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Study of J/ψ meson production from jet fragmentation in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$

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Abstract

A study of the production of prompt J/ψ mesons as fragmentation products of jets in proton-proton collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ is presented. The analysis is based on data corresponding to an integrated luminosity of $19.1\,\mathrm{fb}^{-1}$ collected with the CMS detector at the LHC. For events with at least one observed jet, the angular separation between the J/ψ meson and the jet is used to test whether the J/ψ meson is a jet fragment. The analysis shows that most prompt J/ψ mesons with energy above 15 GeV and rapidity $|y| < 1$ are fragments of jets with pseudorapidity $|\eta_{\mathrm{jet}}| < 1$. The differential distributions of the jet fragmentation probability as a function of jet energy for a fixed J/ψ energy fraction are compared to a theoretical model using the fragmenting jet function approach. The data agree best with fragmenting jet function calculations that use a long-distance matrix element parameter set in which prompt J/ψ mesons are unpolarized. This technique demonstrates a new way to test predictions for prompt J/ψ production using nonrelativistic quantum chromodynamics.

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*See Appendix A for the list of collaboration members

1 Introduction

The mechanism for producing J/ψ mesons as bound states of charm quark pairs ($\mathrm{c\overline{c}}$) in hadronic collisions has been under intensive experimental and theoretical study since the 1974 discovery of the J/ψ meson in proton-nucleon collisions [1] and $\mathrm{e^+e^-}$ annihilations [2]. The initial approach, using the color-singlet model [3, 4], assumed that at large transverse momentum the parent gluon was effectively massless and would produce a fully polarized J/ψ meson. The model predicts that for prompt J/ψ production, i.e., events in which the J/ψ meson is consistent with originating from the primary vertex, the differential cross section as a function of the J/ψ transverse momentum $p_\mathrm{T}^{\mathrm{J}/\psi}$ is an order of magnitude smaller than found in measurements at the Fermilab Tevatron [5]. Subsequent polarization measurements [6, 7] have shown that the prompt J/ψ meson polarization at large $p_\mathrm{T}^{\mathrm{J}/\psi}$ (>12 GeV) is small.

The theoretical problem is to determine the mechanism by which a $\mathrm{c\overline{c}}$ system in an angular momentum state and quark color configuration ${}^{2S+1}L_J^n$ hadronizes into a J/ψ meson. Here, S, L, and J are the spin, orbital, and total angular momentum quantum numbers of the $\mathrm{c\overline{c}}$ system. Its color state is labeled by n, with $n = 1$ or 8 referring to a color-singlet or color-octet configuration, respectively. Nonrelativistic quantum chromodynamics (NRQCD), an approach that includes both color-singlet and color-octet amplitudes, has a set of parameters called long-distance matrix elements (LDME) that can be adjusted to describe J/ψ meson production data [8, 9]. The LDME parameters are process independent. However, each NRQCD calculation uses a specific collection of J/ψ meson production data and J/ψ meson kinematic requirements to produce its own LDME set. Furthermore, the LDME sets do not uniquely predict the J/ψ meson production polarization, because several ${}^{2S+1}L_J^n$ combinations can possibly contribute to J/ψ meson production.

The analysis described in this Letter combines the measurement of jet fragmentation into J/ψ mesons with a theoretical approach based on the fragmenting jet function (FJF) model [10]. The FJF model postulates that the $\mathrm{c\overline{c}}$ pair is not produced directly in the hard scattering, but is a fragmentation product of a high-p_T jet. The model uses the methodology of NRQCD at next-to-leading order to compute the cross section contributions for all relevant ${}^{2S+1}L_J^n$ terms. Each cross section term has a characteristic relation between the jet energy E_jet and the fraction of jet energy carried by the J/ψ meson: $z = E_{\mathrm{J}/\psi}/E_\text{jet}$. By measuring J/$\psi$ mesons produced as fragments of jets, one can look for evidence that a single FJF cross section term dominates the fragmentation process and hence identify the quantum numbers of the $\mathrm{c\overline{c}}$ state.

A study of jet fragmentation to J/ψ mesons in the rapidity region $y_{\mathrm{J}/\psi} > 2$, dominated by charm fragmentation, has been reported by the LHCb Collaboration [11]. The LHCb analysis, which measured the z distribution integrated over jet energy, does not have the sensitivity to individual FJF terms and LDME parameter sets that characterizes this analysis.

The data for this analysis were collected by the CMS detector in proton-proton (pp) collisions from the CERN LHC, corresponding to an integrated luminosity of 19.1 fb^{-1} at $\sqrt{s} = 8\,\mathrm{TeV}$. It is the first experimental study of jet fragmentation to prompt J/ψ mesons in the gluon-dominated central region, where the FJF theory for gluonic jet fragmentation applies. The analysis offers the possibility of resolving both the production and polarization questions by isolating the specific S, L, J, and n configuration that describes J/ψ meson production by jet fragmentation.

2 Theoretical framework

The hadronization process is nonperturbative. It is handled in the FJF approach by an NRQCD expansion of the fragmentation function for a jet initially produced in a hard scattering at a high energy. The observables are E_{jet} and z. Following Ref. [10], the differential cross section for dijet production, with one jet fragmenting to a J/ψ meson, can be written symbolically as

$$\frac{\mathrm{d}^2\sigma(E_{\text{jet}};z)}{\mathrm{d}E_{\text{jet}}\,\mathrm{d}z} = \sum_{A,B,i,j} f_{A/p}\, f_{B/p}\, \mathrm{d}\sigma_{ABij}(\mathrm{c\overline{c}}X, n, \mathcal{J}_j) \otimes \mathcal{F}_S \otimes \mathcal{G}_i^{\mathrm{J}/\psi}(E_{\text{jet}}, z|R,\mu). \tag{1}$$

In this expression, A and B are the partons in the colliding protons with fractional flavor content $f_{A/p}, f_{B/p}$, respectively, while i and j are the outgoing partons. At the perturbative scale, the collision is point-like. The symbolic hard-scattering cross section $\mathrm{d}\sigma_{ABij}(c\overline{c}X, n, \mathcal{J}_j)$ produces the fragmenting jet from outgoing parton i and the recoil jet $\mathcal{J}_j$ from outgoing parton j. The recoil jet properties are integrated out. The fragmenting jet produces a $\mathrm{c\overline{c}}$ system characterized by S, L, J, and n, plus an inclusive hadronic state X that forms the remainder of the jet. The function $\mathcal{F}_S$ controls the evolution of the fragmenting system down to the energy scale $\mu = m_{\mathrm{c\overline{c}}}$, to allow the development of jet structure from soft gluons. The nonperturbative fragmentation of the $\mathrm{c\overline{c}}$ system into the observed J/ψ meson is described by the function $\mathcal{G}_i^{\mathrm{J}/\psi}(E_{\text{jet}}, z|R,\mu)$, where the jet energy E_{jet} is determined in a cone of angular radius R.

The type of parton i that produces the fragmenting jet, and ultimately the J/ψ meson, depends on the jet rapidity region. In the central rapidity region covered by this analysis, gluon fragmentation dominates [12]. The FJF expression for $\mathcal{G}_i^{\mathrm{J}/\psi}$ sums over all contributing partons, but the light flavors make negligible contributions. In Ref. [10], the small central charm quark fragmentation contribution was mixed into the ${}^3S_1^1$ contribution to gluon fragmentation, so $\mathcal{G}^{\mathrm{J}/\psi}$ in this Letter represents only gluon fragmentation.

In Ref. [13], the authors updated the work of Ref. [10] to make an explicit computation of the perturbative dijet double-differential cross section, followed by the fragmentation of one of the jets to a J/ψ meson. They integrated over the kinematic variables of the second jet to give an FJF expression for the absolute differential cross section to produce a jet of energy E_{jet} that fragments into a J/ψ carrying energy fraction z of the parent jet energy along with the remaining fragments. In the NRQCD decomposition of $\mathcal{G}^{\mathrm{J}/\psi}$ for high-energy central J/ψ hadroproduction, four FJF terms are important: ${}^3S_1^1$, ${}^1S_0^8$, ${}^3S_1^8$, and ${}^3P_J^8$. Only the ${}^1S_0^8$ term has all angular momenta zero in the $\mathrm{c\overline{c}}$ rest frame. If this NRQCD term were to dominate the jet fragmentation process, then the J/ψ meson would be produced unpolarized. Thus, this analysis has the potential to explain why the measured polarization of prompt J/ψ mesons is small at large $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ [6, 7].

3 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. When combining information from the entire detector, the jet energy resolution amounts typically to 15% at 10 GeV and 8% at 100 GeV [14]. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid, covering the pseudorapidity range $|\eta| < 2.4$. The silicon tracker measures charged particles within the pseudorapidity range $|\eta| < 2.5$. It consists of 1 440 silicon pixel and 15 148 silicon strip detector modules. For nonisolated particles of $1 < p_{\mathrm{T}} < 10\,\text{GeV}$ and $|\eta| < 1.4$, the track resolutions are typically 1.5% in p_{T} and

25–90 (45–150) μm in the transverse (longitudinal) impact parameter [15]. Matching muons to tracks measured in the silicon tracker results in a relative transverse momentum resolution, for muons with $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$, of 1.3–2.0% in the barrel [16]. Events of interest are selected using a two-tiered trigger system [17]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed time interval of less than 4 μs. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing. This reduces the event rate to around 1 kHz before data storage. 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. [18].

4 Event selection and background subtraction

The experimental methods follow those used by CMS analyses of inclusive J/ψ and $\Upsilon(nS)$ production at $\sqrt{s} = 7\,\mathrm{TeV}$ [19–23]. The event selection is based on a dimuon trigger involving the silicon tracker and muon systems. The trigger for J/ψ studies requires two oppositely charged muons with dimuon rapidity $|y| < 1.25$ and invariant mass range $2.7 < m_{\mu\mu} < 3.5\,\mathrm{GeV}$. The three-dimensional fit to the dimuon vertex must have a χ^2 probability (the p-value of the χ^2 returned by the fit) >0.5%. Only dimuon pairs in which the muons bend away from each other in the magnetic field are used to allow a precise dimuon efficiency determination. The dimuon trigger p_{T} threshold varied from 5 to 9 GeV during the data-taking period. The primary event vertex is defined as the one with the largest summed p_{T} of its associated tracks. All online trigger requirements were rechecked using the offline muon parameters during the offline event sample selection.

The offline selection requires a dimuon pair with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, $|y| < 1$, energy $E > 15\,\mathrm{GeV}$, and vertex fit χ^2 probability >1%. In order to guarantee agreement to within 3% between data-driven and simulated single-muon efficiencies, each muon must have $p_{\mathrm{T}}^{\mu} > 6\,\mathrm{GeV}$ and $|\eta_{\mu}| < 2.1$, or $p_{\mathrm{T}}^{\mu} > 5\,\mathrm{GeV}$ and $|\eta_{\mu}| < 0.8$. The muon candidate must satisfy the CMS “tight” muon quality requirements on the number of tracker hits, the muon track fit quality, and the distance along the beam line from the primary event vertex [16]. No muon isolation requirements are applied, because we look for J/ψ + jet associations. The J/ψ signal invariant mass range is $2.95 < m_{\mu\mu} < 3.20\,\mathrm{GeV}$. After the data selection, we observe at most one J/ψ candidate per event.

The trigger does not use any information about jets in the event. Jets are reconstructed from particle-flow objects [24], using an anti-k_{T} algorithm with distance parameter of 0.5 [25], as implemented in the FASTJET package [26]. The jet response has been corrected to the particle level [14]. Although the J/ψ candidate is not a particle-flow object, its decay muons are. This does not exclude jets that consist only of a J/ψ meson. However, such jets constitute <0.01% of this sample. The jet properties include the energy E_{jet}, the transverse momentum magnitude $p_{\mathrm{T}}^{\mathrm{jet}}$, the number of constituents, and the number of included muons. Each bunch crossing in the data produces, on average, 14 reconstructed pp vertices, corresponding to 21 extra interactions per bunch crossing. The extra interactions produce so-called pileup distortions, which are corrected using the procedure described in Ref. [14]. For this analysis, the jet selection requirements are $p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV}$ and $|\eta_{\mathrm{jet}}| < 1$.

The J/ψ event candidates are classified as prompt, nonprompt, or combinatorial. Nonprompt events include those J/ψ mesons that come from decays of B hadrons. Combinatorial events are accidental pairings of an identified μ^+ and a μ^- such that the dimuon invariant mass falls within the signal mass interval. The nonprompt background is strongly reduced by applying a selection on the variable Σ_{TD}, which is the sum of the squares of the significance (in units of standard deviations) of the transverse distance of closest approach of each muon track to the primary vertex. The Σ_{TD} distribution has a sharp peak near zero from prompt events and a long tail at larger Σ_{TD} from nonprompt sources, which we fit with an exponential function. From a prompt J/ψ Monte Carlo (MC) sample, we find that >99% of the events have $\Sigma_{\mathrm{TD}} < 10$. The simulated Σ_{TD} shape agrees with that of the data in this region, so we require $\Sigma_{\mathrm{TD}} < 10$ to define the prompt dimuon events. In the J/ψ data, the exponential function that describes the nonprompt background is extrapolated into the range $\Sigma_{TD} < 10$ to estimate the fraction of nonprompt events in the prompt signal mass range. This is (5.7 ± 0.1)%. The events in the prompt signal mass range also contain combinatorial background, which is determined by interpolating the $m_{\mu\mu}$ low (2.70–2.90 GeV) and high (3.25–3.50 GeV) sideband regions. We find that the combinatorial background fraction in the prompt signal mass range is (1.4 ± 0.2)%. The quoted uncertainties in the backgrounds are statistical only. All distributions shown in this Letter have had the nonprompt and combinatorial backgrounds subtracted. After background subtraction, there are 1.63×10^6 prompt J/ψ meson candidates.

5 Experimental application of the FJF approach

The authors of Refs. [10, 13] emphasize that experimental sensitivity to the FJF terms in jet fragmentation comes from measuring the jet energy dependence of the function $\mathcal{G}$ in Eq. (1) at fixed z. In the FJF framework, the dependence of the fragmenting jet differential cross section on the J/ψ properties comes solely through the z variable. Integrating Eq. (1) over z gives the single-jet differential cross section as a function of E_{jet}, used as a normalization term in Ref. [13]. Their computation of the differential cross section for a jet to fragment to a J/ψ meson with the energy fraction z was made for jets having $p_{\mathrm{T}}^{\text{jet}} > 25\,\text{GeV}$ and pseudorapidity $|\eta_{\text{jet}}| < 1.2$. The resulting J/$\psi$ meson was required to have energy above 15 GeV and rapidity $|y_{\mathrm{J}/\psi}| < 1$. The jet fragmentation cross section was normalized by integrating over the z range 0.3–0.8. The authors showed that the jet energy dependence of the normalized FJF terms is insensitive to the exact z range used. At a fixed z value, called z_1, the ratio of the fragmenting jet differential cross section due to a single FJF term i to the sum of the cross section integrals for $0.3 < z < 0.8$ for all FJF terms is termed $(\mathrm{d}\tilde{\sigma}_i/\mathrm{d}E_{\text{jet}}\,\mathrm{d}z)|_{z_1}$ in Ref. [13]. The sum of this ratio over all four FJF terms is denoted as $(\mathrm{d}\tilde{\sigma}/\mathrm{d}E_{\text{jet}}\,\mathrm{d}z)|_{z_1}$. For a given LDME parameter set, each of the four FJF terms is different. Also, changing the LDME parameter set changes the FJF predictions for the four terms.

The experimental proxy for $(\mathrm{d}\tilde{\sigma}/\mathrm{d}E_{\text{jet}}\,\mathrm{d}z)|_{z_1}$, evaluated for a jet energy bin centered at E_{c}, is called $\Xi(E_{\mathrm{c}};z_1)$:

$$\Xi(E_{\mathrm{c}};z_1) \equiv \frac{N(E_{\mathrm{c}};z_1)}{\int_{0.3}^{0.8} N(E_{\mathrm{c}};z)\,\mathrm{d}z}, \tag{2}$$

where $N(E_{\mathrm{c}};z_1)$ is the number of events in a z interval Δ_z in that E_{jet} bin, after correcting for jet efficiency and jet energy resolution, as described in Section 8. We use a z interval $\Delta_z = \pm\,0.025$ around z_1, which is small enough to be insensitive to z variations in Ξ and large enough to provide a reasonable number of events in each E_{jet} bin. If a single FJF term i dominates $(\mathrm{d}\tilde{\sigma}/\mathrm{d}E\,\mathrm{d}z)|_{z_1}$, the jet energy dependence of the measured $\Xi(E_{\mathrm{c}};z_1)$ will match that of $(\mathrm{d}\tilde{\sigma}_i/\mathrm{d}E\,\mathrm{d}z)|_{z_1}$. Thus, this analysis has the possibility to discriminate between different FJF terms for a given LDME parameter set and between different LDME parameter sets. If multiple FJF terms contribute, the jet energy dependence of the data is unlikely to agree with the prediction for any single FJF term.

6 Jet fragmentation to J/ψ mesons

The analysis makes no restriction on the number of jets that pass the jet selection requirements, which we term "observed jets". For $p_{\mathrm{T}}^{\text{jet}} > 25\,\mathrm{GeV}$, the fractions of J/$\psi$ meson events that have 0, 1, 2, or 3 observed jets are $(55.12 \pm 0.06)\%$, $(34.03 \pm 0.05)\%$, $(9.58 \pm 0.02)\%$, and $(1.27 \pm 0.08)\%$, respectively, where the uncertainties are statistical only. For events with at least one observed jet, the association of a J/ψ meson with a jet is made using the angular separation $\Delta R = \sqrt{(\eta_{\text{jet}} - \eta_{\mu\mu})^2 + (\phi_{\text{jet}} - \phi_{\mu\mu})^2}$. Here, η_{jet} ($\eta_{\mu\mu}$) and ϕ_{jet} ($\phi_{\mu\mu}$) are the pseudorapidity and azimuthal angle (modulo π), respectively, of the jet ($\mu\mu$) direction. The ΔR distribution for the best matched jet is sharply peaked at zero, as seen for events with one observed jet in Fig. 1 (left). The J/ψ meson and the jet are defined as associated if $\Delta R < 0.5$. Furthermore, if both decay muons from the J/ψ meson are constituents of the jet, we say that the J/ψ meson is a fragmentation product of the jet. We find that $(84.0 \pm 0.1)\%$ of the J/ψ mesons in the one-jet sample arise from jet fragmentation. No jet that has $\Delta R < 0.5$ with respect to the J/ψ meson fails to have both muons included in the jet constituents.

When there are two observed jets in the event, further evidence that J/ψ meson production comes primarily from jet fragmentation is shown in Fig. 1 (right). This plot shows ΔR for the J/ψ meson with respect to each jet in two-jet events. The higher-energy jet has ΔR_1, the lower-energy one ΔR_2. The J/ψ meson is not required to come from either jet. The clusters of events in Fig. 1 (right), near $(\Delta R_1, \Delta R_2) = (0, \pi)$ and $(\pi, 0)$, show that $(94.1 \pm 0.1)\%$ of the time, the J/ψ meson is associated with one of the two jets in the event. In events with a J/ψ meson and two jets, the mean and RMS deviation of the distribution of the number of jet constituents, charged and neutral, for the fragmenting jet (25 ± 8) and the recoil jet (29 ± 8) are similar. The difference in the probability for a jet to fragment into a J/ψ meson in the one- and two-jet cases, along with a discussion of the small excess for $2.4 < \Delta R < 3.5$ in Fig. 1 (left), will be addressed in Section 12.

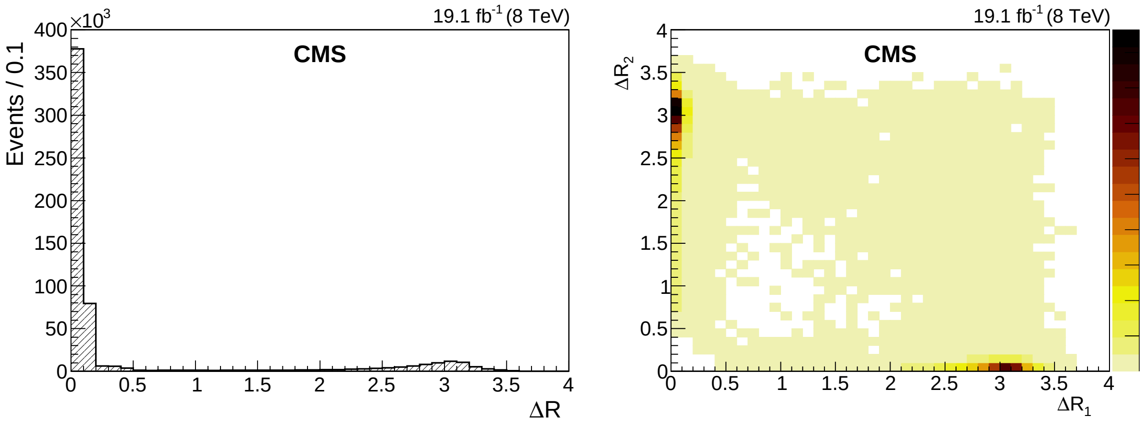

Figure 1: The distributions of (left) ΔR for one-jet events and (right) ΔR_1 vs. ΔR_2 for two-jet events

7 Efficiency corrections

Measuring J/ψ + jet fragmentation properties requires an event-by-event J/ψ meson efficiency correction. Each entry in the signal or background event distributions has an event weight, defined as $1/\epsilon_{\mathrm{J}/\psi}$. The dimuon acceptance times efficiency $\epsilon_{\mathrm{J}/\psi}$ is determined using a simulated sample of unpolarized J/ψ meson events, uniformly distributed in 1 GeV wide p_{T} bins and uniformly distributed over $|y_{\mathrm{J}/\psi}| < 1.5$. Only the J/$\psi$ meson is simulated; studies [22, 23] show that using a complete PYTHIA event simulation does not change the efficiency results. The J/$\psi \to \mu^+\mu^-$ decay is simulated using EVTGEN [27]; radiative effects are treated by PHOTOS [28]; and the detector response to the two muons is simulated using the GEANT4-based [29] CMS simulation program. The simulated J/ψ meson must pass the quality requirements listed in Section 4. The total efficiency $\epsilon_{\mathrm{J}/\psi}$ varies with the rapidity and transverse momentum of the J/ψ meson because the muon reconstruction, dimuon vertex reconstruction, and dimuon trigger efficiencies depend on these variables. The efficiencies are taken from the simulations. There is also an HLT trigger inefficiency if two muons in the event have a small angular separation. This is taken from simulation and checked against data taken using a single-muon trigger.

8 Jet energy corrections and unfolding

A crucial part of the analysis is measuring the energy of the fragmenting jet. To test whether there might be an influence on jet energy due to fragmentation to a J/ψ meson, we study the two-jet events shown in Fig. 1 (right). The energy distributions of the fragmenting jet and the recoil jet are compared for $0.3 < z < 0.8$ and for z ranges of 0.40–0.45, 0.50–0.55, and 0.60–0.70. The shapes of the measured energy distributions of the recoil and fragmenting jets for each sample are indistinguishable. There is no evidence that the fragmentation process affects the jet energy.

The fragmenting jet data are compared to the FJF model predictions in bins of jet energy. Experimentally, the jet energy bin width ΔE_{jet} is constrained by the finite jet energy resolution of the CMS apparatus, which must be unfolded. We use $\Delta E_{\mathrm{jet}} = 8\,\mathrm{GeV}$. The D'Agostini unfolding method from the ROOUNFOLD package [30] is used to extract the unsmeared Ξ distribution. The unfolding procedure uses the CMS jet energy resolution and jet finding efficiency [24]. Simulation shows that for measured jet energy $E_{\mathrm{jet}} > 44\,\mathrm{GeV}$, the jet reconstruction efficiency exceeds 98.5% and is consistent with being energy independent. Thus, 44 GeV is the lowest jet energy considered in the unfolding procedure. The procedure was validated on simulated jet energy test distributions. Based on the unfolding studies in simulation, we use four unfolding iterations and an unfolded jet energy range of $56 < E_{\mathrm{jet}} < 120\,\mathrm{GeV}$. Henceforth, E_{jet} will refer to the unfolded quantity, unless otherwise noted.

The unfolded jet energy distributions for the $\Xi(E; z)$ functions have bin-to-bin correlations. These are evaluated by repeating the unfolding procedure 250 times, forming the covariance matrix, and determining the uncertainty in each jet energy bin. The uncertainties computed by this procedure are 0.02 to 0.06%. The unfolding in z is dominated by the E_{jet} resolution. The changes in z from the unfolding procedure for the region of interest (0.40–0.65) are less than 0.01 in z. Therefore, the measured z values are used in the $\Xi(E_{\mathrm{jet}}; z)$ determinations.

9 Systematic uncertainties

The systematic uncertainties arise from the determination of the event weight, based on the J/ψ meson and the muon properties, and from a bias in the J/ψ-jet association, discussed below. The systematic uncertainty in the jet energy scale is small compared to the jet energy resolution used in the unfolding. Varying the jet energy by the jet energy scale systematic uncertainty before the unfolding made no change in the Ξ results.

The CMS studies at $\sqrt{s} = 8\,\text{TeV}$ using a tag-and-probe method [19, 20] show that, for the offline requirements used in this analysis, the ratio of the single-muon efficiency in data and MC simulation is consistent within <3% of unity, independent of p_{T}^{μ} [31]. The tracking efficiency in data and simulation agree to within 1% per track. The dimuon vertex and trigger simulation also have 1% systematic uncertainties. The dimuon HLT trigger inefficiency varies with $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ in the range 4.5–7.5%. For the few dimuons with $p_{\mathrm{T}} > 60\,\text{GeV}$, it can go up to 15%. The difference between unity (no loss) and the simulated HLT trigger efficiency is assigned as the HLT systematic uncertainty for each event. All of the above-listed systematic uncertainties are added in quadrature to determine the total weight systematic uncertainty for each event. To estimate the impact of the weight systematic uncertainty on the $\Xi(E_{\text{jet}}; z_1)$ function, two additional $\Xi(E_{\text{jet}}; z_1)$ functions are made for each z_1. One uses distributions in which the weight for each event is raised by one standard deviation; in the other, the event weight per event is lowered by one standard deviation. The shifted $\Xi(E_{\text{jet}}, z_1)$ values are compared to the unshifted value in each energy bin. The weight systematic uncertainty ranges from 0.2 to 0.9% of the standard-weight $\Xi(E_{\text{jet}}; z_1)$ values.

In addition, there is a selection bias in the J/ψ meson and jet association that disfavors the configuration when the difference $\eta_{\text{jet}} - \eta_{\mathrm{J}/\psi}$ has the opposite sign to η_{jet}. The bias effect is evaluated from data. The number of events per E_{jet} bin in the biased region is rescaled to match the yield in the unbiased region. Half of the difference between the measured and corrected number of events in each E_{jet} bin is assigned as its bias systematic uncertainty. The weight and bias systematic uncertainties are added in quadrature to obtain the systematic uncertainty in $\Xi(E_{\text{jet}}; z_1)$, which ranges from 0.3 to 1.0%. These uncertainties are then added in quadrature with the uncertainty in the unfolding procedure discussed in the previous section.

10 Matching jet data with the FJF predictions

In this analysis, we use three z_1 values: 0.425, 0.525, and 0.625. These are the centers of three nonoverlapping z subregions with $\Delta z = 0.05$ from the measurement region $0.3 < z < 0.8$. In these three z regions, the four FJF terms have distinctly different jet energy distributions for a given LDME parameter set. The authors of Ref. [13] supplied tables of the FJF terms, computed for $\sqrt{s} = 8\,\text{TeV}$ and jet radius $R = 0.5$. Since we are only interested in the shape of the energy distributions, the data and model distributions are normalized to unit area. We compare the data to the ${}^{1}S_{0}^{8}$, ${}^{3}S_{1}^{8}$, ${}^{3}P_{J}^{8}$, and ${}^{3}S_{1}^{1}$ FJF functions for the LDME parameter sets from Bodwin, Chung, Kim, and Lee (BCKL) [32], and from Butenschoen and Kniehl (BK) [33]. The four FJF terms using the LDME parameters from Chao et al. [34] increase with increasing jet energy. This behavior does not match the trend of the data at any z value, and we do not consider those predictions further. The BCKL and BK LDME parameter sets are derived from different selections of J/ψ meson production measurements, e.g., the BK set includes electroproduction data and uses a lower J/ψ meson p_{T} limit than is used in the hadroproduction-only selection of the BCKL set. Both groups report that their LDME sets produce J/ψ meson differential cross sections that agree with data. Despite the fact that the BK set predicts a large J/ψ meson polarization at large $p_{\mathrm{T}}^{\mathrm{J}/\psi}$, which disagrees with experiment [6, 7], we compare the FJF terms using both the BCKL and BK parameter sets to the fragmentation results from this analysis. We will consider the polarization issue after the comparison.

Figures 2–4 show the $\Xi(E_{\text{jet}}; z_1)$ versus E_{jet} results for the three z_1 values, along with comparisons to the FJF predictions. The FJF curves show the detailed energy dependence. They cross near the midpoint of the energy range because of their near-linearity and their normalization to unit area. The FJF points are derived by averaging the predictions in $8\,\text{GeV}$ wide E_{jet} bins to match the binning in the data, with the average values assigned to the energy of the bin centers. There is no uncertainty associated with the FJF terms. In the figures, the data points and their uncertainties are shifted horizontally by +0.25 GeV to allow the predicted FJF points to be seen more clearly. The vertical bars are the quadrature sum of the unfolded and systematic uncertainties. For each z_1, these average values are used to calculate the χ^2 for the comparisons of the FJF terms to the data. An a priori decision was made that a model prediction is an acceptable match to the data only if $\chi^2 < 21$ for seven degrees of freedom. Otherwise, we say that the model does not match the data.

11 Dominant FJF terms for jet fragmentation

For $z_1 = 0.425$, the comparisons of the data and the FJF model are shown in Fig. 2 for the BCKL (left) and BK (right) LDME parameter sets. The jet fragmentation data clearly discriminate between the four FJF terms. The χ^2 value and the associated p-value for the comparison of the data to each FJF term are given in Table 1 for both LDME parameter sets. Only the BCKL ${}^1S_0^8$ term gives an acceptable match to the data. The relative likelihood for the best BK term (${}^3S_1^1$) compared to the best BCKL term (${}^1S_0^8$) is 1/274. This indicates that the BCKL ${}^1S_0^8$ term dominates jet fragmentation to J/ψ mesons for $z_1 = 0.425$, thus predicting small J/ψ polarization. The $p_\mathrm{T}^{\mathrm{J}/\psi}$ range corresponding to this z range in these data is $12 < p_\mathrm{T}^{\mathrm{J}/\psi} < 20\,\mathrm{GeV}$. CMS measurements [7] of J/ψ polarization at such p_T values show that it is indeed small.

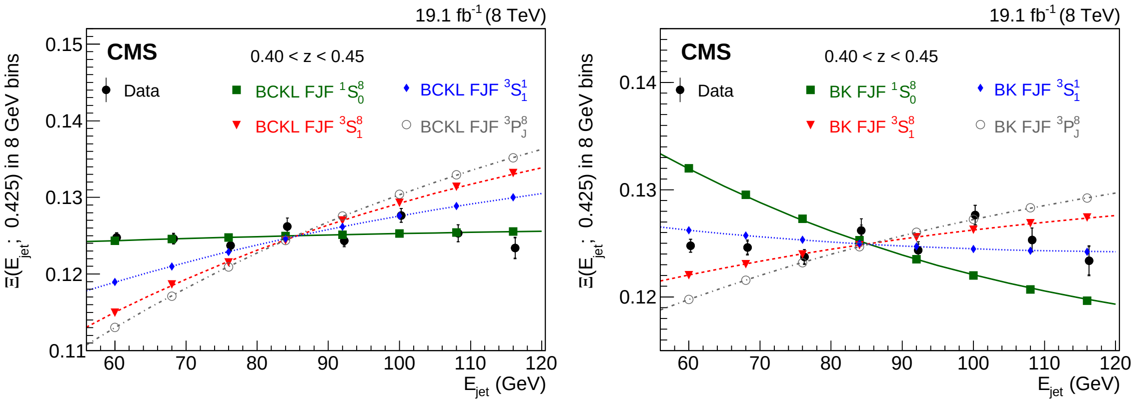

Figure 2: Comparison of $\Xi(E_\mathrm{jet};\, 0.425)$ versus E_jet from data with the FJF predictions from each of the four NRQCD terms, using the BCKL (left) and the BK (right) LDME parameter sets. The curves show the detailed energy dependence of the predictions.

Table 1: For $z_1 = 0.425$, the χ^2 value and the associated p-value (in parentheses) for 7 degrees of freedom from the comparison of the data and the prediction for each FJF term, using the BCKL and BK LDME parameter sets.

	${}^1S_0^8$	${}^3S_1^8$	${}^3S_1^1$	${}^3P_J^8$
BCKL	14.2 (4.8%)	810 (<0.001%)	163 (<0.001%)	675 (<0.001%)
BK	278 (<0.001%)	42 (<0.001%)	29 (0.014%)	122 (<0.001%)

For $z_1 = 0.525$, the comparisons of the data and the FJF terms are shown in Fig. 3 for the BCKL (left) and BK (right) LDME parameter sets. The FJF predictions for the jet energy dependence of the BCKL ${}^1S_0^8$ and BK ${}^3S_1^1$ LDME terms are nearly identical for $z_1 > 0.5$. The χ^2 value and the associated p-value for the comparison of the data to each FJF function are given in Table 2. In these data, the BCKL ${}^1S_0^8$ term and the BK ${}^3S_1^1$ term give acceptable matches. For the BK set, the

${}^3S_1^8$ NRQCD term also gives an acceptable fit, but it is more than 20 times less likely to match the data than the ${}^3S_1^1$ term.

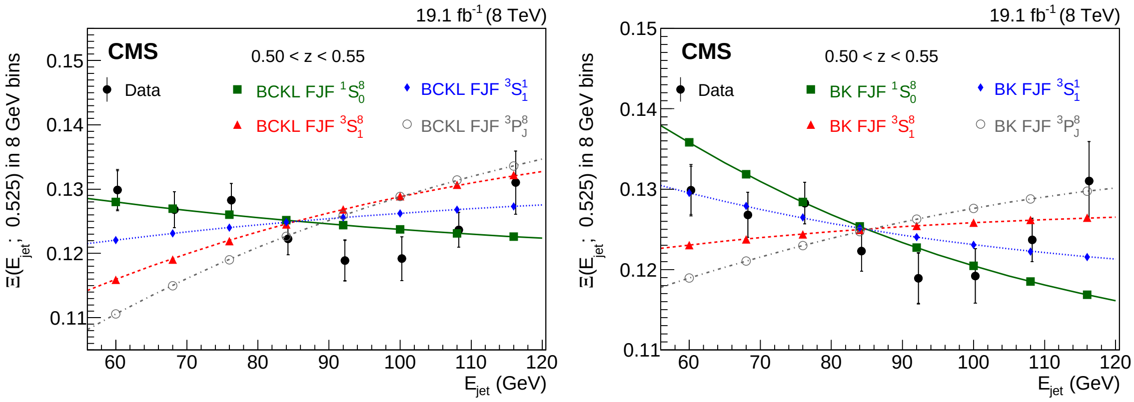

Figure 3: Comparison of $\Xi(E_{\text{jet}};\, 0.525)$ versus E_{jet} from data with the FJF predictions from each of the four NRQCD terms, using the BCKL (left) and the BK (right) LDME parameter sets. The curves show the detailed energy dependence of the predictions.

Table 2: For $z_1 = 0.525$, the χ^2 value and the associated p-value (in parentheses) for 7 degrees of freedom from the comparison of the data and the prediction for each FJF term, using the BCKL and BK LDME parameter sets.

	${}^1S_0^8$	${}^3S_1^8$	${}^3S_1^1$	${}^3P_J^8$
BCKL	10.2 (18%)	54 (<0.001%)	22 (0.24%)	88 (<0.001%)
BK	22 (0.24%)	19 (0.82%)	10 (19%)	36 (<0.001%)

For $z_1 = 0.625$, the comparisons of the data and the FJF terms are shown in Fig. 4 for the BCKL (left) and BK (right) LDME parameter sets. As in the case for $z_1 = 0.525$, the BCKL ${}^1S_0^8$ term and the BK ${}^3S_1^1$ term give acceptable matches to the data. For the BCKL set, the ${}^3S_1^1$ NRQCD term also gives an acceptable fit, but it is more than 10 times less likely to match the data than the ${}^1S_0^8$ term. The corresponding χ^2 values and the associated p-values are given in Table 3.

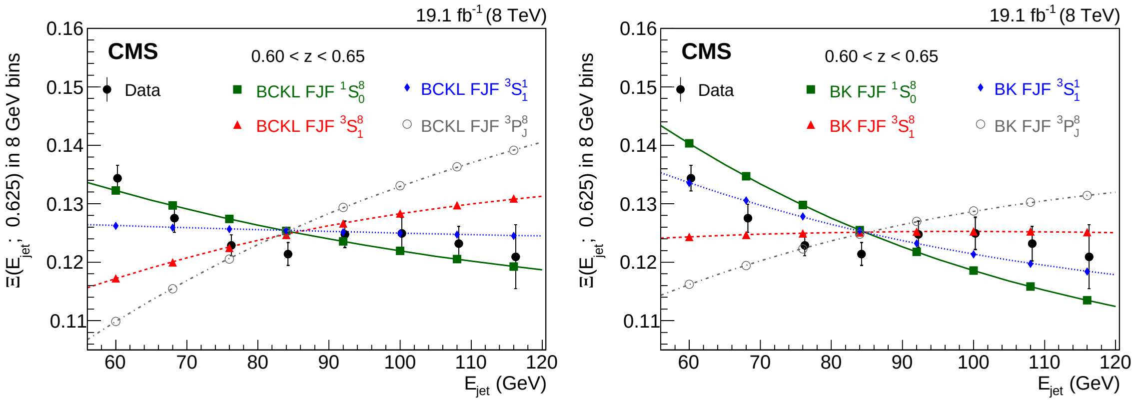

Figure 4: Comparison of $\Xi(E_{\text{jet}};\, 0.625)$ versus E_{jet} from data with the FJF predictions from each of the four NRQCD terms, using the BCKL (left) and the BK (right) LDME parameter sets. The curves show the detailed energy dependence of the predictions.

Summarizing the comparison of the fragmentation results with the FJF predictions, we see that the FJF ${}^3S_1^8$ and ${}^3P_J^8$ terms do not describe the fragmenting jet data. They cannot dominate jet fragmentation to J/ψ mesons in any probed z region for either parameter set. This is an

Table 3: For $z_1 = 0.625$, the χ^2 value and the associated p-value (in parentheses) for 7 degrees of freedom from the comparison of the data and the prediction for each FJF term, using the BCKL and BK LDME parameter sets.

	${}^1S_0^8$	${}^3S_1^8$	${}^3S_1^1$	${}^3P_J^8$
BCKL	14.3 (4.6%)	83 (<0.001%)	21 (0.38%)	501 (<0.001%)
BK	50 (<0.001%)	28 (0.02%)	17 (1.7%)	328 (<0.001%)

important constraint on NRQCD models. For $0.40 < z < 0.45$ ($12 < p_{\mathrm{T}}^{\mathrm{J}/\psi} < 20\,\mathrm{GeV}$), only the BCKL ${}^1S_0^8$ term describes the data, with the resulting prediction of small polarization for these J/ψ mesons. This FJF term can also be primarily responsible for jet fragmentation to J/ψ mesons for all $z > 0.45$, leading to the prediction of small polarization for all $p_{\mathrm{T}}^{\mathrm{J}/\psi}$, consistent with experimental measurements [6, 7]. The BCKL LDME parameters were developed from a completely different data set than the fragmentation data, so there is no a priori reason to expect them to predict the jet fragmentation behavior. The fact that with the BCKL LDME parameters the fragmentation data match the FJF predictions for one and only one specific FJF term at $z_1 = 0.425$, 0.525, and 0.625 is evidence that the FJF analysis describes jet fragmentation to J/ψ mesons in the gluon-rich central region in pp interactions and can discriminate between different LDME parameter sets.

Because of the similarity of the FJF predictions for the jet energy dependence of the BCKL ${}^1S_0^8$ and BK ${}^3S_1^1$ LDME terms for $z > 0.5$, it could be true that the BK ${}^3S_1^1$ LDME term dominates the jet fragmentation process for $z_1 = 0.525$ or 0.625, but not for $z_1 = 0.425$. Note that the BCKL and BK descriptions are mutually exclusive, because they use different LDME sets. Having a ${}^3S_1^1$ LDME term as the fragmentation source would imply a significant transverse polarization for $16 < p_{\mathrm{T}}^{\mathrm{J}/\psi} < 34\,\mathrm{GeV}$, roughly the range corresponding to $z > 0.5$. This range includes about 50% of the J/ψ events in this analysis. Such a polarization effect is not consistent with the J/ψ meson polarization measurements cited above. We conclude that the absence of J/ψ meson polarization at large $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ reflects the dominance of jet fragmentation via the FJF model with the BCKL ${}^1S_0^8$ term for events with observed jets.

12 Total fraction of J/ψ mesons from jet fragmentation

In this section, we determine whether jet fragmentation is the major source of prompt energetic J/ψ meson ($E_{\mathrm{J}/\psi} > 15\,\mathrm{GeV}$) production in the central region ($|y_{\mathrm{jet}}| < 1$). Here, E_{jet} refers to the measured jet energy before unfolding. As shown in Fig. 1 (left), for events with a J/ψ meson and only one observed jet, $(84.0 \pm 0.1)\%$ of the J/ψ candidates are within $\Delta R < 0.5$ of that jet. This is consistent with jet fragmentation being the dominant source of J/ψ production in this kinematic range when there is at least one observed jet in the event. However, events with one or more observed jets having $p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV}$ account for only $(44.9 \pm 0.1)\%$ of the prompt J/ψ meson sample.

To understand the source of J/ψ meson events with no jets passing the $p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV}$ requirement, termed zero-jet events, we note that a fragmenting jet can fail the $p_{\mathrm{T}}^{\mathrm{jet}}$ threshold even though its daughter J/ψ meson is observed. For instance, when the $p_{\mathrm{T}}^{\mathrm{jet}}$ threshold is raised from 25 to 30 GeV, the fraction of zero-jet events with an identified J/ψ meson increases from 55 to 65%. For one-jet events in data with $p_{\mathrm{T}}^{\mathrm{jet}}$ thresholds of 30, 35, and 40 GeV, the observed jet is still within $\Delta R < 0.5$ of the J/ψ meson in the event $(84.0 \pm 0.2)\%$ of the time, i.e., the jet fragmentation probability is independent of $p_{\mathrm{T}}^{\mathrm{jet}}$. Only jets with $E_{\mathrm{jet}} > 44\,\mathrm{GeV}$ pass the $p_{\mathrm{T}}^{\mathrm{jet}} > 25\,\mathrm{GeV}$

requirement with 100% efficiency over the range $0 < |\eta_{\text{jet}}| < 1$. Jets having $E_{\text{jet}} < 44\,\text{GeV}$ can fragment into observed J/ψ mesons with $E_{\text{J}/\psi} > 15\,\text{GeV}$, but some of these jets will not pass the $p_{\text{T}}^{\text{jet}} > 25\,\text{GeV}$ requirement.

In order to correct for this effect, we fit the E_{jet} distribution for jets fragmenting to a J/ψ meson to the sum of two exponential functions in the range $44 < E_{\text{jet}} < 150\,\text{GeV}$. We use the fit to extrapolate the number of fragmenting jets to lower E_{jet} values. Jet reconstruction efficiency corrections are not applied at this stage. The FJF model is valid for $z < 0.8$ [10]. Only (1.3 ± 0.1)% of fragmenting jets in the data have $z > 0.8$; we truncate the model at $z = 0.8$, setting a limit $E_{\text{jet}} > 19\,\text{GeV}$ for the extrapolation. The extrapolation is used to estimate the number of jets with an associated J/ψ meson that would be present in the lower-energy region for full p_{T} acceptance. Some jets in the $E_{\text{jet}} = 25$–$44\,\text{GeV}$ range have sufficiently large polar angles to pass the $p_{\text{T}}^{\text{jet}} > 25\,\text{GeV}$ requirement. These are subtracted from the extrapolation to avoid double counting. The number of jets from extrapolation in each 1 GeV wide jet energy bin i is corrected for the jet reconstruction efficiency ϵ_i to predict the total number N_i of jets with energy E_i.

In order to contribute to the fragmentation sample, a jet with energy E_i must produce a J/ψ meson with energy E_j. The probability P_j for the J/ψ meson to have energy E_j is taken from the results of this analysis, normalized to unity for 55 bins covering the range $15 < E_{\text{J}/\psi} < 70\,\text{GeV}$. The total number A_i of jets with energy E_i that fragment into a J/ψ meson with energy fraction $z_{ij} = E_j/E_i$ in the range 0.3–0.8 is

$$A_i = N_i \sum_{j=1}^{55} P_j\, w(z_{ij}). \tag{3}$$

The function $w(z_{ij})$ is the probability that a jet of energy E_j will fragment into a J/ψ meson having energy E_i. It is taken from a calculation in Ref. [10] for $E_{\text{jet}} = 50\,\text{GeV}$ and is zero for $z > 0.8$. The model predicts that (43 ± 3 (stat))% of the J/ψ mesons should be accompanied by zero observed jets, compared to 55% found in the data.

There are systematic uncertainties in this result. In a private communication, the authors of Ref. [10] also provided a z probability calculation for $E_{\text{jet}} = 20\,\text{GeV}$. The model prediction for the number of zero-jet events using the 20 GeV z probability calculation differs by 3% from the 50 GeV result. This difference is taken as the systematic uncertainty in the z fragmentation probability. The uncertainty in the MC prediction of the low-energy jet efficiency is 13%. We also made a closure test by using the model to predict the number of observed jets lost when the jet p_{T} threshold was raised from 25 to 40 GeV. The model prediction agrees with the actual number of lost jets to within (3.5 ± 0.1)%. However, there is a jet energy dependence in the matching between the data and the prediction. Extrapolating the bin-by-bin jet energy dependence of that difference into the 19–44 GeV range, the closure study gives a 7% systematic uncertainty in the predicted number of zero-jet events having jet energies less than 44 GeV. Adding the systematic uncertainties in quadrature, the predicted fraction of zero-jet events with a J/ψ meson from a fragmenting jet with $p_{\text{T}}^{\text{jet}} < 25\,\text{GeV}$ is (43 ± 3 (stat) ± 7 (syst))%.

If we apply this reasoning to results from Section 6, the small peak in the range $2.5 < \Delta R < 3.4$ in Fig. 1 (left) is actually the recoil jet in a dijet pair for which the fragmenting parent jet of the J/ψ meson was not observed. This increases the fraction of J/ψ mesons that are fragmentation products of a jet in the one-jet sample from (84.0 ± 0.1)% to (94.3 ± 0.1)%. With this interpretation, and the results from Section 6, we find that the one- and two-jet fragmentation fractions are both essentially 94%. The overall fraction of J/ψ mesons that come from jet fragmentation is, then, (0.94)(45%) = 42% from events with one or more observed jets, plus 43% from the zero-jet sample. While the zero-jet model is simple, it passes an experimental closure test. Also, it follows the trend of the data as the jet p_{T} requirement is raised in steps from 25 to 40 GeV. Using it, we conclude that (85 ± 3 (stat) ± 7 (syst))% of the J/ψ mesons within our kinematic acceptance are fragmentation products of a jet with $E_{\text{jet}} > 19\,\text{GeV}$ and $|\eta_{\text{jet}}| < 1$. Jet fragmentation is the dominant source of prompt J/ψ mesons with $E_{\mathrm{J}/\psi} > 15\,\text{GeV}$ and $|y_{\mathrm{J}/\psi}| < 1$.

13 Summary

The first analysis has been presented comparing data for prompt J/ψ mesons produced as fragments of central gluonic jets with a theoretical analysis based on the fragmenting jet function (FJF) approach. The term prompt means that the J/ψ meson is consistent with originating from the primary vertex. In the FJF model, the jet fragments into a $\mathrm{c\overline{c}}$ system in an angular momentum state and quark color configuration ${}^{2S+1}L_J^n$ plus other hadrons. Here, S, L, and J are the spin, orbital, and total angular momentum quantum numbers of the $\mathrm{c\overline{c}}$ system and n indicates a color-singlet (n = 1) or color-octet (n = 8) configuration. The FJF analysis uses the nonrelativistic quantum chromodynamics (NRQCD) approach to compute the cross section for the formation of a J/ψ meson from the $\mathrm{c\overline{c}}$ system for four specific S, J, L, and n configurations: ${}^1S_0^8$, ${}^3S_1^8$, ${}^3S_1^1$, and ${}^3P_J^8$.

The data were collected by the CMS Collaboration in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$, corresponding to an integrated luminosity of 19.1 fb^{-1}. The kinematic selections for the analysis are $E_{\mathrm{J}/\psi} > 15\,\text{GeV}$, $|y_{\mathrm{J}/\psi}| < 1$, $p_{\mathrm{T}}^{\text{jet}} > 25\,\text{GeV}$, and $|\eta_{\text{jet}}| < 1$. The agreement between the data and the FJF predictions over a wide range of z, where z is the J/ψ meson fraction of the jet energy, supports the FJF model predictions for gluon jet fragmentation into J/ψ mesons. For three specific z ranges, 0.40–0.45, 0.50–0.55, and 0.60–0.65, the ${}^3S_1^8$ and ${}^3P_J^8$ FJF terms do not match the fragmentation data for either the Bodwin, Chung, Kim, and Lee (BCKL) [32] or Butenschoen and Kniehl (BK) [33] long-distance matrix element (LDME) parameter sets, indicating that these terms are not the main contributors to J/ψ meson production by jet fragmentation. Only the nonrelativistic quantum chromodynamics (NRQCD) ${}^1S_0^8$ term, using the BCKL LDME parameters, matches the data for jet fragmentation to J/ψ mesons for all three z ranges. The dominance of this term, which has all angular momenta equal to zero in the $\mathrm{c\overline{c}}$ rest frame, would explain the experimental measurements [6, 7] of small J/ψ meson polarization for $p_{\mathrm{T}}^{\mathrm{J}/\psi} > 12\,\text{GeV}$. For $z > 0.5$, the NRQCD ${}^3S_1^1$ term, using the BK LDME parameters, has almost the same jet energy dependence as the BCKL ${}^1S_0^8$ term and could play the dominant role in jet fragmentation to J/ψ mesons. However, the ${}^3S_1^1$ NRQCD term implies a significant J/ψ meson polarization for $z > 0.5$, corresponding to $16 < p_{\mathrm{T}}^{\mathrm{J}/\psi} < 34\,\text{GeV}$, in contradiction with experimental results.

When a jet is observed in an event, the fraction of J/ψ mesons from jet fragmentation is (94.2 ± 0.1)%, averaged over one- and two-jet events. Using a simple model to estimate the fraction of J/ψ mesons that are fragments of jets that fail the analysis $p_{\mathrm{T}}^{\text{jet}}$ requirement, jet fragmentation is found to be the source of (85 ± 3 (stat) ± 7 (syst))% of the J/ψ mesons produced in the kinematic region probed in this study. This analysis shows that jet fragmentation accounts for almost all prompt J/ψ mesons produced at large $p_{\mathrm{T}}^{\mathrm{J}/\psi}$ and is consistent with being dominated by the ${}^1S_0^8$ FJF term using the BCKL parameter set, thus explaining the small J/ψ meson polarization for $p_{\mathrm{T}}^{\mathrm{J}/\psi} > 12\,\text{GeV}$.

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