Measurement of Bose-Einstein correlations in the first LHC-CMS data

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Bose–Einstein correlations have been measured using samples of proton-proton collisions at 0.9 and 2.36 TeV center-of-mass energies, recorded by the CMS experiment at the Large Hadron Collider. The signal is observed in the form of an enhancement of pairs of same-sign charged particles with small relative four-momentum. The size of the correlated particle emission region is seen to increase significantly with the particle multiplicity of the event.

1 Introduction

In particle collisions, the space-time structure of the hadronization source can be studied using measurements of Bose–Einstein correlations (BEC) between pairs of identical bosons. Since the first observation of BEC fifty years ago, a number of measurements have been made by several experiments [1]. The first measurement in pp collisions at 0.9 TeV and the highest energy measurement at 2.36 TeV is reported. Constructive interference affects the joint probability for the emission of a pair of identical bosons with four-momenta p_1 and p_2. Experimentally, the proximity in phase space between final-state particles is quantified by the Lorentz-invariant quantity $Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M^2 - 4m_\pi^2}$, where M is the invariant mass of the two particles, assumed to be pions with mass m_π. The BEC effect is observed as an enhancement at low Q of the ratio of the Q distributions for pairs of identical particles in the same event, and for pairs of particles in a reference sample that by construction is expected to include no BEC effect:

$$R(Q) = (\mathrm{d}N/\mathrm{d}Q)/(\mathrm{d}N_{\mathrm{ref}}/\mathrm{d}Q), \tag{1}$$

which is then fitted with the parameterization

$$R(Q) = C\,[1 + \lambda\Omega(Qr)] \cdot (1 + \delta Q). \tag{2}$$

In a static model of particle sources, $\Omega(Qr)$ is the Fourier transform of the spatial distribution of the emission region of bosons with overlapping wave functions, characterized by an effective size r. It is often parameterized as an exponential function, $\Omega(Qr) = e^{-Qr}$, or with a Gaussian form, $\Omega(Qr) = e^{-(Qr)^2}$ [2]. The parameter λ reflects the BEC strength for incoherent boson emission from independent sources, δ accounts for long-range momentum correlations, and C is a normalization factor.

2 Data selection, reference samples and results

The data used for the present analysis were collected by the CMS experiment [3] in December 2009 from proton-proton collisions at center-of-mass energies of 0.9 and 2.36 TeV. The events were selected by requiring activity in both beam scintillator counters [4]. A minimum-bias Monte Carlo (MC) sample was generated using PYTHIA (with D6T tune) [5] followed by full detector simulation based on the Geant4 program [6]. Additional PYTHIA MC samples were generated to simulate BEC effects with both Gaussian and exponential forms of $\Omega(Qr)$. Charged particles are required to have $p_T > 200$ MeV, which is sufficient for particles emitted from the interaction region to cross all three barrel layers of the pixel detector and ensure good two-track separation. Their pseudorapidity is required to satisfy $|\eta_{\rm track}| < 2.4$. To ensure high purity of the primary track selection, the trajectories are required to be reconstructed in fits with more than five degrees of freedom (dof) and $\chi^2/N_{\rm dof} < 5.0$. The transverse impact parameter with respect to the collision point is required to satisfy $|d_{xy}| < 0.15$ cm. The innermost measured point of the track must be less than 20 cm from the beam axis, in order to reduce electrons and positrons from photon conversions in the detector material and secondary particles from the decay of long-lived hadrons. In total 270 472 (13 548) events were selected at 0.9 (2.36) TeV center-of-mass energy. All pairs of same-charge particles with Q between 0.02 and 2 GeV are used for the measurement. The lower limit is chosen to avoid cases of tracks that are duplicated or not well separated. Coulomb interactions between charged particles modify their relative momentum distribution. This effect, which differs for pairs with same charge (repulsion) and opposite charge (attraction), is corrected for by using Gamow factors [7]. As a cross-check, the enhancement in the production of opposite-charge particle pairs with small values of Q is measured in the data and is found to be reproduced by the Gamow factors to within ±15%. Different methods are designed to pair uncorrelated charged particles and to define reference samples used to extract the distribution in the denominator of Eq. (1). *Opposite-charge pairs*: this data set is a natural choice but contains resonances (η, ρ, ...) which are not present in the same-charge combinations. *Opposite-hemisphere pairs*: tracks are paired after inverting in space the three-momentum of one of the two particles: $(E, \vec{p}) \rightarrow (E, -\vec{p})$; this procedure is applied to pairs with same and opposite charges. *Rotated particles*: particle pairs are constructed after inverting the x and y components of the three-momentum of one of the two particles: $(p_x, p_y, p_z) \rightarrow (-p_x, -p_y, p_z)$. *Pairs from mixed events*: particles from different events are combined with the following methods: i) events are mixed at random; ii) events with similar charged particle multiplicity in the same η regions are selected; iii) events with an invariant mass of all charged particles similar to that of the signal are used to form the pairs. As an example, the ratios $R(Q)$ obtained with the opposite-hemisphere, same-charge reference samples are shown in Fig. 1 (left) both for data and simulation without BEC. A significant excess at small values of Q is observed in the data. Additional details are given in [8]. In order to reduce the bias due to the construction of the reference samples, a double ratio $\mathcal{R}$ is defined:

$$\mathcal{R}(Q) = \frac{R}{R_{\rm MC}} = \left(\frac{{\rm d}N/{\rm d}Q}{{\rm d}N_{\rm ref}/{\rm d}Q}\right) \Big/ \left(\frac{{\rm d}N_{\rm MC}/{\rm d}Q}{{\rm d}N_{\rm MC,ref}/{\rm d}Q}\right), \tag{3}$$

where the subscripts “MC” and “MC,ref” refer to the corresponding distributions from the MC simulated data generated without BEC effects. The results of fits of $\mathcal{R}(Q)$ based on the parameterization of Eq. (2) with $\Omega(Qr) = e^{-Qr}$ are given in Table 1, both for 0.9 and 2.36 TeV data. In the opposite-charge sample, the region with $0.6 < Q < 0.9$ GeV, contains a contribution of $\rho \rightarrow \pi^+\pi^-$ decays not well described by the MC. This region is therefore

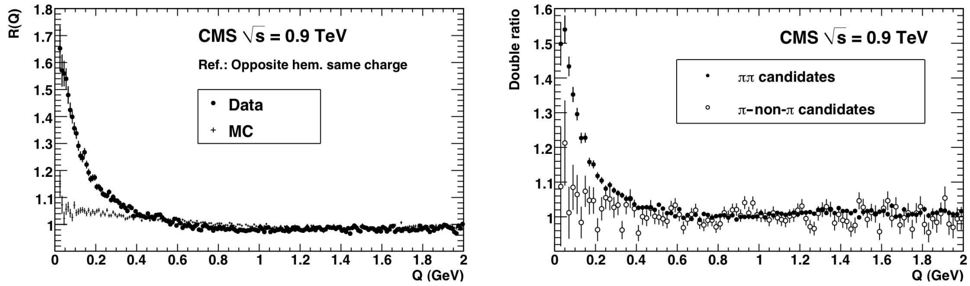

Figure 1: (Left) Ratios $R(Q)$ obtained with the opposite-hemisphere, same-charge reference samples for data (dots) and MC with no BEC effect (crosses). (Right) Double ratios $\mathcal{R}(Q)$ for the same data and reference samples using a $\mathrm{d}E/\mathrm{d}x$ measurement (dots for π-π pairs and open circles for π–not-π pairs).

excluded from the fits with this reference sample and also with the combined sample defined below. As a cross-check, the $\mathrm{d}E/\mathrm{d}x$ measurements of particles in the tracker are used to select a sample enriched in $\pi\pi$ pairs and another sample enriched in π–not-π pairs (Figure 1 right). Enhancement at small Q values is observed only in the first sample. As none of the definitions of the reference samples is preferable *a priori*, an additional, "combined" double ratio $\mathcal{R}^{\mathrm{comb}}$ is formed, where the data and MC distributions are obtained by summing the Q distributions of the seven corresponding reference samples. The distributions of $\mathcal{R}^{\mathrm{comb}}$ for 0.9 and 2.36 TeV data are shown in Fig. 2 (left), and the values of the fit parameters are given in Table 1. The leading source of systematic uncertainty on the measurements arises from the fact that none of the reference samples is expected to give a perfect description of the Q distribution in the absence of BEC. The corresponding contribution to the systematic error is computed as the r.m.s. spread between the results obtained for the different samples, i.e., $\pm 7\%$ for λ and $\pm 12\%$ for r. The systematic uncertainty related to the Coulomb corrections is computed by propagating the measured $\pm 15\%$ agreement margin, resulting in $\pm 2.8\%$ variation for λ and $\pm 0.8\%$ for r. For the 2.36 TeV data the same relative systematic uncertainties as for the 0.9 TeV results are used, in view of the reduced size of the sample and the larger statistical uncertainties of the fit results. The BEC parameters measured with the combined reference sample are: $\lambda = 0.625 \pm 0.021\,(\mathrm{stat.}) \pm 0.046\,(\mathrm{syst.})$ and $r = 1.59 \pm 0.05\,(\mathrm{stat.}) \pm 0.19\,(\mathrm{syst.})\,\mathrm{fm}$ at 0.9 TeV; $\lambda = 0.663 \pm 0.073\,(\mathrm{stat.}) \pm 0.048\,(\mathrm{syst.})$ and $r = 1.99 \pm 0.18\,(\mathrm{stat.}) \pm 0.24\,(\mathrm{syst.})\,\mathrm{fm}$ at 2.36 TeV. The fit parameters for the combined reference sample are shown in Fig. 2 (right) as a function of the track multiplicity for the 0.9 TeV data.

3 Conclusions

In summary, Bose–Einstein correlations have been measured for the first time at the LHC by the CMS experiment in pp collisions at 0.9 and 2.36 TeV center-of-mass energies. The main systematic affecting BEC measurements was studied through the use of multiple reference samples to extract the signal. For all of them an exponential shape fits the data significantly better than a Gaussian shape. An increase of the effective size of the emission region with charged-particle multiplicity in the event has been observed.

Table 1: Results of fits to the double ratios $\mathcal{R}(Q)$ for several reference samples, using the parameterization of Eq. (2) with the exponential form, for 0.9 TeV data (left) and 2.36 TeV data (right). Errors are statistical only.

	Results of fits to 0.9 TeV data			Results of fits to 2.36 TeV data		
Reference sample	λ	r (fm)	δ (10^{-3} GeV^{-1})	λ	r (fm)	δ (10^{-3} GeV^{-1})
Opposite charge	0.56 ± 0.03	1.46 ± 0.06	-4 ± 2	0.53 ± 0.08	1.65 ± 0.23	-16 ± 6
Opposite hem. same ch.	0.63 ± 0.03	1.50 ± 0.06	11 ± 2	0.68 ± 0.11	1.95 ± 0.24	15 ± 5
Opposite hem. opp. ch.	0.59 ± 0.03	1.42 ± 0.06	13 ± 2	0.70 ± 0.11	2.02 ± 0.23	24 ± 5
Rotated	0.68 ± 0.02	1.29 ± 0.04	58 ± 3	0.61 ± 0.07	1.49 ± 0.15	58 ± 6
Mixed evts. (random)	0.62 ± 0.04	1.85 ± 0.09	-20 ± 2	0.74 ± 0.15	2.78 ± 0.36	-40 ± 4
Mixed evts. (same mult.)	0.66 ± 0.03	1.72 ± 0.06	11 ± 2	0.63 ± 0.10	2.01 ± 0.23	20 ± 5
Mixed evts. (same mass)	0.60 ± 0.03	1.59 ± 0.06	14 ± 2	0.73 ± 0.11	2.18 ± 0.23	28 ± 5
Combined	0.63 ± 0.02	1.59 ± 0.05	8 ± 2	0.66 ± 0.07	1.99 ± 0.18	13 ± 4

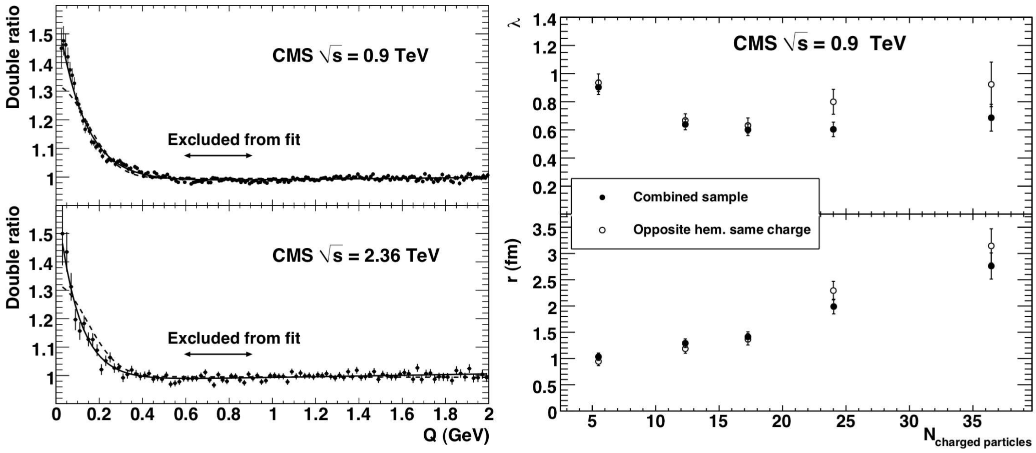

Figure 2: (Left) Fits to the double ratios $\mathcal{R}^{\mathrm{comb}}(Q)$ with exponential (solid lines) and Gaussian (dashed lines) functions, for 0.9 TeV (top) and 2.36 TeV (bottom) data. The range $0.6 < Q < 0.9$ GeV is excluded from the fits. (Right) Values of the λ (top) and r (bottom) parameters as a function of the charged-particle multiplicity for combined (dots) and opposite-hemisphere, same-charge (open circles) reference samples, at 0.9 TeV. The errors shown are statistical only.

References

[1] W. Kittel and E.A. De Wolf, World Scientific (2005) eISBN: 9789812562951.

[2] G.A. Kozlov and O. Utyuzh and G. Wilk and Z. Wlodarczyk, Phys. Atom. Nucl. **71** (2008) 1502.

[3] CMS Collaboration, JINST **3** (2008) S08004.

[4] CMS Collaboration, JHEP **2** (2010) 1.

[5] T. Sjostrand, S. Mrenna, and P. Skands, JHEP **5** (2006) 26.

[6] T. Agostinelli et al., Nucl. Instr. Meth. **A 506** (2003) 250.

[7] M. Gyulassy, S. K. Kaufmann, and L. W. Wilson, Phys. Rev. **C 20** (1979) 2267.

[8] CMS Collaboration, Phys. Rev. Lett. **105** (2010) 032001.