Characterization of the Underlying Event in p-p collisions in CMS

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We present measurements of the Underlying Event (UE) in proton-proton collisions in CMS at the LHC at $\sqrt{s} = 0.9$, 2.76 and 7 TeV using different methods to distinguish the hard scatter system. Charged particle and energy densities are determined in the central ($|\eta| < 2$) and forward ($5.2 < |\eta| < 6.6$) regions as a function of the transverse momentum of the hard interaction characterized by central track-jets or Drell-Yan processes. In addition a novel technique using jet area/median properties to study the UE is presented. All results are corrected to hadron level and compared to various Monte Carlo (MC) models embedding different UE tunes.

1 Introduction

The Underlying Event in proton-proton collisions is everything except the hard scattering between the two high-p_T partons. Elements of this are the presence of Initial State Radiation (ISR), Final State Radiation (FSR), Multiple Partonic Interactions (MPI) and Beam Remnants (BR). The understanding of these phenomena in proton-proton collisions at the LHC is crucial for precision measurements of Standard Model processes and accordingly for the search for new physics. Unfortunately however, its dynamics are not well understood since they are governed by soft and semi-hard interactions which can not be fully described with perturbative QCD. This leads to the need of phenomenological models in MC generators containing parameters which must be tuned using existing data. Given the new unexplored energy domain at the LHC, its data is ideal to do further studies of the UE properties at $\sqrt{s}$ values of up to 7 TeV and constrain the existing models.

When describing collisions, a typical Minimum Bias (MB) event can be regarded as a peripheral collision which is characterised by a small overlap between the interacting protons while an event with a hard scale present is a more central collision with the interacting protons having a bigger overlap. One can thus expect more MPI in events with a high $\hat{p}_T$ than in MB events. The number of interactions in a collisions then thus not only depend on the centre-of-mass energy - the increase of particle densities gives a rise in interactions - but also on the hard scale of the event. This behaviour is reflected in existing phenomenological MPI models developed to describe these soft interactions. To achieve this one has to extend the hard scatter cross section to low $\hat{p}_T$ values and to avoid the divergence a regularisation value $\hat{p}_{T,0}$ has to be introduced: $1/\hat{p}_T^4 \to 1/(\hat{p}_T^2 + \hat{p}_{T,0}^2)^2$, which is also energy dependent: $\hat{p}_{T,0}(\sqrt{s}) = \hat{p}_{T,0}(\sqrt{s_0}) \cdot (\sqrt{s}/\sqrt{s_0})^{\epsilon}$. In these models more MPI activity is then predicted for smaller values of the $\hat{p}_{T,0}$ and ϵ parameters. The study of new data as a function of the hard scale and the centre-of-mass energy of the event can thus help to improve and tune the current models. [1] [2]

2 Underlying Event activity in the Drell-Yan process

One possibility is to study the UE activity using the experimentally clean Drell-Yan interaction. This is a complementary approach to already existing studies [3] and has the additional advantages of providing a clean separation of the hard interaction from the soft components, the absence of FSR and a low probability of photon brehmsstrahlung from the muons. The analysis strategy presented here is to measure the charged particle - and energy densities ($p_T > 0.5$ GeV/c, $|\eta| < 2$, muons from DY excluded) as a function of the di-muon p_T and the di-muon mass in the different geometrical *Towards*, *Transverse* and *Away* regions [4] with respect to the di-muon pair (81 GeV/c^2 $< M_{\mu\mu} <$ 101 GeV/c^2). Analysing the di-muon p_T dependence enables us to probe the ISR spectrum while the studying the di-muon mass behaviour verifies the MPI saturation. The *Away* region is dominated by the hardest ISR that balances the di-muon system while the *Towards* and *Transverse* regions are sensitive to soft emissions due to MPI. Figure 1 shows the results of the energy densities as a function of the di-muon p_T. In the *Towards* and *Transverse* regions a slow growth of the densities is observed with increasing di-muon p_T. POWHEG Z2 and PYTHIA8 4C fail to describe the data while MADGRAPH with tune Z2 succeeds rather well. The *Away* region, sensitive to the spectrum of the hardest emission, is equally well described by all models and tunes. [5]

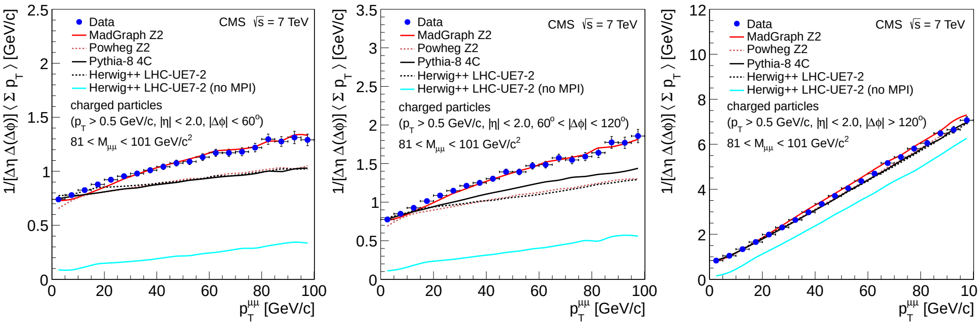

Figure 1: The energy density in the towards (left), transverse (middle), and away (right) regions as a function of $p_T^{\mu\mu}$ for events satisfying $81 < M_{\mu\mu} <$101 GeV/c^2. Predictions of MADGRAPH Z2, POWHEG Z2, PYTHIA8 4C, and HERWIG++ LHC-UE7-2 (with and without MPIs) are superimposed. [5]

3 Jet area/median approach

The second analysis presented uses an alternative approach to study the UE activity at central rapidity. The soft hadronic activity in the event is measured by calculating the ratio of the jet p_T and the area covered by this jet in the (η, ϕ) plane for all jets in the event.

To quantify this we introduce the event variable:

$$\rho = \operatorname*{median}_{j \in \text{jets}} \left[\left\{ \frac{p_{T,j}}{A_j} \right\} \right]$$

This variable naturally isolates the UE contributions assuming that the majority of the event is dominated by soft interactions and has the additional advantage that no geometrical slicing of the phase space is needed. The usage of the median in the definition makes it robust to outliers in the distributions which can be hard interactions. To avoid problems with limited detector acceptance, an adjusted observable ρ' is introduced which uses only jets containing at least one physical particle [6]. The jets to then calculate ρ' are track-jets reconstructed with the k_{T} algorithm (R = 0.6) within $|\eta| < 1.8$. The input tracks to the jets have $p_T > 0.3$ GeV/c and $|\eta| < 2.3$. One can then study the jet area/median behaviour as a function of the leading jet found in the event. Figure 2 shows the results for $\sqrt{s} = 0.9$ and 7 TeV fully corrected to hadron level. Tunes Z1, Z2 and 4C of Pythia are too low at 7 TeV and one can generally see that the amount of events with very high activity is underestimated by the current models. [6]

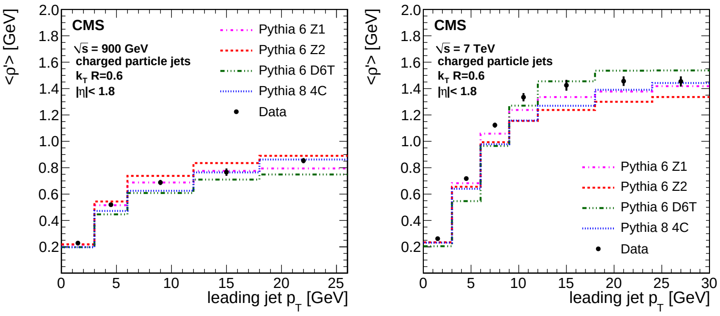

Figure 2: Mean values of the corrected ρ' distributions versus leading charged-particle jet transverse momentum at $\sqrt{s} = 0.9$ TeV (left) and $\sqrt{s} = 7$ TeV (right) in comparison to the predictions by the different generator tunes. [6]

4 Study of the Underlying Event at forward rapidity

The last analysis presented measures the UE activity by studying the energy densities at forward rapidity $5.2 < |\eta| < 6.6$. In this case the UE observables are separated with a large $\Delta\eta$ from the hard interaction and again no division of the phase space is needed. The analysis strategy is to look at the behaviour of the ratio of the energy deposited in inclusive MB events and the energy deposited in events with a hard scale $\hat{p}_T$ as a function of the leading jet of the event with $p_T > 1$ GeV/c and $|\eta| < 2$. The additional advantages of using a ratio of energy densities are that the results are more robust to systematic uncertainties and absolute energy calibration. Figure 3 then shows the hard-to-inclusive ratio as a function of the leading charged jet p_T at $\sqrt{s} = 0.9$, 2.76 and 7 TeV. At 7 TeV the well known UE behaviour of a fast increase at low p_T followed by a plateau above $p_T = 8$ GeV/c is visible while at 2.76 TeV the increase of the ratio is much reduced. At 0.9 TeV however the ratio goes below unity which can be understood as follows: the production of central hard jets accompanied with higher UE activity depletes the energy of the proton remnant which fragments in the rapidity range of the measurement. Although the older D6T tune fails to describe the data, recent models tuned to LHC data (Z2*, 4C, Herwig 2.5) reproduce the results rather well. [7]

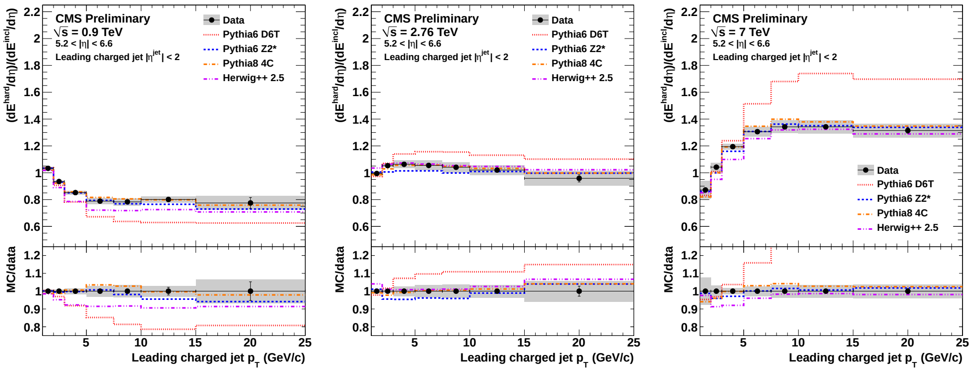

Figure 3: Ratio of the energy deposited in the pseudorapidity range $5.2 < |\eta| < 6.6$ for events with a charged particle jet with $|\eta^{jet}| < 2$ with respect to the energy in inclusive events, as a function of charged particle jet transverse momentum for $\sqrt{s} = 0.9$ (left), 2.76 (middle) and 7 TeV (right). [7]

5 Conclusions

The UE activity is studied in many ways with the CMS experiment at the LHC by measuring energy densities and jet area/median values at central or forward rapidity using leading jets or Drell-Yan processes to determine the hard scale of the event. Models tuned to early LHC data can describe many aspects of the UE, i.e. the evolution of both central & forward energy densities and the behaviour of the jet area/median as a function of the hard scale of the event. Notable discrepancies of the UE activity are observed in the *Towards* & *Transverse* regions in Drell-Yan at high p_T.

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