Proton-Xi interaction studied via the femtoscopy method in p-Pb collisions with ALICE

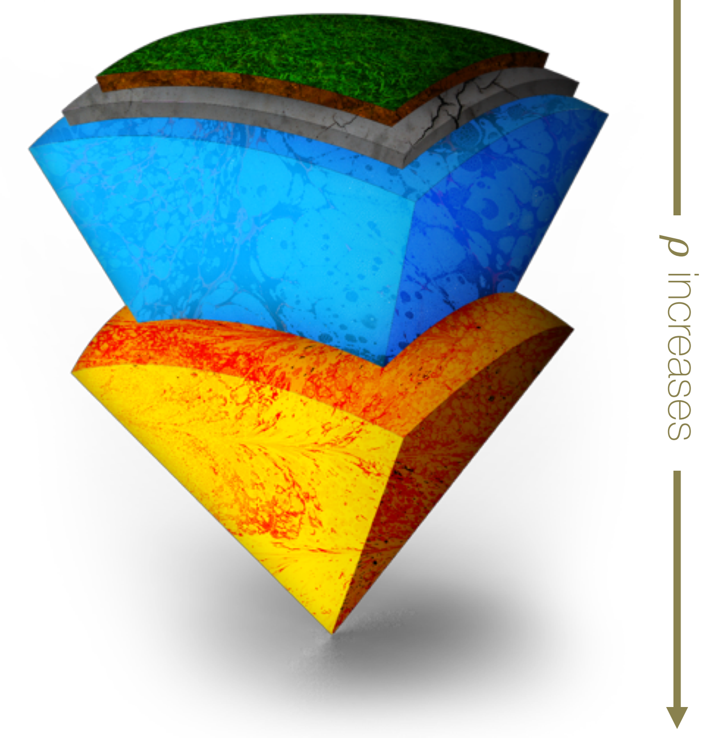
Bernhard Hohlweger on behalf of the ALICE Collaboration
57. International Winter Meeting on Nuclear Physics
21st January 2019

Hyperons in Neutron Stars?

Dimensions
R ~ 10 – 15 km
M ~ 1.5 – 2 $M_{\odot}$

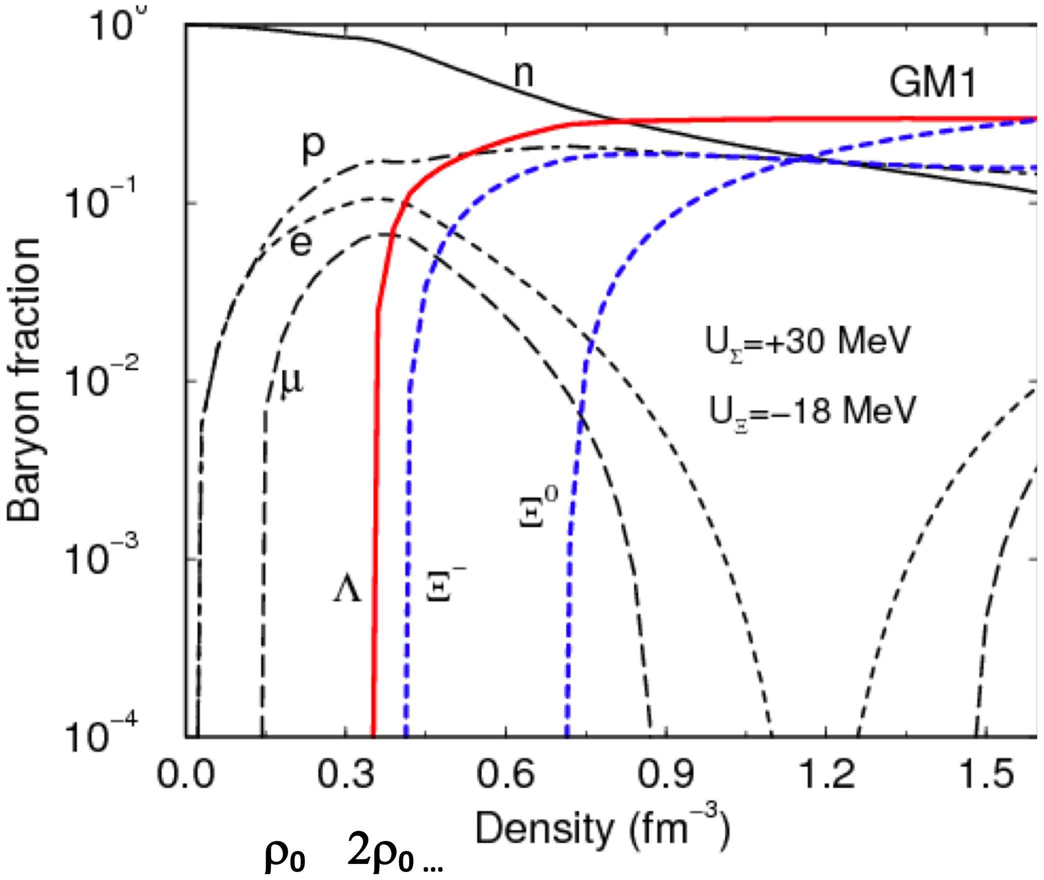
Outer Crust
Ions, electron Gas, Neutrons

Inner Core
Neutrons?
Protons?
Hyperons?
Quark Matter?



- **Neutron Stars:** very dense, compact objects
- What is the EoS?
  - What are the constituents to consider?
  - How do they interact?

Hyperons in Neutron Stars?



J. Schaffner-Bielich, Nucl. Phys. A 804 (2008), 309-321

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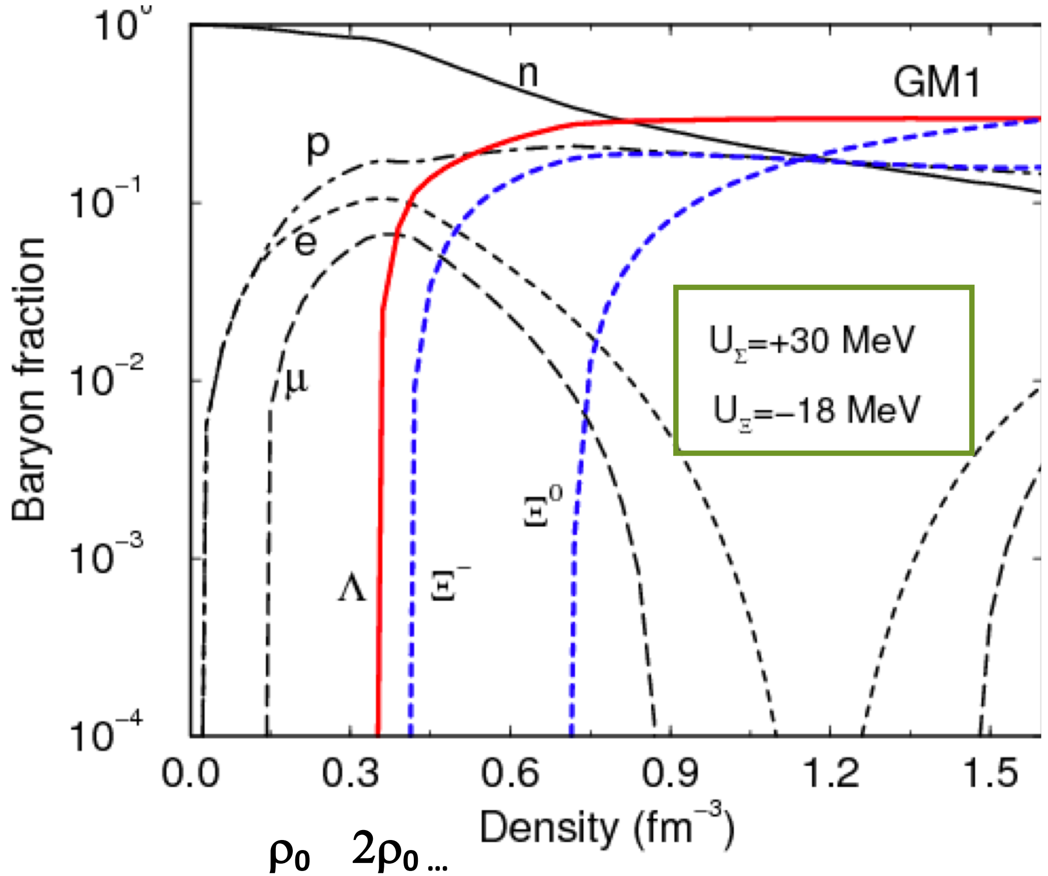


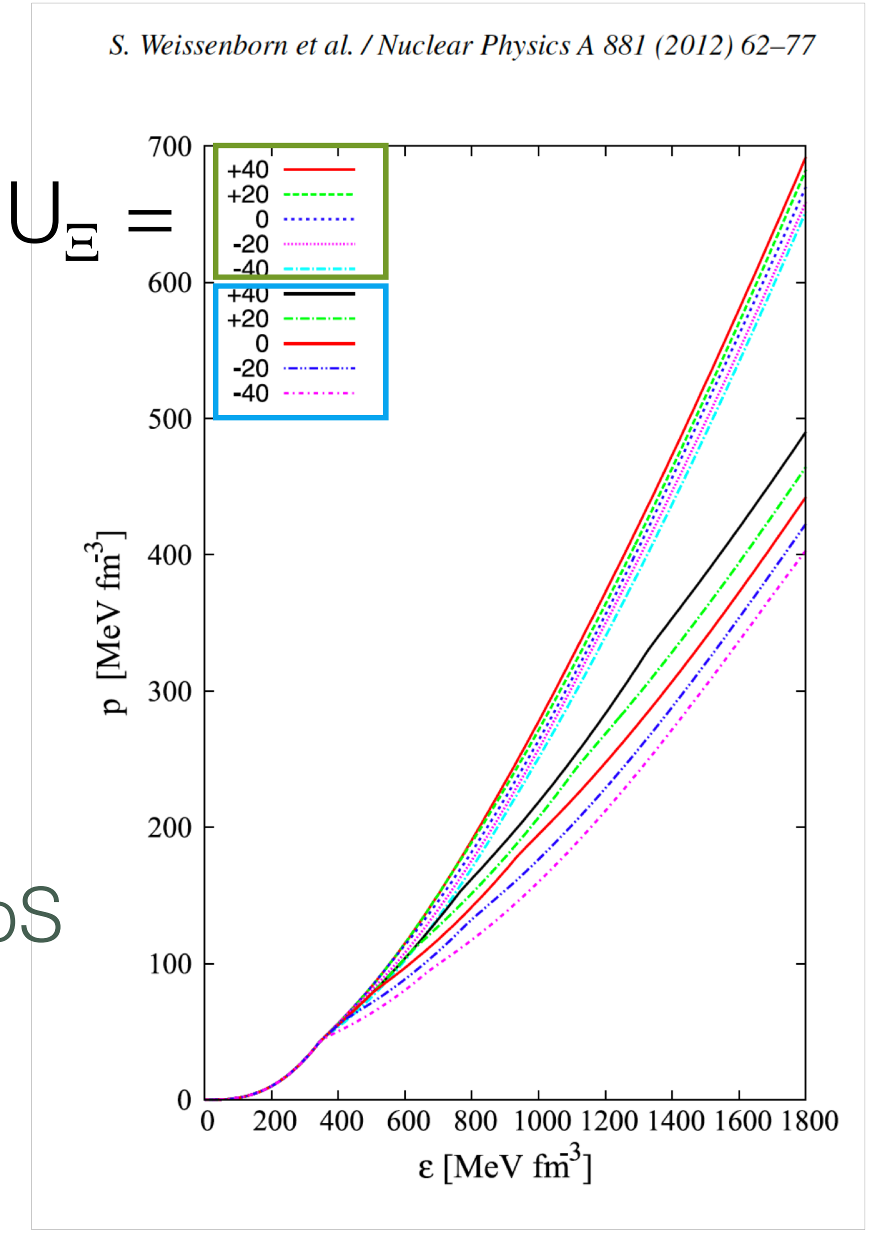
ρ_0 $2\rho_0$ ...

J. Schaffner-Bielich, Nucl. Phys. A 804 (2008), 309-321

- **Neutron Stars:** very dense, compact objects
- What is the EoS?
- At finite densities **hyperon** production becomes energetically favorable
- Onset depends on:
  - **mass**
  - **single particle hyperon potential** in neutron matter

Exemplary equation of state

- Attractive U_Λ = - 30 MeV fitted to data from Hypernuclei
  - For more on the interaction of the Λ: Talk by Steffen Maurus @ Thu, 19:00
- Assumes repulsive U_Σ = 30 MeV
- With and without repulsive Hyperon Hyperon interaction
- Scan of U_Ξ : significant impact on the EoS



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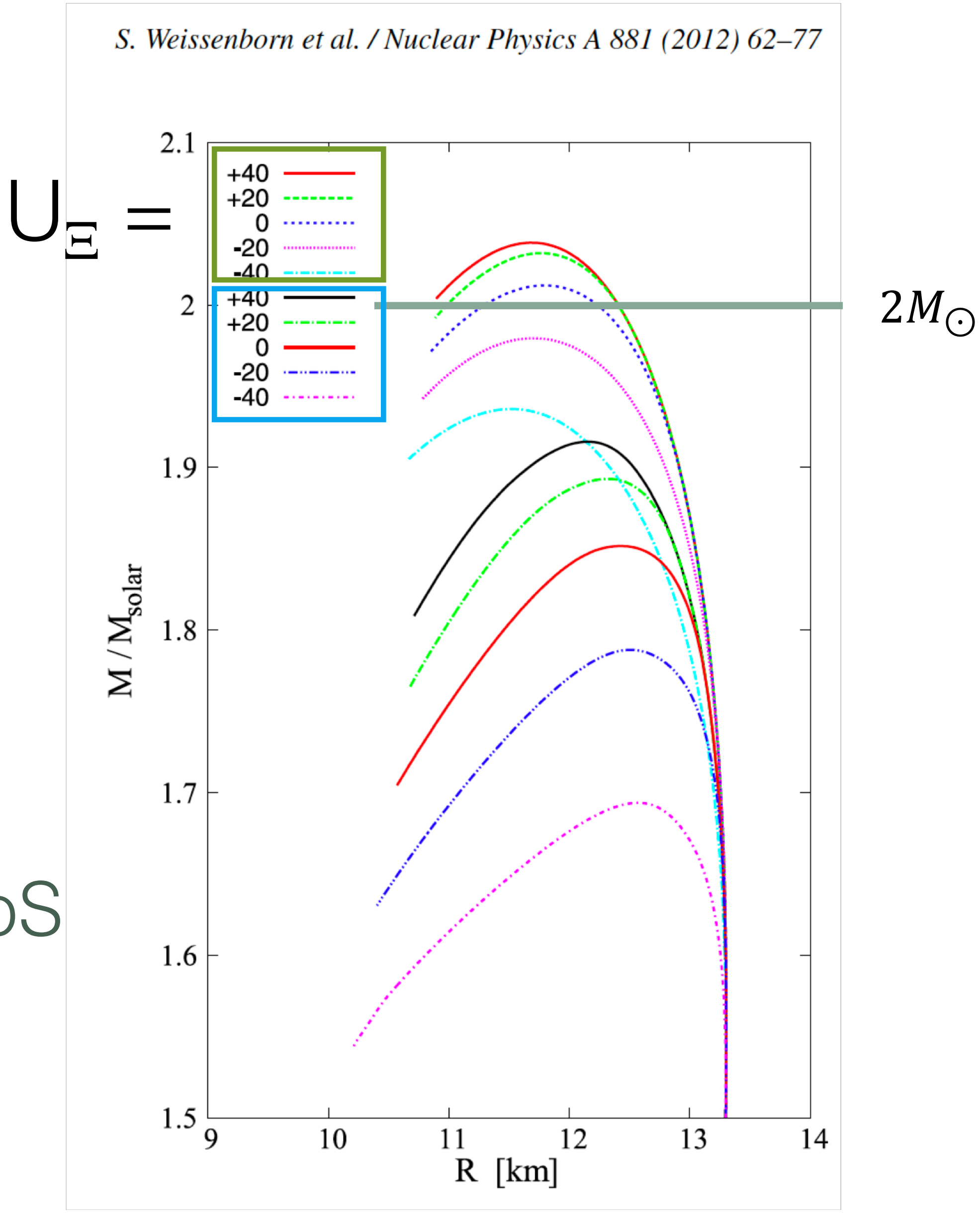
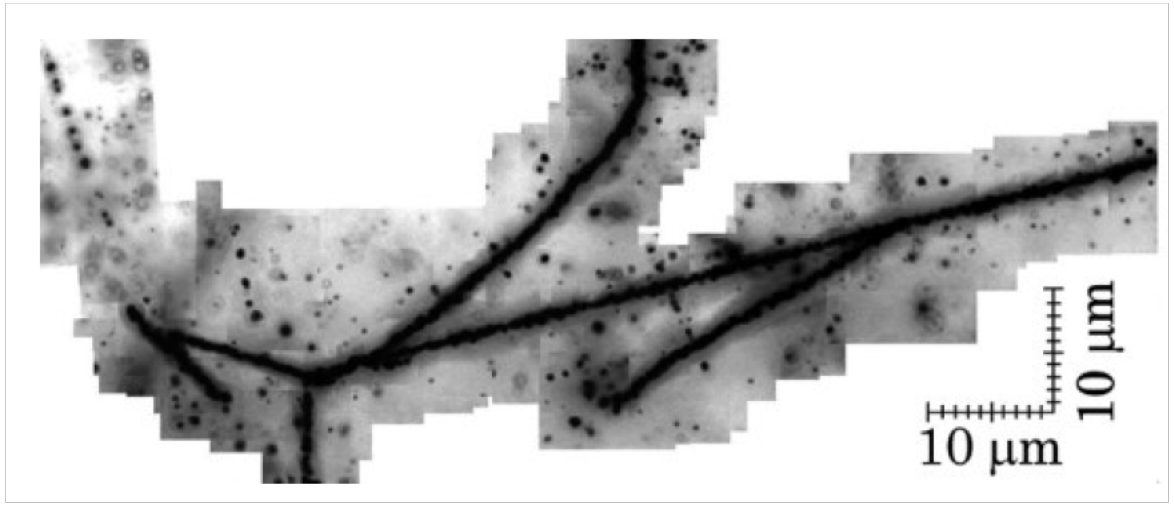
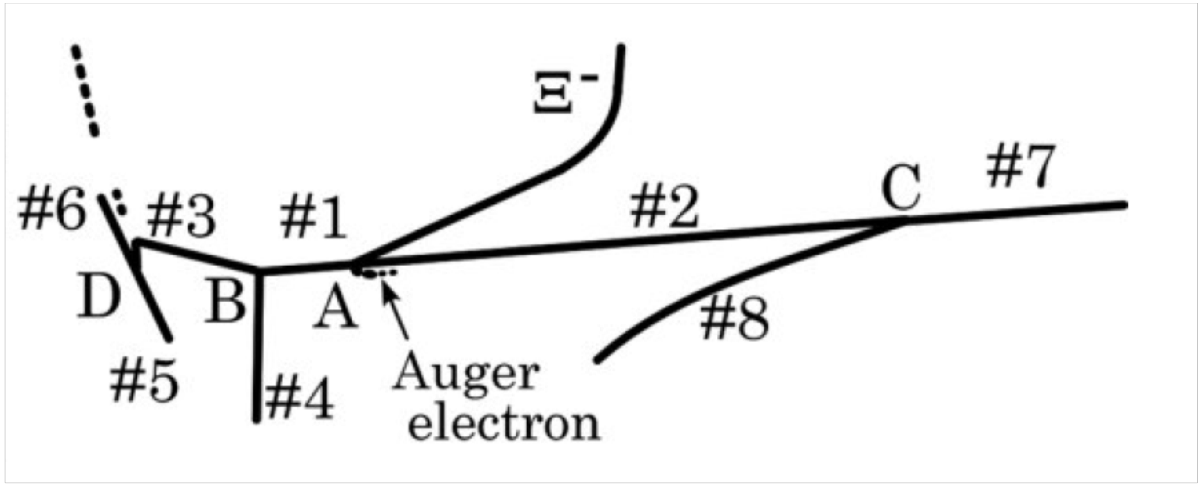
- Scan of U_Ξ : significant impact on the EoS
- Experimental constraints are necessary



Data on Ξ interaction

- Kiso Event: Ξ^- hyper nucleus
- Points towards an attractive interaction
  - Hyper nucleus binding energy $B_{\Xi^-} = 4.38 \pm 0.25$ MeV
- Can we directly observe the attraction with femtoscopy?





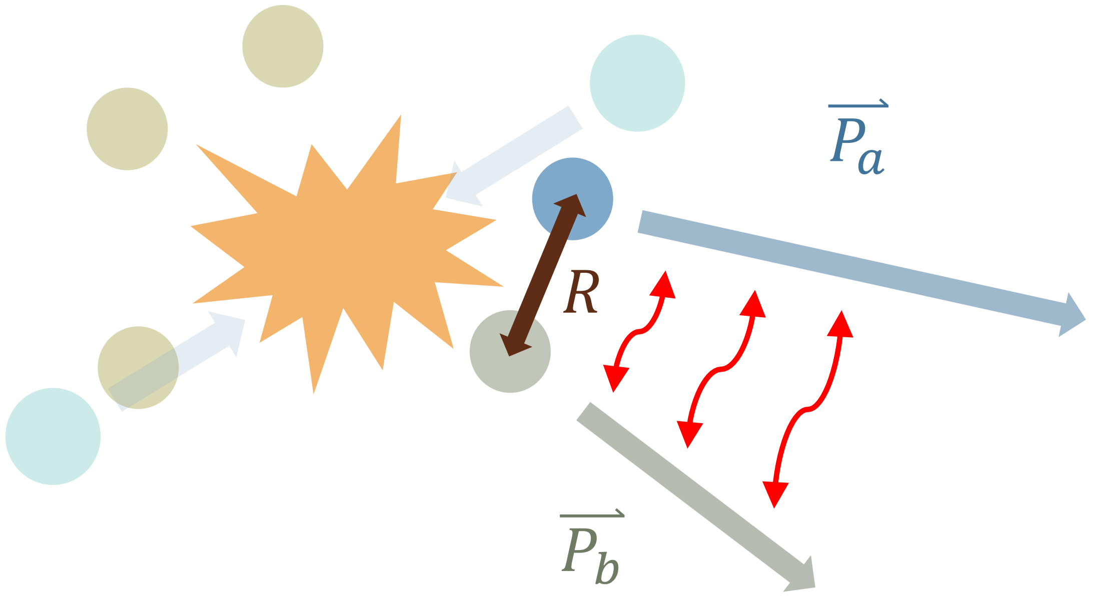
K. Nakazawa et al. PTEP 2015, 033D02

Femtoscopy

Emission source   Two-particle wave function

$$C(k^*) = \frac{P(\mathbf{p}_a, \mathbf{p}_b)}{P(\mathbf{p}_a)P(\mathbf{p}_b)} = \mathcal{N}\frac{N_{same}}{N_{mixed}} = \int S(\mathbf{r})|\Psi(k^*, \mathbf{r})|^2 \, d^3r$$

with $k^* = \frac{1}{2}|\mathbf{p}_a^* - \mathbf{p}_b^*|$ and $\mathbf{p}_a^* + \mathbf{p}_b^* = 0$



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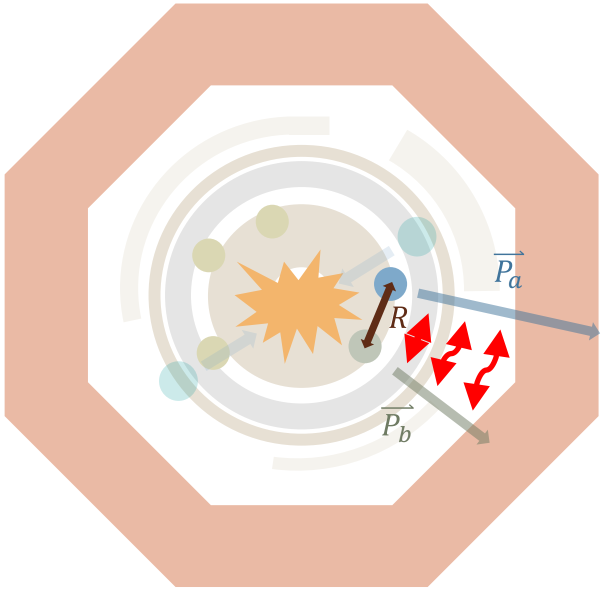
- Use ALICE datasets …
  - pp $\sqrt{s} = 7$ TeV (2010) 2.5 x 10^8 Events
  - pp $\sqrt{s} = 13$ TeV (2016/17) 11 x 10^8 Events
  - p-Pb $\sqrt{s} = 5.02$ TeV (2016) 6.0 x 10^8 Events
- …to study
  - p-p, p-Ξ, p-Λ, Λ–Λ, p-K correlations
  - PID capabilities via TPC and TOF



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- Formalism of λ parameters account for residual correlations from feed down and impurities (arXiv:1805.12455, accepted by PRC)

$$C(k^*) = 1 + \lambda_{genuine} \cdot (C(k^*) - 1) + \sum_{ij} \lambda_{ij} \cdot \left(C_{ij}(k^*) - 1\right)$$

Femtoscopy

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- Evaluation of $C(k^*)$ using the CATS framework
  (D.L. Mihaylov et al., Eur. Phys. J. C78 (2018) no.5, 394)
  - **Numerical solution** of the **Schrödinger equation** yields $\Psi(k^*, \mathbf{r})$
  - Accounts for:
    - Strong potential
    - Coulomb interaction
    - Effects of quantum statistics

Femtoscopy

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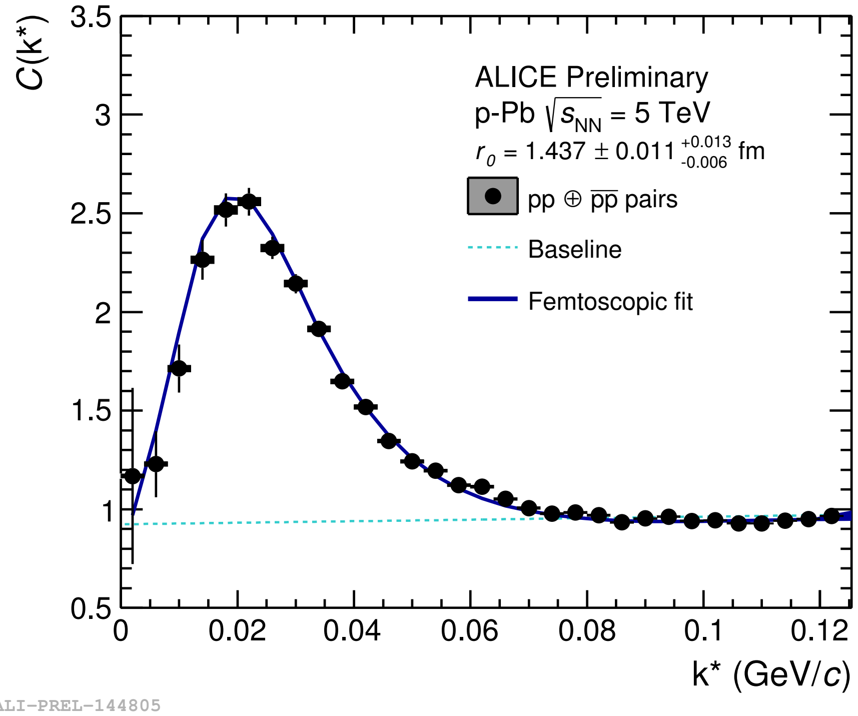
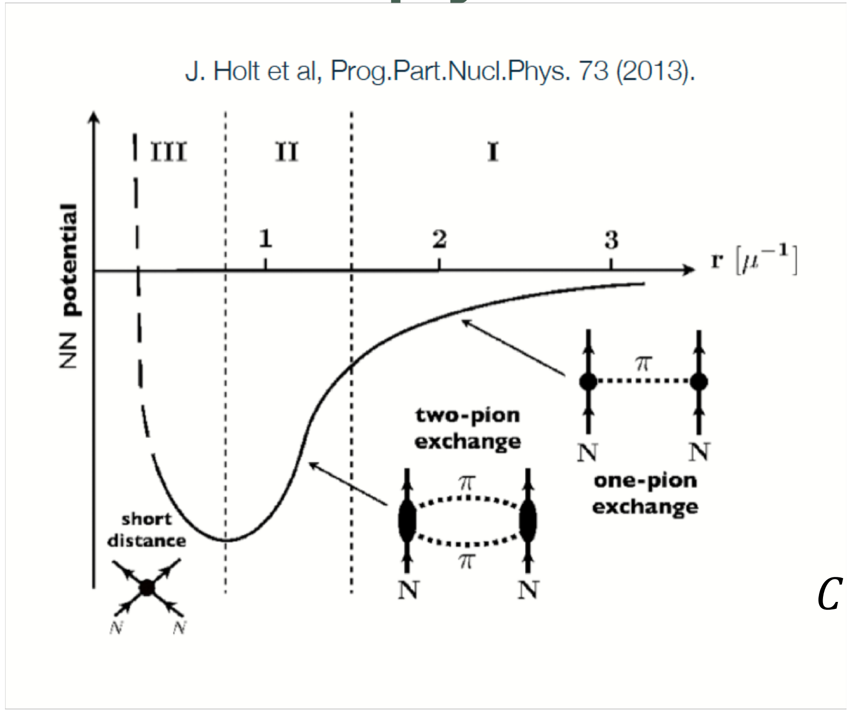
- Evaluation of $C(k^*)$ using the CATS framework
  (D.L. Mihaylov et al., Eur. Phys. J. C78 (2018) no.5, 394)
- Assumption: In small collision systems the emission source is **Gaussian** and approximately the **same** for all baryon pairs

Proton-Proton Femtoscopy

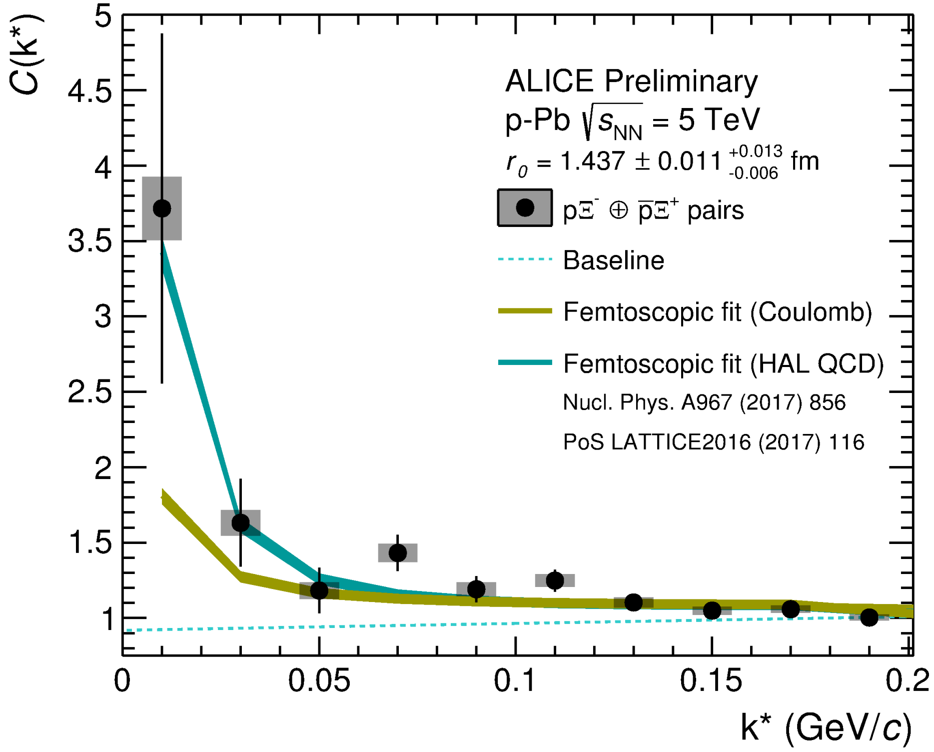




$$C(k^*) \rightarrow \begin{cases} > 1 & \text{attraction} \\ = 1 & \text{no interaction} \\ < 1 & \text{repulsion} \end{cases}$$

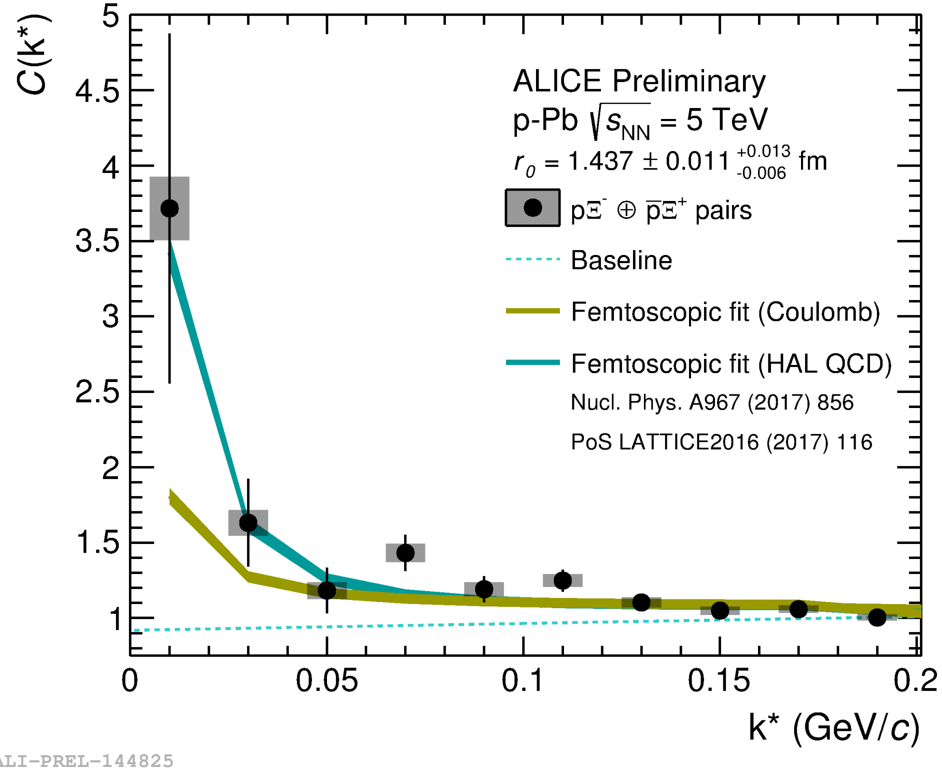
- Described by a Gaussian source and the Argonne v_{18} potential
  - Solve the Schrödinger equation with **CATS**
- Small source $r_{0,\mathrm{p-pB}} = \left(1.437 \pm 0.011\,(stat.)^{+0.013}_{-0.006}(syst.)\right)\,\mathrm{fm}$
- Particularly sensitive to the strong potential

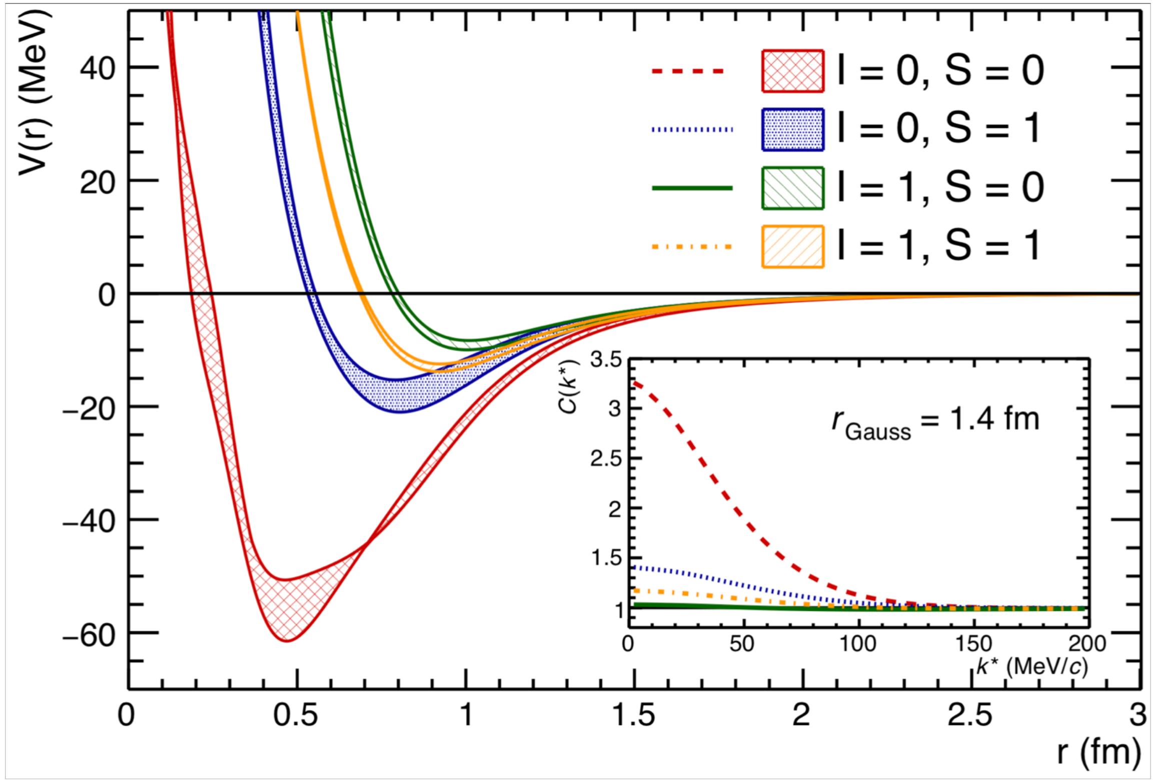
Proton-Ξ Femtoscopy



- First direct observation of the **strong interaction** between a p-Ξ pair by more than **3 sigma**

Proton-Ξ Femtoscopy

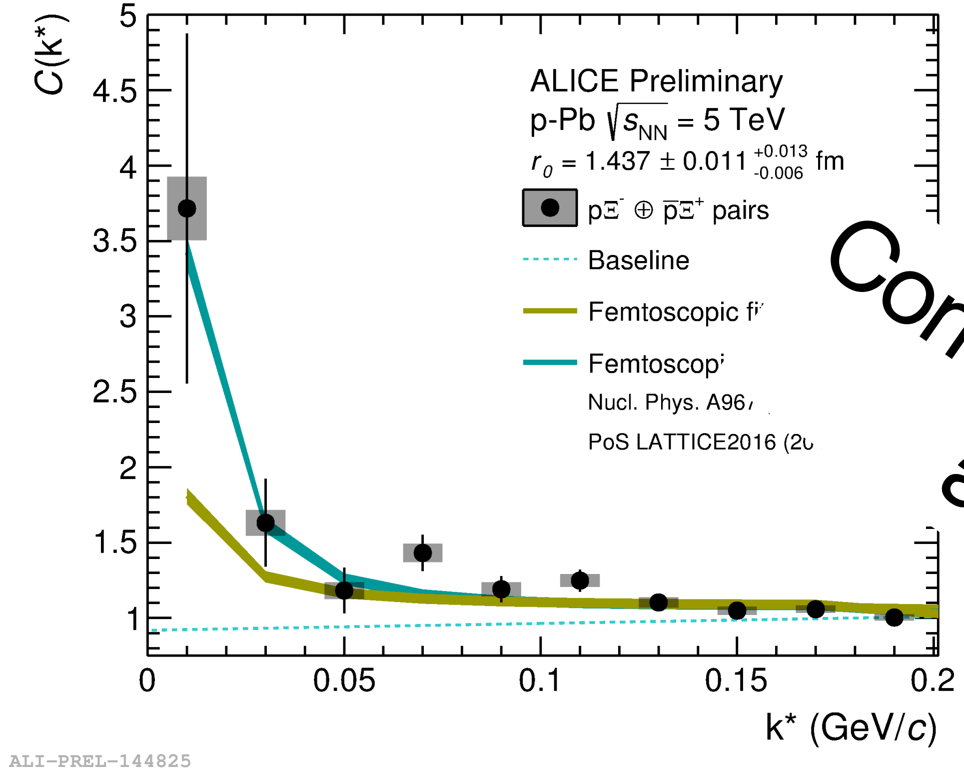


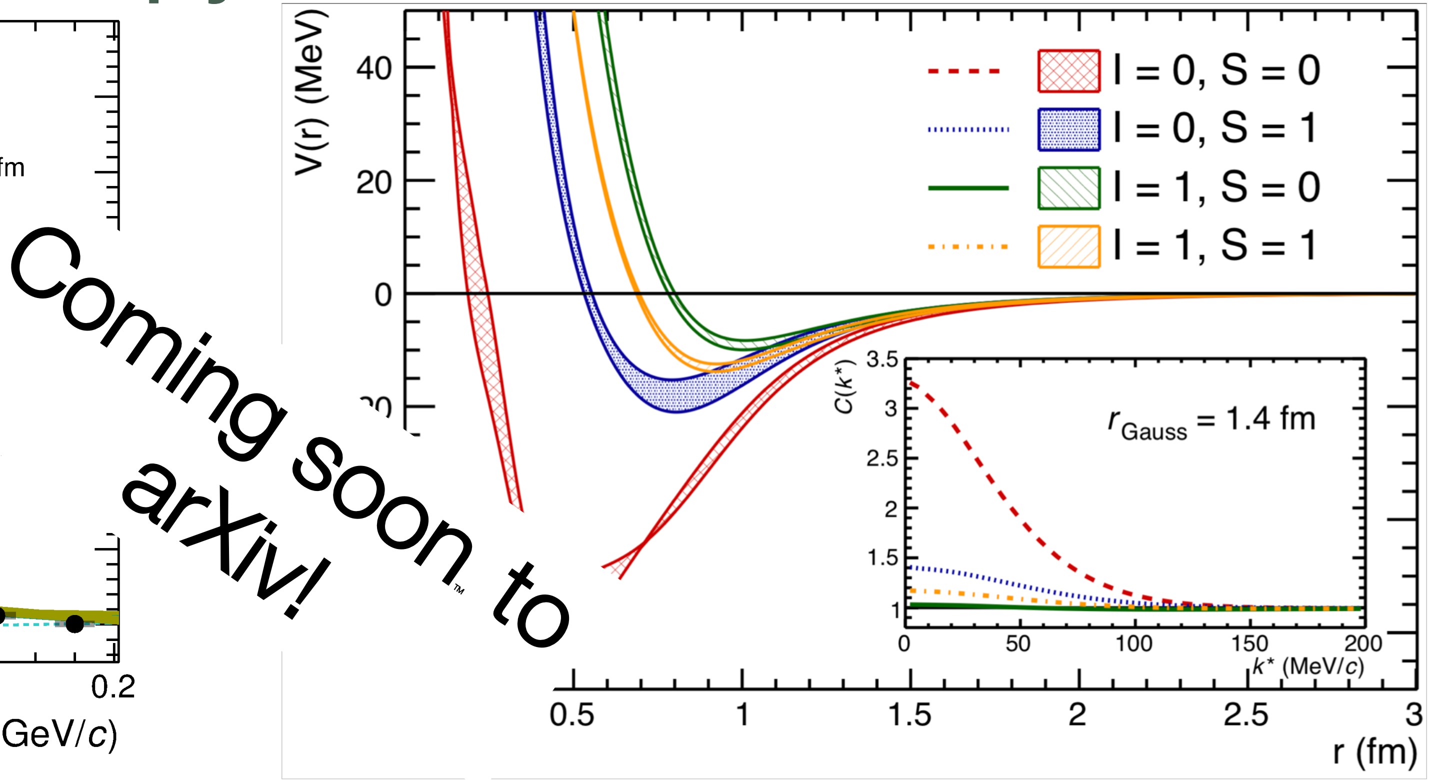


- First direct observation of the **strong interaction** between a p-Ξ pair by more than **3 sigma**
- Test of a strong potential from preliminary HAL QCD calculations

$$C(k^*) = \frac{1}{8} \cdot \left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8} \cdot \left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

Proton-Ξ Femtoscopy





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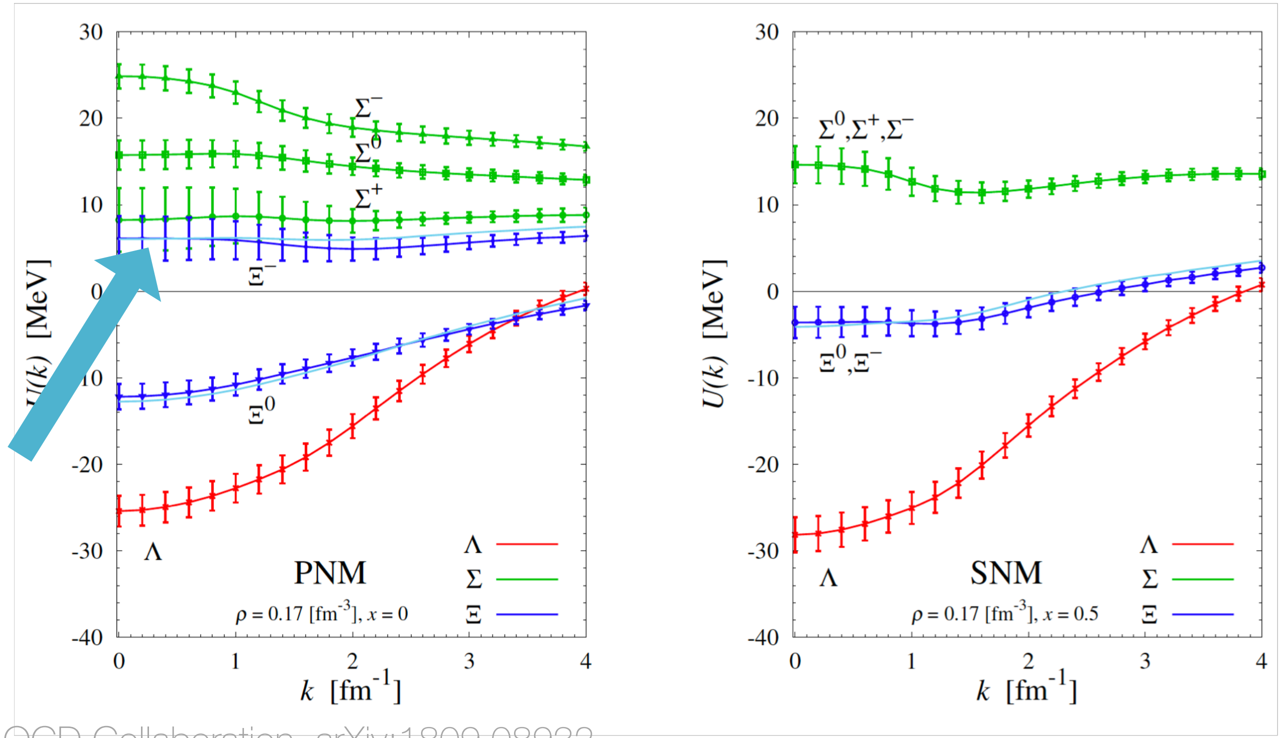
Implications for Neutron Stars



HAL QCD Collaboration, arXiv:1809.08932

- NS → Pure Neutron Matter
  - At saturation density U_{Ξ^-} slightly repulsive

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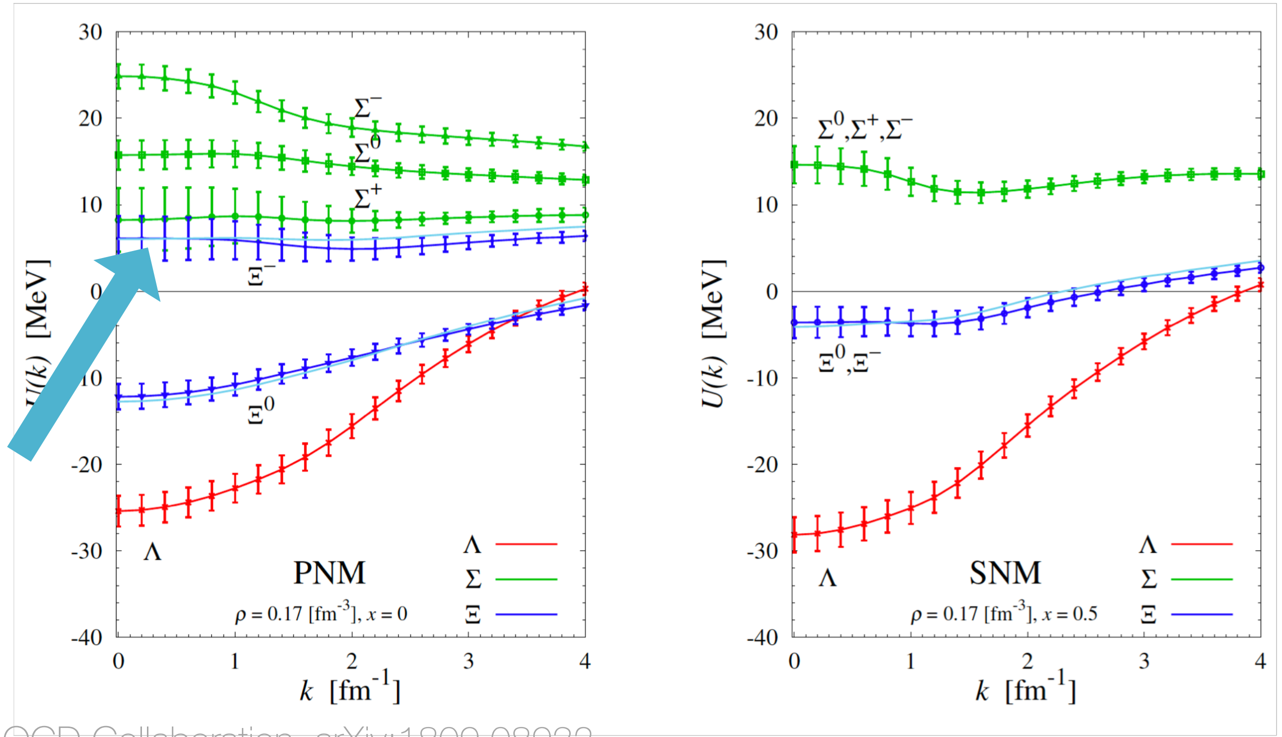

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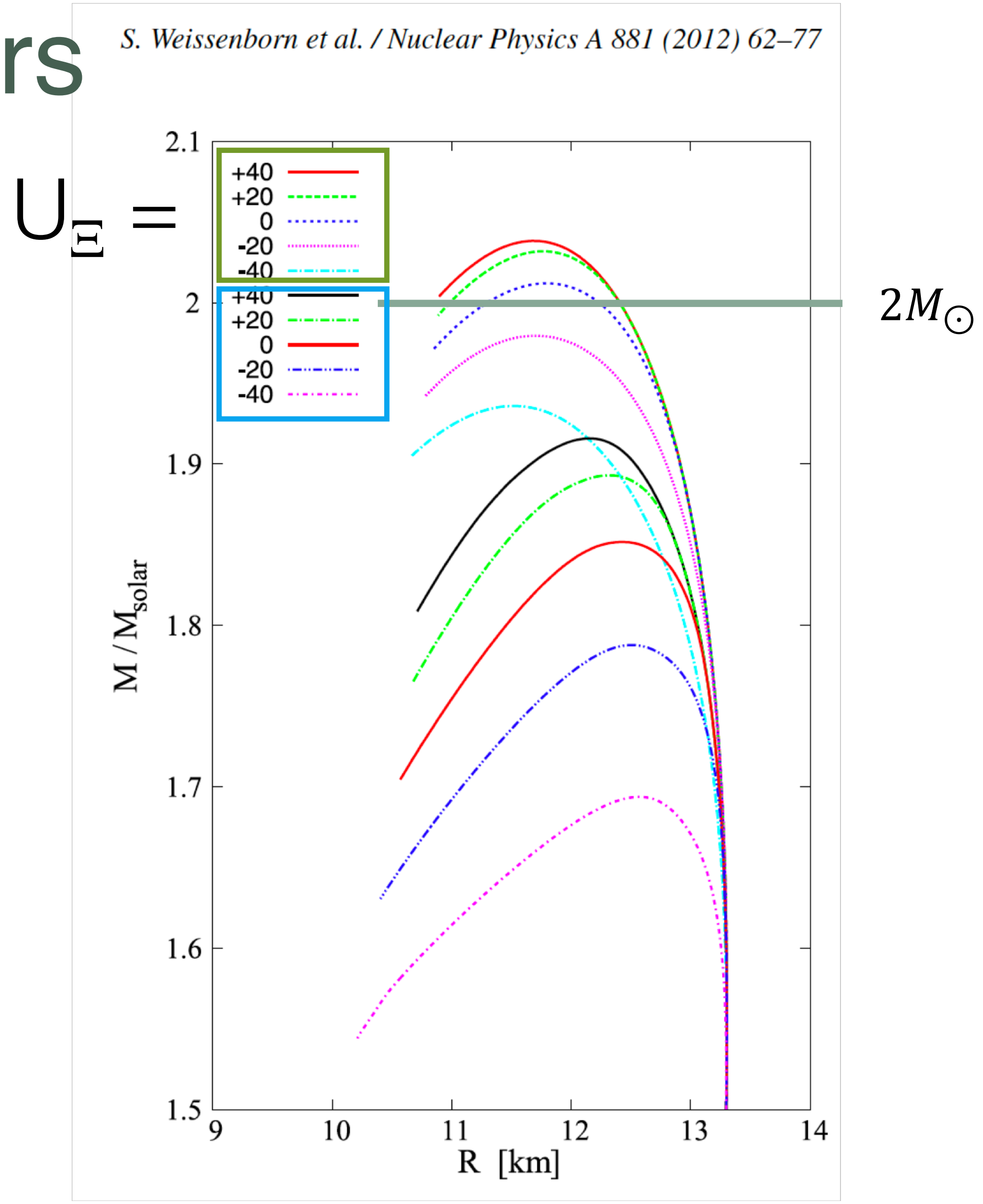

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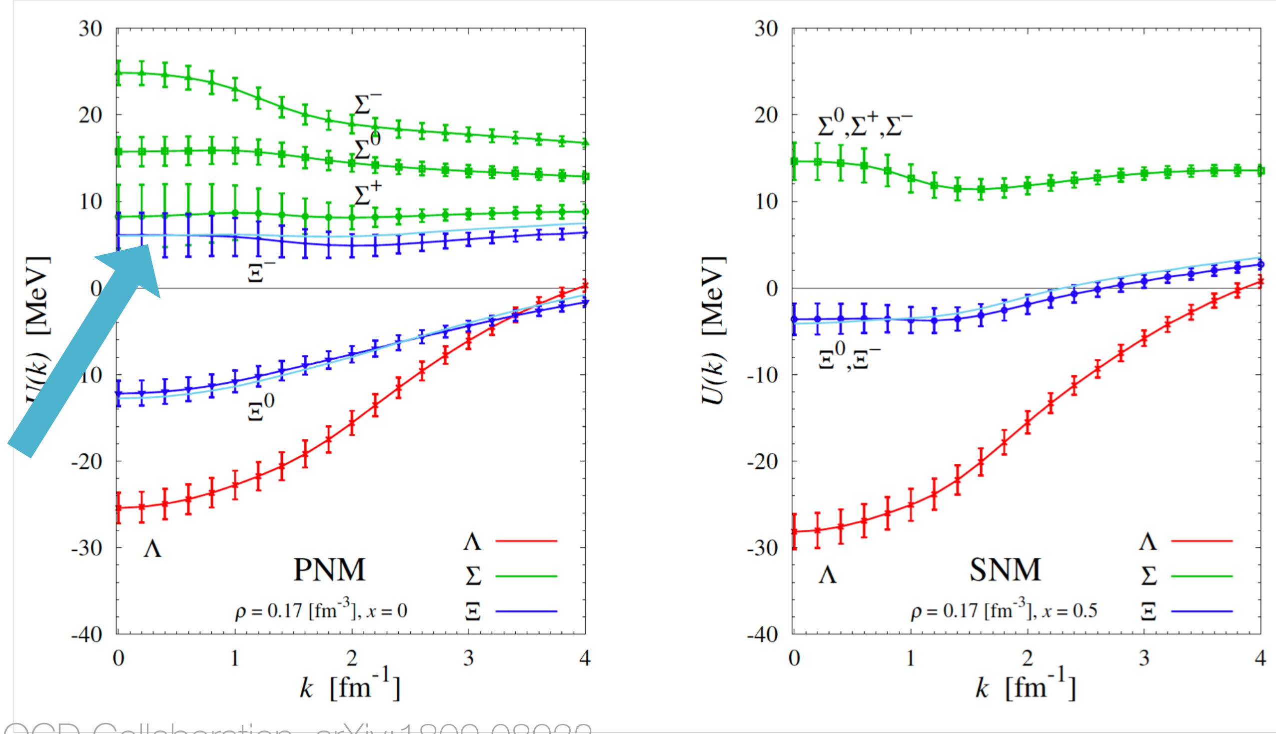

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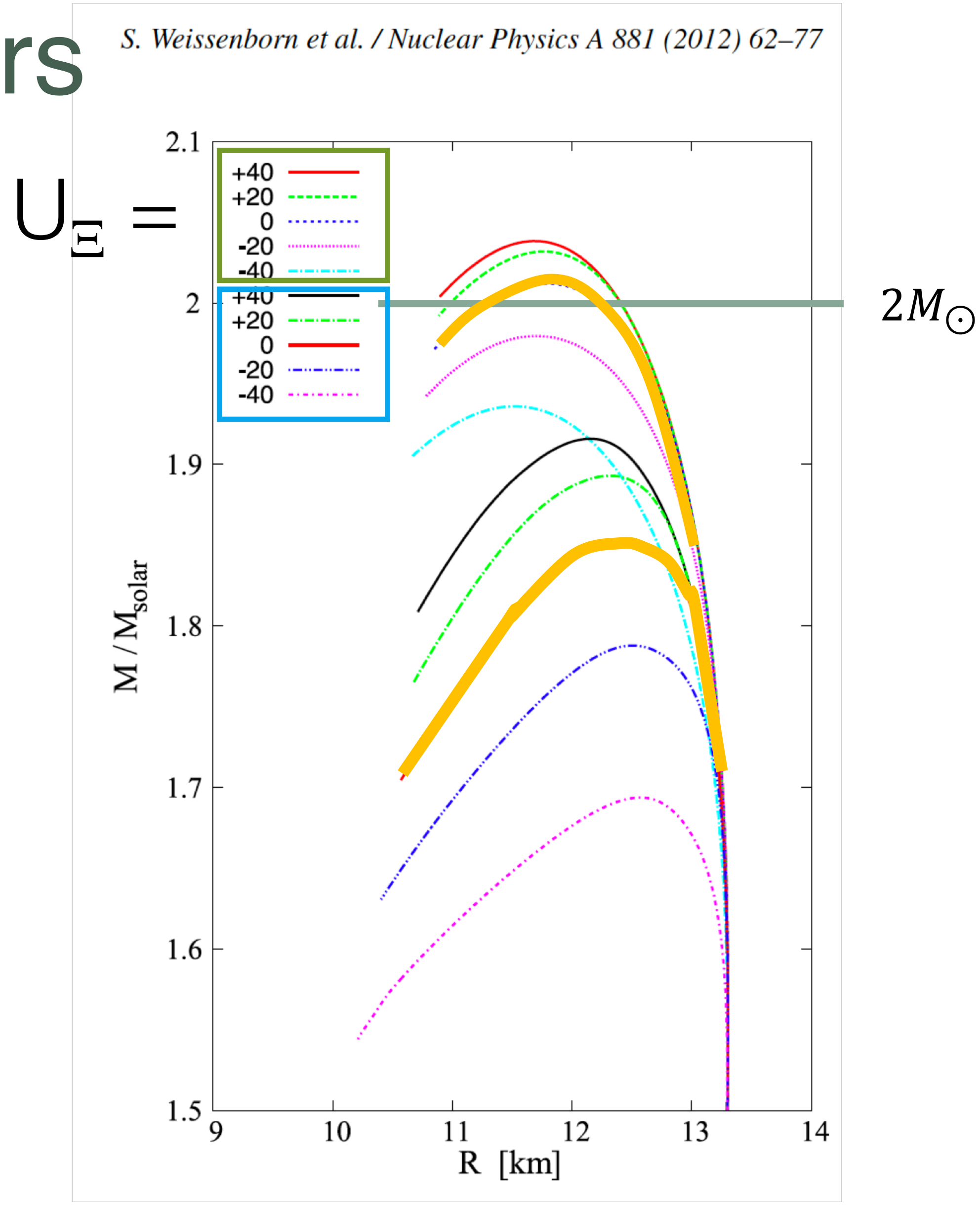

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Summary and Outlook

- Femtoscopy is a new tool to study particle interactions
- Observation of attractive p-Ξ^- interaction for the first time
  - Constrains the average potential of Ξ hyperons at finite densities for NS EoS
- Coming soon to arXiv:
  - Λ–Λ (Poster by A. Mathis), p-K and p-Ξ
- Ongoing analysis:
  - p-Λ, p-Ω^- and p-Σ^0

Thank you for your attention!

Decomposition of the p-p correlation function

$$\{pp\} = pp + p_\Lambda p + p_\Lambda + p_\Lambda + p_{\Sigma^+}p + p_{\Sigma^+}p_{\Sigma^+} + p_\Lambda p_{\Sigma^+} + \tilde{p}p + \tilde{p}p_\Lambda + \tilde{p}p_{\Sigma^+} + \tilde{p}\tilde{p},$$

- Purity from MC (Pythia 8)
- Feed-down fractions from MC template fits to the DCA_{xy} distribution

p–p	
Pair	λ parameter [%]
pp	72.1
$p_\Lambda p$	16.1
Feed-down (flat)	8.7
Misidentification (flat)	3.1

Decomposition of the p-Ξ correlation function

$$
\begin{aligned}
\{p\Xi^-\} = {} & p\Xi^- + p\Xi^-_{\Xi^-(1530)} + p\Xi^-_{\Xi^0(1530)} + p\Xi^-_{\Omega} + p_{\Lambda}\Xi^- + p_{\Lambda}\Xi^-_{\Xi^-(1530)} \\
& + p_{\Lambda}\Xi^-_{\Xi^0(1530)} + p_{\Lambda}\Xi^-_{\Omega} + p_{\Sigma^+}\Xi^- + p_{\Sigma^+}\Xi^-_{\Xi^-(1530)} + p_{\Sigma^+}\Xi^-_{\Xi^0(1530)} + p_{\Sigma^+}\Xi^-_{\Omega} \\
& + \tilde{p}\Xi^- + \tilde{p}\Xi^-_{\Xi^-(1530)} + \tilde{p}\Xi^-_{\Xi^0(1530)} + \tilde{p}\Xi^-_{\Omega} + p\tilde{\Xi}^- + p_{\Lambda}\tilde{\Xi}^- + p_{\Sigma^+}\tilde{\Xi}^- + \tilde{p}\tilde{\Xi}^- .
\end{aligned}
$$

Feeding from

- W (BR very small)
- X^0(1530) and X^-(1530)
  - Isospin partners: assume to be produced in the same amount
  - X(1530)/X^- = 0.32 (https://doi.org/10.1140/epjc/s10052-014-3191-x)
  - BR(X^0(1530) → X^-) = 2/3
  - BR(X^-(1530) → X^-) = 1/3

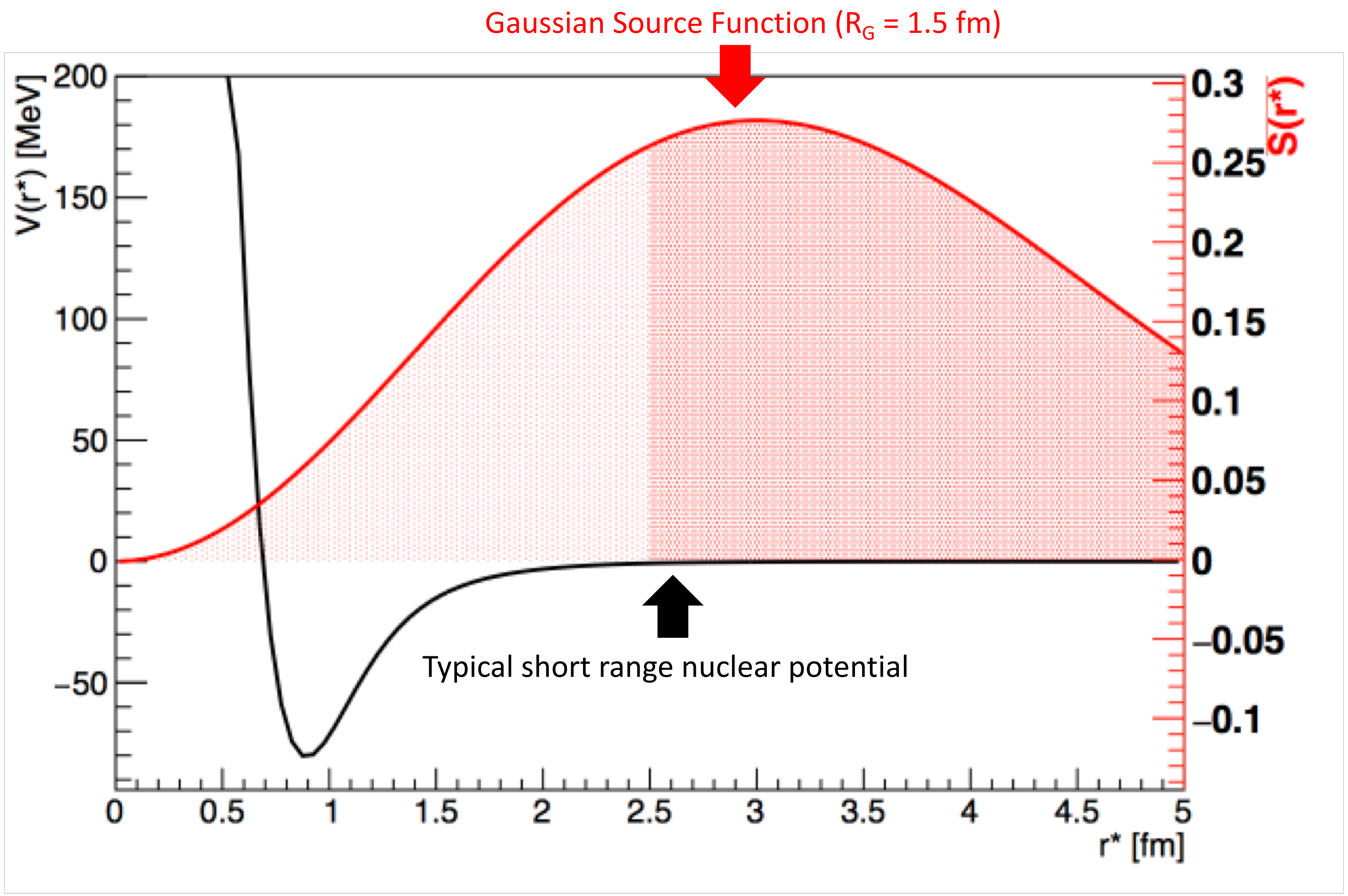
p–Ξ^-	
Pair	λ parameter [%]
$p\Xi^-$	51.3
$p\Xi^-_{\Xi^-(1530)}$	8.2
$p\tilde{\Xi}^-$	8.5
Feed-down (flat)	29.1
Misidentification (flat)	2.9

Some Numbers: p-Pb - $\sqrt{s_{NN}}$ = 5.02 TeV

p-Pb $\sqrt{s_{NN}}$ = 5.02 TeV	
Particle	# baryons (uncorrected)
p	155×10^6
$\bar{p}$	133×10^6
Λ	26×10^6
$\bar{\Lambda}$	24×10^6
Ξ^-	0.9×10^6
Ξ^+	0.9×10^6

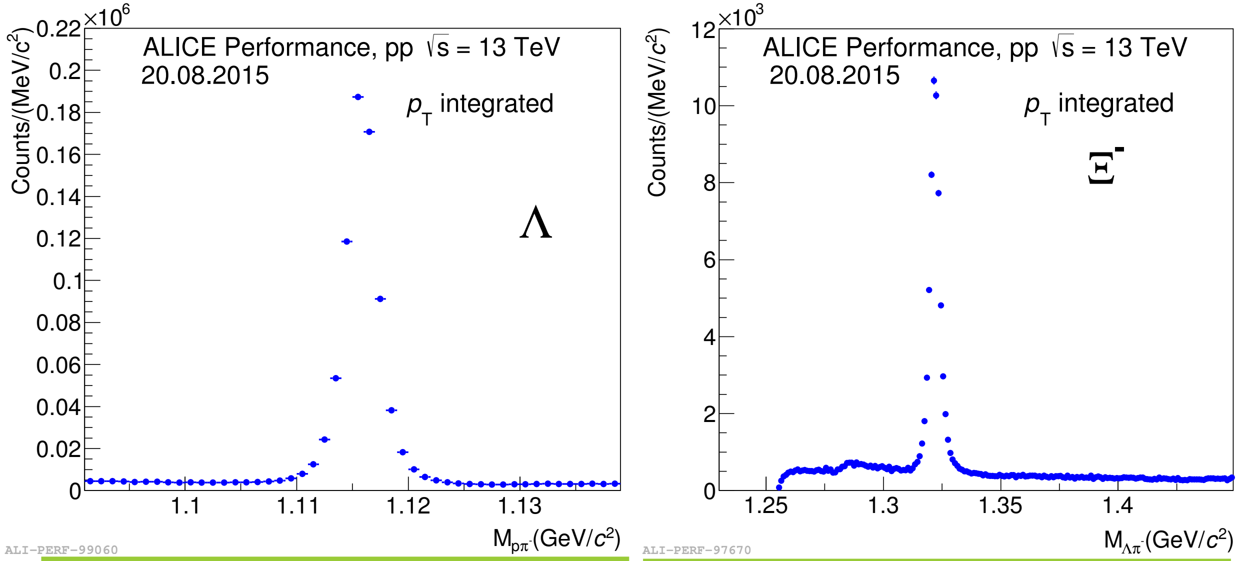
Pair	# of pairs k* < 200 MeV/*c*
$p - p$	517×10^3
$\bar{p} - \bar{p}$	370×10^3
$p - \Lambda$	127×10^3
$\bar{p} - \bar{\Lambda}$	62×10^3
$\Lambda - \Lambda$	13×10^3
$\bar{\Lambda} - \bar{\Lambda}$	12×10^3
$p - \Xi^-$	1.8×10^3
$\bar{p} - \Xi^+$	1.3×10^3

The unique opportunity of small sources



A Large Ion Collider Experiment

- Proton identification with TPC and TOF
- Reconstruction of hyperons
  - $\Lambda \rightarrow p\pi^-$ (BR ~ 64%)
  - $\Xi^- \rightarrow \Lambda\pi^-$ (BR ~ 100%)
- Datasets:
  - pp 7 TeV: $3.4\cdot10^8$ Events
  - pp 13 TeV: $10\cdot10^8$ Events
  - p-Pb 5.02 TeV: $6.0\cdot10^8$ Events



pp $\sqrt{s} = 13$ TeV	
Particle	# baryons (uncorrected)
p	113.7 x 10^6
$\bar{p}$	97.4 x 10^6
Λ	22.3 x 10^6
$\bar{\Lambda}$	21.0 x 10^6
Ξ^-	0.51 x 10^6
Ξ^+	0.53 x 10^6

p-Pb $\sqrt{s_{NN}} = 5.02$ TeV	
Particle	# baryons (uncorrected)
p	155 x 10^6
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Modelling the Correlation function

$$C(k^*) = N \cdot C_{baseline}(k^*) \cdot \left(1 + \lambda_{genuine} \cdot \left(C_{genuine}(k^*) - 1\right) + \sum \lambda_{ij} \cdot \left(C_{ij}(k^*) \ - 1\right)\right.$$

CATS Correlation Analysis Tool Using the Schrödinger Equation		**Lednický**
Numerical Solver		Analytical Model
Analytical source distribution Distributions from transport models	SOURCE	Gaussian source distribution
Solution of the two particle Schrödinger Equation ➢ Can incorporate any strong interaction potential, Coulomb interaction and effects of quantum statistics	WAVE FUNCTION	Based on the effective Range expansion ➢ The interaction is modeled using the scattering length (f_0) and the effective range (d_0)
p-p, p-Ξ and p-Λ (NLO) Correlation function	Used to fit the	p-Λ (LO) and Λ–Λ Correlation function

arXiv:1802.08481 (Accepted by EPJC)

R. Lednicky and V. L. Lyuboshits, Sov. J. Nucl. Phys. **35**, 770 (1982), [Yad. Fiz.35,1316(1981)].

Considered Shapes