New experimental frontiers in the study of the hadronic interactions with ALICE at the LHC

Raffaele Del Grande[1,*]

[1] Physik Department E62, Technische Universität München, 85748 Garching, Germany

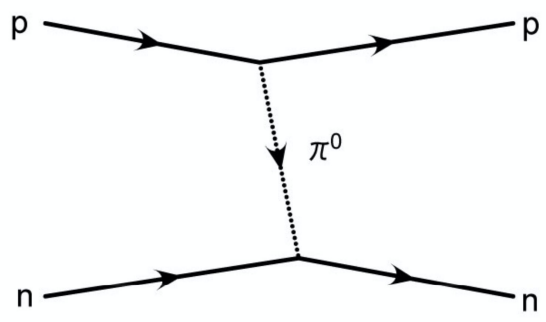
On behalf of the ALICE Collaboration

QNP2022 - The 9th International Conference on Quarks and Nuclear Physics

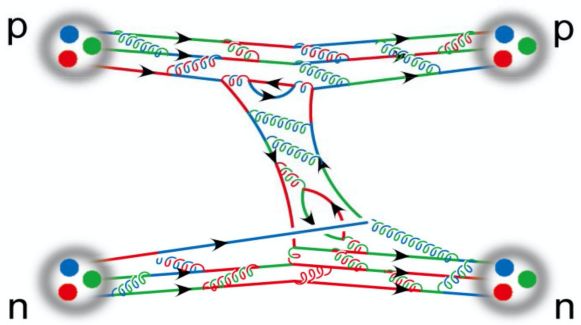
6 September 2022

***raffaele.del-grande@tum.de**

Residual strong interaction among hadrons



$$\mathcal{L}_{EFT}[\pi, N, \ldots; m_\pi, m_N, \ldots, C_i]$$



$$\mathcal{L}_{QCD}[q, \overline{q}, A; m_q, \alpha_s]$$

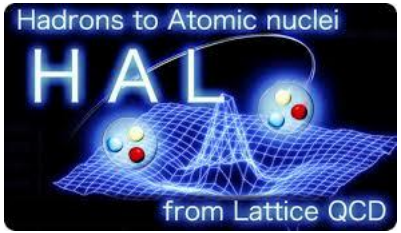
Non-perturbative region of QCD

- **Hadrons** as degrees of freedom
- **Effective Field Theories** (EFT) with low-energy coefficients **constrained by data**

Lattice QCD

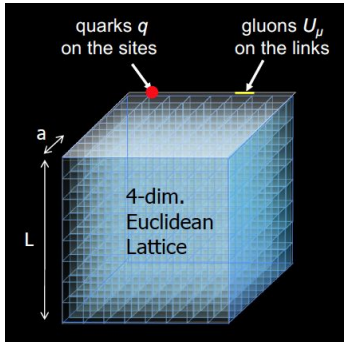
-Understanding of the interaction starting from **quarks and gluons**

Residual strong interaction from lattice



T. Hatsuda, K. Sasaki et al.

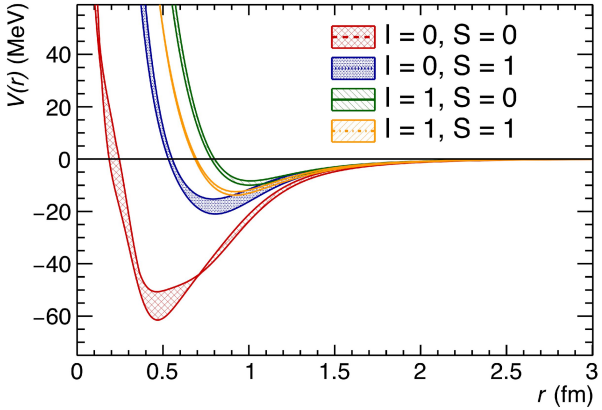
HAL QCD Coll. PLB 792 (2019)
HAL QCD Coll. NPA 998 (2020)
HAL QCD Coll. PRD 99 (2019)



a = 0.085 fm
L = 8.1 fm

$$m_\pi = 146\ \mathrm{MeV}/c^2$$
$$m_\mathrm{K} = 525\ \mathrm{MeV}/c^2$$

Local potentials for the nucleon-Ξ interactions



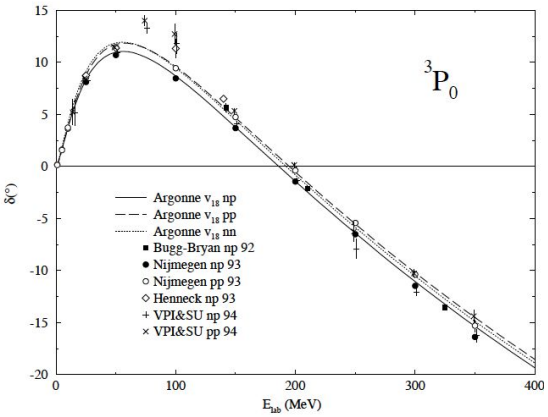
HAL QCD Coll. NPA 998 (2020)

S = 0	S = -1	S = -2	S = -3	S = -4	S = -5	S = -6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ, ΛΩ, ΣΩ	ΞΩ	ΩΩ

Better S/N of LQCD

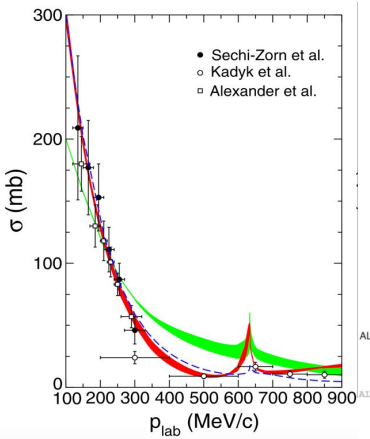
Experimental data for two-body interactions

N–N → N–N



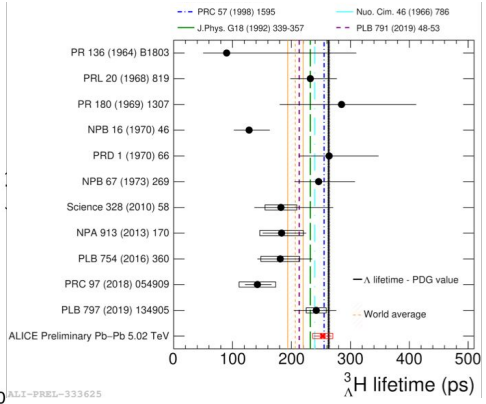
R. B. Wiringa et al. PRC 51 (1995)

p–Λ → p–Λ

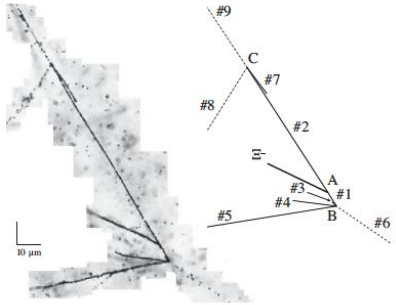


LO from H. Polinder et al. NPA 779 (2006)
NLO from J. Haidenbauer et al. NPA 915 (2013)

Hypertriton



Ξ hypernucleus



J-PARC E07 Coll. PRL 126 (2021)

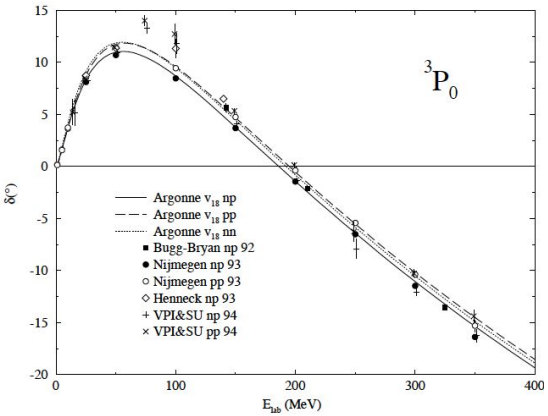
S = 0	S = -1	S = -2	S = -3	S = -4	S = -5	S = -6
NN	NΛ, NΣ	ΛΛ, ΛΣ, ΣΣ, NΞ	ΛΞ, ΣΞ, NΩ	ΞΞ, ΛΩ, ΣΩ	ΞΩ	ΩΩ

Better S/N of LQCD

Experimental data

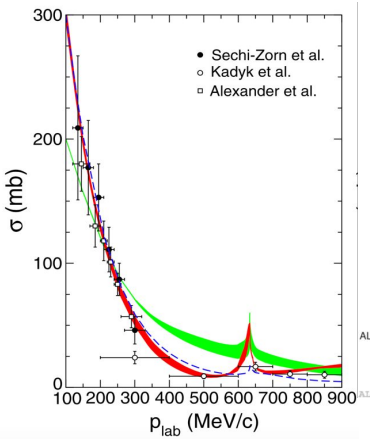
Experimental data for two-body interactions

N–N → N–N



R. B. Wiringa et al. PRC 51 (1995)

p–Λ → p–Λ



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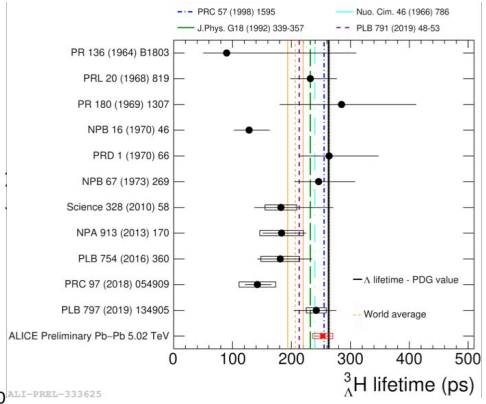
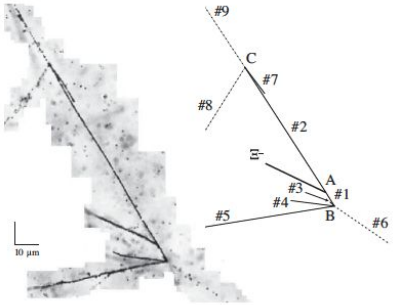
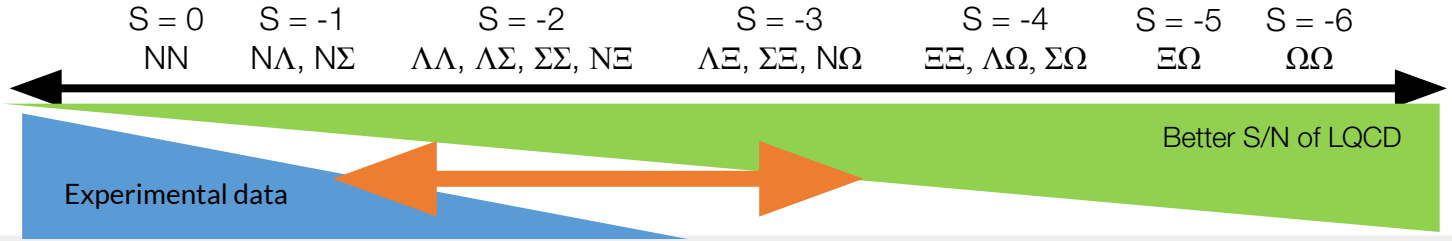


Ξ hypernucleus



J-PARC E07 Coll. PRL 126 (2021)



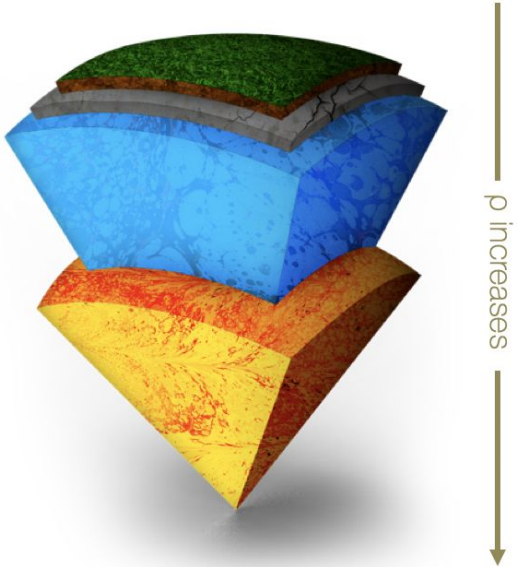
Impact on the Equation of State of neutron stars

Neutron stars

Dimensions
R ~ 10 – 15 km
M ~ 1.5 – 2.2 $M_\odot$

Outer Crust
Ions, electron gas, Neutrons

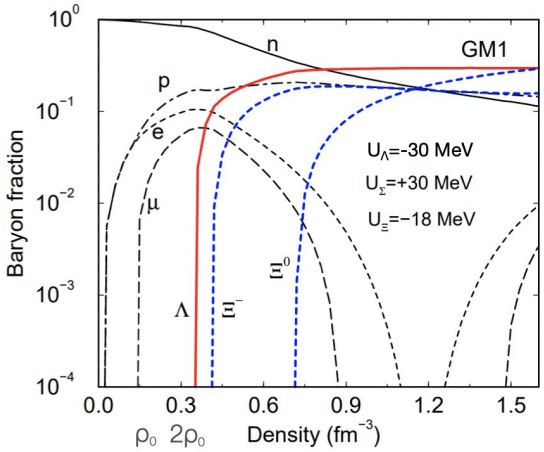
Inner Core
Neutrons?
Protons?
Hyperons?
Kaon condensate?
Quark Matter?



Neutron stars are very dense, compact objects

What is the Equation of State?
What are the constituents to consider?
How do they interact?

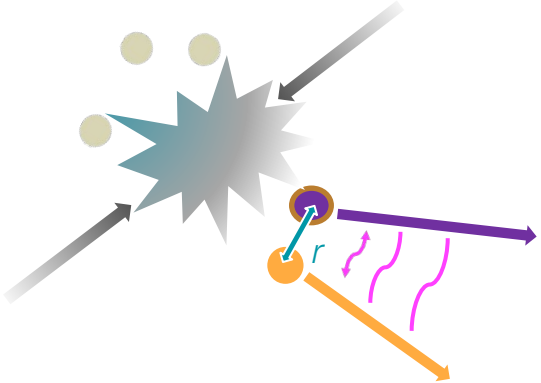
J. Schaffner-Bielich NPA 835 (2010) 279



Investigating hadronic interactions at LHC

ALICE at the LHC

Hadron-hadron strong interactions

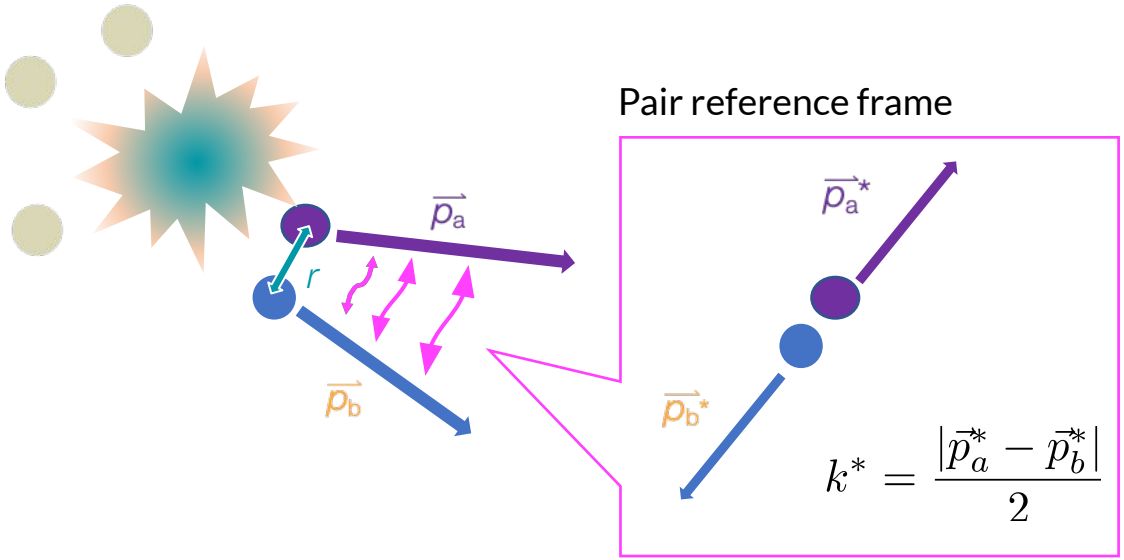


Femtoscopy technique

Two-particle correlation function

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

Femtoscopy technique



Correlation function:

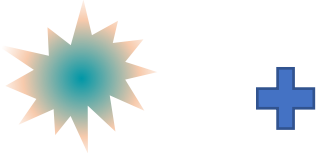
Two-particle wave function

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

Emission source

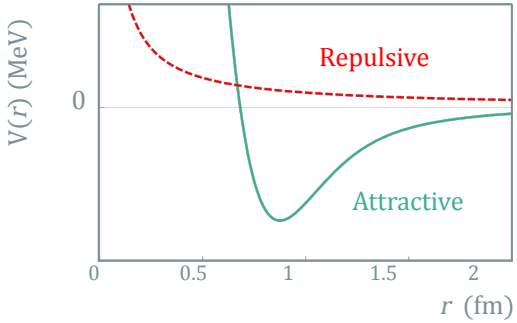
Femtoscopy technique

Source parameterization

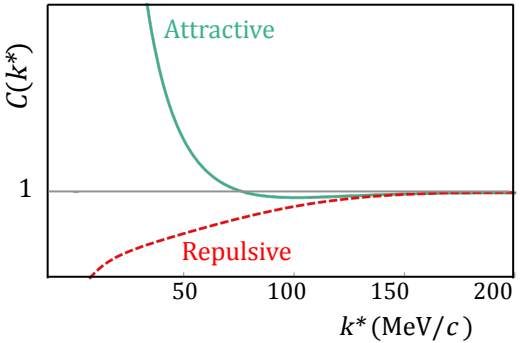


Gaussian source

Interacting potential



Correlation function



Schrödinger equation

CATS (Correlation Analysis Tool using the Schrödinger equation)

D. Mihaylov et al. EPJC 78 (2018)

Correlation function:

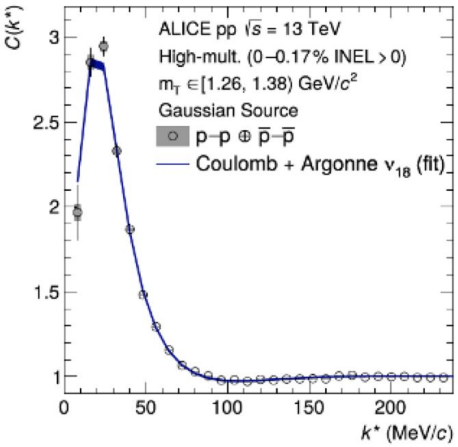
Two-particle wave function

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

Emission source

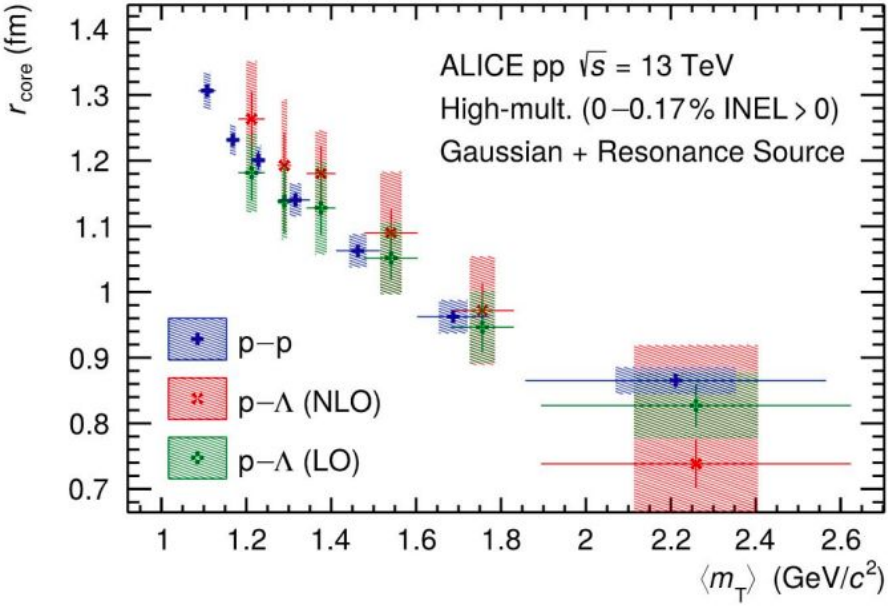
>1 if the interaction is attractive
= 1 if there is no interaction
<1 if the interaction is repulsive

Source model



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

pp Correlation: AV18 + Coulomb potentials used to calculate $\psi(\vec{k}^*, \vec{r})$

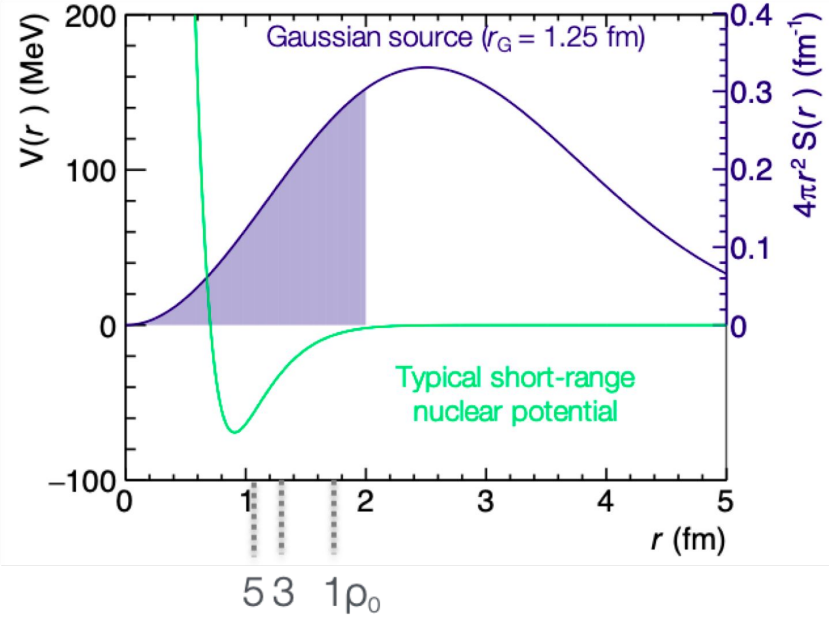


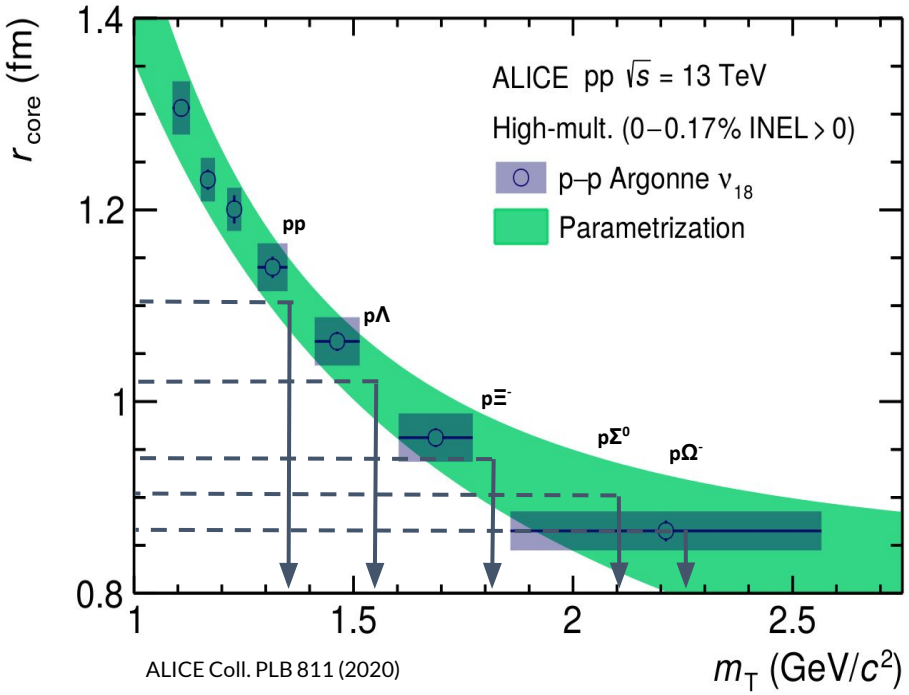
ALICE Coll. PLB 811 (2020)

One universal source for all hadrons with strong resonance decays considered for each pair of interest

Source model

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



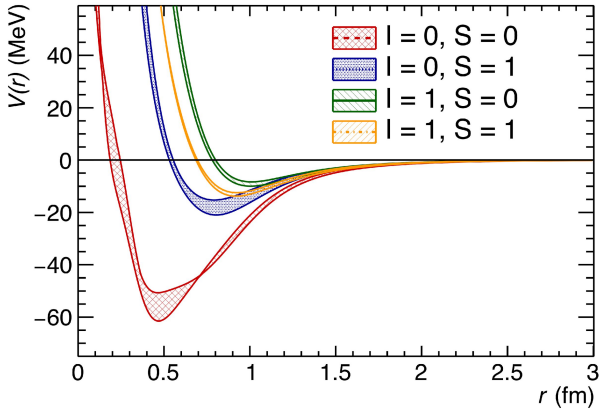


ALICE Coll. PLB 811 (2020)

|S|=2 sector: pΞ⁻ interaction and first test of LQCD

Lattice QCD potentials from HAL QCD collaboration available

Local potentials for the nucleon-Ξ interactions



HAL QCD Coll. NPA 998 (2020)

r_{eff} = 0.85 fm

$$C(k^*) = \int S(r)\,|\psi(k^*,r)|\,d^3r$$

$$\mathcal{H}\cdot\psi(k^*,r) = E\cdot\psi(k^*,r)$$

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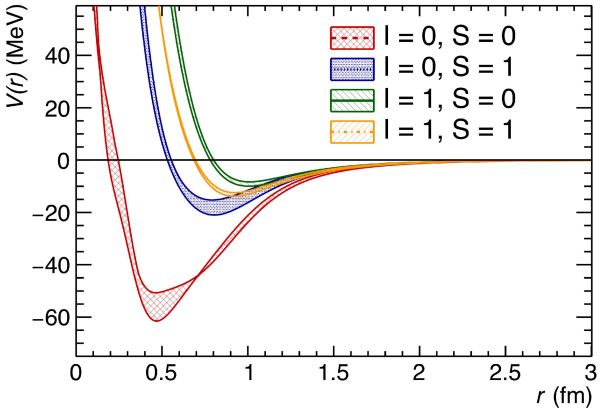
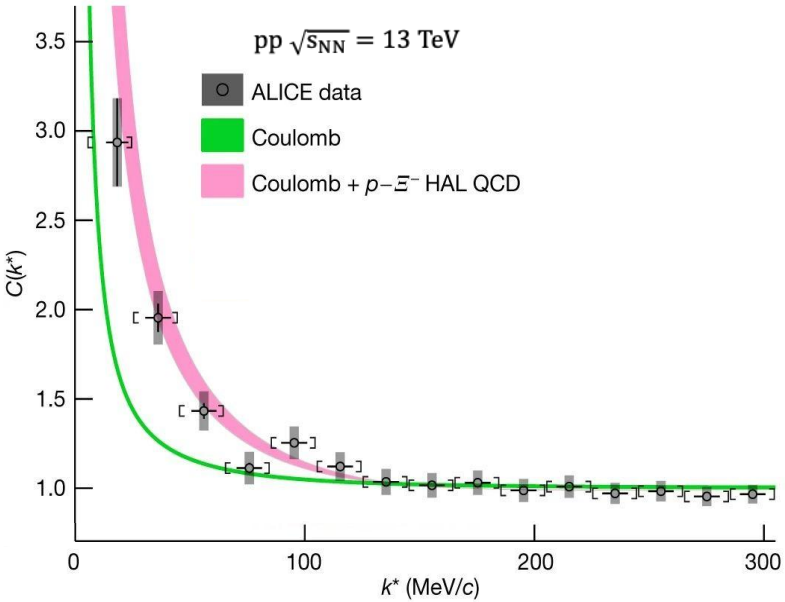
Lattice QCD potentials from HAL QCD collaboration available

Local potentials for the nucleon-Ξ interactions



HAL QCD Coll. NPA 998 (2020)

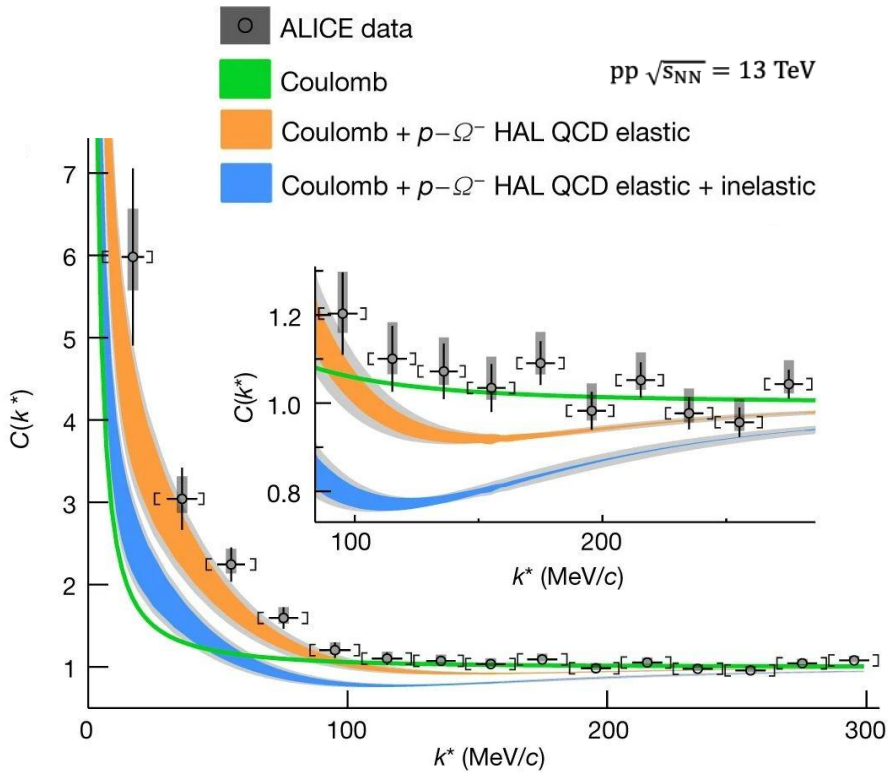
ALICE Coll. Nature 588 232–238 (2020)



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

|S|=3: p–Ω⁻ correlation function in pp at 13 TeV

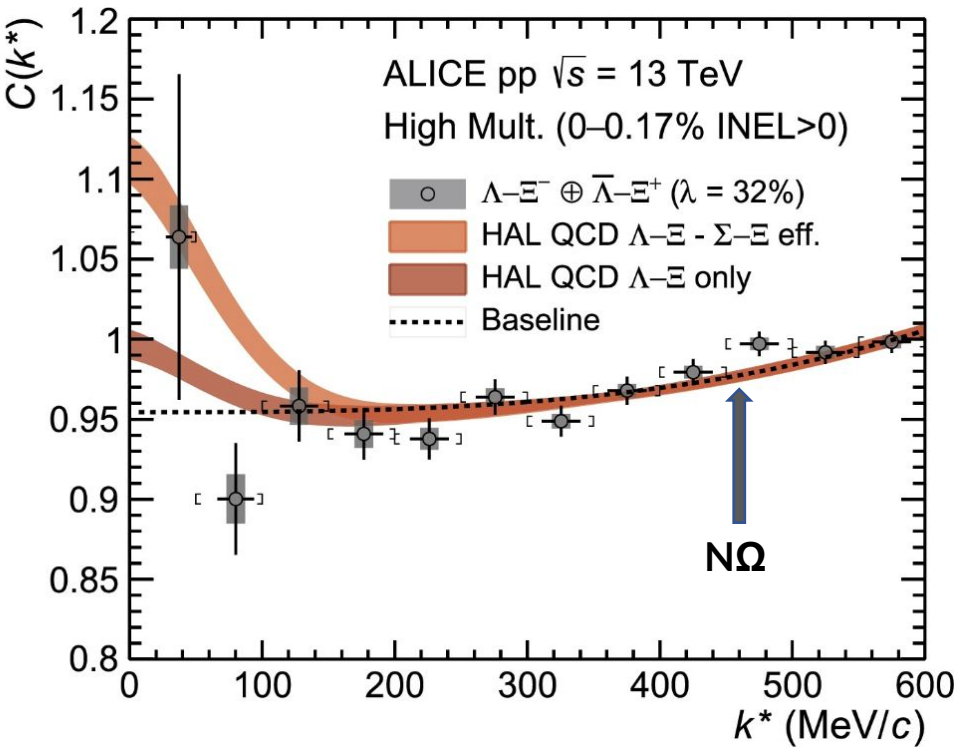
ALICE Coll. Nature 588 232–238 (2020)



- Enhancement above Coulomb
  → Observation of the strong interaction
- Attraction in $^5S_2$ results in the prediction of a bound state (Binding Energy = 1.54 MeV)
- Missing potential of the $^3S_1$ channel
  → Test of two cases:
  - Inelastic channels dominated by absorption
  - Neglecting inelastic channels
- Data more precise than lattice calculations
- So far, no indication of a bound state

|S|=3: Λ-Ξ⁻ interaction with femtoscopy

ALICE Coll. arXiv:2204.10258, Accepted by PLB

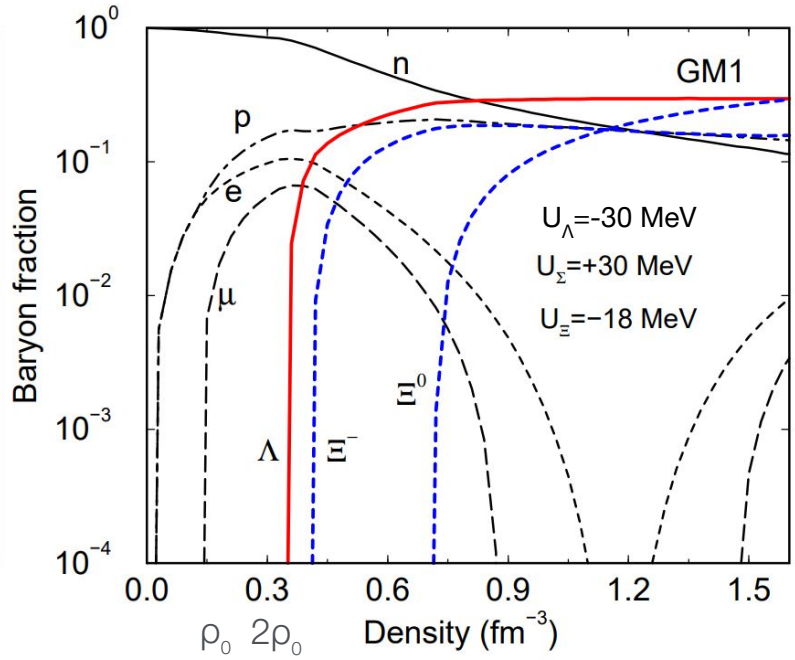


- Unknown contribution from coupled channels in Lattice QCD calculations
  → Coupling ΛΞ−ΣΞ sizable in HAL QCD calculation
  → No sensitivity yet
  ("No coupling" 0.64 nσ VS "Coupling" 1.43 nσ)

- No NΩ cusp visible
  → Hint to negligible NΩ-ΛΞ coupling

Hyperon appearance in neutron stars?

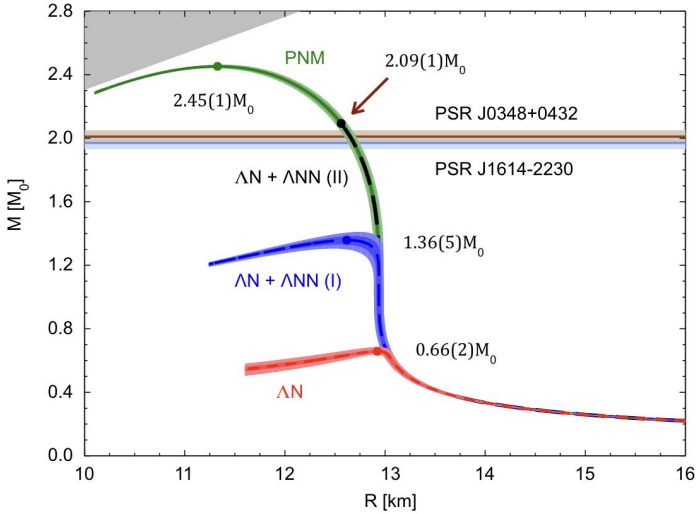
U = single-particle potential



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

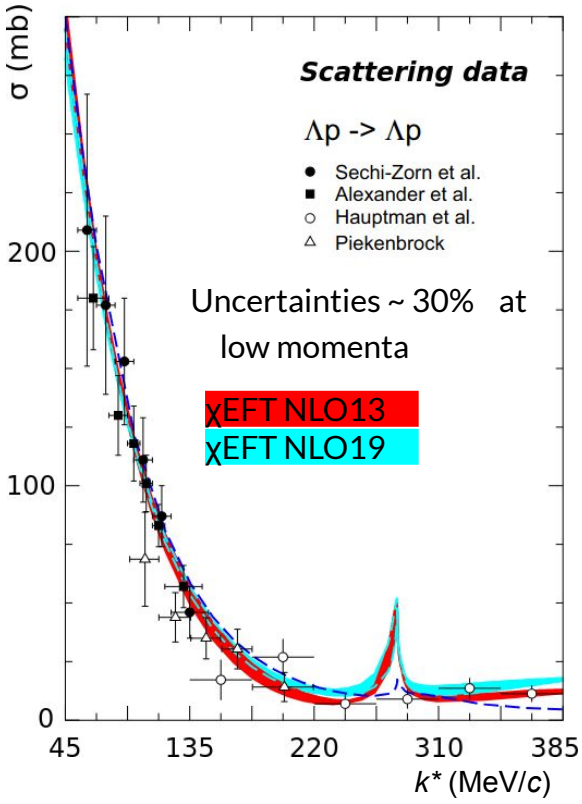
- Hyperons might appear in neutron stars since it is energetically favourable
- But the resulting equation of state might be too soft to explain heavy neutron stars

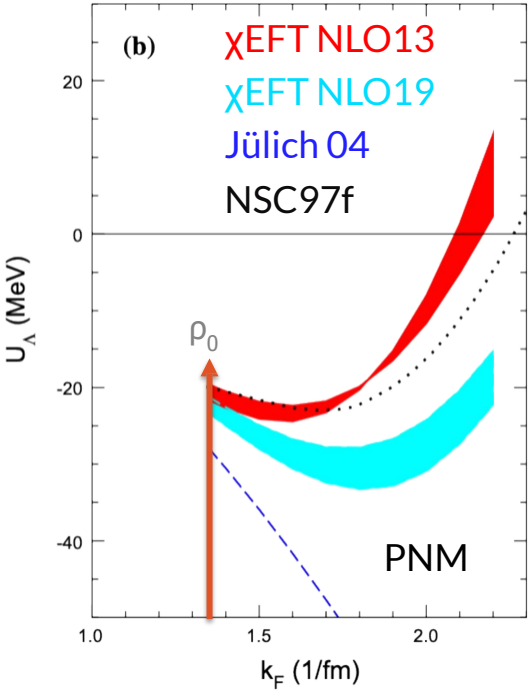
Adapted from D. Lonardoni et al. PRL 114 092301 (2015)



|S| = 1: Λ-p 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

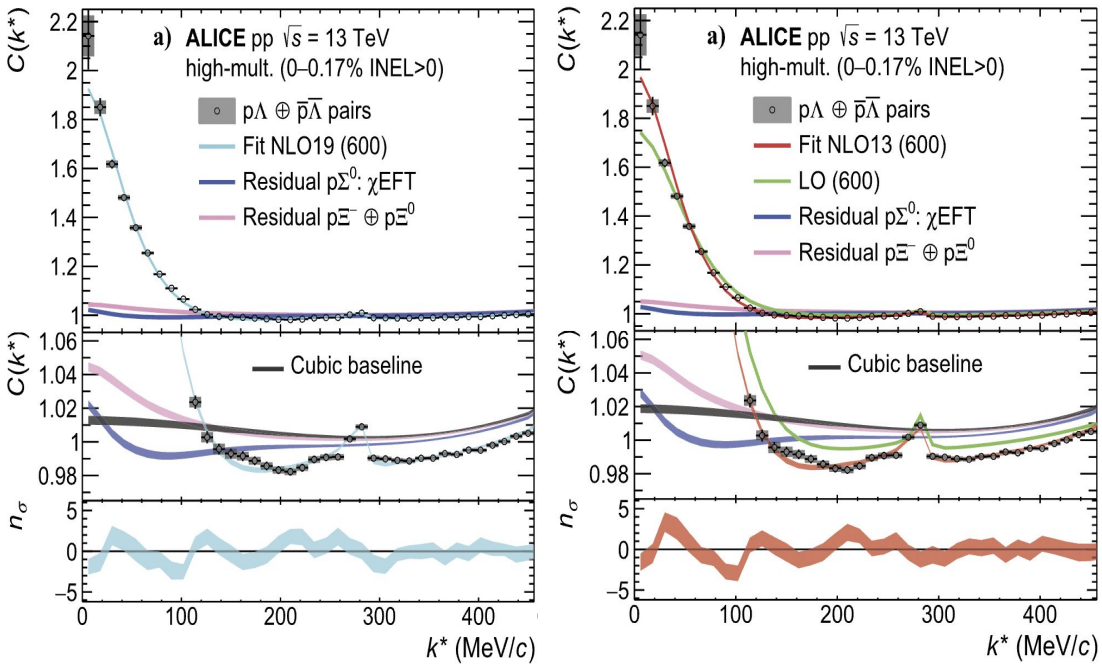




J.Haidenbauer, N.Kaiser et al. NPA 915 24 (2013)
J.Haidenbauer, U. Meißner EPJA 56 (2020)

|S| = 1: Λ-p interaction

- Comparison with χEFT potentials
  - Sensitivity to different ΣN coupling strength
  - NLO19 favoured (n_σ = 3.7) → attractive interaction of Λ at large densities
  - Larger ΛNN repulsion required to stiffen the Equation of State at large densities

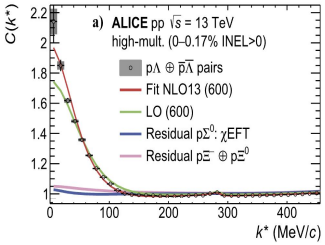


ALICE Coll. PLB 833 137272 (2022)

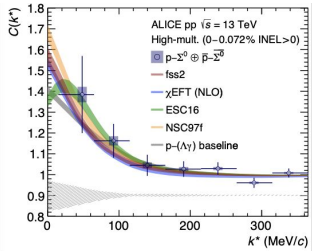
An example of Equation of State for neutron stars

Correlation = two-body interaction

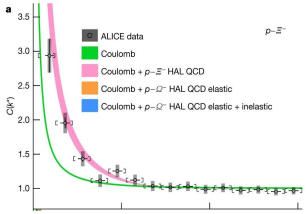
pΛ



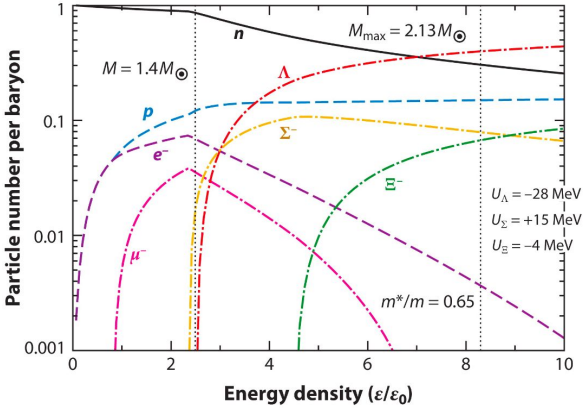
pΣ



pΞ

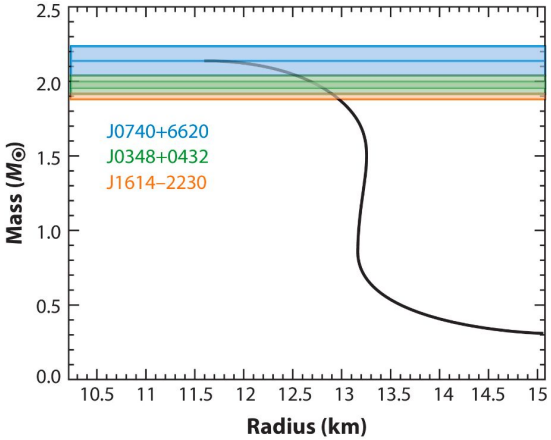


Single-particle potentials = Equation of State



Courtesy J. Schaffner-Bielich 2020

Mass-Radius diagram for hyperon stars



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

What about the three-body strong interaction?

p-p-p and p-p-Λ correlation functions

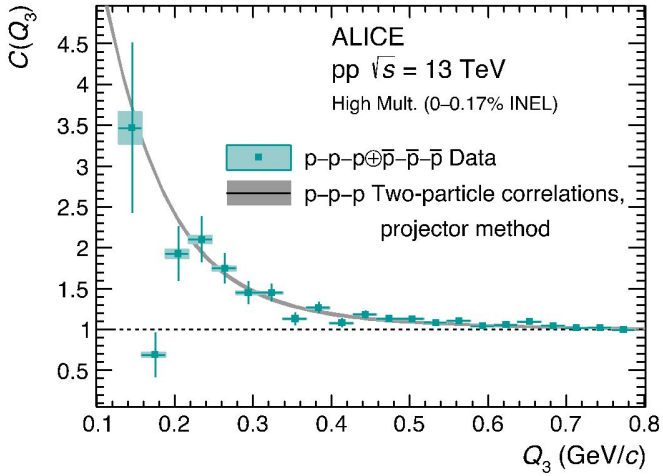
$$C(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3) \equiv \frac{P(\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)}{P(\mathbf{p}_1) \cdot P(\mathbf{p}_2) \cdot P(\mathbf{p}_3)} = = \mathcal{N} \cdot \frac{N_{\text{same}}(Q_3)}{N_{\text{mixed}}(Q_3)}$$

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

$$q_{ij}^{\mu} = \left(p_i - p_j\right)^{\mu} - \frac{\left(p_i - p_j\right) \cdot P_{ij}}{P_{ij}^2} P_{ij}^{\mu} \qquad P_{ij} \equiv p_i + p_j$$

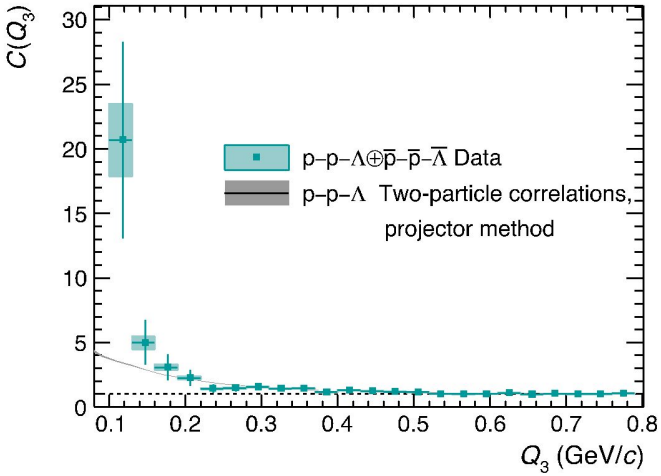
p-p-p correlation function

ALICE Coll. arXiv:2206.03344



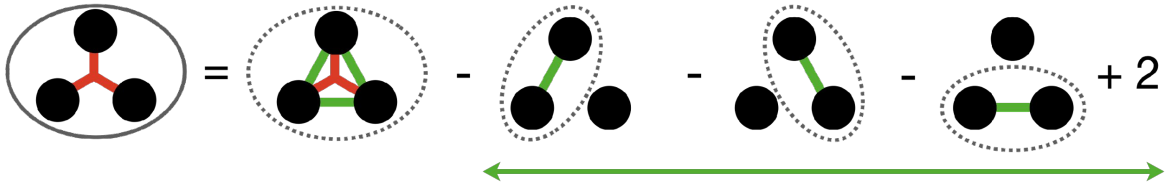
p-p-Λ correlation function

ALICE Coll. arXiv:2206.03344



Cumulants

Genuine three-particle correlations isolated using the Kubo's cumulant expansion method:
R. Kubo, J. Phys. Soc. Jpn. 177 (1962)



Genuine three-body correlations (cumulant)

Measured three-body correlation

Two-body correlations

In terms of correlation functions:

$$c_3(Q_3) = C(Q_3) - \boxed{C_{12}(Q_3) - C_{23}(Q_3) - C_{31}(Q_3) + 2}$$

Projector method

Event-mixing method

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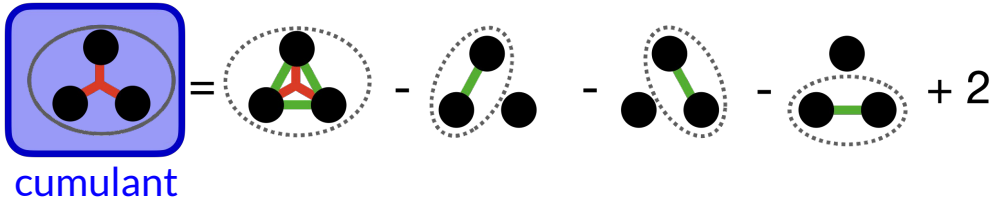
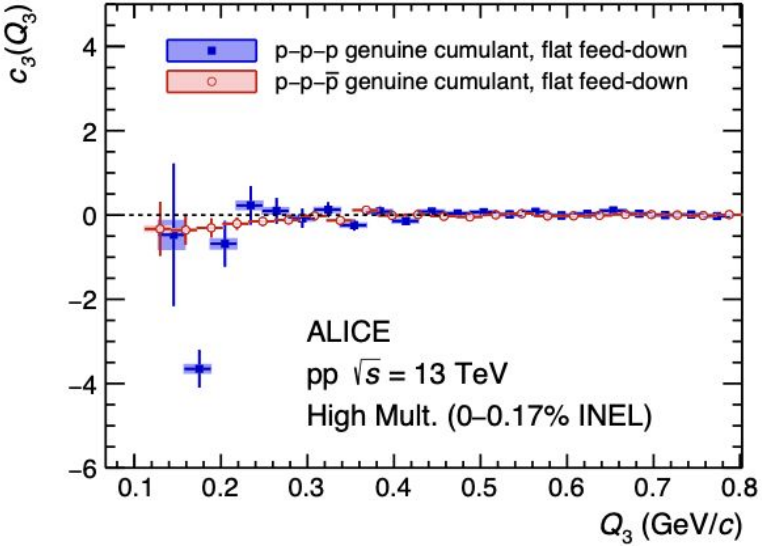
p-p-p cumulant



ALICE Coll. arXiv:2206.03344



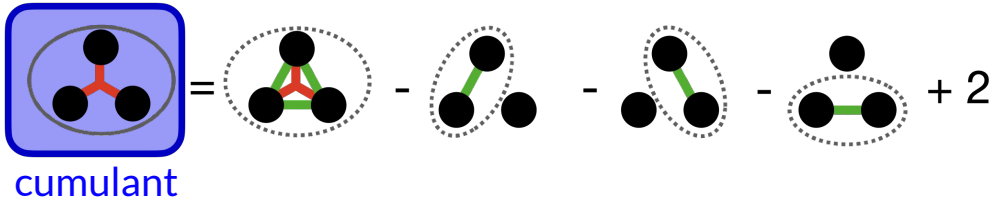
Statistical significance
→ n_σ = 6.7 for Q_3 < 0.4 GeV/c

Conclusion
→ Evidence of a genuine three-body effect in the p-p-p system at the LHC

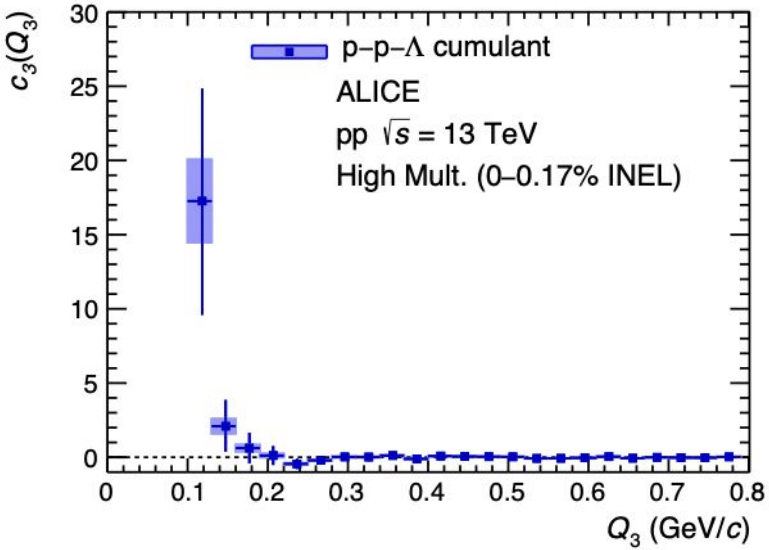
Possible interpretations
→ Pauli blocking at the three-particle level
→ Long-range Coulomb interaction effects
→ Three-body strong interaction

Test with mixed charge particles, cumulant negligible

p-p-Λ cumulant



ALICE Coll. arXiv:2206.03344



Statistical significance
→ n_σ = 0.8 for Q_3< 0.4 GeV/*c*

Conclusion
→ No significant deviation from the null hypothesis

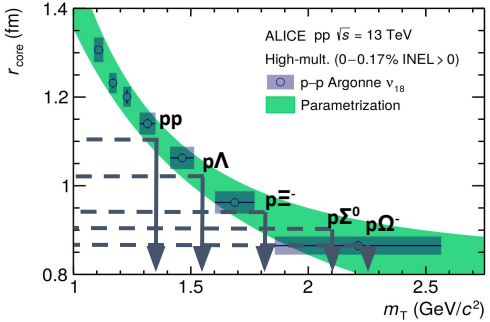
A factor 500 in statistics from the Run 3 data taking

→ Non-zero cumulant can be directly linked to the three-body strong interaction
→ Important measurement for neutron stars

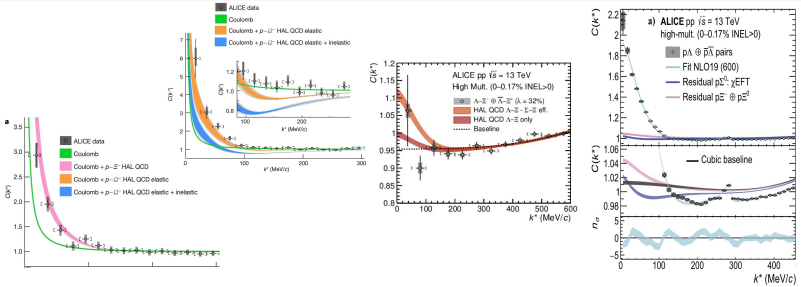
Summary

Femtoscopy in small systems

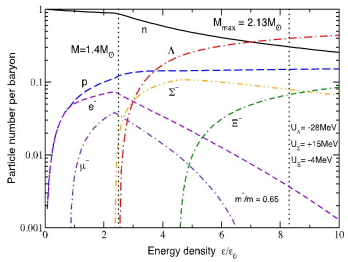
Universal source

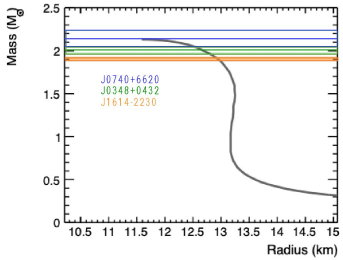


Test of hadron-hadron interactions from EFTs and Lattice QCD



Equation of State for dense pure neutron matter containing hyperons can be improved





High-statistics measurements of three-particle correlations are at horizon