PROCEEDINGS OF SCIENCE

Multi-jets at the LHC

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We present the latest results on multi-jet final states from the ATLAS and CMS Collaborations. This includes the measurement of four-jet production in pp collisions at $\sqrt{s} = 8$ TeV, and transverse energy-energy correlations in pp collisions at $\sqrt{s} = 7$ TeV with ATLAS; as well as results from CMS on the dijet differential cross section as function of $\Delta\phi$ in pp collisions at $\sqrt{s} = 8$ TeV, and a first measurement of the azimuthal decorrelation of most-forward and backward jets in pp collisions at $\sqrt{s} = 7$ TeV.

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1. Introduction

Multi-jet topologies at the LHC are an ideal tool to study QCD at hadron colliders. They can be used to perform precision measurements with central high-p_T jets to test LO or NLO perturbative QCD calculations, and to check the description of various PDF sets. In addition, such topologies are good candidates to challenge the $2 \rightarrow 2$ matrix element Monte Carlo event generators that use so called parton showers to account for higher order effects. Another interesting question that can be addressed is the role of multiple parton interactions (MPI), and more specifically double hard parton scatterings (DPS). At the LHC, such measurements can be conducted in the most extreme corners of available phase space, either at very high transverse momenta at central rapidities, or down to very low transverse momenta in the forward region, where effects of potential new parton dynamics can be probed. Since final states involving jets are quite abundant at the LHC, the measurement of multi-jet topologies is a very active field in both the ATLAS [1] and CMS [2] experiments. It is however challenging, as one has to deal with the presence of pile-up in data, and deduce precise jet energy calibrations.

In these proceedings we present a brief summary of two analyses performed by the ATLAS experiment: the measurement of four-jet production in pp collisions at $\sqrt{s}$ = 8 TeV [3], and the measurement of transverse energy-energy correlations in pp collisions at $\sqrt{s}$ = 7 TeV [4]; followed by two analyses conducted by the CMS experiment: the measurement of the dijet differential cross section as function of $\Delta\phi$ in pp collisions at $\sqrt{s}$ = 8 TeV [5], and a first measurement of the azimuthal decorrelation of most-forward and backward jets in pp collisions at $\sqrt{s}$ = 7 TeV [6].

2. Four-jet production

The ATLAS Collaboration has measured the differential cross section in four-jet production in pp collisions at $\sqrt{s}$ = 8 TeV as function of momentum, mass and angular variables. These observables are selected to maximise the sensitivity of the analysis to different aspects of QCD, and to compare models that are either expected to perform well, or worse in certain areas of phase space. The measurement probes the performance of: all order calculations with the HEJ model, NLO perturbative QCD calculations, predictions of multi-leg matrix element + parton shower combinations, and the widely used $2 \rightarrow 2$ matrix element + parton shower Monte Carlo event generators. The analysis requires at least 4 jets that are reconstructed using the anti-k_T algorithm with R = 0.4, within the region |y| < 2.8. The leading jet $p_T^{(1)}$ is required to be at least 100 GeV, while the remaining jets have $p_T^{(2,3,4)}$ > 64 GeV. All jets are well separated in (η, ϕ) by asking $\Delta R_{min} > 0.65$. The total experimental uncertainty is within 10%, and dominated by the jet energy scale.

Figure 1 shows the $\Delta\phi_{3j}^{min} = \min\limits_{i \neq j \neq k} \left(|\phi_i - \phi_j| + |\phi_j - \phi_k| \right)$ observable. It is the minimum azimuthal separation between any three jets, and it allows to distinguish pairs of nearby jets from the recoil of three jets against one. It is particularly interesting as it can precisely probe the performance of the implemented parton dynamics in various models, and has an additional sensitivity towards jets produced from a single or double hard parton scattering. The results show that Herwig++ performs well in the azimuthal angle variables, while Pythia fails at lower leading jet transverse momenta. The compared NLO predictions are compatible within theoretical uncertainties. In general the analysis provides a thorough test of perturbative QCD, and starts to reveal the

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shortcomings of $2 \rightarrow 2$ matrix element + parton shower Monte Carlo event generator predictions in various scenarios.

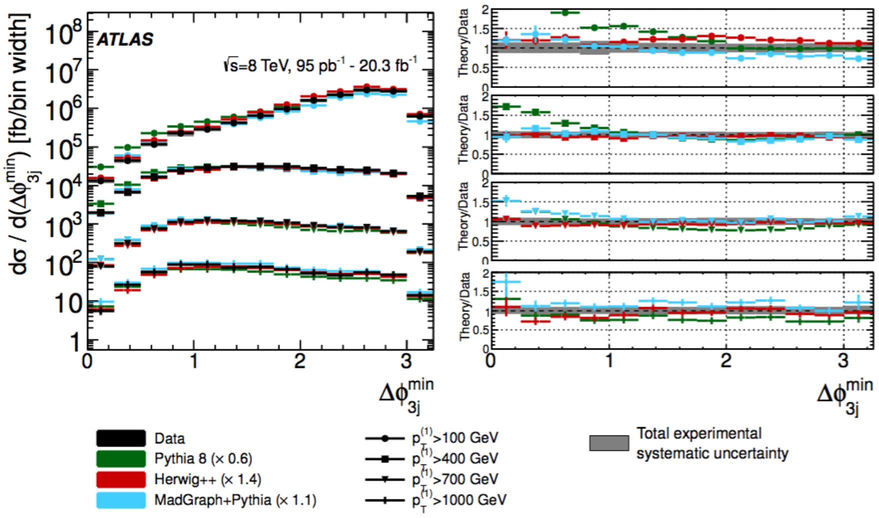

Figure 1: Unfolded four-jet differential cross section as a function of $\Delta\phi_{3j}^{min}$, compared to different model predictions. [3]

3. Transverse energy-energy correlations

Measurements of energy-weighted angular distributions of hadron pairs were proposed in e+e- annihilation experiments as alternative event shape variables, which by construction are not affected by soft divergences. The results of this new approach had significant impact on precision tests of perturbative QCD, and the determination of α_S. At hadron colliders, transverse energy-energy correlations (TEEC) are defined, together with their asymmetrical version (ATEEC) [4]. Both are less affected by experimental effects (e.g. jet energy scale, pile-up) than absolute cross section measurements, and furthermore, uncertainties that are constant over $\cos\phi$ cancel out in the ATEEC distributions. Similarly, PDF uncertainties in theoretical predictions cancel to large extent, which makes the observables well suited to extract α_S. The ATLAS Collaboration has measured the TEEC and ATEEC distributions in pp collisions at $\sqrt{s}$ = 7 TeV, by requiring at least 2 jets with $p_T > 50$ GeV within $|\eta| < 2.5$, and with $p_{T,1} + p_{T,2} > 500$ GeV. The results are in figure 2, which shows that data can be well described by Pythia6 and Alpgen, while Herwig++ has discrepancies up to 30%. By fitting the data with QCD predictions obtained with NLOJET++, which describe the data well, and using the CT10 PDF set, a value of $\alpha_S(m_Z) = 0.1173 \pm 0.0010$ (exp.) ${}^{+0.0063}_{-0.0020}$ (scale) $\pm$ 0.0017 (PDF) $\pm$ 0.0002 (NPC) was found.

4. Dijet azimuthal decorrelations

The CMS Collaboration has measured the dijet differential cross section as function of the azimuthal angle difference, $\Delta\phi$, in pp collisions at $\sqrt{s}$ = 8 TeV. The event selection requires at least 2 jets, with $p_T > 100$ GeV within |y| < 2.5, that are reconstructed with the anti-k_T algorithm

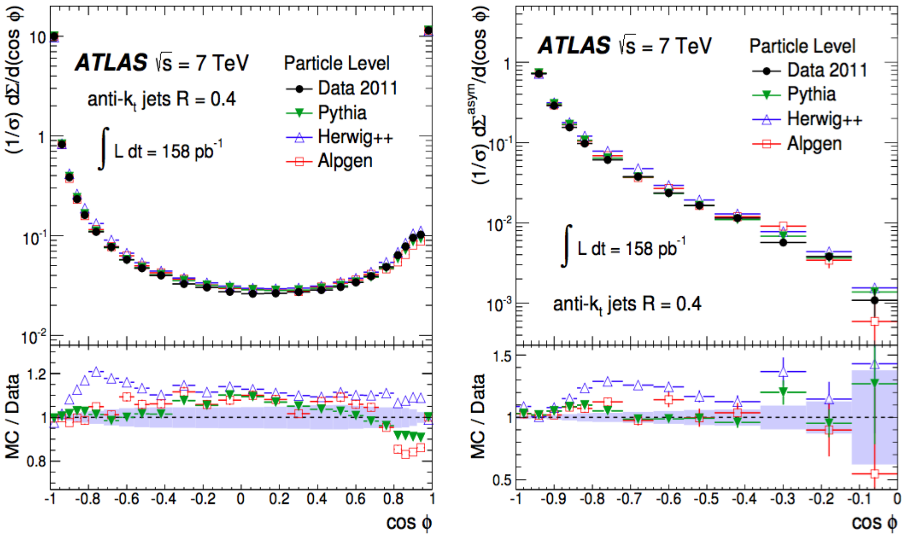

Figure 2: The unfolded distributions for transverse energy - energy correlation (left) and its asymmetry (right) along with comparisons to MC expectations. [4]

using R = 0.7. To reduce the background from $t\bar{t}$ and heavy vector boson production an additional constraint on the missing transverse energy is imposed: $\not{E}_T/\sum E_T > 0.1$, and to further reduce the experimental and theoretical uncertainties, the $\Delta\phi$ distributions are normalised to the total dijet cross section. An advantage of measuring azimuthal angle differences between two hard jets, is that one can probe multi-jet production processes without the need to actually measure jets beyond the leading two.

Figure 3 (left) shows the results compared with LO and NLO calculations using the CT10 NLO PDF set. The 3-jet NLO predictions are able to describe data down to values of $\Delta\phi \approx 5\pi/6$, but start to deviate when approaching the 4-jet region, $\Delta\phi \approx 2\pi/3$, especially at low p_T^{max}. In figure 3 (right) data are compared with $2 \to 2$ matrix element + parton shower Monte Carlo event generators, and multi-leg predictions. The Pythia8 model shows good agreement, while Pythia6 and Herwig++ overshoot the data. A good description is also provided by the tree-level multi-jet generator Madgraph, while the Powheg (dijet NLO) generator deviates, similar to LO dijet models.

5. Low-p_T jets widely separated in rapidity

A first measurement of the azimuthal decorrelation of most-forward and backward jets (so called Mueller - Navelet dijets) in pp collisions at $\sqrt{s}$ = 7 TeV has been performed by the CMS experiment. This analysis probes dijet rapidity separations up to Δy = 9.4 with low-p_T jets: p_T > 35 GeV within |y| < 4.7, reconstructed with the anti-k_T algorithm using R = 0.5. This allows us to access the very forward low-p_T phase space of QCD, and measure effects of (possibly new) low-x parton dynamics in these extreme regions. The measured observables include $\Delta\phi$ distributions between the two jets, as well as the moments of the average cosines of $\Delta\phi$: $C_n(\Delta y, p_{T,min}) = \langle\cos(n(\pi - \Delta\phi))\rangle$, and the ratios (e.g. C_2/C_1) of these average cosines as function of Δy between the Mueller - Navelet jet pair [6]. These average cosines ratios are more sensitive to

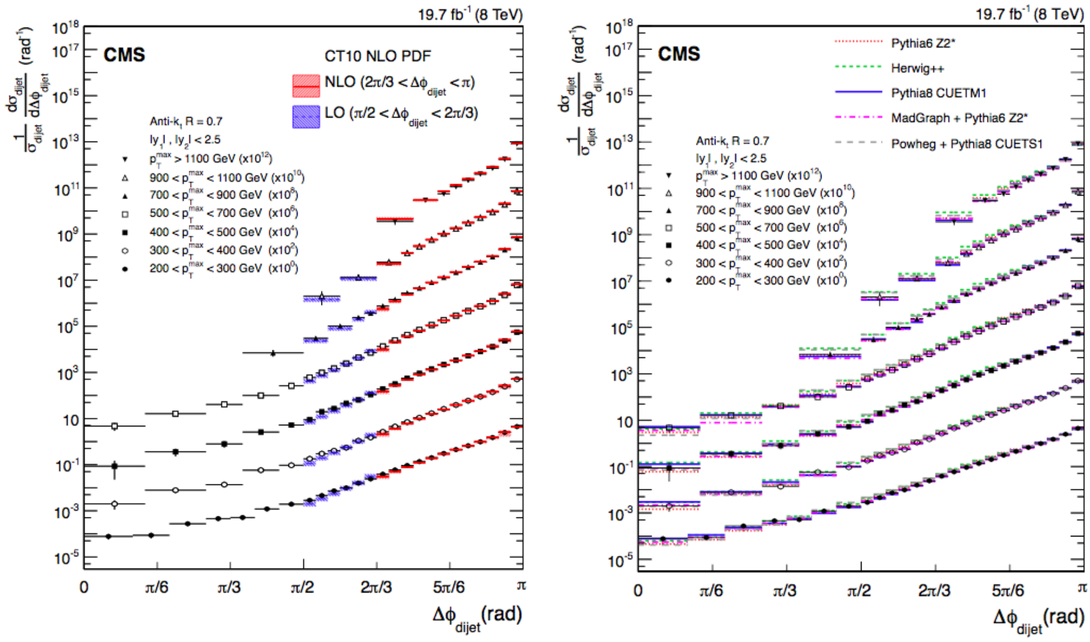

Figure 3: Normalised dijet cross section differential in $\Delta\phi$ for seven p_T regions, scaled by multiplicative factors for presentation purposes. Compared to predictions from LO and NLO calculations using the CT10 NLO PDF set (left), and to predictions from MC event generators (right). [5]

BFKL effects, since one expects a suppression of DGLAP contributions, and in addition allow to reduce uncertainties of factorisation and renormalisation scales.

The results are shown in figure 4 for the ratios C_2/C_1, and compared to various model predictions. One can see that the DGLAP-based Monte Carlo generators become less accurate at large Δy values, and using Powheg (NLO matrix element predictions interfaced with LL parton showers of Pythia) does not improve the overall agreement with data. The HEJ model (LL BFKL matrix element predictions combined with Ariadne for parton showering and hadronisation) performs better for the C_2/C_1 observable at large Δy, but predicts a too strong decorrelation in the $\Delta\phi$ distributions. On the other hand, BFKL calculations performed at NLL accuracy show a good overall agreement for the $\Delta y > 4$ region. These results thus imply that the current kinematical domain lies in a transition between regions described by DGLAP and BFKL approaches. Hence it will be very interesting to see if this is still the case at a higher centre-of-mass energy of $\sqrt{s} = 13$ TeV.

6. Summary

Both ATLAS and CMS performed extensive studies in new kinematic regions of QCD available at the LHC, at several centre-of-mass energies. Multi-jet topologies in pp collisions are an ideal tool to probe QCD dynamics by measuring momentum, mass and angular observables, and can in addition be used to extract α_S. In particular, precision studies with central high p_T jets provide a testing ground for LO and NLO pQCD calculations, which perform quite well. However, Monte Carlo event generators using the $2 \rightarrow 2$ matrix element approach supplemented with phenomenological parton showers and hadronisation start to deviate from data. Finally, the mea-

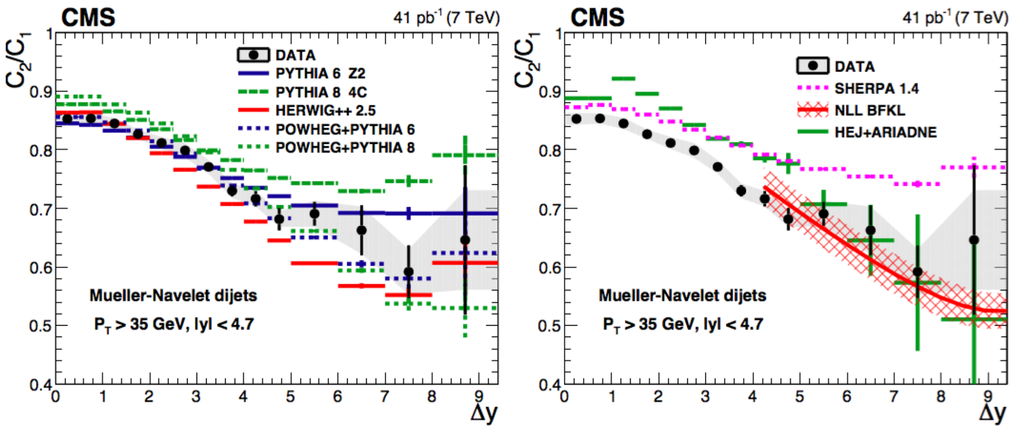

Figure 4: The measured ratios C2/C1 as a function of rapidity difference Δy compared to LL DGLAP parton shower generators and to the NLO generator POWHEG interfaced with PYTHIA 6 and PYTHIA 8 (left); and compared to SHERPA, to the LL BFKL-inspired generator HEJ, and to analytical NLL BFKL calculations at the parton level (right). [6]

surement of forward low-p_T jets probes extreme parton dynamics, and shows that we are in a kinematical domain that lies in the transition between regions described by DGLAP and BFKL approaches.

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