PROCEEDINGS OF SCIENCE

$\Delta\phi$ and multi-jet correlations with CMS

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We present angular correlations in multi-jet events at highest center-of-mass energies and compare the measurements to theoretical predictions including higher order parton radiation and coherence effects.

XXV International Workshop on Deep-Inelastic Scattering and Related Subjects
3-7 April 2017
University of Birmingham, UK

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1. Introduction

Particle jets with large transverse momenta, p_T, are abundantly produced in highly energetic proton-proton collisions at the CERN LHC, when two partons interact with high momentum transfer under the strong interaction. The process is described by Quantum Chromodynamics (QCD) using perturbative techniques (pQCD). The two-final state partons, at leading order (LO) in pQCD, are produced back-to-back in the transverse plane and thus the azimuthal angular separation between the two highest p_T jets in the transverse plane, $\Delta\phi_{1,2} = |\phi_{\text{jet1}} - \phi_{\text{jet2}}|$, equals π. The production of a third or more high-p_T jets leads to a deviation from π in the azimuthal angle. The measurement of the azimuthal angular correlation (or decorrelation from π) in inclusive 2-jet topologies is proven to be an interesting tool to gain insight into multijet production processes. Previous measurements of azimuthal correlation in inclusive 2-jet topologies were reported by the D0 Collaboration [1, 2], ATLAS Collaboration [3], and CMS Collaboration [4, 5]. Multijet correlations have been measured by the ATLAS collaboration at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV [6, 7].

This paper reports measurements of the normalized inclusive 2-jet cross sections as a function of the azimuthal angular separation between the two leading p_T jets for several intervals of the leading jet p_T (p_T^{max}). The measurements are done in the region $\pi/2 < \Delta\phi_{1,2} \leq \pi$. Measurement of inclusive 3-jet and 4-jet cross sections are also available in [8].

Experimental and theoretical uncertainties are reduced by normalizing the $\Delta\phi_{1,2}$ distribution to the total dijet cross section. The measurement is performed using data collected during 2016 with the CMS experiment at the CERN LHC, corresponding to an integrated luminosity of $35.9 fb^{-1}$ of proton-proton collisions at $\sqrt{s} = 13 TeV$.

Concerning the final event selection, in this analysis first we consider all jets with a minimum p_T of 100 GeV and $|y| < 5$. Then for inclusive 2-jets events we require at least 2 jets whith $|y_1| < 2.5$ and $|y_2| < 2.5$. For inclusive 3-jet (4-jet) all jets must have $|y| < 2.5$.

2. Results and Conclusions.

Predictions from different MC event generators are compared to data. The HERWIG++ and the PYTHIA8 event generators are considered. Both of them are based on LO $2 \rightarrow 2$ matrix element calculations. For PYTHIA8, the CUETP8M1 tune [9], which is based on NNPDF2.3LO [10, 11], is considered, while HERWIG++ uses the CUETHppS1 tune [9], based on the CTEQ6L1 PDF set [12]. The MADGRAPH [13] event generator provides LO matrix element calculations with up to four outgoing partons. The NNPDF2.3LO PDF set is used in the matrix element calculation. It is interfaced to PYTHIA8 with tune CUETP8M1. For the matching with PYTHIA8, the kt-MLM matching procedure [14] is used. Predictions based on NLO pQCD are considered using the POWHEG package [15, 16, 17] and the HERWIG7 [18] event generator. The events simulated with POWHEG are matched to PYTHIA8 or to HERWIG++ parton showers and MPI, while HERWIG7 uses similar parton shower and MPI models as HERWIG++. In this analysis, POWHEG provides an NLO dijet calculation [19], referred to as POWHEG 2jet, and an NLO three-jet calculation [20], referred to as POWHEG 3jet, both using the NNPDF30nlo PDF set [21]. The POWHEG 2jet is matched to PYTHIA8 with tune CUETP8M1 and HERWIG++ with tune CUETHppS1, while the POWHEG 3jet is matched only to PYTHIA8 with tune CUETP8M1. Predictions from

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the HERWIG7 event generator make use of NLO dijet matrix elements calculated with the MMHT 2014 PDF set [22] and use the default tune H7-UE-MMHT [18] for the UE simulation. Parton shower contributions are matched to the matrix element within the MC@NLO procedure [23, 24] through angular-ordered emissions.

The unfolded, normalized inclusive 2-jet cross sections differential in $\Delta\phi_{1,2}$ are shown in Fig. 1 for the various p_T^{max} regions considered. The distributions are strongly peaked at π and become steeper with increasing p_T^{max}. Overlaid with the data are predictions from POWHEG 2jet + PYTHIA8 event generator. The error bars on the data points represent the total experimental uncertainty, which is the quadratic sum of the statistical and systematic uncertainties.

Figures 2 (left) shows the ratios of the PYTHIA8, HERWIG++, MADGRAPH + PYTHIA8 event generators predictions to the normalized inclusive 2-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent their statistical uncertainties. Among the LO dijet event generators HERWIG++ exhibits the largest deviations from the measurements. PYTHIA8 behaves much better than HERWIG++ exhibiting some deviations particular around $\Delta\phi = 5\pi/6$. The MADGRAPH + PYTHIA8 event generator provides the best description of the measurements.

Figures 2 (right) shows the ratios of the POWHEG 2jet matched to PYTHIA8 and HERWIG++, POWHEG 3jet + PYTHIA8, and HERWIG7 event generators predictions to the normalized inclusive 2-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{max} regions. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainties in the simulated data. The predictions of POWHEG 2jet or POWHEG 3jet exhibit large deviations from the measurements. It has been checked that POWHEG 2jet predictions at parton level, i.e. without the simulation of MPI, HAD and parton showers, give a reasonable description of the measurement for values of $\Delta\phi_{1,2}$ greater than $\approx 2\pi/3$, while they completely fail for smaller values, where the parton shower has a crucial role. Adding parton showers fills the phase space at low values of $\Delta\phi_{1,2}$ and brings the POWHEG 2jet predictions closer to data, however with the parameter setting used the agreement is not optimal. Unfortunately, no big effect is observed when parton-shower is included. Further investigation showed that the POWHEG 2jet calculation and the POWHEG three-jet calculation at LO are equivalent when initial- and final-state radiation is switched off.

The predictions from POWHEG 2jet matched to PYTHIA8 are describing the normalized cross sections better than those where POWHEG 2jet is matched to HERWIG++. Since the hard process calculation is the same, the difference between the two predictions is entirely due to different parton shower in PYTHIA8 and HERWIG++, which also use different α_S values for initial- and final-state emissions, in addition to a different upper scale used for the parton shower simulation, which is higher in PYTHIA8 than in HERWIG++. The dijet NLO event generator HERWIG7 provides the best description of the measurements, showing a very large improvement in comparison to HERWIG++.

For this observable MC@NLO method of combining parton shower with the NLO parton level calculations has advantages compared to the POWHEG method.

All these observations emphasize the need to improve predictions for multijet production. Similar observations, for the inclusive 2-jet cross sections differential in $\Delta\phi_{1,2}$, were reported previously by CMS [5] at a different centre-of-mass energy.

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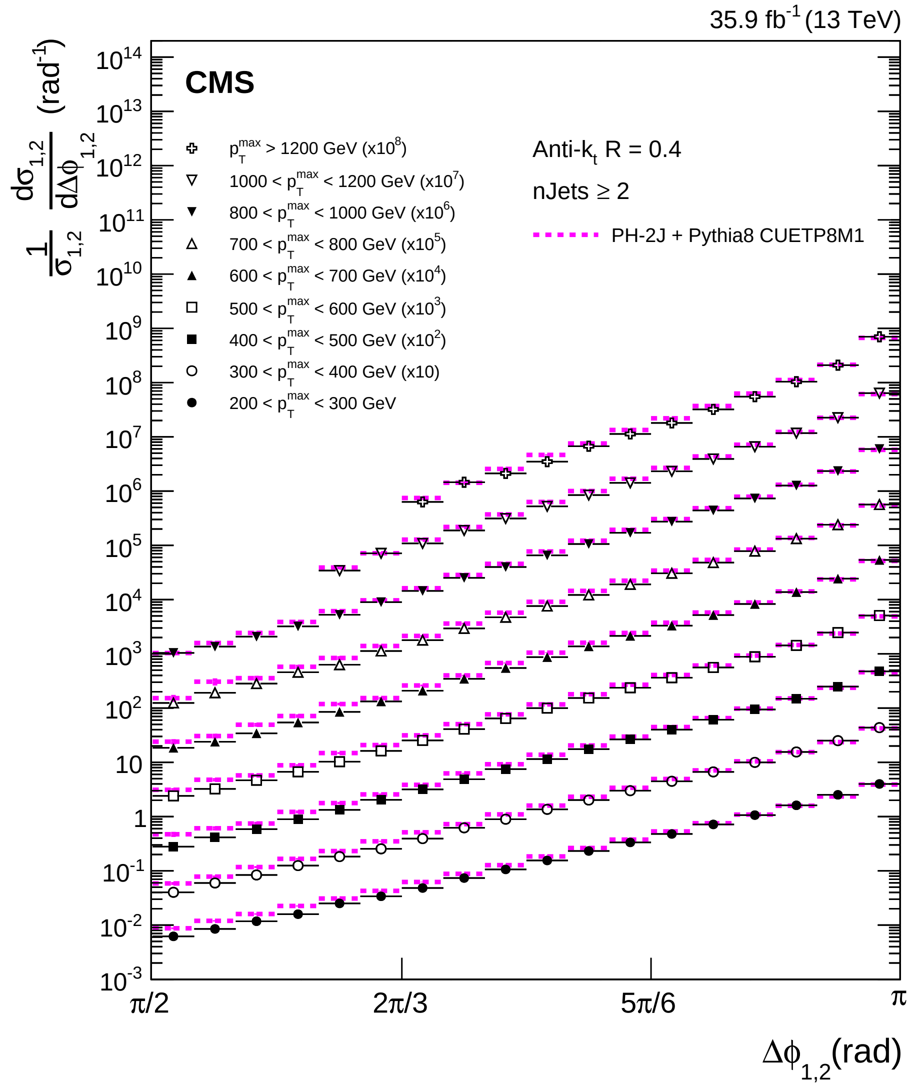

Figure 1: Normalized inclusive 2-jet cross section differential in $\Delta\phi_{1,2}$ for nine p_T^{max} regions, scaled by multiplicative factors for presentation purposes [8]. The error bars on the data points include statistical and systematic uncertainties. Overlaid with the data are predictions from the POWHEG 2jet + PYTHIA8 event generator.

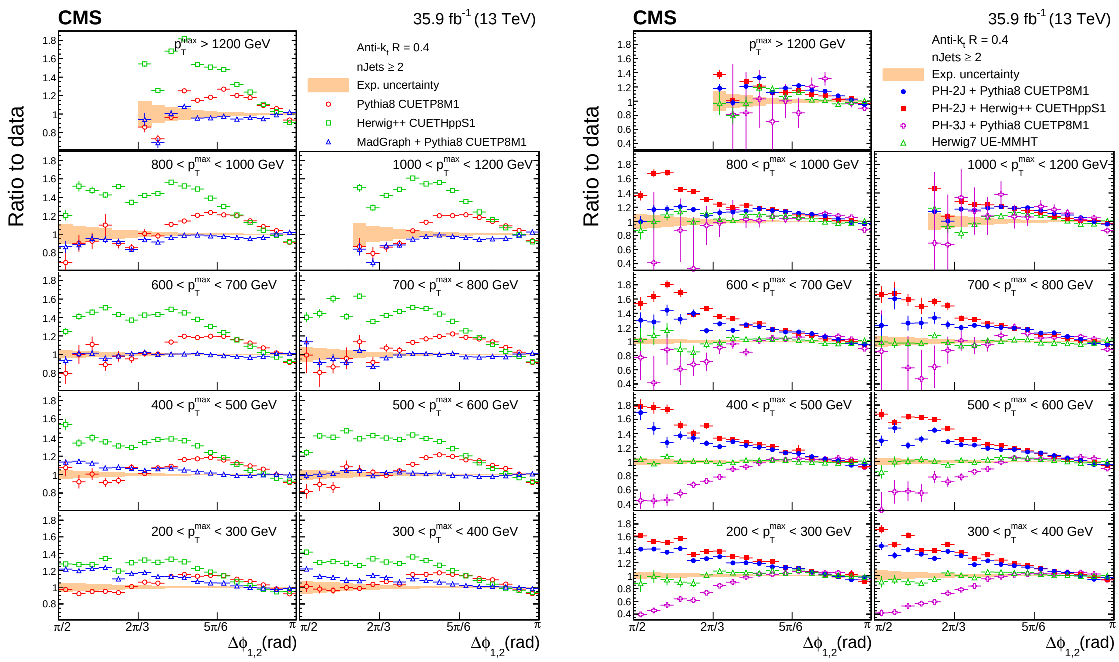

Figure 2: Ratios of PYTHIA8, HERWIG++, MADGRAPH + PYTHIA8 (left), and POWHEG 2jet, POWHEG 3jet, Herwig7 (right) predictions, to the normalized inclusive 2-jet cross section differential in $\Delta\phi_{1,2}$, for all p_T^{max} regions [8]. The solid band indicates the total experimental uncertainty and the error bars on the MC points represent the statistical uncertainties of the simulated data.