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Studies of charm quark diffusion inside jets using PbPb and pp collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$

The CMS Collaboration*

Abstract

The first study of charm quark diffusion with respect to the jet axis in heavy ion collisions is presented. The measurement is performed using jets with $p_{\mathrm{T}}^{\mathrm{jet}} > 60\,\mathrm{GeV}/c$ and D^0 mesons with $p_{\mathrm{T}}^{\mathrm{D}} > 4\,\mathrm{GeV}/c$ in lead-lead (PbPb) and proton-proton (pp) collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$, recorded by the CMS detector at the LHC. The radial distribution of D^0 mesons with respect to the jet axis is sensitive to the production mechanisms of the meson, as well as to the energy loss and diffusion processes undergone by its parent parton inside the strongly interacting medium produced in PbPb collisions. When compared to Monte Carlo event generators, the radial distribution in pp collisions is found to be well-described by PYTHIA, while the slope of the distribution predicted by SHERPA is steeper than that of the data. In PbPb collisions, compared to the pp results, the D^0 meson distribution for $4 < p_{\mathrm{T}}^{\mathrm{D}} < 20\,\mathrm{GeV}/c$ hints at a larger distance on average with respect to the jet axis, reflecting a diffusion of charm quarks in the medium created in heavy ion collisions. At higher $p_{\mathrm{T}}^{\mathrm{D}}$, the PbPb and pp radial distributions are found to be similar.

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*See Appendix A for the list of collaboration members

The quark gluon plasma (QGP), the deconfined matter created in collisions of heavy ions accelerated to ultrarelativistic energies [1, 2], can be probed by studying the remnants of hard scatterings occurring in this medium. The outgoing partons (quarks and gluons), which produce final-state jets of particles, interact strongly with the QGP and lose energy [3–5], a phenomenon known as jet quenching, as has been observed at the BNL RHIC [6, 7] and the CERN LHC [8–10]. Jet quenching results in modifications of the energy and structure of jets observed in heavy-ion collisions, compared to proton-proton (pp) collisions, where it is assumed that a negligible amount, if any, of QGP is formed. These modifications can be related to the thermodynamical and transport properties of the medium via theoretical models [4, 5, 11–14]. One of the most striking features of jet quenching is the enhanced production of low transverse momentum hadrons ($p_\mathrm{T} \approx 2$–$5\,\mathrm{GeV}/c$) at large angles with respect to the final-state jet axis. This phenomenon manifests itself in the form of modifications of the jet fragmentation function [15–17], as well as the jet radial profile and the energy flow [18–21]. Interpretations of experimental results include medium-induced gluon radiation, modification of jet splitting functions, and medium response to the hard scattered partons [4, 5, 11, 13, 22]. Because the QGP temperature is not high enough to radiate the large mass quarks (i.e., charm and beauty quarks), these heavy quarks are produced early in the collision via hard parton scatterings and thus probe the full evolution of the QGP. Therefore, studying heavy flavor (HF) mesons in jets should give further insight into the origin of the observed modifications for light flavored particles [23].

In addition, measurements of the HF meson production inside jets can provide new information about HF jet fragmentation in both pp and lead-lead (PbPb) collisions. Moreover, measurements of angular correlations between HF mesons and jets can be used to constrain parton energy loss mechanisms and to measure heavy-quark diffusion inside the medium [23–27]. This is complementary information to that obtained with measurements of inclusive HF meson spectra [28–32], HF meson azimuthal anisotropy [32–36], and HF-tagged jets [37, 38].

In this Letter, the first measurements of the radial distributions of D^0 mesons in jets in heavy ion and pp collisions are presented. The D^0 mesons are measured via their hadronic decay channels $\mathrm{D}^0 \to \mathrm{K}^-\pi^+$ and $\overline{\mathrm{D}}^0 \to \mathrm{K}^+\pi^-$ with the CMS detector at the LHC. The observable is the normalized angular distribution of the D^0 meson with respect to the jet axis, defined as

$$\frac{1}{N_\mathrm{jD}}\frac{\mathrm{d}N_\mathrm{jD}}{\mathrm{d}r} = \frac{1}{N_\mathrm{jD}}\frac{1}{\Delta r}\frac{N_\mathrm{jD}\Big|_{\Delta r}}{(\alpha\,\epsilon)}, \tag{1}$$

where the distance from the jet axis, $r = \sqrt{(\Delta\phi_\mathrm{jD})^2 + (\Delta\eta_\mathrm{jD})^2}$, is defined as the quadratic sum of the differences in pseudorapidity ($\Delta\eta_\mathrm{jD}$) and azimuth ($\Delta\phi_\mathrm{jD}$) of the D^0 meson with respect to the jet axis, and Δr is the width of the r interval. The quantity $\alpha\,\epsilon$ represents the product of acceptance and efficiency, $N_\mathrm{jD}\Big|_{\Delta r}$ is the number of D^0 mesons in the Δr interval, and N_jD is the integral of the distribution in the r region from 0 to 0.3, the distance parameter used for the jet reconstruction.

The main feature of the CMS detector is a superconducting solenoid, providing a magnetic field of 3.8 T. Within the solenoid volume is a silicon pixel and strip tracker, which is used to detect charged particles, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Hadron forward calorimeters extend the coverage up to $|\eta| = 5.2$ and are used for collision event selection. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [39].

The pp (PbPb) data set used in this analysis corresponds to an integrated luminosity of 27.4 pb^{-1} (404 $\mu\mathrm{b}^{-1}$). High-p_{T} jet events were selected by a high-level trigger algorithms [40] with a $p_{\mathrm{T}}^{\mathrm{jet}}$ threshold of 60 GeV/c. For the offline analysis, events must pass a set of selection criteria designed to reject beam-gas collisions and beam scraping events, as described in Refs. [41, 42].

Several Monte Carlo (MC) simulated event samples are used to evaluate the background contributions, signal efficiencies, and detector acceptance corrections. The simulated events include both prompt (produced directly from the c quark fragmentation) and nonprompt (from b hadron decays) D^0 meson events. The pp collisions are generated using PYTHIA v.8.212 [43], tune CUETP8M1 [44]. The EVTGEN 1.3.0 [45] generator is used to simulate D^0 meson and b hadron decays, and final-state photon radiation in the D^0 meson decays is simulated with PHOTOS 2.0 [46]. For the PbPb MC samples, each PYTHIA event is embedded into a PbPb collision event generated with HYDJET 1.9 [47], which is tuned to reproduce global event properties, such as the underlying event (UE) p_{T} density, the charged-hadron p_{T} spectrum, and the particle multiplicity. The MC events are propagated through the CMS detector using the GEANT4 package [48].

The particle-flow (PF) algorithm [49] is used to reconstruct and identify each individual particle in a pp or PbPb event, with an optimized combination of information from the various elements of the CMS detector. To form jets, the PF particles are clustered using an anti-k_{T} algorithm provided by the FASTJET framework [50, 51] with a distance parameter of 0.3 chosen to minimize the effects of the UE fluctuations. In order to subtract the UE background in PbPb collisions [9, 52], an iterative algorithm [53] is employed. In pp collisions, where the UE level is negligible, jets are reconstructed without UE subtraction. The jet energy corrections are derived from simulation, separately for pp and PbPb data, and are confirmed via energy-balance methods applied to dijet, multijet, photon+jet, and leptonically decaying Z+jet events in pp data [54]. Jets with $|\eta^{\mathrm{jet}}| < 1.6$ and corrected $p_{\mathrm{T}}^{\mathrm{jet}} > 60\,\mathrm{GeV}/c$ are selected for this analysis. Simulation studies show that the jet selection efficiency and the energy resolution are well understood for this kinematic range.

The D^0 candidates are reconstructed by combining pairs of oppositely-charged particle tracks with an invariant mass within 0.2 GeV/c^2 of the world-average D^0 meson mass, 1.8 GeV/c^2 [55]. In order to suppress the combinatorial background, each track is required to have $p_{\mathrm{T}} > 2\,\mathrm{GeV}/c$, to be within $|\eta| < 2$, and pass a set of quality selections [41]. For each pair of selected tracks, two D^0 candidates are created by assuming that one of the particles has the mass of the pion while the other has the mass of the kaon, and vice-versa. The D^0 candidates are required to have rapidity $|y| < 2$ and $p_{\mathrm{T}}^{\mathrm{D}} > 4\,\mathrm{GeV}/c$. In order to further reduce the combinatorial background, the D^0 candidates are selected based on three topological criteria. The three-dimensional (3D) decay length (distance between the primary vertex and D^0 secondary vertex L_{3D}) normalized to its uncertainty is required to be larger than 2.34–4.00. The pointing angle θ_{p} (defined as the angle between the total momentum vector of the D^0 candidate and the vector connecting the primary and secondary vertices) is required to be smaller than 0.020–0.046 radians. In both cases (the 3D decay length and θ_{p}), the selection criteria depend on the $p_{\mathrm{T}}^{\mathrm{D}}$ and r bins, and are optimized separately for the pp and PbPb data. The higher values are found for the low-$p_{\mathrm{T}}^{\mathrm{D}}$ bin, with increasing or decreasing r values, for θ_{p} and the 3D decay length significance, respectively. Finally, the χ^2 probability of the secondary vertex fit is required to be larger than 5%. Two examples of D^0 candidate invariant mass distributions are shown in Fig. 1 for pp (left) and PbPb (right) collisions, for one r interval, $0.05 < r < 0.01$.

The measured D^0 radial distributions are presented in two $p_{\mathrm{T}}^{\mathrm{D}}$ bins, $4 < p_{\mathrm{T}}^{\mathrm{D}} < 20\,\mathrm{GeV}/c$ and $p_{\mathrm{T}}^{\mathrm{D}} > 20\,\mathrm{GeV}/c$, and four r bins, 0–0.05, 0.05–0.1, 0.1–0.3, and 0.3–0.5. The D^0 meson yield in

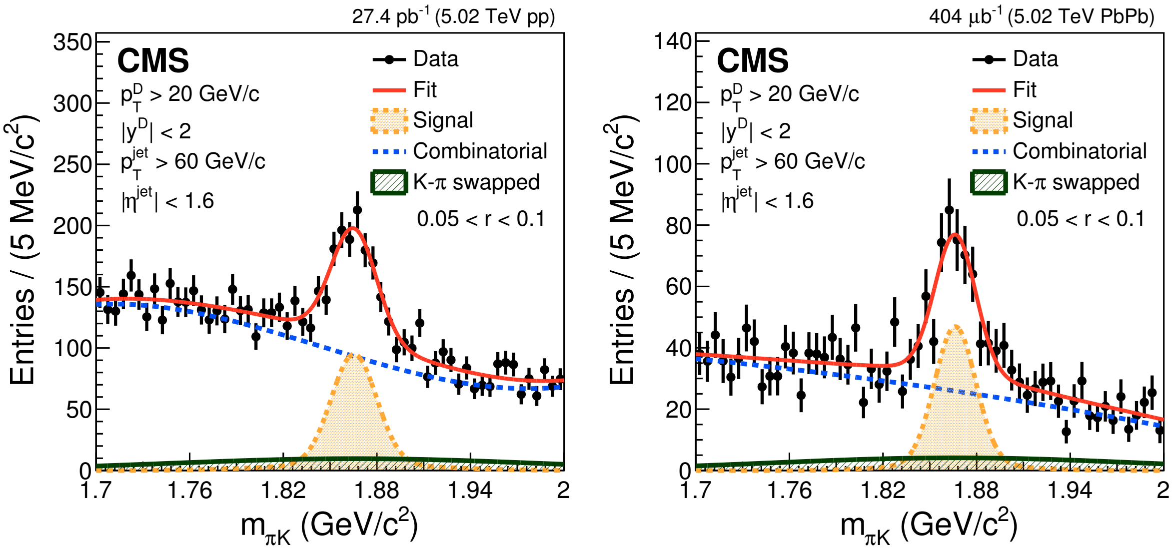

Figure 1: Examples of D^0 candidate invariant mass distributions in pp (left) and PbPb (right) collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

each p_T and r interval is extracted with a binned maximum likelihood fit to the invariant mass distributions in the range $1.7 < m_{\pi K} < 2.0\,\mathrm{GeV}/c^2$. The combinatorial background originating from random pairs of tracks not produced by a D^0 meson decay is modeled by a third-order polynomial. The signal shape is found to be best modeled over the entire p_T range by the sum of two Gaussian functions with the same mean but different widths. The two Gaussians are found to best capture the many contributions to the D^0 peak resolution from tracks with a highly η-dependent p_T resolution. An additional Gaussian function with a larger width is used to describe the invariant mass shape of D^0 candidates with an incorrect mass assignment from the exchange of the pion and kaon designations. Since the decay kinematics of the D^0 mesons are well understood, the widths of the Gaussian functions that describe the D^0 signal shape and the shape of the D^0 candidates with swapped mass assignments are fixed by simulation, after correcting for the difference in resolution between data and MC. The ratio between the numbers of the signal D^0 candidates and the ones with swapped mass assignments is fixed to the value extracted from simulation. No significant variation with r was observed for the shape of the combinatorial background, or in the mean and in the root-mean-square of the distributions of signal D^0 mesons or D^0 candidates with swapped mass.

The D^0 meson yields are corrected for detector acceptance, and for trigger, track reconstruction, and selection inefficiencies in bins of p_T^D and r. The correction factors are obtained from a PYTHIA (PYTHIA +HYDJET) MC sample for the pp (PbPb) analysis. There is also a background contribution from combining a D^0 meson with either a jet not coming from the same hard scattering or with a misreconstructed jet. This contribution is subtracted using an event mixing technique, in which the background is estimated by combining the distributions of D^0-jet pairs formed with i) jets from the signal event and D^0 mesons from minimum bias (MB) events [41], ii) jets from MB events with D^0 mesons from the signal event, and iii) jets and D^0 mesons from MB events. In this procedure, each signal event is mixed with a MB event, which has a similar primary vertex position, amount of energy deposited in the forward hadronic calorimeters, and event plane angle. The event plane angle is an experimental estimation of the reaction plane (defined by the beam direction, and the impact parameter vector between the two colliding nuclei) and it is determined using information from the two HF calorimeters [56]. The resulting background radial distributions, which are in all cases less than 10%, are then subtracted from the raw D^0 radial distributions measured in the signal event. Finally, the background-subtracted jet shape distribution is corrected for jet resolution effects using a bin-by-bin correction, which is obtained from a PYTHIA +HYDJET simulation.

Several sources of systematic uncertainty are considered for the D^0 meson yield extraction and the jet reconstruction, and are studied in bins of $p_{\mathrm{T}}^{\mathrm{D}}$ and r. The uncertainty in the raw yield extraction (2.6–5.4% for pp and 1.4–8.2% for PbPb data) is evaluated by repeating the fit procedure using different background and signal fit functions and by varying the widths of the Gaussian functions that describe the D^0 signal according to the differences between data and simulation. In the signal variation study, the sum of three Gaussian functions with the same mean but different widths is considered, while in the background variation study, a second-order polynomial function is used. This functional form gives a good description of the combinatorial background according to studies performed on same-sign pairs, which provide a pure combinatorial background with the same kinematic conditions. In these studies, the secondary vertex candidates are obtained by combining two same-sign tracks, which are assigned pion and kaon masses. The systematic uncertainty from the selection of the D^0 meson candidates (3.6 and 0.5% for the low- and high-$p_{\mathrm{T}}^{\mathrm{D}}$ bin, respectively, for pp, and 3.5 and 2.7% for PbPb data) is estimated by considering the differences between simulation and data when applying each of the D^0 candidate selection variables. The study is performed by varying one selection at a time in a range that allows a robust procedure for signal extraction and by considering the maximum relative discrepancies in the yield between data and simulation. The total uncertainty is the quadratic sum of the maximum relative discrepancy obtained by varying each of the three topological selection variables separately.

The systematic uncertainties for the jets include components for the uncertainty in the jet energy scale (JES) and jet energy resolution (JER). The systematic uncertainty pertaining to the JES is estimated by varying the $p_{\mathrm{T}}^{\mathrm{jet}}$ by 2.8% (in both pp and PbPb data), which represents the sum in quadrature of the observed data-to-simulation differences (2%) and the nonclosure (i.e., deviation from unity) in simulation, when comparing reconstructed (detector-level) versus truth (generator-level) jets smeared by the known detector and reconstruction effects. An additional uncertainty 1.8–42% for PbPb data is added to account for the different detector response to quark versus gluon jets. The largest variation is observed at high $p_{\mathrm{T}}^{\mathrm{D}}$ and largest r value, a region influenced by the small sample size. The assigned uncertainty represents the maximum difference from the nominal results when applying JES corrections obtained with a pure-gluon sample or a pure-quark sample.

The systematic uncertainty due to the JER in PbPb collisions is estimated by varying the $p_{\mathrm{T}}^{\mathrm{jet}}$ energy resolution by 15% to account for an imperfect description of the fluctuations of the UE in the MC simulation. The variation considered is estimated by studying the effects of these fluctuations using two different methods: the random-cone technique [54, 57] and the embedding procedure. The random cone method consists of reconstructing many jets in a zero bias event, clustering particles in randomly placed cones in the entire (η, ϕ) space. When the method is applied in events with negligible contribution from hard scatterings, as is the case for zero bias events, the standard deviation of the distribution of $p_{\mathrm{T}}^{\mathrm{jet}}$ obtained with this procedure can be used to estimate the magnitude of the UE fluctuations. The relative variations in the D^0 spectra are 0.3–3.0% in pp and 0.6–5.6% in PbPb collisions. The systematic uncertainties from the trigger efficiency correction are estimated by the difference between the result with no correction and the nominal result, which are 0.3–2.7% in pp and 0.7–15% in PbPb data. Finally, a remaining nonclosure observed in MC between generated and reconstructed distributions of D^0 mesons in jets, is corrected bin-by-bin. The magnitude of the correction is quoted as the systematic uncertainty in the resolution unfolding, which varies in the range 1.3–31% in pp and 0.7–32% in PbPb data.

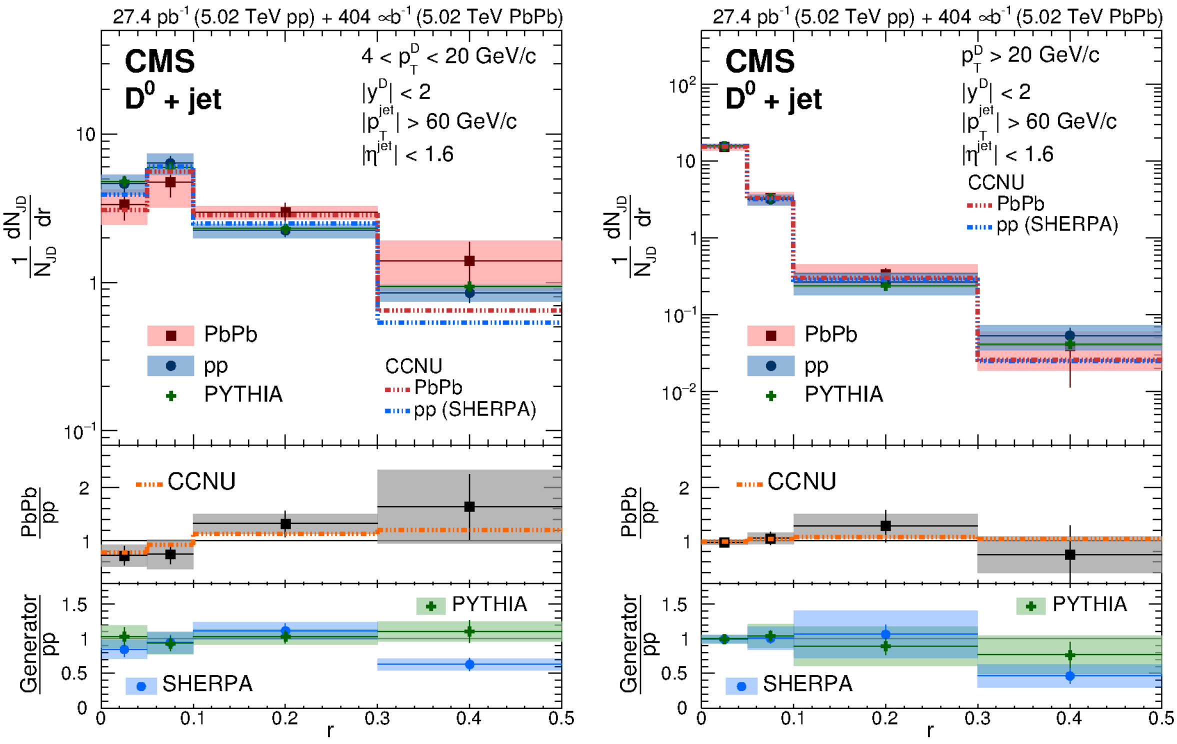

Figure 2: Distributions of $\mathrm{D^0}$ mesons in jets, as a function of the distance from the jet axis (r) for jets of $p_{\mathrm{T}}^{\text{jet}} > 60\,\mathrm{GeV}/c$ and $|\eta^{\text{jet}}| < 1.6$ measured in pp and PbPb collisions at $\sqrt{s_{_{\mathrm{NN}}}} = 5.02\,\mathrm{TeV}$. The measurement is performed in the $p_{\mathrm{T}}^{\mathrm{D}}$ range 4–20 GeV/c (left) and $p_{\mathrm{T}}^{\mathrm{D}} > 20\,\mathrm{GeV}/c$ (right). Each spectrum is normalized to its integral in the region $0 < r < 0.3$. The vertical bars (boxes) correspond to statistical (systematic) uncertainties. The PbPb spectra are compared to the CCNU energy loss model [23], while the pp spectra are compared with predictions from the PYTHIA and SHERPA pp MC event generators. The ratios of the $\mathrm{D^0}$ meson radial distributions in PbPb and pp data are shown in the middle panels. In the bottom panels the ratios of the $\mathrm{D^0}$ meson radial distributions of pp over the two MC event generators are presented.

The top panels of Fig. 2 show the measured $\mathrm{D^0}$ meson radial distributions in pp and PbPb collisions, for two $\mathrm{D^0}$ mesons p_{T} intervals: a low-p_{T} interval $4 < p_{\mathrm{T}}^{\mathrm{D}} < 20\,\mathrm{GeV}/c$, and a high-$p_{\mathrm{T}}$ one, $p_{\mathrm{T}}^{\mathrm{D}} > 20\,\mathrm{GeV}/c$. The calculated $\langle r \rangle$ for the PbPb (pp) distributions is 0.205 ± 0.016 (0.162 ± 0.007) and 0.049 ± 0.003 (0.046 ± 0.001), for the low- and high-$p_{\mathrm{T}}^{\mathrm{D}}$ intervals, respectively, where the quoted uncertainties are statistical. This result indicates that $\mathrm{D^0}$ mesons at low p_{T} are farther away from the jet axis in PbPb compared to pp collisions. At high $p_{\mathrm{T}}^{\mathrm{D}}$, the measured spectra in pp and PbPb collisions fall rapidly, at a similar rate, as a function of r, similarly to what was observed in inclusive jet-hadron correlation functions [20].

The pp results are compared to calculations from two pp MC event generators: PYTHIA [43], a leading-order event generator, and SHERPA [58], which computes the next-to-leading QCD matrix elements matched to parton shower to generate the charm-jet events [23]. For low-p_{T} $\mathrm{D^0}$ mesons, the measured spectrum in pp collisions reaches a maximum at $0.05 < r < 0.1$, consistent with both PYTHIA and SHERPA [23]. In the $r > 0.3$ region however, PYTHIA captures the features of the data better than SHERPA, which underpredicts the pp spectrum, in both $p_{\mathrm{T}}^{\mathrm{D}}$ intervals. The PbPb spectra is compared to an energy-loss model, CCNU [23], which uses SHERPA for simulating the pp baseline. The CCNU calculation includes in-medium elastic (collisional) and inelastic (radiative) interactions for both the heavy and the light quarks. This model, which predicts a small depletion (increase) of the D^0 meson yield at small (large) r compared to pp collisions, is consistent with data within the statistical and systematical uncertainties.

To measure the medium modification of the radial profile, the ratio of PbPb to pp spectra is also presented in the first sub-panel of Fig. 2. In this ratio, the uncertainties from JES, JER and D^0 candidate selections are considered uncorrelated between pp and PbPb datasets, and are not cancelled in the ratio. The uncertainties from the modeling of the signal shape, as well as the nonclosures observed, are partially cancelled: the systematic uncertainties are re-estimated directly on the ratio of the PbPb to pp yields. The ratio increases slightly as a function of r at low $p_{\mathrm{T}}^{\mathrm{D}}$, corresponding to a small shift of the D^0 mesons to larger radii in PbPb, while the ratio is consistent with unity within the uncertainties at high $p_{\mathrm{T}}^{\mathrm{D}}$. This shows that the modification of the radial profile of high $p_{\mathrm{T}}^{\mathrm{D}}$ is small. These features of the ratios at low and high $p_{\mathrm{T}}^{\mathrm{D}}$ are qualitatively different from inclusive charged particle radial distributions with respect to the jet axis measured in similar transverse momentum ranges [20]. The inclusive measurements show a ratio significantly smaller than one, corresponding to a shift of the light quark mesons to smaller radii in PbPb, for all tracks with $p_{\mathrm{T}} > 4\,\mathrm{GeV}/c$ measured in jets with $p_{\mathrm{T}}^{\mathrm{jet}} > 120\,\mathrm{GeV}$, for $r > 0.1$ and more central PbPb collisions. The CCNU model gives a good description of the ratio of PbPb to pp spectra. Although this ratio is less sensitive to the choice of pp reference spectra, the pp measurements presented in this paper could improve the description of the pp baseline, and hence future calculations in PbPb collisions.

In summary, this Letter presents the first measurement of the radial distributions of D^0 mesons with respect to the jet axis in lead-lead (PbPb) and proton-proton (pp) collisions, performed with the CMS detector using jets with transverse momentum $p_{\mathrm{T}}^{\mathrm{jet}} > 60\,\mathrm{GeV}/c$ and D^0 mesons with $p_{\mathrm{T}}^{\mathrm{D}} > 4\,\mathrm{GeV}/c$. When compared to Monte Carlo event generators, the radial distribution in pp collisions is found to be well-described by PYTHIA, while the slope of the distribution predicted by SHERPA is steeper than that of the data. The modification of the D^0 meson radial distributions in PbPb collisions are studied by comparing them to those from pp collisions. The comparisons hint at a modification of the D^0 meson radial profile in PbPb collisions at low $p_{\mathrm{T}}^{\mathrm{D}}$ that vanishes at higher $p_{\mathrm{T}}^{\mathrm{D}}$. The results show that this modification is different from that of the light flavor hadrons. The low $p_{\mathrm{T}}^{\mathrm{D}}$ result is indicative of charm quark diffusion in the medium created in heavy ion collisions. This measurement provides new experimental constraints on the mechanisms of heavy-flavor production in pp collisions, as well as on the processes of parton energy loss and diffusion of heavy quarks inside the quark-gluon plasma.

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