Azimuthal separation in nearly back-to-back jet topologies in inclusive 2- and 3-jet events in pp collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A measurement for inclusive 2- and 3-jet events of the azimuthal correlation between the two jets with the largest transverse momenta, $\Delta \phi_{12}$, is presented. The measurement considers events where the two leading jets are nearly collinear (“back-to-back”) in the transverse plane and is performed for several ranges of the leading jet transverse momentum. Proton-proton collision data collected with the CMS experiment at a center-of-mass energy of 13 TeV and corresponding to an integrated luminosity of 35.9 fb$^{-1}$ are used. Predictions based on calculations using matrix elements at leading-order and next-to-leading-order accuracy in perturbative quantum chromodynamics supplemented with leading-log parton showers and hadronization are generally in agreement with the measurements. Discrepancies between the measurement and theoretical predictions are as large as 15%, mainly in the region $177^\circ < \Delta \phi_{12} < 180^\circ$. The 2- and 3-jet measurements are not simultaneously described by any of models.

Submitted to the European Physical Journal C

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*See Appendix A for the list of collaboration members
1 Introduction

Collimated streams of particles (jets) can be produced in highly energetic parton-parton interactions in proton-proton (s) collisions, and their properties are described by the theory of strong interactions, quantum chromodynamics (QCD). In the lowest order perturbative QCD (pQCD), two jets with high transverse momenta $p_T$ are produced “back-to-back” in the transverse plane. Higher order corrections lead to deviations from this configuration. Experimentally, this can be investigated by the measurement of the azimuthal separation, $\Delta \phi_{12} = |\phi_{jet1} - \phi_{jet2}|$, between the two leading $p_T$ jets in the transverse plane. Within the framework of pQCD, a final state with three or more partons is required for significant deviations from $\Delta \phi_{12} = 180^\circ$. However, when deviations of $\Delta \phi_{12}$ from 180° are small, a pQCD calculation at a fixed order in the strong coupling $\alpha_s$ becomes unstable and a resummation of soft parton emissions to all orders in $\alpha_s$ has to be performed. This resummation is approximated through the use of parton showers in Monte Carlo (MC) event generators.

Azimuthal correlations in inclusive 2-jet events have been measured previously by the D0 Collaboration in $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96$ TeV [1,2], in pp collisions by the ATLAS Collaboration at $\sqrt{s} = 7$ TeV [3], and by the CMS Collaboration at $\sqrt{s} = 7, 8,$ and 13 TeV [4-6], but none of the measurements considered in detail the region close to the back-to-back configuration. A detailed study of azimuthal correlations close to the back-to-back configuration allows a more precise test of different resummation strategies, and it is a first step towards an improved understanding of the effects of soft initial and final state gluons [7,8].

In this article measurements are reported of the normalized inclusive 2-jet distribution as a function of the azimuthal separation $\Delta \phi_{12}$ between the two leading $p_T$ jets (jets 1 and 2),

$$\frac{1}{\sigma_{pT_{max}}} \frac{d\sigma}{d\Delta \phi_{12}},$$

in several intervals of the leading jet $p_T$ ($p_{T_{max}}$) within the rapidity range $|y| < 2.5$. The total dijet cross section $\sigma_{pT_{max}}$ is measured within each range of $p_{T_{max}}^2$ integrated over the full range in $\Delta \phi_{12}$. The binning of the measurement presented here is much finer than that of Ref. [6]. We consider $\Delta \phi_{12}$ in the range $170^\circ < \Delta \phi_{12} \leq 180^\circ$.

The inclusive 3-jet distributions, differential in $\Delta \phi_{12}$ and $p_{T_{max}}$, with the $p_T$ of third highest $p_T$ jet typically being 1-2 orders of magnitude smaller than $p_{T_{max}}^3$, are also suitable to test resummation effects arising from the presence of multiple scales in the interaction. Measurements of the inclusive 3-jet distribution normalized to $\sigma_{pT_{max}}$ are also presented, for several ranges of $p_{T_{max}}$, and within $|y| < 2.5$.

The measurements are performed using data collected from pp collisions at $\sqrt{s} = 13$ TeV during 2016 with the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of 35.9 fb$^{-1}$.

2 The CMS Detector

The central feature of the CMS detector is a superconducting solenoid, 13 m in length and 6 m in inner diameter, providing an axial magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL) and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Charged-particle trajectories are measured by the tracker with full azimuthal
coverage within pseudorapidities $|\eta| < 2.5$. The ECAL, which is equipped with a preshower detector in the endcaps, and the HCAL cover the region $|\eta| < 3.0$. Forward calorimeters extend the pseudorapidity coverage provided by the barrel and endcap detectors to the region $3.0 < |\eta| < 5.2$. Finally, muons are measured up to $|\eta| < 2.4$ by gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A 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. [9].

3 Theoretical predictions

Leading-order (LO) and next-to-LO (NLO) predictions are investigated. Among the LO event generators, both PYTHIA 8 [10] (version 8.219) and HERWIG++ [11] (version 2.7.1) are used for predictions because they feature different parton showering (PS) algorithms for soft and collinear parton radiation at leading-log accuracy. In PYTHIA 8 the PS emissions cover a region of phase space ordered in $x$ (fraction of the proton momentum carried by the parton) and the $p_T$ of the emitted parton, whereas in HERWIG++ the parton emissions are ordered in $x$ and the angle of the radiated parton (angular ordering). The Lund string model [12] is used for hadronization in PYTHIA 8 [10], whereas in HERWIG++ the cluster fragmentation model [13] is applied. Multiparton interactions (MPI) are simulated in PYTHIA 8 (tune CUETP8M1 [14] with the parton distribution function (PDF) set NNPDF2.3LO [15, 16]) and in HERWIG++ (tune CUETHppS1 [14] with the PDF set CTEQ6L1 [17]) with parameters tuned to measurements in pp collisions at the LHC and $p+p$ collisions at the Tevatron.

The MadGraph5_aMC@NLO [18] version 2.3.3 event generator (labelled as MadGraph in the following) interfaced with PYTHIA 8 with tune CUETP8M1 is also used in the analysis. Processes with up to 4 final-state partons at LO accuracy are calculated using the NNPDF2.3LO PDF set. The $k_T$-MLM matching procedure [19] is used with a matching scale of 10 GeV.

Among the NLO event generators, predictions obtained using the POWHEG BOX library [20–22] (version 2) with the PDF set NNPDF3.0NLO [23] are considered. The event generators PYTHIA 8 (tune CUETP8M1) and HERWIG++ (tune CUETHppS1) are used to simulate PS, hadronization, and MPI. The POWHEG generator in dijet mode [24], referred to as PH-2), provides an NLO $2 \rightarrow 2$ calculation, and the POWHEG generator in three-jet mode [25] (using the MiNLO scheme [26, 27]), referred to as PH-3j, provides an NLO $2 \rightarrow 3$ calculation. For the PH-2j matrix elements (ME), a minimum $p_T$ of 100 GeV is required on the partons in the Born process, while for the PH-3j ME the minimum is lowered to 10 GeV to ensure coverage of the full phase space. These thresholds are applied to optimize the generation of events in the phase space of interest. The matching between the POWHEG matrix element calculations and the PYTHIA 8 underlying event (UE) simulation is performed by using the shower-veto procedure (User-Hook option 2 [10]). The matching between the POWHEG matrix element calculations and the HERWIG++ UE is performed by using a truncated shower [20].

Events generated by PYTHIA 8 (tune CUETP8M1), HERWIG++ (tune CUETHppS1), and MadGraph interfaced with PYTHIA 8 (tune CUETP8M1) are passed through a full detector simulation based on GEANT4 [28]. The simulated events are reconstructed with standard CMS programs.

Table [1] summarizes the theoretical predictions used in the present analysis.
Table 1: Monte Carlo event generators, parton densities, and underlying event tunes used for comparison with measurements.

<table>
<thead>
<tr>
<th>Matrix element generator</th>
<th>Simulated diagrams</th>
<th>PDF set</th>
<th>Tune</th>
</tr>
</thead>
<tbody>
<tr>
<td>MadGraph [18,19] + PYTHIA 8.219 [10]</td>
<td>2→2, 2→3, 2→4 (LO)</td>
<td>NNPDF2.3LO [15,16]</td>
<td>CUETP8M1 [14]</td>
</tr>
</tbody>
</table>

4 Jet reconstruction and event selection

The measurements are based on data samples collected with single-jet high-level triggers [29,30]. The five single-jet triggers require at least one jet in the event with $p_T > 140, 200, 320, 400,$ or 450 GeV within the full rapidity coverage of the CMS calorimetry. Table 2 shows the various $p_T^{\text{max}}$ regions accessed by the various triggers and the integrated luminosity for each trigger in the analysis. Each trigger is fully efficient for jets in the corresponding $p_T$ range in Table 2.

Table 2: The integrated luminosity for each trigger sample in the analysis, and trigger used for each $p_T^{\text{max}}$ range.

<table>
<thead>
<tr>
<th>HLT $p_T$ threshold (GeV)</th>
<th>140</th>
<th>200</th>
<th>320</th>
<th>400</th>
<th>450</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{L}$ (fb$^{-1}$)</td>
<td>0.024</td>
<td>0.11</td>
<td>1.77</td>
<td>5.2</td>
<td>36</td>
</tr>
<tr>
<td>$p_T^{\text{max}}$ region (GeV)</td>
<td>200–300</td>
<td>300–400</td>
<td>400–500</td>
<td>500–600</td>
<td>$&gt;600$</td>
</tr>
</tbody>
</table>

Particles are reconstructed and identified using a particle-flow (PF) algorithm [31], which utilizes an optimized combination of information from the various elements of the CMS detector. Jets are reconstructed by clustering the four-vectors of the PF candidates with the infrared- and collinear-safe anti-$k_T$ clustering algorithm [32] with a distance parameter $R = 0.4$. The clustering is performed with the FASTJET package [33]. To reduce the contribution to the reconstructed jets from additional pp interactions within the same bunch crossing (pileup), the charged-hadron subtraction technique [34] is used to remove tracks identified as originating from pileup vertices. The average number of pileup interactions per single bunch crossing observed in the data is about 27. The pileup contribution from neutral hadrons is corrected using a jet-area-based correction technique [35].

For this analysis, jets with rapidity $|y| < 5.0$ are reconstructed. For both the inclusive 2- and 3-jet samples, the events are selected by requiring the two highest $p_T$ jets to have $|y| < 2.5$ and $p_T > 100$ GeV. For the inclusive 3-jet events a third jet with $p_T > 30$ GeV and $|y| < 2.5$ is required. Contributions from pileup are negligible because the pileup removal algorithm has an efficiency of $\sim 99\%$ for jets with $30 < p_T < 50$ GeV and $|y| < 2.5$ [56].

5 Measurements of the normalized inclusive 2- and 3-jet distributions

The normalized inclusive 2- and 3-jet distributions as a function of $\Delta \phi_{12}$ are corrected for detector resolution. We achieve this by unfolding the observables to the level of stable final-state particles. In this way, a direct comparison of these measurements to results from other exper-
iments and to QCD predictions is possible. Particles are considered stable if their mean decay length is larger than 1 cm.

The unfolding procedure is based on the D’Agostini algorithm [37], which is implemented in the RooUNFOLD package [38], by using a response matrix that maps the generated jets onto the jets reconstructed by the CMS detector. The regularization (number of iterations) of the unfolding procedure is chosen by comparing the difference in $\chi^2$ between data and MC at detector level to that between data and MC at particle level. The consistency of the unfolding procedure is checked against the alternative TUNFOLD package [39, 40], which uses a least square minimization with Tikhonov regularization. Both methods provide equivalent results.

The unfolding is performed in $\Delta\phi_{12}$. The response matrices are obtained using simulated events from the PYTHIA 8 event generator with the tune CUETP8M1. The difference between the unfolded distributions and the distributions at detector level range from $\sim$1% for the low $p_T^{\text{max}}$ regions up to $\sim$5% for the high $p_T^{\text{max}}$ regions.

The sources of systematic uncertainties arise primarily from the jet energy scale calibration (JES), the jet energy resolution (JER), the $\Delta\phi_{12}$ resolution, and the model dependence of the unfolding matrix. The effect of migrations between $p_T^{\text{max}}$ regions is very small because of the normalization of the cross sections in each $p_T^{\text{max}}$ range and therefore is neglected.

The $\Delta\phi_{12}$ resolution is $\sim$0.5°, as obtained from fully simulated event samples from PYTHIA 8 and MadGRAPH. A bin size of 1° is a compromise between the ability to study the back-to-back region and the impact of the unfolding correction of $\sim$2%. In Ref. [6] the study is focused on a different $\Delta\phi_{12}$ region, and a coarser bin size is chosen to account for the smaller size of the data sample.

Alternative response matrices are used to unfold the measured spectra by varying the $\Delta\phi_{12}$ resolution by $\pm$10%, an amount motivated by the observed difference between data and simulation in the $\Delta\phi_{12}$ bins.

An additional systematic uncertainty is caused by the dependence of the response matrix on the choice of the MC generator. Alternative response matrices are built using the HERWIG++ and MadGRAPH + PYTHIA 8 event generators. Because this analysis uses a finer binning compared with that of Ref. [6], the sensitivity to the uncertainty in the unfolding is increased. The observed effect from bin migration is less than 2%.

The JER and shifts in the JES can cause events to migrate between the $p_T^{\text{max}}$ regions. The JES uncertainties on the energy measurement are estimated to be 1–2% [34]. The resulting JES uncertainties in the normalized inclusive 2-jet distributions due to bin migrations are less than 2%, whereas for the normalized inclusive 3-jet distributions they are less than 3%. The effect of the JER uncertainties [34] is estimated by varying the JER parameters by one standard deviation up and down and comparing the results before and after the changes. The JER-induced uncertainties are less than 0.2% for the inclusive 2-jet $\Delta\phi_{12}$ measurement and below 0.4% for the normalized inclusive 3-jet measurement.

6 Comparison to theoretical predictions

In this section the measurements are compared with different theoretical predictions introduced in Section 5. In all figures displaying ratios, the solid band indicates the total experimental uncertainty and the error bars represent the statistical uncertainties from the simulation. In the figures displaying the normalized distributions, the statistical uncertainties of the measurements are often so small that the uncertainty bars are smaller than the symbol size.
The unfolded normalized inclusive 2-jet distribution as a function of $\Delta \phi_{12}$ is shown in Fig. 1 and compared with the predictions from HERWIG++ (solid lines) and PH-2J + PYTHIA 8 (dotted lines) for different $p_T^{\text{max}}$ regions. The distributions are strongly peaked at 180° and become steeper with increasing $p_T^{\text{max}}$. The ratio of the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 event generator predictions to data are depicted in Fig. 2 for the inclusive 2-jet distributions in the nine $p_T^{\text{max}}$ ranges. Among the event generators, PYTHIA 8 and HERWIG++ show the largest deviations from the measurements for the $p_T^{\text{max}} < 800$ GeV regions in the inclusive 2-jet case, and the MADGRAPH + PYTHIA 8 event generator gives the best description in the same regions. The three generators show large deviations from the measurements in the $p_T^{\text{max}} > 800$ GeV regions.

The ratios of the NLO predictions to data for the unfolded normalized inclusive 2-jet distributions for the different $p_T^{\text{max}}$ regions are shown in Fig. 3. The NLO calculations considered are PH-2J + PYTHIA 8, PH-2J + HERWIG++, and PH-3J + PYTHIA 8. Among these NLO predictions PH-3J + PYTHIA 8 agrees better with the data. The PH-2J + HERWIG++ prediction is similar to the one of PH-3J + PYTHIA 8, except for the lowest $p_T^{\text{max}}$ region.

In Fig. 4 the unfolded normalized inclusive 3-jet distribution as a function of $\Delta \phi_{12}$ are compared with the predictions from HERWIG++ (solid lines) and PH-2J + PYTHIA 8 (dotted lines) for different $p_T^{\text{max}}$ regions. The ratios of the normalized inclusive 3-jet distributions for the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to data are shown in Fig. 5 for the different $p_T^{\text{max}}$ regions. In contrast to the 2-jet case, MADGRAPH + PYTHIA 8 shows the largest deviations from the measurements close to 180°, whereas PYTHIA 8 and HERWIG++ give a good description of the data.

The ratios of the NLO predictions from PH-2J + PYTHIA 8, PH-2J + HERWIG++, and PH-3J + PYTHIA 8 to data for the normalized inclusive 3-jet distributions are shown in Fig. 6. All the considered NLO+PS predictions fail to describe the measurements close to 180°. The predictions from PH-3J and MADGRAPH (Fig. 5) behave very differently, in contrast to their similar
Figure 2: Ratios of the normalized inclusive 2-jet distributions for the PYTHIA 8, HERWIG++, and MADGRAPH + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all the $p_T^{\text{max}}$ regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data.

trend in the inclusive 2-jet case.

Since PYTHIA 8, PH-2J + PYTHIA 8, PH-3J + PYTHIA 8, and MADGRAPH + PYTHIA 8 use the same parton shower, the observed differences in the predictions can be attributed to the treatment of the additional partons present in the POWHEG and MADGRAPH ME.

In general we observe that the $\Delta\phi_{12}$ region close to $180^\circ$ is not well described by the predictions. The predictions agree better with the measurements for increasing $p_T^{\text{max}}$ and moving further away from the back-to-back region in $\Delta\phi_{12}$, where the contribution of resummation effects becomes smaller. The fact that none of the generators is able to describe the 2- and 3-jet measurements simultaneously suggests that the observed differences (of the order of 10%) are related to the way soft partons are simulated within the PS. The observed differences between $p_T$ and angular ordered PS for the LO generators PYTHIA 8 and HERWIG++ are small (Figs. 2 and 3) compared to the MADGRAPH predictions, which can be attributed to the presence of higher order ME.

The theoretical calculations have an intrinsic uncertainty arising from the freedom of choice of the renormalization and factorization scales ($\mu_r$ and $\mu_f$), the choice of the PDF and $\alpha_S(m_Z)$, and the modeling of nonperturbative effects and PS. The total theoretical uncertainty is the quadratic sum of the uncertainties from the scale, PDF, $\alpha_S$, and PS variations. Despite the better agreement of PH-3J, the PH-2J event generator is used instead for the estimation of the scale, PDF, and $\alpha_S$ uncertainties, because of the larger event sample. For the estimation of the PS uncertainty PYTHIA 8 is utilized. The following four sources of theoretical uncertainties are analyzed:

- The uncertainties due to the renormalization and factorization scales of the hard pro-
Inclusive 2-jet distributions for the PH-2J + PYTHIA8, PH-3J + PYTHIA8, and PH-2J + HERWIG++ predictions to data as a function of the azimuthal separation of the two leading jets $\Delta \phi_{12}$, for all the $p_T^{\text{max}}$ regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data. The PH-3J prediction is not shown for the highest bin in $p_T^{\text{max}}$ because of the large statistical fluctuations.

The uncertainty due to PS is evaluated with the PYTHIA 8 event generator by varying the default choice $\mu_r = \mu_f = p_T$ of the underlying Born configuration between $p_T/2$ and $2p_T$. The envelope of the following seven combinations is considered: $(\mu_r/p_T, \mu_f/p_T) = (0.5, 0.5), (0.5, 1), (1, 0.5), (1, 1), (1, 2), (2, 1), (2, 2)$.

- The PDF uncertainties are evaluated according to the prescriptions for the NNPDF3.0 NLO PDF set. There are 100 replicas of the NNPDF3.0 NLO PDF set. For each replica the cross section is calculated and the uncertainty is taken as the envelope from all the replicas.

- The uncertainty due to the value of the strong coupling $\alpha_S$ is obtained by a variation of $\alpha_S(m_Z)$ by $\pm 0.001$, as recommended in Ref. [11].

- The uncertainty due to PS is evaluated with the PYTHIA 8 event generator by varying the default renormalization scale choice $\mu_r = p_T$ of the branching in initial state (ISR) and final state radiation (FSR) between $\mu_r/2$ and $2\mu_r$. The envelope of the following nine combinations is considered: $(\text{ISR } \mu_r/p_T, \text{FSR } \mu_r/p_T) = (0.5, 0.5), (0.5, 1), (0.5, 2), (1, 0.5), (1, 1), (1, 2), (2, 0.5), (2, 1), (2, 2)$.

The nonperturbative contributions (MPI and hadronization) are included in the calculations above. The uncertainty from these contributions are estimated from the different choices of the UE tune and found to be negligible.

The uncertainty from PS dominates for the normalized inclusive 2-jet distributions. It is one order of magnitude larger than the rest of the sources near $\Delta \phi_{12} = 180^\circ$. On the other hand, for the normalized inclusive 3-jet distributions, the main contributions come from PS and PDF.
Figure 4: Normalized inclusive 3-jet distributions as a function of the azimuthal separation of the two leading jets $\Delta \phi_{12}$ for different $p_T^{\text{max}}$ regions (left and right). The data are represented by the markers and the theory by histograms. Overlaid with the data are predictions from the HERWIG++ event generator (solid lines) and PH-PYTHIA8 (dotted lines). The total experimental uncertainty is depicted as error bars on the predictions.

Figure 5: Ratios of the normalized inclusive 3-jet distributions for the PYTHIA8, HERWIG++, and MADGRAPH + PYTHIA8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta \phi_{12}$, for all the $p_T^{\text{max}}$ regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data.

uncertainties. The predictions from PH-2J + PYTHIA8 and PH-2J + HERWIG++ (Fig. 3) show the differences from using different PS models together with different matching procedures.
Figure 6: Ratios of the normalized inclusive 3-jet distributions for the PH-2J + PYTHIA 8, PH-3J + PYTHIA 8, and PH-2J + HERWIG++ predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all $p_T^{\text{max}}$ regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainty of the simulated data. The PH-3J prediction is not shown for the highest bin in $p_T^{\text{max}}$ because of the large statistical fluctuations.

Figs. 7(8) show the ratios of the PH-2J predictions to data for the normalized inclusive 2(3)-jet distributions for the different $p_T^{\text{max}}$ regions. The solid beige band indicates the total experimental uncertainty, and the hatched band represents the total theoretical uncertainty. For the inclusive 2-jet distributions, the theoretical uncertainty is larger than the experimental one in the region close to $\Delta\phi_{12} = 180^\circ$ (Fig. 7). This is because the contribution from PS dominates in this region, and its uncertainty is large. For the inclusive 3-jet distributions (Fig. 8), the theoretical uncertainty is smaller in the region close to $180^\circ$. In this case, the region close to $180^\circ$ is not filled by the partons from the PS, but by the third parton from PH-2J, leading to a smaller PS uncertainty.

7 Summary

Measurements of the normalized inclusive 2- and 3-jet distributions as a function of the azimuthal separation $\Delta\phi_{12}$ between the two jets with the highest transverse momentum $p_T$, in the collinear back-to-back region, are presented for several $p_T^{\text{max}}$ ranges of the leading jet. The measurements are performed using data collected with the CMS experiment at the LHC, corresponding to an integrated luminosity of 35.9 fb$^{-1}$ of pp collisions at a center-of-mass energy of 13 TeV.

The measured $\Delta\phi_{12}$ distributions generally agree with predictions from PYTHIA 8, HERWIG++, MadGRAPH + PYTHIA 8, PH-2J + HERWIG++, and POWHEG (PH-2J and PH-3J) matched to PYTHIA 8. Discrepancies between the measurement and theoretical predictions are as large as 15%, mainly in the region $177^\circ < \Delta\phi_{12} < 180^\circ$. The predictions agree better with the measure-
Figure 7: Ratios of the normalized inclusive 2-jet distributions for the PH-2J + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all $p_T^{\text{max}}$ regions. The solid beige band indicates the total experimental uncertainty and the hatched band represents the total theoretical uncertainty.

Figure 8: Ratios of the normalized inclusive 3-jet distributions for the PH-2J + PYTHIA 8 predictions to data as a function of the azimuthal separation of the two leading jets $\Delta\phi_{12}$, for all $p_T^{\text{max}}$ regions. The solid beige band indicates the total experimental uncertainty, the hatched band represents the total theoretical uncertainty.
ments for larger $p_T^{\text{max}}$ and smaller $\Delta \phi_{12}$, where the contribution of resummation effects becomes smaller. The 2- and 3-jet measurements are not simultaneously described by any of models.

The tree-level multijet event generator MadGraph in combination with Pythia 8 for showering, hadronization, and multiparton interactions, shows deviations from the measured $\Delta \phi_{12}$ for the inclusive 2-jet case, and even larger deviations for the 3-jet case. The Pythia 8 and Herwig++ predictions show deviations (up to 10%) for the 2-jet inclusive distributions, whereas their predictions are in reasonable agreement with the inclusive 3-jet distributions.

The next-to-leading-order PH-2j + Pythia 8 prediction does not describe the data and a different trend compared to Pythia 8 and Herwig++ towards $\Delta \phi_{12} = 180^\circ$ is observed. The PH-3j + Pythia 8 predictions agree with the measurements except for the last bin in the low $p_T^{\text{max}}$ intervals. The PH-2j + Herwig++ prediction agrees well with the measurement in the highest $p_T^{\text{max}}$ ranges. For the inclusive 3-jet case, PH-2j + Pythia 8 performs similarly to Pythia 8 and Herwig++ in the whole $\Delta \phi_{12}$ range for high $p_T^{\text{max}}$ intervals. MadGraph + Pythia 8, PH-3j + Pythia 8, and PH-2j + Herwig++ show deviations from the measurements of up to 15%.

The measurement of correlations for collinear back-to-back dijet configurations probes the multiple scales involved in the event and, therefore, the differences observed between predictions and the measurements illustrate the importance of improving the models of soft parton radiation accompanying the hard process.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, FAPERGS, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (USA).

Individuals have received support from the Marie-Curie program and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A.P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l’Industrie et dans l’Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the F.R.S.-FNRS and FWO (Belgium) under the “Excellence of Science – EOS” – be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No.
Z181100004218003; the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Lendület (“Momentum”) Program and the János Bolyai Research Scholarship of the Hungarian Academy of Sciences, the New National Excellence Program ÚNKP, the NKFIHA research grants 123842, 123959, 124845, 124850, and 125105 (Hungary); the Council of Science and Industrial Research, India; the HOMING PLUS program of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus program of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998, and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Estatal de Fomento de la Investigación Científica y Técnica de Excelencia María de Maeztu, grant MDM-2015-0509 and the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (USA).
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