# Measurement of **Bose-Einstein Correlations** in pp Collisions at $\sqrt{s}$ =0.9 and 7 TeV with the CMS detector (*)

P. Checchia[1)], T. Dorigo [1)], M. Galanti [2)], S. Lacaprara [1)], M. Margoni [1)], M. Nespolo [1)], S. Padula [3)], L. Perrozzi [1)], F. Simonetto [1)], E. Torassa [1)]

[1)]University & INFN Padova; [2)]University of Cyprus; [3)] IFT-UNESP São Paulo

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## Theoretical 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 due to constructive interference that affects the joint probability for the emission of a pair of identical bosons with four-momenta $p_1$ and $p_2$. The proximity in phase space between final-state particles is quantified by the Lorentz-invariant quantity

$$Q = \sqrt{-(p_1 - p_2)^2} = \sqrt{M^2 - 4m_\pi^2}$$

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: $R(Q) = (dN/dQ)/(dN_{ref}/dQ)$ which is then fitted with the parametrization

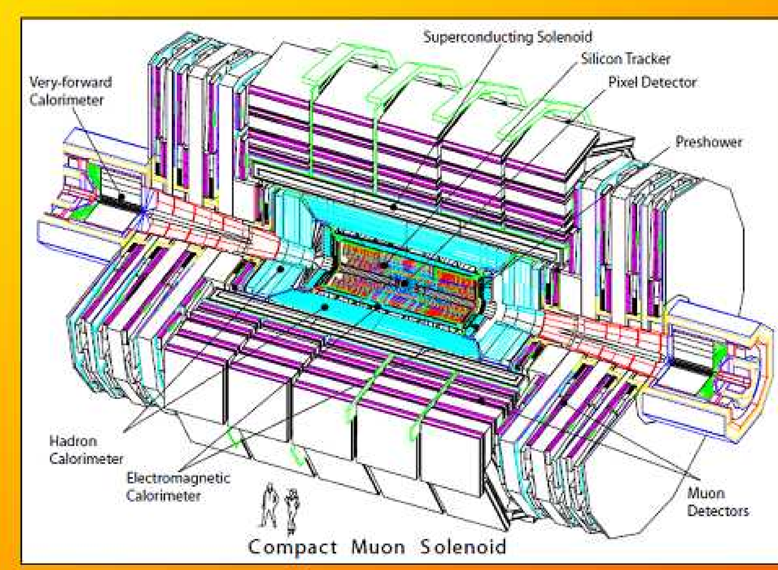
$$R(Q) = C \cdot [1 + \lambda\Omega(Qr)] \cdot (1 + \delta Q)$$

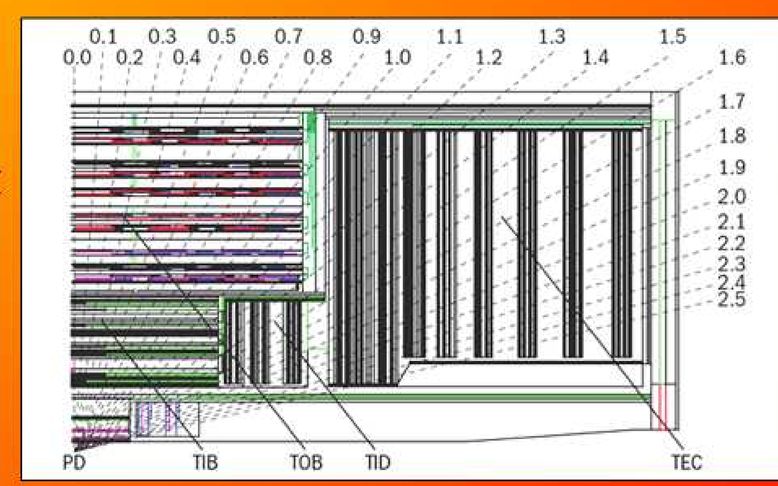
$\Omega$ is often phenomenologically parameterized as $\Omega(Qr) = e^{-(Qr)^2}$ or $\Omega(Qr) = e^{-Qr}$ where the parameter r is the effective size of the source, $\lambda$ measures the strength of BEC for incoherent boson emission from independent sources, $\delta$ accounts for long-distance correlations, and $C$ is a normalization factor.

## CMS inner detector and track selection

The central feature of the CMS apparatus is a superconducting solenoid providing an axial magnetic field of 3.8 T. The inner tracking system, the most relevant detector for the present analysis, consists of three layers of pixels (up to 11 cm radius) and ten layers of silicon strips, out to a radius of 1.1 m.

Selected charged particles are required to have $p_T$>200 MeV, pseudorapidity $|\eta|$<2.4, the trajectories are required to be reconstructed in fits with $N_{dof}$ > 5 and $\chi^2/N_{dof}$<5. The transverse impact parameter 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, in order to reduce electrons and positrons from photon conversions in the detector material and secondary particles from the decay of long-lived hadrons ($K_s^0$, $\Lambda$, etc.).

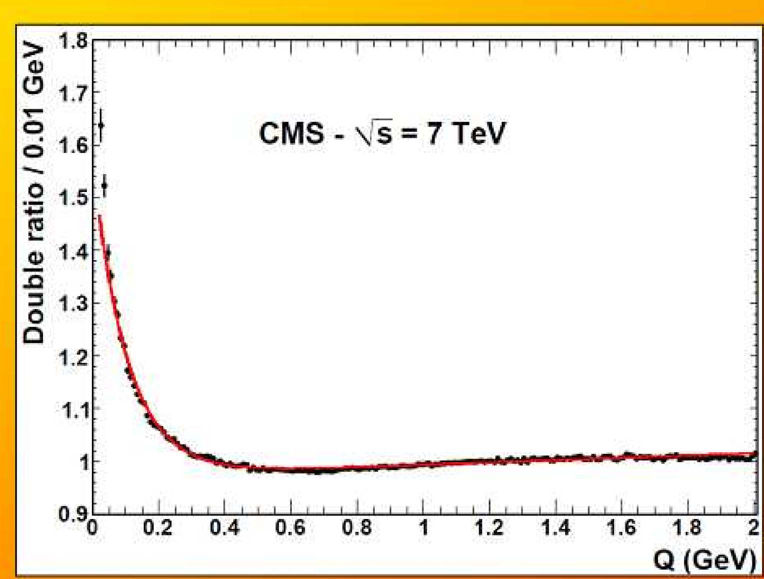



## Definition of signal and reference sample

The signal is obtained by combining all pairs of same-charge particles with $Q$ between 0.02 and 2 GeV. The range is chosen to avoid both cases of tracks that are not well separated and to allow verification of a good match between signal and reference samples far enough beyond the signal region. The most suitable method to combine uncorrelated charged particles is obtained by mixing particles in events with similar charged particle multiplicity in the same $\eta$ region. In order to reduce the bias due to the construction of the reference samples, a double ratio defined as:

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

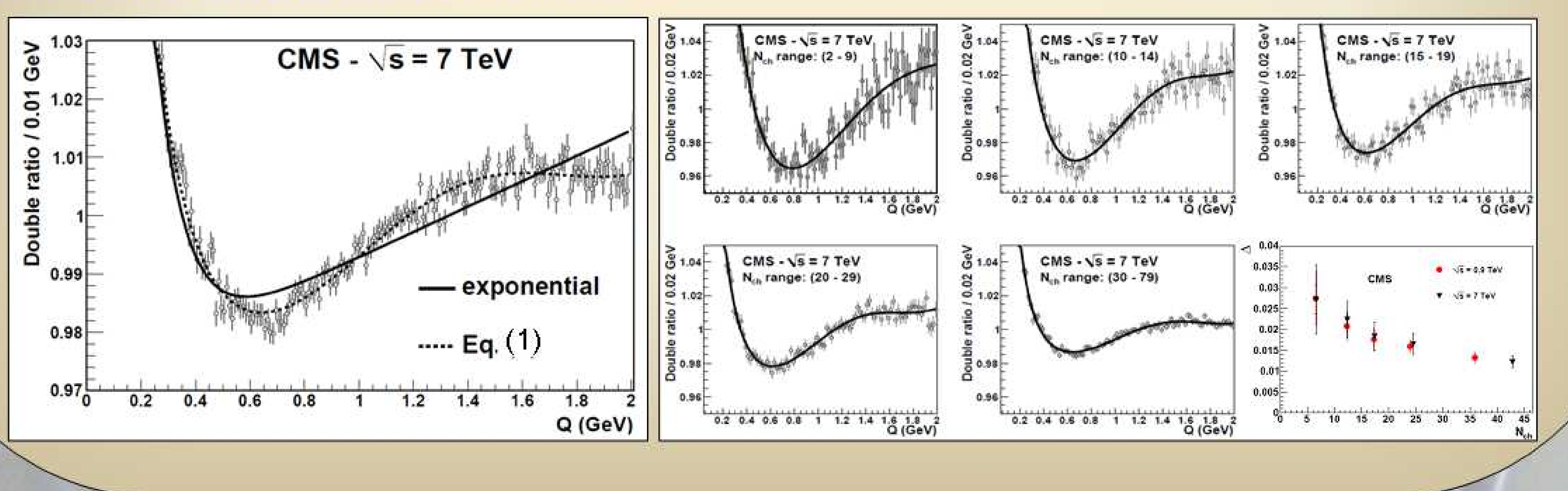



## BEC fitting functions

The $\Omega$ functions used in literature to fit the BEC distribution, are not able to provide a good description of the $\mathcal{R}$ distributions. This is mainly due to an anticorrelation effect between same-sign charged particles for Q values just above the signal region (dip with R<1). This anticorrelation is observed in the double ratio at both energies with many choices of reference sample and MC simulation. Such a structure was observed in $e^+e^-$ collisions at LEP by the L3 collaboration. A parameterization for R(Q) has been proposed, aimed at describing the time evolution of the source:

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

where $r_0$ is related to the proper time of the onset of particle production, and r enters in both the exponential and the oscillation factors. Fits with Eq. (1) are of very good quality, and the $\chi^2/N_{dof}$ is 1.1 both for the 0.9 and 7 TeV data. The depth of the dip in the anticorrelation region is measured as the difference $\Delta$ between the baseline curve defined as $C \cdot (1+\delta Q)$ and the value of R defined by Eq. (1). The depths are found to decrease with $N_{ch}$ consistently for the two centre-of-mass energies. It has been checked that these results are robust: when the fitting range is extended to Q = 5 GeV the results are consistent within errors and the trend is similar.




## Determination of BEC parameters

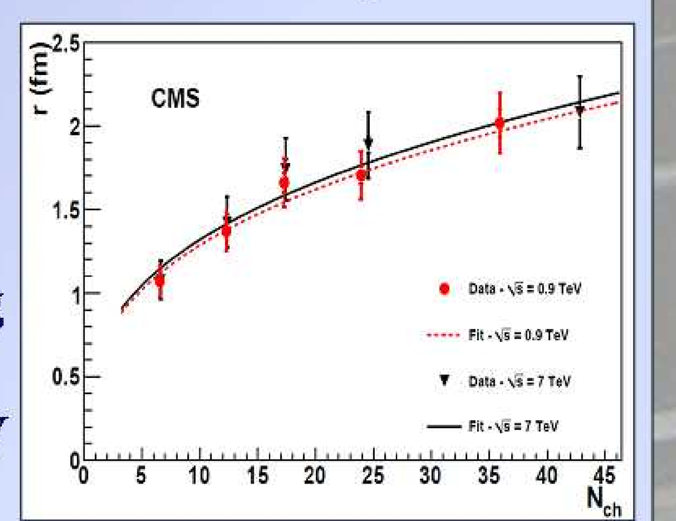
The fits to the double ratio performed with exponential $\Omega$ form lead to:

| $\sqrt{s}$ | $\chi^2/N_{dof}$ | C | $\lambda$ | r (fm) | $\delta$ ($10^{-2}$ GeV$^{-1}$) |
|---|---|---|---|---|---|
| 0.9 TeV | 2.5 | $0.965 \pm 0.001$ | $0.616 \pm 0.011$ | $1.56 \pm 0.02$ | $2.8 \pm 0.1$ |
| 7 TeV | 3.8 | $0.971 \pm 0.001$ | $0.618 \pm 0.009$ | $1.89 \pm 0.02$ | $2.2 \pm 0.1$ |

the main systematics uncertainties, coming from the choice of the MC tune and the reference sample, are estimated to be 4.2% (6.3%) for $\lambda$ and 7.9% (10.1%) for $r$ at 0.9 TeV (7 TeV). The increase of r is mainly related to the different average charged-particle multiplicities in the event ($N_{ch}$) at the two energies. Indeed if we measure the parameter r as a function of $N_{ch}$ for both centre-of-mass energies, the measurements are consistent. Using the fitting function $r(N_{ch}) = a \cdot (N_{ch})^{1/3}$ we obtain

a= 0.597 ±0.009(stat.)±0.047(syst.) fm at 0.9 TeV

a = 0.612 ±0.007(stat.)±0.063(syst.) fm at 7 TeV.




The BEC signal is also studied as a function of the charged-particle multiplicity in the event, $N_{ch}$, and of the pair average transverse momentum $k_T$, defined as $k_T = |\mathbf{p}_{T,1} + \mathbf{p}_{T,2}|/2$. In fact a dependence on $k_T$ has been observed at the Tevatron and at RHIC, where it is associated with the system collective expansion. Using the exponential $\Omega$ parameterization, the effective radius r is observed again to increase with multiplicity; at low multiplicity, r is approximately independent of $k_T$, and it decreases with $k_T$ as $N_{ch}$ increases. The $\lambda$ parameter decreases with increasing multiplicity and $k_T$.