Non-identical particle correlation analysis in the presence emission time delays

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Heavy-ion collision evolution

- HIC is expected to go through a QGP phase, where matter is strongly interacting – resulting in the development of collective motion.

- Radial flow dominates, with elliptic flow as azimuthal modification.

Transverse plane

M. Chojnacki, W. Florkowski,
PRC 74 (2006) 034905
Thermal emission from collective medium

- A particle emitted from a medium will have a collective velocity $\beta_f$ and a thermal (random) one $\beta_t$.

- As observed $p_T$ grows, the region from where pairs with small relative momentum can be emitted gets smaller and shifted to the outside of the source.

Consequences of flow

- “Collective” flow should apply to all particles
  - Ideal 1D hydro $\rightarrow m_T$ scaling for all particles
  - “Real” 3+1D hydro + viscosity (no rescattering) $\rightarrow$ approximate scaling in LCMS
  - Heavier/faster particles give smaller size of the system

- System size decrease – change of the second moment (width) of the emission function

- Measurement of the first moment (average emission position) not possible for identical particles

AK, M. Gałążyn, P. Bożek; Phys.Rev.C90 (2014) 6, 064914
Collectivity and emission asymmetry

- As particle mass (or $p_T$) grows, average emission point moves more “outwards” - origin of this “emission asymmetry” the same as $m_T$ scaling.

- Average emission points for primordial particles with same velocity but different mass:
  
  \[
  \langle r_{\text{out}}^\pi \rangle \approx \langle x_{\text{out}}^\pi \rangle - \langle x_{\text{out}}^K \rangle
  \]

  \[
  \begin{align*}
  \text{Pions} & : \langle x_{\text{out}}^\pi \rangle = 2.83 \text{ fm} \\
  \text{Kaons} & : \langle x_{\text{out}}^K \rangle = 4.47 \text{ fm} \\
  \text{Protons} & : \langle x_{\text{out}}^p \rangle = 5.61 \text{ fm}
  \end{align*}
  \]

- Heavier particles (resonances) are pushed even further out.

- Significant difference between particles’ average emission points at same velocity, different mass.

AK, PRC 81 (2010) 064906
Resonances and pion emission

- If flow is off → no shift of emission
- Pions → decay momentum of most resonances larger than pion mass. Decay acts similarly to thermal smearing with large temperature.
- Emission points of pions from resonances strongly randomized – average very close to system center.
- Overall average emission point of pions closer to the center than just flow.

\[
\beta = (0.6, 0.8)
\]

Pions

- Primordial
- Scrambled
- Resonances
- All

\[
\langle x_{\text{out}}^\pi \rangle_{\text{primodial}} \quad 2.83 \text{ fm} \\
\langle x_{\text{out}}^\pi \rangle_{\text{all}} \quad 2.00 \text{ fm}
\]

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AK, PRC 81 (2010) 064906

WPCF 2018; Kraków; 24 May 2018
Resonances and kaon emission

- Kaons → decay momentum of most resonances smaller than Kaon mass. Kaons retain the shift of the heavy (shifted more!) resonances.

- Emission points of kaons from resonances strongly pushed by flow – average far from system center.

\[
\langle x_{out}^K \rangle \\
\text{primordial} \quad \text{all} \\
4.47 \text{ fm} \quad 5.54 \text{ fm}
\]

- Overall: resonances enhance flow-induced difference between pion and kaon average emission points.
Difference in emission time

- Hydrodynamics predicts emission of higher $p_T$ particles earlier (on average) than low $p_T$.

- This would mean that at the same velocity pions are emitted later than kaons.

- This effect goes in the same direction as emission asymmetry from flow.

- In addition pions are more abundantly produced from resonances, which naturally introduce emission delay.

- This again produces later emission of pions – in the same direction as flow.

- Estimates show both time differences are comparable in magnitude.
Emission delay in data

- ALICE kaon data in hydro-based parametrization: kaons emitted on average later than pions.
- It comes from rescattering via K* resonance (not included in blast-wave or Therminator 2 or hydro)
- Goes in opposite direction to all other asymmetries

<table>
<thead>
<tr>
<th>method</th>
<th>$T$ (GeV)</th>
<th>$\alpha_\pi$</th>
<th>$\alpha_K$</th>
<th>$\tau_\pi$ (fm/c)</th>
<th>$\tau_K$ (fm/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>fit with BW Eq. (8)</td>
<td>0.120</td>
<td>-</td>
<td>-</td>
<td>9.6 ± 0.2</td>
<td>10.6 ± 0.1</td>
</tr>
<tr>
<td>fit with BW Eq. (8)</td>
<td>0.144</td>
<td>-</td>
<td>-</td>
<td>8.8 ± 0.2</td>
<td>9.5 ± 0.1</td>
</tr>
<tr>
<td>fit with Eq. (9)</td>
<td>0.144</td>
<td>5.0</td>
<td>2.2</td>
<td>9.3 ± 0.2</td>
<td>11.0 ± 0.1</td>
</tr>
<tr>
<td>fit with Eq. (9)</td>
<td>0.144</td>
<td>4.3 ± 2.3</td>
<td>1.6 ± 0.7</td>
<td>9.5 ± 0.2</td>
<td>11.6 ± 0.1</td>
</tr>
</tbody>
</table>

Table 4: Emission times for pions and kaons extracted using the Blast-wave formula Eq. (8) and the analytical formula Eq. (9).
How to measure which sort of particles was emitted earlier and which later

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Abstract

A method allowing to directly measure delays in the emission of particles of different types at time scales as short as $10^{-21}$–$10^{-22}$ s is suggested.
Measuring space-time extent: femtoscopy

- Use two-particle correlation, coming from the interaction $\Psi$ (quantum statistics (HBT), coulomb and/or strong)
- Measure $C(q)$
- Try to invert the Koonin-Pratt eq. to gain information about $S$ from known $\Psi$ and measured $C$

The Integral Equation for Correlation

$$C(\vec{q}) = \int S(r)|\Psi(\vec{q}, r)|^2 d^4r = \langle |\Psi(\vec{q}, r)|^2 \rangle_{pairs}$$
Correlation – charged particles

- Two charged particles interact via Coulomb and strong after their last scattering
  - This gives the final form of the wave-function, for pion-kaon pairs the Coulomb interaction dominates

\[
\Psi_{-k^*} (r^*) = e^{i\delta_c \sqrt{A_c(\eta)}} e^{-ik^* r^*} F(-i\eta,1,i\xi) + f_c (k^*) \tilde{G}(\rho, \eta)/r^*
\]

\[
\xi = k^* r^* + k^* r^* \equiv \rho (1 + \cos(\theta^*)), \quad \rho = k^* r^*, \quad \eta = (k^* a)^{-1}, \quad a = (\mu z_1 z_2 e^2)^{-1}
\]

\[
F(k^*, r^*, \theta^*) = 1 + r^* (1 + \cos \theta^*) / a + (r^* (1 + \cos \theta^*) / a)^2 + i k^* r^* (1 + \cos \theta^*)^2 / a + \ldots
\]

\(\theta^*\) is an angle between separation \(r^*\) and relative momentum \(k^*\)
Accessing asymmetry

\[ k^*_{\text{out}} \equiv k^* \cos(\Psi) \]
\[ k^*_{\text{side}} \equiv k^* \sin(\Psi) \]

Transverse plane

\[ \Psi = \phi + \theta^* \]

We want to measure \( \langle r^*_\text{out} \rangle \equiv \langle r^* \cos(\varphi) \rangle \)

- But we only measure relative \( k^* \) and total momentum \( v \), so we only know \( \Psi \)

- We also know that the CF depends on \( \theta^* \)

- The three angles are connected by a simple sum rule: average cosine signs must also follow

- By looking at the CF vs \( \cos(\Psi) \) we are able to access asymmetries

\[ \cos(\Psi) = \cos(\varphi) \cos(\theta^*) + \sin(\varphi) \sin(\theta^*) \]
\[ \text{sign} \langle \cos(\Psi) \rangle = \text{sign} \langle \cos(\varphi) \rangle \text{sign} \langle \cos(\theta^*) \rangle \]

\[
\begin{align*}
\text{if } |C(\langle \cos(\Psi) \rangle > 0) - 1| > |C(\langle \cos(\Psi) \rangle < 0) - 1| \text{ then } \langle \cos(\varphi) \rangle < 0
\end{align*}
\]
The pion-kaon correlation dominated by Coulomb (effect is quite narrow and opposite for same-sign and opposite-sign pairs)

Only the $l=0, m=0$ and $l=1, m=1$ real components sufficient for analysis

$l=0, m=0$ component sensitive to overall system size

$l=1, m=1$ component maximizes sensitivity to emission asymmetry

Higher $l$ – finer details of correlation – not analyze here

$$C^m_l(q) = \int C(\vec{q}) Y^m_l(\cos(\theta), \phi) d\phi d\cos(\theta)$$
Sensitivity to emission asymmetries

\[ \mathcal{R} \{ C_1^1 \} \sim \int C(\phi, \cos(\theta)) \cos(\phi) d\phi d\cos(\theta) \]

- Increasing emission asymmetry mainly affects \( \mathcal{R} \{ C_1^1 \} \)
- No asymmetry gives flat \( \mathcal{R} \{ C_1^1 \} \)
- Fitting the two components allows to extract asymmetry

AK, PRC 81 (2010) 064906

Asymmetry:
- 0 fm
- -2 fm
- -4 fm
- -6 fm
- -8 fm

Response to asymmetry increase
Space and time asymmetry

- The non-identical particle femtoscopy sensitive to the emission asymmetry between particle types, possible because they are not identical
- Measurement sensitive to the difference of the spatial and time asymmetries, not possible to distinguish between them
  \[ \mu_{out} = \langle r_{out}^* \rangle = \langle \gamma r_{out} - \beta \gamma \Delta t \rangle \]
- “Spatial” asymmetry \( r_{out} \) arises in flowing medium, difficult to produce otherwise
- “Time” asymmetry \( \Delta t \) may have various origins, some not connected to flow
Simulations in Therminator2

- Used hypersufrace from (3+1)D viscous hydrodynamic code coupled to Therminator2 statistical hadronization
  - Tuned to ALICE Pb-Pb Collisions, 2.76 ATeV
  - Centrality 0-10%, 10-20%, 20-30%, 30-40%, 40-50%
  - The same dataset as used for identical pion/kaon calculation
  - Calculated separately for $\pi^+K^-$, $\pi^-K^+$, $\pi^+K^+$, $\pi^-K^-$, then statistically averaged to get one datapoint per centrality

- Optional: Introduce ad-hoc emission time delay for kaons with delay for each particle selected randomly from a Gaussian distribution of a given width and mean

- Calculated correlation function with only Coulomb
Fitting non-identical correlation

• Calculate numerically the correlation function for points on the \((R, \mu)\) grid, where source is defined in LCMS as:

\[
S(\vec{r}) \sim \exp\left( -\frac{(r_{\text{out}}-\mu_{\text{out}})^2}{R^2} - \frac{r_{\text{side}}^2}{R^2} - \frac{r_{\text{long}}^2}{\alpha^2 R^2} \right)
\]

\(\chi^2\) map

![Graph showing correlation functions](image)

Example fit

AK, arXiv.org: 1804.06781
Results

- First model calculation for pion-kaon correlations for Pb-Pb collisions at the LHC
- Introduction of time delay has little influence on size. Width of time delay dist. also small effect
- Emission asymmetry directly sensitive to time delay introduced in the calculation, as expected
- Direct measurement of emission time delays possible also for heavy-ion environment with flow (but model dependent)

AK, arXiv.org: 1804.06781
Linearity of response

- Difference between “default” calculation and one with time delay plotted vs. the introduced time delay
- Clear monotonic, linear, one-to-one correspondence observed, regardless of the system size. Very robust probe.
Comparison to data

- ALICE has shown first pion-kaon results from LHC at QM2018
- System size well reproduced (similarly to identical pion and kaon femtoscopy)
- Emission asymmetry in “default” case larger than in data
- Asymmetry with 2.1 fm/c kaon delay consistent with data: internal consistency with identical kaon femtoscopy
Fits vs. pair velocity

- Calculations also done vs. pair transverse velocity – combining two collectivity signatures in one measurement
- Size of the system decreases with pair velocity – clear signature of collectivity
- Emission asymmetry is also clearly observed for both pair velocity intervals
Centrality dependence

- Correlations show linear size dependence with cube root of multiplicity, similar to all identical-particle correlation analyses (pion, kaon, proton, 1D, 3D, etc.)

- Emission asymmetry also seems to linearly scale with multiplicity, regardless of pair velocity range
Scaled asymmetry

- Emission asymmetry scaled with system size:
  - Relatively constant with multiplicity – may be smaller at peripheral collisions
  - Grows with pair velocity
Summary

- Pion-kaon correlations an unique way to analyze the collectivity and emission time ordering in heavy-ion collisions
- Emission asymmetry directly sensitive to emission time delays between particle species (but some model dependence)
- New, precise, independent measure of time delays, which can probe effects such as emission time delay from rescattering via resonances
- Addition of pair velocity dependence combines two signatures of collectivity in one analysis
- Relative asymmetry increase and total size decrease observed for high velocity, first time both effects seen together.