

# Unprecedented precision studies of multi-strangeness hadronic interactions with ALICE at the LHC

Raffaele Del Grande<sup>1,\*</sup>

<sup>1</sup>Physik Department E62, Technische Universität München, 85748 Garching, Germany

*On behalf of the ALICE Collaboration*



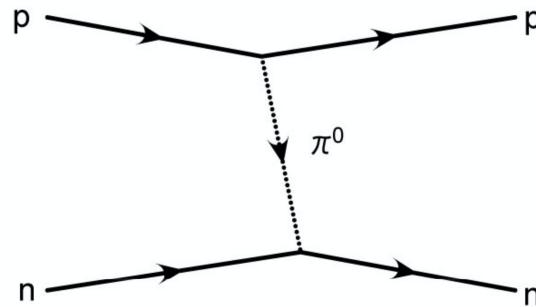
European Nuclear Physics Conference 2022 (EuNPC2022)

Santiago de Compostela, Spain

25<sup>th</sup> October 2022

\*raffaele.del-grande@tum.de

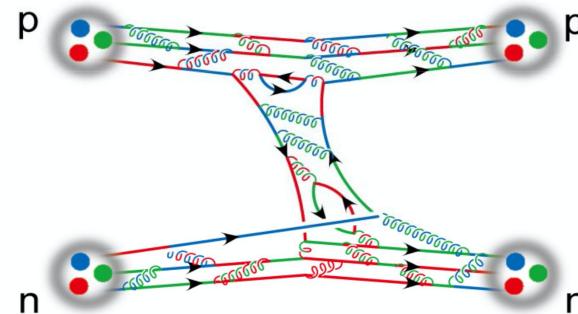
# Residual strong interaction among hadrons



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

## Effective Field Theories (EFT)

- hadrons as degrees of freedom
- low-energy coefficients constrained by data

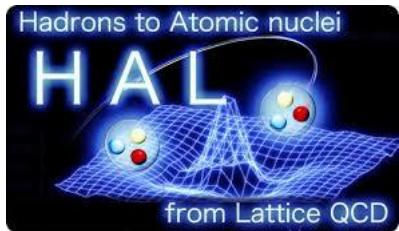


$$\mathcal{L}_{QCD}[q, \bar{q}, A; m_q, \alpha_s]$$

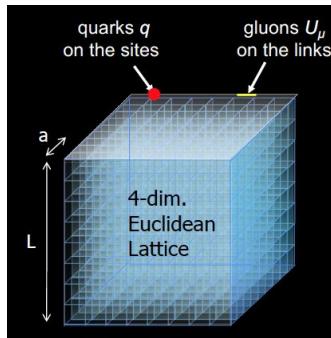
## Lattice QCD

- 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)



$$a = 0.085 \text{ fm}$$

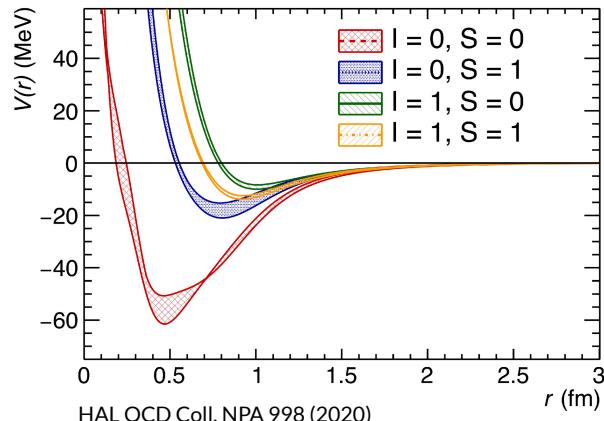
$$L = 8.1 \text{ fm}$$

$$m_\pi = 146 \text{ MeV}/c^2$$

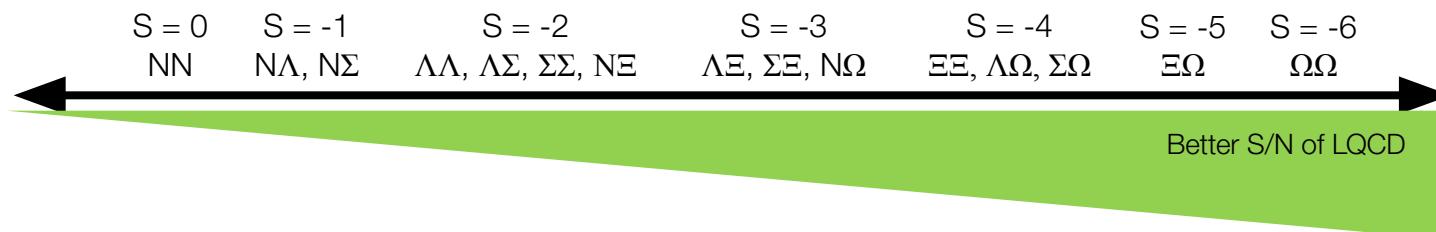
$$m_K = 525 \text{ MeV}/c^2$$



Local potentials for the nucleon- $\Xi$  interactions

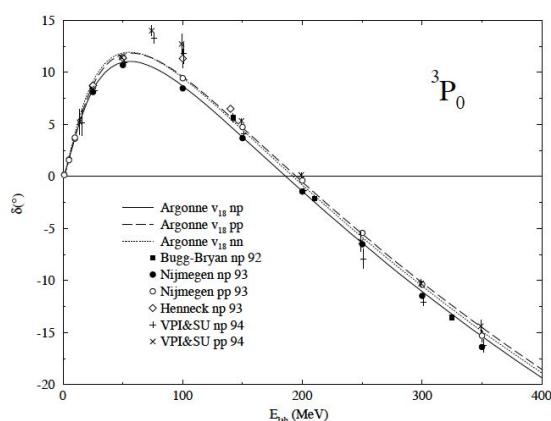


HAL QCD Coll. NPA 998 (2020)



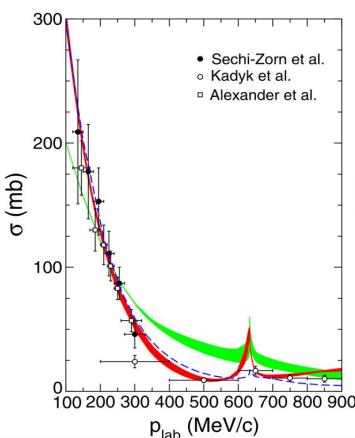
# Experimental data for two-body interactions

$N-N \rightarrow N-N$



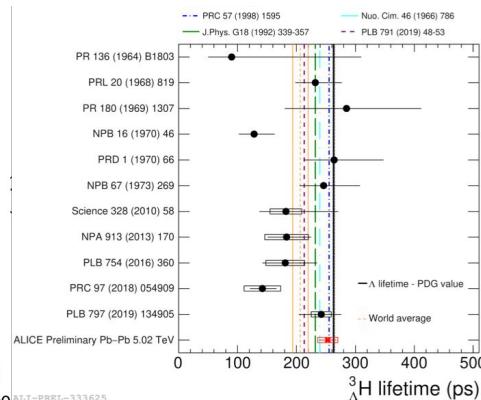
R. B. Wiringa et al. PRC 51 (1995)

$p-\Lambda \rightarrow p-\Lambda$

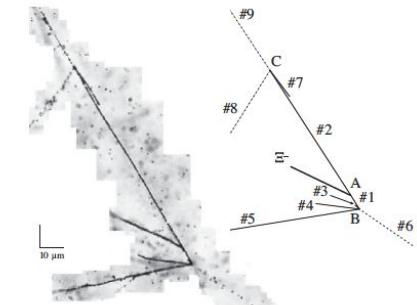


LO from H. Polinder et al. NPA 779 (2006)  
NLO from J. Haidenbauer et al. NPA 915 (2013)

Hypertriton



$\Xi$  hypernucleus



J-PARC E07 Coll. PRL 126 (2021)

$S = 0$

NN

$S = -1$

$N\Lambda, N\Sigma$

$S = -2$

$\Lambda\Lambda, \Lambda\Sigma, \Sigma\Sigma, N\Sigma$

$S = -3$

$\Lambda\Sigma, \Sigma\Sigma, N\Omega$

$S = -4$

$\Xi\Sigma, \Lambda\Omega, \Sigma\Omega$

$S = -5 \quad S = -6$

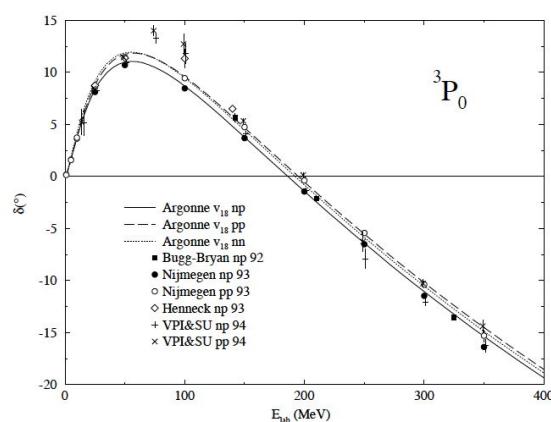
$\Xi\Omega \quad \Omega\Omega$

Better S/N of LQCD

Experimental data

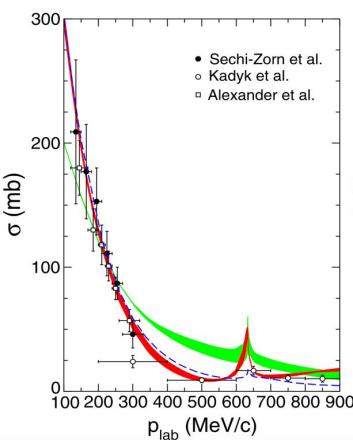
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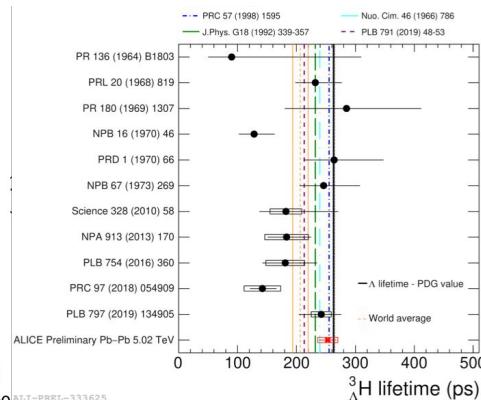
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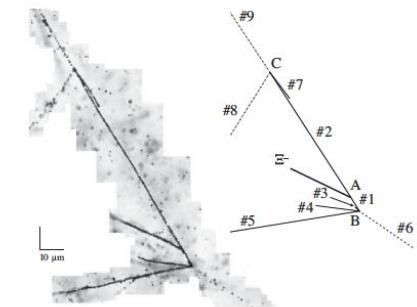


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$\Xi\Sigma, \Lambda\Omega, \Sigma\Omega$

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$\Xi\Omega$      $\Omega\Omega$

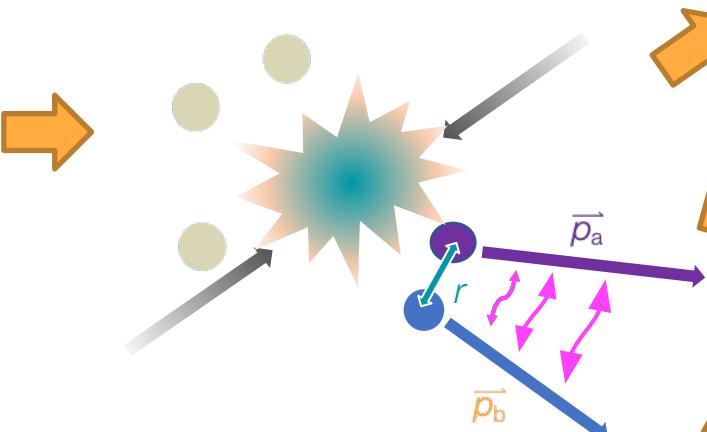


# Investigating hadronic interactions at LHC

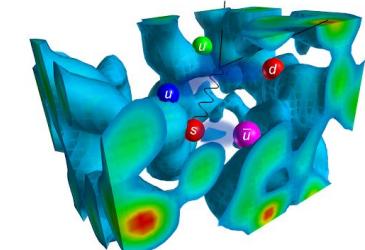
ALICE at the LHC



Hadron-hadron  
strong interactions



Test of Lattice  
QCD and  $\chi$ EFT  
calculations



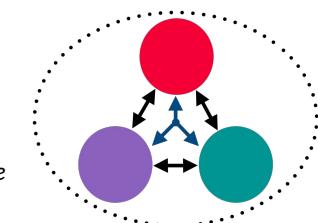
D. B. Leinweber/University of Adelaide

Impact on the  
Equation of State  
(EoS) of neutron  
stars



Three-body  
interactions

see talk by O. Vazquez Doce  
25/10/2022 P6 h.18:20

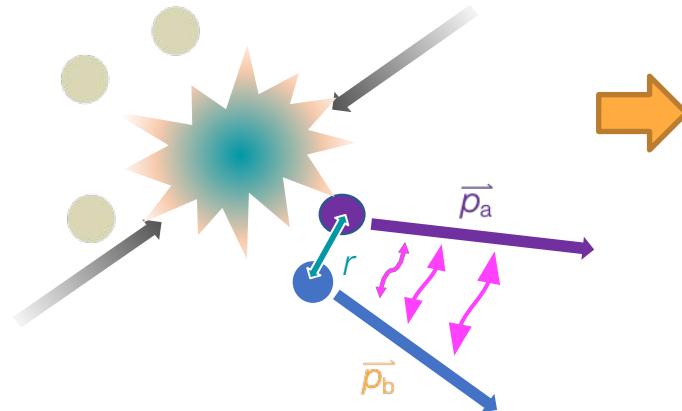


# Investigating hadronic interactions at LHC

ALICE at the LHC



Hadron-hadron  
strong interactions



Femtoscopy technique

Two-particle correlation function

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

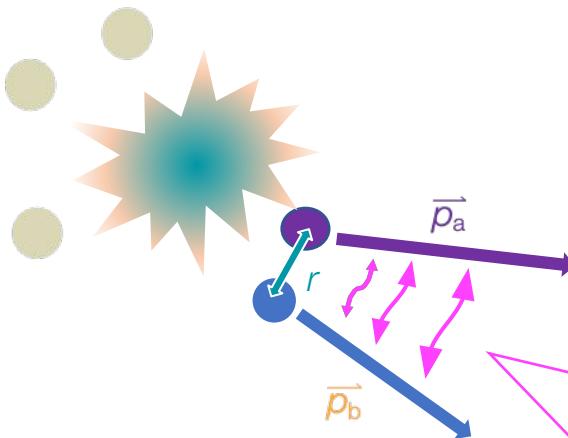
In this talk:

Colliding system: pp @  $\sqrt{s} = 13$  TeV

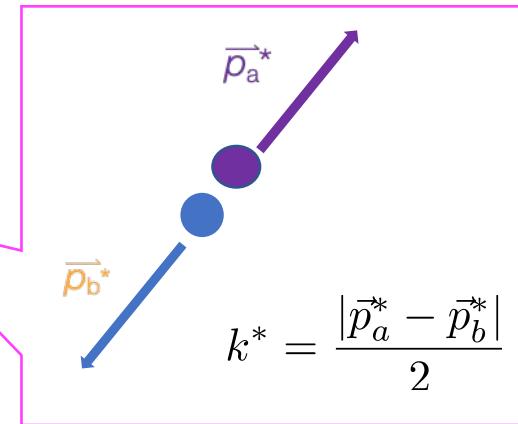
Data set: High-multiplicity events

p- $\Xi$ , p- $\Lambda$ , p- $\Omega^-$ ,  $\Lambda$ - $\Xi^-$

# Femtoscopy technique



Pair reference frame



Correlation function:

S. E. Koonin et al. PLB 70 (1977)

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

Two-particle wave function  
Emission source

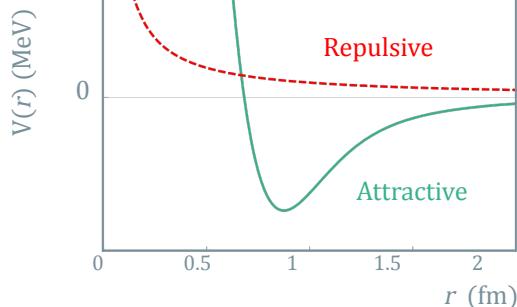
# Femtoscopy technique

Source parametrization

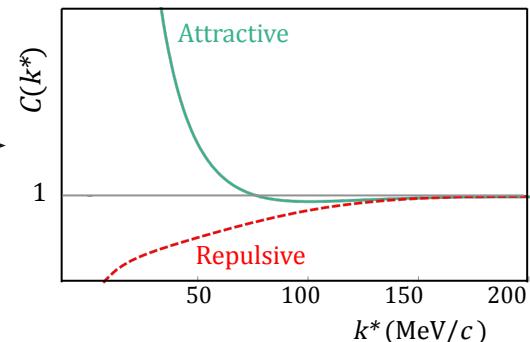


Gaussian source

Interacting potential



Correlation function



Correlation function:

S. E. Koonin et al. PLB 70 (1977)

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

Emission source

Schrödinger equation

CATS (Correlation Analysis Tool using the Schrödinger equation)  
D. Mihaylov et al. EPJC 78 (2018)

Two-particle wave function

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

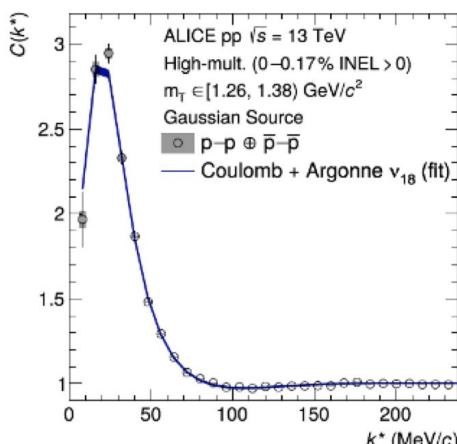
# Source determination

Femtoscopy used in a “traditional” way: known interaction → determine the source size

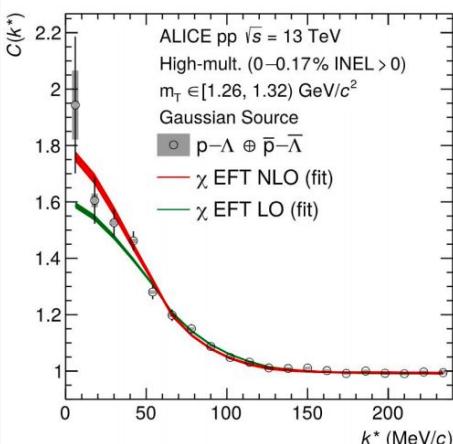
$$C(k^*) = \int S(r) |\psi(k^*, r)|^2 d^3r$$

p-p interaction:

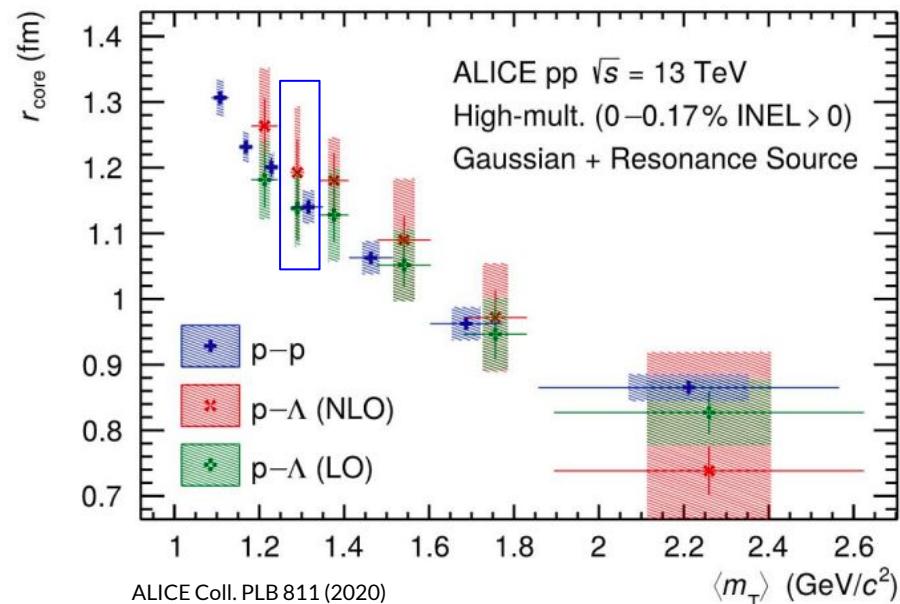
Coulomb + Argonne v18



p- $\Lambda$  interaction:  
 $\chi$ EFT NLO and LO

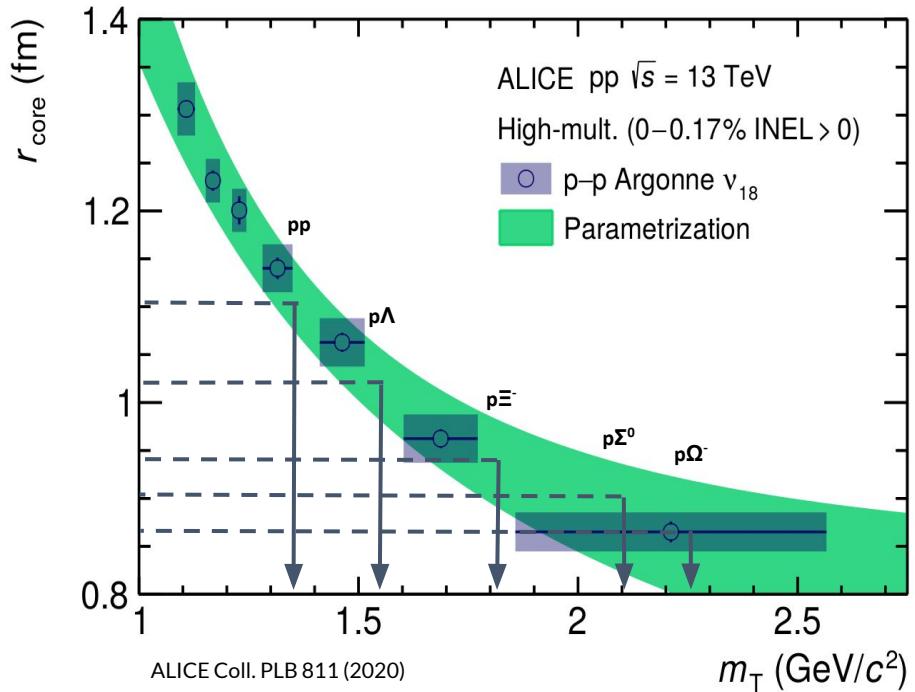
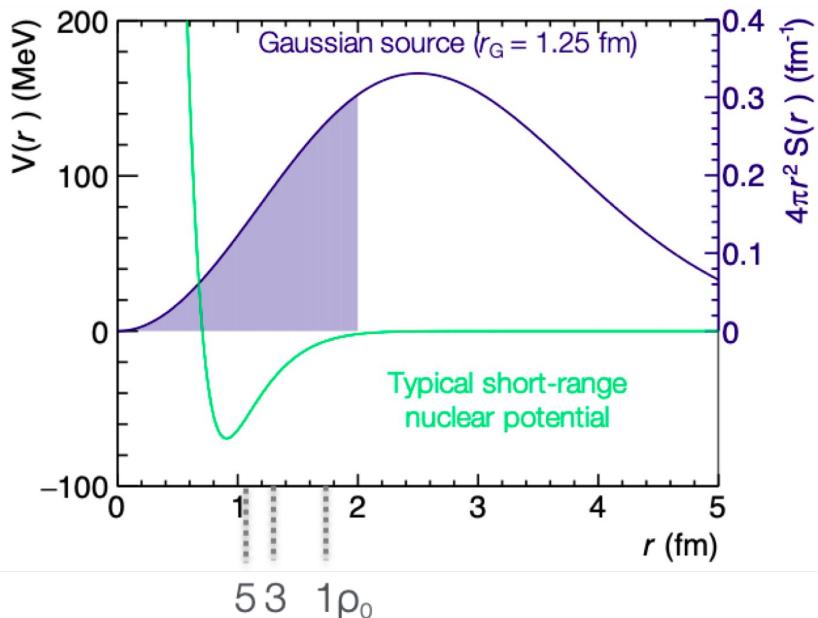


One universal source for all hadrons with strong resonance decays considered for each pair of interest



# Source determination

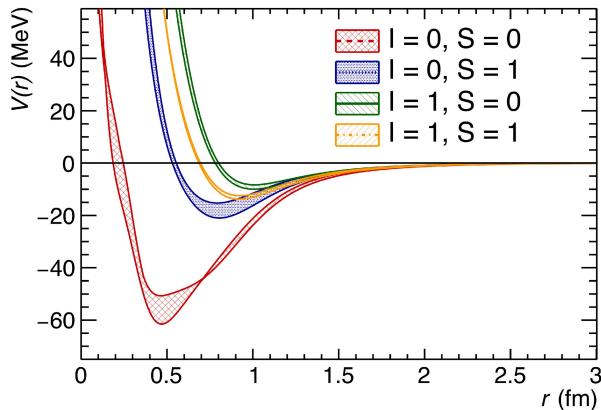
Small particle-emitting source created in pp and p-Pb collisions at the LHC.



# $|S|=2$ sector: p- $\Xi^-$ interaction and first test of LQCD

Lattice QCD potentials from HAL  
QCD Collaboration available

Local potentials for the nucleon-  
 $\Xi$  interactions



$$r_{\text{eff}} = 0.85 \text{ fm}$$

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

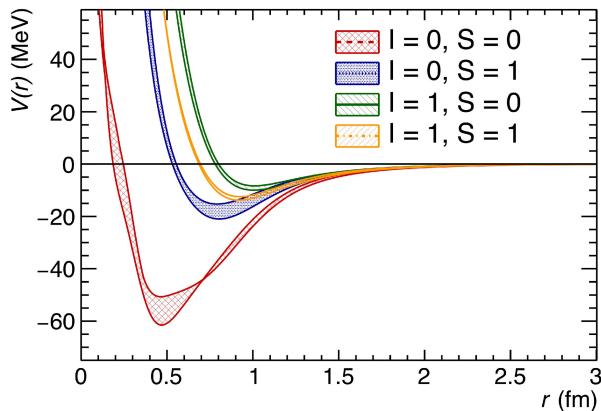
$$\mathcal{H} \cdot \psi(k^*, \mathbf{r}) = E \cdot \psi(k^*, \mathbf{r})$$

HAL QCD Coll. NPA 998 (2020)

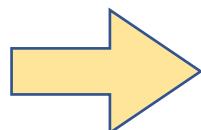
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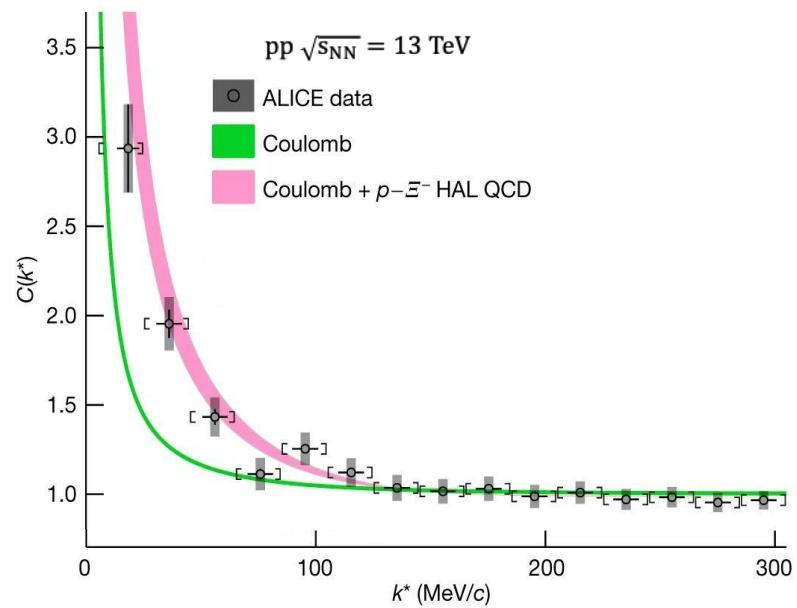
Local potentials for the nucleon-  
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HAL QCD Coll. NPA 998 (2020)



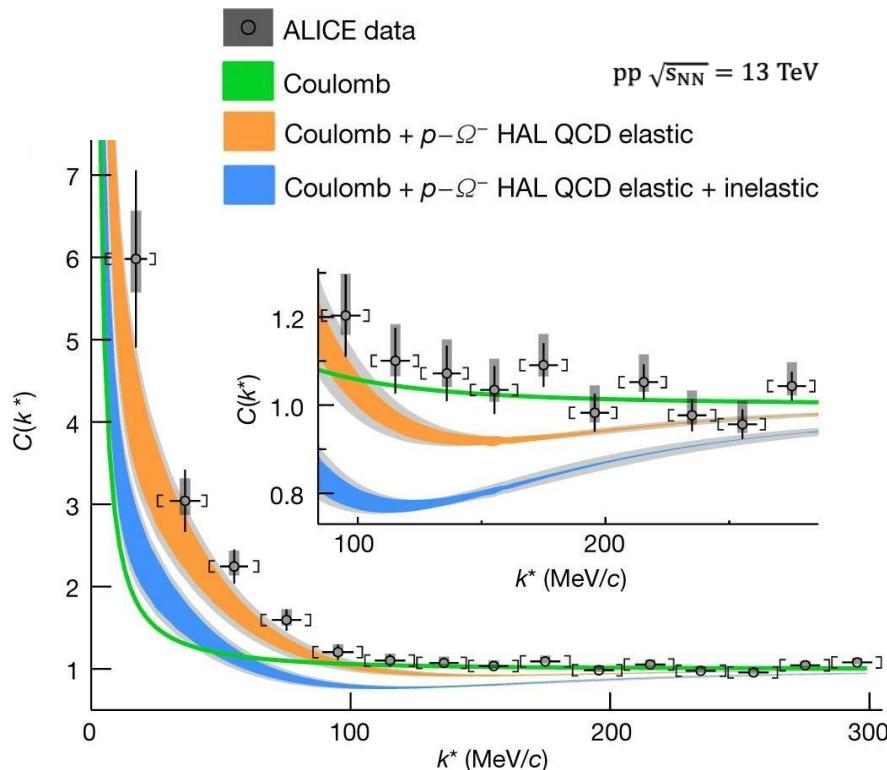
ALICE Coll. Nature 588 232–238 (2020)



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

# $|S|=3$ : $p-\Omega^-$ correlation function in pp at 13 TeV

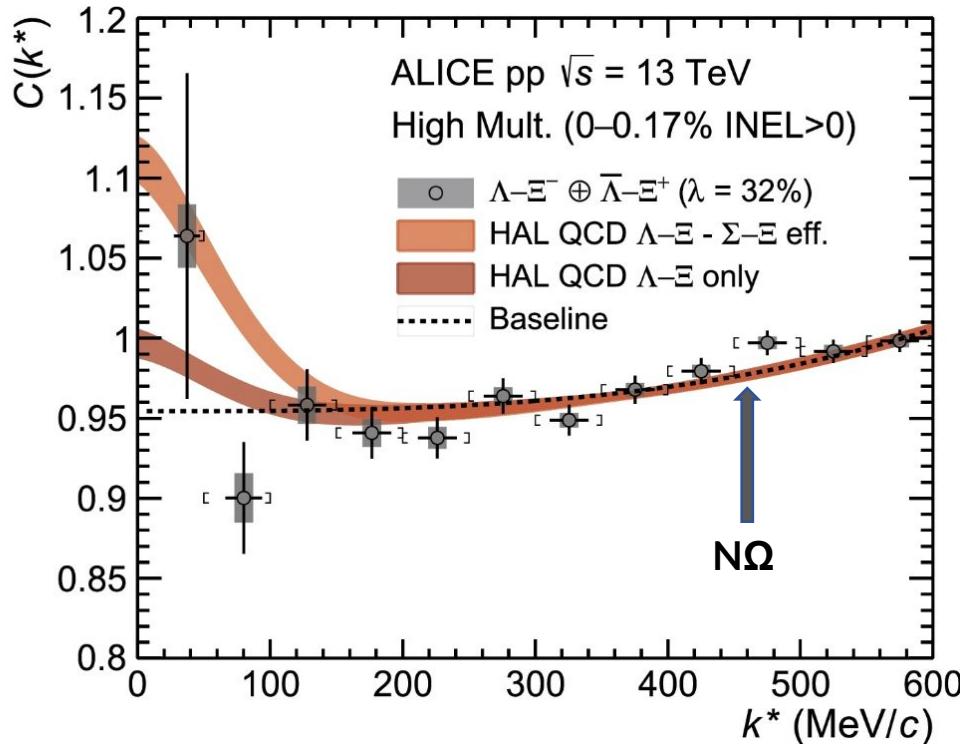
ALICE Coll. Nature 588 232–238 (2020)



- 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

# $|S|=3$ : $\Lambda$ - $\Xi^-$ interaction with femtoscopy

ALICE Coll. arXiv:2204.10258, Accepted by PLB



- Unknown contribution from coupled channels in Lattice QCD calculations  
→ Coupling  $\Lambda\Xi-\Sigma\Xi$  sizable in HAL QCD calculation
- → No sensitivity yet (“No coupling”  $0.64\text{ n}\sigma$  VS “Coupling”  $1.43\text{ n}\sigma$ )
- No  $N\Omega$  cusp visible  
→ Hint to negligible  $N\Omega-\Lambda\Xi$  coupling

# Impact on the EoS of neutron stars

Neutron stars are very dense and compact objects:

$$R \sim 10 - 15 \text{ km}$$

$$M \sim 1.5 - 2.2 M_{\odot}$$

## Outer Crust

Ions, electron gas, neutrons

## Inner Core

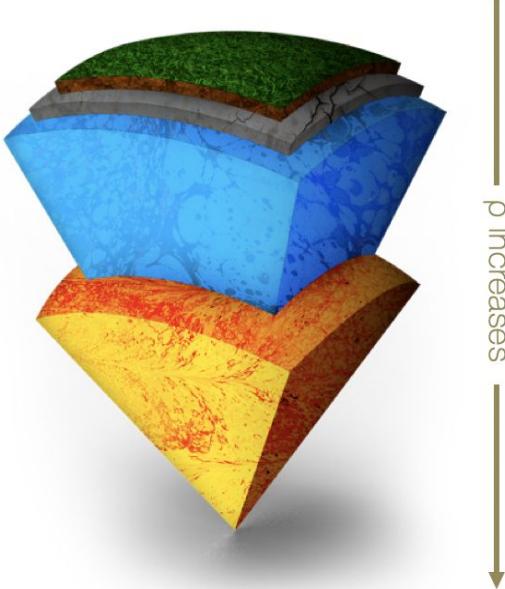
Neutrons?

Protons?

Hyperons?

Kaon condensate?

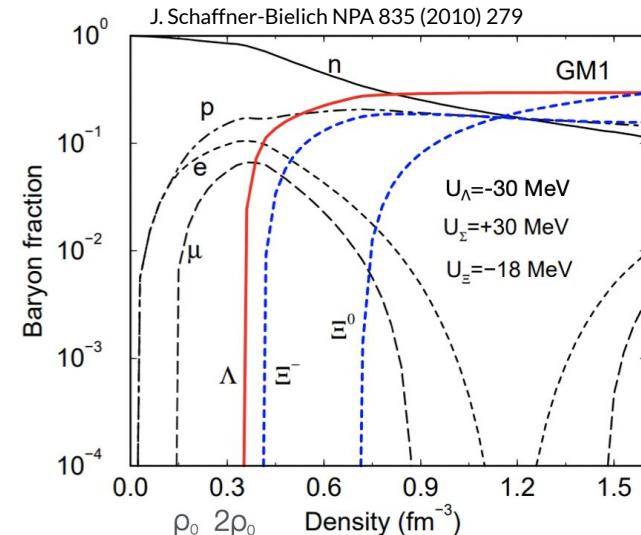
Quark Matter?



What is the EoS?

What are the constituents to consider?

How do they interact?



# Impact on the EoS of neutron stars

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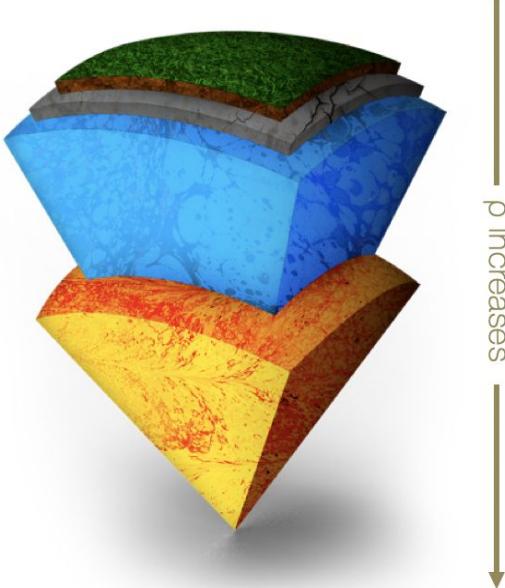
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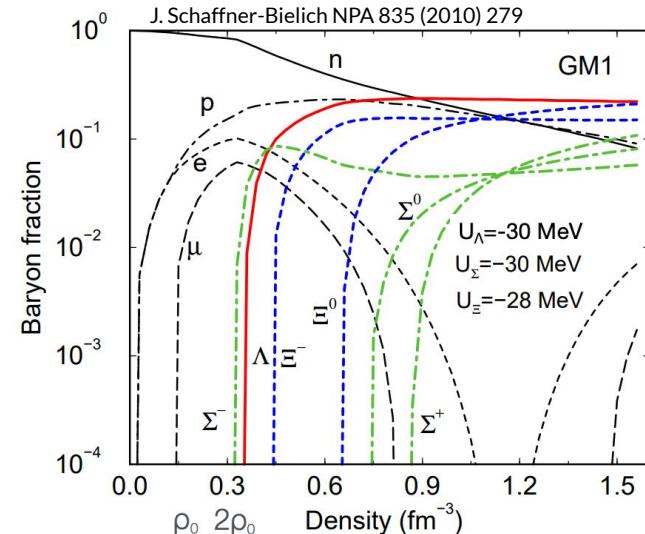
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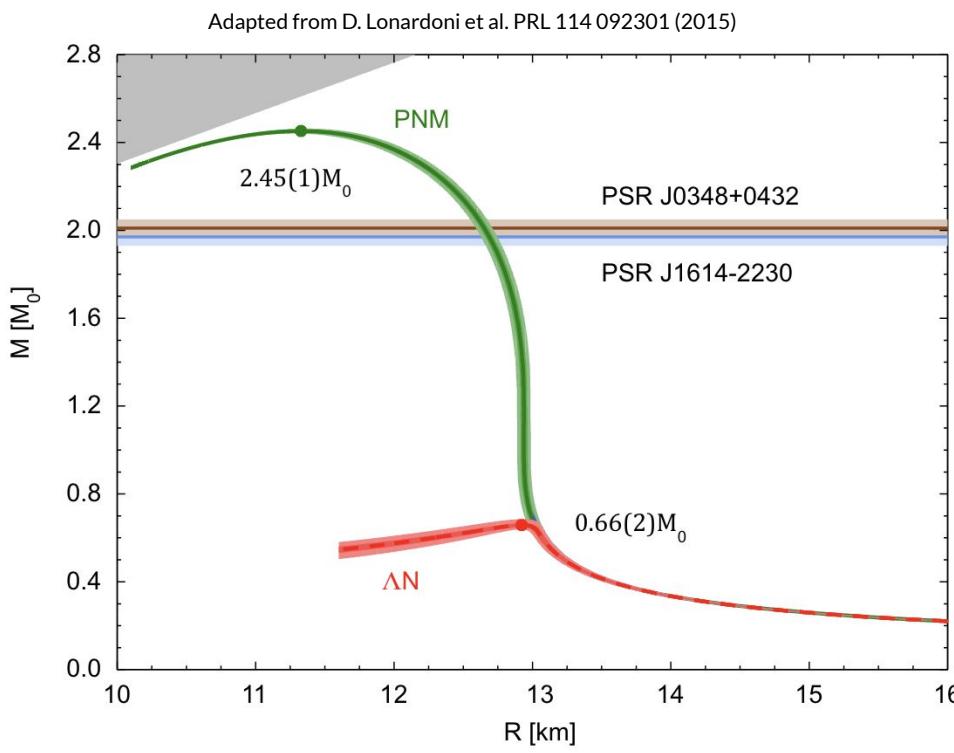
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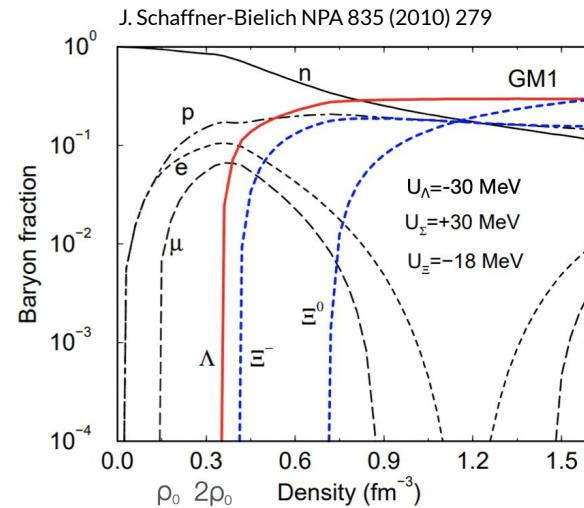
How do they interact?



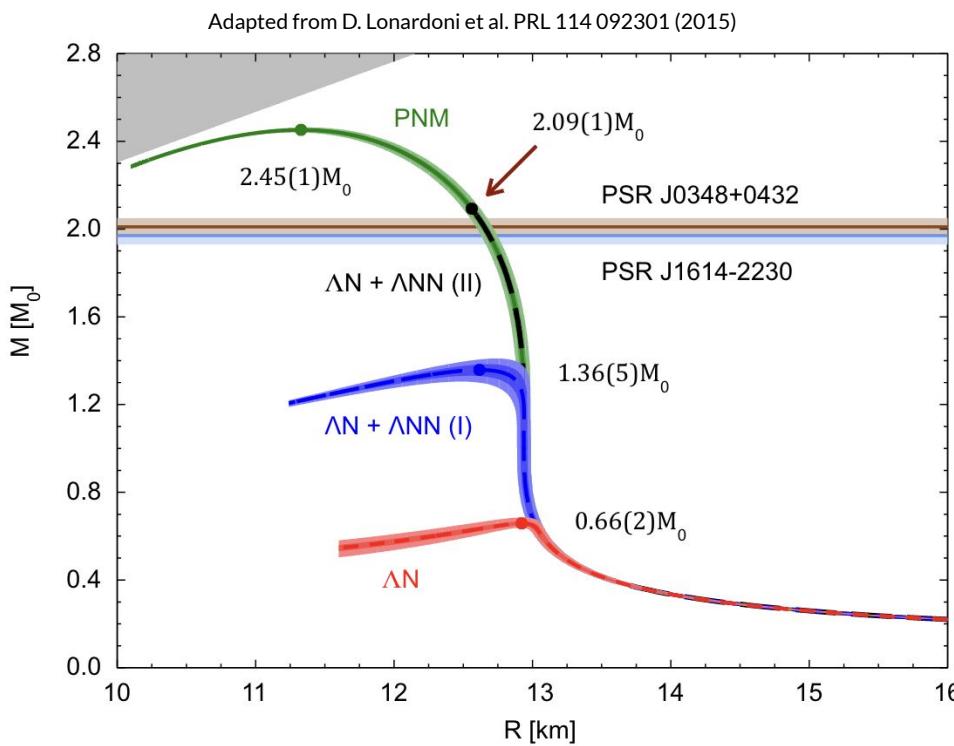
# Hyperon appearance in neutron stars?



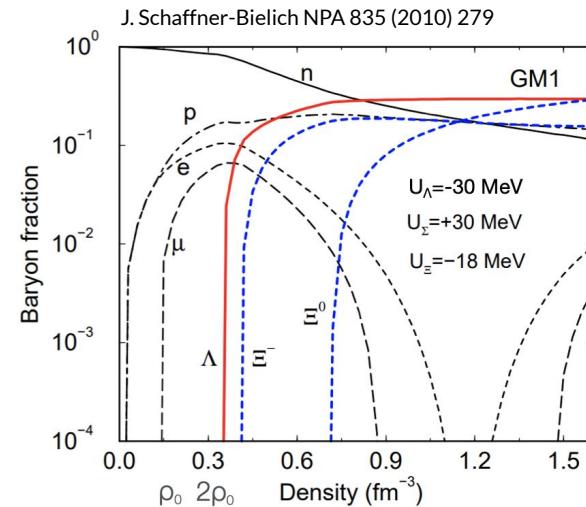
- Hyperons might appear in neutron stars since it is energetically favourable
- But the resulting EoS might be too soft to explain heavy neutron stars



# Hyperon appearance in neutron stars?

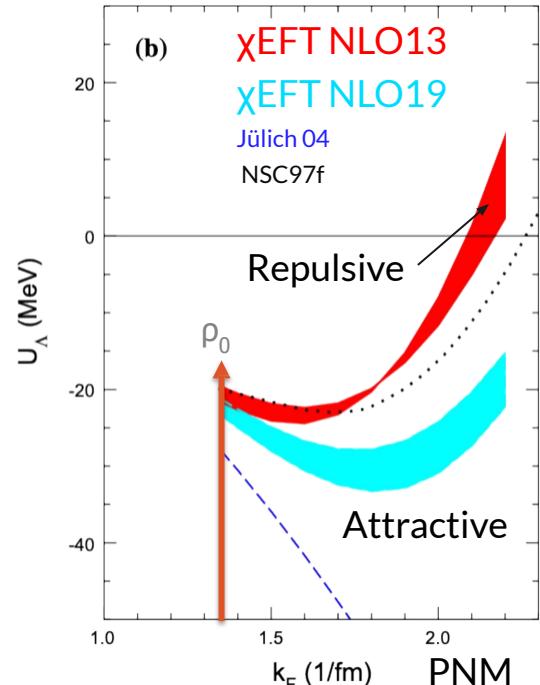
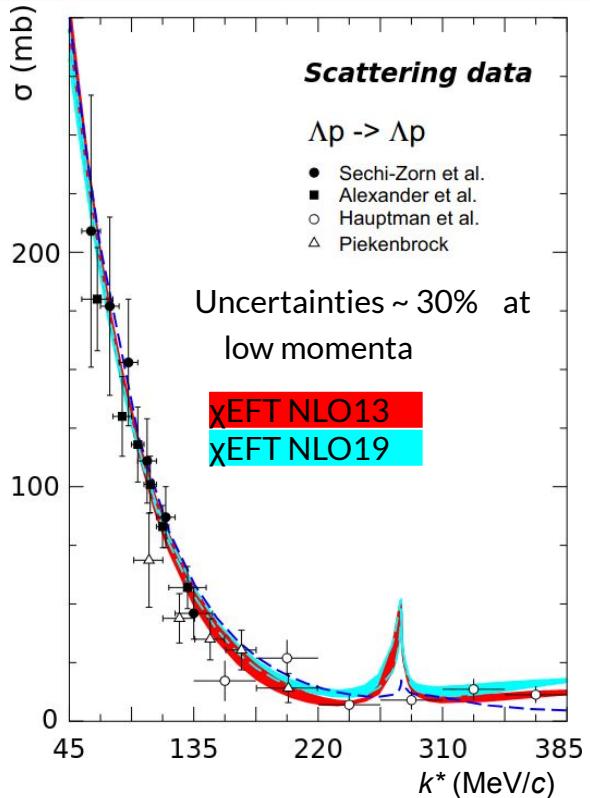


- Hyperons might appear in neutron stars since it is energetically favourable
- But the resulting EoS might be too soft to explain heavy neutron stars
- Possible solution: repulsive three-body interaction



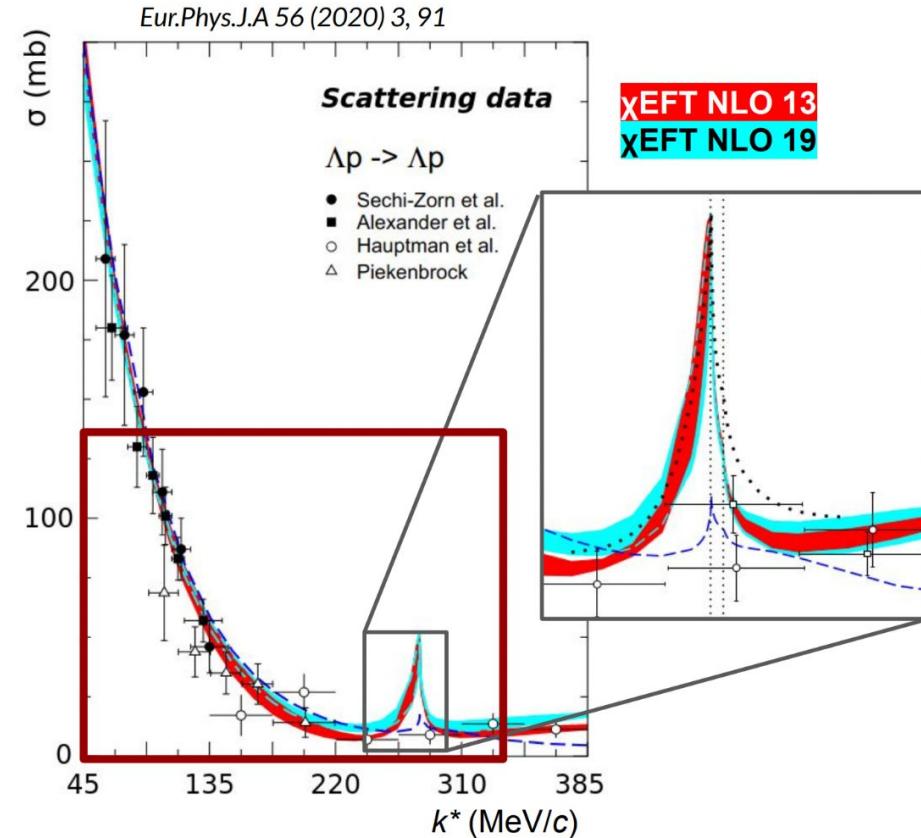
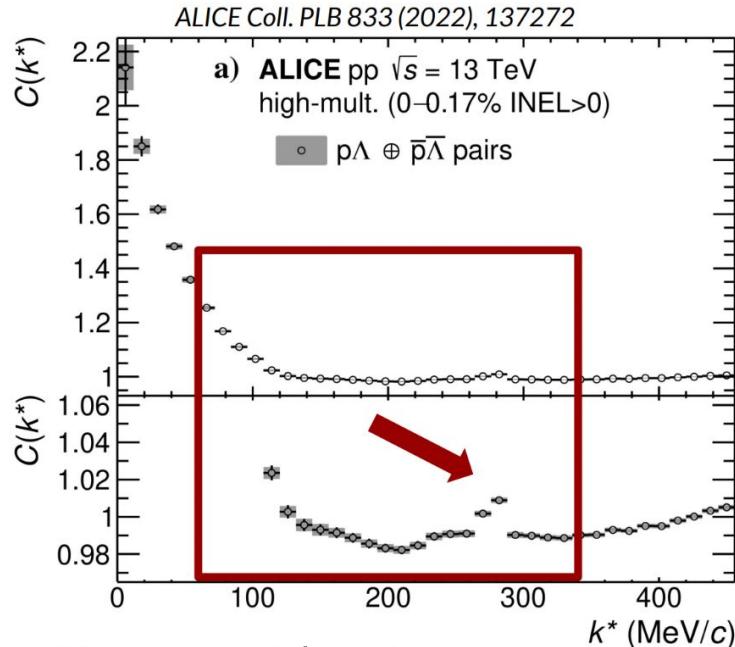
# $|S| = 1$ : p- $\Lambda$ interaction

- Low statistics and not available at low momenta
- $\Lambda N$ - $\Sigma N$  coupled system  $\rightarrow$  two-body coupling to  $\Sigma N$  is not (yet) measured
- $\Sigma N$  coupling strength relevant for EoS
  - Strongly affects the behaviour of  $\Lambda$  at finite density
  - Implications for  $\Lambda NN$  interactions
- NLO19 predicts weak coupling  $N\Lambda$ - $N\Sigma$ 
  - Attractive  $\Lambda$  interaction in neutron matter



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

# $|S| = 1$ : p- $\Lambda$ interaction

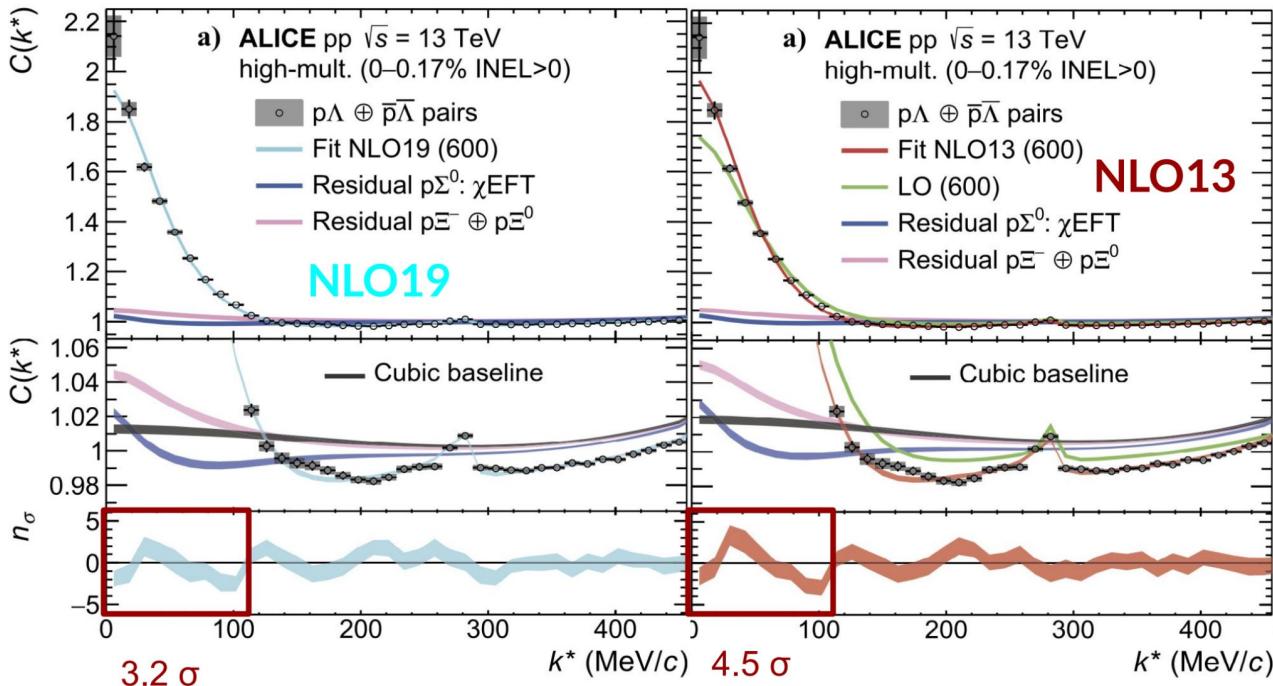


- Measurement down to zero momentum
- Factor 20 improved precision in data (<1%)
- First experimental evidence of  $\Sigma N$  cusp in 2-body channel

# $|S| = 1$ : p- $\Lambda$ interaction

Comparison with  $\chi$ EFT potentials

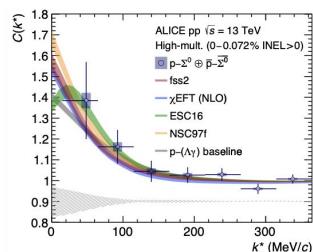
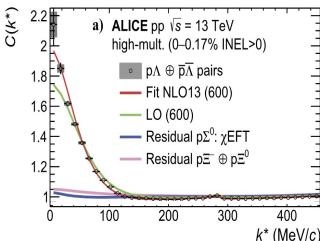
- Sensitivity to different  $\Sigma N$  coupling strength
- NLO19 favoured ( $n_\sigma = 3.2$ )  
 $\rightarrow$  attractive interaction of  $\Lambda$  at large densities



ALICE Coll. PLB 833 137272 (2022)

# An example of Equation of State for neutron stars

Correlation = two-body interaction

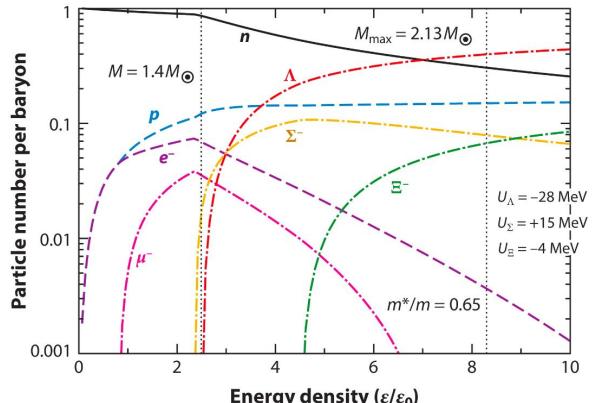


pΛ

pΣ

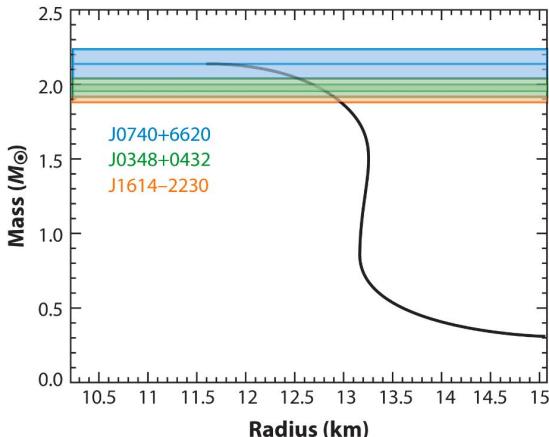
pΞ

Single-particle potentials = Equation of State



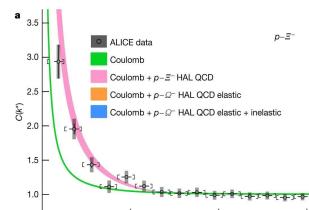
Courtesy J. Schaffner-Bielich 2020

Mass-Radius diagram for hyperon stars



Radius (km)

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

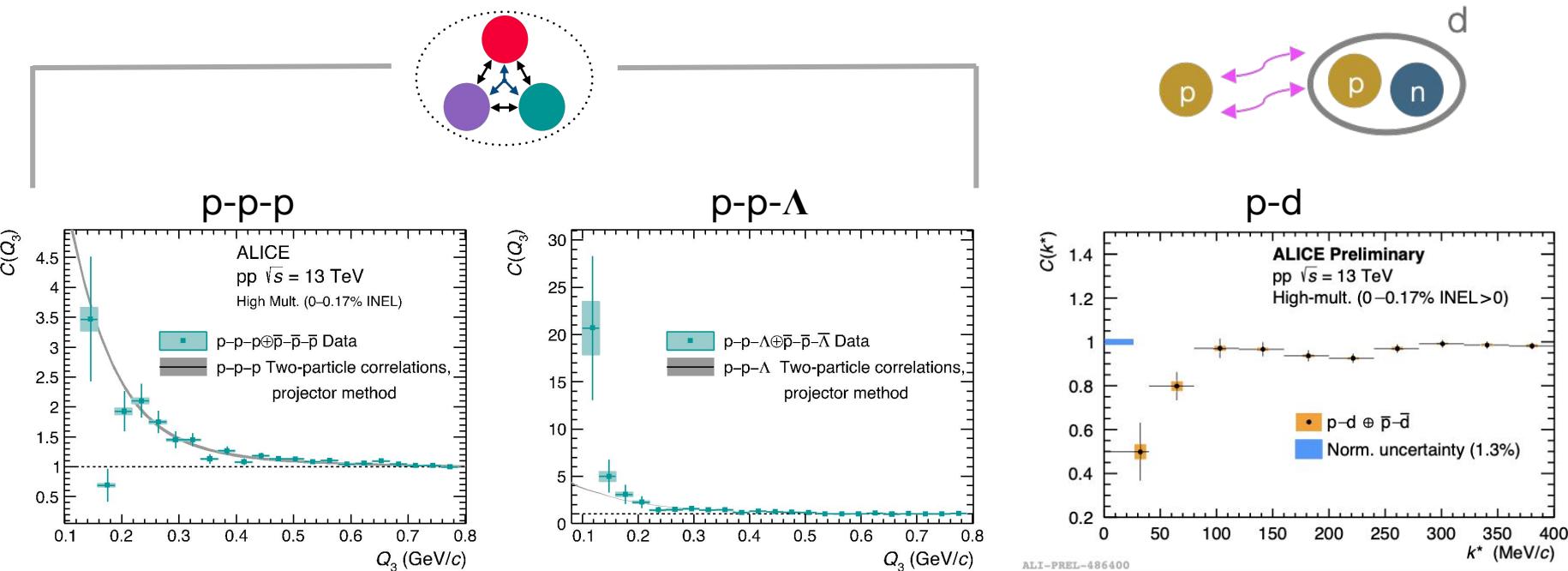


What about the three-body strong interaction?

# Three-body systems

Femtoscopy technique applied to three-body systems → three-body interaction

see talk by O. Vazquez Doce 25/10/2022 P6 h.18:20

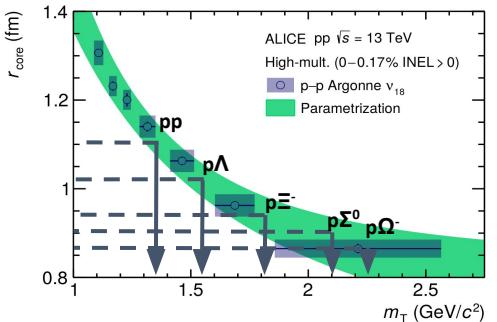


ALICE Coll. arXiv:2206.03344, accepted by EPJA

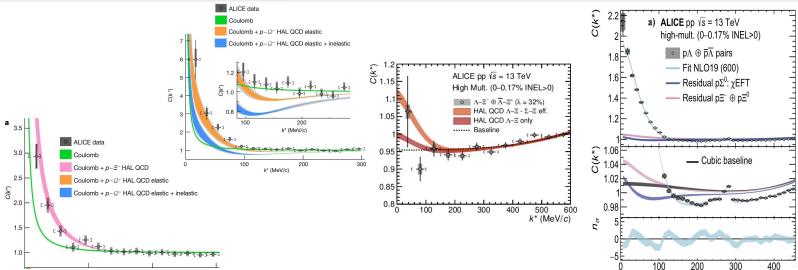
# Summary

Femtoscopy in small systems

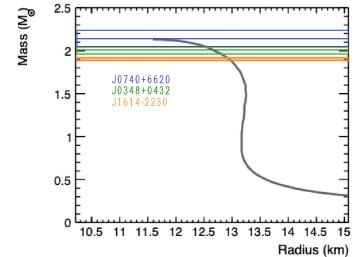
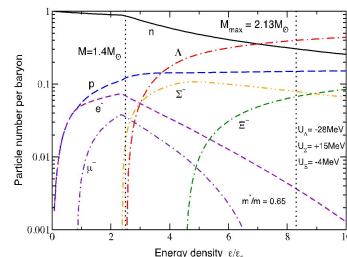
Universal source



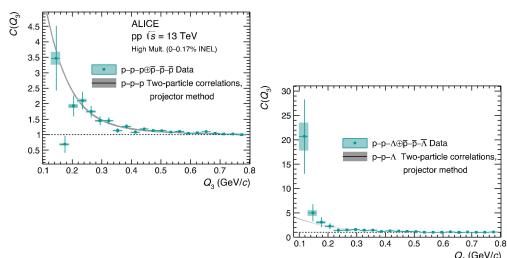
Test of hadron-hadron interactions from EFTs and Lattice QCD



EoS for dense pure neutron matter containing hyperons can be improved



Unprecedented studies of three-body dynamics using three-particle and hadron-nucleus correlations



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# THANKS

# Source determination

The first step is “traditional” femtoscopy: known interaction → determine source size

- p-p interaction: Argonne v18 potential
- crosscheck with p- $\Lambda$  ( $\chi$ EFT)

Determine gaussian “core” radius

- As a function of pair  $\langle m_T \rangle$
- Common to all hadron-hadron pairs



Effect of strong short-lived resonances

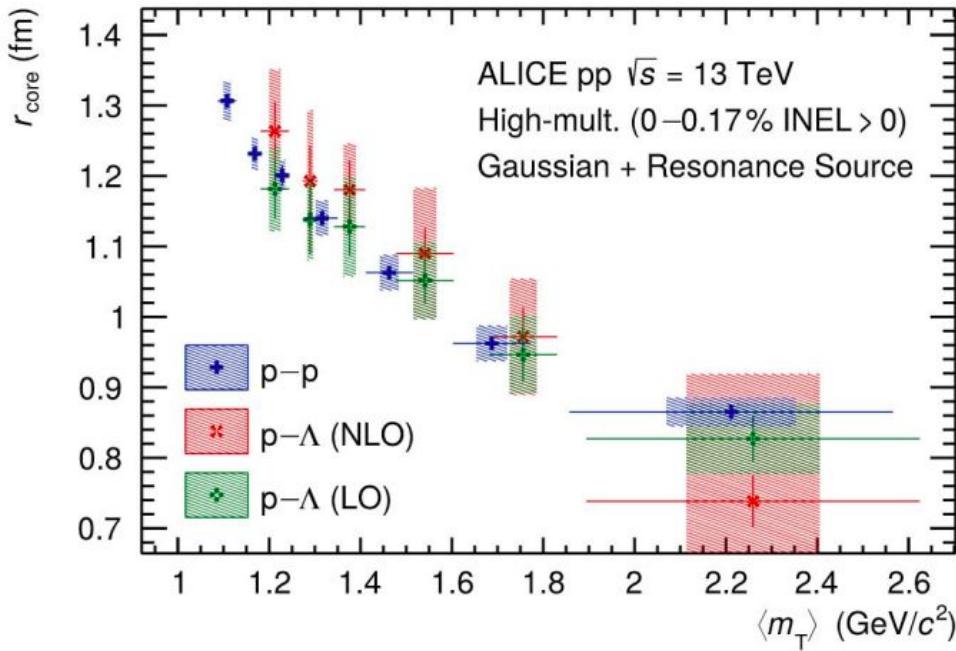
- Adds exponential tail to the source profile  
→ Angular distributions from EPOS

→ Production fraction from SHM

	Primordial	Resonances lifetime
p	35.8 %	1.65 fm
$\Lambda$	35.6 %	4.69 fm

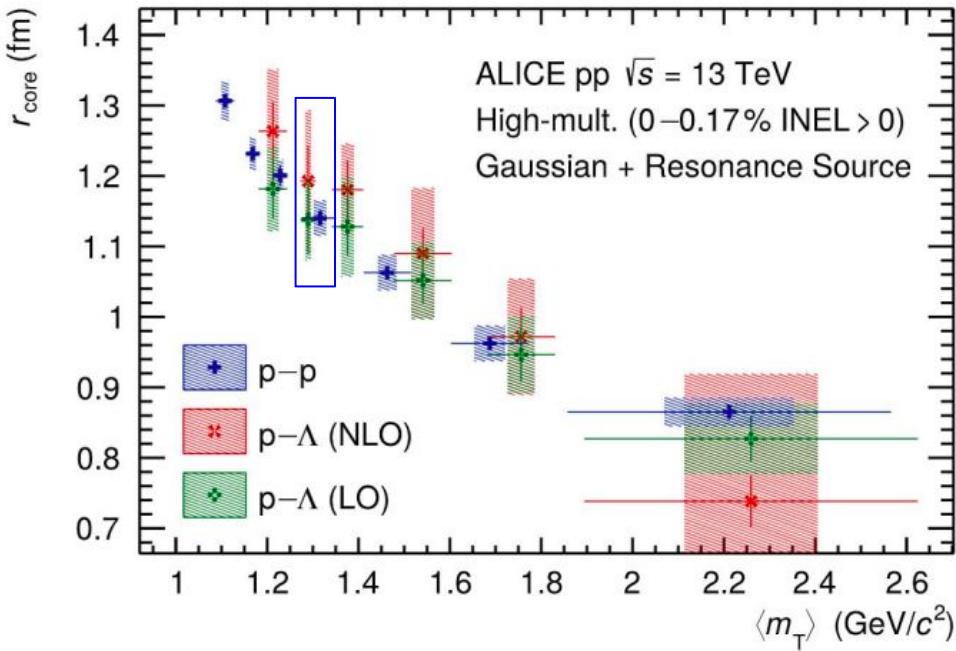
[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

# Source determination

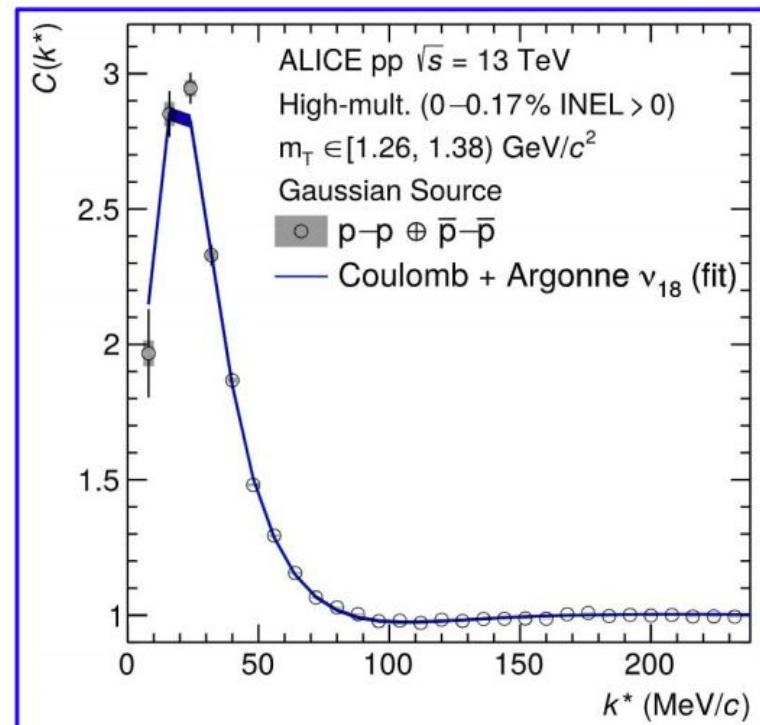


[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

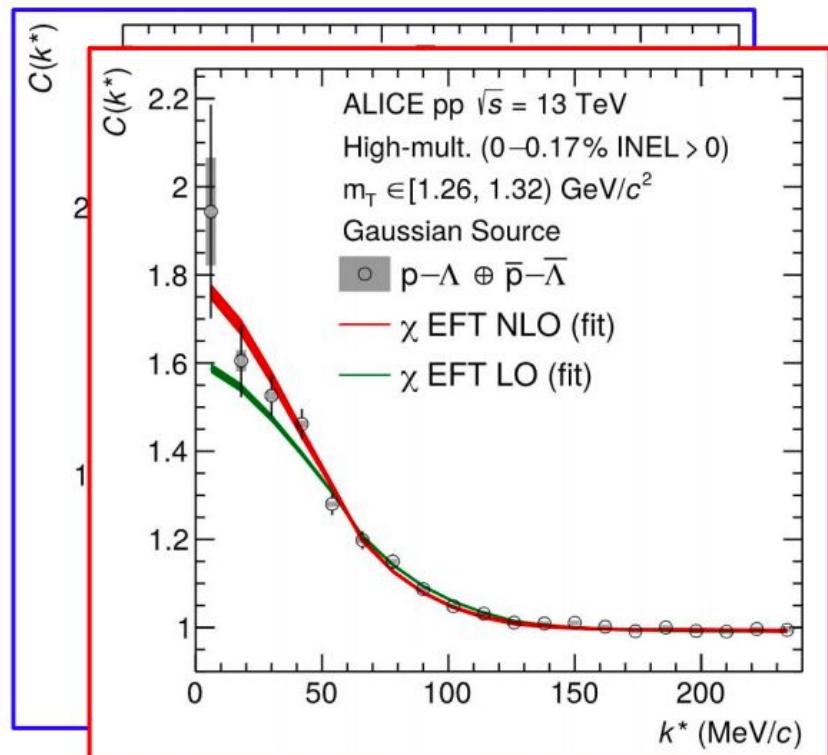
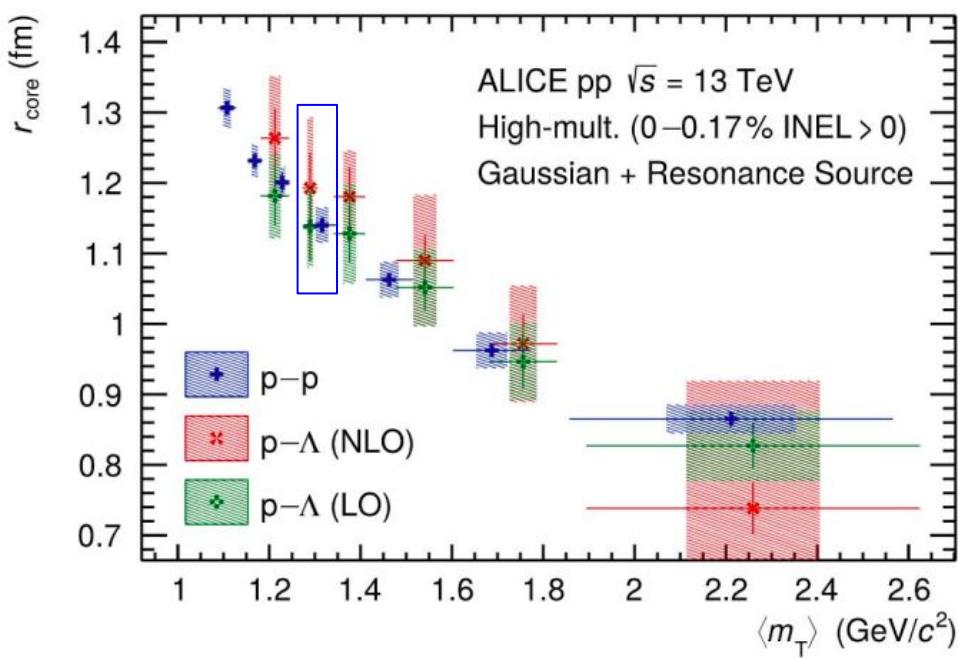
# Source determination



[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

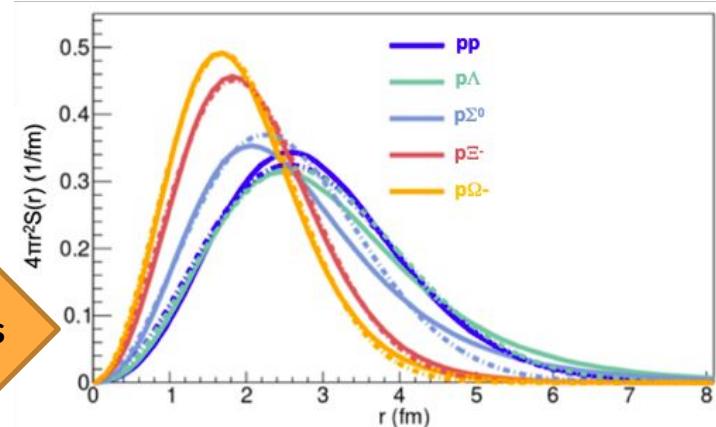
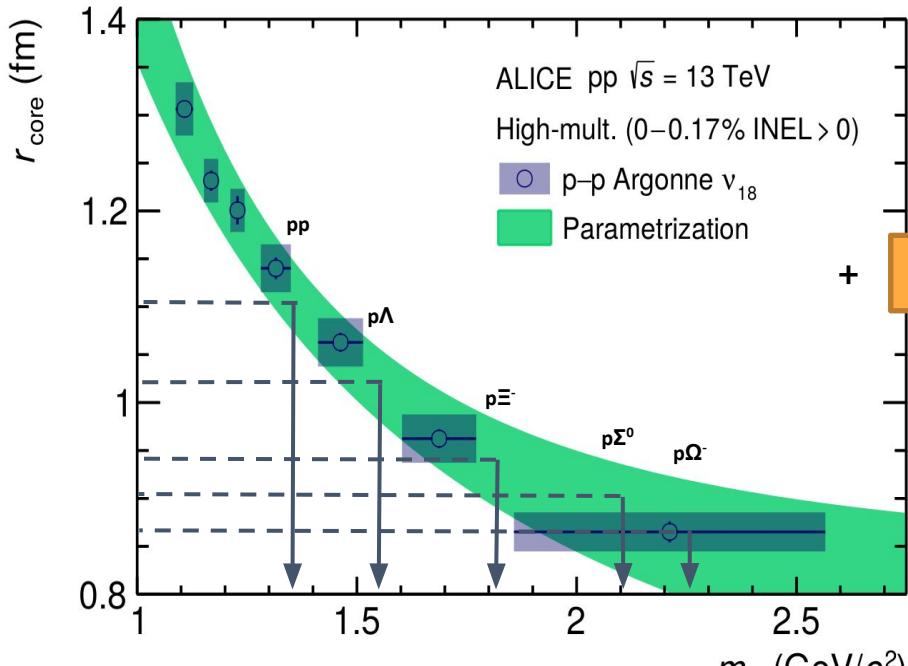


# Source determination



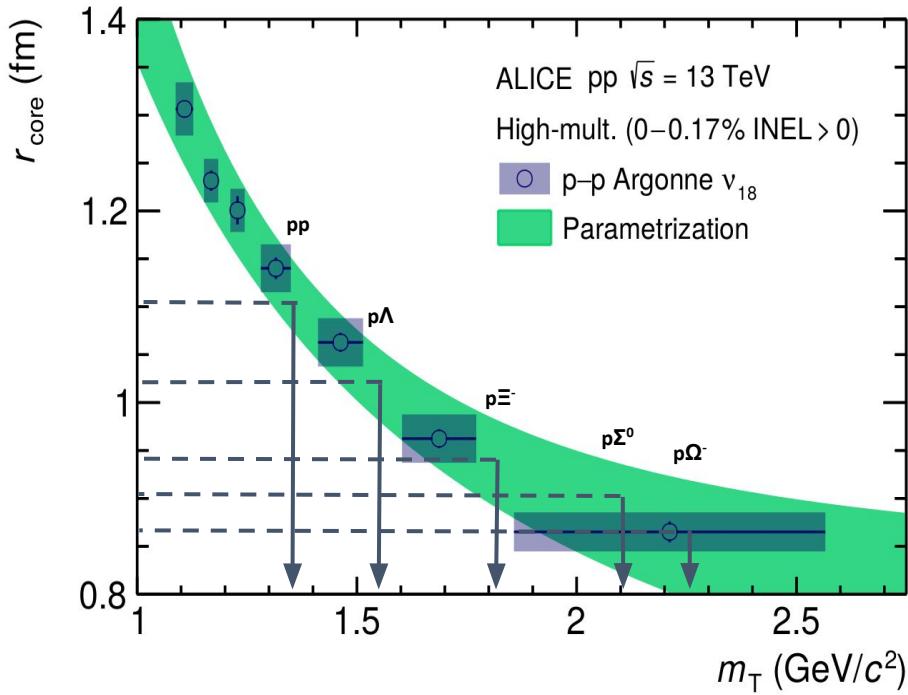
[ALICE Coll., Phys. Lett. B 811 (2020) 135849]

# Gaussian source with resonances



Pair	$r_{\text{Core}}$ [fm]	$r_{\text{Eff}}$ [fm]
p-p	1.1	1.2
p- $\Lambda$	1.0	1.3
p- $\Sigma^0$	0.87	1.02
p- $\Xi^-$	0.93	1.02
p- $\Omega^-$	0.86	0.95

# Small particle-emitting sources



ALICE Coll. PLB 811 (2020)

