Constraining the $\bar{K}N$ coupled channel dynamics using femtoscopic correlations with ALICE at the LHC

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SQM22: Strange Quark Matter 2022

13 — 17 June 2022
Overview $\bar{K}N$ interaction

- What is known so far …
  - use $K^- p$ as proxy for $\bar{K}N$
  - attractive strong interaction
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\[
\begin{align*}
(\pi^-\Sigma^+, \pi^0\Sigma^0, \pi^+\Sigma^-) \\
\pi^0\Lambda & \quad \pi\Sigma & \quad K^-p
\end{align*}
\]

\[
E (\text{MeV}/c^2) \\
- 177 & \quad - 100
\]
Overview $\bar{K}N$ interaction

- What is known so far …
  - use $K^-p$ as proxy for $\bar{K}N$
  - attractive strong interaction
  - appearance of coupled channels
  - Conditions
    - Close in mass
    - Matching quantum numbers

\begin{itemize}
  \item $\pi^0\Lambda$
  \item $\pi^0\Sigma$
  \item $K^-p$
  \item $\bar{K}^0n$
\end{itemize}

- 177
- 100
58

$E$ (MeV/$c^2$)
Overview $\bar{K}N$ interaction

- What is known so far …
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  - dynamic generation of $\Lambda(1405)$

\[ \Lambda(1405) \]

\[ \pi^0 \Lambda \]

\[ \pi \Sigma \]

\[ K^-p \]

\[ \bar{K}^0n \]

\[ \Lambda(1520) \]

$E$ (MeV/$c^2$):

- 177
- 100
- 27

- 58
- 234
Overview $\bar{K}N$ interaction

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  - attractive interaction
  - appearance of coupled channels
  - dynamic generation of $\Lambda(1405)$

- Experimental results
  - at threshold Kaonic atoms
  - above threshold scattering experiments

$\pi^0\Lambda$  $\pi\Sigma$  $\Lambda(1405)$  $K^-p$  $\bar{K}^0n$  $\Lambda(1520)$

- 177  - 100  - 27  58  234

$E$ (MeV/c$^2$)  $\sqrt{s}$ [MeV]

Y. Ikeda et al. NPA 881 (2012)
SIDDHARTA PLB 704 (2011)
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\[ \sigma(K^-p \rightarrow K^-p) \text{ [mb]} \]

\[ P_{\text{lab}} \text{ [MeV/c]} \]

$\Lambda(1520) \quad E (\text{MeV/c}^2)$

\[ \bar{K}^0n \text{ cusp} \]

Y. Ikeda et al. NPA 881 (2012)
New access to $\bar{K}N$ interaction

- Close to and at threshold enables
  - fixing low-energy constants in SU(3) \( \chi \)EFT
  - quantification of coupled-channel contribution
  - falsification of current models

- New approach: Analysis of momentum correlations
  - deliver high precision data
  - sensitivity to coupling parameters
Analysis with ALICE

- Data sets (# evts)
  - **pp 13 TeV**
    (1000 M high mult.)
  - **p–Pb 5.02 TeV**
    (800 M 0–100% mult. interval)
  - **Pb–Pb 5.02 TeV**
    (65 M 60–90% cent. interval)

Direct detection of charged particles (protons, kaons) by TPC and TOF

Purity of used particles **99%**
Basics of Femtoscopy

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

where

\[ S(\vec{r}^*) = \frac{1}{(4\pi r_0^2)^{3/2}} \exp \left( -\frac{r_*^2}{4r_0^2} \right) \]

Schrödinger Equation for relative wavefunction

Relative momentum \( k^* = \frac{1}{2} |\vec{p}_1 - \vec{p}_2| \) and \( \vec{p}_1^2 + \vec{p}_2^2 = 0 \)

Relative distance \( r^* = \vec{r}_1^* - \vec{r}_2^* \)

Nature 588 (2020)
Femtoscopic result

New!

ALICE

\[ C(k^*) \]

**pp \( \sqrt{s} = 13 \text{ TeV} \)**

\[ K_p \oplus K^*\bar{p} \]

0.7 < \( S_T \) ≤ 1

\[ n_{\text{calt}} \]

\[ n_{\text{calt}} \]

\[ n_{\text{calt}} \]

\[ n_{\text{calt}} \]

\[ n_{\text{calt}} \]

\[ n_{\text{calt}} \]

\[ n_{\text{calt}} \]

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arXiv:2205.15176
Femtoscopy: Coupled Channels

\[ C(k^*) = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* + \sum_j \int S_j(\vec{r}^*) \left| \psi_j(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* \]

- Conversion weights (\(\omega\))
  - control CC contribution
  - depend on primary yield and kinematics

- System-size survey
  - study impact on correlation

\[ \pi^0 \Lambda \quad \pi \Sigma \quad \Lambda(1405) \quad K^- p \quad K^0 n \]

\( r_0 = 1 \text{ fm} \)

J. Haidenbauer NPA 981 (2019)
Y. Kamiya et al. PRL 124 (2020)
Estimation of $\omega$

$$C(k^*) = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* + \sum_j \omega_j \int S_j(\vec{r}^*) \left| \psi_j(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^*$$

- Calculation of expected primary yields
  - Thermal model (Thermal-FIST) [1]
    - for each collision system

- Estimate amount of pairs in FSI sensitive kinematic region ($k^* < 200 \text{ MeV}/c$)
  - Distribute particles according to Blast-wave (BW) model [2,3,4]
  - Normalize to expected yields

Pinning down the emitting source

- Universal source ansatz
- Decompose source
  - Gaussian core source driven by thermal production
  - Exponential decays of particle-specific resonances
    - fractions from thermal model
    - kinematics from transport model
- Steps to generate the sources
  - Determine core by fitting \( C(k^*) \) from \( K^+-p \) (same system and mult./cent. interval)
  - Use as input for \( K^--p \)
  - Add for each channel resonance decays (Monte Carlo procedure)
Femtoscopy results

**New!**

arXiv:2205.15176
Femtoscopy result (with scaling factor)

\[ C(k^*) = \int S(\vec{r}^*) \left| \psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* + \sum_j \alpha_j \omega_j \int S_j(\vec{r}^*) \left| \psi_j(\vec{k}^*, \vec{r}^*) \right|^2 d^3\vec{r}^* \]
Scaling factors

- Experimental results
  - improved data situation near threshold
  - hints at revising the coupling strengths in SU(3) $\chi$EFT
  - first experimental constraint of the $\bar{K}^0$–n channel

New! arXiv:2205.15176
Summary & Outlook

• Measurement of the two-particle momentum correlation $K^-\text{--}p$
• High resolution of cusp structure $K^-\text{--}p \leftrightarrow \bar{K}^0\text{--}n$
• Quality data available for model tuning (SU(3) $\chi$EFT)
• Kyoto model fits:
  – scaling factor needed to accommodate data
  – necessitates revision of coupling strengths
Back-up

Content
- CC for r_core = 1.5 fm (Pb-Pb peripheral)
- Femtoscopy: Information about the source
Last scaling bin

- Prediction SU(3) $\chi$EFT
  - Gaussian $S(r^*)$ ($r_0 = 1.5$ fm)
    same for all channels
  - Weights at unity
  - Cusp still pronounced
    - non negligible contribution predicted
    - difficult to resolve with current statistics

New!
arXiv:2205.15176
Femtoscopy: Source

Source modifications

• Increase in apparent source size by short lived strongly-decaying resonances (e.g. Δ)
Femtoscopy: Source Resonances (example)

Protons

$\Lambda$s

$\Sigma^0$s

<table>
<thead>
<tr>
<th>Particle</th>
<th>$M_{res}$ [MeV]</th>
<th>$\tau_{res}$ [fm]</th>
</tr>
</thead>
<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>

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

$E(r, M_{res}, \tau_{res}, p_{res}) = \frac{1}{s} \exp\left(-\frac{r}{s}\right)$
**Femtoscopy: Source**

**Universal source model**
- $r_{\text{core}}$ fixed for each pair based on $<m_T>$
- Particle-specific resonances are added to the core

**Notice**
- Small radii probe large densities

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ALICE $pp \sqrt{s} = 13$ TeV
High-mult. (0–0.17% INEL > 0)
- p–p Argonne $v_{18}$
- Parametrization
Formula up-keep

\[ S(r^*) = \frac{1}{(4\pi r_0^2)^{\frac{3}{2}}} \exp\left(-\frac{r^{2}}{4r_0^2}\right) \]

\[ C_{\text{model}}(k^*) = b(k^*)[\lambda_{p\Sigma^0}C_{p\Sigma^0}(k^*) + \lambda_{p(\gamma\Lambda)}C_{p(\gamma\Lambda)}(k^*) + \lambda_{ff} + \lambda_{\tilde{p}\Sigma^0}] \]

\[ C_{\text{model}}(k^*) = (a + b \cdot k^*)[1 + \lambda_{K-p}(C_{K-p}^{CC}(k^*) - 1) + \sum_{ij}\lambda_{ij}(C_{ij}(k^*) - 1)] \]

\[ C(k^*) = \int S(\vec{r}^*) \left |\psi(\vec{k}^*,\vec{r}^*)\right |^2 d^3\vec{r}^* + \sum_j \alpha_j \cdot \omega_j \int S_j(\vec{r}^*) \left |\psi_j(\vec{k}^*,\vec{r}^*)\right |^2 d^3\vec{r}^* \]

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