Measurements of Bose-Einstein correlations with the ATLAS detector

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Overview

- **Motivation**
  - probing geometry and dynamics of hadronization via BEC enhancement in the relative momentum spectrum of pairs of identically charged particles

- **Experimental procedure**

- **Extraction of an effective radius of hadroproduction region and the incoherence parameter from the fits of the two-particle spectra**

- **Summary**

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Motivation

Symmetric wave function for two identical bosons:
\[ \Psi_{1,2}(x_1, x_2) = \frac{1}{\sqrt{2}} \left( e^{-ik_1 x_1} e^{-ik_2 x_2} + e^{-ik_2 x_1} e^{-ik_1 x_2} \right) \]

Production amplitude (schematic):
\[ A(k_1, k_2) \sim \int dx_1 dx_2 j(x_1)j(x_2) \Psi_{1,2}(x_1, x_2) = \]
\[ = \int dx_1 dx_2 j(x_1)j(x_2) \sqrt{2} \exp \left( -i \frac{k_1 + k_2}{2} (x_1 + x_2) \right) \cos \left( \frac{k_1 - k_2}{2} (x_1 - x_2) \right) \]

Production rate:
\[ N(k_1, k_2) \sim \int dx_1 dx_2 dx_1' dx_2' \langle j(x_1)j^*(x_1') j(x_2)j^*(x_2') \rangle \times \]
\[ \times \exp \left( -i \frac{k_1 + k_2}{2} (x_1 - x_1' + x_2 - x_2') \right) \cos \left( \frac{k_1 - k_2}{2} (x_1 - x_2) \right) \cos \left( \frac{k_1 - k_2}{2} (x_1' - x_2') \right) \]

Fully incoherent case: \[ \langle j(x_1)j^*(x_1') j(x_2)j^*(x_2') \rangle = \]
\[ = \rho(x_1)\rho(x_2) (\delta(x_1 - x_1')\delta(x_2 - x_2') + \delta(x_1 - x_2')\delta(x_2 - x_1')) \Rightarrow \]
\[ \Rightarrow N(k_1, k_2) \sim \int dx_1 dx_2 \rho(x_1)\rho(x_2) \cos^2 \left( \frac{k_1 - k_2}{2} (x_1 - x_2) \right) \]

... coherent? →
Motivation (continued)

A qualitative example with incoherent and coherent terms in \(j(x)j^*(y):\)

\[
j(x)j^*(y) = \lambda \rho(x) \delta(x - y) + (1 - \lambda) \sqrt{\rho(x)\rho(y)} C(x - y),
\]

where \(C(x - y)\) vanishes for \(|x^0 - y^0|, |\vec{x} - \vec{y}| \gtrsim r_{corr}\), where correlation radius is small compared to the size of the production region, \(r_{corr} \ll R\), and “incoherence parameter” \(0 \leq \lambda \leq 1\).

Fourier transformation:

\[
\int dx dy \, j(x)j^*(y) \, e^{i(k_1 x - k_2 y)} = \lambda \rho_{k_1 - k_2} + (1 - \lambda) \tilde{\rho}_k,
\]

with \(k = \frac{1}{2}(k_1 + k_2)\) and \(|(k_1 - k_2)^2| \ll k_0^2\).

Production rate for two identical bosons with momenta \(k_1, k_2:\)

\[
N(k_1, k_2) \sim \int dx_1 dx_2 dx'_1 dx'_2 j(x_1)j^*(x'_1)j(x_2)j^*(x'_2) \Psi_{1,2}(x_1, x_2)\Psi^*_{1,2}(x'_1, x'_2) \sim
\]

\[
\sim |\lambda \rho_{k_1 - k_2} + (1 - \lambda) \tilde{\rho}_k|^2 \Leftrightarrow \text{the 1st incoherent term is sensitive to } Q = k_1 - k_2,
\]

and hence can be large if the overall size of the production region \(R \sim 1/|Q|\), while the second coherent term becomes large if wavelength \(\frac{2\pi}{k} \sim \text{correlation radius encoded in } C(x - y) \Rightarrow \text{Bose-Einstein correlations should be suppressed as } k \text{ increases.}\)

Normalizing the 2-boson rate to the product of inclusive 1-boson rates:

\[
C_2(k_1 - k_2) = \frac{N(k_1, k_2)}{N(k_1)N(k_2)} = \frac{|\lambda \rho_{k_1 - k_2} + (1 - \lambda) \tilde{\rho}_k|^2}{|\lambda \rho_0 + (1 - \lambda) \tilde{\rho}_k|^2}, \quad (k_1 \simeq k_2 \simeq k = \frac{1}{2}(k_1 + k_2)).
\]
$C_2$ parameterizations

Normalize the 2-particle density function to a \textit{reference function} ideally containing all correlations except BEC:

$$C_2(k_1 - k_2) = \frac{N(k_1, k_2)}{N_{\text{ref}}(k_1, k_2)}$$

- **GSSg** (Goldhaber model, a static spherical source with a radial Gaussian density distribution):

  $$C_2(Q) = C_0(1 + \lambda e^{-Q^2R^2}) \cdot (1 + Q\epsilon)$$

  $Q = \sqrt{- (k_1 - k_2)^2}$, $R$ is the source radius, $0 \leq \lambda \leq 1$ is an empirical incoherence factor, $\epsilon$ accounts for long $Q$ distance correlations not fully cancelled in the ratio, $C_0$ is the normalization constant chosen to have $C_2(Q) \to 1$ at large $Q$

- **GSSe** (static spherical source with a radial Lorentzian density distribution):

  $$C_2(Q) = C_0(1 + \lambda e^{-QR}) \cdot (1 + Q\epsilon)$$

  \leftarrow \text{found to reproduce the observed $Q$ dependence better and used as a baseline in this analysis}

- **QOg** (Quantum Optics model):

  $$C_2(Q) = C_0 \left(1 + 2\lambda(1 - \lambda)e^{-Q^2R^2} + \lambda^2 e^{-2R^2Q^2}\right) (1 + Q\epsilon)$$

- **QOe** (QO inspired empirical model):

  $$C_2(Q) = C_0 \left(1 + 2\lambda(1 - \lambda)e^{-QR} + \lambda^2 e^{-2RQ}\right) (1 + Q\epsilon)$$
C2 and double ratio definition in this measurement

\[ C_2(Q) = \frac{N^{++,-\cdot -}(Q)}{N^{\text{ref}}(Q)} \]

No particle identification \( \Rightarrow \) treat all particles as \( \pi^{\pm} \) \((h^{\pm}h^{\pm} \text{ purity is } \approx 70\%: 69\% \text{ of } \pi^{\pm}\pi^{\pm}, 1\% \text{ of } K^{\pm}K^{\pm})\), use \( h^+h^+ + h^-h^- \) rate normalized to 2-particle rate in the reference sample with no BEC but containing all other correlations:

- opposite-sign particles from the same event \( \Leftarrow \) used in this analysis
  - Caveats: resonances, different correlation pattern due to charge conservation, Coulomb attraction vs repulsion in the final state \( \Leftarrow \) an explicit Coulomb correction is applied to the data \( \Rightarrow \) see backup

- same-sign particles from opposite hemispheres of the same event
  - Caveats: momentum conservation ...

- same-sign particles from two different events with the same total multiplicity
  - Caveats: momentum conservation, loss of non-BEC correlations present in the same event

Monte-Carlo models are known to decently simulate resonances (and hence their reflections) and other non-BEC correlations but ignore BEC in hadronization \( \Rightarrow \) using double ratio to cancel non-BEC correlations in ‘++ / −−’ and ‘ref’:

\[ R_2(Q) = \frac{C_2^{\text{data}}(Q)}{C_2^{\text{MC}}(Q)} = \frac{N^{\text{data}}(++, --)}{N^{\text{data}}(+-)} / \frac{N^{\text{MC}}(++, --)}{N^{\text{MC}}(+-)} \]
Data and MC samples, $\sqrt{s_{pp}} = 0.9$ and 7 TeV

**The data** (low pileup event samples, exactly one primary vertex is required):

- $\sqrt{s} = 0.9$ TeV: $3.6 \times 10^5$ events selected with the minimum-bias trigger, $4.5 \times 10^6$ charged primary tracks with $p_T > 100$ MeV and $|\eta| < 2.5$
- $\sqrt{s} = 7$ TeV: $\sim 10^7$ minimum-bias events with $2.1 \times 10^8$ charged tracks
- $\sqrt{s} = 7$ TeV, high multiplicity sample (selected with the HMT trigger, $> 124 \ p_T > 400$ MeV tracks from a single vertex): $1.8 \times 10^4$ events with $2.7 \times 10^6$ selected tracks ($< 1$ parasite pileup track per event)

**MC:** *(BEC not implemented or switched off)*

- Pythia 6.421 minimum-bias sample: a mixture of non-diffractive, single- and double-diffractive events *(AMBT2B tune using Tevatron and early 900 GeV ATLAS data)*
- Systematics samples:
  - PHOJET 1.12.1.35 (dual parton model for the scatter) + Pythia (fragmentation) with Perugia0 tune
  - EPOS 1.99_v2965 (QCD-inspired Gribov–Regge theory describing soft and hard scatters simultaneously) tuned to LHC minimum-bias data.

$C_2(Q)$ single-ratio is well modelled by MC at $Q > 0.5$ GeV while BEC
Data correction procedure and systematics

**Corrections to the raw data:**
- Tracks enter the distributions with weights accounting for reconstruction inefficiency and admixture of secondary particles and fake tracks.
- Event-by-event weights are applied to particle pairs to account for trigger and vertex inefficiencies.
- $Q$ dependent Coulomb correction for each particle pair.
- Track multiplicity distributions are unfolded to particle level using Bayesian iterative technique with the detector response matrix built from MC sample generated with Pythia interfaced to the full detector simulation. The unfolding is verified using closure tests.

**Systematics:**
- Variation of track weights according to uncertainties in track reconstruction efficiency.
- Using different MC generators to account for mismodelling of $C_2$ single ratio (dominates the uncertainty of the fitted $R$ and $\lambda$).
- Variation of the final state Coulomb correction.
- Effect of $\gamma \rightarrow e^+e^-$ conversions (negligible).

[more on systematics]
Results: $R_2(Q)$ correlator at $\sqrt{s_{pp}} = 0.9$ and 7 TeV

Fits with $C_2(Q) \sim 1 + \lambda e^{-Q^2R^2}$ and $1 + \lambda e^{-QR}$ are shown. Mismodelled $\rho(770)$ region is excluded from the fits. The double ratio should be 1 in case of no BEC.

$R_2$ for different $n_{ch}$ ranges
Fitted $R$ and $\lambda$ vs. charged multiplicity

$R \sim n_{ch}^{1/3}$ for $n_{ch} \lesssim 50$ (NB: same $R$ for the given $n_{ch}$ at all $\sqrt{s}$, qualitatively consistent with Pomeron-based models) and for $\sqrt{s} = 7$ TeV saturates at $\sim 2r_p$ $\Leftarrow$ coincidence? maximum $pp$ overlap?

Pomeron models, however, suggest a decrease of $R$ at $n_{ch} \gtrsim 70$ due to higher contribution of high-$p_T$ jet events, compared to multiple Pomeron exchange yielding the same multiplicity but different particle $p_T$ spectrum

[ In this analysis, high-multiplicity events are not classified into dijets and MPI-induced ‘spherical’ events ]

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Fitted $R$ and $\lambda$ vs. $k_T = \frac{1}{2} |\vec{p}_{T,1} + \vec{p}_{T,2}|$
Summary

- The 2-particle Bose-Einstein correlations of same-sign charged hadrons with $p_T > 100$ MeV and $|\eta| < 2.5$ are measured at $\sqrt{s_{pp}} = 0.9$ and 7 TeV in events with total charged multiplicity up to $n_{ch} \approx 200$.

- Bose-Einstein correlations are manifested by an enhancement in the same-sign two-particle spectrum at low relative momenta $Q = k_1 - k_2$.

- Correlators are fitted by Gaussian (poor description) and exponential (the preferred) parameterizations. Effective radius, $R$, and incoherence parameter, $\lambda$, of the hadroproduction region are extracted for various values of the total charged multiplicity, $n_{ch}$, and $k_T = \frac{1}{2}|\vec{k}_{T,1} + \vec{k}_{T,2}|$ ranges.

- $R$ increases as $\sim n_{ch}^{1/3}$ for $n_{ch} \lesssim 50$, without a significant dependence from $\sqrt{s}$, and remains approximately constant for $50 < n_{ch} < 250$ (this region is measured for the first time at $\sqrt{s_{pp}} = 7$ TeV only).

- $\lambda$ exponentially decreases with $n_{ch}$, the slope depends on $\sqrt{s}$.

- As a function of $k_T$, $R$ exponentially decreases towards higher $k_T$ for any $n_{ch}$, while $\lambda$ decreases with $k_T$ without a significant $n_{ch}$ dependence.

- ATLAS results are compared to other experiments at the same and lower $\sqrt{s_{pp}}$: particularly, an exponential decrease of $R$ with $k_T$ is confirmed.
Backup
Macroscopic BEC: Hanbury Brown – Twiss interferometer

$C(d) = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} = 1 + A \cos(d_{AB})$

$d_{AB} = \lambda / \theta$

$I_{1(2)}$ - intensities, $\langle x \rangle$ - averaging over random phases

$\lambda$ is the wavelength of the light, $\theta = d_{12} / L$

Figure 10.1 The first stellar intensity interferometer; the pilot model of the stellar intensity interferometer at Jodrell Bank in 1955. Two Army searchlights were used to make the first measurement of the angular diameter of a main sequence star (Sirio).
Coulomb correction

Correct for systematic momentum shift between same-sign and opposite-sign pairs by the Gamow factor:

\[ N_{corr}(k_1, k_2) = \frac{N(k_1, k_2)}{G(k_1 - k_2)} \]

\[ G(Q) = \frac{2\pi \zeta}{e^{2\pi \zeta} - 1} \]

\[ \zeta = \pm \frac{\alpha m_\pi}{Q}, \quad \text{'}+\text{' for same-sign and ' - ' for opposite-sign pairs} \]

The correction is \( \approx 20\% \) at \( Q = 30 \) MeV.

Final state Coulomb interaction is not modelled by MC, thus the correction is applied only to the data.
Systematics for fitted $\lambda$ and $R$

<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>
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<td>0.3</td>
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<td>Negligible</td>
<td>Negligible</td>
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<td>Monte Carlo samples</td>
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<tr>
<td>Total</td>
<td>14.8</td>
<td>13.0</td>
<td>9.6</td>
</tr>
</tbody>
</table>
$R_2(Q)$ for different $N_{ch}$ slices

\begin{align*}
\text{\textbf{ATLAS}} & & \\text{s = 0.9 TeV} \\
\text{p}_T \geq 100 \text{ MeV}, |\eta| < 2.5, n_{ch} = 36 - 45 \\
\text{\textbullet data} & & \text{\textit{Exponential fit}}
\end{align*}

\begin{align*}
\text{\textbf{ATLAS}} & & \\text{s = 7 TeV} \\
\text{p}_T \geq 100 \text{ MeV}, |\eta| < 2.5, n_{ch} = 68 - 79 \\
\text{\textbullet data} & & \text{\textit{Exponential fit}}
\end{align*}

\begin{align*}
\text{\textbf{ATLAS}} & & \\text{s = 7 TeV HM} \\
\text{p}_T \geq 100 \text{ MeV}, |\eta| < 2.5, n_{ch} = 183 - 197 \\
\text{\textbullet data} & & \text{\textit{Exponential fit}}
\end{align*}

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