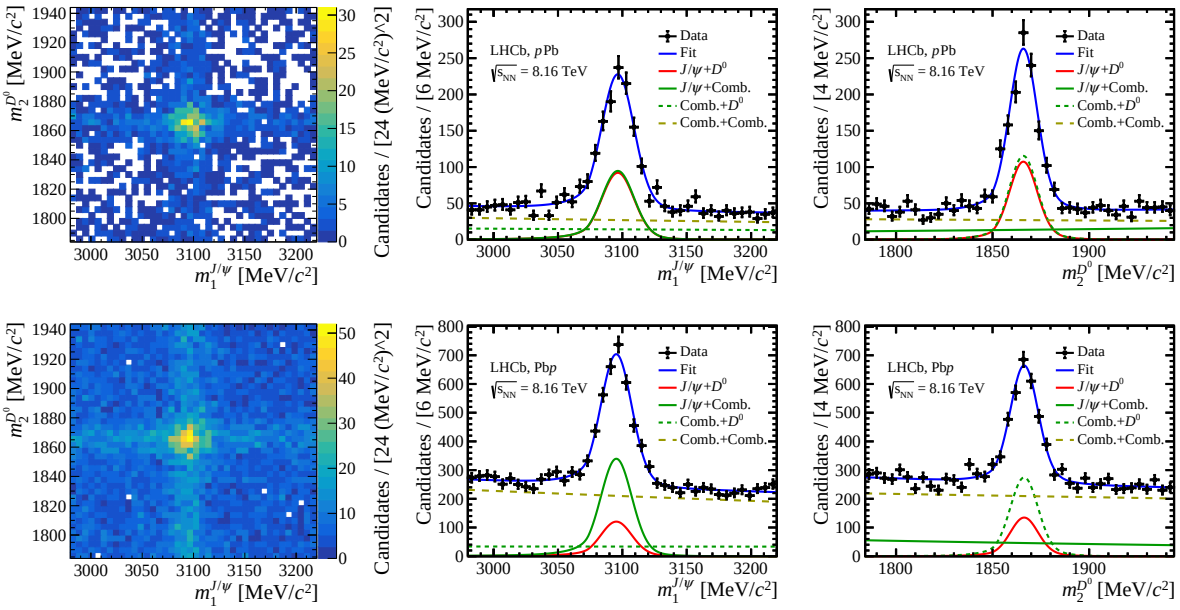

Figure 6: (Left) Two-dimensional invariant-mass distributions of $(m_1^{J/\psi}, m_2^{D^0})$ for $J/\psi D^0$ pairs and the projections on (middle) $m_1^{J/\psi}$ and (right) $m_2^{D^0}$ with the fit results superimposed. Shown in the projection plots are (points with error bars) data data, (solid blue) the total fit and the four fit components. The plots in the top (bottom) row correspond to pPb (Pbp) data.

Cross-sections and cross-section ratios

The total cross-sections measured in the reduced charm hadron rapidity ($y(H_c)$) range $1.7 < y(H_c) < 3.7$ ($-4.7 < y(H_c) < -2.7$) for pPb (Pbp) are shown in Table 2 under the requirement, $p_{\rm T} > 0\,{\rm GeV}/c$ for $J/\psi, D^0$ and $p_{\rm T} > 2\,{\rm GeV}/c$ for D^+, D_s^+. The cross-section of $J/\psi D^0$ pair production is compared with the theoretical calculation of SPS production using the reweighted EPPS16 nuclear PDF [89–92]. Those with the additional requirement $p_{\rm T}(D^0) > 2\,{\rm GeV}/c$ are shown in Table 3, and those in full rapidity acceptance for D^0D^0, $D^0\overline{D}^0$ and $J/\psi D^0$ pairs are shown in Table 4.

In Table 5 and Fig. 7, the ratio between cross-sections of like-sign and opposite-sign pairs is shown in bins of charm hadron rapidity for $p_{\rm T}(H_c) > 2\,{\rm GeV}/c$.

Table 2: Total cross-sections of charm pair production (in mb) in pPb and Pbp data for the $p_{\rm T}$ requirement on the charm hadron, $p_{\rm T} > 0\,{\rm GeV}/c$ for $J/\psi, D^0$ and $p_{\rm T} > 2\,{\rm GeV}/c$ for D^+, D_s^+. The rapidity range is for each charm hadron in the pair. The first uncertainty is statistical and the second is systematic. The prediction of SPS $J/\psi D^0$ production calculated using the weighted EPPS16 nuclear PDF [89–92] is also listed for comparison, where the first uncertainty is from uncertainties of scales, feed-down contribution and model parameters, and the second due to nuclear PDF uncertainties.

Quantity	$1.7 < y(H_c) < 3.7$	$-4.7 < y(H_c) < -2.7$
$D^0 D^0$	$11.0 \pm 0.7 \pm 1.2$	$16.5 \pm 1.1 \pm 3.5$
$D^0 \overline{D}^0$	$34.1 \pm 1.2 \pm 3.6$	$35.1 \pm 1.3 \pm 5.9$
$D^0 D^+$	$4.0 \pm 0.3 \pm 0.6$	$5.3 \pm 0.4 \pm 1.7$
$D^0 D^-$	$12.7 \pm 0.4 \pm 1.7$	$11.6 \pm 0.4 \pm 2.8$
$D^0 D_s^+$	$2.1 \pm 0.6 \pm 0.3$	$3.6 \pm 0.7 \pm 1.2$
$D^0 D_s^-$	$5.4 \pm 0.6 \pm 0.8$	$7.1 \pm 1.0 \pm 1.8$
$D^+ D^+$	$0.46 \pm 0.05 \pm 0.09$	$0.53 \pm 0.08 \pm 0.24$
$D^+ D^-$	$1.38 \pm 0.07 \pm 0.22$	$1.26 \pm 0.08 \pm 0.42$
$D^+ D_s^-$	$1.43 \pm 0.21 \pm 0.25$	$1.32 \pm 0.20 \pm 0.44$
$D^+ D_s^+$	$0.32 \pm 0.12 \pm 0.05$	$0.80 \pm 0.27 \pm 0.40$
$J/\psi D^0$	$0.46 \pm 0.05 \pm 0.04$	$0.57 \pm 0.07 \pm 0.09$
$J/\psi D^+$	$0.08 \pm 0.01 \pm 0.01$	$0.10 \pm 0.01 \pm 0.02$
$J/\psi D^0$ SPS [89–92]	$0.051^{+0.467+0.009}_{-0.043-0.009}$	$0.055^{+0.426+0.004}_{-0.053-0.003}$

Table 3: Total production cross-sections (in mb) of open charm pairs involving the D^0 meson in pPb and Pbp data with the $p_{\rm T}(D^0) > 2\,{\rm GeV}/c$ requirement. The rapidity range is for each charm hadron in the pair. The first uncertainty is statistical and the second is systematic. Predictions for the $D^0\,D^0$ and $D^0\,\overline{D}^0$ cross-sections from Ref. [42] are given in the last two rows of the Table.

Pairs	$1.7 < y(H_c) < 3.7$	$-4.7 < y(H_c) < -2.7$
$D^0 D^0$	$2.36 \pm 0.16 \pm 0.24$	$2.28 \pm 0.15 \pm 0.33$
$D^0 \overline{D}^0$	$7.36 \pm 0.28 \pm 0.71$	$6.01 \pm 0.24 \pm 0.81$
$D^0 D^+$	$1.83 \pm 0.12 \pm 0.26$	$1.97 \pm 0.13 \pm 0.54$
$D^0 D^-$	$6.27 \pm 0.19 \pm 0.82$	$5.06 \pm 0.17 \pm 1.07$
$D^0 D_s^+$	$0.84 \pm 0.19 \pm 0.13$	$1.46 \pm 0.50 \pm 0.38$
$D^0 D_s^-$	$3.03 \pm 0.34 \pm 0.45$	$2.38 \pm 0.29 \pm 0.50$
$J/\psi D^0$	$0.21 \pm 0.02 \pm 0.02$	$0.22 \pm 0.02 \pm 0.03$
$D^0 D^0$ [42]	$3.62^{+5.92}_{-3.37}$	$2.93^{+4.72}_{-2.69}$
$D^0 \overline{D}^0$ [42]	$6.34^{+8.66}_{-4.79}$	$5.59^{+7.41}_{-3.79}$

Table 4: Total cross-sections (in mb) in pPb and Pbp data for full rapidity acceptance without any $p_{\rm T}(H_c)$ requirement. The first uncertainty is statistical and the second is systematic.

Pairs	$1.5 < y(H_c) < 4$	$-5 < y(H_c) < -2.5$
D^0D^0	$14.72 \pm 1.10 \pm 2.25$	$24.05 \pm 2.12 \pm 5.19$
$D^0\overline{D}^0$	$45.99 \pm 2.09 \pm 5.04$	$52.05 \pm 2.40 \pm 8.91$
$J/\psi D^0$	$0.51 \pm 0.12 \pm 0.05$	$0.82 \pm 0.13 \pm 0.14$

Table 5: Ratios of differential cross-sections in bins of charm hadron rapidity for charm $p_{\rm T}(H_c) > 2\,{\rm GeV}/c$. The average over all the pairs in each rapidity interval is also presented.

Pairs	$-4.7 < y(H_c) < -3.7$	$-3.7 < y(H_c) < -2.7$	$1.7 < y(H_c) < 2.7$	$2.7 < y(H_c) < 3.7$
$D^0D^0/D^0\overline{D}^0$	$0.286 \pm 0.067 \pm 0.011$	$0.363 \pm 0.040 \pm 0.009$	$0.305 \pm 0.041 \pm 0.009$	$0.335 \pm 0.060 \pm 0.012$
D^0D^+/D^0D^-	$0.239 \pm 0.046 \pm 0.017$	$0.387 \pm 0.047 \pm 0.026$	$0.259 \pm 0.045 \pm 0.010$	$0.256 \pm 0.037 \pm 0.009$
D^+D^+/D^+D^-	$0.300 \pm 0.090 \pm 0.037$	$0.518 \pm 0.157 \pm 0.079$	$0.332 \pm 0.070 \pm 0.018$	$0.266 \pm 0.061 \pm 0.012$
$D^0D_s^+/D^0D_s^-$	$0.321 \pm 0.260 \pm 0.043$	$0.504 \pm 0.172 \pm 0.028$	$0.201 \pm 0.096 \pm 0.006$	$0.303 \pm 0.139 \pm 0.014$
$D^+D_s^+/D^+D_s^-$	$0.291 \pm 0.590 \pm 0.080$	$0.582 \pm 0.340 \pm 0.113$	$0.143 \pm 0.116 \pm 0.009$	$0.234 \pm 0.113 \pm 0.013$
Average	$0.262 \pm 0.035 \pm 0.019$	$0.384 \pm 0.029 \pm 0.019$	$0.278 \pm 0.026 \pm 0.010$	$0.274 \pm 0.027 \pm 0.011$

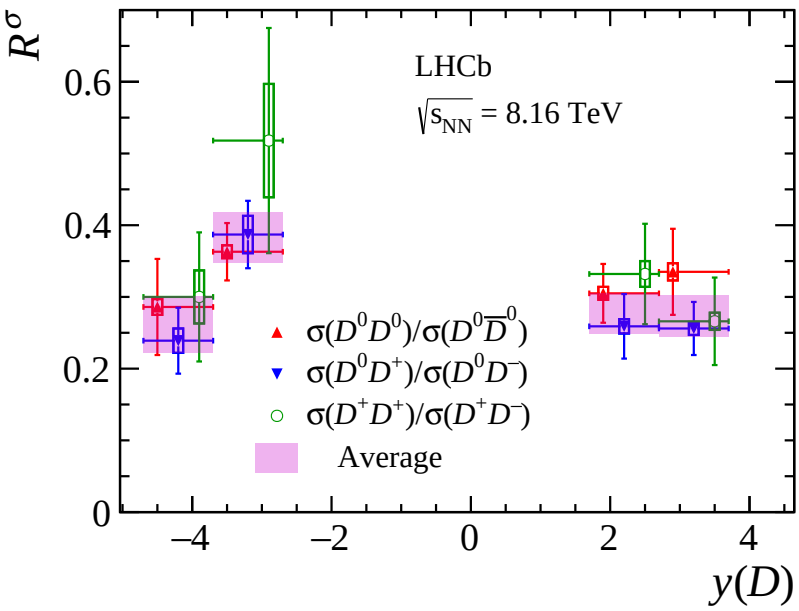

Figure 7: Ratios of differential cross-sections in bins of charm hadron rapidity under the $p_{\rm T}(D) > 2\,{\rm GeV}/c$ requirement. The average over all the pairs listed in Table 5 for each rapidity interval is also presented. The boxes (bars) correspond to systematic (statistical) uncertainties. Points are shifted horizontally to improve visibility.

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