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Study of jet quenching with isolated-photon+jet correlations in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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ABSTRACT

Measurements of azimuthal angle and transverse momentum (p_T) correlations of isolated photons and associated jets are reported for pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The data were recorded with the CMS detector at the CERN LHC. For events containing a leading isolated photon with $p_T^\gamma > 40$ GeV/c and an associated jet with $p_T^{jet} > 30$ GeV/c, the photon+jet azimuthal correlation and p_T imbalance in PbPb collisions are studied as functions of collision centrality and p_T^γ. The results are compared to pp reference data collected at the same collision energy and to predictions from several theoretical models for parton energy loss. No evidence of broadening of the photon+jet azimuthal correlations is observed, while the ratio p_T^{jet}/p_T^γ decreases significantly for PbPb data relative to the pp reference. All models considered agree within uncertainties with the data. The number of associated jets per photon with $p_T^\gamma > 80$ GeV/c is observed to be shifted towards lower p_T^{jet} values in central PbPb collisions compared to pp collisions.

1. Introduction

Quantum chromodynamics predicts that in relativistic heavy ion collisions a state of deconfined quarks and gluons known as the quark–gluon plasma (QGP) can be formed [1,2]. Parton scatterings with large momentum transfer, which occur very early ($\approx$0.1 fm/c) compared to the timescale of QGP formation ($\approx$1 fm/c), provide tomographic probes of the plasma [3]. The outgoing partons interact strongly with the QGP and lose energy [4–9]. This phenomenon, known as "jet quenching", has been observed through measurements of hadrons with high transverse momentum (p_T) [10–15] and of jets [16–22], both created by the fragmentation of the high-momentum partons.

Since electroweak bosons do not interact strongly with the QGP [23–26], measurements of jets produced in the same hard scattering in conjunction with these bosons have, in contrast to dijet measurements, a controlled configuration of the initial hard scattering [27–29]. The electroweak boson p_T reflects, on average, the initial energy of the associated parton that fragments into the jet, before any medium-induced energy loss has occurred [30,31]. At LHC energies, the production of jets with $p_T > 30$ GeV/c that are associated with electroweak bosons is dominated by quark fragmentation [32]. Hence, the study of correlations in boson-jet events, such as the azimuthal angle (ϕ) difference and p_T ratio between the boson and the associated jets, opens the possibility for in-depth studies of the parton energy loss mechanisms utilizing theoretically well-controlled initial production processes. These studies also facilitate the extraction of QGP properties via comparisons with theoretical models [31,33–37]. Measurements of this kind were first performed in PbPb collisions at a nucleon–nucleon center-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV with isolated-photon+jet events [38] and at 5.02 TeV with Z-jet events [39] by the CMS Collaboration at the CERN LHC. The precision of these previous measurements was limited by the available number of boson-jet pairs.

In the results reported in this paper, the electroweak boson is an isolated photon, which is selected experimentally by using an isolation requirement, namely that the additional energy in a cone of fixed radius around the direction of the reconstructed photon is less than a specified value [23,24]. This restriction suppresses the background contributions from photons originating from decays of neutral mesons ("decay photons"), and gives a sample containing mostly prompt photons. Prompt photons are photons produced directly in the hard scattering process, or emitted in the fragmentation of a high-p_T parton ("fragmentation photons"). This Letter reports the measurement of correlations of isolated photons and associated jets in PbPb and pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The

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PbPb and pp data samples were collected by the CMS experiment in 2015 and correspond to integrated luminosities of 404 μb^{-1} and 27.4 pb^{-1}, respectively. The measurement characterizes parton energy loss through the ϕ and p_T correlations between isolated photons and the associated jets. The azimuthal angle difference $\Delta\phi_{j\gamma} = |\phi^{jet} - \phi^{\gamma}|$, the p_T ratio $x_{j\gamma} = p_T^{jet}/p_T^{\gamma}$ and its average $\langle x_{j\gamma} \rangle$, the average number of associated jets per photon, $R_{j\gamma}$, and the ratio of the yield of associated jets in PbPb data to pp data, I_{AA}^{jet}, are presented. The results from PbPb collisions are compared to those from pp collisions, with the pp data serving as a reference to extract information about the modifications due to the presence of the QGP.

2. 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 which measures charged particles within the pseudorapidity range $|\eta| < 2.5$, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. The barrel and endcap calorimeters provide $|\eta|$ coverage out to 3. Photon candidates used in this analysis are reconstructed using the energy deposited in the barrel region of the ECAL, which covers a range of $|\eta| < 1.48$. Hadron forward (HF) calorimeters extend the $|\eta|$ coverage of the HCAL to $|\eta| = 5.2$. In PbPb collisions, the HF calorimeters are used to determine the centrality of the collisions, which is related to the impact parameter of the two colliding Pb nuclei [16], and the azimuthal angle of maximum particle density (the event plane) [40]. 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. [41].

3. Analysis procedure

3.1. Event selection

Events containing high-p_T photon candidates are selected by the CMS trigger system, which consists of a level-1 (L1) and a high-level trigger (HLT) [42]. Events are first selected by requiring an ECAL transverse energy deposit larger than 21 (20) GeV during the PbPb (pp) data-taking period. Photon candidates are then reconstructed at the HLT using the "island" clustering algorithm [24,43], which is applied to energy deposits in the ECAL. The HLT selection efficiency was determined in data and was found to be greater than 98% for events containing a photon with $p_T^{\gamma} > 40$ GeV/c and $|\eta^{\gamma}| < 1.44$ reconstructed offline. The η^{γ} interval of the photons used in this analysis is restricted to the barrel region of the ECAL, which has the best performance in terms of photon reconstruction and triggering and has the lowest rate of misreconstructed tracks.

A pure sample of inelastic hadronic pp and PbPb collisions is obtained with further offline selection criteria applied to the triggered events [16,44]. Notable among these, a reconstructed event vertex and at least three (one) calorimeter towers in the HF on each side of the interaction point with energy >3 GeV are (is) required in the PbPb (pp) analysis. Events with spurious energy depositions in the HCAL (i.e., sporadic uncharacteristic noise and signals from malfunctioning calorimeter channels) are rejected by established algorithms that flag such events, to remove possible contamination of the jet sample [45]. Events with multiple collisions have a negligible effect on the measurement since the average number of collisions per bunch crossing is around 0.9 for pp collisions, and less than 0.01 for PbPb collisions.

In PbPb collisions, the centrality measurement is based on percentiles of the distribution of the total energy measured in both HF calorimeters. The event centrality observable corresponds to the fraction of the total inelastic hadronic cross section, starting at 0% for the most central collisions, i.e., those with the smallest impact parameter and the largest nuclear overlap [16].

3.2. Jet reconstruction

Offline jet reconstruction is performed using the CMS particle-flow (PF) algorithm [46]. By combining information from all subdetector systems, the PF algorithm identifies final-state particles in an event, classifying them as electrons, muons, photons, charged hadrons, or neutral hadrons. To form jets, these PF objects are clustered using the anti-k_T sequential recombination algorithm provided in the FastJet framework [47,48]. A small jet radius parameter of $R = 0.3$ is chosen to minimize the effects of heavy ion background fluctuations (~ 10 GeV in central PbPb collisions) and for consistency with the previous measurement at 2.76 TeV [38].

For the PbPb data, the underlying background from soft collisions (i.e., the underlying event, UE) is subtracted during jet reconstruction by employing the iterative algorithm described in Ref. [49], using the same implementation as in the PbPb analysis of Ref. [16]. In pp collisions, jets are reconstructed without UE subtraction. For pp and PbPb samples, the reconstructed jet energies are corrected to the energies of final-state particle jets using a factorized multistep approach [50]. The corrections are derived using simulated dijet and photon+jet events generated with the pythia 8.212 [51] (CUETP8M1 tune [52]) Monte Carlo (MC) event generator which, for the case of PbPb corrections, are embedded into a simulated underlying background event from hydjet 1.9 [53]. The background simulation is tuned to reproduce the observed charged-particle multiplicity and p_T spectrum in PbPb data. Reconstructed jets are required to have $|\eta^{jet}| < 1.6$ and corrected $p_T^{jet} > 30$ GeV/c, to ensure that the jet reconstruction efficiency and energy resolution (JER) are well understood, i.e., results from data are in agreement with expectations from MC.

3.3. Photon reconstruction

Photon candidates are reconstructed from clusters of energy deposited in the ECAL. The "hybrid" algorithm used for the analysis in pp collisions is detailed in Ref. [43], while the description of the island clustering algorithm optimized for high-multiplicity PbPb collisions can be found in Ref. [24].

In order to reduce electron contamination, photon candidates are discarded if the differences in pseudorapidity and azimuthal angle between the photon candidate and any electron candidate track with $p_T > 10$ GeV/c are less than 0.02 and 0.15 radians, respectively [24]. These matching windows are conservative choices based on the detector angular resolution. The relatively large azimuthal angle window allows for the curvature of the electron trajectories. Anomalous signals caused by the interaction of highly ionizing particles directly with the silicon avalanche photodiodes used for the ECAL barrel readout are removed using the prescription given in Ref. [24]. The energy of the reconstructed photons is corrected to account for the effects of the material in front of the ECAL and for the incomplete containment of the shower energy. For PbPb data, an additional correction is applied to account for energy contamination from the UE. The magnitude of the combined energy correction for isolated photons varies from 0 to 10%, depending on the centrality of the collision and p_T^{γ}. The cor-

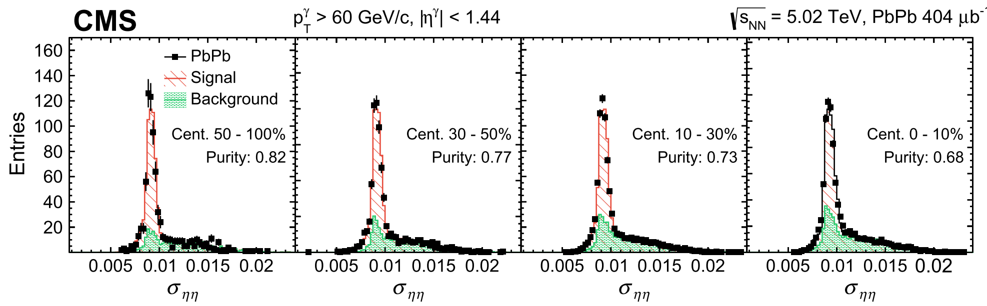

Fig. 1. The centrality dependence of the shower shape variable $\sigma_{\eta\eta}$ for photons with $p_T^\gamma > 60$ GeV/c. The black points show the PbPb experimental results, the red histograms are the signal templates from PYTHIA+HYDJET simulations, and the green histograms are the background templates obtained from a nonisolated sideband region in data. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

rections are obtained from simulated PYTHIA and PYTHIA+HYDJET photon events.

Similar to Ref. [54], a generator-level photon candidate is considered isolated if the p_T sum of final-state generated particles, excluding neutrinos, in a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ around the direction of the candidate, SumIso, is less than 5 GeV/c. For a reconstructed photon candidate, the corresponding isolation variable, SumIso$^{\text{UE-sub}}$, is calculated with respect to the centroid of the cluster, not including the p_T of the cluster and after correcting for the UE (only in PbPb collisions), and is required to be less than 1 GeV/c. The isolation criterion for reconstructed photons is tighter than for generated photons to minimize the impact of UE fluctuations in PbPb collisions, where a downward fluctuation in the UE could inadvertently allow a nonisolated photon candidate to pass the isolation criteria. A systematic uncertainty is assigned to account for the effect of this difference on the final observables, as detailed in Section 3.5.

Imposing the isolation requirement suppresses the background contributions from fragmentation and decay photons, resulting in a sample enriched in isolated prompt photons. The dominant remaining backgrounds for isolated photon candidates are ECAL showers initiated by isolated hadrons, and real photons that are decay products of isolated neutral mesons, e.g., π^0, η, and ω. The hadron-induced showers are rejected using the ratio of HCAL over ECAL energy inside a cone of radius $\Delta R = 0.15$ around the photon candidate, H/E. Only photon candidates with $H/E < 0.1$ are selected for this analysis. The decay photons can be significantly reduced using a cut on the shower shape, a measure of how energy deposited in the ECAL is distributed in ϕ and η [54], as discussed in Section 3.4. The efficiencies of these criteria in selecting photons are extracted from simulations as a function of p_T^γ and corrected for in collision data.

3.4. Photon+jet pair selection

To form photon+jet pairs, the highest p_T isolated photon candidate that passes the selection criteria is paired with all jets in the same event. The combinatorial background in PbPb collisions, which includes misidentified jets that arise from UE fluctuations, as well as jets from multiple hard parton–parton scatterings in the same collision, needs to be subtracted in order to study the energy loss effects on the jets produced in the same hard scattering as the photon. This background subtraction is performed by correlating each leading isolated photon candidate with reconstructed jets found in 40 different events, randomly selected from minimum bias PbPb data such that the event centrality, the interaction vertex position along the beam axis, and the event plane, are within 5%, 5 cm, and $\pi/10$, respectively, of those from the signal event. The values were optimized such that the statistical uncertainty due to the subtraction is negligible compared to the statistical uncertainty of the photon sample.

The background contribution from pairs of decay photons and jets is subtracted with a procedure based on collision data, using a two-component template fit of the electromagnetic shower shape variable $\sigma_{\eta\eta}$, which is defined as a modified second moment of the ECAL energy cluster distribution around its mean η position [54, 55]:

$$\sigma_{\eta\eta}^2 = \frac{\sum_i^{5\times5} w_i(\eta_i - \eta_{5\times5})^2}{\sum_i^{5\times5} w_i},$$
$$w_i = \max\left(0, 4.7 + \ln\frac{E_i}{E_{5\times5}}\right), \quad (1)$$

where E_i and η_i are the energy deposit and η of the ith ECAL crystal within a 5×5 crystal array centered around the electromagnetic cluster, and $E_{5\times5}$ and $\eta_{5\times5}$ are the total energy and mean η of the 5×5 crystal matrix, respectively. The shape of the signal distribution is obtained from PYTHIA+HYDJET simulations of isolated prompt photon+jet processes, while the background templates are obtained from a nonisolated sideband region in data, $10 < \text{SumIso}^{\text{UE-sub}} < 20$ GeV/c. The purity of the photon sample (fraction of prompt photons within the remaining collection of candidates) is determined from the fit. Examples of the template fits are shown in Fig. 1 for the lowest p_T^γ photons and the four centrality intervals used in this analysis. The purity decreases in more central collisions, reflecting an increase in the backgrounds.

The yields and kinematic characteristics of the background arising from pairs of decay photons and jets are estimated by analyzing events with a larger photon shower width ($0.011 < \sigma_{\eta\eta} < 0.017$), which are dominated by decay photons. The background contribution fraction is then subtracted from the yield for the signal events, which have a smaller photon shower width ($\sigma_{\eta\eta} < 0.01$), according to the purity obtained from the template fits.

The detector response for low-p_T jets can exhibit significant nonlinearity and biases because of the background subtraction procedure of the current jet algorithm, as well as the high magnetic field of the CMS detector. This is neither well-modeled nor well-understood. Hence, the distributions are not unfolded for the detector resolution, but the approach instead is to smear, i.e., convolve with a Gaussian resolution adjustment term, the jet energy in pp events to match the JER in each of the PbPb centrality classes in which the comparison is made. This is done in every figure except Fig. 10. The JER $\sigma(p_T^{\text{gen}})$ is defined as the Gaussian standard deviation of the $p_T^{\text{reco}}/p_T^{\text{gen}}$ ratio, where p_T^{reco} is the UE-subtracted, detector-level jet p_T, and p_T^{gen} is the generator-level jet p_T without any contributions from a PbPb UE. For PbPb (pp) collisions, the JER is calculated from PYTHIA+HYDJET (PYTHIA) events that are

Table 1
Jet resolution parameters for pp and PbPb collisions. A global uncertainty of 7% is assigned to the smearing parameters, evaluated as described in text.

	Centrality [%]	C	S [(GeV/c)$^{1/2}$]	N [GeV/c]
pp	–	0.06	0.95	0
PbPb	0–30	0.06	1.24	6.83
	30–100			0
	0–10	0.06	1.24	8.42
	10–30			5.54
	30–50			2.37
	50–100			0

propagated through the GEANT4 [56] package. The UE produced by HYDJET with GEANT4 simulation has been compared to data by observing the energy collected inside randomly oriented cones with the same radius as the distance parameter of the jet algorithm. The MC simulation is found to be in good agreement with the experimental results. The JER is parametrized using the expression

$$\sigma\left(p_{\mathrm{T}}^{\mathrm{gen}}\right)=\sqrt{C^2+\frac{S^2}{p_{\mathrm{T}}^{\mathrm{gen}}}+\frac{N^2}{\left(p_{\mathrm{T}}^{\mathrm{gen}}\right)^2}}. \quad (2)$$

The stochastic term S describes the p_{T} dependence of the jet energy resolution, the constant term C represents the high-p_{T} limit of the resolution, and the noise term N reflects the effect of UE fluctuations on the energy resolution. All parameters for $\sigma(p_{\mathrm{T}}^{\mathrm{gen}})$ are determined using PYTHIA and PYTHIA+HYDJET samples with their numerical values provided in Table 1. Following the smearing to 0–30% PbPb data, the energy resolutions of jets with $p_{\mathrm{T}}^{\mathrm{jet}}=30(60)$ GeV/c measured in pp data changes from 18%(14%) to 35%(22%) respectively. Compared to the JER, the jet ϕ resolution has a negligible effect.

3.5. Systematic uncertainties

Systematic uncertainties are estimated separately for the pp and PbPb analyses. The uncertainties are determined for each centrality and p_{T}^{γ} interval using similar procedures as described in Ref. [38]. Seven sources of uncertainty are considered: photon purity, isolation definition, photon energy scale, electron contamination, photon efficiency, JER, and jet energy scale (JES). The total systematic uncertainties are calculated by summing in quadrature the uncertainties from all sources.

The uncertainty on the photon purity estimate is evaluated by varying the nonisolated sideband regions used to obtain the background template. The maximum deviation from the nominal values is $\pm$10%($\pm$6%) for central (peripheral) PbPb collisions, and $\pm$5% in pp collisions. The varied purity values are then used to perform the background subtraction, and the maximum difference from the nominal results is quoted as the uncertainty. The uncertainty due to the isolated photon definition is determined by comparing the photon+jet observables when using generator-level and detector-level definitions of the isolation variables. The photon energy scale uncertainty is based on the residual data-to-simulation photon energy scale difference after applying the photon energy corrections, amounting to about 1%, independent of p_{T}^{γ} and event centrality. The uncertainty due to electron contamination is evaluated by repeating the analysis without applying electron rejection, and scaling the difference in the final observables to the residual electron contamination after applying electron rejection. The electron rejection efficiency is determined to be 66% from MC studies. The uncertainty on the photon efficiency correction is determined by varying the selection criteria for matching reconstructed photons with generator-level photons. The uncertainty on the JER has two sources. The first source is the difference between the JER in data and simulation, which is around 15% for all centralities in both pp and PbPb collisions. The associated systematic uncertainty is evaluated by propagating the effects of having a JER that differs by 15% relative to the nominal value. The second source (7%) accounts for the uncertainty in the resolution and the modeling of the JER distributions, and was obtained by considering the differences between the extracted JER in each $p_{\mathrm{T}}^{\mathrm{gen}}$ bin and the parametrization using Eq. (2), and determining the value at one standard deviation of that distribution, assuming that the differences are normally distributed.

Finally, the JES uncertainty arises from three contributions that are added in quadrature for the final value. Two are common to both the pp and PbPb samples: the residual deviation from unity in simulation (i.e., the closure) of the JES after applying all jet energy corrections (2%) and the difference between data and simulation (2%). These two effects are independent of centrality and together amount to 2.8%. The closure of the JES depends on the flavor of the fragmenting parton: simulations show that the energy scale of quark jets is consistently higher than that of gluon jets. For pp collisions, the fragmentation dependence of the JES has been studied and is accounted for in the uncertainty from the difference between data and simulation. However, in PbPb collisions, the ratio of quarks and gluons can be different from pp data because of expected differences in centrality-dependent quenching of jets initiated by quarks or gluons. The subtraction of the UE in PbPb collisions results in the JES having a larger dependence on the fragmentation pattern than found for pp collisions, since one can only distinguish between soft particles from the jet fragmentation and the underlying event on average. Hence, an additional uncertainty, evaluated using collision data and simulation, is applied in PbPb collisions to account for these fragmentation effects on the JES arising from the subtraction algorithm, underlying event, and quenching. The photon-tagged jet fragmentation function in PbPb data is constructed and fit by a two-component model of the jet fragmentation functions for quark and gluon jets that were obtained from MC simulations. For $p_{\mathrm{T}}^{\gamma}>60$ GeV/c, the results show that the fraction of jets originating from gluon fragmentation in data can be constrained to between 0% and approximately 26%, which corresponds to the fraction found in PYTHIA+HYDJET MC samples. Hence, in this kinematic region, the difference between the JES for a pure quark jet sample and the inclusive sample is used in the uncertainty estimation. For $40<p_{\mathrm{T}}^{\gamma}<60$ GeV/c, where the results of the template fit are inconclusive because of the large statistical uncertainties, the full difference in the JES between having 0% and 100% gluon jet fraction is used. This difference is approximately 2–5%(1.5–2.5%) in central (peripheral) collisions. The final systematic uncertainty associated with the unknown quark–gluon ratio in data is taken as the maximum deviation from varying the JES up and down according to the quark–gluon ratio constraints mentioned above for each p_{T}^{γ} interval.

A summary of the systematic uncertainties for $R_{\mathrm{j}\gamma}$, $\langle x_{\mathrm{j}\gamma}\rangle$, and $\Delta\phi_{\mathrm{j}\gamma}$ in PbPb collisions is shown in Tables 2 and 3, averaged over multiple p_{T}^{γ} and/or event centrality intervals. The dominant sources of uncertainties in both pp and PbPb collisions are from JES and photon purity estimation. The systematic uncertainties for PbPb and pp collisions are considered uncorrelated.

4. Results and discussion

4.1. Photon+jet azimuthal correlation

Possible modification of the back-to-back photon and recoiling jet alignment by the medium can be studied by comparing

Table 2
Summary of the relative systematic uncertainties (in %) for $p_T^\gamma > 40$ GeV/c.

Source of systematic uncertainty [%]	pp		PbPb			
			0–30% centrality		30–100% centrality	
	$\langle x_{j\gamma}\rangle$	$R_{j\gamma}$	$\langle x_{j\gamma}\rangle$	$R_{j\gamma}$	$\langle x_{j\gamma}\rangle$	$R_{j\gamma}$
Photon energy scale	<0.5	<0.5	0.7	<0.5	<0.5	0.5
Photon isolation	0.8	0.9	0.8	1.0	0.8	0.7
Photon purity	<0.5	0.5	3.1	3.5	2.0	2.2
Photon efficiency	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5
Electron contamination	<0.5	<0.5	0.5	0.9	<0.5	0.9
Jet energy scale	1.9	1.8	2.8	7.3	2.8	5.1
Jet energy resolution	0.9	1.1	2.3	3.6	1.0	1.5

Table 3
Summary of the absolute systematic uncertainties on $(1/N_{j\gamma})(dN/d\phi_{j\gamma})$ for $p_T^\gamma > 40$ GeV/c, averaged over the $\Delta\phi_{j\gamma}$ distributions.

Source of systematic uncertainty	pp	PbPb	
		0–30% centrality	30–100% centrality
Photon energy scale	$<0.01 \times 10^{-2}$	2.12×10^{-2}	0.08×10^{-2}
Photon isolation	0.27×10^{-2}	0.26×10^{-2}	0.16×10^{-2}
Photon purity	0.13×10^{-2}	0.78×10^{-2}	0.61×10^{-2}
Photon efficiency	$<0.01 \times 10^{-2}$	0.09×10^{-2}	0.03×10^{-2}
Electron contamination	0.05×10^{-2}	0.19×10^{-2}	0.14×10^{-2}
Jet energy scale	0.23×10^{-2}	1.63×10^{-2}	0.86×10^{-2}
Jet energy resolution	0.31×10^{-2}	0.46×10^{-2}	0.48×10^{-2}

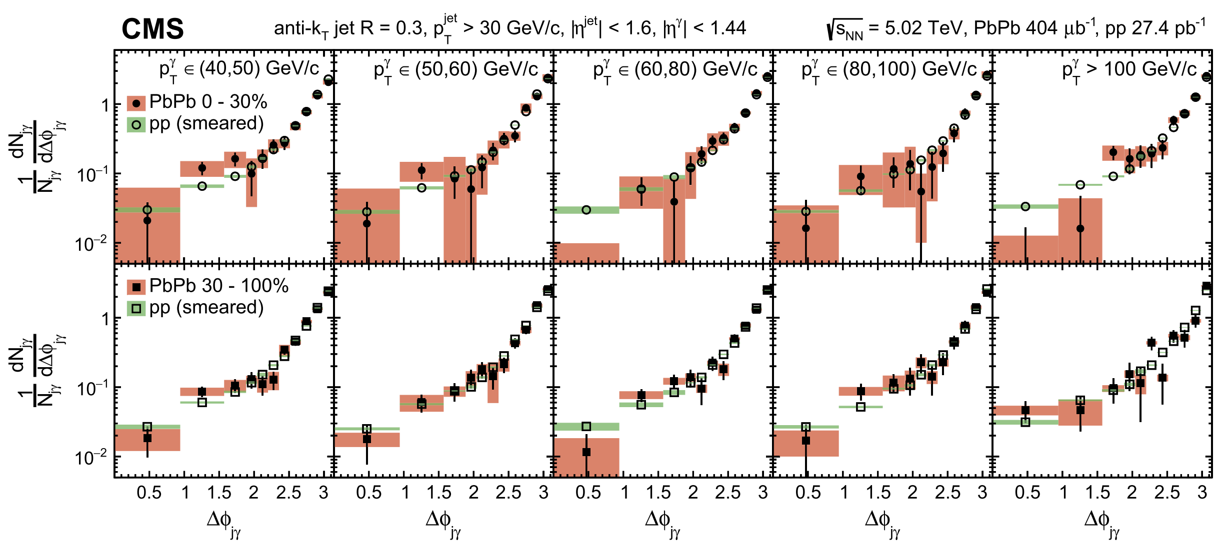

Fig. 2. The azimuthal correlation of photons and jets in five p_T^γ intervals for 0–30% centrality (top, full circles) and 30–100% centrality (bottom, full squares) PbPb collisions. The smeared pp data (open symbols) are included for comparison. The vertical lines (bands) through the points represent statistical (systematic) uncertainties.

the relative azimuthal angle ($\Delta\phi_{j\gamma}$) distributions in pp and PbPb collisions [16,17]. The distributions are normalized by the number of photon+jet pairs. The shape of the $\Delta\phi_{j\gamma}$ distribution in pp and PbPb collisions is studied in intervals of leading photon p_T and two event centrality classes, as shown in Fig. 2. The exponentially falling region ($\Delta\phi_{j\gamma} > 2\pi/3$) is fit to a normalized exponential function, as in Ref. [38], and the values of the exponents in PbPb and pp collisions from the fits are compared. Within the quoted statistical and systematic uncertainties, the PbPb results with different photon p_T and event centrality selections are consistent with the corresponding smeared pp reference data, i.e., no broadening of the distributions is observed.

4.2. Photon+jet transverse momentum imbalance

The asymmetry ratio $x_{j\gamma} = p_T^{jet}/p_T^\gamma$ is used to quantify the photon+jet p_T imbalance due to in-medium parton energy loss. In addition to the photon and jet selections used in the $\Delta\phi_{j\gamma}$ study, a $\Delta\phi_{j\gamma} > (7\pi)/8$ selection is applied to select back-to-back photon+jet topologies, suppressing the contributions from background jets as well as photon-multijet events. Fig. 3 shows the $x_{j\gamma}$ distributions for different centrality and p_T^γ regions in pp and PbPb collisions, normalized by the number of photons. In 0–30% centrality PbPb collisions, significant modifications (lower mean and smaller integral values) of the $x_{j\gamma}$ spectra with respect to the smeared pp reference data are observed, while the modifications are smaller in the 30–100% centrality PbPb collisions.

The mean values, $\langle x_{j\gamma}\rangle$ (in effect, a truncated mean because of the p_T^{jet} threshold), of the $x_{j\gamma}$ distributions are shown as a function of p_T^γ in Fig. 4 (top). The $\langle x_{j\gamma}\rangle$ values in PbPb and smeared pp collisions are consistent with each other within the quoted uncertainties over the whole p_T^γ interval probed in 30–100% centrality PbPb collisions and in the region $p_T^\gamma < 60$ GeV/c for 0–30%

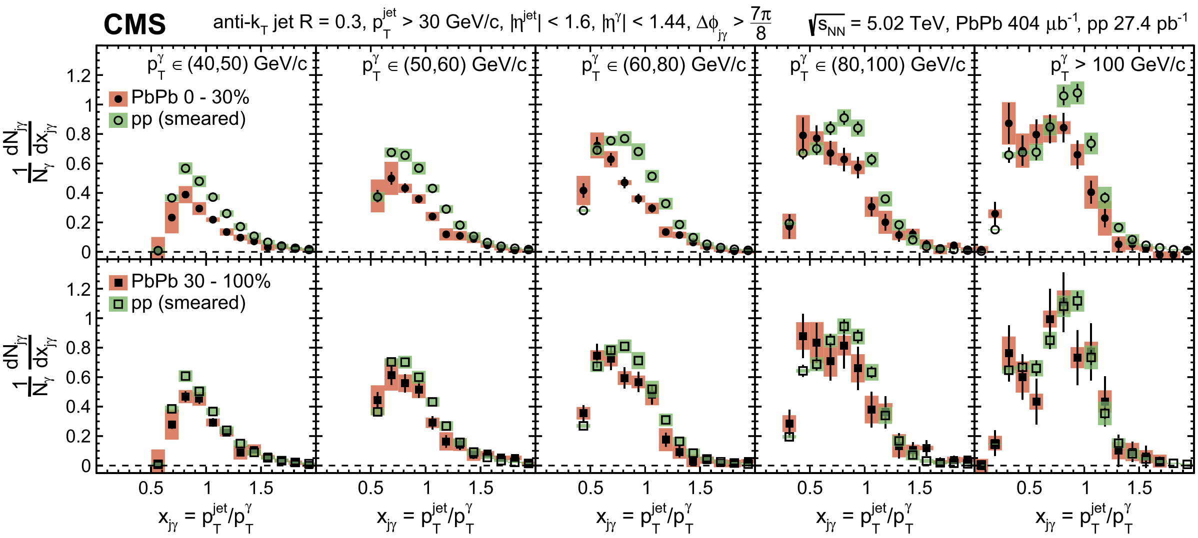

Fig. 3. Distribution of $x_{j\gamma} = p_T^{jet}/p_T^{\gamma}$ in five p_T^{γ} intervals for 0–30% centrality (top, full circles) and 30–100% centrality (bottom, full squares) PbPb collisions. The smeared pp data (open symbols) are included for comparison. The vertical lines (bands) through the points represent statistical (systematic) uncertainties.

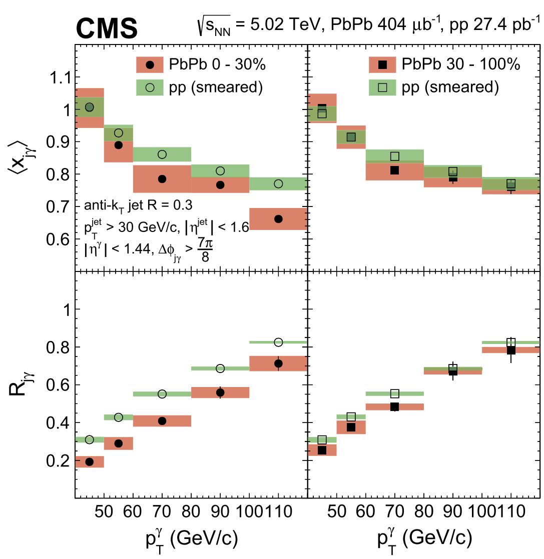

Fig. 4. The $\langle x_{j\gamma}\rangle$ values (top) and $R_{j\gamma}$, the number of associated jets per photon (bottom), in 0–30% centrality (left, full circles) and 30–100% centrality (right, full squares) PbPb collisions. The smeared pp data (open symbols) are added for comparison. The vertical lines (bands) through the points represent statistical (systematic) uncertainties.

centrality PbPb collisions. At higher p_T^{γ} in the more central PbPb events, the $\langle x_{j\gamma}\rangle$ value is lower than in pp data.

With a jet p_T threshold of 30 GeV/c, the $\langle x_{j\gamma}\rangle$ values observed for the selected photon+jet pairs likely underestimates the actual imbalance. Photon+jet pairs for which the momentum of the associated jets falls below the jet p_T threshold do not contribute to the $\langle x_{j\gamma}\rangle$ value. To assess how the "missing" jets might affect the $\langle x_{j\gamma}\rangle$ results, the average number of associated jets per photon passing the analysis selections, $R_{j\gamma}$, is shown in Fig. 4 (bottom). In the 0–30% most central PbPb collisions, the value of $R_{j\gamma}$ is found to be lower than in the smeared pp data in all leading photon p_T intervals. The absolute difference is approximately constant as a function of p_T^{γ}, but the relative difference is larger at lower p_T^{γ}, since the $R_{j\gamma}$ in pp collisions is itself lower in that region.

4.3. Jet yield ratio

Fig. 5 shows, as a function of p_T^{jet} for several p_T^{γ} intervals and two PbPb event centrality intervals, the ratio of the associated jet yields in PbPb and smeared pp events, I_{AA}^{jet}:

$$I_{AA}^{jet} = \left(\frac{1}{N_{PbPb}^{\gamma}}\frac{dN_{PbPb}^{jet}}{dp_T^{jet}}\right) \Bigg/ \left(\frac{1}{N_{pp}^{\gamma}}\frac{dN_{pp}^{jet}}{dp_T^{jet}}\right). \quad (3)$$

This variable reflects the modification of the associated jet p_T spectra by the medium. In 30–100% PbPb events, the I_{AA}^{jet} values are slightly suppressed for photon candidates with $p_T^{\gamma} < 80$ GeV/c, and consistent with unity for photon candidates with $p_T^{\gamma} > 80$ GeV/c. For 0–30% centrality PbPb events, a suppression of approximately a factor of 2 is observed at low p_T^{γ}. As the p_T^{γ} increases, the larger phase space allows quenched jets to remain above the kinematic selections, which translates to a slight excess of quenched jets appearing at low p_T^{jet}. This is seen in the top row, where I_{AA}^{jet} for low p_T^{jet} increases with p_T^{γ} while the I_{AA}^{jet} at large p_T^{jet} stays roughly constant.

4.4. Centrality dependence

The centrality dependence in PbPb collisions of $x_{j\gamma}$ spectra for $p_T^{\gamma} > 60$ GeV/c is shown in Fig. 6. In the most peripheral collisions (50–100% centrality), the $x_{j\gamma}$ distribution agrees with the smeared pp reference data. As collisions become more central, the PbPb distributions shift towards lower $x_{j\gamma}$ and the integrals of the $x_{j\gamma}$ spectra become smaller. This is consistent with the expectation that a larger amount of parton p_T is transported out of the jet cone as a consequence of the larger average path length that the parton needs to travel through in more central PbPb collisions [57,58].

Fig. 7 shows $\langle x_{j\gamma}\rangle$ and $R_{j\gamma}$ in pp and PbPb collisions as a function of event centrality, quantified by $\langle N_{part}\rangle$, which is the mean number of participating nucleons within a given centrality interval. The $\langle N_{part}\rangle$ values are estimated from a MC Glauber model [15,59]. In central collisions, a suppression of both $\langle x_{j\gamma}\rangle$ and $R_{j\gamma}$ is observed in comparison to the smeared pp reference data, con-

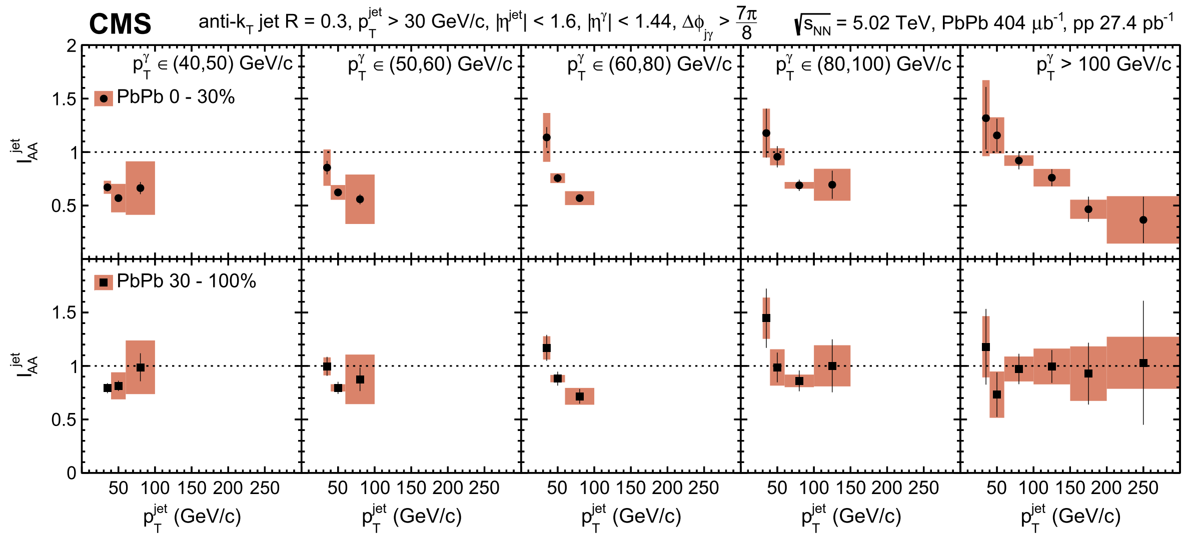

Fig. 5. The I_{AA}^{jet} *vs.* p_T^{jet} for 0–30% centrality (top) and 30–100% centrality (bottom) PbPb collisions. The vertical lines (bands) through the points represent statistical (systematic) uncertainties.

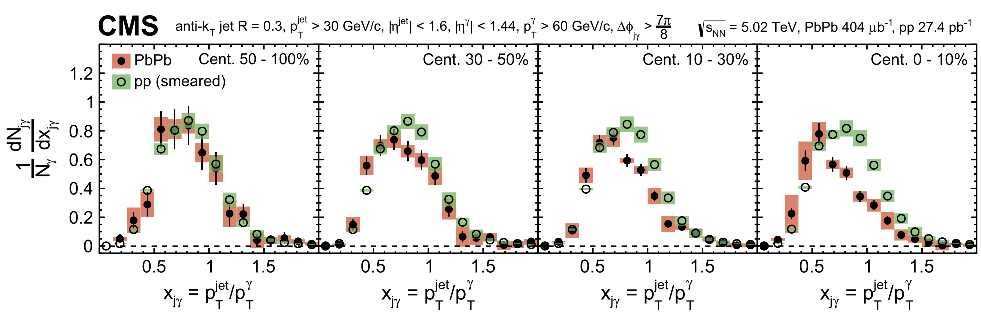

Fig. 6. The centrality dependence of $x_{j\gamma}$ of photon+jet pairs normalized by the number of photons for PbPb (full markers) and smeared pp (open markers) data. The vertical lines (bands) through the points represent statistical (systematic) uncertainties.

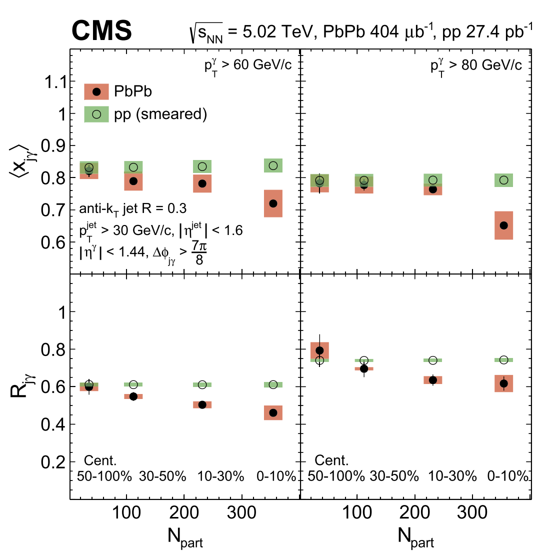

Fig. 7. The $\langle x_{j\gamma}\rangle$ (top) and $R_{j\gamma}$ (bottom) as a function of $\langle N_{part}\rangle$ for $p_T^{\gamma} > 60$ GeV/c (left) and $p_T^{\gamma} > 80$ GeV/c (right). The PbPb results (full markers) are compared to pp results (open markers) smeared by the relative jet energy resolution corresponding to each centrality interval. The vertical lines (bands) through the points represent statistical (systematic) uncertainties.

sistent with significant in-medium energy loss of the associated jets.

4.5. Comparison to theoretical models

The results for PbPb collisions presented in Fig. 2 for $\Delta\phi_{j\gamma}$ and Fig. 3 for $x_{j\gamma}$ are compared with several theoretical calculations with different approaches to modeling the jet energy loss in Figs. 8 and 9, respectively. The $x_{j\gamma}$ distributions assumed by the different model calculations in pp collisions are compared to the unsmeared pp data in Fig. 10. The JEWEL model is a dynamical, perturbative framework for jet quenching, which has been extended to simulate boson-jet events [37,60]. The LBT 2017 model [34] uses a linearized Boltzmann transport model for jet propagation through the medium, including the recoiled medium partons in the reconstruction of the partonic jets. The hybrid model [35,36] combines a perturbative description of the weakly coupled physics of jet production and evolution with a gauge/gravity duality description of the strongly coupled dynamics of the medium, and of the soft exchanges between the jet and the medium. The calculations from the JEWEL and hybrid models have been smeared to the corresponding JER in pp or PbPb collisions.

Predictions from the JEWEL and hybrid models have previously shown reasonable agreement with measurements of inclusive jet nuclear modification factors [36,61]. For the results reported in this Letter, all models describe well the pp results. They also capture the general features of the 0–30% PbPb data, although the hybrid model appears to better describe the $x_{j\gamma}$ results. As shown in Fig. 9, the JEWEL and LBT models appear to underestimate the $x_{j\gamma}$ spectra in the high $x_{j\gamma}$ region ($x_{j\gamma} > 0.9$) for central PbPb col-

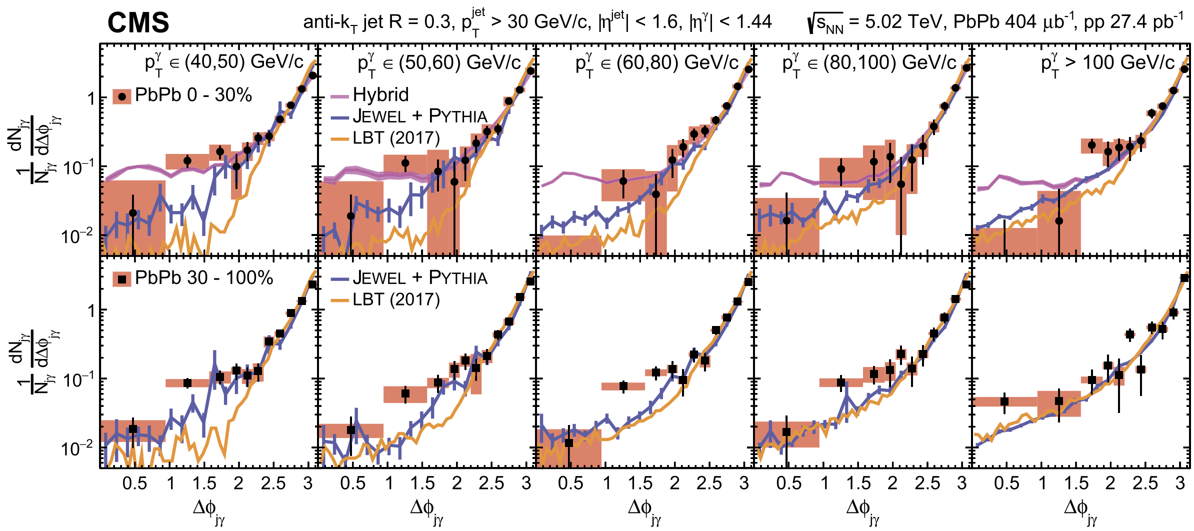

Fig. 8. The azimuthal correlation of photons and jets in five p_T^γ intervals for 0–30% centrality (top, full circles) and 30–100% centrality (bottom, full squares) PbPb collisions. The data points shown are identical to those in Fig. 2. Theoretical calculations from JEWEL [37,60], LBT [34], and hybrid model [35,36] are included for comparison.

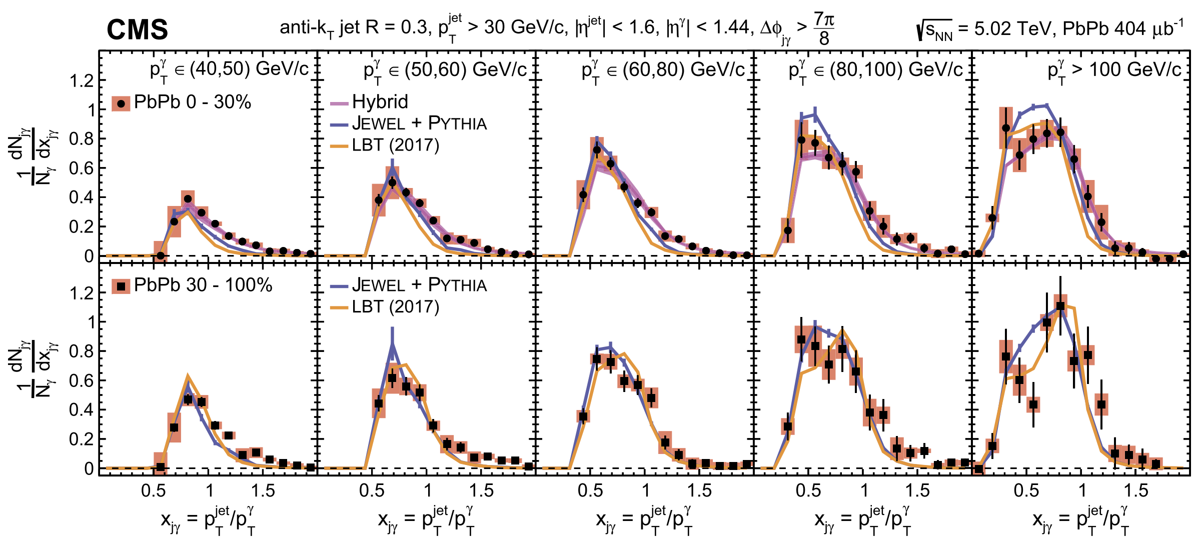

Fig. 9. The $x_{j\gamma}$ distributions in five p_T^γ intervals for 0–30% centrality (top, full circles) and 30–100% centrality (bottom, full squares) PbPb collisions. The data points shown are identical to those in Fig. 3. Theoretical calculations from JEWEL [37,60], LBT [34], and hybrid model [35,36] are included for comparison.

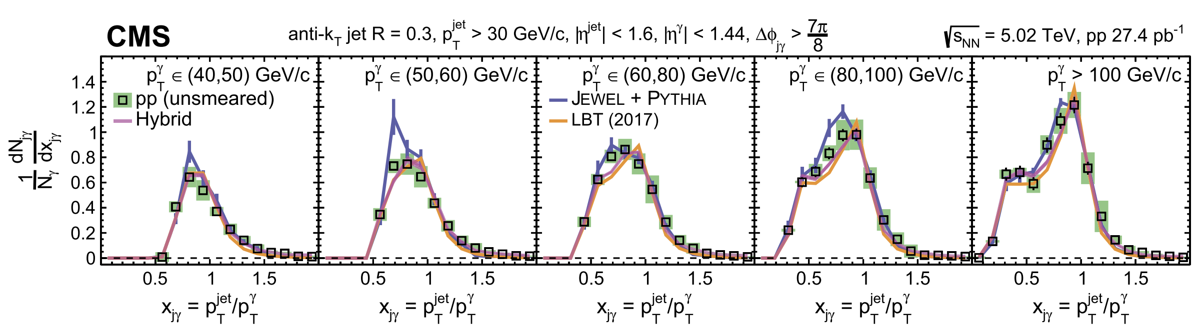

Fig. 10. The $x_{j\gamma}$ distributions in five p_T^γ intervals for unsmeared pp data (full squares). The $x_{j\gamma}$ distributions in pp collisions assumed by the JEWEL [37,60], LBT [34], and hybrid models [35,36] discussed in this Letter are also shown for comparison.

lisions, which suggests that the amount of energy transported out of the jet cone is larger in these models than in data. A similar effect is also hinted at in the 30–100% PbPb data, which can be attributed to the fact that those distributions are dominated by events in the 30–50% centrality interval, where energy loss effects are still significant. The models are also consistent with data in that none of them show a broadening of the observed $\Delta\phi_{j\gamma}$ distributions in PbPb compared to pp collisions in the photon and jet kinematic ranges presented, despite their implementing contributions from partonic collisions.

5. Summary

Correlations of isolated photons with transverse momentum $p_T^\gamma > 40$ GeV/c and pseudorapidity $|\eta^\gamma| < 1.44$ and associated jets with $p_T^{jet} > 30$ GeV/c and $|\eta^{jet}| < 1.6$, have been studied for the first time in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, using a large data sample collected by the CMS experiment. No significant azimuthal angular broadening between photons and the associated jets is observed in PbPb data as compared to pp data, for all event centralities and multiple photon p_T intervals. The $x_{j\gamma} = p_T^{jet}/p_T^\gamma$ and the average number of associated jets per photon, $R_{j\gamma}$, are studied in different leading photon p_T and PbPb collision centrality intervals. For all $p_T^\gamma > 60$ GeV/c intervals, the $\langle x_{j\gamma} \rangle$ and $R_{j\gamma}$ values in the 0–30% most central PbPb collisions are found to be lower than those in the corresponding pp reference data, indicating that a larger fraction of jets lose energy and thus fall below 30 GeV/c in PbPb collisions. The differences between the pp and PbPb results increase as collisions become more central. A shift of the jet spectra towards lower p_T^{jet} is observed when comparing the yields of associated jets in the 0–30% most central PbPb collisions to those in pp collisions. These new results are qualitatively similar to those reported at $\sqrt{s_{NN}} = 2.76$ TeV and to calculations from various theoretical models. The better statistical precision of the new higher energy data provides an opportunity to test theoretical models against data over a wide kinematic range in p_T^γ and $x_{j\gamma}$, and for different event centralities, using a selection of partons with defined flavor (quark/gluon) and initial kinematics.

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