First Measurement of Bose-Einstein Correlations in Proton-Proton Collisions at $\sqrt{s} =$ **0.9 and 2.36 TeV at the LHC**

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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 CERN 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.

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 50 years ago in proton-antiproton interactions [1], a number of measurements have been made by several experiments using different initial states; a detailed list of the experimental results can be found in [2,3]. Boson interferometry at the Large Hadron Collider provides a powerful tool to investigate the space-time structure of the particle emission source on femtometric length scales at different center-of-mass energies and with different initial states, using the same detector. This Letter reports the first measurements of BEC at the LHC with the CMS detector, namely, the first measurement in pp collisions at 0.9 TeV and the highest energy measurement at 2.36 TeV.

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:

$$R(Q) = (dN/dQ)/(dN_{\text{ref}}/dQ), \quad (1)$$

which is then fitted with the parametrization

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

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 parametrized as an exponential function $\Omega(Qr) = e^{-Qr}$, or with a Gaussian form $\Omega(Qr) = e^{-(Qr)^2}$ (see [4] and references therein). 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 in December 2009 from proton-proton collisions at center-of-mass energies of 0.9 and 2.36 TeV. A detailed description of the CMS detector can be found in [5]. The central feature of the CMS apparatus is 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. It is composed of a pixel detector with three barrel layers at radii between 4.4 and 10.2 cm and a silicon strip tracker with 10 barrel detection layers extending outwards to a radius of 1.1 m. Each system is completed by two end caps, extending the acceptance up to a pseudorapidity $|\eta| = 2.5$. The transverse-momentum (p_T) resolution, for 1 GeV charged particles, is between 0.7% at $\eta = 0$ and 2% at $|\eta| = 2.5$. The events were selected by requiring activity in both beam scintillator counters [6]. A minimum-bias Monte Carlo (MC) sample was generated using PYTHIA (with D6T tune) [7] followed by full detector simulation based on the GEANT4 program [8]. 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 $|\eta_{\text{track}}| < 2.4$. To ensure high purity of the primary track selection, the trajectories are required to be reconstructed in fits with more than 5 degrees of freedom (dof) and $\chi^2/N_{\text{dof}} < 5.0$. 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 (K_S^0, Λ, etc.). In a total of 270 472 (13 548) events selected at 0.9 (2.36) TeV center-of-mass energy, 2 903 754 (188 140) tracks are accepted by these selection criteria.

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, while the upper limit extends far enough beyond the signal region to verify a good match between signal and reference samples. A study with simulated data shows that the ratio of the tracking efficiencies of particle pairs in the signal and in the reference samples is independent of Q in the measurement region.

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 [9]. 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 (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, and (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 [10].

In order to reduce the bias due to the construction of the reference samples, a double ratio $\mathcal{R}$ is defined:

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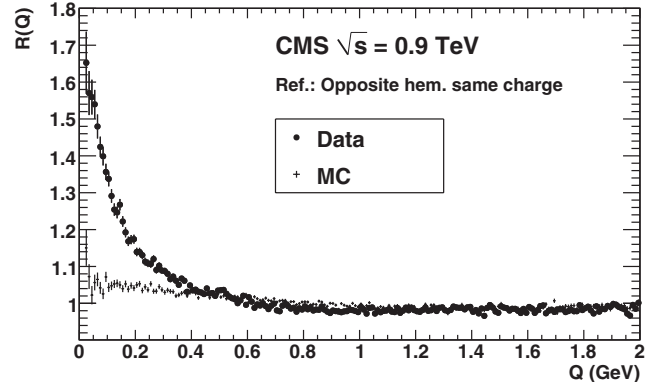

FIG. 1. Ratios $R(Q)$ obtained with the opposite-hemisphere, same-charge reference samples for data (dots) and MC calculations with no BEC effect (crosses).

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 parametrization of Eq. (2) with $\Omega(Qr) = e^{-Qr}$ are given in Table I, both for 0.9 and 2.36 TeV data. In the case of the opposite-charge sample, it is found that the region with $0.6 < Q < 0.9$ GeV, containing a sizable contribution of pairs from $\rho \rightarrow \pi^+\pi^-$ decays, is not well described by the MC calculations [10]. This region is therefore excluded from the fits with this reference sample and also with the combined sample defined below.

As a cross-check, the dE/dx [11] 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 2 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 $\mathcal{R}^{comb}$ is formed, where the data and MC distributions are obtained by summing the Q distributions of the seven corresponding reference samples.

The distributions of $\mathcal{R}^{comb}$ for 0.9 and 2.36 TeV data are shown in Fig. 3, and the values of the fit parameters are given in Table I. A large correlation is found between the parameters λ and r, as well as between δ and C (correlation coefficients of 0.82 and -0.97 at 0.9 TeV, respectively). The data are described by Eq. (2) with an exponential form for $\Omega(Qr)$, as shown by the solid lines in Fig. 3 and confirmed by the fit probability (p value) in Table I. The fit with a Gaussian form, $\Omega(Qr) = e^{-(Qr)^2}$, which yields $\lambda = 0.32 \pm 0.01$, $r = 0.98 \pm 0.03$ fm, does not correctly describe the $\mathcal{R}(Q)$ distribution, as shown by the dashed lines in Fig. 3 and by a p value of 10^{-21}. Gaussian shape fits also proved to offer a poor description of the data in previous measurements [12–14].

TABLE I. Results of fits to the double ratios $\mathcal{R}(Q)$ for several reference samples, using the parametrization of Eq. (2) with the exponential form, for 0.9 TeV data (left) and 2.36 TeV data (right). Errors are statistical only, and quoted as if independent.

Reference sample	Results of fits to 0.9 TeV data					Results of fits to 2.36 TeV data			
	p value (%)	C	λ	r (fm)	δ (10^{-3} GeV^{-1})	p value (%)	C	λ	r (fm)	δ (10^{-3} GeV^{-1})
Opposite charge	21.9	0.988 ± 0.003	0.56 ± 0.03	1.46 ± 0.06	-4 ± 2	57	1.004 ± 0.008	0.53 ± 0.08	1.65 ± 0.23	-16 ± 6
Opposite hemisphere same charge	7.3	0.978 ± 0.003	0.63 ± 0.03	1.50 ± 0.06	11 ± 2	42	0.977 ± 0.006	0.68 ± 0.11	1.95 ± 0.24	15 ± 5
Opposite hemisphere opposite charge	11.9	0.975 ± 0.003	0.59 ± 0.03	1.42 ± 0.06	13 ± 2	46	0.969 ± 0.005	0.70 ± 0.11	2.02 ± 0.23	24 ± 5
Rotated	0.02	0.929 ± 0.003	0.68 ± 0.02	1.29 ± 0.04	58 ± 3	42	0.933 ± 0.007	0.61 ± 0.07	1.49 ± 0.15	58 ± 6
Mixed events (random)	1.9	1.014 ± 0.002	0.62 ± 0.04	1.85 ± 0.09	-20 ± 2	23	1.041 ± 0.005	0.74 ± 0.15	2.78 ± 0.36	-40 ± 4
Mixed events (same multiplicity)	12.2	0.981 ± 0.002	0.66 ± 0.03	1.72 ± 0.06	11 ± 2	35	0.974 ± 0.005	0.63 ± 0.10	2.01 ± 0.23	20 ± 5
Mixed events (same mass)	1.7	0.976 ± 0.002	0.60 ± 0.03	1.59 ± 0.06	14 ± 2	73	0.964 ± 0.005	0.73 ± 0.11	2.18 ± 0.23	28 ± 5
Combined	2.9	0.984 ± 0.002	0.63 ± 0.02	1.59 ± 0.05	8 ± 2	89	0.981 ± 0.005	0.66 ± 0.07	1.99 ± 0.18	13 ± 4

Although the values of r obtained in the exponential fits cannot be compared directly with results obtained with a Gaussian function, it should be noted for comparison purposes that the first moment of the $\Omega(Qr)$ distribution corresponds to $1/r$ for an exponential shape and to $1/r\sqrt{\pi}$ for a Gaussian form. The first moments measured at the two energies are consistent within errors with most of the previous measurements [2,3]. Alternative functions, as defined in [13,15,16], also describe the data well with similar p values. In particular, for the Lévy parametrization $\Omega(Qr) = e^{-(Qr)^{\alpha}}$, the fitted values are $\lambda = 0.93 \pm 0.11$, $r = 2.46 \pm 0.38$ fm, and $\alpha = 0.76 \pm 0.06$, with a p value of 12.8%.

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, and that none of them can be preferred or discarded _a priori_. The corresponding contribution to the systematic error is computed as the rms 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
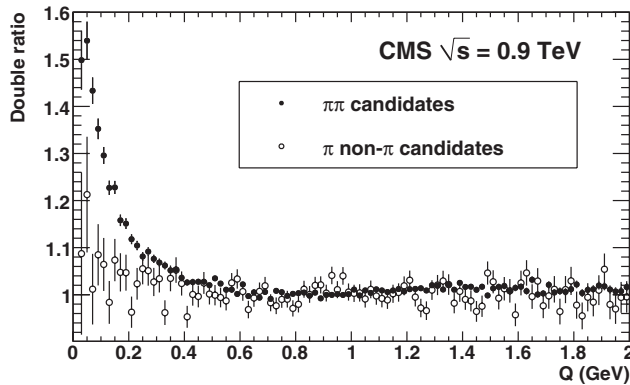

FIG. 2. Double ratios $\mathcal{R}(Q)$ for the 0.9 TeV data, using the opposite-hemisphere, same-charge reference samples for combinations enriched, using a dE/dx measurement, in pion-pion pairs (dots) and in pion-nonpion pairs (open circles), respectively.
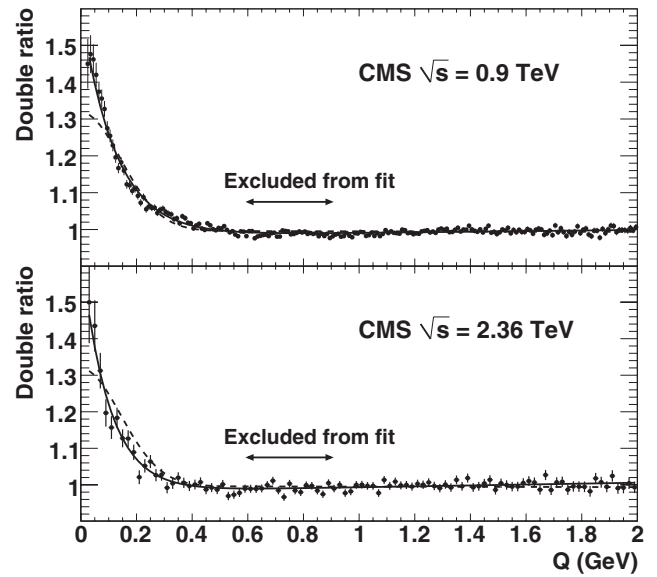

FIG. 3. Fits to the double ratios $\mathcal{R}^{\text{comb}}(Q)$ with exponential (solid lines) and Gaussian (dashed lines) functions, for 0.9 TeV (top panel) and 2.36 TeV (bottom panel) data. The range $0.6 < Q < 0.9$ GeV is excluded from the fits.

TABLE II.   Results of the fits to the double ratio $\mathcal{R}^{\text{comb}}$ for the combined reference samples, using the parametrization 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 (second error) uncertainties are given.

Multiplicity range	p value (%)	C	λ	r (fm)	δ (10^{-3} GeV^{-1})
2–9	97	0.90 ± 0.01	$0.89 \pm 0.05 \pm 0.20$	$1.00 \pm 0.07 \pm 0.05$	72 ± 12
10–14	38	0.97 ± 0.01	$0.64 \pm 0.04 \pm 0.09$	$1.28 \pm 0.08 \pm 0.09$	18 ± 5
15–19	27	0.96 ± 0.01	$0.60 \pm 0.04 \pm 0.10$	$1.40 \pm 0.10 \pm 0.05$	28 ± 5
20–29	24	0.99 ± 0.01	$0.59 \pm 0.05 \pm 0.17$	$1.98 \pm 0.14 \pm 0.45$	13 ± 3
30–79	28	1.00 ± 0.01	$0.69 \pm 0.09 \pm 0.17$	$2.76 \pm 0.25 \pm 0.44$	10 ± 3

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 $\lambda = 0.625 \pm 0.021(\text{stat}) \pm 0.046(\text{syst})$ and $r = 1.59 \pm 0.05(\text{stat}) \pm 0.19(\text{syst})$ fm at 0.9 TeV and $\lambda = 0.663 \pm 0.073(\text{stat}) \pm 0.048(\text{syst})$ and $r = 1.99 \pm 0.18(\text{stat}) \pm 0.24(\text{syst})$ 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 II and shown in Fig. 4 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. 4. The systematic errors on λ and r in each multi-

plicity bin are taken as the rms spread of the results obtained with the various reference samples. Because of 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 [3].

In summary, Bose-Einstein correlations have been measured 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 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 [3], is now very clearly observed in pp collisions with a single experiment.
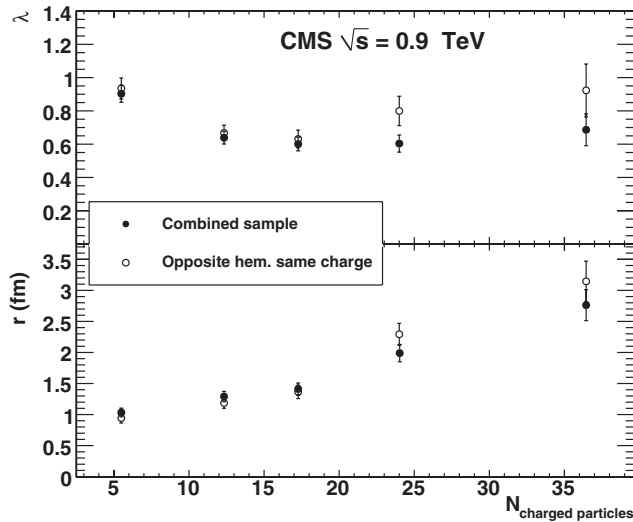
FIG. 4.   Values of the λ (top panel) and r (bottom panel) parameters as a function of the charged-particle multiplicity in the event for combined (dots) and opposite-hemisphere, same-charge (open circles) reference samples, at 0.9 TeV. The errors shown are statistical only. The points are placed on the horizontal scale at the average of the multiplicity distribution in the corresponding bin.

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