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Studies of the underlying-event properties and of hard double parton scattering with the ATLAS detector

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A correct modelling of the underlying event in proton-proton collisions at Large Hadron Collider is important for the proper simulation of kinematic distributions of final state objects. The ATLAS collaboration performed a study at 13 TeV, measuring the number and transverse-momentum sum of charged particles in different regions with respect to the direction of the reconstructed leading track. These measurements are sensitive to the underlying-event activity. The results are compared to predictions of several Monte Carlo generators.

Inclusive four-jet events produced in proton-proton collisions at a centre-of-mass energy of 7 TeV in the ATLAS detector have been analysed for the presence of hard double parton scattering. The fraction of events originating from hard double parton scattering has been extracted, and used to measure the effective proton cross section. Distributions sensitive to the presence of double parton scattering were unfolded to the parton level and compared to various tunes of a selected Monte Carlo simulation.

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1. Introduction

Proton-proton collisions studied at colliders are classified as elastic or inelastic, with the total pp cross section given by their sum,

$$\sigma_{\rm tot} = \sigma_{\rm el} + \sigma_{\rm inel}. \tag{1.1}$$

It is dominated by the inelastic cross section (roughly 75% at LHC centre-of-mass energies). Inelastic processes involving parton interaction at a large energy scale, characterised by the production of high-transverse-momentum (high-$p_{\rm T}$) objects (particles, jets), are of the greatest interest at the LHC experiments. Apart from high-$p_{\rm T}$ objects, a typical hard-scattering event contains extra hadronic activity, which occurs during the fragmentation and hadronization process. This activity is called *underlying event (UE)*, and, in terms of Quantum Chromodynamics (QCD), involves soft gluon emission, hard initial and final state radiation and multiple parton interaction (MPI), and is not fully calculable perturbatively. On an event-by-event basis, it is not possible to determine which object comes from the main interaction of interest, and what is coming from UE, mainly because energy scales of produced objects overlap to large extent. An underlying event thus contributes to the measurement of event properties and needs to be understood before extracting physical quantities. One of the sources of the UE, the multiple parton interactions, is enhanced with increasing centre-of-mass (cms) energy of pp collision, and the interaction of two pairs of partons at a large energy scale becomes more probable. Such processes are referred to as hard double parton scattering.

This contribution describes a measurement of the underlying event properties as a function of the transverse momentum $p_{\rm T}^{\rm lead}$ of the leading charged particle, and studies of hard double parton scattering in inclusive four-jet final states, both measured with the ATLAS detector [1] at the Large Hadron Collider.

2. Charged-particle distributions sensitive to underlying event

Charged-particle distributions were measured [2] using 13 TeV data corresponding to an integrated luminosity of 1.6 nb^{-1}. The data collected with low instantaneous luminosity were used, in order to suppress effects of the pile-up. Charged particle tracks were measured in the pseudorapidity region $|\eta| < 2.5$ and reconstructed from hits in silicon microstrip detector (SCT) and straw-tube transition radiation tracker (TRT). The distributions were measured as a function of properties of the leading charged particle. The leading charged particle was defined as the particle with highest $p_{\rm T}$, which should be larger than 1 GeV. All other charged particles used for the construction of observables, are required to have $p_{\rm T} > 500$ MeV. The events were selected using minimum bias trigger. Each event was required to have a primary vertex reconstructed with at least two tracks with $p_{\rm T} > 1$ GeV. Further cleaning requirements are documented in detail in [2] and [3]. The observables measured at the detector level (tracks) were unfolded to particle level (charged particles) using Monte Carlo (MC) models.

The study follows the established approach of investigating observables in different kinematic regions with respect to the direction of the charged particle with the largest $p_{\rm T}$ in the event: toward ($|\Delta\phi| < 60$), away ($120 < |\Delta\phi| < 180$), and transverse ($60 < |\Delta\phi| < 120$), where $|\Delta\phi|$ is the absolute difference in particle azimuthal angle between the leading charged particle and other particles in the event. The transverse region, which is by construction perpendicular to the direction of the leading track, is expected to be most sensitive to the underlying event.

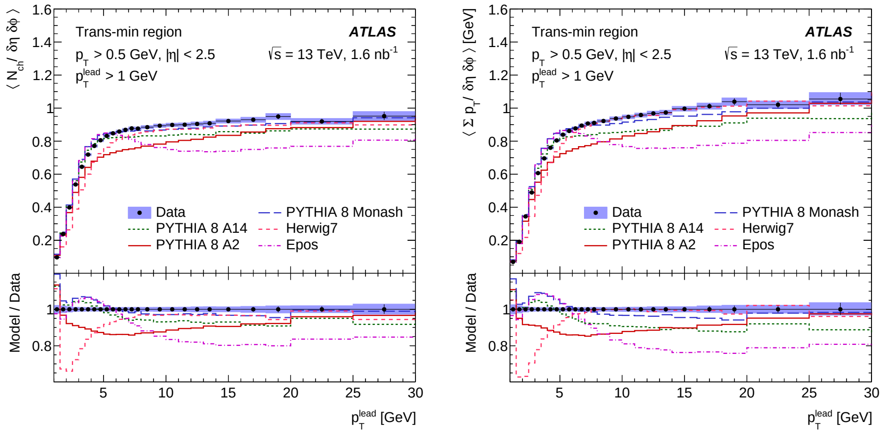

Figure 1: Mean densities of the number of charged particles (left) and of the sum of charged particles transverse momenta (right) in the trans-min region [2].

The measured distributions sensitive to the UE were compared to MC simulations based on various phenomenological approaches. The PYTHIA8 MC with different versions of parameter tunes (ATLAS tunes A2 and A14 and the Monash tune, prepared by the authors of PYTHIA), HERWIG7 and EPOS MC were used for the comparison. The MC tunes were adjusted to fit data from earlier measurements, at lower centre-of-mass energies. Comparison to the new 13 TeV measurement allows testing of these tunes in new regions of the phase space.

In Figure 1, the average values of the number of charged particles, $\langle N_{\rm ch}/\delta\eta\delta\phi\rangle$, and of the sum of tracks transverse momenta, $\langle \Sigma p_{\rm T}/\delta\eta\delta\phi\rangle$, per unit of rapidity, η, and azimuthal angle, ϕ, are shown as a function of the $p_{\rm T}^{\rm lead}$ in the trans-min region. This region is the least sensitive to the presence of the hard interaction in the event. Since it also doesn't include high-$p_{\rm T}$ contaminations of the transverse region (which are by definition the part of the trans-max region), it is expected to be most sensitive to low-energy UE component, in particular MPI. The MC expectations are spread around data, mostly underestimating the level of activity, especially at high $p_{\rm T}^{\rm lead}$. Typically various tunes of PYTHIA give better description of the data in the soft region than HERWIG. Among these tunes, the PYTHIA Monash gives the best overall description. EPOS fails in describing the quantities in the high-$p_{\rm T}^{\rm lead}$ region and predicts a shape that noticeably differs from the data, as well as other MC models. Similar effects are seen for the average number of charged particles as a function of $p_{\rm T}^{\rm lead}$. Again, PYTHIA Monash gives the best overall description, while HERWIG and EPOS fail in the low-, and high-$p_{\rm T}^{\rm lead}$ regions, respectively.

Further distributions shown in Figure 2 give a more detailed look at the UE-related parameters. The dependence of the mean track $p_{\rm T}$ on the number of charged particles in the transverse region shows that all MC models predict faster increase of $\langle p_{\rm T}\rangle$ vs N_{ch} than is observed in the data, although for EPOS the agreement is better than for other models. The right panel of Figure 2 demonstrates a clear increase of the underlying event activity with the increase of the centre-of-mass energy of the collision.

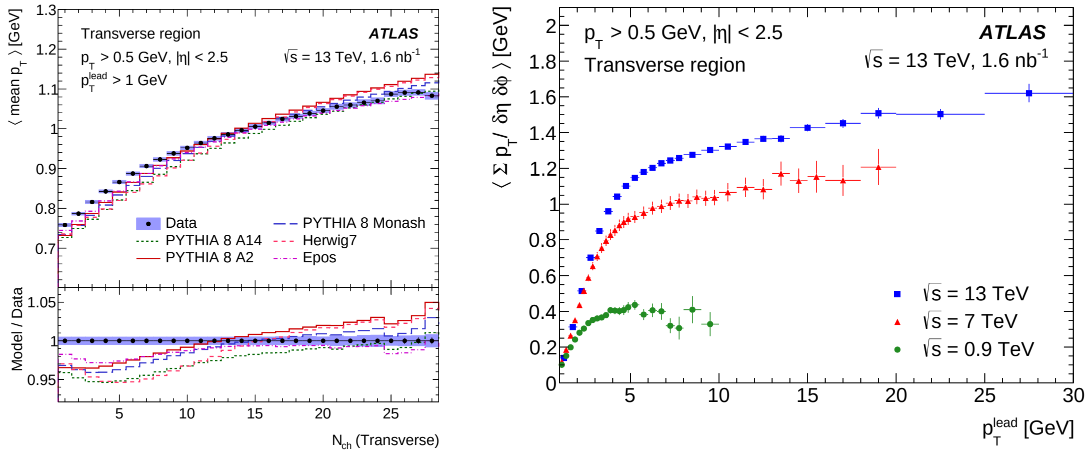

Figure 2: In the region transverse to the leading charged particle, average transverse momentum of charged particles as a function of the number of charged particles (left), and the density of the charged-particle transverse momenta sum as a function of the transverse momentum of the leading charged particle at different values of the centre-of-mass energy of pp collisions (right) [2].

Overall, the comparisons between data and MC in Figs. 1 and 2 show that the understanding of the underlying event is not complete. The new 13 TeV data bring further information for tuning the parameters of MC models and for a better understanding of the UE.

3. Hard double parton scattering

The measurement of the hard double parton scattering [4] was performed using inclusive four-jet events collected during a 7 TeV low-pileup LHC run. The selected dataset corresponds to an integrated luminosity of 37.3 pb^{-1}. The events were selected by requiring the presence of at least four jets within the pseudorapidity region $|\eta| < 4.4$ and with transverse momenta $p_{\mathrm{T}} >$ 20 GeV, among which at least one jet was required to have $p_{\mathrm{T}} > 42.5$ GeV in order to match trigger requirements. The jets were defined by the anti-k_t algorithm with radius parameter R = 0.6, where topological clusters reconstructed from calorimeter cells were used as the input.

The topology of four jets was used to estimate the contribution of hard DPS in the inclusive four-jet sample. A set of 21 variables was constructed using the jet kinematic variables. It was used as input for training an artificial neural network to distinguish between single- (SPS) and double-parton scattering (DPS) events. During DPS MC studies, it was found that in many cases three out of the four selected jets originated from one of the subscatterings while the remaining jet originated from the other subscattering. Therefore it was decided to classify events into three categories: SPS (four jets from the same parton interaction), complete DPS (cDPS, two pairs of jets from two different parton subscatterings) and semi-DPS (sDPS, three jets from one subscattering, one jet from the other subscattering). The neural network was trained to distinguish these three types of events, using event sets of defined categories for the training. Monte Carlo modelling by ALPGEN, interfaced to HERWIG and JIMMY (AHJ), was used for the simulation of multijet SPS events. DPS (cDPS and sDPS) events were modelled by overlaying two dijet data events.

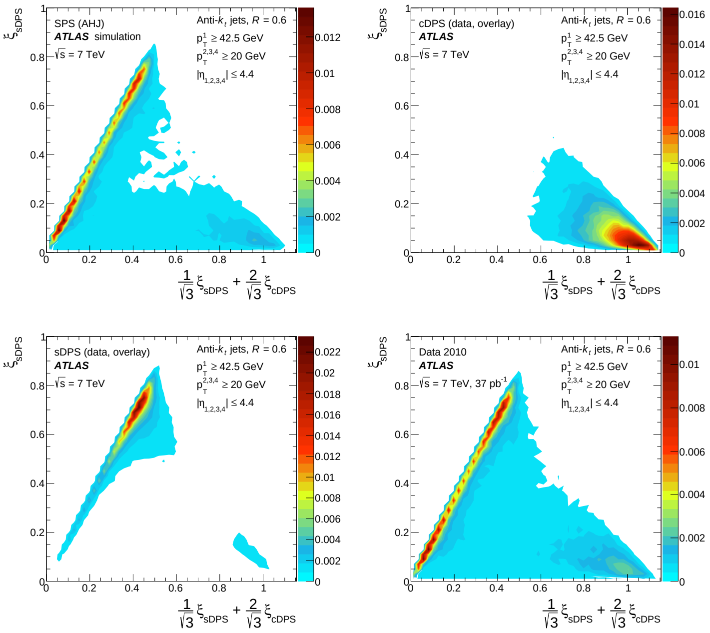

Figure 3: Distributions of the output variables of the neural network for the SPS (top left), sDPS (top right), cDPS (bottom left) processes, and data (bottom right) [4].

The distributions of the output variables of the neural network are shown in Figure 3. The output variables, which can be naively understood as probabilities for an event to be of an SPS, cDPS or sDPS type, are normalised by the condition $\xi_{\mathrm{SPS}} + \xi_{\mathrm{cDPS}} + \xi_{\mathrm{sDPS}} = 1$ and are represented by the distances between the centre of an equilateral triangle and its three sides. It is seen that the three types of processes mostly populate three vertices of the triangle and a reasonable separation between cDPS and other event classes is achieved. The separation between sDPS and SPS is less prominent. The distributions in Figure 3 were used to fit the sum of MC templates to the data. It was found that the fraction of DPS (sDPS + cDPS) events is $f_{\mathrm{DPS}} = 0.092^{+0.005}_{-0.011}(\mathrm{stat.})^{+0.033}_{-0.037}(\mathrm{syst.})$. The precision of the measurement is mostly limited by the systematic uncertainty (30%) due the jet energy scale uncertainty.

Once the fraction of DPS is known, it is possible to determine the effective proton cross section, σ_{eff} - the parameter that characterises the cross section area of the proton within which the parton interactions occur. The value of the effective cross section was extracted from the phenomenological expression for the DPS cross section,

$$\sigma_{4\mathrm{j}}^{\mathrm{DPS}} = s \cdot \frac{\sigma_{2\mathrm{j}}^{\mathrm{A}} \sigma_{2\mathrm{j}}^{\mathrm{B}}}{\sigma_{\mathrm{eff}}}, \tag{3.1}$$

where $\sigma_{2\mathrm{j}}^{\mathrm{A}}$ and $\sigma_{2\mathrm{j}}^{\mathrm{B}}$ are the SPS dijet cross sections in phase spaces labelled A and B, and s is a symmetry factor. The symmetry factor s is defined by the overlap level of the phase spaces A and B. It was determined to be $s = 0.9353 \pm 0.0003$. After measuring the needed dijet and four-jet cross sections and using the relation $\sigma_{4\mathrm{j}}^{\mathrm{DPS}} = f_{\mathrm{DPS}} \sigma_{4\mathrm{j}}$ the effective cross section was determined to be $\sigma_{\mathrm{eff}} = 14.9^{+1.2}_{-1.0}(\mathrm{stat.})^{+5.1}_{-3.8}(\mathrm{syst.})$ mb, compatible with previous measurements performed at various experiments and centre-of-mass energies (see [4] and references therein).

An example of distributions of four-jet variables sensitive to the presence of DPS, unfolded to particle level, are shown in Figure 4. Also shown in the figure is the comparison of data to the AUET1 and AUET2 tunes of the AHJ Monte Carlo. Clearly, seen are regions where one of the tunes describes better the data than the other.

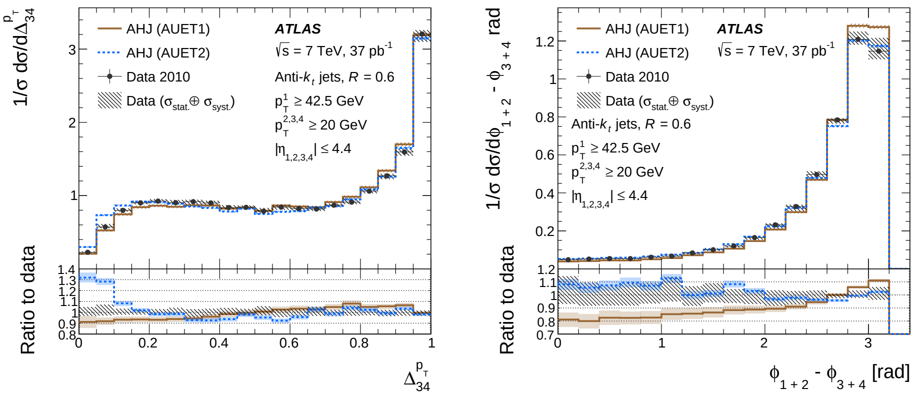

Figure 4: Particle level distributions of the ratio of the absolute value of the vector p_T sum and absolute p_T sum of third and fourth (p_T-ordered) jet in the event (left) and the azimuthal angle between two dijet systems (right). Also shown are expectations of two different tunes of the AHJ MC as indicated in the legend [4].

4. Summary

Detailed study of the underlying event properties at 13 TeV centre-of-mass energy, performed in different regions with respect to the direction of the leading charged particle, points to phase space regions where there is room for improvement of the MC models and their tunes. In particular, there is a hint that the dependence of the tune parameters on the centre-of-mass energy may need to be further improved.

Measurement of the hard double parton scattering with four-jet final state shows that at the centre-of-mass energy of 7 TeV, roughly $(9 \pm 4)\%$ of inclusive 4-jet events, within the phase space of the measurement, originate from double parton scattering, which suggests that DPS contribution may be important for measurements and searches at the LHC.

References

[1] ATLAS Collaboration, JINST **3** (2008) S08003.

[2] ATLAS Collaboration, JHEP **03** (2017) 157.

[3] ATLAS Collaboration, Phys. Lett. B **758** (2016) 67.

[4] ATLAS Collaboration JHEP **11** (2016) 110.