PROCEEDINGS OF SCIENCE

Measurements on hadron production in proton-proton collisions with the ATLAS detector

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Studies of correlated hadron production are an important source of information about the early stages of hadron formation, not yet understood from first principles. Although experimental high energy physics employs several semiclassical models of hadronization which describe the formation of jets with remarkable accuracy, correlation phenomena are more elusive. In this proceeding, we will discuss Bose-Einstein correlations measured with the ATLAS detector at the LHC and provide a unique opportunity for detailed understanding of the space-time geometry of the hadronization region.

25th International Workshop on Deep Inelastic Scattering and Related Topics
3-7 April 2017
University of Birmingham, Birmingham, UK

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https://pos.sissa.it/

PoS(DIS2017)037

ATL-PHYS-PROC-2017-260
27 November 2017

1. Introduction

Bose-Einstein correlations (BEC) represent a unique probe of the space-time geometry of the hadronization region and allow the determination of the size and shape of the source from which particles are emitted. BEC effect corresponds to an enhancement in two identical boson correlation function when the two particles are near in momentum space. It is a consequence of their wave function symmetry. Studies of the dependence of BEC on particle multiplicity and transverse momentum are of special interest. They help in the understanding of multiparticle production mechanisms.

This contribution presents results on the soft hadron physics concerning the BEC using data collected with the ATLAS experiment at the LHC in proton-proton (pp) collisions at centre-of-mass-energies $\sqrt{s} = 0.9$ and 7 TeV. Full details of this study were published in [1].

2. The ATLAS detector

The ATLAS detector is described in detail elsewhere [2]. The beam-line is surrounded by the inner detector (ID) — a tracking detector that uses silicon pixel, silicon strip and straw tube technologies and is embedded in a 2 T magnetic field. The tracking system covers the pseudorapidity range $|\eta| < 2.5$. It is surrounded by electromagnetic and hadronic calorimeters covering $|\eta| < 3.2$ which are complemented by a forward calorimeter covering $3.1 < |\eta| < 4.9$.

The Minimum Bias Trigger Scintillator (MBTS) detectors, the detectors used in the soft QCD measurements, are mounted in front of the endcap calorimeters on both sides of the interaction point at $z = \pm 3.56$ m and cover the range $2.09 < |\eta| < 3.84$.

3. Bose-Einstein correlations

The BEC effect corresponds to an enhancement in two identical boson correlation function when the two particles are near in momentum space. In general two-particle correlation function C_2 is defined as a ratio of the probability to observe simultaneously two particles with four-momenta $\mathbf{p}_1$ and $\mathbf{p}_2$ and a product of two one-particle distributions:

$$C_2(\mathbf{p}_1, \mathbf{p}_2) = \frac{P(\mathbf{p}_1, \mathbf{p}_2)}{P(\mathbf{p}_1) \cdot P(\mathbf{p}_2)} \tag{3.1}$$

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

$$C_2^{\mathrm{G}}(Q) = C_0 \left(1 + \lambda \exp\left(-R^2 Q^2\right)\right)(1 + \varepsilon Q) \tag{3.2}$$

$$C_2^{\mathrm{E}}(Q) = C_0 \left(1 + \lambda \exp\left(-RQ\right)\right)(1 + \varepsilon Q) \tag{3.3}$$

where $Q^2 = -(\mathbf{p}_1 - \mathbf{p}_2)^2$ is the Lorentz invariant four-momentum difference of the two particles squared, C_0 is a normalization constant and ε is a correction for long distance correlations.

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From experimental point of view the correlation C_2 function is defined as a ratio of a signal distribution $N^{\mathrm{LS}}(Q)$ containing the BEC effect and a reference distribution $N^{\mathrm{ref}}(Q)$ which does not contain it:

$$C_2(Q) = \frac{N^{\mathrm{LS}}(Q)}{N^{\mathrm{ref}}(Q)} \tag{3.4}$$

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. The reference distribution can be created of unlike-sign pairs or artificial distribution (event mixing, opposite hemisphere, ...). In this ATLAS study instead of the $C_2(Q)$ function so called double ratio $R_2(Q)$ is used:

$$R_2(Q) = \frac{C_2^{\mathrm{data}}(Q)}{C_2^{\mathrm{MC}}(Q)} \tag{3.5}$$

The R_2 ratio eliminates problems with energy-momentum conservation, topology, ... in reference distributions. In addition, the $C_2^{\mathrm{MC}}(Q)$ does not contain BEC but it should contain all other correlations present in $C_2^{\mathrm{data}}(Q)$.

4. Data and Monte-Carlo samples

This BEC study is based on the minimum-bias data sets and Monte-Carlo (MC) samples generated by PYTHIA 6 [3] with ATLAS MC09, DW, Perugia tunes, PHOJET 1.12.1.35 [4], and EPOS 1.99 [5]. The MC samples do not contain the BEC effect. The minimum-bias data contain 3.6×10^4 (1×10^7) events with 4.5×10^6 (2.1×10^8) tracks matching integrated luminosity 7 (190) μb^{-1} for energy 0.9 (7) TeV. The tracks and events must pass selection criteria: events pass quality criteria (all ID sub-systems on nominal condition, stable beam, defined beam spot), accept on the single-arm Minimum Bias Trigger Scintillator. The event contains at least one primary vertex with at least two good tracks with no additional vertices with 4 or more tracks. The event must contain at least two tracks passing criteria: $p_{\mathrm{T}} > 100$ MeV, $|\eta| < 2.5$, at least 1 Pixel first layer hit, 2, 4 or 6 SCT hits for $p_{\mathrm{T}} > 100, 200, 300$ MeV respectively, transverse impact parameter $|d_0| < 1.5$ mm, longitudinal impact parameter $|z_0 \sin\Theta| < 1.5$ mm and track fit χ^2 probability > 0.01 for tracks with $p_{\mathrm{T}} > 10$ GeV.

In addition of the minimum-bias data, the BEC study was first time performed using a High Multiplicity (HM) dataset at 7 TeV. The HM dataset contains 1.8×10^4 events with 2.7×10^6 selected tracks. Corresponding integrated luminosity is 12.4 nb^{-1}.

Four recent versions of MC event generators were used to provide calculation of R_2 correlation functions and for systematic studies. Large MC samples of minimum-bias and high-multiplicity events were generated with PYTHIA 6.421 using ATLAS MC09 set of optimised parameters with non-diffractive, single-diffractive and double-diffractive processes included in proportion to the cross sections predicted by the model. For the study of systematic effects, additional MC samples were produced using the PHOJET 1.12.1.35, PYTHIA with the Perugia0 tune, and the EPOS 1.99 v2965 for the HM analysis. The PHOJET program uses the Dual Parton Model for low-p_{T} physics and is interfaced to PYTHIA for the fragmentation of partons. The EPOS generator is based on an implementation of the QCD inspired Gribov-Regge field theory describing soft and hard scattering simultaneously, and relies on the same parton distribution functions as used in PYTHIA.

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The measured distributions were unfolded to the particle level correcting for detector effects. Practically, a weighting procedure was applied to take into account inefficiencies due to the trigger selection, vertexing, and track reconstruction. The weight includes the track reconstruction efficiency $\varepsilon(p_{\mathrm{T}},\eta)$, the fraction of secondary particles $f_{\mathrm{sec}}(p_{\mathrm{T}},\eta)$, The fraction of selected tracks for which the corresponding primary particles are outside the kinematic range: $f_{\mathrm{okr}}(p_{\mathrm{T}},\eta)$ and the fake tracks $f_{\mathrm{fake}}(p_{\mathrm{T}},\eta)$. The final weight applied for each track is:

$$w_i = \frac{(1 - f_{\mathrm{sec}}(p_{\mathrm{T}},\eta)) \cdot (1 - f_{\mathrm{okr}}(p_{\mathrm{T}},\eta)) \cdot (1 - f_{\mathrm{fake}}(p_{\mathrm{T}},\eta))}{\varepsilon(p_{\mathrm{T}},\eta)} \tag{4.1}$$

The effect of events lost due to the trigger (vertex) reconstruction efficiencies $\varepsilon_{\mathrm{trig}}(n)$ ($\varepsilon_{\mathrm{vert}}(n)$) was corrected using event-by-event weights $w(n) = 1/\varepsilon_{\mathrm{trig}}(n)\varepsilon_{\mathrm{vert}}(n)$ applied to each pair of particles. In addition, due to Coulomb interaction in the final state, we need to remove the Coulomb effect from the measured $N_{\mathrm{meas}}(Q)$: $N_{\mathrm{meas}}(Q) = G(Q)N(Q), G(Q) = 2\pi\upsilon/(\exp(2\pi\upsilon) - 1)$ where υ is the Sommerfeld parameter.

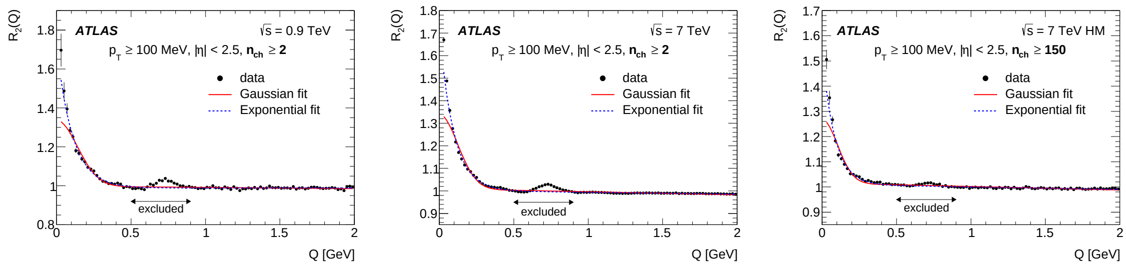
5. Systematic uncertainties

The systematic uncertainties were studied for the parameters R and λ of double-ratio correlation function $R_2(Q)$. 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 systematic uncertainties include the reconstruction efficiency uncertainties, track splitting and merging effects, deviations between MC generators, variation force of the Coulomb effect, Q-rang of fitting, bin size and exclusion interval of Q. 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.

6. Results

The output of the R_2 correlation function analysis are the parameters: R (hadronization radius) and λ (incoherence factor). Fig. 1 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 functions (3.2), (3.3).

Figure 1: Correlation $R_2(Q)$ function for data taken at $\sqrt{s} = 0.9$ TeV (left), 7 TeV (middle) and 7 TeV HM (right) [1].



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 $\rho \to \pi\pi$).

The obtained values of the parameters R and λ are:

- $\lambda = 0.74 \pm 0.11, R = 1.83 \pm 0.25$ at $\sqrt{s} = 0.9$ TeV for $n_{\mathrm{ch}} \geq 2$,
- $\lambda = 0.71 \pm 0.07, R = 2.06 \pm 0.22$ at $\sqrt{s} = 7$ TeV for $n_{\mathrm{ch}} \geq 2$,
- $\lambda = 0.52 \pm 0.06, R = 2.36 \pm 0.30$ at $\sqrt{s} = 7$ TeV for $n_{\mathrm{ch}} \geq 150$.

The statistical uncertainties for the 7 TeV sample are below 2% therefore only total uncertainties are shown. The total uncertainties include the systematic and statistical uncertainties rescaled by the factor $\sqrt{\chi^2/\mathrm{ndf}}$.

Figure 2: Multiplicity n_{ch} dependence of the parameters λ (left) and R (right) for data taken at $\sqrt{s} = 0.9$ and 7 TeV [1].

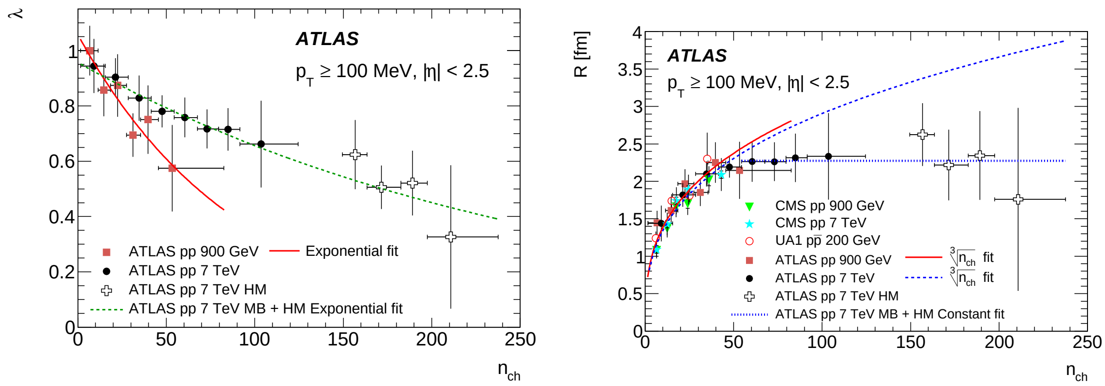


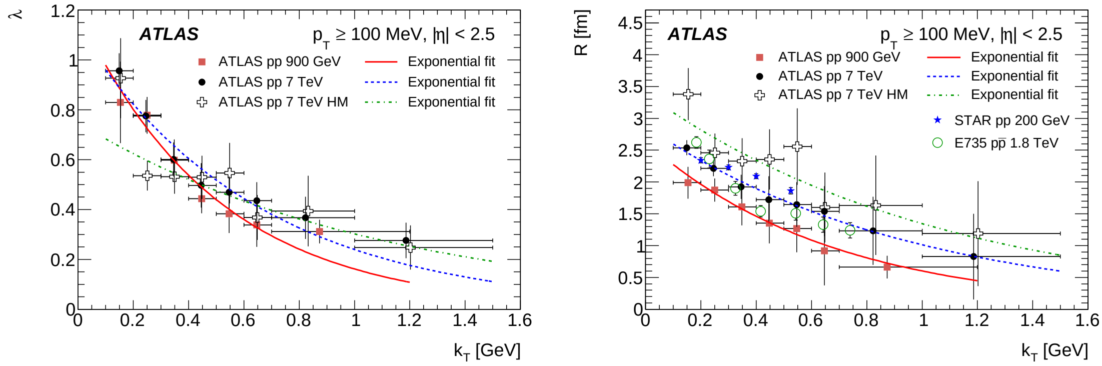
Fig. 2 shows multiplicity n_{ch} dependence of the parameters λ (left) and R (right) obtained from the exponential fit to the two-particle double-ratio correlation functions $R_2(Q)$ at $\sqrt{s} = 0.9$ and 7 TeV, compared to the equivalent measurements of the CMS [6][7] and UA1 [8] experiments. The solid and dashed curves are the results of the exponential (left) and $\sqrt[3]{n_{\mathrm{ch}}}$ for $n_{\mathrm{ch}} < 55$ (right) fits. The dotted line (right) is a result of a constant fit to minimum-bias and high-multiplicity events data at 7 TeV for $n_{\mathrm{ch}} \geq 55$. The error bars represent the quadratic sum of the statistical and systematic uncertainties.

Fig. 3 shows the k_{T} dependence of the fitted parameters λ (left) and R (right) obtained from the exponential fit to two-particle double-ratio at $\sqrt{s} = 0.9$ and 7 TeV and 7 TeV high-multiplicity events. The average transverse momentum k_{T} of the particle pairs is defined as $k_{\mathrm{T}} = |p_{\mathrm{T},1} + p_{\mathrm{T},2}|/2$. The solid, dashed and dash-dotted curves are results of the exponential fits at 0.9 TeV, 7 TeV and 7 TeV HMT, respectively. The results are compared to the corresponding measurements by the E735 experiment at Tevatron [9], and by the STAR experiment at RHIC [10]. The error bars represent the quadratic sum of the statistical and systematic uncertainties.

7. Conclusions

The Bose-Einstein correlations of the pairs of identical charged particles have been measured with $|\eta| < 2.5$ and $p_{\mathrm{T}} > 100$ MeV in pp collisions at 0.9 and 7 TeV with the ATLAS detector at the

Figure 3: The k_T dependence of the parameters λ (left) and R (right) for data taken at $\sqrt{s} = 0.9$ and 7 TeV [1].



LHC. Multiplicity dependence of the BEC was investigated up to very high multiplicities (≈ 240). A saturation effect in multiplicity dependence of the extracted BEC radius was observed at level $R = 2.28 \pm 0.32$ fm. Dependence of the BEC parameters on track pair k_T and on particle p_T was investigated. The dependence of the BEC parameters on k_T is investigated for different multiplicity regions up to high multiplicity.

Acknowledgments

This work was supported by the Slovak funding agency (The Ministry of Education, Science, Research and Sport of the Slovak Republic).

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

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