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

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Investigation of the underlying event in pp collisions at the LHC with CMS

Paolo Bartalini for the CMS Collaboration

Abstract

We report on recent investigations of the underlying event in pp collisions at the LHC. The underlying event activity has been studied in Drell–Yan processes, using the jet area method and at forward rapidity. Strangeness production in the underlying event has been measured.

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Investigation of the underlying event in pp collisions at the LHC with CMS

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*National Taiwan University
(on behalf of the CMS collaboration)*

Abstract. We report on recent investigations of the underlying event in pp collisions at the LHC. The underlying event activity has been studied in Drell–Yan processes, using the jet area method and at forward rapidity. Strangeness production in the underlying event has been measured.

Keywords: <QCD, LHC, Multiple Parton Interactions, Underlying Event>

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PARTICLE YIELDS AND KINEMATIC DISTRIBUTIONS

Measurements of particle yields and kinematic distributions are an essential first step in exploring a new energy regime of particle collisions.

The methodologies which push the cluster counting below 50 MeV and allow for track reconstruction (with p_T measurement) from 75 MeV/c threshold have been introduced in the first CMS paper on collision data, reporting the transverse momentum and pseudorapidity distributions of charged hadrons in proton-proton interactions at $\sqrt{s} = 0.9$ and 2.36 TeV [1], subsequently complemented by the extension of the same measurement at 7 TeV [2]. Calorimeter-based high-transverse-energy triggers are employed to enhance the statistical reach of the high- p_T measurements [3].

The CMS charged multiplicity studies [4] rely on a bayesian unfolding technique taking into account the detector effects [5]. Traditionally, the s dependence of the multiplicity distributions P_n and its moments has been much discussed [6] in relation to Koba-Nielsen-Olesen (KNO) scaling [7, 8]. In this framework, one studies the KNO function $\Psi(z) = \langle n \rangle P_n$, where $z = n / \langle n \rangle$. For a large pseudorapidity interval of $|\eta| < 2.4$, a strong violation of KNO scaling between $\sqrt{s} = 0.9$ TeV and 7 TeV is observed. However at small pseudorapidity interval of $|\eta| < 0.5$ KNO scaling holds. These CMS observations and the older phenomenology from SPS and LEP point to the increasing importance of multiple parton interactions (MPI) in high energy hadron-hadron inelastic collisions at high $\sqrt{s}$.

UNDERLYING EVENT

In the presence of a hard process, characterized by the presence of particles or clusters of particles with a large transverse momentum p_T with respect to the beam direction, the final state of hadron-hadron interactions can be described as the superposition of several contributions: products of the partonic hard scattering with the highest scale, including

initial and final state radiation; hadrons produced in additional MPI; and “beam-beam remnants” (BBR) resulting from the hadronization of the partonic constituents that did not participate in other scatterings. Products of MPI and BBR form the Underlying Event (UE). The UE cannot be uniquely separated from initial and final state radiation.

FIGURE 1. Comparison of the UE activity measured in hadronic and Drell–Yan events (around the Z resonance peak) as a function of leading jet p_T and di-muon p_T respectively: (left) particle density, (centre) energy density, and (right) ratio of energy and particle densities in the transverse region.

The conventional CMS UE measurement in jet final states [9] concentrates on the study of the transverse region, which is defined considering the azimuthal distance of the reconstructed tracks with respect to the leading track-jet of the event: $60^\circ < |\Delta\phi| < 120^\circ$. The jet reconstruction algorithm used in these studies is SisCone [10]. The Drell–Yan (DY) process with muonic final state, $q\bar{q} \rightarrow \mu^+\mu^-$, due to the presence of the quarks in the initial state, provides an excellent complementary way to study the underlying event. The CMS UE measurement [11] in DY events focuses on the di-muon invariant mass region between 81 and 101 GeV/c^2 . The UE observables defined in the jet final states are extended to the DY case replacing the track-jet with the di-muon. Figure 1 shows the comparison of the UE activity measured in the hadronic and the DY events (around the Z peak) in the transverse region as a function of the leading jet p_T and di-muon p_T , respectively. For the hadronic events two components are visible: a fast rise for leading jet p_T up to 10 GeV/c due to an increase in the MPI activity, followed by an almost constant particle density and a slow increase in the energy density with leading jet p_T . The increase in the particle and energy densities for leading jet p_T above 10 GeV/c is mainly due to the increase of ISR and FSR. Owing to the presence of a hard energy scale ($81 < M_{\mu\mu} < 101 \text{ GeV}/c^2$), densities in the DY events do not show a sharply rising part, but only a slow growth with the di-muon p_T due to the ISR contribution. No dependence of the UE observables on the di-muon invariant mass is observed. Extrapolating to the point with minimal radiative and maximal MPI contribution, the UE activity in DY events turns out to be around 25% lower with respect to the jet case. In Ref. [12] this is interpreted in terms of the reduced transverse size of the gluons with respect to the quarks. A significant growth of the UE activity is observed, for the same value of the leading jet p_T (or di-muon p_T), from $\sqrt{s} = 0.9 \text{ TeV}$ to $\sqrt{s} = 7 \text{ TeV}$ (not shown here). These observations are consistent with the ones obtained at Tevatron [13, 14]. The evolution with the hard scale of the ratio of the UE activity at 7 TeV and 0.9 TeV is remarkably well described by the Z1 tune [9]. The trend is also reproduced by PYTHIA 8 tune 4C [15]. The strong growth of UE activity with charged particles is also striking

FIGURE 2. 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 p_T for $\sqrt{s} = 0.9$ (left), 2.76 (middle) and 7 TeV (right). Corrected results are compared to the PYTHIA and HERWIG++ MC models. Error bars indicate the statistical error on the data points, while the grey band around data points represents the statistical and systematic uncertainties added in quadrature.

in the comparison of the distributions of charged particle multiplicity, p_T and scalar p_T sum (not shown here) which corroborate the presence of a hard component in the UE, hence the adoption of the MPI models.

The strange component of the underlying event in pp collisions at $\sqrt{s} = 7$ TeV at the LHC is studied in Ref. [16], providing valuable additional input to the modeling of strangeness production and to the tuning of MC generators for high-energy proton-proton collisions. Consistently to the inclusive results, a steep rise of the strange component of the underlying event activity is seen with increasing leading track-jet p_T , followed by a “plateau” region for track-jet $p_T > 10$ GeV/c. All recent PYTHIA tunes underestimate the production of K_S^0 mesons and $\Lambda + \bar{\Lambda}$ baryons in the transverse region. K_S^0 production is 15-30% too low while $\Lambda + \bar{\Lambda}$ is typically 50% too low. Accounting for the different p_T ranges of strange particles considered, the deficits are consistent with previously published studies in non-single diffractive events, supporting the hypothesis of a universal strangeness production.

CMS reports measurements of the energy flow in the forward region [17, 18] for minimum bias, di-jet and DY events. These measurements are connected to the central region UE ones as the basic philosophy is the same: they concentrate on the complementary activity of a pp interaction for different energy scales of the reconstructed leading objects. The UE results are qualitatively similar to the ones obtained in the central region at all the investigated centre of mass energies. The measured forward energy flow is found to be significantly different between MB and di-jet events, with a sensitive increase and a more central activity seen in the latter topology.

A more recent CMS study [19] extends the pseudorapidity coverage of the UE measurements to $5.2 < |\eta| < 6.6$ by measuring the ratio of the forward energy density, $dE/d\eta$ for events with a charged particle jet produced at central rapidity ($|\eta^{jet}| < 2$)

FIGURE 3. Mean values of the corrected p' 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. The p' distributions in each slice are unfolded with the Bayesian method. The error bars, which are mostly smaller than the symbol sizes, correspond to the total uncertainty.

and inclusive events. Figure 2 shows the hard-to-inclusive forward energy ratios, defined as 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 for inclusive, dominantly non-diffractive events, as a function of charged particle jet transverse momentum p_T . Results are compared to a wide set of MC generators using multi parton interaction models and to cosmic-ray generators (not shown here). At $\sqrt{s} = 7$ TeV, a fast increase is seen at low p_T followed by a plateau above $p_T = 10$ GeV/c, consistent with the UE measurement in the central region. Good performances of the MPI MC models tuned on the central UE phenomenology is observed. However the conclusions on the agreement of the tunes slightly differ with respect to the ones drawn restricting to the central region, indicating the need of a global optimization relying on both the central and the forward UE measurements. At $\sqrt{s} = 2.76$ TeV, the increase of the energy ratio with jet p_T is much reduced. This tendency is consistent with the result at $\sqrt{s} = 0.9$ TeV, where the ratio becomes less than unity. Here, the energy density per unit of pseudorapidity in events with a central charged particle jet is thus lower than the energy density in inclusive events. This can be understood as a kinematic effect where the production of central hard jets, accompanied with higher underlying event activity (as seen in studies at central rapidity), depletes the energy of the proton remnant which at $\sqrt{s} = 0.9$ TeV fragments within the investigated pseudorapidity acceptance. The energy dependence of the UE activity in the pseudorapidity range $5.2 < |\eta| < 6.6$ is well taken by the most models tuned on the central UE phenomenology. Most of the tested cosmic ray models also describe the data well.

On top of the conventional approach, a new methodology to quote the UE adopting anti- k_T jets [20] and relying on the measurement of their area [21] is adopted for the first time by CMS using charged particles in pp collision data collected at $\sqrt{s} = 0.9$ and 7 TeV [22]. The new set of UE observables consider the whole pseudorapidity-azimuth plane instead of the transverse region and inherently take into account the leading jets of an event. This new technique to quote the UE activity relies on the introduction of “ghosts”, virtual deposits of very low energy filling the overall phase space which are taken into account by the jet clustering algorithm. The estimator of the

overall soft background activity in an event can be derived as the median of the ratio between the transverse momentum and the area of the jets. In order to cope with the low occupancy events, CMS redefines such observable restricting the median only to those jets which have physical deposits on top of ghosts:

$$\rho' = \text{median} \left[\left\{ \frac{p_{Tj}}{A_j} \right\} \right] \cdot C \quad (1)$$

where C is the occupancy of the event, which is the summed area $\sum_j A_j$ covered these jets divided by the considered detector region A_{tot} . In the CMS analysis jets are reconstructed with the anti- K_T algorithm [20] using tracks with $|\eta| < 2.0$ and $p_T > 0.3$ GeV/c. The general pattern of deviations from data with respect to the considered PYTHIA tunes looks rather similar to the one observed with the traditional UE measurement. As in conventional UE measurements it is possible for the ρ' observable to be investigated not only inclusively but also as a function of the hardness of an event, which is given by the “event scale”. Figure 3 reports the mean ρ' as a function of the transverse momentum of the leading jet. In agreement with the conventional UE analysis, a steep rise of the UE activity with increasing leading jet transverse momentum up to about 10 GeV is observed. For higher transverse momenta a plateau is reached. The ratio of the UE activity in this saturation region at 7 TeV to that at 0.9 TeV is approximately 1.8, which is close to the ratios of around 2 measured with the conventional UE observables.

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