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Double parton scattering and multiple parton interactions in ATLAS & CMS

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Double parton scattering and multiple parton interaction results from the ATLAS and the CMS experiments at the Large Hadron Collider (LHC) are presented. Many measurements on underlying events with different processes at different energy scales are available from the two major experiments at LHC. Nowadays, the primary focus of the LHC experiments is on studying double parton scattering, where the effective cross section is considered as the most important link to the theories. As a first step to the measurement, CMS provides the data distributions of the observables which are sensitive to double parton scattering. ATLAS provides first measurement of effective cross section.

The European Physical Society Conference on High Energy Physics -EPS-HEP2013
18-24 July 2013
Stockholm, Sweden

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PoS(EPS-HEP 2013)438

1. Introduction

The underlying event (UE) in a hadron-hadron interaction consists of all the processes other than the hard component which is characterized by the presence of a particle or cluster of particles with a large transverse momentum. The UE is a superposition of various components: initial and final state radiations (ISR, FSR), particles produced from multiple parton interactions (MPI) and beam-remnants resulting from the hadronization of the partonic constituents that did not participate in other scatterings. These are relatively soft interactions and can not be described by perturbative QCD [1]. At the high center-of-mass energies of the Large Hadron Collider (LHC), the proton-proton collisions probe small values of the momentum fraction x carried by the colliding partons. The large parton densities at small-x values, increase the probability of having two simultaneous parton-parton scatterings producing two independently-identifiable hard scatterings in a single p-p interaction. Double parton scattering can also contribute sizably at larger x if the second process occurs with a large rate, as is the case in W + 2 jets [2].

A good understanding of UE properties is important for precision measurements of standard model processes and the search for new physics at high energies. The study of DPS processes provides not only valuable information on the spatial structure of the hadrons and multi-parton correlations in the hadronic wave-function, but also constitute a background in the new physics searches at the LHC. The CMS and ATLAS experiments have published UE measurements at 0.9 TeV and 7 TeV center-of-mass energy using events containing a leading jet [3, 4]. The Drell-Yan (DY) process provides a complementary approach for the UE measurement [1]. UE measurements are also done in forward rapidity region and as well for strange particle production [5]. A study of jet and UE properties as a function of jet multiplicities is also done [6]. The ATLAS collaboration provides the first quantitative measurement of effective cross section at 7 TeV using the W + 2-jet process [7]. The CMS collaboration also publishes its results on DPS in W + 2-jet process and 4-jet final state process [2, 8].

2. Underlying event activity

Measurements of charged particle distributions, sensitive to the underlying event, have been performed with the ATLAS and the CMS detectors at the LHC at 0.9 TeV and 7 TeV of center-of-mass energies [3, 4]. The transverse region, defined by the difference in azimuthal angle between the leading track and charged particle directions, $60^\circ<|\Delta\phi|<120^\circ$ is considered most sensitive to multiparton interactions. A strong increase of the UE activity, represented through the average multiplicity and the average scalar transverse momentum sum of charged particles in this region, is observed with increasing leading track p_T. The ATLAS data show generally higher underlying event activity than that predicted by Monte Carlo models tuned to pre-LHC data as shown in Figure 1 (left). At the two center-of-mass energies studied, this fast rise is followed by a plateau region with nearly constant multiplicity and only a small a p_T increase as shown in Figure 1 (right). A strong growth with increasing center-of-mass energy of the hadronic activity in the transverse region is also observed for the same values of the leading track p_T.

Underlying event activity is also studied in p-p collisions at 7 TeV of center-of-mass energy, through the production of primary K^0_S mesons and Λ baryons [9]. The production of K^0_S mesons

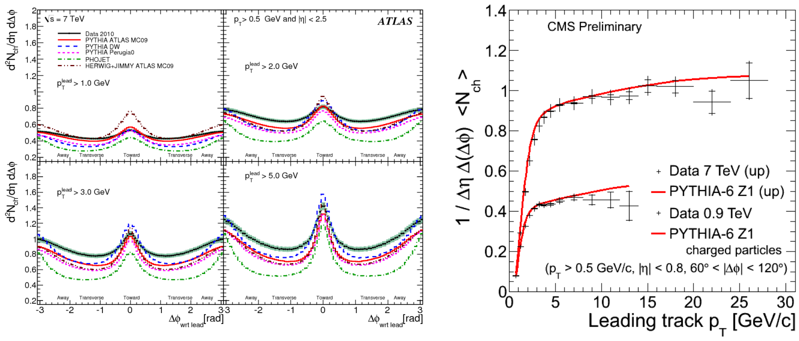

Figure 1: Underlying event activity measurements using charged particle distributions from ATLAS data (left). Fully corrected data (CMS) measurement of average multiplicity for charged particles in transverse region at 0.9 TeV and 7 TeV of center-of-mass energies as a function of leading track p_T (right).

and Λ baryons in the kinematic range $p_T^{K_S^0} > 0.6$ GeV/c, $p_T^{\Lambda} > 1.5$ GeV/c and $|\eta| < 2$ is analysed in the transverse region. The average multiplicity and the average scalar p_T sum of primary particles per event are studied as a function of the leading charged-particle jet p_T, shown in Figure 2. A steep rise of the underlying event activity is seen with increasing leading jet p_T, followed by a saturation region for jet $p_T > 10$ GeV/c. This trend and the p_T scale above which saturation occurs are very similar to those observed with charged primary particles. The PYTHIA simulations underestimate the data by 15–30% for K_S^0 mesons and by about 50% for Λ baryons, a MC deficit similar to that observed for the inclusive strange particle production in p-p collisions. The constant strange- to charged-particle activity ratios and the similar trends for mesons and baryons indicate that the MPI dynamics is decoupled from parton hadronization, with the latter occurring at a later stage.

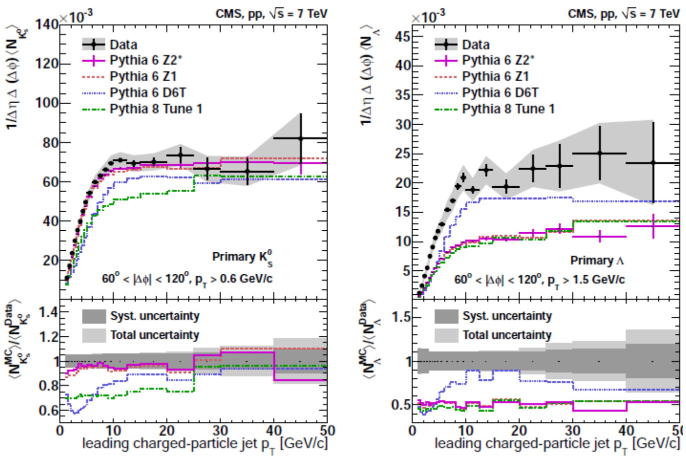

Figure 2: Fully corrected average multiplicity for K_S^0 mesons (left) and Λ (right) as a function of leading track p_T.

The underlying event activity at forward pseudorapidity ($6.6 < |\eta| < 5.2$) is also studied with the CMS detector at the LHC, with a novel observable: the ratio of the forward energy density, $dE/d\eta$, for events with a charged particle jet produced at central pseudorapidity ($|\eta_{jet}| < 2$) to the forward energy density for inclusive events [5]. This forward energy density ratio is measured as a function of the central jet transverse momentum, p_T, at three different p-p center-of-mass energies($\sqrt{s}$ = 0.9, 2.76, and 7 TeV). In addition, the $\sqrt{s}$ evolution of the forward energy density is studied in inclusive events and in events with a central jet. The dependence of the forward energy density ratio on jet p_T at each $\sqrt{s}$ separately can be well reproduced by some models. However all models fail to simultaneously describe the increase of the forward energy density with $\sqrt{s}$ in both inclusive events and in events with a central jet.

Another measurement of the underlying event (UE) activity in proton–proton collisions at a center-of-mass energy of 7 TeV is performed using Drell–Yan events in a data sample corresponding to an integrated luminosity of 2.2 fb^{-1}, collected by the CMS experiment at the LHC [1]. The dependence of the UE activity on the dimuon invariant mass is well described by PYTHIA and HERWIG++ tunes derived from the leading jet/track approach, illustrating the universality of the UE activity. The UE activity is observed to be independent of the dimuon invariant mass in the region above 40 GeV$/c^2$, while a slow increase is observed with increasing transverse momentum of the dimuon system. The dependence of the UE activity on the transverse momentum of the dimuon system is accurately described by MADGRAPH, which simulates multiple hard emissions.

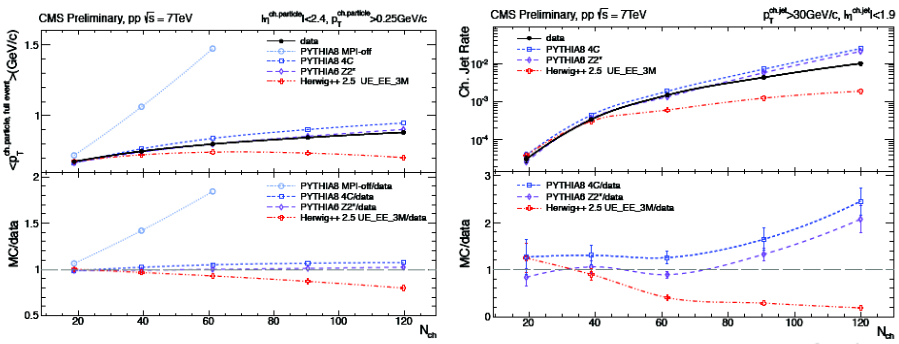

Figure 3: Distributions of average p_T of UE tracks (left) and jet rates as a function of N_{ch} (right).

The characteristics of multi-particle production in p-p collisions at 7 TeV of center-of-mass energy are also studied as a function of the event charged particle multiplicity (N_{ch}), by classifying the measured tracks into two distinct classes, those belonging to jets and those belonging to the underlying event (UE) [6]. Charged tracks are measured within pseudorapidity $|\eta| < 2.4$ and transverse momenta above p_T = 0.25 GeV/c, and charged-particle jets are reconstructed above p_T = 5 GeV/c with track-only information. The distributions of jet p_T, average p_T of UE tracks and jets, jet rates, and jet shapes are studied as a function of N_{ch}. As the event-multiplicity increases, PYTHIA systematically predicts higher jet rates and harder p_T spectra than seen in the data, whereas HERWIG shows the opposite trend. Predictions without multi-parton interactions fail completely to describe the data. In the lowest-multiplicity events, the data show narrower jets than predicted by both MC generators, as shown in Figure 3.

3. Double parton scattering

Two distinct hard parton-parton scatterings in a hadron-hadron collision are termed as double parton scattering (DPS). The effective cross section or effective interaction area (σ_{eff}), the most natural link to the theories, is a measure of the size of the DPS contributions, which depend on the transverse distribution of the partons in the hadrons and their overlap in a collision. The effective cross section is defined in terms of the cross section for the two processes to occur simultaneously and those of the individual processes. If A and B are two independent processes, whose production cross-sections are σ_A and σ_B respectively, σ_{eff} can be written as:

$$\sigma_{\text{eff}} = \frac{m}{2}\frac{\sigma_A \cdot \sigma_B}{\sigma^{DPS}_{A+B}}, \tag{3.1}$$

where m is a combinatorial factor for indistinguishable ($m = 1$) and distinguishable ($m = 2$) final-states and σ^{DPS}_{A+B} is the cross-section of the two processes to occur simultaneously. Kinematics of the DPS events are quite different than the same from single parton scattering (SPS), so one can construct variables which are sensitive towards DPS. From the study of the shapes of these variables, one can extract the fraction of the DPS events in the selected event sample. This DPS fraction is an important parameter for the calculating σ_{eff}.

The measured distributions of DPS sensitive observables are corrected to particle level as a first step toward measurement of double parton scattering by the CMS collaboration for W + 2-jet process and 4-jet final state at center-of-mass energy of 7 TeV. The availability of corrected distribution will provide an opportunity to perform the extraction of DPS fraction for various MC event generators and different definitions of signal and background.

A measurement of exclusive four jets has been performed using data collected with the CMS experiment in 2010 and corresponding to 36 pb^{-1} [8]. The cross section of a final state with a pair of hard jets with $\text{p}_\text{T} > 50$ GeV/c and another pair with $\text{p}_\text{T} > 20$ GeV/c within a range in pseudorapidity of the jets $|\eta| < 2.5$ has been measured to be $\sigma(4jet) = 201 \pm 3(stat.) \pm 34(sys.)$. The cross section as a function of p_T and $|\eta|$ of each of the four jets together with the cross section as a function of correlation variables $\Delta\phi$, Δ^{rel} p_T and $\Delta\eta$ are studied and compared to several theoretical predictions. Figure 4 shows the cross section as a function of the normalised $\Delta^{\text{rel}}_{\text{hard}}$ p_T (left) and $\Delta^{\text{rel}}_{\text{soft}}$ p_T (right) compared to theoretical predictions of PYTHIA 6, HERWIG ++ and POWHEG. POWHEG is shown with and without contributions from MPI. The theoretical predictions agree essentially with the measurements. The NLO dijet calculation matched with parton showers (POWHEG) agrees with the measurement for specific tunes used in the simulation of multiparton interactions, however, the sensitivity to the parameters used in the parton shower simulation is significant.

Double parton scattering is also investigated in proton-proton collisions at a center-of-mass energy of 7 TeV using final states including one W boson decaying into a muon and neutrino plus two associated jets [2]. The data sample corresponds to an integrated luminosity of 5 fb^{-1}, collected by the CMS experiment at the LHC. Observables sensitive to the double parton scattering which can be used to discriminate against the single parton scattering process are investigated. In case of DPS, the W and two-jet system are independent of each other, while for SPS events these are highly correlated. Therefore, it is possible to define several observables which discriminate between DPS and SPS events. We investigate $\Delta\phi$ (the azimuthal angle between two jets), Δ^{rel} p_T (the relative p_T-balance between two jets) and ΔS (the azimuthal angle between the W and two-jet system).

These observables are compared with the predictions from various Monte Carlo event generators after correcting for detector effects and selection efficiency. The measured value of the

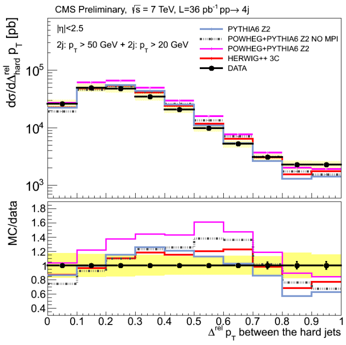

Figure 4: Cross section as a function of the normalised $\Delta^{\rm rel}_{\rm hard}$ $p_{\rm T}$ (left) and $\Delta^{\rm rel}_{\rm soft}$ $p_{\rm T}$ (right) compared to theoretical predictions of PYTHIA 6, HERWIG ++ and POWHEG. The lower panel shows the ratio of theory prediction to data.

integrated cross section for exclusive 2 jets events is 60.6 ± 6.1 pb and is found to be in agreement with the MADGRAPH which predicts 65.1 ± 3.3 pb. Figure 5 shows the comparison of data with simulations for the DPS-sensitive observables, $\Delta\phi$ (left), $\Delta^{\rm rel}$ $p_{\rm T}$ (centre), and ΔS (right). Monte Carlo predictions without MPI do not describe the measurement and the integrated value of the cross section is underestimated by 18%. The different observables have different sensitivity in separating DPS contributions from SPS. The shape of the $\Delta\phi$ distribution is almost un-affected when MPI is turned off whereas ΔS shows a deviation of 40–100% in DPS sensitive region. PYTHIA 8 underestimate the measurements by a factor 1.5–2, specially in the DPS sensitive region. This discrepancy is not due to wrong or missing contribution of DPS, but this is the effect of missing hard process contribution as PYTHIA 8 generate only $2 \rightarrow 1$ and $2 \rightarrow 2$ process. Thus, there is a significant effect of higher-order hard process in DPS sensitive regions.

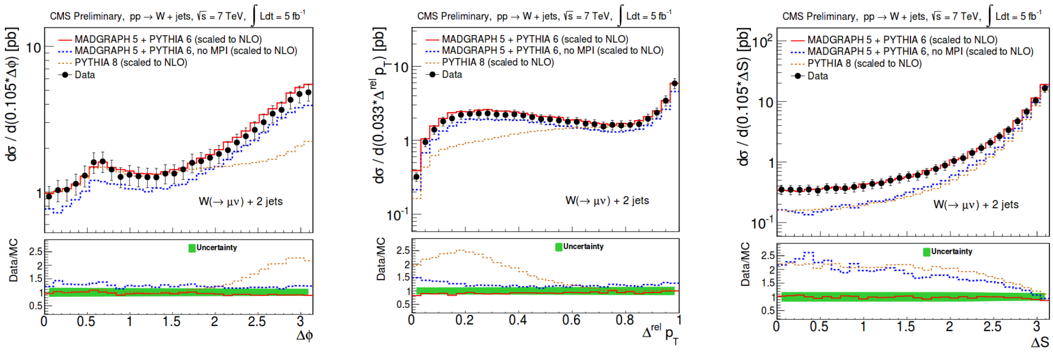

Figure 5: Comparison of data with simulations for the DPS-sensitive observables, at detector level, $\Delta\phi$ (left), $\Delta^{\rm rel}$ $p_{\rm T}$ (centre), and ΔS (right). Simulation uncertainty includes systematic due to variation of matching and factorization scales.

The ATLAS collaboration provides the first measurement of $\sigma_{\rm eff}$ alongwith corrected particle level distributions of the observables sensitive to DPS at center-of-mass energy of 7 TeV in W + 2-jet process [7]. In case of W + 2-jet events, Eq. (3.1) can be rewritten as:

$$\sigma_{\rm eff} = \frac{N_{W_{0j}} N_{2j}}{f^{(D)}_{DPS} \cdot N_{W+2j}} \cdot \frac{1}{\varepsilon_{2j}} \cdot \frac{1}{L_{2j}}, \tag{3.2}$$

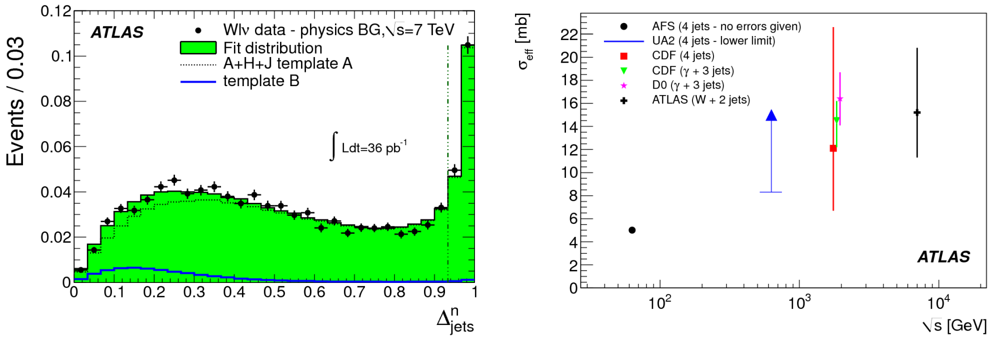

Figure 6: Fit distribution (green) for the extraction of $f_{DPS}^{(D)}$ in the background subtracted data (left) and the center-of-mass energy dependence of σ_{eff} extracted in different processes in different experiments (right) is shown.

where the fraction of events arising from double-parton interactions, $f_{DPS}^{(D)}$, has been measured through the p_T balance between the two jets and amounts to $f_{DPS}^{(D)} = 0.08 \pm 0.01$ (stat.) $\pm\, 0.02$ (sys.) for jets with transverse momentum $p_T > 20$ GeV/c and rapidity $|y| < 2.8$ The fit distribution is shown in Figure 6 (left). This corresponds to a measurement of the effective area parameter for hard double-parton interactions of $\sigma_{\text{eff}} = 15 \pm 3$ (stat.) $^{+5}_{-3}$ (sys.) mb, which is consistent with the previous measurements, as shown in Figure 6 (right) [7].

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