Recent Measurements of Hadron Interactions from Heavy-ion Collisions

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Outline:
● Motivation
● Recent measurements: Baryon-Baryon, Baryon-meson
● Summary

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Hadron Interactions

- Hadron interactions are of fundamental interest in Nuclear Physics and Astrophysics
- Hypernuclear interactions - hyperon puzzle in Neutron stars
- Understanding production and the structure of hypernuclei
- Exotic hadrons (tetraquarks, pentaquark, dibaryons) – long standing challenge in hadron physics
Hyperon Puzzle in Neutron Stars (NS)

- Many hyperonic matter EOS models predict the presence of hyperons (Y) in the NS core and gives $M_{\text{max}} < 2M_\odot$, incompatible with measured NS masses.

- This baffling problem likely originates from our incomplete knowledge (model dependence) of the hypernuclear interactions.

- Need for new experimental data to improve understanding of YN, YY two-body interaction and three-body forces: YNN, YYN, YYY.
Exotic Hadrons

- Within Standard Model, baryons are made up of 3 quarks and mesons are made up of a pair of quark-antiquark
- 1977: using the Quark Bag Model, Jaffe predicted H-dibaryon made of six quarks (uuddss) \( (\text{Phys. Rev. Lett. 38,195 (1977); 38, 617(E)(1977)} \)
- Exotic hadrons – long standing challenge in hadron physics

Tetraquark
Meson-Meson molecule

Hexaquark
Baryon-Baryon molecule

Pentaquark
Meson-Baryon molecule
Baryons in HIC

- Hot and dense, strongly interacting partonic matter
- Comparable number of baryons and anti-baryons are produced in HIC

**Diagram:**

- Data, ALICE
- Statistical Hadronization

**Graph:**

- **Pb-Pb** $\sqrt{s_{NN}}=2.76$ TeV, 0-10% centrality
- **Au+Au** $\sqrt{s_{NN}}=200$ GeV

**References:**

Two-particle Correlation Function

Femtoscopy: Probe the spatial and temporal extent of particle emitting source

\[ C_{K}^{ab}(\mathbf{q}) = \frac{d^6N_{ab}/(dp_a^3dp_b^3)}{(d^3N_a/dp_a^3)/(d^3N_b/dp_b^3)} = \int d^3\mathbf{r}' \cdot S_{K}^{ab}(\mathbf{r}') \cdot |f(\mathbf{q}, \mathbf{r}')|^2 \]

\( S(\mathbf{r}') \rightarrow \) normalized separation distribution

\( f(\mathbf{q}, \mathbf{r}') \rightarrow \) two-particle wave function, where

(Quantum statistics (QS), FSI: Coulomb int., Strong int.)
An attractive interaction allows to describe both STAR and ALICE experiment data

The scattering length is constrained to $f_0^{-1} < 0.8$ fm$^{-1}$

A shallow attractive potential is in very good agreement with the experimental results

The binding energy, $B_{\Lambda\Lambda} = 3.2^{+1.6}_{-2.4}\text{(stat)}^{+1.8}_{-1.0}\text{(syst)}$ MeV

Larger statistics data-sets at RHIC and LHC to yield a conclusive answer
The ratio of correlation function for the small (peripheral collisions) to large (central collisions) system is smaller than unity at low relative moment.

Measurement supports the existence of a deeply bound state decaying into the proton \( \Omega \) final state.

Spin-2 P\( \Omega \) potentials

<table>
<thead>
<tr>
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<th>( V_I )</th>
<th>( V_{II} )</th>
<th>( V_{III} )</th>
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</thead>
<tbody>
<tr>
<td>Binding energy ( E_B ) (MeV)</td>
<td>-</td>
<td>6.3</td>
<td>26.9</td>
</tr>
<tr>
<td>Scattering length ( a_0 ) (fm)</td>
<td>-1.12</td>
<td>5.79</td>
<td>1.29</td>
</tr>
<tr>
<td>Effective range ( r_{eff} ) (fm)</td>
<td>1.16</td>
<td>0.96</td>
<td>0.65</td>
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</table>

● An attractive interaction exists and exceeds the strength of the Coulomb interaction.

● The theoretical calculations predict the existence of a $p-\Omega^-$ bound state with a binding energy of 2.5 MeV, which causes a depletion in the correlation function in the $k^*$ region between 100 and 300 MeV/c.

● The lattice QCD predictions underestimate the data.

● Additional measurements are necessary to draw a firm conclusion on the existence of the bound state.
The measured p-$$\Xi$$ correlation function shows deviation from expectation based on the Coulomb interactions.

An attractive p-$$\Xi$$ strong interaction is observed.

The p-$$\Xi$$ interactions from HAL-QCD collaboration are found to be consistent with the measurement.
The measured $p-\Xi$ correlation function show deviation from expectation based on the Coulomb interactions.

An attractive $p-\Xi$ strong interaction is observed.

The ratio of $p-\Xi$ correlation function for the peripheral to central collisions is consistent with the $p-\Xi$ interactions from HAL-QCD collaboration.
Lattice QCD/chiral EFT calculations indicate an attractive interaction, but not strong enough to form a bound state.

- The result shows anti-correlation at $Q_{inv} < 0.25$ GeV/c.
  - qualitatively matches with coulomb strength.
  - to cancel quantum statistics (negative correlation), strong interaction needs to be positive correlation.
Proton-$\Lambda$ Correlation Function

- Calculations based on chiral effect field theory predicts a repulsive core of the interaction potential for NLO

- Discrimination of the LO and NLO not possible due to the lack of data

\[ p+Nb \text{ at } \sqrt{s_{NN}} = 3.18 \text{ GeV} \]

\[ \Lambda p \rightarrow \Lambda p \]

\[ \sigma \text{ (mb)} \]

\[ p+Nb \text{ at } \sqrt{s_{NN}} = 3.18 \text{ GeV} \]

\[ \text{HADES} \]


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The coupling of $p\Lambda$ to $N\Sigma$ is manifested as a cusp-like enhancement present at the corresponding threshold energy.

Different modelling for the $p-\Sigma^0$ feed-down leads to modification of the measured $p\Lambda$ correlation, implying an indirect sensitivity to the genuine $p-\Sigma^0$ correlation.
The imaginary part of the scattering length vanishes within uncertainties, indicating that inelastic processes do not play a prominent role for the p-φ interaction.

The p-φ interaction in vacuum is attractive and dominated by elastic scattering.

The N-φ Coupling constant, using Yukawa-type potential, is

\[ g_{N-\phi} = 0.14 \pm 0.03 \text{(stat)} \pm 0.02 \text{(syst)} \]
The measurement suggests that the $\Lambda K^+$ interaction is repulsive, the $\Lambda K^-$ and $\Lambda K_0^S$ interaction is attractive.
The $\Lambda K$ systems source radii is larger than expected from extrapolation from identical particle femtoscopic studies.

The larger radii arising from the separation in space-time of the single particle source distributions of $\Lambda$ and $K$. 

$\Lambda$–$\Lambda$ Correlation Function

Kaon-Proton Correlation Function

- An accurate measurement of kaon–proton scattering parameters at low relative momentum, allowing precise access to the K–p → K–p process.

- A complementary tool to the study of exotic atoms with comparable precision.

- The obtained scattering length is comparable to the values from scattering and exotic kaonic atoms experiment as well as model calculations.
Summary

• The femtoscopy measurements from heavy-ion collisions provides a unique opportunity to explore strong interactions and search for exotics.

• The upcoming high luminosity Run-3 and Run-4 at LHC and planned data taking for Au+Au at 200 GeV in 2023 and 2025 at RHIC will allow us to significantly improve the precision of the extracted inter-action parameters for many hadron pairs.

Thank you!