ALICE unveils strong interaction among stable and unstable hadrons

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Overview

ALICE at the LHC

Effective strong interactions

Equation of state of neutron stars

Test of first principle calculations

Search for new bound states

Equation of state of neutron stars

D. B. Leinweber/University of Adelaide
Residual strong interaction among hadrons

Running coupling constant defines the boundaries of Low energy QCD
-> $Q \sim 1 \text{ GeV}, R \sim 1 \text{ fm}$
-> No perturbative methods are applicable
-> Effective theories with hadrons as degrees of freedom
Residual strong interaction among hadrons

Running coupling constant defines the boundaries of Low energy QCD

\[ Q \sim 1 \text{ GeV}, \quad R \sim 1 \text{ fm} \]

\[ \rightarrow \text{No perturbative methods are applicable} \]

\[ \rightarrow \text{Effective theories with hadrons as degrees of freedom} \]

Next Step: Understanding of the interaction starting from quark and gluons
Strong interaction between (strange) hadrons

T. Hatsuda, K. Sasaki et al.

HAL QCD Coll., PLB 792 284-289 (2019)
HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737

\[ \mathbf{S} = 0 \]

\[ \mathbf{S} = \pm 1 \]

\[ \mathbf{S} = \pm 2 \]

\[ \mathbf{S} = \pm 3 \]

\[ \mathbf{S} = \pm 4 \]

\[ \mathbf{S} = \pm 5 \]

\[ \mathbf{S} = \pm 6 \]

\[ \begin{align*}
\mathbf{NN} & \quad \mathbf{N\Lambda, N\Sigma} & \quad \mathbf{\Lambda\Lambda, \Lambda\Sigma, \Sigma\Sigma, N\Xi} & \quad \mathbf{\Lambda\Xi, \Sigma\Xi, N\Omega} & \quad \mathbf{\Xi\Xi, \Lambda\Omega, \Sigma\Omega} & \quad \mathbf{\Xi\Omega} & \quad \mathbf{\Omega\Omega}
\end{align*} \]

\[ a = 0.085 \text{ fm} \]

\[ L = 8.1 \text{ fm} \]

\[ m_{\pi} = 146 \text{ MeV}/c^2 \]

\[ m_{K} = 525 \text{ MeV}/c^2 \]

Local potentials for the Nucleon-\( \Xi \) interactions

Better S/N of LQCD
Strong interaction between (strange) hadrons

$S = 0$
$S = -1$
$S = -2$
$S = -3$
$S = -4$
$S = -5$
$S = -6$

NN  \quad N\Lambda, N\Sigma  \quad \Lambda\Lambda, \Lambda\Sigma, \Sigma\Sigma, N\Xi  \quad \Xi\Xi, \Sigma\Omega, N\Omega  \quad \Xi\Omega, \Lambda\Omega, \Sigma\Omega  \quad \Xi\Omega  \quad \Omega\Omega$

Experimental data

Better S/N of LQCD


K. Nakazawa et al. PTEP 2015, 033D02


K. Nakazawa et al. PTEP 2015, 033D02
The femtoscopy method

\[ E_A, \vec{P}_A \]

\[ E_B, \vec{P}_B \]
Nuclear collisions

$E_A, \overrightarrow{P_A}$

$E_B, \overrightarrow{P_B}$
Particle production and propagation

Pair reference frame

\[ k^* = \frac{|\vec{p}_a^* - \vec{p}_b^*|}{2} \]
Schrödinger Equation:
\[ V(r) \rightarrow |\psi(\vec{k}^*, \vec{r})|^2 \] relative wave function for the pair

Pair reference frame

\[ k^* = \frac{|\vec{p}_a - \vec{p}_b^*|}{2} \]
The femtoscopy technique

Schrödinger Equation:

\[ V(r) \rightarrow |\psi(k^*, r)|^2 \] relative wave function for the pair

\[
C(k^*) = \int S(r) \left| \psi(k^*, r) \right|^2 d^3 r = \zeta(k^*) \cdot \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)}
\]

Emission source \hspace{1cm} Two-particle wave function

>1 if the interaction is attractive
=1 if there is no interaction
<1 if the interaction is repulsive

Pair reference frame

\[ k^* = \frac{p_a^* - p_b^*}{2} \]

The two-particle wave function $\Psi(k^*, r)$ is defined as:

$$S(r) = (4\pi r_0^2)^{-3/2} \cdot \exp\left(-\frac{r^2}{4r_0^2}\right)$$

The emission source is given by:

$$C(k^*) = \int S(r) \left|\psi(k^*, \vec{r})\right|^2 d^3r = \zeta(k^*) \cdot \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

>1 if the interaction is attractive

= 1 if there is no interaction

<1 if the interaction is repulsive
Femtoscopy with small sources

Small particle-emitting source created in pp and p–Pb collisions at the LHC

○ Essential ingredient for detailed studies of the strong interaction
ALICE data

- Data set:
  pp 13 TeV (1000 M high multiplicity events), p-Pb 5.02 TeV (600 M minimum bias)
- Direct detection of charged particles (protons, kaons, pions)
- Reconstruction of hyperons:
  \[
  \begin{align*}
  \Lambda &\rightarrow p\pi^- \\
  \Xi^- &\rightarrow \Lambda\pi^- \\
  \Omega^- &\rightarrow \Lambda K^- \\
  \Sigma^0 &\rightarrow \Lambda\gamma
  \end{align*}
  \]

The very good PID capabilities of the detector result in very pure samples!
Hyperons @ ALICE in pp collisions

\[ \Lambda \rightarrow p\pi^- \]
\[ \Xi^- \rightarrow \Lambda\pi^- \]
\[ \Omega^- \rightarrow \Lambda K^- \]
\[ \Sigma^0 \rightarrow \Lambda\gamma \]
Collective effects and strong resonances

Anisotropic +
pressures gradients Radial

Different effect on different masses

Resonances with $c\tau \sim r_0 \sim 1\text{fm}$ ($\Delta^{++}, N^*, \Sigma^*$)

<table>
<thead>
<tr>
<th>Particle</th>
<th>Primordial fraction</th>
<th>Resonances $&lt;c\tau&gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>33 %</td>
<td>1.6 fm</td>
</tr>
<tr>
<td>Lambda</td>
<td>34 %</td>
<td>4.7 fm</td>
</tr>
</tbody>
</table>

$S(r) = G(r, r_{\text{core}}(m_T)) = \frac{1}{(4\pi r_{\text{core}}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{\text{core}}^2}\right)$

$E(r, M_{\text{res}}, \tau_{\text{res}}, p_{\text{res}}) = \frac{1}{s} \exp(-\frac{r}{s})$

$S = \beta \gamma \tau_{\text{res}} = \frac{p_{\text{res}}}{M_{\text{res}}} \tau_{\text{res}}$

U. Wiedemann U. Heinz (PRC56 R610, 1997)
pp and pΛ correlations

\[ C(k^*) = \int |S(r)|^2 |\psi(\vec{k}^*, \vec{r})|^2 \, d^3r \]

**pp Correlation:**
AV18 + Coulomb potentials used with CATS to calculate \( \psi(\vec{k}^*, \vec{r}) \)

**pΛ Correlation:**
\( \chi \)EFT LO and NLO \( \psi(\vec{k}^*, \vec{r}) \) are used

A fit with a Gaussian profile for the source delivers different source dimensions \( r_0 \) for pp and pΛ pairs.

A Gaussian source with resonances

- Radii measured from the p-p and p-Λ correlation function
  - Input: production fraction/life-times (Statistical Hadronization Model*) and angular distributions (EPOS event generator**)
- Observation of a common $m_T$ scaling of the core radius
  - Hypothesis of a universal emission source of baryons

**T. Pierog et al. PRC 92 (2015) 3, 034906
A Gaussian source with resonances

![Graph](physics-lett-B-811-135849)

<table>
<thead>
<tr>
<th>Pair</th>
<th>r&lt;sub&gt;Core&lt;/sub&gt; [fm]</th>
<th>r&lt;sub&gt;Eff&lt;/sub&gt; [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-p</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>p-Λ</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>p-Σ⁰</td>
<td>0.87</td>
<td>1.02</td>
</tr>
<tr>
<td>p-Ξ⁻</td>
<td>0.93</td>
<td>1.02</td>
</tr>
<tr>
<td>p-Ω⁻</td>
<td>0.86</td>
<td>0.95</td>
</tr>
</tbody>
</table>
QCD $p-\Xi^-$ and $p-\Omega^-$ lattice potentials

Better S/N of LQCD
QCD $p-\Xi^-$ and $p-\Omega^-$ lattice potentials

- Interaction of $p-\Xi^-$ pairs in four Isospin ($I = 0,1$) and Spin ($S=0,1$) states

HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737
QCD $p-\Xi^-$ and $p-\Omega^-$ lattice potentials

- Interaction of $p-\Xi^-$ pairs in four isospin ($I=0,1$) and spin ($S=0,1$) states
- Interaction of $p-\Omega^-$ pairs in $^3S_1$ or $^5S_2$ ($S=1, 2$) states
  - Inelastic channels (e.g. $p\Omega^- \rightarrow \Lambda\Xi^-$) in $^3S_1$ not yet calculated on the lattice
  - Attraction in $^5S_2$ results in the prediction of a bound state (B.E. = 1.54 MeV)

HAL QCD Coll., Nucl.Phys.A 998 (2020) 121737
Correlation functions and bound states

Correlation functions and bound states

\[ C(k^*) = \int S(r) |\psi(k^*, r)|^2 d^3r \]

\[ \vec{H} \cdot \psi(k^*, r) = E \cdot \psi(k^*, r) \]

Correlation functions and bound states

Correlation functions and bound states

Correlation functions and bound states

• Predicted correlation function sensitive to changes of the B.E.
• Femtoscopy in pp collisions at the LHC sensitive to small differences among the interaction potentials

Enhancement above Coulomb
→ Observation of the strong interaction
• Missing potential of the $^3S_1$ channel
  → Test of two cases:
  • Inelastic channels dominated by absorption
  • Neglecting inelastic channels
• Data more precise than lattice calculations
• So far, no indication of a bound state
p–Ω⁻ correlation function in pp at 13 TeV


![Graph showing correlation function](image)
Excursion to neutron stars
Hyperon appearance in neutron stars?

Dimensions:
R ~ 10 – 15 km
M ~ 1.2 – 2.2 M⊙

Outer crust:
Ions, electron gas, neutrons

Inner core:
Neutrons?
Protons?
Hyperons?
Kaon condensate?
Quark matter?

Neutron stars: very dense, compact objects

- How does the equation of state of neutron star look like?
  - What are the constituents to consider?
  - How do they interact?
Hyperon appearance in neutron stars?

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- Ions, electron gas, neutrons

**Inner core**:
- Neutrons?
- Protons?
- Hyperons?
- Kaon condensate?
- Quark matter?
Hyperon appearance in neutron stars?

Neutron stars: very dense, compact objects

- With increasing baryonic densities, hyperon production becomes energetically favorable.
- Exact composition strongly depends on constituent interactions and couplings!

p–Ξ⁻ correlation function in pp at 13 TeV

- Enhancement above Coulomb → Observation of the strong interaction
- Measurement in different collision system retains excellent agreement with lattice predictions (HAL-QCD)
- Continuation of the study in the p-Pb system Phys. Rev. Lett. 123, 112002
Attractive pΞ⁻ interaction lead to slightly attractive single particle potential in symmetric nuclear matter (SNM) and slight repulsion in neutron rich matter. Ξ⁻ appears at larger densities in NS.
The resulting equation of state for neutron star is stiffer and the observation of 2 solar masses is matched. This is not the end of the story…
The Hyperon Puzzle
Outlook

The shown studies can be extended to more hadron pairs
Projection for the Run 3 data taking:

CERN-LHCC-2020-018 ; LHCC-G-179
Future high-energy pp programme with ALICE
Summary

- Femtoscopy technique can be used to provide unprecedented constraints on hadron-hadron interactions
- We have tested lattice calculations
- We can study bound states
- We provide important constraints to the equation of state of neutron stars
- More precision studies within reach with the large data samples collected in Run 3 & 4
  - Direct measurements of three-body interactions for the first time
  - And then we move to charmed hadrons...

Test of first principles calculations
Search for new bound states
Equation of state of neutron stars
Stay tuned for much more to come…