Femtoscopy of Proton, Light nuclei, and Strange hadrons in Au+Au Collisions at STAR

Ke Mi  (for the STAR Collaboration)
Central China Normal University
Heidelberg University
2022/04/07
Outline

1. Introduction
2. STAR Experiment & Datasets
3. Results
   1) Meson-Meson Correlation Function ($K^0 - K^0_s$)
   2) Baryon-Baryon Correlation Function (p-p, p-$\Xi^-$)
   3) Light Nuclei Correlation Function (p-d, d-d)
4. Summary & Outlook
Two-particle correlations at small relative momenta contain information about the space-time characteristics of the emitting source and final-state interaction effects.

1. **Meson-Meson Interaction -> neutral kaons correlation**
   1) Kaon can provide complementary information to pions
   2) Kaon correlation measurement offers space-time evolution involving strangeness

2. **Baryon-Baryon Interaction -> p-p and p-\(\Xi^-\) correlations**
   1) p-p interaction can be used as baseline for other systems
   2) Hyperon-Nucleon\((Y-N)\) & Hyperon-Hyperon\((Y-Y)\) interaction: Important for understanding the inner structure of compact stars and the formation of bound states

3. Light Nuclei Correlation -> p-d, d-d correlations

1) A systematic measurement of p-p, p-d, and d-d correlation functions may tell us whether deuterons are directly emitted from the fireball or formed due to final-state interactions.

2) A large amount of light nuclei produced at 3 GeV ->
   Allowing precision measurements
Analysis Method: Femtoscopy

- Femtoscopy (HIC) is inspired by Hanbury Brown and Twiss interferometry method (Astronomy)\(^1\)
- Study the spatial and temporal extent of emission source
  - Quantum Statistics (Fermi-Dirac, Bose-Einstein)
  - Final-state Interactions (Coulomb, Strong)
  - Collision Dynamics

- Two-particle correlation function:

\[
C(k^*) = \frac{P(p_a p_b)}{P(p_a) P(p_b)} = \int S(\vec{r}) |\Psi(\vec{k}^*, \vec{r})|^2 d^3\vec{r} = \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}
\]

\(k^* = \frac{|p_a - p_b|}{2}\), relative momentum

\(\vec{r}\): relative distance

\(N_{\text{same}}(k^*)\): same event
\(N_{\text{mixed}}(k^*)\): mixed event

>1: Attraction
=1: No Correlation
<1: Replusion

\(^1\)Nature 178 1046-1048(1956)
STAR Detector and Datasets

- Excellent Particle Identification
- Large, Uniform Acceptance at Mid-rapidity

### Datasets

<table>
<thead>
<tr>
<th>Energy $\sqrt{s_{NN}}$</th>
<th>Year</th>
<th>Mode</th>
<th>Statistics (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 GeV</td>
<td>2018</td>
<td>Fixed-Target</td>
<td>~260</td>
</tr>
<tr>
<td>39 GeV</td>
<td>2010</td>
<td>Collider</td>
<td>~86</td>
</tr>
<tr>
<td>200 GeV</td>
<td>2010</td>
<td>Collider</td>
<td>~230</td>
</tr>
</tbody>
</table>

### STAR Fixed-target Experiment Setup

- Fixed Target $z = 2.01 \text{ m}$
- Datasets
  - Energy $\sqrt{s_{NN}}$
  - Year
  - Mode
  - Statistics (M)
Particle Identification and Acceptance at $\sqrt{s_{NN}} = 3$ GeV

TPC PID

TOF PID

- p and d: Identified by TPC and TOF
- $\Xi^{-}$: Reconstructed via KFParticle Package
  - $\Xi^{-} \rightarrow \Lambda + \pi^{-} \rightarrow p + \pi^{-} + \pi^{-}$, b.r. 99.887%

Quark Matter 2022- Krakow, Poland - Ke Mi
Results
\[ CF(q_{\text{inv}}) = 1 + \lambda e^{-R_{\text{inv}}^2q_{\text{inv}}^2} \]

- Quantum statistics correlation function (Gaussian)
- Lednicky & Lyuboshitz model (QS + FSI)

\[ CF(q_{\text{inv}}) = 1 + \lambda \left( e^{-R_{\text{inv}}^2q_{\text{inv}}^2} + \frac{1}{2} \left( \frac{f(k^*)}{R_{\text{inv}}} \right)^2 + \frac{4\Re f(k^*)}{\sqrt{\pi R_{\text{inv}}}} F_1(q_{\text{inv}} R_{\text{inv}}) - \frac{2\Im f(k^*)}{\sqrt{\pi R_{\text{inv}}}} F_2(q_{\text{inv}} R_{\text{inv}}) \right) \]

For details, see poster by Diana Pawłowska

0.4 < p_T < 2.0 GeV/c

|y| < 0.5

FSI is needed to reproduce the dip structure

\[ q_{\text{inv}} = 2k^* \]
1. Centrality dependence: $R_{0-10\%} > R_{10-70\%}$
2. Energy dependence: $R_{200\text{GeV}} > R_{39\text{GeV}}$
3. Significant difference in radii between QS and Lednicky & Lyuboshitz models

Final state interactions

Antonelli: eConf C020620, THAT06 (2002)  
1. Large uncertainties due to limited proton-$\Xi^-$ pairs at low energy
2. Modelled by hadronic transport model UrQMD + an afterburner, model results show a similar trend as data

CARB: https://web.pa.msu.edu/people/pratts/freecodes/crab/home.html
1. Clear centrality dependence seen -> Smaller source size in peripheral collisions
2. More significant rapidity dependence in peripheral collisions
Proton-Deuteron Femtoscopy in Au+Au Collisions at 3 GeV

1. Clear depletion at small k* range seen in data
2. Data compared with Lednicky & Lyuboshitz model\textsuperscript{1,2}
   - A spherical source size with r = 3-4 fm is consistent with data

\textsuperscript{1} Lednicky Ř, Lyuboshitz V. Sov. J. Nucl. Phys. 35:770 (1982)

First measurement of p-d CF at STAR
Deuteron-Deuteron Femtoscopy in Au+Au Collisions at 3 GeV

1. Clear depletion at small k* range seen in data
2. Data compared with Lednicky & Lyuboshitz model\textsuperscript{1,2}
   – A spherical source size with \( r = 4-5 \text{ fm} \) is consistent with data \( \rightarrow \) Larger than p-d


Quark Matter 2022- Krakow, Poland - Ke Mi
1. Compared with SMASH + Correlation after burner (CRAB) model
2. CF calculated with coalescence of deuterons is in better agreement with data
   ➢ Support the deuteron formation at 3 GeV is dominated by coalescence
3. SMASH source size: 4.3 - 5.9 (fm) from peripheral to central collisions

Summary

1. $K^0_S K^0_S$ Correlation Function (39 GeV & 200 GeV)
   1) Significant difference in radii between QS and L&L models → Final state interactions

2. Baryon-Baryon Correlation Function (3 GeV)
   1) Strong centrality dependence found in p-p CF → Smaller source size in peripheral
   2) p-$\Xi^-$: UrQMD+Crab model result shows similar trend as data

3. Light Nuclei Correlation Function (3 GeV)
   1) First measurement of p-d and d-d correlation functions from STAR
   2) p-d and d-d CF qualitatively described by L&L model → d-d has larger emission
      source size than p-d
   3) d-d CF described better by the model including coalescence

   → Light nuclei are likely to be formed via coalescence

Outlook

- In the 2nd phase of BES, STAR has collected 10-20 times more data in Au+Au collisions
  at the energy range $\sqrt{s_{NN}} = 3$ - 19.6 GeV. These data allow us to perform precision
  femtoscopy analysis.

Stay tuned for the RHIC BES-II!
Thank you for your attention!