First experimental test of HAL QCD lattice calculations for the multi strange hyperon-nucleon interaction with ALICE

Dimitar Mihaylov for the ALICE collaboration at QM 2019
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Overview

The goal

Study the interaction between a proton and multi-strange baryons $\Xi^-(ssd)\Omega^-(sss)$
A fundamental problem in hadron physics (e.g. relevant for the nuclear equation of state)

The theory

- **Lattice QCD potentials** (HAL-QCD Collaboration)
  - $p-\Xi^-$: predicted attractive interaction
    -> Consequences for the possible appearance in neutron stars
  - $p-\Omega^-$: predicted very attractive interaction
    -> Opens the door for a $N\Omega$ di-baryon

The experimental knowledge

- $p-\Xi^-$: hypernuclei (Kiso event) K. Nakazawa et al. PTEP 2015, 033D02
Femtoscopy @ ALICE

The very good PID capabilities of the detector result in very pure samples!

- Data set: 
  \textbf{pp 13 TeV (1000 M high multipl. events)}
- Direct detection of charged particles (protons, kaons, pions)
- Reconstruction of hyperons:
  \[ \Xi^- \rightarrow \Lambda \pi^- \rightarrow p\pi^- \pi^- \]
  \[ \Omega^- \rightarrow \Lambda K^- \rightarrow p\pi^- K^- \]

The very good PID capabilities of the detector result in very pure samples!

- The purity of the protons is > 99%
- The purity of $\Xi^-$ is 92%
- The purity of $\Omega^-$ is 75%

\textit{Scheme based on Int.J.Mod.Phys. A29 (2014) 1430044}
Femtoscopy
Overview

Source function $S(\vec{r})$

Measure the correlation function $C(k^*)$

$\Psi(\vec{k}, \vec{r})$

two particle wave function
Femtoscopy
Overview

Source function $S(\vec{r})$

Measure the correlation function $C(k^*)$

two particle wave function

Statistical definition

$$C(k^*) = \frac{\mathcal{P}(\vec{p}_a, \vec{p}_b)}{\mathcal{P}(\vec{p}_a)\mathcal{P}(\vec{p}_b)} = N \frac{N_{\text{Same}}(k^*)}{N_{\text{Mixed}}(k^*)} = \int S(\vec{r}) |\Psi(\vec{k}^*, \vec{r})|^2 \, d^3r \xrightarrow{k^* \to \infty} 1$$

Experimental definition

Relative distance / reduced momentum in the rest frame of the pair

Theoretical definition

Single-particle momenta

- Modelling/fitting performed using CATS

Femtoscopy Overview

Small collision systems (pp) probe the “inner” part of the interaction. Assumption: The source is similar for all produced baryons.

\[ C(k^*) = \int S(\vec{r}) |\Psi(\vec{k}^*, \vec{r})|^2 d^3 \vec{r} \xrightarrow{k^* \to \infty} 1 \]

Measure the correlation function \( C(k^*) \)

\( \Psi(\vec{k}, \vec{r}) \)

two particle wave function

Relative distance / reduced momentum in the rest frame of the pair

Further details in the talk of Prof. Laura Fabbietti

- Modelling/fitting performed using CATS

Fixing the source

From \( p-p \) correlations

- The effects of **short-lived resonances** are modeled by assuming a “core” Gaussian source, from which resonances and primordial particles are emitted.

- The resonances are added to the “core”

- Fix the value of \( r_{\text{core}} \) of each particle species based on their \( <m_T> \)

\[
\begin{align*}
\text{p-}\Xi^-: & \quad r_{\text{core}} = 0.80 \pm 0.03 \text{ fm} \\
& \quad r_{\text{eff}} = 0.92 \text{ fm (Gaussian)} \\
\text{p-}\Omega^-: & \quad r_{\text{core}} = 0.73 \pm 0.05 \text{ fm} \\
& \quad r_{\text{eff}} = 0.85 \text{ fm (Gaussian)}
\end{align*}
\]
### N-$\Xi^-$ interaction

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<tr>
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N-$\Xi^-$ interaction

- Null Hypothesis: Coulomb only
- HAL QCD Potential
- NEW: Potential by Nijmegen group

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HAL-QCD: *AIP Conf.Proc. 2130 (2019) no.1, 020002*
ESC16: *Phys. Rev. C 99, 044003*
Results for p-Ξ⁻

Published results for p-Pb collisions


“First Observation of an Attractive Interaction between a Proton and a Cascade Baryon”
Results for $p-\Xi^-$

Published results for $p$-Pb collisions


“First Observation of an Attractive Interaction between a Proton and a Cascade Baryon”

- An enhanced statistical significance of the agreement with Lattice calculations*
- The ESC 16 is excluded => important for hypernuclei studies

Results for $p-\Xi^-$

$p-\Xi^-$ potential in pure neutron matter

In medium: Many body interaction, average $\Xi^-$ Single particle potential ($U_{\Xi}$)

Lattice QCD:
Prediction for repulsive $U_{\Xi^+} \sim 6$ MeV in pure neutron matter
$\Rightarrow$ The existence of $\Xi^-$ in neutron stars is disfavored.

- An enhanced statistical significance of the agreement with Lattice calculations*
- The ESC 16 is excluded $\Rightarrow$ important for hypernuclei studies

Models for the $p-\Omega^-$ interaction

- **Lattice HAL-QCD** potential with **physical quark masses** ($^5S_2$ channel)
  - $m_\pi = 146$ MeV/$c^2$
  - $m_K = 525$ MeV/$c^2$

- **Sekihara**: Meson-exchange model ($^5S_2$ channel)
  - Short range attractive interaction fitted to previous HAL-QCD scattering parameters

### Model Comparison

<table>
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<tr>
<th>Model</th>
<th>$p\Omega^-$ binding energy (strong interaction only)</th>
</tr>
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<tr>
<td>HAL-QCD</td>
<td>1.54 MeV</td>
</tr>
<tr>
<td>Sekihara</td>
<td>0.1 MeV</td>
</tr>
<tr>
<td></td>
<td>+1 MeV with Coulomb</td>
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</tbody>
</table>

→ Models provide so far only $^5S_2$ channel (weight %)

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Results for p-Ω⁻

- “Coulomb only” scenario discarded by ALICE data (> 6 σ) showing the attractive character of the interaction
- More attractive than p-Ξ⁻
Results for $p-\Omega^-$

- “Coulomb only” scenario discarded by ALICE data (> 6 $\sigma$) showing the attractive character of the interaction
- More attractive than $p-\Xi^-$
- Large uncertainties on the theory due to the $^3S_1$ channel
- Precision of ALICE data exceeds the theoretical predictions

$p-\Omega^-$: $r_{\text{core}} = 0.73 \pm 0.05$ fm
$r_{\text{eff}} = 0.85$ fm (Gaussian)
Summary and outlook

- ALICE delivers the first **precise data** to test $p-\bar{\Xi}$ and $p-\bar{\Omega}$ interaction
- Both system show an **attractive** nature of the strong interaction
- $p-\bar{\Xi}$ is well described by lattice computations, which are compatible with **stiffer equation of state**
- $p-\bar{\Omega}$ is **not compatible** with a large binding energy
- $p-\bar{\Omega}$ is very **sensitive** to the **source** size
  *Important to study different collision systems*

- Improve the systematic uncertainties
- Study the $p-\bar{\Omega}$ correlation for different collision systems (source sizes), e.g. $p$-$\text{Pb}$
- Study $p-\Xi^+$
- Run 3/4 will provide even higher statistics:
  *Achieve higher precision*
  *Study additional isospin systems such as $p-\Xi^0$*
  *Possibly access $\Omega$-$\Omega$ correlation*
Thank you for your attention!
感謝諸位的時間
Femtoscopy

Decomposition of $C(k^*)$

- Determine the amount of impurities and secondaries based on a data-driven MC study as done in *Phys.Rev. C99 (2019) no.2, 024001*

\[
C_{tot}(k^*) = \lambda_0 C_0 \oplus \lambda_1 C_1 \oplus \lambda_2 C_2 + \ldots
\]

Correlation of interest

Contributions from impurities, secondaries etc.

- Purity ($P$) from fits to the invariant mass distribution or MC data
- Feed-down fractions ($f$) from MC template fits
- $\lambda_i = P_{i_1} f_{i_1} P_{i_2} f_{i_2}$, where $i_{1,2}$ denote the two particles of the $i$-th contribution
Reconstruction of $\Xi^-$ and $\Omega^-$

Data: **pp collisions** at $\sqrt{s} = 13$ TeV

- Analyzed $10^9$ events
- **High multiplicity** trigger

9.3$\times$10$^6$ $\Xi^-$⊕$\Xi^+$ selected candidates

- identified by $\Xi \rightarrow \Lambda \pi \rightarrow (p\pi)\pi$
- **Purity** 92%.
- 3$\times$10$^4$ $p$-$\Xi^-$⊕$p$-$\Xi^+$ pairs at $k^*<$200 MeV/c

1.2$\times$10$^6$ $\Omega^-$⊕$\Omega^+$ selected candidates

- identified by $\Omega \rightarrow \Lambda K \rightarrow (p\pi)K$.
- **Purity** 75%.
- 0.6$\times$10$^6$ $p$-$\Omega^-$⊕$p$-$\Omega^+$ pairs (700 at $k^*<$100 MeV/c)
Reconstruction of $\Xi^-$ and $\Omega^-$

Data: **pp collisions** at $\sqrt{s} = 13$ TeV
- Analyzed $10^9$ events
- **High multiplicity** trigger

$9.3 \times 10^6 \Xi^- \oplus \Xi^+$ selected candidates
- identified by $\Xi \rightarrow \Lambda \pi \rightarrow (p \pi) \pi$
- **Purity 92%**.
- $3 \times 10^4$ p-$\Xi^- \oplus$ p-$\Xi^+$ pairs at $k^* < 200$ MeV/c

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- **Purity 75%**.
- $0.6 \times 10^6$ p-$\Omega^- \oplus$ p-$\Omega^+$ pairs (700 at $k^* < 100$ MeV/c)

- sidebands analysis to describe the background under the signal peak
Implications for neutron stars with hyperon content

RMF models: EOS of neutron-rich matter with hyperon content

→ use single particle potential at saturation densities as input

\[ U_{NN}(\rho_0), U_{\Lambda N}(\rho_0), U_{\Sigma N}(\rho_0), U_{\Xi N}(\rho_0) \]

-30 MeV

+30 MeV

variable →

Weissenborn et al., NPA881 (2012) 62-77
Implications for neutron stars with hyperon content

RMF models: EOS of neutron-rich matter with hyperon content

→ use single particle potential at saturation densities as input

\[ U_{NN}(\rho_0), U_{\Lambda N}(\rho_0), U_{\Sigma N}(\rho_0), U_{\Xi N}(\rho_0) \]

-30 MeV  +30 MeV  variable →

Repulsive interaction

⇒ Production of \( \Xi \) pushed to higher densities
⇒ stiffer EoS, higher masses

Weissborn et al., NPA881 (2012) 62-77
Previous experimental data: STAR

- Observable: ratio of the correlation function peripheral/central collisions.
- Comparison with Lattice QCD calculations (with large masses)

- Test different fits to Lattice QCD data (delivering three different binding energies of the NΩ):

  Binding energy ($E_b$), scattering length ($a_0$) and effective range ($r_{\text{eff}}$) for the Spin-2 proton-Ω potentials [24].

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<td>$E_b$ (MeV)</td>
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<td>$r_{\text{eff}}$ (fm)</td>
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STAR data favor $V_{III}$, with $E_b = 27 \text{ MeV}$
HAL-QCD potential with heavy quarks

- Based on Lattice calculations with heavy quark masses
  - $m_{\pi} = 875$ MeV/$c^2$
  - $m_K = 916$ MeV/$c^2$

- Used in the STAR $p\Omega$ analysis in Au-Au collisions at $\sqrt{s_{NN}} = 200$GeV

- Lattice calculations fitted by an attractive Gaussian core + an attractive tail, varying the range parameter at long distance ($b_5$)
  - $V_{II}$: best fit to Lattice calculations
  - $V_I / V_{III}$: weaker / stronger attraction

$$V(r) = b_1 e^{-b_2 r^2} + b_3 (1 - e^{-b_4 r^2})(e^{-b_5 r / r})^2$$

Binding energy ($E_b$), scattering length ($a_0$) and effective range ($r_{\text{eff}}$) for the Spin-2 proton-$\Omega$ potentials [24].

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Results for p-Ω⁻

Calculations provide the potential shape for the $^5S_2$ channel (weight $\frac{5}{6}$).

Currently, no model for the other channel in S-wave interaction, $^3S_1$ (weight $\frac{1}{6}$).
Requires coupled channel treatment.
Assume two different (~extreme) scenarios:

1.- Complete absorption for distances $r < r_0$.
   $r_0$ chosen from the condition $|V(^5S_2)| < |V(Coulomb)|$ for $r > r_0$


2.- Complete elastic with a similar attraction as $^5S_2$
Results for $p-\Omega^-$
Results for $p-\Omega^-$

“Coulomb only” scenario discarded by ALICE data (> 6 σ) showing the attractive character of the interaction.

Precision of ALICE data exceeds the theoretical predictions.

\[ r_{\text{core}} = 0.73 \pm 0.05 \text{ fm} \]

Comparison with the model favoured by STAR data:

\[ V_{\text{III}} \]: Ad-hoc fit to previous HAL-QCD calculations with non-physical quark masses with $p\Omega$ dibaryon $E_b = 27 \text{ MeV}$.
Sensitivity of ALICE and STAR data

- Expected correlation function from heavy quark Lattice QCD potentials
- **Smaller radius** source offers the ideal conditions to test the models
- Better purity of ALICE data increases the sensitivity of the test

**purity 75% (ALICE)**
Sensitivity to the source size

Plot from the presentation of Prof. Akira Ohnishi during the FemTUM19 workshop

\( a_0 (pΩ) \sim 3.4 \text{ fm}, R(\text{ALICE}) \sim 0.7 \text{ fm}, R(\text{STAR}) \sim 3 \text{ fm} \)
Correlation function ($^5S_2$) with distance cutoff

- Correlation function from $^5S_2$ channel with cutoff in $r$ (for $r < r_{\text{cutoff}} \Rightarrow V = 0$)
- HAL-QCD with physical quark masses ($t=12$): maximum of the $C(k^*)$ for $r_{\text{cutoff}} = 0.5$ fm
- For VI potential (no bound state) $C(k^*)$ always increases with decreasing $r_{\text{cutoff}}$
Fixing the source

From p-p correlations

- Effects of momentum resolution and feed-down contributions are applied to the fit function.

- The effects of short-lived resonances are modeled by assuming a “core” source, from which resonances and primordial particles are emitted.

\[ r_{\text{core}} = 0.995 \pm 0.006^{+0.024}_{-0.022} \text{(syst.)} \text{ fm} \]
The source function

**Effect of short-lived resonances**

- Effects of **strong resonances** on the correlation function
  - **Introduction of an exponential tail** → non-gaussian contribution
  - **Resonances with** $c\tau \sim r_0 \sim 1$ fm
    - $N^* (\Gamma \sim 150 - 200 \text{ MeV})$
    - $\Delta (\Gamma \sim 150 \text{ MeV})$...

- The modification is **different** for the **distinct particle species**


- The momentum of the resonance computed based on the assumption of a 2-body decay into a final momentum of $k^*=0$

\[
s = \beta \gamma \tau_{\text{res}} = \frac{p_{\text{res}}}{M_{\text{res}}} \tau_{\text{res}}
\]

\[
E(r, M_{\text{res}}, \tau_{\text{res}}, p_{\text{res}}) = \frac{1}{s} \exp\left(-\frac{r}{s}\right)
\]
The source function

Effect of short-lived resonances

- For $\Xi^-$ and $\Omega^-$ no contributions!
- Average mass and average $\tau$ determined by the weighted average values of all resonances

<table>
<thead>
<tr>
<th>Particle</th>
<th>$M_{\text{res}}$ [MeV]</th>
<th>$\tau_{\text{res}}$ [fm]</th>
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<tbody>
<tr>
<td>$p$</td>
<td>1361.52</td>
<td>1.65</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>1462.93</td>
<td>4.69</td>
</tr>
<tr>
<td>$\Sigma^0$</td>
<td>1581.73</td>
<td>4.28</td>
</tr>
</tbody>
</table>
Gaussian core + resonances

\[ 4\pi r^2 S(r) \text{ (1/fm)} \]

- \( p-p \langle m_T \rangle = 1.35 \text{ GeV/c}^2 \) \( (R_{\alpha_{\text{eff}}} = 1.28 \text{ fm}) \)
- \( p-\Lambda \langle m_T \rangle = 1.55 \text{ GeV/c}^2 \) \( (R_{\alpha_{\text{eff}}} = 1.30 \text{ fm}) \)
- \( p-\Sigma^0 \langle m_T \rangle = 2.07 \text{ GeV/c}^2 \) \( (R_{\alpha_{\text{eff}}} = 1.12 \text{ fm}) \)
- \( p-\Xi^- \langle m_T \rangle = 1.85 \text{ GeV/c}^2 \) \( (R_{\alpha_{\text{eff}}} = 0.92 \text{ fm}) \)
- \( p-\Omega^- \langle m_T \rangle = 2.17 \text{ GeV/c}^2 \) \( (R_{\alpha_{\text{eff}}} = 0.85 \text{ fm}) \)
The source (based on $<m_T>$)

- Radius for **pure Gaussian** or **Gaussian core + Res.** taken from p-p $<m_T>$ scaling with the specific value of average $m_T$ mass for each pair (see slides 11-12)
Effect on the source when smearing the resonances