

Measurement of the particle production properties with the ATLAS Detector

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In this contribution, the results on soft hadron physics concerning the underlying event and Bose-Einsten correlations obtained using data collected in proton-proton collisions with the ATLAS experiment are presented.

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1 Introduction

Experiments at hadron colliders are usually aimed at study of deep inelastic processes connected with tests of the Standard model (SM) or searches for a new physics. But the deep inelastic studies or the searches need not only a good understanding of the primary short-distance hard scattering process, but also understanding of the accompanying interactions of the rest of the proton–proton (pp) collision, usually called the underlying event (UE). In addition, this contribution deals also with two particles Bose-Einstein correlations (BEC). Presence of BEC is another manifestation of the soft hadron physics that can provide us with the space-time characteristics of hadronization process. In this contribution results on the UE and BEC effects using data collected with the ATLAS detector in pp collisions at centre-of-mass-energies $\sqrt{s} = 0.9, 7$ TeV (BEC) and 13 TeV (UE) are presented.

2 Underlying event in $\sqrt{s} = 13$ TeV pp collisions

Main underlying event sources are: initial- and final-state radiation (ISR, FSR), QCD evolution of colour connections between the parton hard scattering and the beam-proton remnants and additional hard scatters in the pp collision (multiple partonic interactions (MPI)).

The measurement of UE observables with the ATLAS detector [1] was carried out using charged particles in 1.6 nb^{-1} of pp collisions at $\sqrt{s} = 13$ TeV [2]. The UE observables have been constructed from primary charged particles in the pseudorapidity range $|\eta| < 2.5$ and with particle transverse momentum $p_T > 500$ MeV. For the measurement of UE observables, the azimuthal plane of the event is segmented into several distinct regions with differing sensitivities to the UE. The azimuthal angular difference with respect to the leading (highest- p_T) charged particle, $\Delta\phi = |\phi - \phi_{\text{lead}}|$, is used to define the regions: $\Delta\phi < 60^\circ$, the towards region; $60^\circ < \Delta\phi < 120^\circ$, the transverse region; and $\Delta\phi > 120^\circ$, the away region. The towards and away regions are dominated by particle production from the hard process and are hence relatively insensitive to the softer UE. In contrast, the transverse region is more sensitive to the UE, and observables defined inside it are the primary focus of UE measurements. The observables used to study the UE, which are summarized in Table 1, are investigated with respect to the leading particle transverse momentum, p_T^{lead} , number of charged particles in the transverse region, N_{ch} , and azimuthal angle from the leading charged particle, $\Delta\phi$. The PYTHIA 8 [3, 4], HERWIG 7 [5] and EPOS [6, 7] Monte Carlo (MC) event generator models with different tunes are used either for data corrections or for comparison to the final corrected data distributions.

Unfolding to particle level. The measured UE distributions were unfolded to a particle level, i.e. the reconstructed observables were corrected for detector effects.

Symbol	Description
$\langle N_{\text{ch}}/\delta\eta\delta\phi \rangle$	Mean number of charged particles per unit $\eta - \phi$ (in radians)
$\langle \Sigma p_{\text{T}}/\delta\eta\delta\phi \rangle$	Mean scalar p_{T} sum of charged particles per unit $\eta - \phi$ (in radians)
$\langle \text{mean } p_{\text{T}} \rangle$	Mean per-event average p_{T} of charged particles (≥ 1 charged particle required)

Table 1: Definition of the measured observables.

Practically, a weighting procedure was applied to take into account inefficiencies due to the trigger selection, vertexing, and track reconstruction. Additionally, also a correction of azimuthal re-orientation of the event, based on HBOM method [8], was applied. This correction is connected with the fact that the leading charged particle can be reconstructed incorrectly and thereby identification of the towards, transverse, and away regions can differ from that at particle level.

Systematic uncertainties. The following sources of systematic uncertainties were taken into account: trigger and vertexing, track reconstruction - mainly from imperfect knowledge of the material in the inner detector, non-primary particles - from modification of track weights obtained using variations of the fit range in the tail of impact parameter distributions for different MC generators, and unfolding procedure - uncertainties associated with the HBOM unfolding at event azimuthal re-orientation correction. All these uncertainties are at the level below 1% and are added quadratically to get the total systematic uncertainty - see details in [2].

Results. Fig. 1 shows the mean densities of charged-particle multiplicity N_{ch} (top row) and Σp_{T} (bottom row) as a function of leading charged-particle p_{T} in the UE-dominated transverse region, and its per-event sub-regions trans-min, -max, and -diff. The trans-min is the most sensitive to MPI effects, while the trans-max includes both MPI and hard process contaminations. Hence, the trans-diff is the clearest measure of the hard process contaminations. The comparisons to MC models are also shown in these plots. The best performance comes from the PYTHIA 8 Monash and A2 tunes, with HERWIG 7 and PYTHIA 8 A14 both wrong by 5-10%. Study of the mean densities of N_{ch} and Σp_{T} as a function of $p_{\text{T}}^{\text{lead}}$ shows an increase in UE activity of approximately 20% when going from 7 TeV to 13 TeV pp collisions.

3 Bose-Einstein correlations.

The Bose-Einstein correlations (BEC) were studied by the ATLAS experiment in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV [9]. From theoretical point of view the BEC effect corresponds to an enhancement in two identical boson correlation function when the two particles are near in momentum space. They represent a sensitive probe of the spacetime geometry of the hadronization region and allow determination of the size and the shape of the source from which particles are emitted. In general

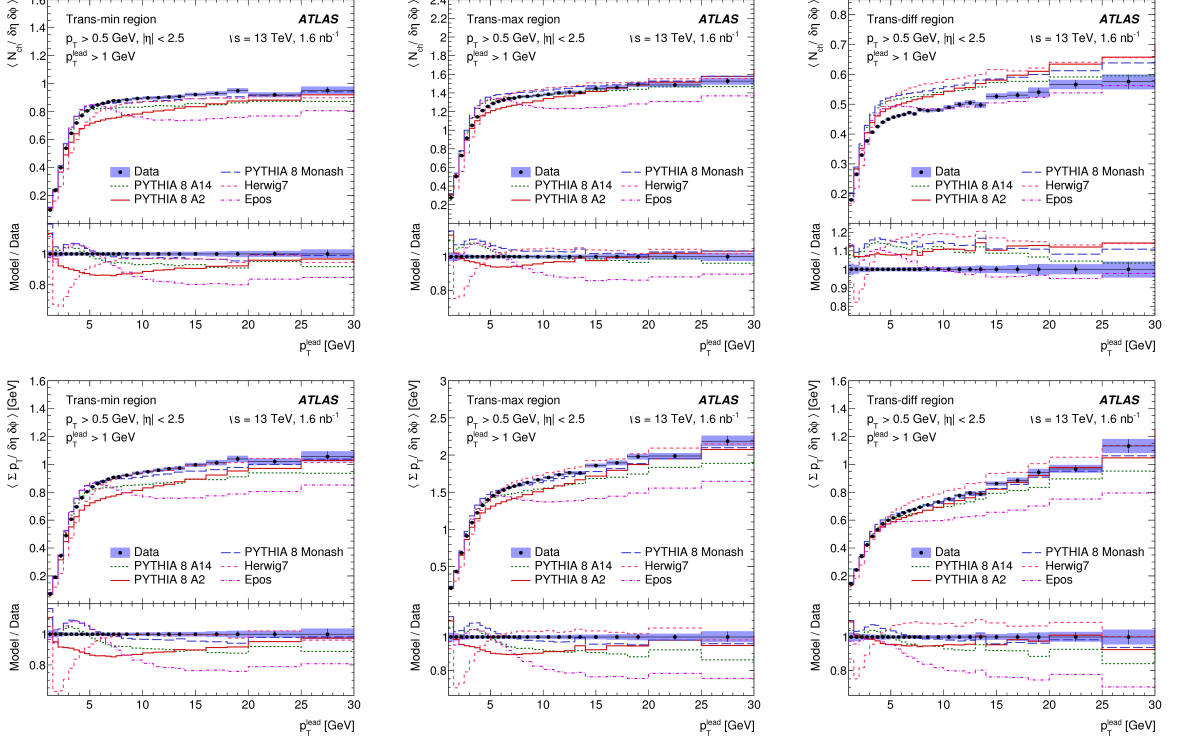


Figure 1: Mean densities of charged-particle multiplicity N_{ch} (top row) and Σp_T (bottom row) as a function of p_T^{lead} , in the trans-min (left), trans-max (middle) and trans-diff (right) azimuthal regions. The error bars represent statistical uncertainty and the blue band the total combined statistical and systematic uncertainty.

two-particle correlation function is defined as a ratio of the probability to observe simultaneously two particles with four-momenta p_1 and p_2 and a product of two one-particle distributions ($C_2(p_1, p_2) = P(p_1, p_2) / P(p_1)P(p_2)$).

The BEC effect is usually described by a function with two parameters: the effective radius parameter R and the strength parameter λ . In this study two parametrizations are used for the correlation C_2 function:

$$C_2^G(Q) = C_0 (1 + \lambda e^{-R^2 Q^2}) (1 + \epsilon Q), \quad C_2^E(Q) = C_0 (1 + \lambda e^{-RQ}) (1 + \epsilon Q), \quad (1)$$

where $Q^2 = -(p_1 - p_2)^2$ is the Lorentz invariant four-momentum difference squared of the two particles squared. The parametrization with the Gaussian and exponential form of C_2 function, which are commonly used, are used also in this study. From experimental point of view the correlation C_2 function is defined as a ratio of a signal distribution (N^{LS}) containing the BEC effect and a reference distribution (N^{ref}) which does not contain it: $C_2(Q) = N^{\text{LS}}(Q) / N^{\text{ref}}(Q)$. The signal distribution should be created by pairs of identical particles (like-sign pairs) while the reference distribution

should not contain effect of identical particles – can be created of unlike-sign pairs or artificial distribution (event mixing, opposite hemisphere, ...), see details in Ref. [9]. In this ATLAS study, instead of the C_2 function so called double ratio $R_2(Q)$ is used:

$$R_2(Q) = C_2^{\text{Data}}(Q)/C_2^{\text{MC}}(Q), \quad (2)$$

The R_2 ratio eliminates problems with energy-momentum conservation, topology, etc. in reference distributions. In addition C_2^{MC} does not contain BEC effect but it should contain all other correlations present in C_2^{Data} .

Event and object selection. Data are selected with a minimum bias trigger (≥ 1 minimum-bias trigger scintillators hits). In addition, there are requirements on primary vertex selection and on track selection: each event was required to contain a primary vertex reconstructed from at least two tracks with $p_T > 100$ MeV; the primary vertex was identified as that with the highest Σp_T^2 of its associated tracks; events containing more than 1 primary vertex with at least 4 associated tracks were removed. Each track was required to have hits in both the pixel system and the silicon microstrip detector and in the innermost pixel layer.

Track pair Q -distribution correction. Due to inefficiencies in trigger and vertex reconstruction, the measured track pair Q -distribution, $N_{\text{meas}}(Q)$, should be corrected – the true Q -distribution reads $N(Q) = N_{\text{meas}}(Q)/(\epsilon_{\text{trig}}\epsilon_{\text{vert}})$, where ϵ_{trig} (ϵ_{vert}) is the trigger (vertex) efficiency. In addition, due to Coulomb interaction in the final state, we need to remove the Coulomb effect from the measured $N_{\text{meas}}(Q)$: $N_{\text{meas}}(Q) = G(Q) \cdot N(Q)$, $G(Q) = 2\pi\kappa/(e^{2\pi\kappa} - 1)$ where κ is the Sommerfeld parameter; $\kappa > 0$ ($\kappa < 0$) for like-sign (unlike-sign) pairs [2].

Systematic uncertainties. The systematic uncertainties were studied for the parameters R and λ of double-ratio correlation function $R_2(Q)$ (see ref. [2]). The exponential fit, which gives better results, was studied. The BEC studies were performed for the full kinematic region at $\sqrt{s} = 0.9$ and 7 TeV for the minimum-bias and high-multiplicity (HM) events. The total systematic uncertainty for the hadronization radius R (factor λ) is 13% (14.8%) at 0.9 TeV and 10.7% (9.6%) at 7 TeV.

Results. The output of the R_2 correlation function analysis are the parameters R (hadronization radius) and λ (incoherence factor). Much better description was

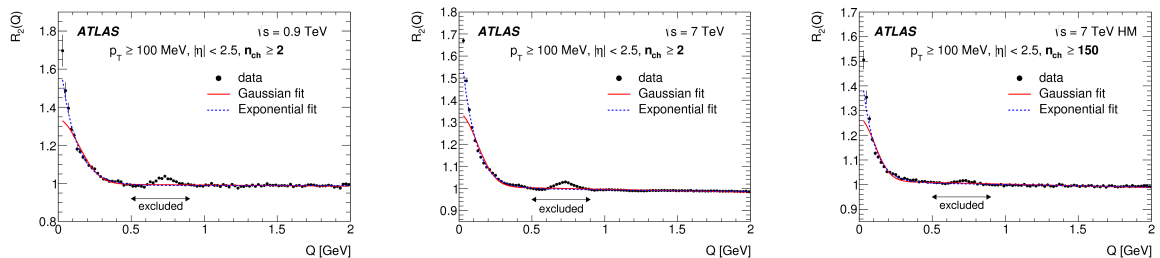


Figure 2: Correlation $R_2(Q)$ function for data taken at $\sqrt{s} = 0.9$ TeV (left), 7 TeV (middle) and 7 TeV HM (right).

obtained for the exponential fit. Fig. 2 shows the R_2 functions reconstructed at $\sqrt{s} = 0.9, 7$ TeV and 7 TeV with the HM trigger. The data are fitted with Gaussian and exponential fits. From Fig. 2 it is clear that the data are much better described by the exponential fit. The bump in resonance region is due to MC overestimation of resonances (mainly $\rho \rightarrow \pi\pi$). The region 0.5 - 0.9 GeV was excluded from the fit. The obtained values of the parameters R and λ are the following:

$R = 1.83 \pm 0.25$, $\lambda = (0.74 \pm 0.11)$ fm

at $\sqrt{s} = 0.9$ TeV for $n_{\text{ch}} \geq 2$

$R = 2.06 \pm 0.22$, $\lambda = (0.71 \pm 0.07)$ fm

at $\sqrt{s} = 7$ TeV for $n_{\text{ch}} \geq 2$

$R = 3.36 \pm 0.30$, $\lambda = (0.74 \pm 0.11)$ fm

at $\sqrt{s} = 7$ TeV for $n_{\text{ch}} \geq 150$.

Multiplicity dependence of the BEC parameters was investigated and a saturation effect for the source size R is seen for multiplicity $n_{\text{ch}} > 55$ – see Fig. 3. The BEC parameters dependences on track pair transverse momentum and on particle p_T were also studied.

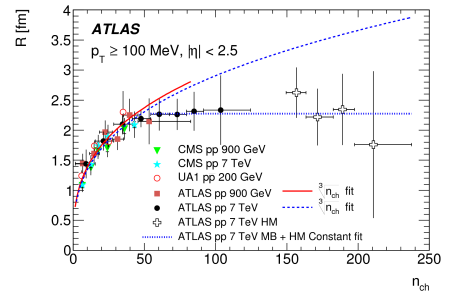


Figure 3: Hadronization radius (R) vs. multiplicity (n_{ch}).

4 Conclusions

Several distributions sensitive to UE measured by the ATLAS experiment at 13 TeV pp collisions are presented. An improvement upon previous ATLAS measurements of UE, performed at 0.9 and 7 TeV, are achieved. An increase in UE activity by $\approx 20\%$ is observed when going from 7 TeV to 13 TeV pp collisions. MC generators: for most observables the models describe the UE data to a better than 5% accuracy, but it is greater than the experimental uncertainty. BEC of the pairs of identical charged particles were measured within $|\eta| < 2.5$ and $p_T > 100$ MeV in pp collisions at 0.9 and 7 TeV. Multiplicity dependence of the BEC parameters revealed a saturation effect.

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