Measurement of Bose-Einstein correlations in pp collisions at √s=0.9 and 7 TeV

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Measurement of Bose-Einstein correlations in pp collisions at $\sqrt{s} = 0.9$ and 7 TeV

The CMS collaboration

Abstract: Bose-Einstein correlations between identical particles are measured in samples of proton-proton collisions at 0.9 and 7 TeV centre-of-mass energies, recorded by the CMS experiment at the LHC. The signal is observed in the form of an enhancement of number of pairs of same-sign charged particles with small relative momentum. The dependence of this enhancement on kinematic and topological features of the event is studied. Anticorrelations between same-sign charged particles are observed in the region of relative momenta higher than those in the signal region.

Keywords: Hadron-Hadron Scattering

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Contents

1 Introduction

In particle collisions, the space-time structure of the hadron emission region can be studied using measurements of Bose-Einstein correlations (BEC) between pairs of identical bosons. Since the first observation of BEC in proton-antiproton interactions fifty years ago [1], a large number of measurements have been performed by experiments using different initial states [2, 3]. At the CERN Large Hadron Collider (LHC), BEC were observed for the first time by CMS using data at centre-of-mass energies $\sqrt{s} = 0.9$ and 2.36 TeV, collected in 2009 [4]; measurements by ALICE at 0.9 TeV were reported in [5]. The present paper reports measurements using data taken in 2010 at 0.9 TeV, with a sample increase by a factor 15, and at 7 TeV, for the first time. The analysis method is similar to that in [4], where more details can be found. In this article the results at the two energies are compared and additional studies are performed.

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, to that for pairs of particles in a reference sample that by construction is expected to include no BEC effect:

$$R(Q) = (\mathrm{d}N/\mathrm{d}Q)/(\mathrm{d}N_{\mathrm{ref}}/\mathrm{d}Q). \tag{1.1}$$

The ratio is fitted with the parameterization

$$R(Q) = C\,[1 + \lambda\Omega(Qr)] \cdot (1 + \delta Q). \tag{1.2}$$

In most formulations of BEC, $\Omega(Qr)$ is the modulus square of a Fourier transform of the space-time region emitting bosons with overlapping wave functions, characterized by an effective size r. 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 correlation function is often parameterized as an exponential $\Omega(Qr) = e^{-Qr}$ or with a Gaussian form $\Omega(Qr) = e^{-(Qr)^2}$. Other forms have also been used ([6] and references therein), and several of them are mentioned below. In addition a formulation aimed at describing the time evolution of the source [7, 8] is considered and compared with the data.

2 Data and track selection

A detailed description of the CMS detector can be found in [9]. The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing an axial 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 endcaps, 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 $|\eta| = 2.5$.

Minimum-bias events were selected by requiring activity in both beam scintillator counters [10]. Charged particles are required to have $|\eta| < 2.4$ and $p_{\mathrm{T}} > 200$ MeV, ensuring that particles emitted from the interaction region cross all three barrel layers of the pixel detector and thus have good two-track separation. To achieve a high purity of the primary track selection, the trajectories are required to be reconstructed in fits with more than five degrees of freedom (N_{dof}) and $\chi^2/N_{\mathrm{dof}} < 5.0$. The transverse impact parameter with respect to the collision point is required to be less than 0.15 cm. The innermost measured point of the track must be within 20 cm of the beam axis, in order to reduce contamination from electrons and positrons from photon conversions in the detector material and secondary particles from decay of long-lived hadrons.

For this analysis a total of 4.2 million events were selected at $\sqrt{s} = 0.9$ TeV, with 51.5 million tracks passing the selection criteria. At 7 TeV, 2.7 million events with 51.7 million tracks were selected from data taken during low-intensity runs. Neither of the two energy samples is affected by event pileup. Several minimum-bias Monte Carlo (MC) samples were generated, followed by detailed detector simulation based on the GEANT4 package [11]. At 0.9 TeV, the MC simulations were generated with several PYTHIA6.4 [12] tunes (D6T, DW, Perugia0, Z1 and Z2 [13–15]). At 7 TeV, the simulations use PYTHIA6.4 tunes (ProPt0, Perugia0, Z1 and Z2) and PYTHIA8.1 [16].

3 Definition of signal and reference samples

All pairs of same-sign charged 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 (confined to $Q < 0.4$ GeV) to allow verification of a good match between signal and reference samples.

The Q resolution in the signal region is better than 10 MeV. 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 using Gamow factors [17].

As discussed in [4], the reference sample in the denominator of eq. (1.1) can be defined in several ways: *opposite-charge pairs*; *opposite-hemisphere pairs*, where particles are paired after inverting the three-momentum of one of them, this procedure being applied to pairs with same and opposite charges; *rotated particles*, where pairs are constructed by inverting the x and y components of the three-momentum of one of the two particles; *pairs from mixed events*. In the case of 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 multiplicities 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. In this paper, we use the sample obtained by pairing same-sign charged particles from different events that have similar charged-particle multiplicities in the same η regions. This method avoids the possible effect of remaining correlations [18] between particles within the same event. The r.m.s. spread of the results obtained from the different samples is taken as a conservative systematic uncertainty. In [4] an additional, "combined" reference sample was obtained by summing the Q distributions of the seven corresponding reference samples. It has been checked that the results obtained with the "combined" reference sample are compatible within errors with those presented here.

In order to reduce possible biases in the construction of the reference sample, a double ratio $\mathcal{R}$ is defined,

$$\mathcal{R}(Q) = \frac{R}{R_{\mathrm{MC}}} = \left(\frac{\mathrm{d}N/\mathrm{d}Q}{\mathrm{d}N_{\mathrm{ref}}/\mathrm{d}Q}\right) \Big/ \left(\frac{\mathrm{d}N_{\mathrm{MC}}/\mathrm{d}Q}{\mathrm{d}N_{\mathrm{MC,\,ref}}/\mathrm{d}Q}\right), \tag{3.1}$$

where the subscripts "MC" and "MC, ref" refer to the corresponding distributions from the simulated events, generated without BEC effects.

4 Determination of Bose-Einstein correlation parameters

Figure 1 shows the distributions of the double ratio $\mathcal{R}$ for $Q > 0.02$ GeV and both centre-of-mass energies, computed using the tune Z2 of the PYTHIA6.422 simulation, which best describes the measured track distributions (in particular the charged-particle multiplicity). The shapes fitted with the exponential parameterization $\Omega(Qr) = e^{-Qr}$ in eq. (1.2) are superimposed and the results of the fits are given in table 1. The values of the two parameters r and λ are basically related to different features of the distributions: the width of the peak at small Q to r and the height to λ; they are, however, strongly correlated, with correlation coefficients of about 86%. The fit quality is poor, as can be seen from the values of χ^2/N_{dof}. Gaussian parameterizations, which are used by some experiments, provide values of χ^2/N_{dof} larger than 9, which confirms the observation in [4] that an exponential parameterization is preferred.

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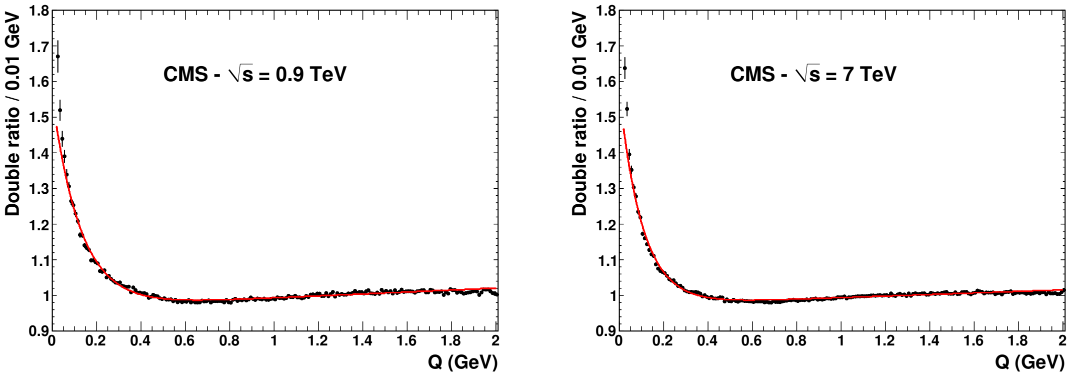

Figure 1. Distribution, for $Q > 0.02\,\mathrm{GeV}$, of the double ratio $\mathcal{R}$ defined in eq. (3.1), for data at $\sqrt{s} = 0.9$ (left) and 7 TeV (right). The reference sample is obtained from same-sign charged particles from mixed events with similar multiplicities, and the MC simulation is PYTHIA6.4 tune Z2. The lines are the results of fits using the exponential parameterization for $\Omega(Qr)$, with the values of the parameters given in the text. The error bars on the data points are statistical only.

$\sqrt{s}$	χ^2/N_{dof}	C	λ	r (fm)	δ ($10^{-2}\,\mathrm{GeV}^{-1}$)
0.9 TeV	485/194	0.965 ± 0.001	0.616 ± 0.011	1.56 ± 0.02	2.8 ± 0.1
7 TeV	739/194	0.971 ± 0.001	0.618 ± 0.009	1.89 ± 0.02	2.2 ± 0.1

Table 1. Results of fits using the exponential parameterization for $\Omega(Qr)$ to the double ratio $\mathcal{R}$, at $\sqrt{s} = 0.9$ and 7 TeV. The reference sample is obtained from same-sign charged particles from mixed events with similar multiplicities, and the MC simulation is PYTHIA6.4 tune Z2. Errors are statistical only.

Compared to an exponential shape, alternative functions, as defined in [19, 20], and the Lévy parameterization, $\Omega(Qr) = e^{-(Qr)^\alpha}$ [21], yield fits of only slightly better quality. For the Lévy parameterization the fitted values are $\lambda = 0.847 \pm 0.057$, $r = 2.20 \pm 0.17\,\mathrm{fm}$, $\alpha = 0.806 \pm 0.033$, with $\chi^2/N_{\mathrm{dof}} = 453/193$ at 0.9 TeV and $\lambda = 0.896 \pm 0.051$, $r = 2.83 \pm 0.18\,\mathrm{fm}$, $\alpha = 0.792 \pm 0.024$, with $\chi^2/N_{\mathrm{dof}} = 676/193$ at 7 TeV. These values confirm the data tendency to prefer an exponent $\alpha < 1$ as in [4]. Large (anti)correlations are, however, observed among various parameters, which can lead to large variations of numerical values. As a cross-check of the stability of the measurement of the width of the peak at small Q and of the fact that it does not depend on the fit quality, the average values (first moment) of the $\Omega(Qr)$ distributions over the same interval in Q are found to be consistent for the different functions. More discussion on the shape of the $\mathcal{R}$ distribution and on the fit quality can be found at the end of this section.

As discussed in [4], the main experimental uncertainty is due to the choice of the reference sample. In addition, we consider here the systematic uncertainty due to the choice of the MC sample; it is obtained from the r.m.s. spread of results obtained using the various MC simulations listed in section 2. The results at 7 TeV show a larger dependence on the MC choice than at 0.9 TeV. The uncertainty related to the Coulomb corrections

$\sqrt{s}$	0.9 TeV		7 TeV	
	λ	r (fm)	λ	r (fm)
Choice of the reference sample	0.017	0.11	0.015	0.10
Choice of MC dataset	0.009	0.05	0.032	0.16
Effect of Coulomb corrections	0.017	0.01	0.017	0.02
Fit range	0.014	0.08	0.016	0.08
Total	0.029	0.15	0.042	0.21

Table 2. Systematic uncertainties on the parameters λ and r at two different centre-of-mass energies.

is taken to be ±15%, as determined in [4], which covers the spread from the different parameterizations [22]. The Coulomb corrections affect the signal mainly at very low Q, leading to an uncertainty of ±2.8% on λ and ±0.8% on r. Finally we consider the uncertainty due to the choice of the fit range. It is evaluated as the r.m.s. spread of the results obtained by moving the upper limit of the fit from $Q = 1.8\,\text{GeV}$ to $Q = 2.4\,\text{GeV}$. The first value (1.8 GeV) is chosen such that the anticorrelation region (see below) is fully contained in the fit range, while the second one is limited by the fact that for higher values the fit quality further degrades, indicating that the functions do not provide a good description of the baseline curve in that region (this observation does not depend on the choice of the function in the signal region). Contributions to the systematic uncertainties are reported in table 2, and the total systematic uncertainties are obtained from their quadratic sum. It was checked that reducing the fit range to $0.04 < Q < 2\,\text{GeV}$, thus excluding the first two points at low Q in figure 1, gives consistent results within errors.

The BEC parameters are thus measured to be

$$\begin{aligned} r &= 1.56 \pm 0.02\,(\text{stat.}) \pm 0.15\,(\text{syst.})\ \text{fm} \\ \lambda &= 0.616 \pm 0.011\,(\text{stat.}) \pm 0.029\,(\text{syst.}) \end{aligned}$$

at $\sqrt{s} = 0.9\,\text{TeV}$ and

$$\begin{aligned} r &= 1.89 \pm 0.02\,(\text{stat.}) \pm 0.21\,(\text{syst.})\ \text{fm} \\ \lambda &= 0.618 \pm 0.009\,(\text{stat.}) \pm 0.042\,(\text{syst.}) \end{aligned}$$

at $\sqrt{s} = 7\,\text{TeV}$.

As will be shown below, the increase of r is related to the different average charged-particle multiplicities at the two energies, while the value of the λ parameter is constant within errors.

The BEC signal is studied as a function of the charged-particle multiplicity in the event, N_{ch}, as in [4], and of the pair average transverse momentum k_{T}, defined as half of the absolute vector sum of the two transverse momenta, $k_{\text{T}} = |\mathbf{p}_{\text{T},1} + \mathbf{p}_{\text{T},2}|/2$. A dependence on k_{T} has been observed at the SPS [23], at the Tevatron [24] and at RHIC [25], where it is associated with the system collective expansion. Figure 2 shows the double

k_{T} (GeV)	N_{ch} ($< N_{\mathrm{ch}} >$)	χ^2/N_{dof}	C	λ	r (fm)	δ (10^{-2} GeV^{-1})
$\sqrt{s} = 0.9$ TeV						
0.10 - 0.30	2 - 9 (6.6)	220/194	0.925 ± 0.006	1.011 ± 0.051	1.211 ± 0.057	6.1 ± 0.6
0.10 - 0.30	10 - 24 (15.5)	285/194	0.969 ± 0.002	0.761 ± 0.034	1.652 ± 0.057	2.9 ± 0.2
0.10 - 0.30	25 - 79 (31.2)	216/194	0.984 ± 0.002	0.828 ± 0.077	2.331 ± 0.153	1.6 ± 0.2
0.30 - 0.50	2 - 9 (6.6)	213/194	0.912 ± 0.007	0.754 ± 0.027	1.046 ± 0.049	6.0 ± 0.6
0.30 - 0.50	10 - 24 (15.5)	247/194	0.970 ± 0.002	0.636 ± 0.023	1.643 ± 0.051	2.3 ± 0.2
0.30 - 0.50	25 - 79 (31.2)	223/194	0.984 ± 0.002	0.549 ± 0.033	1.839 ± 0.089	1.2 ± 0.2
0.50 - 1.00	2 - 9 (6.6)	228/194	0.911 ± 0.009	0.626 ± 0.039	1.034 ± 0.079	6.6 ± 0.8
0.50 - 1.00	10 - 24 (15.5)	218/194	0.957 ± 0.003	0.508 ± 0.024	1.331 ± 0.059	3.4 ± 0.2
0.50 - 1.00	25 - 79 (31.2)	211/194	0.979 ± 0.003	0.428 ± 0.029	1.456 ± 0.086	1.5 ± 0.2
$\sqrt{s} = 7$ TeV						
0.10 - 0.30	2 - 9 (6.6)	216/194	0.910 ± 0.008	1.025 ± 0.057	1.144 ± 0.062	7.3 ± 0.7
0.10 - 0.30	10 - 24 (16.4)	287/194	0.970 ± 0.002	0.865 ± 0.041	1.856 ± 0.065	2.8 ± 0.2
0.10 - 0.30	25 - 79 (38.5)	295/194	0.984 ± 0.001	0.899 ± 0.039	2.544 ± 0.076	1.5 ± 0.1
0.30 - 0.50	2 - 9 (6.6)	202/194	0.935 ± 0.008	0.807 ± 0.039	1.187 ± 0.066	4.1 ± 0.7
0.30 - 0.50	10 - 24 (16.4)	288/194	0.964 ± 0.002	0.639 ± 0.023	1.606 ± 0.050	2.8 ± 0.2
0.30 - 0.50	25 - 79 (38.5)	328/194	0.982 ± 0.001	0.592 ± 0.018	2.015 ± 0.048	1.3 ± 0.1
0.50 - 1.00	2 - 9 (6.6)	181/194	0.883 ± 0.013	0.655 ± 0.042	0.919 ± 0.078	9.4 ± 1.1
0.50 - 1.00	10 - 24 (16.4)	263/194	0.936 ± 0.003	0.554 ± 0.026	1.430 ± 0.057	5.2 ± 0.2
0.50 - 1.00	25 - 79 (38.5)	341/194	0.973 ± 0.001	0.446 ± 0.016	1.611 ± 0.048	2.0 ± 0.1

Table 3. Results of fits using the exponential parameterization for $\Omega(Qr)$ to the double ratios $\mathcal{R}$, for three intervals in k_{T} and three intervals in charged-particle multiplicity in the event, N_{ch}, for $\sqrt{s} = 0.9$ and 7 TeV. The errors are statistical only. The systematic uncertainties, which are point-to-point correlated, are estimated from the relative uncertainties affecting the overall measurements (see text).

ratio $\mathcal{R}$ as a function of Q for different values of N_{ch} and k_{T}. The k_{T} dependence of the r and λ parameters for three intervals of multiplicity, obtained with the exponential parameterization, is shown in figure 3 and given in table 3 for the 0.9 and 7 TeV data. The effective radius r is observed to increase with multiplicity, for all reference samples and for all MC models and tunes, in agreement with previous results. At low multiplicity, r is approximately independent of k_{T}, and it decreases with k_{T} as N_{ch} increases. The λ parameter decreases with increasing multiplicity and k_{T}. The systematic uncertainties are estimated to be the same as for the overall measurements (4.7% and 6.8% for λ, 9.6% and 11.1% for r, at 0.9 and 7 TeV, respectively). It should be noted that these uncertainties are point-to-point correlated, since the effects of the choice of the various reference samples and of the various MC simulations are very similar for the different subsamples. The 0.9 TeV results agree with those of ALICE [5].

Figure 4 presents the distribution of the parameter r as a function of N_{ch} for both centre-of-mass energies. The measurements are consistent, indicating that the difference between the values of r obtained for the two global samples are accounted for by the different average charged-particle multiplicities, which are 12.1 and 19.2 for the 0.9 and 7 TeV cases, respectively. This trend is consistent with the result of a similar comparison between data at 0.9 and 2.36 TeV [4]. The multiplicity dependence is fitted as $r(N_{\mathrm{ch}}) = a \cdot N_{\mathrm{ch}}^{1/3}$ [26], giving $a = 0.597 \pm 0.009$ (stat.) ± 0.057 (syst.) fm at 0.9 TeV and $a = 0.612 \pm 0.007$ (stat.) ± 0.068 (syst.) fm at 7 TeV.

As was noted above and can be deduced from the χ^2/N_{dof} in table 1, none of the quoted

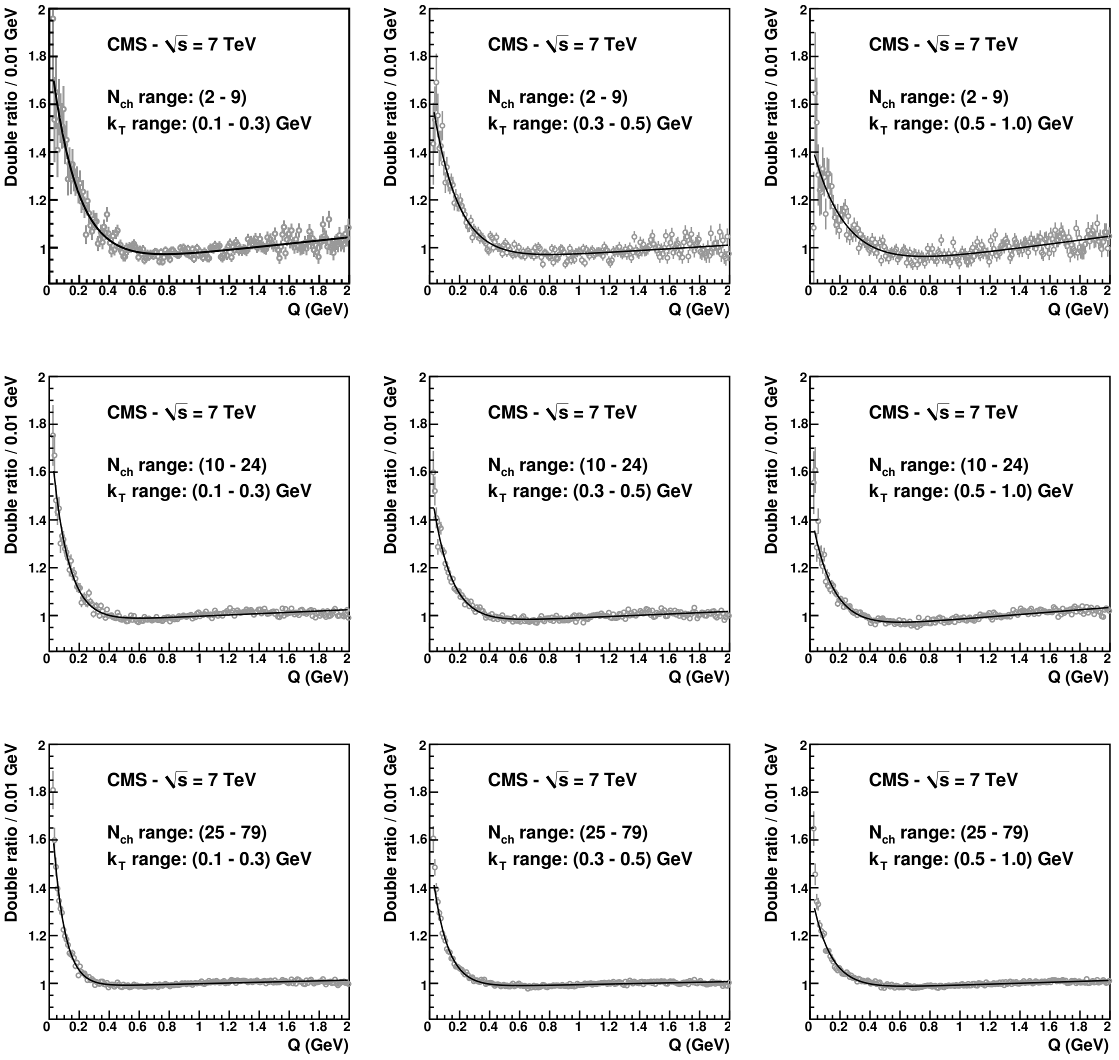

Figure 2. Distributions of the double ratio $\mathcal{R}$ as a function of Q, for three intervals in k_{T} and three intervals in charged-particle multiplicity in the event, N_{ch}, for $\sqrt{s} = 7\,\mathrm{TeV}$. The lines are the results of fits using the exponential parameterization for $\Omega(Qr)$, with the values of the parameters given in table 3. The error bars are statistical only.

functions is able to provide a good description of the $\mathcal{R}$ distributions. This is due to an anticorrelation effect between same-sign charged particles for Q values just above the signal region (dip with $\mathcal{R} < 1$), as shown in figure 5. This anticorrelation is observed in the double ratio at both energies with any choice of reference sample and MC simulation. It shows little sensitivity to k_{T}, while it decreases with increasing charged-particle multiplicity in the event, as shown in figure 6 for the 7 TeV data. This detailed observation is made possible by the large data samples studied here, and constitutes the first evidence of this effect at the LHC. Such a structure was observed in e^+e^- collisions at LEP [27]. The presence of a region of anticorrelation between same-sign charged particles has been explained in [8],

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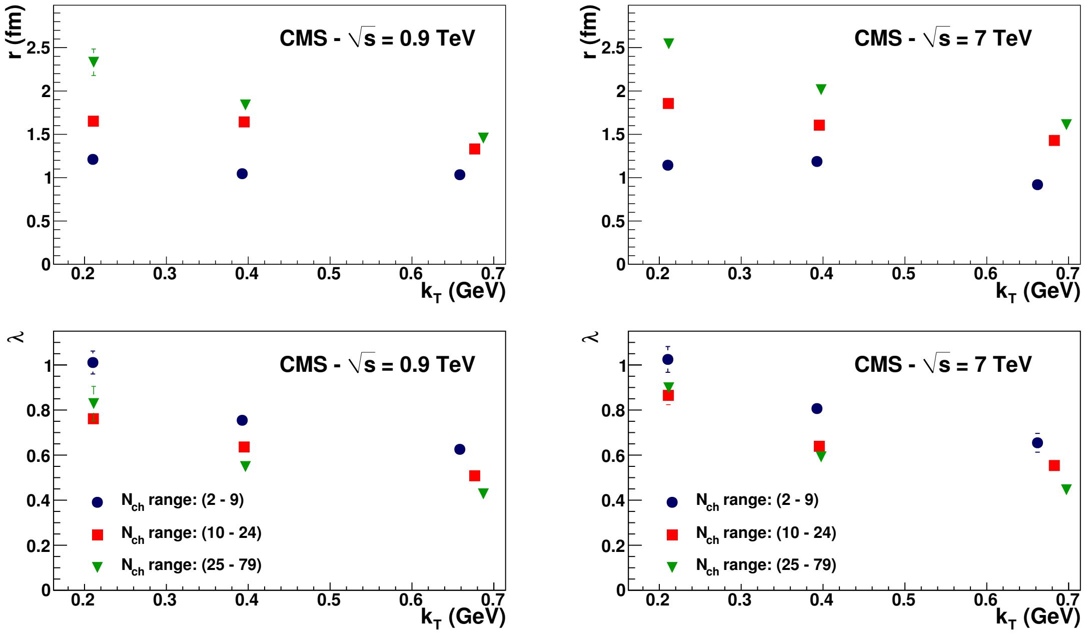

Figure 3. Values of the parameters r (top) and λ (bottom), as a function of k_{T} in three intervals of charged-particle multiplicity in the event, N_{ch}, for $\sqrt{s} = 0.9$ (left) and 7 TeV (right). The points are presented at the position corresponding to the mean value of k_{T} in the considered interval of N_{ch}. The error bars are statistical only (in some cases they are smaller than the marker size). The systematic uncertainties are discussed in the text.

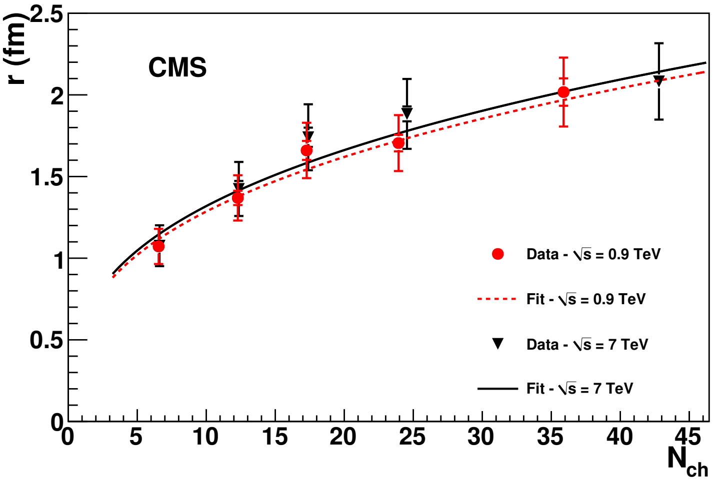

Figure 4. Parameter r as a function of the charged-particle multiplicity in the event, N_{ch}, for $\sqrt{s} = 0.9$ and 7 TeV. The dotted and solid lines represent the results of the fits described in the text to the 0.9 and 7 TeV data, respectively. The inner error bars represent the statistical uncertainties and the outer error bars the statistical and systematic uncertainties, added in quadrature. The systematic uncertainties are dominating and are point-to-point correlated.

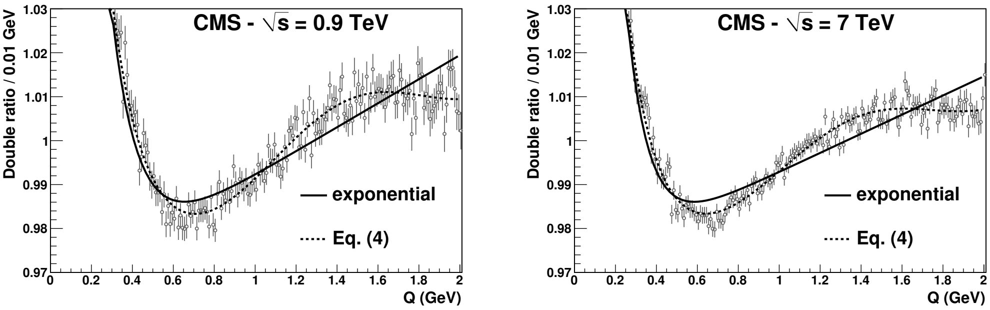

Figure 5. Detail of the distribution of the double ratio $\mathcal{R}$ for $\sqrt{s} = 0.9$ (left) and 7 TeV (right). The dotted lines correspond to fits with eq. (4.1), and the solid lines to exponential fits. Note the enlarged scale on the y axis. The error bars are statistical only.

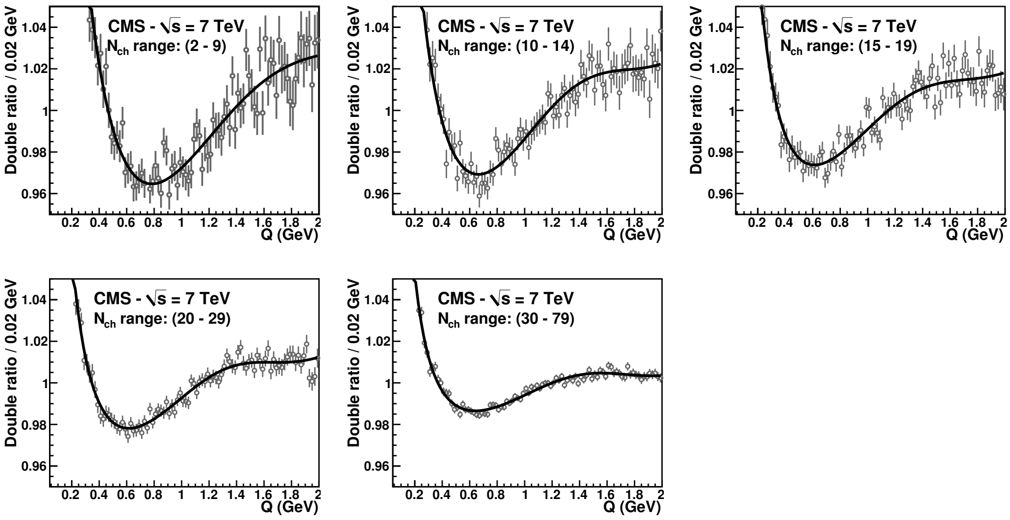

Figure 6. Detail of the distribution of the double ratio $\mathcal{R}$ for $\sqrt{s} = 7$ TeV using different intervals of charged-particle multiplicity in the event (N_{ch}). The lines are fits to the data with eq. (4.1). The error bars are statistical only.

where the following parameterization has been proposed for $R(Q)$:

$$R(Q) = C\left[1 + \lambda(\cos\left[(r_0 Q)^2 + \tan(\alpha\pi/4)(Qr_\alpha)^\alpha\right] e^{-(Qr_\alpha)^\alpha})\right] \cdot (1 + \delta Q). \tag{4.1}$$

Equation (4.1) corresponds to a parameterization describing the time evolution of the source by means of a one-sided asymmetric Lévy distribution. The parameter r_0 is related to the proper time of the onset of particle emission, r_α is a scale parameter entering in both the exponential and the oscillating factors, and α corresponds to the Lévy index of stability. This model was derived initially in [7] for describing point-like interactions, such as in $\mathrm{e^+e^-}$ collisions. It assumes that particle production has a broad distribution in proper time but the phase-space distribution of emitted particles is dominated by strong correlations between the space-time coordinates and the momentum components of the emitted particles.

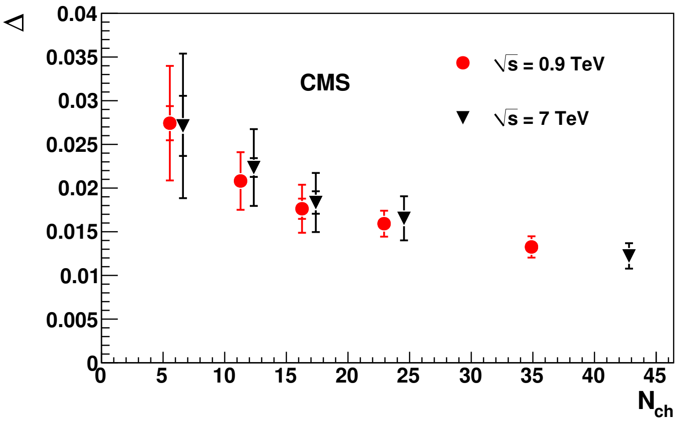

Figure 7. Depth Δ of the dip in the anticorrelation region, as a function of the charged-particle multiplicity in the event, for $\sqrt{s}$ = 0.9 and 7 TeV. The inner error bars represent the statistical errors and the outer error bars the statistical and systematic errors, added in quadrature. The systematic uncertainties are dominating and are point-to-point correlated. To improve the clarity of the presentation, the points at 0.9 TeV are shifted to the left by one unit in N_{ch}.

In figures 5 and 6 eq. (4.1) is used to parameterize the correlation functions. Fits are of good quality, with $\chi^2/N_{\mathrm{dof}} = 213/192$ and $\chi^2/N_{\mathrm{dof}} = 215/192$ at 0.9 and 7 TeV, respectively. However, as for the Lévy function, large (anti)correlations among parameters are observed, which induce a variability of their nominal values. The depth of the dip in the anticorrelation region is measured as the difference Δ between the baseline curve defined as $C \cdot (1 + \delta Q)$ and the value of R defined by eq. (4.1) at its minimum. Results are shown in figure 7. The depths are found to decrease with N_{ch} consistently for the two centre-of-mass energies. The systematic errors have been computed from the r.m.s. spread of the results obtained with the various reference samples, MC simulations and fit ranges. It has been checked that these results are robust: when the fitting range is extended as far as to Q = 5 GeV, where the baseline description may not be good, the results are consistent within errors and the trend is similar.

5 Conclusions

Bose-Einstein correlations have been measured using data collected with the CMS experiment in proton-proton collisions at the LHC, with centre-of-mass energies of 0.9 and 7 TeV. The signal is observed as an enhancement of pairs of same-sign charged particles with small relative momentum. The parameters are obtained from fits using the exponential parameterization for $\Omega(Qr)$ to the distribution of Q. In agreement with previous results, an increase of the effective emission radius r with charged-particle multiplicity in the event is observed, which accounts for the increase of r from 0.9 to 7 TeV. The parameter r is nearly independent of the average transverse momentum of the pair of particles at the lowest multiplicity range, and decreases with k_{T} in events with large charged-particle multiplicity. For the first time in pp interactions, anticorrelations between same-sign charged particles are observed for Q values above the signal region, as previously reported with LEP data. The anticorrelation effects decrease with increasing charged-particle multiplicity in the event considered in this analysis.

The numerical values of the data presented in figure 1 can be found in ref. [28].

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