Bose-Einstein correlations and $b\bar{b}$ correlations in p-p collisions with LHCb

Bartosz Małecki, on behalf of the LHCb Collaboration
Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

Quark Matter 2018
Venice, 16.05.2018
Outline

• LHCb detector
• Bose-Einstein correlations
• study of $b\bar{b}$ correlations
• summary
LHCb detector

- single-arm spectrometer designed mainly to study CP violation in B physics
- fully instrumented in $2 < \eta < 5$ can serve as a **general purpose detector**
- complementary results wrt other LHC experiments

- $\Delta p/p \sim 0.5\%-1.0\%$ between 5-200 GeV/c
- impact parameter resolution of 20 μm
- good PID separation up to 100 GeV (misID (π->K) ~ 5%)

Bose-Einstein correlations

[JHEP 12 (2017) 025]
HBT interferometry in particle physics

- correlations in four-momenta \((q_1, q_2)\) of indistinguishable particles emitted from the same source:

\[ Q = \sqrt{-(q_1 - q_2)^2} \]

- due to symmetrization (Bose-Einstein correlations – BEC) or antisymmetrization (Fermi-Dirac correlations – FDC) of the total wave function

- useful **tool to probe** the spatial and temporal **structure of the hadron emission volume**

- many results on BEC from SPS, LEP, RHIC, LHC (ALICE, ATLAS, CMS)

- LHCb measurement in a unique acceptance region
Correlation function

- **correlation function** (experimentally):
  \[ C_2(Q) = \frac{N(Q)^{SAME}}{N(Q)^{REF}} \]

- **event-mixed reference sample** is used:
  - pairs of pions from different events from PVs with same VELO track multiplicity
  - other correlations also removed -> construct **double ratio** (next slide)

- in this analysis - **Levy parametrization** + long-range correlations:
  \[ C_2(Q) = N(1 \pm \lambda e^{-RQ}) \times (1 + \delta Q) \]

- **distribution for pairs of same-sign pions from same PV** [BEC effect present]
- **distribution for reference sample** [no BEC effect]

- **distribution for pairs of same-sign pions from same PV** [BEC effect present]
- **distribution for reference sample** [no BEC effect]

\[ \lambda \text{ – chaoticity parameter} \\
(0 \text{ – coherent source, 1 \text{ – chaotic emission}}) \\
N \text{ – normalization factor} \\
\delta \text{ – long-range correlations} \]
Double ratio

- **double ratio** $r_d(Q)$ – an improved correlation function:

$$r_d(Q) = \frac{C_2(Q)^{DATA}}{C_2(Q)^{MC}}$$

- MC correlation function contains *similar pattern of distortions* as correlation function for data, therefore constructing double ratio:
  - reduces possible imperfections of the reference sample
  - eliminates second order effects to large extent
  - corrects for long-range correlations (if properly simulated)

- Coulomb effect is not simulated in MC – corrected by applying **Gamov penetration factor** $G_2(Q)$ to the $Q$ distribution for signal pairs in data:

$$G_2(Q) = \frac{2\pi \zeta}{e^{2\pi \zeta} - 1}, \text{ where } \zeta = \pm \frac{\alpha m}{Q}$$

**BEC effect not simulated in MC**
Event multiplicity bins

- BEC parameters depend on total multiplicity of an event
- **VELO track multiplicity** ($N_{ch}$) is a good probe of that quantity
- PVs are split into 3 multiplicity bins based on $N_{ch}$
- **activity classes** are defined as fractions of $N_{ch}$ distribution (relative way):
  - independent of specific experiment features (e.g. efficiency, acceptance)
- unfolding of $N_{ch}$ was also performed, which allows for comparison between experiments after taking into account different $\eta$ acceptances (model-dependent)

### Table: VELO $N_{ch}$ multiplicity

<table>
<thead>
<tr>
<th>$N_{ch}$ range</th>
<th>activity class</th>
<th>unfolded $N_{ch}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10</td>
<td>(52-100)%</td>
<td>8-18</td>
</tr>
<tr>
<td>11-20</td>
<td>(15-52)%</td>
<td>19-35</td>
</tr>
<tr>
<td>21-60</td>
<td>(0-15)%</td>
<td>36-96</td>
</tr>
</tbody>
</table>

*track multiplicities unfolded using PYTHIA 8 (in $2 < \eta < 5$)
Results (I)

- Fits to double ratio with Levy parametrization:
  \[ C_2(Q) = N (1 \pm \lambda e^{-RQ}) \times (1 + \delta Q) \]

- Clear enhancement due to BEC effect observed in \( Q > 0 \)

<table>
<thead>
<tr>
<th>Activity class</th>
<th>( R ) [fm]</th>
<th>( \lambda )</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>1.01 ± 0.01 ± 0.10</td>
<td>0.72 ± 0.01 ± 0.05</td>
</tr>
<tr>
<td>medium</td>
<td>1.48 ± 0.02 ± 0.17</td>
<td>0.63 ± 0.01 ± 0.05</td>
</tr>
<tr>
<td>high</td>
<td>1.80 ± 0.03 ± 0.16</td>
<td>0.57 ± 0.01 ± 0.03</td>
</tr>
</tbody>
</table>

Results show a trend compatible with previous observations at LEP and other LHC experiments:
- Source size increases with activity
- \( \lambda \) decreases with growing activity

Systematic uncertainty (~10%) dominated by generator tunings and pile-up effects.
Correspondence of unfolded $N_{ch}$ bins between ATLAS ($|\eta| < 2.5$, $p_T > 0.1$ GeV/c) and LHCb ($2 < \eta < 5$) acceptances at 7 TeV found using PYTHIA 8:

- $R$ and $\lambda$ parameters measured in the forward region are slightly lower than results for central rapidity obtained by ATLAS
- need to measure the BEC parameters using a full 3D analysis to perform a more detailed comparison

LHCb: JHEP 12 (2017) 025
Study of $b\bar{b}$ correlations

[JHEP 11 (2017) 030]
Motivation

• heavy-flavour production - important tests of QCD
• inclusive single-heavy-flavour production - limited sensitivity to higher-order QCD corrections (e.g. gluon splitting, flavour-excitation)
• those contributions can be studied in correlations between heavy quark and antiquark
• correlation measurements for $b\bar{b}$ were done at SPS, Tevatron and LHC
• LHCb – unique acceptance coverage + detector dedicated for B physics
Analysis method

- beauty hadrons from inclusive decays into $J/\psi$:
  \[ b \to J/\psi \chi, \quad \text{where} \quad J/\psi \to \mu^+ \mu^- \]

- **signal yield** determined from a fit to the 2D mass distribution of $\mu^+ \mu^-$ pairs:
  \[
  f(m_1, m_2) = N_{SS} \times S(m_1)S(m_2) + \frac{N_{SB}}{2} \times (S(m_1)B'(m_2) + B'(m_1)S(m_2)) + N_{BB} \times B''(m_1, m_2)
  \]

**signal term**

**(J/ψ + J/ψ)**

**J/ψ + combinatorial background**

**pure combinatorial background**

- \( p_T^{J/\psi} > 3 \text{ GeV/c} \)
- \( \sqrt{s} = 7,8 \text{ TeV} \)
- \( \text{Candidates/(10 MeV/c}^2) \)
- \( \text{Candidates/(2 MeV/c}^2) \)

JHEP 11 (2017) 030
for a number of kinematic variables, **normalized differential cross-sections** are presented, defined here in a generic way:

$$\frac{1}{\sigma} \frac{d\sigma}{dv} \equiv \frac{1}{N_{cor}} \frac{\Delta N_{i,cor}}{\Delta v_i}$$

**kinematic variables** are defined below:

- $|\Delta \Phi^*|$ - difference in azimuthal angle of 2 beauty hadrons**
- $|\Delta \eta^*|$ - difference in pseudorapidity of 2 beauty hadrons**
- $A_T \equiv (p_T^{J/\psi_1} - p_T^{J/\psi_2})/(p_T^{J/\psi_1} + p_T^{J/\psi_2})$ – asymmetry between $p_T$ of $J/\psi$ mesons
- $m^{J/\psi}, p_T^{J/\psi}, y^{J/\psi}$ - mass, $p_T$ and rapidity of the $J/\psi$ pair

Systematic uncertainty is much smaller than the statistic one and can be neglected (most of systematic sources cancel out in the $\Delta N_{i,cor} / N_{cor}$ ratio).

(**) both $\Phi^*, \eta^*$ are estimated from the direction of the vector between PV to the $J/\psi$ decay vertex
• distributions are compared with expectations from PYTHIA (@LO) and POWHEG (@NLO), as well as an artificial data-driven model of uncorrelated $b\bar{b}$ production

• both PYTHIA and POWHEG well describe the data – small NLO effects compared to the experimental precision

• small contribution from gluon splitting at low $|\Delta \Phi^*|$ (otherwise than for $c\bar{c}$) -> expected, since it is suppressed due to a large mass of beauty quark
Summary

Bose-Einstein correlations studied for same-sign pions at 7 TeV

- first measurement in the forward region $2 < \eta < 5$
- observed trends compatible with previous results and predictions
- BEC parameters in the forward region slightly lower wrt central rapidities
- this study shows the LHCb potential in BEC analyses

Kinematic correlations for $b\bar{b}$ pairs from $p$-$p$ collisions at 7 and 8 TeV

- observed correlations agree with both PYTHIA (@LO) and POWHEG (@NLO), suggesting that the NLO effects in $b\bar{b}$ production are small compared to the experimental precision
- however, discriminating theory predictions is not possible with the present data - future measurements with larger samples needed
Thank you for your attention
BACKUP SLIDES
BEC - track selection

• relatively loose selection of pions

  Long track traversing whole detector
  • loose particle identification cuts on pions
  • $2 < \eta < 5$
  • good track quality ($\chi^2/ndf < 2$)
  • $p > 2 \text{ GeV/c}
  • $p_T > 0.1 \text{ GeV/c}$
  • $IP < 0.4 \text{ mm}$
  • cut on probability to be a ghost track

• correlation function is not sensitive to single track efficiency, but can be sensitive to two-track effects such as cloned or ghost tracks*

• ghosts/clones not perfectly simulated -> cannot be fully corrected by DR

• if tracks share all same VELO hits -> keep one with best $\chi^2$ - effect from clones/ghosts under control for $Q > 0.05 \text{ GeV/c}^2$

• clones also suppressed by removing tracks with small tracks slope differences

• effects from ghosts present both in same-sign pairs and unlike-sign pairs – controlled by looking at $DR$ for unlike-sign pairs (no BEC effect)

* clones – fake tracks reconstructed from hits originating mainly from a single particle
ghosts – fake tracks reconstructed from hits deposited by multiple particles
### BEC - systematics

<table>
<thead>
<tr>
<th>Source</th>
<th>Low activity</th>
<th>Medium activity</th>
<th>High activity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\Delta R$ [%]</td>
<td>$\Delta \lambda$ [%]</td>
<td>$\Delta R$ [%]</td>
</tr>
<tr>
<td>Generator tunings</td>
<td>6.6</td>
<td>4.3</td>
<td>8.9</td>
</tr>
<tr>
<td>PV multiplicity</td>
<td>5.9</td>
<td>5.8</td>
<td>6.1</td>
</tr>
<tr>
<td>PV reconstruction</td>
<td>1.8</td>
<td>0.1</td>
<td>1.4</td>
</tr>
<tr>
<td>Fake tracks</td>
<td>0.4</td>
<td>1.1</td>
<td>1.7</td>
</tr>
<tr>
<td>PID calibration</td>
<td>1.3</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Requirement on pion PID</td>
<td>2.9</td>
<td>1.8</td>
<td>1.6</td>
</tr>
<tr>
<td>Fit range at low-$Q$</td>
<td>1.2</td>
<td>1.0</td>
<td>1.2</td>
</tr>
<tr>
<td>Fit range at high-$Q$</td>
<td>1.8</td>
<td>0.1</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>9.8</strong></td>
<td><strong>7.6</strong></td>
<td><strong>11.4</strong></td>
</tr>
</tbody>
</table>
BEC - results

LHCb
\[ \sqrt{s} = 7 \text{ TeV} \]

<table>
<thead>
<tr>
<th>Activity</th>
<th>( R [\text{fm}] )</th>
<th>( \chi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>low</td>
<td>1</td>
<td>0.5</td>
</tr>
<tr>
<td>medium</td>
<td>1.5</td>
<td>0.7</td>
</tr>
<tr>
<td>high</td>
<td>2</td>
<td>0.9</td>
</tr>
</tbody>
</table>

LHCb
\[ \sqrt{s} = 7 \text{ TeV} \]
b\bar{b} - results (I)

\[ p_T^{J/\Psi} > 2 \text{ GeV/c} \]

\[ p_T^{J/\Psi} > 3 \text{ GeV/c} \]
$b\bar{b}$ - results (II)

$p_T^{J/\Psi} > 5$ GeV/c  

$p_T^{J/\Psi} > 7$ GeV/c
**b\bar{b} - systematics**

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal determination</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Muon identification</td>
<td>0.4</td>
</tr>
<tr>
<td>Track reconstruction</td>
<td>1.7</td>
</tr>
<tr>
<td>Trigger</td>
<td>1.2</td>
</tr>
<tr>
<td>Simulated sample size</td>
<td>&lt; 0.1</td>
</tr>
</tbody>
</table>