PARTICLE CORRELATIONS AT LHCb

Miłosz Zdybał
Institute of Nuclear Physics PAN, Kraków, Poland

on behalf of the LHCb Collaboration

XXVI Cracow EPIPHANY Conference, 7-10 January 2020
QUANTUM CORRELATIONS IN PARTICLE PHYSICS

• Goldhaber, Goldhaber, Lee and Pais, 1959
  • Bevalac/LBL experiment in Berkeley
  • Observation of the resonances by comparing Q distribution of unlike-sign pion pairs to same-sign – unexpected angular correlation [Phys. Rev. 120, 300]

• Correlations in four-momenta of indistinguishable particles emitted from the same source

\[ Q_{12} = \sqrt{-(q_1 - q_2)^2} = \sqrt{M^2 - 4\mu^2} \]

• Total wave function:
  • Bosons: symmetrization – Bose-Einstein Correlations
  • Fermions: anti-symmetrization – Fermi-Dirac Correlations

• Useful tool to probe spatial and temporal structure of hadronization region
LHCb EXPERIMENT

- Single arm spectrometer fully instrumented in forward region
- Designed to study CP violation in B, but also fixed target, heavy ion physics
- Precision coverage unique for LHCb: $2 < \eta < 5$
- Accurate momentum measurements
- Very good particle identification over momentum range 2 GeV/c – 100 GeV/c
- Complementary results with respect to other LHC experiments
BEC ANALYSES AT LHCb

• Published:
  • BEC for pions in proton-proton collisions at 7 TeV [JHEP 12 (2017) 025]

• Ongoing:
  • BEC for pions in proton-lead collisions at 5 TeV (in multiplicity and $k_T$ bins)
  • 3-body correlations in proton-proton collisions at 7 TeV
DEFINITION

- $C_2(q_1, q_2) = \frac{P(q_1, q_2)}{P(q_1)P(q_2)}$

- Parameterization:
  - Levy parameterization with $\alpha = 1$ (Cauchy) + long-range correlations

$$C_2(Q) = N(1 + \lambda e^{-|RQ|^\alpha}) \times (1 + \delta \cdot Q)$$

EXPERIMENTALLY

- $C_2(Q) = \frac{N(Q)^{DATA}}{N(Q)^{REF}}$
  - BEC present
  - No BEC (mix, MC, unlike)

- Reference sample: event mix – different events, same VELO multiplicity

- $R$ – the radius of a spherical static source
- $\lambda$ – chaoticity parameter
- $N$ – normalization factor
- $\delta$ – long-range correlations

(0 – coherent source, 1 – chaotic source)
DATA SAMPLES AND CUTS
THE SAME AS FOR TWO-PION CORRELATIONS [JHEP12(2017)025]

• Data 2011@7TeV
  • MinimumBias
• MC 2011
  • NoBias
  • PYTHIA 8, ~20M events
  • BEC effect switched off

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>2.0 – 5.0</td>
</tr>
<tr>
<td>Track $\chi^2$</td>
<td>&lt; 2.0</td>
</tr>
<tr>
<td>$p$</td>
<td>&gt; 2.0 GeV</td>
</tr>
<tr>
<td>$p_T$</td>
<td>&gt; 0.1 GeV</td>
</tr>
<tr>
<td>IP</td>
<td>&lt; 0.4 mm</td>
</tr>
</tbody>
</table>
MULTIPLICITY BINS AND REFERENCE SAMPLE

- Effect depends on charged particle multiplicity
- Analysis performed in three bins of VELO track multiplicity per PV
- Reference sample: event mix
  - The same multiplicity, each particle from different event

<table>
<thead>
<tr>
<th>VELO $N_{ch}$</th>
<th>Unfolded $N_{ch}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-10</td>
<td>8-18</td>
</tr>
<tr>
<td>11-20</td>
<td>19-35</td>
</tr>
<tr>
<td>21-60</td>
<td>36-96</td>
</tr>
</tbody>
</table>

[Refs: JHEP12(2017)025]
RESULTS ON TWO-PION CORRELATIONS

\[ r_d(Q) = \frac{C(Q)^{\text{DATA}}}{C(Q)^{\text{MC}}}_\text{MC without BEC} \]

<table>
<thead>
<tr>
<th>Activity</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>

Systematic uncertainty (~10%) dominated by the generator tunings and pile-up effects
DEPENDENCE ON MULTIPLICITY

Source size increases with activity

Chaoticity decreases with activity

Direct comparison between experiments not straightforward (different $\eta$ ranges).

A trend compatible with previous observations at LEP and the other LHC experiments and with some theoretical models.

$R$ and $\lambda$ parameters measured in the forward region slightly lower wrt e.g. ATLAS [Eur. Phys. J. C75 (2015) 466]
THREE-PION CORRELATIONS

- Three-body correlation function:
  \[ C_3(q_1, q_2, q_3) = \frac{P(q_1, q_2, q_3)}{P(q_1)P(q_2)P(q_3)} \]

- Parameterization (within Core-Halo model) [T. Novak, arXiv:1801.03544]:
  \[ C_3^{(fit)} = N(1 + \delta Q_{12})(1 + \delta Q_{13})(1 + \delta Q_{23})G_3C_3^{(0)}(Q_{12}, Q_{13}, Q_{23}) \]
  \[ G_3: \text{Coulomb corrections factorized according to Riverside method [Phys. Rev. C 92, 014902]} \]

- Levy-type \( C_3^{(0)} \) function of the \( Q_{12}, Q_{13}, Q_{23} \) of the pion triplet
  \[ C_3^{(0)}(Q_{12}, Q_{13}, Q_{23}) = 1 + \lambda_3 e^{-0.5 |Q_{12}R|\alpha} + e^{-|Q_{13}R|\alpha} + e^{-|Q_{23}R|\alpha} + \lambda_2 (e^{-|Q_{12}R|\alpha} + e^{-|Q_{13}R|\alpha} + e^{-|Q_{23}R|\alpha}) \]
  \[ \lambda_2, R: \text{from the previous analysis on the two-pion BEC [T. Novak, arXiv:1801.03544], } \]
  \[ \lambda_3 = C_3(Q_{12} = Q_{13} = Q_{23} \rightarrow 0) - 1 = \lambda_3 + 3 \lambda_2 \]

Only the idea of the analysis presented because results are not published yet!
THREE-PION CORRELATIONS
CORE-HALO MODEL

- Core
  - Direct production of pions
  - Hydrodynamic evolution or particle production from excited strings, followed by subsequent re-scattering of the particles
- Halo
  - Core is surrounded by pions emitted from the decay of long-lived hadronic resonances ($\omega, \eta, \eta', K^0$) which are treated as belonging to the hadronic source
THREE-PION CORRELATIONS
CORE-HALO MODEL – WHAT CAN WE MEASURE

- Analysis of $C_3(Q_{12}, Q_{13}, Q_{23})$ for the diagonal $Q_{12} = Q_{13} = Q_{23}$
- Fraction of the core
  \[ f_c = \frac{N_{\text{core}}}{N_{\text{core}} + N_{\text{halo}}} \]
  - We may directly determine from the two- and three-pion correlations
- Partially coherent emission from the core
  \[ p_c = \frac{N_{\text{coherent}}}{N_{\text{coherent}} + N_{\text{incoherent}}} \]
  - Correlation strength depends on partial coherence (within core-halo model)
- Values of $f_c$ and $p_c$ can be determined using $\lambda_2$ and $\lambda_3$
- Core-halo independent parameter
  \[ \kappa_3 = 0.5 \frac{(\lambda_3 - 3 \lambda_2)}{\lambda_2^{3/2}} = 1 \]
  - The deviation of $\kappa_3$ from one may indicate extra effects in the core, for example not fully thermalized core, or partial coherence in the core
STATUS OF THE 3-PION ANALYSIS

• Fit is ready using $C_3^{(fit)}(Q_{12}, Q_{13}, Q_{23})$ (Gamow factor used for factorized Coulomb correction)
• Dependence on $N_{ch}$ (dependence on $k_T$ also planned)
• Central values of following parameters are measured:
  • $\lambda_2, \lambda_3, f_c, p_c, \kappa_3$
• The systematics is still to be done (ongoing)!
CONCLUSIONS

First measurement of BEC in the forward region $2 < \eta < 5$
  • measured correlation parameters slightly lower as compared to results in central $\eta$ region

3-pion BEC analysis
  • Interpretation within core-halo model
  • Work ongoing

LHCb shows a potential to perform a set of BEC analyses in unique kinematic region, complementary to the central rapidity detectors.
BACKUP SLIDES
BEC – CLONES AND GHOSTS

**Cloned tracks**

two or more tracks reconstructed by mistake from the hits originating from a single particle

- Cloned pairs of tracks with small opening angle
  - → *in low-Q region*
  - → may affect BEC signal

**Ghost tracks**

wrongly reconstructed tracks which combine the hits deposited by multiple particles

- Ghosts populate wide $Q$ range

ghosts / clones may affect the BEC signal forming pairs with small opening angle → *low $Q$*

not perfectly simulated → *cannot be fully corrected by DR*

**Effect from ghosts present in LIKE and UNLIKE**

- *controled by double ratio for unlike-sign pairs corrected for Coulomb effect (no BEC effect)*

Contamination from clones investigated looking at tracks slope differences at $Q \to 0$
BEC – TRACK PAIR SELECTION

**Ghost tracks**
- most of ghosts already removed → *tracks with high probability to be a ghost removed*
- additional cut: *if tracks share same VELO hits* → *keep one with best χ²*

→ *after selection ghosts are under control for Q > 0.05 GeV/c²*
→ *systematic uncertainty low compared to dominant contributions*

**Cloned tracks**
- clones removed by cut on: $|Δt_x| < 0.3$ mrad & $|Δt_y| < 0.3$ mrad
  * (t - tangent of the track momenta of two particles)

→ *contribution from clones marginal for Q > 0.05 GeV/c²*

**Two-particle efficiencies under control in Q > 0.05 GeV/c²**
→ analysis in 0.05 GeV/c² < Q < 2.0 GeV/c²

**Coulomb effect**
Removed with Gamov penetration factor for Q distribution in data:

$$G_2(Q) = \frac{2\pi \zeta}{e^{2\alpha m Q}}$$

where $\zeta = \pm \frac{α m}{Q}$

→ *systematics due to Coulomb correction found to be negligible*
### 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>
THREE-PION CORRELATIONS

- Source function: Levy-type source
  \[ S(r) = L(\alpha, R, r) = \frac{1}{(2\pi)^{3/2}} \int d^3 q e^{i q r} e^{-\frac{1}{2} q R} |\alpha| \]

- Three-body correlation function:
  \[ C_3(q_1, q_2, q_3) = \frac{P(q_1, q_2, q_3)}{P(q_1)P(q_2)P(q_3)} \]

- Parameterization (fit function) [T. Novak, arXiv:1801.03544]:
  \[ C_3^{(fit)} = N(1 + \delta Q_{12})(1 + \delta Q_{13})(1 + \delta Q_{23})G_3 C_3^{(0)}(Q_{12}, Q_{13}, Q_{23}) \]
  \[ \delta, N: \text{background and normalization} \]

- Levy-type \( C_3^{(0)} \) function of the \( Q_{12}, Q_{13}, Q_{23} \) of the pion triplet
  \[ C_3^{(0)}(Q_{12}, Q_{13}, Q_{23}) = 1 + \ell_3 e^{-0.5(|Q_{12}R|^{\alpha} + |Q_{13}R|^{\alpha} + |Q_{23}R|^{\alpha})} + \ell_2 (e^{-|Q_{12}R|^{\alpha}} + e^{-|Q_{13}R|^{\alpha}} + e^{-|Q_{23}R|^{\alpha}}) \]
  \[ \lambda_2, R: \text{from the previous analysis on the two-pion BEC [T. Novak, arXiv:1801.03544, JHEP12(2017)025]} \]
  \[ \alpha = 1: \text{Cauchy} \]

Only the methodology of the analysis because results are not published yet!
Three-Pion Correlations

- Analysis of $C_3(Q_{12}, Q_{13}, Q_{23})$ for the diagonal $Q_{12} = Q_{13} = Q_{23}$
- Three-pion correlation strength:
  - $\lambda_3 = C_3(Q_{12} = Q_{13} = Q_{23} \to 0) - 1 = \ell_3 + 3\ell_2$
- Coulomb corrections
  - factorized according to Riverside method [Phys. Rev. C 92, 014902]
  - $G_3(Q_{12}, Q_{13}, Q_{23}) \approx G_2(Q_{12})G_2(Q_{13})G_2(Q_{23})$
  - Thus we correct $C_2(Q_{12}), C_2(Q_{13}), C_2(Q_{23})$ independently (the same as for two-pion analysis) using Gamow factor