Precision studies of the strong interaction in Λ-hadron systems up to S=-3 with ALICE

V. Mantovani Sarti on behalf of the ALICE Collaboration
06.04.2022
Quark Matter 2022, Kraków
Strong interaction between $\Lambda$ and hadrons

- Perfect probe for understanding strong interaction with strangeness

- $|S| = 1$: $\Lambda N$ interaction
  - Equation of state of nuclear matter in neutron stars with hyperons
  - Input for three-body YNN

- $|S| = 2$ and $|S| = 3$: $\Lambda \Lambda$ and $\Lambda \Xi$ interaction
  - Constraints for hypernuclei and effective QCD theories in multi-strange sector
  - Exotic bound states as $H$-dibaryon and $N \Omega$ dibaryon

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R.L. Jaffe PRL 38 (1977) 195-198
HAL QCD Coll. Nucl.Phys.A 998 (2020) 121737
\(\Lambda\)-hadron interaction: theory and experiment

| \(|S| = 0\) | \(|S| = 1\) | \(|S| = 2\) | \(|S| = 3\) | \(|S| > 3\) |
|---|---|---|---|---|
| NN | \(\Lambda N\) | \(\Lambda\Lambda\) | \(\Lambda\Xi\) | \(\Xi\Xi, \Lambda\Omega, \Sigma\Omega, \Xi\Omega, \Omega\Omega\) |

Scattering experiments
Λ-hadron interaction: theory and experiment

|S| = 0  |S| = 1  |S| = 2  |S| = 3  |S| > 3  
-------------------|-------------------|-------------------|-------------------|-------------------|-------------------
NN  |ΛN |ΛΛ |ΛΞ |ΞΞ, ΛΩ, ΣΩ, ΞΩ, ΩΩ  

Scattering experiments

Hypernuclei

H. Takahashi et al., PRL 87 (2001) 212502
T. Nagae et al., PRL 80 (1998) 1605-1609
S.H. Hayakawa et al. PRL. 126 (2021), 062501
J.K Ahn et al., PRC 88 (2013), 014003
$\Lambda$-hadron interaction: theory and experiment

Scattering experiments

Hypernuclei

Chiral effective field theory

$|S| = 0$

$|S| = 1$

$|S| = 2$

$|S| = 3$

$|S| > 3$

$NN$

$\Lambda N$

$\Lambda\Lambda$

$\Lambda\Xi$

$\Xi\Xi, \Lambda\Omega, \Sigma\Omega, \Xi\Omega, \Omega\Omega$

J. Haidenbauer, N. Kaiser et al., NPA 915 (2013)
J. Haidenbauer, U. Meißner, EPJ.A 56 (2020)
\( \Lambda \)-hadron interaction: theory and experiment

\[ \begin{align*}
|S| &= 0 & \text{NN} \\
|S| &= 1 & \Lambda N \\
|S| &= 2 & \Lambda \Lambda \\
|S| &= 3 & \Lambda \Xi \\
|S| &> 3 & \Xi \Xi, \Lambda \Omega, \Sigma \Omega, \Xi \Omega, \Omega \Omega
\end{align*} \]

**Scattering experiments**

**Hypernuclei**

**Chiral effective field theory**

**Lattice QCD**

HAL QCD Coll. Nucl.Phys.A 998 (2020) 121737

V. Mantovani Sarti – Quark Matter 2022
\( \Lambda \)-hadron interaction: theory and experiment

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<tbody>
<tr>
<td>(</td>
<td>S</td>
<td>= 0)</td>
<td>(</td>
<td>S</td>
</tr>
<tr>
<td>(\text{NN})</td>
<td>(\Lambda N)</td>
<td>(\Lambda\Lambda)</td>
<td>(\Lambda\Xi)</td>
<td>(\Xi\Xi, \Lambda\Omega, \Sigma\Omega, \Xi\Omega, \Omega\Omega)</td>
</tr>
</tbody>
</table>

Scattering experiments

Hypernuclei

Chiral effective field theory

Lattice QCD

Correlations

Can we improve this scenario with femtoscopy?
The femtoscopy technique at ALICE

The femtoscopy technique at ALICE

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

Measuring $C(k^*)$, fixing the source $S(\vec{r}^*)$, study the interaction

The emitting source in small colliding systems

- Data-driven analysis on p-p and p-Λ pairs
  - Possible presence of collective effects \( \rightarrow m_T \) scaling of the core radius
  - Contribution of strongly decaying resonances with \( c\tau \sim 1 \) fm (*)

- Common universal core source for baryons

- Core constrained from p-p pairs
  - Fixing of the source at corresponding \( \langle m_T \rangle \)
    \( \Rightarrow \) direct access to the interaction

<table>
<thead>
<tr>
<th>Particle</th>
<th>Res.</th>
<th>( &lt;c\tau&gt; ) (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>( \Delta, N^* )</td>
<td>1.6</td>
</tr>
<tr>
<td>Λ</td>
<td>( \Sigma, \Sigma^* )</td>
<td>4.7</td>
</tr>
</tbody>
</table>

\( r_{\text{eff}} = 1 - 1.25 \) fm

Based on ALICE Coll. PLB 811 (2020) 135849
|S| = 1: Λp interaction

- Low statistics and not available at low momenta
$|S| = 1$: $\Lambda p$ interaction

- Low statistics and not available at low momenta
- $\Lambda N - \Sigma N$ coupled system $\rightarrow$ 2-body coupling to $\Sigma N$ is not (yet) measured

**Uncertainties ~ 30% at low momenta**

![Scattering data graph](image)

$\sigma$ (mb)

$k^*$ (MeV/c)

J. Haidenbauer, N. Kaiser et al., NPA 915, 24 (2013)
\(|S| = 1: \Lambda p\) interaction

- Low statistics and not available at low momenta
- \(\Lambda N-\Sigma N\) coupled system \(\rightarrow\) 2-body coupling to \(\Sigma N\) is not (yet) measured

- \(\Sigma N\) coupling strength relevant for EoS
  - Strongly affects the behaviour of \(\Lambda\) at finite density
  - Implications for \(\Lambda NN\) interactions (*)

- NLO19 predicts weak coupling \(N\Lambda-N\Sigma\)
  - Attractive \(\Lambda\) interaction in neutron matter

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\(\chi_{\text{EFT NLO13}}\)
\(\chi_{\text{EFT NLO19}}\)

\(Jülich 04\)
\(\text{NSC97f}\)

\(k^* (\text{MeV/c})\)

\(U_\Lambda (\text{MeV})\)

\(\rho_0\)

\(\text{PNM}\)

\(\text{NLO13: J. Haidenbauer, N. Kaiser et al., NPA 915, 24 (2013)}\)

|S| = 1: pΛ interaction in the femtoscopic era

- Factor 20-35 improved precision of the measurement (<1%)
- Most precise data available on the Λp interaction down to zero momenta
- First direct experimental evidence of ΣN cusp in 2-body channel

Uncertainties ~ 30% at low momenta

\( k^* (\text{MeV}/c) \)

\( \sigma \) (mb)

ALICE high-mult. (0-0.17% INEL>0) pp, \( \sqrt{s} = 13 \text{ TeV} \)

\( p-\Lambda \oplus \beta-\Xi \) pairs
- Statistical uncertainty
- Systematic uncertainty

\( \chi_{\text{EFT NLO13}} \)
\( \chi_{\text{EFT NLO19}} \)

$|S| = 1$: $Λp$ interaction and access to the $ΣN$ coupling

- Comparison with $χ$EFT potentials
  - Sensitivity to different $ΣN$ coupling strength
  - NLO19 favoured ($n_σ = 3.9$) → attractive interaction of $Λ$ at large densities
  - Larger $ΛNN$ repulsion required to stiffen the Equation of State at large densities(*)

Three-body correlations (R. Del Grande)
Parallel Session T08 06/04 15:00

- New constraints to improve current theory
$|S| = 2$ : constraining the $\Lambda\Lambda$ interaction with femtoscopy

- Important for existence of $H$-dibaryon
- $\Lambda\Lambda$ correlation measured in pp MB 7, 13 TeV and $p$-Pb 5.02 TeV
- Scan in scattering parameter space ($f_0^{-1}$, $d_0$) and express agreement data/model in number of $\sigma$ deviations

ALICE pp $\sqrt{s} = 13$ TeV

$C(k^*)$

$|S| = 2$ : constraining the $\Lambda\Lambda$ interaction with femtoscopy

- Important for existence of H-dibaryon
- $\Lambda\Lambda$ correlation measured in pp MB 7, 13 TeV and p-Pb 5.02 TeV
- Scan in scattering parameter space ($f_0^{-1}$, $d_0$) and express agreement data/model in number of $\sigma$ deviations
  - Agreement with hypernuclei data and lattice predictions
- Most precise upper limit on the binding energy of the H-dibaryon

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

$|S| = 3$: first measurements of the $\Lambda \Xi$ interaction

- $\Lambda \Xi$: correlation in high-multiplicity pp collisions 13 TeV
- Presence of inelastic channels:
  - Sizeable $\Lambda \Xi - \Sigma \Xi$ coupling from HAL QCD
    - data favour results with only $\Lambda \Xi$ elastic ($n\sigma = 1.64$)
    - data not yet sensitive to the coupling

ALICE Preliminary pp $\sqrt{s} = 13$ TeV
High Mult. (0−0.17% INEL>0)

HAL QCD $\Lambda-\Xi - \Sigma-\Xi$ eff.
HAL QCD $\Lambda-\Xi$ only
Baseline

NEW

ALICE-PUBLIC-2022-009
https://cds.cern.ch/record/2805489
(*) HAL QCD Coll. EPJ Web of Conferences 175, 05013 (2018)
$|S| = 3$ : constraining chiral effective field theories

- $ΛΞ$ correlation in high-multiplicity pp collisions 13 TeV

- Scattering parameters from state-of-the-art $χEFT(\star)$:
  - Potentials with large interaction overestimate the data

<table>
<thead>
<tr>
<th>Model</th>
<th>Cut-off</th>
<th>Singlet (fm)</th>
<th>Triplet (fm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$f_0$</td>
<td>$d_0$</td>
</tr>
<tr>
<td>NLO19</td>
<td>500</td>
<td>0.99</td>
<td>5.77</td>
</tr>
</tbody>
</table>

ALICE Preliminary pp $\sqrt{s} = 13$ TeV
High Mult. (0–0.17\% INEL>0)

NEW

$ΛΞ$ – $ΞΛ$ correlation in high-multiplicity pp collisions 13 TeV

$ΛΞ$ – $ΞΛ$ correlation in high-multiplicity pp collisions 13 TeV

$ΛΞ$ – $ΞΛ$ correlation in high-multiplicity pp collisions 13 TeV

ALICE-PUBLIC-2022-009
https://cds.cern.ch/record/2805489
$|S| = 3$ : constraining chiral effective field theories

- $\Lambda\Xi$- correlation in high-multiplicity pp collisions 13 TeV
  - $k^*\sim300$
  - $k^*\sim460$

- Scattering parameters from state-of-the-art $\chi$EFT(*):
  - Potentials with large interaction overestimate the data
  - Data favour potentials with shallow interaction

- First experimental constraint in $|S|=3$ sector for $\chi$EFT

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$|S| = 3 : \Lambda \Xi$ interaction and its role in $p\Omega$ interaction

- $\Lambda \Xi$ correlation in high-multiplicity pp collisions 13 TeV
- Presence of inelastic channels:

\begin{align*}
\Lambda \Xi & \quad \Sigma \Xi & \quad \Lambda - \Xi & \quad \Sigma - \Xi & \quad N - \Omega \\
2437 & \quad 2514 & \quad 2609 & \quad \text{k}^* \sim 300 & \quad \text{k}^* \sim 460
\end{align*}

- No $p - \Omega$ cusp structure visible with current statistics → indications of a negligible coupling to $N\Omega$

ALICE Preliminary pp $\sqrt{s} = 13$ TeV
High Mult. (0–0.17% INEL>0) = 3.2% ($\lambda = 32\%$)

NEW

ALICE-PUBLIC-2022-009
https://cds.cern.ch/record/2805489
$|S| = 3 : \Lambda \Xi$ interaction and its role in $p\Omega$ interaction

- Attractive $p\Omega$ interaction $\rightarrow$ di-baryon with $E_b \sim 2.5$ MeV
- Presence of inelastic channels:
  - First measurements of $p\Omega$ in pp HM 13 TeV by ALICE
    - Strong attractive interaction
  - Comparison with lattice predictions in two cases:
    - No / dominant inelastic contributions
  - Data in agreement with
    - Negligible inelastic contributions $\rightarrow$ support the scenario obtained in $\Lambda \Xi$ measured correlations
    - No evidence of bound state

ALICE Coll. Nature 588 (2020) 232-238
Summary and Outlook

• Femtoscopy in small colliding systems → unique way to access multi-strange QCD sector

• Precision studies of |S| = 1,2,3 sector with Λ-hadrons correlations in ALICE
  – Most precise data on the Λp interaction → physics of neutron stars
  – Most precise upper limit on H-dibaryon energy
  – First measurements of ΛΞ interaction → constraints for lattice QCD calculations and chiral potentials

• More precision studies within reach with large statistics in Run 3 & 4!

For additional interesting femtoscopic results at ALICE:

Three-body interactions, R. Del Grande Parallel Session T08 06/04 15:00
Interaction with charmed mesons, F. Grosa Parallel Session T08 06/04 15:40
Additional slides
High multiplicity pp collisions

- pp collisions at ALICE are a perfect factory to produce a large amount of multi-strange hyperons
  

- In the paper:
  - High multiplicity events pp 13 TeV → enhanced yields of multi-strange hadrons

- High capability for particle identification at transverse momenta below 1 GeV/c
  - hyperons detected through weak decays
    
    \[
    \Xi^- \rightarrow \Lambda \pi^-
    \]
    
    \[
    \Omega^- \rightarrow \Lambda K^-
    \]

  - low contamination and high purity samples
Hyperons @ ALICE in pp Collisions

\[ \Lambda \rightarrow p\pi^- \]
\[ \Xi^- \rightarrow \Lambda\pi^- \]
\[ \Omega^- \rightarrow \Lambda K^- \]
\[ \Sigma^0 \rightarrow \Lambda\gamma \]
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

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

- 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
The source function - Effect of short-lived resonances

- For $\Xi^-$ and $\Omega^-$ no contributions!
- Average mass and average $c\tau$ 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>
</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>
The common source - The source pdf
Influence of the $\Lambda N - \Sigma N$ coupled channel

- $\Sigma N - \Lambda N$ acts as an effective attraction
- Repulsion for $\Lambda - p$ when the $\Sigma N - \Lambda N$ coupled channel is neglected
  - strong coupling $\implies$ dispersion repulsive effects $\implies$ Shift of hyperon appearance towards higher densities
  - weak coupling $\implies$ more attractive $U_{\Lambda}(\rho_0,0)$

Λ-Λ correlations

\(|S|=2 : \Lambda\Lambda\) interaction models

- \(\Lambda\Lambda\) correlation measured in pp MB 13 TeV and p-Pb 5.02 TeV

- Comparison with available theoretical models
  - large attraction and very weakly bound state discarded
  - data compatible with a bound state (ND46) or shallow attraction (ESC08)

- Scan in scattering parameter space and express agreement data/model in number of \(\sigma\) deviations

\[
C(k^*)
\]

\(ALICE\) pp \(\sqrt{s} = 13\) TeV

- \(\Lambda-\Lambda\) and \(\bar{\Lambda}-\bar{\Lambda}\) pairs
- ND46, NF44, Ehime, ESC08, HKMYY, Quantum statistics

$|S|=2 : \Lambda\Lambda$ interaction and the H-dibaryon

- H-dibaryon: hypothetical bound state of $uuddss$
  - No final experimental evidences so far
  - Recent lattice QCD calculations at physical point with $\Lambda\Lambda$-$N\Xi$ coupled-channel($^\ast$) → no bound state around $\Lambda\Lambda$ or $N\Xi$ threshold ($^{**}$)

- Double-$\Lambda$ hypernuclei measurements
  - weak attractive interaction
  - H-dibaryon binding energy $B_{\Lambda\Lambda} = 6.91 \pm 0.16$ MeV

Can we improve the knowledge on the $\Lambda\Lambda$ interaction and the fate of the H dibaryon?

$\Delta B_{\Lambda\Lambda} = 0.67 \pm 0.17$ MeV

H. Takahashi et al., PRL 87 (2001) 212502

(*) HAL QCD Coll. Nucl.Phys.A 998 (2020) 121737
A. Ohnishi et al., Few Body Syst. 62 (2021) 3, 42
Y. Kamiya et al., PRC 105 (2022)

Lattice QCD potentials of the $|S| = 2$ sector: $p-\Xi^-$ interaction

- Direct comparison to HAL QCD potentials near physical quark masses (*)
- Presence of coupled-channels
  
  \[
  \begin{array}{cccccc}
  \Lambda-\Lambda & n-\Xi^0 & p-\Xi^- & \Lambda-\Sigma^0 & \Sigma^0-\Sigma^0 & \Sigma^+-\Sigma^-
  \\
  2232 & 2255 & 2260 & 2309 & 2386
  \end{array}
  \]
  
  Threshold $k^* = 233 \text{ MeV/c}$, $k^* = 378 \text{ MeV/c}$

- Weak coupling to $\Lambda-\Lambda$ channels expected from HAL QCD potentials
  - confirmed from femtosopic (**) and hypernuclei measurements (***)

|S|=2 sector: p-Ξ' interaction and first test of LQCD

- Observation of the strong interaction beyond Coulomb
- Agreement with lattice calculations confirmed in pp and p-Pb colliding systems
- At finite density HAL QCD potentials predict in PNM a slightly repulsive $U_{Ξ} \sim +6$ MeV$^{(*)} \rightarrow$ stiffening of the EoS

*HAL QCD Coll., PoS INPC2016 (2016) 277*
Implications for neutron stars

- Using HAL QCD predictions at finite density → $\Xi$ production pushed to higher densities → stiffening of EoS compatible with current measurements
- What about the three-body interactions?

Based on:

V. M. S., L. Fabbietti and O. Vazquez-Doce nucl-ex 2012.09806

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p–Ω− correlation function in pp at 13 TeV

**ALICE Collaboration Nature 588 (2020) 232-238**

- Model corrected for residual correlations and corrections
- Radius extracted from $m_T$ differential p-p correlations ($r \sim 0.9$ fm)

- Enhancement above Coulomb
  → Observation of the strong interaction
- Agreement of lattice prediction depends on the treatment of inelastic channels
  - No clear depletion corresponding in the data
ΛΞ correlation in pp HM 13 TeV

<table>
<thead>
<tr>
<th>potential</th>
<th>cut-off (MeV) / version</th>
<th>singlet</th>
<th>triplet</th>
<th>$n_\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi$EFT LO [11]</td>
<td>550</td>
<td>33.5</td>
<td>-0.33</td>
<td>3.06 – 5.12</td>
</tr>
<tr>
<td></td>
<td>700</td>
<td>-9.07</td>
<td>-0.31</td>
<td>0.78 – 1.60</td>
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<tr>
<td>$\chi$EFT NLO16 [14]</td>
<td>500</td>
<td>0.99</td>
<td>-0.026</td>
<td>0.56 – 0.93</td>
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<td></td>
<td>650</td>
<td>0.91</td>
<td>32.02</td>
<td>0.91 – 1.61</td>
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<td>$\chi$EFT NLO19 [15]</td>
<td>500</td>
<td>0.99</td>
<td>1.49</td>
<td>5.47 – 7.26</td>
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<td>650</td>
<td>0.91</td>
<td>6.33</td>
<td>1.30 – 2.10</td>
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<td>NSC97a [12]</td>
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<td>0.80</td>
<td>-0.47</td>
<td>0.68 – 1.04</td>
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<tr>
<td>HAL QCD [2]</td>
<td>$\Lambda\Xi$ eff.</td>
<td>0.60</td>
<td>5.36</td>
<td>1.43 – 2.34</td>
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<tr>
<td></td>
<td>$\Lambda\Xi$ only</td>
<td>-</td>
<td>-</td>
<td>0.64 – 1.04</td>
</tr>
<tr>
<td>Baseline</td>
<td></td>
<td>-</td>
<td>-</td>
<td>0.78</td>
</tr>
</tbody>
</table>

ALICE Preliminary pp $\sqrt{s} = 13$ TeV
High Mult. (0–0.17% INEL>0)

$\Lambda$–$\Xi$ $\oplus \bar{\Lambda}$–$\Xi^+$ ($\lambda = 32\%$)

$\chi$EFT LO
$\Lambda$EFT NLO16
$\chi$EFT NLO19
NSC97a
Baseline

$0.9$ $1.0$ $1.1$ $1.2$ $1.3$
$0$ $50$ $100$ $150$ $200$ $250$ $300$

k* (MeV/c)

ALI-PREL-516888
Femtoscopy in small colliding systems

- Accessing the strong interaction → relative distances of ~1-1.4 fm → pp and p-Pb collisions
- Small interparticle distance → doorway to studying large densities

**Typical short-range nuclear potential**

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Couple channels in $|S| = 3$

- Absorption of $p-\Omega^-$ pairs in $^3S_1 (2S+1L_J)$ configuration by the channels below threshold dominate interaction
  - Not included in the lattice calculations so far → Test of two cases:
    - Total absorption of all $J = 1$ pairs: $V^{J=1}(r) = -i\theta(r_0 - r) V_0$ with $V_0 \to \infty$ for $r < 2$ fm
    - Neglecting the absorption and same behavior as in the $^5S_2$ configuration
  - Coupled channel treatment missing so far
- Inelastic interactions suppressed for $p-\Omega^-$ pairs in $^5S_2$ configuration

Pair Mass (MeV/c^2)

- $\Lambda-\Xi^-$
- $\Sigma^- - \Xi^0$
- $\Sigma^0 - \Xi^-$
- $p-\Omega^-$
Small Sources: Collective Effects and Strong Resonances

Elliptic flow

- Anisotropic pressure gradients within the source

Radial flow

- Expanding source with constant velocity
- Different effect on different masses

Strong decays of broad resonances

- Resonances with $c \tau \sim r_0 \sim 1$ fm ($\Delta^*$, $N^*$, $\Sigma^*$) introduce an exponential tail to the source
- Different for each particle species


Core Radius

Strong decays of specific resonances

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