Sofia University
St. Kliment Ohridski

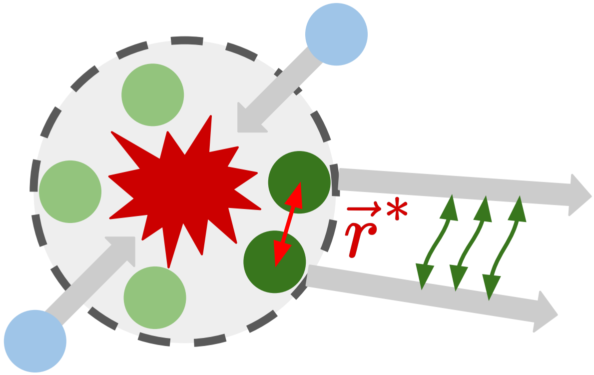
Hadron-hadron interactions from femtoscopy and their applications

Dimitar Mihaylov @ EMMI 2025

13th November 2025, Salerno, Italy

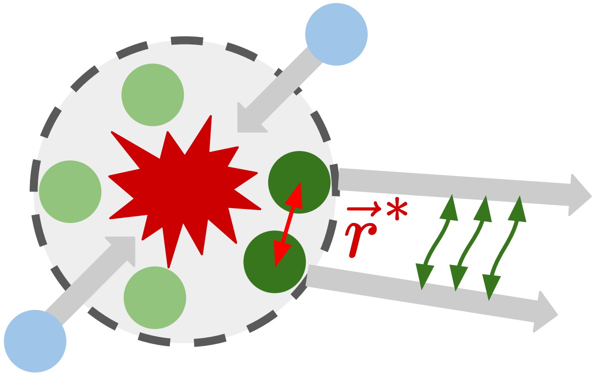
Femtoscopy

Overview (2-body)

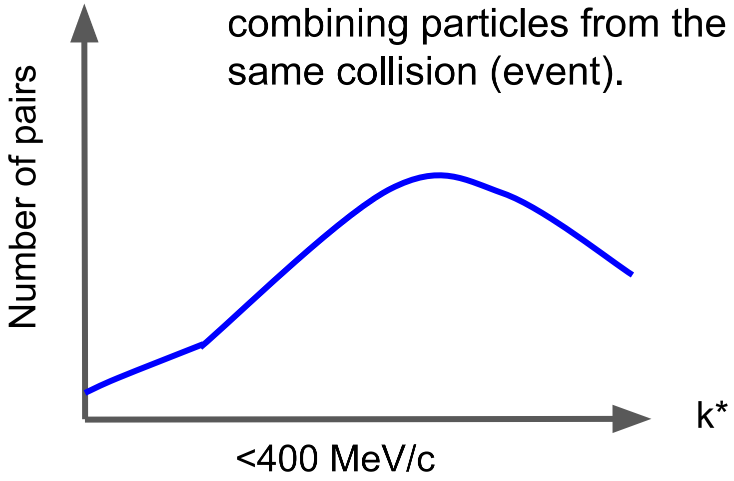


Femtoscopy

Overview (2-body)



- ***Same event sample (SE)*:** Correlated pairs, obtained by combining particles from the same collision (event).



Femtoscopy

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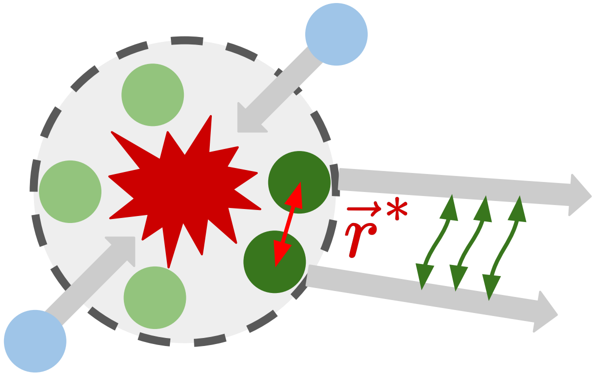
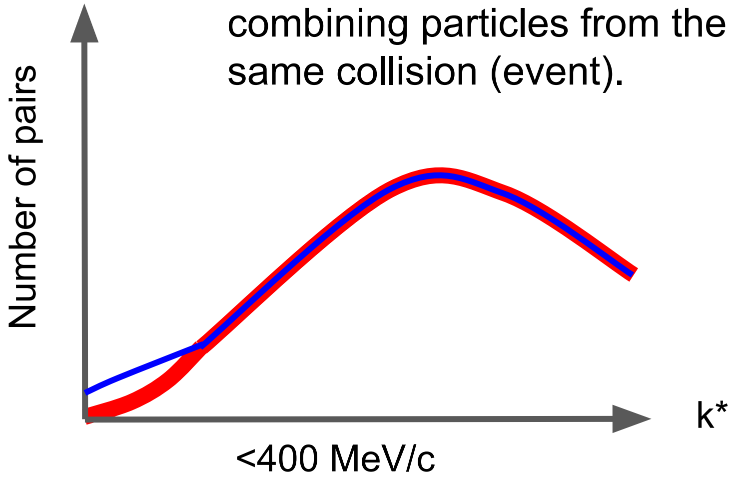
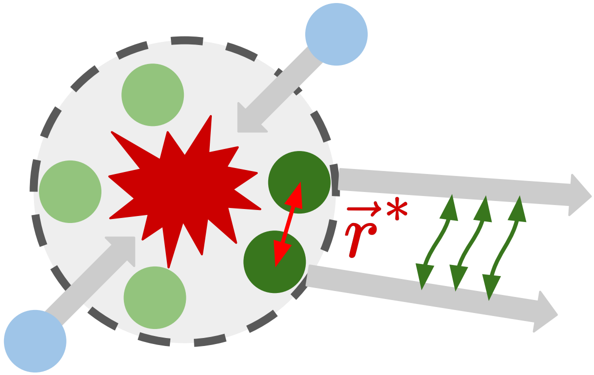


- ***Same event sample (SE)*:** Correlated pairs, obtained by combining particles from the same collision (event).
- ***Mixed event sample (ME)*:** Uncorrelated pairs, obtained by combining particles from two different collisions (events).

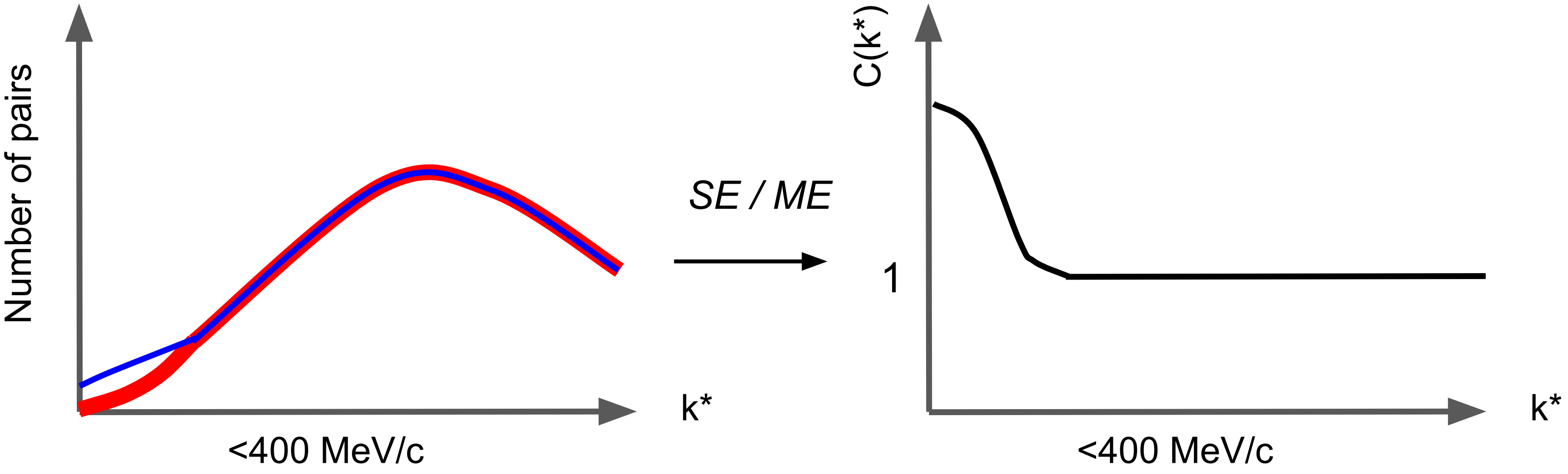


Femtoscopy

Overview (2-body)



- The ***correlation function C(k*)*** = *SE / ME*, ideally equal to unity in the absence of any correlations.



Femtoscopy

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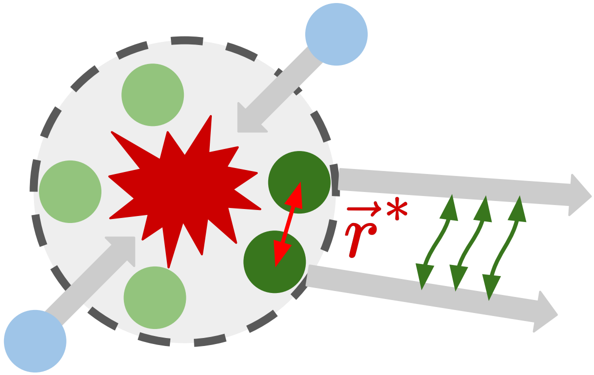
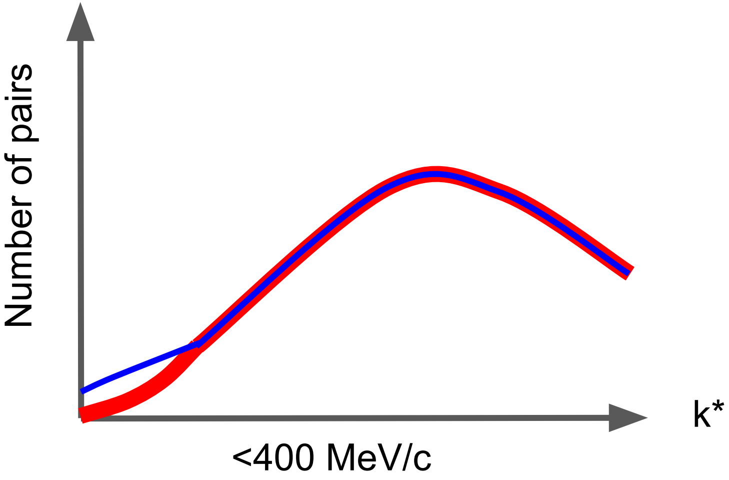
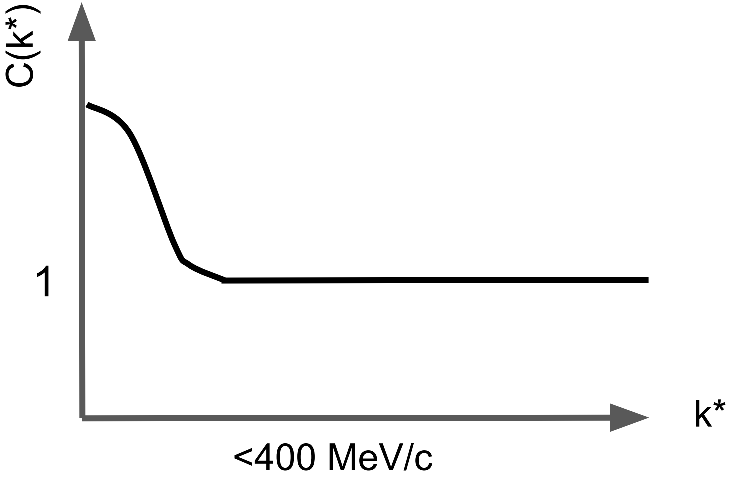


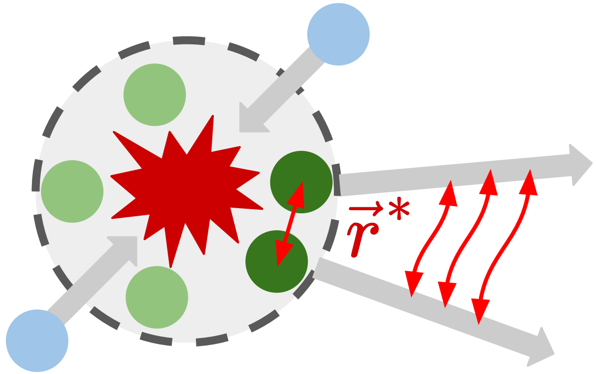
- **Attractive** final state interaction (FSI)



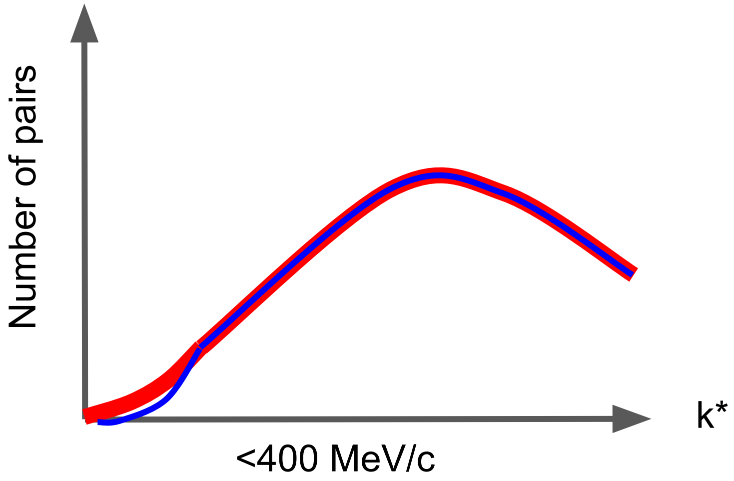


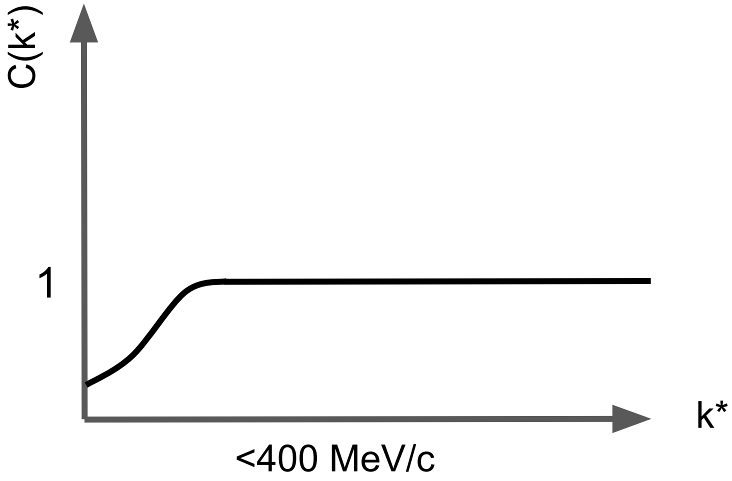
Femtoscopy

Overview (2-body)



- **Repulsive** final state interaction (FSI).





Femtoscopy

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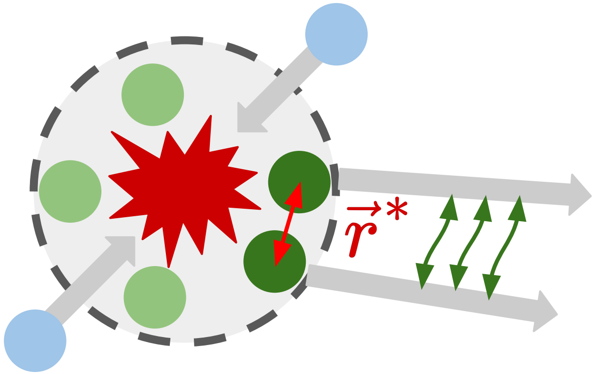
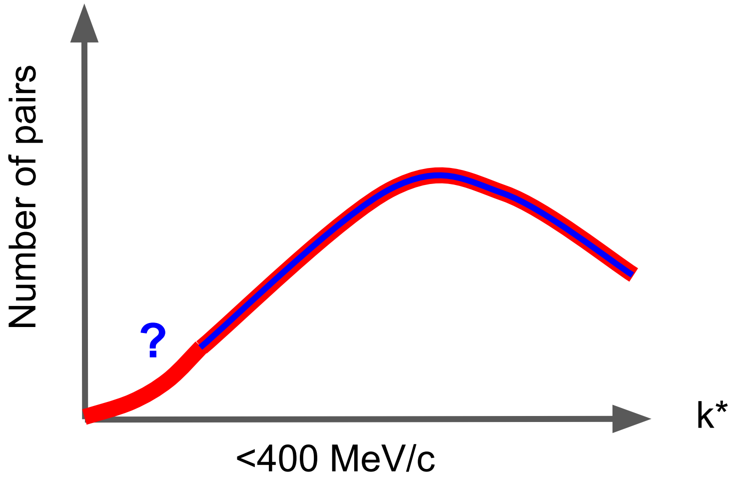
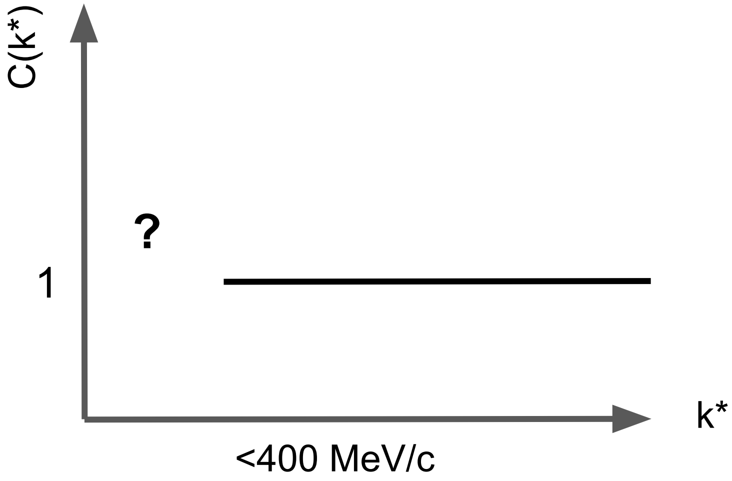


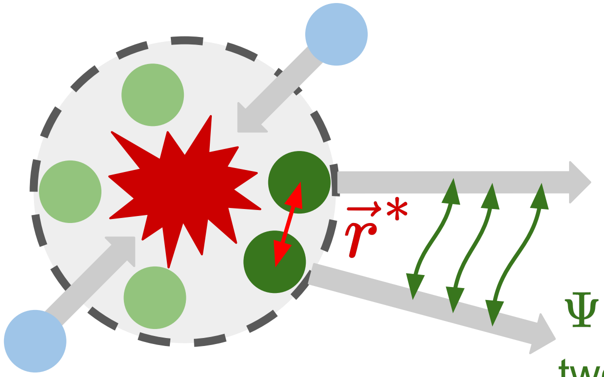
- In case of **bound states** or **coupled channels** there is big interplay with the radius, and in general there is not trivial shape to observe.





Femtoscopy

Koonin-Pratt equation



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

two-particle wave function

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

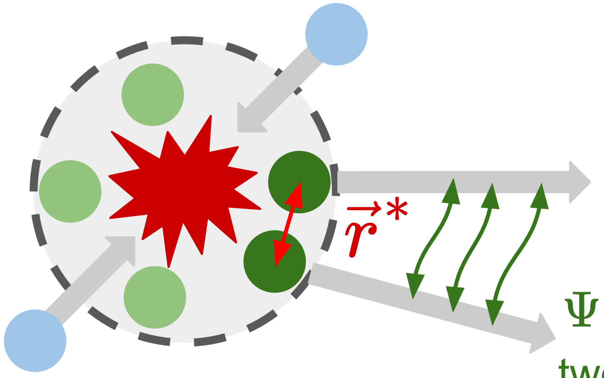
[Lisa et al. *Ann.Rev.Nucl.Part.Sci.55:357-402, 2005*]()

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

- Measure C(k*), fix S(r*), study the interaction.
- Detailed studies of the source in pp:
  ALICE Coll. *Phys.Lett.B 811 (2020) 135849*
  Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590
- CATS framework to evaluate the above integral Mihaylov et al. *EPJC* 78 (2018) 5, 394

Femtoscopy

Study the FSI



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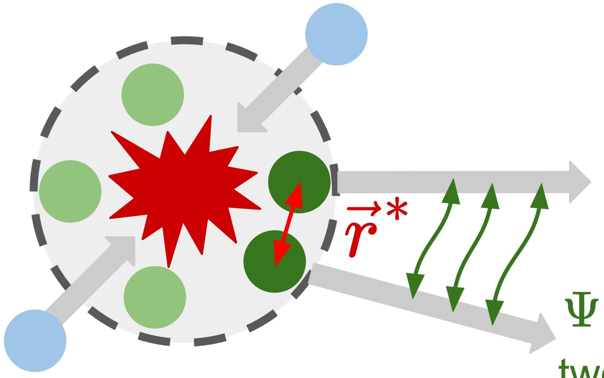
Strategy 1:

- Use the Lednický-Lyuboshitz (LL) model to fit correlations for which the source size > effective range and there are little direct contributions from coupled-channels.
- Good approximation for HI collisions, good to get basic insights in pp as an exploratory tool. Firm conclusions difficult in small collisions!

Femtoscopy

Study the FSI



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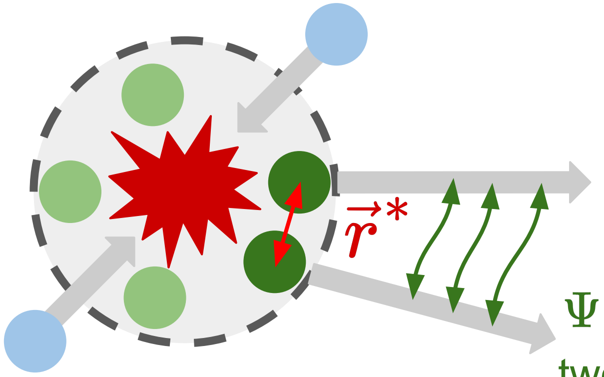
Lisa et al. *Ann.Rev.Nucl.Part.Sci.55:357-402, 2005*

Strategy 2:

- Fit a (real) potential V(r*) to the correlation, get out the scattering parameters
- Use the results to constrain other theories/models e.g. χEFT
- We will see examples today

Femtoscopy

Study the FSI



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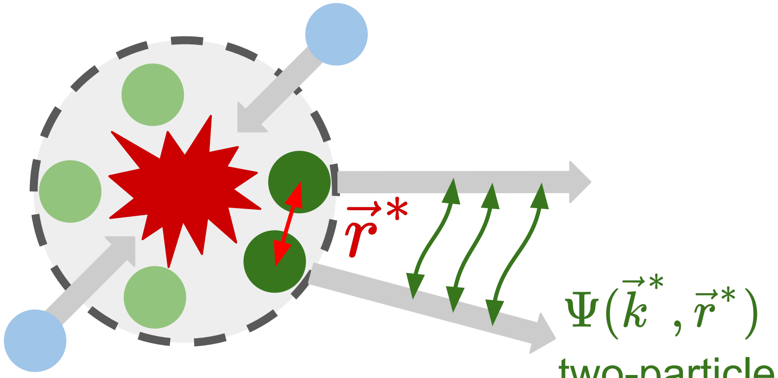
[Lisa et al. *Ann.Rev.Nucl.Part.Sci.55:357-402, 2005*]()

Strategy 3:

- Test a certain model, by obtaining an “external” correlation function
- Typical approach for coupled channel dynamics (perturbation theories)

Femtoscopy

Coupled channels



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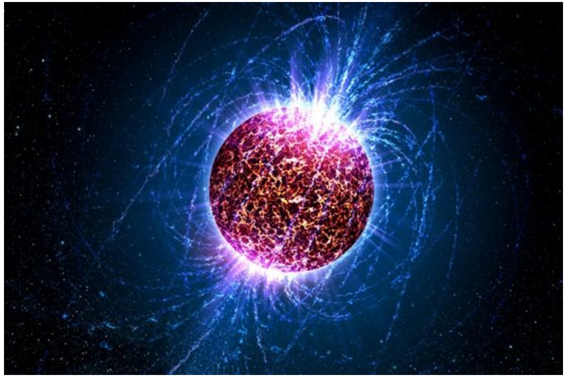
Lisa et al. *Ann.Rev.Nucl.Part.Sci.55:357-402, 2005*

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

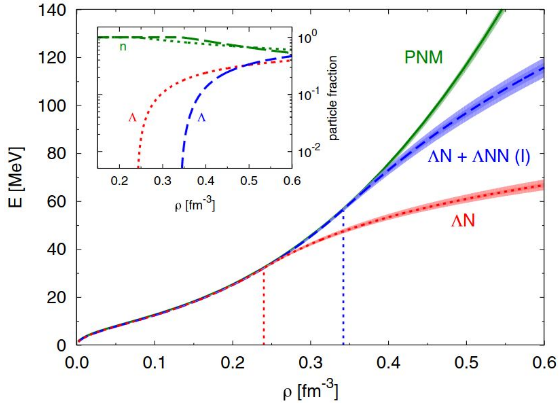
- In the presence of coupled channels we have off-diagonal contribution from the scattering matrix
- These enter the correlation function as extra terms
- These terms converge to zero at large r* => for large sources become effectively zero, but have BIG direct contribution in small collision systems

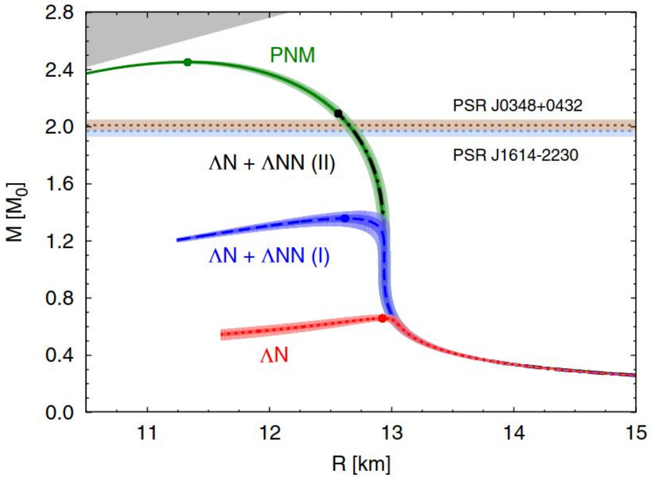
A long standing puzzle



- Do we have hyperons inside neutron stars (NS)?
- Can happen at high density due to the large fermi pressure, but disfavored from due to the existence of very heavy NS, suggesting stiff equation of state (EoS).

[Lonardoni et al. *Phys.Rev.Lett.* 114 (2015) 9, 092301]

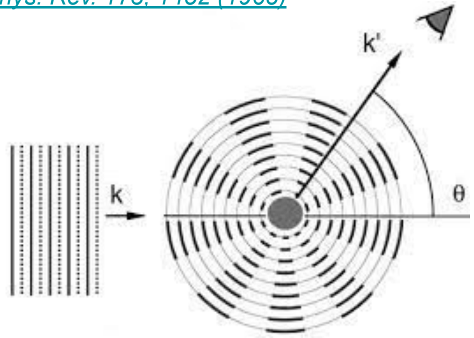




The “traditional” approaches to study hyperons

- As density increases, it might become **possible to form hyperons.**
  N.B. This depends on the chemical potential, i.e. sum of Fermi energy and the effective in-medium mass of the particles.
- Their effective **in-medium mass (and potential U_Λ) depends on the interaction** with the surrounding particles
- **Attractive NΛ interaction**.
  Known from e.g. scattering experiments

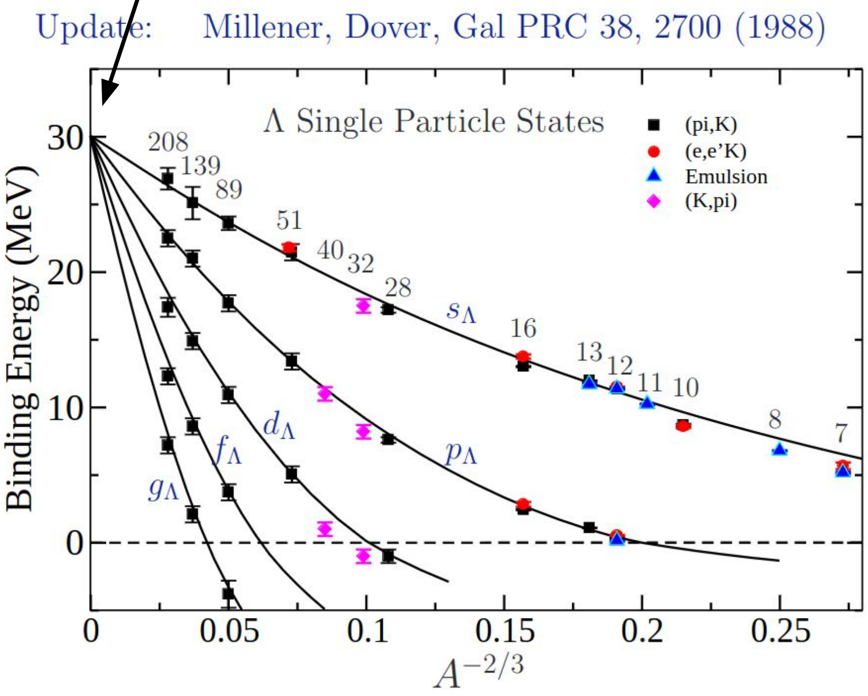
Sechi-Zorn et al. *Phys. Rev. 175, 1735 (1968)*
Alexander et al. *Phys. Rev. 173, 1452 (1968)*



Scattering experiments with limited reach for low energies and challenged by statistics.

In-medium $U_\Lambda(\rho)$ potential

U_Λ @ $\rho_0 \approx -30$ MeV



Friedman and Gal, *Nucl.Phys.A 1039 (2023) 122725*

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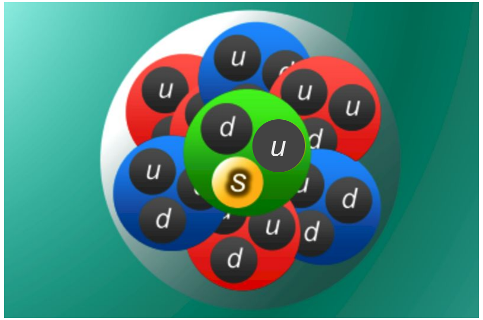
- **Repulsion**, e.g. due to many- (three-) body forces, may prohibit their formation.
  In agreement with hypernuclei experiments.



Hashimoto and Tamura, *Prog. Part. Nucl. Phys., 57:564–653, 2006*

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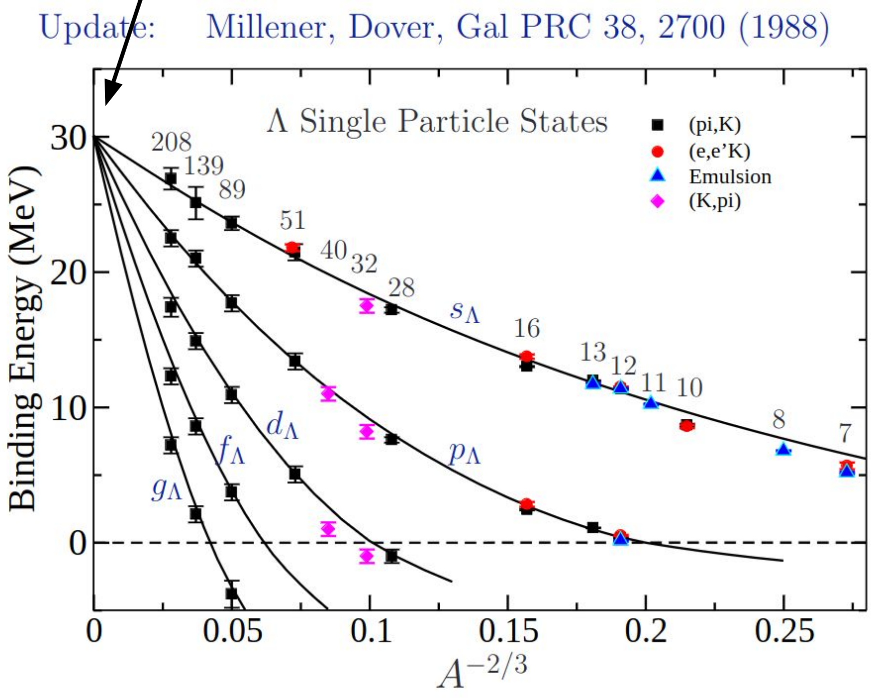

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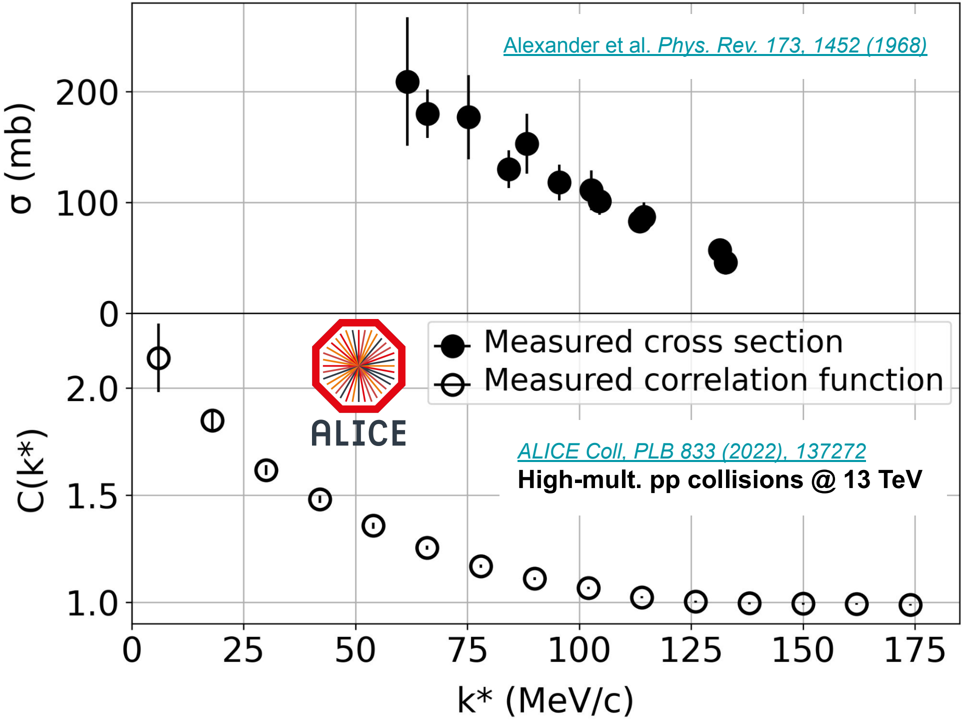
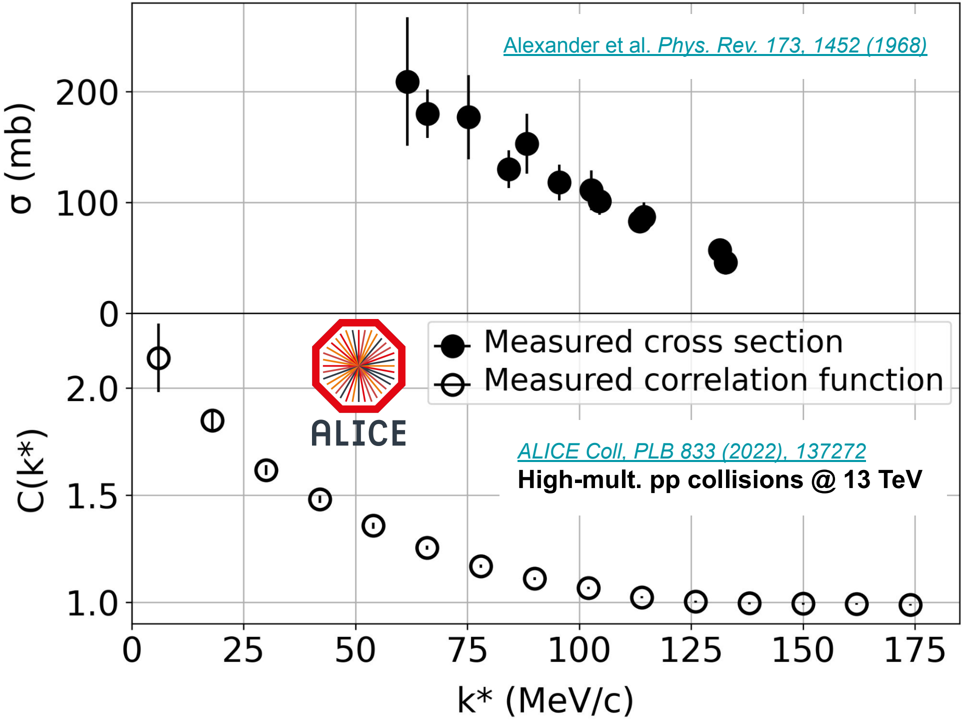
- **Ongoing efforts to improve scattering/hypernuclei measurements both at JLab and J-PARC.**
  Statistical challenges are still large, and typically the very low momentum region is not accessible

EoS from pΛ correlation measurements



High precision measurements are now available!

EoS from pΛ correlation measurements



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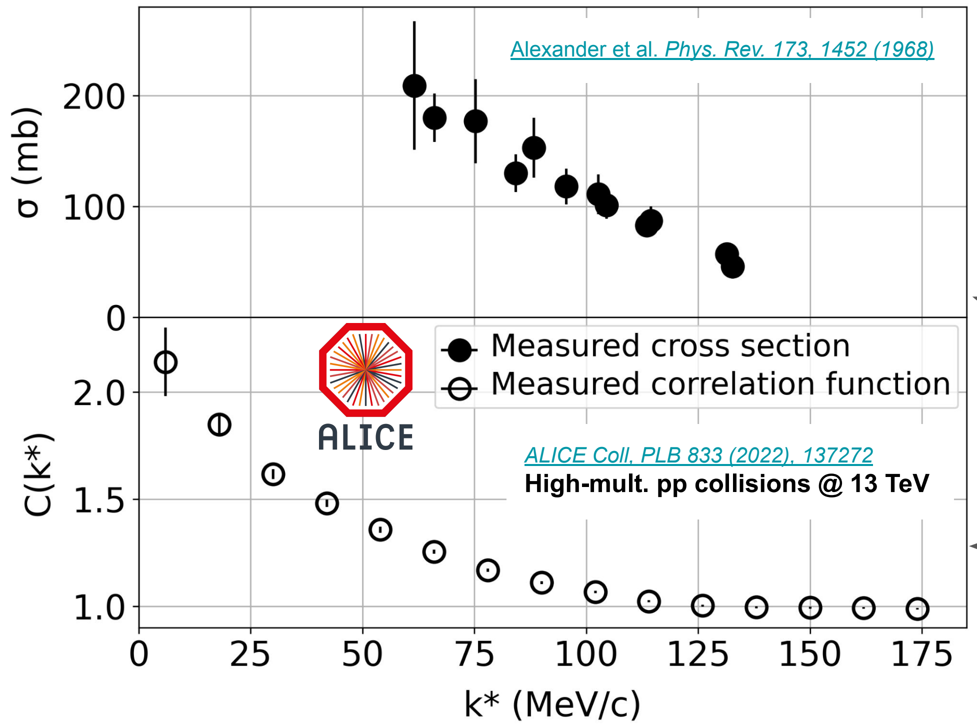
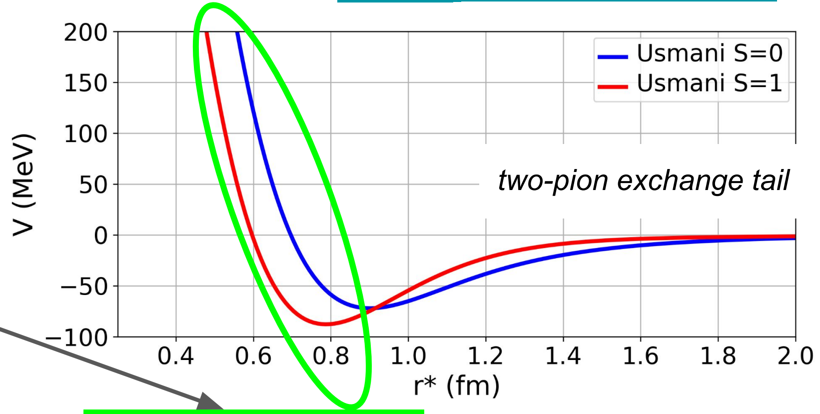


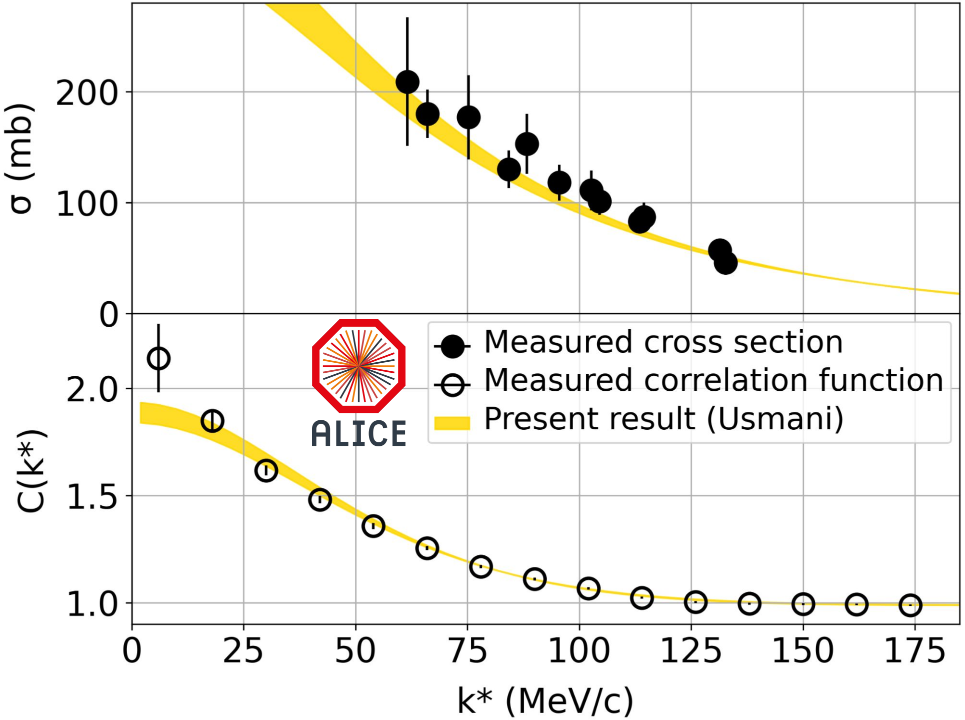
Potential: **Usmani** et al, PRC, 29:684–687, 1984



Phenomenological repulsive core

FIT

EoS from pΛ correlation measurements



Disclaimer: the data is fitted differentially, for details:

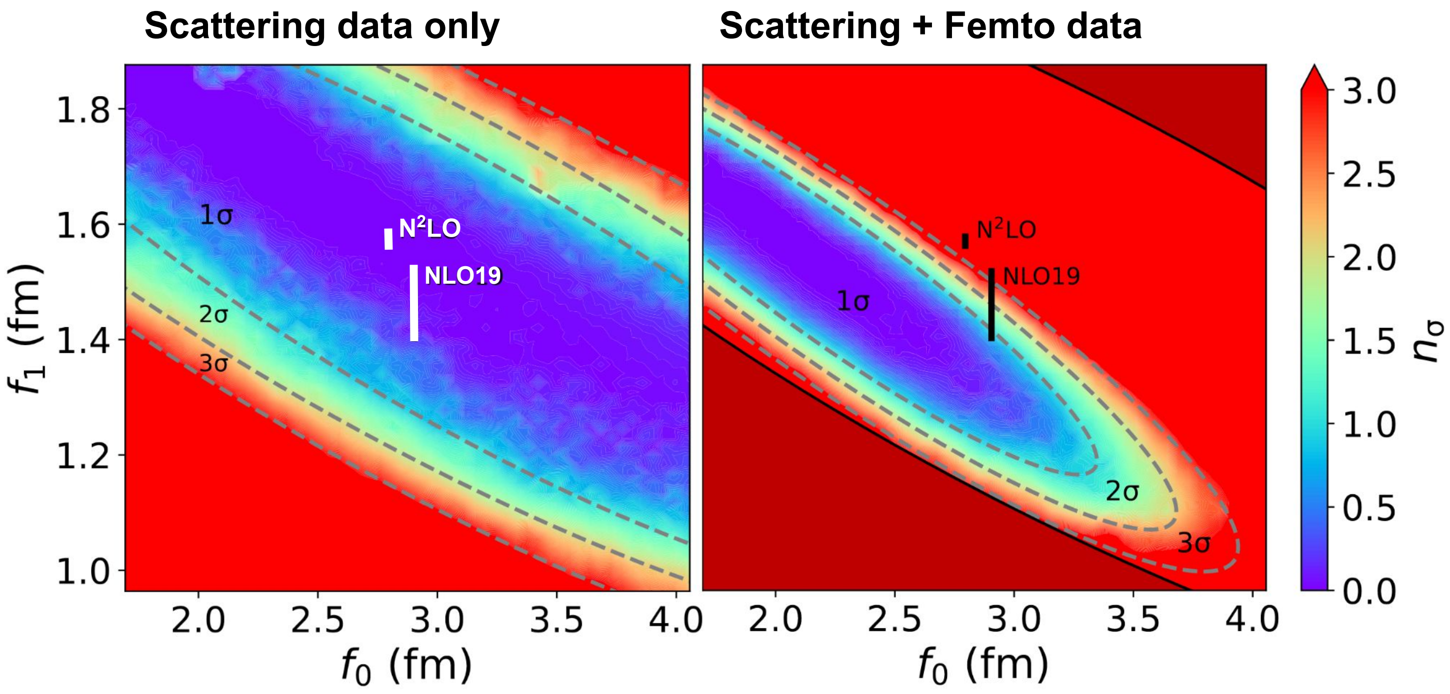
Mihaylov, Haidenbauer and Mantovani Sarti, PLB 850 (2024), 138550

Mihaylov and Gonzalez Gonzalez, *EPJC* 83 (2023) 7, 590

Scattering length (pΛ)

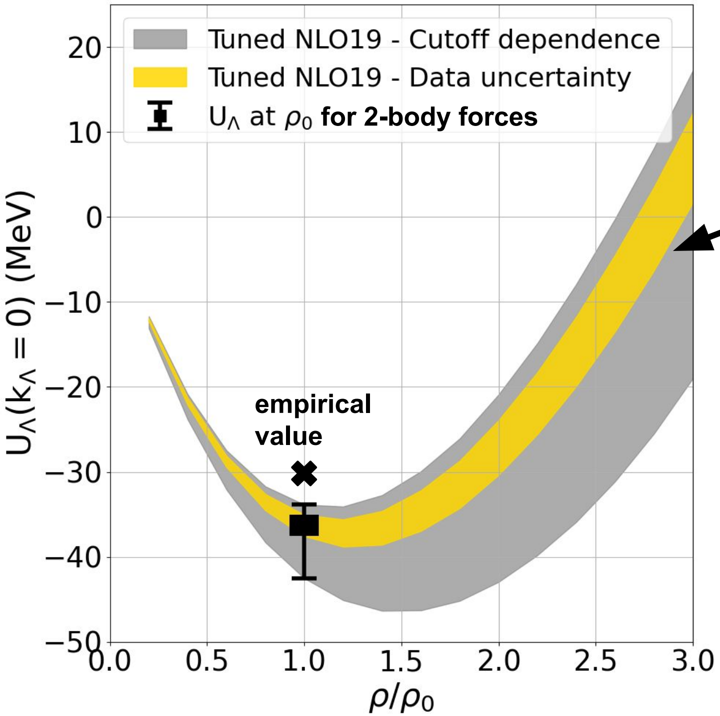
PLB 850 (2024), 138550

since 2024

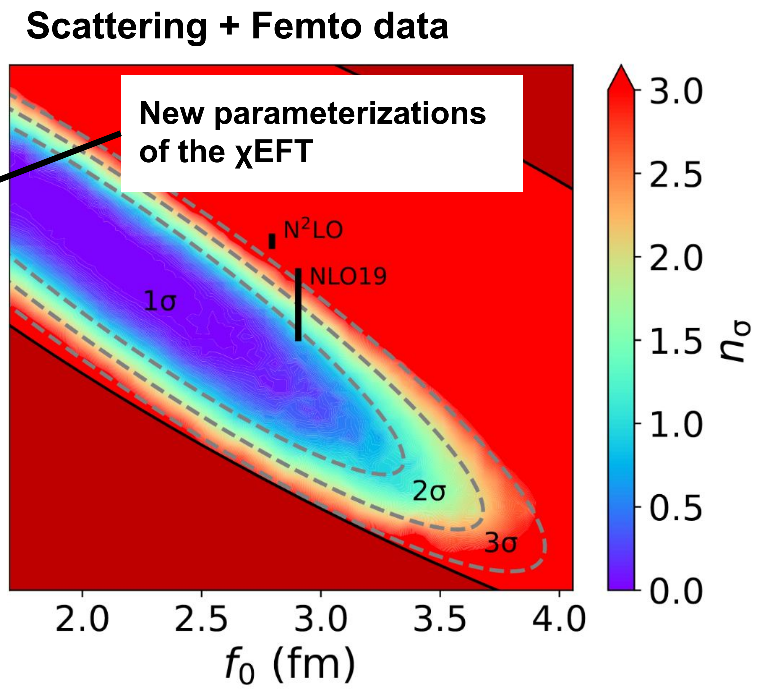


In-medium **$U_\Lambda(\rho)$** potential ($p\Lambda$)

PLB 850 (2024), 138550



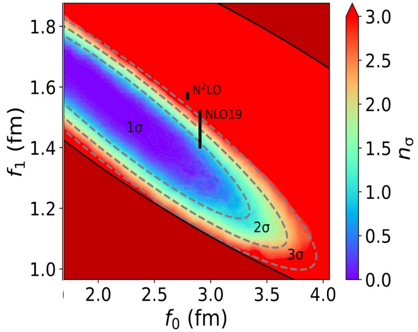
Scattering + Femto data



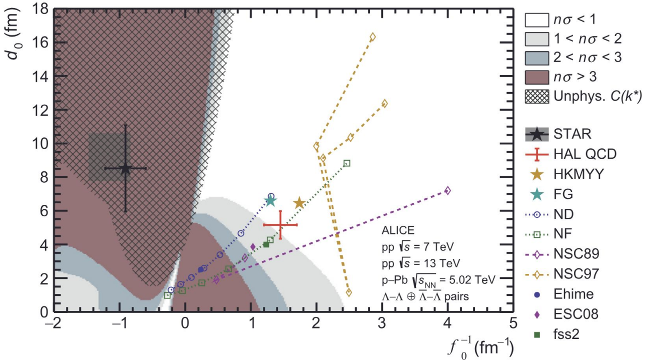
- A result compatible with repulsive 3-body forces

What about the EoS?

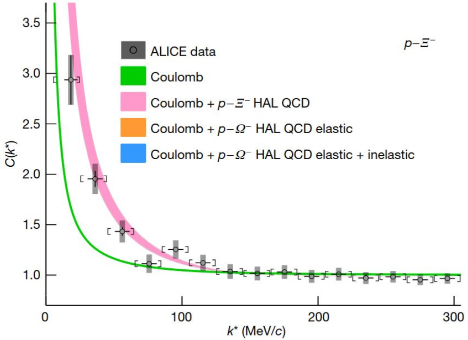
Let's use all we have



[*Mihaylov et al, PLB 850 (2024), 138550*]()
Modelling of pΛ by χEFT



[*ALICE Coll, PLB 797 (2019) 134822*]()
Good description by HAL QCD potentials:
[*HAL QCD Coll, Nucl.Phys.A 998 121737, 2020*]()

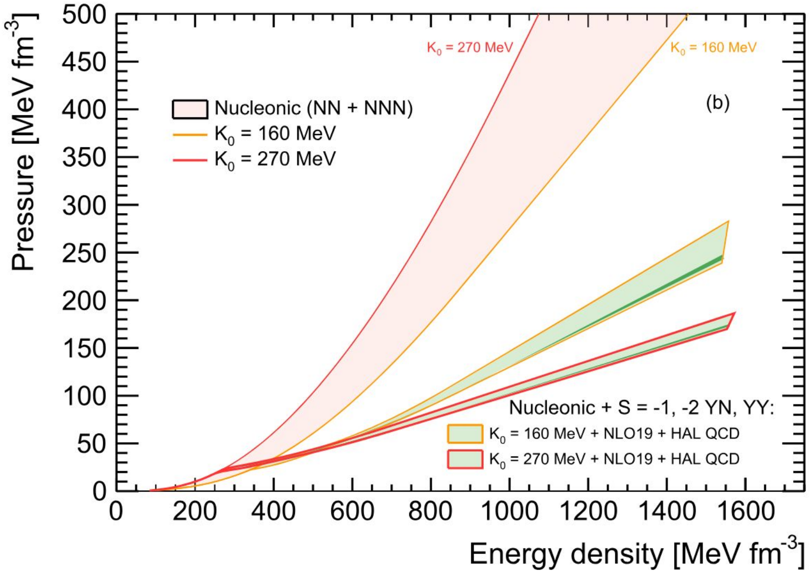


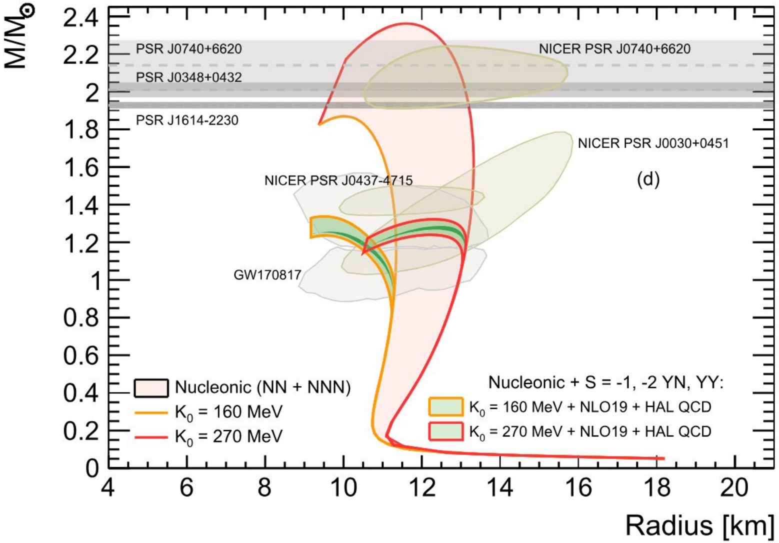
[*ALICE Coll, Nature 588 232-238, 2020*]()
Good description by HAL QCD potentials:
[*HAL QCD Coll, Nucl.Phys.A 998 121737, 2020*]()

- Take available (femto) data on the Λ and Ξ interaction.
  pΣ0 data available but low statistical significance
  Preliminary ALICE results on pΣ+ available but not used in this analysis
- A Brueckner–Hartree–Fock (BNF) approach adopted by ***Isaac Vidaña***, using potentials from the theories describing the ALICE data, to construct the EoS.
- Adopt the Tolman–Oppenheimer–Volkoff to evaluate the corresponding mass-radius relation for neutron stars.
  [*I. Vidana et al, EPJA 61 (2025), 3, 59*]()

The “two-body” equation of state

[I. Vidana et al, EPJA 61 (2025), 3, 59](#)



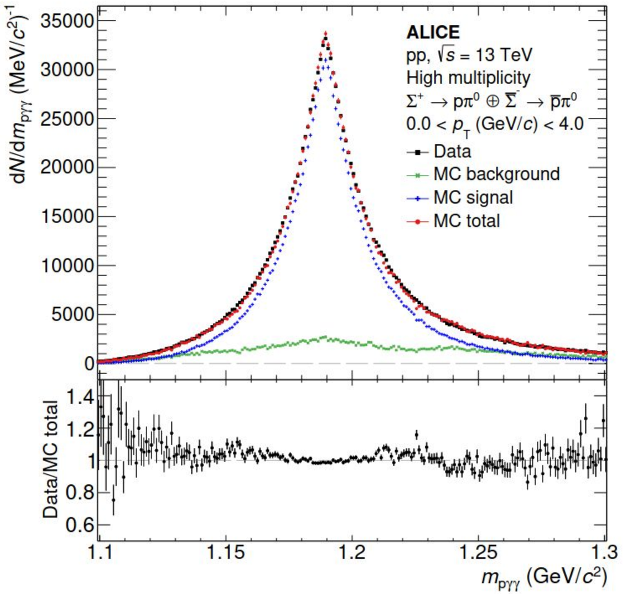


- State of the art data and models are unable to describe the existence of heavy NS. **The hyperon puzzle remains an open question!**
- Possible solutions introduce additional repulsion, e.g. three body forces.
- Three-body data and more systems in the two-body sector will help.
- A more exotic solution is proposed by introducing QCD axions in neutron stars.

Expanding our knowledge using pΣ^+

ALICE Collaboration, arXiv:2510.14448 (2025)

A novel technique to reconstruct the Σ by detecting the proton and a single photon. The second photon is inferred using momentum conservation constraints.



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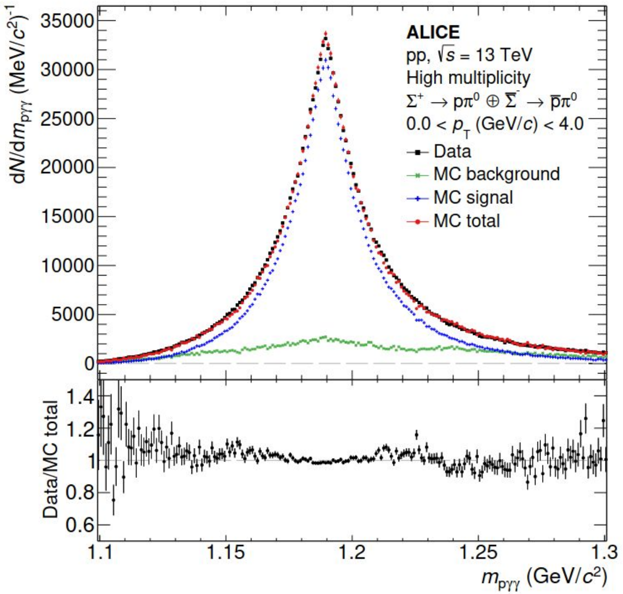
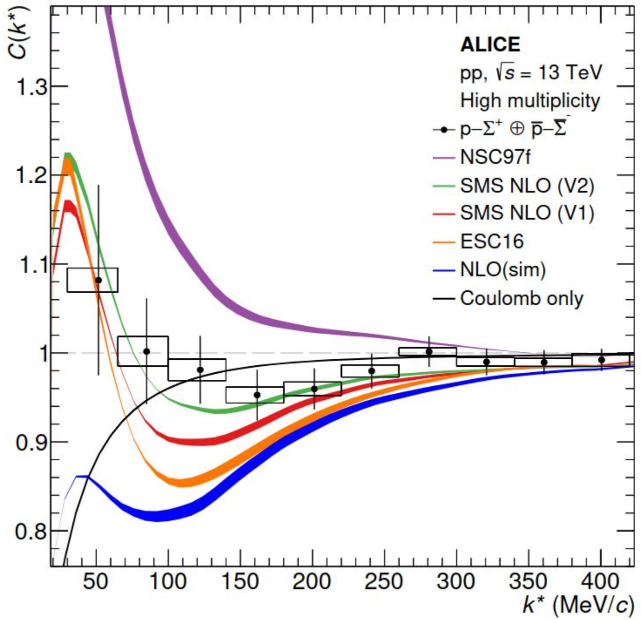
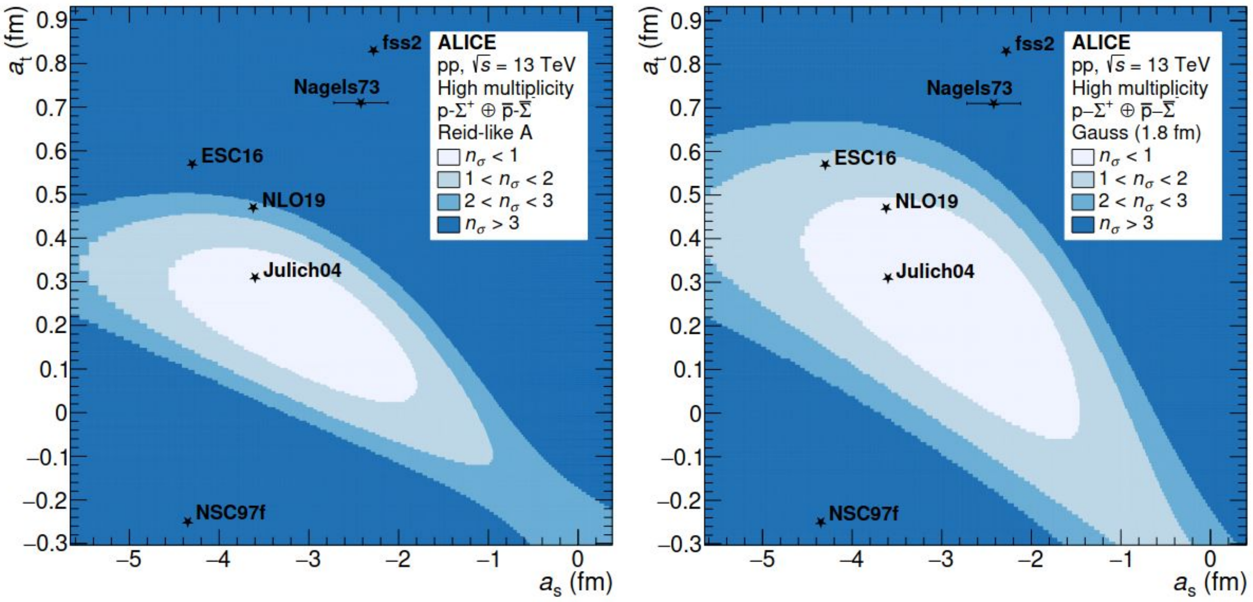




Expanding our knowledge using pΣ^+

ALICE Collaboration, arXiv:2510.14448 (2025)

- The scattering parameters we extracted using two different potentials
- Some small tension to χEFT, highlighting ones again the benefits of the femtoscopy data, even in a system difficult to reconstruct!



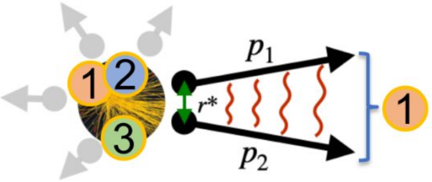
Let’s switch gears

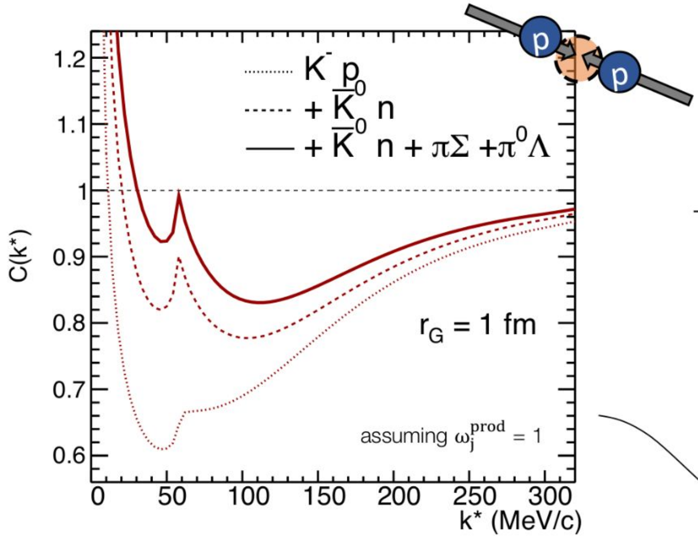
COUPLED CHANNELS

Further recent developments

Study coupled channels in S=-1 and S=-2

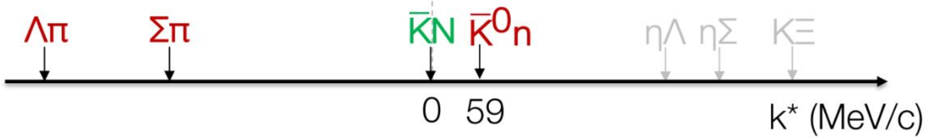
$$C(k^*) = \underbrace{\int S_1(\vec{r}^*)\ |\psi_{1\to1}(\vec{k}^*,\vec{r}^*)|^2\, d^3r^*}_{\text{elastic } 1\to1} + \underbrace{\sum_{j\neq1} \omega_j^{prod} \int S_j(\vec{r}^*)\ |\psi_{j\to1}(\vec{k}_j^*,\vec{r}^*)|^2\, d^3r^*}_{\text{inelastic } 2,3,\ldots\to1}$$





Below threshold:
increase the strength of CF
→ shift upward of CF e.g. Σπ

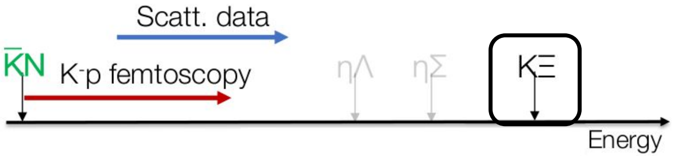
Above threshold:
modify the shape of CF
→ cusp structure e.g. $\bar{K}^0 n$



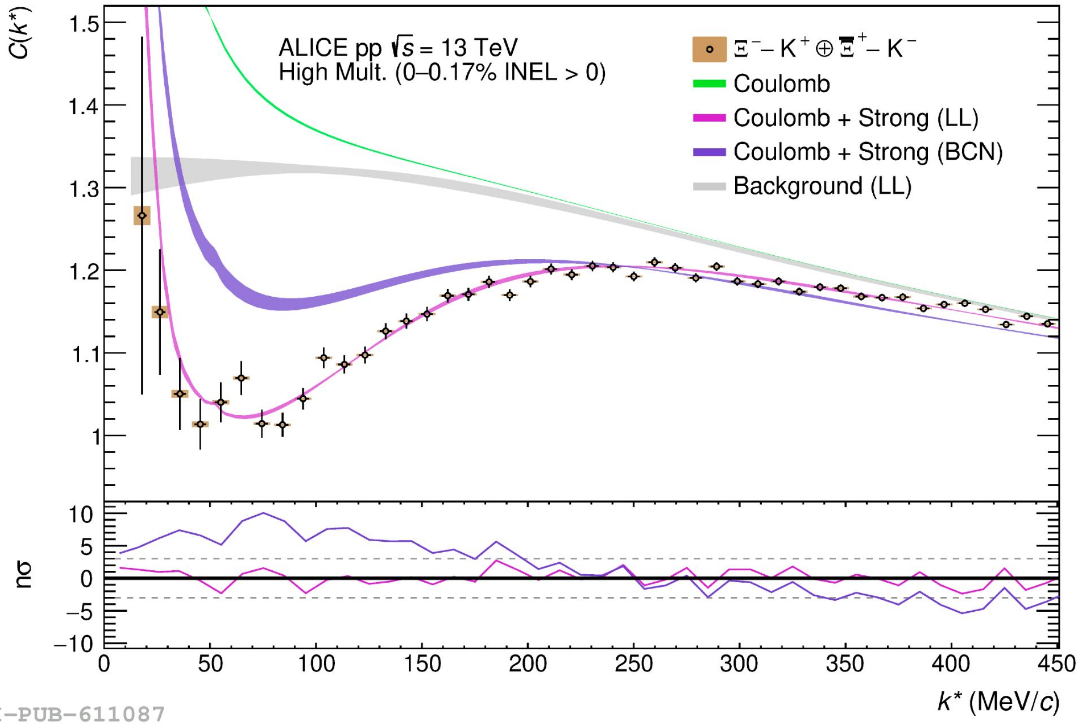
For more details: J. Haidenbauer NPA 981 (2019), Y. Kamiya et al. PRL 124 (2020)
L. Fabbietti, VMS, O. Vazquez Doce Ann.Rev.Nucl.Part.Sci. 71 (2021)

Accessing the $\Xi^{-}K^{+}$ system with femtoscopy

Study coupled channels in *<u>S=-1</u>* *and S=-2*



ALICE Collaboration, arXiv:2509.24519 (2025)



- Complement previous Kbar-p results using Ξ-K correlations
- Extracted scattering length (LL fit, strategy 1) is larger (both Re and Im) compared to theory prediction
- N.B. Zero-effective range approximation used, for which LL gives most accurate results

$$\Re f_0 = -0.61 \pm 0.02(\text{stat}) \pm 0.07(\text{syst})\ \text{fm}$$

$$\Im f_0 = 0.41 \pm 0.04(\text{stat}) \pm 0.01(\text{syst})\ \text{fm}$$

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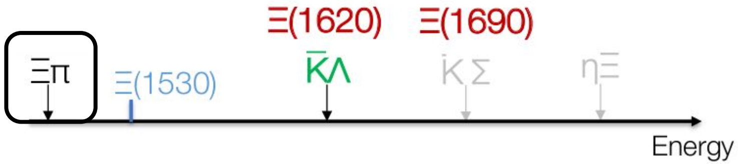

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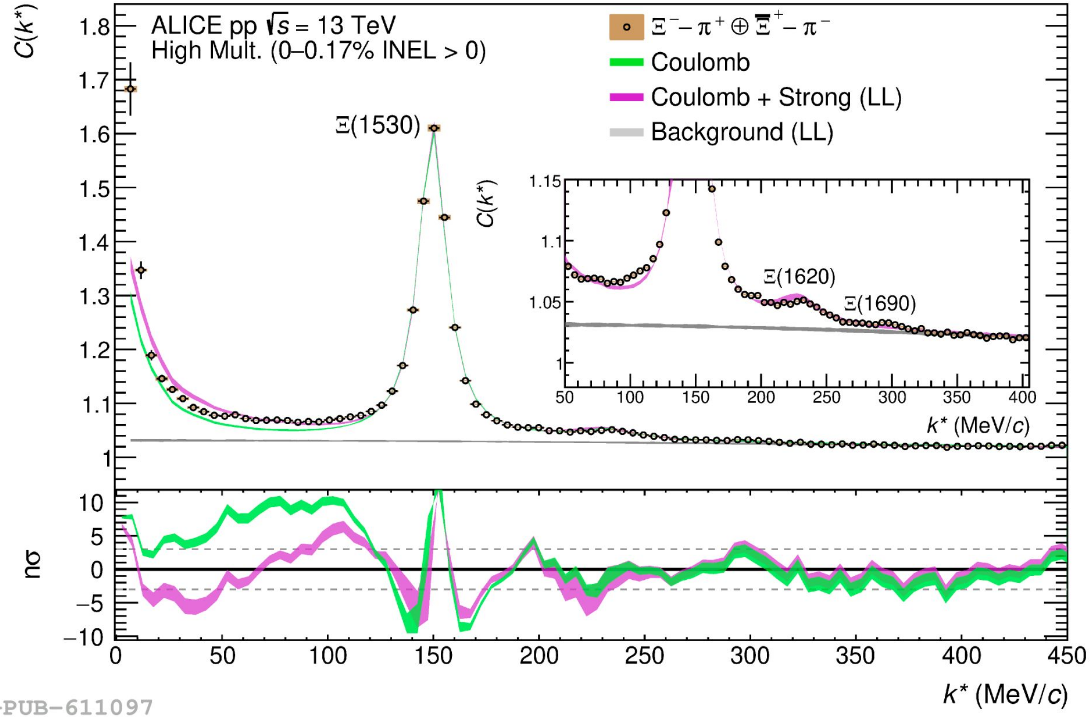


ALI-PUB-611097

- Complement previous Kbar-Λ results using Ξ-π correlations
- Extracted scattering length (LL fit, strategy 1), showing imaginary part compatible with zero
- N.B. Zero-effective range approximation used, take the values with a grain of salt

$$\Re f_0 = 0.070 \pm 0.004(\text{stat}) \pm 0.003(\text{syst})\ \text{fm}$$

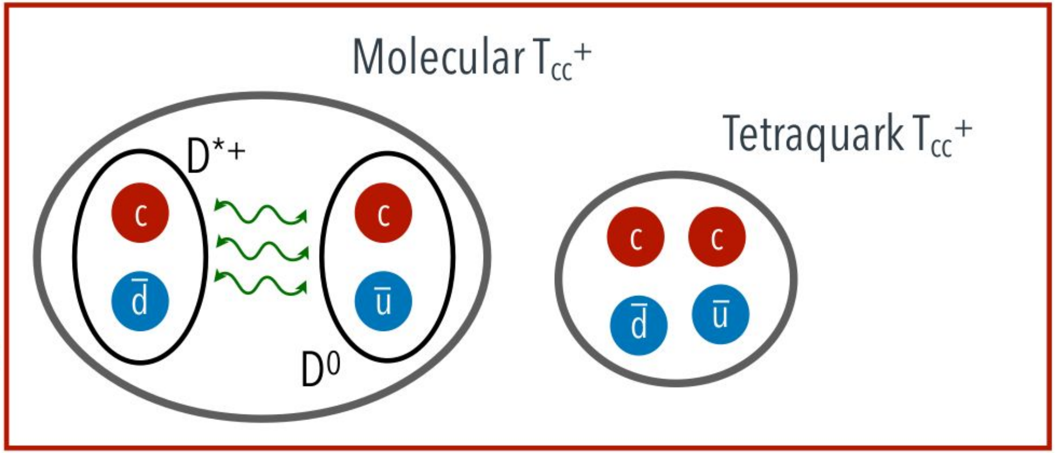
$$\Im f_0 = 0.0021 \pm 0.003(\text{stat}) \pm 0.010(\text{syst})\ \text{fm}$$

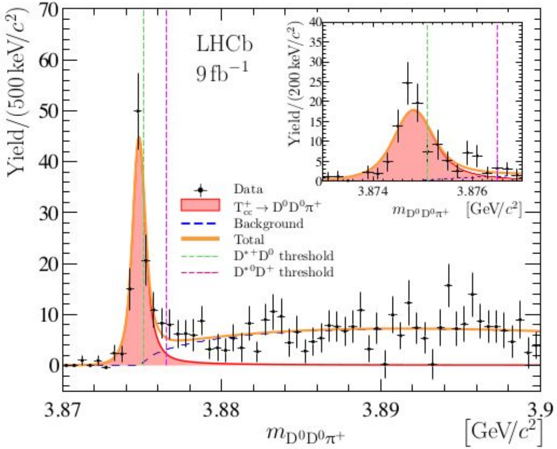
Outlook: the future is charming

- Charm molecules?

System	I ($J^{P(C)}$)	Candidate
np	0 (1^+)	deuteron
ND	0 ($1/2^-$)	$\Lambda_c(2765)$
ND*	0 ($3/2^-$)	$\Lambda_c(2940)$
ND	0 ($1/2^-$)	$\Sigma_c(2800)$
$D^*\bar{D}$	0 (1^{++})	X(3872)
D*D	0 (1^+)	T_{cc}
$D_1\bar{D}$	0 (1^{--})	Y(4260)
$D_1\bar{D}^*$	0 (1^{--})	Y(4360)
$\Sigma\bar{D}$	1/2 ($1/2^-$)	$P_c(4312)$
$\Sigma\bar{D}^*$	1/2 ($1/2^-$)	$P_c(4457)$
$\Sigma\bar{D}^*$	1/2 ($3/2^-$)	$P_c(4440)$

Peng et al, Phys. Rev. D 105, 034028 (2022)





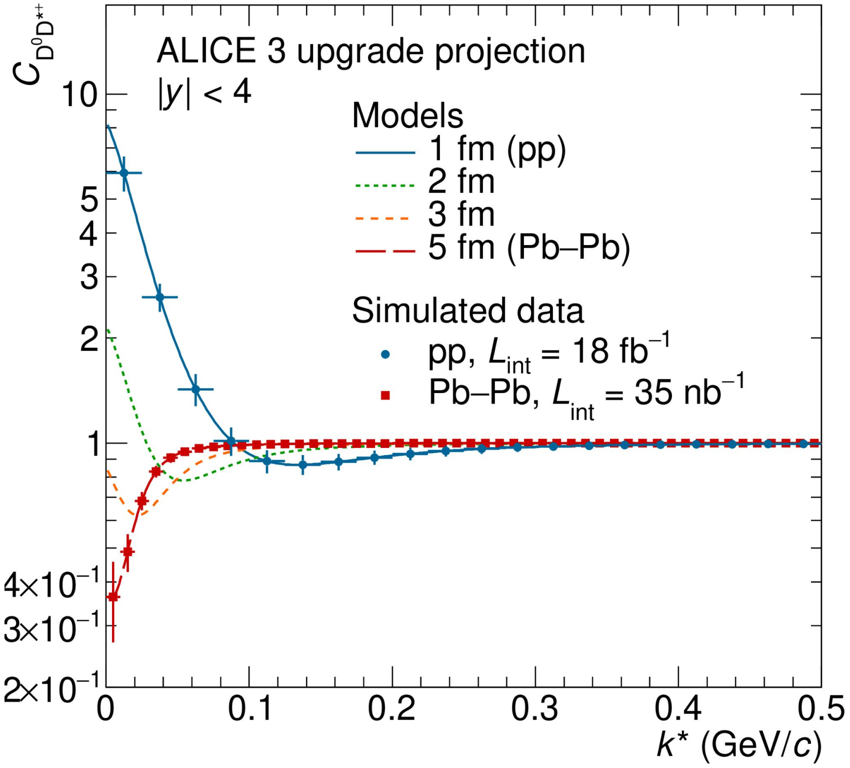
- Just below the D*D threshold **Ideal candidate to be a molecular state**

LHCb: Nature Phys. 18 (2022) 7, 751-754

Outlook: the future is charming

- Charm molecules?

ALICE3 LOI: CERN-LHCC-2022-009



- ALICE 3: large acceptance, high luminosity, excellent spatial resolution.
- Run 5: ideal laboratory for the measurement of charm-hadron momentum correlations in different colliding systems.
- Source size dependent modification of the correlation function in presence of a bound state. Yuki Kamyia et al, EPJA 58 (2022) 7, 131

p-ρ^0 femtoscopy

The latest gem in correlations

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STRONG INTERACTIONS | NEWS

ALICE observes ρ–proton attraction

7 November 2025

A report from the ALICE experiment.

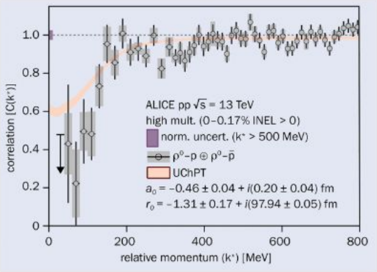


Fig. 1. The measured ρ^0–proton correlation in high-multiplicity pp collisions. The suppression of ρ^0–proton pairs at low relative momenta indicates an attractive interaction consistent with theoretical predictions. Credit: ALICE Collab. 2025 arXiv:2508.09867

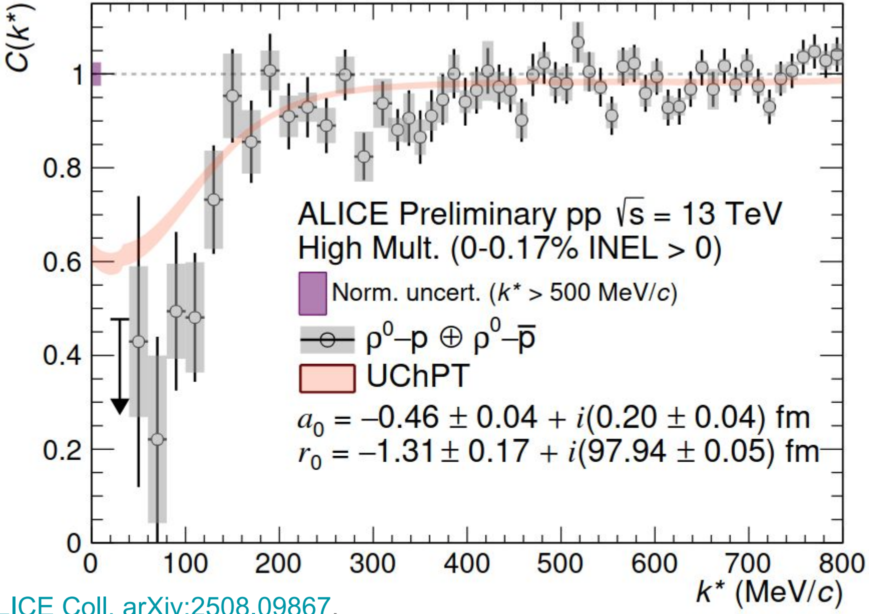
The ALICE collaboration recently obtained the first direct measurement of the attraction between a proton and a ρ^0 meson – a particle of particular interest due to its fleeting lifetime and close link to chiral symmetry breaking. The result establishes a technique known as femtoscopy as a new method for studying interactions between vector mesons and baryons, and opens the door to a systematic exploration of how short-lived hadrons behave.

p-ρ^0 femtoscopy

The latest gem in correlations

Strategy 3:

- Test a certain model, by obtaining an “external” correlation function, here from UχEFT



ALICE Coll, arXiv:2508.09867, Phys.Rev.D 111 (2025) 1, 014009

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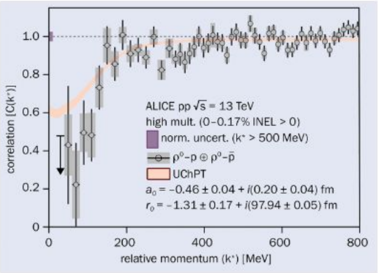

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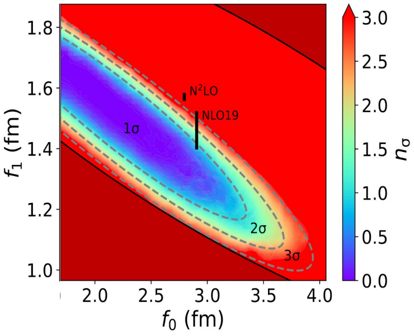
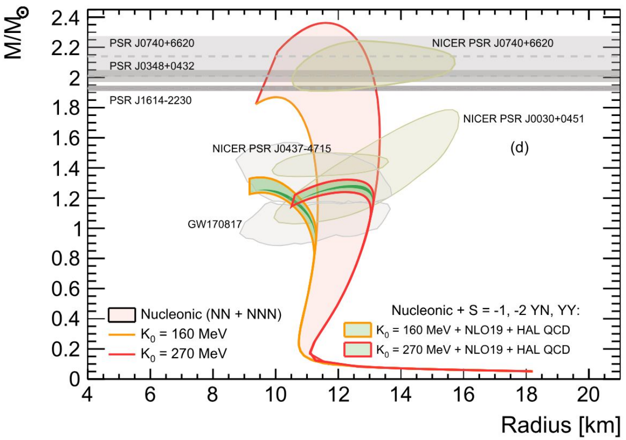
Summary

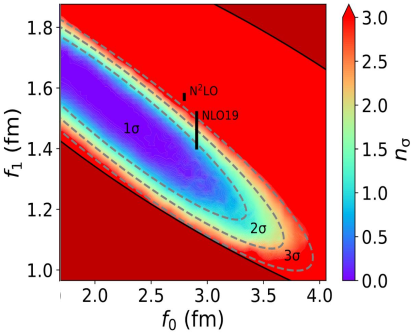


N²LO
NLO19
1σ
2σ
3σ
f_1 (fm)
f_0 (fm)
n_σ

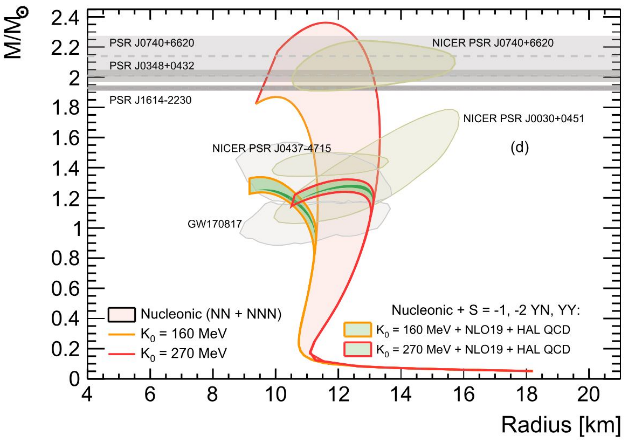


M/M⊙
Radius [km]
PSR J0740+6620
NICER PSR J0740+6620
PSR J0348+0432
PSR J1614-2230
NICER PSR J0030+0451
NICER PSR J0437-4715
(d)
GW170817
Nucleonic (NN + NNN)
K₀ = 160 MeV
K₀ = 270 MeV
Nucleonic + S = -1, -2 YN, YY:
K₀ = 160 MeV + NLO19 + HAL QCD
K₀ = 270 MeV + NLO19 + HAL QCD

Summary



N^{2}LO
NLO19
1σ
2σ
3σ
f_1 (fm)
f_0 (fm)
n_σ



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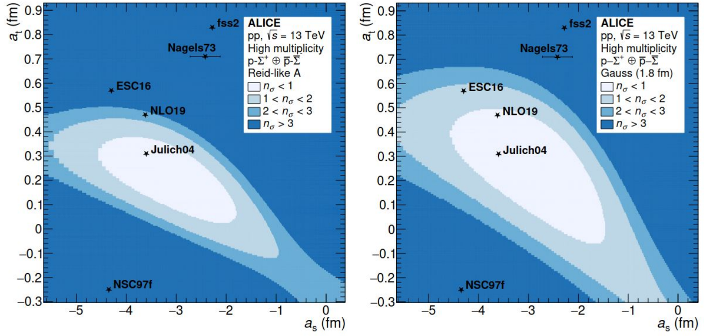
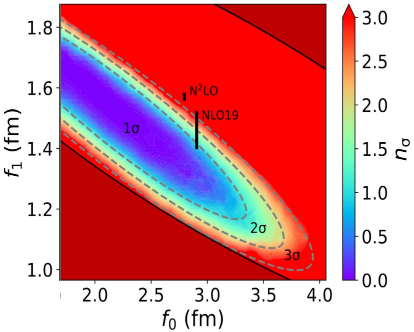
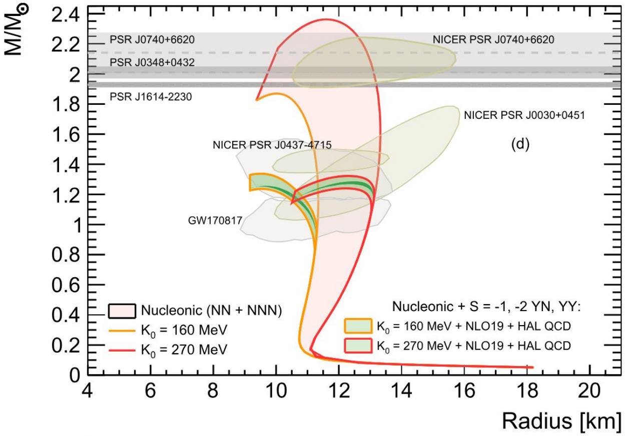
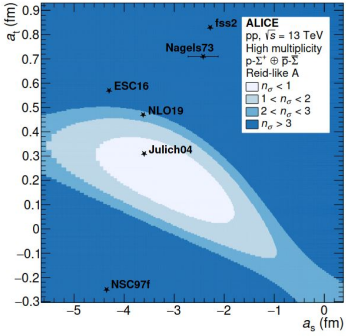


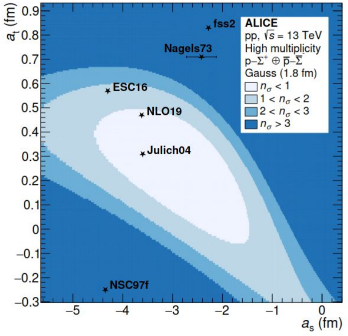
ALICE
pp, $\sqrt{s}$ = 13 TeV
High multiplicity
p-Σ$^+$ ⊕ p̄-Σ̄
Reid-like A
Gauss (1.8 fm)
n_σ < 1
1 < n_σ < 2
2 < n_σ < 3
n_σ > 3
fss2
Nagels73
ESC16
NLO19
Julich04
NSC97f
a_t (fm)
a_s (fm)

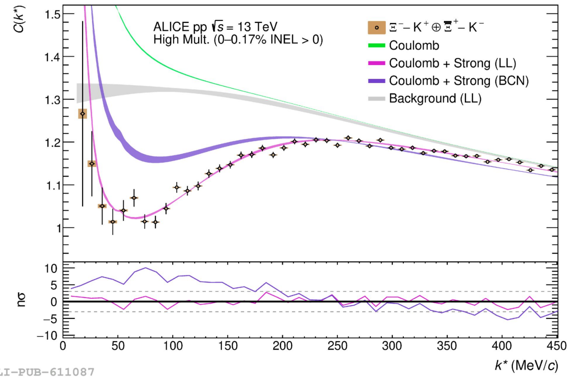
Summary



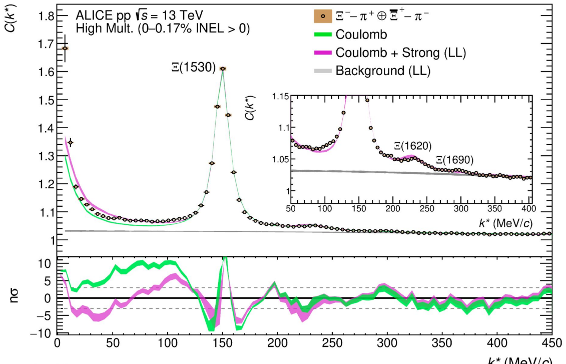






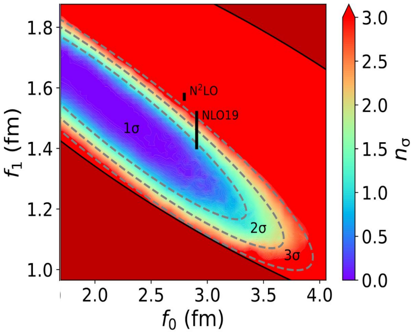


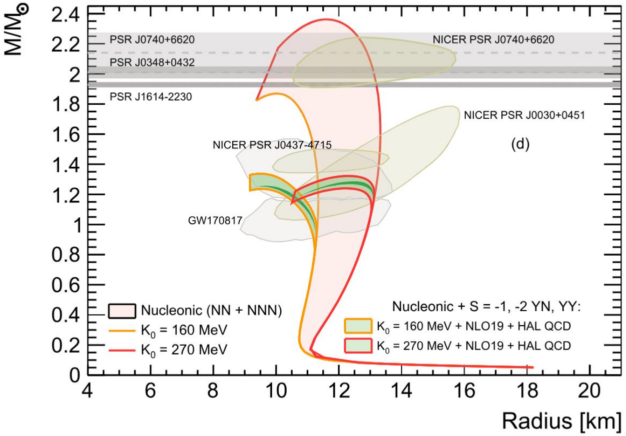
ALI-PUB-611087

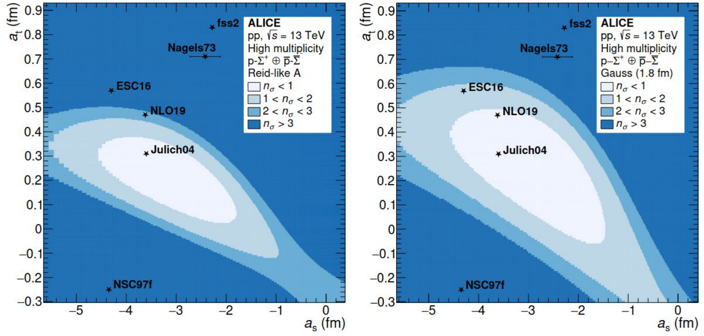


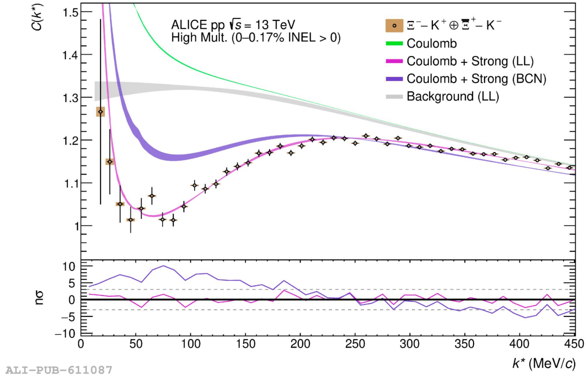
ALI-PUB-611097

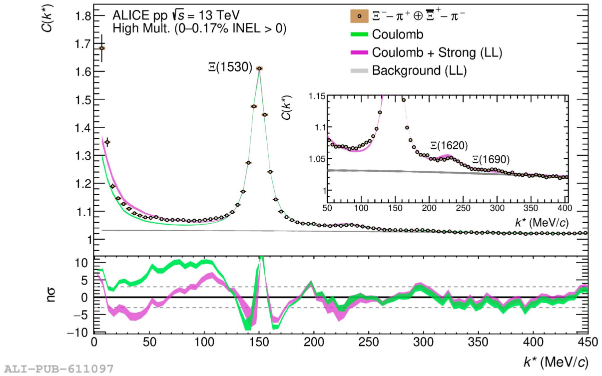
Summary











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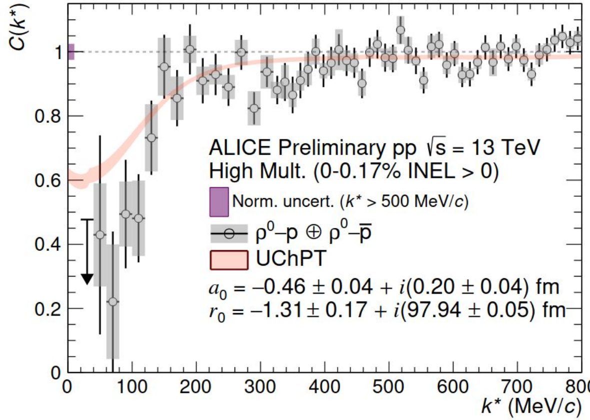


A take home message / wish

- N.B. The **hyperon puzzle must be addressed** not by one method alone, but by **using all means possible**!
- The nuclear physics methods include **correlations, scattering and hypernuclei experiments**, and we must not forget to combine our results with astrophysical observations.

- Same synergy is valid for **correlations / spectroscopy** measurements and description of exotic states.

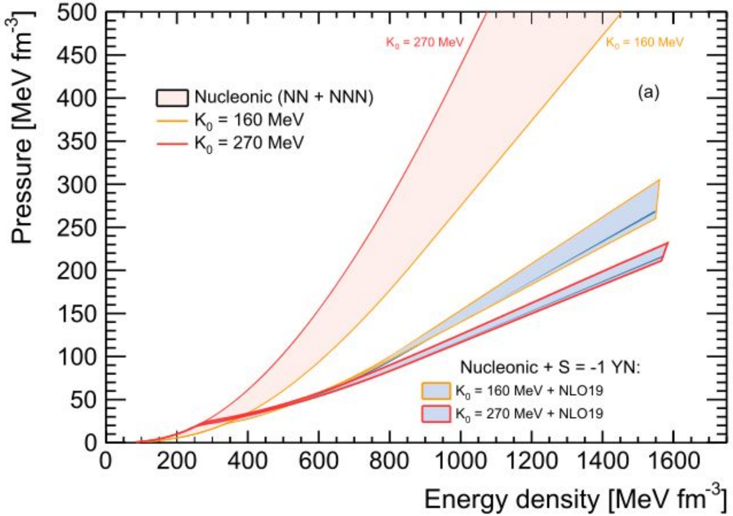
- Such workshops are a great opportunity to get a broader vision.

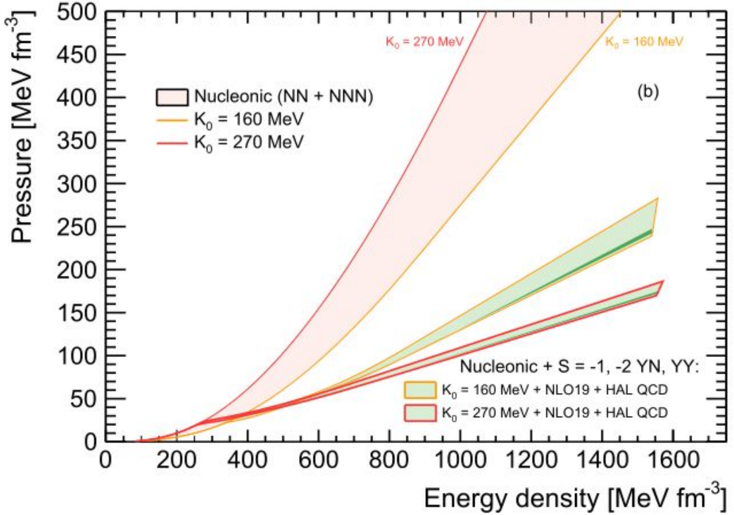
Thank you for the invitation and for your attention

Backup

EoS

I. Vidana et al, EPJA 61 (2025), 3, 59





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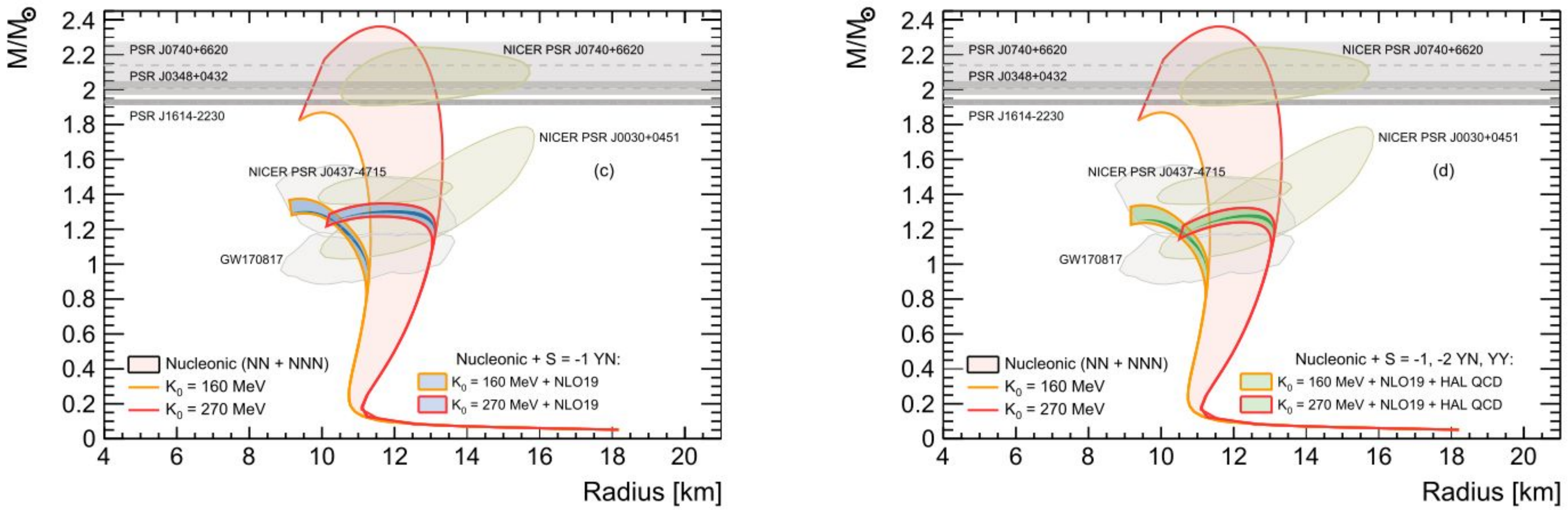

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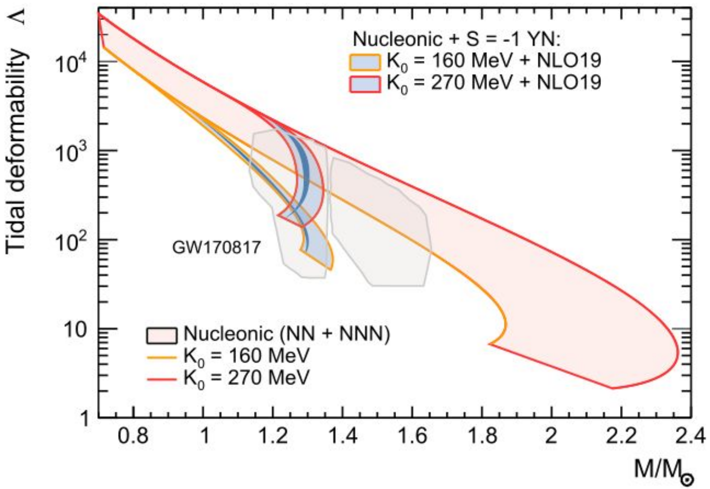
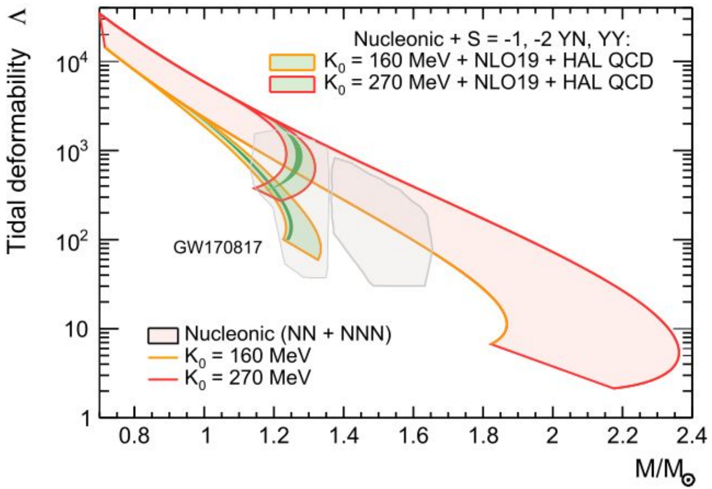
EoS [I. Vidana et al, EPJA 61 (2025), 3, 59]





Backup

Lambda-Kbar

ALICE Coll, Phys.Lett.B 845 (2023) 138145