Measurements of Forward Energy Flow and Forward Jet Production with CMS

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1 Introduction

With proton–proton collisions at a centre-of-mass energy of 7 TeV the Large Hadron Collider (LHC) allows to explore QCD effects in completely new regions of phase space. At these energies parton densities become very large and small-x effects may be observed. The large available phase space, especially in the region of large pseudo-rapidities η, the so-called forward region, facilitates a high sensitivity for additional QCD radiation and multiple parton interactions. Measurements undertaken at large values of η complement studies performed in the central region, and thus allow to gain a more complete picture of QCD effects.

The presented analyses are performed with the Central Muon Solenoid (CMS) [1], mainly its Hadronic Forward Calorimeters (HF), which consist of a steel absorber with embedded quartz fibres and are located on both sides of the detector, covering the region of $2.9 < |\eta| < 5.2$.

2 Inclusive Forward Jets

The inclusive forward jet spectrum is measured in the region $3.2 < |\eta| < 4.7$ with data collected in the low luminosity phase in the beginning of 2010, corresponding to an integrated luminosity of $3.14\,\mathrm{pb}^{-1}$. The jets are reconstructed from the HF calorimeter information utilising the anti-k_T algorithm [2] with $R = 0.5$. All jets with a transverse momentum of $p_T > 35\,\mathrm{GeV}$ are considered.

Figure 1 shows the inclusive cross section in bins of p_T, corrected to hadron level. The yellow band indicates the total experimental uncertainty of the measurement, which is in the region of 25% – 40%. The result is compared to different Monte Carlo event generators. Predictions from leading order Monte Carlos with DGLAP based parton showers (Herwig [3, 4, 5], Pythia 6 [6, 7, 8, 9, 10], Pythia 8 [11]), next-to-leading order generators (Nlojet++ [12, 13], Powheg [14, 15, 16]), and a Monte Carlo with a parton evolution governed by the CCFM equation (Cascade [17, 18]) are presented. All of them show a good agreement with the measurement within the experimental uncertainty. Only CASCADE predicts a more concave shape and its predictions are outside the error band in a few bins. The measured inclusive forward jet cross section confirms the predictions from the current models very well. An extensive discussion of this analysis is presented in [19].

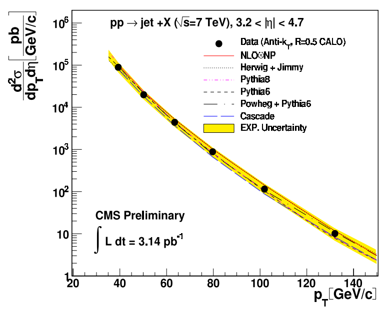

Figure 1: Inclusive forward jet cross section compared to various Monte Carlo predictions. The yellow band indicates the total systematic uncertainty of the measurement.

3 Simultaneous Production of Forward and Central Jets

The data set used for the measurement of the inclusive forward jet cross sections is used to investigate the simultaneous production of forward and central jets, again utilising the anti-k_T algorithm with $R = 0.5$. Jets are considered to be central when they fulfil $|\eta| < 2.8$ while the forward jets are required to be contained in the region $3.2 < |\eta| < 4.7$. The analysis focusses on events in which at least one jet in the central and another one in the forward region is observed. The required minimum transverse momentum for both jets is $p_T > 35\,\text{GeV}$.

Figure 2 presents the cross section for forward and central jets in bins of p_T. The forward jet spectrum is depicted for events with at least one central jet with $p_T > 35\,\text{GeV}$ and vice versa. In case more than one jet in one of the particular regions fulfils the requirement, the highest-p_T jet is considered. The data is corrected to hadron level and compared to different Monte Carlo predictions. The yellow bands show the combined statistical and systematic uncertainties.

The data is compared to various Monte Carlo predictions. In addition to the models already used in section 2, the HEJ model [20, 21], that is based on the BFKL evolution equation, is utilised. HERWIG yields the best description of the data. None

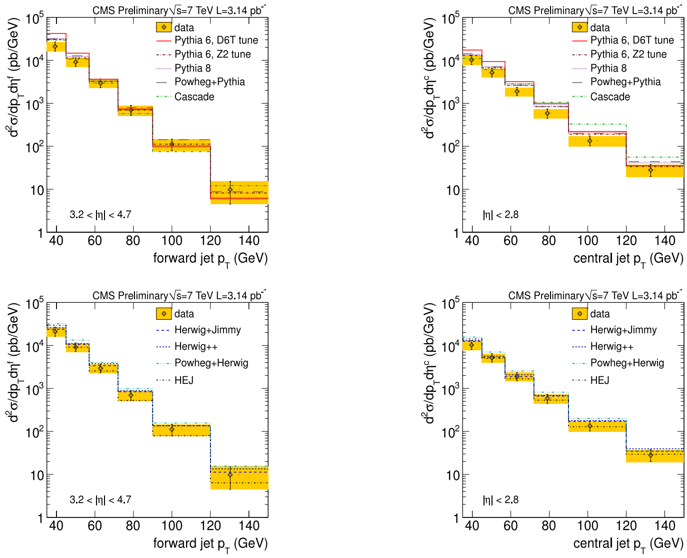

Figure 2: Left: Forward jet cross section for events with at least one central jet with $p_T > 35\,\mathrm{GeV}$. Right: Central jet cross section for events with at least one forward jet with $p_T > 35\,\mathrm{GeV}$. Top: Comparison to Monte Carlos related to PYTHIA. Bottom: Comparison to Monte Carlos related to HERWIG and HEJ. The yellow bands indicate the total experimental uncertainties.

of the other Monte Carlos can describe shape and normalisation correctly, especially the central jet distribution is not well modeled. Including next-to-leading order calculations via POWHEG worsens the agreement. While the CCFM based model implemented in CASCADE predicts a different shape of the distribution, the BFKL governed HEJ model can at least provide a reasonable description of the measurement. More details about this study can be found in [22].

4 Forward Energy Flow in Minimum Bias and Di-jet Events

The energy flow in the forward region is analysed in Minimum Bias events at 900 GeV and 7 TeV for $231\,\mathrm{pb}^{-1}$ and $206\,\mathrm{pb}^{-1}$, respectively. In addition, a di-jet selection is applied to the same events and the forward energy flow determined for this event type for both energies. The two highest p_T jets are required to be contained in the central region $|\eta| < 2.5$ and to have a minimum transverse momentum of 8 GeV (20 GeV) for the 900 GeV (7 TeV) data.

Figure 3 shows the data corrected to hadron level, whereat the error bars indicate the total systematic uncertainties. The yellow band shows the region covered by various PYTHIA 6 tunes (CW, D6T, DW, P0, ProPT0, ProQ20, Z2). Additional comparisons to PYTHIA 8, HERWIG++ [23], PYTHIA 6 tune D6T without multiple parton interactions, and for the di-jet case CASCADE, are presented.

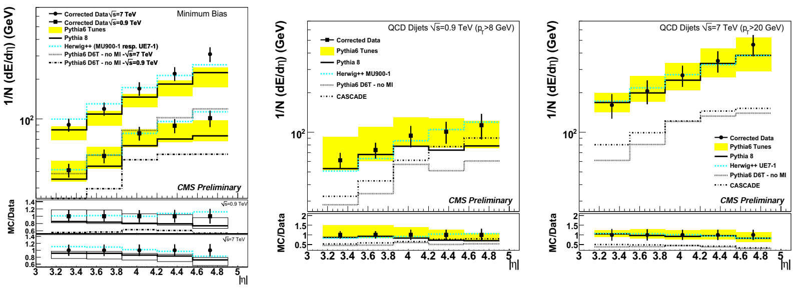

Figure 3: The forward energy flow in bins of η is presented for Minimum Bias events at 900 GeV and 7 TeV in the left panel, for di-jet events at 900 GeV in the central panel, and for di-jet events at 7 TeV in the right panel. The error bars indicate the total experimental uncertainty. The yellow band is the region covered by various PYTHIA 6 tunes.

In the left panel of figure 3 the forward energy flow is depicted for Minimum Bias events for both energies. A clear dependence on the centre-of-mass energy can be observed. The other two panels present the energy flow in events with a hard scale, i. e. events with a di-jet system in the central region. The energy flow in the forward region rises with the presence of a hard process in the central region. The different PYTHIA 6 tunes cover in most bins the measurement but none of the tunes can describe all distributions. The two models without multiple parton interactions (PYTHIA 6 D6T - no MI, and CASCADE) underestimate the data significantly, even though the CCFM based shower seems to fill a part of the uncovered phase space. Nevertheless, multiple parton interactions turn out to be crucial for the description of this measurement by the standard Monte Carlo models. While none of the presented HEP generators can describe all distributions with one single setting of its parameters, different Monte Carlo generators, that are originally dedicated to cosmic ray analyses, provide very good descriptions of all measurements (not shown).

In summary, a dependence of the forward energy flow on the centre-of-mass energy as well as on a present hard scale is observed. Multiple parton interactions seem to be fundamental for a proper description while none of the HEP Monte Carlo generators is able to describe all measurements satisfactorily. The full analysis is presented in [24].

5 Forward Energy Flow in Events with Z and W Bosons

Central track multiplicity and forward energy flow are analysed for events with leptonically decaying Z and W bosons. The study is performed at a centre-of-mass energy of 7 TeV for an integrated luminosity of 36 pb^{-1}, corresponding to the full data sample recorded by CMS in 2010.

W events are identified by requiring a charged lepton in $|\eta| < 1.4$ with $p_T >$ 25 GeV, and missing transverse energy above 30 GeV. The invariant mass of lepton and neutrino candidate has to exceed 60 GeV. For Z events two opposite charged leptons of the same flavour with $p_T > 25$ GeV and an invariant mass between 60 GeV and 120 GeV are required, whereat at least one of the leptons has to be contained in $|\eta| < 1.4$. The results gained the different selections are very similar.

Figure 4 shows the track multiplicity in the central region ($|\eta| < 2.5$) and the summed energy flow in the forward region measured by the two HF calorimeters for $W \to e\nu$ events. The error bars indicate the statistical uncertainties, the yellow band in the right panel takes an HF energy scale uncertainty of 10% into account. The data is compared to different Pythia 6 tunes, from which none can describe the distributions correctly.

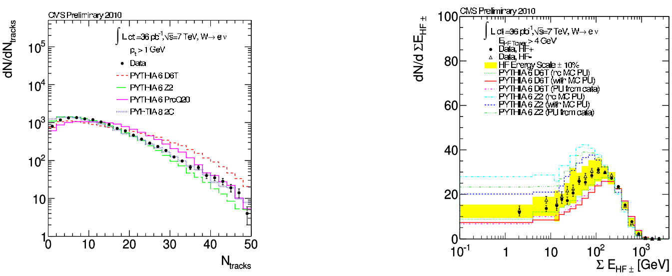

Figure 4: Central track multiplicity (left) and summed forward energy flow for the two HF calorimeters (right) for events with a reconstructed W boson. The error bars indicate the statistical uncertainties, the yellow band in the energy flow shows the uncertainty du to a 10% uncertainty on the HF energy scale.

A subset of these events is selected by requiring a rapidity gap , i. e. at least one HF side without any energy deposit above the threshold of 4 GeV. Figure 5 shows the track multiplicity and forward energy distributions for $W \to l\nu$ events with a rapidity gap. The Monte Carlo predictions underestimate the high track multiplicity bins significantly and fail also in the description of the energy flow. In the right panel of figure 5 the pseudo-rapidity of the charged lepton with respect to the gap is depicted, in which a positive sign indicates that the lepton and the gap are in the same hemisphere. The measured asymmetry is -0.22 ± 0.06. The PYTHIA 6 models predict a flat distribution, in clear contradiction to the measurement. Only the inclusion of a fit to data with POMPYT, which is based on diffractive production, can describe the distribution correctly, thereby giving a strong indication that some of the observed events with electro-weak bosons are produced by a diffractive process. More details on this study can be found in [25].

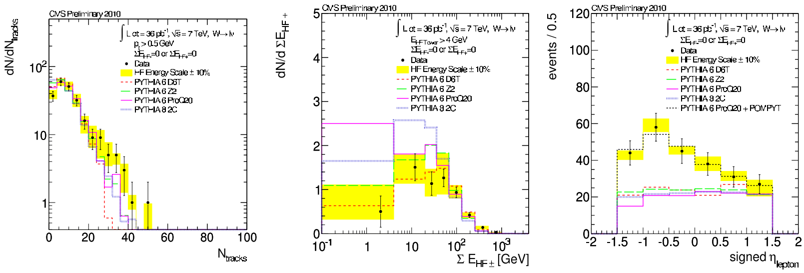

Figure 5: Central track multiplicity (left) and summed forward energy flow for the two HF calorimeters (centre) for events with a reconstructed W boson and a rapidity gap. The right panel presents the η distribution of the lepton resulting from the W decay with respect to the rapidity gap, whereat a positive sign is assigned if both lepton and gap are located in the same hemisphere. The error bars indicate the statistical uncertainties, the yellow bands show the uncertainty du to a 10% uncertainty on the HF energy scale.

6 Conclusions

The presented CMS studies are performed in phase regions not explored by former experiments. While the theoretical predictions can describe well the inclusive forward jet spectrum and provide a reasonable description of the correlated central and forward jets, they fail in describing the various measurements of the energy flow. From the energy flow studies the necessity of multiple parton interactions in the current models becomes apparent, and a clear indication for the presence of a diffractive component in the production of electro-weak gauge bosons is suggested. These analyses are an important complement of measurements performed in the central region to achieve more complete parameter sets for Monte Carlo event generator tunes. The presented results will help to improve the understanding of QCD and to constrain the different physics models.

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