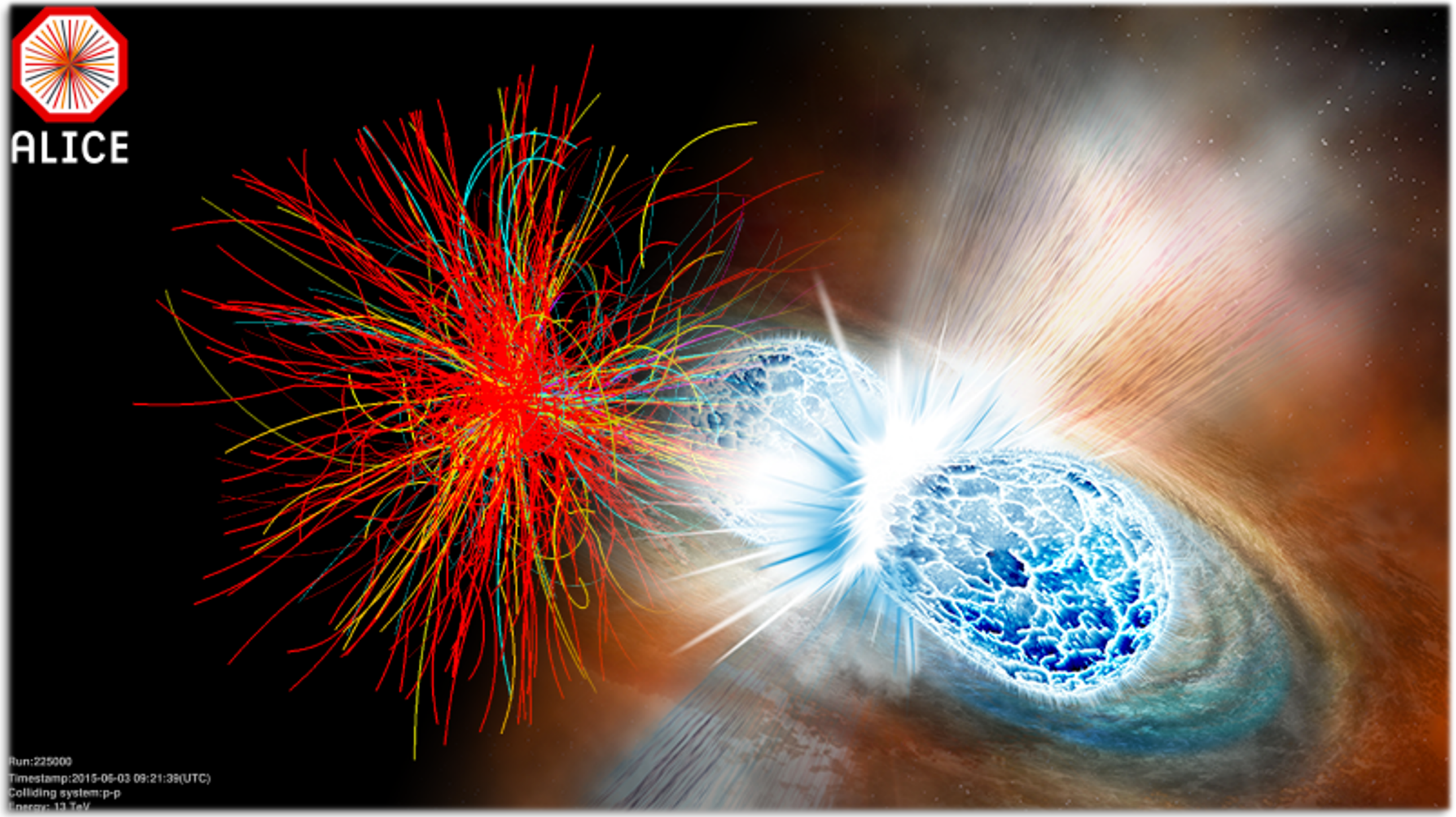


ALICE unveils strong interaction among stable and unstable hadrons.

SFB 1258 Neutrinos Dark Matter Messengers

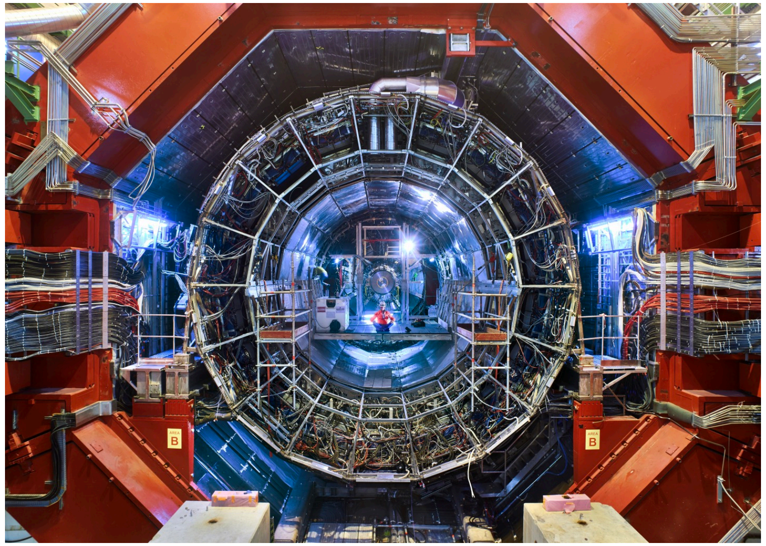
ALICE

Laura Fabbietti, Technische Universität München

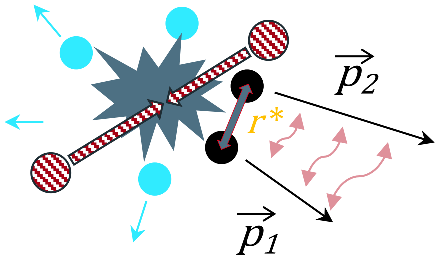
HADRON 2021: 19th International Conference on Hadron Spectroscopy and Structure

Outline

ALICE at the LHC

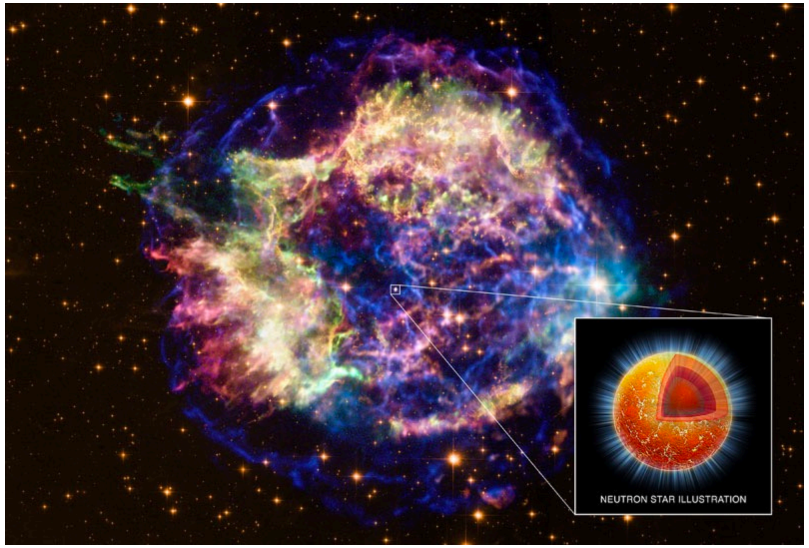


Femtoscopy



Hyperon-nucleon
Hyperon-Hyperon
Hyperon-NN…

Hyperon Stars

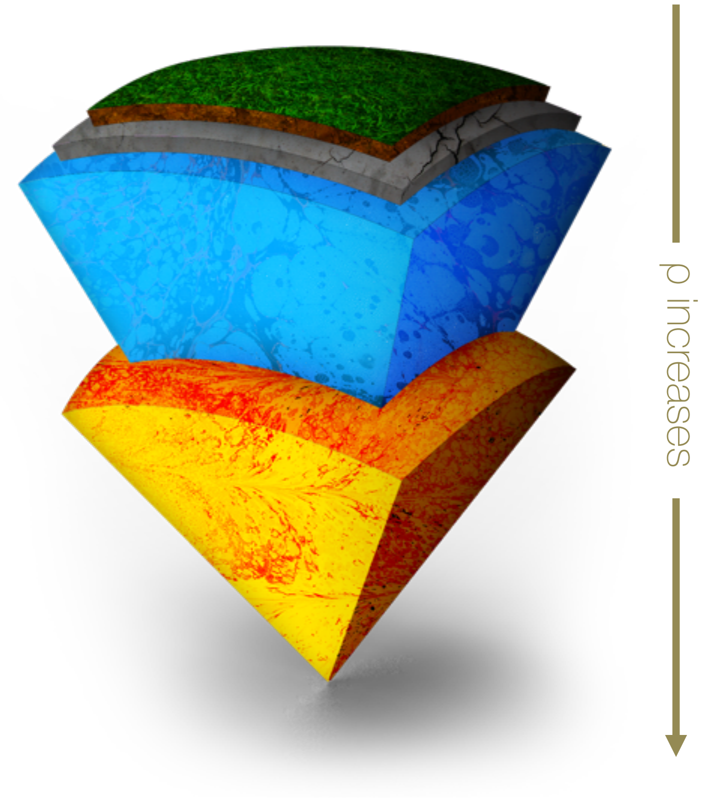


Hyperon appearance in neutron stars?

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

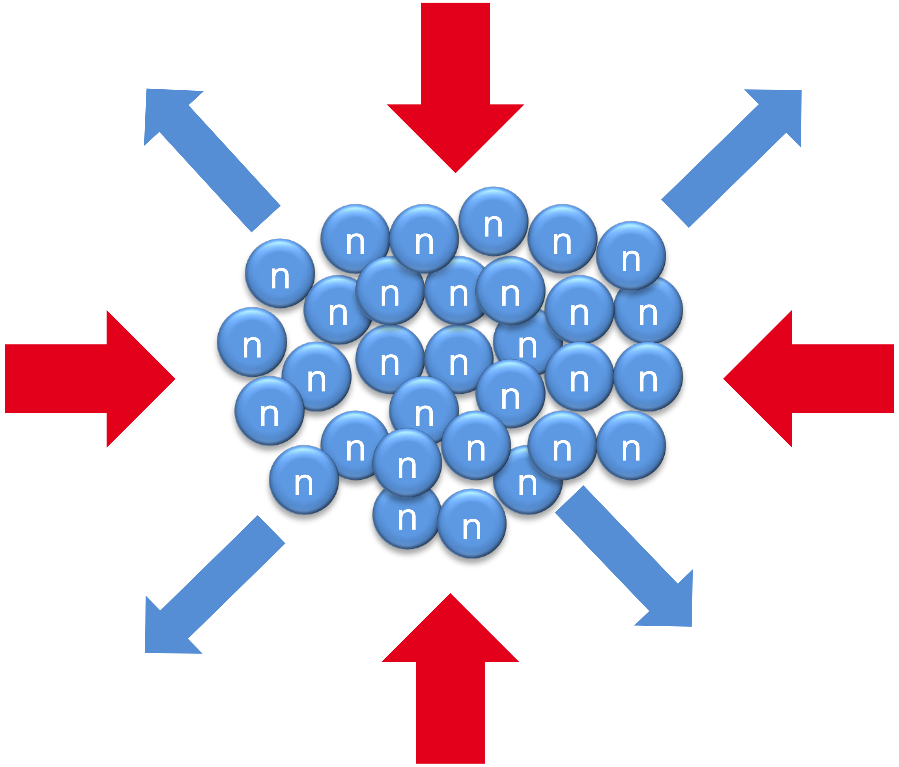
Outer Crust
Ions, electron gas,
Neutrons

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



Neutron Stars: very dense, compact objects

- What is the EoS?
  - What are the constituents to consider?
  - How do they interact?



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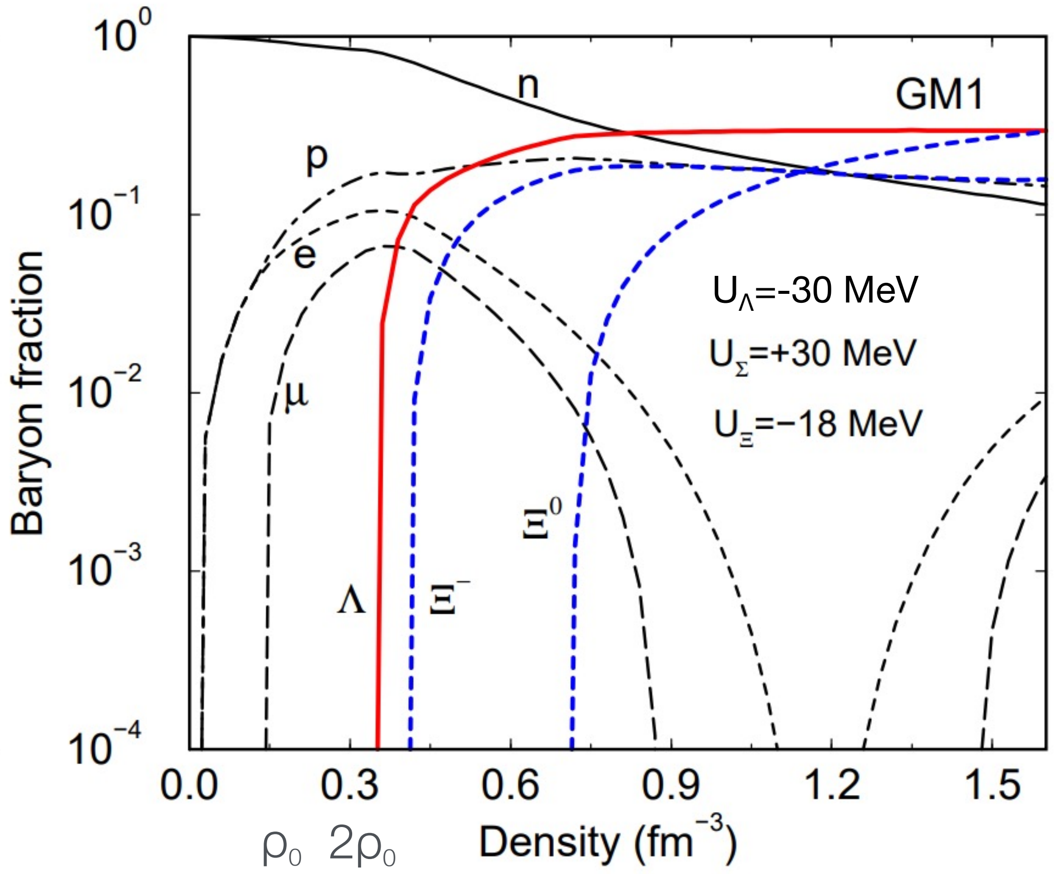
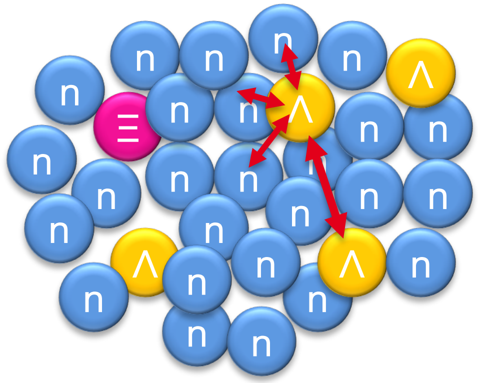


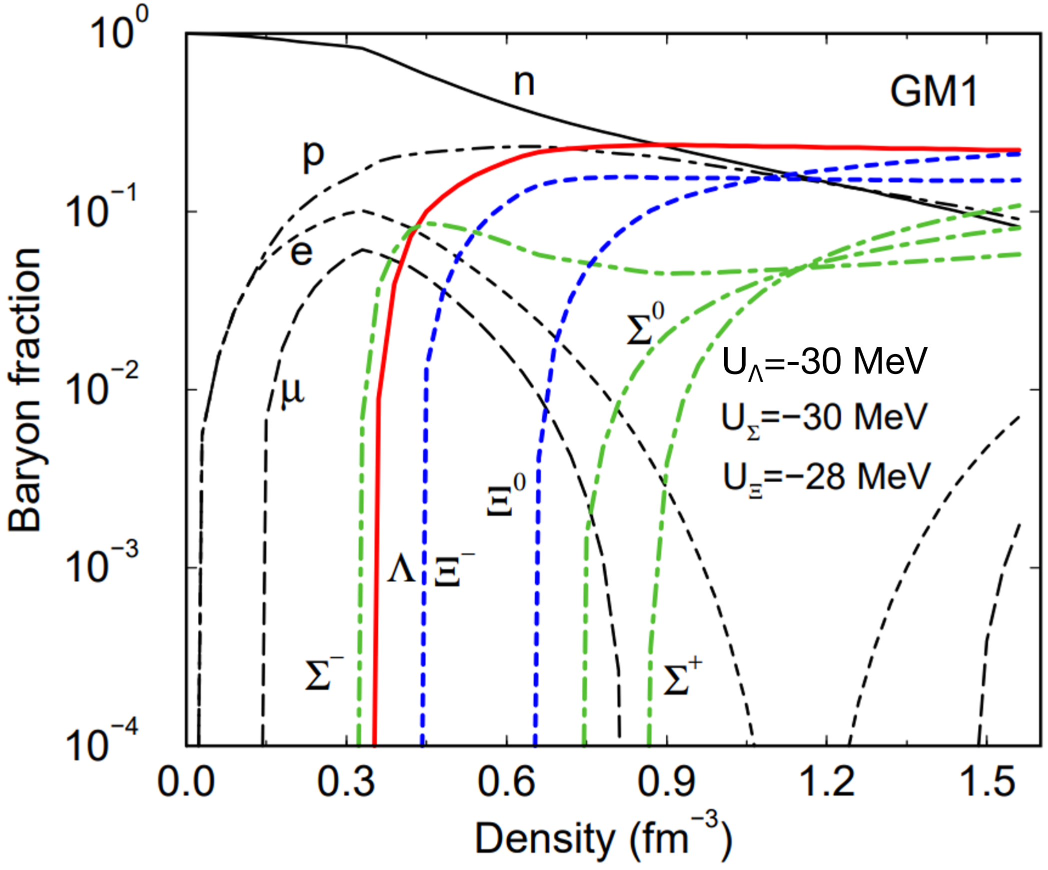
J. Schaffner-Bielich, Nucl. Phys. A 835 (2010) 279

Neutron Stars: very dense, compact objects

- At finite densities **hyperon** production becomes energetically favorable ⇒ softening of EoS
  - Appearance as a a function of ρ depends on the Y interaction with medium and Y interactions among themselves
  - Naïve introduction of Λ incompatible with astrophysical observations



Hyperon appearance in neutron stars?



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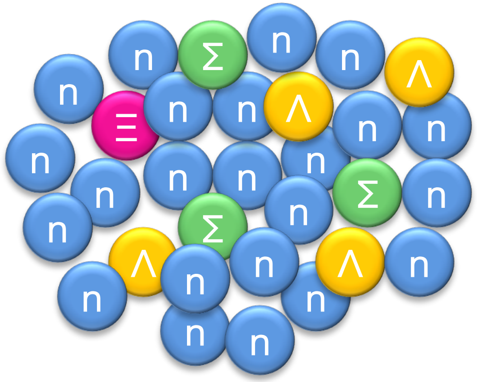
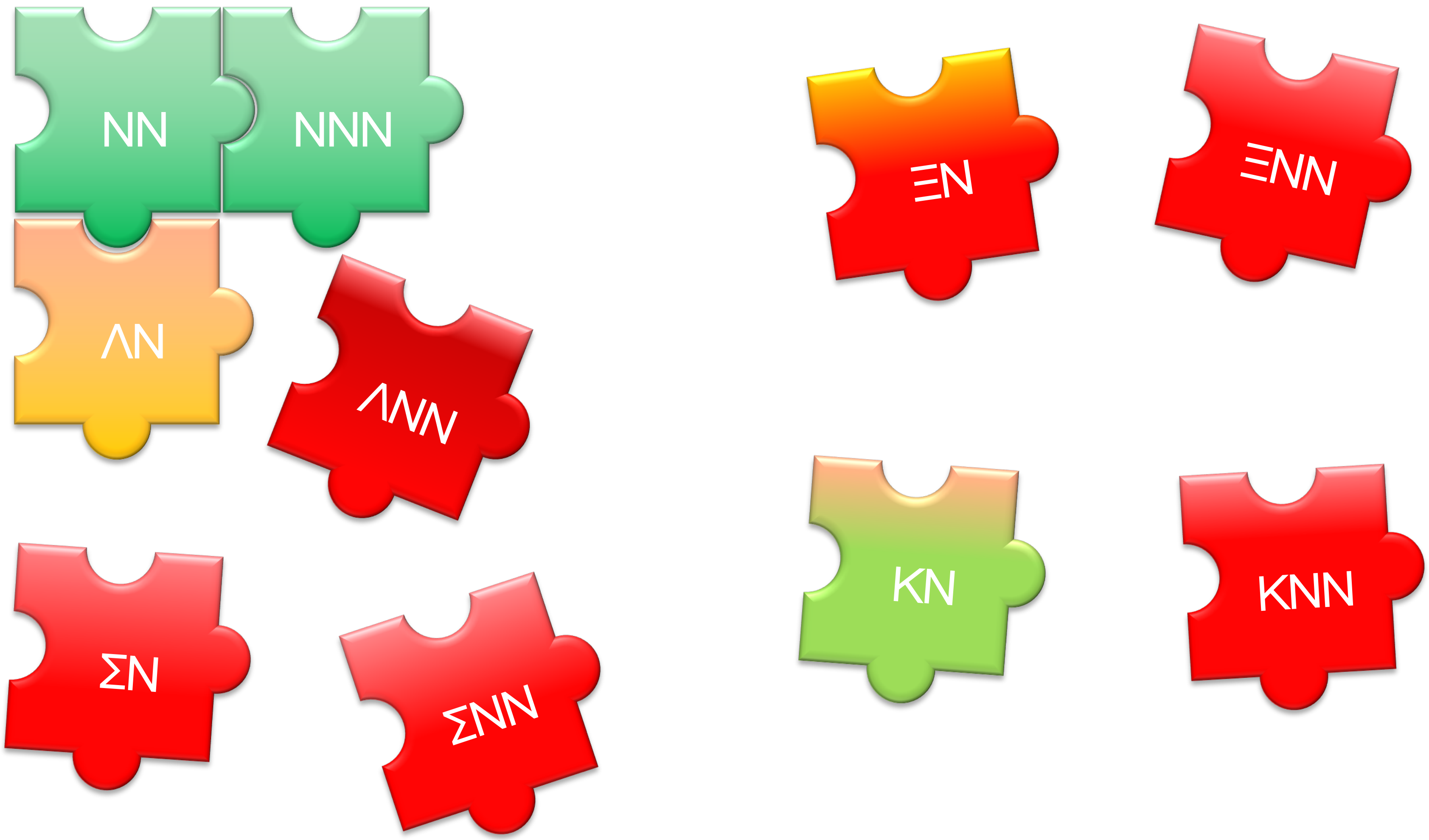
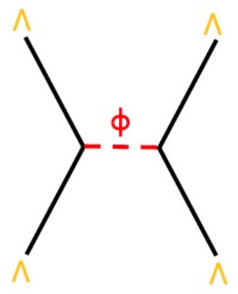


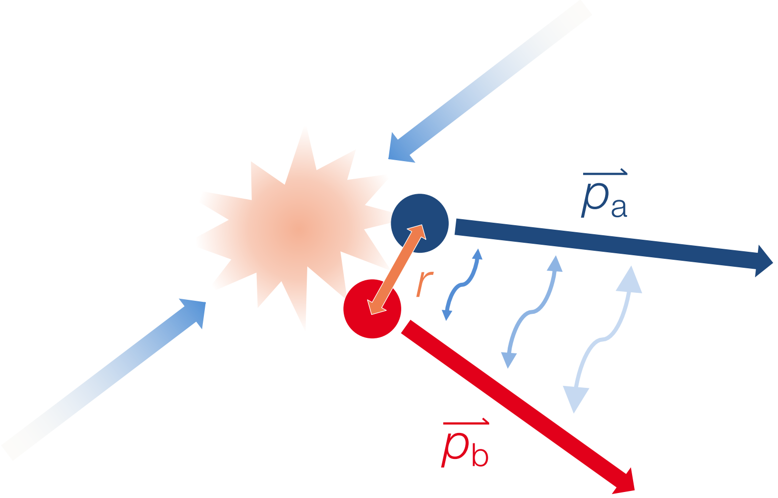
The building blocks for the EoS of hyperon stars: two- and three-body interactions

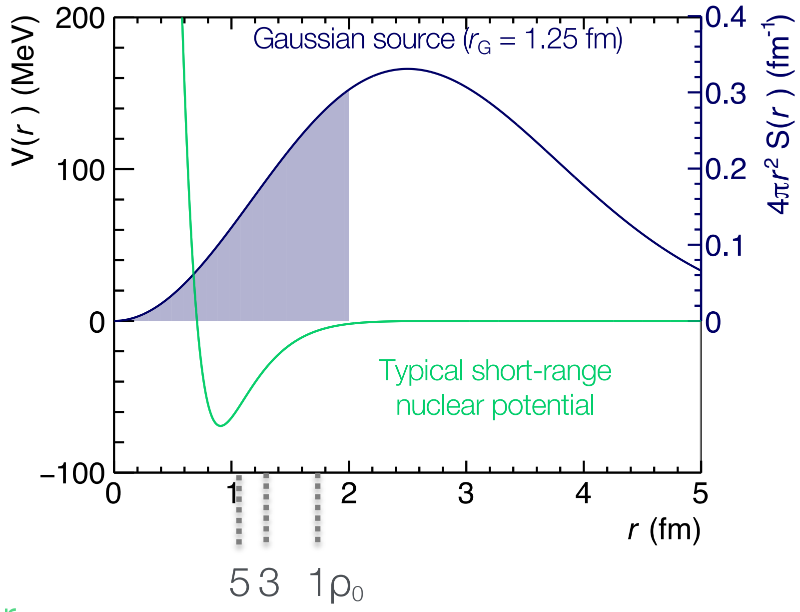


Vector meson exchange to describe $\Lambda\Lambda$ interaction



Femtoscopy with small sources





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

Emission source — Two-particle wave function

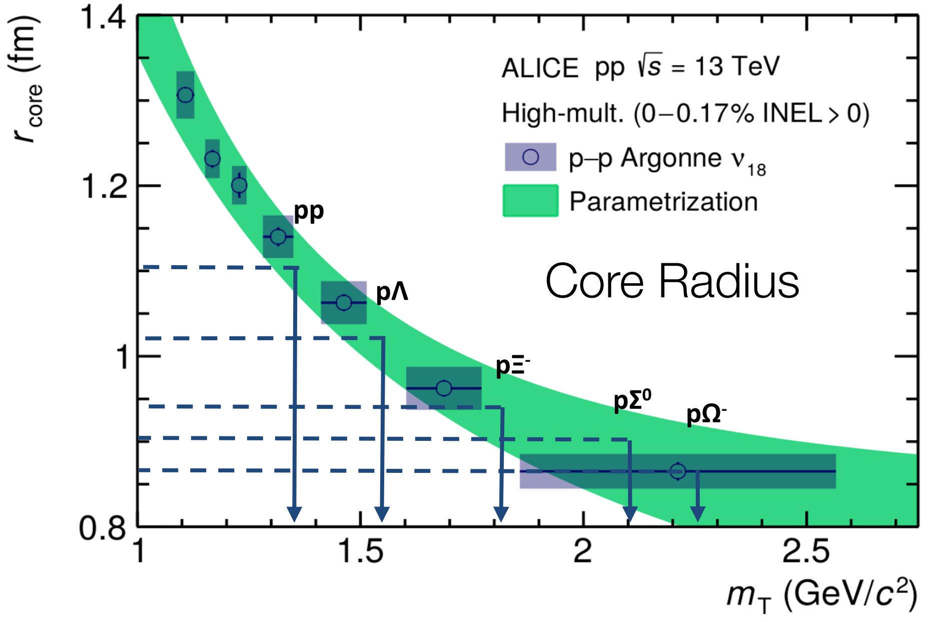
- > 1 Attract
- $= 1$ No Inter.
- < 1 Repulsive

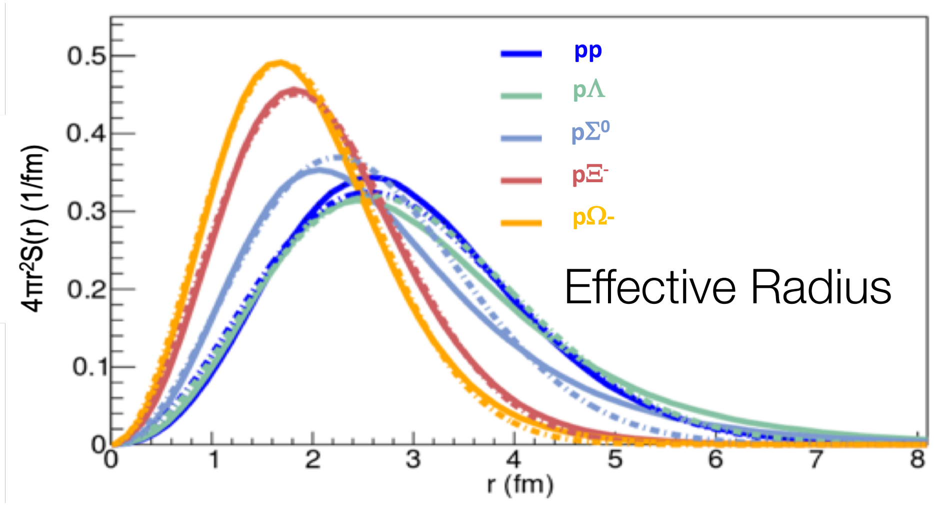
- Small particle-emitting source created in pp and p–Pb collisions at the LHC
  - Essential ingredient for detailed studies of the strong interaction
    - D. Mihaylov *et al.*, *Eur. Phys. J.* **C78** (2018) 394
  - Small interparticle distance → doorway to studying large densities

Small Sources: Collective Effects and Strong Resonances

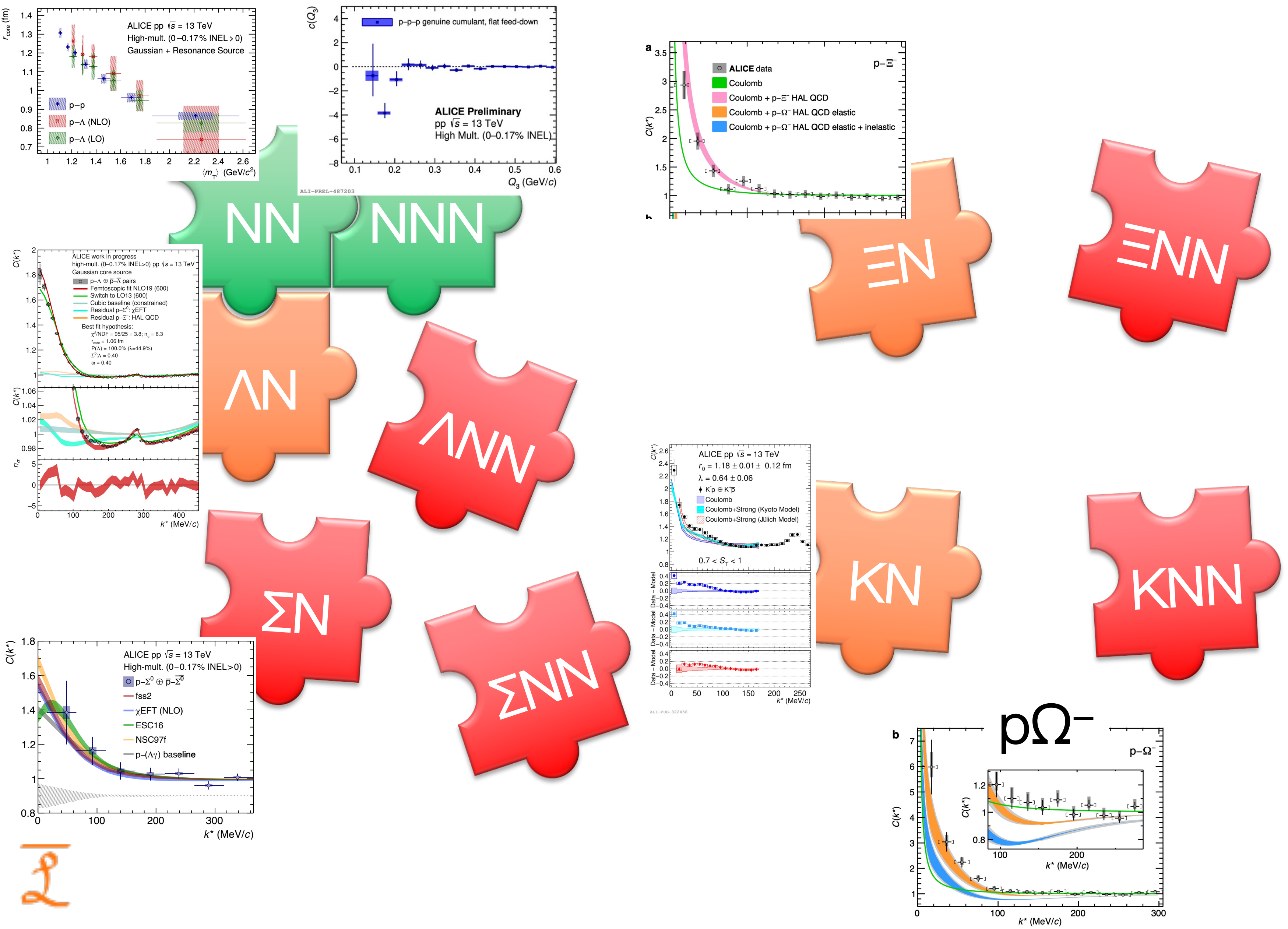
- Modeling of the emitting source in pp collisions with a common core + halo of strongly decaying resonances for each pair
- Core constrained with femtoscopic studies for p-p pairs in pp HM 13 TeV
- Resonance contributions evaluated from statistical models and kinematics from transport models
- Determination of the source for each pair at the corresponding $<m_T>$ ⟹ direct access to the interaction signal of the correlation function

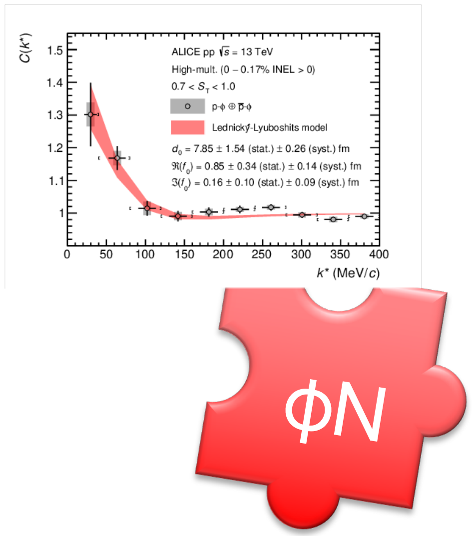
ALICE coll., Phys. Lett. B 811 (2020) 135849





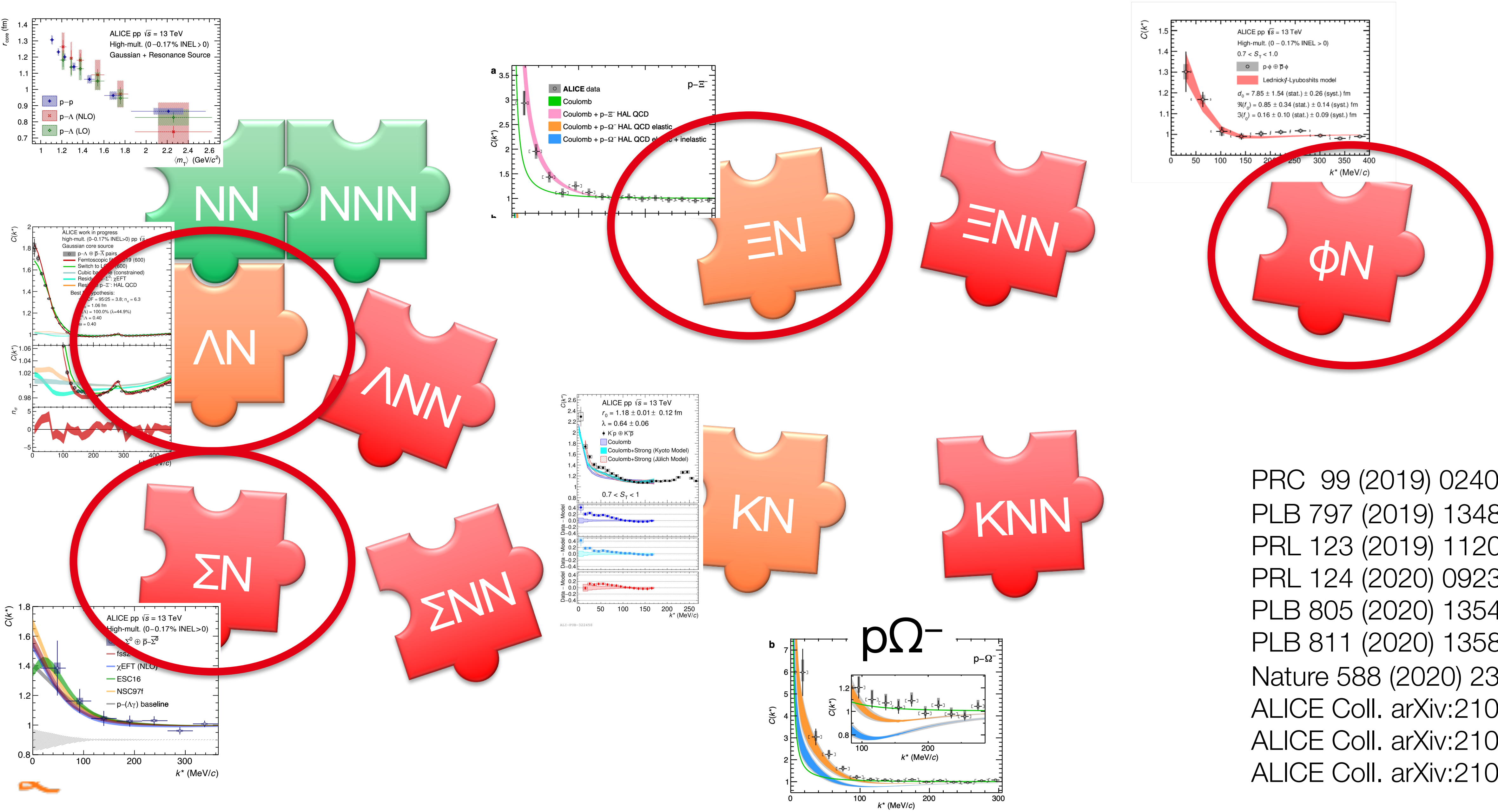
Harvest of LHC Run 1 & 2





PRC 99 (2019) 024001
PLB 797 (2019) 134822
PRL 123 (2019) 112002
PRL 124 (2020) 09230
PLB 805 (2020) 135419
PLB 811 (2020) 135849
Nature 588 (2020) 232-238
ALICE Coll. arXiv:2104.04427
ALICE Coll. arXiv:2105.05578
ALICE Coll. arXiv:2105.05190

Harvest of LHC Run 1 & 2 – What we will see today



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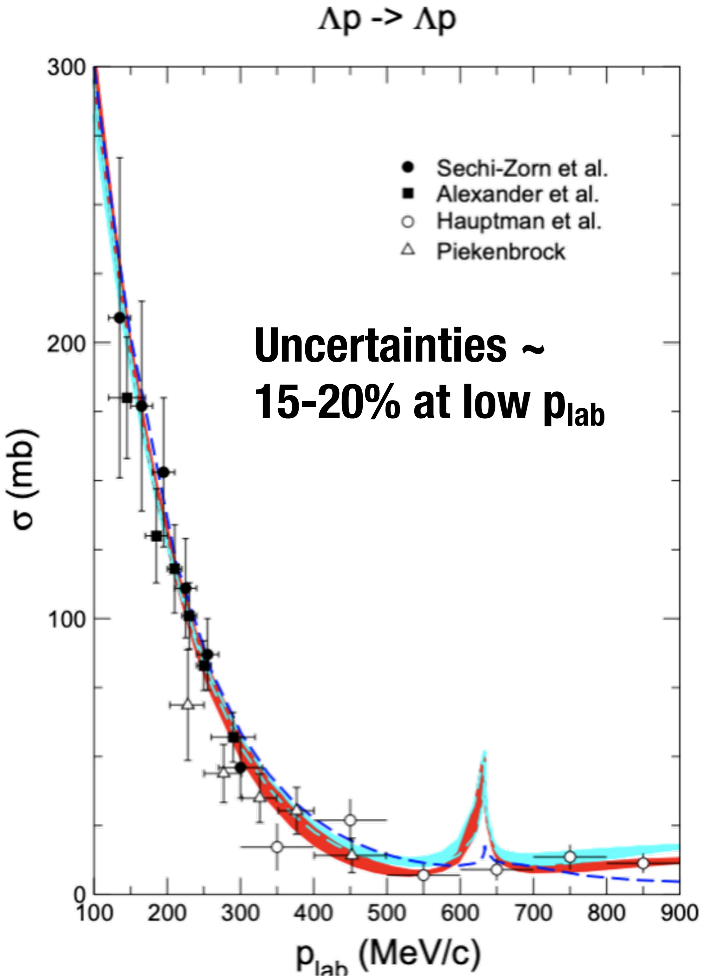
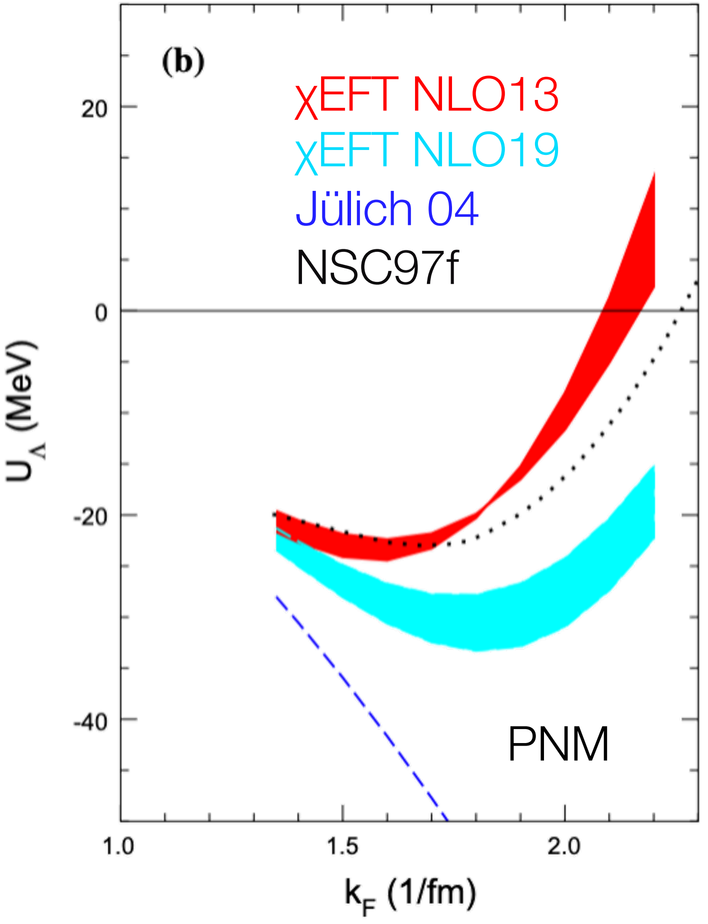
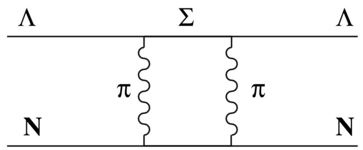
|S|=1: pΛ Interaction and role of the ΣN coupling





NLO13: J.Haidenbauer, N.Kaiser et al., NPA 915, 24 (2013)
NLO19: J.Haidenbauer, U. Meißner, Eur.Phys.J.A 56 (2020)

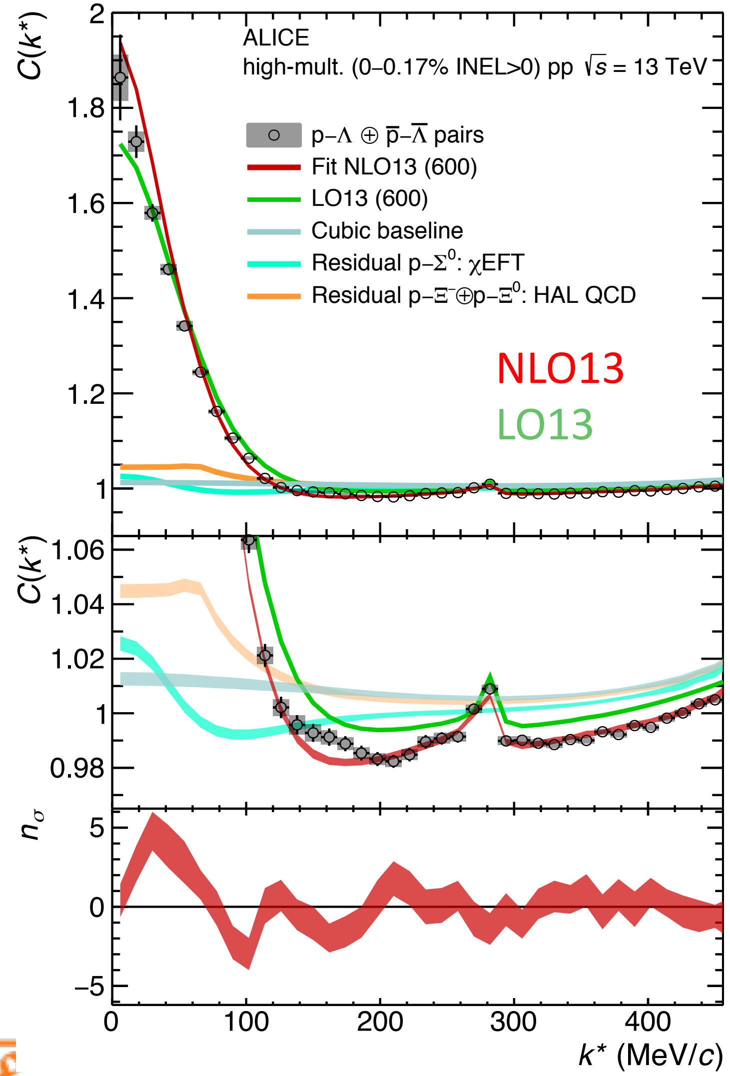
- pΛ interaction:
  - low-statistics scattering data and hypernuclei, not available at low momenta (plab> 100 MeV/c)
  - 2-body coupling to ΣN is experimentally not (**yet**) measured
- ΣN coupling strength deeply affects the behaviour of Λ at finite density

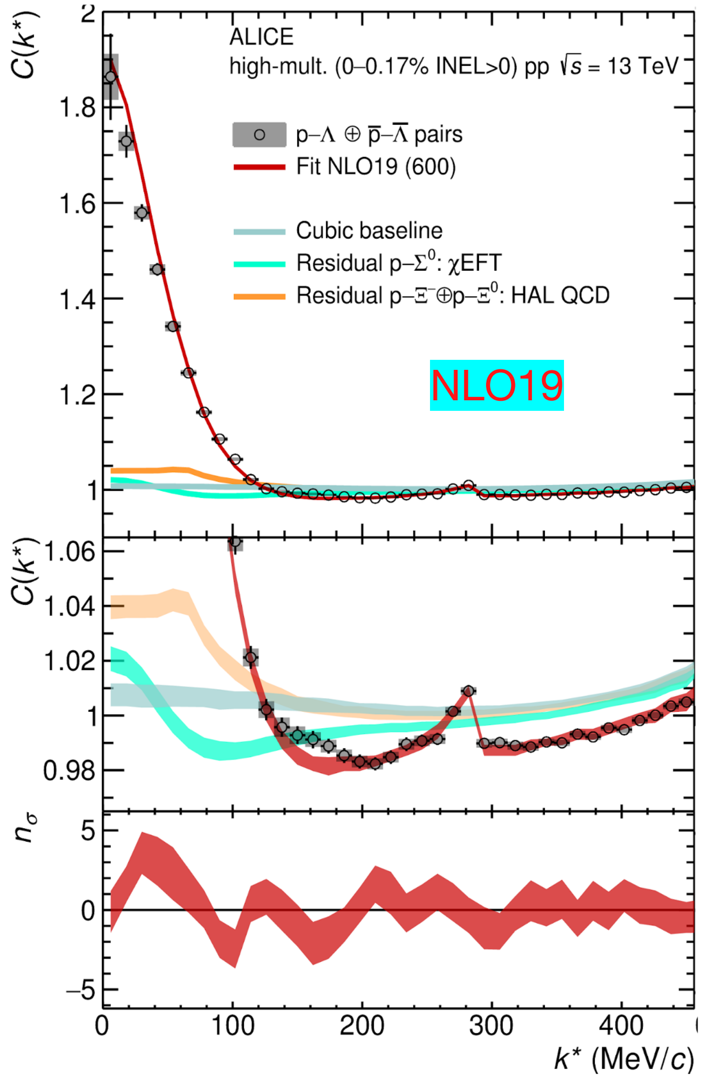


  - Relevance for EoS in NS (“hyperon puzzle”) and for connection to role of ΛNN three-body interaction
- Updated NLO19 with weaker coupling strength in NΛ-NΣ leading to different Λ properties in nuclear matter

|S|=1 :Λp Interaction and access to the ΣN coupling

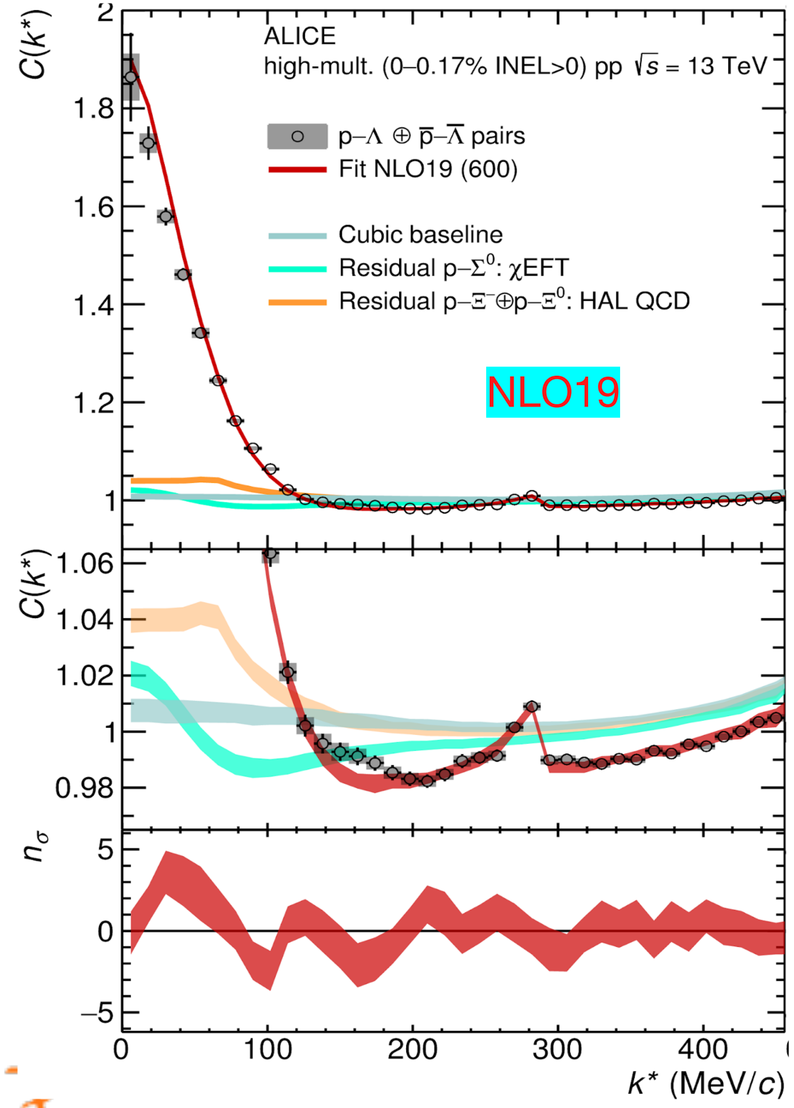
ALICE Coll. arXiv:2104.04427 submitted to PRL





- Extension of the kinematic range
- **Factor 20 improved precision of the measurement**
- **First experimental evidence ΣN opening in 2 body channel**
- Sensitivity to different strength of ΣN coupling (NLO13 vs NLO19)
- Sensitivity to residual $p\Sigma^0$ contribution ⟹ shallow interaction
- **NLO19 favoured ⟹ very attractive U_Λ ⟹ too soft EoS….**

|S|=1 :Λp Interaction and access to the ΣN coupling



p–Σ^0 (→) p–Λ (↓)	χEFT	Flat
LO13-600	4.7 (5.7)	7.7 (10.8)
NLO13-500	5.3 (7.4)	3.3 (3.7)
NLO13-550	3.7 (4.5)	2.5 (2.5)
NLO13-600	4.4 (4.5)	2.9 (3.3)
NLO13-650	4.1 (4.0)	3.1 (3.8)
NLO19-500	4.0 (4.8)	2.8 (2.8)
NLO19-550	3.4 (3.5)	2.3 (2.7)
NLO19-600	3.2 (3.1)	2.3 (2.9)
NLO19-650	3.2 (3.2)	2.6 (3.4)

- Extension of the kinematic range
- **Factor 20 improved precision of the measurement**
- **First experimental evidence ΣN opening in 2 body channel**
- Sensitivity to different strength of ΣN coupling (NLO13 vs NLO19)
- Sensitivity to residual pΣ^0 contribution ⟹ shallow interaction
- **NLO19 favoured ⟹ very attractive U_Λ ⟹ too soft EoS….**

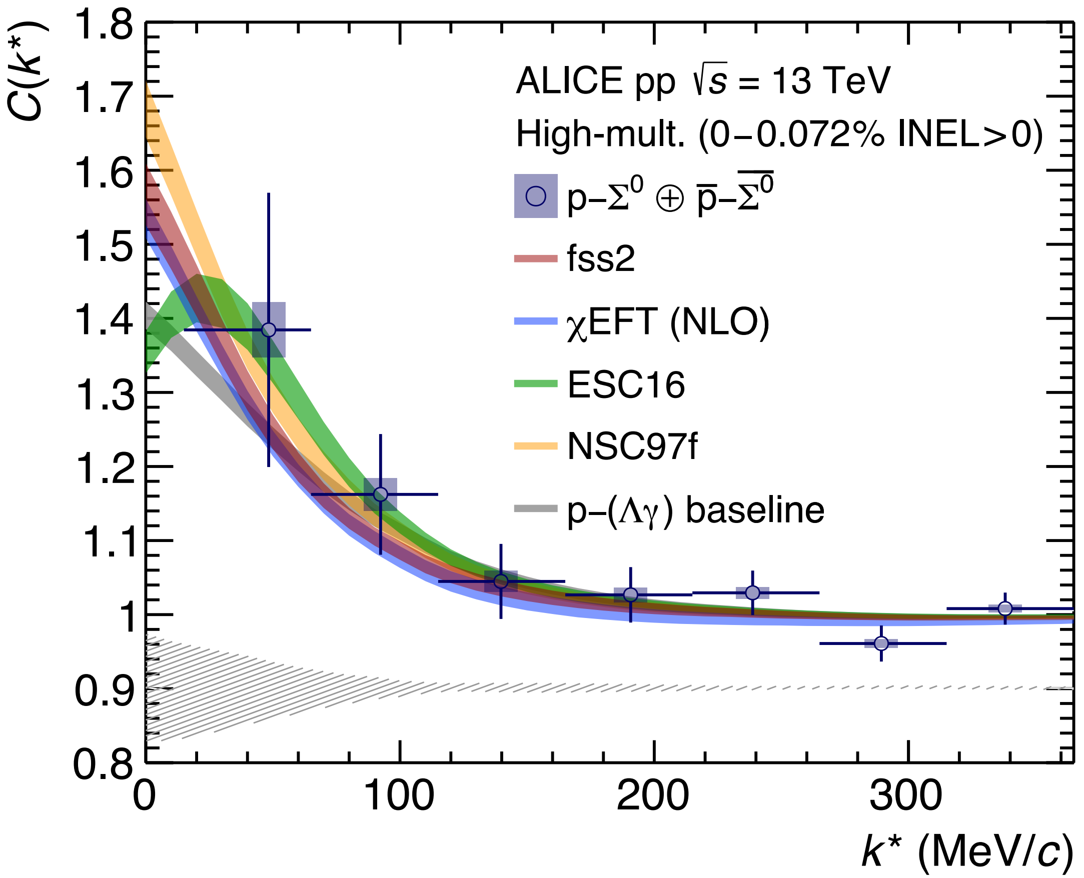
|S|=1 : First measurement of the pΣ^0 interaction

- Experimental data on hypernuclei too scarce for a final conclusion: attractive or repulsive interaction?
- Very challenging measurement via the difficult electromagnetic decay $\Sigma^0 \rightarrow \Lambda\ \gamma$
- **Correlation function is above the background ⟹ pointing to a very shallow attractive interaction**

Model	p–(Λγ) baseline	fss2	χEFT	NSC97f	ESC16
n_σ ($k^* < 150$ MeV/c)	0.2–0.8	0.2–0.9	0.3–1.0	0.2–0.6	0.1–0.5

- Relevant for dense neutron matter is the interaction with neutrons and the interaction of $\Sigma^{+,-}$!
  - Disentangle the different isospin contributions
- **Larger statistics in Run3 and Run4 will definitely increase the precision and constraints on the Σ-N interaction**

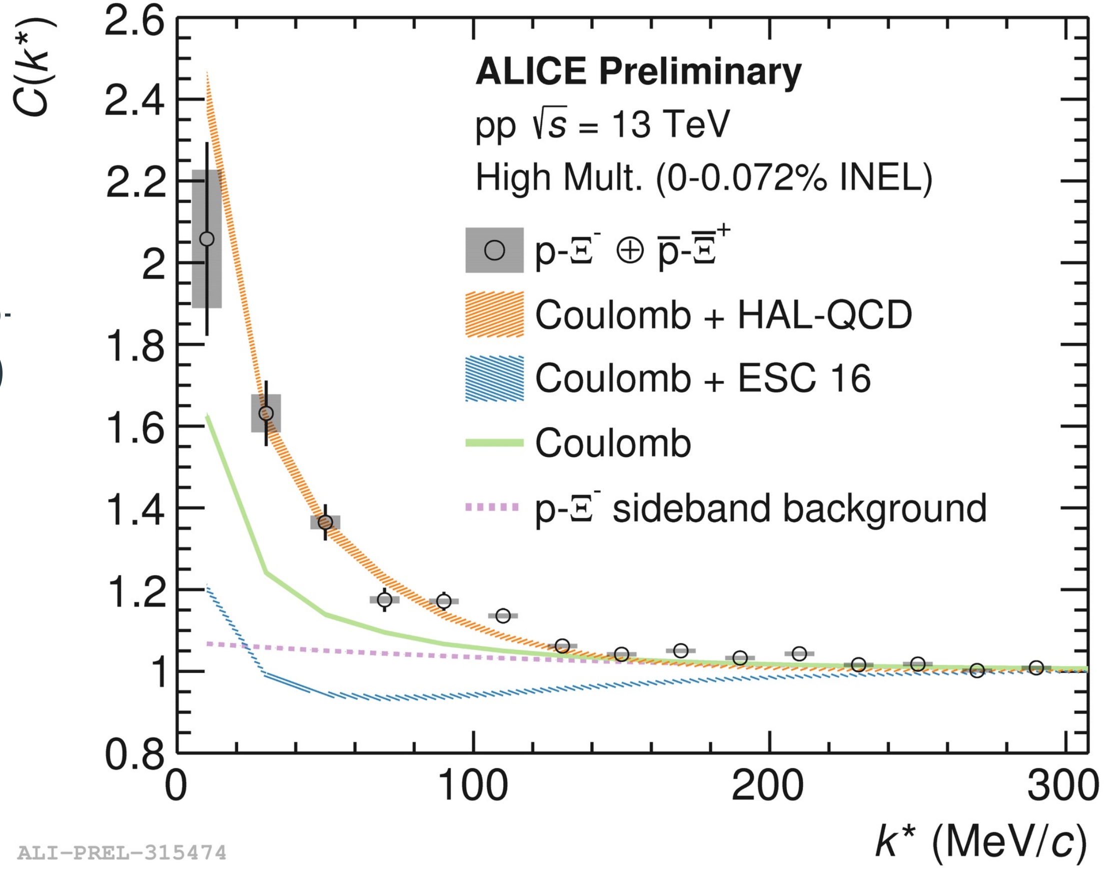
ALICE coll., PLB 805 (2020) 135419



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

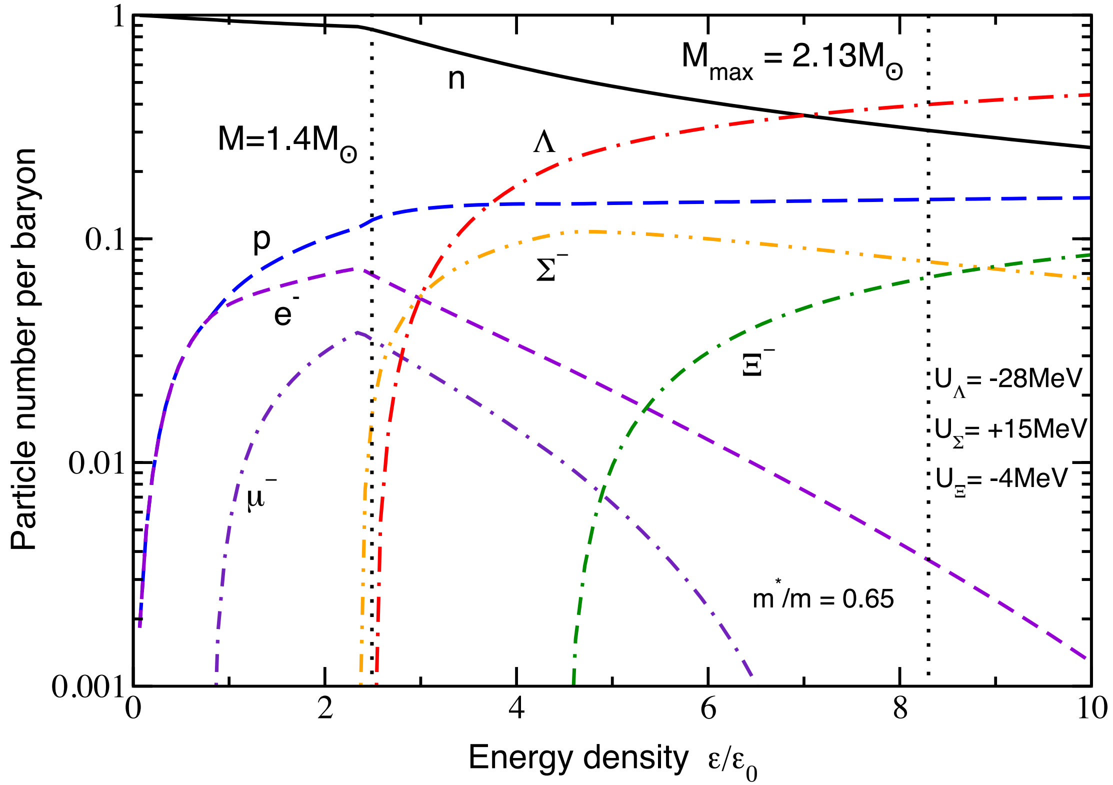
- Lattice QCD potentials from HAL QCD collaboration available ⟹ femtoscopy unique tool to study this system
- Observation of the strong interaction beyond Coulomb
- Agreement with LQCD calculations confirmed in pp and p-Pb colliding systems (Phys. Rev. Lett 123, (2019) 112002)
- **At finite density HAL QCD potentials predict in PNM a slightly repulsive U_Ξ ~+6 MeV (HAL QCD Coll., PoS INPC2016 (2016) 277)**
  - **pushing production of Ξ to higher densities ⟹ stiffer EoS**

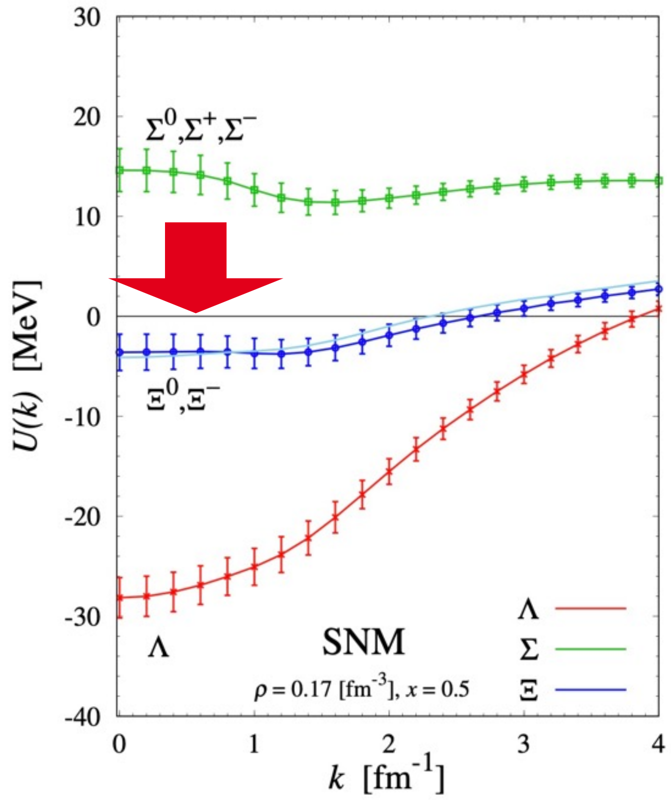
Nature 588 (2020) 232-238



Single particle potentials from lattice QCD

Courtesy J. Schaffner-Bielich 2020



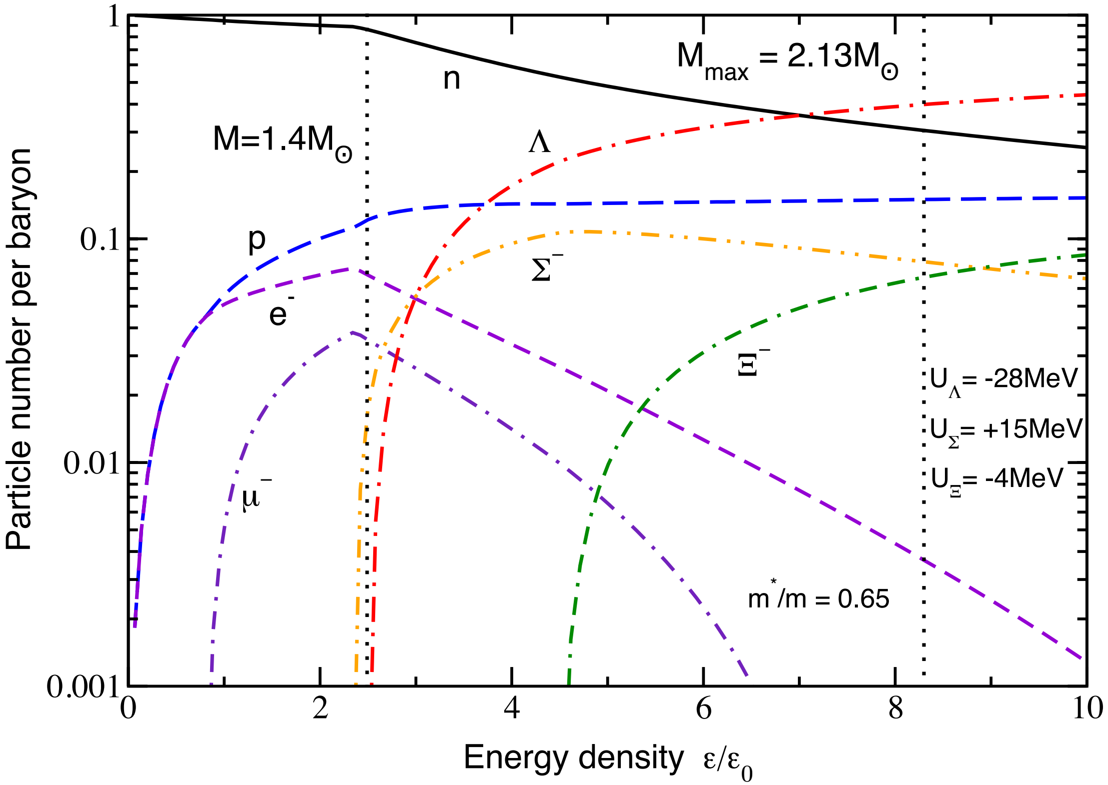


Attractive $p\Xi^-$ interaction lead to slightly attractive single particle potential in symmetric nuclear matter (SNM) and slight repulsion in neutron rich matter. Ξ^- appears at larger densities in NS

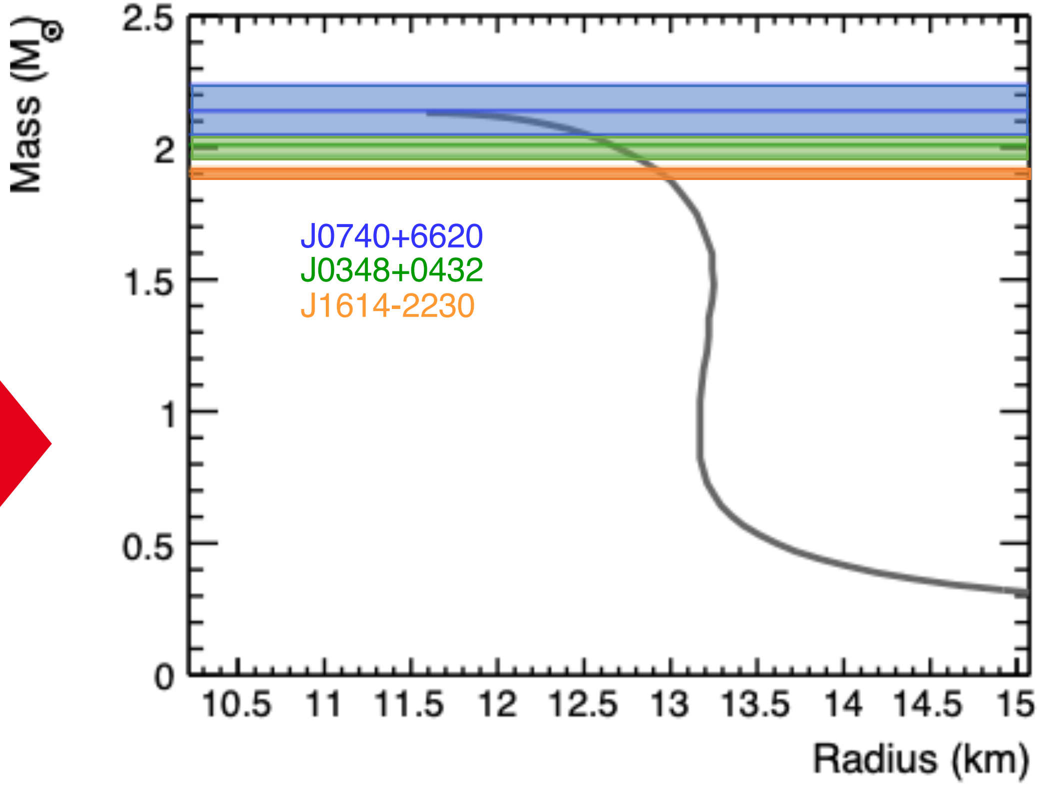
Inoue, T. Strange nuclear physics from QCD on lattice. AIP Conference Proceedings 2130, 020002 (2019)

Equation of state for neutron stars

Courtesy J. Schaffner-Bielich 2020



LF, V. Mantovani Sarti, O. Vazquez Doce arXiv:2012.09806

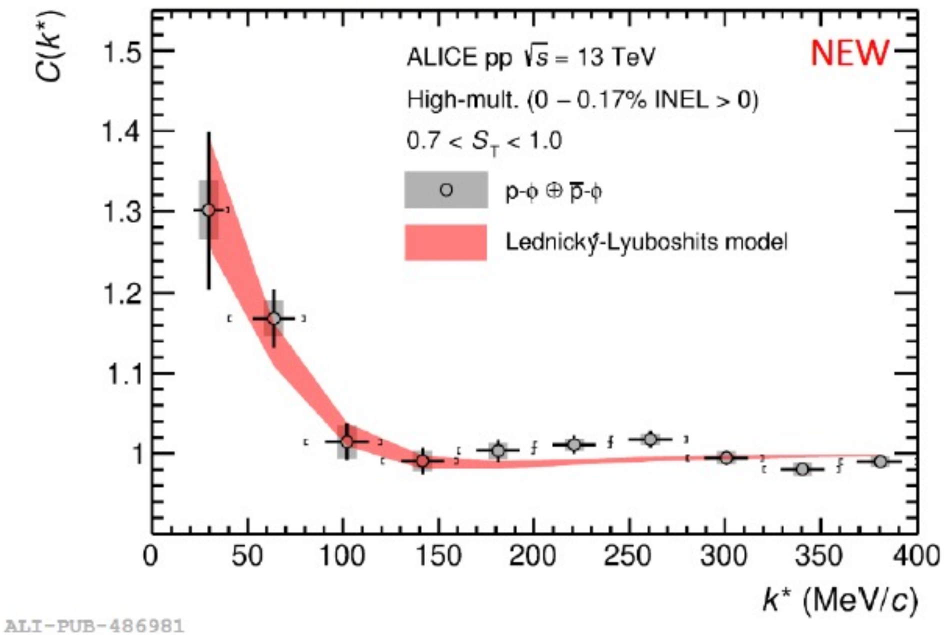


The resulting equation of state for neutron star is stiffer and the observation of 2 solar masses is matched.

This is not the end of the story…

Proton-ϕ Interaction

https://arxiv.org/abs/2105.05578



ALI-PUB-486981

Extracted genuine correlation function
After the subtraction of combinatorics, mini-jets and unfolding according to the genuine p-ϕ contribution.

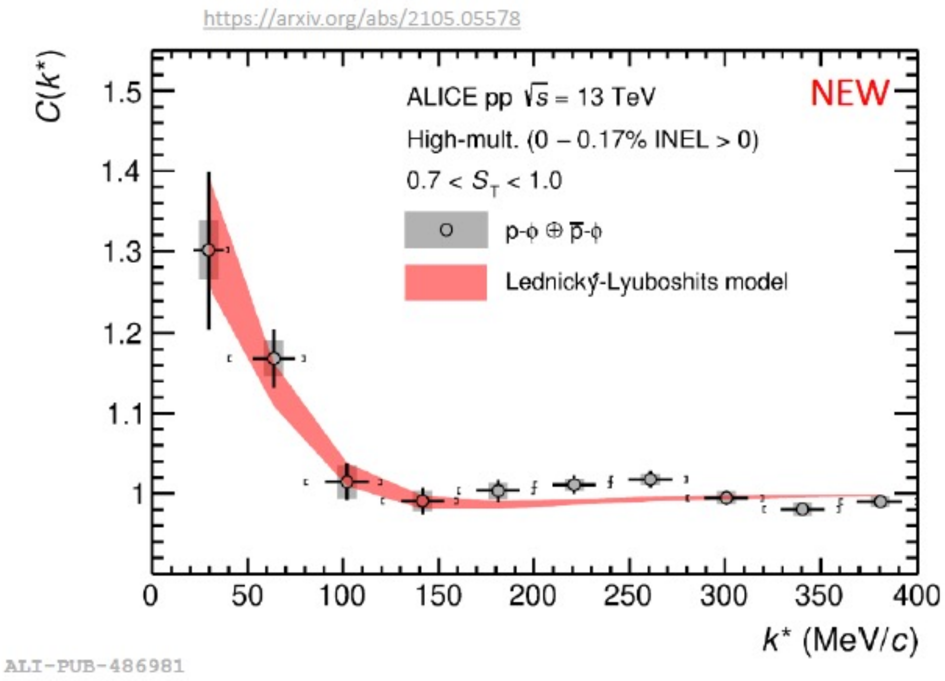
1) Lednicky-Lyuboshits Model

$$C(k^*) = \sum_S \rho_S \left[\frac{1}{2}\left|\frac{f(k^*)}{r_0}\right|^2 \left(1 - \frac{d_0}{2\sqrt{\pi} r_0}\right) + \frac{2\Re f(k^*)}{\sqrt{\pi} r_0} F_1(2k^* r_0) - \frac{\Im f(k^*)}{r_0} F_2(2k^* r_0)\right]$$

$$d_0 = 7.85 \pm 1.54(stat.) \pm 0.26(syst.)\text{fm}$$
$$Re(f_o) = 0.85 \pm 0.34(stat.) \pm 0.14(syst)\text{fm}$$
$$Im(f_o) = 0.16 \pm 0.10(stat.) \pm 0.09(syst.)$$

Large range
Dominant elastic interaction!

Proton-ϕ Interaction



Extracted genuine correlation function
After the subtraction of combinatorics, mini-jets and unfolding according to the genuine p-ϕ contribution.

2) Yukawa-type potential with real parameters

$$V(r) = -A\frac{e^{\alpha r}}{r}$$

Correlation obtained with CATS
Fit Results:

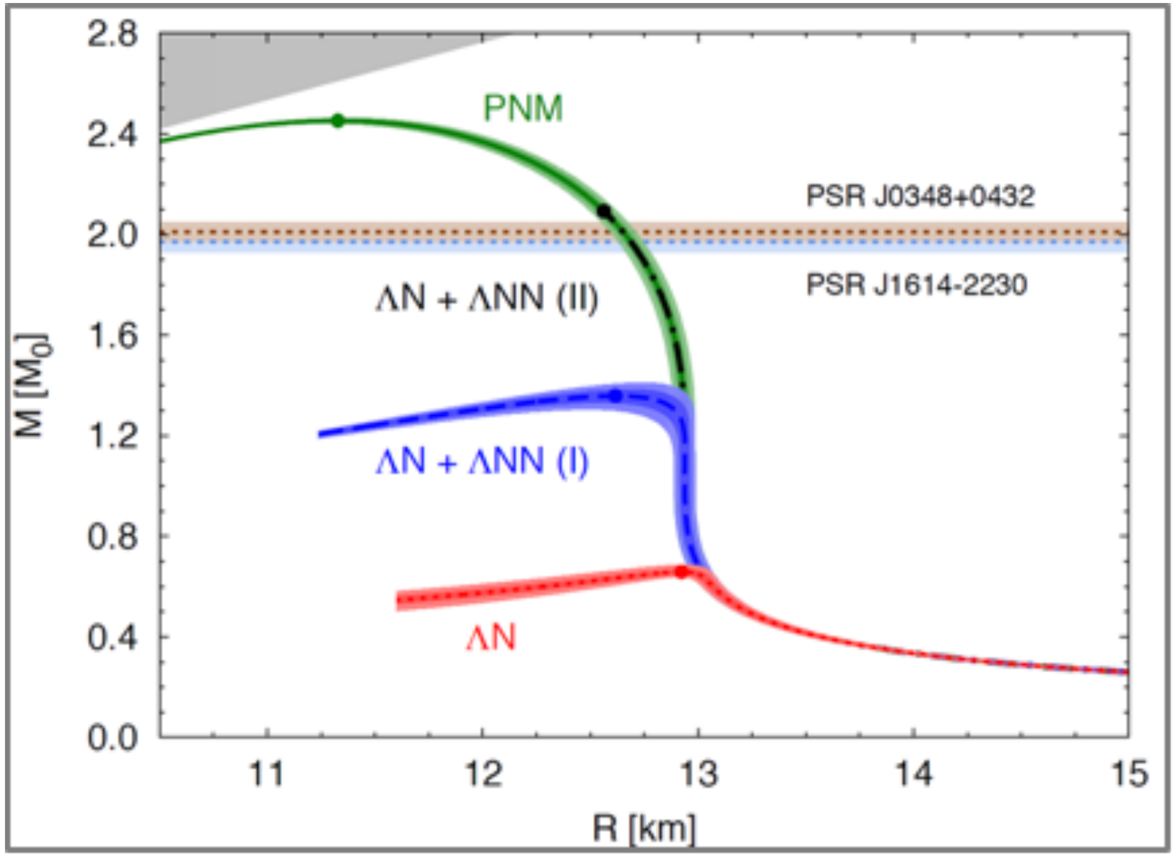
$$A = 0.021 \pm 0.009(stat.) \pm 0.006(syst.)$$

$$\alpha = 65.9 \pm 38.0(stat.) \pm 17.5(syst)$$

Extraction of the N-ϕ coupling constant as $\sqrt{A}$

$$g_{\phi N} = \ 0.14 \pm 0.03(stat.) \pm 0.02(syst.)$$

Effect of the 3-body Forces



D. Lonardoni, A. Lovato, S. Gandolfi, F. Pederiva Phys. Rev. Lett. 114, 092301 (2015)

Repulsive 3-body forces can contribute to stiffen the hyperon stars equation of state

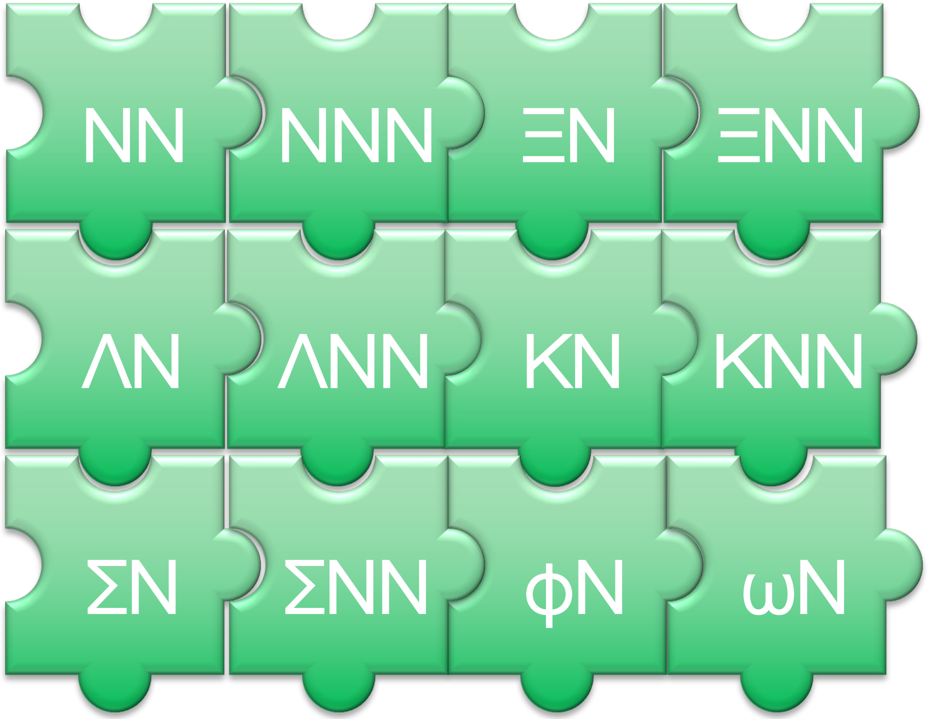
Prediction from Quantum Montecarlo adjust repulsive 3-body forces to hypernuclei binding energies

Current χEFT calculations predict an overall attractive 3-body contribution and a repulsive 2-body core

(S. Petschauer et al Theory. Front. Phys. 8 (2020) 12)
(D.Logoteta et al Eur. Phys. J. A (2019) 55: 207)

Need a direct measurement!
Talk by Dr. Raffaele Del Grande Tue 19:00

… towards the solution of the puzzle

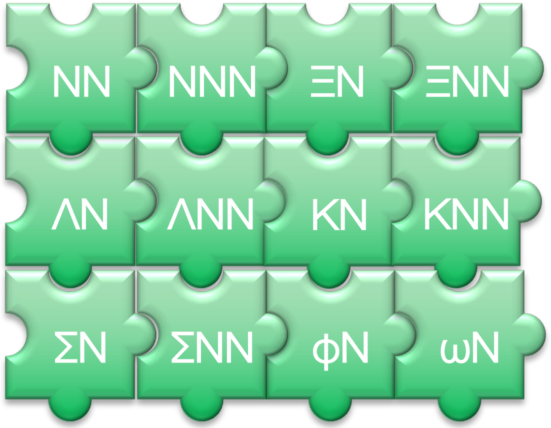


Summary

- Femtoscopy as a tool to provide unprecedented constraints on hadron-hadron interactions

- Most precise data on several YN interactions providing constraints for hadron-hadron potentials
- First measurement of the proton-ϕ interaction

- More precision studies within reach with the large data samples collected in Run 3 & 4
  - Direct measurements of three-body interactions for the first time
  - Eventually solve the hyperon puzzle…
  - Probing QCD bound states



Thank you!