Two-particle correlations in the LHCb experiment

Marcin Kucharczyk on behalf of LHCb collaboration

HNI Krakow

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Outline

- LHCb - general purpose forward experiment
- Physics motivation
- BEC for pion pairs in $p$-$p$ collisions at 7 TeV
- Ridge effect in $p$-$Pb$ collisions at 5 TeV
- Conclusions
LHCb detector

- single arm spectrometer fully instrumented in forward region → GPD in forward region
- designed to study CP violation in $B$, but also fixed target, heavy ion physics
- precision coverage unique for LHCb: $2 < \eta < 5$
- complementary results wrt other LHC experiments

- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of 20 μm for high-$p_T$ tracks
- good PID separation up to 100 GeV (miss ID ($\pi \rightarrow K$) ≈ 5 %)
Bose-Einstein Correlations


accepted by JHEP
Motivation - HBT

Historically

- In 1950s Robert Hanbury Brown an Richard Q. Twiss found correlations between photons from different radio sources (**HBT interferometry**)
- 1959: experiment at the Bevalac/LBL in Berkeley
  - looking at the resonances by comparing $Q$ distribution of unlike-sign pion pairs to same-sign
  - unexpected angular correlation for same-sign pions

**In particle physics:**

- symmetrization (**Bose-Einstein Correlations - BEC**) and antisymmetrization (**Fermi-Dirac Correlations - FDC**) of total wave function
- correlations in four-momenta of indistinguishable particles emitted from the same source:

$$Q = \sqrt{-(q_1 - q_2)^2} = \sqrt{M^2 - 4\mu^2}$$

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

- many results on BEC from LEP, RHIC, SPS, ...
- already done by ALICE, ATLAS and CMS at central rapidities
- **LHCb can add measurements in the forward region !**
Correlation function

Experimentally: \[ C_2(Q) = \frac{N(Q)^{DATA}}{N(Q)^{REF}}, \quad \text{REF} = \text{mix, MC, unlike} \]

\(N(Q)^{DATA}\) - distribution for same-sign pairs in data  
(BEC present)

\(N(Q)^{REF}\) - distribution for reference sample with no BEC effect

**Event-mixed reference sample used**
- pions from different events from PVs with same VELO track multiplicity (*long-range correl.*)
- derived from data
- other correlations also removed \(\rightarrow\) construct double ratio (*next slide*)

**Parametrization of correlation function**
- Levy parametrization with \(\alpha = 1\) (Cauchy) + long-range correlations

\[
C_2(Q) = N(1 + \lambda e^{-RQ}) \times (1 + \delta \cdot Q)
\]

- \(R\) - the radius of a spherical static source
- \(\lambda\) - chaoticity parameter  
(0 – coherent source, 1 – chaotic case)
- \(N\) - normalisation factor
- \(\delta\) - long range correlations
Double ratio

Improved correlation function - double ratio (DR)

\[ DR(Q) = \frac{C_2(Q)^\text{data}}{C_2(Q)^\text{MC}} \quad MC \text{ without BEC} \]

- reduce possible imperfections in the construction of the reference sample
- eliminate second order effects to large extent
- correct for long range correlations (if properly simulated)

By constructing of the correlation function we should be independent of:

- single particle acceptance and efficiency
- effects due to the detector occupancy, acceptance and material
- selection cuts
- two-track efficiency effects if properly simulated
Single track selection

Relatively loose selection of pions

**Long track traversing whole detector**
- loose particle identification cuts on pions
- $2 < \eta < 5$
- good track quality ($\chi^2 / ndf < 2$)
- momentum > 2 GeV/c
- transverse momentum > 0.1 GeV/c
- impact parameter (IP) < 0.4 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

Two-track effects do not influence the baseline LHCb analyses but for BEC one has to pay special attention.
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 → 0
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 $\chi^2$
  → after selection ghosts are under control for $Q > 0.05$ GeV/c$^2$
  → systematic uncertainty low compared to dominant contributions

**Cloned tracks**
- clones removed by cut on: $|\Delta t_x| < 0.3$ mrad & $|\Delta t_y| < 0.3$ mrad
  (t - tangent of the track momenta of two particles)
  → contribution from clones marginal for $Q > 0.05$ GeV/c$^2$

Two-particle efficiencies under control in $Q > 0.05$ GeV/c$^2$
→ analysis in $0.05$ GeV/c$^2 < Q < 2.0$ GeV/c$^2$

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

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

→ systematics due to Coulomb correction found to be negligible
Event-activity bins

BEC effect depends on the charge particle multiplicity
- charged particle multiplicity is not a good observable to compare results with other experiments
  → detector acceptances may not overlap & reconstruction efficiencies may differ

Three activity classes are defined as fractions of PV VELO track multiplicity distrib.
- good probe of the total multiplicity in the full solid angle
- defined in relative way → scaling in different η acceptances
- specific features of different experiments cancel out

<table>
<thead>
<tr>
<th>VELO $N_{ch}$</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>

charged-particle multiplicities unfolded using Pythia 8 ($2 < \eta < 5$)
Results (I)

Fits to DR with Levy parametrization for 3 activity bins

- clear BEC related enhancement observed
- $\chi^2 / ndf$ for the fits $\sim 1.6$
- Levy parametrization
  $\rightarrow$ effective 1D approximation for static source
- 3D parametrization to be used in the future
  $\rightarrow$ fits better data as it includes information about time evolution of the emitting source

<table>
<thead>
<tr>
<th>Activity</th>
<th>R [fm]</th>
<th>$\lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>$1.01 \pm 0.01 \pm 0.10$</td>
<td>$0.72 \pm 0.01 \pm 0.05$</td>
</tr>
<tr>
<td>Medium</td>
<td>$1.48 \pm 0.02 \pm 0.17$</td>
<td>$0.63 \pm 0.01 \pm 0.05$</td>
</tr>
<tr>
<td>High</td>
<td>$1.80 \pm 0.03 \pm 0.16$</td>
<td>$0.57 \pm 0.01 \pm 0.03$</td>
</tr>
</tbody>
</table>

Systematic uncertainty ($\sim 10\%$) dominated by the generator tunings and pile-up effects
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
Comparison with central rapidities

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 relations obtained from PYTHIA 8.

- $R$ and $\lambda$ parameters measured in the forward region are slightly lower wrt ATLAS.
- Need to measure the BEC parameters using a full three-dimensional analysis to perform a more detailed comparison.
• Bose-Einstein correlations studied for same-sign pions at 7 TeV
  - first measurement in the forward region 2 < η < 5
  - three activity classes to measure the dependence on $N_{ch}$
  - event-mixed reference sample used
  - observed trends compatible with previous observations and predictions
  - $R$ and $\lambda$ parameters measured in the forward region slightly lower wrt central rapidities ($GPDs$)

• Analysis shows the LHCb potential in HBT field
  - many possible future analyses with different collisions ($p-p$, $p-Pb$), collision energies ($7, 8, 13$ TeV for $p-p$ and $5$ TeV for $p-Pb$), different hadrons etc.
  - full three-dimensional analysis
  - possible study of 3-body correlations for pions
Ridge effect

Physics motivation - ridge effect

Two-particle angular \((\Delta \eta, \Delta \phi)\) correlations of prompt charged particles

- long-range correlations on the near side \((ridge \ at \ \Delta \phi = 0)\)
- reported first by RHIC in \(Au-Au\)
- measured by ATLAS, CMS, ALICE in \(Pb-Pb, p-p\) and \(p-Pb\) collisions at central rapidities
  \(\rightarrow\) central rapidity region \((|\eta| < 2.5)\)
- LHCb can confirm such effect at large rapidities \((2 < \eta < 5)\)
  \(\rightarrow\) long-range correlations in both hemispheres \((p-Pb\ and \ Pb-p)\)
  \(\rightarrow\) measured in different \(p_T\) regions as well as in relative and absolute activity classes

\(pPb\) - probe collective effects in dense environment of high energy collisions

- \(p-Pb\) collisions as a reference for \(Pb-Pb\), but interesting by themselves
- theoretical interpretation of ridge is still under discussion \((e.g. \ gluon\ saturation,\ collective\ effects)\)
  \(\rightarrow\) study of the ridge at large \(\eta\) in both \(p-Pb\ and \ Pb-p\)
  \(\rightarrow\) new input for theory
LHCb setup for proton-nucleus

- p-Pb / Pb-p data collected at $\sqrt{s_{NN}} = 5$ TeV (2013)
- **Asymmetric beams**: nucleon-nucleon center-of-mass system shifted by $\Delta y = 0.47$ in the proton beam direction

**Forward production ($p$-$Pb$)**
rapidity coverage: $1.5 < y_{CMS} < 4.5$
collected data (2013): $\sim 1.1$ nb$^{-1}$

**Backward production ($Pb$-$p$)**
rapidity coverage: $-5.5 < y_{CMS} < -2.5$
collected data (2013): $\sim 0.5$ nb$^{-1}$

Rapidity coverage $2.5 < |y_{CMS}| < 4.5$ for both configurations

$y_{CMS} = y^*$: rapidity in nucleon-nucleon centre-of-mass system, with forward direction (**positive values**) in direction of the proton beam
Data selection

LHCb data at 5 TeV using minimum bias sample (randomly selected minimum bias events)

- lumi used: \( p-Pb \) (\( \sim 0.5 \text{ nb}^{-1} \)) and \( Pb-p \) (\( \sim 0.3 \text{ nb}^{-1} \))
- events with exactly 1 PV in luminous region \( \pm 3\sigma \) around mean interaction point
  \( \rightarrow \) pile-up only \( \sim 2\% \)
- prompt particles
  \( \rightarrow \) small IP with respect to PV
  \( \rightarrow \) reconstructed in full tracking system
- kinematic range: \( p > 2 \text{ GeV}, \quad p_T > 150 \text{ MeV}, \quad 2.0 < \eta < 5.0 \)

- \( Pb-p \) multiplicity higher wrt \( p-Pb \)
- comparable multiplicity distributions for \( p-p \) and \( p-Pb \)
Correlation function

Correlation function described as a per-trigger particle associated yield (binned)

- event-mixed reference sample

\[
\frac{1}{N_{\text{trig}}} \frac{d^2 N_{\text{pair}}}{d\Delta\eta d\Delta\Phi} = \frac{S(\Delta\eta, \Delta\Phi)}{B(\Delta\eta, \Delta\Phi)} \times B(0,0)
\]

- different \( p_T \) bins \([0.15-1.0], [1.0-2.0], [2.0-3.0]\) GeV/c and activity classes
- mixing with particles from 5 random events of the same activity and \( p_T \)

![Graphs showing the correlation function](image)

Normalized yield of same event particle pairs

Normalized yield of different event particle pairs

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Activity classes

Hit multiplicity in VELO is a good probe of the global event multiplicity

- 5 relative event activity classes
  → fractions of VELO hit multiplicity distributions of the minimum-bias sample
  → separately for p-Pb and Pb-p

- 5 common absolute activity classes
  → in high-multiplicity region 2200 < VELO hits < 3500
  → possible comparison p-Pb wrt Pb-p
Ridge effect in $p_T \in (1.0-2.0) \text{ GeV/c}$

Jet peak at $\Delta \phi=0$, $\Delta \eta=0$ truncated to make other effects visible

Low event-activity (50-100%)
$\Delta \phi=\pi$ away-side ridge
$\Delta \phi=0$ jet peak

High event-activity (0-3%)
$\Delta \phi=\pi$ away-side ridge
$\Delta \phi=0$ jet peak + near side ridge

- near-side ridge present in both configurations
- ridge in Pb-p more pronounced
Ridge evolution in relative activity

1D projection of correlation function on $\Delta \phi$

$$Y(\Delta \phi) \equiv \frac{1}{N_{\text{trig}}} \frac{dN_{\text{pair}}}{d\Delta \phi} = \frac{1}{\Delta \eta_b - \Delta \eta_a} \int_{\Delta \eta_a}^{\Delta \eta_b} \frac{1}{N_{\text{trig}}} \frac{d^2N_{\text{pair}}}{d\Delta \eta d\Delta \phi} d\Delta \eta$$

→ study the ridge evolution
→ integrated over $2 < |\eta| < 2.9$ (exclude jet peak)

- correlation yield increases with event activity
- away-side ridge decreases for higher $p_T$
- near-side ridge maximum for $p_T$ bin 1.0–2.0 GeV/c
- near side ridge more pronounced in $Pb-p$ than in $p-Pb$
  → larger event activity in backward configuration
Ridge evolution in absolute activity

Common absolute activity ranges

- 5 identical activity ranges for $p$-$Pb$ and $Pb$-$p$ in $2200 < \text{VELO hits} < 3500$
- $2.0 < \Delta \eta < 2.9$

- away-side and near-side ridge depends only on activity in the direction of measurement
- near-side correlation yields compatible for both configurations
- increase of correlation strength with increasing event activity
Summary on ridge effect

Two-particle angular correlations produced in $p$-$Pb$ collisions at $\sqrt{s_{NN}} = 5$ TeV have been measured for the first time in the forward region

- Near-side ridge effect has been observed in both $p$-$Pb$ and $Pb$-$p$ beam configurations, being most pronounced for $1.0 < p_T < 2.0$ GeV/c
- Effects on the near-side and away-side grow with increasing event activity
- Near-side ridge is more pronounced in $Pb$-$p$ configuration for relative activity
- Ridge effects are compatible for $p$-$Pb$ and $Pb$-$p$ collisions for absolute activity
- Analysis for $p$-$p$ at 13 TeV is ongoing
Conclusions

First measurement of BEC in the forward region $2 < \eta < 5$

- measured HBT parameters slightly lower wrt results in central $\eta$ region
- full three-dimensional analysis needed for more detailed comparison
- LHCb shows a potential to perform a set of further HBT analyses with different hadrons, collision energies, collision types etc.

Long-range correlations on the near-side (the ridge) observed for the first time in the forward region

- statistically limited - *more data expected from Run II*
- Analyses with different collision types or collision energies planned
  
  $\rightarrow$ *study with p-p collisions at 13 TeV ongoing*
Backup
## Systematics - BEC

<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>