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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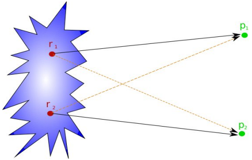
Motivation

Symmetric wave function for two identical bosons:

$$\Psi_{1,2}(x_1, x_2) = \frac{1}{\sqrt{2}} \left(e^{-ik_1x_1} e^{-ik_2x_2} + e^{-ik_2x_1} e^{-ik_1x_2} \right)$$



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:

$$N(k_1, k_2) \sim \int dx_1 dx_2 dx_1' dx_2'\, \langle j(x_1) j^*(x_1')\; j(x_2) j^*(x_2') \rangle\, \times$$

$$\times exp \left(-i \tfrac{k_1 + k_2}{2} (x_1 - x_1' + x_2 - x_2') \right)\, cos \left(\tfrac{k_1 - k_2}{2} (x_1 - x_2) \right) cos \left(\tfrac{k_1 - k_2}{2} (x_1' - x_2') \right)$$

Fully **incoherent** case: $\langle j(x_1) j^*(x_1')\; j(x_2) j^*(x_2') \rangle =$

$$= \rho(x_1)\rho(x_2) \left(\delta(x_1 - x_1')\delta(x_2 - x_2') + \delta(x_1 - x_2')\delta(x_2 - x_1') \right) \Rightarrow$$

$$\Rightarrow N(k_1, k_2) \sim \int dx_1 dx_2\, \rho(x_1)\rho(x_2)\, cos^2 \left(\tfrac{k_1 - k_2}{2} (x_1 - x_2) \right)$$,... *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" $0 \le \lambda \le 1$

Fourier transformation: $$\int dxdy\, j(x)j^*(y)\, e^{i(k_1x - k_2y)} = \lambda\rho_{k_1-k_2} + (1-\lambda)\tilde{\rho}_k\,,$$

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:

$$N(k_1,k_2) \sim \int dx_1 dx_2 dx_1' dx_2'\, j(x_1)j^*(x_1')j(x_2)j^*(x_2')\,\Psi_{1,2}(x_1,x_2)\Psi^*_{1,2}(x_1',x_2') \sim$$

$\sim |\lambda\rho_{k_1-k_2} + (1-\lambda)\tilde{\rho}_k|^2 \Leftarrow$ 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 $\frac{2\pi}{k} \sim$ correlation radius encoded in $C(x-y) \Rightarrow$ Bose-Einstein correlations should be suppressed as k increases.

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

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

▸ A macroscopic analog of the effect

C_2 parameterizations

Normalize the 2-particle density function to a *reference function* ideally containing all correlations except BEC:

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

- **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, ϵ 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): $\Leftarrow$ found to reproduce the observed Q dependence better and used as a baseline in this analysis):

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

- **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):

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

C_2 and double ratio definition in this measurement

$$C_2(Q) = N^{++,--}(Q) / N^{ref}(Q)$$

No particle identification $\Rightarrow$ treat all particles as $\pi^{\pm}$ ($h^{\pm}h^{\pm}$ purity is $\simeq 70\%$: 69% of $\pi^{\pm}\pi^{\pm}$, 1% 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 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*':

$$R_2(Q) = \frac{C_2^{data}(Q)}{C_2^{MC}(Q)} = \frac{N^{data}(++,--)/N^{data}(+-)}{N^{MC}(++,--)/N^{MC}(+-)}$$

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

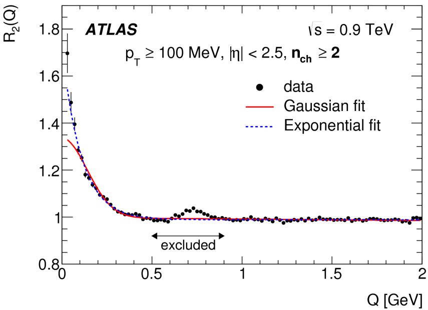
- Tracks enter the distributions with weights accounting for reconstruction inefficiency and admixture of secondary particles and fake tracks.
- Event-by-event weights are applied to particle pairs to account for trigger and vertex inefficiencies.
- Q dependent Coulomb correction for each particle pair.
- 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.

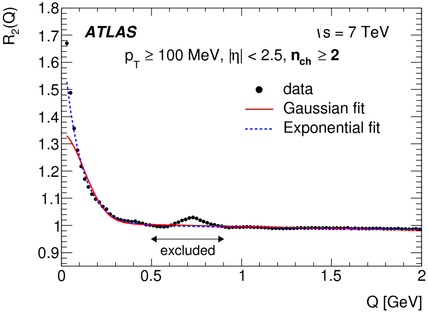
Systematics:

- 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 λ).
- Variation of the final state Coulomb correction.
- Effect of $\gamma \rightarrow e^+e^-$ conversions (negligible).

more on systematics

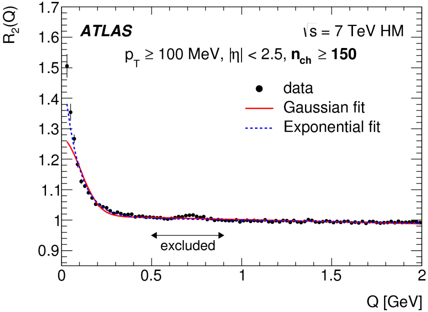
Results: $R_2(Q)$ correlator at $\sqrt{s_{pp}} = 0.9$ and 7 TeV





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

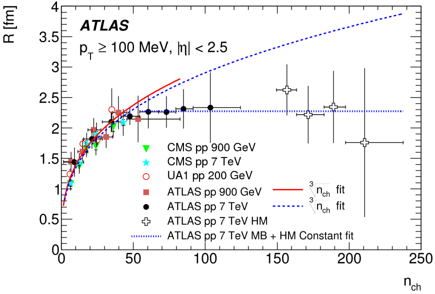


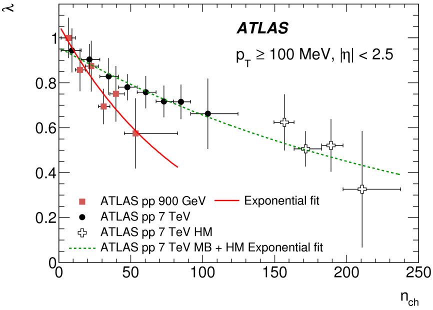
Fitted R and λ vs. charged multiplicity

$R \sim n_{ch}^{1/3}$ 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 [a]

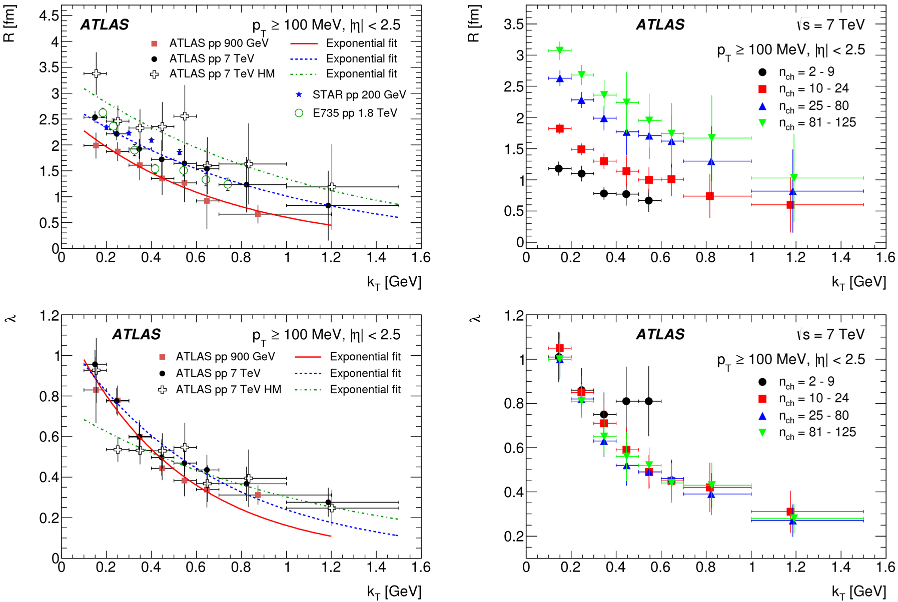
[In this analysis, high-multiplicity events are not classified into dijets and MPI-induced 'spherical' events]





[a] See, e.g., V.A. Schegelsky *et al.*, Phys. Lett.B703 (2011) 288

Fitted R and λ 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 $n_{ch} \simeq 200$
- 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, λ, 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).
- λ 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 λ 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 inteferometer

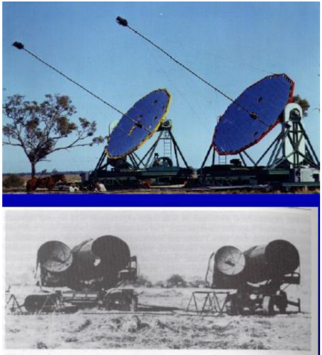
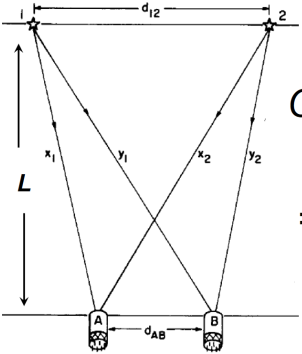


Figure 10.1 The first stellar intensity interferometer; the pilot model of the stellar intensity interferometer at Jodrell Bank in 1955. Two Army searchlights were used to make the first measurement of the angular diameter of a main sequence star (Sirius).



$$C(d) = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle}$$

$$= 1 + A\cos(d_{AB})$$

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

$I_{1(2)}$ - intensities, $<x>$ - averaging over random phases

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

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Coulomb correction

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

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

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

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

The correction is $\simeq 20\%$ at $Q = 30$ MeV.
Final state Coulomb interaction is not modelled by MC, thus the correction is applied only to the data.

back

Systematics for fitted λ and R

Table 1 Systematic uncertainties on λ 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

	0.9 TeV		7 TeV		7 TeV (HM)	
Source	λ (%)	R (%)	λ (%)	R (%)	λ (%)	R (%)
Track reconstruction efficiency	0.6	0.7	0.3	0.2	1.3	0.3
Track splitting and merging	Negligible	Negligible	Negligible	Negligible	Negligible	Negligible
Monte Carlo samples	14.5	12.9	7.6	10.4	5.1	8.4
Coulomb correction	2.6	0.1	5.5	0.1	3.7	0.5
Fitted range of Q	1.0	1.6	1.6	2.2	5.5	6.0
Starting value of Q	0.4	0.3	0.9	0.6	0.5	0.3
Bin size	0.2	0.2	0.9	0.5	4.1	3.4
Exclusion interval	0.2	0.2	1	0.6	0.7	1.1
Total	14.8	13.0	9.6	10.7	9.4	10.9

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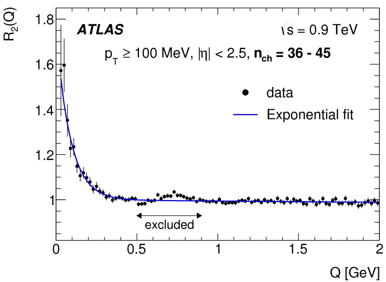
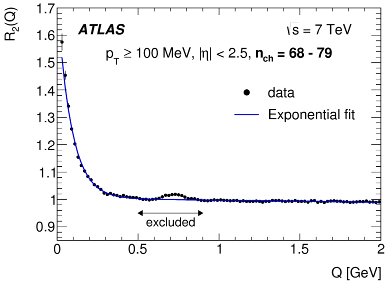
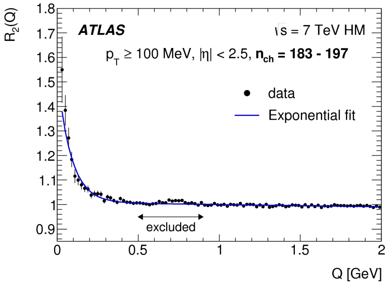
$R_2(Q)$ for different N_{ch} slices







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