The Compact Muon Solenoid Experiment

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Multidimensional and one-dimensional quantum-statistical (Bose-Einstein) correlations are measured in proton-proton collisions at 0.9, 2.76 and 7 TeV, in proton-lead collisions at 5.02 TeV/nucleon pair and peripheral lead-lead collisions at 2.76 TeV/nucleon pair center-of-mass energy with the CMS detector at the LHC. The correlation functions are extracted in terms of different components of the relative momentum of the pair, in order to investigate the extension of the emission source in different directions. The results are presented for different intervals of transverse pair momentum, k_T , and charged particle multiplicity of the collision, N_{tracks} , as well as for their integrated values. Besides inclusive charged particles, charged pions and kaons, identified via their energy loss in the silicon tracker detector, can also be correlated. The extracted source radii increase with increasing multiplicity, and decreases with increasing k_T . The results open the possibility to study scaling and factorization properties of these radii as a function of multiplicity, k_T , colliding system size and center-of-mass energy.

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Bose-Einstein correlation measurements at CMS

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Abstract

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Keywords: Identified particle, Bose-Einstein correlations, pp, pPb, and PbPb collisions at the LHC

1. Introduction

Bose-Einstein correlations (BEC) of identical-pion pairs resulting in an enhancement at low relative momentum was first observed in $p\bar{p}$ collisions by Goldhaber, Goldhaber, Lee, and Pais more than 50 years ago [1]. This technique, also known as Hanbury Brown–Twiss (HBT) interferometry, and femtoscopy, has been extensively used to probe the space- time structure of the created system. At the CERN Large Hadron Collider (LHC), BEC were first observed by the CMS (Compact Muon Solenoid) experiment in pp collisions at $\sqrt{s_{NN}} = 0.9, 2.36$ and 7 TeV using unidentified charged particles [2, 3]. A systematic study of identified particle femtosopic measurements in pp collisions at $\sqrt{s} = 0.9, 2.76$, and 7 TeV, pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and peripheral PbPb collisions $\sqrt{s_{NN}} = 2.76$ TeV from the CMS Collaboration are presented here. The CMS detector is described in detail in Ref. [4] and consists of a superconducting solenoid of 6 m internal diameter providing a uniform magnetic field of 3.8 T. The inner tracking system is the most relevant detector for the present analysis, which consist of silicon pixels and strips covering the pseudorapidity range $|\eta| < 2.4$. The event selection, the reconstruction of charged particles in the silicon tracker, the procedure of finding interaction vertices, as well as pile-up subtraction are identical to the ones used in the previous CMS papers [5, 6] on the spectra of identified charged hadrons.

2. Bose-Einstein Correlations

Experimentally, the two-particle correlation function $C_2(\vec{q})$ of identical bosons is defined as the ratio

¹ A list of members of the CMS Collaboration and acknowledgements can be found at the end of this issue.

$$C_2(\vec{q}) = \frac{N_{\text{signal}}(\vec{q})}{N_{\text{bckgnd}}(\vec{q})}, \quad (1)$$

where $N_{\text{signal}}(\vec{q})$ is the measured distribution of pair momentum difference $\vec{q} = \vec{p}_2 - \vec{p}_1$ in the same event, and $N_{\text{bckgnd}}(\vec{q})$ is a similar distribution formed by using pairs of particles from different events. This correlation function is sensitive to several interesting physics effects: the quantum statistics obeyed by the pairs being studied, the quantum field configuration (thermal, coherent, etc.), the source geometry, the source dynamics (space momentum correlations, flow, jets, etc.), and final state interactions FSI (Coulomb, strong, etc.). The broader goal of HBT studies is to isolate the quantum-statistical effects from those other ones by understanding these individual effects in various systems under different conditions.

The Coulomb FSI affect the behavior of the spectra of two charged particles at very small relative momenta. It is often taken into account by means of the Coulomb factor, the modulus squared of the non-relativistic Coulomb wave function at zero distance given by $G(\eta) = |\Psi(0)|^2 = 2\pi\eta/(\exp(2\pi\eta) - 1)$, where $\eta = \pm\alpha m/q_{\text{inv}}$ is the Landau parameter, α is the fine-structure constant, m is the mass of the particle. The positive sign is used for repulsion (like-sign, ++ or --), and the negative sign for attraction (unlike-sign, +-). This procedure overcorrects the correlation function in heavy ion collisions and will have to be modified. The full Coulomb correction formula is used as described in [7].

After removing the trivial phase space effect, another contribution which strongly contaminate the extraction of the HBT radius parameters and of the intercept parameter originates from mini-jets, and multi-body decays of resonances, here denominated simply as cluster contribution. An important element in both mini-jet and multi-body resonance decays is the conservation of electric charge that results in a stronger correlation for unlike-sign pairs than for like-sign pairs. Hence the cluster contribution is expected to be also present for like-sign pairs, with similar shape but a with a smaller amplitude. The form of the cluster-related contribution obtained from unlike-sign pairs, but now multiplied by a relative amplitude is used to fit the like-sign correlation as described in [7].

After disentangling the Bose-Einstein part C_{BE} from the correlation function C_2 , C_{BE} can ideally be related to the Fourier transform of the source density distribution $f(r)$. There are several possible functional forms that are commonly used to fit C_{BE} the data *e.g.* Gaussian, exponential and Lévy type of distributions among others. The Lévy distributions with index of stability $0 < \alpha \leq 2$, is used in this analysis to fit the Bose-Einstein correlation function with index of stability $\alpha = 1$, (the Gaussian would correspond to the special case of $\alpha = 2$). The forms used for fitting one-dimensional ($q_{\text{inv}} = \sqrt{-q^\mu q_\mu}$), two-dimensional (q_l, q_t), and three-dimensional (q_l, q_o, q_s) correlation functions are

$$C_{BE}(q_{\text{inv}}) = 1 + \lambda \exp[-q_{\text{inv}}R], \quad (2)$$

$$C_{BE}(q_l, q_t) = 1 + \lambda \exp\left[-\sqrt{(q_l R_l)^2 + (q_t R_t)^2}\right], \quad (3)$$

$$C_{BE}(q_l, q_o, q_s) = 1 + \lambda \exp\left[-\sqrt{(q_l R_l)^2 + (q_o R_o)^2 + (q_s R_s)^2}\right], \quad (4)$$

denominated as *stretched exponential* [8]. In Eq. (3) and (4) the system in multi-dimensions is considered as an ellipsoid with radii R_l, R_t (in 2-D), or R_l, R_o , and R_s (in 3-D). Here q_o is the component of the transverse relative momentum q_t parallel to k_T , while q_s is the component of q_t perpendicular to k_T , where $k_T = |p_{T1} + p_{T2}|$. The fit parameters are commonly denominated as chaoticity parameter λ , and lengths of homogeneity (R), of the particle emitting source.

In present analysis, the systematic uncertainties are dominated by two sources: the way the background distribution is constructed using the mixed event technique, and the uncertainties of the amplitude of the cluster contribution for like-sign pairs with respect to those for unlike-sign. Another source of systematics is from the effect of multiply reconstructed particles and misidentified photon conversions, which is avoided by excluding the low q region (< 0.02 GeV/c) from the fits. The systematic uncertainties from various sources were added in quadrature. For plotting the results of the fits, the statistical uncertainties are indicated by vertical error bars, while the combined systematic uncertainties are given by open boxes.

Figure 1. The dependence of the radius parameters on the charge particle multiplicity of the collision, N_{ch} , is shown for identified pion correlations for one- dimensional (top left), two- dimensional (middle, R_l - open symbols, R_t - closed symbols) and three- dimensional cases (top right, bottom left, middle) for pp collision at $\sqrt{s} = 0.9, 2.76, 7$ TeV, pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV and peripheral PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The N_{ch} dependence of the one-dimensional kaon case (bottom right) is also shown

3. Results and Summary

The one-, two-, and three-dimensional radius fit parameters measured in Local Co-Moving Frame (LCMS, where the longitudinal momentum of the pair vanishes) for pions and kaons for various center-of-mass energies pp, pPb, and peripheral PbPb collisions are shown in Fig. 1 as a function of the charged-particle multiplicity N_{tracks} of the event for all k_T . The extracted *stretched exponential* radii fit parameters are in the range 1 to 5 fm for pions, which increases with increasing multiplicity for all systems and center-of-mass energies studied, in one-, two-, and three- dimensions, as shown in Fig. 1. In general, for two- and three- dimensions, there is an ordering, $R_l > R_t$, and $R_l > R_s > R_o$, in the pp and pPb cases suggesting that the corresponding sources are elongated in the beam direction. In the case of peripheral PbPb the source is quite symmetric, and shows a slightly different multiplicity dependence, with largest differences for R_l and R_o , while there is a good agreement for R_l and R_s . The most visible divergence among pp, pPb and PbPb results is seen in R_o which could point to different lifetimes of the created systems in those collisions.

The kaon radius fit parameters also show some increase with multiplicity, but increase with multiplicity is small compared to the pions. Longer lived resonances and re-scattering may play a role here. The pion radius parameters decrease with increasing k_T and increase with multiplicity in pPb collision for the three-dimensional case, as shown in Fig. 2. A similar trend is observed for one- and two- dimensional measurements in all systems. The similarities observed in the multiplicity dependence may point to a common critical hadron density in pp, pPb, and peripheral PbPb collisions, since the correlation technique measures the characteristic size of the system near the time of the last interactions.

The dependence of the radius parameters on the multiplicity and on k_T factorizes and can be fitted with a product of two independent functions of multiplicity and k_T , as

$$R_{param}(N_{tracks}, k_T) = [a^2 + (bN_{tracks}^\beta)^2]^{1/2} \cdot (0.2\text{GeV}/c/k_T)^\gamma \quad (5)$$

where the minimal radius a and the exponent γ of k_T are kept the same for a given radius component, for all collision types. This choice of parametrization is based on previous results [9]. The minimal radius could be connected to the

 Figure 2. k_T dependence of the three-dimensional radius parameters are shown for pPb collisions at 5.02 TeV.

 Figure 3. Left: Radius fit parameters as a function of N_{tracks} scaled to $k_T = 0.45$ GeV/c with help of the parametrization R_{param} (Eq.5). Right: ratio of the radius parameter and the value of the parametrization R_{param} (Eq.5) at $k_T = 0.45$ GeV/c as a function k_T .

size of the proton, while the power-law dependence on N_{tracks} is often attributed to the freeze-out density of hadrons. The ratio of radius parameter and the value of the above parametrization at $k_T = 0.45$ GeV/c as a function multiplicity (N_{tracks}) and k_T is shown in Fig. 3 for one-dimensional case. The points were shifted to left and to right with respect to the center of the k_T bin for better visibility. The degree to which these points lined up in Fig. 3 with each other vertically at each N_{tracks} (left plot) (k_T , right plot) shows how well the parameterization vs k_T (left plot) (N_{tracks} , right plot) works and the degree to which these points agree with the solid line at each N_{tracks} (left plot) (k_T , right plot) shows how well the parameterization vs N_{tracks} (left plot) (k_T , right plot) works. Similar results are obtained for the two - and three- dimensional case but with different slopes and are also shown in [7].

References

- [1] G. Goldhaber, S. Goldhaber, W. Lee, and A. Pais, Phys. Rev. 120 (1960) 300.
- [2] CMS Collaboration, “The CMS Experiment at the CERN LHC”, JINST 3 (2008) S08004.
- [3] CMS Collaboration, “First Measurement of Bose-Einstein Correlations in proton-proton Collisions at $\sqrt{s} = 0.9$ and 2.36 TeV at the LHC”, Phys. Rev. Lett. 105 (2010) 032001.
- [4] CMS Collaboration, “Measurement of Bose-Einstein Correlations in pp Collisions at $\sqrt{s} = 0.9$ and 7 TeV”, JHEP 05 (2011) 029.
- [5] CMS Collaboration, “Study of the inclusive production of charged pions, kaons, and protons in pp collisions at $\sqrt{s} = 0.9, 2.76$, and 7 TeV”, Eur. Phys. J. C 72 (2012) 2164.
- [6] CMS Collaboration, “Study of the production of charged pions, kaons, and protons in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV”, EPJC 74 (2014) 2847.
- [7] CMS Collaboration, “Femtoscopy with identified charged hadrons in pp, pPb, and peripheral PbPb collisions at LHC energies”, CMS Physics Analysis Summary HIN-14-013, CMS(2014).
- [8] T. Csorgo, S. Hegyi, and W. Zajc, “Bose-Einstein correlations for Lévy stable source distributions, Eur. Phys. J. C 36 (2004) 6778.
- [9] M. Lisa, “Femtoscopy in heavy ion collisions: Wherefore, whence, and whither?, AIP Conf. Proc. 828 (2006) 226237.