Forward Energy and Particle Flow with CMS

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The energy flow measurement in the CMS detector forward region ($3.15 < |\eta| < 4.9$) for various center-of-mass energies $\sqrt{s} = 0.9, 2.36$ and 7 TeV is presented. The measurement has been performed in two different event classes: in minimum bias events and in events with a hard scale provided by a dijet system at central pseudo-rapidities ($|\eta| < 2.5$) and with transverse energy $E_{T,jet} > 8$ GeV at $\sqrt{s} = 0.9, 2.36$ TeV and with $E_{T,jet} > 20$ GeV at $\sqrt{s} = 7$ TeV. The result of the forward energy flow measurement for the two event classes is compared to predictions from Monte Carlo event generators that were tuned to describe the charged particle spectra seen at central rapidities. A study of the forward jets reconstruction in the pseudo-rapidity range $3.2 < |\eta| < 4.7$ is presented for $\sqrt{s} = 7$ TeV. The jets are reconstructed with Anti-k$_T$ algorithm ($R = 0.5$).

1 Introduction

The measurement of energy flow in the forward region is directly sensitive to the parton radiation at large η 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 underlying event measurements have been performed using charged particle spectra in the central rapidity range. The energy flow measurement is sensitive to MPI and dijet events, whereas in dijet events are also sensitive to the initial state parton radiation. Comparison of the forward energy flow in events from a minimum bias sample (with zero or more partonic interactions) to events with central jet activity (and therefore one or more partonic interactions), can be used as an important tool to extract the physics details of the MPI and parton radiation and provides an independent constraint on underlying event models.

Forward jet production at the Large Hadron Collider (LHC) is also an ideal process to investigate small-x QCD effects [2]. Here, first measurement of forward jets and the energy flow in the forward region ($3.15 < |\eta| < 4.9$) of the Compact Muon Solenoid (CMS) detector is presented [3, 4].

Figure 1 shows a prediction for the energy flow as a function of pseudo-rapidity for minimum bias events and for events which have a dijet with $E_{T,jet} > 20$ GeV in the central pseudo-rapidity region $|\eta| < 2.5$ at $\sqrt{s} = 7$ TeV. The energy flow is defined as:

$$\frac{1}{N_{event}} \frac{d \sum E_i}{d\eta}. \tag{1}$$

The energy E_i of charged and neutral stable particles i is summed in bins of η. The predictions from the PYTHIA [5] 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 [6] and the dashed line the D6T tune [7]. 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.

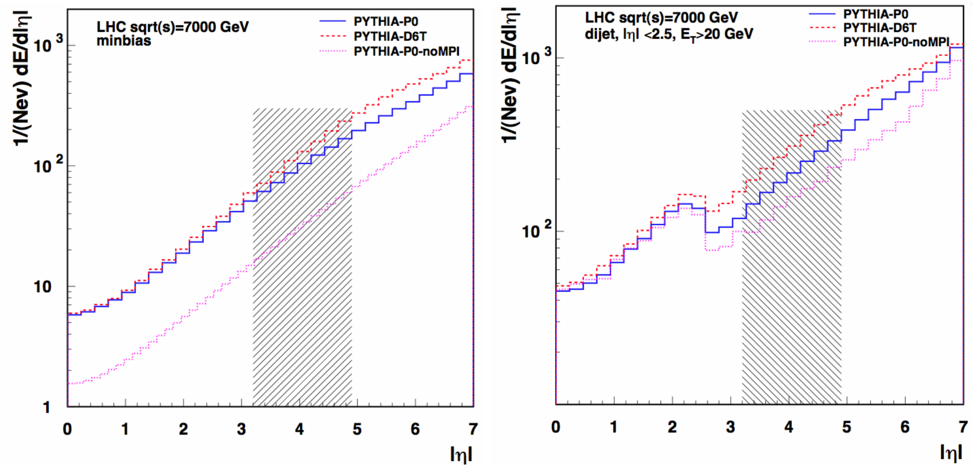

Figure 1: The predicted energy flow by PYTHIA MC event generator at $\sqrt{s} = 7$ TeV for particles with $E > 0.1$ GeV as a function of the pseudo-rapidity for minimum bias events (left) and for events containing a dijet with $E_{T,jet} > 20$ GeV in the central rapidity region of $|\eta| < 2.5$ (right). The shaded area indicates the region of measurement.

2 Experimental Aspect

2.1 CMS Hadron Forward Calorimeter

The general purpose detector CMS is designed for the exploration of physics at the TeV energy scale and has an excellent colorimetric coverage ($-6.6 < \eta < 5.2$). A detailed description of the CMS detector can be found elsewhere [16]. A brief outline of the components which are the most relevant for the present measurement is given here. Two hadron forward calorimeter (HF), one on each side of the CMS interaction point (IP), at ~ 11 m, cover the very forward angles of CMS, in the pseudo-rapidity range $3 < |\eta| < 5.2$. Due to the high radiation around beam pipe, HF calorimeters are built with radiation hard quartz fibers embedded in steel absorbers. The signal in HF is produced in the form of Cerenkov light generated by the showering particles passing through quartz fibers. Half of the fibers run over the full depth of the absorber whereas the other half, read out separately, start at a depth of 22 cm from the front face of the detector. This structure enables to distinguish showers generated by electrons and photons from those generated by hadrons. The objectives with the HF detector are to improve the measurement of the transverse energy and to measure very forward jets.

Two subsystems, the Beam Scintillator Counters (BSC) and the Beam Pick-up Timing for the eXperiments (BPTX) were used to trigger the detector readout. The two BSCs are located at a ±10.86 m from the IP and are cover the range of $3.23 < |\eta| < 4.65$. Each BSC is a set of 16 scintillator tiles. The BPTXs detectors are designed in order to provide precise information on the bunch structure and timing of the incoming beam, with better than 0.2 ns time resolution.

2.2 Event and Jet Selection

The data collected with the CMS detector at 3 different values of center-of-mass energies of $\sqrt{s} = 0.9, 2.36$ and 7 TeV were analyzed in this study. The following selection criteria were applied to select the minimum bias sample.

- The trigger signal in the BSC counters to be in coincidence with BPTX signals from both beams passing the IP is required. This condition refers the minimum bias trigger condition and rejects a large fraction of diffractive events.
- To ensure the event is a collision candidate at least one primary vertex with a distance to the interaction point with $z < 15$ cm is required.

All the cuts introduced for the minimum bias sample selection are also applied to select events with central dijet events. Jets are reconstructed with the Anti-k_T jet algorithm [9] with a distance parameter of R = 0.5. The dijet sample consists of events with at least two leading jets with $|\eta| < 2.5$ and $||\Delta\phi(j_1, j_2)| - \pi| < 1.0$. The η cut ensures that the jets are contained in a region of CMS outside of the HF calorimeters. The jets are required to have $p_T > 8$ GeV for $\sqrt{s} = 0.9$ and 2.36 TeV, and $p_T > 20$ GeV for $\sqrt{s} = 7$ TeV.

All the measured quantities are detector-level quantities. The measured distributions in the data are compared to those in MC samples of minimum bias and dijet events that are passed through the full CMS detector simulation based on Geant4 [9].

3 Results

Figures 2 - 3 show the measured energy flow in the HF acceptance range ($3.15 < |\eta| < 4.9$) at the detector level for minimum bias and dijet samples at the center-of-mass energies of $\sqrt{s} = 0.9, 2.36$ and 7 TeV. The error bars correspond to the statistical uncertainty. The systematic errors are marked as shaded bands. The dominant systematic uncertainty, global energy scale uncertainty of the HF calorimeters, is assumed to be ±15%. Simulated events are processed and reconstructed in the same manner as collision data. Various tunes for the parameters of the simulation of the underlying event in PYTHIA are used: D6T [7], DW [7], PROQ20 [10], Perugia-0 (P0) [6], which is using a new multiple interaction model implemented in PYTHIA [11]. Also the PYTHIA8 [12] and PHOJET MC generator samples are used [13, 14].

With increasing center-of-mass energies, the forward energy flow in the minimum bias event and dijet samples show a significant energy dependency. The energy flow in the minimum bias sample at 0.9 TeV is best described by the D6T tune, whereas the PROQ20 and P0 tunes and PHOJET underestimate the data. At $s = 7$ TeV, all the MC predictions underestimate the data, with PYTHIA8 being close to the PROQ20 tune. In the dijet sample, the D6T tune is too high compared to the data, the P0 tune and PHOJET are too low, and the best description is given by the PROQ20 tune and PYTHIA8. The drop in the measured values for $|\eta| > 4.5$ is caused by inactive material in front of the HF calorimeters in that η region, as was verified by varying the amount of inactive material in the MC simulation. The Pythia DW tune was found to describe best the charged particle spectra at central rapidities in a complementary study of underlying event properties [15].

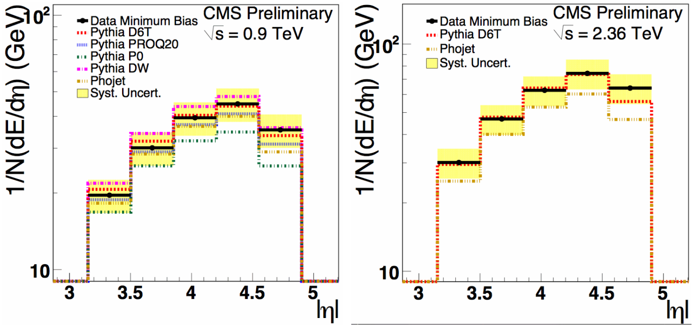

Figure 2: The detector level energy flow in the minimum bias sample as a function of pseudo-rapidity η at $\sqrt{s} = 0.9$ (left), at $\sqrt{s} = 2.36$ (center) and at $\sqrt{s} = 0.9$ (right). The uncorrected data (full points) compared with the prediction from PYTHIA and PHOJET. Error bars represent the statistical errors, whereas the systematic uncertainties are indicated as shaded bands.

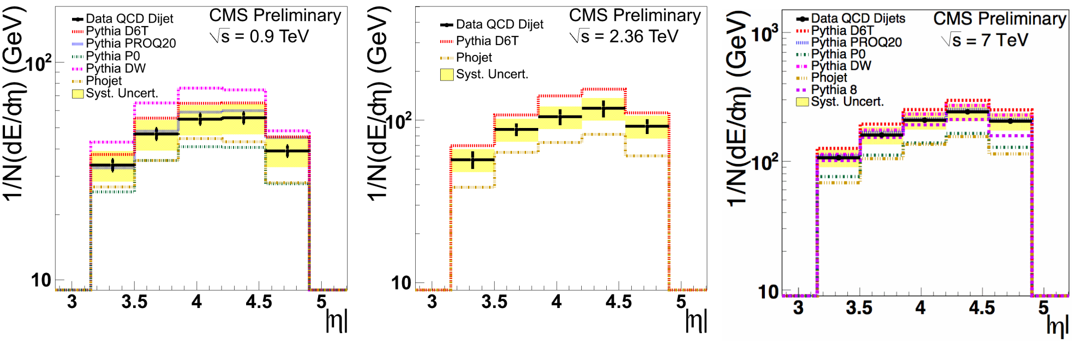

Figure 3: The detector level energy flow in the dijet sample as a function of pseudo-rapidity η at $\sqrt{s} = 0.9$ (left), at $\sqrt{s} = 2.36$ (center) and at $\sqrt{s} = 0.9$ (right). The uncorrected data (full points) compared with the prediction from PYTHIA and PHOJET.

4 Forward Jets

The jets have never been measured in such a forward region in the hadron pp collisions. The CMS detector with its large colorimetric coverage ($|\eta| < 5.2$) gives a great opportunity to measure the jets in high pseudo-rapidity region. In this section, the jet performance study in HF calorimeter based on the Anti-k_T jet reconstruction algorithm with radius of $R = 0.5$ is presented [4]. The first step is the validation of jet reconstruction in the forward region before measuring the jets in the HF acceptance. Events are selected from a minimum bias sample described in the previous section. Furthermore, the jets which satisfy the requirements of

$35 < p_T < 120$ GeV and $3.2 < |\eta| < 4.7$ were selected. Figure 4 shows the detector level forward jet transverse momentum p_T and pseudo-rapidity $|\eta|$ spectra, for a total integrated luminosity of 10 nb^{-1}. A reasonable agreement between the data and MC simulation, PYTHIA6 using the D6T tune, is found.

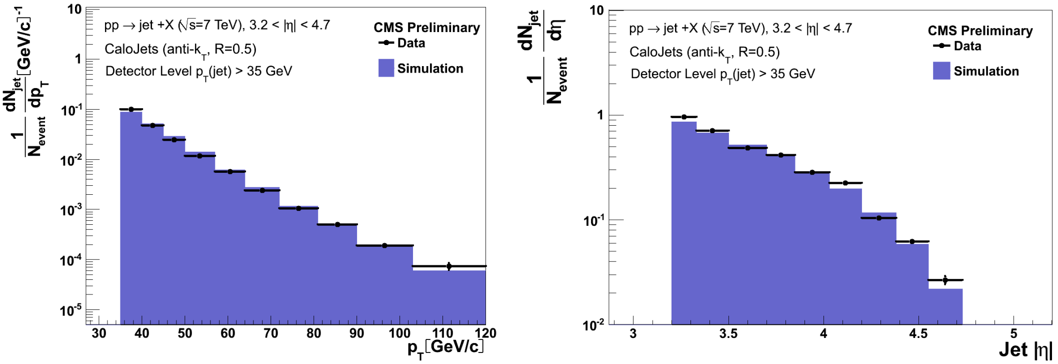

Figure 4: The detector level forward jet transverse momentum p_T and pseudo-rapidity $|\eta|$ spectra are compared with the predictions from the MC event generator PYTHIA6 using the D6T tune. Only the statistical error bars are shown.

5 Conclusion

The first measurement of the energy flow in hadron-hadron collisions for minimum bias events and events having a hard scale defined by a dijet has been presented in the forward region of $3.15 < |\eta| < 4.9$. A significant increase of energy flow has been observed with increasing center-of-mass energy. The energy dependence is reproduced by the MC simulations for events with dijets, whereas it is not described for minimum bias events. Particularly, the measured minimum bias events at $\sqrt{s} = 7$ TeV are larger than any of the MC predictions. The MC predictions giving the best description of energy flow in the forward region is found to be different from these giving the best description of the charged particle spectra in the central region. The reconstructions of forward jets measured within the HF acceptance at $\sqrt{s} = 7$ TeV has been also presented.

6 Acknowledgments

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