Exploring the residual strong interaction among thee hadrons at the LHC

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MENU 2023

16th edition of the "International Conference on Meson-Nucleon Physics and the Structure of the Nucleon"
Mainz, Germany
19th October 2023

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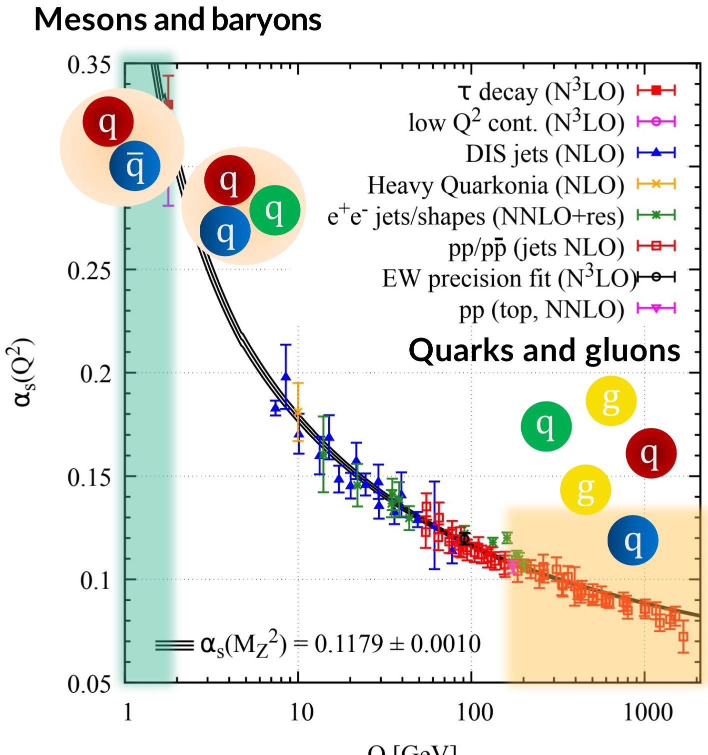
Why do we study hadronic interactions?



PDG, PTEP 2022, 083C01(2022)

- Understanding how QCD evolves from high-energy to low-energy regime

How do hadrons emerge?

How do hadrons interact?

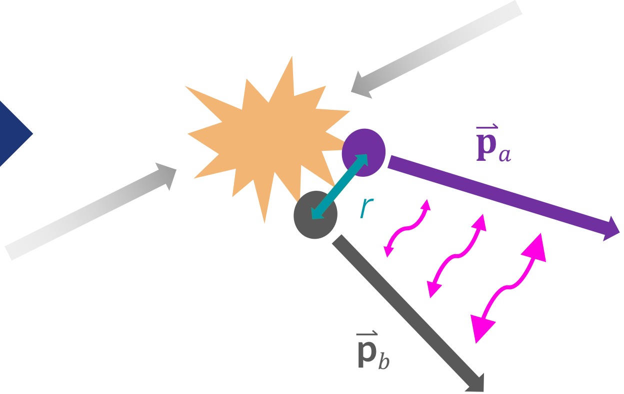
2-body and many-body interactions

Need for experimental data

The femtoscopy technique at the LHC

ALICE at the LHC

Hadronic interaction

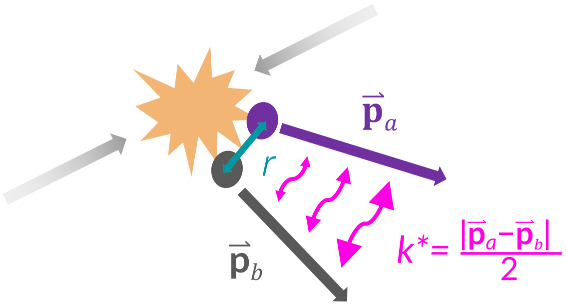


Femtoscopy technique

Correlation function

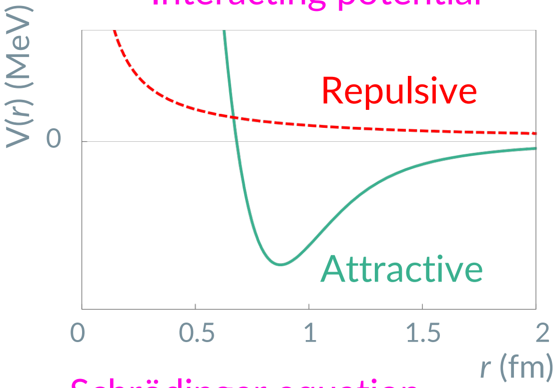
$$C(\vec{\mathbf{p}}_a, \vec{\mathbf{p}}_b) \equiv \frac{P(\vec{\mathbf{p}}_a, \vec{\mathbf{p}}_b)}{P(\vec{\mathbf{p}}_a)\, P(\vec{\mathbf{p}}_b)}$$

The femtoscopy technique at the LHC

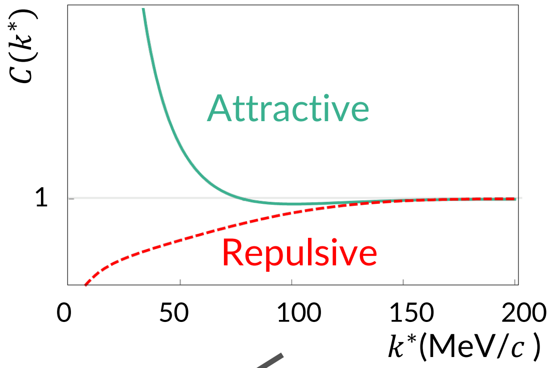


Emission source $S(\vec{r})$

Interacting potential



Correlation function



Schrödinger equation

CATS Framework: D. Mihaylov et al., Eur. Phys. J. C78 (2018) 394

Two-particle wave function

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

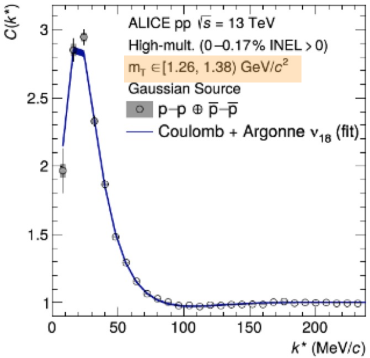
Measuring $C(k^*)$, fixing the source $S(\vec{r})$, study the interaction

Source determination

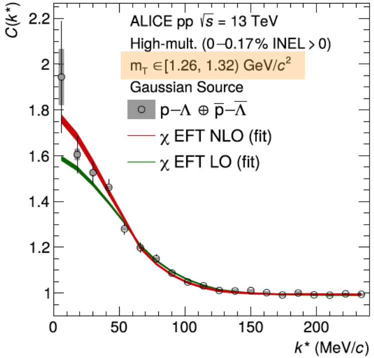
Fix the the interaction to study the source: $C(k^*) = \int S(\vec{r})\left|\psi(\vec{k}^*,\vec{r})\right|^2 d^3\vec{r}$

ALICE Coll. PLB 811 (2020)

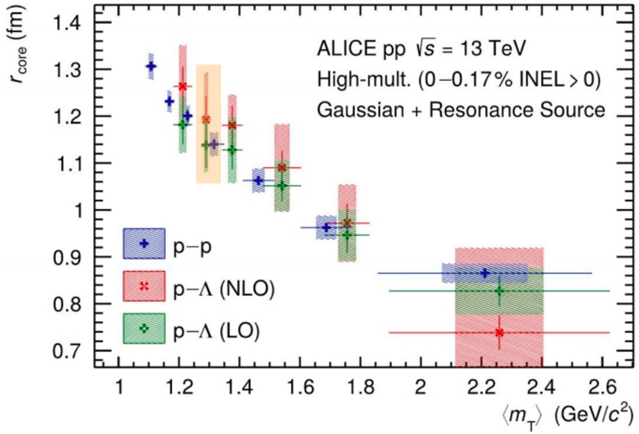
p-p



p-Λ

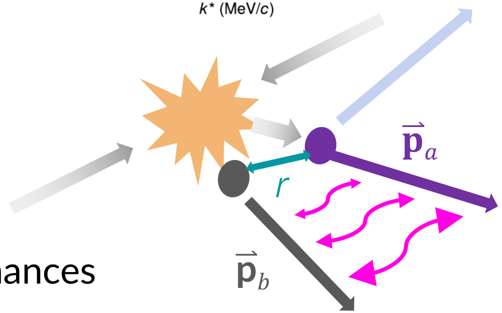


ALICE Coll. PLB 811 (2020)



$$S(r) = G[r, r_{core}(m_T)] = \frac{1}{(4\pi r_{core}^2)^{3/2}} \exp\left(-\frac{r^2}{4r_{core}^2}\right)$$

× effect of the short-lived resonances



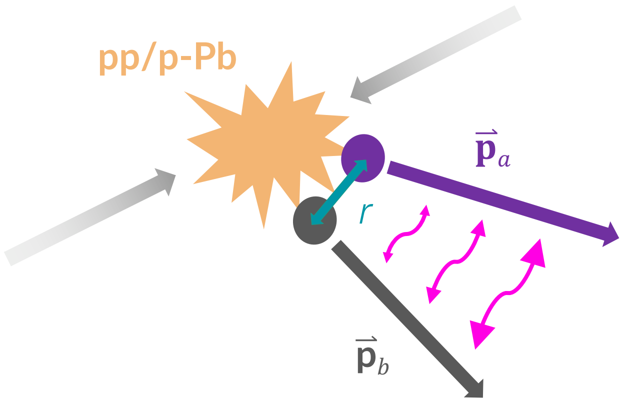
One <u>universal source for all hadrons</u>

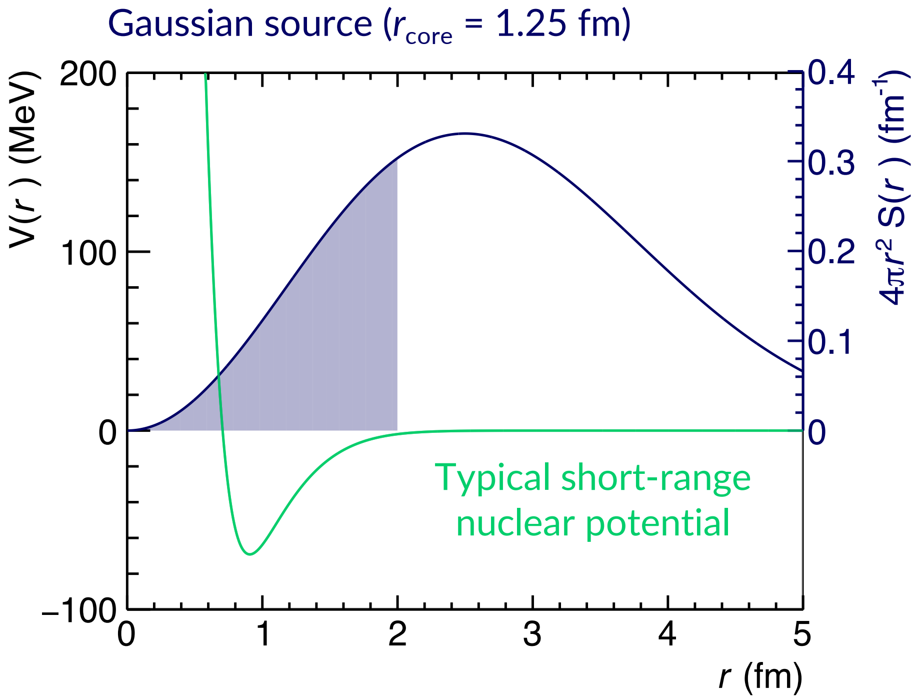
Similar results in K⁺p, ππ

Femtoscopy in small colliding systems

Small particle-emitting source created in pp and p–Pb collisions at the LHC:

- **Essential ingredient for detailed studies of the strong interaction**



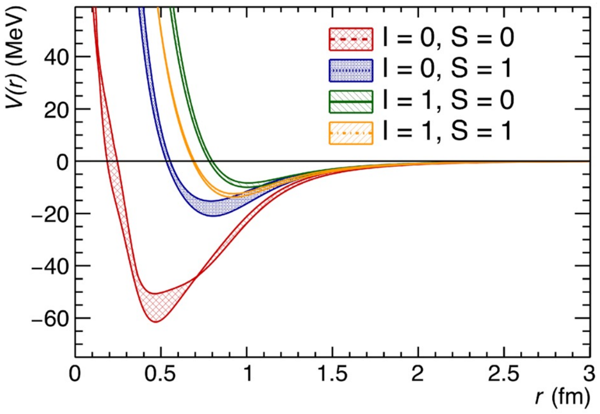


|S|=2 sector: p–Ξ⁻ interaction

Lattice QCD potentials from
HAL QCD Collaboration

HAL QCD Coll. NPA 998 (2020)

Local potentials for the nucleon-Ξ interactions → *D.L. Mihaylov et al, EPJ C78 (2018)* **Schrödinger equation**



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

r_{eff} = 1.02 +- 0.05 fm

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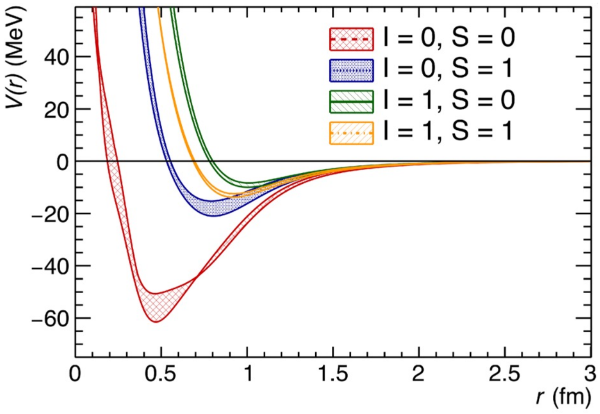

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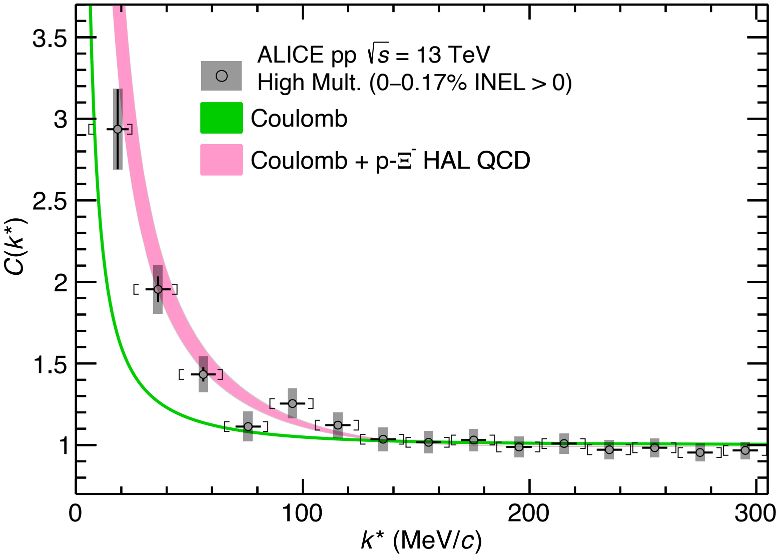
ALICE Coll. Nature 588 232–238 (2020)



→ Observation of a strong attractive interaction beyond Coulomb in agreement with lattice predictions

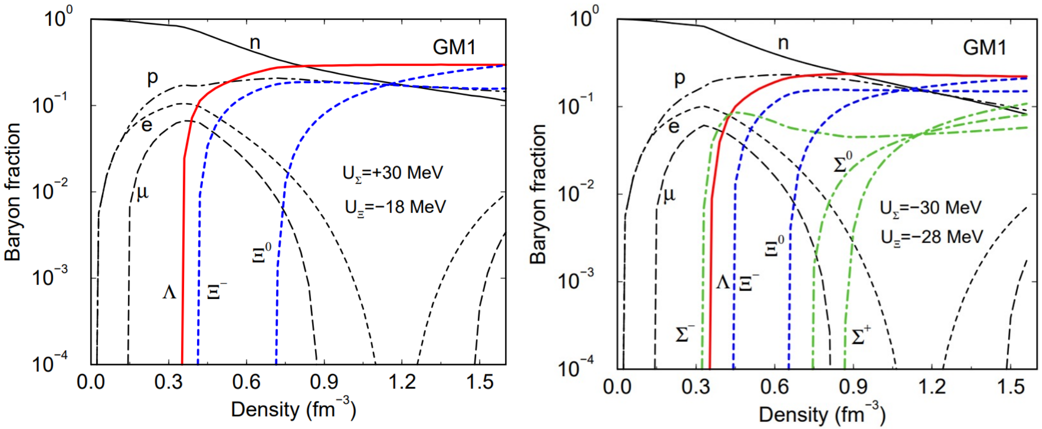
Hyperons in neutron stars?

J. Schaffner-Bielich et al NPA 835 (2010)

Neutron Stars: very dense, compact objects

At finite densities **hyperon** production becomes energetically favorable

- Softening of the Equation of State (EoS)
- Appearance as a a function of ρ depends on the Y interaction with medium
- Exact composition strongly depends on constituent interactions and couplings!



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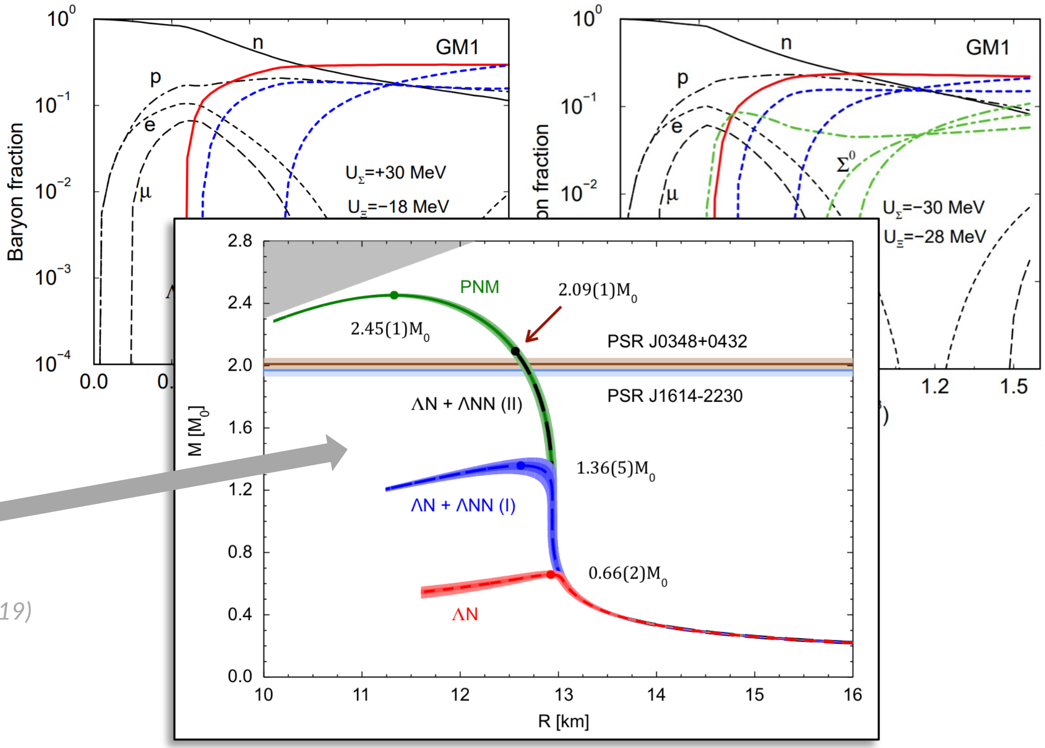
- Softening of the Equation of State (EoS)
- Appearance as a a function of ρ depends on the Y interaction with medium
- Exact composition strongly depends on constituent interactions and couplings!
- Repulsive three-body ΛNN interaction can stiffen the EoS….but:
  - → its effect on EoS largely model dependent

D. Logoteta et al., EPJA 55 (2019); D. Lonardoni et al., PRL 114 (2019)

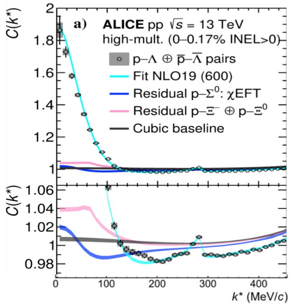
J. Schaffner-Bielich et al NPA 835 (2010)



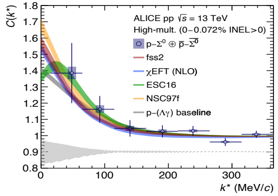
An example of EoS for neutron stars

Correlation
two-body interaction

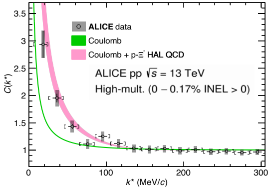
pΛ



pΣ

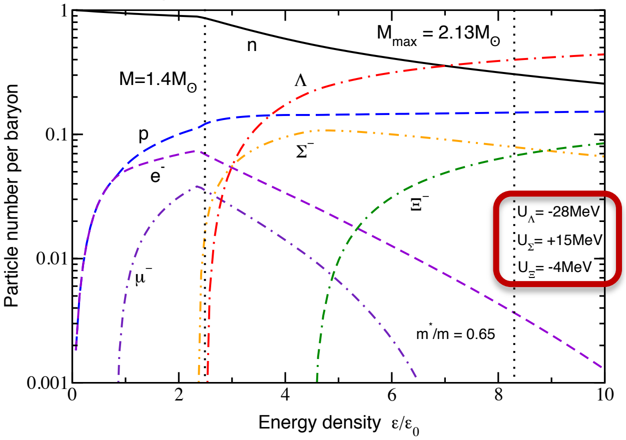


pΞ



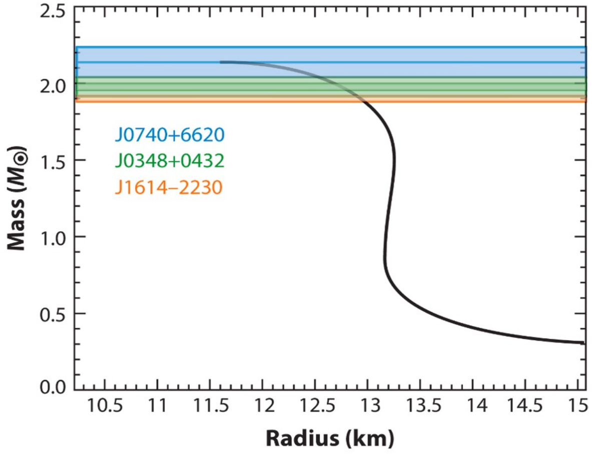
Single-particle potentials
EoS

Courtesy J. Schaffner-Bielich 2020



Mass vs Radius relation
for hyperon stars

Courtesy J. Schaffner-Bielich and B. Dönigus 2020

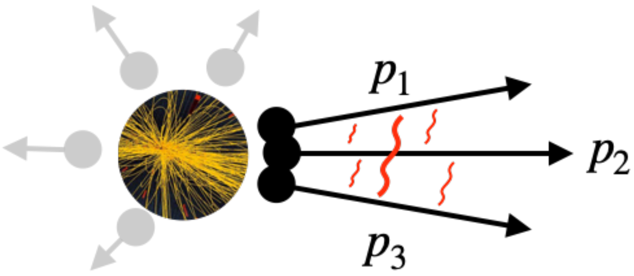


L. Fabbietti et al. Ann.Rev.Nucl.Part.Sci. 71 (2021)

This is only an example. Experimental uncertainties need to be propagated and some interactions are missing …

- What about the three-body strong interaction?

p–p–p and p–p–Λ correlation functions



- Three-particle correlation function:

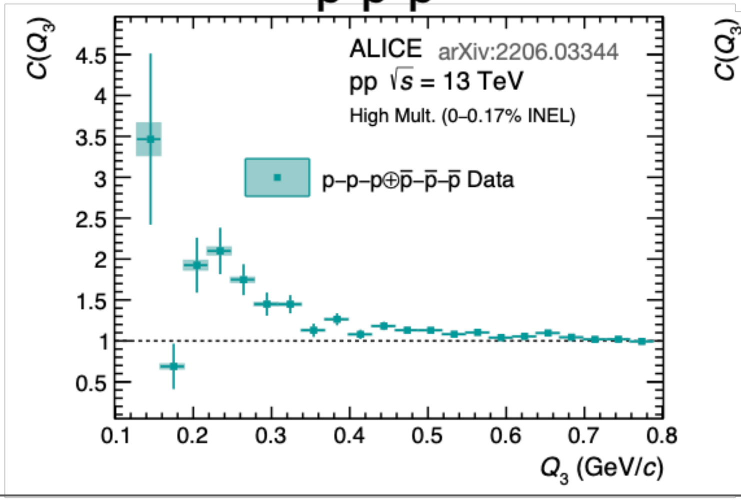
$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) = \iiint S_3(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) \left| \psi_{\mathbf{p}_1,\mathbf{p}_2,\mathbf{p}_3}(\mathbf{x}_1, \mathbf{x}_2, \mathbf{x}_3) \right|^2 d^3x_1 d^3x_2 d^3x_3 = \mathcal{N} \cdot \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

- Lorentz-invariant Q_3 is defined as:

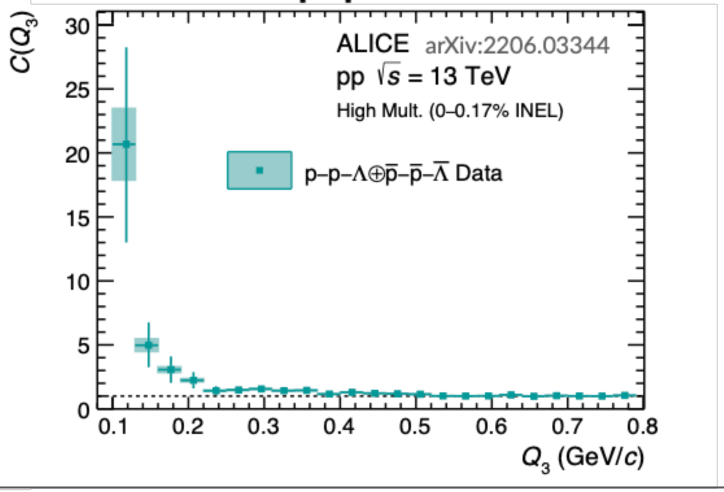
$$Q_3 = \sqrt{-q_{12}^2 - q_{23}^2 - q_{31}^2}$$

$$q_{ij}^{\mu} = 2\left(\frac{m_j E_i}{m_i + m_j} - \frac{m_i E_j}{m_i + m_j}, \frac{m_j}{m_i + m_j}\mathbf{p}_i - \frac{m_i}{m_i + m_j}\mathbf{p}_j\right)$$

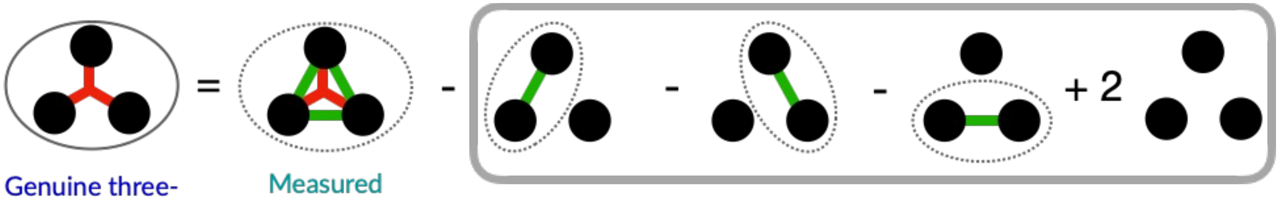
p-p-p



p-p-Λ



Cumulants in femtoscopy



Genuine three-particle correlations (cumulant)

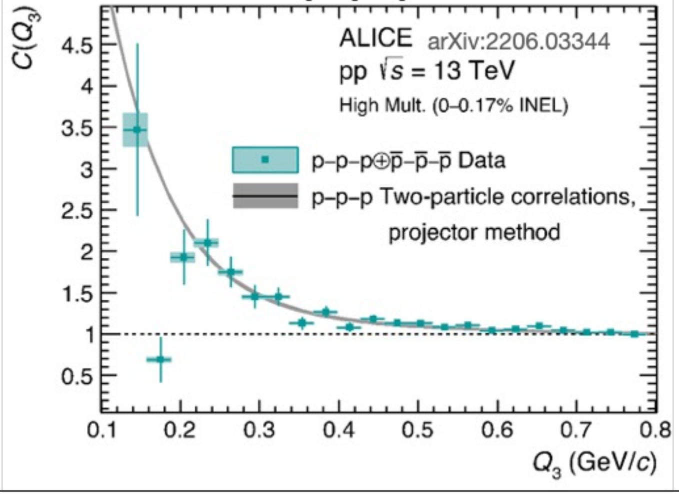
Measured three-particle correlation

Lower-order correlations

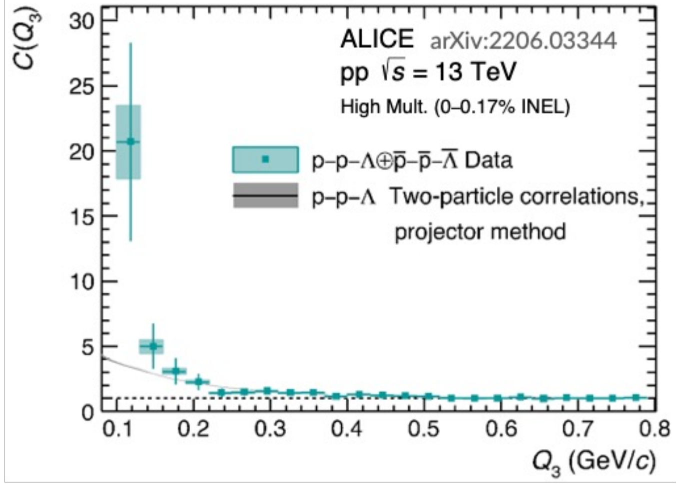
R. Del Grande et al, EPJC 82 (2022)

R. Kubo, J. Phys. Soc. Jpn. 177 (1962)

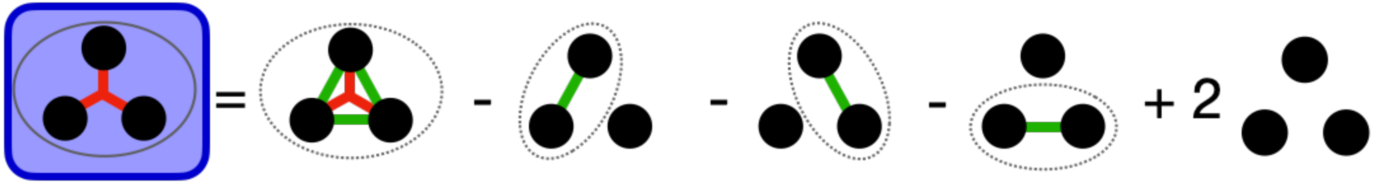
p-p-p



p-p-Λ



p–p–p cumulant

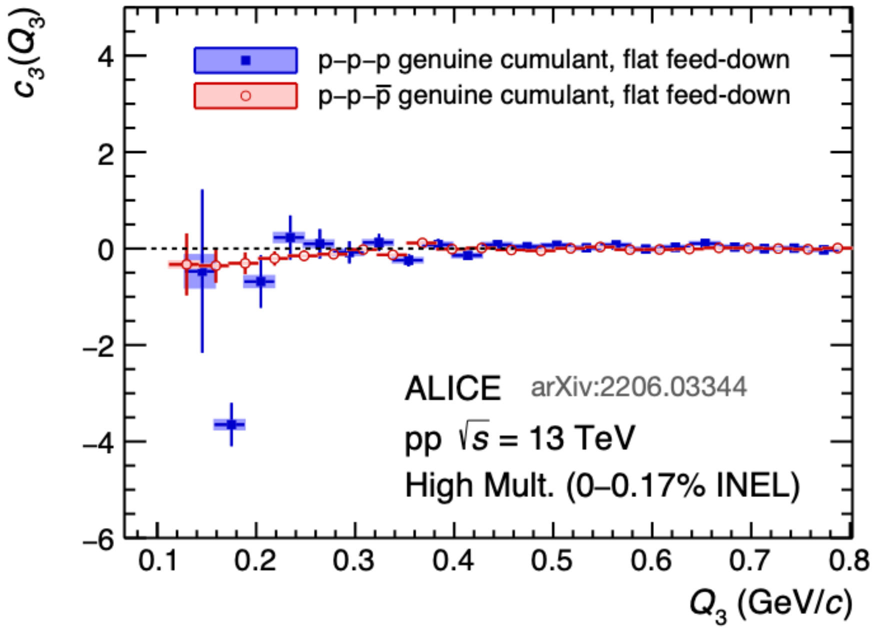


Negative cumulant for p-p-p
Possible effects at play:
- Pauli blocking at the three-particle level
- three-body strong interaction

Statistical significance:

n_σ =6.7 for Q_3 < 0.4 GeV/c

Calculations in progress in collaboration with A. Kievsky, E. Garrido, M. Viviani, L. Marcucci



Test with mixed-charge particles, cumulant negligible.

p-p-p correlations

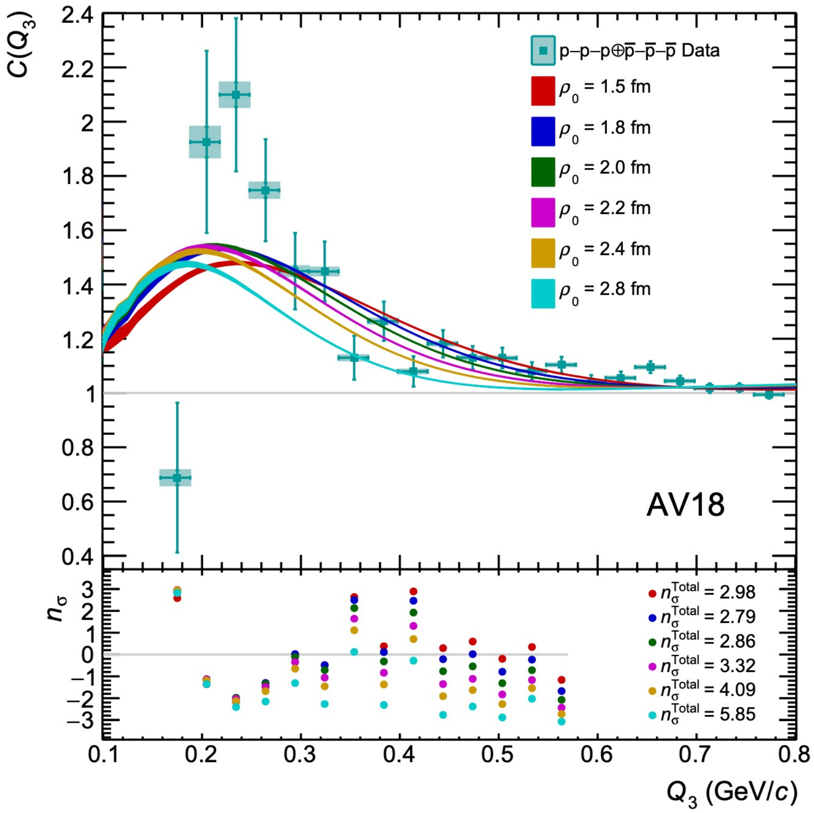
- Three-body calculations:

$$C(Q_3) = \int S(\rho)|\psi(Q_3, \rho)|^2 \rho^5 \, d\rho$$

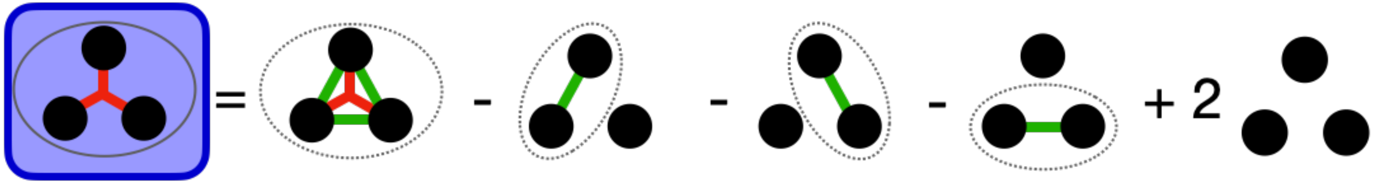
with hyperspherical harmonics method in collaboration with A. Kievsky, M. Viviani, L. Marcucci and E. Garrido.

A. Kievsky et al., arXiv:2310.10428(2023)

- Wave function: AV18 + Coulomb + Quantum Statistics
- Quantum statistics causes the depletion at low Q_3



p–p–Λ cumulant



Positive cumulant for p-p-Λ

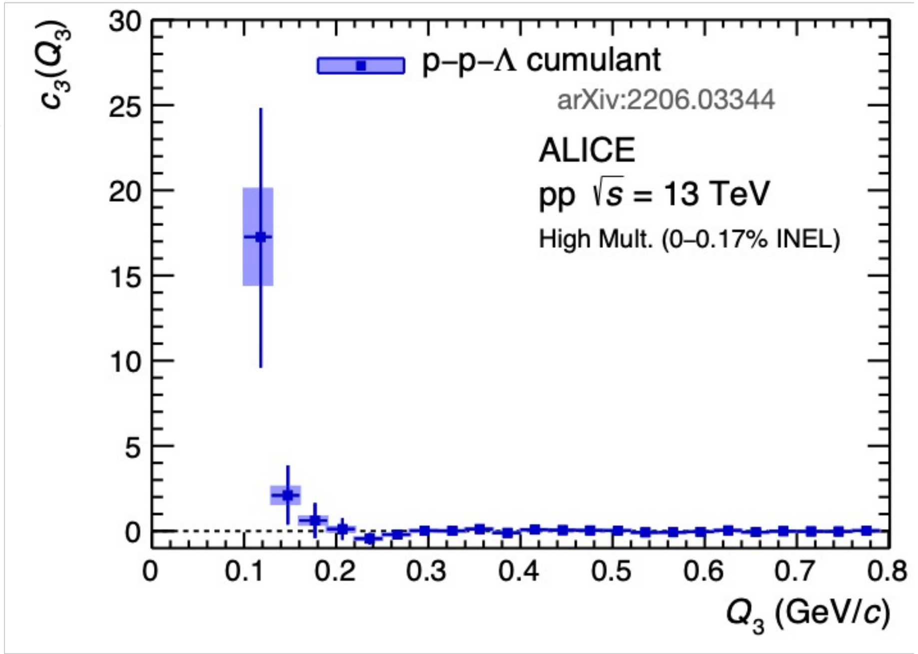
- Only two identical and charged particles
  → Main expected contribution from three-body strong interaction

- Relevant measurement for EoS of neutron stars

Statistical significance:

n_σ =0.8 for Q_3 < 0.4 GeV/c

In Run 3, two orders of magnitude gain in statistics expected!



Proton-deuteron correlation

- Point-like particle models anchored to scattering experiments

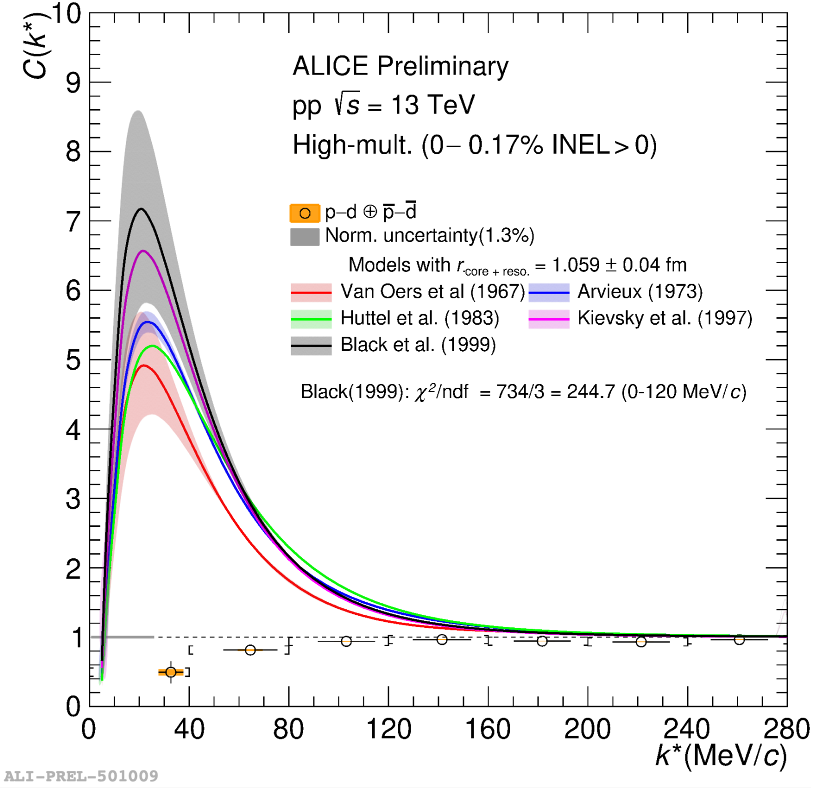
  W. T. H. Van Oers et al., NPA 561 (1967);
  J. Arvieux et al., NPA 221 (1973); E. Huttel et al., NPA 406 (1983);
  A. Kievsky et al., PLB 406 (1997); T. C. Black et al., PLB 471 (1999);

- Coulomb + strong interaction using the Lednický model

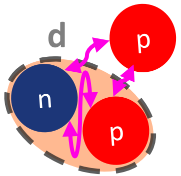
  Lednický, R. Phys. Part. Nuclei 40, 307–352 (2009)

- Only s-wave interaction
- Source radius evaluated using the hadron-hadron universal m_T scaling

Point-like particle description doesn't work for p-d



Proton-deuteron correlation

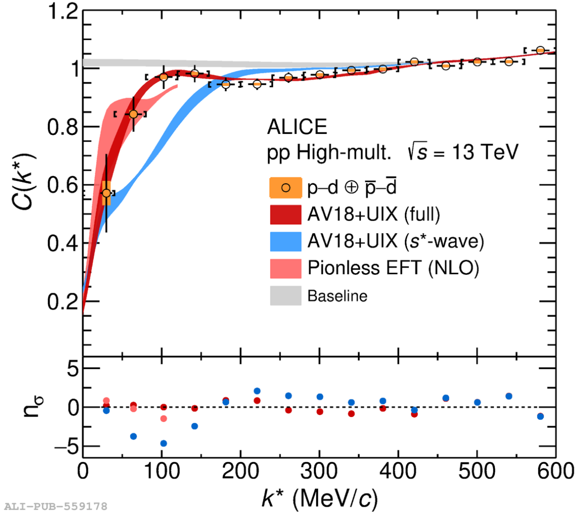


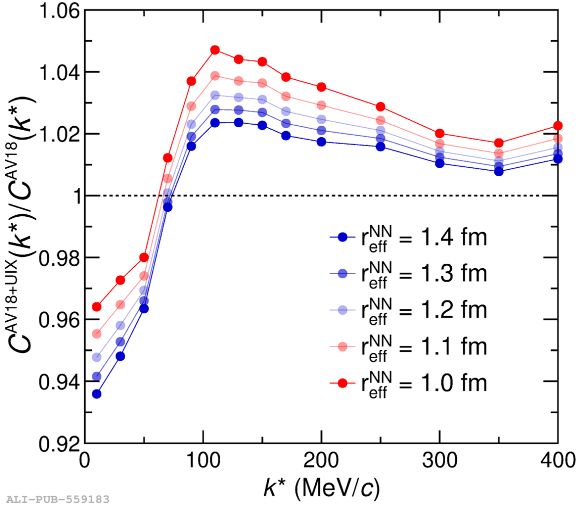
The measured p-d correlation function reflects the full three-nucleon dynamics:

Coulomb + strong interaction (NN and NNN) + Quantum Statistics

M. Viviani et al., arXiv:2306.02478 (2023)

ALICE Coll. arXiv:2308.16120 (2023)



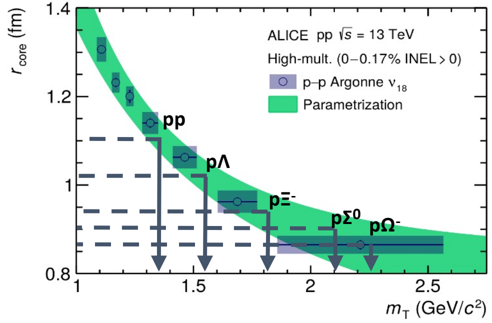


- ➢ Sensitivity to the short inter-particle distances
- ➢ Hadron-nuclei correlations at the LHC can be used to study many-body dynamics

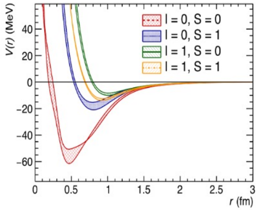
Summary

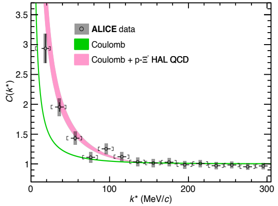
Femtoscopy in small systems

Universal source

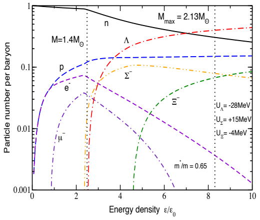


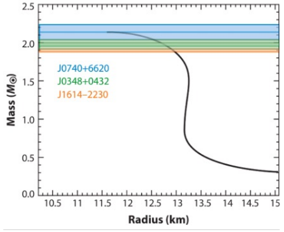
Test of hadron-hadron interactions from Lattice QCD



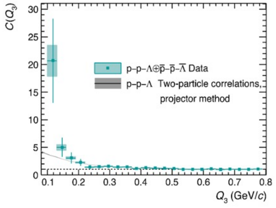


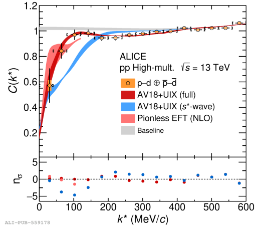
EoS for dense pure neutron matter containing hyperons can be improved

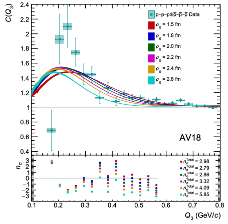




Three-body femtoscopy and hadron-nuclei correlations at the LHC can be used to study many-body dynamics



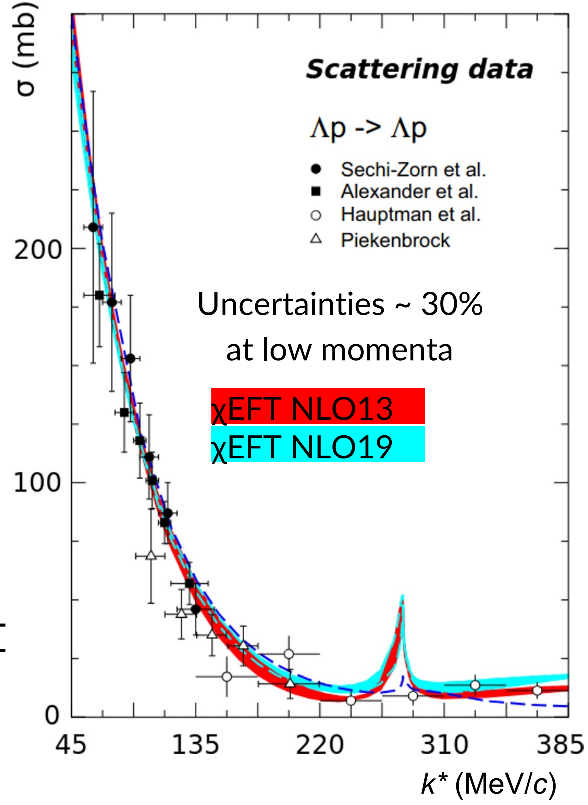


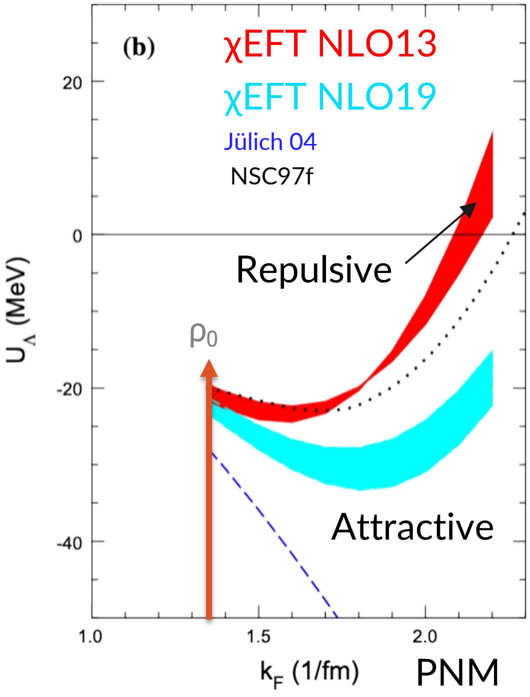


Backup

|S| = 1 sector: p–Λ interaction

- Low statistics and not available at low momenta
- ΛN-ΣN coupled system → two-body coupling to ΣN is not (yet) measured
- ΣN coupling strength relevant for EoS
  → Strongly affects the behaviour of Λ at finite density
  → Implications for ΛNN interactions
- NLO19 predicts weak coupling NΛ-NΣ
  → Attractive Λ interaction in neutron matter

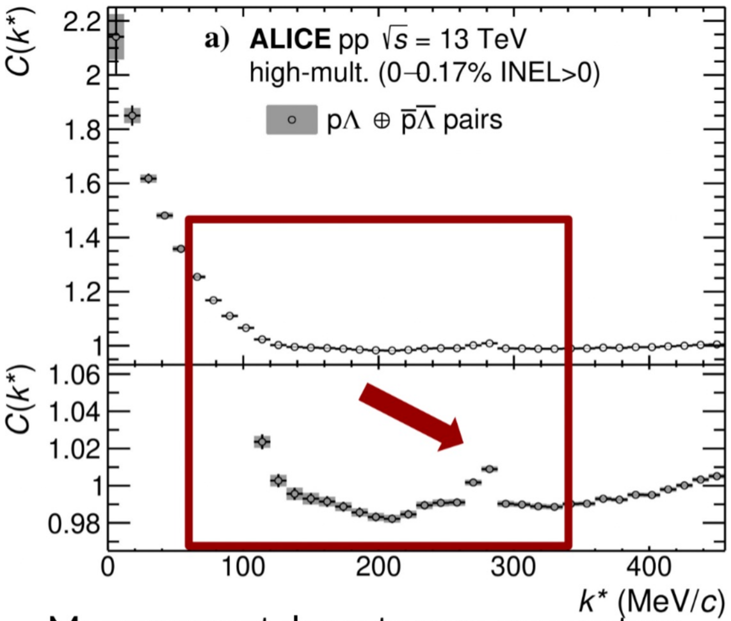




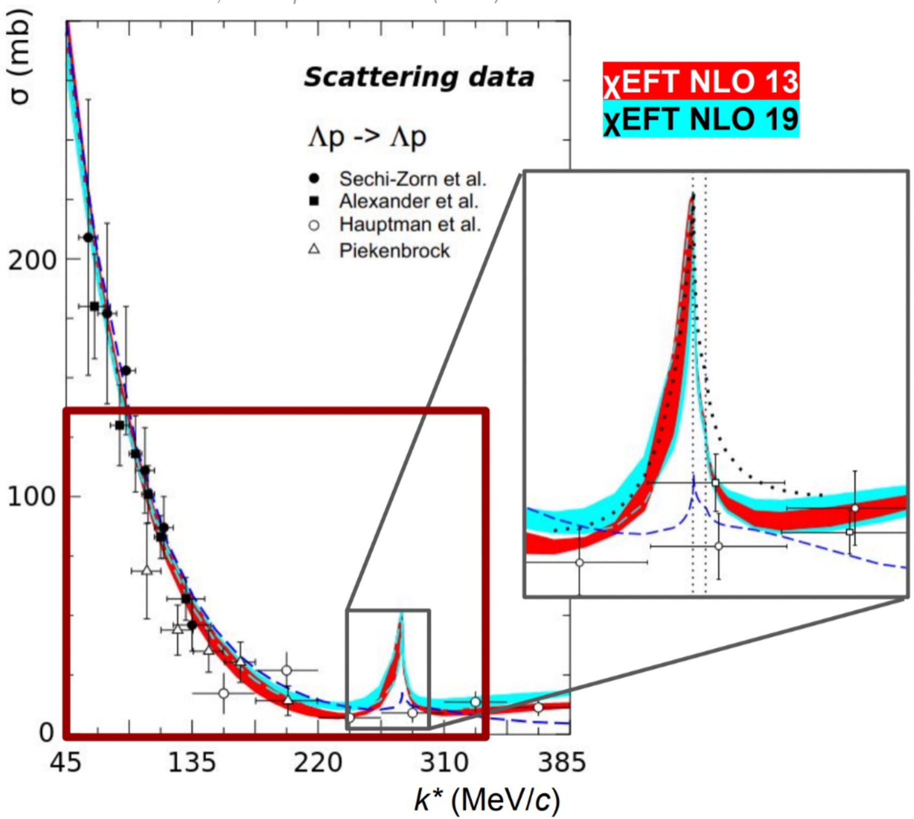
J.Haidenbauer, N.Kaiser et al. NPA 915 24 (2013)
J.Haidenbauer, U. Meiβner EPJA 56 (2020)

|S| = 1 sector: p–Λ interaction

ALICE Coll. PLB 833 (2022)



J.Haidenbauer, U. Meißner EPJA 56 (2020)



- Measurement down to zero momentum
- Factor 20 improved precision in data (<1%)
- First experimental evidence of ΣN cusp in 2-body channel

|S| = 1 sector: p–Λ interaction

Comparison with χEFT potentials

- Sensitivity to different ΣN coupling strength
- NLO19 favoured (n_σ = 3.2) → attractive interaction of Λ at large densities

ALICE Coll. PLB 833 (2022)