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Bose-Einstein correlations with first LHC data in CMS

L. Perrozzi on behalf of the CMS Collaboration
Università di Padova and INFN - Padova, Italy

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Summary. — 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 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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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 [1], a number of measurements have been made by several experiments [2]. 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 can be parameterized as an exponential function $\Omega(Qr) = e^{-Qr}$

or with a Gaussian form $\Omega(Qr) = e^{-(Qr)^2}$ [3], where the parameter λ reflects the BEC strength, δ accounts for long-range correlations, and C is a normalization factor.

This study reports the measurement of BEC parameters in pp collisions at 0.9 and 2.36 TeV with the CMS detector [4] at the Large Hadron Collider. The central feature of the CMS apparatus is a superconducting solenoid 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 an inner pixel detector and a silicon strip tracker extending outwards to a radius of 1.1 m. The events were selected by requiring activity in both beam scintillator counters [5]. A minimum-bias Monte Carlo (MC) sample was generated using PYTHIA (with D6T tune) [6] followed by full detector simulation based on the Geant4 program [7]. Charged particles are required to have $p_T > 200\,\mathrm{MeV}/c$ to ensure good two-track separation, pseudorapidity $|\eta_{\mathrm{track}}| < 2.4$, more than five degrees of freedom (dof), $\chi^2/N_{\mathrm{dof}} < 5.0$ and transverse impact parameter with respect to the beam spot $|d_{xy}| < 0.15\,\mathrm{cm}$. 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. A total of 270 472 (13 548) events are selected at 0.9 (2.36) TeV center-of-mass energy. All pairs of same-charge particles with Q greater than 0.02 are used for the measurement to avoid cases of tracks that are duplicated or not well separated. The effect of Coulomb interactions between charged particles is corrected for by using Gamow factors [8]. Different methods are designed to define reference samples used to extract the distribution in the denominator of eq. (1): *opposite-charge pairs*, *opposite-hemisphere pairs* $(E,\vec{p}) \to (E,-\vec{p})$, *rotated particles* $(p_x,p_y,p_z) \to (-p_x,-p_y,p_z)$, *pairs from mixed events*. In the latter case 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 similar invariant mass of all charged particles. Additional details are given in ref. [9]. In order to reduce the bias due to the construction of the reference samples, a double ratio $\mathcal{R}$ is defined:

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

where the subscripts “MC” and “MC,ref” refer to the corresponding distributions from the MC simulated data generated without BEC effects. 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. 1. The data are described by eq. (2) with an exponential form for $\Omega(Qr)$, as shown by the solid lines in fig. 1. The fit with a Gaussian form, $\Omega(Qr) = e^{-(Qr)^2}$, which yields $\lambda = 0.32 \pm 0.01$, $r = 0.98 \pm 0.03\,\mathrm{fm}$ a 0.9 TeV, does not correctly describe the $\mathcal{R}(Q)$ distribution, as shown by the dashed lines in fig. 1. Gaussian shape fits also proved to offer a poor description of the data in previous measurements [10].

The leading source of systematic uncertainty on the measurements arises from the fact that none of the reference samples 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.*, ±7% for λ and ±12% for r. The systematic uncertainty related to the Coulomb corrections is ±2.8% variation for λ and ±0.8% for r. For the 2.36 TeV data the same relative systematic uncertainties

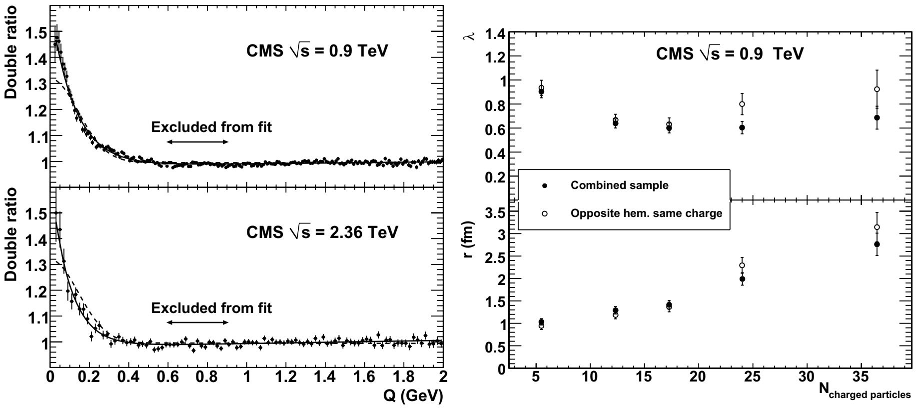

Fig. 1. – Left: fits to the double ratios $\mathcal{R}^{\text{comb}}(Q)$ with exponential (solid lines) and Gaussian (dashed lines) functions, for 0.9 TeV (top) and 2.36 TeV (bottom) data. The range $0.6 < Q < 0.9$ GeV is excluded from the fits. Right: values of the λ (top) and r (bottom) parameters as a function of the charged-particle multiplicity in the event at 0.9 TeV for combined (filled circles) and opposite-hemisphere, same-charge (open circles) reference samples.

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 $\lambda = 0.625 \pm 0.021\,(\text{stat.}) \pm 0.046\,(\text{syst.})$ and $r = 1.59 \pm 0.05\,(\text{stat.}) \pm 0.19\,(\text{syst.})$ fm at 0.9 TeV; $\lambda = 0.663 \pm 0.073\,(\text{stat.}) \pm 0.048\,(\text{syst.})$ and $r = 1.99 \pm 0.18\,(\text{stat.}) \pm 0.24\,(\text{syst.})$ fm at 2.36 TeV. A significant dependence of r on the charged-particle multiplicity in the event is observed for all reference samples. The fit parameters for the combined reference sample are shown in fig. 1 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. 1. 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. The dependence of r on multiplicity was already observed in previous measurements as discussed in detail in [2].

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. Several reference samples were used 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.

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