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BOSE–EINSTEIN CORRELATIONS WITH CMS DETECTOR AT THE LHC AT $\sqrt{s} = 0.9$ AND 2.36 TeV

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Bose–Einstein correlations between identical particles are measured using samples of proton–proton collisions at 0.9 and 2.36 TeV centre-of-mass energy, recorded by the CMS experiment at the CERN Large Hadron Collider. The signal is observed in the form of an enhancement of pairs of the same-sign charged particles with small relative momentum. A significant increase of the size of the correlated particle emission region with the particle multiplicity in the event is observed.

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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. Many measurements have been performed in a variety of initial states by several experiments [1, 2]. In this note, the first measurements of BEC at the LHC with the CMS detector, in pp collisions at $\sqrt{s} = 0.9$ and 2.36 TeV are 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 with respect to that of a reference sample that by construction is expected to include no BEC effect:

$$R(Q) = \frac{dN/dQ}{dN_{\rm ref}/dQ}, \tag{1}$$

which is then fitted with the parameterization

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

In a static model of particle sources, $\Omega(Qr)$ is the Fourier transform of the spatial distribution of the emission region of bosons, characterized by an effective size r. It is often parameterized as an exponential function, $\Omega(Qr) = \mathrm{e}^{-Qr}$, or with a Gaussian form, $\Omega(Qr) = \mathrm{e}^{-(Qr)^2}$ [3]. 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.

The data used for the present analysis were collected by the CMS experiment [4] in December 2009 from proton–proton collisions at center-of-mass energies of 0.9 and 2.36 TeV. Charged particles are required to have $p_{\mathrm{T}} > 200$ 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 $|\eta_{\mathrm{track}}| < 2.4$. Track quality criteria require a fit with more than five degrees of freedom (dof) and $\chi^2/N_{\mathrm{dof}} < 5.0$. To remove photon conversions and secondary particles from the decay of long-lived hadrons (K_S^0, Λ, etc.), the transverse impact parameter with respect to the collision point is required to be $|d_{xy}| < 0.15$ cm. The innermost measured point of the track must be less than 20 cm from the beam axis

A total of 270 472 (13 548) events are selected at $\sqrt{s} = 0.9(2.36)$ TeV, by these selection criteria, with 2 903 754 (188 140) tracks. 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 $\Omega(Qr)$.

All pairs of the 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 the 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 $\pm 15\%$.

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 ($\eta, \rho, \ldots$) 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: $(E, \mathbf{p}) \to (E, -\mathbf{p})$; this procedure is applied to pairs with the 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: $(p_x, p_y, p_z) \to (-p_x, -p_y, p_z)$. *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 both for data and for 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:

$$\mathcal{R}(Q) = \frac{R}{R_{\mathrm{MC}}} = \left(\frac{dN/dQ}{dN_{\mathrm{ref}}/dQ}\right) \Bigg/ \left(\frac{dN_{\mathrm{MC}}/dQ}{dN_{\mathrm{MC,ref}}/dQ}\right), \tag{3}$$

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 $\Omega(Qr) = \mathrm{e}^{-Qr}$ are given in Table 1, both for 0.9 and 2.36 TeV data. The region with $0.6 < Q < 0.9$ GeV,

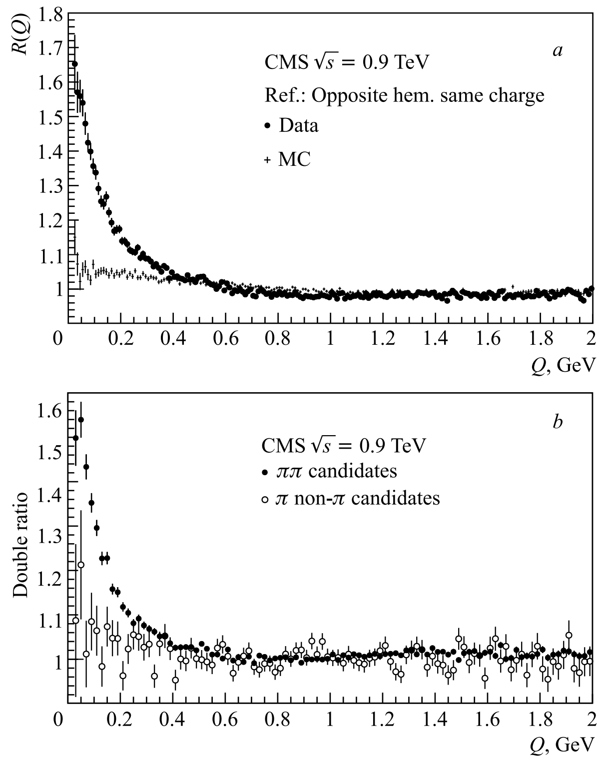

Fig. 1. *a*) Ratios $R(Q)$ obtained with the opposite-hemisphere, same-charge reference samples for data (dots) and MC without BEC effect (crosses). *b*) Double ratios $\mathcal{R}(Q)$ for the 0.9 TeV data, using the opposite-hemisphere, same-charge reference samples for combinations enriched, using a dE/dx measurement, in pion–pion pairs (dots) and in pion–nonpion pairs (open circles), respectively

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 and only the combined reference sample for 2.36 TeV data. Errors are statistical only, and quoted as if independent**

Reference sample	λ	r, fm	δ, 10^{-3} GeV^{-1}
Results of fits to 0.9 TeV data			
Opposite charge	0.56 ± 0.03	1.46 ± 0.06	-4 ± 2
Opposite hemisphere, same charge	0.63 ± 0.03	1.50 ± 0.06	11 ± 2
Opposite hemisphere, opposite charge	0.59 ± 0.03	1.42 ± 0.06	13 ± 2
Rotated	0.68 ± 0.02	1.29 ± 0.04	58 ± 3
Mixed events (random)	0.62 ± 0.04	1.85 ± 0.09	-20 ± 2
Mixed events (same mult.)	0.66 ± 0.03	1.72 ± 0.06	11 ± 2
Mixed events (same mass)	0.60 ± 0.03	1.59 ± 0.06	14 ± 2
Combined	0.63 ± 0.02	1.59 ± 0.05	8 ± 2
Results of fits to 2.36 TeV data			
Combined	0.66 ± 0.07	1.99 ± 0.18	13 ± 4

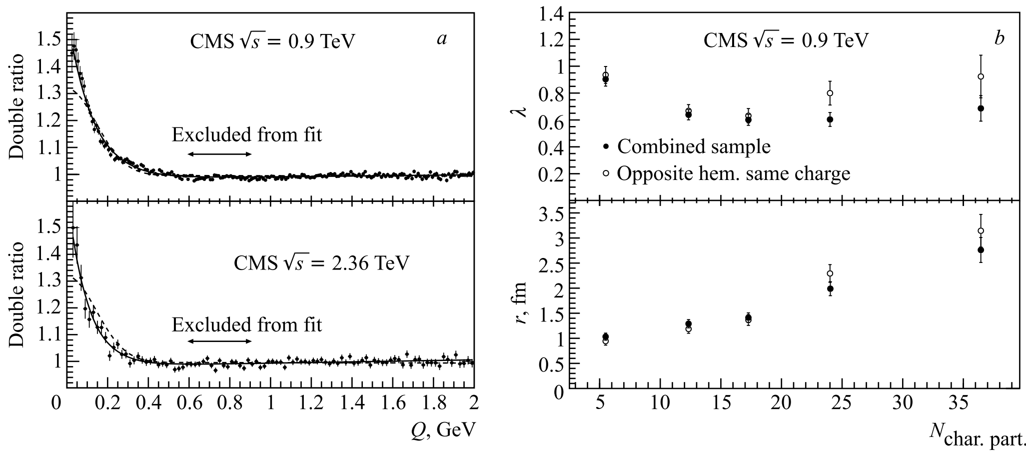

Fig. 2. *a*) Fits to the double ratios $\mathcal{R}^{\rm comb}(Q)$ with exponential (solid lines) and Gaussian (dashed lines) functions, for 0.9 TeV (top) and 2.36 TeV (bottom) data. The range $0.6 < Q < 0.9$ GeV is excluded from the fits. *b*) Values of the λ (top) and r (bottom) parameters as a function of the charged-particle multiplicity in the event for combined (black circles) and opposite-hemisphere, same-charge (open circles) reference samples, at 0.9 TeV. The errors shown are statistical only. The points are placed on the horizontal scale at the average of the multiplicity distribution in the corresponding bin

containing a sizeable contribution of pairs from $\rho \to \pi^+\pi^-$ decays, is not well described by the MC, and is therefore excluded from the fit for opposite charge reference sample.

As a cross-check, the dE/dx [9] measurements of particles in the tracker are used to select a sample enriched in $\pi\pi$ pairs, and another sample with one of the particles not consistent with the pion hypothesis. Figure 1 presents the double ratios for these two samples at $\sqrt{s} = 0.9$ TeV, showing that an enhancement at small Q values is observed only in the case of identified $\pi\pi$ pairs.

As none of the definitions of the reference samples is preferable *a priori*, an additional, «combined» double ratio $\mathcal{R}^{\rm comb}$ is formed, where the data and MC distributions are obtained by summing the Q distributions of the seven corresponding reference samples. The distributions of $\mathcal{R}^{\rm comb}$ for 0.9 and 2.36 TeV data are shown in Fig. 2, and the values of the fit parameters, using an exponential form for $\Omega(Qr)$, are given in Table 1. A Gaussian form, also shown in the figure, fails to describe the data.

The leading source of systematic uncertainty of 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, and that none of them can be preferred or discarded *a priori*. 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. The presence of a possible bias introduced by the track reconstruction and selection requirements was studied by comparing the results obtained at the generator and reconstruction levels in the MC simulation that incorporates BEC effects. The differences in the fitted parameter values for the different reference samples are smaller than the statistical errors and no systematic bias is observed for r. No correction is therefore applied and no additional systematic error is included. 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 $r = (1.59 \pm 0.05\,(\mathrm{stat.}) \pm 0.19\,(\mathrm{syst.}))$ fm at 0.9 TeV; $\lambda = 0.663 \pm 0.073\,(\mathrm{stat.}) \pm 0.048\,(\mathrm{syst.})$ and $r = (1.99 \pm 0.18\,(\mathrm{stat.}) \pm 0.24\,(\mathrm{syst.}))$ fm at 2.36 TeV.

The possible dependence of the BEC signal on various track and event observables has been studied. A significant dependence of r on the charged-particle multiplicity in the event is observed for all reference samples. Here, the only mixed-event reference sample used is the one constructed by combining charged particles from events in the same multiplicity range. The fit parameters for the combined reference sample are given in Table 2 and shown in Fig. 2 as a function of the track multiplicity for the 0.9 TeV data. As an example, the results for the opposite-hemisphere, same-charge reference sample are also shown in Fig. 2. The systematic errors on λ and r in each multiplicity bin are taken as the r.m.s. spread of the results obtained with the various reference samples. Due to the limited sample size of the 2.36 TeV data only two multiplicity bins are considered, one for multiplicities smaller than 20 tracks, the other for multiplicities between 20 and 60 tracks. The values measured for the parameters with the combined reference samples are: $\lambda = 0.65 \pm 0.08$ and $\lambda = 0.85 \pm 0.17$, and $r = (1.19 \pm 0.17)$ fm and $r = (2.85 \pm 0.38)$ fm for these two multiplicity bins, where the errors are statistical only. For comparison, the values obtained for the same multiplicity bins at 0.9 TeV are $\lambda = 0.65 \pm 0.02$ and $\lambda = 0.63 \pm 0.05$, and $r = (1.25 \pm 0.05)$ fm and $r = (2.27 \pm 0.12)$ fm, respectively. These measurements are consistent within errors. The dependence of r on multiplicity was already observed in previous measurements as discussed in detail in [2].

Table 2. **Results of the fits to the double ratio $\mathcal{R}^{\mathrm{comb}}$ for the combined reference samples, using the parameterization of Eq. (2) with the exponential form, as a function of the charged-particle multiplicity in the event, for 0.9 TeV data. Errors are statistical only, except for λ and r, where statistical (first error) and systematic uncertainties (second error) are given**

Multiplicity range	λ	r, fm	δ, 10^{-3} GeV^{-1}
2–9	$0.89 \pm 0.05 \pm 0.20$	$1.00 \pm 0.07 \pm 0.05$	72 ± 12
10–14	$0.64 \pm 0.04 \pm 0.09$	$1.28 \pm 0.08 \pm 0.09$	18 ± 5
15–19	$0.60 \pm 0.04 \pm 0.10$	$1.40 \pm 0.10 \pm 0.05$	28 ± 5
20–29	$0.59 \pm 0.05 \pm 0.17$	$1.98 \pm 0.14 \pm 0.45$	13 ± 3
30–79	$0.69 \pm 0.09 \pm 0.17$	$2.76 \pm 0.25 \pm 0.44$	10 ± 3

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 issue affecting BEC measurements was studied through the use of multiple reference samples to extract the signal. We have observed, for the first time with this degree of significance, and for all reference samples, that the shape of the signal is not described by a Gaussian function, but rather by exponential or more complex functions. An increase of the effective size of the emission region with charged-particle multiplicity, disputed for a long time [2], is now very clearly observed in pp collisions with a single experiment.

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