Measurement of Bose–Einstein Correlations in 0.9 and 2.36 TeV proton-proton Collisions with the CMS Experiment

(Dated: April 16, 2010)

Bose–Einstein correlations between identical particles are measured using samples of proton-proton collisions at 0.9 and 2.36 TeV center-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 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.

PACS numbers:

In elementary particle collisions the space-time structure of particle emission can be studied through measurements of Bose-Einstein correlations (BEC) between identical bosons. BEC effects are revealed by the enhanced emission of boson pairs with small relative momenta.

Since the first observation of BEC fifty years ago in proton-antiproton interactions [1], a number of measurements have been produced by several experiments using different initial states: e^+e^- [2–7], $\bar{p}p$ [8], pp [9], πN [10], ep [11, 12], and ν_μN [13]. This letter reports the first measurement of BEC parameters in pp collisions at 0.9 and 2.36 TeV with the CMS detector at the Large Hadron Collider.

The interference can be studied using the ratio R between the joint probability for the emission of a pair of identical bosons, $P(p_1, p_2)$, and the product of the single-particle probabilities $P(p)$, $R = \frac{P(p_1,p_2)}{P(p_1)\ P(p_2)}$, where p_1 and p_2 are the particle four-momenta. Experimentally R is measured using the distribution of the variable $Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{m_{inv}^2 - 4m_\pi^2}$ where m_{inv} is the invariant mass of the two particles, assumed to be pions with mass m_π. The ratio R is obtained by dividing the Q distribution of pairs of same-charge particles by a reference sample built with pairs of particles which by construction are expected to have no Bose-Einstein correlation:

$$R = (dN/dQ)/(dN/dQ_{ref}). \tag{1}$$

A widely used parameterization of R is given by:

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

In a static model of particle emission, $\Omega(Qr)$ is the Fourier transform of the emission region characterized by an effective size r. It is often parameterized as $\Omega(Qr) = e^{-Qr}$ or $\Omega(Qr) = e^{-(Qr)^2}$ ([14] and references therein). The parameter λ measures the strength of BEC for incoherent boson emission from independent sources, δ accounts for long-distance 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 LHC collisions at a center-of-mass energy of 0.9 and 2.36 TeV. A detailed description of the CMS detector can be found in [15]. The events were selected by the High-Level Trigger requiring activity in the beam scintillator detectors [16] and offline they are required to contain at least two and at most 150 charged particles. A minimum-bias Monte Carlo (MC) sample was generated with PYTHIA [17], using a full detector simulation. These MC samples, which do not include a modeling of Bose–Einstein correlations, are referred to as "default simulation". For cross-checks, additional PYTHIA MC samples which simulate some of the BEC effects were produced with $r = 1.6$ fm and $\lambda = 0.9$, with a Gaussian and with an exponential functional form of the correlation function Ω.

Charged particles are required to have $p_{\mathrm{T}} > 200$ MeV, which is sufficient for particles emitted from the primary vertex to cross all three layers of the silicon pixel detector and ensure two-track separation. Particle pseudorapidity is required to be $|\eta| < 2.4$, within the tracker acceptance. To ensure high purity of the primary track selection, particles are required to be reconstructed by fits with more than five degrees of freedom and $\chi^2/N_{\mathrm{dof}} < 5.0$. The transverse impact parameter with respect to the collision point is required to be $|d_{xy}| < 0.15$ cm, and the innermost measured point of the track at a radius $R < 20$ cm, in order to remove 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 the above selection criteria.

Pairs of same-charge particles passing the selection are used to construct the distribution of Q. All pairs with $0.02 < Q < 2$ GeV are considered for the measurement. The lower limit is chosen to avoid cases of not well-separated or duplicated tracks, while the upper limit extends far enough from the signal region to verify a good match between signal and reference samples.

As the Q distribution is normalized to the reference samples described below, the knowledge of the absolute value of the tracking efficiency is not mandatory to perform the measurement. The important feature is that the ratios between the tracking efficiencies of particle pairs in the signal and in the reference samples are found to be independent of Q in the region considered in the measurement.

Coulomb interactions between charged particles modify their relative momentum distribution differently for pairs with same charge (repulsion) and different charges (attraction). This effect is corrected for by using the Gamow factors [18]. The enhancement in the production of opposite-charge particle pairs with small values of Q observed in the data is successfully corrected.

Different methods are used to combine uncorrelated charged particles, to define reference samples describing the denominator of Eq. (1). *Opposite-charge pairs*: this data set is a natural choice, but it contains resonances (η, ρ, ...) which are not present in the same-charge combinations. In practice, events in the range $0.6 < Q < 0.9$ with a sizeable contribution from the ρ are escluded from the measurements done with this reference sample and with the combined reference set defined below. *Opposite-hemisphere pairs*: tracks are paired after inverting in space the three-momentum of one of the two particles: $(E, \vec{p}) \to (E, -\vec{p})$; 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: $(p_x, p_y, p_z) \to (-p_x, -p_y, p_z)$. *Mixing events:* particles from different events are combined with the following methods: i) events are paired at random; ii) events with similar charged particle density in different η regions are selected; iii) events with an invariant mass of all charged particles similar to that of the signal are paired.

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

$$\mathcal{R} = R/R_{\mathrm{MC}} = \left(\frac{\mathrm{d}N/\mathrm{d}Q}{\mathrm{d}N/\mathrm{d}Q_{\mathrm{ref}}}\right) \Big/ \left(\frac{\mathrm{d}N/\mathrm{d}Q_{\mathrm{MC}}}{\mathrm{d}N/\mathrm{d}Q_{\mathrm{MC,ref}}}\right), \quad (3)$$

where Q_{MC} and $Q_{\mathrm{MC,ref}}$ refer to the Q distributions from the default simulation, which does not include a modeling of Bose–Einstein correlations.

As a cross check, the $\mathrm{d}E/\mathrm{d}x$ [19] measurements of particles in the tracker have been used to select a sample enriched in $\pi\pi$ pairs, and another sample with one of the particles rejected by pion identification. Figure 1 presents the double ratios for these two samples, showing that an enhancement at small Q values is observed only in the case of identified $\pi\pi$ pairs.

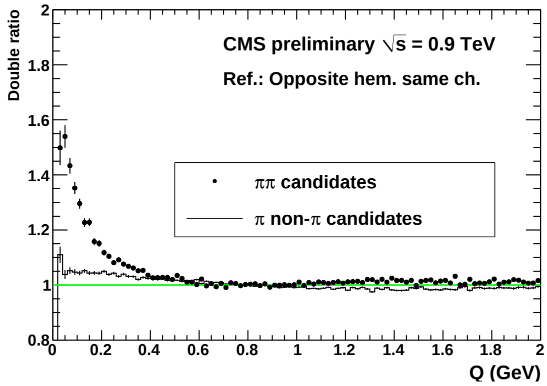

FIG. 1: The double ratio $\mathcal{R}$ as a function of Q for the same-charge sample to the reference sample formed with same-charge, opposite-hemisphere pairs, for combinations enriched in pion/pion pairs (points) and in pion/non-pion pairs (histogram), respectively. A line at $\mathcal{R} = 1$ is also shown.

The results of the fits to the double ratios $\mathcal{R}$ for several reference samples, using the parameterization of Eq. (2) with $\Omega(Qr) = e^{-Qr}$, are reported in Table I both for the 0.9 and the 2.36 TeV data. Sizable BEC effects are observed with all reference samples. As *a priori* none of the definitions of the reference samples is preferable, a combined value is extracted, by forming a new reference sample as the following combination of the $m = 7$ reference sets:

$$\mathcal{R}^{comb} = \frac{\mathrm{d}N/\mathrm{d}Q}{\mathrm{d}N/\mathrm{d}Q_{\mathrm{MC}}} \left(\frac{\sum_{i=1}^{m} \mathrm{d}N/\mathrm{d}Q^{i}_{\mathrm{MC,ref}}}{\sum_{i=1}^{m} \mathrm{d}N/\mathrm{d}Q^{i}_{\mathrm{ref}}}\right). \quad (4)$$

This choice, besides equally dealing with the abundance of used reference samples, accounts for the statistical correlations among the different measurements, all sharing the same signal but differing in the composition of the reference sample. In addition, it allows a well-defined estimate of the systematic uncertainty related to the choice of the reference sample (see below).

The distributions of $\mathcal{R}^{comb}$ for 0.9 and for 2.36 TeV data are shown in Fig. 2, 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, as shown in Table II.

In order to test the agreement of different functional parameterizations of the Bose–Einstein correlation with the data, the double ratio $\mathcal{R}$ is fitted assuming the Gaussian form $\Omega(Qr) = e^{-(Qr)^2}$, which is often used by other experiments. Results are shown by the dashed line in Fig. 2. The exponential hypothesis reproduces the data significantly better than the Gaussian one, which gives a fit probability (p-value) of 1.07×10^{-21} in 0.9 TeV data.

The fact that a Gaussian shape is not a good representation of experimental data could be observed also in previous analyses [12, 20]. Hence in the following only the parameters obtained from an exponential shape fit will be quoted. It should be noted that the values of r obtained in the exponential fits cannot compare directly with results obtained with a Gaussian function. However, for comparison purposes, it can be noted that the

TABLE I: Results of fits to 0.9 TeV data (left) and 2.36 TeV data (right) of the double ratios $\mathcal{R}$ with different definitions of the reference sample, using the exponential function. The last line shows the results with the combined sample obtained from the by bin average of all the reference samples. Errors are statistical only, and quoted as if independent.

	Results of fits to 0.9 TeV data					Results of fits to 2.3 TeV data				
Reference sample	p-value (%)	C	λ	r (fm)	$\delta \times 10^3$ (GeV^{-1})	p-value (%)	C	λ	r (fm)	$\delta \times 10^3$ (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 hem. same ch.	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 hem. opp. ch.	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 evts. (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 evts. (same mult.)	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 evts. (same mass)	17.0	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

TABLE II: Correlation coefficients for the fit parameters obtained with the combined reference samples. Left: coefficients from the fit to 0.9 TeV data; right: coefficients from the fit to 2.36 TeV data.

	0.9 TeV				2.36 TeV			
	C	λ	r	δ	C	λ	r	δ
C	1				1			
λ	0.33	1			0.27	1		
r	0.72	0.82	1		0.62	0.83	1	
δ	-0.97	-0.30	-0.67	1	-0.96	-0.24	-0.57	1

first moment of the distribution corresponds to $1/r$ for an exponential shape and to $\frac{1}{r\sqrt{\pi}}$ for a Gaussian. Alternative functions, as defined in [20, 21] and the Levy parameterization $\Omega(Qr) = e^{-(Qr)^{\alpha}}$ (where α is an additional free parameter) , yield fits of quality similarly good to the pure exponential form.

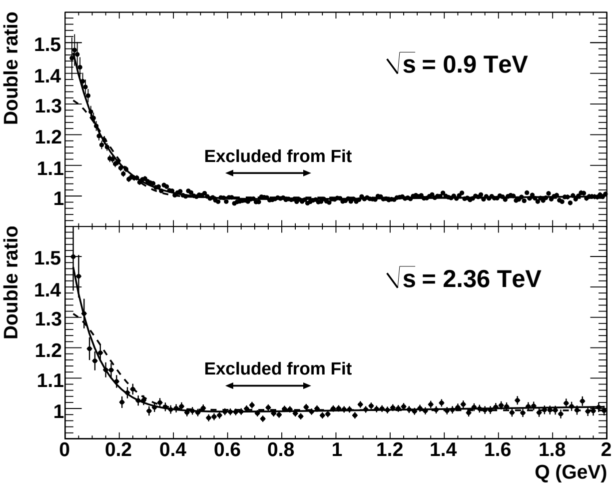

FIG. 2: Results of the exponential (continuous line) and Gaussian (dashed line) fits to the double ratio $\mathcal{R}^{comb}$ obtained by combining all reference samples, for 0.9 TeV (top) and 2.36 TeV (bottom) data. The range $0.6 < Q < 0.9$ GeV is excluded from the fit.

The systematic uncertainty of the fitted values is computed as the r.m.s. spread between the results obtained for the different samples. The uncertainties obtained are $\pm 7\%$ for λ and $\pm 12\%$ for r.

The uncertainty related to the Coulomb corrections was determined with the opposite-charge sample, the predicted strength of the Coulomb effect being compatible with the data within $\pm 15\%$. The corresponding changes are 0.8% for r and 2.8% for λ, which are used as systematic errors.

The presence of a possible bias introduced by the track reconstruction and selection requirements was studied by comparing the results obtained at the particle and reconstruction levels in the MC simulation which incorporates some of the BEC effects. The differences in the fitted values of the parameters for the different reference samples are smaller than the statistical errors, the largest effect being of 6% for λ and 3.3% for r. In particular no systematic effect is observed for r. No correction is thus applied and no additional systematic error is included, since this is covered by the global systematic error derived from the r.m.s. spread of the measurements.

For 2.36 TeV data the same relative systematic uncertainties as for 0.9 TeV values are used, in view of the reduced size of the sample and the larger statistical uncertainty of fit results. Using the combined reference sample the BEC parameters are thus measured as:
$r = 1.59 \pm 0.05_{stat.} \pm 0.19_{syst.}$ fm and
$\lambda = 0.625 \pm 0.021_{stat.} \pm 0.046_{syst.}$, for 0.9 TeV data;
$r = 1.99 \pm 0.18_{stat.} \pm 0.24_{syst.}$ fm and
$\lambda = 0.663 \pm 0.073_{stat.} \pm 0.048_{syst.}$, for 2.36 TeV data.

The possible dependence of the BEC signal has been studied as a function of various track and event observables. A significant dependence of the r parameter with 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 obtained as a function of the track multiplicity are shown in Fig. 3 and given in Table III. The systematic error on r in each multiplicity bin is taken as the r.m.s. spread of the results obtained with the various reference samples.

Given the limited statistics, 2.36 TeV data are divided

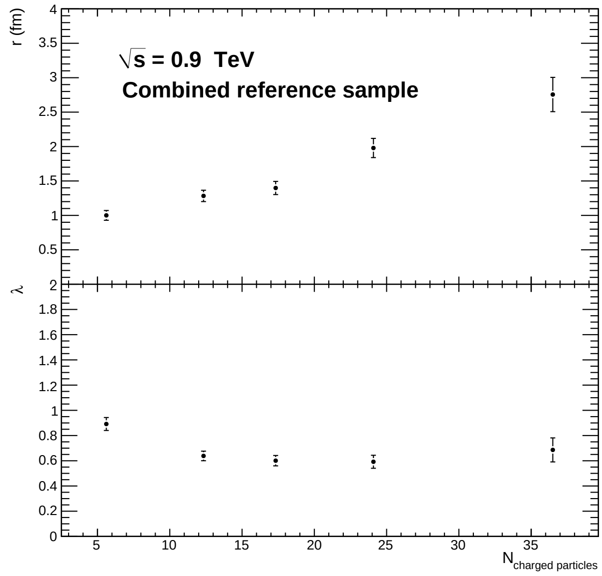

FIG. 3: Values of the r and λ parameters as a function of charged-particle multiplicity in the event. The errors are statistical only.

TABLE III: Results of fits to 0.9 TeV data of the double ratio $\mathcal{R}$, obtained by averaging the five reference samples listed in the text, as a function of the charged-particle multiplicity in the event. Errors for all parameters are statistical, but for r where we show first the statistical and then the systematic uncertainty.

Results of fits to 0.9 TeV data					
Mult. range	p-value (%)	C	λ	r (fm)	$\delta \times 10^3$ (GeV^{-1})
2 - 9	97	0.90 ± 0.01	0.89 ± 0.05	$1.00 \pm 0.07 \pm 0.05$	72 ± 12
10 - 14	38	0.97 ± 0.01	0.64 ± 0.04	$1.28 \pm 0.08 \pm 0.09$	18 ± 5
15 - 19	27	0.96 ± 0.01	0.60 ± 0.04	$1.40 \pm 0.10 \pm 0.05$	28 ± 5
20 - 29	24	0.99 ± 0.01	0.59 ± 0.05	$1.98 \pm 0.14 \pm 0.45$	13 ± 3
30 - 79	28	1.00 ± 0.01	0.69 ± 0.09	$2.76 \pm 0.25 \pm 0.44$	10 ± 3

in just two bins of multiplicity: one for multiplicities smaller than 20 tracks, the other for multiplicities between 20 and 60 tracks. The values measured for the parameters 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, respectively. 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.

In summary, Bose–Einstein correlations have been measured using data collected with the CMS experiment at the LHC in December 2009 from pp collisions at 0.9 and 2.36 TeV center-of-mass energy. Several reference samples were used to extract the signal. Exponential parameterizations fit the data better than a Gaussian form. The BEC parameters extracted from fits using an exponential form are: $r = 1.59 \pm 0.05$ (stat.) ± 0.19 (syst.) fm and $\lambda = 0.625 \pm 0.021$ (stat.) ± 0.046 (syst.) in 0.9 TeV data, and $r = 1.99 \pm 0.18$ (stat.) ± 0.24 (syst.) fm and $\lambda = 0.663 \pm 0.073$ (stat.) ± 0.048 (syst.) in 2.36 TeV data. An increase of the parameter r with charged-particle multiplicity in the event is observed.

Acknowledgements

The authors would like to thank T. Sjöstrand for the useful discussions on the simulation of Bose–Einstein correlation effects with the PYTHIA MC program.

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