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# Dijet Azimuthal Decorrelations in pp Collisions at $\sqrt{s} = 7$ TeV

The CMS Collaboration\*

## Abstract

Measurements of dijet azimuthal decorrelations in pp collisions at  $\sqrt{s} = 7$  TeV using the CMS detector at the CERN LHC are presented. The analysis is based on an inclusive dijet event sample corresponding to an integrated luminosity of  $2.9 \text{ pb}^{-1}$ . The results are compared to predictions from perturbative QCD calculations and various Monte Carlo event generators. The dijet azimuthal distributions are found to be sensitive to initial-state gluon radiation.

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\*See Appendix A for the list of collaboration members



High-energy proton-proton collisions with high momentum transfer are described within the framework of Quantum Chromodynamics (QCD) as point-like scatterings between the proton constituents, collectively referred to as partons. The outgoing partons manifest themselves, through quark and gluon soft radiation and hadronization processes, as localized streams of particles, identified as jets. At Born level, dijets are produced with equal transverse momenta  $p_T$  with respect to the beam axis and back-to-back in the azimuthal angle ( $\Delta\varphi_{\text{dijet}} = |\varphi_{\text{jet1}} - \varphi_{\text{jet2}}| = \pi$ ). Soft-gluon emission will decorrelate the two highest  $p_T$  (leading) jets and cause small deviations from  $\pi$ . Larger decorrelations from  $\pi$  occur in the case of hard multijet production. Three-jet topologies dominate the region of  $2\pi/3 < \Delta\varphi_{\text{dijet}} < \pi$ , whereas angles smaller than  $2\pi/3$  are populated by four-jet events.

Dijet azimuthal decorrelations, i.e., the deviation of  $\Delta\varphi_{\text{dijet}}$  from  $\pi$  for the two leading jets in hard-scattering events can be used to study QCD radiation effects over a wide range of jet multiplicities without the need to measure all the additional jets. Such studies are important because an accurate description of multiple-parton radiation is still lacking in perturbative QCD (pQCD). Experiments therefore rely on Monte Carlo (MC) event generators to take these higher-order processes into account in searches for new physics and for a wide variety of precision measurements. The observable chosen to study the radiation effects is the differential dijet cross section in  $\Delta\varphi_{\text{dijet}}$ , normalized by the dijet cross section integrated over the entire  $\Delta\varphi_{\text{dijet}}$  phase space,  $(1/\sigma_{\text{dijet}})(d\sigma_{\text{dijet}}/d\Delta\varphi_{\text{dijet}})$ . By normalizing the  $\Delta\varphi_{\text{dijet}}$  distributions in this manner, many experimental and theoretical uncertainties are significantly reduced. Measurements of dijet azimuthal decorrelations at the Tevatron have previously been reported by the D0 collaboration [1]. In this Letter, we present the first measurements of dijet azimuthal decorrelations in pp collisions at  $\sqrt{s} = 7$  TeV at the CERN Large Hadron Collider (LHC).

The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid, of 6 m internal diameter, providing an axial field of 3.8 T. Charged particle trajectories are measured by the silicon pixel and strip tracker, covering  $0 < \varphi < 2\pi$  in azimuth and  $|\eta| < 2.5$ , where pseudorapidity  $\eta = -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle relative to the counterclockwise proton beam direction with respect to the center of the detector. A lead-tungstate crystal electromagnetic calorimeter and a brass/scintillator hadronic calorimeter surround the tracking volume. The calorimeter cells are grouped in projective towers of granularity  $\Delta\eta \times \Delta\varphi = 0.087 \times 0.087$  at central pseudorapidities. The granularity becomes coarser at forward pseudorapidities. A preshower detector made of silicon sensor planes and lead absorbers is installed in front of the electromagnetic calorimeter at  $1.653 < |\eta| < 2.6$ . Muons are measured in gas-ionization detectors embedded in the steel magnetic field return yoke. A detailed description of the CMS detector can be found elsewhere [2].

CMS uses a two-tiered trigger system to select events online; Level-1 (L1) and the High Level Trigger (HLT). In this analysis, events were selected using two inclusive single-jet triggers that required an L1 jet with  $p_T > 20$  GeV (30 GeV) and an HLT jet with  $p_T > 30$  GeV (50 GeV). The jets at L1 and HLT are reconstructed using energies measured by the electromagnetic and hadronic calorimeters and are not corrected for the jet energy response of the calorimeters. The trigger efficiency for a given corrected  $p_T$  threshold of the leading jet ( $p_T^{\text{max}}$ ) was measured using events selected by a lower-threshold trigger. For the event selection,  $p_T^{\text{max}}$  thresholds were chosen so that this efficiency exceeded 99%. The corresponding offline corrected  $p_T^{\text{max}}$  values are 80 GeV (110 GeV) for the low (high) threshold jet trigger.

Jets were reconstructed offline using the anti- $k_T$  clustering algorithm with a distance parameter  $R = 0.5$  [3]. The four-vectors of particles reconstructed by the CMS particle-flow algorithm were used as input to the jet-clustering algorithm. The particle-flow algorithm combines in-

formation from all CMS sub-detectors to provide a complete list of long-lived particles in the event. Muons, electrons, photons, and charged and neutral hadrons are reconstructed individually. As a result, the residual corrections to the jet four-vectors, arising from the detector response, are relatively small (at the level of 5-10% in the central region) [4]. A detailed description of the particle-flow algorithm can be found elsewhere [5, 6].

Spurious jets from noise and non-collision backgrounds were eliminated by applying loose quality cuts on the jet properties [7]. Events were required to have a primary vertex reconstructed along the beam axis and within 24 cm of the detector center [8]. Further cuts were applied to reject interactions from the beam halo. Events were selected having two leading jets each with  $p_T > 30$  GeV and rapidity  $|y| < 1.1$ , where  $y = \frac{1}{2} \ln[(E + p_z) / (E - p_z)]$ , with  $E$  being the total jet energy and  $p_z$  the projection of the jet momentum along the beam axis. Each event is put into one of five mutually exclusive regions, which are based on the  $p_T^{\max}$  in the event. The five regions are:  $80 < p_T^{\max} < 110$  GeV,  $110 < p_T^{\max} < 140$  GeV,  $140 < p_T^{\max} < 200$  GeV,  $200 < p_T^{\max} < 300$  GeV, and  $300 \text{ GeV} < p_T^{\max}$ . The data correspond to an integrated luminosity of  $0.3 \text{ pb}^{-1}$  for the lowest  $p_T^{\max}$  region and  $2.9 \text{ pb}^{-1}$  for the other  $p_T^{\max}$  regions. The uncertainty on the integrated luminosity is estimated to be 11% [9]. After the application of all selection criteria, the numbers of events remaining in each of the five  $p_T^{\max}$  regions, starting from the lowest, are: 60837, 160388, 69009, 14383, and 2284.

The  $\Delta\varphi_{\text{dijet}}$  distributions are corrected for event migration effects due to the finite jet  $p_T$  and position resolutions of the detector. The distributions are sensitive to the jet  $p_T$  resolution because fluctuations in the jet response can cause low-energy jets to be misidentified as leading jets, and events can migrate between different  $p_T^{\max}$  regions. The finite resolution in azimuthal angle causes event migration between  $\Delta\varphi_{\text{dijet}}$  bins, while the resolution in rapidity can move jets in and out of the central rapidity region ( $|y| < 1.1$ ). The correction factors were determined using two independent MC samples: PYTHIA 6.422 (PYTHIA6) [10] tune D6T [11], and HERWIG++ 2.4.2 [12]. The  $p_T$ , rapidity, and azimuthal angle of each generated jet were smeared according to the measured resolutions [13]. The ratio of the two dijet azimuthal distributions (the generated distribution and the smeared one) determined the unfolding correction factors for each  $p_T^{\max}$  region, for a given MC sample. The average of the correction factors for each  $p_T^{\max}$  region from the two MC samples were used as the final unfolding correction applied to data. The unfolding correction factors modify the measured  $\Delta\varphi_{\text{dijet}}$  distributions by less than 2% for  $5\pi/6 < \Delta\varphi_{\text{dijet}} < \pi$ . For  $\Delta\varphi_{\text{dijet}} \sim \pi/2$ , the changes range from  $-11\%$ , for the highest  $p_T^{\max}$  region, to  $-19\%$ , for the lowest.

The main sources of systematic uncertainty arise from uncertainties in the jet energy calibration, the jet  $p_T$  resolution, and the unfolding correction. The jet energy calibration uncertainties have been tabulated for the considered phase space in the variables of jet  $p_T$  and  $\eta$  [4]. Typical values are between 2.5% and 3.5%. The resulting uncertainties on the normalized  $\Delta\varphi_{\text{dijet}}$  distributions range from 5% at  $\Delta\varphi_{\text{dijet}} \sim \pi/2$  to 1% at  $\Delta\varphi_{\text{dijet}} \sim \pi$ . The effect of jet  $p_T$  resolution uncertainty on the  $\Delta\varphi_{\text{dijet}}$  distributions was estimated by varying the jet  $p_T$  resolutions by  $\pm 10\%$  [13] and comparing the  $\Delta\varphi_{\text{dijet}}$  unfolding correction before and after the change. This yields a variation on the normalized  $\Delta\varphi_{\text{dijet}}$  distributions ranging from 5% at  $\Delta\varphi_{\text{dijet}} \sim \pi/2$  to 1% at  $\Delta\varphi_{\text{dijet}} \sim \pi$ . The uncertainties on the unfolding correction factors were estimated by comparing the corrections from different event generators and PYTHIA6 tunes that vary significantly in their modelling of the jet kinematic distributions and  $\Delta\varphi_{\text{dijet}}$  distributions. The resulting uncertainty varies from 8% at  $\Delta\varphi_{\text{dijet}} \sim \pi/2$  to 1.5% at  $\Delta\varphi_{\text{dijet}} \sim \pi$ . The systematic uncertainty from using a parametrized model to simulate the finite jet  $p_T$  and position resolutions of the detector to determine the unfolding correction factors was estimated to be about 2.5% in all  $p_T^{\max}$  regions. The combined systematic uncertainty, calculated as the quadratic

sum of all systematic uncertainties, varies from 11% at  $\Delta\varphi_{\text{dijet}} \sim \pi/2$  to 3% at  $\Delta\varphi_{\text{dijet}} \sim \pi$ .

The corrected differential  $\Delta\varphi_{\text{dijet}}$  distributions, normalized to the integrated dijet cross section, are shown in Fig. 1 for the five  $p_T^{\text{max}}$  regions. The distributions are scaled by multiplicative factors for presentation purposes. Each data point is plotted at the abscissa value for which the predicted differential  $\Delta\varphi_{\text{dijet}}$  distribution has the same value as the bin average obtained using PYTHIA6 tune D6T, which provides a good description of the data [14].

The  $\Delta\varphi_{\text{dijet}}$  distributions are strongly peaked at  $\pi$  and become steeper with increasing  $p_T^{\text{max}}$ . The simulated  $\Delta\varphi_{\text{dijet}}$  distributions from the PYTHIA6 (D6T and Z2 [15] tunes), PYTHIA 8.135 (PYTHIA8) [16], HERWIG++, and MADGRAPH 4.4.32 [17] event generators are presented for comparison. The MADGRAPH generator is based on leading-order matrix element multiparton final-state predictions, using PYTHIA6 for parton showering and hadronization, and the MLM method [18] to map the parton-level event into a parton shower history. The MADGRAPH predictions included tree-level processes of up to four partons. For PYTHIA6, PYTHIA8, and MADGRAPH event generators the CTEQ6L [19] parton distribution functions (PDFs) were used; for HERWIG++, the MRST2001 PDFs [20].

Figure 2 shows the ratios of the measured  $\Delta\varphi_{\text{dijet}}$  distributions to the predictions of PYTHIA6, PYTHIA8, HERWIG++, and MADGRAPH in the five  $p_T^{\text{max}}$  regions. The combined systematic uncertainty on the experimental measurements is shown by the shaded band. The predictions from PYTHIA6 and HERWIG++ describe the shape of the data distributions well, while MADGRAPH (PYTHIA8) predicts less (more) azimuthal decorrelation than is observed in the data.

Figure 3 displays a comparison between the measured  $\Delta\varphi_{\text{dijet}}$  distributions and the predictions of pQCD calculations from the parton-level generator NLOJET++ [21] within the FASTNLO framework [22]. The predictions near  $\Delta\varphi_{\text{dijet}} = \pi$  have been excluded because of their sensitivity to higher-order corrections not included in the present calculations. The leading-order (LO) curves represent processes with three partons in the final state, normalized to the LO  $\sigma_{\text{dijet}}$  ( $2 \rightarrow 2$ ) cross section. The next-to-leading-order (NLO) predictions include  $2 \rightarrow 3$  processes at NLO, normalized to  $\sigma_{\text{dijet}}$  at NLO:

$$\frac{1}{\sigma_{\text{dijet}}} \Big|_{(\text{N})\text{LO}} \times \frac{d\sigma_{\text{dijet}}}{d\Delta\varphi_{\text{dijet}}} \Big|_{(\text{N})\text{LO}}.$$

Uncertainties due to the renormalization ( $\mu_r$ ) and factorization ( $\mu_f$ ) scales are evaluated by varying the default choice of  $\mu_r = \mu_f = p_T^{\text{max}}$  between  $p_T^{\text{max}}/2$  and  $2p_T^{\text{max}}$  in the following six combinations:  $(\mu_r, \mu_f) = (p_T^{\text{max}}/2, p_T^{\text{max}}/2), (2p_T^{\text{max}}, 2p_T^{\text{max}}), (p_T^{\text{max}}, p_T^{\text{max}}/2), (p_T^{\text{max}}, 2p_T^{\text{max}}), (p_T^{\text{max}}/2, 2p_T^{\text{max}}),$  and  $(2p_T^{\text{max}}, p_T^{\text{max}})$ . These scale variations modify the predictions of the normalized  $\Delta\varphi_{\text{dijet}}$  distributions by less than 50%. The PDFs and the associated uncertainties were obtained from CTEQ6.6 [19]. The PDF uncertainties were derived using the 22 CTEQ6.6 uncertainty eigenvectors and found to be 9% at  $\Delta\varphi_{\text{dijet}} \sim \pi/2$  and 2% at  $\Delta\varphi_{\text{dijet}} < \pi$ . Following the proposal of the PDF4LHC working group [23], the impact of other global PDF fits [24–26] was investigated and found to be negligible in the context of this analysis.

Non-perturbative corrections due to hadronization and multiple-parton interactions were applied to the pQCD predictions. The correction factors were determined from the PYTHIA6 and HERWIG++ simulations and modify the predictions from +4% ( $\Delta\varphi_{\text{dijet}} \sim \pi$ ) to –13% ( $\Delta\varphi_{\text{dijet}} \sim \pi/2$ ). The uncertainty due to the non-perturbative corrections is estimated to be 6% at  $\Delta\varphi_{\text{dijet}} \sim \pi/2$  and 2% at  $\Delta\varphi_{\text{dijet}} \sim \pi$ . The ratios of the measured  $\Delta\varphi_{\text{dijet}}$  distributions to the NLO pQCD predictions are shown in Fig. 4. The effect due to the scale variations, as well as the uncertainties due to PDFs and non-perturbative corrections, are also shown. The NLO

predictions provide a good description of the shape of the data distributions over much of the  $\Delta\varphi_{\text{dijet}}$  range. Compared to the data, the reduced decorrelation in the theoretical prediction and the increased sensitivity to the  $\mu_r$  and  $\mu_f$  scale variations for  $\Delta\varphi_{\text{dijet}} < 2\pi/3$  shown in Fig. 4 are attributed to the fact that the pQCD prediction in this region is effectively available only at leading order, since the contribution from tree-level four-parton final states dominates.

The sensitivity of the  $\Delta\varphi_{\text{dijet}}$  distributions to initial-state parton shower radiation (ISR) is investigated by varying the input parameter  $k_{\text{ISR}}$  (PARP(67)) in PYTHIA6 tune D6T. The product of  $k_{\text{ISR}}$  and the square of the hard-scattering scale gives the maximum allowed parton virtuality (i.e., the maximum allowed  $p_T$ ) in the initial-state shower. Previous studies have shown that  $k_{\text{ISR}}$  is the only parameter in PYTHIA6 that has significant impact on the  $\Delta\varphi_{\text{dijet}}$  distributions [27]. The default value of  $k_{\text{ISR}}$  in PYTHIA6 tune D6T is 2.5, determined from the D0 dijet azimuthal decorrelation results [1]. Figure 5 shows comparisons of the measured  $\Delta\varphi_{\text{dijet}}$  distributions to PYTHIA6 distributions with various  $k_{\text{ISR}}$  values. The effects are more pronounced for smaller  $\Delta\varphi_{\text{dijet}}$  angles, where multi-gluon radiation dominates. Varying  $k_{\text{ISR}}$  by  $\pm 0.5$  about its default value yields a change of about 30% on the PYTHIA6 prediction for  $\Delta\varphi_{\text{dijet}} \sim \pi/2$ , suggesting that our results could be used to tune parameters in the MC event generators that control radiative effects in the initial state. In PYTHIA6 tune D6T, the maximum  $p_T$  allowed in final-state radiation parton shower is controlled through the parameter PARP(71). We varied the value of this parameter from 2.5 to 8 (the default value is 4.0) and observed less than  $\sim 10\%$  changes in the  $\Delta\varphi_{\text{dijet}}$  distributions in all  $p_T$  regions.

In summary, we have measured dijet azimuthal decorrelations in different leading-jet  $p_T$  regions from pp collisions at  $\sqrt{s} = 7$  TeV. The PYTHIA6 and HERWIG++ event generators are found to best describe the shape of the measured distributions over the entire range of  $\Delta\varphi_{\text{dijet}}$ . The predictions from NLO pQCD are in reasonable agreement with the measured distributions, except at small  $\Delta\varphi_{\text{dijet}}$  where multiparton radiation effects dominate. The  $\Delta\varphi_{\text{dijet}}$  distributions are found to be sensitive to initial-state gluon radiation.

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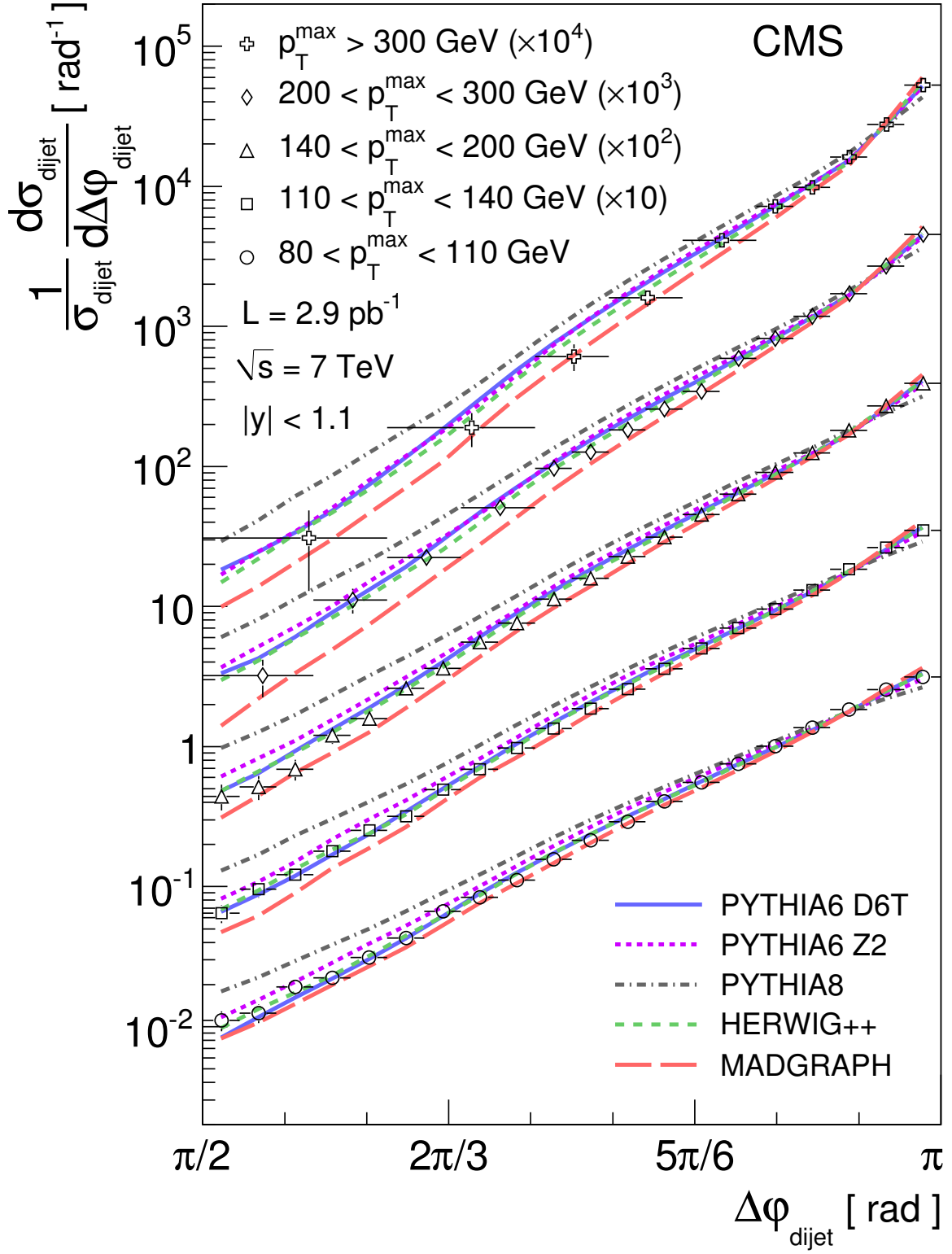


Figure 1: Normalized  $\Delta\phi_{\text{dijet}}$  distributions in several  $p_T^{\text{max}}$  regions, scaled by the multiplicative factors given in the figure for easier presentation. The curves represent predictions from PYTHIA6, PYTHIA8, HERWIG++, and MADGRAPH. The error bars on the data points include statistical and systematic uncertainties.

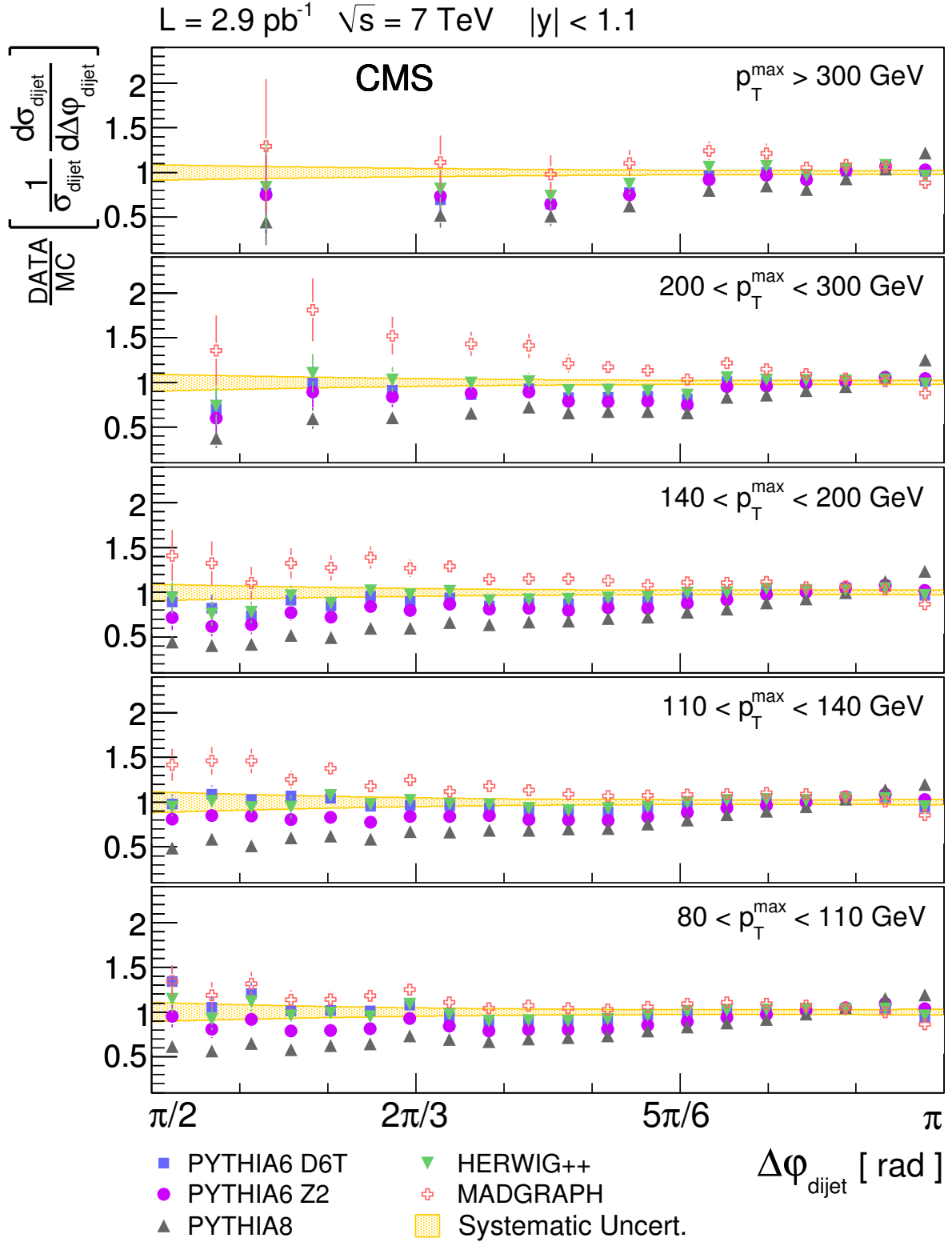


Figure 2: Ratios of measured normalized  $\Delta\phi_{\text{dijet}}$  distributions to PYTHIA6, PYTHIA8, HERWIG++, and MADGRAPH predictions in several  $p_T^{\max}$  regions. The shaded bands indicate the total systematic uncertainty.

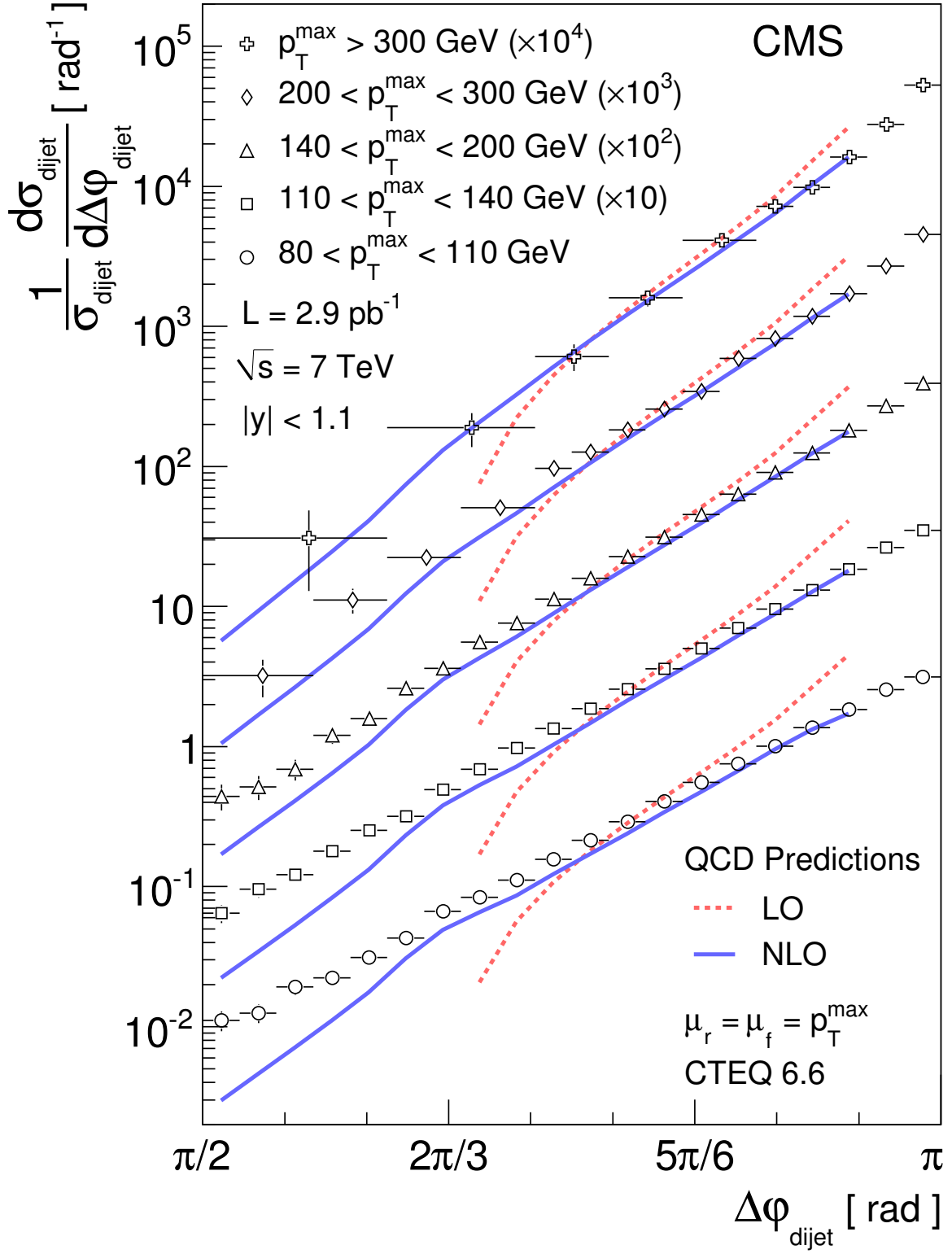


Figure 3: Normalized  $\Delta\phi_{\text{dijet}}$  distributions in several  $p_T^{\max}$  regions, scaled by the multiplicative factors given in the figure for easier presentation. The curves represent predictions from LO (dotted line) and NLO pQCD (solid line). Non-perturbative corrections have been applied to the predictions. The error bars on the data points include statistical and systematic uncertainties.

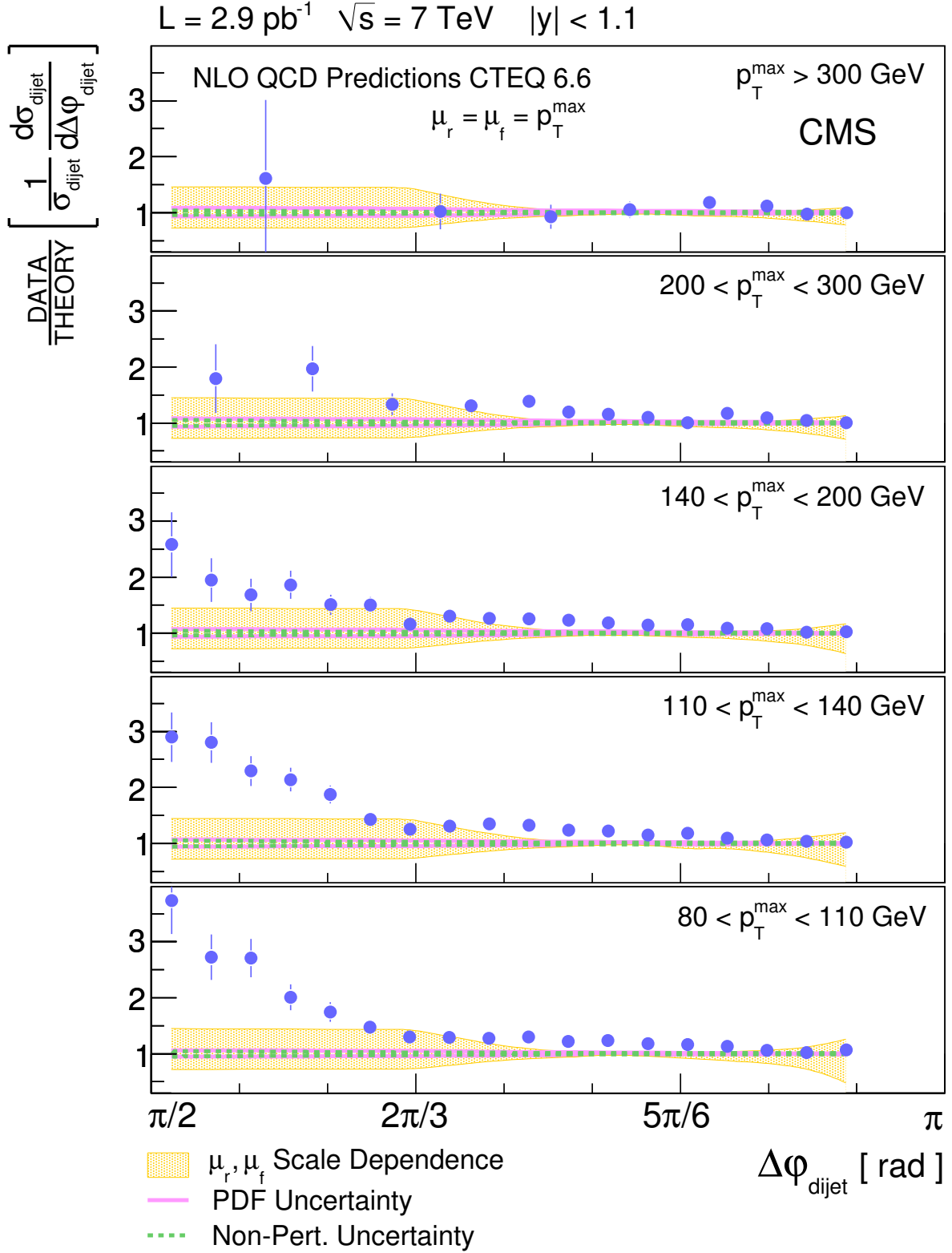


Figure 4: Ratios of measured normalized  $\Delta\phi_{\text{dijet}}$  distributions to NLO pQCD predictions with non-perturbative corrections in several  $p_T^{\max}$  regions. The error bars on the data points include statistical and systematic uncertainties. The effect on the NLO pQCD predictions due to  $\mu_r$  and  $\mu_f$  scale variations and PDF uncertainties, as well as the uncertainties from the non-perturbative corrections are shown.

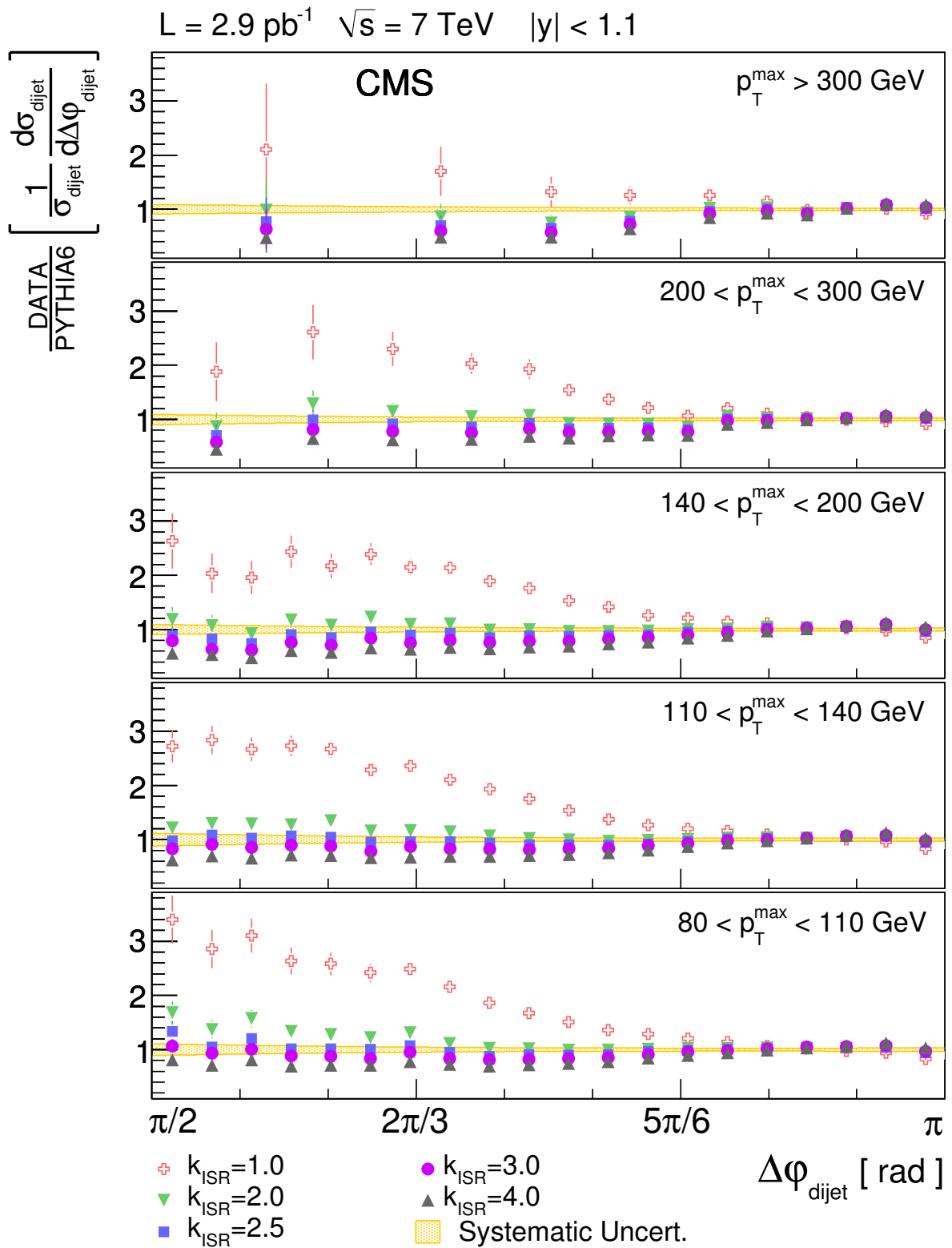


Figure 5: Ratios of measured normalized  $\Delta\phi_{\text{dijet}}$  distributions to PYTHIA6 tune D6T with various values of  $k_{\text{ISR}}$  in several  $p_T^{\text{max}}$  regions. The shaded bands indicate the total systematic uncertainty.



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