

RECENT ADVANCES IN STRANGENESS NUCLEAR PHYSICS

Progress Report (2018-2022)

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QNP2022 – The 9th International Conference on
Quarks and Nuclear Physics

5-10 September 2022



UNIVERSITAT DE
BARCELONA

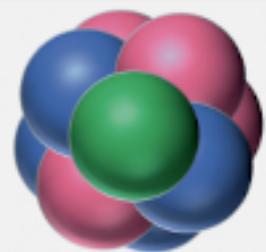


EXCELENCIA
MARÍA
DE MAEZTU

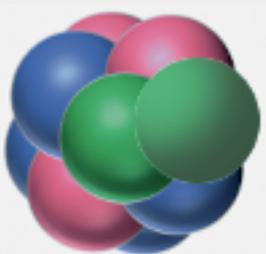
Strangeness nuclear physics

→ studies nuclear phenomena involving one or more **strange** particles (containing the **s** quark or antiquark)

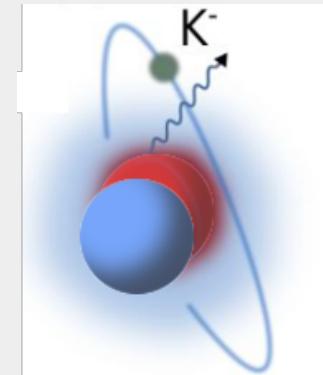
Baryon (Hyperon)	quarks	Mass (MeV/c ²)	Charge
p	u u d	938	+1
n	u d d	939	0
Λ	u d s	1116	0
Σ^+	u u s	1189	+1
Σ^0	u d s	1193	0
Σ^-	d d s	1197	-1
Ξ^0	u s s	1315	0
Ξ^-	d s s	1321	-1



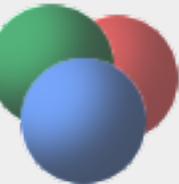
- single Λ hypernuclei
- double Λ hypernuclei
- Ξ^- atoms
- Ξ hypernuclei



Meson	quarks	Mass (MeV/c ²)	Charge
K^0	d s	498	0
K^-	u s	494	-1
K^+	u s	494	+1
K^0	d s	498	0



- kaonic atoms

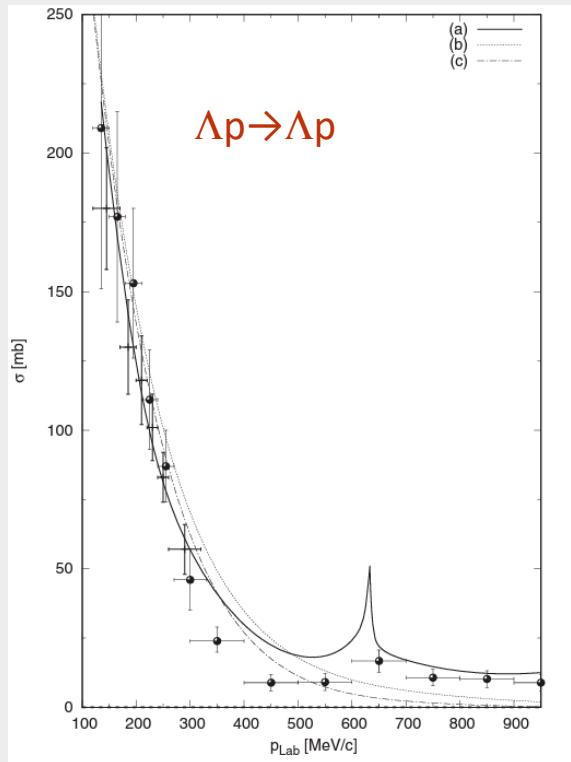


- nuclear kaonic clusters

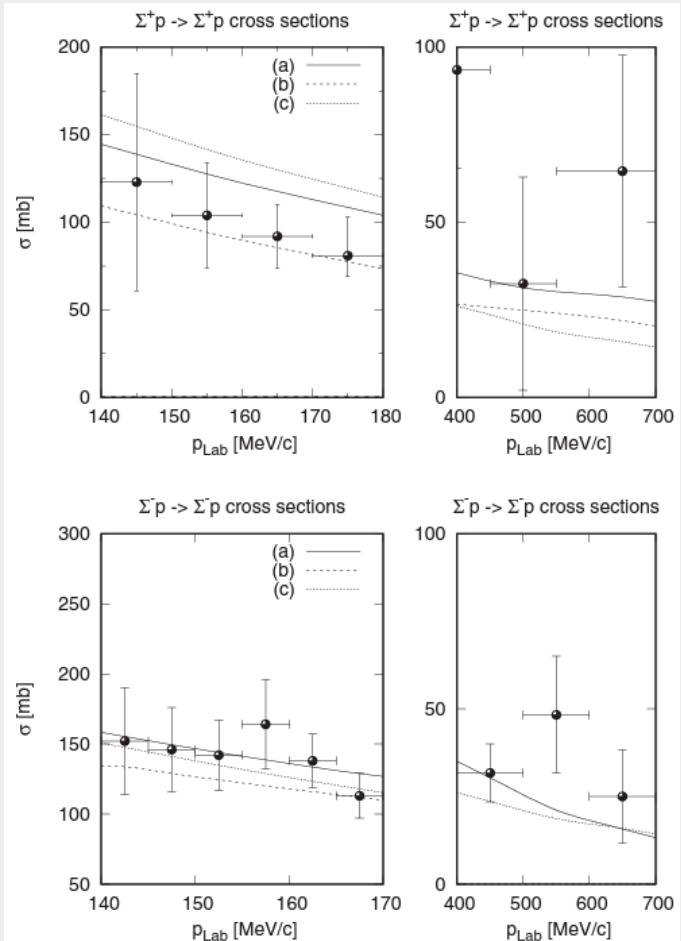
Elementary YN, YY interactions

YN Cross Sections

Hyperons are short-lived. Scattering experiments difficult!
(scarce amount of data)

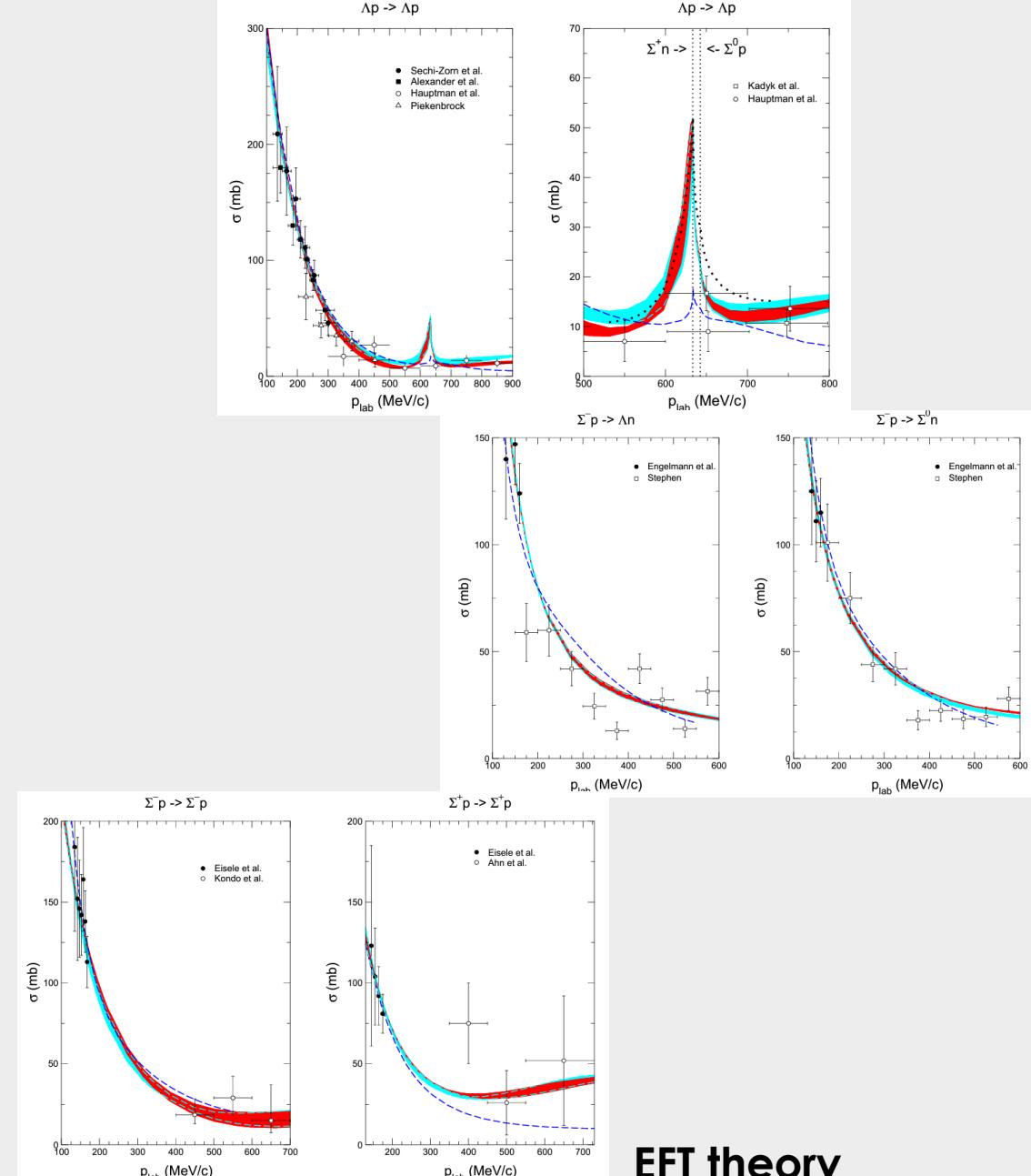


$\Lambda p \rightarrow \Lambda p$



Phenomenological meson-exchange model

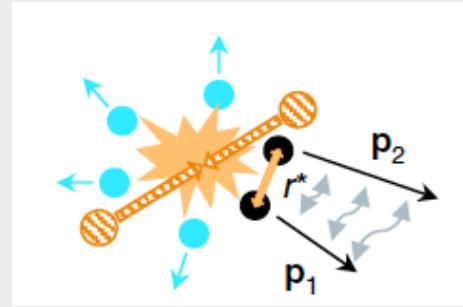
Nagels, Rijken, Yamamoto, PRC (2019)



EFT theory

Haidenbauer, Meißner, Nogga, EPJA (2020)

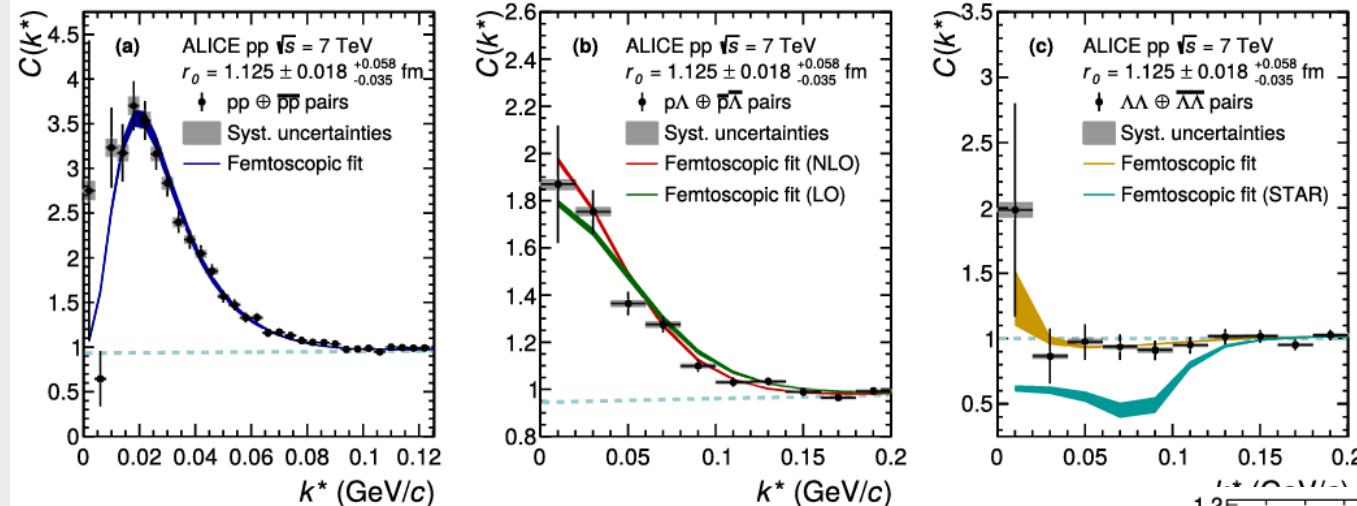
Femtoscopy studies are bringing information on low-energy YN, YY interactions!



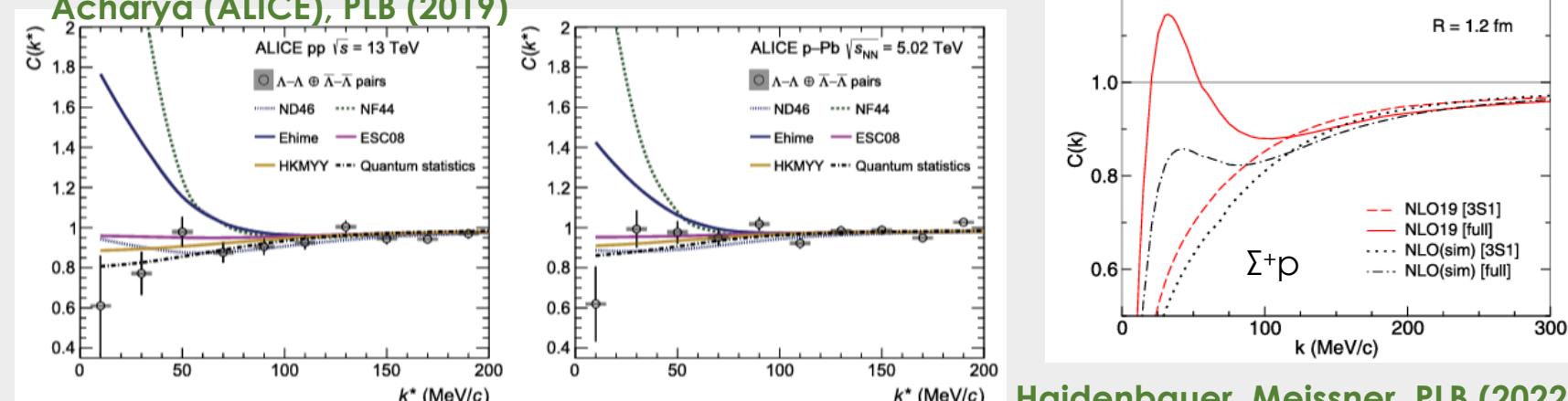
STAR@RHIC ALICE@LHC

From the experimental distribution of pairs of particles, a correlation function is obtained

Acharya (ALICE), PRC (2019)

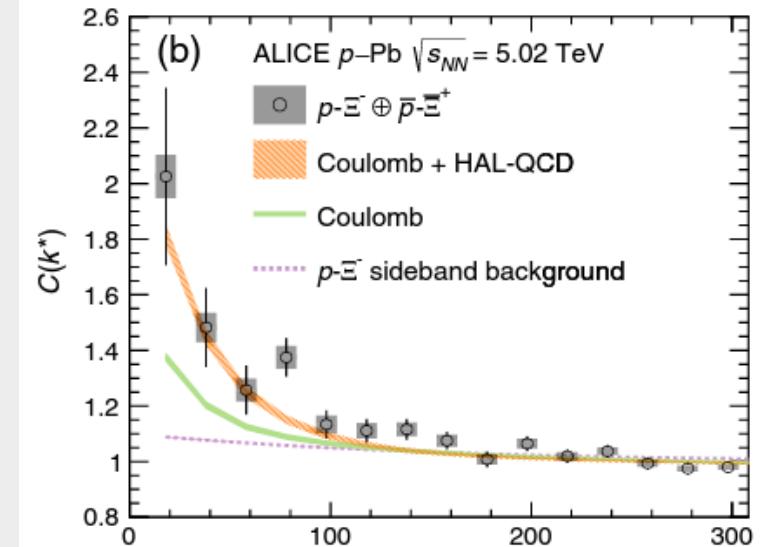


Acharya (ALICE), PLB (2019)

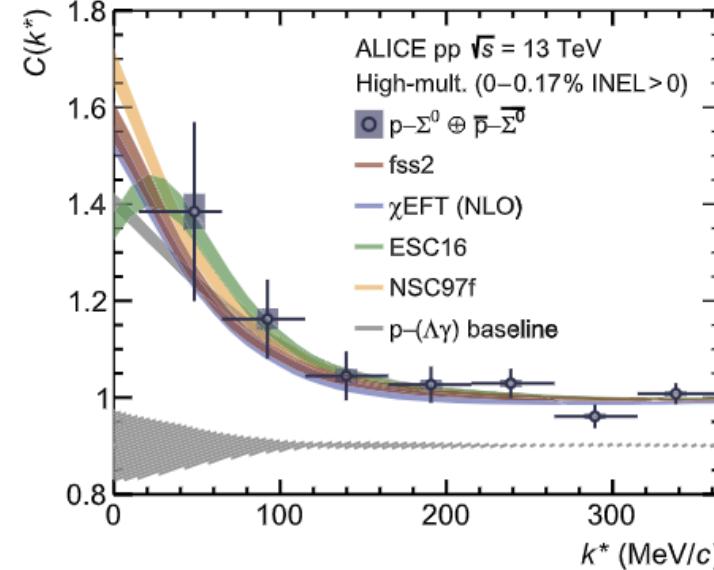


Haidenbauer, Meissner, PLB (2022)

Acharya (ALICE), PRL (2019)



PLB (2020)

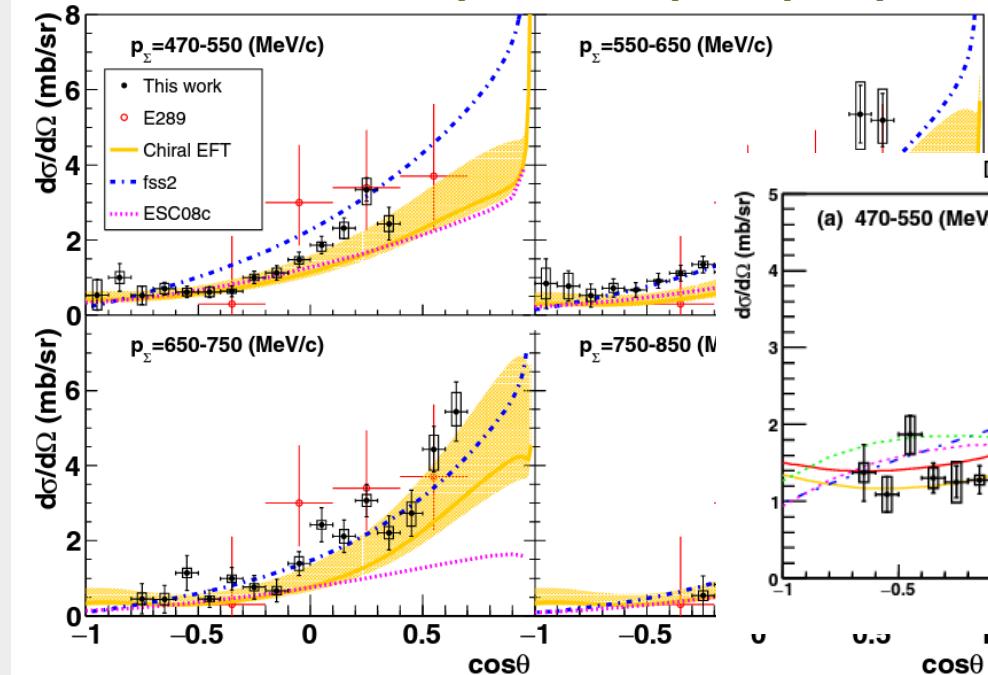


Improved YN scattering experiments!

J-PARC E40

differential x-sections for $\Sigma^- p$

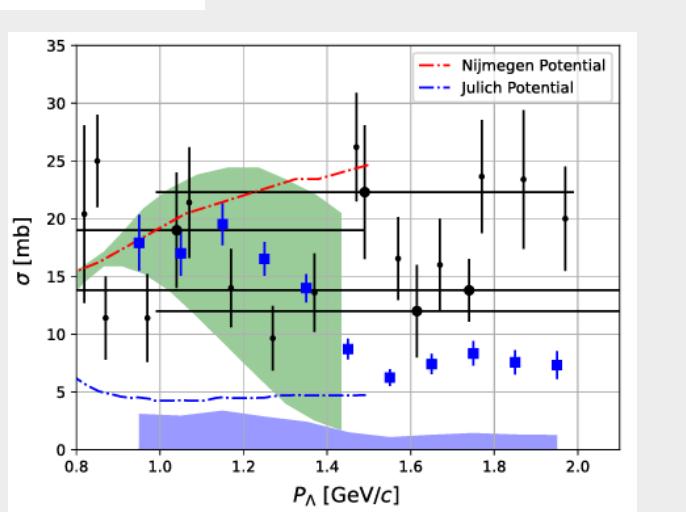
Miwa (J-PARC E40) PRC (2021)



CLAS

Λp elastic scattering x-sections

T. Rowley (CLAS), PRL (2021)



differential x-sections
for $\Sigma^- p \rightarrow \Lambda n$ PRL (2022)

Differential cross section of $\Sigma^- p \rightarrow \Lambda n$ reaction

(a)

470-550 (MeV/c)

(b)

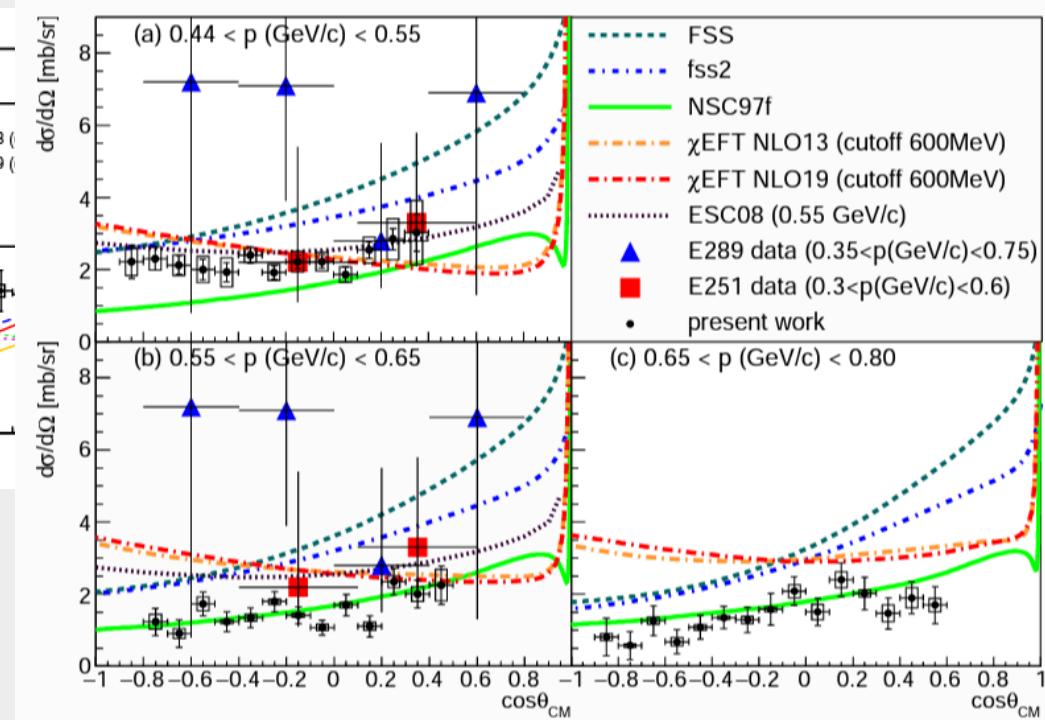
550-650 (MeV/c)

cosθ

cosθ

differential x-sections for $\Sigma^+ p$

Nanamura (J-PARC E40), arXiv:2203.08393

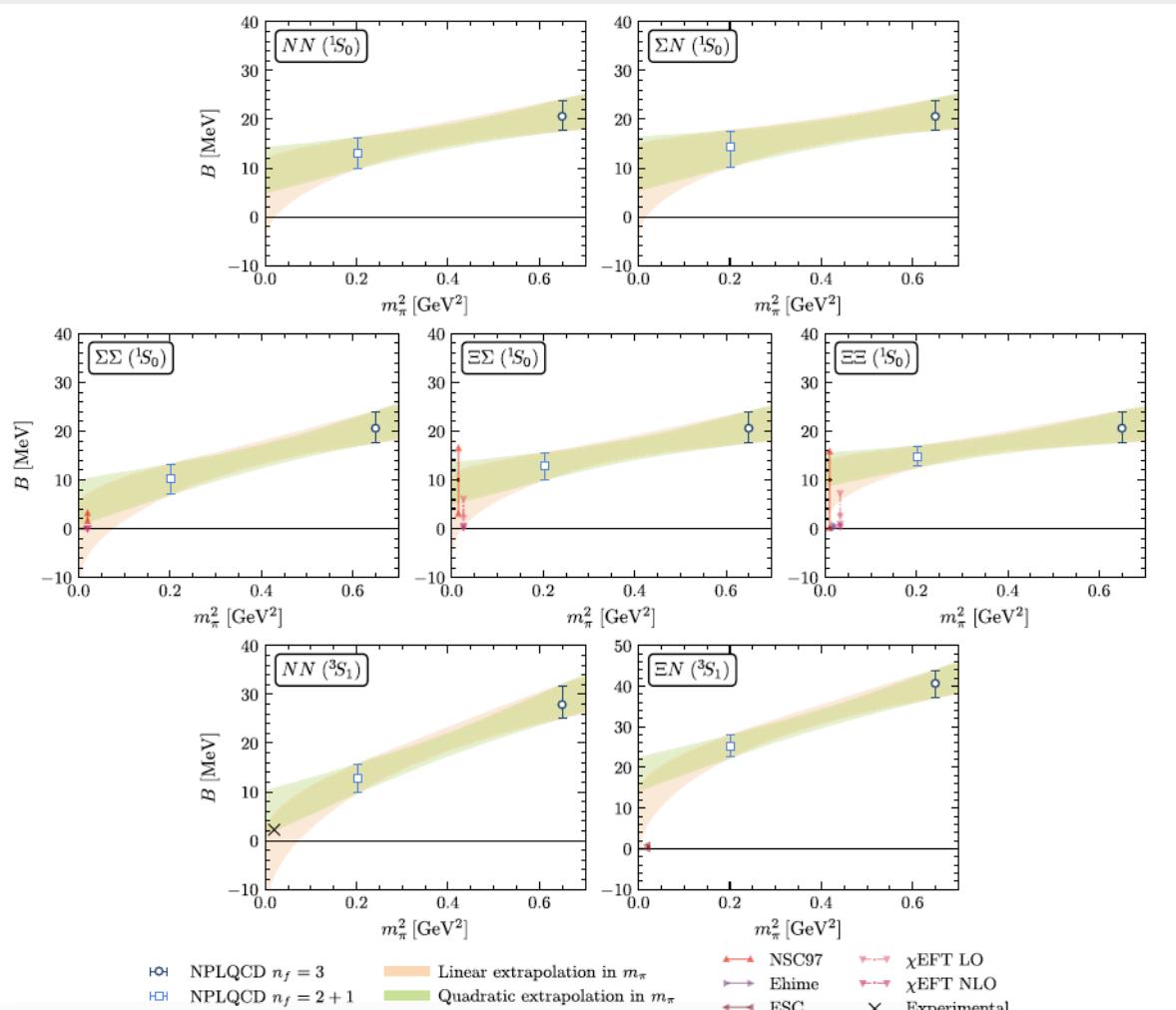


Lattice QCD

BB (strangeness ranging from 0 to -4)

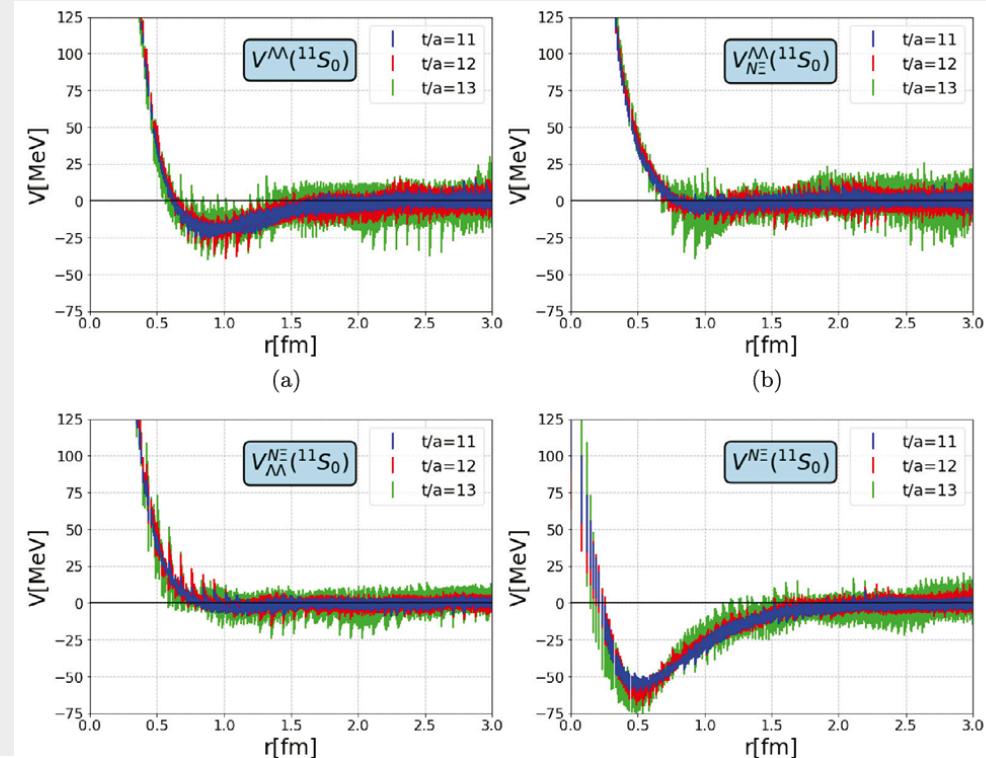
NPLQCD

IIIa, PRD (2021)

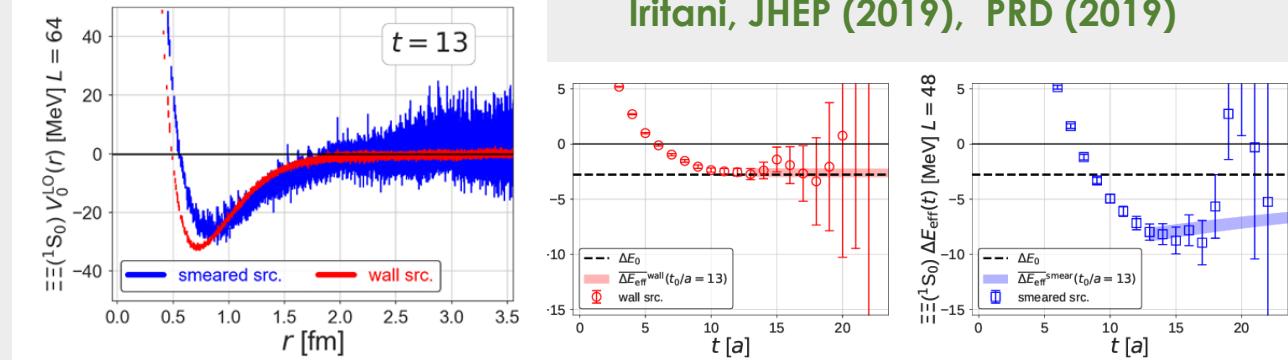


HAL QCD

Sasaki, NPA (2020)



Iritani, JHEP (2019), PRD (2019)

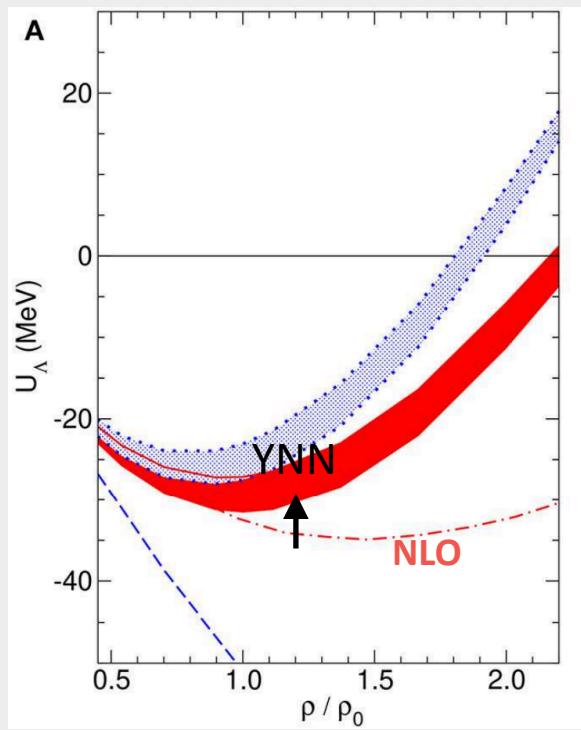


Lyu, PRD (2022)

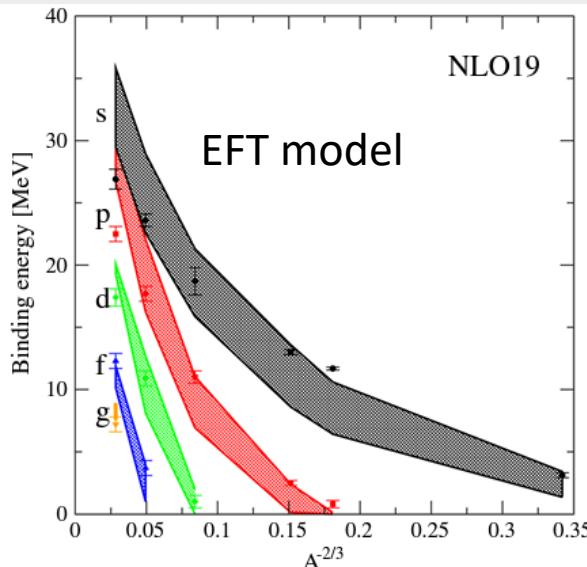
1. Testing (and constraining) YN, YY interactions with hypernuclei

mean-field Y-nucleus potentials are obtained from in-medium modified **G-matrix** interactions in nuclear matter

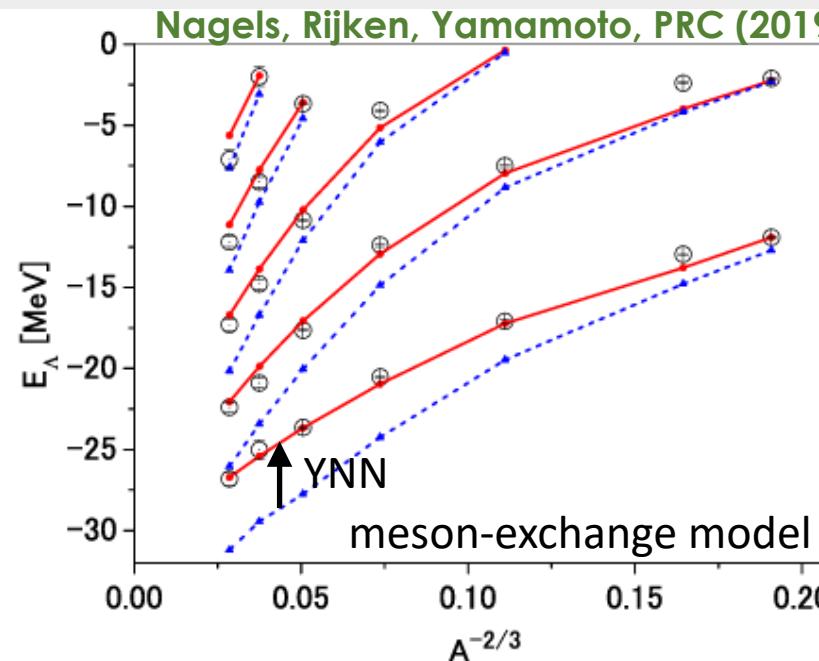
Petschauer, Haidenbauer, Kaiser, Meißner, Weise, Front.Phys (2020)



Haidenbauer, Vidaña, EPJA (2020)



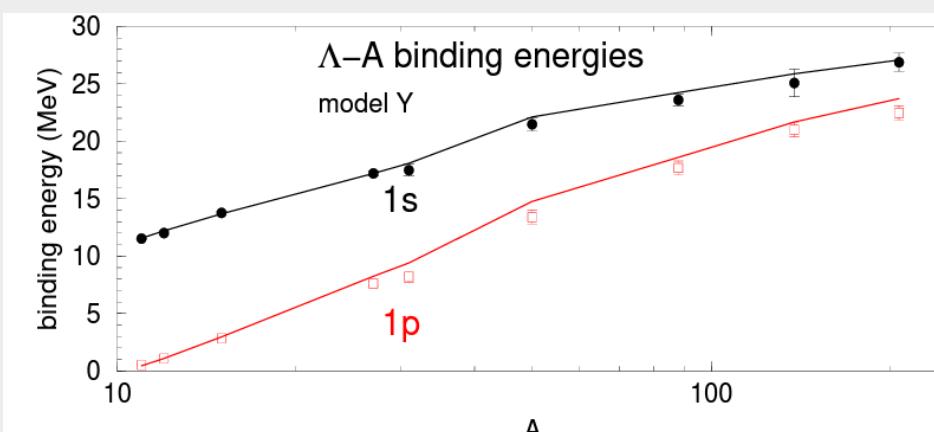
Nagels, Rijken, Yamamoto, PRC (2019)



Friedman, Gal, PLB (2022)

Phenomenological Λ -nucleus density dependent potential (fitted to $1s_\Lambda$ and $1p_\Lambda$ states for $12 \leq A \leq 208$)

$$\rightarrow U^{\Lambda\text{NN}}(\rho_0) = +14 \text{ MeV}$$



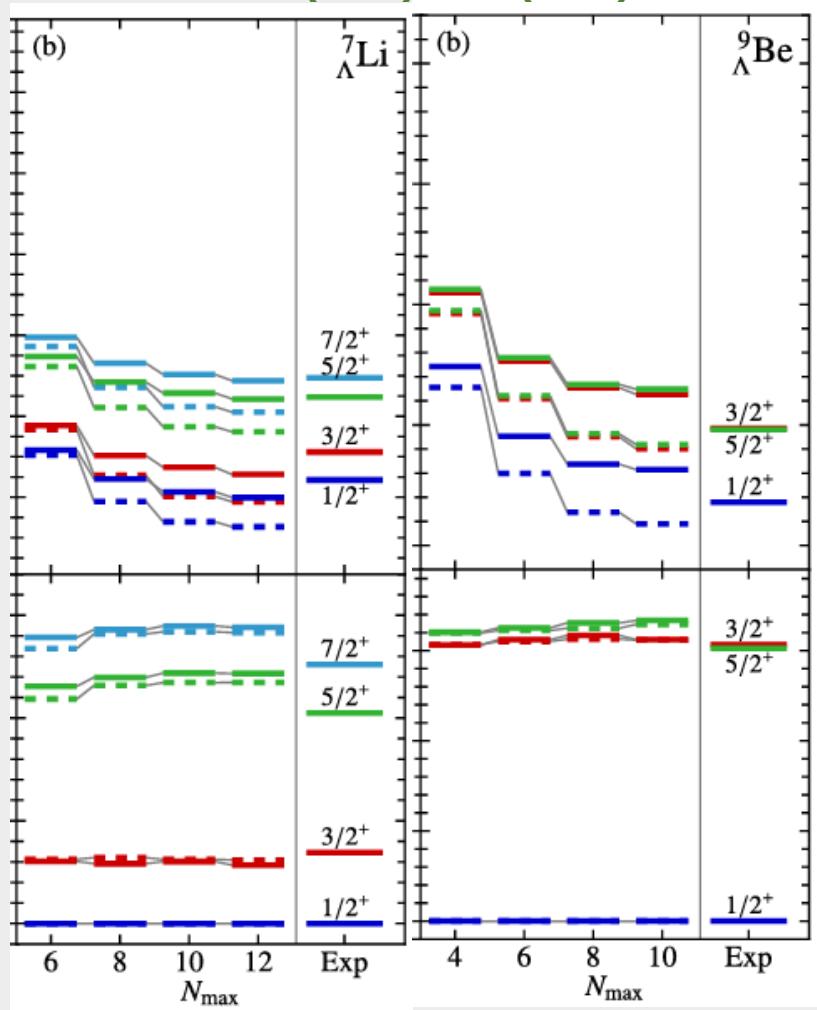
2. Testing (and constraining) YN, YY interactions with hypernuclei

ab-initio No Core Shell Model calculations

Slater determinant basis of HO states

Wirth, Gazda, Navrátil, Roth, PRC (2018)

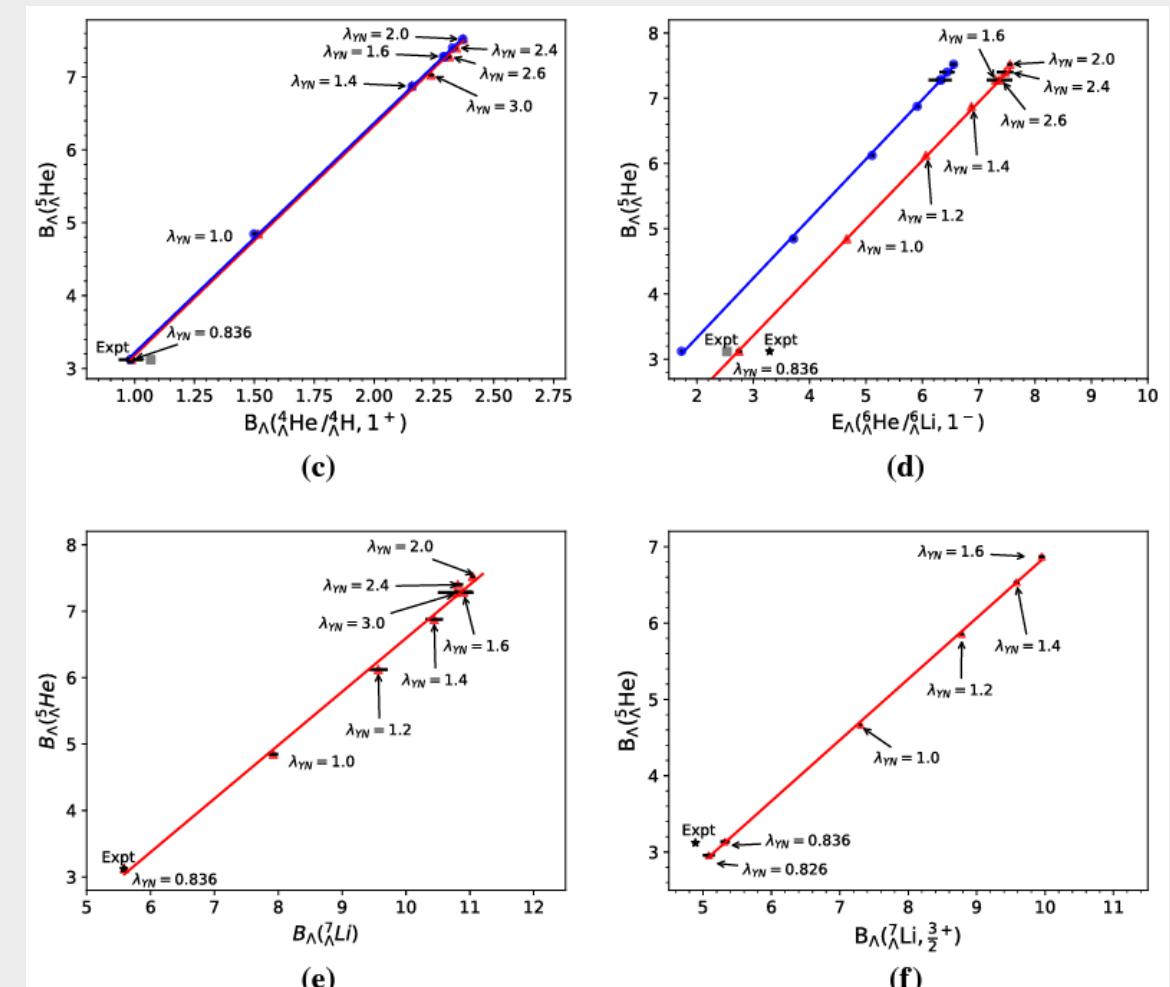
Wirth, Roth, PLB (2018); PRC (2019)



Jacobi coordinates and symmetry-adapted basis

Le, Haidenbauer, Meißner, Nogga, EPJA (2020)

Lambda-Lambda hypernuclei: EPJA (2021)



3. Testing (and constraining) YN, YY interactions with **few-body** hypernuclei

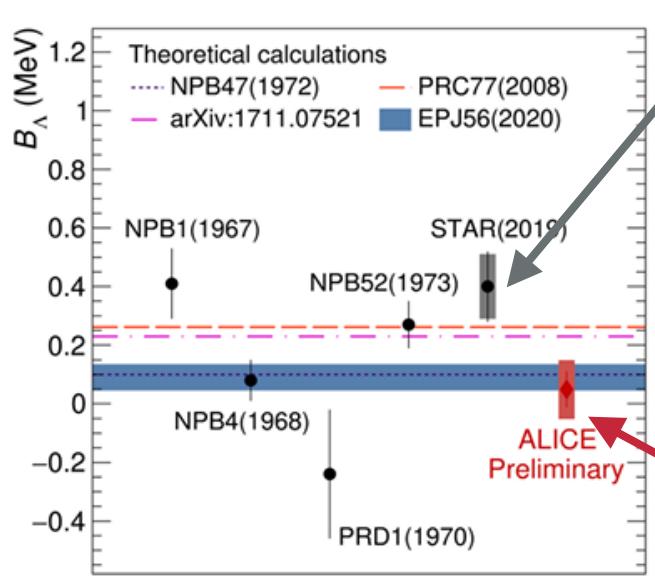
“exact” wavefunction is known → best benchmark for testing the YN interaction

There still are a few puzzles to be resolved!

- Hypertriton B_Λ (is it larger than before?)
- Charge Symmetry Breaking (CSB) in hypernuclei
- Is there a Λnn resonant state? and a $\Sigma^0 nn$ one?
- Lifetime of the hypertriton

- Hypertriton B_Λ (is it larger than before?) pre-2020 **average value:** $B_\Lambda = 0.13 \pm 0.05$ MeV

Adam (STAR), Nature Phys. (2020)



STAR 2020 measurement: $B_\Lambda = 0.41 \pm 0.12$ MeV

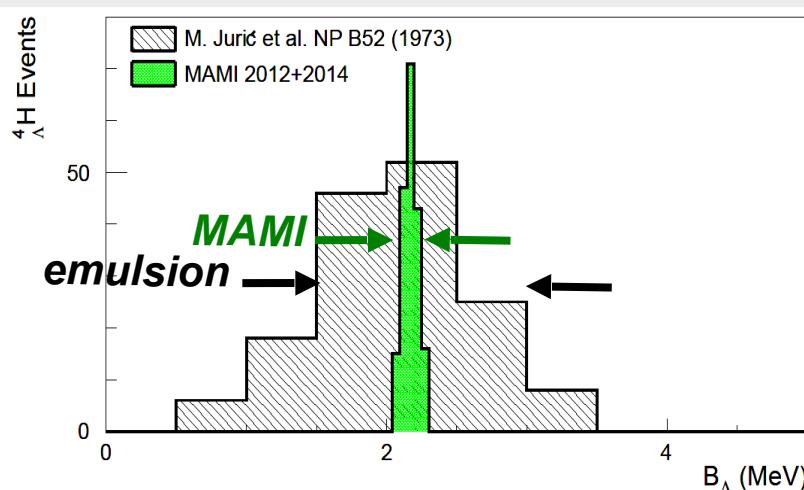
Le, Haidenbauer, Mei  ner, Nogga, PLB (2020)

(the new value used to constrain the relative weight of the singlet/triplet ΛN interaction)

YN interaction	NLO19	Fit A
a_s	-2.91	-4.00
a_t	-1.41	-1.22

→ An increased B_Λ is compatible with a good description of hypernuclei

preliminary ALICE measurement (2022): $B_\Lambda \sim 0$

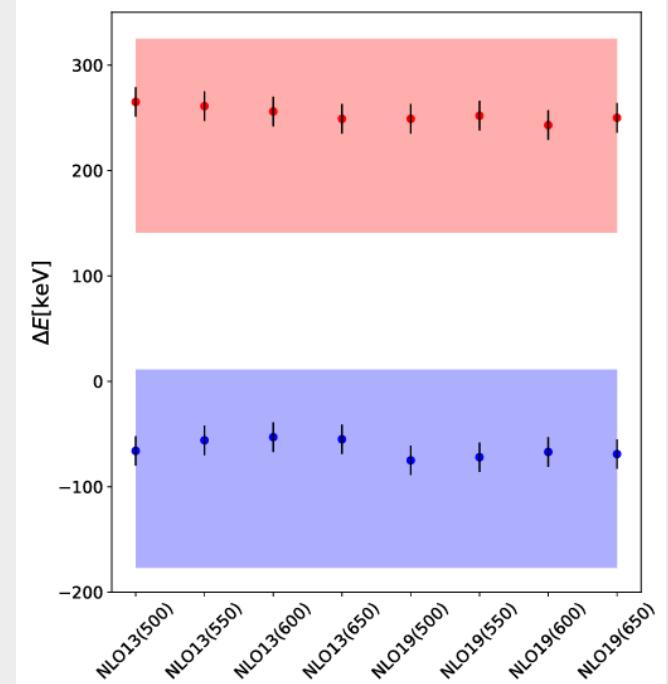
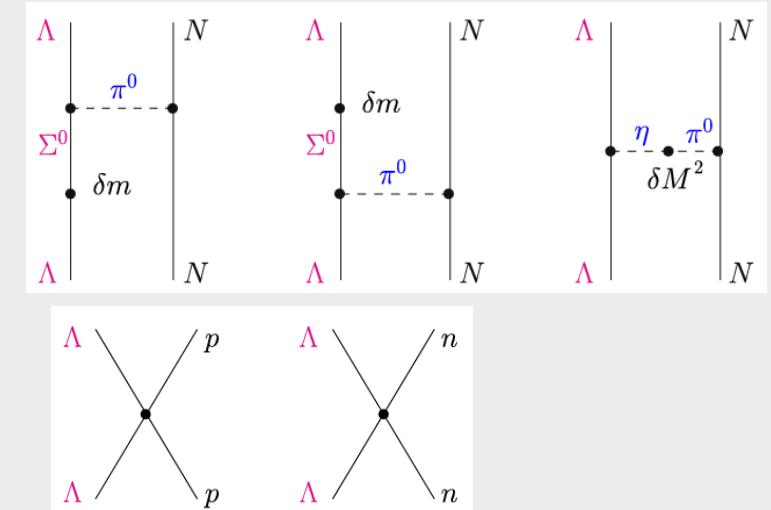
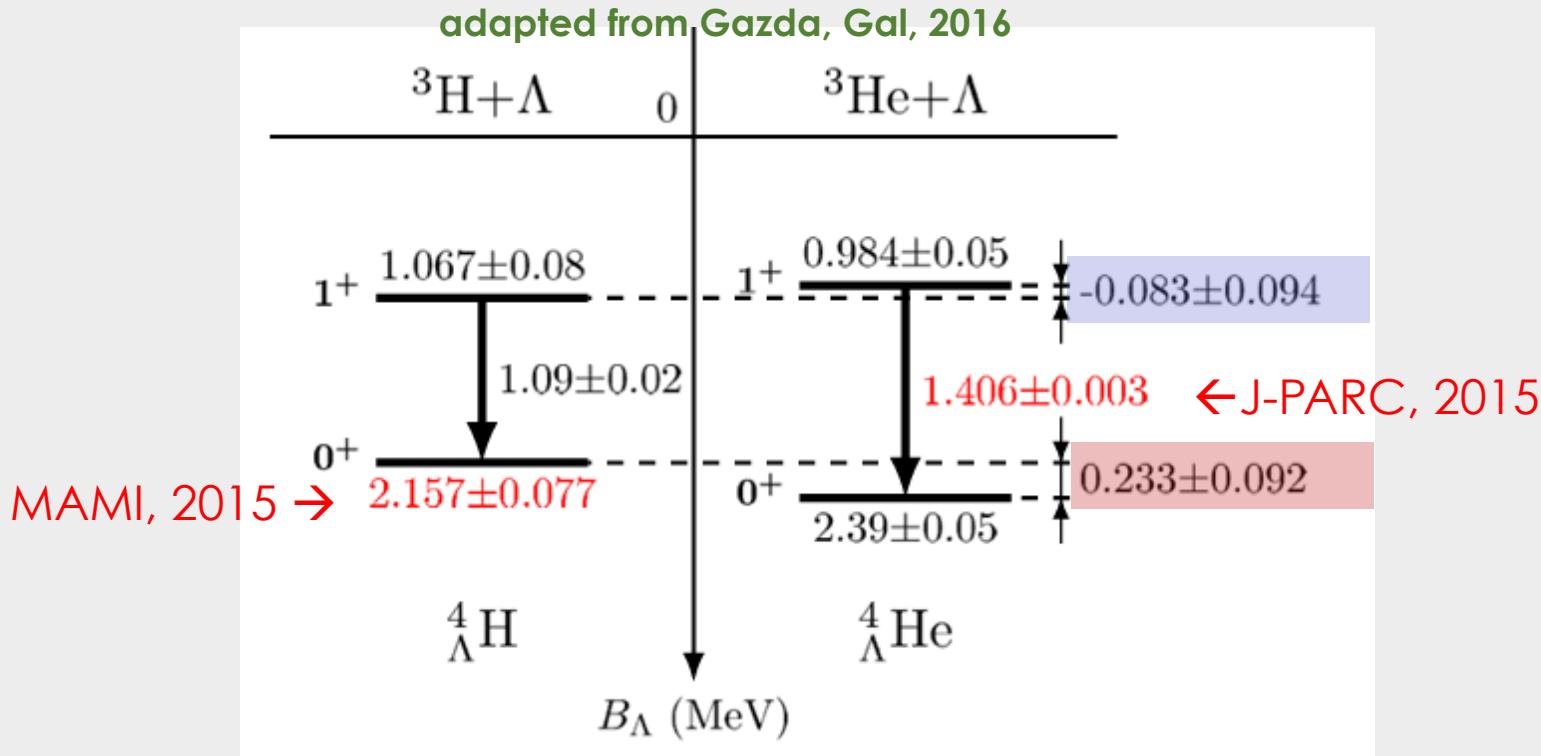


New measurement @MAMI coming soon!

(pion decay spectroscopy with statistical and systematic errors of ~20 keV
(commissioning: summer 2022)

- Charge Symmetry Breaking (CSB) in hypernuclei

Haidenbauer, Meißner, Nogga, 2021



J-PARC E63 experiment:

→ gamma-transition energy ($1^+ \rightarrow 0^+$) in ${}^4_\Lambda\text{H}$

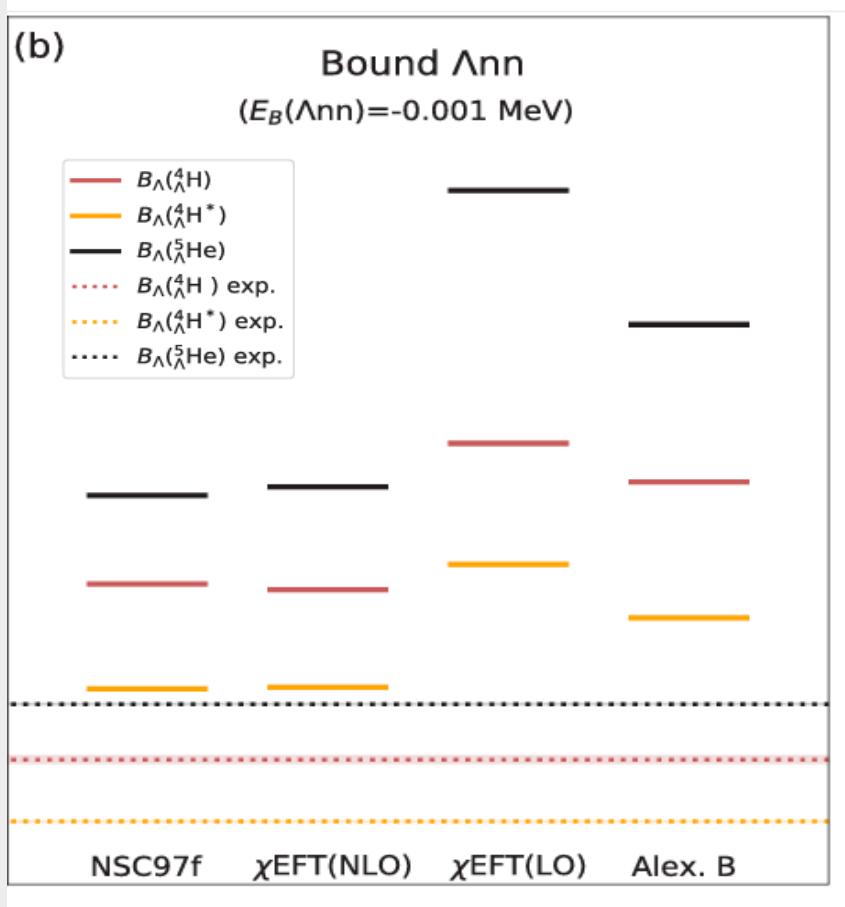
(a triple coincidence measurement with the in-flight (K^- , π^-) reaction, gamma-ray, and weak decay)

- Is there a Λnn resonant state? (and a $\Sigma^0 nn$ one?) (HypHI Collaboration, 2013)

If it exists, it will put severe constraints on the Λn interaction!

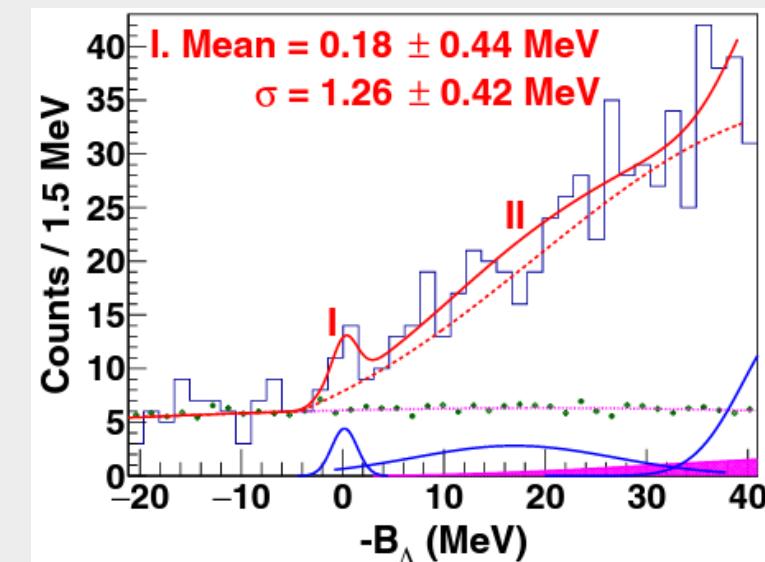
Schäfer, Bazak, Barnea, Mareš, PLB 2020, PRC2021

LO pionless EFT + 2- and 3-body contact terms
(strength of 3-body force varied)



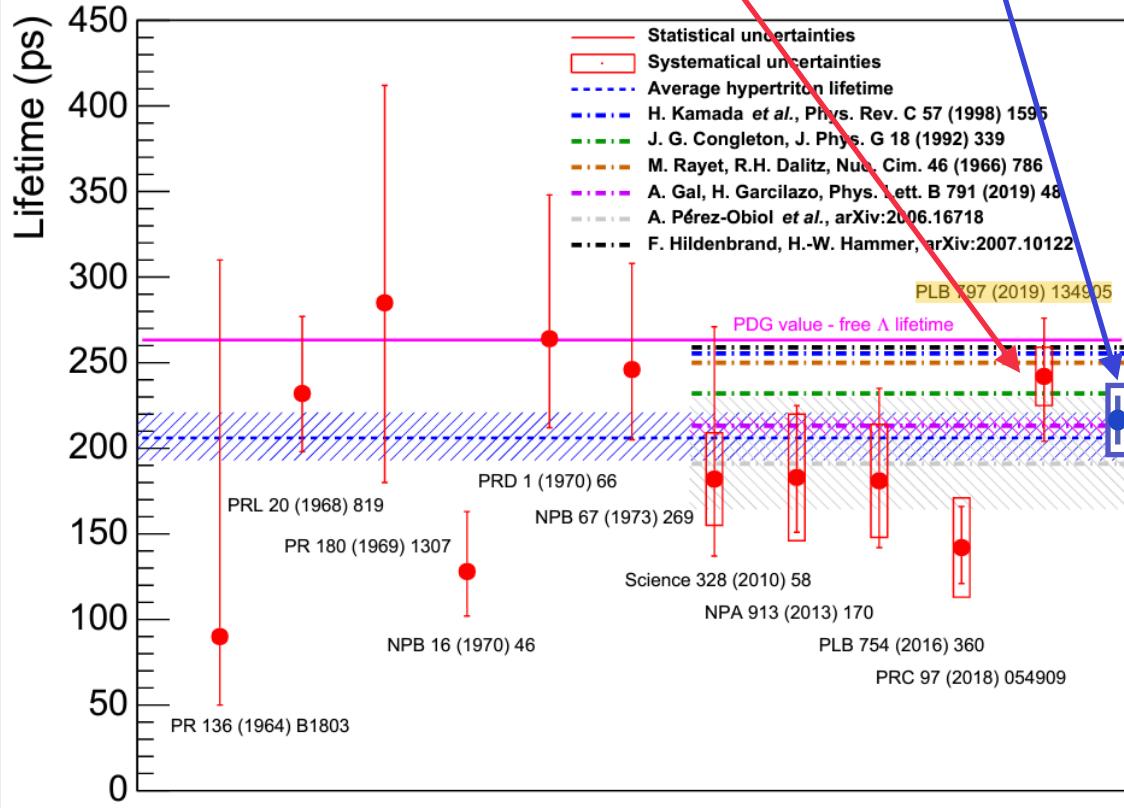
E12-17-003 in Hall A@J-lab:
(enhancements seen)
→ a possible Λnn resonance
and a pair of ΣNN states ?

E12-17-003, Suzuki PTEP 2022,
Pandey PRC 2022



- Lifetime of the hypertriton (is it shorter or similar to the free Λ lifetime?)

New results: ALICE@LHC, PLB 2019 STAR, PRL 2022



New measurements planned at:

HADES **J-Lab E12-19-002**

STAR BES II **J-PARC E73**

WASA-FRS HypHI

ab initio no-core shell model including ΣNN admixtures and $\pi^- - {}^3\text{He}$ FSI

Pérez-Obiol, Gazda, Friedman, Gal, PLB (2020)

Λ_{UV}	B_Λ	$\tau({}^3\Lambda \text{ H})$
800	69	234 ± 27
900	135	190 ± 22
1000	159	180 ± 21
-	410	163 ± 18

Lifetime and decay branching ratios in pionless EFT

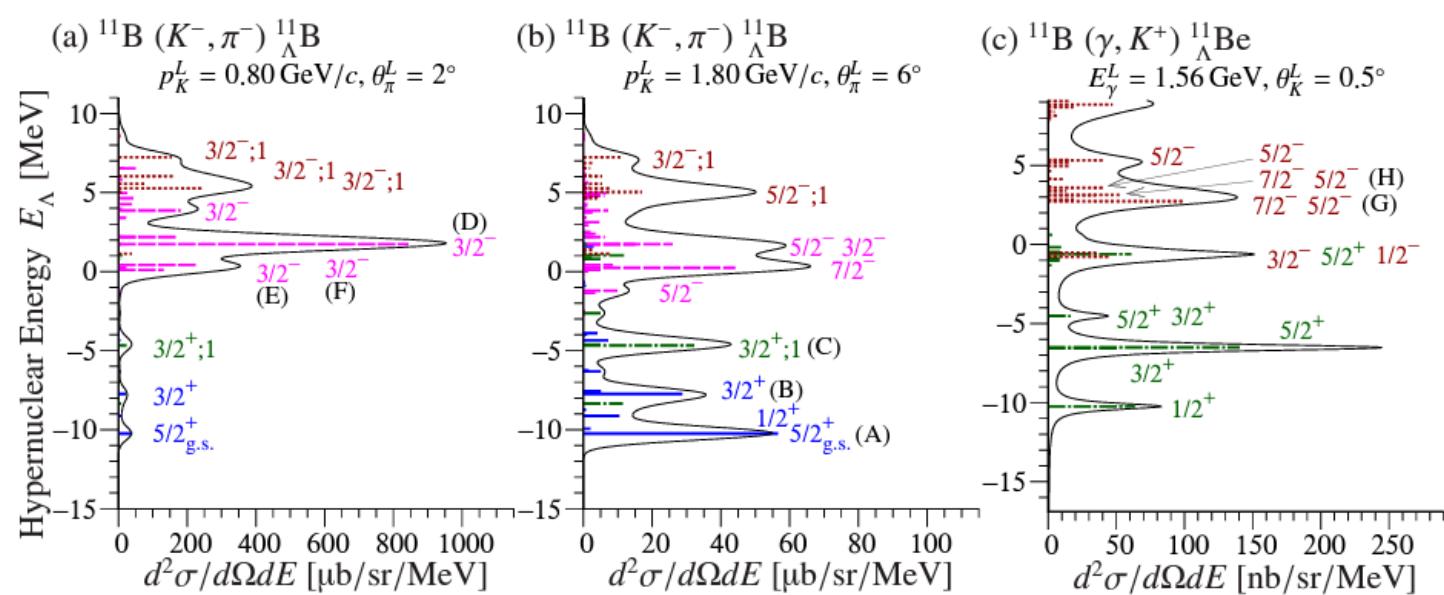
Hildenbrand, Hammer, PRC (2020)

Observable	$B_\Lambda = 0.13 \text{ MeV}$		$B_\Lambda = 0.41 \text{ MeV}$	
	α_-	0.642	0.732	0.642
$(\Gamma_{pd} + \Gamma_{nd})/\Gamma_\Lambda$	0.612	0.612	0.415	0.416
$(\Gamma_{}^3\text{He} + \Gamma_{}^3\text{H})/\Gamma_\Lambda$	0.382	0.363	0.569	0.541
$\Gamma_{}^3\text{H}/\Gamma_\Lambda$	0.992	0.975	0.984	0.956
$\Gamma_{}^3\text{He}/(\Gamma_{}^3\text{He} + \Gamma_{pd})$	0.384	0.373	0.578	0.566
$\tau_{}^3\text{H}_\Lambda [\text{ps}]$	264.7	269.8	267.6	275.0

HYPERNUCLEAR SPECTROSCOPY

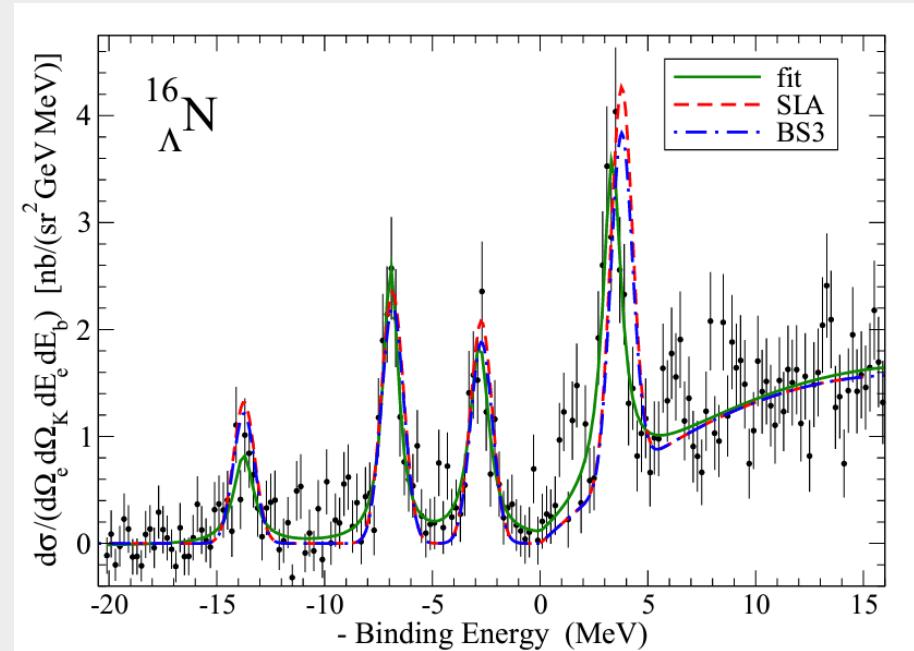
DWIA x-sections of (K^- , π^-), (π^+ , K^+), and (γ , K^+) reactions
(within the extended model space)

Umeya, Motoba, Itonaga,



(e, e K^+) reactions

Garibaldi (J-Lab E94-107) PRC (2019)



JLab E12-15-008 $^{40}_\Lambda\text{K}$ and $^{48}_\Lambda\text{K}$ targets

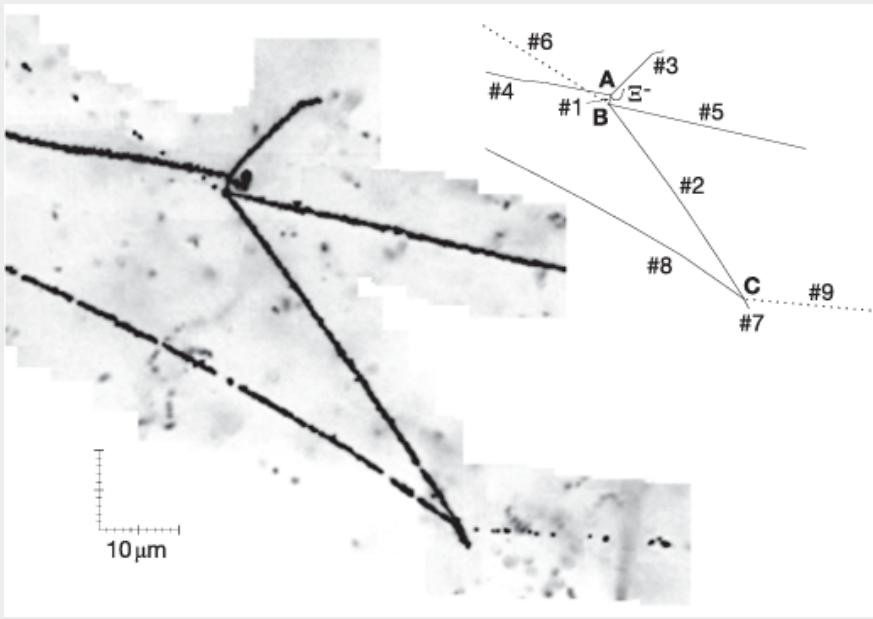
Beam line HIHR at JPARC:
supra-precision (π, K^+) Λ -hypernuclei spectroscopy

$S=-2$

$\Lambda\Lambda$ – hypernuclei / Ξ hypernuclei / Ξ^- - atoms

Observation of a new $\Lambda\Lambda$ hypernucleus (MINO event)

(J-PARC E07) Ekawa, PTEP (2019)



← most probable



$$B_{\Lambda\Lambda} = 19.07 \pm 0.11 \text{ MeV}$$

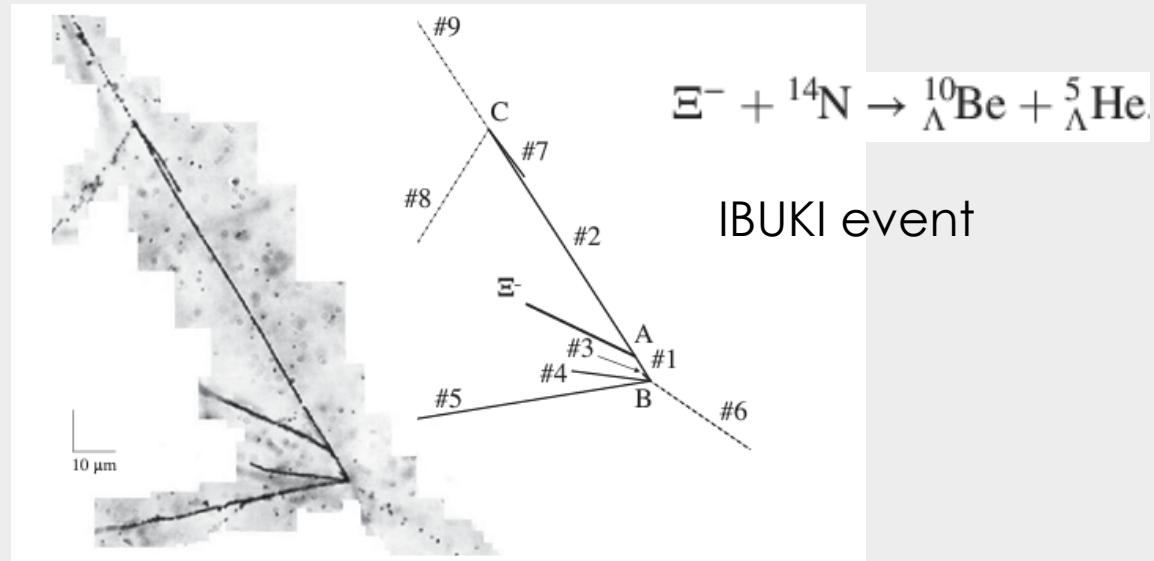
$$\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37 \text{ MeV}$$

Ξ^- -Nuclear Bound States

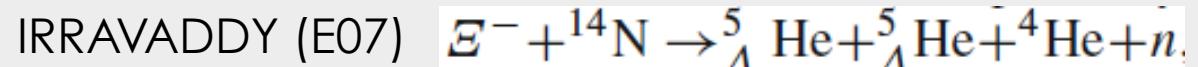
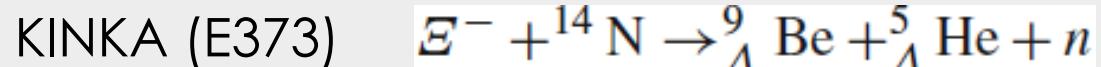
KEK E373 and J-PARC E07 experiments

Coulomb-Assisted Ξ^- - ^{14}N 1p_{Ξ^-} - nuclear bound state

Hayakawa (J-PARC E07), PRL (2021)



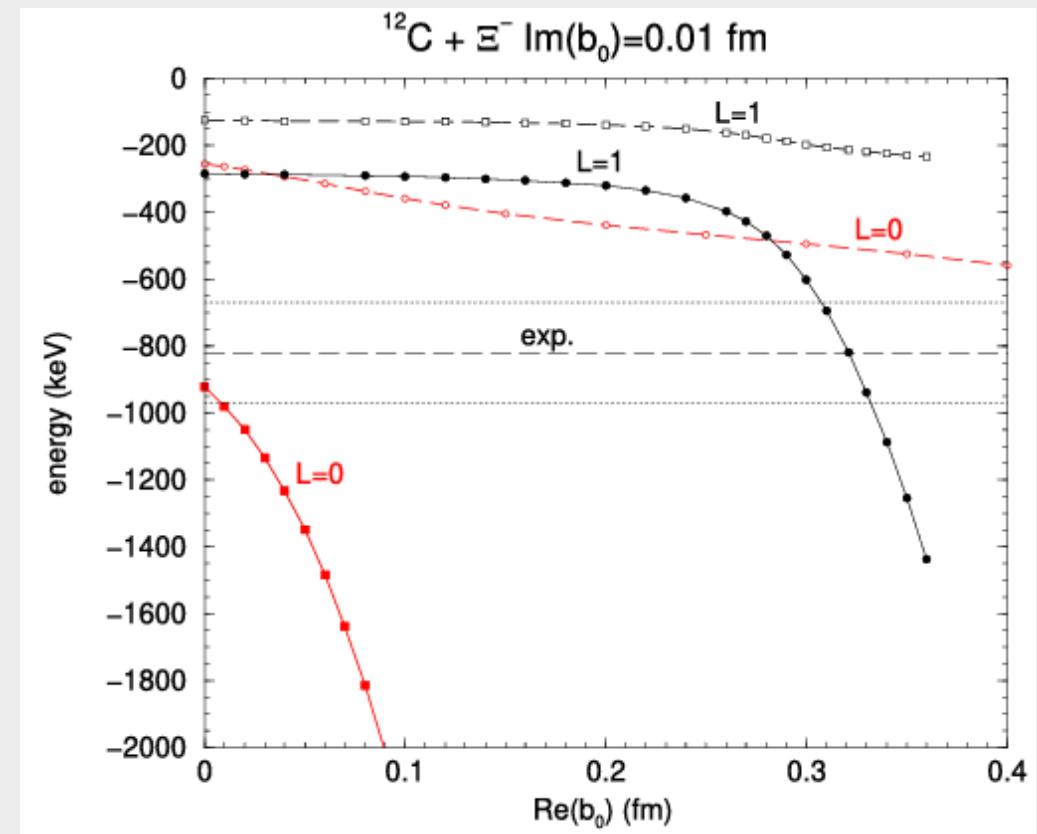
Yoshimoto, PTEP (2021)



→ 1s_{Ξ^-} - nuclear state

Analysis of emulsion events where Ξ^- is captured in 1p_{Ξ^-} - nuclear states

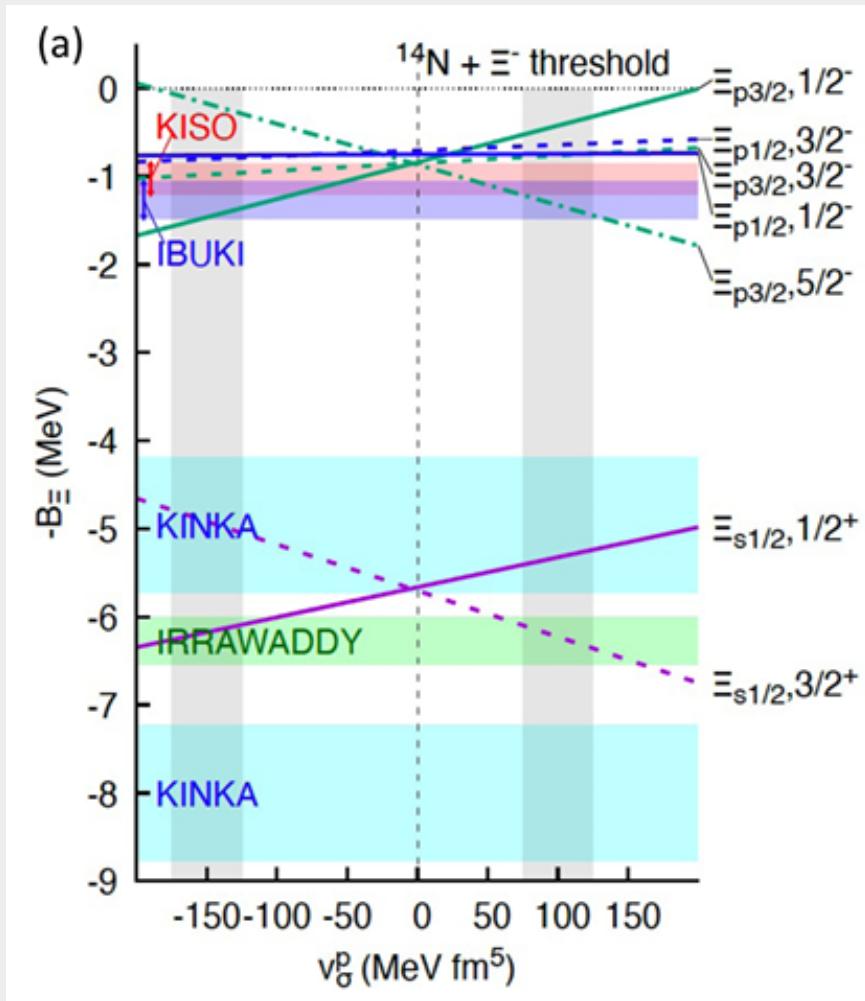
Friedman ,Gal, Phys.Lett.B (2021)



→ attractive potential depth: $V_{\Xi} \gtrsim 20 \text{ MeV}$

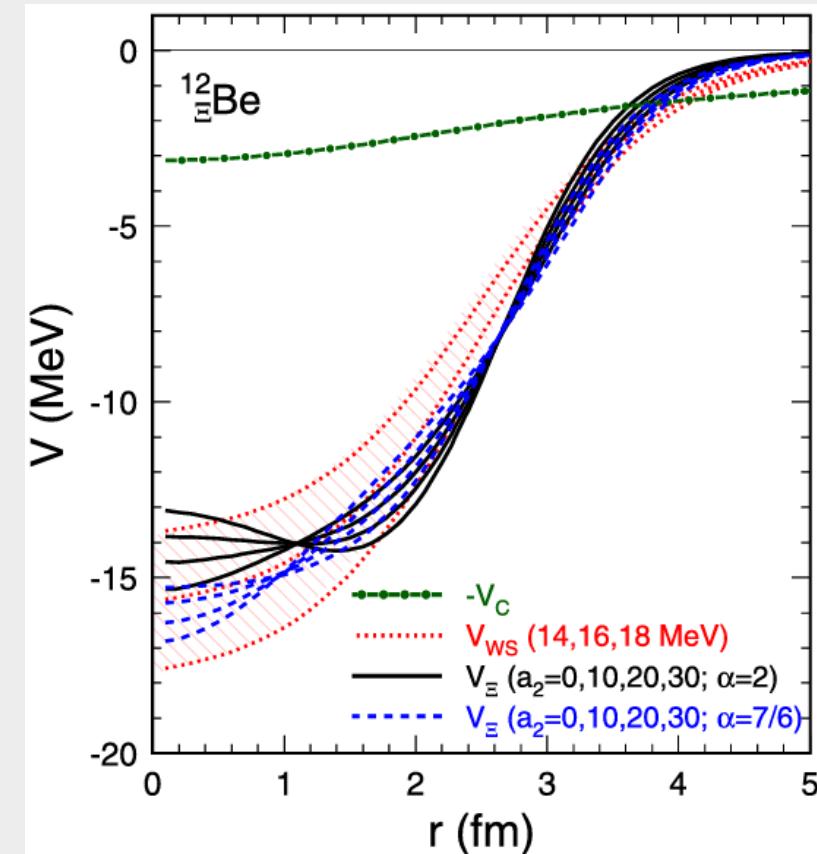
Energy spectra of Ξ -hypernuclei within a RMF model
(constrained to the new observations)

Tanimura, Sagawa, Sun, Hiyama, PRC (2022)



Skyrme-Hartree-Fock mean-field method
(constrained to the new observations)

Guo, Zhou, Schulze, PRC (2021)



Lighter Ξ -Nuclear systems

Few body calculations with realistic potentials: AV8
 NN potential combined with a ΞN potential
 (either Nijmegen or HAL QCD)

Chiral NN and ΞN interactions

Le, Haidenbauer, Meissner, Nogga, EPJA (2021)

Hiyama et al., PRL (2020)

$NN\Xi$			$NNN\Xi$			
(T, J^π)	$(\frac{1}{2}, \frac{1}{2}^+)$ $(\frac{1}{2}, \frac{3}{2}^+)$		$(0, 0^+)$	$(0, 1^+)$	$(1, 0^+)$	$(1, 1^+)$
ESC08c	...	7.20	...	10.20	3.55	10.11
HAL QCD	0.36(16)(26)

	B_Ξ [MeV]	Γ [MeV]
${}^4_\Xi H(1^+, 0)$	0.48 ± 0.01	0.74
${}^4_\Xi n(0^+, 1)$	0.71 ± 0.08	0.2
${}^4_\Xi n(1^+, 1)$	0.64 ± 0.11	0.01
${}^4_\Xi H(0^+, 0)$	—	—

→ the $NNN\Xi$ system ($T = 0$, $J^\pi = 1^+$) appears to be bound

Experiments Planned:

Ξ - atomic X-ray measurement (**J-PARC E07**) (Ξ^- Ag and Ξ^- Br)

Production of light Ξ -nuclei (**J-PARC E75**) $^7\text{Li}(\text{K}^-, \text{K}^+) \ ^7_{\Xi}\text{H}$

High-resolution spectroscopy of Ξ hypernuclei
via the (K^-, K^+) reaction (**J-PARC E70**) $^{12}\text{C}(\text{K}^-, \text{K}^+) \ ^{12}_{\Xi}\text{Be}$

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

Review: T. Hyodo and W. Weise, arXiv:2202.06181

$\bar{K}N$ interaction

Lorentz-invariant formulation of chiral effective field theory (LO)

Ren, Epelbaum, Gegelia, Meißner, EPJC (2021)

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

$|l=1 \bar{K}n \rightarrow \pi^-\Lambda$ amplitude at threshold

Piscicchia (AMADEUS@DAFNE) (2019)

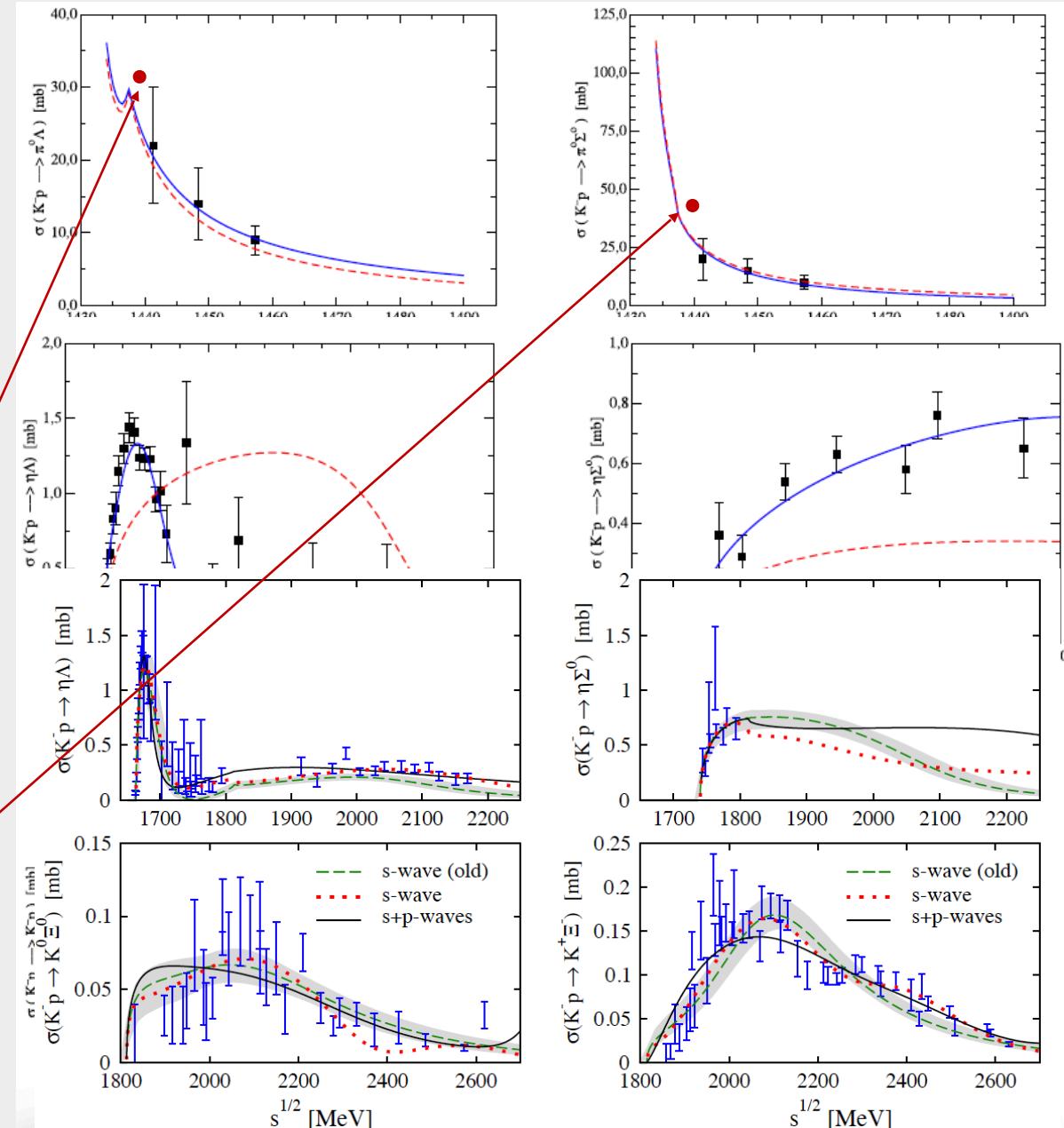
$$|A_{K^-n \rightarrow \Lambda\pi^-}| = (0.334 \pm 0.018 \text{ stat})^{+0.034}_{-0.058} \text{ syst) fm.}$$

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

Piscicchia (AMADEUS@DAFNE) (2022)

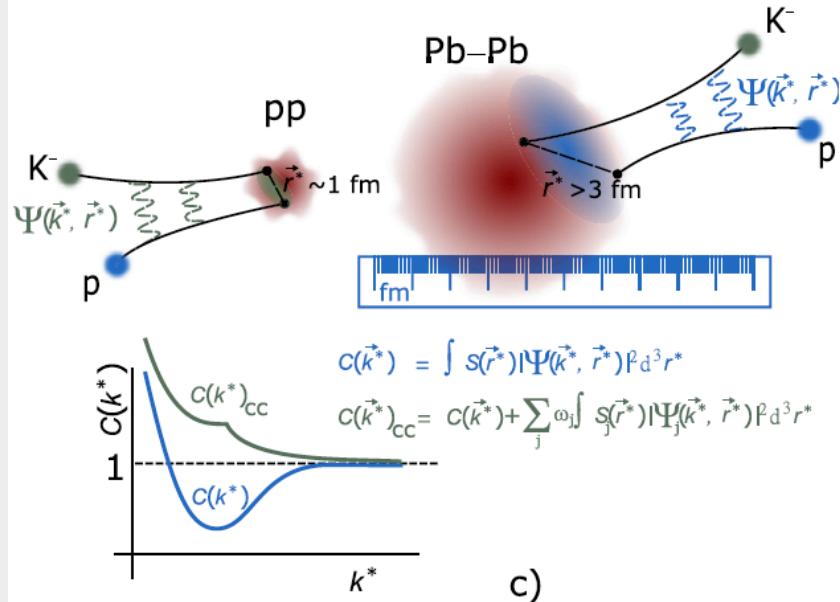
$$\sigma_{K^-p \rightarrow \Lambda\pi^0} = 31.0 \pm 0.5 (\text{stat.})^{+1.2}_{-1.2} (\text{syst.}) \text{ mb}$$

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



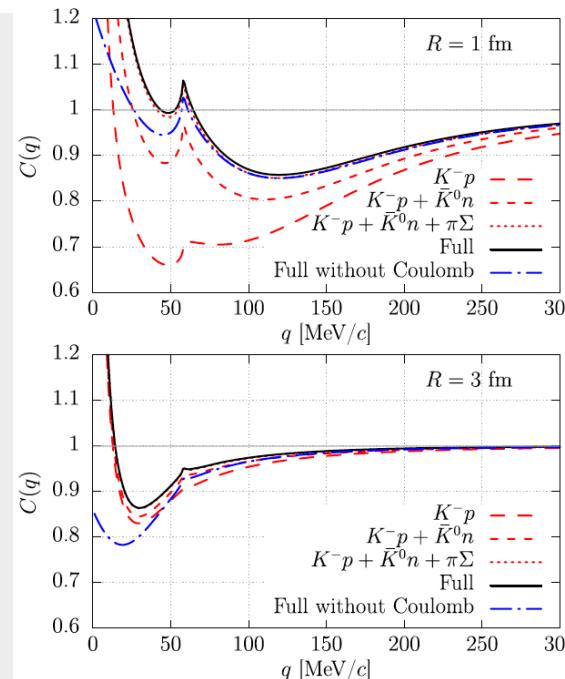
(adapted from Phys. Lett. B822 (2021) 136708)

Femtoscopy



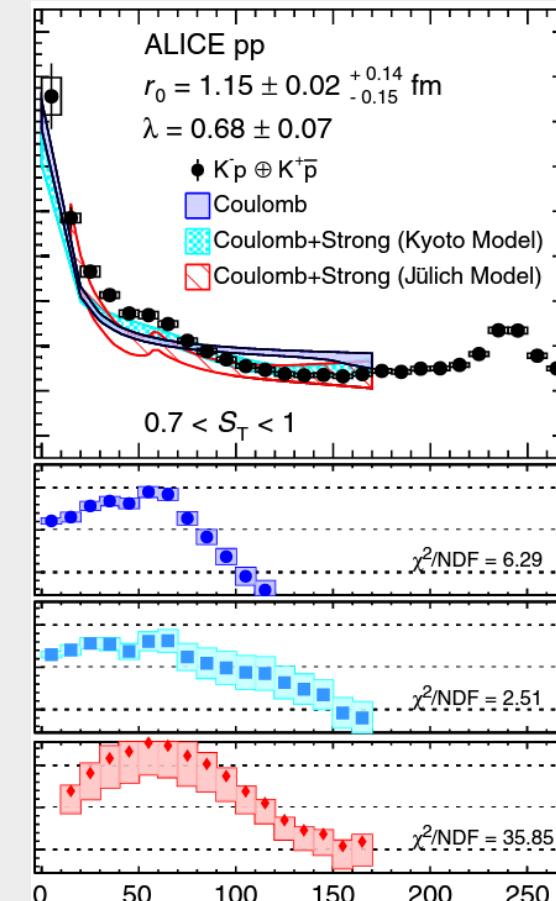
Importance of coupled channels ($K^- p - K^0 n$) and dependence on source size R

Kamiya, Hyodo, Morita, Ohnishi, Weise, PRL (2020)

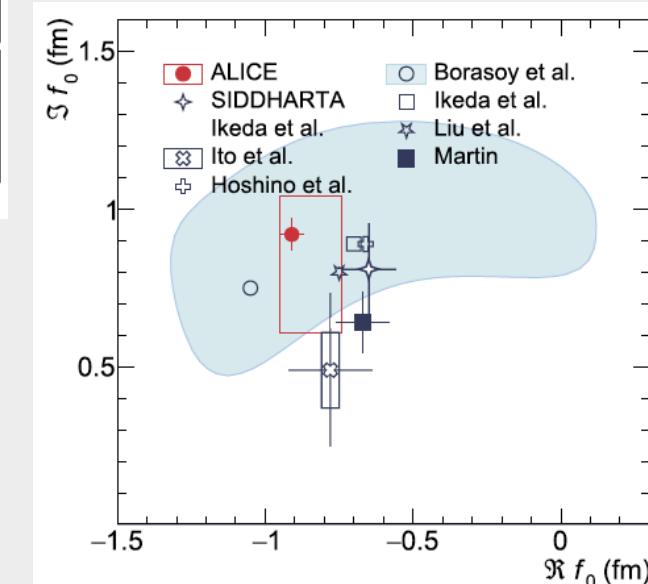
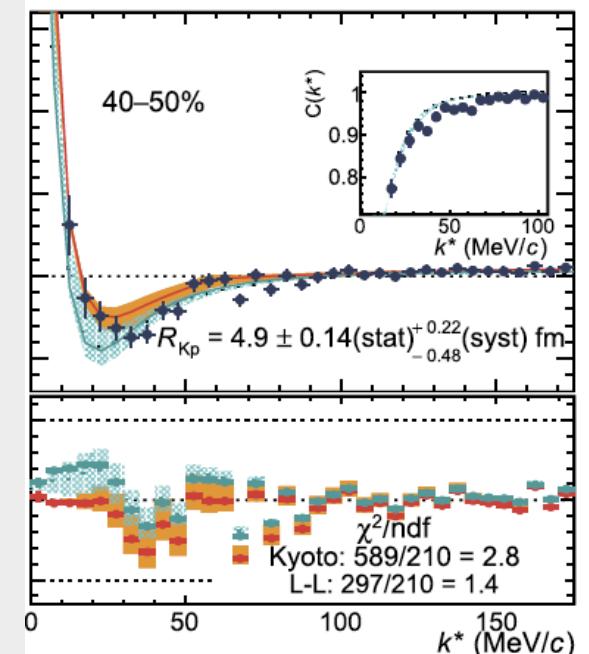


Femtoscopy ALICE@LHC

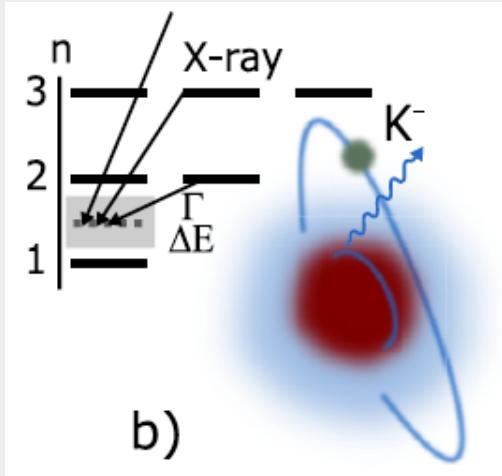
pp collisions
Acharya (ALICE), PRL (2020)



Pb Pb collisions
Acharya (ALICE), PLB 2021

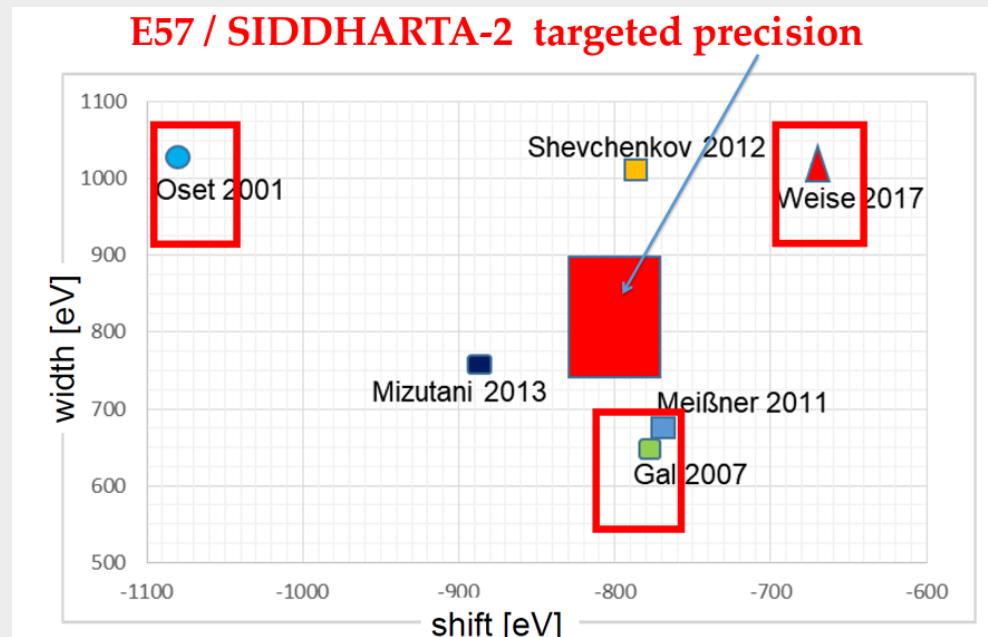
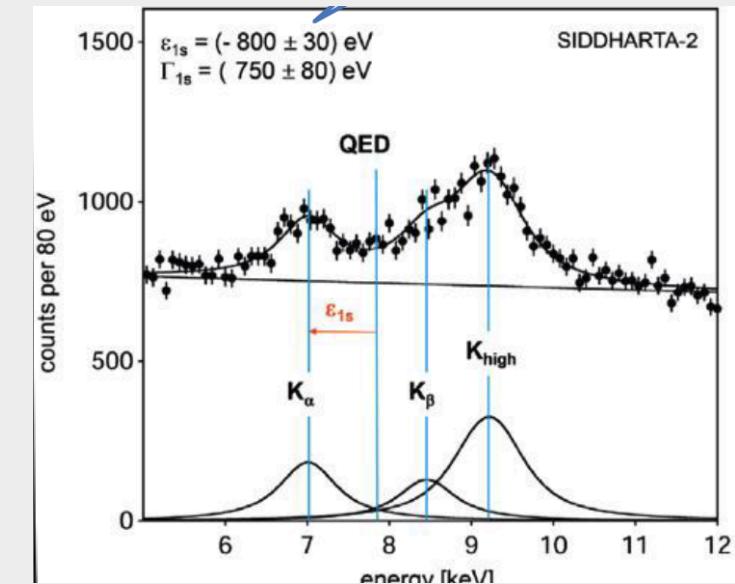


Light kaonic atoms



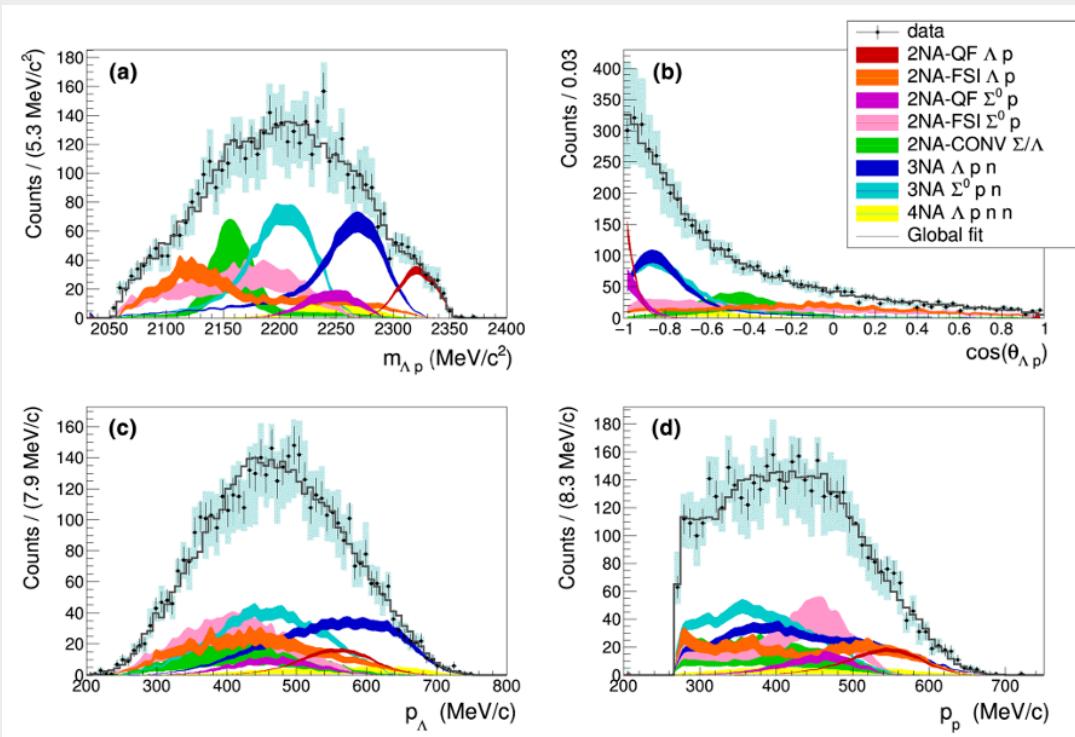
The **K-n** interaction will be pinned down from the measurement of the energy shift and width of the **kaonic deuterium** ground state (data being taken now at **SIDDHARTA2@DAFNE**)

(and planned at J-PARC)



K⁻ multi-nucleon absorption in ^{12}C

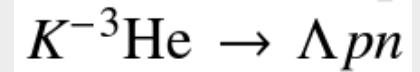
Del Grande (AMADEUS), EPJC (2019)



Study of KNN absorption with chiral models.
Branching ratios to various absorption channels well reproduced.

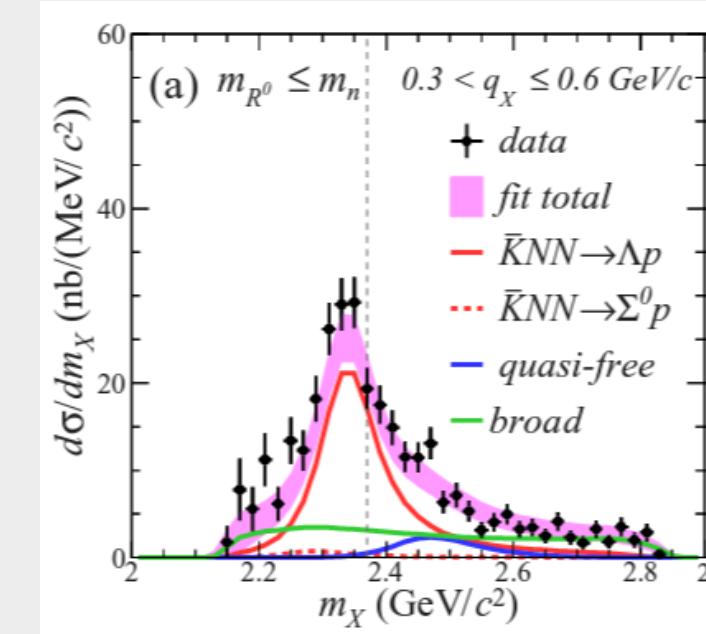
Hrtáčkova, Ramos, PRC (2020)

K-pp bound state

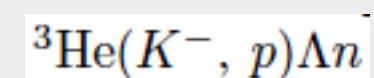


$$B_K = 42 \pm 3(\text{stat.})^{+3}_{-4}(\text{syst.}) \text{ MeV}$$

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



Future: search for K-pn / heavier clusters: KNNN



Schevchenko, FBS (2021)



Kanada-En'yo, EPJA (2021)

Ajimura, PLB 2019,
Yamaga, PRC 2020
(J-PARC E15)

Strangeness in matter and in neutron stars

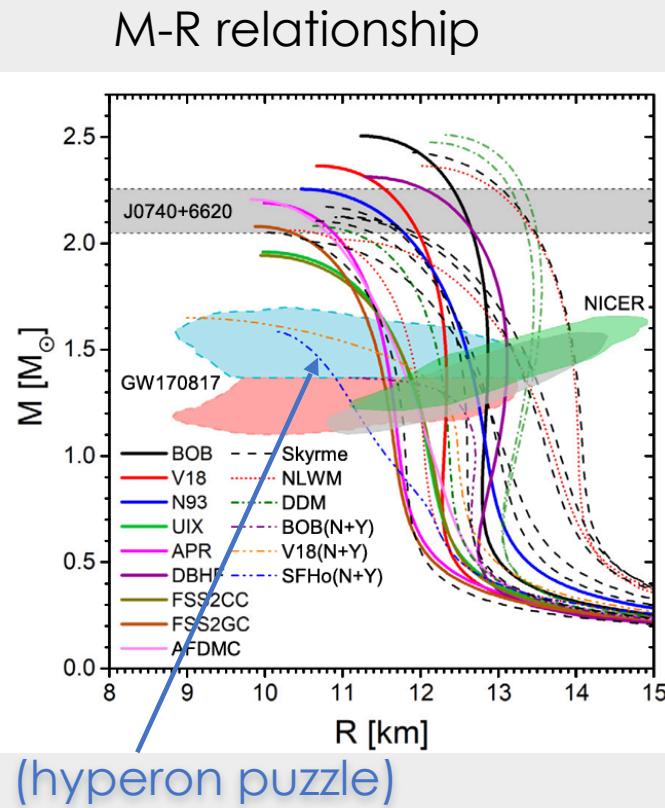
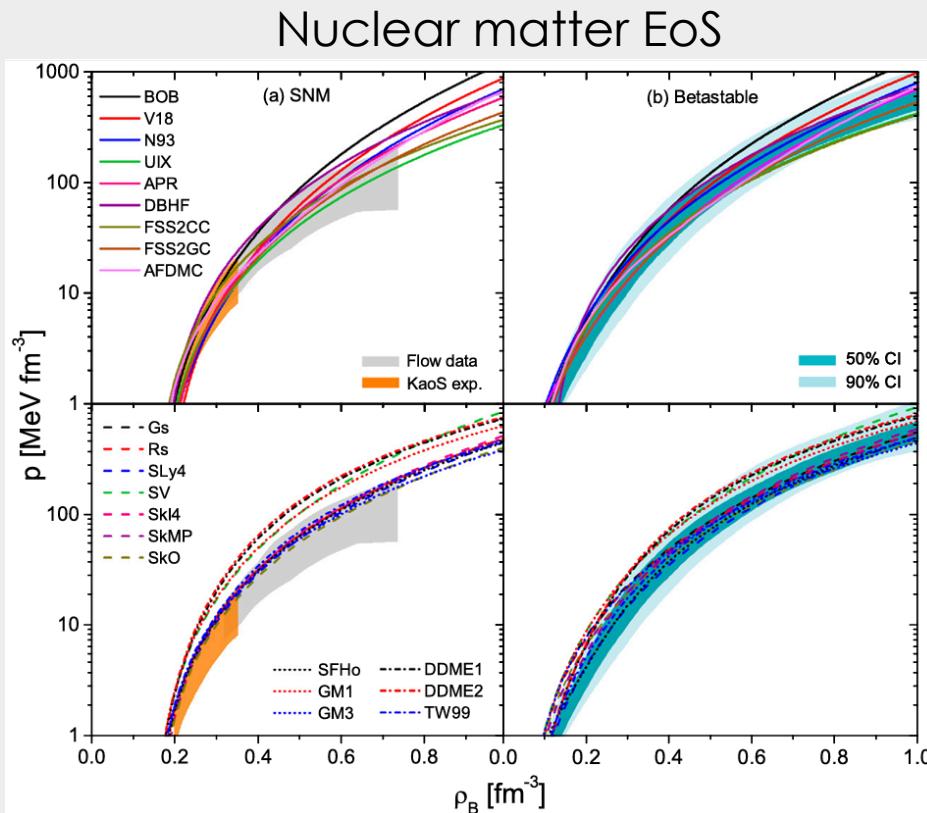
Laura Tolos, Laura Fabbietti

Prog.Part.Nucl.Phys. 112 (2020) 103770

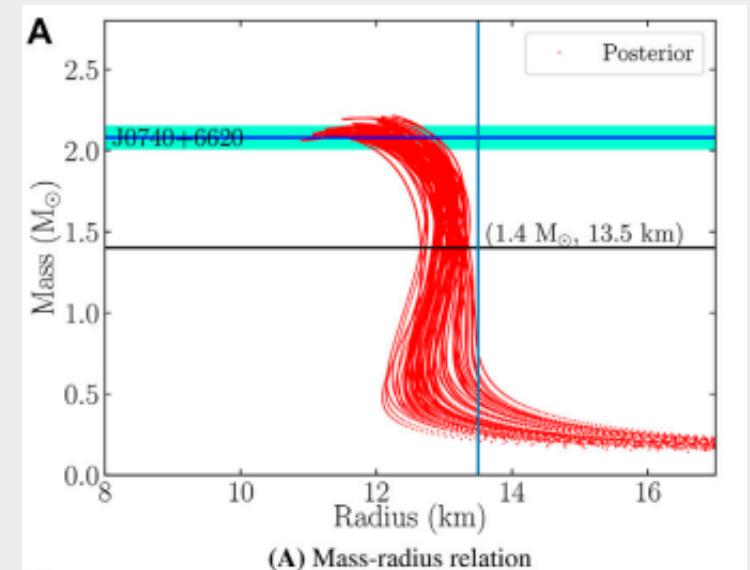
G.F. Burgio, H.-J. Schulze, I. Vidana, J.-B. Wei,

Prog.Part.Nucl.Phys. 120 (2021) 103879

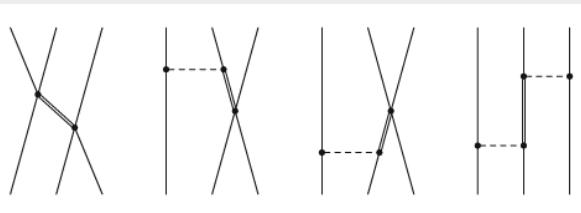
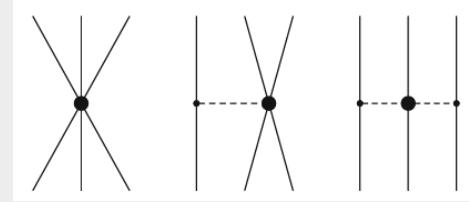
From the compilation in: **Prog.Part.Nucl.Phys. 120 (2021) 103879**



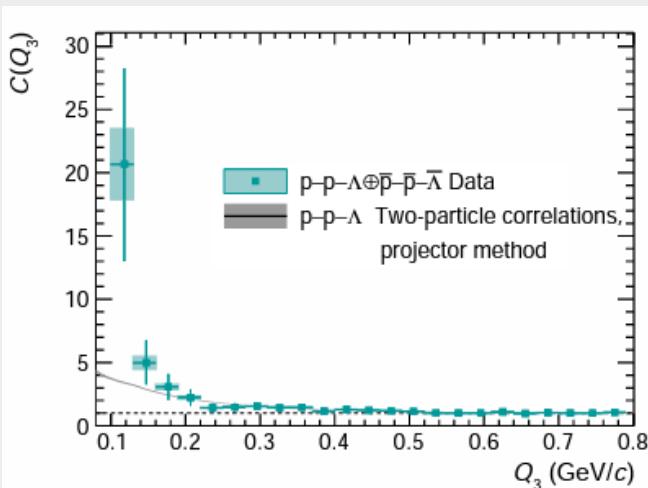
Multi-Physics Constraints in
Hyperonic Neutron Stars (RMF)
Ghosh, Pradhan, Chatterjee, Schaffner-Bielich
Front.Astron.Space (2022)



YNN force? Hyperon–nucleon three-body forces and strangeness in neutron stars

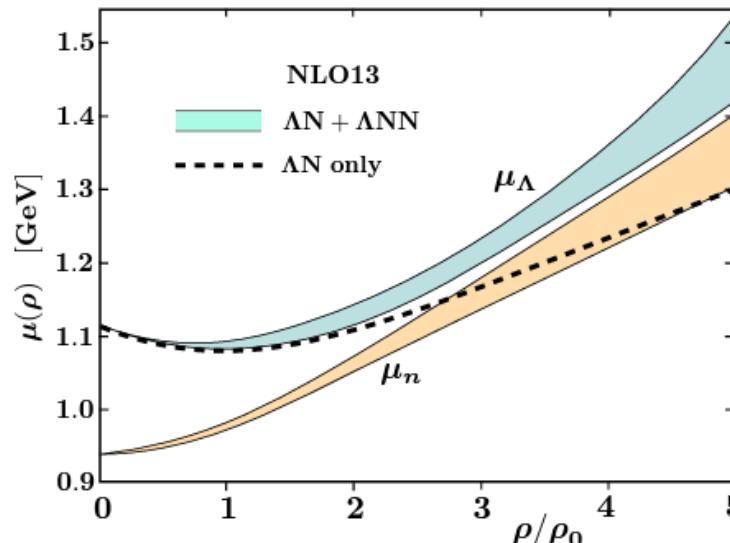


pp Λ correlations (**ALICE**)
arXiv:2206.03344v1



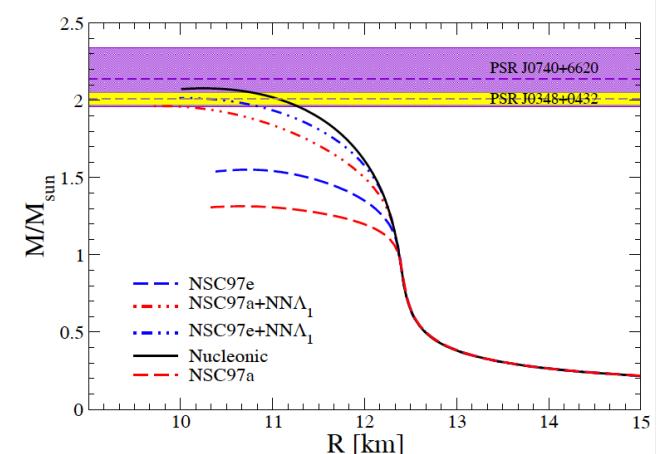
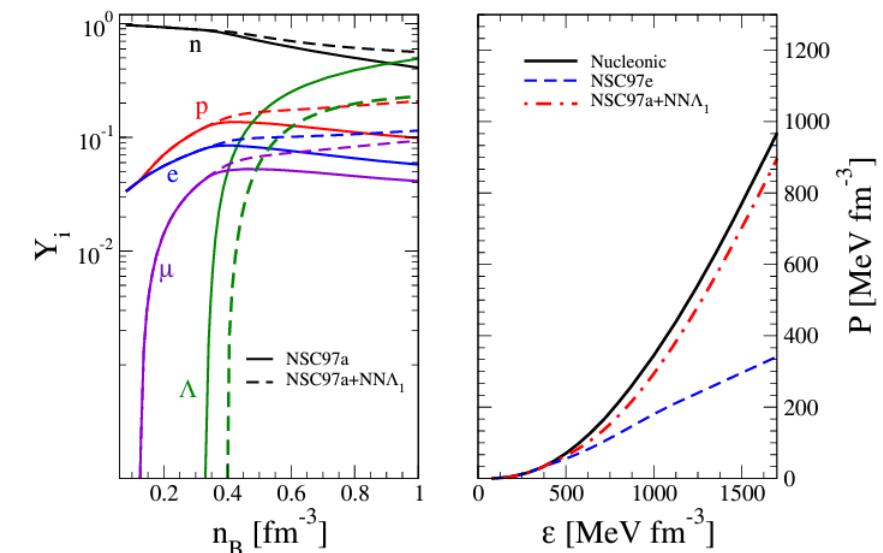
YNN (repulsive) prevents the appearance of hyperons

Gerstung, Kaiser, Weise EPJA (2020)



Hyperons appear in the core even with YNN
 $2M_\odot$ maximum mass reproduced

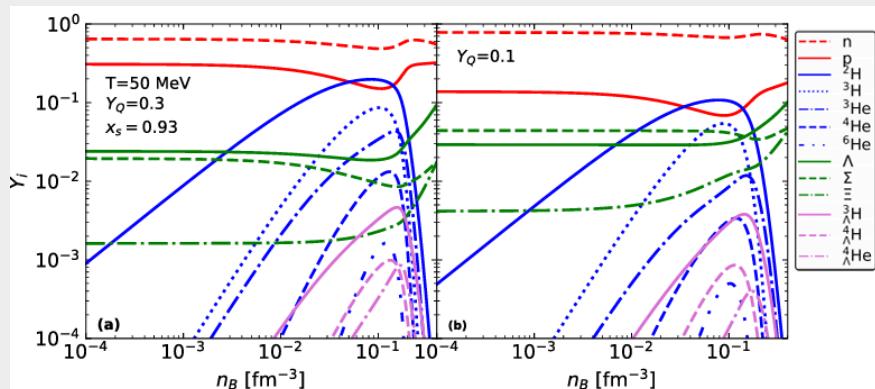
Logoteta, Vidaña, Bombaci, EPJA (2019)



Hyperons in neutron star matter at finite T (supernovas, binary neutron star mergers)

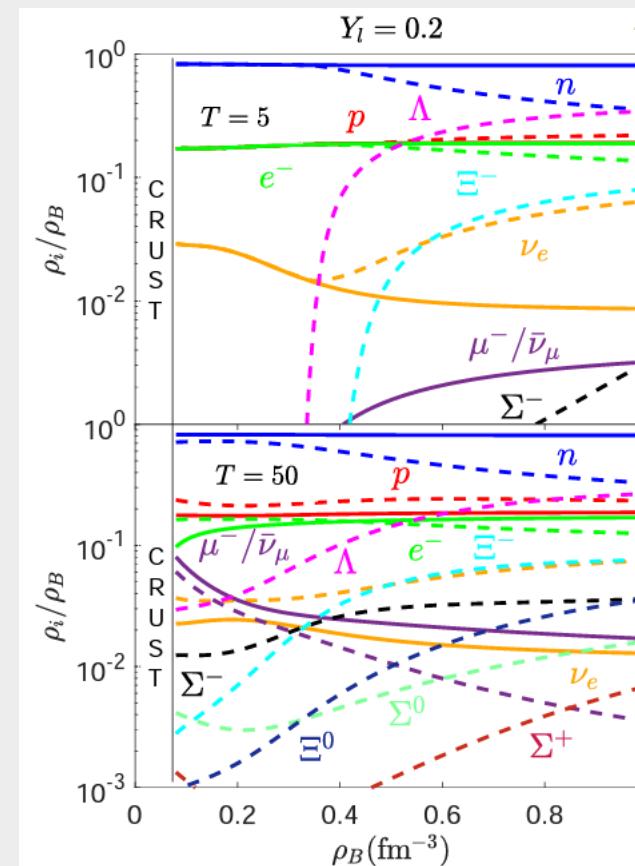
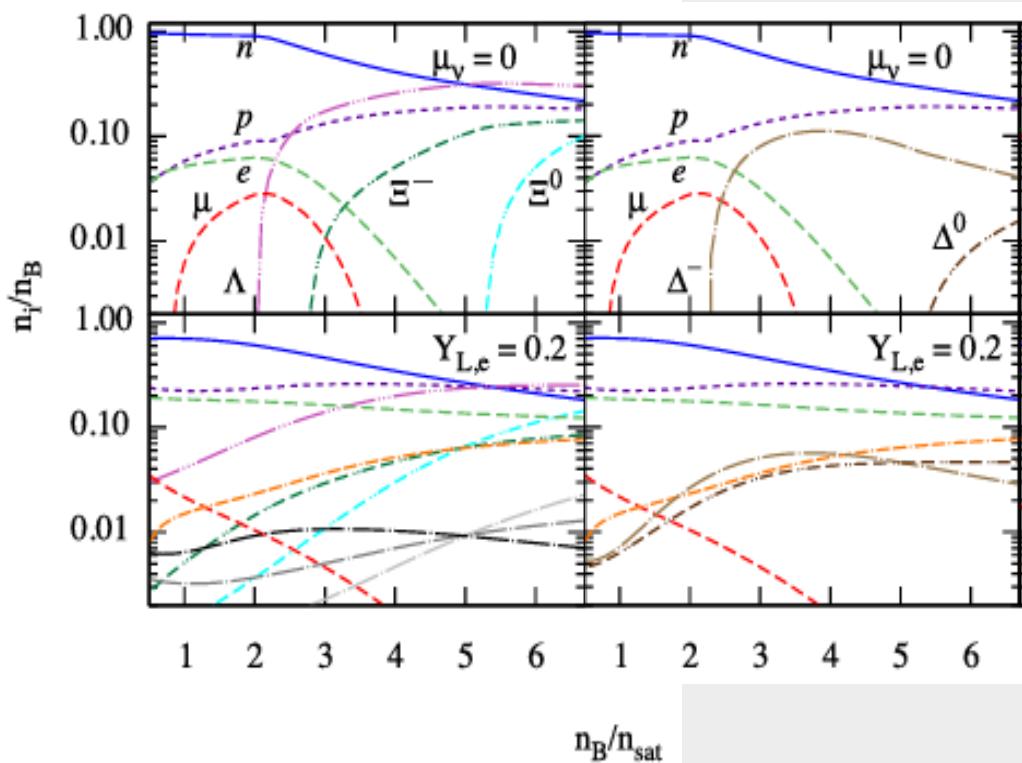
Light nuclei and hypernuclei
are present in the **crust**

Custódio, Pais, Providênciia, PRC (2021)



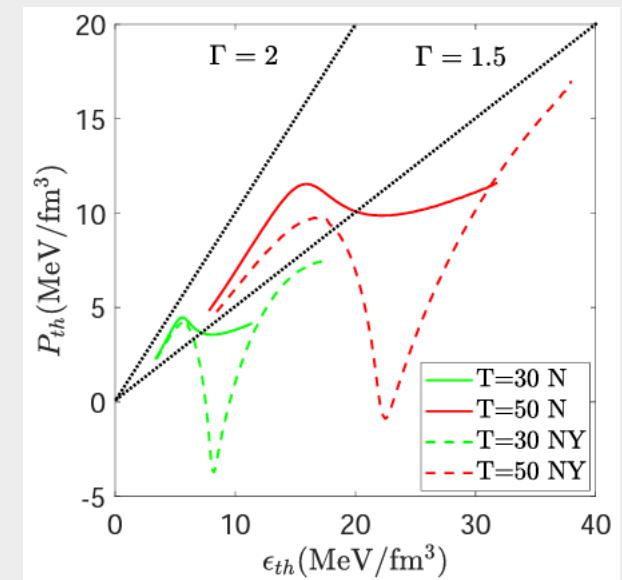
Hyperons are all over the **core** at T=50 MeV

Sedrakian, Harutyunyan, 2202.12083 [nucl-th]



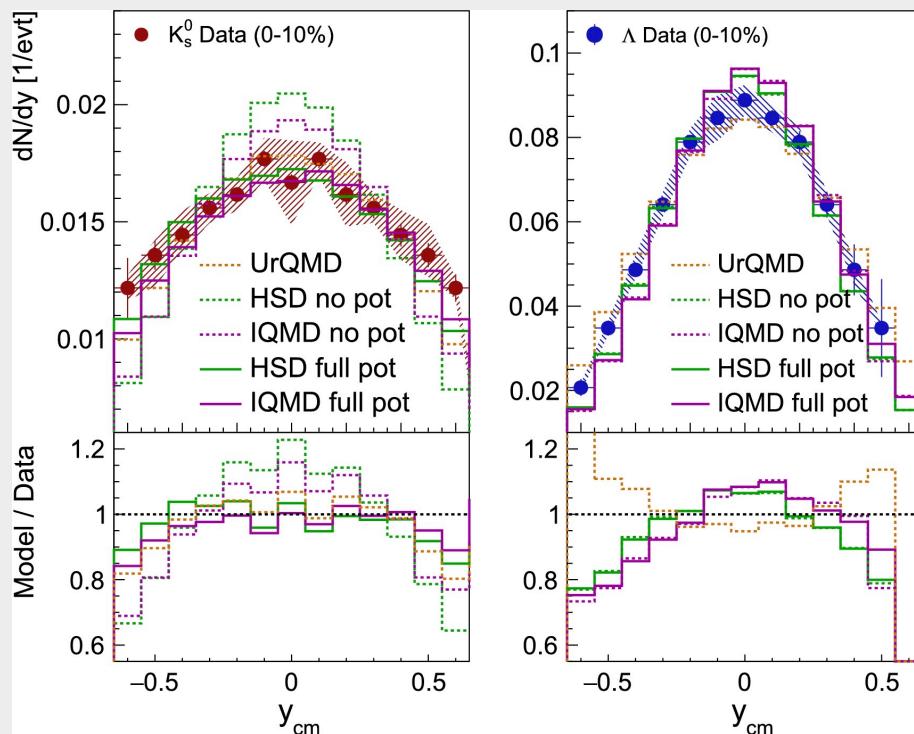
Kochankowski, Ramos, Tolos,
2206.11266 [astro-ph.HE]

Hyperons affect strongly
the P_th - epsilon_th relation



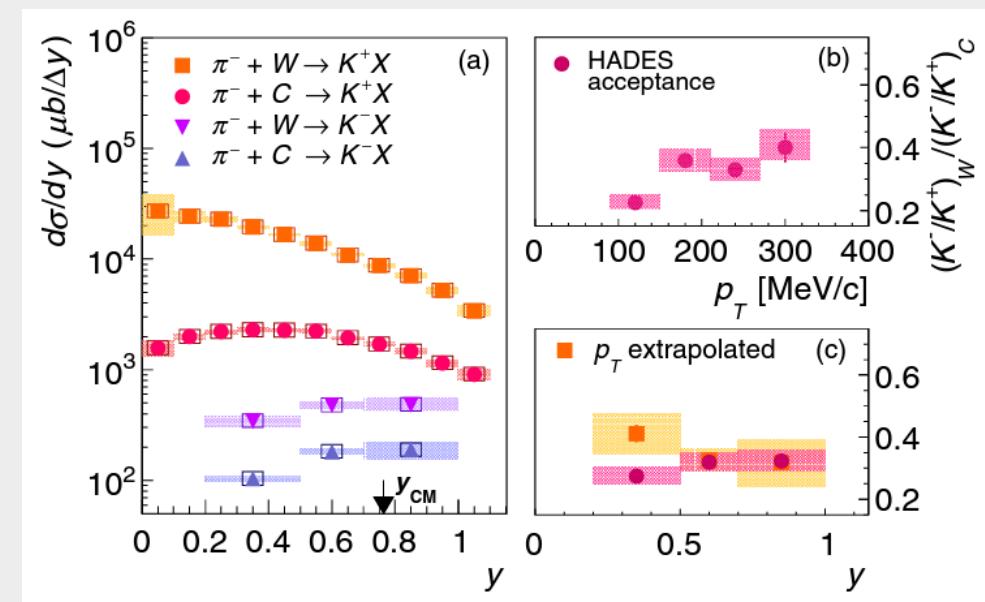
In-medium properties of strange particles from heavy-ion collision experiments

Sub-threshold production of K_s^0 and Λ
in Au+Au collisions at $\sqrt{s}_{NN} = 2.4$ GeV
with HADES **Leifels (HADES) PLB (2019)**



Comparison of **K- absorption** from π^- induced reactions **on C and W** @1.7 GeV/c (HADES at SIS18/GSI)

Adamczewski-Musch (HADES), PRL (2019)



Strangeness Nuclear Physics is an active field of research that extends the scope of conventional **Nuclear Physics** to a new degree of freedom (**strangeness**) and, by doing so, it accommodates a variety of new phenomena which have fascinating consequences in other fields of research, such as **Particle Physics** and **Astrophysics**.

Thank you for your attention!