Measurements of forward energy flow and forward jet production with CMS

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Abstract. We present measurements of the forward (3 < |η| < 5) energy flow in minimum bias events and in events with either hard jets or W and Z bosons produced at central rapidities, as well as measurements of the inclusive forward jet cross section and of associated production of forward and central jets. Results are compared to MC models with different parameter tunes for the description of the underlying event and to perturbative QCD calculations, the PYTHIA and HERWIG parton shower event generators, as well as to the CASCADE Monte Carlo.

1. Introduction

At high energies, the \( pp \rightarrow XY \) reaction can be described in terms of a perturbative parton-parton interaction and of proton remnants carrying a large fraction of the total energy. This picture leads to a final state \( X \) and an underlying event \( Y \) consisting of mostly soft hadrons, originating from parton showers and non-perturbative multi-parton interactions. The latter are largely independent of the hard interaction, increase the particle multiplicity and are leading to correlations between the energy flow in the central and forward regions.

The measurement of energy flow in the forward region is directly sensitive to the parton radiation at large \( \eta \) and to multiparton interactions (MPI) \([1]\). Such a measurement in \( pp \) collisions not only discriminates between different models of MPI but also improves the understanding of the basic process responsible for multiparton radiation and thus can provide additional input to the determination of the parameters in MPI models. The currently available models of MPI have mainly been tuned to minimum bias data and to final states including jets with large transverse momentum \( (p_T) \), using the observed central track multiplicities and the transverse momentum spectra of hadrons which are not associated to the hard jets. Models for a detailed simulation of MPI are under a rapid development and new features, including diffractive components in the energy flow, are extensively studied. The analysis of the underlying event structure and energy flow correlation in processes with colorless final states, such as \( pp \rightarrow W(Z)X \rightarrow l\nu(l\nu)X \), can provide new insights into so far unexplored aspects of multiparton interactions. In particular, the study of such processes with colorless final states allows for a straightforward separation of the hard interaction and the underlying event. \( W(Z) \) events with high track multiplicities in the central detector indicate a possibly large contribution from multi-parton interactions. Studies of correlations between the track multiplicity in the central

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rapidity range and energy deposits at large rapidities, in the forward regions of the experiment, should give additional information. Fig. 1 shows a prediction for the energy flow as a function of pseudorapidity for minimum bias events and for events which have a dijet with $E_{T,jet} > 20$ GeV in the central pseudorapidity region $|\eta| < 2.5$ at $\sqrt{s} = 7$ TeV. The energy flow is defined as: $(1/N_{\text{event}})(d\sum E_i/d\eta)$ where $N_{\text{event}}$ is the number of events. The energy $E_i$ of charged and neutral stable particles $i$ is summed in bins of $\eta$. The predictions from the \textsc{pythia} \cite{2} Monte Carlo (MC) event generator using different sets of parameters which were tuned to describe the Tevatron measurements are shown. The solid line uses the Perugia tune \cite{3} and the dashed line the D6T tune \cite{4}. The prediction without multiparton interaction (dotted line) is also shown. Significant differences of the energy flow in the forward region ($|\eta| > 3$) can be observed.

Jet production in hadron-hadron collisions is sensitive to the underlying partonic QCD processes, to the details of parton radiation and to the parton density functions (PDF) of the colliding hadrons. At previous colliders, the measured jet cross sections at large transverse momenta ($p_T$) are successfully described by perturbative QCD (pQCD) calculations over several orders of magnitude \cite{5}. The measurements, however, are limited to central pseudorapidities, $|\eta| < 2.5$, where the momentum fractions $x_1, x_2$ of the incoming partons are of the same order. Jets produced in the forward/backward hemispheres result from scatterings between colliding partons with increasingly different momentum fractions $x_2 \ll x_1$, and thus allows one to study QCD in the small-$x$ region where the PDFs are well constrained by deep-inelastic electron-proton data, and where deviations of the parton dynamics beyond the standard Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution \cite{6} e.g. as modelled in the Balitski-Fadin-Kuraev-Lipatov (BFKL) \cite{7}, Ciafaloni-Catani-Fiorani-Marchesini (CCFM) \cite{8}, or gluon saturation \cite{9} approaches are expected. However, we do not see any deviations until now. Understanding the dynamics of forward jet production accompanied with or without central jets is also essential for the control of the QCD backgrounds in searches of the Higgs boson produced via the vector-boson-fusion (VBF) mechanism as well as for general VBF scattering cross sections which are fundamental to understand the Electroweak Symmetry Breaking mechanism (see for example \cite{10}).
The large calorimetric coverage of CMS allows to study jet production over a region of pseudorapidity extending to $|\eta| < 5.2$ never investigated before. The production of forward jets [11] alone or in conjunction with a central jet [12] is measured using the early data collected by the CMS detector at LHC during 2010 in proton-proton (p–p) collisions at a center of mass energy of 7 TeV. The differential cross section $d^2\sigma/dp_Td\eta$ for single inclusive forward jets, as well as the differential cross sections $d^2\sigma/dp_T^2d\eta$ and $d^2\sigma/dp_T^2d\eta^c$ for the simultaneous production of at least one forward jet (f) in conjunction with at least one central jet (c) are presented. The axis of the forward jet is required to be in the fiducial Hadronic-Forward (HF) calorimeters acceptance (3.2 < $|\eta|$ < 4.7), and that of the central jet is measured within $|\eta| < 2.8$. In all cases, jets are reconstructed with the calorimeter energy deposits for transverse momenta above $p_T = 35$ GeV/c.

2. Experimental Aspect
A complete description of the CMS detector can be found elsewhere [13]. A brief outline of the components which are the most relevant for the present measurement is given here. Two hadron forward calorimeters (HF), one on each side of the CMS interaction point (IP), at $\sim$ 11 m, cover the pseudo-rapidity range 3 < $|\eta|$ < 5. Two elements of the CMS monitoring system, the Beam Scintillator Counters (BSC) and the Beam Pick-up Timing eXperiment (BPTX) devices, are used to trigger the CMS readout. The two BSC are located at a distance of $\pm$10.86 m from the nominal interaction point (IP) and are sensitive in the $|\eta|$ range from 3.23 to 4.65. The two BPTX, located around the beam pipe at a distance of $\pm$175 m from the IP on either side, are designed to provide precise information on the bunch structure and timing of the incoming beam, with better than 0.2 ns time resolution.

3. Analysis Strategy
The average energy flow at forward rapidities is determined separately in two different event classes: in minimum bias events and in events with a hard scale provided by a dijet system at central rapidities [14]. The analysis is carried out at two different centre-of-mass energies, 900 GeV and 7 TeV. The amount of activity in the underlying event is expected to vary strongly with both the QCD scale of the reaction and the centre-of-mass energy. The forward energy flow is measured by the HF calorimeters, by summing up all energy deposits of the HF towers above a noise threshold. In the minimum bias sample a search for dijets in the central region of the CMS detector is performed. Jets are reconstructed by means of the anti-$k_T$ jet algorithm (with $R = 0.5$). The dijet sample consists of events in which the two hardest jets have $|\eta| < 2.5$ and $|\Delta\phi(jet_1, jet_2) - \pi| < 1.0$. The $\eta$ cut ensures that the jets are contained in a region of CMS outside of the HF calorimeters. At $\sqrt{s} = 900$ GeV, the leading and the sub-leading jets are required to have $p_T > 8$ GeV, while at $\sqrt{s} = 7$ TeV, the jets are required to have $p_T > 20$ GeV.

Next we look at W and Z production where the identification of W and Z bosons is based on the presence of isolated electrons and muons with high transverse momentum [15]. The transverse momentum of the electron candidate is required to be larger than 25 GeV and $|\eta| < 2.5$. Two algorithms are used to identify muons. One is based on the matching of a reconstructed high transverse momentum track candidate with a track candidate found in the CMS muons system. The second applies a global fit of tracker and muon system hits. Muons in this analysis have to pass two different selection algorithms. The reconstructed muon candidate transverse momentum has to be larger than 25 GeV and $|\eta| < 2.5$.

The observables used to study the underlying event structure in W and Z events are the track multiplicity in the central detector, the energy deposits in both HF calorimeters and the correlations between them. In the following only the distributions for $W \rightarrow l\nu$ events are discussed. No significant differences are observed between W events selected with decays to electrons or muons. The same analysis has been performed with the $pp \rightarrow ZX$ data samples and, taking the
smaller number of $Z$ events into account, essentially identical distributions and conclusions are obtained.

As a further investigation of the forward energy distribution, the jets in the forward region are taken into account. The anti-$k_T$ jet clustering algorithm [16] is used to reconstruct all jets with a distance parameter of $R = 0.5$, with their reconstructed axis within $3.2 < |\eta| < 4.7$, and with $p_T > 20$ GeV.

4. Results

The energy flow is measured with the CMS HF calorimeters in the region $3.15 < |\eta_{obs}| < 4.9 <$, and corrected to hadron level. The hadron level is defined by Monte Carlo generated events in which unstable particles ($\tau < 10^{-12}$ s) decay. The particles on hadron level are required to have the same rapidity range as in the measurement ($3.15 < |\eta| < 4.9$), and do not have any selection on their energy. Moreover, at least one particle each is required on both sides of the BSC acceptance in order to suppress the diffractive events. The result is shown in Fig. 2 for minimum bias events and in Fig. 3 for dijet events, at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV. The systematic uncertainties are indicated as error bars, while the statistical errors are not shown since they are comparably small. The data are compared to various Monte Carlo predictions on hadron level.

![Figure 2](image1.png)

**Figure 2.** Energy flow as a function of $\eta$ for the Minimum Bias analyses at $\sqrt{s} = 900$ GeV and at $\sqrt{s} = 7$ TeV, corresponding to integrated luminosities of $239 \mu b^{-1}$ and $206 \mu b^{-1}$, respectively. The corrected data are shown as points. a) The histograms are the predictions from various MC generators. The yellow bands illustrates predictions from the different Pythia 6 tunes. The error bars on the data represent the systematic uncertainties, which are strongly correlated between the bins. The statistical errors of the data are less than 0.1%. b) The histograms are the predictions from Pythia 6 with various tunes.

Fig. 4 shows the HF energy sum for $W \rightarrow \mu \nu$ events and for several different MC tunes of the underlying event. As can be seen from Fig. 4, besides the ProQ20 tune [17], none of the studied MC models provides a good description of the HF energy distribution as observed in
Figure 3. Energy flow as a function of $\eta$ for the dijet analyses at $\sqrt{s} = 900$ GeV and at $\sqrt{s} = 7$ TeV, corresponding to integrated luminosities of $239 \mu b^{-1}$ and $206 \mu b^{-1}$, respectively. The corrected data are shown as points, the histograms are the predictions from various MC generators. The yellow bands illustrate predictions from the different Pythia 6 tunes.

Figure 4. The summed HF energy distribution for $W \rightarrow \mu \nu X$ candidate events are shown for data and MC simulations with different tunes for the underlying event.

the data. For energy deposits between $10 - 150$ GeV, large differences between the data and the different tunes are observed. In particular, the number of events in data is about 30% to 50% higher than predicted by the D6T tune, and 50% lower than predicted by the Z2 tune. In order to investigate the correlations of the forward energy flow and the central track multiplicity the energy on one side of HF is summed and checked how the energy on the other side of HF behaves. For this study events with energy deposits in the HF$^-$ calorimeter between $20 - 100$ GeV (low), $200 - 400$ GeV (medium) and above $500$ GeV (high) are selected. Analyzing the HF$^+$ energy distributions, the distributions corresponding to the medium HF$^-$ energy interval...
(Fig. 5b) shows smaller differences between the data and the different tunes. On the other hand, requiring a low HF$-\,$ energy deposit results in a measured HF$+\,$ energy distribution, which is badly modeled by all MC tunes (Fig. 5a). Finally, when selecting events with high energy deposits in HF$-\,$ we find that PYTHIA 8 [18], which in the inclusive case underestimates the number of events with such large HF$-\,$ energy deposits, provides a rather good description of the energy in HF$+\,$. In contrast to that, all other tunes predict more events with large HF$+\,$ energy than observed in data (Fig. 5c).

The observed energy distribution in the HF$+\,$ calorimeter, shown for different HF$-\,$ energy intervals: a) 20$-\,$100 GeV, b) 200$-\,$400 GeV, c) > 500 GeV, for data and different MC tunes. The plots are shown for $pp \rightarrow W^{\pm}X \rightarrow \mu^{\pm}\nu X$.

The differential inclusive jet cross-section is measured as a function of transverse momentum $p_T$ with the total integrated luminosity of $\mathcal{L} = 3.14\,\text{pb}^{-1}$. The statistical uncertainties are small compared to the systematic uncertainties at all $p_T$s. The primary sources of systematic uncertainties in the cross-section measurement are the jet energy scale (JES) and resolution, as well as the estimated integrated luminosity. The total systematic uncertainty, obtained adding in quadrature these three uncertainties, is shown in Fig. 6a. Fig. 6b shows all the sources of theoretical uncertainty: the non-perturbative (NP) corrections dominate for $p_T < 50\,$ GeV whereas PDF+$\alpha_S$ uncertainties dominate above that $p_T$; scale uncertainties are subleading at all transverse momenta. We have added in quadrature these three sources of uncertainty into a single theoretical uncertainty band. Fig. 6c shows the same NP and scale uncertainties with the PDF envelope obtained using the HERAPDF1.0 parton densities [19] which provides a different uncertainty estimate.

The jet cross section as a function of $p_T$ is shown in Fig. 7a compared to all the theoretical models considered. The total experimental systematic uncertainty is shown as a yellow band. Fig. 7b shows the fractional difference between the experimental jet cross section and the theoretical predictions following the PDF4LHC prescription (see Fig. 6b). The predictions agree reasonably with the measurements within the theoretical and experimental uncertainties. However, CASCADE [20] appears to have a more concave spectral shape than the data in the intermediate $p_T$ region.

The fully corrected cross section for simultaneous production of at least one central and at least one forward jet is presented in Fig. 8 as a function of the forward and central jet $p_T$. The uncertainty bands take into account both the statistical and the systematic uncertainties, summed in quadrature. In all $p_T$ bins of the measured cross section, the statistical uncertainty (of the order of 1$-\,$2% in the low $p_T$ bin and 5$-\,$10% in the highest) is subdominant with respect to the systematic one, which amounts to $\approx 30\%$, dominated by the uncertainty on the
Figure 6. a) Systematic uncertainties in the forward jet measurement, b) theoretical uncertainties on the forward jet spectrum including non-perturbative (NP), PDF4LHC and scale uncertainties, c) including NP, HERAPDF and scale uncertainties.

Figure 7. a) Inclusive jet cross section (anti-$k_T$, R = 0.5) measured at forward pseudorapidities ($3.2 < |\eta| < 4.7$), fully corrected and unfolded, b) fractional differences between the fully-corrected forward jet spectra.

jet energy scale (JES).

To better evaluate the compatibility of the Monte Carlo predictions with the measured cross section, the ratio of the data over various Monte Carlo simulations are plotted on top of the band corresponding to the total uncertainty in Fig. 9. The ratios are shown as a function of the jet $p_T$. Discrepancies between data and MC models are observed. The prediction from Z2 model, which is tuned to reproduce the underlying event data at the LHC and reproducing more satisfactorily the central jet spectrum than D6T or PYTHIA 8, still lies above the data (the same holds true for the lower $p_T$ range of the forward jet spectrum). The NLO MC POWHEG matched with HERWIG parton shower describes the shape well, but not the normalization. CASCADE predicts a different shape of the $p_T$ cross sections, indicating a non trivial correlation between the forward and central jet transverse momenta. The HEJ event generator, which provides all-order description of the dominant radiative corrections for hard, wide angle emissions, is used here only at parton level. It describes the data reasonably well.
Figure 8. The cross sections for the hadronic final state, as a function of $p_T$, for the forward jets and the central jets.

Figure 9. Ratio of the fully corrected $p_T$ differential jet cross section in data over the various Monte Carlo models considered. The yellow band corresponds to the total uncertainty for the forward region (left) and the central one (right).

5. Conclusions

The energy flow in the forward region, $3.15 < |\eta_{obs}| < 4.9$, is measured in hadron-hadron collisions for minimum bias events and events having a hard scale defined by a dijet system in the central region, $|\eta_{jet}| < 2.5$, with $E_{T,\text{jet}} > 8 \text{ GeV}$ ($E_{T,\text{jet}} > 20 \text{ GeV}$) for $\sqrt{s} = 900 \text{ GeV}$ ($\sqrt{s} = 7 \text{ TeV}$). Requiring a hard sub-system in the central region works as a lever arm for the forward energy flow. Thus, the forward energy flow is significantly higher in the dijet measurement compared to the minimum bias measurement. The increase in energy flow in the forward region with increasing centre-of-mass energy is significant and is reproduced by the Monte Carlo for minimum bias and dijet events. Besides, it is shown that including multiple interactions helps to describe the data better. The MC predictions without multiple interactions significantly underestimate the data.

Central track multiplicities, forward energy flow and correlations among them have been studied in $W$ and $Z$ events, identified by the vector boson decays to electrons and muons. None of
the studied MC tunes provides simultaneously a satisfactory description of the track multiplicity in the central rapidity region ($|\eta| < 2.5$) and of the forward energy flow ($3 < |\eta| < 4.9$). Strong positive correlations between the energy measured on one side HF, the track multiplicity and on the other side energy deposits are observed in data and in Monte Carlo models with different tunes. However, the correlations in the various MC tunes are different than those seen in the data.

The forward jet production in the pseudorapidity range $3.2 < |\eta| < 4.7$ is measured. The jet transverse momentum spectrum is obtained with the anti-$k_T$ algorithm ($R = 0.5$) in the Hadronic Forward calorimeters in the $p_T$ range of $35 - 150$ GeV. The total systematic uncertainties are of the order of $\pm 25\%$ and dominated by the absolute jet energy scale. Within the current experimental and theoretical uncertainties, perturbative calculations – as implemented in parton shower Monte Carlos PYTHIA and HERWIG, and at NLO accuracy both in fixed-order (NLOJET++) and parton-shower-matched (POWHEG) frameworks, as well as accounting for combined DGLAP+BFKL resummations in the CASCADE model – reproduce globally well the measured forward jet cross section. The data-model comparison shows that, in general, all PYTHIA tunes overestimate the jet spectra when requiring the simultaneous production of jets in both regions. The disagreement is larger for the central jet spectrum and for the lowest $p_T$ bins at forward rapidity. Calculations including resummation of low-$x$ logarithms, as in the CASCADE Monte Carlo, do not reproduce well the central jet spectrum, whereas the HEJ model is in good agreement with the measurement.

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