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Measurement of four-jet production in proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$

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Abstract

Measurements of the differential cross sections for the production of exactly four jets in proton-proton collisions are presented as a function of the transverse momentum p_T and pseudorapidity η, together with the correlations in azimuthal angle and the p_T balance among the jets. The data sample was collected in 2010 at a center-of-mass energy of 7 TeV with the CMS detector at the LHC, with an integrated luminosity of $36\,\mathrm{pb}^{-1}$. The cross section for a final state with a pair of hard jets with $p_\mathrm{T} > 50\,\mathrm{GeV}$ and another pair with $p_\mathrm{T} > 20\,\mathrm{GeV}$ within $|\eta| < 4.7$ is measured to be $\sigma(\mathrm{pp} \to 4\mathrm{j} + \mathrm{X}) = 330 \pm 5\,(\mathrm{stat.}) \pm 45\,(\mathrm{syst.})\,\mathrm{nb}$. The measured differential cross sections agree with predictions involving parton showers in only some regions of the phase space. It is found that including a contribution from double parton scattering in the models brings the predictions closer to the measurements.

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1 Introduction

The production of jets with large transverse momenta (p_T) in high-energy proton-proton collisions can be described within the theory of strong interactions, quantum chromodynamics (QCD), by the scattering of partons. The partonic matrix element (ME) is convoluted with the density functions of partons inside the protons. The inclusive cross section for high-p_T jets has been measured by the ATLAS [1] and Compact Muon Solenoid (CMS) [2] Collaborations and is in good agreement with predictions obtained at next-to-leading order (NLO). However, the production cross section of a forward jet in association with a jet in the central region of the detector is not very well described [3].

In multi-jet production, correlations between the jets can be studied in detail. The production of four jets at large p_T involves terms of fourth power in the strong coupling, α_S^4. This allows correlations between pairs of jets at different p_T scales to be investigated. The hard scatterings produce a pair of partons at high-p_T and their evolution results in additional jets at lower p_T. This 2→4 partonic process, coming from single parton scattering (SPS), is a crucial test for higher-order QCD calculations, as well as for the description of high-p_T jets within the parton shower (PS) formalism.

Proton-proton collisions at high center-of-mass energy access the low-x region, where the parton densities are large and where the probability to have more than one partonic interaction becomes non-negligible. In this regime, the pair of hard jets and the pair of softer jets can also be produced via double parton scattering (DPS) [4]. The SPS and DPS processes result in different distributions of angular correlations, as discussed in Ref. [5]. A final state arising from SPS tends to have a strongly correlated configuration in azimuthal angle and p_T-balance between the two jet systems. In contrast, DPS events generally have uncorrelated topologies. At large jet transverse momenta, the contribution from DPS is expected to be small, or at least much smaller than at low p_T. Therefore it is essential to perform a differential cross section measurement over a large region of phase space, and to compare it with theoretical predictions. Only if the region at large p_T is appropriately described, can an extraction of a possible DPS contribution at smaller p_T be performed.

Four-jet production at high-p_T is measured in pp collisions at a center-of-mass energy $\sqrt{s} = 7\,\text{TeV}$ using the data sample collected with the CMS detector at the Large Hadron Collider (LHC) in 2010 for an integrated luminosity of $36\,\text{pb}^{-1}$. The jets are reconstructed with the anti-k_T algorithm [6–8], with a distance parameter of 0.5, in the pseudorapidity range $|\eta_{\text{jet}}| < 4.7$. The pseudorapidity is defined as $\eta = -\ln[\tan(\theta/2)]$, where θ is the polar angle with respect to the counterclockwise-beam direction. A final state with exactly four jets (hereafter referred to as "exclusive") is selected with the two leading (highest p_T) jets having $p_T > 50\,\text{GeV}$ and two additional jets with $p_T > 20\,\text{GeV}$.

The differential cross sections as a function of transverse momentum and pseudorapidity of the four jets are presented. In addition, the normalized differential cross sections are measured as a function of correlation variables defined from the hard and soft pair of jets as follows:

- the azimuthal angular differences between the jets belonging to the soft pair

$$\Delta\phi_{\text{soft}} = |\phi(\text{j}^{\text{soft}_1}) - \phi(\text{j}^{\text{soft}_2})|; \tag{1}$$

- the balance in transverse momentum of the two soft jets

$$\Delta_{\text{soft}}^{\text{rel}}p_T = \frac{|\vec{p}_T(\text{j}^{\text{soft}_1}) + \vec{p}_T(\text{j}^{\text{soft}_2})|}{|\vec{p}_T(\text{j}^{\text{soft}_1})| + |\vec{p}_T(\text{j}^{\text{soft}_2})|}; \tag{2}$$

- the azimuthal angle ΔS between the two dijet pairs, defined as:

$$\Delta\text{S} = \arccos\left(\frac{\vec{p}_\text{T}(j^{\text{hard}_1}, j^{\text{hard}_2}) \cdot \vec{p}_\text{T}(j^{\text{soft}_1}, j^{\text{soft}_2})}{|\vec{p}_\text{T}(j^{\text{hard}_1}, j^{\text{hard}_2})| \cdot |\vec{p}_\text{T}(j^{\text{soft}_1}, j^{\text{soft}_1})|}\right), \tag{3}$$

where j^{soft_1} (j^{soft_2}) and j^{hard_1} (j^{hard_2}) stand for the leading (subleading) soft and hard jet pairs, respectively.

Distributions are presented for the correlation observables, normalized to the measured cross section. The systematic uncertainties for the correlation observables are smaller than those for the cross section measurements. The measurements are compared to predictions from Monte Carlo (MC) event generators using $\mathcal{O}(\alpha_S^2)$ ME improved with PS and multiparton interactions (MPI) and to predictions for dijet production at NLO matched to PS. Comparisons are also made to predictions from higher-order tree level diagrams matched with PS.

The outline of this paper is as follows. In Section 2, the detector and the MC simulation are described. In Section 3, the event selection, correction procedure, and systematic uncertainties are discussed. Section 4 covers the results and conclusions are presented in Section 5.

2 Detector description and MC simulation

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Charged particle trajectories are measured using silicon pixel and strip trackers [9] that cover the pseudorapidity region $|\eta| < 2.5$. An electromagnetic crystal calorimeter (ECAL) [10] and a brass/scintillator hadron calorimeter (HCAL) [11] surround the tracking volume and cover $|\eta| < 3.0$. A forward quartz-fibre Cherenkov hadron calorimeter (HF) [12] extends the coverage to $|\eta| = 5.2$. Events are collected by using a two-level trigger system consisting of level-1 and high-level triggers (HLT) [13].

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x-y plane. A more detailed description of the CMS apparatus can be found in Ref. [14].

The particle-flow event reconstruction consists in reconstructing and identifying each single particle with an optimized combination of all subdetector information. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The energy of muons is obtained from the corresponding track momentum. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for zero-suppression effects, and calibrated for the nonlinear response of the calorimeters. Finally the energy of neutral hadrons is obtained from the corresponding calibrated ECAL and HCAL energies.

For each event, hadronic jets are clustered from these reconstructed particles with the infrared and collinear safe anti-k_T algorithm [6–8], operated with a size parameter R of 0.5. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found in the simulation to be within 5% to 10% of the true momentum over the whole p_T spectrum

and detector acceptance. An offset correction is applied to take into account the extra energy clustered in jets due to additional proton-proton interactions within the same bunch crossing (pileup). Jet energy corrections are derived from the simulation, and are confirmed with in situ measurements of the energy balance of dijet and photon+jet events. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions. The jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV, to be compared to about 40%, 12%, and 5% obtained when the calorimeters alone are used for jet clustering.

Jet momenta are corrected for pileup [15]. This ranged from nearly zero additional collisions during the very early period of LHC data taking in 2010 to an average of about three near the end of the 2010 running period. Finally, the jet momentum resolution is determined from simulation, as a function of the jet p_T and η. Comparing the p_T balance in dijet events between data and simulation, the jet p_T resolution in the simulation is scaled upwards by 10% in the barrel and by 20% in the endcaps to match the resolution in the data [16, 17].

Simulated event samples for four-jet production are produced with different MC event generators: PYTHIA 6.426 [18], HERWIG++ (version 2.5.0) [19, 20], and PYTHIA 8.140 [21]. In PYTHIA, the PS are generated by ordering the parton splittings in p_T and the momentum fraction x. The Lund string model [22] is used for hadronization. In contrast, HERWIG++ generates PS in an angular-ordered region of phase space and uses a cluster fragmentation model for hadronization. MPI are simulated in both PYTHIA and HERWIG. The free parameters describing MPI are obtained from tunes [23] to measurements in pp collisions at the LHC. The PYTHIA 6 generator with the tune Z2* [24] applies a new model [25] where MPI are interleaved with parton showering. The PYTHIA 8 generator is used with the tune 4C [26] based on underlying event data from the LHC, using CTEQ6L1 PDF set. It implements a more sophisticated model for MPI with respect to PYTHIA 6, by introducing color reconnection and rescattering between the partons [27]. The HERWIG++ generator tuned to LHC data (tune LHC-UE-EE-3 [20]) with the MRST2001 PDF set is also used for comparison.

The data are also compared to perturbative NLO dijet QCD predictions obtained with the POWHEG package [28, 29] matched with PYTHIA 6 PS including the MPI simulation. The description of inclusive jet cross sections [2] and underlying event measurements [30, 31] has been verified for different PYTHIA tunes interfaced with the POWHEG BOX [32, 33]. A good representation of these data is obtained when the underlying event is provided by PYTHIA 6 tune Z2*. The agreement improves when the contribution of the parton shower in the tune Z2* is decreased (by changing the PYTHIA parameters PARP(67) and PARP(71) to 1.0, from the default value of 4.0), since a hard emission is already included the POWHEG matrix element. These parameters regulate the upper scale of the initial- and final-state radiations, respectively. This modified tune is chosen for the final comparison and it is referred to as Z2' in the following. The MADGRAPH event generator [34, 35] is also used for the comparison. It produces parton-level events with up to four partons in the final state on the basis of Leading Order (LO) ME calculations. The PS for MADGRAPH is provided by the PYTHIA 6 tune Z2*, including the contribution of MPI. The goodness of this tune has been verified by comparison to the inclusive jet cross sections and underlying event measurements. A good agreement for the Z2* tune is obtained. Predictions from the SHERPA 1.4.0 event generator [36] are also considered. This event generator produces tree level $2 \rightarrow 2 + n$ ME matched to PS (in this work $n = 1$ is used). The MPI are based on the model used in the PYTHIA 6 underlying event, but with different parameter values [37]. The predictions for the SHERPA generator with these parameters give a good description of inclusive jet cross section measurements but they are not able to reproduce the underlying event data, with discrepancies up to 20%.

The differences between the LO predictions of PYTHIA, HERWIG, SHERPA and MADGRAPH lie in the hard subprocess as well as in the parton showering and MPI. PYTHIA and HERWIG use 2→2 $\mathcal{O}(\alpha_S^2)$ ME, SHERPA uses 2→3 and MADGRAPH uses 2→4 ME. POWHEG is a NLO prediction for dijets, using 2→2 and 2→3 ME, but for the four-jet measurement is still a LO prediction. In MADGRAPH, the four jets can originate from the matrix element, while in all the other simulations at least one jet must come from parton shower or MPI.

The detector response is simulated in detail by using the GEANT4 package [38]. All simulated samples are processed and reconstructed in the same manner as done for collision data.

3   Event selection and analysis

The data, recorded with the CMS detector in 2010 at $\sqrt{s} = 7\,\text{TeV}$, correspond to an integrated luminosity of approximately $36\,\text{pb}^{-1}$ with low-pileup conditions. The mean value of overlapping interactions ranges between 1.5 and 3. The MC samples include simulated pileup interactions with a distribution matching that in data. For this study, two HLT trigger sets are analyzed: a trigger with jet threshold of 30 GeV is used for leading jets with $50 < p_T < 140\,\text{GeV}$, while for jets with $p_T > 140\,\text{GeV}$, a trigger with threshold of 50 GeV is applied. In the region of transverse momenta between 50 and 80 GeV, where the trigger is not fully efficient, a p_T and η dependent trigger efficiency correction is applied.

Events with at least one good primary vertex and exactly four jets in the region $|\eta| < 4.7$ are selected: two of them with $p_T > 50\,\text{GeV}$ and two with $p_T > 20\,\text{GeV}$. A primary vertex is defined as the vertex to which the charged particle with the largest p_T is associated. The two jets with highest p_T are labelled as "hard-jet pair", while the other two jets form the "soft-jet pair".

The kinematic distributions of the selected jets are in agreement with MC predictions and are described to a 20% accuracy by PYTHIA 6 and HERWIG++ at detector level, except in the forward region of the detector. The pseudorapidity distribution is reasonably described by the simulation in the central region of the detector, while differences (20–80%) are observed between data and simulation for $|\eta| > 3$ for the leading and subleading jets. However, large scale uncertainties up to 60% are associated with those jets in the forward region [3]. In addition, the predicted cross sections for $|\eta| > 3$ are different by up to 30 % depending on the model calculation. Discrepancies of the same order have also been observed at detector level for inclusive and dijet samples with $p_T > 50\,\text{GeV}$. A small difference between PYTHIA 6 and HERWIG++ is observed for leading and subleading jets, coming from the different PS models used in the two generators. The p_T distributions are reproduced by PYTHIA 6 and HERWIG++ at detector level for all the selected jets. The differences with respect to the observed measurements are less than 20% in the whole selected p_T range.

3.1   Corrections and systematic uncertainty

The p_T and η distributions, and the correlation observables are corrected for selection efficiencies and detector effects. The data are corrected to stable-particle level ($c\tau > 10\,\text{mm}$) by applying an iterative unfolding [39] as implemented in ROOUNFOLD [40]. In addition, a bin-to-bin correction has been performed and found to be in agreement with the iterative unfolding. The response matrix is obtained with PYTHIA 6. A closure test shows that stable results, within 5% with respect to the true distributions, are obtained when HERWIG++ is unfolded with the PYTHIA 6 response matrix. The final correction is performed with PYTHIA 6 and HERWIG++. The deviation from the average value is taken as a systematic uncertainty due to the model de-

pendence, and is applied to the unfolded result. The unfolding to stable-particle level includes corrections for pileup effects.

Various systematic effects are investigated and the corresponding uncertainty is calculated for each of the distributions. The total uncertainties are obtained by summing in quadrature the individual contributions.

The following systematic uncertainties are considered:

- **Model dependence**: the unfolded cross sections obtained with the two different MC generators PYTHIA 6 and HERWIG++ are averaged and the difference of the unfolded results is used as a systematic uncertainty. The resulting uncertainty ranges from 3 to 5% for the absolute cross sections and from 3 to 4% for the normalized cross sections. This reflects the difference in the response matrix obtained from the two generators.

- **Jet Energy Scale (JES)**: the momentum of the jets is varied within the uncertainty associated to the reconstructed p_T. This leads to an uncertainty of 15–18% for the absolute cross sections which is the dominant contribution. For the normalized cross sections, the JES uncertainty is about 3% and is of the same size as the other contributions.

- **Jet Energy Resolution (JER)**: the JER differs between data and simulation by 6–19% depending on the pseudorapidity range, which introduces a systematic uncertainty of about 1–4% for both cross section measurements and normalized cross sections.

- **Pileup**: an uncertainty due to pileup modeling in the simulation is evaluated and found to be negligible ($<0.1\%$) for both cross section measurements and normalized cross sections.

- **Luminosity**: the systematic uncertainty on the luminosity for 2010 data adds an additional uncertainty of 4% [41] to the cross section.

A summary of the systematic uncertainties is given in Table 1.

Table 1: Total systematic uncertainties affecting the differential cross sections for p_T, and η, and the normalized differential cross sections for $\Delta\phi_{\text{soft}}$, $\Delta^{\text{rel}}_{\text{soft}}p_T$, and ΔS. In the last column, the total uncertainty for each observable is listed. This is obtained by summing the individual uncertainties in quadrature.

Measured observable	Model	Jet Energy Scale	Jet Energy Resolution	Pileup reweighting	Luminosity	Total
jet p_T	2%	13%	1%	$<0.1\%$	4%	15%
jet η	2%	13%	1%	$<0.1\%$	4%	15%
$\Delta\phi_{\text{soft}}$	3%	3%	2%	$<0.1\%$	—	5%
$\Delta^{\text{rel}}_{\text{soft}}p_T$	3%	3%	2%	$<0.1\%$	—	5%
ΔS	4%	3%	3%	$<0.1\%$	—	5%

4 Results

The cross sections for exclusive production of four jets for $|\eta| < 4.7$ and $p_T > 50\,(20)\,\text{GeV}$ for the hard (soft) jet pairs are shown in Fig. 1 and Fig. 2.

The measured value of the cross section for the exclusive four-jet final state is $330 \pm 5\,\text{(stat.)} \pm 45\,\text{(syst.)}\,\text{nb}$. This value is compared with various theoretical predictions in Table 2. While PYTHIA 8, tune 4C, gives a value for the cross section higher than that measured, HERWIG++

is in good agreement with it. The MADGRAPH generator, interfaced with PYTHIA 6, tune Z2*, predicts a lower value, while SHERPA is in good agreement with the measured cross section. We have verified that the differences between the predictions obtained with MADGRAPH and SHERPA are due to the different contributions coming from MPI, while the predictions agree with each other if MPI are switched off. The NLO dijet prediction of POWHEG, interfaced with PYTHIA 6, tune Z2', including MPI, is compatible with the measurement.

Table 2: Cross sections for MC predictions and measured data for pp $\rightarrow$ 4j + X: the jets are selected within $|\eta| < 4.7$, and with $p_T > 50$ GeV for the two leading jets and $p_T > 20$ GeV for the other jets.

Sample	Cross section (nb)
PYTHIA 8, tune 4C	423
HERWIG++, tune UE-EE-3	343
MADGRAPH + PYTHIA 6, tune Z2*	234
SHERPA	293
POWHEG + PYTHIA 6, tune Z2'	378
Data	330 ± 5 (stat.) ± 45 (syst.)

The cross sections as a function of p_T and η of each of the four jets are presented in Fig. 1. The cross sections fall rapidly with increasing p_T for all the jets in the final state. For the highest p_T jets, the cross section decreases by two orders of magnitude for p_T between 50 and 200 GeV. For the softer jets, the cross section decreases over 5 orders of magnitude for the same p_T range. The shape of the cross section as a function of η (Fig. 1 right) is different for the hard and soft jets. Specifically, the cross section for hard jets drops very rapidly for $|\eta| \sim 4$. Conversely, the distributions of the soft jets are flatter, with the cross section dropping by only about a factor 10 between $|\eta| \sim 0$ and the forward region ($|\eta| \sim 4.7$).

The measured cross sections are also compared to theoretical predictions. Ratios between the theoretical predictions and the observed measurements are presented in Fig. 2. All predictions, except HERWIG++, are in agreement with the measurement for the leading and subleading jets at large transverse momenta $p_T \gtrsim 300$ GeV (Fig. 2 left). However, differences appear at smaller p_T: POWHEG and SHERPA are in agreement with the measurement for the leading and sub-leading jets, while PYTHIA 8 and MADGRAPH deviate significantly from the data. The soft jets are not very well described: POWHEG and PYTHIA 8 are significantly above the measurement, while the SHERPA and MADGRAPH predictions are outside the systematic uncertainties for some bins. HERWIG++ is similar in shape to PYTHIA 8 but has a different cross section (Tab. 2), which leads to a better agreement at small p_T and a worse description at large p_T.

The differential cross sections as a function of η are described reasonably well by SHERPA and HERWIG++. The distribution of the leading and subleading jets are described by SHERPA, HER-WIG++ and MADGRAPH within the systematic uncertainties, taking into account the differences in the total cross section (Tab. 2), while POWHEG and PYTHIA 8 tend to be below the measurement at large η. The distributions of the soft jets are described only by SHERPA and HERWIG++ for both absolute normalization and shape, while all other predictions are significantly off at large η.

In summary, the description of the differential cross section as a function of p_T and η for pp $\rightarrow$ 4j + X in $|\eta| < 4.7$ is not trivial. While the description of the cross section at large transverse momenta is reasonable, significant differences arise at smaller p_T values, especially for the subleading and soft jets.

The correlation between hard and soft jet pairs can provide additional information on the pro-
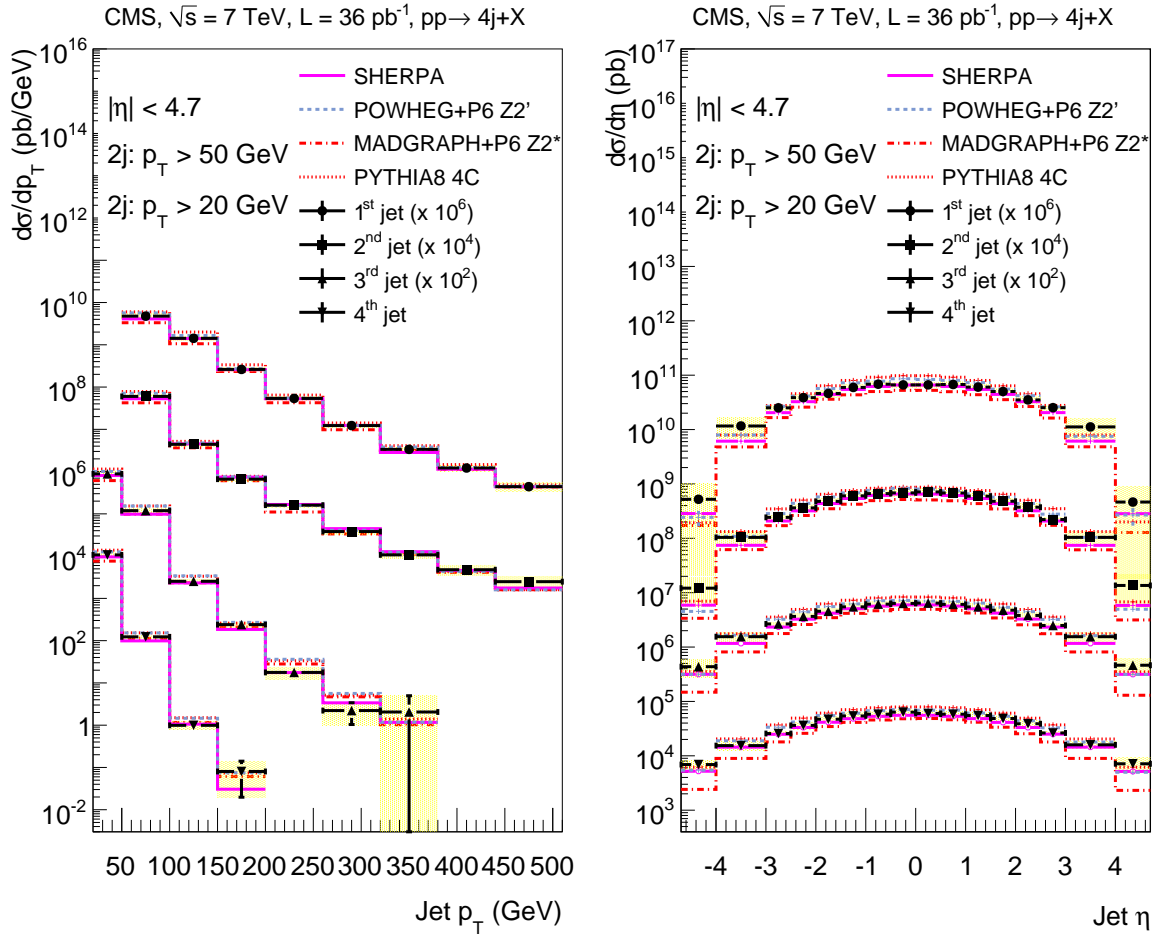
Figure 1: Differential cross sections as a function of the jet transverse momenta p_T (left) and pseudorapidity η (right) compared to theoretical predictions of POWHEG, MADGRAPH, SHERPA, and PYTHIA 8. Scale factors of 10^6, 10^4 and 10^2 are applied to the measurement of the leading, subleading and third jet, respectively. The yellow band represents the total uncertainty, including the statistical and systematic components.
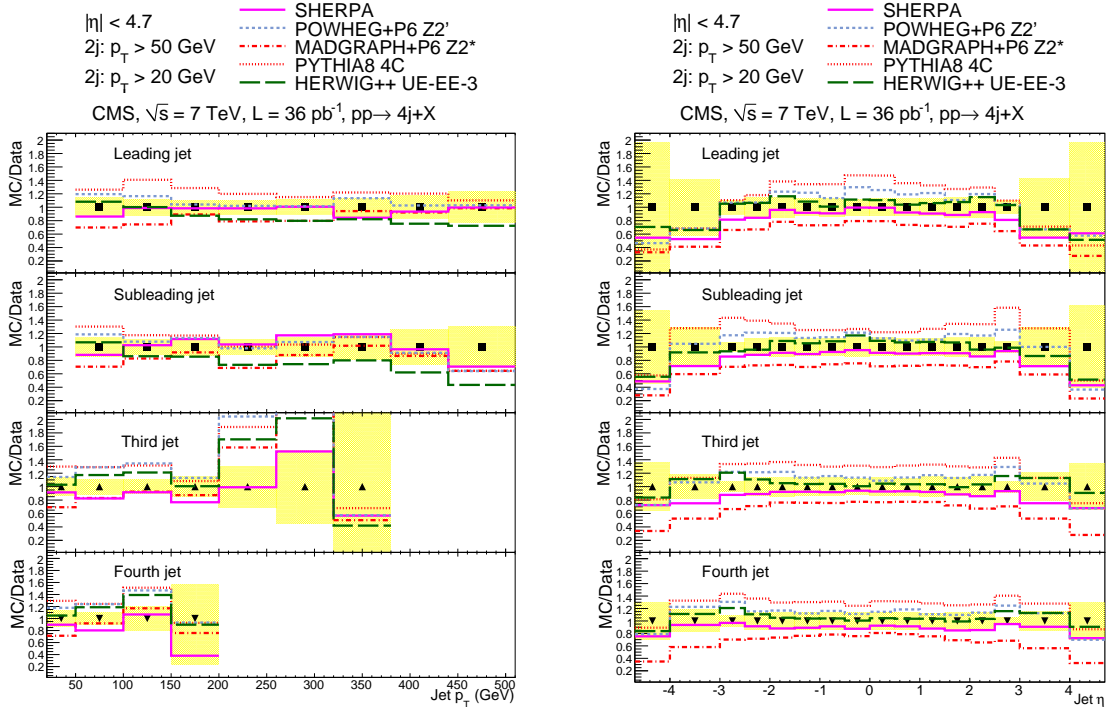
Figure 2: Ratios of theoretical predictions of POWHEG, MADGRAPH, SHERPA, PYTHIA 8 and HERWIG++ to data as a function of the jet transverse momenta p_T (left) and pseudorapidity η (right) for each specific jet. The yellow band represents the total uncertainty, including the statistical and systematic components.

duction process and help to disentangle the contributions of SPS and DPS diagrams. The normalized differential cross section is measured as a function of the correlation observables, defined in Section 1. The normalized differential cross section as a function of $\Delta\phi_{\text{soft}}$ is shown in Fig. 3 (left). The distribution has a maximum at $\Delta\phi \sim \pi$ and falls by less than an order of magnitude towards very small $\Delta\phi$. At small $\Delta\phi$ the jets are uncorrelated. A local maximum is visible at values around $\Delta\phi \sim 0.5$–0.8 because the anti-k_T jet algorithm merges jets originating from collinear parton emissions with an angular separation less than the jet radius of $R = 0.5$.

In Fig. 3 (center), the balance in transverse momentum between the soft jets, $\Delta_{\text{soft}}^{\text{rel}} p_T$, is shown. It covers an order of magnitude and has its largest value around unity, indicating that the soft jets are predominantly not balanced in p_T. This would be expected if they come from radiation of the initial- or final-state of the hard pair of jets.

The cross section as a function of the azimuthal angle between the planes of the two dijet systems, ΔS, is shown in Fig. 3 (right). The distribution falls over almost two orders of magnitude over the entire phase space. At low ΔS values, the dijet systems are not correlated.

The normalized differential cross section as a function of $\Delta\phi_{\text{soft}}$ is well described by all predictions, but shows very little sensitivity to contributions from DPS, as illustrated by the POWHEG prediction without MPI. The normalized differential cross section as a function of $\Delta_{\text{soft}}^{\text{rel}} p_T$ is reasonably described by all predictions for $\Delta_{\text{soft}}^{\text{rel}} p_T \gtrsim 0.4$ but significant differences show up at smaller values. The prediction of POWHEG without MPI shows clearly the need of additional contributions in this region. The normalized differential cross section as a function of ΔS is not well described by any of the predictions. In the range $\Delta S < 2.5$ SHERPA is above the data while all other predictions are significantly below the measurement. The prediction from POWHEG

without MPI is several standard deviations away from the measurement at small ΔS.

The comparison of the normalized differential cross sections as a function of $\Delta\phi_{\text{soft}}$, $\Delta_{\text{soft}}^{\text{rel}}p_{\text{T}}$, and ΔS for pp $\rightarrow$ 4j+X in $|\eta| < 4.7$ shows that the present calculations based on 2$\rightarrow$2 , 2$\rightarrow$3 and 2$\rightarrow$4 matrix elements matched with parton showers and including a simulation of MPI agree within uncertainties only in some regions of the phase space. The contributions from SPS can be improved by higher order calculations and the predictions including MPI need to be validated also with underlying event measurements [30, 31], before a direct extraction of the DPS contribution can be performed. Especially the ΔS distribution leaves room for additional contributions from SPS at larger values of ΔS. However, the measurement of $\Delta_{\text{soft}}^{\text{rel}}p_{\text{T}}$, and ΔS may be taken as an indication for the need of DPS in the investigated models.
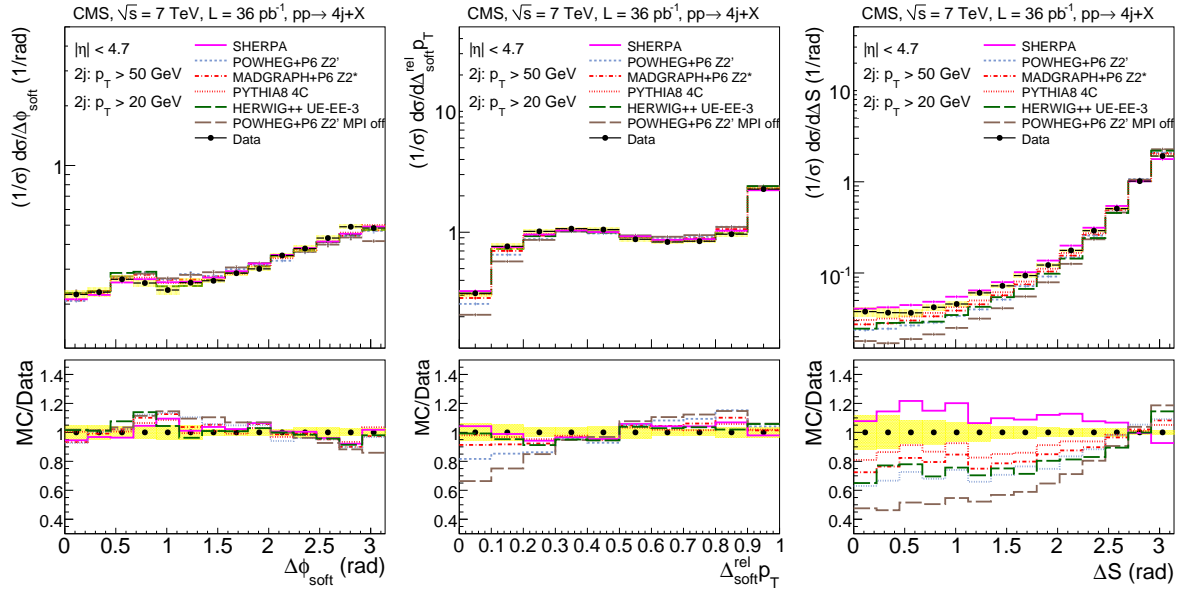

Figure 3: Normalized differential cross sections as a function of the difference in azimuthal angle $\Delta\phi_{\text{soft}}$ (left), $\Delta_{\text{soft}}^{\text{rel}}p_{\text{T}}$ (middle), and ΔS (right) compared to the theoretical predictions of POWHEG, MadGraph, SHERPA, PYTHIA 8 and HERWIG++. A comparison with the POWHEG predictions interfaced with the parton shower PYTHIA 6 tune Z2' without MPI is also shown. The lower panel shows the ratios of the theoretical prediction to the data. The yellow band represents the total uncertainty, including the statistical and systematic components.

5 Conclusions

Measurements of exclusive four-jet observables have been performed based on data collected with the CMS experiment in 2010 with an integrated luminosity of 36 pb^{-1}. The cross section for a final state with a pair of hard jets with $p_{\text{T}} > 50$ GeV and another pair with $p_{\text{T}} > 20$ GeV within $|\eta| < 4.7$ is measured to be $\sigma(\text{pp} \rightarrow 4\text{j} + X) = 330 \pm 5\,(\text{stat.}) \pm 45\,(\text{syst.})$ nb. The differential cross sections as a function of p_{T} and η of each of the four jets together with the normalized differential cross sections, as a function of correlation variables $\Delta\phi_{\text{soft}}$, $\Delta_{\text{soft}}^{\text{rel}}p_{\text{T}}$, and ΔS, are compared to several theoretical predictions.

The models considered are able to describe the differential cross sections only in some regions of the phase space. Although the predictions of the differential cross sections at large transverse momenta are reasonable, significant differences arise at smaller p_{T} especially for the subleading and soft jets.

The comparison of the normalized differential cross sections, as a function of $\Delta\phi_{\mathrm{soft}}$, $\Delta_{\mathrm{soft}}^{\mathrm{rel}}p_{\mathrm{T}}$, and ΔS for pp $\rightarrow$ 4j+X for $|\eta| < 4.7$, shows that the present calculations based on $2\rightarrow 2$, $2\rightarrow 3$ and $2\rightarrow 4$ matrix elements matched with parton showers, and including a simulation of MPI, agree only in some regions of the phase space. The contributions from SPS can be improved by higher order calculations. The predictions including MPI need to be validated with underlying event measurements before a direct extraction of the DPS contribution can be performed. In particular, the ΔS distribution leaves room for additional contributions from SPS at larger values of ΔS. However, the measurements of $\Delta_{\mathrm{soft}}^{\mathrm{rel}}p_{\mathrm{T}}$, and ΔS may be taken as an indication for the need of DPS in the investigated models.

Acknowledgments

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