Small size sources of secondaries observed in pp-collisions via Bose-Einstein correlations with the LHC ATLAS experiment

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Abstract

Bose-Einstein correlations in proton-proton collisions at the LHC are well described by the formula with two different scales. It is shown for the first time that the pions are produced by few small size sources distributed over a much larger area in impact parameter space occupied by the interaction amplitude. The dependencies of the two radii obtained in this procedure on the charged particle density and the mean transverse momentum of the pion/hadron in the correlated pair are discussed.

1 Introduction

An effective tool to study the space-time structure of the production amplitude is to measure the Bose-Einstein correlations (BEC) between two identical particles produced in the inclusive hadron interaction, see, for example, [1]−[4]. The idea is as follows. To satisfy the Bose-Einstein statistics we have to sum up the amplitudes with all the permutations of the identical secondary bosons. After the permutation of two bosons (pions) the amplitude gets the factor \( \exp(iq r) \), where \( q = p_2 - p_1 \) is the difference between the pions momenta while \( r = r_1 - r_2 \) is the space separation between these pions. So the two particle cross section corresponding to the bare production amplitude \( M(\ldots r_1, r_2, \ldots) \) becomes

\[
\frac{E_1 E_2 d^2 \sigma}{d^3 p_1 d^3 p_2} = \frac{1}{2!} |M|^2 \langle 2 + 2 e^{i q r} \rangle = |M|^2 \langle 1 + e^{i q r} \rangle
\]

proportional to the the factor \( (1 + \langle \exp(iq r) \rangle) \). The \( \langle \ldots \rangle \) denote the averaging over \( r_1 \) and \( r_2 \). Due to fast oscillations, for a large \( q \) the mean value of this exponent vanishes after the integration over the \( r_{1,2} \)-coordinates. On the other hand \( \langle \exp(iq r) \rangle \to 1 \) for
a very low $q$, enlarging the cross section two times. So we have a peak at $q \to 0$ and
the inverse width of the peak characterizes the size of the domain from which the pions
were emitted.

To extract the effect the measured $Q$ spectrum

$$Q = \sqrt{-(p_1 - p_2)^2}. \quad (2)$$

is compared with a similar one but without BEC. $Q$ is the invariant mass of two BEC
particles considered as massless. To be precise we form the ratio

$$C_2(Q) = \frac{dN/dQ - dN_{\text{ref}}/dQ}{dN_{\text{ref}}/dQ} \quad (3)$$

where $dN/dQ$ is the two pion distribution integrated over all the variables except $Q$, and
$dN_{\text{ref}}/dQ$ is the distribution expected in a world without BEC. There are different
ways to choose $dN_{\text{ref}}/dQ$. We may measure the $\pi^+\pi^-$ $Q$-distribution for non-identical
pions; or we may change the sign of the three momentum of the second pion $\vec{p}_2 \to -\vec{p}_2$
in the calculation $Q$ value; and so on (e.g. see very first LHC CMS BEC analysis [5]).

For the conventional ‘one-radius’ fit the simplest parametrization is usually used:

$$C_2(Q) = \lambda e^{-RQ} + a + bQ. \quad (4)$$

Parameter $R = \bar{r}$ is the radius of the radiation area, $\lambda$ can be called as a strength
of BEC, and $a$ and $b$ describe a simplest background to BEC. The exponential form
approximates the case when radiation sources are uniformly distributed over the sur-
face of the sphere with radius $\bar{r}$. The values of $R$ are extracted from the data, using
one or another reasonable reference function $dN_{\text{ref}}/dQ$, are close to each other. Such
analysis of high energy proton-proton interactions at the LHC have been performed by
ATLAS [6], CMS [7] and ALICE [8]. For an analysis of lower energy data see, for
example, the review in Ref. [4].

However it was argue in [9] that the distribution of the coordinates of emission
requires two scales and secondaries produced in high energy hadron collisions may be
radiated by small size sources distributed over a much larger area of the proton-proton
interaction. To study this point experimentally we re-analyze the existing ATLAS data
on BEC at $\sqrt{s} = 0.9$ and 7 TeV fitting the $dN/dQ$ distribution by the formula with two
tables

$$C_2(Q) = \lambda e^{-R_1Q} + (1 - \lambda) e^{-R_2Q} + a + bQ. \quad (5)$$

Note that we do not introduce two parameters, $\lambda_1$ and $\lambda_2$ but in agreement with (1)
fix the sum $\lambda_1 + \lambda_2 = 1$; i.e. $\lambda_1 = \lambda$ and $\lambda_2 = 1 - \lambda$. We define $R_1$ to be the larger than
$R_2$. In such approach $R_2$ may be considered as the radius of radiation source while

1The ‘mean’ radius, $\bar{r}$, is such that $e^{-\bar{r}Q}$ approximates the value of $e^{\bar{r}Q}$ averaged over $r$. 
R1 is the distance between two sources i.e. full size of the radiation zone.

The ATLAS experiment set up and event selection are described in [6]. Here we just emphasize that it is a huge statistics available in the LHC experiments (about $3.6 \cdot 10^6$ minimum bias events in the case of ATLAS at 7 TeV corresponding to more than $10^9$ pairs of same sign secondary hadrons) which allow to reanalyze data with the two scales and to study not just the size of the radiative domain but the structure of the hadron production process.

## 2 Two scales analysis

The ‘reference’ distribution $dN_{ref}/dQ$ was obtained by changing the sign of three momentum of the second hadron $\vec{p}_2 \rightarrow -\vec{p}_2$. In our re-analysis of the minimum bias data obtained by ATLAS at 0.9 and 7 TeV were used. For the details of the experiment and events selection see [6]. Here we consider all charged hadrons as pions and select the particles with transverse momentum $p_t > 0.1$ GeV in the pseudorapidity interval $|\eta| < 2.5$ observed in the central detector. In addition, single diffraction events have been excluded by requirement that at least one particle has been detected in each endcap scintillator detector. The majority of hadrons selected are pions.

Results of global fits of data - integrated over multiplicity ($N_{ch}$) and the mean transverse momentum $k_t = |(\vec{p}_{t1} + \vec{p}_{t2})|/2$ of BEC pair - are presented on Fig 1. One scale fits are shown on Figs 1ab and Figs 1cd show two scales results.

In the traditional analysis one can see quite interesting feature - the size of a radiation zone looks as independent on beam energy 900 GeV or 7 TeV. At the same time mean multiplicities at these energies are very much different. It might be an artifact because of pure statistical quality of experimental distribution data description. Recall that the value of mean radius, $R$, is independent on beam energy but depends on $dN_{ch}/d\eta$. This effect was observed for the first time [10] by UA1 collaboration in 1989. The quality of the fits with two scales model is much better. The value of $\chi^2/ndof$ turns out to be more than order of magnitude smaller than that in conventional one scale fit (Eq 4). In two scales analysis the overall radiation zone size R1 has a strong dependence on the beam energy, while the source size R2 looks as independent on energy. The two scale model fits have rather high confidence level ($\chi^2/ndof$). However it is important to investigate fit parameters dependence on multiplicity and $k_t$.

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2This is not only difference with [6]. In the publication [6] unlike pairs distribution used as a reference with a huge influence of low mass resonance produced and the double ratio approach does not exclude this feature. Moreover, large regions in $Q$-distributions have to be excluded making impossible to study a space structure of the radiation zone.

3$dN_{ch}/d\eta$ should be used if experiments have different $\eta$ acceptance; ATLAS and CMS LHC experiments have nearly identical $\eta$ acceptance and multiplicity distribution $N_{ch}$ instead of the particle density may be used.
Figure 1: One and two radii global fit of $C_2(Q)$ distributions at $\sqrt{s} = 900$ GeV and 7 TeV.
One has to stress that there is a correlation between fits parameters. In particular, BEC strength has also a large change with multiplicity. The qualitative features of such dependencies are very similar at 900 GeV to that at 7 TeV but the statistics at 7 TeV is much larger. Therefore below we will present the detailed analysis results for 7 TeV only.

The dependencies of the radii and fit $\chi^2/ndof$ on particles multiplicity $N_{ch}$ are shown in Fig 2. One can see that overall radiation zone size have strong dependence on particles multiplicity indeed. The radiation source size is small and independent on multiplicity. The statistical quality of fits nearly perfect for the two scales analysis: $\chi^2/ndof$ corresponds to p-value of 0.3.

Figs 3 show the BEC strength dependence on multiplicity and there is evident correlation with large radii: radii increase lead to correlation decrease. Fig 3b indicates that small number of particles are generated by small sources: for $N_{ch} < 15 - 20$ the correlation strength $\lambda_2 > 0.5$, each source radiates a small number ($< 15 - 20$) of particles. High multiplicity BEC is being dominated by pairs from different sources (the corresponding correlation strength is large then .5). Recall that we have keep the sum of these two correlation strength parameters to be 1.

Fig. 4 shows the radius dependence on the mean transverse momentum $k_t = \langle |\vec{p}_t| \rangle$ of BEC pair. This is a typical picture for an interferometry measurement: the smaller a radiation wave length ($\sim 1/k_t$) the smaller objects might be seen.

The drop of R1 value in two scales analysis may indicate that two pions with relatively large $p_t$ are mainly produced from some limited size domain (group of Pomerons) which has its own velocity (flow) in transverse plain.
Figure 2: $C_2$ Fit parameters dependence on multiplicity, LHC energy 7TeV
Figure 3: Correlation strength multiplicity dependencies, LHC energy 7TeV

Figure 4: Fit results of radii dependencies on $k_t$ integrated over multiplicity, LHC energy 7TeV
3 Discussion

Following the original paper [9], where it was proposed to introduce two scales description of BEC, we will focus on the interpretation of obtained result in terms of a multi-Pomeron approach. Here the 'Pomeron' denotes the subset of Feynman diagrams which provides the interaction across a large rapidity gap, and whose cross section does not decreases with energy. This may be BFKL pomeron built of gluons [11] or the multiperipheral ladder diagrams based on the colorless hadron degrees of freedom. It was studied first by Amati et al. in [12]. In the case of general purpose Monte Carlo (MC) generators such an elementary interaction is described by some hard subprocess supplemented by the backward DGLAP evolution down to the low scale proton wave function. Each time we deal with the colorless object which in general can be decomposed in terms of the colorless (hadron) degrees of freedom.

We have to emphasize that all the process of multi-particle production can be described in terms of the colorless objects – incoming colorless hadron wave function, new colorless pairs produced from the vacuum fluctuations and the secondary color dipoles (or more complicated but the colorless objects). That is it can be reworded in terms of the colorless (hadron) degrees of freedom. Indeed, many years ago V.N. Gribov discussed the possibility to treat the Pomeron as the high energy vacuum fluctuation which contains the ln s Feynman partons including the “wee” partons with low rapidities in the wave function of a fast hadron. See [14] where the space-time structure of the process was analysed in details.

However the one Pomeron exchange is only the beginning of the story. Starting from the one Pomeron amplitude the s-channel unitarity generates the sequence of the multi-Pomeron diagrams [15]. The simplest and the most important subset of such diagrams is given by the eikonal model. It corresponds to the expansion of the elastic amplitude (calculated at fixed impact parameter $b$)

$$A(b,s) = i(1 - e^{-\Omega(b,s)/2})$$

in powers of opacity $\Omega(b,s)$. Then the multi-particle production from one or few ‘cut’ Pomerons can be calculated with the help of the AGK cutting rules [16].

Using the AGK rules it is easy to see that the mean number of ‘cut’ Pomerons $N_P = \Omega(b,s)$. In particular, for the central pp-collision at $\sqrt{s} = 7$ TeV based on the TOTEM elastic data [17] we expect $N_P = \Omega(0,s) \simeq 9$ [18]. Recall that according to AGK the particle density generated in the central rapidity interval is proportional to the number of cut Pomerons.

In the case of MC the process analogous to the multi-Pomeron exchange is generated via the Multiple Interaction (MI) option (see e.g. [19]).

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4In MC this is actually done via the hadronization algorithm, implemented, for example, as the LUND string [13].
That is in BEC we have to see at least two different radii - one corresponding to the correlation of two pions emitted from the same string/Pomeron and another one caused by the observation of two pions radiated from two different strings/Pomerons. The first radius is expected to be rather small. Its value is characterized by the value of the slope, $\alpha'_P$, of the Pomeron trajectory or by the typical scale in the DGLAP evolution chain generated by the MC. However, since it is 'measured' via the pion correlations (and a pion is not a point-like particle) it can not be much less than the pion radius $R_2^\pi \simeq 0.6 \text{ fm}$. The second radius should be larger. The space separation between different Pomerons is of the order of two proton-proton interaction radius. The last can be evaluated through the total elastic slope $B_{el}$. The value of $B_{el} \simeq 20 \text{ GeV}^{-2}$ corresponds to mean $R_p \sim 2.2 \text{ fm}$.

The results presented in Fig.2,3 are in a good agreement with the picture described above. Indeed, the small radius $R_2$ practically does not depend on the multiplicity, that is on the number of 'cut' Pomerons in an event (Fig.2a) and decreases with $\vec{k}_t$. When with $\vec{k}_t$ increasing the resolution of our "femptosoc" improves we observe $R_2 \rightarrow R_\pi$ (see Fig.3a). At a low multiplicities we deal mainly with the events caused by the one Pomeron exchange and here the contribution of the small radius component, $\lambda_2 = 1 - \lambda_1$, is large. At a larger $N_{ch}$ which corresponds to a larger number of Pomerons, $N_P$, the value of $\lambda_2$ decreases while $\lambda_1$ increases (see Fig.2b) since we have a larger combinatorial probability to observe two pions emitted from two different Pomerons. The value of large radius $R_1$ increases with multiplicity – selecting the events with a larger $N_{ch}$ i.e. - a larger $N_P$ we consider the configurations with a larger area where the wave functions of two incoming protons overlaps. That is the Pomerons are distributed over a larger area. For a low $\vec{k}_t$ the value of $R_1$ does not depends on $\vec{k}_t$ but for a larger $\vec{k}_t$ it starts to decrease (Fig.3b) – The events with a high transverse momenta (scales) are mainly concentrated in the central part of the collision area.

## 4 Conclusion

We have shown that the observed $Q$-distribution of identical pions is much better described by the expression (5) with two different radii. This may indicate that secondaries are produced by some small size sources distributed over a much larger domain (of order of the whole radiation size). These sources may be considered as the individual Pomerons or as the minijets or the color strings between the jets which emit the 'spray' of hadrons.

At last, not least, the value of the radius of a small size object is independent on LHC energy, i.e. this object is a universal one. For a low particle density $dN_{ch}/d\eta < 2$ the radiation area is less than the proton size - that is we deal with only one hot spot.

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8Of course distribution over the number of Pomerons is washed out due to the fluctuations in particle densities produced by the individual Pomerons.
In terms of the Quark-Gluon-Plasma/Liquid, that is in terms of collective degrees of freedom, our observation may be treated/interpreted as a hint in favor of scenario where the hadronization of quark-gluon system passes via the formation of a number of relatively small size colorless bubbles/drops which finally produce the hadrons.

Note however that due to a small size (R2) of radiative sources the probability of this "hot spots" to overlap is rather small even in the case of a heavy ions collision; while the energy density inside each small size "hot spot" is large.

4.1 Outlook

Having the particle identification it would be interesting to perform the two scales BEC fit for the kaons and/or the protons – are the space-time structure (BEC) of the production mechanism observed in this case is the same as that for the pions?

Next step is to study the two scales BEC in events with high $E_T$ jet and/or W/Z bosons.

Finally, looking for the two scales BEC in the events with a Large Rapidity Gap (LRG) we expect to see a much smaller contribution of the large size component. Indeed, in the case of a Pomeron interpretation observing the LRG we select the events without an additional Pomeron exchange across the gap region. That is the probability of a Multiple Interaction is suppressed and in the first approximation one may say that the large size component should be absent. To be more precise we may observe some large size contribution corresponding to the multi-Pomeron exchange in the Pomeron-proton collision. However the probability of the multi-Pomeron interactions in Pomeron-proton collisions should be smaller due to a smaller Pomeron-proton cross section.

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