Underlying event, minimum bias and forward energy flow measurements with CMS

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A measurement of the underlying activity in scattering processes using leading track-jet and Drell-Yan events with energy scale over a wide range has been presented. Studies of inclusive and identified hadron production in proton-proton collisions, including charged particle transverse momentum, pseudorapidity and event-by-event multiplicity distributions at $\sqrt{s} = 0.9$, 2.36 and 7 TeV are shown. Results on two-particle angular correlations are also presented. We also present the measurements of the forward energy flow in Minimum Bias events and in events with hard jets produced at central rapidities, as well as in the events having a W/Z boson in the central region. Results are compared to various Monte Carlo models and to perturbative QCD calculations.

1 Introduction

In hadron-hadron scattering the "underlying event" (UE) is defined as any hadronic activity that is additional to what can be attributed to the hadronization of partons involved in the hardest scatter and its initial and final state QCD radiation. The UE activity is thus due to the hadronization of partonic constituents that have undergone multiple parton interactions (MPI), as well as to beam-beam remnants, concentrated along the beam direction. It is important for the precision measurements of Standard Model processes and the search for new physics at high energies.

The majority of proton-proton (pp) collisions at hadron colliders are soft, i.e., without any hard scattering of the proton partonic constituents. It is important to measure inclusive and identified hadron production in proton-proton collisions, including charged particle transverse momentum, pseudorapidity, event-by-event multiplicity distributions and particle correlations. The energy flow measured in the forward region is directly sensitive to the parton radiations and MPIs.

These measurements have been performed at various centre-of-mass energies by the CMS [1] experiment and compared with various MC predictions.

2 Results

The UE measurement is performed in plane *transverse* to the beam direction in the regions having least contamination from hard interactions, even though it cannot in principle be

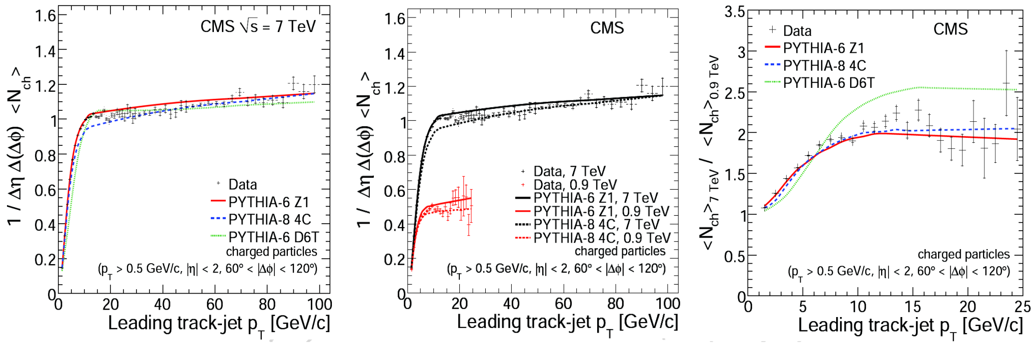

Figure 1: (left) Particle density as function of leading track-jet p_T in *transverse* region for data and prediction of various MCs at $\sqrt{s} = 7$ TeV. (centre) Comparison of particle density for $\sqrt{s}$ of 0.9 TeV and 7 TeV. (right) Ratio of particle density at 0.9 and 7 TeV centre-of-mass energy for data and different MCs predictions.

uniquely separated from initial and final state radiation. Two different approaches have been considered by CMS, analyzing dijet events at $\sqrt{s} = 0.9$ and 7 TeV and di-muon final states in Drell-Yan events at 7 TeV. In the first analysis [2, 3] the direction of the hard scatter is identified with that of the leading track-jet, i.e. the object with largest p_T formed using a jet algorithm applied to reconstructed tracks. The leading track-jet p_T is taken to define the hard scale in the event. In the Drell-Yan analysis [5] the lowest scale is set by the di-muon invariant mass, and UE observables are studied as a function of resultant p_T and invariant mass of the muon pair.

A strong increase of the UE activity, quantified through the particle density (Figure 2) and the energy density (here not shown) of charged particles in the *transverse* region ($60^o < \Delta\phi < 120^o$), is observed with increasing leading track-jet p_T. At $\sqrt{s} = 7$ TeV this fast rise is followed above $\sim$ 8 GeV/c by a *saturation* region with nearly constant multiplicity and small Σp_T increase. By comparing data taken at $\sqrt{s} = 0.9$ and 7 TeV, a strong growth with increasing centre-of-mass energy of the hadronic activity in the transverse region is also observed for the same value of the leading track-jet p_T, as reported in Figure 2 (right). The predictions of several tunes of the PYTHIA program version 6 [15] and of the new version PYTHIA-8 [9] have been compared to the measurements, with a good description of most distributions at $\sqrt{s} = 7$ TeV and of the $\sqrt{s}$ dependence from 0.9 to 7 TeV provided by the Z1 tune [4].

After excluding the muons in DY events, both the *towards* ($\Delta\phi < 60^o$) and the *transverse* region are equally sensitive for the UE measurement. The UE activity in the DY events shows flat dependency on invariant mass (60-120 GeV/c^2), which confirm the *saturation* hypothesis (illustrated in Figure 2 (right)). The UE activity as a function of $p_T^{\mu\mu}$ (illustrated in Figure 2 (left, centre)) shows very slow increase, both in the *towards* and *transverse* region, in particle density and do not show the fast rise as in case of track-jet analysis because the energy scale for selected DY events is very high and lies in the *saturation* region. The activity in the *transverse* region is higher than the *towards* region, which is due to spill-over contribution of hard-component in *away* region ($\Delta\phi > 120^o$).

Inclusive primary charged-hadron multiplicity densities have been measured with three different and complementary techniques [6, 7] as a function of the particle transverse mo-

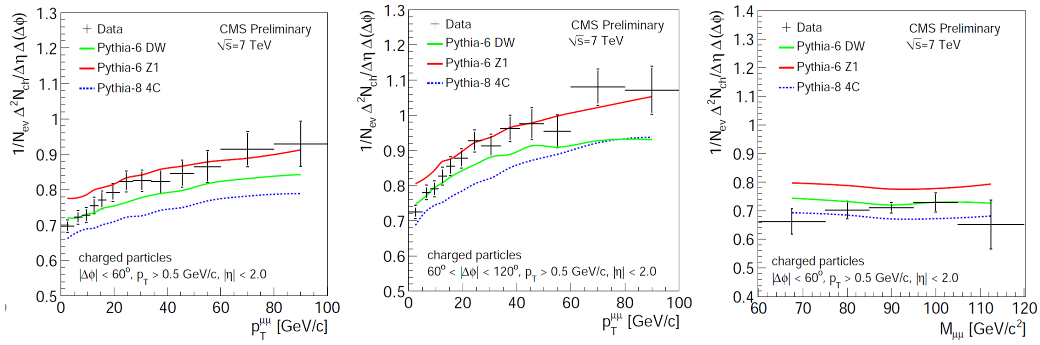

Figure 2: (left) Particle density as function of transverse momentum of muon pair ($p_T^{\mu\mu}$) in the *towards* region for the Drell-Yan events for data and prediction of various MCs at $\sqrt{s} = 7$ TeV. (centre) Corresponding particle density in the *transverse* region. (right) Particle density as a function of invariant mass of muon pair ($M_{\mu\mu}$) in the *towards* region.

mentum p_T and pseudorapidity η, in the pseudorapidity region of $|\eta| < 2.4$ for inelastic non-single-diffractive (NSD) Minimum Bias interactions. The results at 0.9 TeV have been found to be in agreement with previous measurements in pp and p$\bar{\text{p}}$ collisions. The new measurements at 2.36 and 7 TeV, higher than most predictions, show a steeper than expected increase of charged-hadron multiplicity density with collision energy, as shown in Figure 3 (left) for central η region.

Minimum Bias measurements of the phase-space-invariant differential yield Ed^3N_{ch}/dp^3, with N$_{ch}$ the number of primary charged particles, have also been extended in the hundreds GeV/c region by using jet triggers [8]. As shown in Figure 3 (centre), the 7 TeV data are most consistent with PYTHIA-8, which agrees at the 10% level over the full p_T range of the measurement. Additionally, as shown in Figure 3 (right), the consistency of the 0.9 and 7 TeV spectra has been demonstrated with an empirical $x_T = 2p_T/s$ scaling that unifies the differential cross sections from a wide range of collision energies onto a common curve. Furthermore, within the theoretical uncertainties of the next-to-leading-order (NLO) calculations, the residual breaking of x_T scaling above $p_T \approx 8$ GeV/c is consistent between the measured cross sections and the NLO calculations. This result has removed a large uncertainty from an important ingredient of existing and future heavy-ion PbPb measurements, namely the pp reference spectrum corresponding to the energy of the LHC 2010 PbPb run: 2.76 TeV per nucleon. By employing a combination of techniques to interpolate between the CMS results at $\sqrt{s} = 0.9$ and 7 TeV, including information from existing CDF measurements at $\sqrt{s} = 0.63$, 1.8, and 1.96 TeV [10, 11, 12], a pp reference at $\sqrt{s} = 2.76$ TeV (here not shown) has been constructed over a large range of transverse momentum (p_T = 1-100 GeV/c) with systematic uncertainties of less than 13%.

Production of K_S^0, Λ, and Ξ^- identified particles has been measured at $\sqrt{s}$ of 0.9 and 7 TeV [13]. From a sample of 10 million strange particles, the p_T distributions (here not shown) were measured out to 10 GeV/c for K_S^0 and Λ, and out to 6 GeV/c for Ξ^-. The Tsallis function fits [14] of the distributions show for all the species a flattening of the exponential decay as the $\sqrt{s}$ increases. The average p_T values are found to increase with particle mass and $\sqrt{s}$, in agreement with predictions and other experimental results. While the PYTHIA [15] p_T

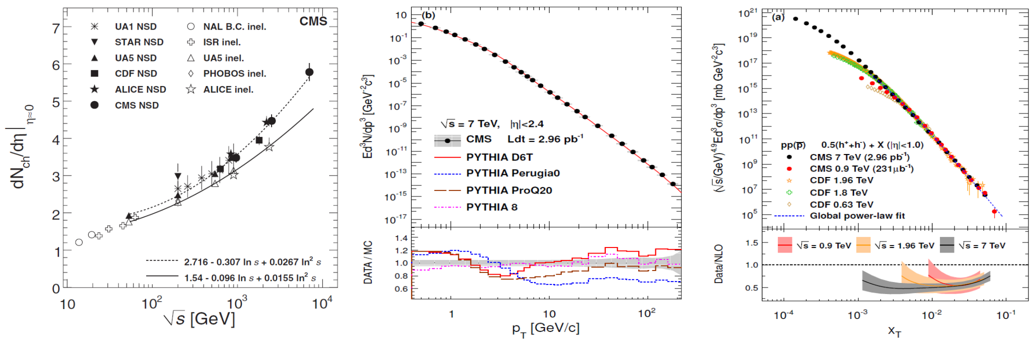

Figure 3: (left) Average value of charged multiplicity density $dN_{ch}/d\eta$ in the central η region as a function of $\sqrt{s}$ in pp and p$\bar{\text{p}}$ collisions (the solid and dashed curves are second-order polynomial fits for the inelastic and non-single-diffractive event selections, respectively). (centre) Invariant charged particle differential yield at $\sqrt{s} = 7$ TeV compared with the predictions of four tunes of the PYTHIA MC generator; lower panel: the ratio of the CMS measurement to the four PYTHIA tunes (the grey band corresponds to the statistical and systematic uncertainties added in quadrature). (right) Inclusive charged particle invariant differential cross sections, scaled by $\sqrt{s}^{4.9}$, for $|\eta| < 1.0$ as a function of the scaling parameter x_T (the result is the average of the positive and negative charged particles.

distributions used in the analysis show significant variation based on tune and version, they are all broader than the data distributions. The measurement of the production in function of rapidity y (illustrated in Figure 4 (left) for K^0_S) shows a $\sqrt{s}$ increase in strange particles production approximately consistent with the results for inclusive charged particles. As in the inclusive charged particle case, PYTHIA fails to match this increase, the deficit between PYTHIA and data being significantly larger for the two hyperons at both energies with a factor of three discrepancy for Ξ^- production at $\sqrt{s} = 7$ TeV. An enhancement of double-strange baryons to single-strange baryons, and/or an enhancement of strange baryons to strange mesons, would be an indication of a quark-gluon plasma or other collective effects. However, the production ratios $N(\Lambda)/N(K^0_S)$ and $N(\Xi^-)/N(\Lambda)$ versus p_T (here not shown) and y (reported in Figure 4 (centre) for $N(\Lambda)/N(K^0_S)$) show no change with $\sqrt{s}$. Thus, the deficiency in PYTHIA is likely originating from parameters regulating the frequency of strange quarks appearing in colour strings.

The charged hadron multiplicity distributions P_n of non-single-diffractive events were measured from an analysis of the Minimum Bias data at the three $\sqrt{s}$ of 0.9, 2.36, and 7 TeV [16]. Charged tracks are reconstructed down to $p_T = 100$ MeV/c with high efficiency and low background contamination. A full correction for detector resolution and acceptance effects and an extrapolation to zero transverse momentum yield measurements of the charged hadron multiplicity distribution for increasing central pseudorapidity ranges from $|\eta| < 0.5$ to $|\eta| < 2.4$, shown in Figure 4 (right). Although some event generators provide an adequate description of Tevatron and LEP data, none is able to describe simultaneously the multiplicity distributions and the p_T spectrum at $\sqrt{s} = 7$ TeV. In general, models predict too few low-momentum particles, indicating that by increasing the amount of multiple-parton interactions (MPI) one effectively introduces too many hard scatters in the event. The change of slope in P_n in the widest central pseudorapidity intervals observed at $\sqrt{s} = 7$ TeV, combined with the strong

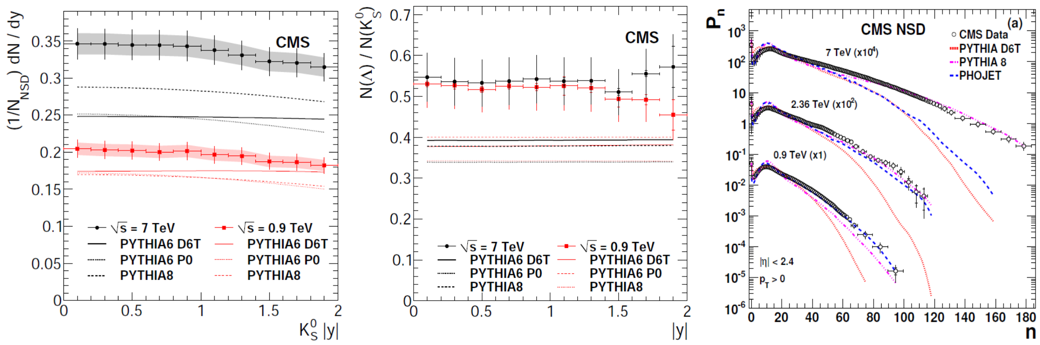

Figure 4: (left) K_S^0 production per non-single-diffractive (NSD) events versus $|\eta|$: the inner vertical error bars, when visible, show the statistical uncertainties, the outer the statistical and point-to-point systematic uncertainties summed in quadrature; the normalization uncertainty is shown as a band; three PYTHIA predictions are overlaid. (centre) The production ratio $\mathrm{N}(\Lambda)/\mathrm{N}(\mathrm{K}_S^0)$ in non-single-diffractive events versus $|\eta|$ at each $\sqrt{s}$ (the inner vertical error bars, when visible, show the statistical uncertainties, the outer the statistical and all systematic uncertainties summed in quadrature), together with three PYTHIA predictions. (right) The charged hadron multiplicity distributions with $|\eta| < 2.4$ for $p_T > 500$ MeV/c at $\sqrt{s} = 0.9$, 2.36, and 7 TeV, compared to two different PYTHIA models and the PHOJET model; for clarity, results for different $\sqrt{s} = 0.9$ are scaled by powers of 10 as given in the plots.

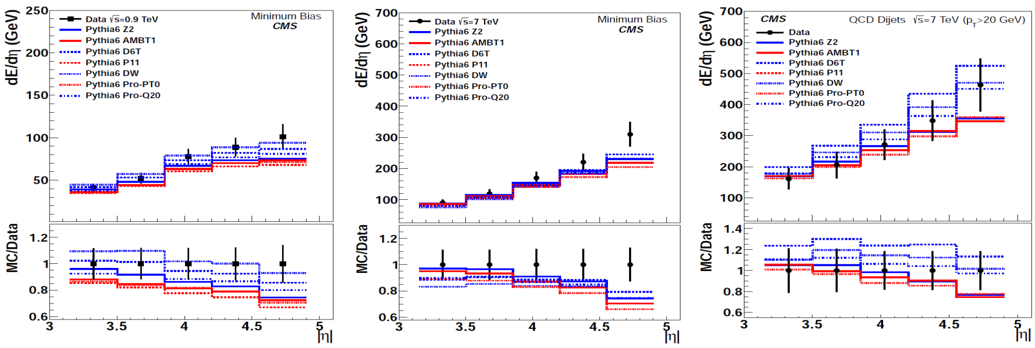

Figure 5: (left) Forward energy flow in Minimum Bias events for centre-of-mass energy of $\sqrt{s} = 0.9$ TeV for data and prediction of various tunes for PYTHIA-6. (centre) Forward energy flow in Minimum Bias events for centre-of-mass energy of $\sqrt{s} = 7$ TeV for data and prediction of various tunes for PYTHIA-6. (right) Energy flow for events with dijet events with transverse momentum $p_T > 20$ GeV/c for centre-of-mass energy of $\sqrt{s} = 7$ TeV for data and prediction of various tunes for PYTHIA-6.

linear increase of the normalized C_q moments (here not shown), indicates a clear violation of KNO scaling [17] with respect to lower energies. Such observation merits further studies.

A measurement of the energy flow in the forward region ($3.15 < |\eta| < 4.9$) was done for $\sqrt{s} = 0.9$ and 7 TeV [18]. The energy flow, corrected for detector effects, is measured both in Minimum Bias events and in events with a hard scale provided by a dijet system at central

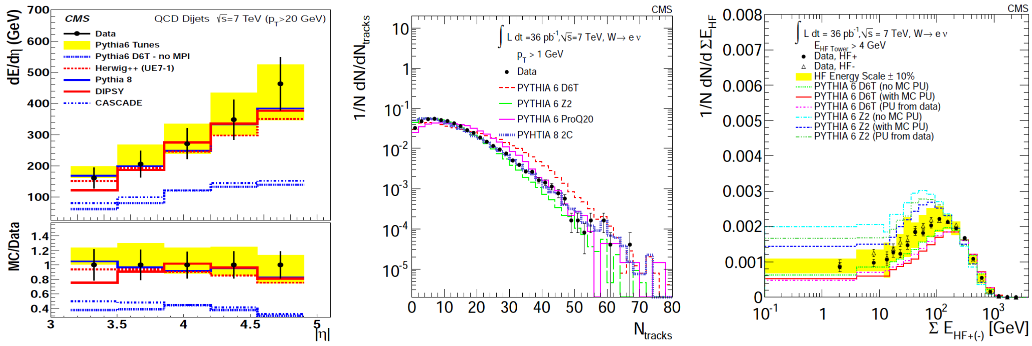

Figure 6: (left) Energy flow for events with dijet events with transverse momentum $p_T > 20$ GeV/c for centre-of-mass energy of $\sqrt{s} = 7$ TeV for data and prediction of various event generators. (centre) Number of tracks in central region of detector and with transverse momentum p_T 1 GeV for events having $W \to e\nu$ candidates for data and various MCs. (right) Forward energy for events having $W \to e\nu$ candidates, summing all HF towers with energy larger than 4 GeV, for data and various MCs.

pseudorapidities ($|\eta| < 2.5$) as illustrated in Figure 5. The jets are required to have transverse energy greater than 8 (20) GeV at $\sqrt{s} = 0.9$ (7) TeV. There is significant increase in energy as centre-of-mass energy increases from 0.9 TeV to 7 TeV (shown in Figure 5 (left and centre)) and measurement are different for Minimum Bias and QCD dijet events (clear from Figure 5 (centre and right)). Even if this increase is reproduced by the MCs for Minimum Bias and dijet events, none of the MC simulations can describe all four energy flow measurements. In general the MC generators produce a somewhat too flat energy flow distribution for the Minimum Bias data. Multiple interactions are needed in order to describe the data, since it is found that MC predictions without MPI (PYTHIA-6 run without MPI and CASCADE [20]) significantly undershoot the data. The description given by cosmic ray MC generators (such as EPOS [21], QGSJET [22] and SIBYLL [23]) is found to be excellent as clear from 6 (left). Central charged-particle multiplicities, forward energy flow, and correlations between them have been studied in W and Z events, identified by the vector-boson decays to electrons and muons [19]. None of the studied MC tunes provides simultaneously a satisfactory description of the charged particle multiplicity in the central pseudorapidity region ($|\eta| < 2.5$) and the forward energy flow ($3 < |\eta| < 4.9$) as illustrated in Figure 6 (centre, right). The PYTHIA-6 Z2 and PYTHIA-6 2C tunes give a reasonable description of the central charged-particle multiplicity, but predict too many events with relatively low energy depositions in the forward calorimeters. The PYTHIA-6 D6T tune predicts too many events with high charged-particle multiplicities, too few events with low-energy depositions, and too many events with very large energy depositions in the forward calorimeters. The Pro-Q20 tune provides the best description of the forward energy distribution and a good description of the charged-particle multiplicity, when a track p_T threshold of 0.5 GeV is applied. However, the charged-particle multiplicity with $p_T > 1.0$ GeV is not well described, though the prediction is closer to the data than that for the D6T tune. Strong positive correlations between the energy measured in the two forward calorimeters (i.e.at positive and negative rapidities) and the charged-particle multiplicity are observed in the data and in Monte Carlo models (not shown here). However, the correlations in the various MC tunes are different from those seen in the data.

3 Conclusion

In the present proceeding a measurement of the underlying event in different processes at different centre-of-mass energies, some of Minimum Bias measurements and measurements of forward energy flow in different processes with different centre-of-mass energies conducted by the CMS collaboration at the LHC are briefly summarized. The huge amount of data coming from the first two years of data acquisition has provided important information to better constrain phenomenological models of the soft hadron production and provide insight on understanding MPI. These measurements are crucial for precision measurements of Standard Model processes and for new physics searches.

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