STRANGENESS HADRON PHYSICS

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Present and future perspectives in Hadron Physics

Jun 17 – 19, 2024
Laboratori Nazionali di Frascati INFN

UNIVERSITAT DE BARCELONA

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EXCELENCIA MARÍA DE MAEZTU

Ever since the discovery of the first "strange" particles (K^-, K^+, Λ, $\Sigma's$, $\Xi's$ ...) in the late 40s and mid 50s, it was soon realized that the phenomena associated to their interactions (with nucleons, with nuclei, with other hadrons) would have a big impact on several fields of research:

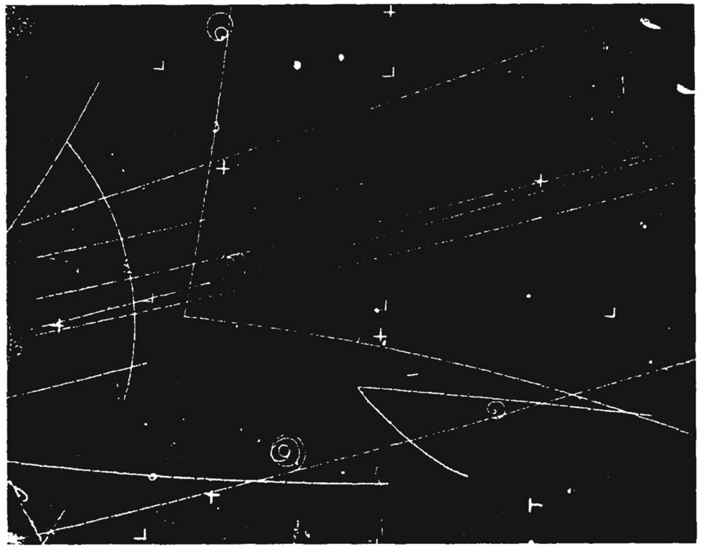


Fig.1. $\pi^- + p \rightarrow K^0 + \Lambda$.

Particle physics: birth of SU(3) symmetry and the "eightfold way" scheme (Gell-Mann), $\Lambda(1405)$, …

Nuclear physics: Λ-hypernuclei, kaonic atoms, bound nucelar kaonic clusters …

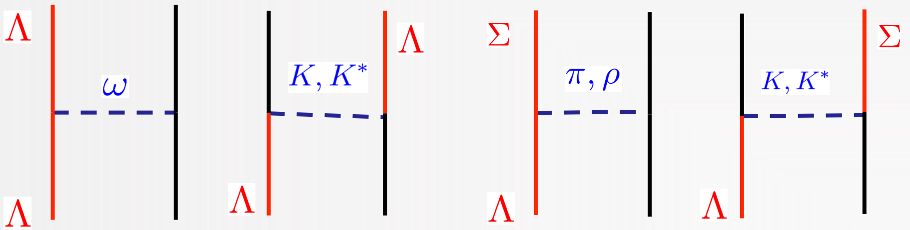
Astrophysics: hyperons in neutron stars (maximum mass puzzle, cooling, GW…)

Elementary YN interactions

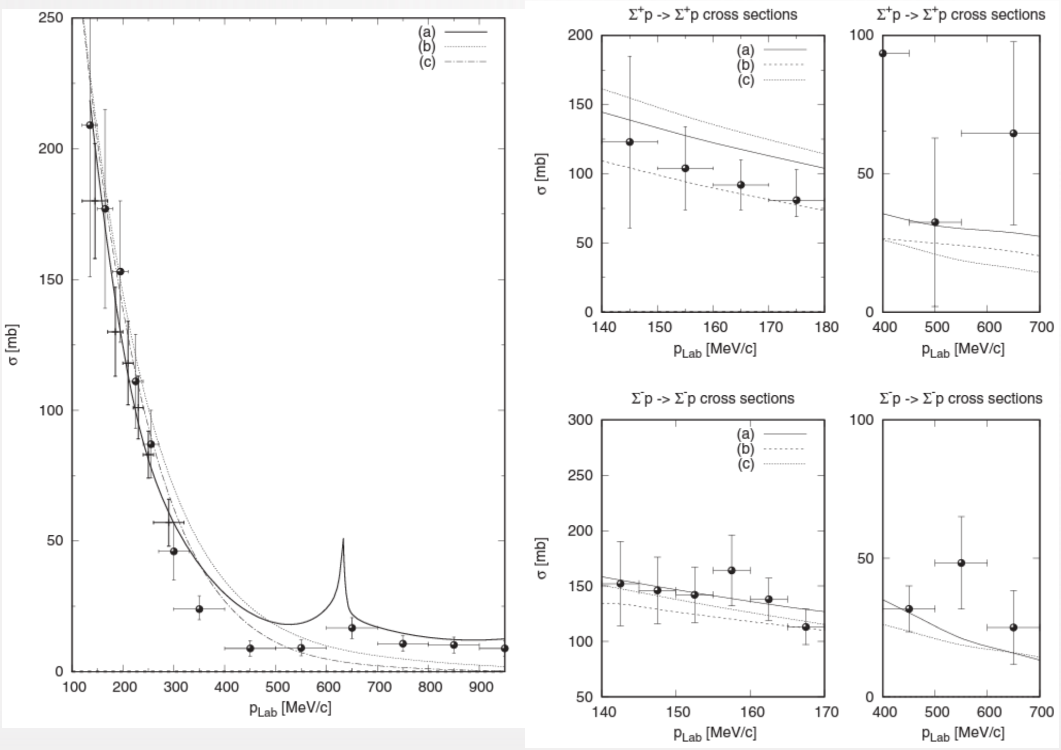
YN Cross Sections   very limited data base!

$\tau_\Lambda \sim 2.631 \times 10^{-10}$ s   (late 60s, 70s)

Traditional approach (Meson-exchange Models)

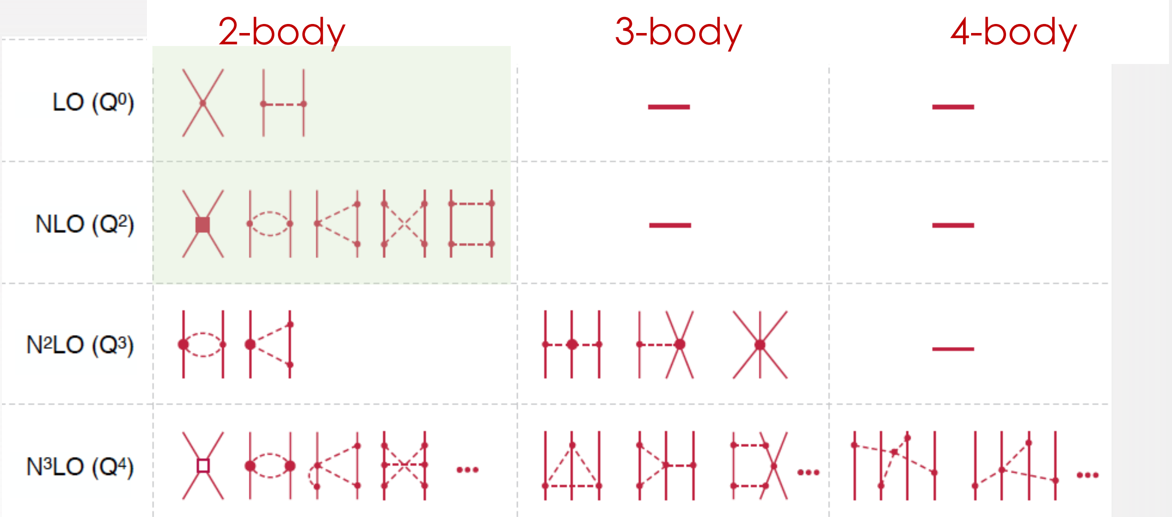


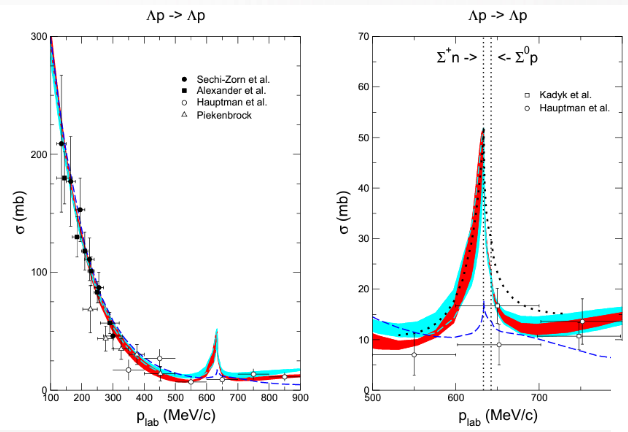
Nagels, Rijken, Yamamoto, PRC (2019)

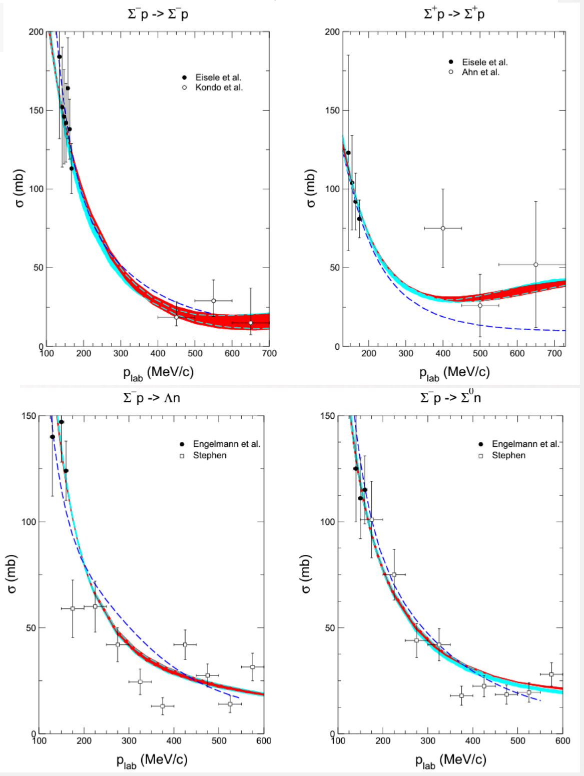


Modern approach (Effective Field Theory → χEFT)

(systematically organized hierarchy in powers of Q/Λ_χ)



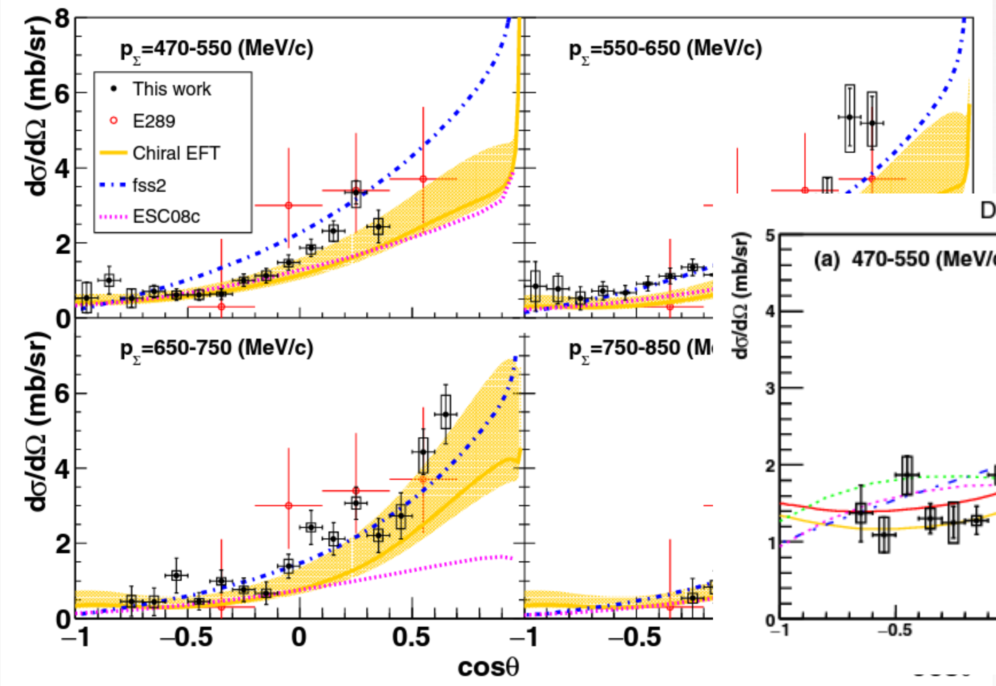




Haidenbauer, Meißner, Nogga, EPJA (2020)

differential x-sections for Σ^-p

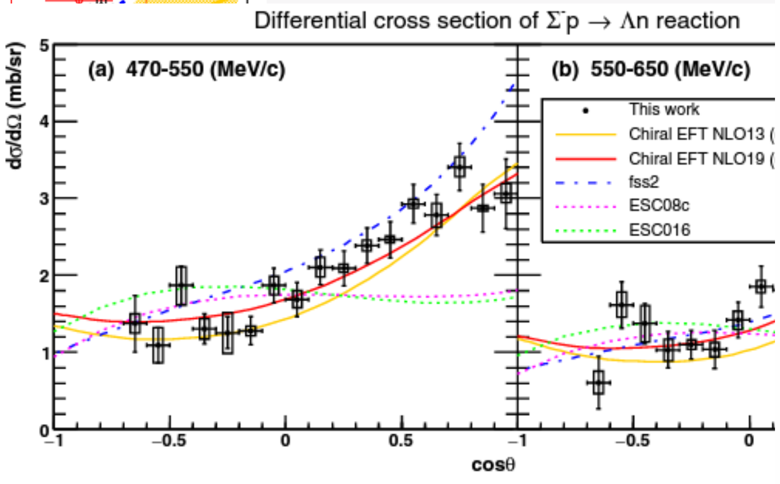
Miwa (J-PARC E40) PRC (2021)



J-PARC E40

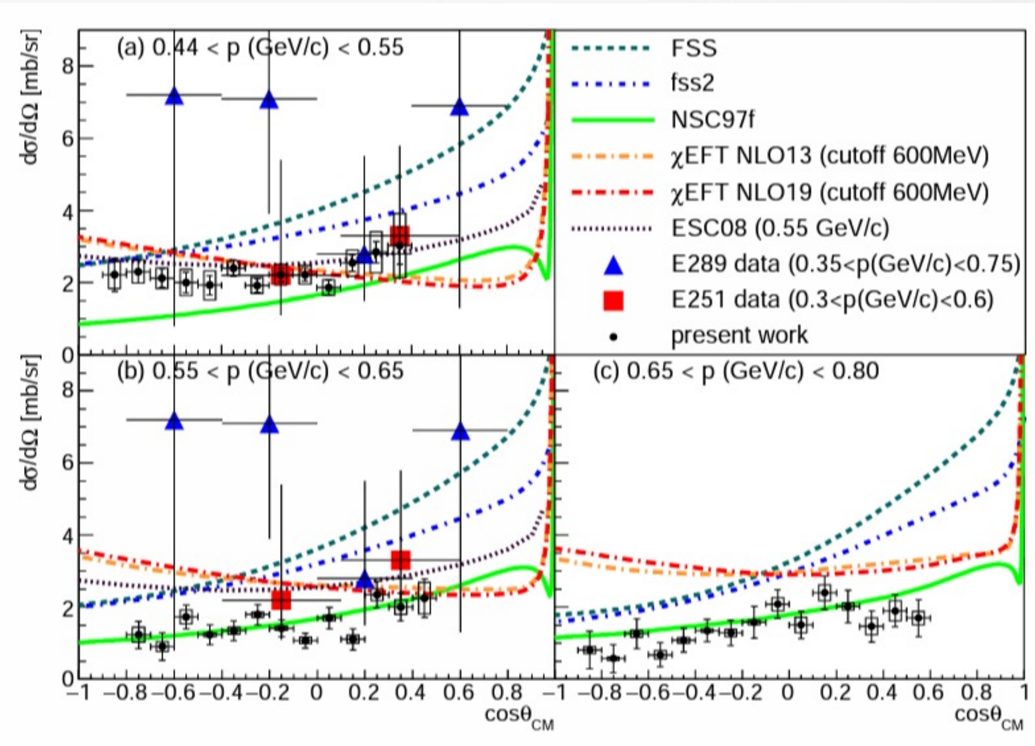
differential x-sections for $\Sigma^-p \to \Lambda n$

PRL (2022)



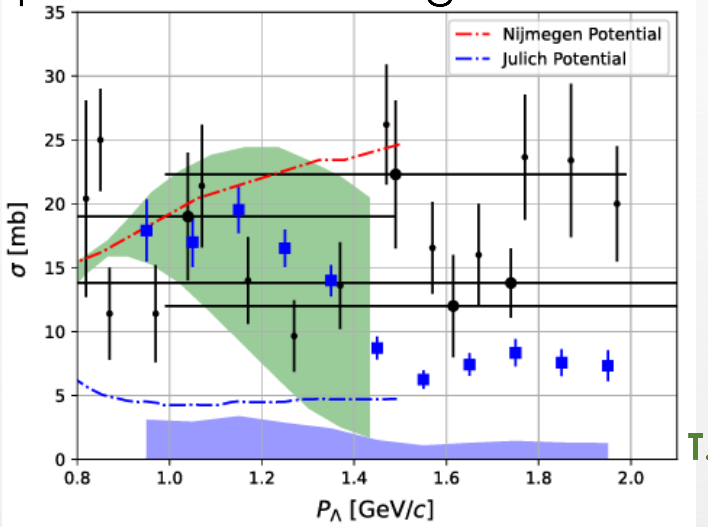
differential x-sections for Σ^+p

Nanamura (J-PARC E40), PTEP (2022)



Λp elastic scattering x-sections

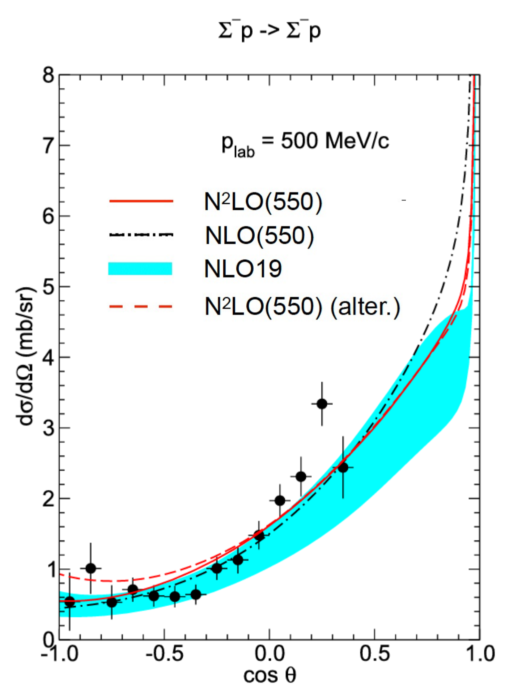
CLAS

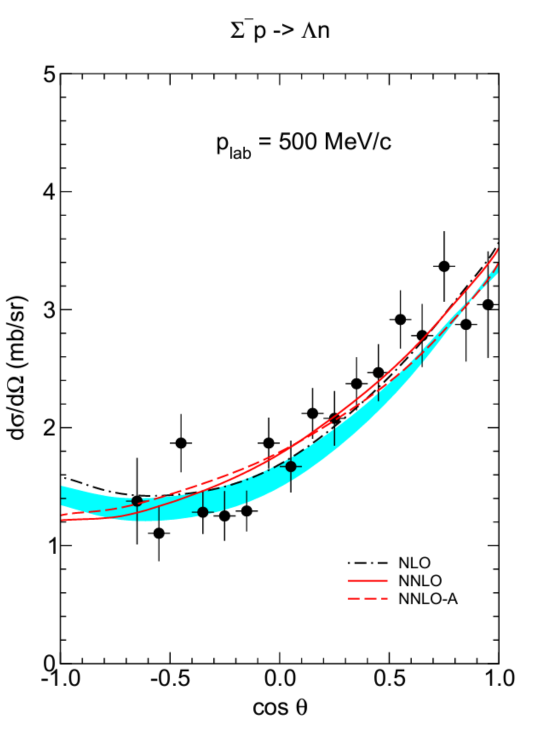


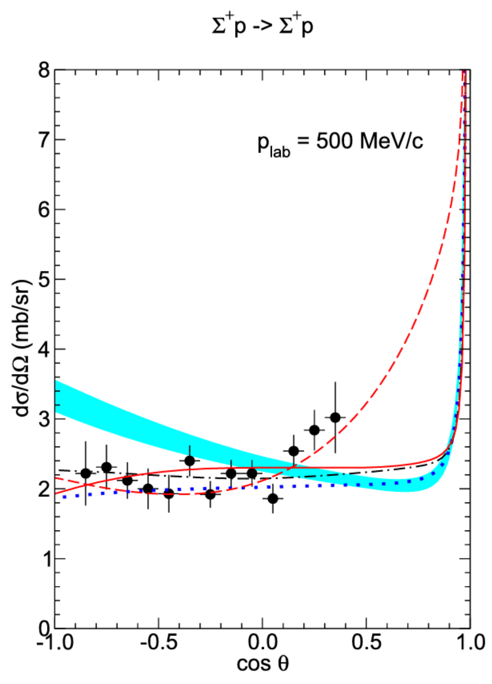
T. Rowley (CLAS), PRL (2021)

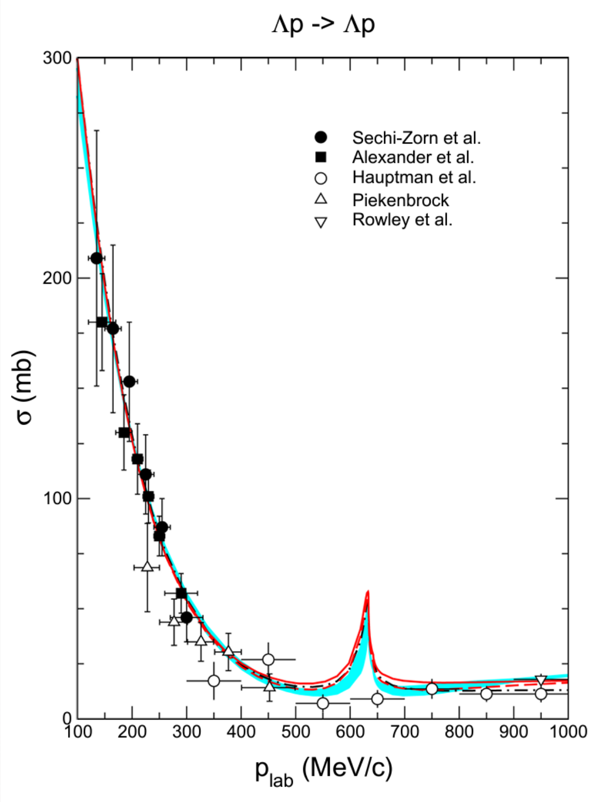
Models revisited with the new data from J-PARC and CLAS

Haidenbauer, Meißner, Nogga, Le, EPJA (2023)







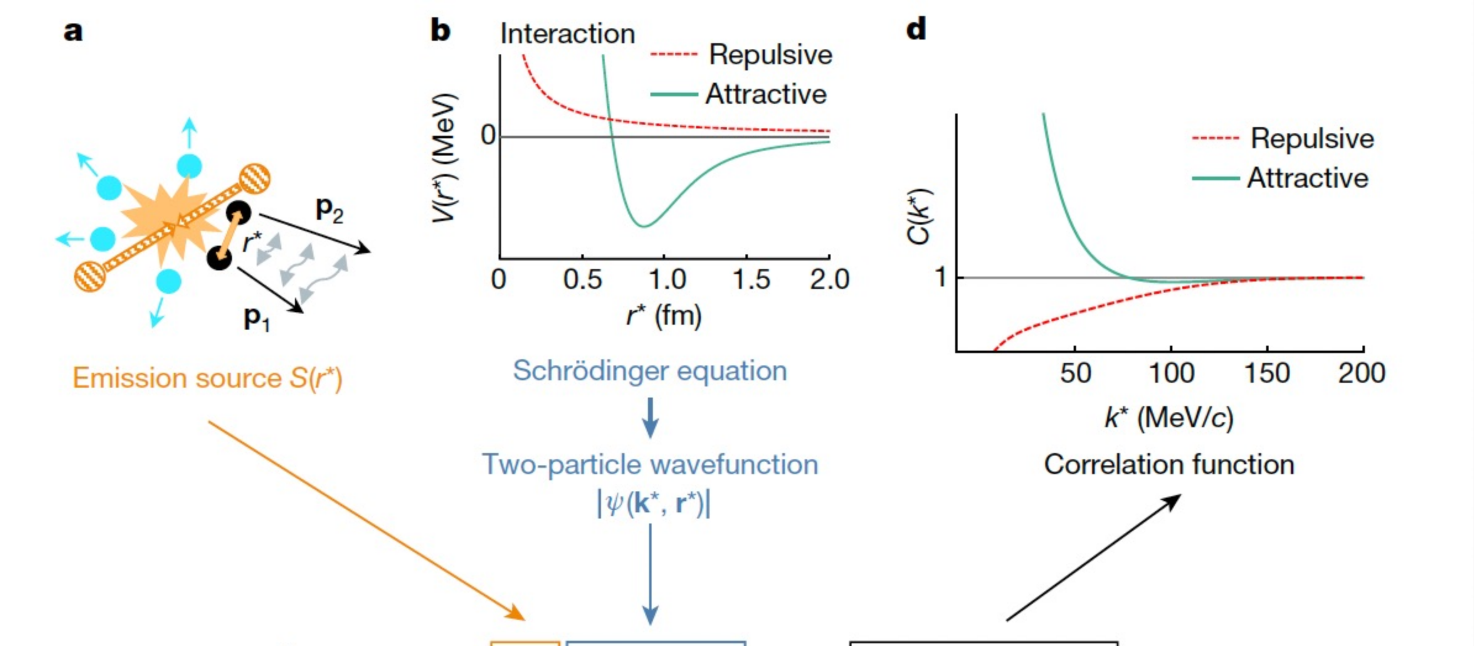


Femptoscopy: promising new method to understand hadron-hadron interactions at low energy.

ALICE collaboration, Nature 588 (2020) 232

Fabbietti, Mantovani-Sarti, Vazquez-Doce,, Annu. Rev. Nucl. Part. Sci. 71 (2021) 377

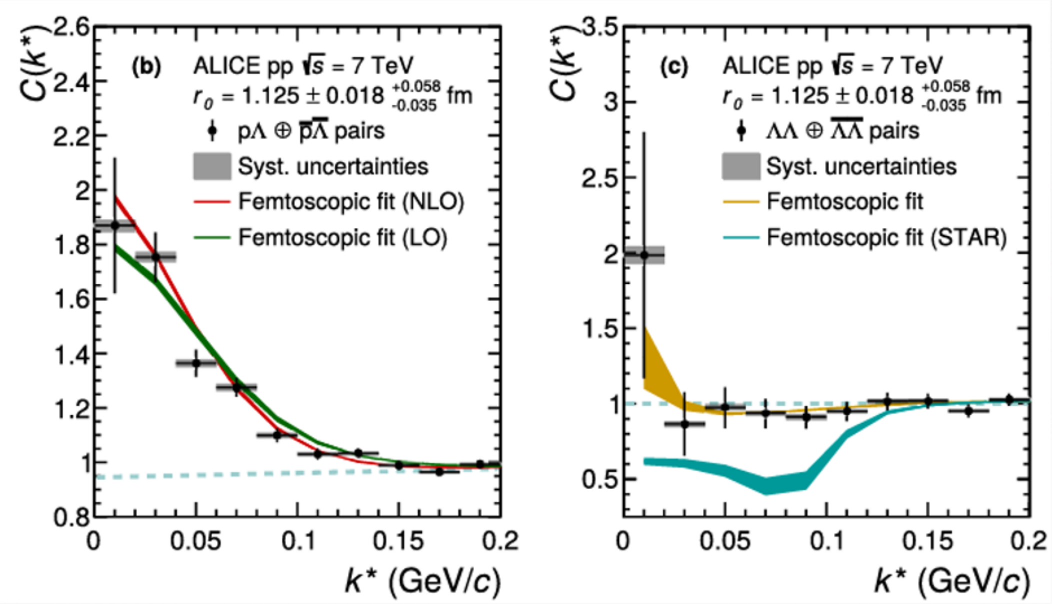
ultrarelativistic p–p, p-^{208}Pb, or ^{208}Pb-^{208}Pb collisions at LHC@CERN



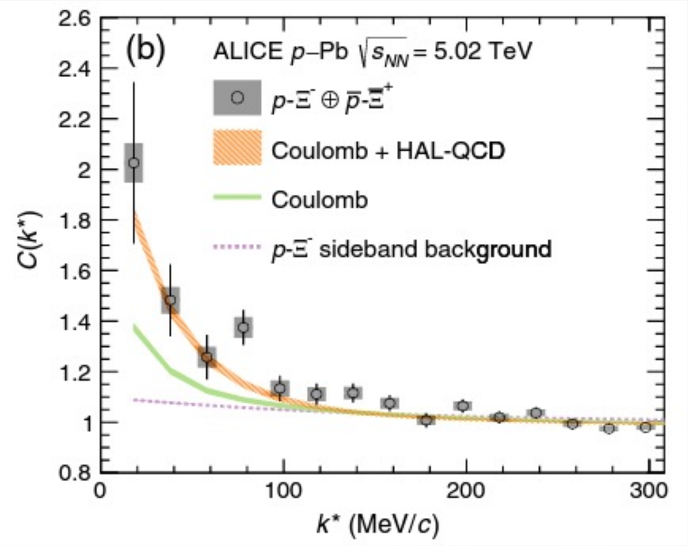
$$C(k^*) = \int S(r^*)\,|\psi(\mathbf{k}^*, \mathbf{r}^*)|^2\, d^3r^* = \xi(k^*)\frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

Femtoscopy studies are bringing information on low-energy YN, YY interactions! → **ALICE@LHC**

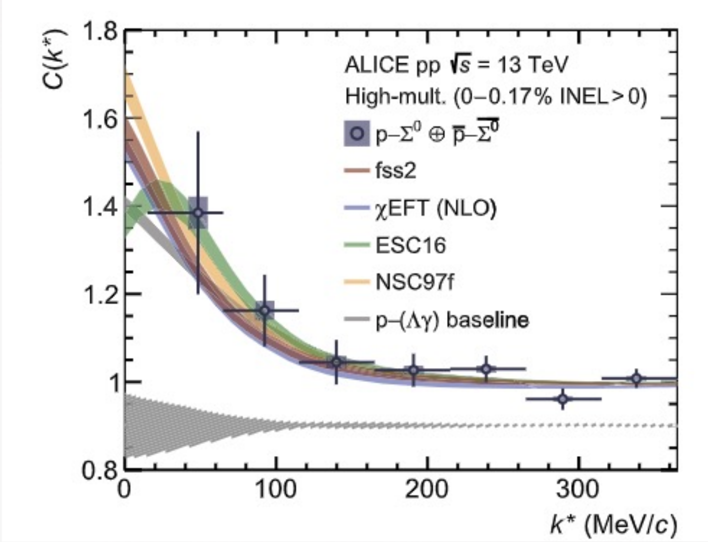
ALICE, PRC (2019)



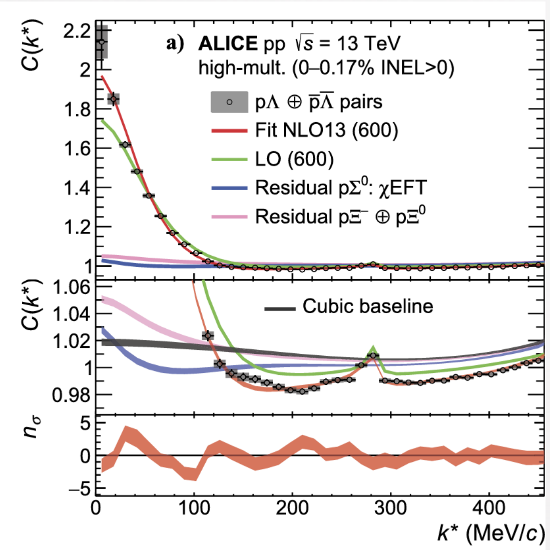
ALICE, PRL (2019)



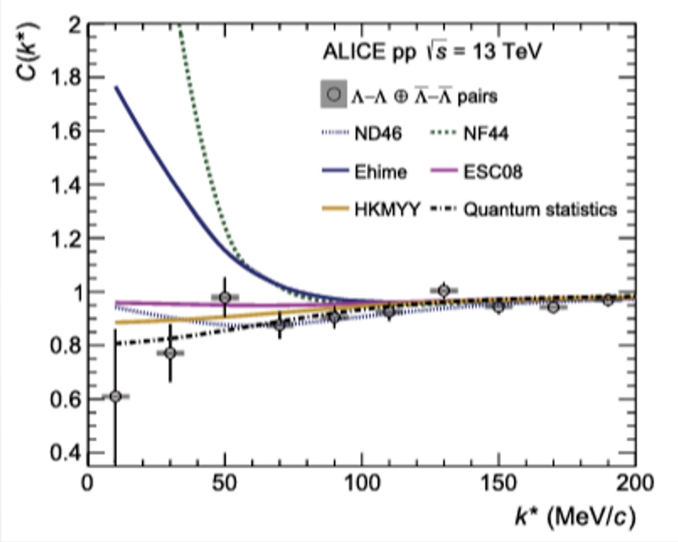
ALICE, PLB (2020)



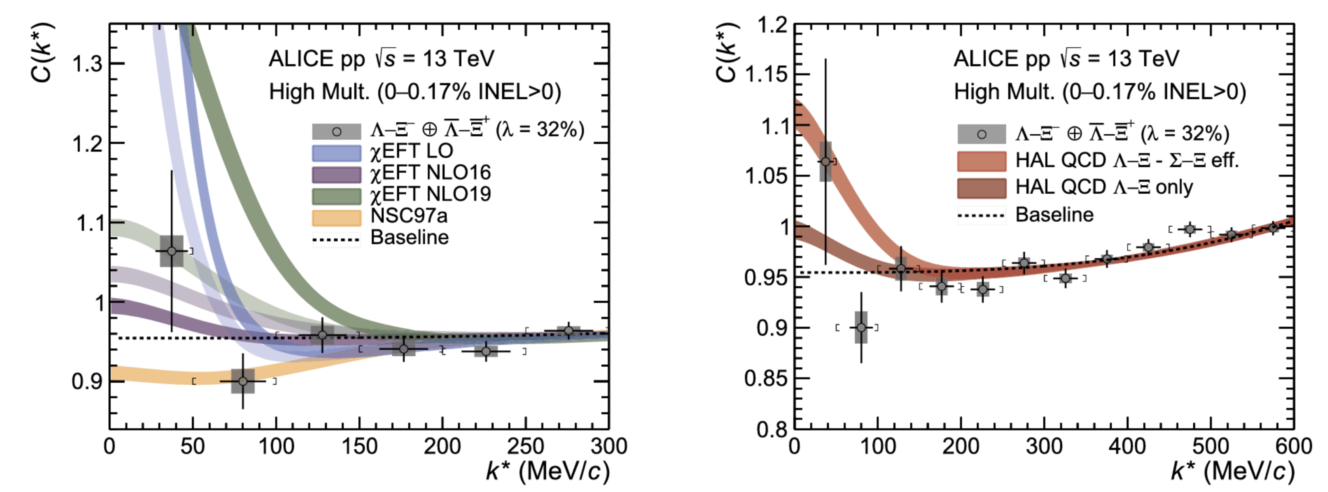
ALICE, PLB (2022)



ALICE, PLB (2019)

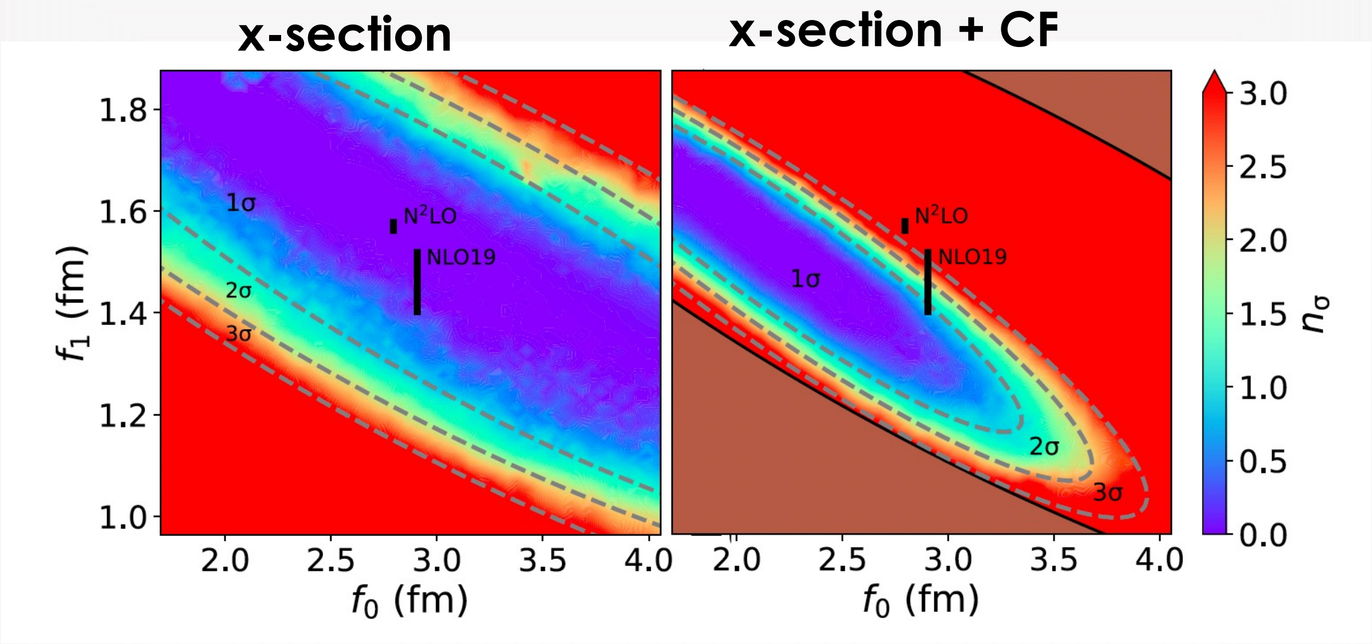


ALICE, PLB (2023)



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

The first **combined analysis** of low-energy **femtoscopic** and **x-section scattering data** to constrain the *S*-wave scattering parameters of the pΛ interaction

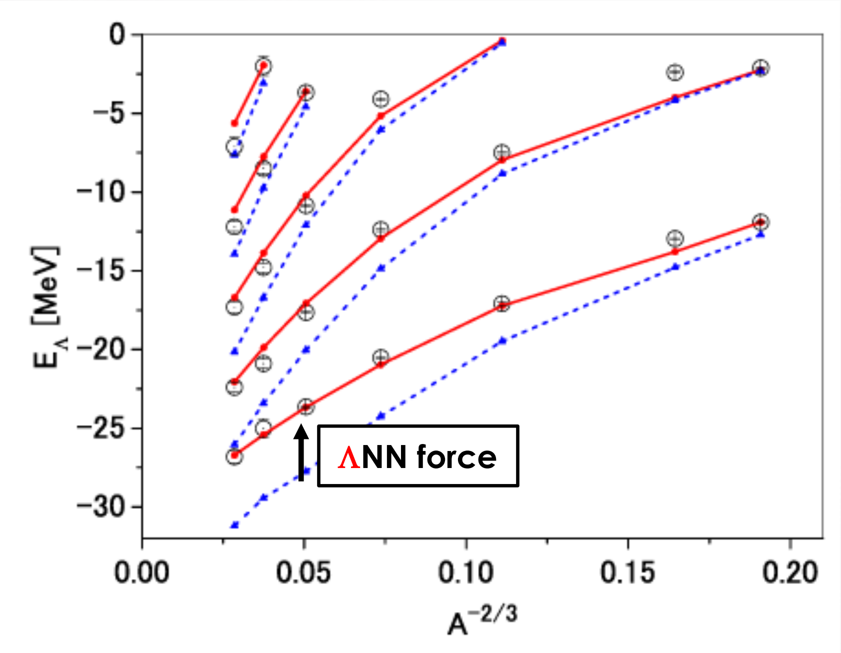


→ The pΛ interaction is overall less attractive

Testing (and constraining) YN interactions with hypernuclear data

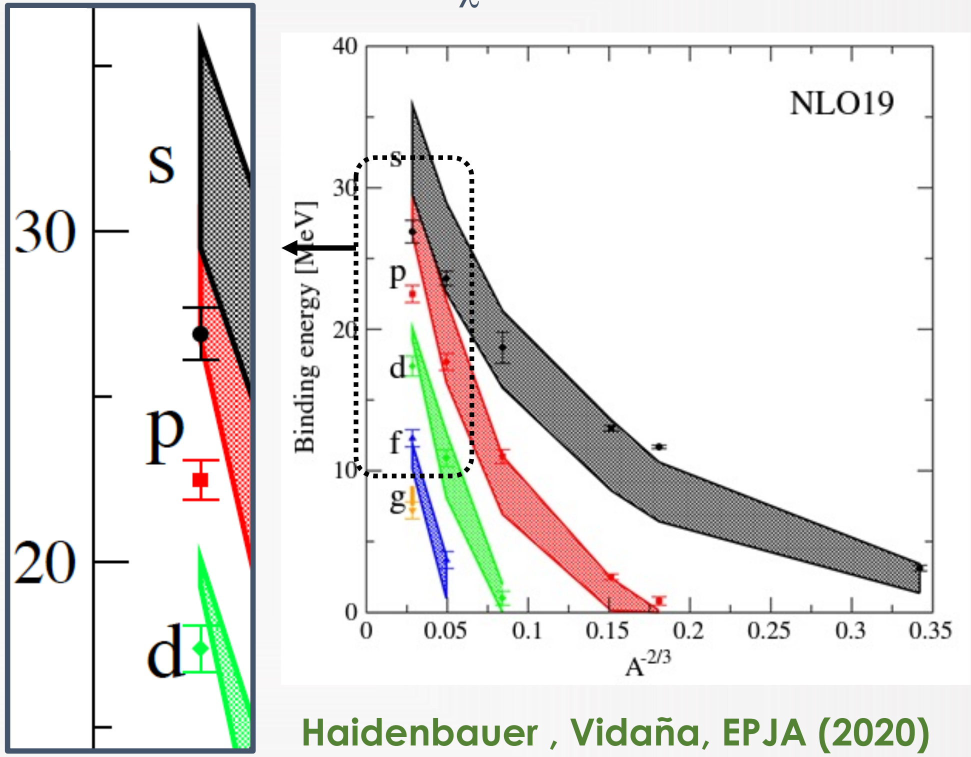
ΛN interaction → many-body corrections → in-medium ΛN interaction → Λ–nucleus potential

with meson-exchange model



Nagels, Rijken, Yamamoto, PRC (2019)

with χEFT at NLO



Haidenbauer , Vidaña, EPJA (2020)

YNN forces are needed to reproduce the Λ hypernuclear s- (and p-) levels in hypernuclei

See also: Friedman, Gal, PLB (2023), NPA (2023)

Strangeness in Neutron stars (hyperon puzzle)

A neutron star is one of the densest manifestations of massive objects in the universe.

It is the compact remnant from the gravitational collapse of a massive star ($8\ M_\odot < M < 25\ M_\odot$) in a Type II, Ib or Ic supernova event

Mass $M \sim 1 - 2\ M_\odot$

Radius $R \sim 10 - 12$ km

Central density $\rho_c \sim 10^{14} - 10^{15}$ g cm^{-3}

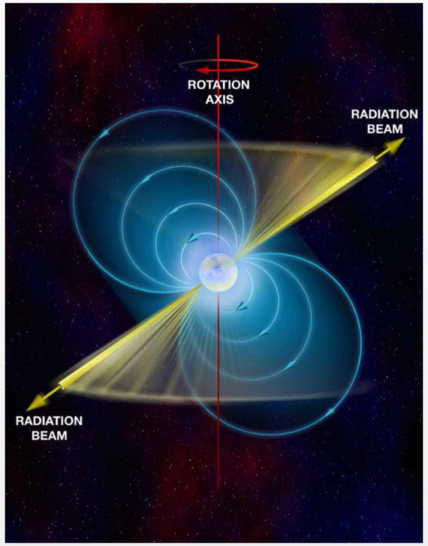
(in a nucleus: $\rho_c = 2.8 \times 10^{14}$ g cm^{-3})

Rotation period (two types): $P \sim$ s

$P \sim$ ms

Magnetic field (intense!):

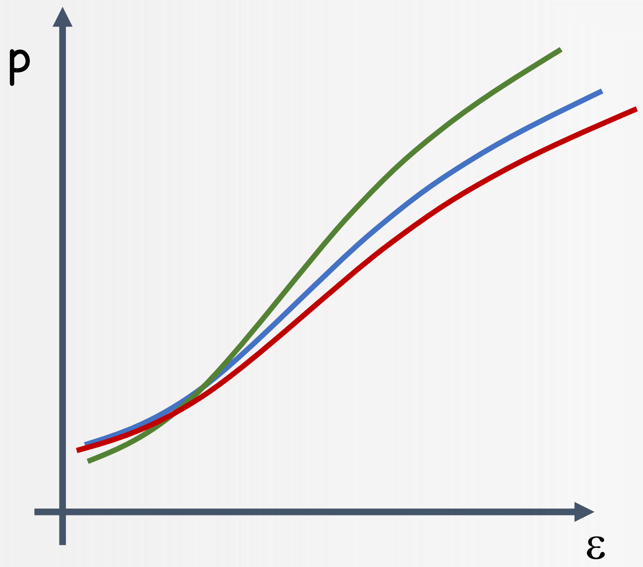
Type of Pulsar	Surface magnetic field
Millisecond	$10^8 - 10^9$ G
Normal	10^{12} G
Magnetar	$10^{14} - 10^{15}$ G



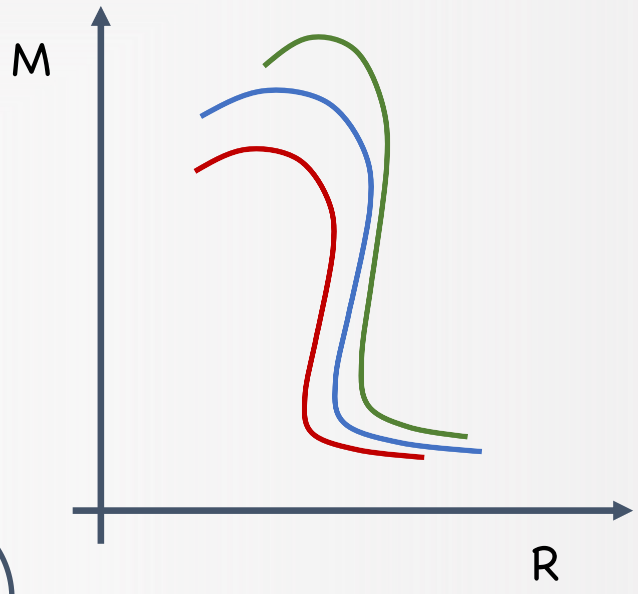
Crab Nebula: remains of a supernova explosion (1054 AD). A rapidly rotating neutron star (pulsar) sits at its center

An **Equation of State** is needed to describe the properties of neutron stars

EoS



M-R relationship



Tolman-Oppenheimer-Volkov equations:

$$\frac{dp}{dr} = -\frac{(m + 4\pi r^3 p)(\varepsilon + p)}{r(r - 2m(r))}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

given a value of p_c (and correspondig ε_c) determine the star mass **M** and radius **R**

Why is it likely to have hyperons in the inner core of a neutron star?

The core of a neutron star is a cold fluid (T~0) fluid of neutron-rich matter (neutrally charged) in equilibrium with respect to the weak interactions

➔ known as β-stable nuclear matter

$$\mu_i = \frac{\partial \varepsilon}{\partial \rho_i}$$

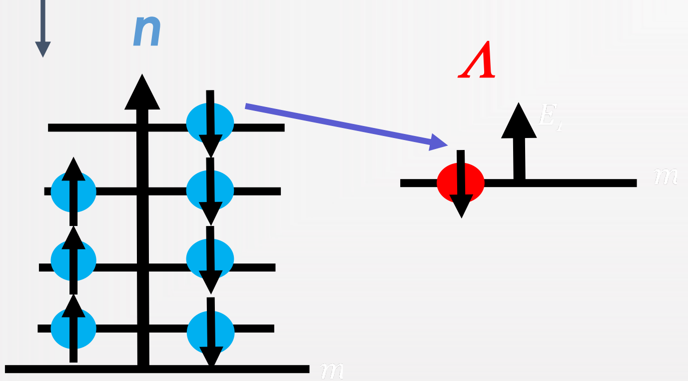
increasing density ↓

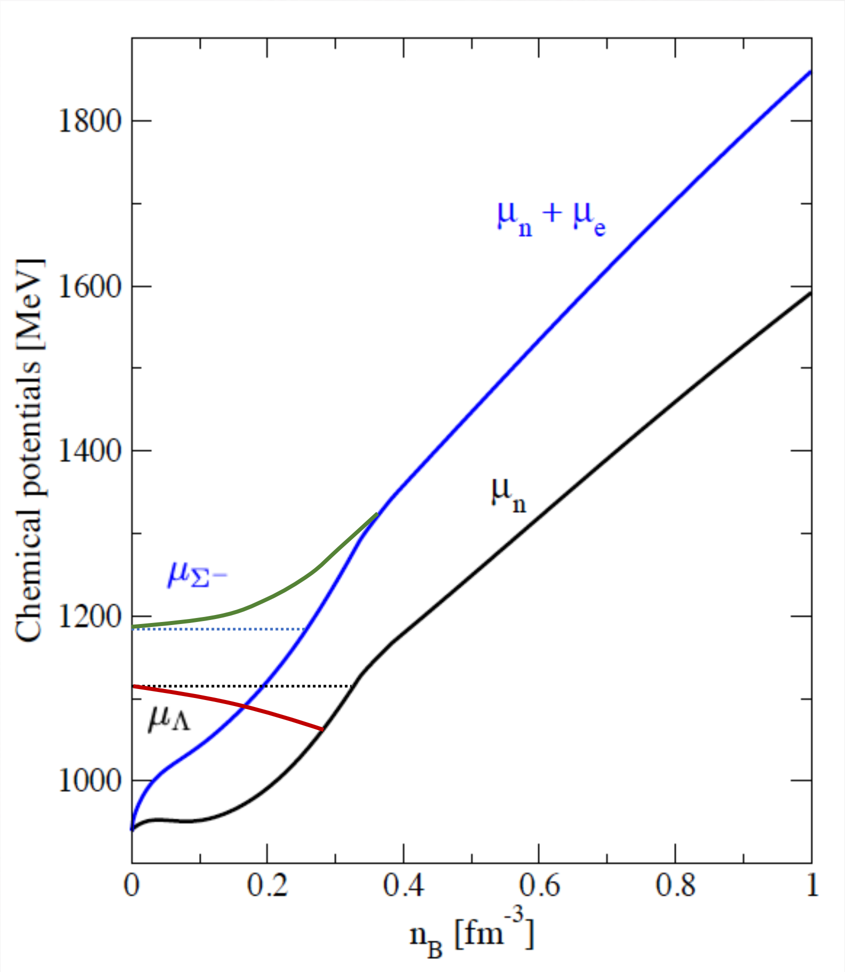
n, p, e-: $n \leftrightarrow p\, e^- \,\bar{\nu}_e$ $\quad \mu_n = \mu_p + \mu_e$

n, p, e-, μ- : $n \leftrightarrow p\, \mu^- \,\bar{\nu}_e$ $\quad \mu_n = \mu_p + \mu_\mu \rightarrow \mu_\mu = \mu_e$

n, p, e-, μ- + hyperons: $\Lambda \leftrightarrow p\, e^- \,\bar{\nu}_e$ $\quad \mu_\Lambda = \mu_n$

$\Sigma^- \leftrightarrow n\, e^- \,\bar{\nu}_e$ $\quad \mu_{\Sigma^-} = \mu_n + \mu_e$



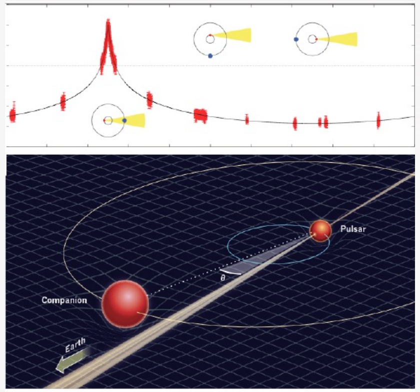


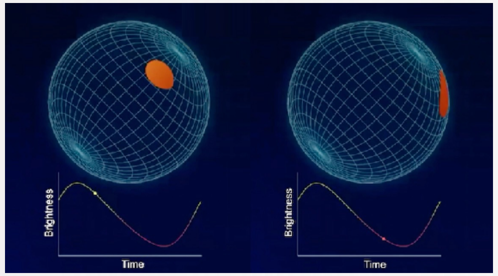
Hyperon onset depends on the YN interaction !

How hyperons affect the M-R relation?

Burgio, Schulze, Vidana, Wei, Prog.Part.Nucl.Phys. 120 (2021) 103879

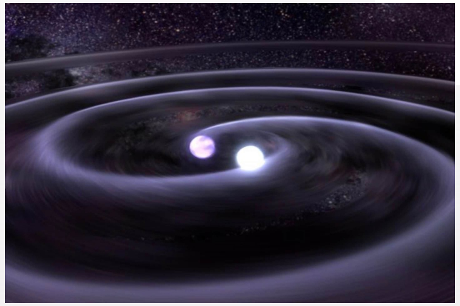
J0740+6620
Shapiro-delay measurements in NS-white dwarf binary system

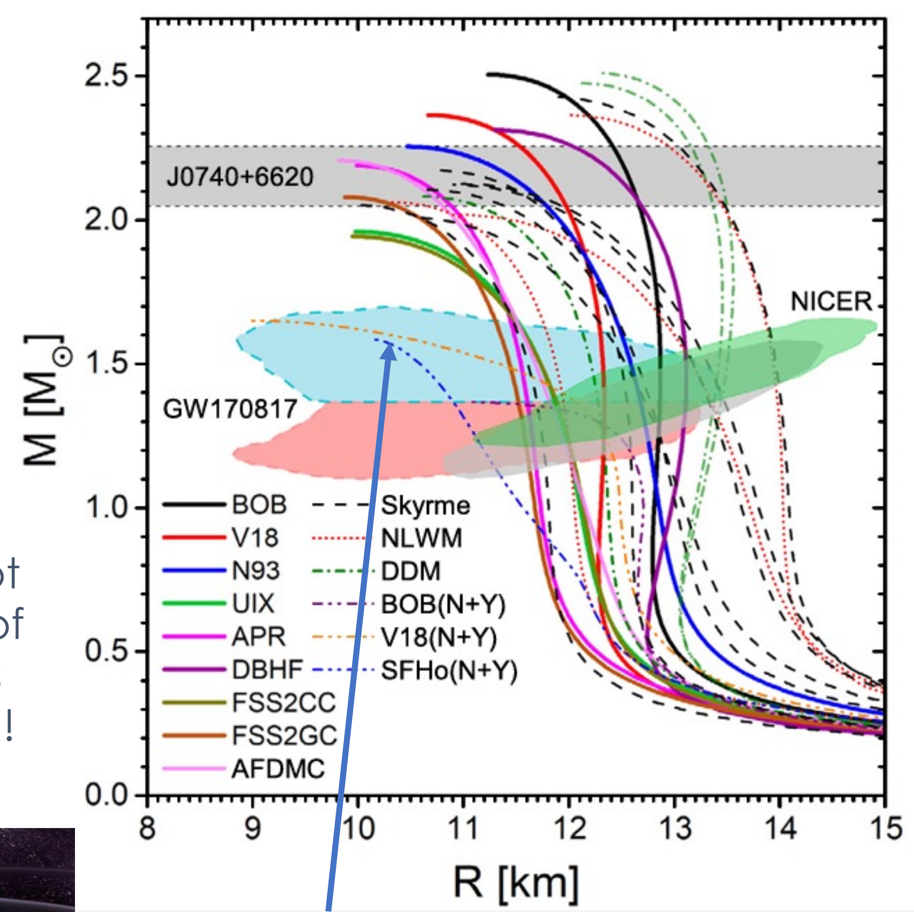


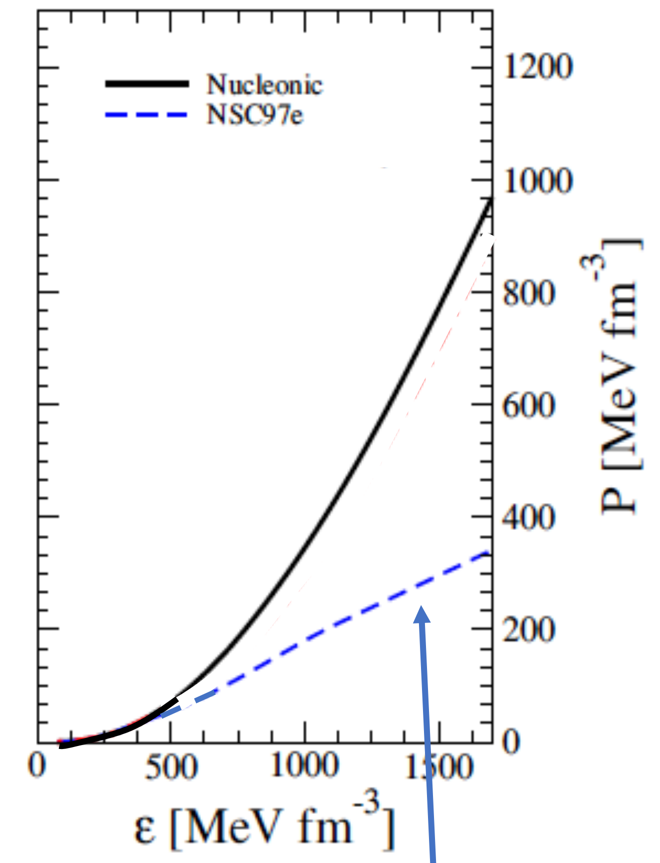


NICER: X rays from hot spots at the surface of rotating neutron stars ➔ access to M **and** R!

GW170817
LIGO&Virgo: gravitational waves from a Binary Neutron Star Merger







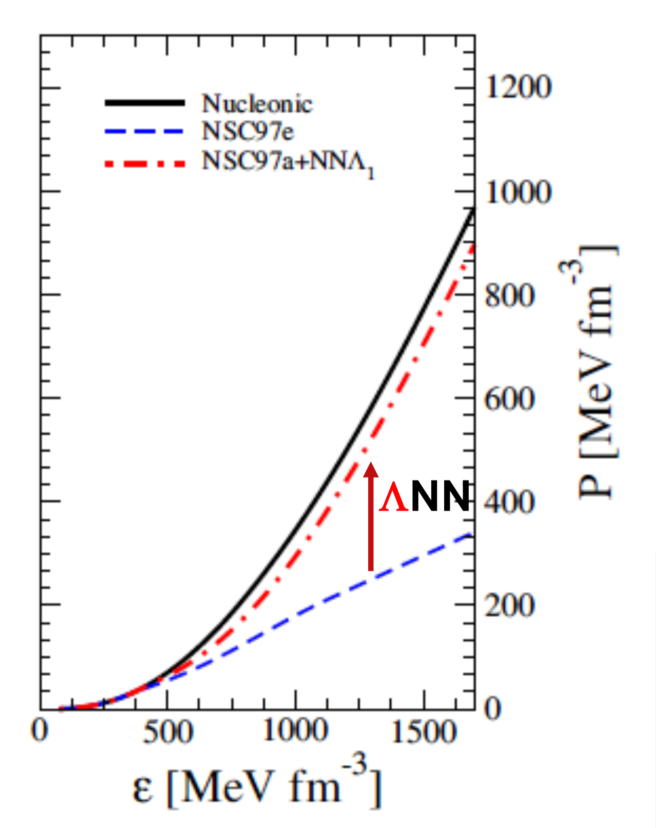
hyperon puzzle!

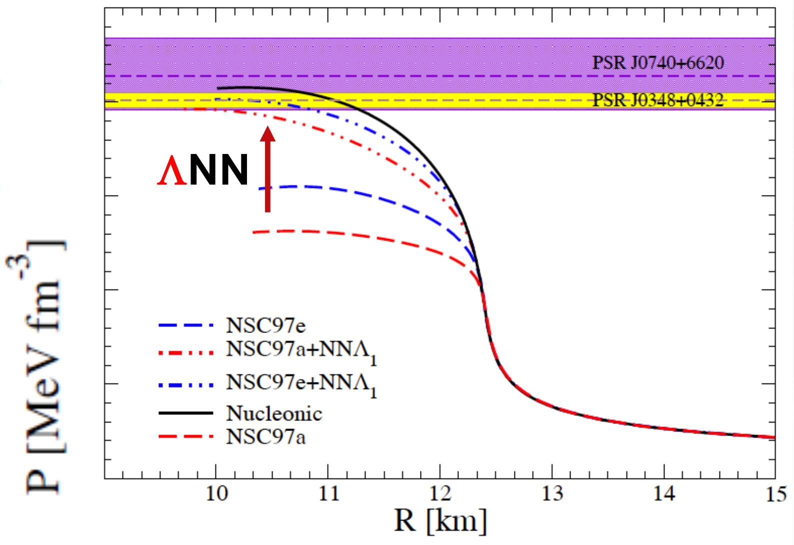
with hyperons

(maximum masses not compatible with the observation of pulsars with M ~2M$_\odot$)

Can the hyperon puzzle be solved?

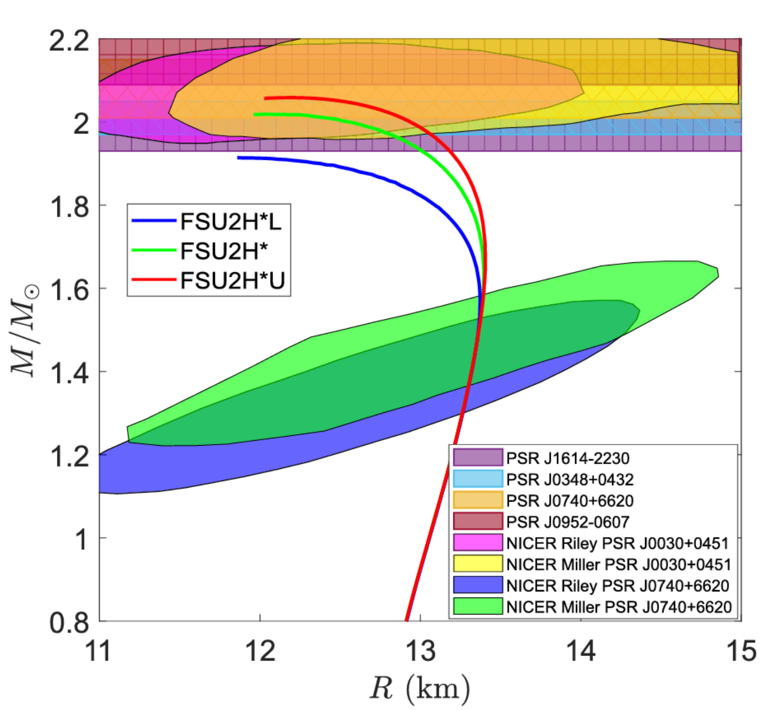
Logoteta, Vidaña, Bombaci, EPJA (2019)





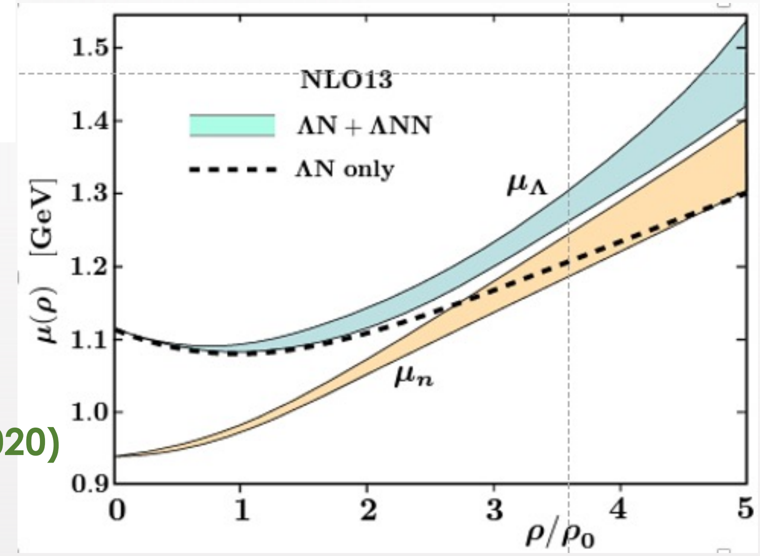
- ✓ The loss of pressure induced by hyperons can be compensated by a repulsive enough YNN force
  - ✓ This can be effectively mimicked by repulsive vector meson contributions in Relativistic Mean Field models.

Kochankovski, Ramos, Tolos, MNRAS (2024)



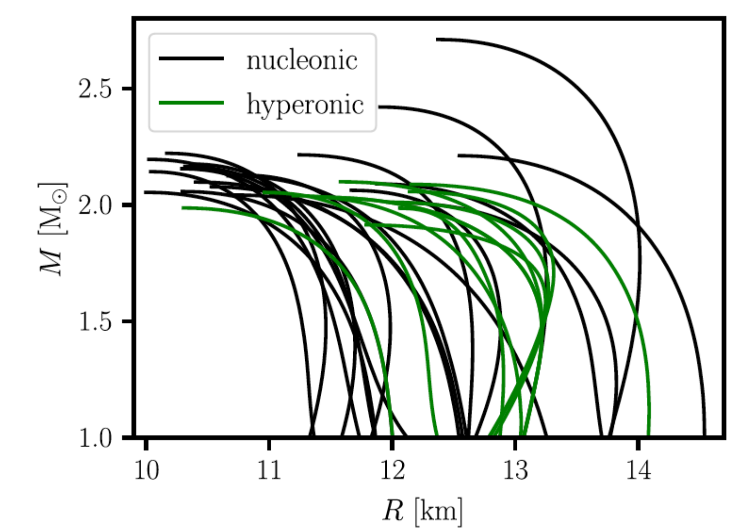
Y NN might even prevent the appearance of hyperons!

Gerstung, Kaiser, Weise EPJA (2020)



Is there a clear signal of the presence of hyperons in NS?

The M-R relation for cold (T=0) NS cannot distinguish nucleonic from hyperonic models.

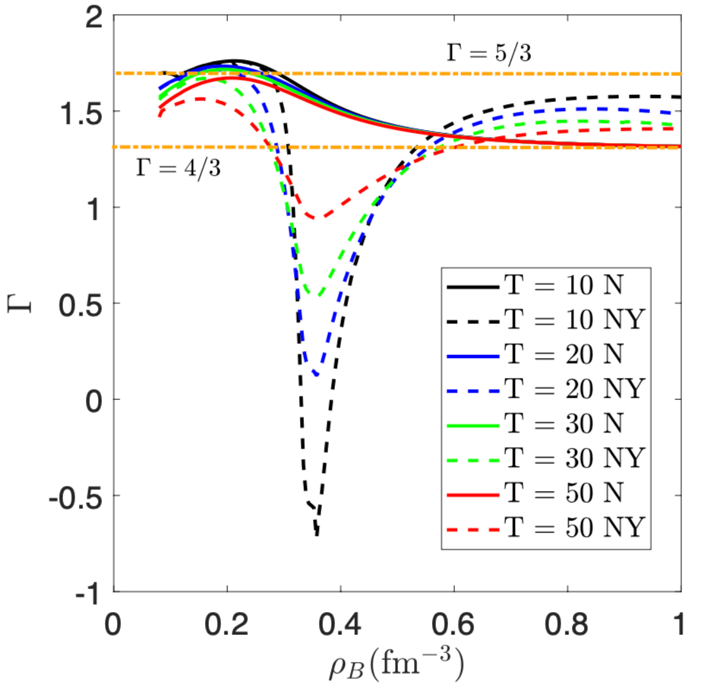


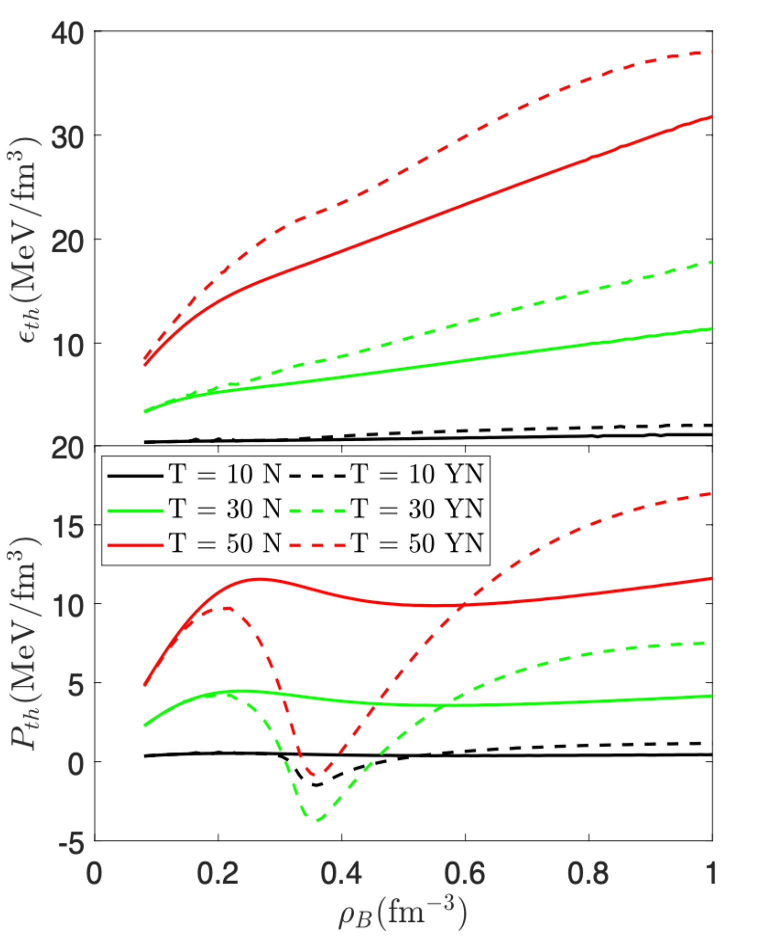
Solution? → thermal effects !

$$P_{th} = P(\rho_B, T) - P(\rho_B, T=0)$$
$$\epsilon_{th} = \epsilon(\rho_B, T) - \epsilon(\rho_B, T=0)$$

FSU2* RMF model
Kochankovski, Ramos, Tolos, MNRAS (2022)

$$\Gamma(\rho_B, T) \equiv 1 + \frac{P_{th}}{\epsilon_{th}}$$



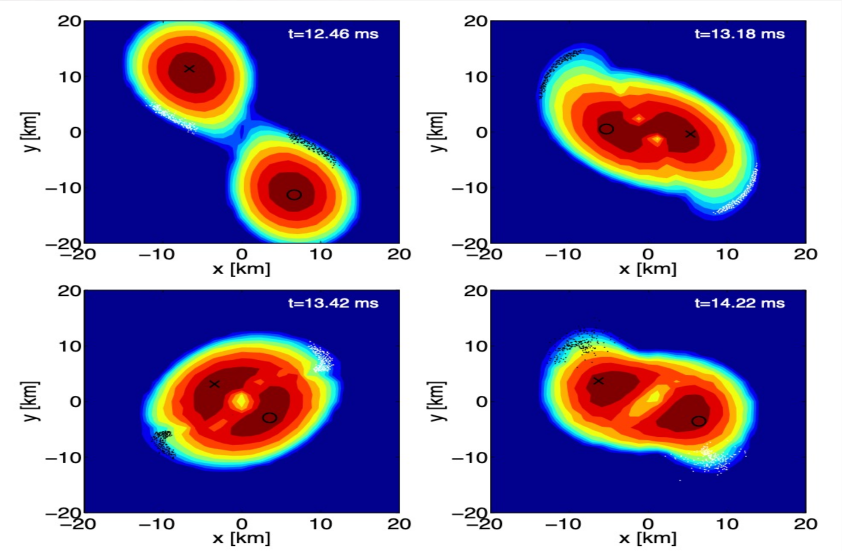


Neutron star mergers offer the ideal opportunity to look for the presence of **hyperons**.

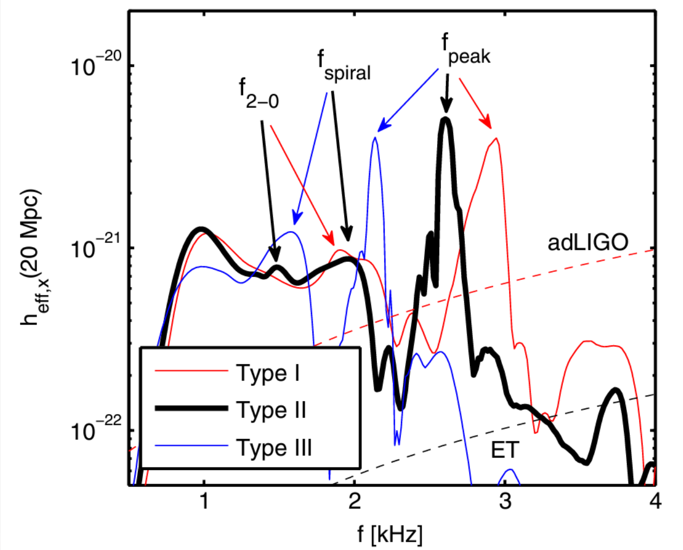
Warning: merger simulations usually implement thermal effects with a constant $\Gamma \sim 1.5 - 2$

Thermal behavior as indicator for hyperons in NS mergers (I)

Blacker, Kochankovski, Bauswein, Ramos, Tolos PRD (2024)



Bauswein, Stergioulas, PRD (2015)



→ **Influence of hyperons in the dominant frequency of the post-merger GW spectrum**

We consider a big set of nucleonic and hyperonic EoSs

Full 3D EoS

$P(\rho, T, Y_e), \varepsilon(\rho, T, Y_e)$

(two different teratments of thermal effects)

Cold (1D) EoS + $\Gamma_{th}^{1.75}$

$P_{th} = \varepsilon_{th}(\Gamma - 1)$

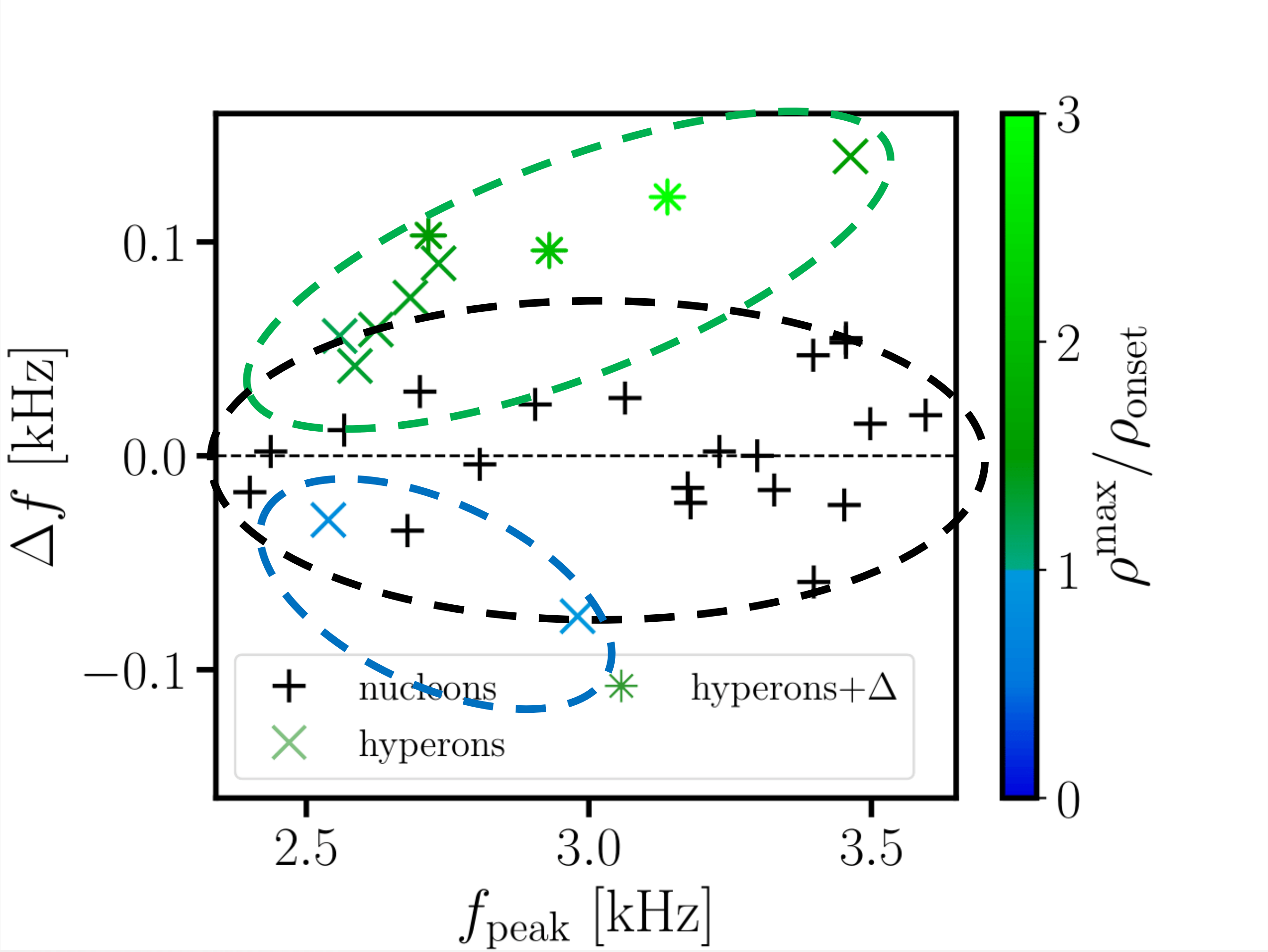
(Γ constant = 1.75)

We simulate the merger of two neutron stars with $1.4 M_{\odot}$ mass each

$$\Delta f = f_{peak}(3D) - f_{peak}(1D + \Gamma_{th}^{1.75})$$

Thermal behavior as indicator for hyperons in NS mergers (II)

Blacker, Kochankovski, Bauswein, Ramos, Tolos PRD (2024)



Systematic shift toward higher frequencies in the hyperonic EoS models

Nucleonic models are scattered around the reference values.

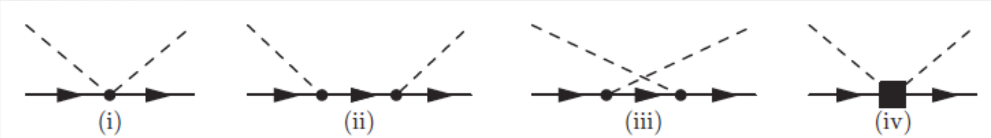
If hyperons are present in very small quantities, the corresponding EoS behave like a nucleonic one

Hyperons produce a characteristic increase of the dominant postmerger GW frequency by up to ~150 Hz

(in principle measurable if the EOS and stellar parameters of cold neutron stars are sufficiently well-determined)

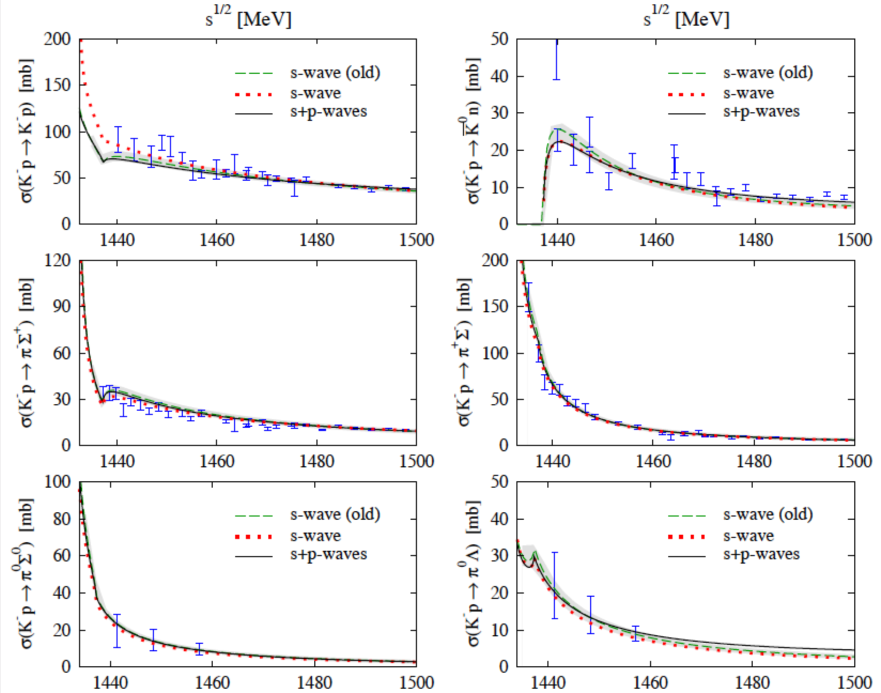
$\bar{K}N$ and $\bar{K}$-nucleus interactions

$\bar{K}N$ χEFT models :



constrained to:

✓ $K^-p \;\rightarrow K^-p, \bar{K}^0 n, \pi^-\Sigma^+, \pi^+\Sigma^-, \pi^0\Sigma^0, \pi^0\Lambda, \ldots,$ x-sections



✓ Precise measurement of ΔE and Γ of the **kaonic hidrogen** 1s state

$\Delta E = 283 \pm 36$ eV

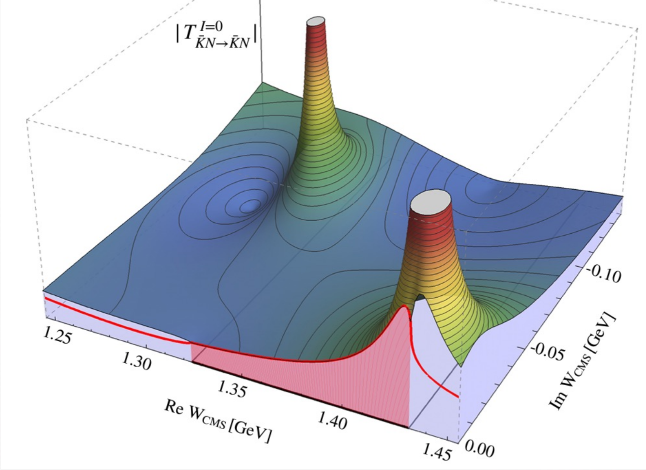
$\Gamma = 541 \pm 92$ eV

SIDDHARTA@DAPHNE (2011)

The $\Lambda(1405)$ is **dynamically generated**: it emerges in the (unitarized) meson-baryon scattering amplitude with the strangeness S = −1 and isospin I = 0 (in the same spirit as Daliz &Tuan, 1959)

~750 articles (WoS)
~22000 citations

M. Mai, Eur. Phys. J. Spec. Top. (2021)

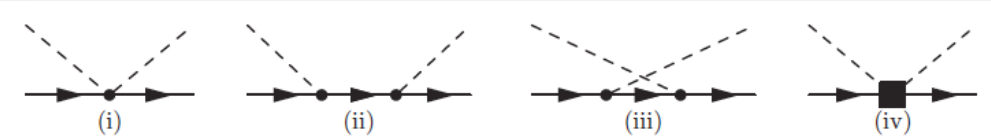


two-pole structure

Confirmed by recent Lattice QCD simulations!

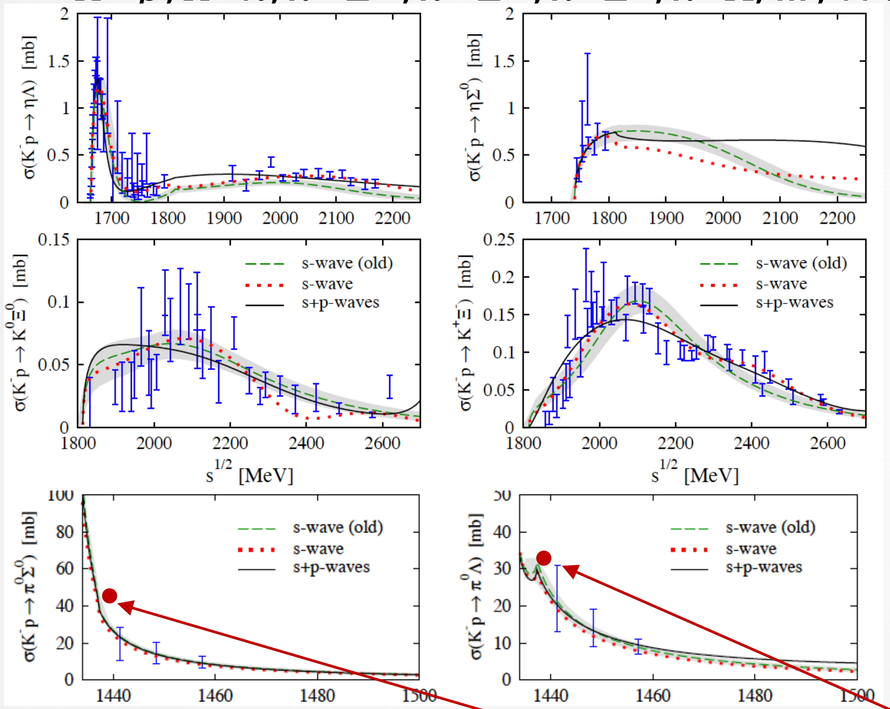
Bulava et al. (BaSc), PRD and PRL (2024)

$\bar{K}N$ χEFT models :



constrained to:

✓ $K^- p \rightarrow K^- p, \bar{K}^0 n, \pi^- \Sigma^+, \pi^+ \Sigma^-, \pi^0 \Sigma^0, \pi^0 \Lambda, \ldots,$ x-sections



✓ Precise measurement of ΔE and Γ of the **kaonic hidrogen** 1s state

ΔE=283 ± 36 eV

Γ=541 ± 92 eV

SIDDHARTA@DAPHNE (2011)

Extension to higher energies (LO+NLO):

Feijoo, Magas, Ramos, PRC 2019

Bruns, Cieplý, NPA 2022

and higher partial waves:

Feijoo, Gazda, Magas, Ramos, Symmetry 2021

I=1 $K^- n \rightarrow \pi^- \Lambda$ amplitude at threshold

Piscicchia (AMADEUS@DAFNE) (2019)

$$|A_{K^- n \rightarrow \Lambda \pi^-}| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\,\mathrm{syst})\ \mathrm{fm}.$$

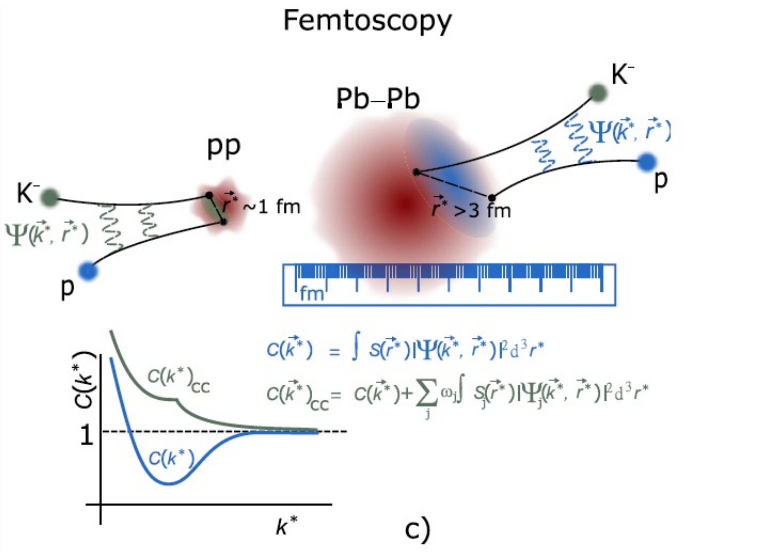
K-p → $\pi^0\Lambda$, $\pi^0\Sigma^0$ x-section

Piscicchia (AMADEUS@DAFNE) (2022)

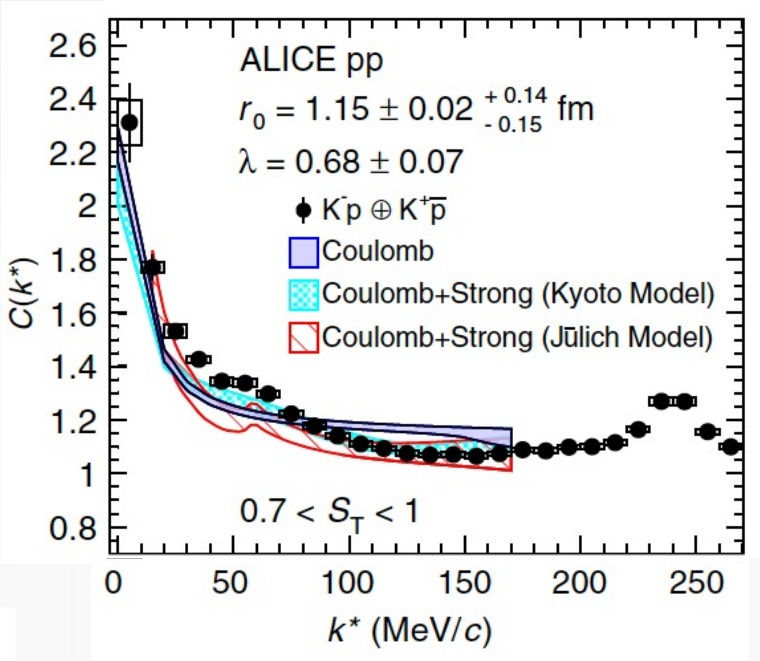
$$\sigma_{K^- p \rightarrow \Lambda \pi^0} = 31.0 \pm 0.5(stat.)^{+1.2}_{-1.2}(syst.)\ \mathrm{mb}$$

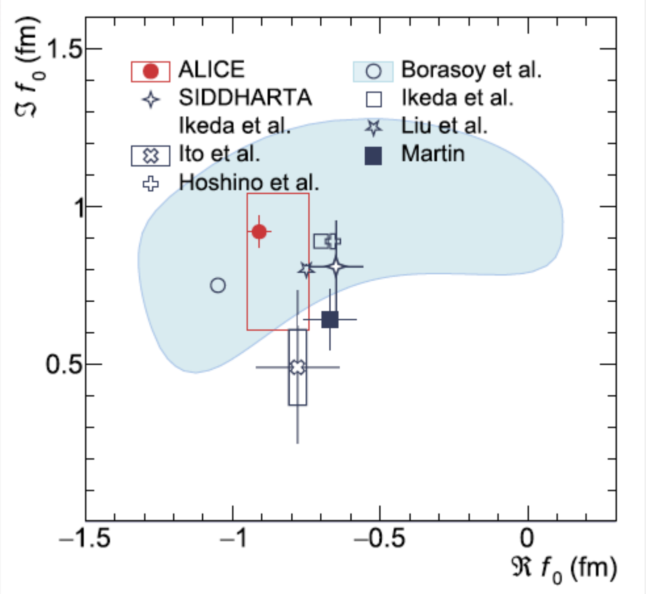
$$\sigma_{K^- p \rightarrow \Sigma^0 \pi^0} = 42.8 \pm 1.5(stat.)^{+2.4}_{-2.0}(syst.)\ \mathrm{mb}$$

(adapted from Phys. Lett. B822 (2021) 136708)

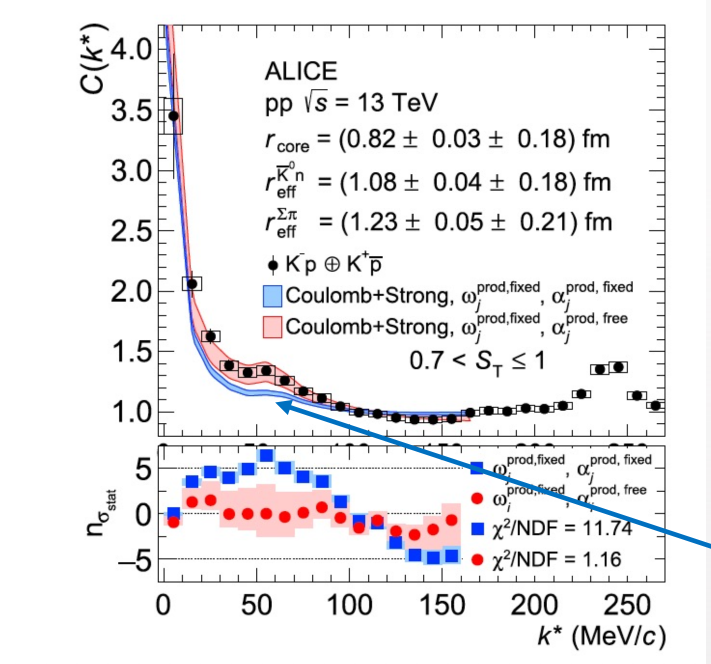


Acharya (ALICE), PRL (2020)





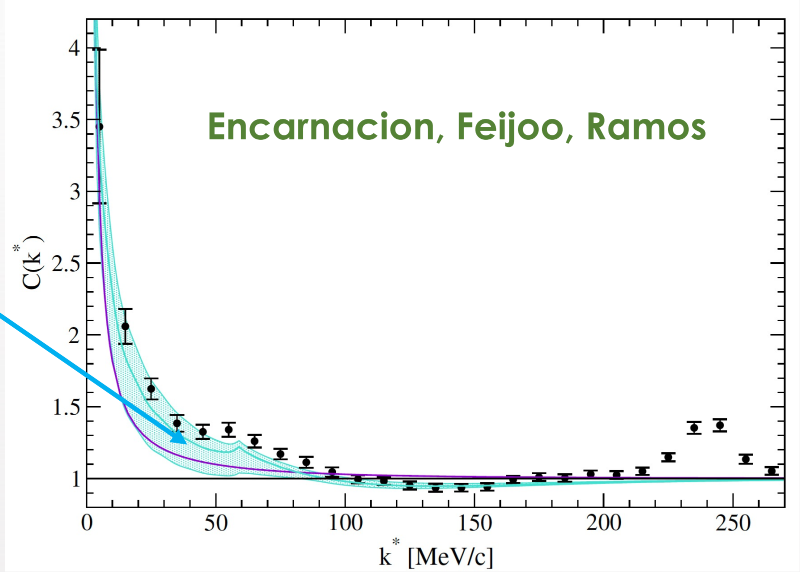
ALICE, EPJC (2023)



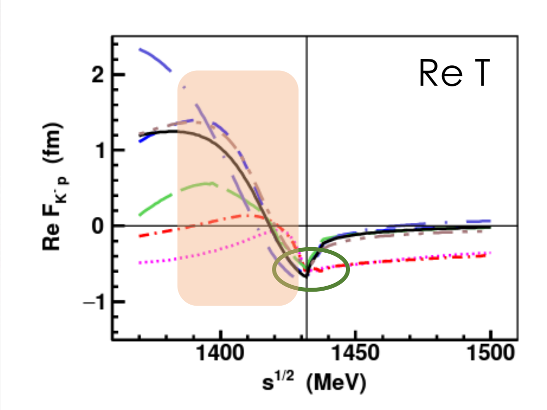
Feijoo, Magas, Ramos, PRC (2019)

Hyodo, Weise model PRC (2008)

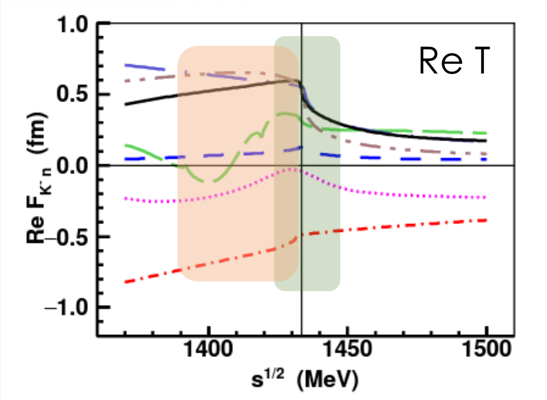
Encarnacion, Feijoo, Ramos



$K^-p \rightarrow K^-p$ scattering amplitude (models)



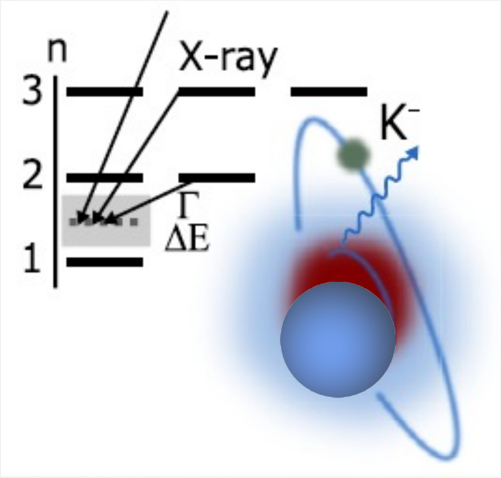
$K^-n \rightarrow K^-n$ scattering amplitude (models)



Lack of experimental K-n constraint !

Subthreshold region
(explored by Kaons in the nuclear medium)

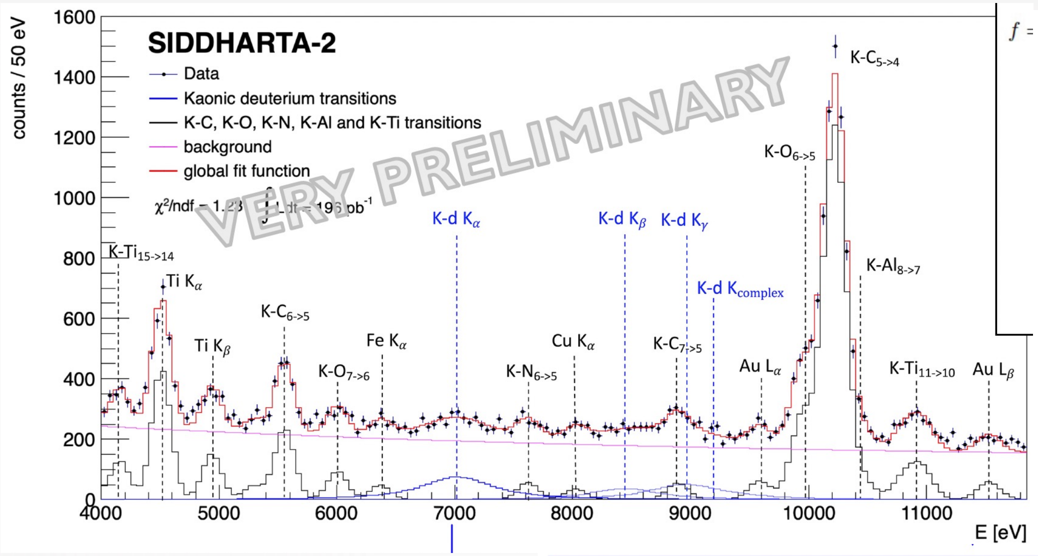
Kaonic deuterium

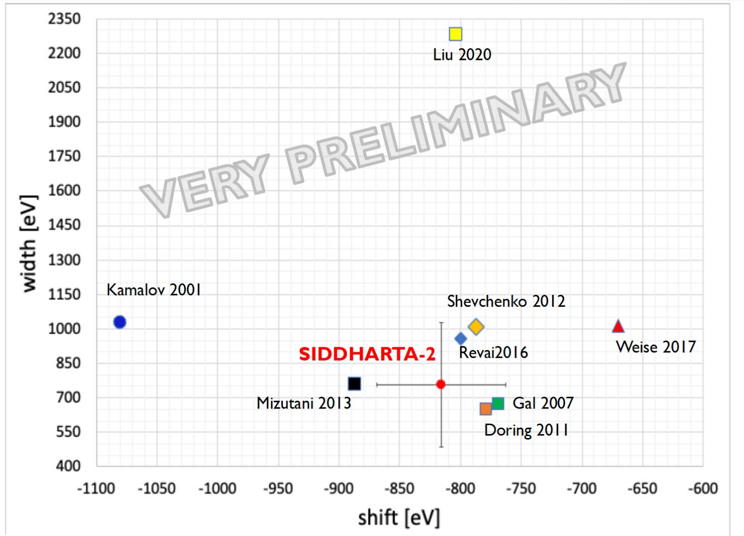


The **K⁻n** interaction will be pinned down from the measurement of the energy shift and width of the **kaonic deuterium** ground state (**SIDDHARTA2@DAFNE**)

(and planned at J-PARC)

Francesco Sgaramella, this workshop





First measurement ever of the **energy shift** and **width** of the **1s level** in **kaonic deterium.**

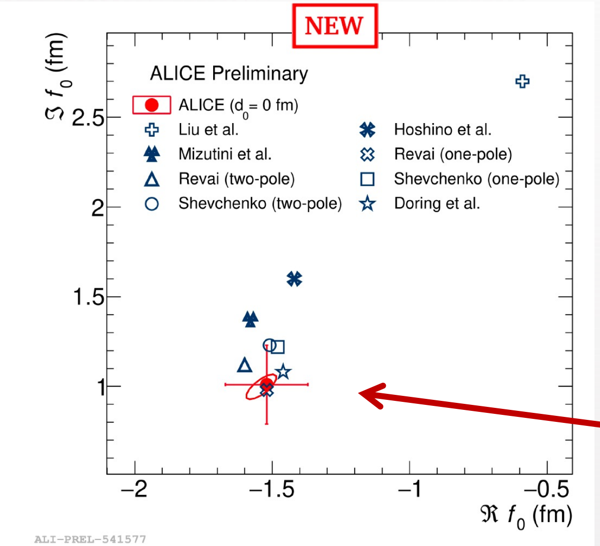
Congratulations!

$$\varepsilon_{1s} = E^{meas}_{2p\to 1s} - E^{e.m.}_{2p\to 1s} = -816 \pm 53\,(\text{stat}) \pm 2\,(\text{syst})\ \text{eV}$$

$$\Gamma_{1s} = 756 \pm 271\,(\text{stat})\ \text{eV}$$

$$\epsilon^d_{1s} - \mathrm{i}\,\frac{\Gamma^d_{1s}}{2} = -2\alpha^3\mu_r^2 A_{Kd}\left\{1 - 2\alpha\mu_r A_{Kd}(\ln\alpha - 1) + \cdots\right\}$$

K^-d **scattering length**



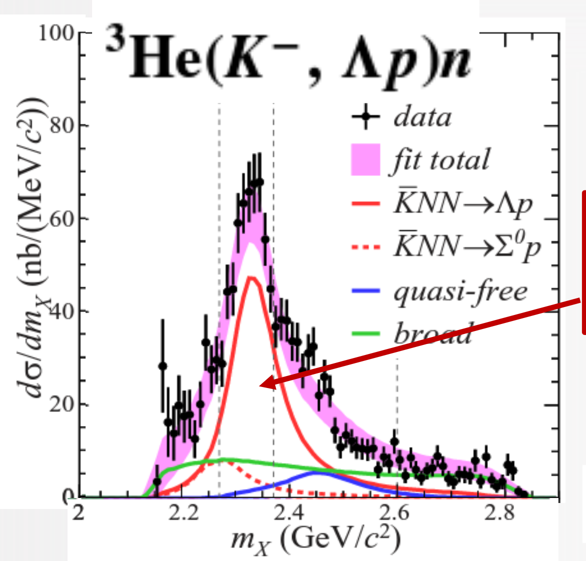
Wioleta Rzęsa, HADRON2023

Also from femtoscopy!

(see Oton Vazquez-Doce talk)

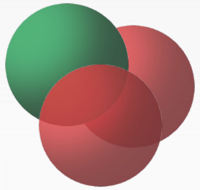
Nuclear Kaonic clusters

The **subthreshold energy** region can be tested in **Kaonic Nuclear Bound** states (difficult experiments)



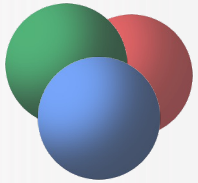
J-PARC E15 experiment

K⁻ p p
bound state



$$B_K = 42 \pm 3(\text{stat.})^{+3}_{-4}(\text{syst.})\ \text{MeV}$$
$$\Gamma_K = 100 \pm 7(\text{stat.})^{+19}_{-9}(\text{syst.})\ \text{MeV}$$

J-PARC plans to measure the K^- p n system



as well as heavier ones!

Three-body Faddeev-type AGS calculations with **three** coupled particle channels $\bar{K}NN - \pi\Sigma N - \pi\Lambda N$

Shevchenko, FBS (2024)

	$V^{1,\text{SIDD}}_{\bar{K}N}$		$V^{2,\text{SIDD}}_{\bar{K}N}$		$V^{\text{Chiral}}_{\bar{K}N}$	
	B_{K^-pp}	Γ_{K^-pp}	B_{K^-pp}	Γ_{K^-pp}	B_{K^-pp}	Γ_{K^-pp}
$V^{2\text{ch}}_{\text{Prev}\Sigma N,\pi N}$	52.2	67.1	46.6	51.2	29.4	46.4
$V^{3\text{ch}}_{\text{New}\Sigma N,\pi N}$	33.8	67.6	46.0	65.3	27.8	68.6

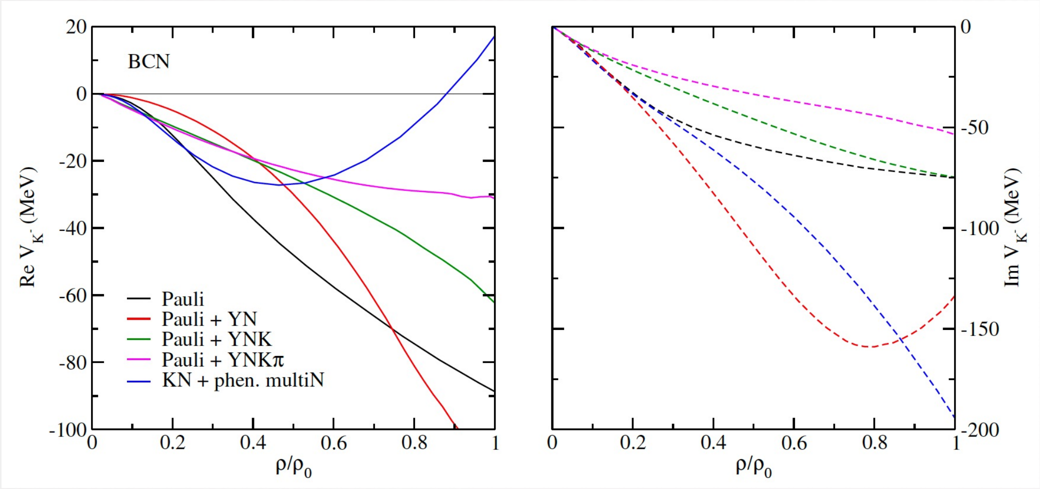
Heavier Kaonic systems

(many-body effects need to be handled properly)

Multinucleon antikaon absorption model in nuclear matter

Hrtánková (now Obertova), Ramos, PRC (2020)

→ Recently mproved with antikaon and pion self-energies



BCN		Pauli + YN	Pauli + YNK	Pauli + YNKpi	phen.
		$K^-N + K^-NN$	$t\rho + V^{corr}_{K^-NN}$	$t\rho + V^{corr}_{K^-NN}$	K^-N + phen. multiN
^{12}C	$\Delta(\epsilon)$	0.81	0.02	0.36	1.76
	Γ	17.48	3.15	0.00	0.70
	Γ^*	3.98	3.08	3.46	2.74
^{31}P	$\Delta(\epsilon)$	1.84	0.15	0.01	0.03
	Γ	12.85	2.49	0.18	0.24
	Γ^*	0.08	0.03	0.02	0.30
^{32}S	$\Delta(\epsilon)$	25.48	7.80	2.28	1.24
	Γ	74.33	23.85	7.05	9.24
	Γ^*	0.43	0.06	0.08	0.47
^{35}Cl	$\Delta(\epsilon)$	0.86	0.03	0.02	2.10
	Γ	12.35	1.28	0.14	0.00
	Γ^*	0.06	0.05	0.07	0.15
^{63}Cu	$\Delta(\epsilon)$	0.06	2.04	5.12	3.19
	Γ	7.73	2.71	0.98	2.25
	Γ^*	2.79	1.86	1.81	1.52
^{118}Sn	$\Delta(\epsilon)$	5.59	1.44	0.74	2.15
	Γ	1.33	0.41	0.11	0.29
	Γ^*	2.97	3.55	3.81	4.09
^{208}Pb	$\Delta(\epsilon)$	3.36	0.04	0.87	0.34
	Γ	0.49	0.39	0.33	0.39
	Γ^*	0.46	0.54	0.57	0.52
$\chi^2(21)$	total	175.34	54.98	28.00	33.71
χ^2/d.p.	total	8.35	2.62	1.33	1.61
$\chi^2(18)$	S^{32}out	75.10	23.27	18.60	22.76
χ^2/d.p.	S^{32}out	4.17	1.29	1.03	1.26

The chiral $\bar{K}N$ model with in-medium effects reproduces kaonic atom data very satisfactorily

Strangeness Hadron Physics covers a variety of phenomena in several fields of research,

- ✓ ranging from **Particle physics** (elementary interactions, dynamically generated strange resonances, like the $\Lambda(1405)$ and many others)
- ✓ to strangeness in **Nuclear systems** (hypernuclei, kaonic atoms and kaonic nuclear clusters)
- ✓ and with important implications in **Astrophysics** (hyperon puzzle, influence of hyperons in the post-merger GW spectrum).

Thank you!