Jet and Multi-Jet Production at Large Rapidity (Separation) with the CMS Experiment

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Recent CMS results on the production of forward jets, of forward–central dijet systems and of dijet systems with large rapidity separation are reported. The measurements are intended to shed additional light on the long-standing question of parton evolution in the proton and to provide separation power between the various approximations.

1 Introduction

Hadronic jets have for a long time been a vital tool for investigations of the theory of strong interactions, quantum chromodynamics (QCD). At the LHC (as before at HERA and at the Tevatron), jet and multi-jet measurements especially at central rapidity values ($|y| < 2.5$) are well described by QCD calculations at next-to-leading order (NLO) based on collinear factorisation and the DGLAP approximation [1]. However, these jets offer access only to limited regions of phase space, in particular to not too small values of parton momentum fraction x and not too large rapidity separations $|\Delta y|$ of the hard jets created in the collision. In contrast, the behaviour of the proton and QCD jet phenomenology at smaller values of x are still to a certain extent *terra incognita*. Previous collider experiments — e.g. at HERA and the Tevatron — have endeavoured to explore this region, to look for signs of deviations from the collinear-factorisation DGLAP picture and to establish the necessity of alternative approaches to parton evolution like the BFKL [2] or CCFM [3] evolution approximations. Also phenomena like gluon saturation [4] and k_T factorisation [5] have been topics of many studies.

A particularly promising region to look for the breakdown of DGLAP assumptions is the "forward region", i.e. the regime of large (pseudo)rapidities: Here, in the vicinity of the beams, highly energetic parton radiation is suppressed in the DGLAP picture. Furthermore, in proton–proton collisions the forward region — compared to the central region — is populated by more asymmetric events in terms of the momentum fractions $x_{1,2}$ of the two incoming partons, thus potentially allowing for an extension of the phase space to smaller x values. Finally, a large rapidity reach opens up a large phase space (a long parton ladder) between the scattering protons, thus giving a lot of room for parton emissions and for the realisation of the underlying evolution mechanisms. It is due to its extended rapidity reach and its increased centre-of-mass energy that measurements in the forward region at the LHC promise results and insights beyond those achieved in (for example) forward-jet measurements at HERA or measurements of Mueller–Navelet jet events at the Tevatron. Furthermore, the increased reach in x is interesting also for studies of the proton PDFs.

2 CMS, jets and the event samples

The measurements presented here were performed with the CMS experiment in 33 nb^{-1} to 5 pb^{-1} of data recorded in 2010 at centre-of-mass energies of 7 TeV, when there was still little pile-up contamination for the collected event samples. Jets in CMS can be reconstructed either using calorimeter energy deposits, tracks from the inner detector or a so-called "particle flow" algorithm which maximises the resolution by optimally combining calorimeter and tracking information. For the presented measurements, calorimeter jets have been used. The anti-k_T algorithm with a radius parameter of 0.5 was chosen. Jets are categorised as "central" or "forward" according to their pseudorapidity η, with the central region being defined by $|\eta| < 2.8$ and the forward region by $3.2 < |\eta| < 4.7$.

Events were typically triggered with a single-jet trigger with an uncalibrated threshold of the transverse momentum p_T of 15 GeV; in case of dijet selections, dedicated dijet triggers were also employed. Trigger efficiencies were studied using minimum-bias events and lower-threshold triggers; all triggers were found to be fully efficient for calibrated transverse jet momenta p_T of at least 35 GeV. The typical selection of the events also comprised — among other requirements — a well-reconstructed primary vertex.

3 Forward jets

A forward-jet analysis was performed in 3.14 pb^{-1} of data [6]. The data were corrected for the dependence of the jet response on the transverse momentum and the pseudorapidity, p_T and η, and for pile-up effects using MC simulations ad p_T balancing in dijet and photon–jet events [7]. The corrected data are well described by leading-order MC predictions from both HERWIG and PYTHIA. The good description of the data enables an unfolding of the data using a bin-by-bin method. The correction factors determined with PYTHIA and HERWIG are averaged to yield the actually used correction, and the difference to an ansatz method is taken as a systematic uncertainty on the correction procedure. The corrections are of the order of 10% (40%) for p_T values of 35 (140) GeV, and the uncertainty is below 10% for all p_T bins.

The experimental systematic uncertainties of the measurement are typically of the order of 20%; the dominant contribution is the jet energy scale uncertainty. The theory uncertainties are typically of the order of 10% and driven by the model uncertainty at low p_T and the PDF uncertainty at high p_T.

Figure 1 (left) shows the result of the analysis — the corrected and unfolded inclusive forward-jet cross section as a function of the jet transverse momentum, p_T, compared to various predictions (NLO calculations and various MC models). The data are in general described by all predictions within the considerable uncertainties, as can be seen from the ratios of the predicted cross sections to the measured one in the right side of the figure.

Particular emphasis was given to the effect of different PDF parametrisations. It was found that all PDF sets used are similar and consistent with the data, even if on average the data points are overshot by about 20% by the NLO calculations.

In a further analysis in the same data set [6], a dijet sample consisting of one central and one forward jet is selected (in case of more than one sufficiently hard jet in either region, the hardest one is chosen). The selection and correction procedure for this dijet analysis follows closely that of the forward-jet analysis just discussed, and also the size of the corrections and their uncertainties, the quality of the description of the data by the MC models and the

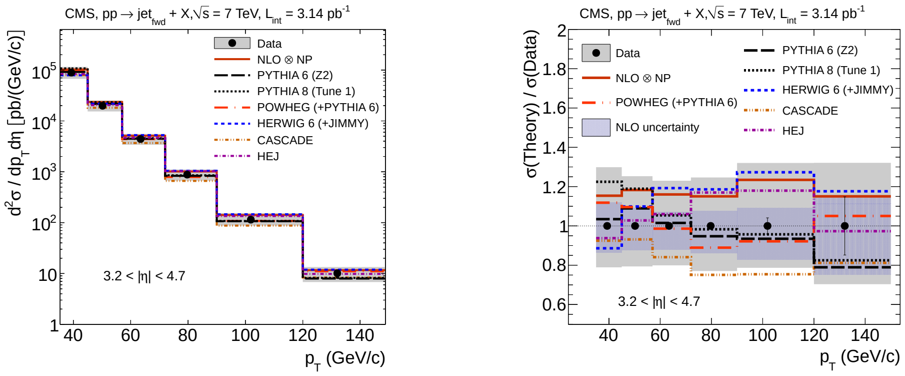

Figure 1: Left: inclusive forward-jet cross section as a function of p_T. The data points are compared to various models and predictions. Right: ratios of the predictions to the data.

experimental and systematic uncertainties are similar.

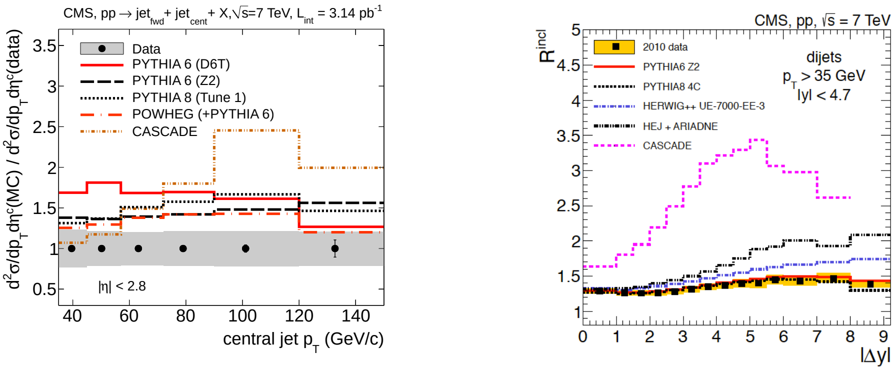

Figure 2: Left: the cross section of central–forward dijet production as a function of the central jet p_T. Shown are ratios between various predictions and the data. Right: R^{incl} for data and various models.

Figure 2 (left) shows the ratio of various predictions of the dijet cross section to the measured one as a function of the p_T of the central jet. HERWIG, HERWIG++, POWHEG+HERWIG and the HEJ generator describe the data slightly better than the models shown in the figure. The forward jet in the dijet system is typically better described than the central one, although at low p_T PYTHIA, POWHEG+PYTHIA and CASCADE are all too high and the POWHEG+HERWIG prediction is significantly to high for all p_T bins.

4 Dijet ratios at large rapidity separation

A third measurement by CMS also focused on dijet systems and used 33 nb^{-1} and 5 pb^{-1}, respectively, for dijets with small and large rapidity separation, $|\Delta y|$ [8]. Dijet events were studied as a function of this observable, and the quantity studied is the ratio of the inclusive to the exclusive dijet cross section, $\sigma^{incl}/\sigma^{excl}$ [9]. Here, events with exactly one pair of jets passing the selection criteria (mainly the already well-known minimum p_T cut of 35 GeV) are counted for the "exclusive" sample; for the "inclusive" sample, each pairwise combination of jets above that threshold is counted. The Mueller-Navelet (MN) sample is a subset of the inclusive sample and considers only the jet at highest (most forward) and that at lowest (most backward) rapidity [10]. The ratio of inclusive (MN) to exclusive dijets is called R^{incl} (R^{MN}).

Figure 2 (right) displays the experimental situation. The plot shows R^{incl} as a function of $|\Delta y|$ (note that the inclusive and the Mueller-Navelet cases are quite similar, and that — as expected — at large rapidity separations the two quantities agree). R^{incl} increases with increasing $|\Delta y|$ because of increasing phase space; for kinematic reasons the quantity decreases again at the highest rapidity separations.

The data are well described by the various PYTHIA models, whereas HERWIG overshoots the data especially at medium and high rapidity separation values. The HEJ and CASCADE predictions are significantly off.

5 Summary and conclusions

The large rapidity range and large available phase space at the LHC offer excellent opportunities for detailed studies of parton dynamics. Many relevant measurements have already been performed in this very active field. Here, measurements of inclusive forward-jet cross sections, of central–forward dijet systems and of the ratio of inclusive to exclusive dijet production have been presented.

The data and their description by the various predictions do not give a consistent picture of forward physics and of parton evolution. Depending on the phase space, different models fail or succeed in describing the data, and no firm conclusions on the necessity for alternatives to the DGLAP evolution scheme can be drawn. For progress in this direction, a more consistent and more complete understanding of parton dynamics is required.

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