Measurements of Bose-Einstein correlations with the ATLAS detector

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on behalf of the ATLAS collaboration
Outline

- Bose-Einstein correlations
- Two-particle correlation function
- Data and Monte Carlo samples
- Parameterizations of BEC
- Applied corrections
- Results
- Conclusions
A Toroidal LHC Apparatus

Minimum Bias Trigger Scintillator (MBTS)

Inner Detector (ID)
Bose-Einstein Correlations

- **First ATLAS BEC results** publication → arXiv:1502.07947 - submitted to EPJC (Feb. 2015)

- Bose-Einstein correlations - correlations between two identical bosons (consequence of the symmetry of identical bosons wave function) - **BEC effect** corresponds to an enhancement in two identical boson **correlation function** when the two particles are near in momentum space.

- **BEC** - sensitive probe of the space-time geometry of the hadronization region - allows the determination of the size and the shape of the source from which particles are emitted.

- Dependence of BEC on particle multiplicity and transverse momentum - helps to understand the multiparticle production mechanism.
Two particle correlation function

\[ C_2(q) = \frac{P(p_1, p_2)}{P(p_1)P(p_2)} \]

\[ q = p_1 - p_2 \quad , \quad p = p_1 + p_2 \]

\[ Q = \sqrt{|p_1 - p_2|^2} \]

Probability to observe two particles with momenta \( p_1 \) and \( p_2 \)

Probability to observe one particle with momenta \( p_1 \) or \( p_2 \)

Density function - parameterized in terms of the Lorentz invariant four-momentum difference squared: \( Q^2 = -(p_1 - p_2)^2 \)

\[ C_2(Q) = C_0 [1 + \Omega(\lambda, QR)](1 + \varepsilon Q) \]

BEC effect - described by a function with two parameters:
- the effective radius \( R \) and
- the strength parameter \( \lambda \) - incoherence or chaoticity factor.
The $C_2(Q)$ correlation function is a ratio of like-sign (LS) particle (track) pairs $Q$ distribution – signal distributions $N(Q)$ with BEC and particle (track) pairs $Q$ distribution – reference distribution $N_{ref}(Q)$ with no BEC.

Experimentaly constructed $C_2(Q)$ correlation function

$$C_2(Q) = \frac{N^{ls}(Q)}{N^{ref}(Q)}$$

Basic reference distributions:

- **unlike-sign track pairs (UCP)** – pairs of non-identical particle (with opposite charge) taken from the same event,

- **mixed-event** (like-sign track pairs created from different events),

- **opposite-hemisphere pairs** (OHP- one of track: $p_x \rightarrow -p_x$, $p_y \rightarrow -p_y$, $p_z \rightarrow -p_z$) with $++--$ track combinations,

- **rotated track technique** (one of track: $p_x \rightarrow -p_x$, $p_y \rightarrow -p_y$) with $++--$ track combinations.

**double ratio correlation function**

$$R^{DR}_2(Q) = \frac{C_2^{Data}(Q)}{C_2^{MC}(Q)}$$
**GSSg model.** The Goldhaber spherical source model of a static Gaussian source in the plane-wave approach.

\[ C^{(G)}_2 = C_0 \left( 1 + \lambda e^{-R^2Q^2} \right) \cdot (1 + Q\varepsilon) \]

**GSSe model.** The exponential parameterization of a static source - assumes a radial Lorentzian distribution of the source.

\[ C^{(E)}_2 = C_0 \left( 1 + \lambda e^{-RQ} \right) \cdot (1 + Q\varepsilon) \]

\( \lambda \) is the **incoherence factor** \((0, 1)\)

**QOg model.** Quantum Optics model - Gaussian form.

\[ C^{(GO)}_2 = C_0 \left( 1 + 2p(1 - p)e^{-R^2Q^2} + p^2 e^{-2R^2Q^2} \right) \cdot (1 + Q\varepsilon) \]

**QOe model.** Quantum Optics model - exponential form

\[ C^{(EO)}_2 = C_0 \left( 1 + 2p(1 - p)e^{-RQ} + p^2 e^{-2RQ} \right) \cdot (1 + Q\varepsilon) \]

\( p \) is the chaoticity: \( =0 \ ( =1) \) for purely **coherent** (chaotic) sources.
Data and MC samples

- Study based on the Min Bias data sets and MC samples generated by PYTHIA 6 with ATLAS MC09, DW, Perugia runes, Phojet 1.12.1.35, and EPOS 1.99.

- Statistics: at 900 GeV: $3.6 \times 10^5$ events with $4.5 \times 10^6$ tracks and at 7 TeV: $1 \times 10^7$ events with $2.1 \times 10^8$ tracks passed selection criteria.

- High Multiplicity (HM) dataset at 7 TeV was studied for the first time in BEC analyses. Statistic for 7 TeV (HM) $1.8 \times 10^4$ events ($2.7 \times 10^6$ tracks) were selected (integrated luminosity $\sim 12.4 \text{ nb}^{-1}$).

- Integrated luminosities: 7 $\mu$b$^{-1}$ at 0.9 TeV and 190 $\mu$b$^{-1}$ at 7 TeV.

- Track and event selection criteria applied (details in backup s.24)

- Tracking and event efficiencies, unfolding to particle level.
Applied corrections
The measured $N(Q)$ distribution for the like or unlike signed particle pairs in presence of the Coulomb interaction is given by:

$$N_{\text{meas}}(Q) = G(Q)N(Q)$$

where $N_{\text{meas}}(Q)$ is the measured distribution, $N(Q)$ is the distribution free of Coulomb interaction.

Gamow penetration $G(Q)$ factor

$$G(Q) = \frac{2\pi\eta}{e^{2\pi\eta} - 1}$$

Sommerfeld parameter $\eta$

$$\eta = \frac{\pm \alpha m}{|Q|}$$

The size of this correction not to exceed 20% for $Q > 0.03$ GeV.
Event corrections

- The trigger efficiency – $\varepsilon_{\text{trig}}(n)$,
- The vertex reconstruction efficiency – $\varepsilon_{\text{vert}}(n)$,

We use the formula: 

$$w(n) = \frac{1}{\varepsilon_{\text{trig}}(n) \cdot \varepsilon_{\text{vert}}(n)}$$

For multiplicities $n \geq 3$ these corrections are close to 1

Trigger efficiency $\varepsilon_{\text{tr}}(n)$ at 7 TeV:
- $\varepsilon_{\text{tr}}(1) = 0.968$
- $\varepsilon_{\text{tr}}(2) = 0.978$
- $\varepsilon_{\text{tr}}(3) = 0.993$
- $\varepsilon_{\text{tr}}(>5) = 1.0$

The multiplicity distributions - corrected to the particle level using an iterative method (Bayesian approach).

The unfolding matrix is built using the ATLAS MC09 PYTHIA tune.

Fraction of pile-up in the HM events

Fraction of events with pile-up: 1-2%, $\Rightarrow$ charged particle from the pile-up vertex do not contribute much to each primary vertex (negligible).
Performed corrections for:
1. The track reconstruction efficiency $\varepsilon (p_t, \eta)$,
2. The fraction of secondary particles $f_{\text{sec}}(p_t, \eta)$,
3. The fraction of selected tracks for which the corresponding primary particles are outside the kinematic range $f_{\text{okr}}(p_t, \eta)$,
4. The fake tracks $f_{\text{fake}}(p_t, \eta)$,

We use the formula:

$$w_i(p_t, \eta) = \frac{(1 - f_{\text{sec}}(p_t, \eta)) \cdot (1 - f_{\text{okr}}(p_t, \eta)) \cdot (1 - f_{\text{fake}}(p_t, \eta))}{\varepsilon(p_t, \eta)}$$

We take measured ATLAS $\varepsilon (p_t, \eta)$ and $f (p_t, \eta)$ distributions.

- The effect of events lost due to the trigger and vertex reconstruction - corrected using event-by-event weights applied to each pair of particles.
- The resolution of Q - obtained to be better than 5 MeV - to exclude track fake reconstruction the Q-threshold 20 MeV was taken.
Systematic uncertainties

Systematic uncertainties on $\lambda$ and $R$ for the exponential fit of the two-particle double-ratio correlation function $R_2(Q)$ in the full kinematic region at $\sqrt{s} = 0.9$ and 7 TeV for minimum-bias and high-multiplicity (HM) events.

<table>
<thead>
<tr>
<th>Source</th>
<th>0.9 TeV</th>
<th>7 TeV</th>
<th>7 TeV (HM)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\lambda$</td>
<td>$R$</td>
<td>$\lambda$</td>
</tr>
<tr>
<td>Track reconstruction efficiency</td>
<td>0.6%</td>
<td>0.7%</td>
<td>0.3%</td>
</tr>
<tr>
<td>Track splitting and merging</td>
<td>negligible</td>
<td></td>
<td>negligible</td>
</tr>
<tr>
<td>Monte Carlo samples</td>
<td>14.5%</td>
<td>12.9%</td>
<td>7.6%</td>
</tr>
<tr>
<td>Coulomb correction</td>
<td>2.6%</td>
<td>0.1%</td>
<td>5.5%</td>
</tr>
<tr>
<td>Fitted range of $Q$</td>
<td>1.0%</td>
<td>1.6%</td>
<td>1.6%</td>
</tr>
<tr>
<td>Starting value of $Q$</td>
<td>0.4%</td>
<td>0.3%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Bin size</td>
<td>0.2%</td>
<td>0.2%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Exclusion interval</td>
<td>0.2%</td>
<td>0.2%</td>
<td>1%</td>
</tr>
<tr>
<td>Total</td>
<td>14.8%</td>
<td>13.0%</td>
<td>9.6%</td>
</tr>
</tbody>
</table>
Correlation function $R_2(Q)$: Gaussian and exponential fits

The two-particle double-ratio correlation function $R_2(Q)$ in pp collisions at (a) $\sqrt{s} = 0.9$ TeV, (b) 7 TeV and (c) 7 TeV high-multiplicity events. Region excluded from the fits - bump is due to an overestimate of $\rho \rightarrow \pi^+\pi^-$ decays in the Monte Carlo simulation. Only statistical uncertainties shown.

The results of BEC parameters for fits (exponential) of $R_2(Q)$, the unlike-charge particle reference sample used:

$$\lambda = 0.74 \pm 0.11, \quad R = 1.83 \pm 0.25 \text{ at } \sqrt{s} = 0.9 \text{ TeV for } n_{ch} \geq 2,$$

$$\lambda = 0.71 \pm 0.07, \quad R = 2.06 \pm 0.22 \text{ at } \sqrt{s} = 7 \text{ TeV for } n_{ch} \geq 2,$$

$$\lambda = 0.52 \pm 0.06, \quad R = 2.36 \pm 0.30 \text{ at } \sqrt{s} = 7 \text{ TeV for } n_{ch} \geq 150.$$
Parameters $\lambda$ and $R$ vs particle multiplicity

**Multiplicity, $n_{ch}$, dependence** of (a) $\lambda$ and (b) $R$ from the exponential fit to $R_2(Q)$ functions at $\sqrt{s} = 0.9$ and 7 TeV, compared to measurements of the CMS and UA1 experiments.

The curves are the results of (a) the exponential and (b) $3\sqrt{n_{ch}}$ for $n_{ch} < 55$ fits.

The dotted line in (b) is a result of a constant fit to minimum-bias and high-multiplicity events data at 7 TeV for $n_{ch} \geq 55 \Rightarrow$ saturation of $R$ at high multiplicities: $R[fm] = 2.28 \pm 0.32$

- expected in a Pomeron-based model

The error bars - quadratic sum of the statistical and systematic uncertainties.
Parameters $\lambda$ and $R$ vs track pair $k_T$

The $k_T$ dependence of $\lambda$ (a) and $R$ (b) - from the exponential fit to two-particle double ratio at $\sqrt{s} = 0.9$ TeV, 7 TeV and 7 TeV high-multiplicity events. The curves - results of the exponential fits.

The average transverse momentum $k_T$ of the particle pairs $k_T = |p_{T,1} + p_{T,2}|/2$.

Results - compared to measurements by the E735 experiment (Tevatron), and by the STAR experiment (RHIC).

The error bars - the quadratic sum of the statistical and systematic uncertainties.
The $k_T$ dependence of $\lambda$ (a) and $R$ (b) - from the exponential fit to $R_2(Q)$ function at $\sqrt{s} = 7$ TeV for the different multiplicity regions:

- $2 \leq n_{ch} \leq 9$ (circles),
- $10 \leq n_{ch} \leq 24$ (squares),
- $25 \leq n_{ch} \leq 80$ (triangles) and
- $81 \leq n_{ch} \leq 125$ (inverted triangles).

The decrease of $\lambda$ with $k_T$ is nearly independent of multiplicity for $n_{ch} > 9$.

$R$-parameter decreases with $k_T$ and exhibits an increase with increasing multiplicity.

The error bars - the quadratic sum of the statistical and systematic uncertainties.
Comparison with previous measurements

Most of the previous experiments provided $R$ measurement with a Gaussian fit.

The comparison to the exponential fit can be done using the scale factor $\sqrt{\pi}$:

$$R^{(G)} = R^{(E)} / \sqrt{\pi}$$

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>$R$ [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>1.03 ± 0.14</td>
</tr>
<tr>
<td>7</td>
<td>1.16 ± 0.12</td>
</tr>
<tr>
<td>7 (HM)</td>
<td>1.33 ± 0.17</td>
</tr>
</tbody>
</table>
Conclusions

• The Bose-Einstein correlations of the pairs of identical charged particles have been measured in $|\eta|<2.5$ and $p_T>100$ MeV in $pp$ collisions at 0.9 and 7 TeV with the ATLAS detector at the LHC.

• A clear signal of BEC enhancement was observed in the region of small relative momentum. The studies are carried out using the double ratio correlation function.

• Multiplicity dependence of the BEC was investigated up to very high multiplicities ($\approx240$). A saturation effect in multiplicity dependence of the extracted BEC radius was observed at level $R = 2.28 \pm 0.32$ fm.

• Dependence of the BEC parameters on track pair $k_T$ and on particle $p_T$ was investigated.
Thank you for attention
Back-up slides
Bose-Einstein Correlations of Particles

- Two plane-waves:
  \[
  \Psi_1 = e^{-i k_1 x_1} \\
  \Psi_2 = e^{-i k_2 x_2}
  \]

- (Identical) bosons need to be symmetrized
  \[
  \Psi_{1,2} = \frac{1}{\sqrt{2}} (e^{-i k_1 x_1} e^{-i k_2 x_2} + e^{-i k_1 x_2} e^{-i k_2 x_1})
  \]

- Spectrum:
  \[
  N_1(k_1) = \int S(x_1, k_1) |\Psi_1|^2 dx_1
  \]
  \(S(x,k)\) is the source distribution

- Two-particle spectrum (momentum distribution):
  \[
  N_2(k_1, k_2) = \int S(x_1, k_1) S(x_2, k_2) |\Psi_{1,2}|^2 dx_1 dx_2
  \]

- The invariant correlation function depends on relative and average moments
  \[
  C_2(k_1, k_2) = \frac{N_2(k_1, k_2)}{N_1(k_1) N_1(k_2)} \approx 1 + \left( \frac{\tilde{S}(q, K)}{\tilde{S}(0, K)} \right)^2
  \]
  \[
  C(q) - 1 \sim \exp \left( -q_x^2 R_x^2 - q_y^2 R_y^2 - q_z^2 R_z^2 \right)
  \]
  \[
  q = k_1 - k_2, \quad K = 0.5(k_1 + k_2)
  \]

- We can give the information about the size of the emitting source from identical boson correlations

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Tracks characteristics at 0.9, 7 TeV MBT

Trigger:
- L1_MBTS_1 | L1_MBTS_2 | L1_MBTS_1_1 trigger
- good run/luminosity blocks

Vertex Selection:
- Pile-up Removal cut
- Only one vertex
- $\geq 2$ "selected" track (as vertex requires 2 tracks)

Track Selection:
- $p_T \geq 100$. MeV
- $|\eta| < 2.5$
- $|d_0| < 1.5$ mm
- $|z_0 \sin \theta| < 1.5$ mm
- b-layer hit if one expected
- $\geq 1$ pixel hit
- $\geq 2,4,6$ SCT hits for $p_T > 100,200,300$ MeV
- $\chi^2$ prob $> 0.01$ for $p_T > 10$ GeV (to remove the mis-measured tracks).

Tracks characteristics at 7 TeV HMT

Trigger:
- mbSpTrkVtxMh
- Another Luminosity blocks

Vertex:
- only one good primary vertex (type 1). Removed pile-up cut as defined by the MB 2.0 analysis. Instead if second vertex has higher multiplicity than the primary, skip event.

At least 108 tracks with:
- $|\eta| < 2.5$
- $p_T \geq 100$. MeV
- Reconstructed by the inside-out or low- $p_T$ tracking algorithms.
- $\geq 1$ pixel hit*
- $\geq 2,4,6$ SCT hits for $p_T > 100,200,300$ MeV
- $|d_0| < 1.5$ mm
- $|z_0 \sin \theta| < 1.5$ mm
- fit probability $\geq 0.01$ for $p_T > 10$ GeV

*No b-layer requirement. After MB 2.0 definition of expectHitInBLayer changed.

**http://indico.cern.ch/getFile.py/access?contribId=6&resId=0&materialId=slides&confId=106091

High multiplicity trigger efficiency is 100% for multiplicity more than 120 EF tracks

HM trigger conditions:
1. Seeded by L1 TE20 (L1 calo ETsum> 20 GeV)
2. At least 1999 SCT (Semicond. tracker) space-points at L2.
3. At least 125 tracks on a single vertex at EF ($p_T>400$ MeV)
Systematic uncertainties for track reconstruction efficiency

Table 6 from ATL-PHYS-INT-2011-001. Summary of all tracking efficiency systematic. The tracking efficiency systematic  are given in bins of track $p_T$ and $\eta$. **All numbers are in percent and relative to the corresponding tracking efficiencies.** The total uncertainty is the sum in quadrature of the listed components:  
- a) MC material description, 
- b) track selection, and  
- (if given) c) the $p_T$ turn-on systematic.  
For tracks with $p_T$$>$10 GeV, an additional uncertainty of 10% due to the $\chi^2$ cut, the systematic uncertainties due to badly-measured tracks, as well as the impact of the degraded core $p_T$ resolution in data (up to $\sim$7%) have to be considered.

| pT bin [MeV] | $|\eta| < 1.3$ | $1.3 < |\eta| < 1.9$ | $1.9 < |\eta| < 2.1$ | $2.1 < |\eta| < 2.3$ | $2.3 < |\eta| < 2.5$ |
|--------------|--------------|----------------|----------------|----------------|----------------|
| 100 < pT ≤ 150 | 8 ± 1 ± 5 | 8 ± 1 ± 5 | 10 ± 1 ± 5 | 10 ± 1 ± 5 | 15 ± 1 ± 5 |
| 200 < pT ≤ 250 | 3 ± 1 | 5 ± 1 | 6 ± 1 | 7 ± 1 | 12 ± 1 |
| 250 < pT ≤ 300 | 2 ± 1 | 4 ± 1 | 6 ± 1 | 6 ± 1 | 11 ± 1 |
| 300 < pT ≤ 350 | 2 ± 1 | 4 ± 1 | 5 ± 1 | 6 ± 1 | 9 ± 1 |
| 350 < pT ≤ 400 | 2 ± 1 | 4 ± 1 | 5 ± 1 | 5 ± 1 | 8 ± 1 |
| 400 < pT ≤ 450 | 2 ± 1 | 3 ± 1 | 4 ± 1 | 5 ± 1 | 8 ± 1 |
| 450 < pT ≤ 500 | 2 ± 1 | 3 ± 1 | 4 ± 1 | 4 ± 1 | 7 ± 1 |
| 500 < pT | 2 ± 1 | 3 ± 1 | 4 ± 1 | 4 ± 1 | 7 ± 1 |
Multiplicity and momentum intervals

- Bins chosen to have similar pair statistics
- Small bins to be comparable with other LHC and pre-LHC data

Table 3: The multiplicity binning statistics.

<table>
<thead>
<tr>
<th>$n_{ch}$</th>
<th>0.9 TeV Fraction of pairs (%)</th>
<th>7 TeV Fraction of pairs (%)</th>
<th>7 TeV high-multiplicity Fraction of pairs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 – 11</td>
<td>6.4</td>
<td>2 – 15</td>
<td>138 – 163 2.8</td>
</tr>
<tr>
<td>12 – 18</td>
<td>14.1</td>
<td>16 – 28</td>
<td>164 – 182 26.4</td>
</tr>
<tr>
<td>28 – 35</td>
<td>20.7</td>
<td>42 – 54</td>
<td>198 – 237 37.6</td>
</tr>
<tr>
<td>36 – 45</td>
<td>19.9</td>
<td>55 – 67</td>
<td></td>
</tr>
<tr>
<td>46 – 82</td>
<td>17.4</td>
<td>68 – 79</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>80 – 91</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\geq 92$</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Table 6: The pair transverse momentum binning statistics.

<table>
<thead>
<tr>
<th>$k_T$ (MeV)</th>
<th>0.9 TeV Fraction of pairs (%)</th>
<th>7 TeV Fraction of pairs (%)</th>
<th>7 TeV high-multiplicity Fraction of pairs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 – 200</td>
<td>2.4</td>
<td>12.6</td>
<td>9.2</td>
</tr>
<tr>
<td>200 – 300</td>
<td>13.6</td>
<td>16.5</td>
<td>13.0</td>
</tr>
<tr>
<td>300 – 400</td>
<td>19.4</td>
<td>15.5</td>
<td>13.9</td>
</tr>
<tr>
<td>400 – 500</td>
<td>18.2</td>
<td>12.6</td>
<td>12.9</td>
</tr>
<tr>
<td>500 – 600</td>
<td>14.4</td>
<td>9.6</td>
<td>11.1</td>
</tr>
<tr>
<td>600 – 700</td>
<td>10.7</td>
<td>7.2</td>
<td>9.2</td>
</tr>
<tr>
<td>700 – 1000</td>
<td>12.1</td>
<td></td>
<td>18.2</td>
</tr>
<tr>
<td>700 – 2000</td>
<td>21.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000 – 1500</td>
<td>6.4</td>
<td>12.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 9: The transverse momentum binning statistics.

<table>
<thead>
<tr>
<th>$p_T$ (MeV)</th>
<th>0.9 TeV Fraction of pairs (%)</th>
<th>7 TeV Fraction of pairs (%)</th>
<th>7 TeV high-multiplicity Fraction of pairs (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 – 300</td>
<td>30.9</td>
<td>26.3</td>
<td>12.2</td>
</tr>
<tr>
<td>300 – 500</td>
<td>32.7</td>
<td>27.4</td>
<td>20.5</td>
</tr>
<tr>
<td>500 – 1000</td>
<td>36.4</td>
<td>30.9</td>
<td>47.7</td>
</tr>
<tr>
<td>1000 – 2000</td>
<td>5.0</td>
<td>19.6</td>
<td></td>
</tr>
</tbody>
</table>
Table 1: The results of fits of the $R_2$ BEC double-ratio function for 0.9 TeV and 7 TeV events with the unlike-charge reference sample for different parameterisations of $\Omega$. The first (only) error shows the statistical uncertainty and the second error shows the systematic uncertainty.

<table>
<thead>
<tr>
<th>$\sqrt{s}$ (TeV)</th>
<th>$\Omega$</th>
<th>$C_0$</th>
<th>$\lambda, \rho$</th>
<th>$R$ (fm)</th>
<th>$\epsilon$ (GeV$^{-1}$)</th>
<th>$\chi^2/ndf$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>$\Omega^{(G)}$</td>
<td>0.998±0.002</td>
<td>0.34±0.01±0.03</td>
<td>1.00±0.03±0.08</td>
<td>−0.006±0.002</td>
<td>149/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(GO)}$</td>
<td>0.997±0.002</td>
<td>0.19±0.01±0.02</td>
<td>0.98±0.03±0.07</td>
<td>−0.006±0.002</td>
<td>144/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(E)}$</td>
<td>0.989±0.003</td>
<td>0.74±0.03±0.09</td>
<td>1.83±0.07±0.20</td>
<td>0.000±0.002</td>
<td>86/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(EO)}$</td>
<td>0.987±0.002</td>
<td>0.61±0.06±0.21</td>
<td>1.55±0.03±0.22</td>
<td>0.001±0.002</td>
<td>87/75</td>
</tr>
<tr>
<td>7</td>
<td>$\Omega^{(G)}$</td>
<td>1.0034±0.0003</td>
<td>0.327±0.002±0.022</td>
<td>1.130±0.005±0.086</td>
<td>−0.0132±0.0002</td>
<td>4589/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(GO)}$</td>
<td>1.0033±0.0003</td>
<td>0.186±0.002±0.015</td>
<td>1.111±0.005±0.084</td>
<td>−0.0131±0.0002</td>
<td>4368/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(E)}$</td>
<td>0.9961±0.0003</td>
<td>0.718±0.006±0.062</td>
<td>2.067±0.012±0.182</td>
<td>−0.0083±0.0002</td>
<td>923/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(EO)}$</td>
<td>0.9948±0.0003</td>
<td>0.635±0.014±0.108</td>
<td>1.779±0.007±0.148</td>
<td>−0.0074±0.0002</td>
<td>628/75</td>
</tr>
<tr>
<td>7 (HM)</td>
<td>$\Omega^{(G)}$</td>
<td>1.017±0.001</td>
<td>0.251±0.010±0.018</td>
<td>1.38±0.04±0.12</td>
<td>−0.015±0.001</td>
<td>397/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(GO)}$</td>
<td>1.017±0.001</td>
<td>0.138±0.006±0.011</td>
<td>1.36±0.04±0.12</td>
<td>−0.015±0.001</td>
<td>387/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(E)}$</td>
<td>1.013±0.001</td>
<td>0.531±0.024±0.046</td>
<td>2.46±0.08±0.22</td>
<td>−0.012±0.001</td>
<td>165/75</td>
</tr>
<tr>
<td></td>
<td>$\Omega^{(EO)}$</td>
<td>1.012±0.001</td>
<td>0.363±0.026±0.056</td>
<td>2.35±0.07±0.22</td>
<td>−0.012±0.001</td>
<td>150/75</td>
</tr>
</tbody>
</table>
The two-particle double-ratio correlation function $R_2(Q)$ for charged particles in pp collisions for multiplicity intervals:

(a) $36 \leq n_{ch} < 45$ at $\sqrt{s} = 0.9$ TeV,  
(b) $68 \leq n_{ch} < 79$ at 7 TeV and  
(c) $183 \leq n_{ch} < 197$ at 7 TeV high-multiplicity events.

The exponential fit used, the region excluded from the fits is indicated. Only statistical uncertainties shown.
The two-particle double-ratio correlation function $R_2(Q)$ for charged particles in pp collisions for $500 \leq k_T < 600$ MeV interval at (a) $\sqrt{s} = 0.9$ TeV, (b) 7 TeV and (c) 7 TeV high-multiplicity events.

The average transverse momentum $k_T$ of the particle pairs is defined as $k_T = |p_{T,1} + p_{T,2}|/2$.

The lines - exponential fits. The region excluded from the fits is indicated. The error bars only the statistical uncertainties shown.
## Fit summary

<table>
<thead>
<tr>
<th>BEC param.</th>
<th>Fit function</th>
<th>0.9 TeV</th>
<th>7 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(n_{ch})$</td>
<td>$p_0 \frac{3^{\sqrt{n_{ch}}}}{p_0}$</td>
<td>$p_0 = 0.64 \pm 0.07$ fm ($n_{ch} \leq 82$)</td>
<td>$p_0 = 0.63 \pm 0.05$ fm ($n_{ch} &lt; 55$)</td>
</tr>
<tr>
<td>$\lambda(n_{ch})$</td>
<td>$p_0 e^{-p_1 n_{ch}}$</td>
<td>$p_0 = 1.06 \pm 0.10$</td>
<td>$p_0 = 0.96 \pm 0.07$</td>
</tr>
<tr>
<td>$p_1 = 0.011 \pm 0.004$</td>
<td>$p_1 = 0.0038 \pm 0.0008$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$R(k_T)$</td>
<td>$p_0 e^{-p_1 k_T}$</td>
<td>$p_0 = 2.64 \pm 0.33$ fm</td>
<td>$p_0 = 2.88 \pm 0.27$ fm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$p_1 = 1.48 \pm 0.67$ GeV$^{-1}$</td>
<td>$p_1 = 1.05 \pm 0.58$ GeV$^{-1}$</td>
</tr>
<tr>
<td>$\lambda(k_T)$</td>
<td>$p_0 e^{-p_1 k_T}$</td>
<td>$p_0 = 1.20 \pm 0.18$</td>
<td>$p_0 = 1.12 \pm 0.10$</td>
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<tr>
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<td></td>
<td>$p_1 = 2.00 \pm 0.35$ GeV$^{-1}$</td>
<td>$p_1 = 1.54 \pm 0.26$ GeV$^{-1}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$p_1 = 0.91 \pm 0.45$ GeV$^{-1}$</td>
</tr>
</tbody>
</table>

Errors - the quadratic sum of the statistical and systematic uncertainties.

Results of fitting the multiplicity, $n_{ch}$, and the transverse momentum of the pair, $k_T$, dependence of the BEC parameters $R$ and $\lambda$ with different functional forms and for different data samples.