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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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Highlights in Forward Physics from CMS

Vadim Oreshkin for the CMS Collaboration

Abstract

A few CMS analyses based on data collected during 2009-2010 data taking period are reviewed, including forward jet production cross-section measurements, energy flow measurement for Minimum Bias events as well as for events with presence of hard scale, and observation of single diffraction.

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Highlights in Forward Physics from CMS

Vadim Oreshkin, on behalf of CMS collaboration

Petersburg Nuclear Physics Institute, Gatchina, 188300, Russia

Abstract

A few CMS analyses based on data collected during 2009-2010 data taking period are reviewed, including forward jet production cross-section measurements, energy flow measurement for Minimum Bias events as well as for events with presence of hard scale, and observation of single diffraction.

Keywords:

Jets, energy flow, diffractive events, LHC, CMS

1. Introduction

Taking benefit from the excellent calorimetric pseudorapidity coverage as well as unprecedented center-of-mass colliding energies, CMS [1] experiment at Large Hadron Collider has a rich forward physics program (e.g. see [2, 3]). In these proceedings, presented are only a few analyses, which have been accomplished using data taken during 2009 and 2010 years.

CMS calorimetry covers pseudorapidity range, which have never been available at previous hadron-hadron colliders. This is achieved using three forward calorimeters Handronic Forward (HF), CASTOR and Zero Degree Calorimeters, which cover pseudorapidity range $2.9 < |\eta| < 5.2$, $-6.6 < \eta < -5.3$, and $|\eta| > 8.3$, respectively. In the present analyses only HF was used. The HF have been specifically designed for forward jet and missing-energy measurements. Its towers have granularity in pseudorapidity and azimuthal angle of $\Delta\eta \times \Delta\phi \sim 0.175 \times 0.175$ for $|\eta| < 4.7$, and 0.175×0.35 for $|\eta| > 4.7$. Detailed description of HF and other parts of CMS detector can be found in Ref. [1].

2. Inclusive forward jet p_T spectrum

In the analysis [4], measured high- p_T jets at forward rapidities are used to verify how well various Monte

Carlo generators describe experimental data in an unexplored earlier kinematic region with highly asymmetric parton momentum fractions ($x_1 \ll x_2$) in the hard subprocess, where x_1 can reach $x_1^{\min} = 2p_T^{\min} \exp(-y)/\sqrt{s} \approx 10^{-4}$ for current analysis conditions, namely $p_T^{\min} > 35$ GeV (where trigger efficiency reaches 100%), maximal jet $\eta < 4.7$ (a jet should be fully contained within the fiducial acceptance of HF). The infrared and collinear safe anti- k_T jet clustering algorithm [5] was used to reconstruct all jets with a distance parameter of 0.5.

The corrected for detector effects jet cross section as a function of p_T obtained from data with integrated luminosity 3.14 pb^{-1} was compared to predictions from various Monte Carlo generators. Figure 1 shows the fractional difference between the experimental jet cross-section and the theoretical predictions from Monte Carlo generators. The total experimental systematic uncertainty is shown as a yellow band. It is dominated by the uncertainty associated with the absolute jet energy scale (20%-30%), jet resolution (3%-6%), model dependence of unfolding (3%), and luminosity (4%).

Theoretical uncertainties are shown as orange band. Theoretical uncertainties associated to non-perturbative corrections coming from parton radiation and hadronisation modelling dominate for $p_T < 50$ GeV whereas PDF uncertainties dominate above that p_T . The former corrections were estimated as a half spread between pre-

Figure 1: Fractional differences between the fully-corrected forward jet spectra measured in p-p at 7 TeV and various hadron-level theoretical predictions: NLO, POWHEG, PYTHIA 6, PYTHIA 8, HERWIG 6 and CASCADE. Points have been slightly displaced to the right and left for visibility purposes. The error-bars on the data points show statistical uncertainties. The systematical and theoretical uncertainty bands, plotted separately.

dictions from PYTHIA 6.4 [6] and HERWIG 6+Jimmy [7] hadronisation and underlying event simulation.

In summary, 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.

3. Simultaneous production of central and forward jets

The same dataset was used also for the analysis [8], where production cross section of at least one forward jet in conjunction with central jet $|\eta| < 2.8$ was measured as a function of p_T of each of two jets. When more than one forward (central) jet were observed, only the hardest was selected. Such final state can give information on multi-jet production. In particular such measurements can allow one to study different types of parton radiation dynamics as implemented in the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) or the Balitski-Fadin-Kuraev-Lipatov (BFKL), or the Ciafaloni-Catani-Fiorani-Marchesini (CCFM) evolution equations.

The cross sections compared to various Monte Carlo predictions are shown on top of the band corresponding to the total uncertainty in Figure 2.

The MC event generators do not describe the data well over the full p_T range. PYTHIA 8 with Tune 1 and PYTHIA 6 with Z2 [9] tune (i.e. p_T -ordered showering)

describe the data better than the D6T [10] tune (i.e. Q^2 -ordered showering). The data-model discrepancy is not improved when varying the modeling of the multiparton interactions and beam remnants in PYTHIA. The Z2 model, tuned to reproduce the underlying event data at the LHC [11], although it reproduces 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 cross sections, indicating a non-trivial correlation between the forward and central jet transverse momenta. HEJ is used here only at parton level. It describes the data reasonably well.

4. Energy flow

Besides the hard subprocess and initial and final state parton radiation associated with it, it is the underlying event (UE), including multiple-parton-interactions and beam-beam remnants interactions, which contribute largely to the amount of energy deposited at forward region. Predictions on the energy flow, average energy deposited per event in a calorimeter, from various Monte Carlo generators and their tunes differ quite a lot, especially for the forward region (e.g., see Fig. 3).

Before proceeding to the analysis description, let us mention that pre-LHC tunes consistent with UE measurements at CDF (D6T [10], DW [12], P0 [13], ProQ20 [14]) as well as tunes driven by CMS UE studies at 0.9 GeV and 7 TeV (Z1 and Z2 [9], CW [15]) were used for comparison with data in this and the next section.

In the analysis [16, 17], the event-by-event average energy deposited in the HF calorimeter ($3.15 < |\eta| < 4.9$) is measured as a function of pseudorapidity at center-of-mass colliding energies 900 GeV, and 7 TeV.

In order to observe the so-called “pedestal” effect, that is the fact that hard scattering processes has much more activity than an average minimum bias event (see [18] for review), measurement was performed for two events samples: Minimum Bias events and events with a hard scale, so called “dijet events”. In order to eliminate single diffraction only events with at least one charged particle in coincidence on both sides in the ranges $3.9 < |\eta| < 4.4$ are selected.

The di-jet event sample used in the analysis was a subset of the minimum-bias sample. Events where the two highest p_T jets satisfy the condition $|\Delta\phi(jet_1, jet_2) - \pi| < 1.0$, within the central region ($|\eta| < 2.5$), were selected. At $\sqrt{s}=0.9$ TeV ($\sqrt{s}=7$ TeV), the leading and

sub-leading jets were required to have $p_{T,jet} > 8$ GeV ($p_{T,jet} > 20$ GeV). The selection in η ensures that the jets are contained in the central region of CMS, outside the acceptance of the HF calorimeters.

The dominant systematic effect in the measurement of forward energy flow is the global energy scale uncertainty of the HF calorimeters, which is estimated to be 10% of the measured energy. The other systematic uncertainties, including HF channel-by-channel miscalibration, HF noise caused by charged particle hitting photomultiplier, primary interaction vertex shift from the nominal interaction point (0,0,0) by several centimeters, contribute 1-3% each and are subdominant.

The systematic uncertainties due to the model dependence of the bin-by-bin corrections were estimated from the difference between the average calculated correction factor and the correction factor obtained from the various tunes. The uncertainties were applied to the data points symmetrically. Depending on the centre-of-mass energy and the $|\eta|$ bin, they are between 1% and 17%.

Results for various PYTHIA tunes and HERWIG are shown in Fig. 3. In general, for dijet events the rise of the average energy with increasing pseudorapidity is described by all tunes. The agreement with the data is better than in the case of minimum-bias events, where all tunes underestimate energy flow for high η . The prediction without multiple parton interactions is too low (not shown here). The energy flow obtained from center-of-mass specific tunes of HERWIG++ at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 0.9$ TeV is in good agreement with the measurement.

The predictions from proton-proton collision generators used in cosmic ray physics are much closer to the data at highest rapidities, than those from PYTHIA and HERWIG (not shown here), however a larger deviation is observed in the di-jet measurement at $\sqrt{s} = 0.9$ TeV, where QGSJET II and SIBYLL underestimate the data at the lowest $|\eta|$ bins.

5. Single diffraction

There is a class of events which has zero or little energy deposition in at least one of the HF. These are diffractive events which could be characterized by absence of particle emissions in large rapidity range.

This was observed in the analyses [19] and [20]. Analysis [19] is based on the data collected by the CMS experiment in December 2009, which correspond to an integrated luminosity of approximately $10 \mu\text{b}^{-1}$ at a centre-of-mass energy of 900 GeV, and $0.4 \mu\text{b}^{-1}$ at

2360 GeV; and analysis [20] and $20 \mu\text{b}^{-1}$ for 7 TeV. In contrast to energy flow measurements described above, trigger signal was required only from at least one of the sides from interaction point, so that not to eliminate the diffractive events.

Figure 4 show the distributions of the events as a function of E_{HF+} . A comparison to Pythia 6 tunes D6T, DW, CW, P0 and Z1 is available in [20] (not shown here).

An enhancement at zero energy in HF is seen, which is dominantly coming from diffractive events (as suggested by Monte Carlo simulation).

To enhance the diffractive component in the data, a cut was applied to the HF energy sum. For such sample enriched with diffractive events, the E_{HF-} distributions was obtained (Fig. 5).

For distributions in HF, PHOJET [21, 22] gives a fair description of the data, notably of the high-mass diffractive systems, at large values of E_{HF} , while PYTHIA8 performs significantly worse. None of the PYTHIA6 tunes considered describes the data.

6. Summary

In summary, inclusive p_T spectrum of forward jets measured by Hadronic Forward calorimeters agrees well the existing predictions from various Monte Carlo generators within current experimental uncertainties.

Spectra of simultaneously produced forward and central jets are not fully consistent with measured data, especially for lower p_T bins.

The Energy flow for events with a hard scale (with back-to-back pair of jets with high p_T) is described better than for minimum bias events. The large spread of the Pythia 6 tunes illustrates that the forward data can be used as a complementary to other UE measurements in order to improve the MC generators.

None of the PYTHIA6 tunes considered reproduces the diffractive component of the data, which is instead described reasonably well by PHOJET and PYTHIA8; PHOJET performs better in the forward region and PYTHIA8 in the central region. None of the simulations considered describes all features of the data.

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Figure 2: The cross sections for the hadronic final state, as a function of p_T , for the forward jets and the central jets to different sets of MCs.

Figure 3: Energy flow as a function of η for minimum-bias events at $\sqrt{s}=0.9$ TeV and $\sqrt{s}=7$ TeV (upper) and dijet events for $\sqrt{s}=7$ TeV (lower). The data are shown as points, while the histograms correspond to predictions obtained from various PYTHIA6 tunes. The error bars represent the systematic uncertainties, which are strongly correlated between the bins. The statistical uncertainties are negligible.

Figure 5: Distribution of E_{HF-} , after the requirement of $E_{HF+} < 8$ GeV. The distribution is uncorrected. The bands illustrate the effect of a 10% energy scale uncertainty in the calorimeters. The data are compared to PYTHIA6 (tune D6T), PYTHIA8 and PHOJET, normalised to the data.

Figure 4: Distribution of the accepted events as a function of E_{HF+} . The distribution is uncorrected (see text). The predictions of PYTHIA6 (tune D6T), PYTHIA8 and PHOJET are also shown, normalised to the data. The bands illustrate the effect of a 10% energy scale uncertainty in the calorimeters.