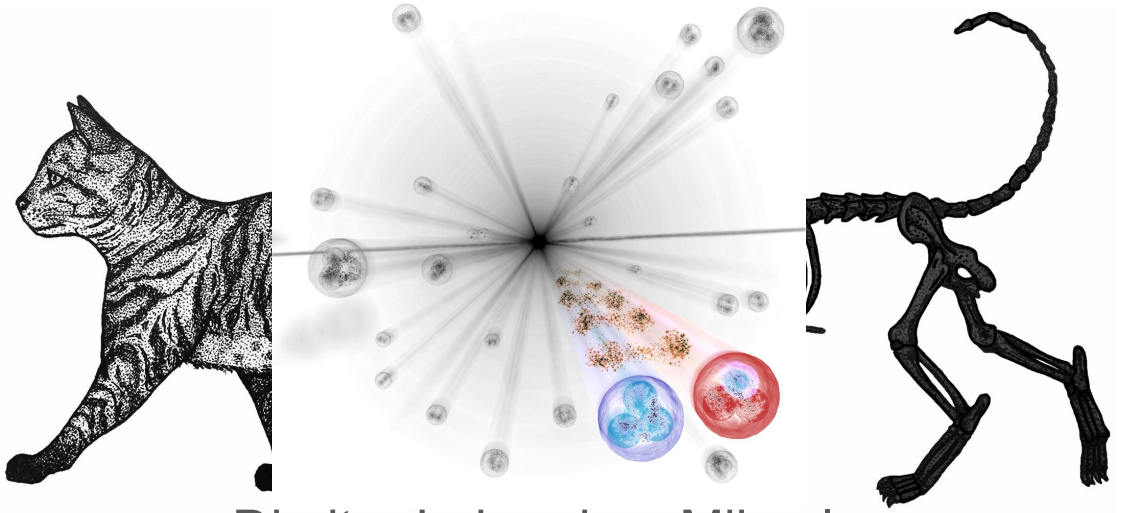
Precision QCD measurements from ALICE

using correlation techniques



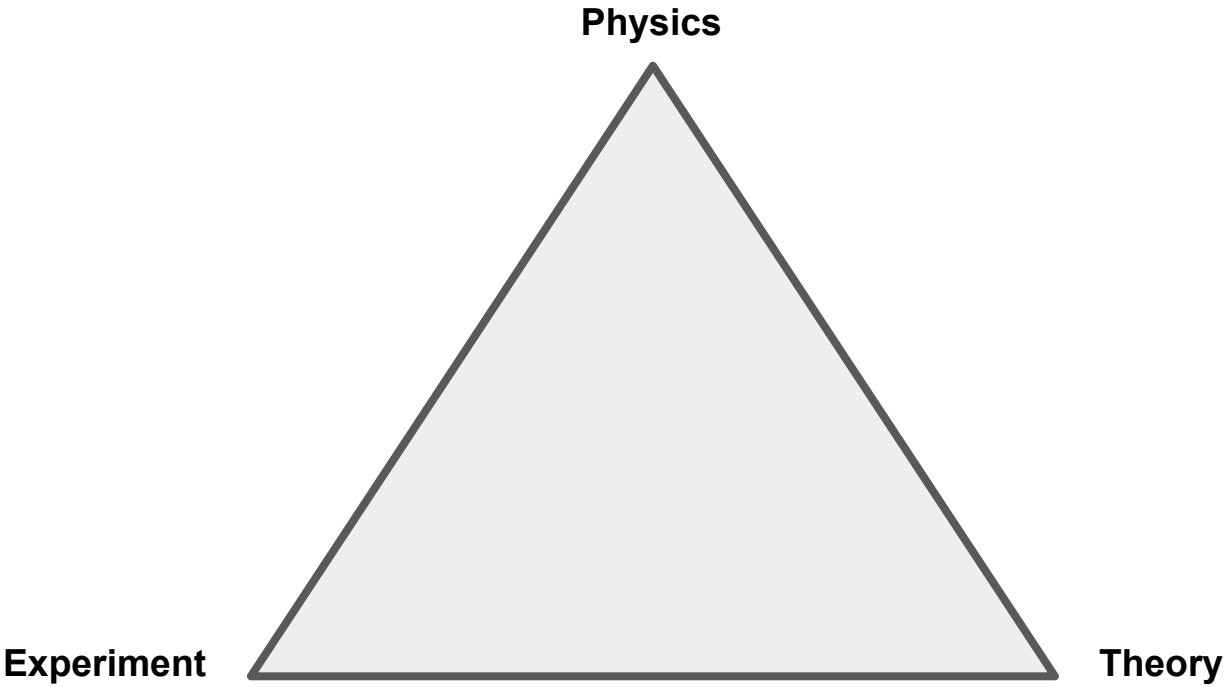
Dimitar Lubomirov Mihaylov

on behalf of the ALICE collaboration

LHCP 2021, 10th June

Study of hadron-hadron interaction

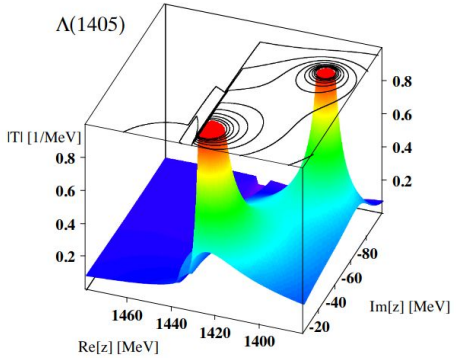
Overview



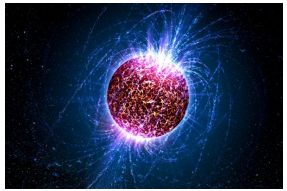
Study of hadron-hadron interaction

Physics

T.Hyodo et al. Prog.Part.Nucl.Phys. 67, 2012



- *E.g. Nature of Λ(1405)*



- *Large densities*
- *Three-body forces*
- *Neutron stars*

Physics

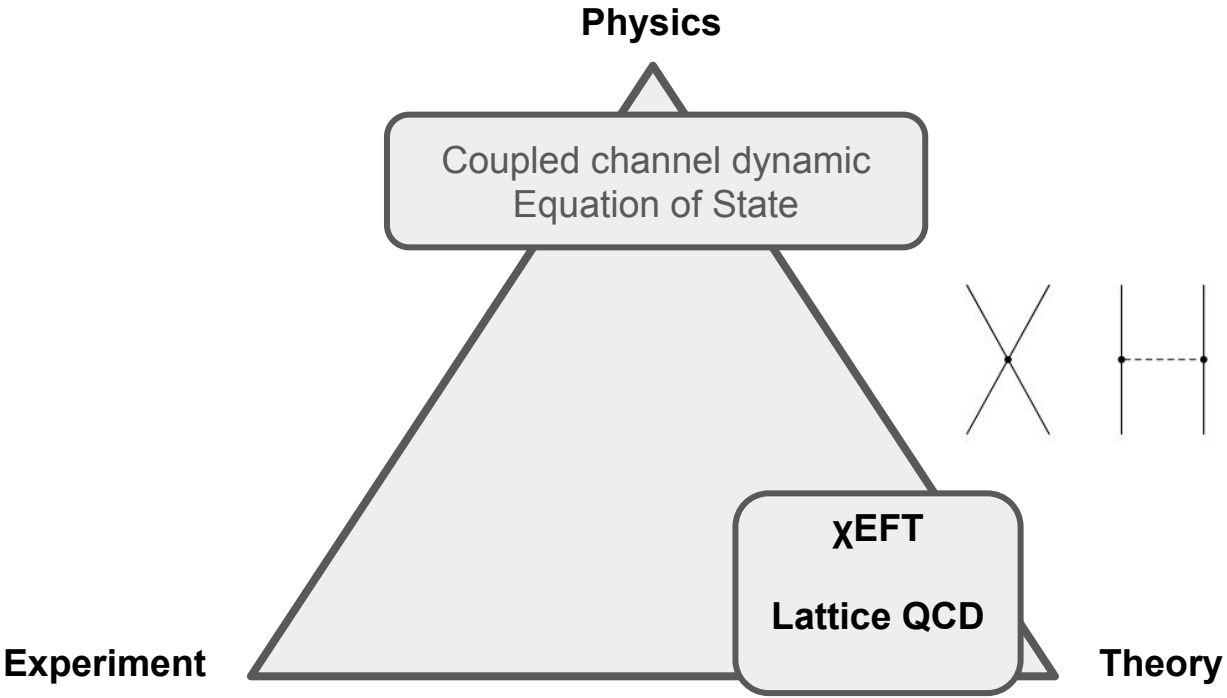
Coupled channel dynamic Equation of State

Experiment

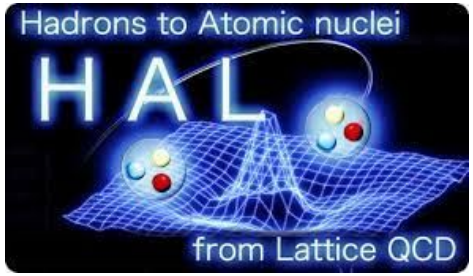
Theory

Study of hadron-hadron interaction

Theory



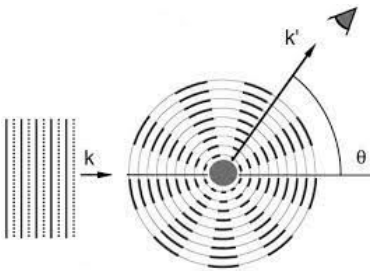
J. Haidenbauer et al.
Nucl. Phys. A, 915:24–58, 2013

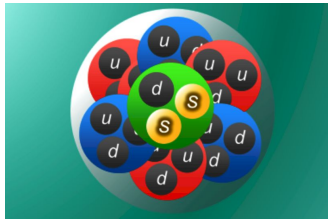


HAL QCD Collaboration,
PTEP 2012 01A105

Study of hadron-hadron interaction

Scattering and hypernuclei experiments





Experiment

Physics

Coupled channel dynamic
Equation of State

Scattering exp.

Hypernuclei

Correlations

χEFT

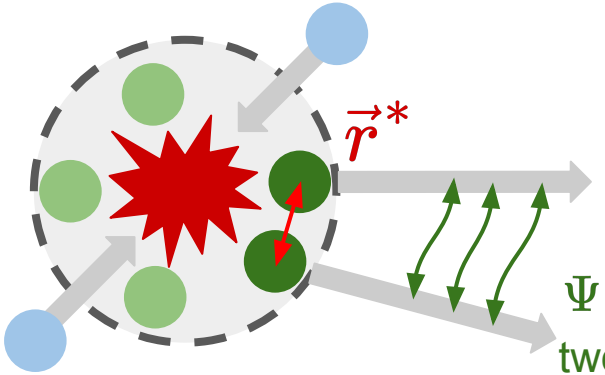
Lattice QCD

Theory

- Two/three body interaction
- Limited precision at low energies
- Not directly sensitive to coupled channels
- Sufficient data for S=-1 (Λ)
  O. Hashimoto, H. Tamura, Prog. Part. Nucl. Phys., 57:564–653, 2006
- Very little data for S=-2 (ΛΛ,Ξ)
  Nagara and Kiso events:
  H. Takahashi et al. Phys. Rev. Lett. 87, 212502
  K. Nakazawa et al. PTEP 2015 (2015) 3, 033D02
- Lattice provides sufficient precision only for |S|>=2

Two-particle momentum correlations

Overview



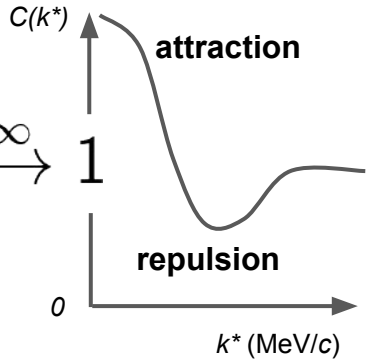
Measure the correlation function *C(k*)*

$\Psi(\vec{k}^*, \vec{r}^*)$

two-particle wave function

$$C(k^*) = \int S(r^*) \left| \Psi(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^* \xrightarrow{k^* \to \infty} 1$$

Relative distance and ½ relative momentum evaluated in the pair rest frame

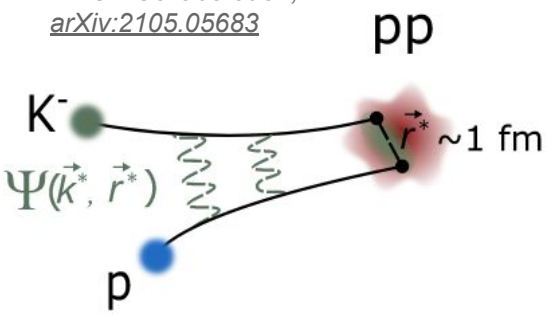


- Measure *C(k*)*, fix *S(r*)*, study the interaction. *ALICE Collaboration, Phys. Lett. B 811 135849, 2020*

Collision systems and coupled channels

Example for the K^-p *system*

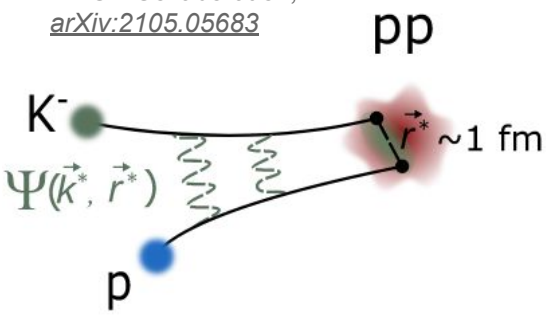
ALICE Collaboration,
arXiv:2105.05683



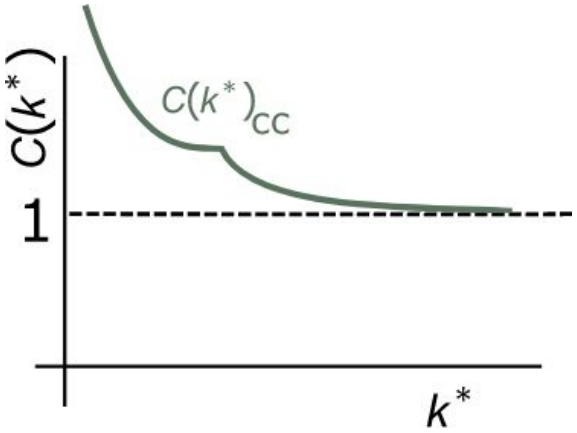
Collision systems and coupled channels

Example for the K^-p *system*

ALICE Collaboration,
arXiv:2105.05683



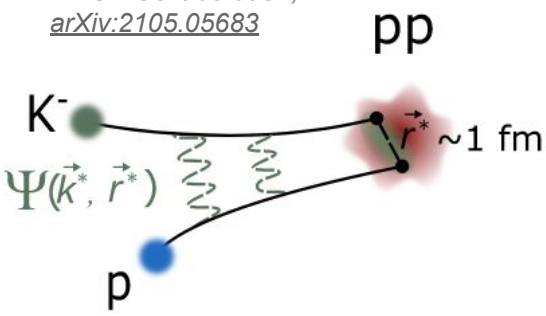
$$C(k^*)_{CC} = C(k^*) + \sum_j \omega_j \int S_j(r^*) \left| \Psi_j(\vec{k}^*, \vec{r}^*) \right|^2 d^3 r^*$$



Collision systems and coupled channels

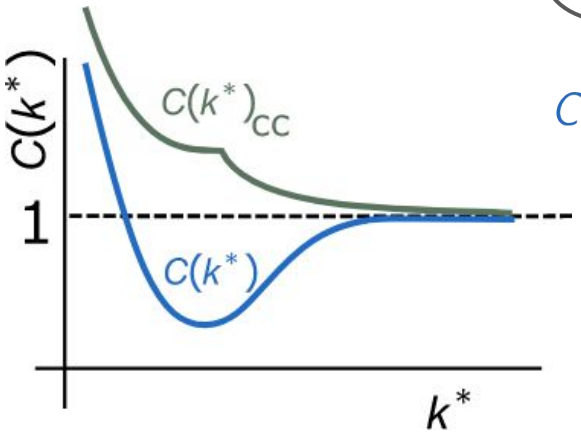
Example for the K^-p *system*

ALICE Collaboration,
arXiv:2105.05683



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

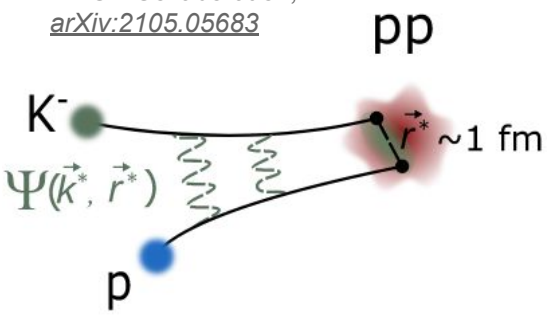
$$C(k^*) = \int S(r^*) \left|\Psi(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^*$$

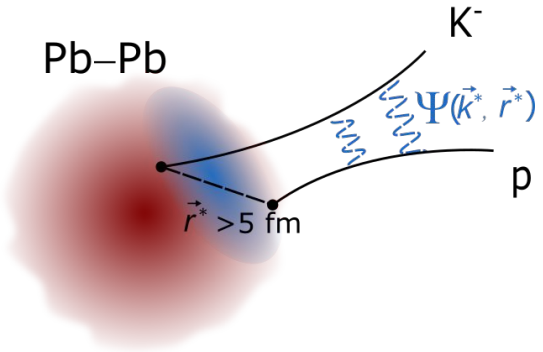


Collision systems and coupled channels

Example for the K^-p system

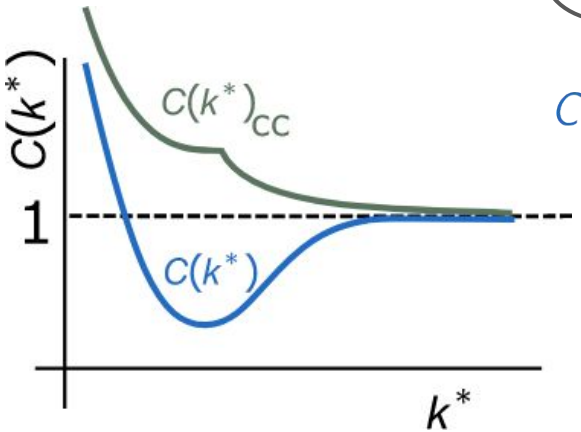
ALICE Collaboration, arXiv:2105.05683





$$C(k^*)_{CC} = C(k^*) + \cancel{\sum_j \omega_j \int S_j(r^*) \left|\Psi_j(\vec{k}^*, \vec{r}^*)\right|^2 d^3r^*}$$

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

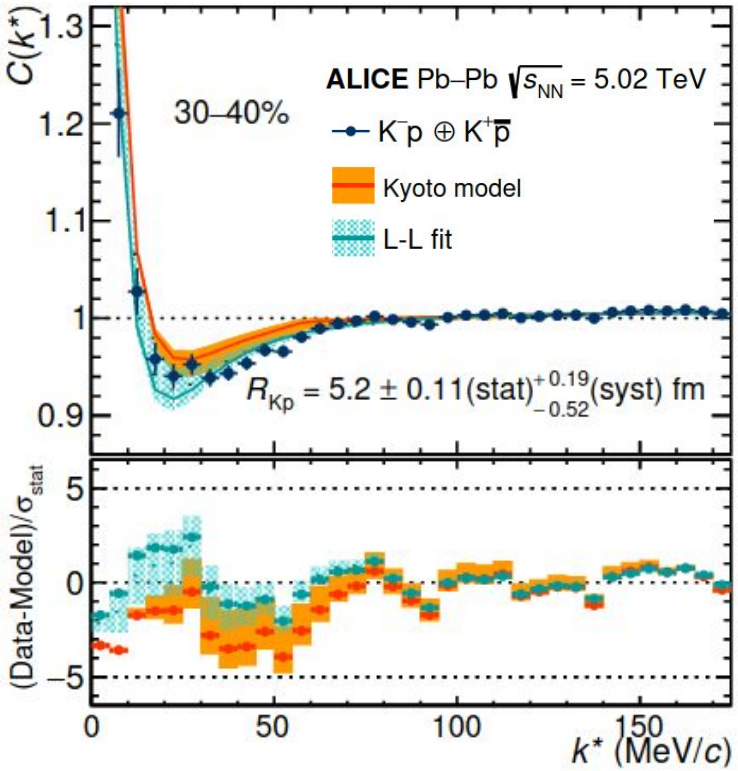


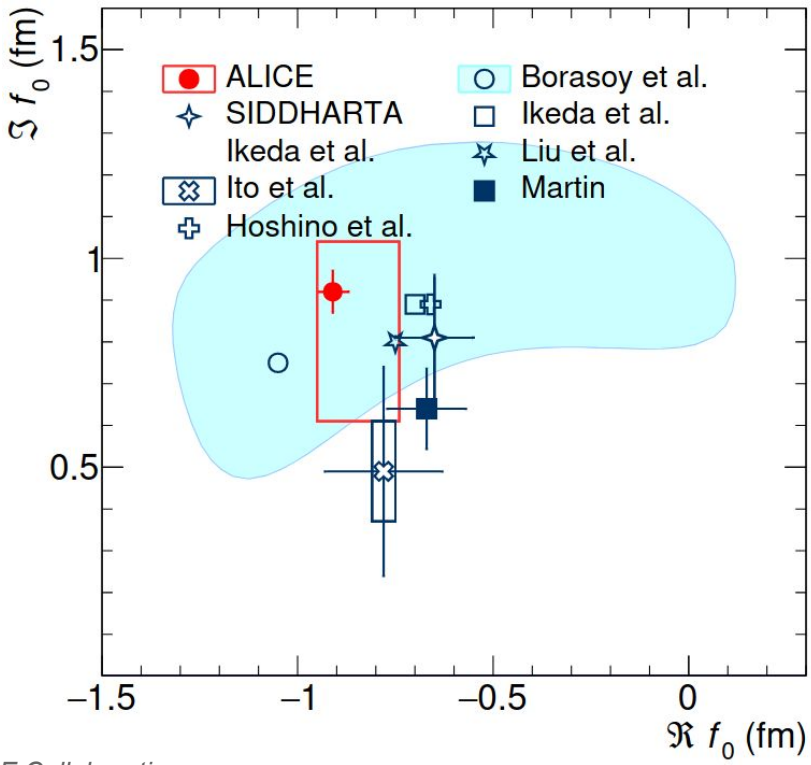
A unique feature of femtoscopy:

- The direct contribution of **inelastic channels** is only present in **small sources**
- **Large** collision **systems** are sensitive only to the **elastic channel**

K⁻p correlations in Pb–Pb collisions

Sensitivity to the elastic channel





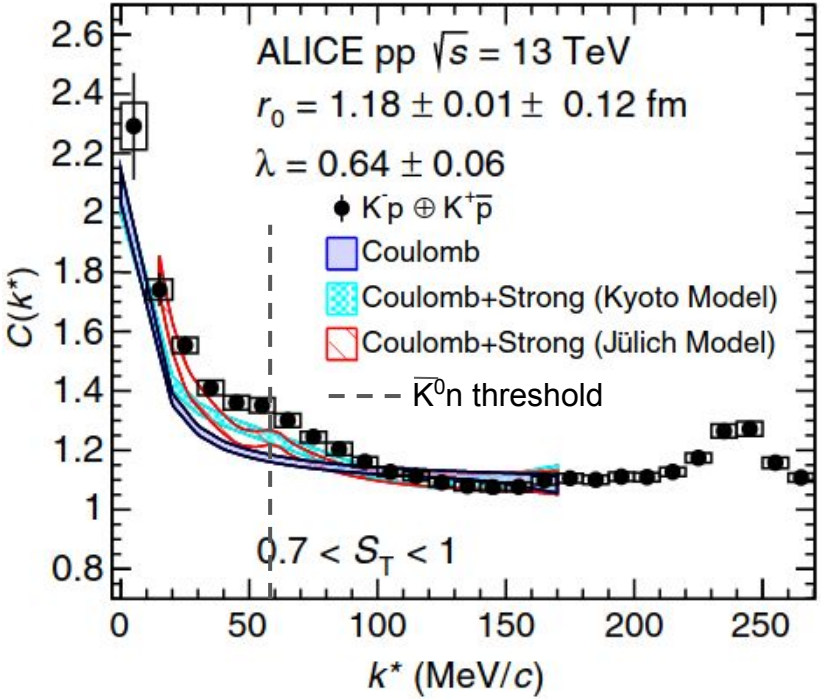
ALICE Collaboration, arXiv:2105.05683

K^-p correlations in pp collisions

*High-precision data at low k**

ALICE data

PRL 124, 092301, 2020



Y. Ikeda, T. Hyodo, W. Weise, Nuclear Physics A 881 98–114, 2012

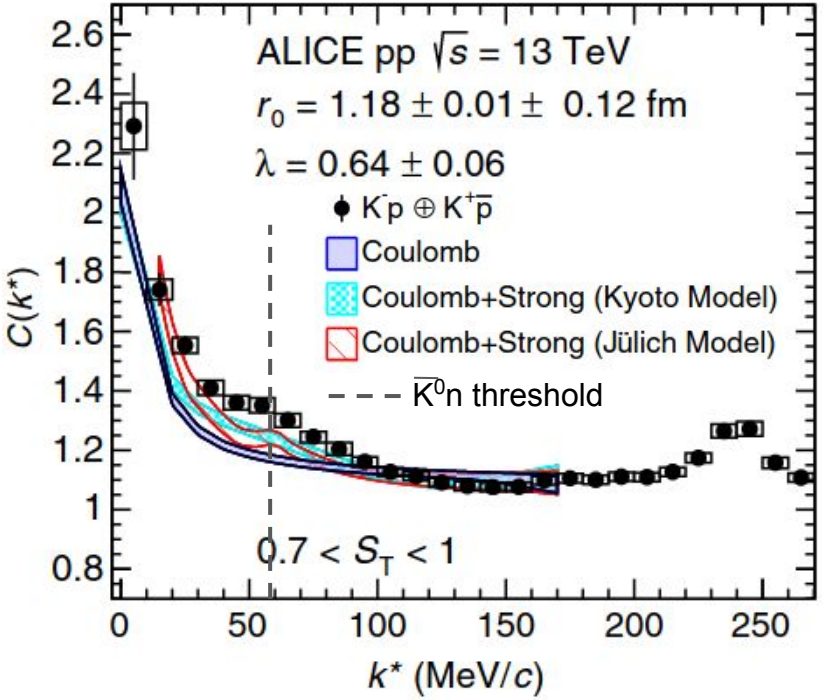
J. Haidenbauer et al. Eur. Phys. J. A47 18, 2011

K^-p correlations in pp collisions

Complementing existing data

ALICE data

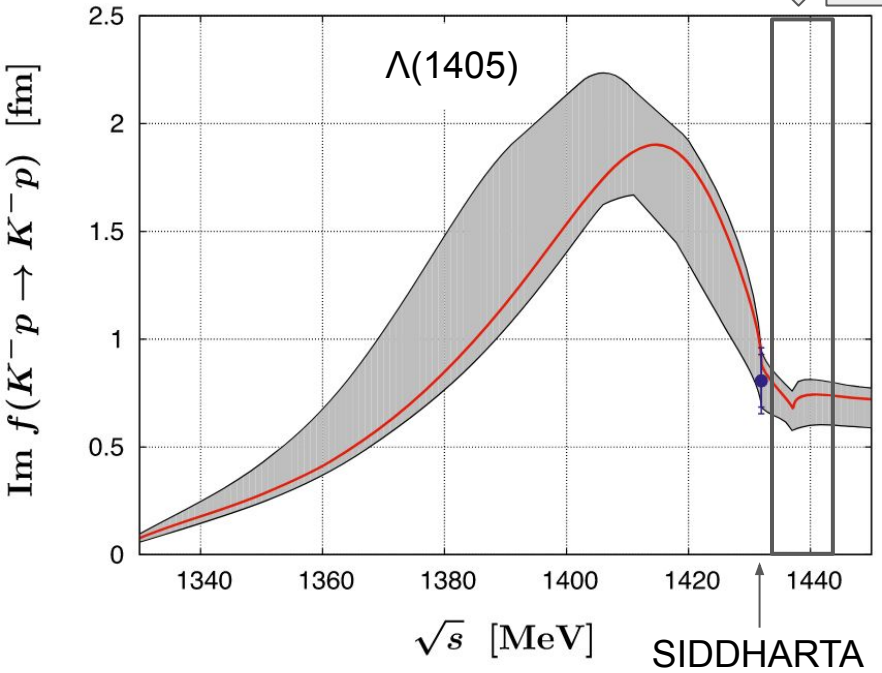
PRL 124, 092301, 2020



Y. Ikeda, T. Hyodo, W. Weise,
Nuclear Physics A 881 98–114, 2012

femtoscopy

scattering



SIDDHARTA

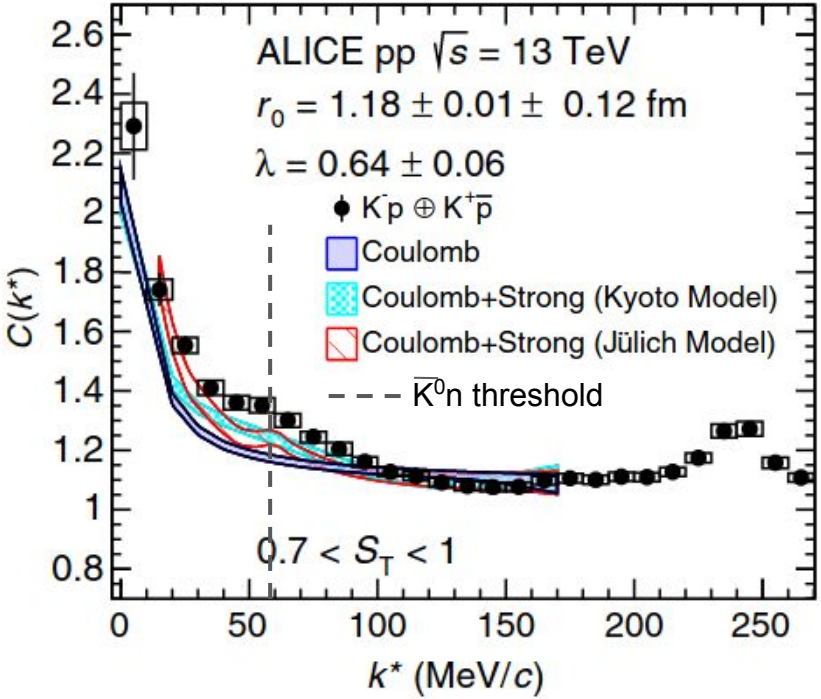
PLB 704:113-117

K⁻p correlations

Improving the theory

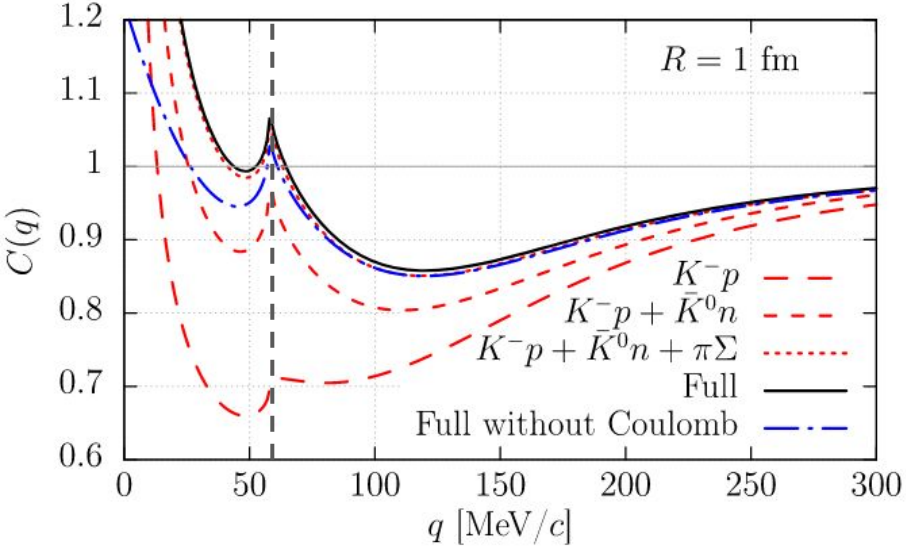
ALICE data

PRL 124, 092301, 2020



The "improved" Kyoto model

Y. Kamiya et al. Phys.Rev.Lett. 124 13, 2020



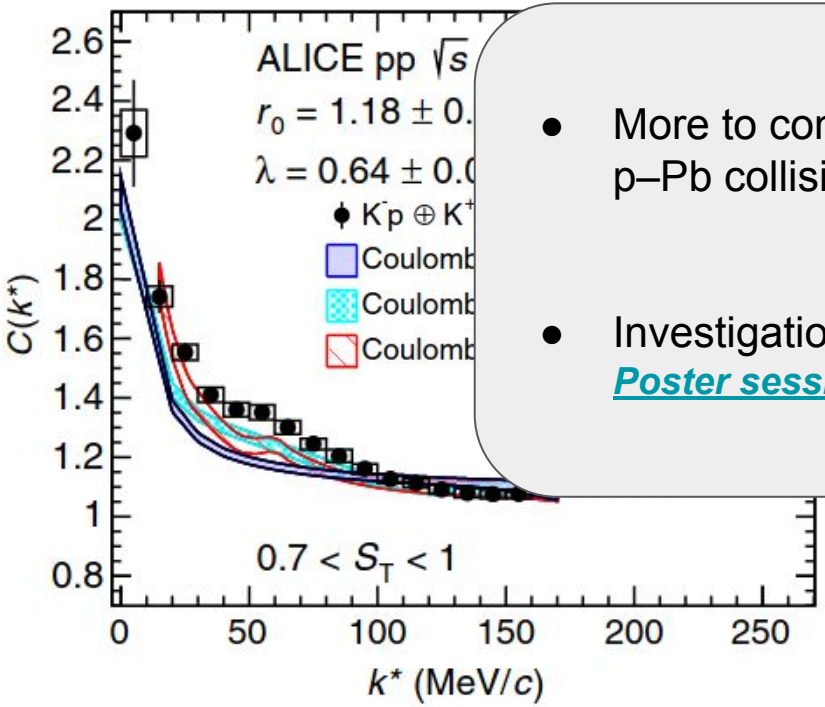
- The Kyoto model can be further constrained by the ALICE data

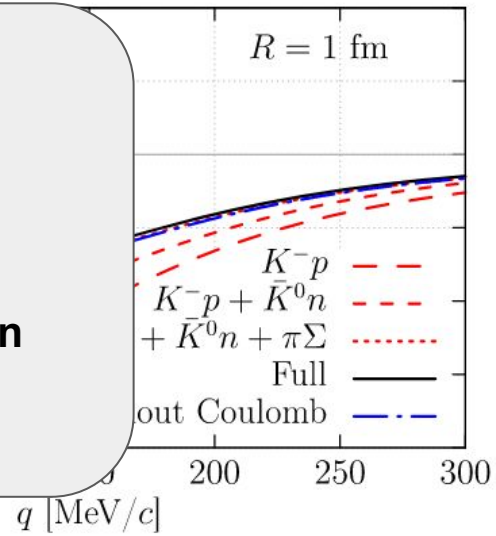
K⁻p correlations

Improving the theory

ALICE data
PRL 124, 092301, 2020

The “improved” Kyoto model
Y. Kamiya et al. Phys.Rev.Lett. 124 13, 2020



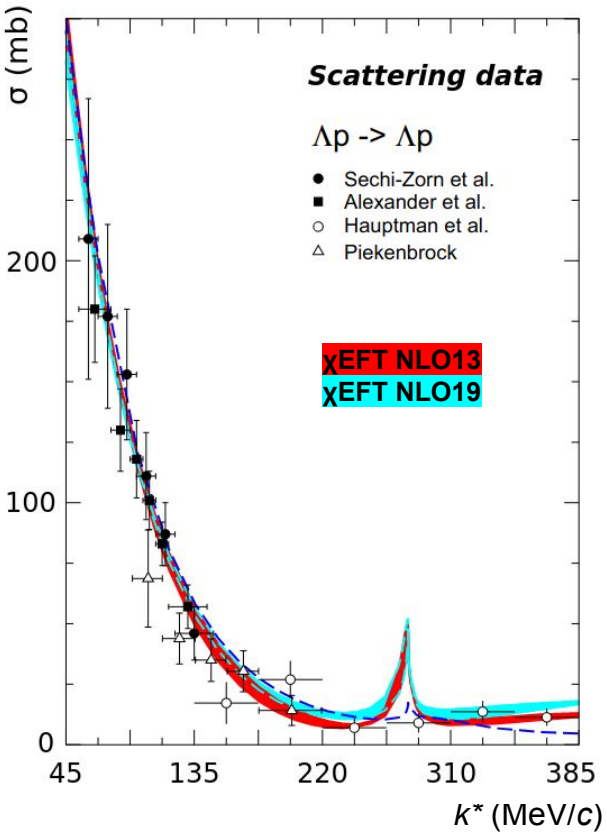


- More to come from studying p–Pb collisions
- Investigation of the **pK^0_S interaction**
  Poster session (today): Marta Urioni

- The Kyoto model can be further constrained by the ALICE data

pΛ correlations

Precision data from high-multiplicity pp collisions



J. Haidenbauer et al. Eur. Phys. J. A56 91, 2020

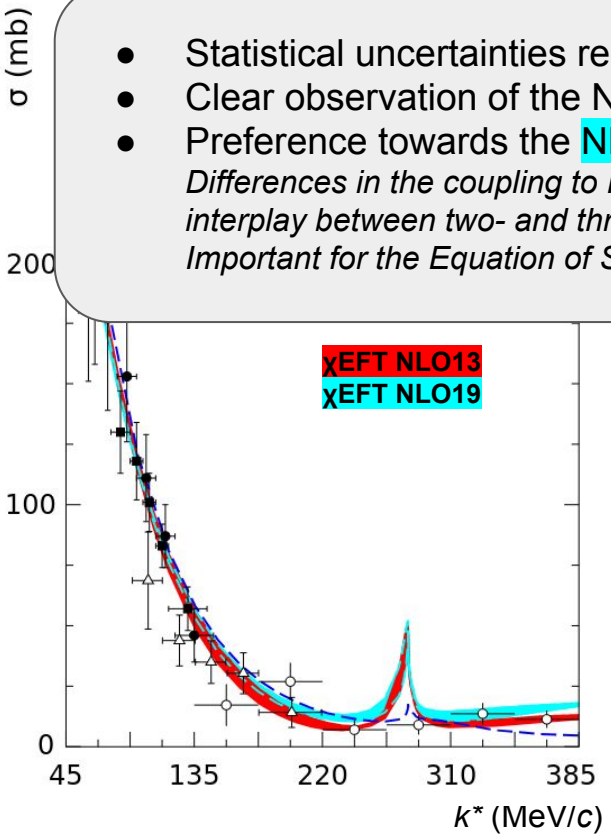
pΛ correlations

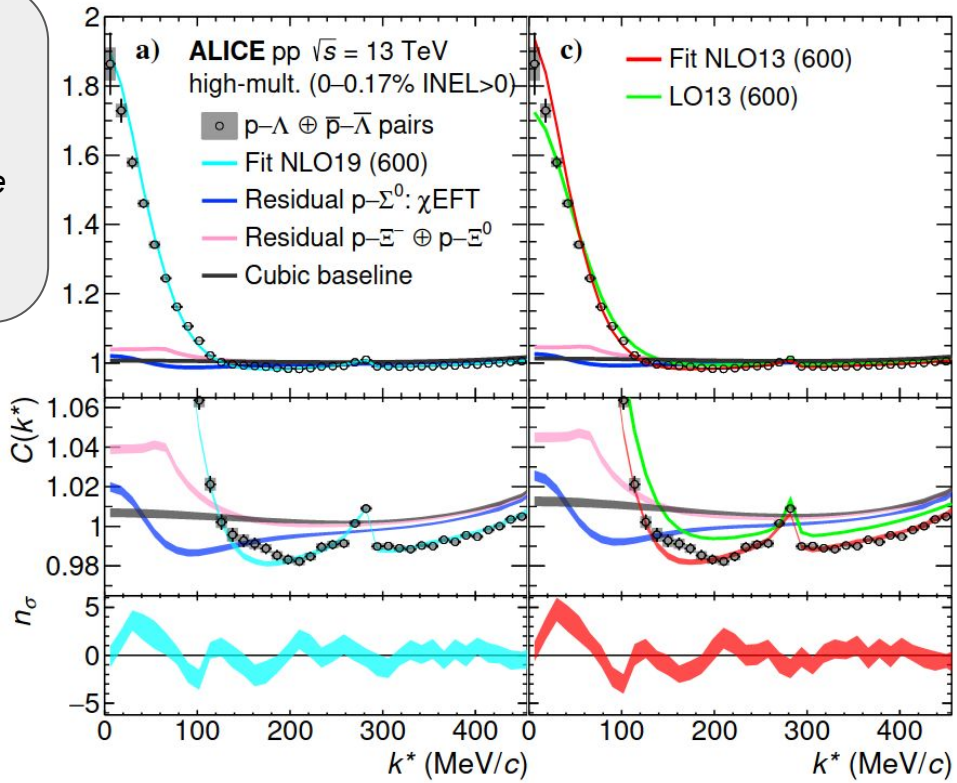
Precision data from high-multiplicity pp collisions

ALICE Collaboration, arXiv:2104.04427

- Statistical uncertainties reduced >10x
- Clear observation of the NΛ↔NΣ cusp
- Preference towards the NLO19 model

  Differences in the coupling to NΣ, as well as in the interplay between two- and three-body forces. Important for the Equation of State.

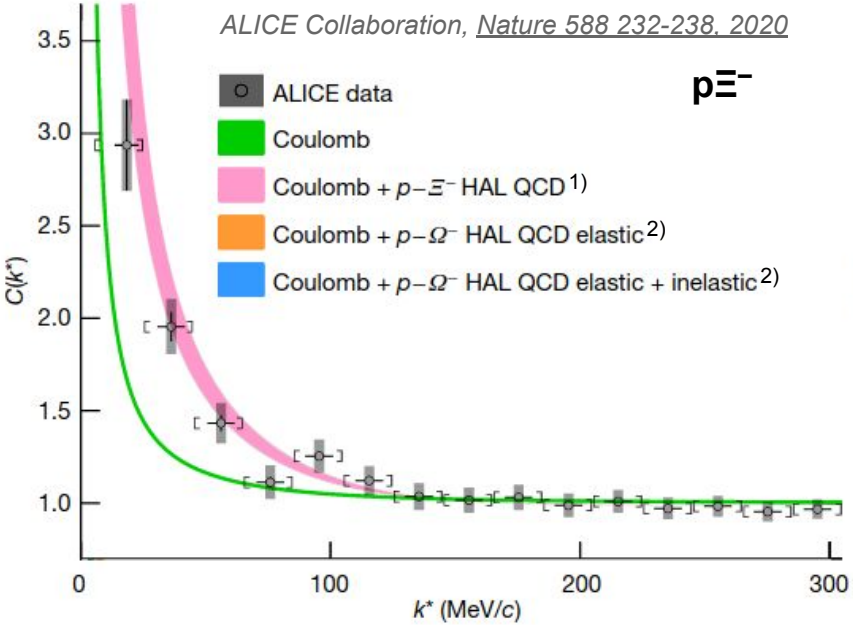




J. Haidenbauer et al. Eur. Phys. J. A56 91, 2020

S=-2 and S=-3 sector

Testing the lattice using pΞ and pΩ correlations

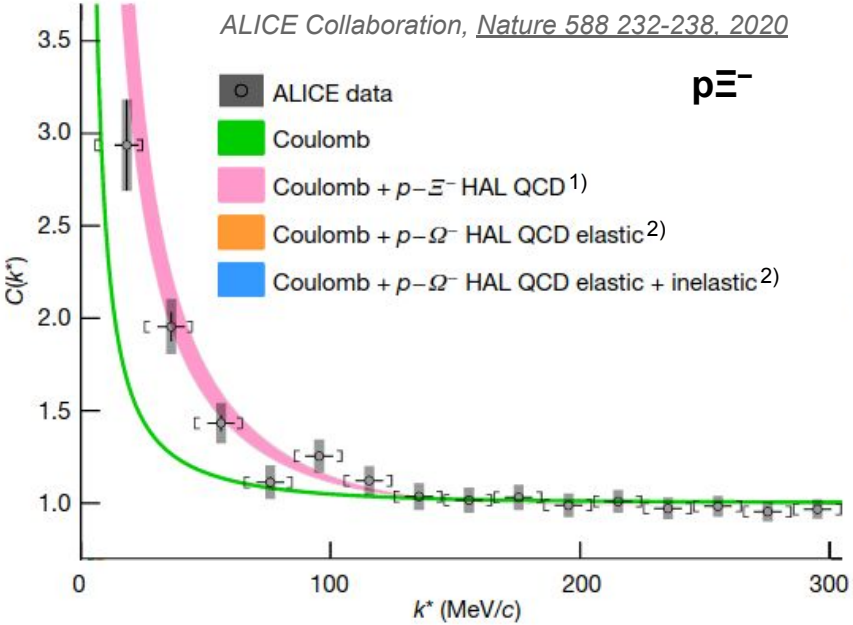


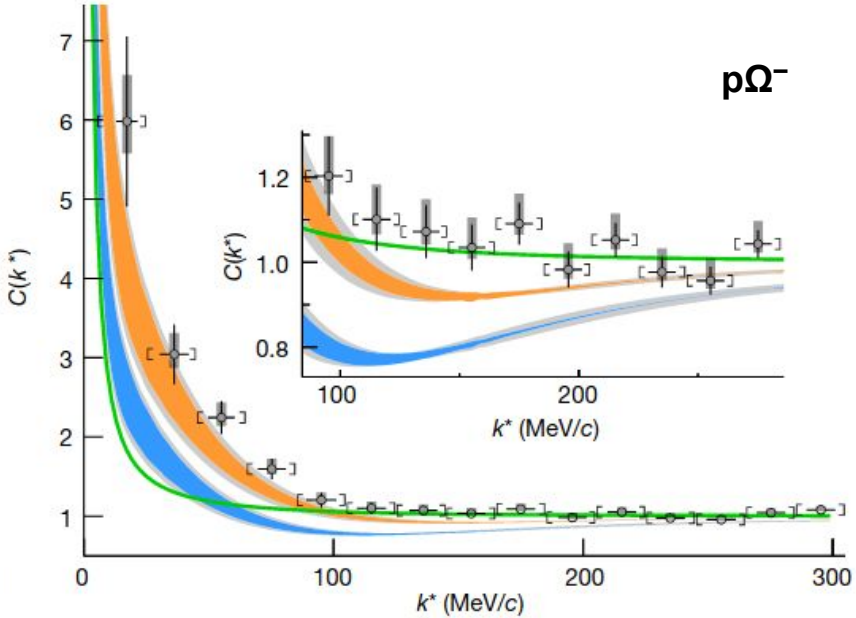
- Agreement with lattice predictions
- The lattice disfavours the onset of Ξ particles inside neutron stars[3)]

1) HAL QCD Collaboration, Nucl.Phys.A 998 121737, 2020
2) HAL QCD Collaboration, Phys.Lett. B792 284-289, 2019
3) HAL QCD Collaboration, AIP Conf.Proc. 2130 1, 020002, 2019

S=-2 and S=-3 sector

Testing the lattice using pΞ and pΩ correlations



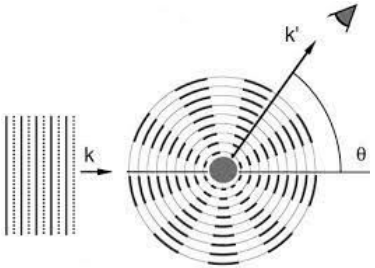


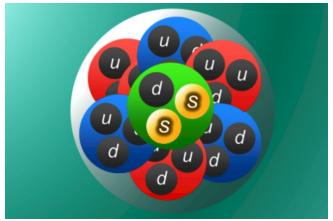
- Agreement with lattice predictions
- The lattice disfavours the onset of Ξ particles inside neutron stars[3)]

- Agreement with lattice predictions
- A new benchmark for theory
- Strong attraction
- A bound state is not observed, but cannot be excluded

1) HAL QCD Collaboration, Nucl.Phys.A 998 121737, 2020
2) HAL QCD Collaboration, Phys.Lett. B792 284-289, 2019
3) HAL QCD Collaboration, AIP Conf.Proc. 2130 1, 020002, 2019

Summary





Physics

Coupled channel dynamic
Equation of State

Experiment

Scattering exp.

Hypernuclei

Correlations

Theory

χEFT

Lattice QCD

Summary

Physics

Coupled channel dynamic
Equation of State

Scattering exp.

Hypernuclei

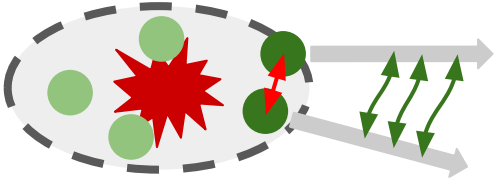
Correlations

χEFT

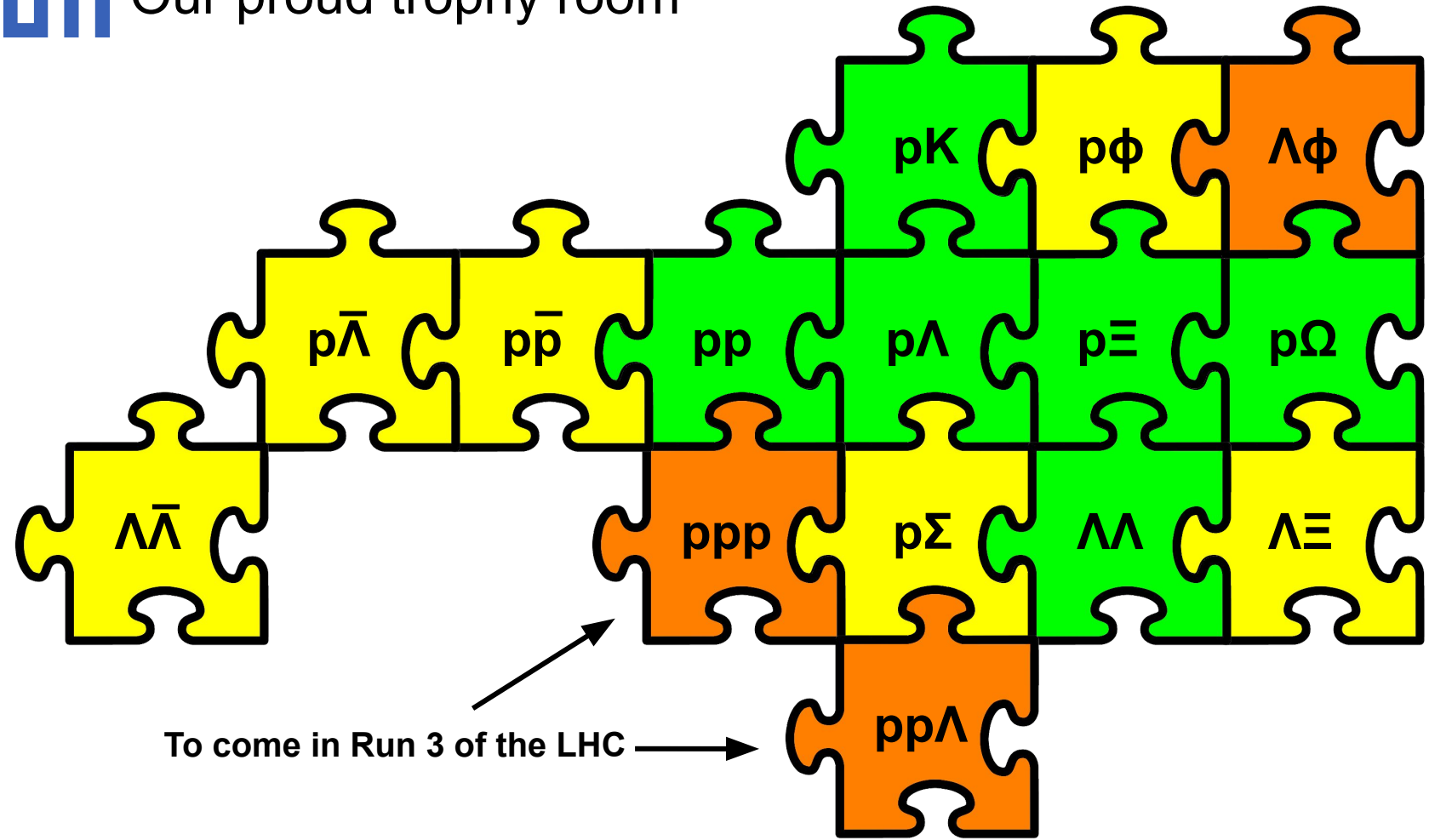
Lattice QCD

Experiment

Theory

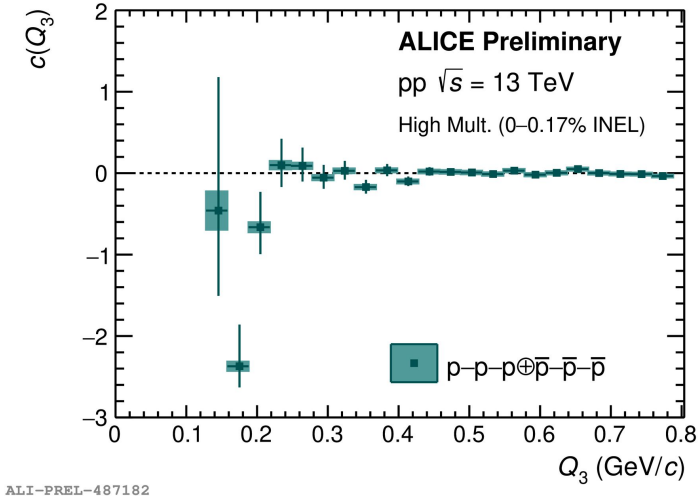


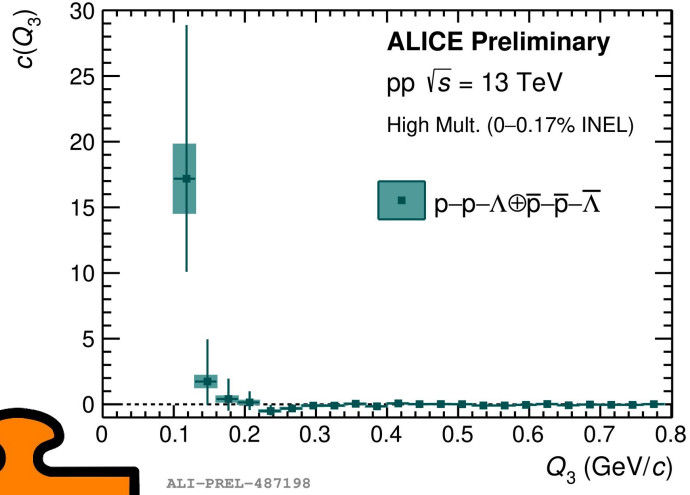
Our proud trophy room

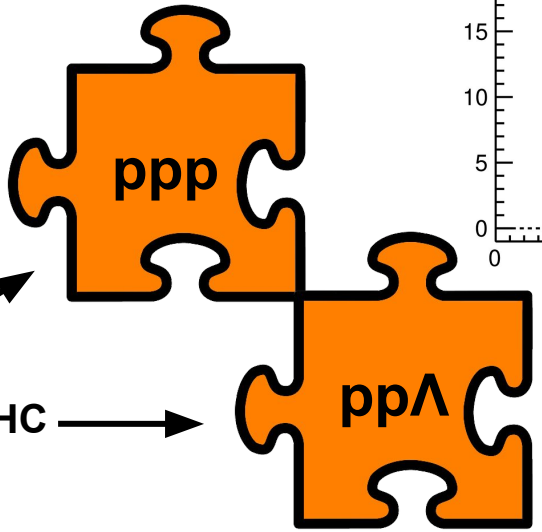


Thank you for your attention

Using cumulants to access the genuine three-body interaction







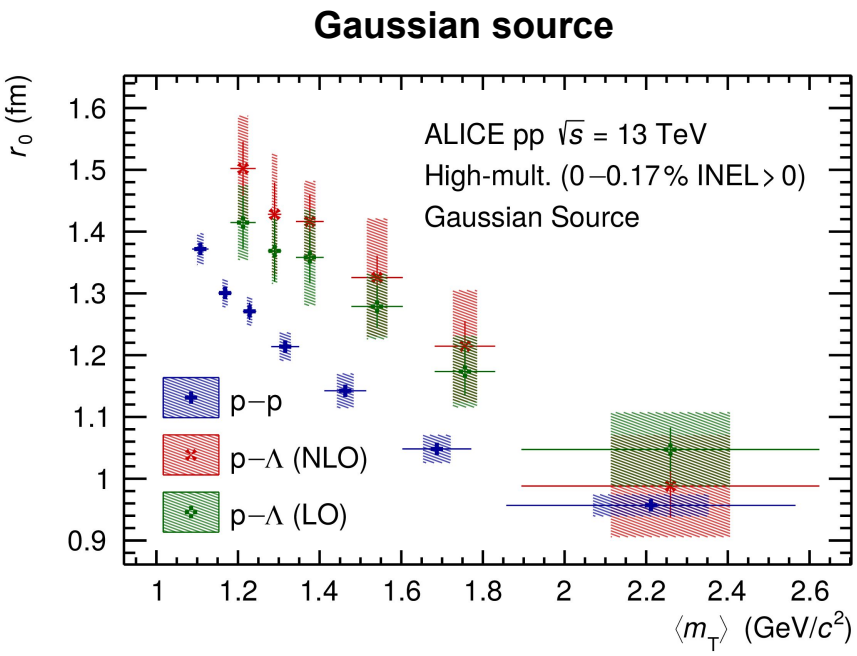
To come in Run 3 of the LHC

BACKUP

A common source

Gaussian profile

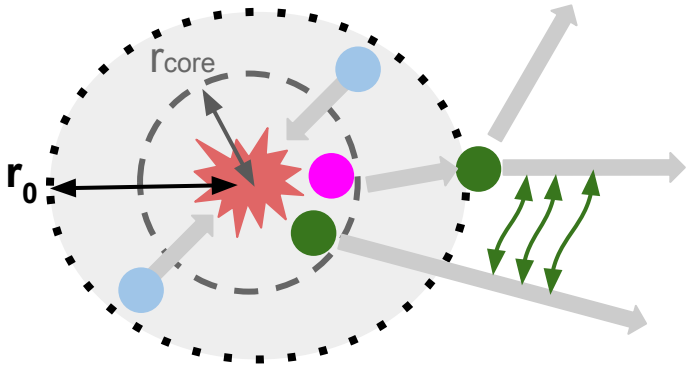
Phys. Lett. B 811 (2020) 135849



- **Different source size** for p-p and p-Λ pairs

- The Statistical Hadronization Model tells us:
  c.a. ⅔ of protons and Λs stem from resonances.
  The average lifetimes (cτ) are:
  1.6 fm for X→proton
  4.7 fm for X→Λ

- **Production through short-lived resonances**

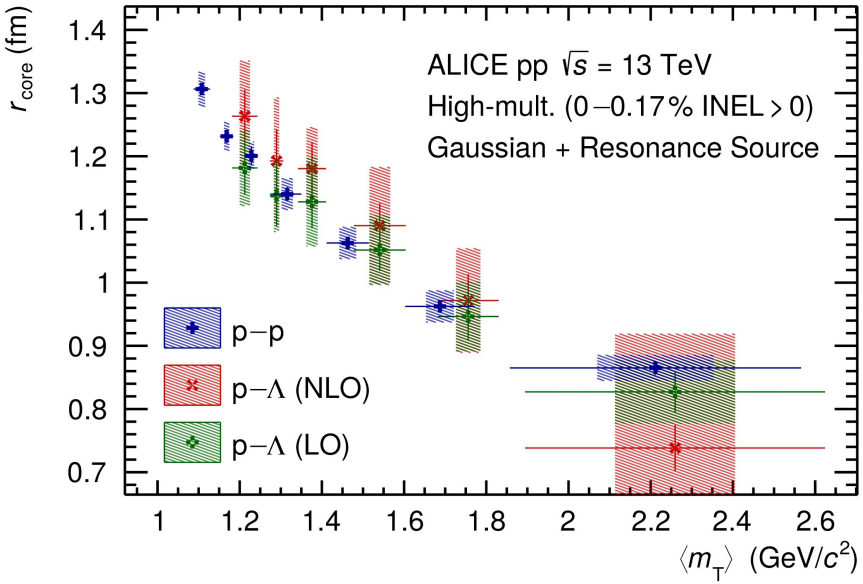


A common source

The numerical "resonance source model"

Phys. Lett. B 811 (2020) 135849

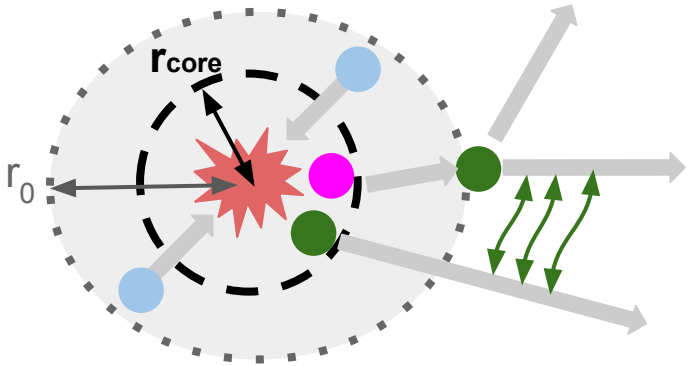
Gaussian core + resonances



- **Common source** for p-p and p-Λ pairs. Ones measured (from p-p), it is fixed for ANY baryon-baryon pair!

- The Statistical Hadronization Model tells us: c.a. ⅔ of protons and Λs stem from resonances. The average lifetimes (cτ) are:
  1.6 fm for X→proton
  4.7 fm for X→Λ

- **Production through short-lived resonances**

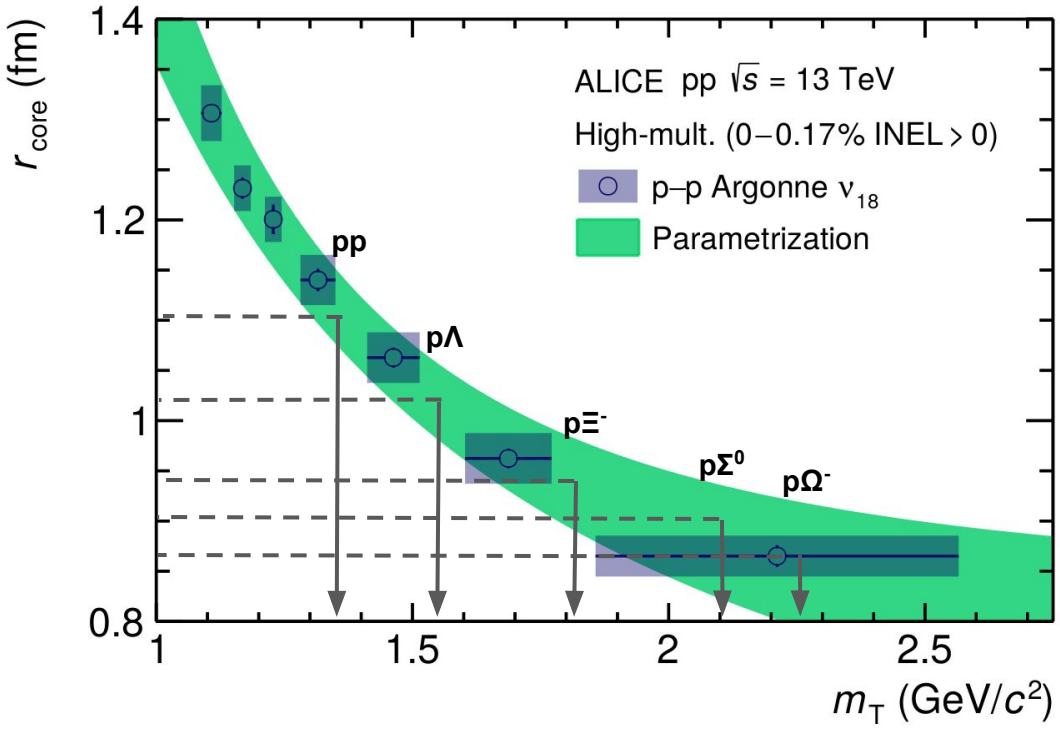


The source function: Summary

Gaussian core + resonances with m_T scaling

- **Fit the p-p** result with a power law
- r_{core} for each system to be determined by the 3σ band of the fit (green band)
- Fix the value of r_{core} of each particle species based on their $\langle m_T \rangle$
- Further investigations ongoing

The r_{core} is NOT the same as the effective source size r_0!

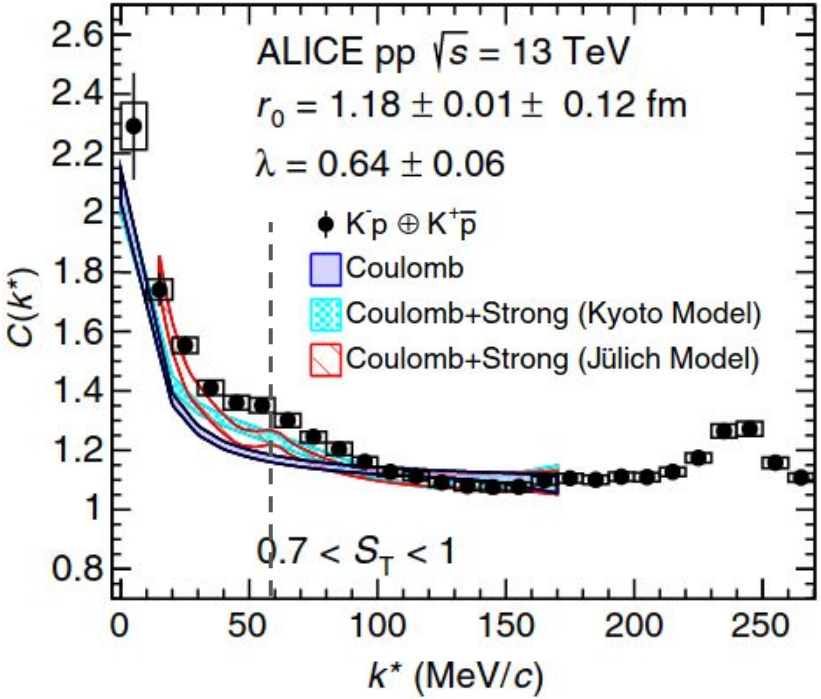


K^--p correlations in pp collisions

Direct sensitivity to the inelastic channels

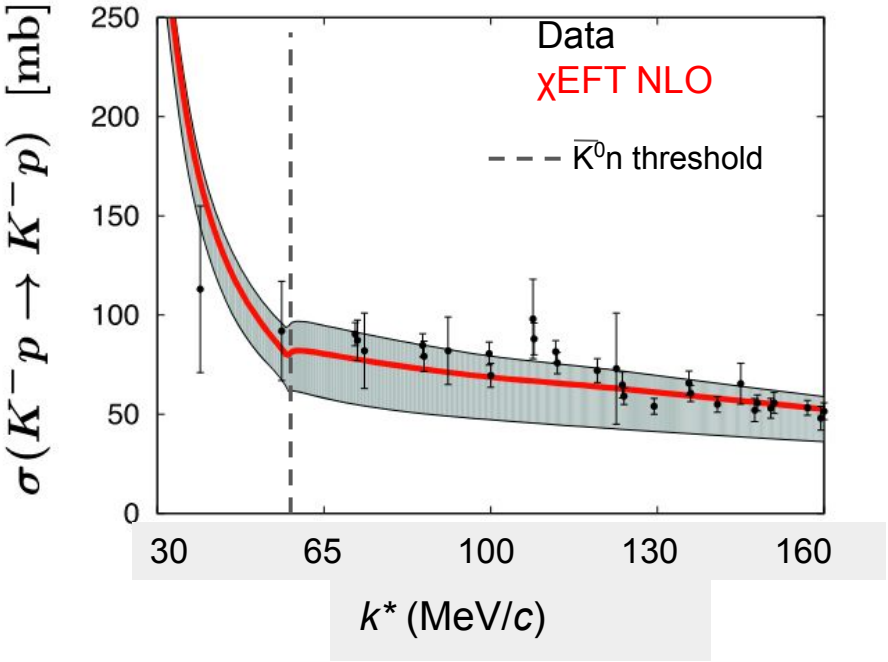
Femtoscopy data

PRL 124, 092301 (2020)



Scattering data

Nuclear Physics A 881 (2012) 98–114



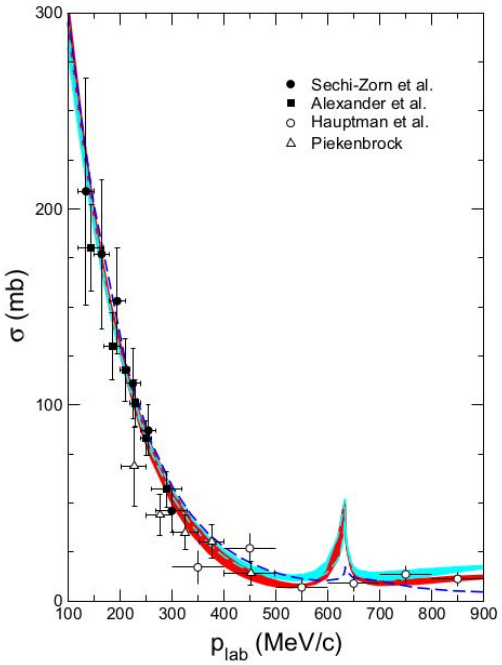
Chiral effective field theory (χEFT)

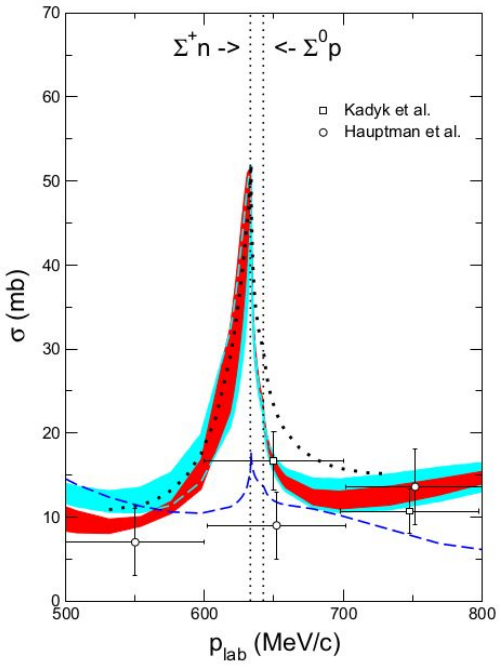
Experimental constraints

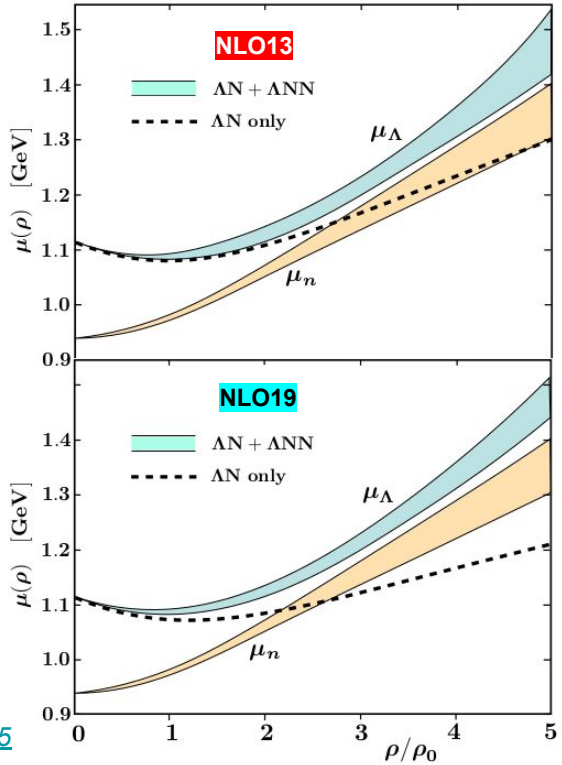
- Coupled channel dynamics (pΛ↔NΣ).
- Existing constraints from scattering and hypernuclei data.
  Limited statistics, in particular related to NΣ coupling and 3-body forces.

NLO13 has slightly stronger 2-body attraction in vacuum

NLO19 has stronger 3-body repulsion in-medium







Eur.Phys.J.A 56 (2020) 3, 91

Eur.Phys.J.A 56 (2020) 6, 175

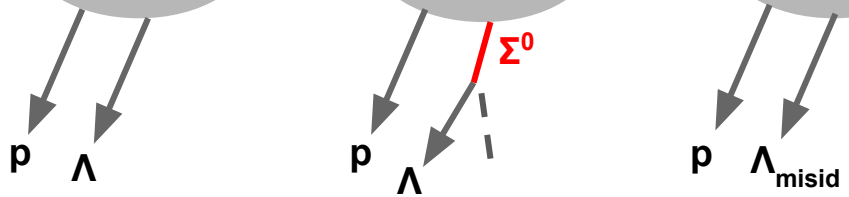
p-Λ correlation function

Overview

$$C_{\mathrm{exp}}(k^*) = b(k^*)C_{\mathrm{th}}(k^*) = b(k^*)\sum_i \lambda_i C_{\mathrm{th},i}(k^*)$$

Non-femto baseline

$$\lambda_0 C_{\mathrm{th},0}(k^*) + \lambda_1 C_{\mathrm{th},1}(k^*) + \lambda_2 C_{\mathrm{th},2}(k^*) \cdots$$



Modeled using χEFT

corrected for using a "sideband" analysis

The femto era begins!