FORWARD JETS, DIJET CORRELATIONS AT LARGE RAPIDITY SEPARATION AND FORWARD ENERGY FLOW AT THE LHC*

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CMS results on the observables measured at high pseudorapidities ($3.0 < |\eta| < 5.2$) are presented. The results give an insight into Multi Parton Interactions (MPI), Underlying Event (UE) and QCD evolution.

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1. Introduction

Compact Muon Solenoid (CMS) is one of the two large, multi-purpose experiments at the Large Hadron Collider (LHC) at CERN. The geometrical coverage of the experiment allows to detect particles at high pseudorapidities, that is in $3.0 < |\eta| < 5.2$ range, and measure correlations between objects separated with a large rapidity interval. These features make CMS a perfect tool to study QCD at small values of parton fractional momentum. This topic is not only appealing on its own (BFKL QCD evolution, recombination and saturation effects) but is an essential prerequisite for predicting a large variety of hadron, photon and neutrino scattering cross sections at very high energies. Good understanding of effects measured in the forward region is also important for Higgs particle studies (production via vector–boson-fusion). Natural experimental probes used in these studies are jets. The accurate reconstruction of jet energy requires a precise estimation of energy deposits inside the jet cone which are not connected directly with the jet activity, that is energy from the Underlying Event. Therefore, the energy flow measurement in the forward rapidities, for different classes of events, is being also performed. The forward energy flow is directly sensitive to the

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amount of parton radiation and multiparton interaction and thus provides a measurement complementary to those for the central region alone allowing for discrimination between different models.

The CMS experiment has an excellent calorimetric coverage in the pseudorapidity, $|\eta| < 5.2$. In the region $|\eta| < 1.74$, the Hadronic Calorimeter (HCAL) cells have widths of 0.087 in η and 0.087 rad in ϕ. In the (η, ϕ) plane, and for $|\eta| < 1.48$, the HCAL cells map on to 5×5 ECAL crystals arrays to form calorimeter towers. At larger values of $|\eta|$, the size of the towers increases and the matching ECAL arrays contain fewer crystals. Within each tower, the energy deposits in ECAL and HCAL are summed and subsequently used to provide the energies and directions of hadronic jets. ECAL and HCAL extend to $|\eta| < 3.0$. The two Hadronic Forward (HF) calorimeters cover the region of $3.0 < |\eta| < 5.2$. They consist of iron absorbers and embedded radiation hard quartz fibres, which provide a fast collection of Cerenkov light. Half of the fibres run over the full depth of the absorber, while the other half start at a depth of 22 cm from the front of the detector. This structure makes it possible to distinguish showers generated by electrons and photons, from those generated by hadrons. The tower segmentation of the HF calorimeters in η and ϕ is 0.175×0.175 except for $|\eta|$ above 4.7, where the segmentation is 0.175×0.135.

2. Forward energy flow

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 ($|\eta| < 2.5$) [1]. The analysis is carried out at two different centre-of-mass energies, 900 GeV and 7 TeV. For 900 GeV (7 TeV), the leading and the sub-leading jets in the dijet system are required to have $p_{\mathrm{T}} > 8$ GeV/c ($p_{\mathrm{T}} > 20$ GeV/c). The measurement is restricted to $3.15 < |\eta| < 4.9$ range. The measured quantities are corrected for detector effects, and the distributions in the data are compared to Monte Carlo predictions on the corresponding hadron level. Both, at detector and at hadron level in MC and also in data, events are selected by requiring activity in the $3.9 < |\eta| < 4.4$ range in coincidence at both sides of CMS. This selection suppresses diffractive events. The dominant systematic effect in the measurement is the global energy scale uncertainty of the HF calorimeters, which is estimated to be 10% of the measured energy. The results are shown in Fig. 1. 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. The Pythia 6 tunes (Q^2 ordered — CW, D6T, DW, ProQ20 and p_{T} ordered — Z2, P0, ProPT0) are shown as bands, which are constructed from the maximum and minimum variation in the Pythia 6 predictions in each

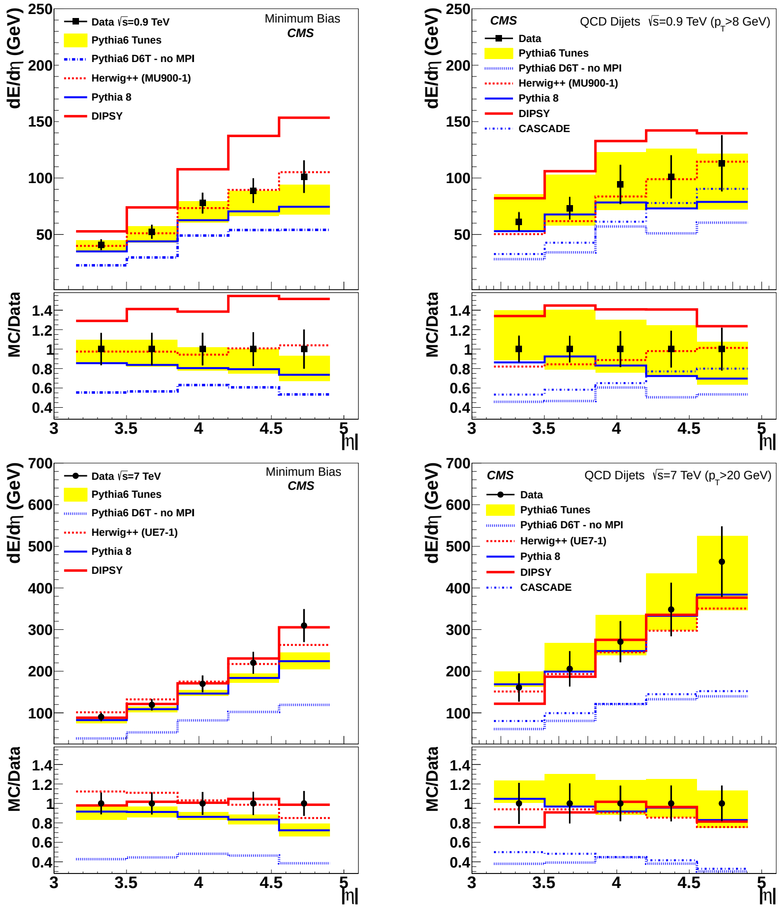

Fig. 1. Forward energy flow for centre-of-mass 900 GeV (top) and 7 TeV (bottom), for minimum bias (left) and dijet (right) samples.

bin. The spread of forward energy flow for the different PYTHIA 6 tunes is fairly large, which may be a consequence of the fact that the forward region was not considered when the tunes were performed. The MC predictions without multiple interactions obtained with PYTHIA 6 D6T and CASCADE, undershoot the data by at least 40%. HERWIG++, which uses specific tunes describes well the measurements at both energies. PYTHIA 8 predictions are within the tune uncertainty band of the PYTHIA 6.

3. Forward and forward–central jets

The inclusive production cross sections for forward jets, as well for jets in dijet events with at least one jet emitted at central and the other at forward pseudorapidities, are measured in the range of transverse momenta

$p_T = 35$–150 GeV$/c$, at centre-of-mass energy of 7 TeV [2]. Forward jets are reconstructed within $3.2 < |\eta| < 4.7$, and central jets within the $|\eta| < 2.8$ range. The jets p_T spectra are corrected to account for the migration of events across bins due to finite energy resolution of the calorimeters. Finally, the corrected differential cross sections $d^2\sigma/dp_T d\eta$ are plotted. The dominant systematic uncertainty is coming from the jet energy scale in the calorimeters which propagated to the steeply falling jet spectra, translate into uncertainties of the order of $\pm(20$–$30)\%$ in the measured jet cross sections. The measured cross sections are compared to predictions from different pQCD approaches: *(i)* general-purpose event generators Pythia 6 with D6T and Z2 tunes, Pythia 8 with Tune 1, Herwig 6 with UE modelled with JIMMY, and Herwig++, *(ii)* NLO calculations obtained with the POWHEG package (matched with Pythia and Herwig parton showers) as well as with NLOJET++ within the FASTNLO package, for different sets of parton densities, and *(iii)* the Cascade and Hej. Before comparing the data to parton-level predictions such as NLOJET++ or HEJ, the uncertainties from non-perturbative (NP) effects are determined, by comparing the Pythia 6 and Herwig 6+Jimmy parton-level spectra with the corresponding particle-level predictions after hadronisation and UE activity. Half of the difference between the correction factors coming from these two model predictions is taken as an estimate of the total uncertainty associated with the NP effect. The uncertainty associated with higher-order corrections neglected in the NLO calculation are evaluated by changing the renormalisation and factorisation scales by factors proportional to the jet p_T ($p_T/2$ and $2p_T$). The uncertainties associated with the PDF and the strong coupling α_S is estimated following the PDF4LHC interim recommendation [3]. The fully corrected inclusive forward jet cross section as a function of p_T is shown in Fig. 2. Within the theoretical (dark band) and systematic experimental (grey band) uncertainties, all the predictions are in agreement with

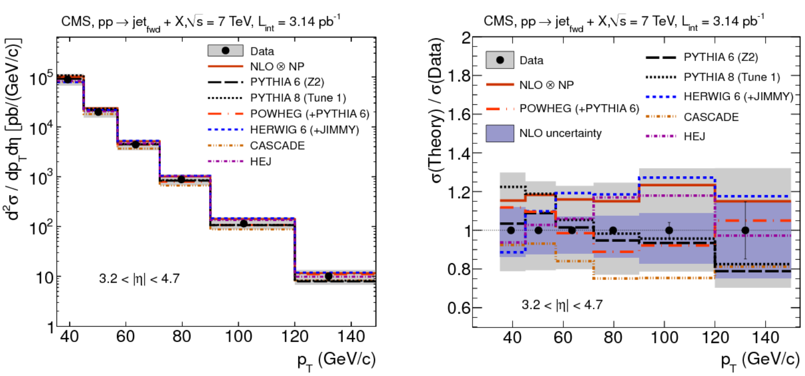

Fig. 2. Inclusive jet cross section at $3.2 < |\eta| < 4.7$, compared to predictions (left). Ratio of theory/data (right).

the measurement. Similar plots for the cross section for the simultaneous production of at least one forward and at least one central jet are presented in Fig. 3. The HERWIG and HERWIG++ appear to be consistent with the data. The other generators, and different tunes, do not describe the data over the full range of p_{T} values. The discrepancies are larger for jets at central values of η. In the case of forward jets, the comparison of the inclusive p_{T} spectrum with that requiring the simultaneous presence of a jet in the central pseudorapidity region shows that the inclusive spectrum is about a factor of four higher in the lowest p_{T} bin but that both distributions agree progressively better at larger p_{T} values. This suggests that inclusive forward jets of $p_{\mathrm{T}} \approx 35$–$70$ GeV$/c$ may be balanced by other forward jets or by soft central jets that do not surpass the p_{T} threshold of 35 GeV$/c$, thereby producing the overall deficit of central jets in the data.

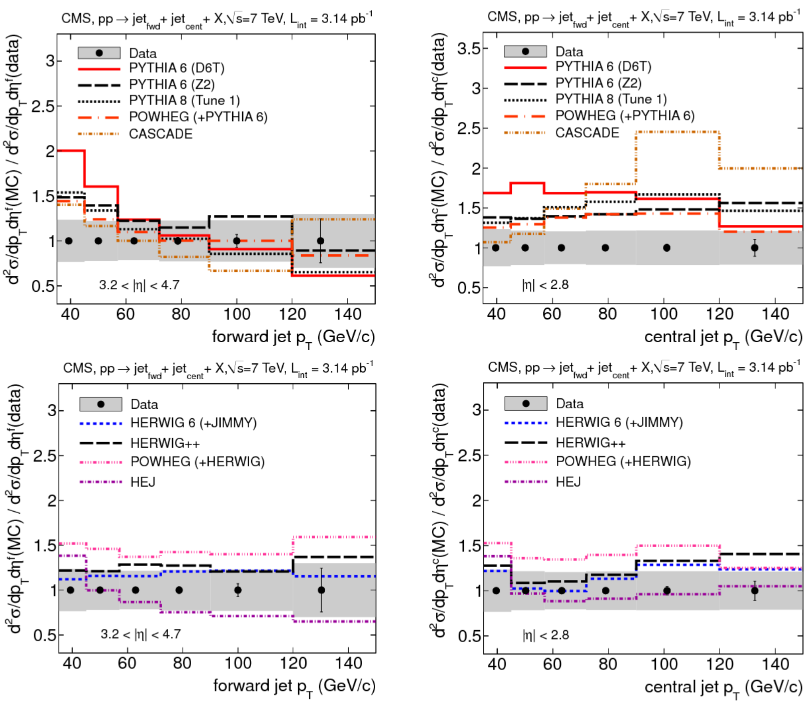

Fig. 3. Theory/data for cross sections for forward (left) and central (right) jets produced in dijet events. The error bars on data points reflect statistical uncertainties, with systematic uncertainties plotted as grey bands.

4. Ratio of inclusive to exclusive dijet production

For this studies, events containing at least two jets with $p_{\mathrm{T}} > 35$ GeV$/c$ and within $|y| < 4.7$ acceptance are selected [4]. Events with at least one pair of such jets are denoted as "inclusive". Events with exactly one pair of jets are called "exclusive". The ratio of the cross section of all pairwise combinations of jets to the exclusive dijet cross section as a function of the rapidity difference between jets $|\Delta y|$ is measured ($R^{\rm inc}$). The ratio of the cross section for the pair consisting of the most forward and the most backward jet from the inclusive sample to the exclusive dijet cross section is also calculated (R^{MN}) (see Fig. 4). The ratios, corrected for detector effects, are compared to the MC predictions at the stable-particle level: Pythia 6 tune Z2, Pythia 8 tune 4C, Herwig++ tune UE-7000-EE-3, Cascade and Hej+Ariadne. The Pythia 6 and Pythia 8 generators agree with the measurements. The predictions of the Herwig++ generator are larger than the measurement especially at large Δy. The BFKL-motivated generators Cascade and Hej+Ariadne predict for these ratios a significantly stronger rise than observed. The moderate rise of the measured dijet ratios indicates that the BFKL effects are not dominant for jets with $p_{\rm T} > 35$ GeV/c at the present collision energy of 7 TeV.

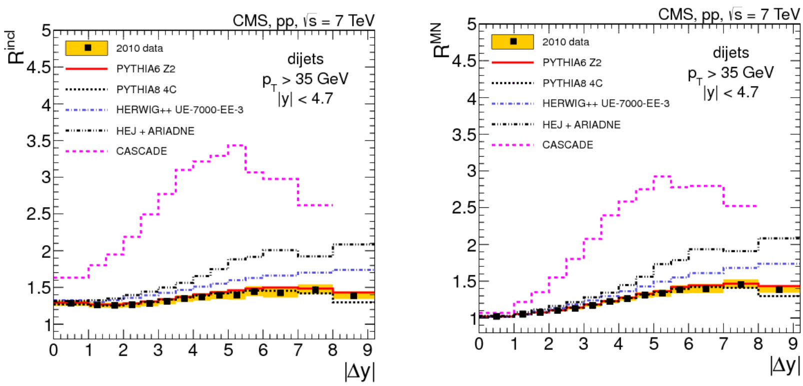

Fig. 4. $R^{\rm inc}$ (left) and R^{MN} (right) as a function of the rapidity separation. The shaded band indicates the size of the systematic uncertainty.

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