Centrality dependent Lévy HBT analysis at CMS

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WPCF

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BASICS OF FEMTOSCOPY

  - Momentum correlation of pions
  - Bose-Einstein correlation \( C(q) \equiv |q_{\text{LCMS}}|, q = p_1 - p_2 \)
  - Relation to the source: \( C(q) \approx 1 + |\vec{S}(q)|^2 \)
  - Gaussian source: \( C(q) = 1 + e^{-|qR|^2} \)
  - Lévy-type source + core-halo model: \( C(q) = 1 + \lambda e^{-|qR|^\alpha} \)
  - Final state interactions \( \rightarrow \) Coulomb correction

- Goals:
  - Measure \( C(q) \) in different centrality and \( K_T \) classes
  - Obtain the parameters via fitting
  - Study the centrality and \( K_T \) dependence of the parameters
CONCEPT: LÉVY HBT

- Gaussian assumption not precise enough

- Lévy distribution: $L(\alpha, R; r) = \frac{1}{2\pi} \int dq \ e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$

- Many possible reasons i.e. anomalous diffusion, critical phenomena …

- Detailed centrality dependent Lévy shape analysis
  - Measurement of:
    - Lévy stability index $\alpha \rightarrow$ shape
    - Lévy scale parameter $R \rightarrow$ scale
    - Correlation strength $\lambda \rightarrow$ core-halo
DATA SELECTION

• 2018 5.02 TeV PbPb data
• Event selection $\rightarrow \approx 2.65$ billion events
• Track selection $\rightarrow \approx 662$ billion tracks
• Pair selection
• No particle identification
  • $\approx 80\text{-}90\%$ pion, $\approx 10\text{-}20\%$ kaon+proton
  • $K_T$ dependent ratios
  • Only influences $\lambda$
CALCULATING THE CORRELATION FUNCTION

- Pair distributions: quantum statistics + acceptance + kinematics → background sample needed

- Calculating the correlation function: $C(q) = \frac{A(q)}{B(q)} \cdot \int \frac{B}{A}$
  - $A(q)$ actual pair distribution: all same charged pairs of a given event
  - $B(q)$ background pair distribution: obtained by event mixing
  - Calculate $C(q)$ for different $K_T$ and centrality classes

- Event mixing:
  - Mixed event contains particles from different events
  - No physical correlation
  - Background pairs from mixed event
  - Remove remaining long-range background → $DR(q)$
FITTING THE CORRELATION FUNCTION

- Example of the correlation function fit
- Small q: not reliable because of track-pair resolution
  - Checked using MC simulations
- Fitted function: Bowler-Sinyukov method
  \[ DR(q) = N(1 + \epsilon q)[1 - \lambda + \lambda(1 + e^{-|qR|^\alpha})K_C(q; \alpha, R)] \]
  - \( K_C(q; \alpha, R) \): Coulomb correction
- 5 fit parameters:
  - N: normalisation factor
  - \( \epsilon \): necessary because of still remaining background
  - R, \( \alpha \), \( \lambda \): physical meaning

CMS-PAS-HIN-21-011

PbPb 0.58 nb\(^{-1}\) (5.02 TeV)

\( K_T = 1.30-1.35 \text{ GeV/c, 20-30\% cent., } h^+h^- \)
THE LÉVY SCALE PARAMETER: $R$ vs $m_T$

- $m_T = \sqrt{m^2 + (K_T/c)^2}$
- Generalized homogeneity length of the source
- Smooth $m_T$ dependence
- Centrality dependent
- Boxes: uncorrelated systematic uncertainties
- Error bars: statistical uncertainties

![Graph showing $R$ vs $m_T$ for different centralities in PbPb collisions with 0.58 nb$^{-1}$ at 5.02 TeV.](image)

CMS Preliminary

Correl. syst. = $+2.0\%$ $-2.4\%$ for $h^+h^-$
HYDRO SCALING OF $1/R^2$ vs $m_T$

- Hydrodynamic model: $1/R^2 \sim m_T$ ($\alpha = 2$)
  - Slope ($A$) $\rightarrow$ QGP Hubble constant: $A = \frac{H^2}{T_f}$
  - Intercept ($B$) $\rightarrow$ Size at freeze-out: $B = \frac{1}{R_f^2}$

- Uncorrelated syst. + stat. uncertainties for fitting
- Verifies hydrodynamic scaling
- Hubble constant between $0.12$ fm$^{-1}$ and $0.18$ fm$^{-1}$
- Centrality dependence

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PARAMETERS OF THE HYDRO FIT

- A decreasing monotonically with $\langle N_{\text{part}} \rangle$
- Centrality dependent expansion speed
- $B$ negative, close to constant
- Caused by Lévy source?
THE LÉVY SCALE PARAMETER: $R$ vs $N_{\text{part}}$

- $\langle N_{\text{part}} \rangle^{1/3} \sim$ one-dimensional size
- If $R \sim \langle N_{\text{part}} \rangle^{1/3} \rightarrow$ geometrical meaning of $R$
- Linear scaling verified
THE LÉVY STABILITY INDEX: $\alpha$

- Source deviation from Gaussian ($\alpha = 2$)
- Almost constant at each centrality
- Centrality dependent source
- Average value between 1.6 and 2.0
  - $\langle\alpha\rangle$ increasing with $\langle N_{\text{part}} \rangle$
  - Systematically larger for positive pairs
- Lévy assumption correct
THE CORRELATION STRENGTH: $\lambda$

- Value of $\lambda$ determined by:
  - Core-halo model:
    \[ \lambda = \left( \frac{N_{\text{core}}}{N_{\text{core}} + N_{\text{halo}}} \right)^2 \]
  - Lack of particle identification:
    \[ \lambda \leq \left( \frac{N_{\text{pion}}}{N_{\text{hadron}}} \right)^2 \]
- Decreasing trend
  - Caused by increasing kaon, proton ratio?
- Minimal centrality dependence
**THE CORRELATION STRENGTH: $\lambda$**

- $m_T$ and centrality dependent $K/\pi$ and $p/\pi$ ratios
- Rescaling with the pion ratio:
  - $\lambda^* = \frac{\lambda}{(N_{\text{pion}}/N_{\text{hadron}})^2}$
- Almost constant trend at each centrality
- Centrality dependent core-halo ratio
SUMMARY

- **Bose-Einstein correlations** CMS 5.02 TeV PbPb

- Centrality dependent **Lévy HBT analysis**
  - PAS: CMS-PAS-HIN-21-011

- **Results:**
  - $1/R^2$ linear scaling in $m_T \rightarrow$ hydrodynamic model verified
    - Hubble constant between $0.12$ fm$^{-1}$ and $0.18$ fm$^{-1}$ and centrality dependent
  - $R$ linear scaling in $\langle N_{\text{part}} \rangle^{1/3} \rightarrow$ generalized homogeneity length of the source
  - $\alpha$ between 1.6 and 2.0 $\rightarrow$ Lévy source
    - Centrality dependent
    - Almost constant at each centrality
  - Decreasing $\lambda$
    - Caused by the lack of PID
    - Centrality dependent

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Thank you for your attention!
Backup slides
17 SYSTEMATIC UNCERTAINTIES

- Zvertex cut
- All particle selection cuts
- Pair cut
- Limits of the fits → biggest effect
- Centrality calibration
- Loose, default, tight settings in all cases
- Separated into “correlated” and “uncorrelated” parts

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>Default</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zvertex cut</td>
<td>&lt; 15 cm</td>
<td>&lt; 12 cm</td>
<td>&lt; 18 cm</td>
</tr>
<tr>
<td>$p_T$ cut</td>
<td>&gt; 0.5 GeV/c</td>
<td>&gt; 0.55 GeV/c</td>
<td>&gt; 0.5 GeV/c</td>
</tr>
<tr>
<td>$\delta p_T$ cut</td>
<td>&lt; 10%</td>
<td>&lt; 5%</td>
<td>&lt; 15%</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>$ cut</td>
<td>&lt; 0.95</td>
</tr>
<tr>
<td>$N_{\text{pixel hit}}$ cut</td>
<td>&gt; 1</td>
<td>&gt; 2</td>
<td>&gt; 0</td>
</tr>
<tr>
<td>$\chi^2/N_{\text{dof}}/N_{\text{layer}}$ cut</td>
<td>&lt; 0.18</td>
<td>&lt; 0.15</td>
<td>&lt; 0.18</td>
</tr>
<tr>
<td>$</td>
<td>d_{xy}/\sigma(d_{xy})</td>
<td>$ cut</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>$</td>
<td>d_z/\sigma(d_z)</td>
<td>$ cut</td>
<td>&lt; 3</td>
</tr>
<tr>
<td>$\Delta \eta, \Delta \phi$ pair cut</td>
<td>$\Delta \eta_{\text{cut}}=0.014$</td>
<td>$\Delta \phi_{\text{cut}}=0.022$</td>
<td>$\Delta \eta_{\text{cut}}=0.017$</td>
</tr>
<tr>
<td>$q_{\min}$ lower fit limit</td>
<td>$q^0_{\min}(K_{T,\text{cent}})$</td>
<td>$q^0_{\min}-0.004$</td>
<td>$q^0_{\min}+0.004$</td>
</tr>
<tr>
<td>$q_{\max}$ upper fit limit</td>
<td>$q^0_{\max}(K_{T,\text{cent}})$</td>
<td>$0.85 \cdot q^0_{\max}$</td>
<td>$1.15 \cdot q^0_{\max}$</td>
</tr>
</tbody>
</table>

Cent. edges:
- Default values
- Lower values
- Higher values
**CALCULATION OF THE SYSTEMATIC UNCERTAINTY**

\[
\delta P^\uparrow(i) = \sqrt{\sum_{n=\text{cuts}} \frac{1}{N_n^\uparrow} \sum_{j \in J_n^\uparrow} (P_{n}^j(i) - P^0(i))^2}
\]

\[
\delta P^\downarrow(i) = \sqrt{\sum_{n=\text{cuts}} \frac{1}{N_n^\downarrow} \sum_{j \in J_n^\downarrow} (P_{n}^j(i) - P^0(i))^2}
\]

- \( n \) : different cuts i.e. \( p_T \) cut, \( N_{\text{hit}} \) cut, pair cut, lower fit limit …
- \( j \) : loose or tight setting
UNCORRELATED AND CORRELATED SYSTEMATICS

- Calculate the average effect of a cut on a parameter
  - Average of all centrality, $K_T$ and charge classes

- Uncorrelated systematic error:
  - Calculate using the differences from the averages
  - Different for every centrality, $K_T$ and charge classes

- Correlated systematic error:
  - Calculate using the difference between the average and the default
  - Same for every centrality, $K_T$ and charge classes

- Use $\sqrt{\text{uncorrelated}^2 + \text{statistical}^2}$ for fitting
# AVERAGE SYSTEMATIC EFFECTS

<table>
<thead>
<tr>
<th>$\delta R[%]$</th>
<th>Track and event cuts</th>
<th>Pair cut</th>
<th>Fit limits</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cent.[%]</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>0-5</td>
<td>1.0</td>
<td>0.4</td>
<td>0.0</td>
<td>2.9</td>
</tr>
<tr>
<td>5-10</td>
<td>0.7</td>
<td>0.5</td>
<td>0.0</td>
<td>2.1</td>
</tr>
<tr>
<td>10-20</td>
<td>0.6</td>
<td>0.4</td>
<td>0.0</td>
<td>1.4</td>
</tr>
<tr>
<td>20-30</td>
<td>0.6</td>
<td>0.3</td>
<td>0.2</td>
<td>1.6</td>
</tr>
<tr>
<td>30-40</td>
<td>0.5</td>
<td>0.2</td>
<td>0.6</td>
<td>1.5</td>
</tr>
<tr>
<td>40-60</td>
<td>0.5</td>
<td>0.5</td>
<td>0.7</td>
<td>1.4</td>
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<tr>
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<td>0.6</td>
<td>0.7</td>
<td>4.8</td>
<td>0.0</td>
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<td>0.6</td>
<td>3.2</td>
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<td>2.0</td>
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<tr>
<td>40-60</td>
<td>0.4</td>
<td>0.4</td>
<td>1.7</td>
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<th>Overall</th>
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THE PHYSICAL MEANING OF THE FIT PARAMETERS

• Usually plot them vs transverse mass: \( m_T = \sqrt{m^2 + (K_T/c)^2} \)

• Lévy scale parameter \( R \):
  • Generalised homogeneity length of the source
  • Hydrodynamic model: \( 1/R^2 \sim m_T \) (if \( \alpha = 2 \))
    • Slope of the line (A) \( \rightarrow \) QGP’s Hubble constant: \( A = \frac{H^2}{T_f} \)
    • Intercept of the line (B) \( \rightarrow \) geometrical size at freeze-out

• Lévy stability index \( \alpha \):
  • Difference compared to Gaussian distribution (\( \alpha = 2 \))
    • Anomalous diffusion, fragmentation of jets …
  • Sign of the QCD critical point (not at LHC energies)

• Correlation strength \( \lambda \):
  • Core-halo model: \( C(q \rightarrow 0) = 1 + \lambda \)
  • Other possible causes i.e. coherent pion production, restoration of the chiral symmetry …