Understanding Lambda Nucleon Interaction from Proton Proton Collisions at LHC

BERNHARD HOHLWEGER
ASTRA WORKSHOP TRENTO
TECHNISCHE UNIVERSITÄT MÜNCHEN
E62 – DENSE AND STRANGE MATTER
GROUP PROF. DR. LAURA FABBIETTI
Outline

• Neutron Stars and what we learn from Femtoscopy
  • The Hyperon Puzzle
  • How can Femtoscopy help?

• Correlation functions
  • Theoretical description of the correlation function
  • Experimental correlation functions

• Results of the Analysis in the p-p collision system at 7 TeV
  • pp and Δp Correlations
  • ΔΔ Correlations
  • Future prospects with CATS

• Summary and Outlook
Neutron Stars

- Observation from X-Ray measurements of binary Systems:
  - Neutron star masses $m > m_\odot$ and radii between 5 – 15 km
  - Neutron star $m = (1.97 \pm 0.04)m_\odot$
- Large nucleon chemical potential ($\rho > \rho_0$)

Hyperon production becomes energetically possible? e.g. $\Lambda, \Xi, \Sigma$

Ozel et al. 2015 (arXiv:1505.05155v2)
The Equation of State (EoS)

- Interaction potential between hyperons and neutron matter governs the onset of production and behavior of the EoS
- Quantum Monte Carlo study of pure nuclear matter and hyper neutron matter
  - Attractive $\Lambda N$ interaction softens EoS
  - Repulsive $\Lambda NN$ interaction stiffens EoS

Mass – Radius Relation of Neutron Stars

- EoS allows to solve the Tolman-Oppenheimer-Volkoff Equations
  - Mass Radius Relation

- Repulsive 3 body interaction shifts onset of hyperon production to larger densities and allows for higher masses
  - Not well constrained

- To understand the role of hyperons in neutron stars more constraints on the hyperon-neutron force are needed

Global Proton-Λ Scattering Data

- Data from scattering experiments from 1968 and 1971 in bubble chambers
  - $K^- + p \to \Sigma^0 + \pi^0, \Sigma^0 \to \Lambda + \gamma$
  - Production threshold for Λ’s: $p \gtrsim 100$ MeV
- Different type of measurement needed to obtain constraints at low momentum
- Can we use Femtoscopic measurements?

Nuclear Collisions

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

\[ E_B, \vec{P}_B \]
Nuclear Collisions
Particle Production

\[ \vec{P}_G \]

\[ \vec{P}_H \]

\[ \vec{R} \]

\[ \vec{P}_a \]

\[ \vec{P}_b \]
Particle Propagation

\[ R \]

\[ P_a \]

\[ P_b \]
The Correlation Function

Theoretical formulation of the Correlation Function:

\[ C(p_a, p_b) = \frac{P(p_a, p_b)}{P(p_a)P(p_b)} = C(k) = \int S(\vec{r}, k)|\psi(\vec{r}, k)|^2 d\vec{r} \]

If we know about the source, we can learn about the interaction.

Fix the parametrization of the source by fitting the pp and Λp Correlation Function simultaneously to test different models of the pΛ interaction.
The pp Correlation Function

- Governed by:
  - Coulomb Interaction
  - Strong Interaction
  - Quantum Statistics

- Koonin Fit Function
  - Assumes a **Gaussian source** of size $R_G$
  
  $$C(k) = \int dr^3 \phi_{rel}^2(r, k) \exp \left( -\frac{r^2}{4R_G^2} \right)$$

  S. Pratt et al., Nucl. Phys. A 566 (1994) 103c

- $\phi_{rel}$ from solving the Schrödinger Equation with the **known potentials** for the Coulomb and Strong interaction
The $\Lambda p$ Correlation Function

- Governed by:
  - Strong Interaction
  - No Coulomb Interaction

- Lednický model
  - Assumes a **Gaussian source** of size $R_G$
  - Based on the effective Range expansion
  - The interaction is modeled using the **scattering length** ($f_0$) and the **effective range** ($d_0$)


\[
C(k) = 1 + \sum S \rho_S \left[ \frac{1}{2} \left| \frac{f_s(k)}{R_G^{\Lambda p}} \right|^2 \left( 1 - \frac{d_0^S}{2\sqrt{\pi}R_G^{\Lambda p}} \right) + 2 R f_s(k) \frac{\sqrt{\pi} R_G^{\Lambda p}}{R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{f_s(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right]
\]
The $\Lambda p$ Correlation Function

• Governed by:
  • Strong Interaction
  • No Coulomb interaction

• Lednický model
  • Assumes a Gaussian source of size $R_G$
  • Based on the effective Range expansion
  • The interaction is modeled using the scattering length ($f_0$) and the effective range ($d_0$)


\[
C'(k) = 1 + \sum_S \rho_S \left[ \frac{1}{2} \left( \frac{f^S(k)}{R_G^{\Lambda p}} \right)^2 \left( 1 - \frac{d_0^S}{2\sqrt{\pi} R_G^{\Lambda p}} \right) + \frac{R}{\sqrt{\pi} R_G^{\Lambda p}} F_1(Q R_G^{\Lambda p}) - \frac{\tau f^S(k)}{R_G^{\Lambda p}} F_2(Q R_G^{\Lambda p}) \right]
\]
Choice of Parameters: LO vs. NLO

- Calculations based on an chiral effect field theory calculations
- Discrimination of the two models not possible due to the lack of data
- NLO predicts a repulsive core of the interaction potential

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<th>NLO</th>
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<td>550</td>
<td>600</td>
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<td>$a_s^{\Lambda p}$</td>
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<td>$a_t^{\Lambda p}$</td>
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<td>2.83</td>
<td>2.72</td>
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A Large Ion Collider Experiment

- Tracking and Particle Identification (PID) of charged particles
  - $|\eta| < 0.9$
  - $2\pi$ coverage in the azimuth
- Inner Tracking System (ITS)
- Time Projection Chamber (TPC)
- Time of Flight (TOF) System
The Experimental Correlation Function

\[ C(\vec{p_a}, \vec{p_b}) = \frac{P(\vec{p_a}, \vec{p_b})}{P(\vec{p_a})P(\vec{p_b})} = \mathcal{N} \frac{N_{SE}(k)}{N_{ME}(k)} \]
The Experimental Correlation Function

\[ C(\mathbf{p}_a, \mathbf{p}_b) = \frac{P(\mathbf{p}_a, \mathbf{p}_b)}{P(\mathbf{p}_a)P(\mathbf{p}_b)} = \mathcal{N} \frac{N_{SE}(k)}{N_{ME}(k)} \]

\[ C'(k^*) = \]

Pair of interest  
Pair from feed-down  
Pair from mis-identification
The Experimental Correlation Function

\[ C(\mathbf{p}_a, \mathbf{p}_b) = \frac{P(\mathbf{p}_a, \mathbf{p}_b)}{P(\mathbf{p}_a)P(\mathbf{p}_b)} = \mathcal{N} \frac{N_{SE}(k)}{N_{ME}(k)} = \lambda_1 C_1(k) + \lambda_2 C_2(k) + \cdots \]

Correlation function of interest
Contributions from impurities, secondaries etc.

\[ \lambda \text{ Parameters can be related to measured single-particle quantities, e.g. Purity } \mathcal{P} \text{ or feed-down fractions } f \]

The p-p collision system

- Mini Jet Background not present for baryon baryon pairs
- Evolution of the system is better understood compared to Pb-Pb
  ➢ Same freeze out times and source size for all particles
- Small source sizes
  ➢ Stronger signal
  ➢ Sensitivity to the shape of the potential

24.10.17 – ASTRA Workshop Trento

Bernhard Hohlweger (Technical University Munich Physics Department – E62)
The \( \text{pp} \) and \( \Lambda p \) Correlation Function

- NLO and LO Parameters show different features at low \( k^* \)
- More statistics are required to distinguish between the two calculations
  - LHC Run 2
  - Other collision systems e.g. p-Pb
• Analysis of the $\Lambda\Lambda$ correlation function in Au-Au Collisions (STAR):
  • Fit of the Lednický Model with an additional residual term as a free parameter
  • Results in a slightly repulsive interaction ($a_0 < 0$ fm)

• Modeled correlation function does not describe ALICE Data with an adjusted source
The $\Lambda\Lambda$ Correlation Function

- Reanalysis of the data (K. Morita et al., T. Furumoto, AO PRC91(‘15) 024916) finds an attractive interaction ($a_0 > 1.25$ fm)
- An attractive interaction allows to describe both STAR and ALICE data
- Larger statistics of Run 2 could yield a conclusive answer
Future prospects of Femtoscopy

• Leaving scattering length and effective range as a free parameters
  ➢ Reduce degrees of freedom by fitting different collision systems at different energies at the same time

➢ Scattering experiments: intermediate region outside the core of the potential

• Femtoscopy: pairs are also produced in the region inside the core
  ➢ Access to the shape of the potential?
Lednicky Model

Source
- Analytic

Potential
- Scattering parameters
  - Eff. range expansion => phase shifts
  - Approximate solution

Wave function

Correlation function

Analytic Transport model

Potential

Full Scattering parameters

Correlation function

Numerically solve the Schrödinger eq.

Eff. range expansion => phase shifts

Approximate solution
$C(k) = \int S(\vec{r}, k) |\psi(\vec{r}, k)|^2 \, d\vec{r} \xrightarrow{k \to \infty} 1$

Source
- Analytic
- Transport model

Potential
- Full Scattering parameters

Numerically solve the Schrödinger eq.

Eff. range expansion => phase shifts

“Exact” solution

Approximate solution

Wave function

Correlation function

http://www.denseandstrange.ph.tum.de/index.php?id=78
Phase Shift calculations for $pp$ ($S = 0$)

- Using CATS phase shifts $\delta_l$ can be extracted for any given potential
- Comparison to global data
Cross section calculations for $\Lambda p$

- $\Lambda p$ cross sections for any given potential can be extracted
- Comparison to global data
Comparison CATS to Lednicky

**CATS:**
- Usmani Potential for the interaction
- Gaussian Source

**Lednicky:**
- Scattering parameters and effective range obtained from the Usmani Potential

Comparison CATS to Lednicky

- **CATS:**
  - Usmani Potential for the interaction
  - Gaussian Source

- **Lednicky:**
  - Scattering parameters and effective range obtained from the Usmani Potential
  - Agreement within 4% for a source size $R_G = 1.30$ fm
  - Corrections for small source sizes in the Lednicky Model play a role

• CATS allows to describe experimental data of our ALICE analysis
• **Input 1:**
  • Argonne V18 Potential
  • Gaussian Source function with $R_G = 1.30 \text{ fm}$
• **Input 2:**
  • Argonne V18 Potential
  • Source Distribution from EPOS
• EPOS not suitable to describe the source
Femtoscopy in small systems is feasible

New method to calculate different contributions to the total correlation function based on single particle properties

Modelling of the correlation function with CATS

Analysis of Run 2 Data in p-p and p-Pb Collisions

Additionally obtain the Σ and Ξ Correlation Function

Universal and Robust Femto Analysis Tool

Fit the correlation function of various systems simultaneously in combination with CATS
Thank you for your attention!