STRANGENESS NUCLEAR PHYSICS

Progress Report (2018-2022)

Angels Ramos

(University of Barcelona and Institute of Cosmos Sciences)

UNIVERSITAT DE BARCELONA

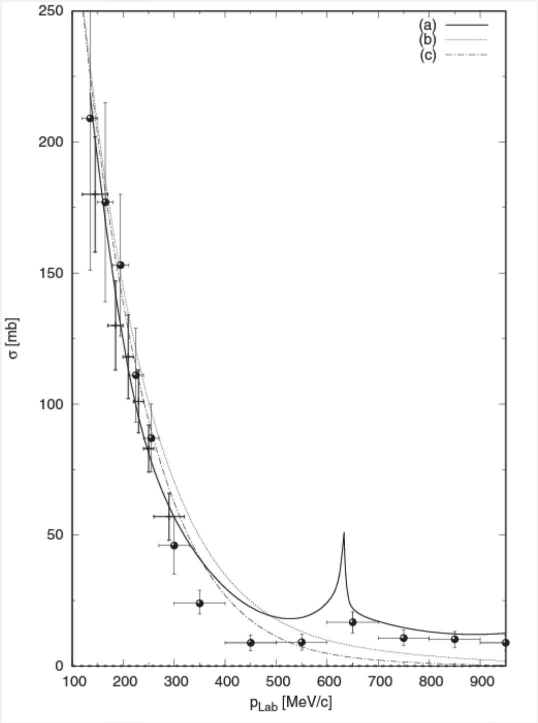
ICCUB

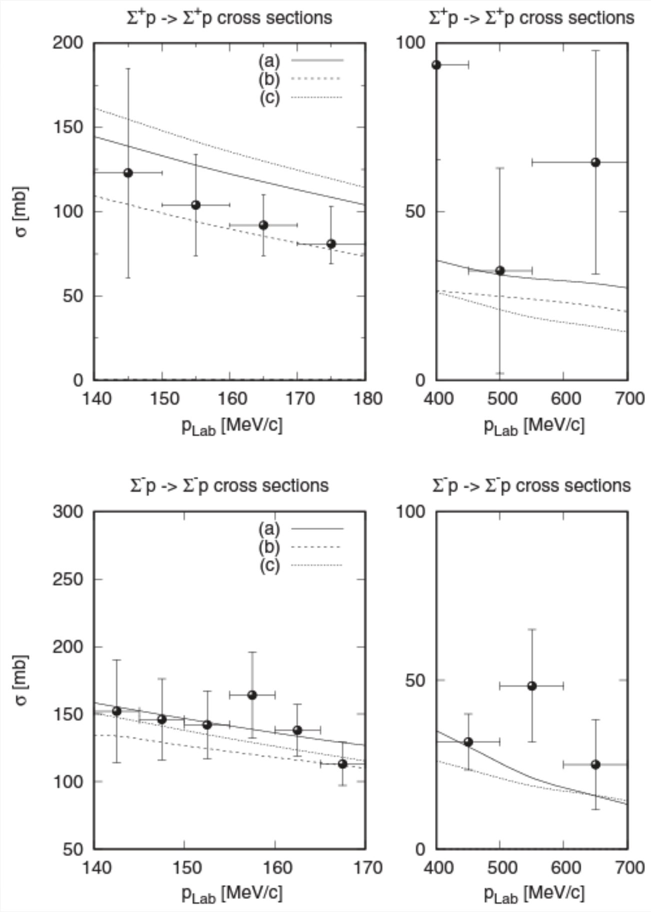
EXCELENCIA MARÍA DE MAEZTU

Elementary YN, YY interactions

YN Cross Sections

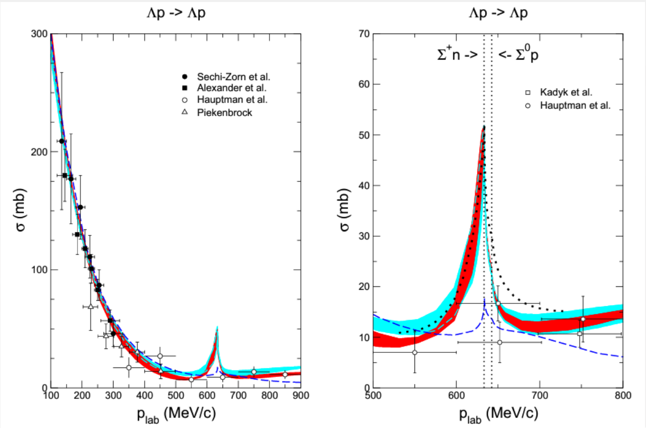
Hyperons ar short-lived. Scattering sperments difficult!
(scarce amount of data)

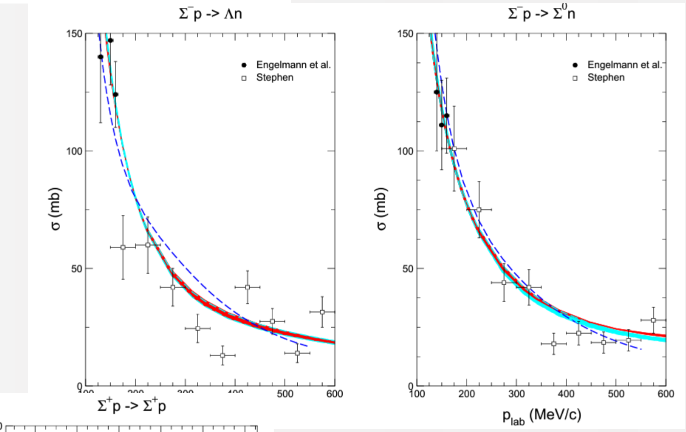


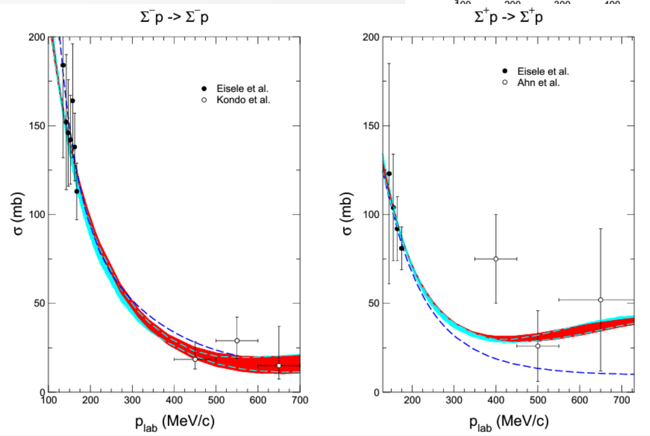


Meson-exchange model

Nagels, Rijken, Yamamoto, PRC (2019)





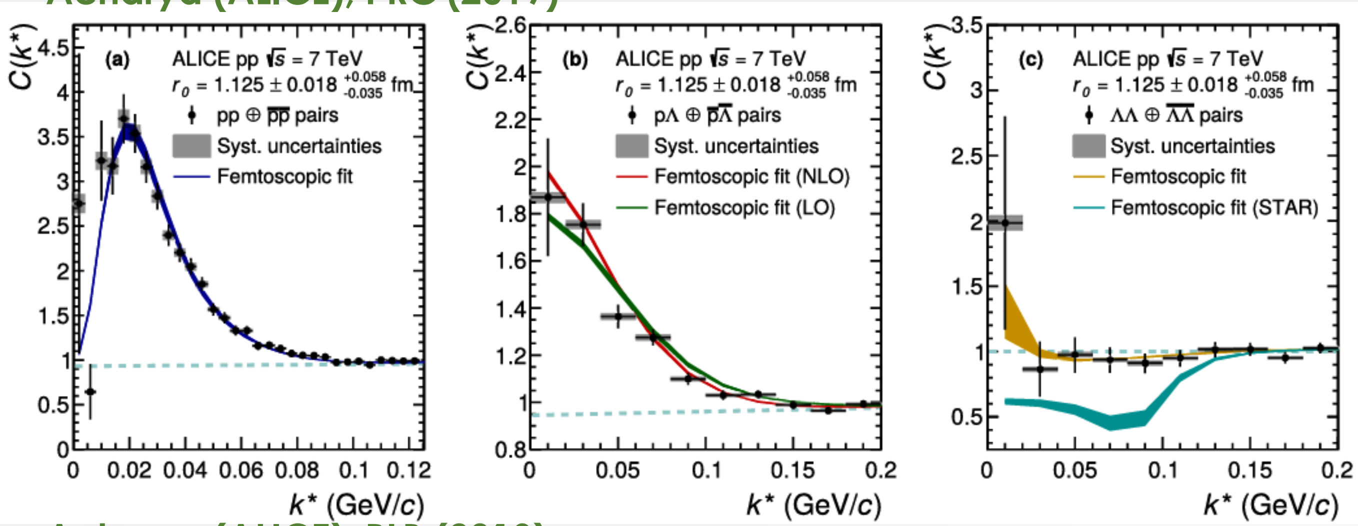


EFT theory

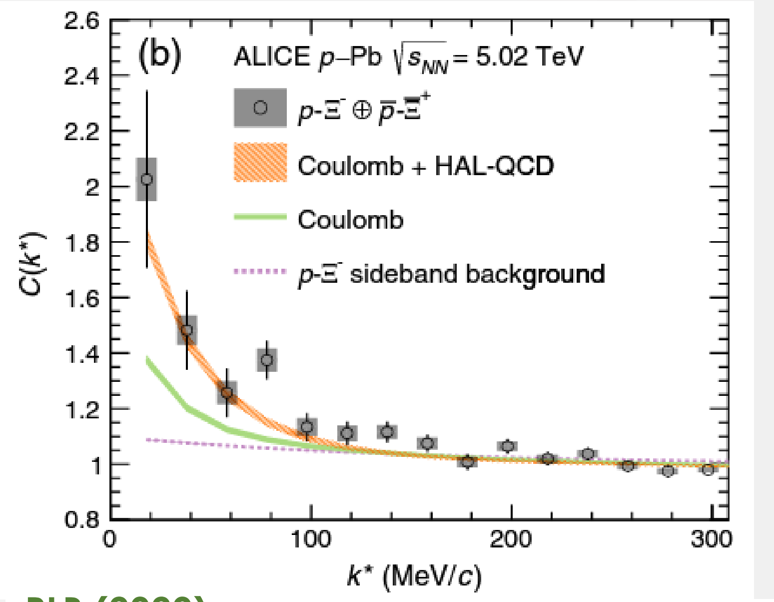
Haidenbauer, Meißner, Nogga, EPJA (2020)

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

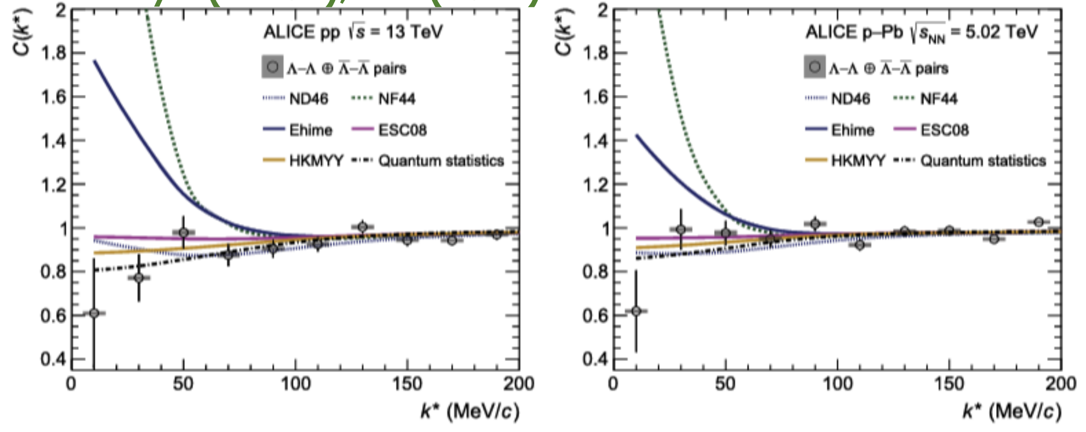
Acharya (ALICE), PRC (2019)



Acharya (ALICE), PRL (2019)

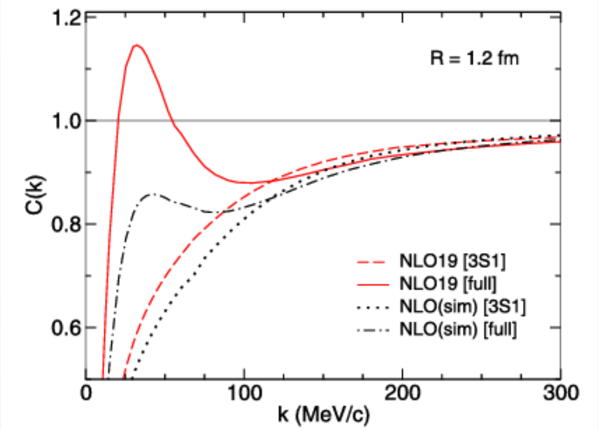


Acharya (ALICE), PLB (2019)

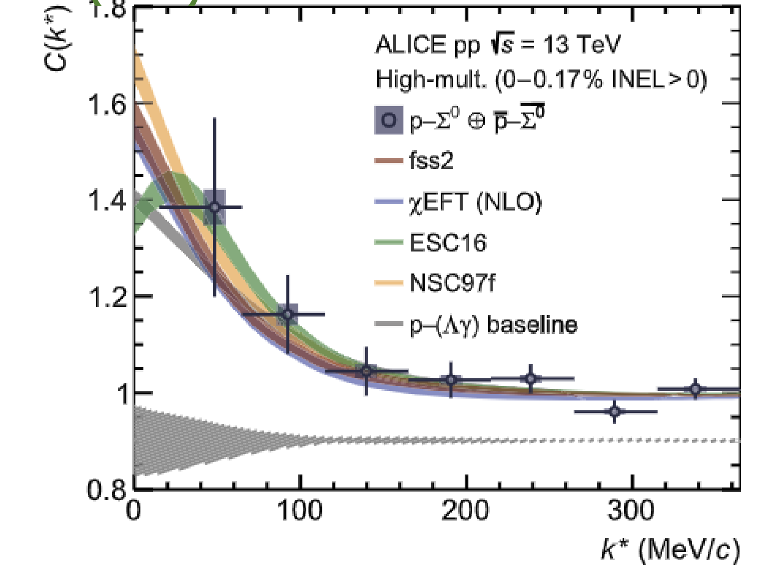


Haidenbauer, Meissner, PLB (2022)

$\Sigma^+ p$



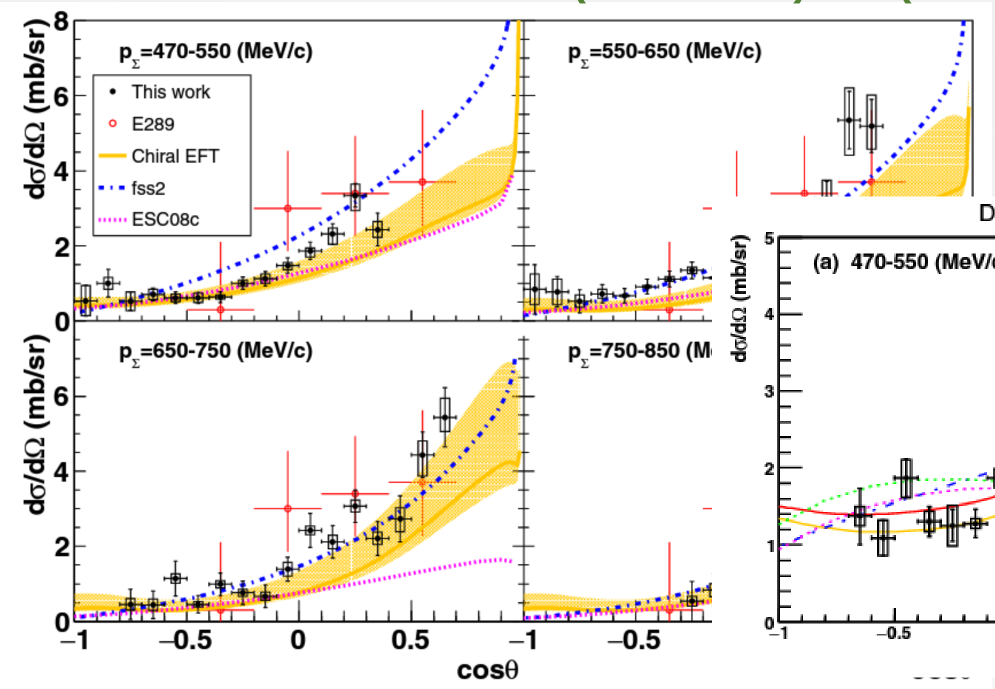
PLB (2020)



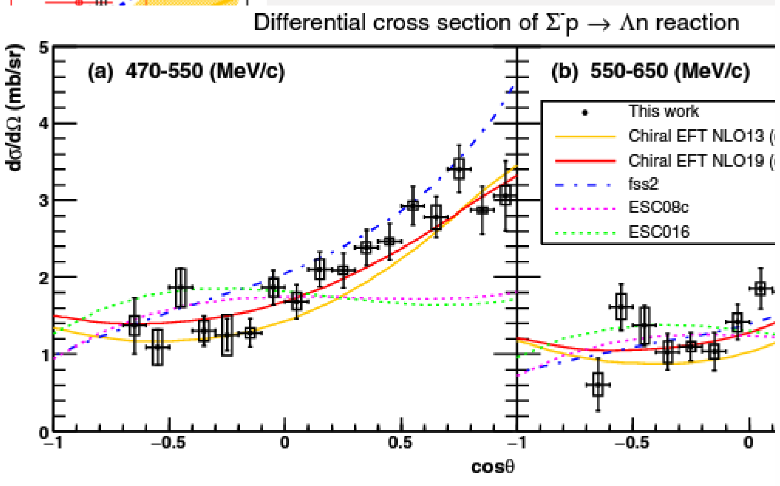
J-PARC E40

differential x-sections for Σ^-p

Miwa (J-PARC E40) PRC (2021)

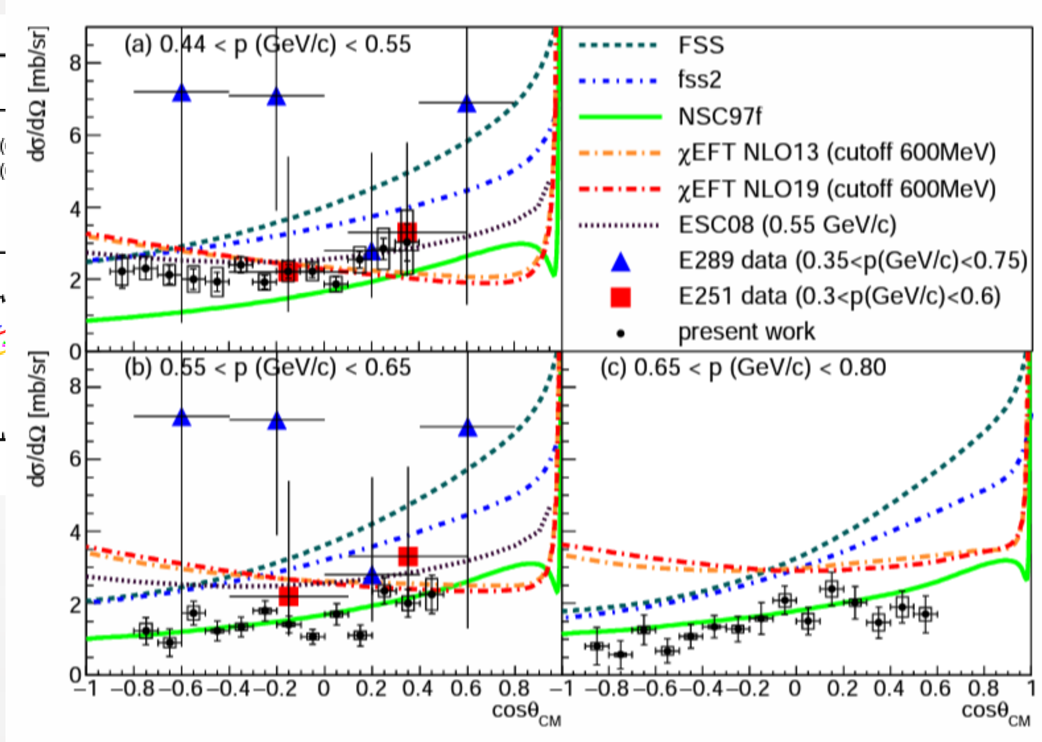


differential x-sections for $\Sigma^-p\to\Lambda n$ PRL (2022)



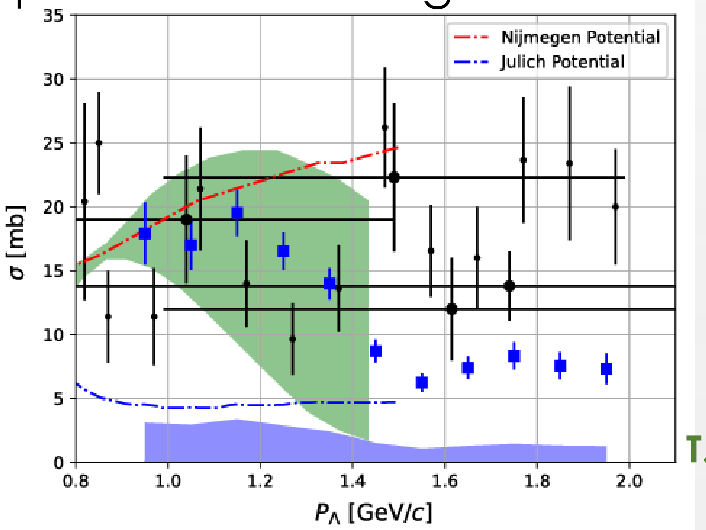
differential x-sections for Σ^+p

Nanamura (J-PARC E40), arXiv:2203.08393



CLAS

Λp elastic scattering x-sections



T. Rowley (CLAS), PRL (2021)

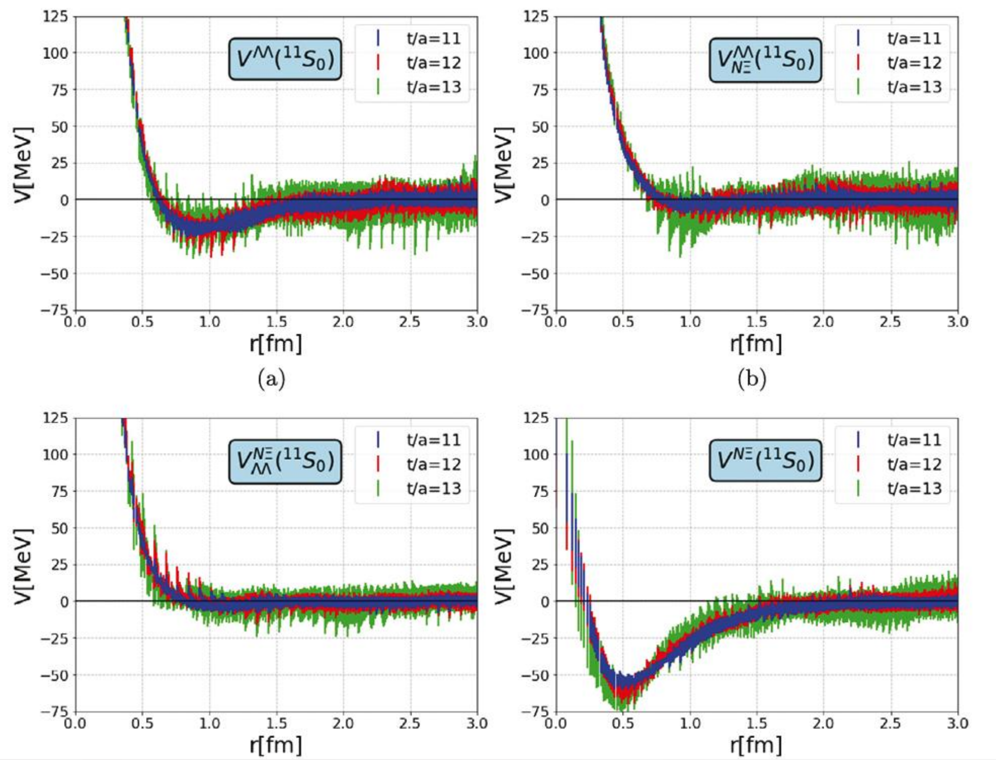
Lattice QCD

HAL QCD

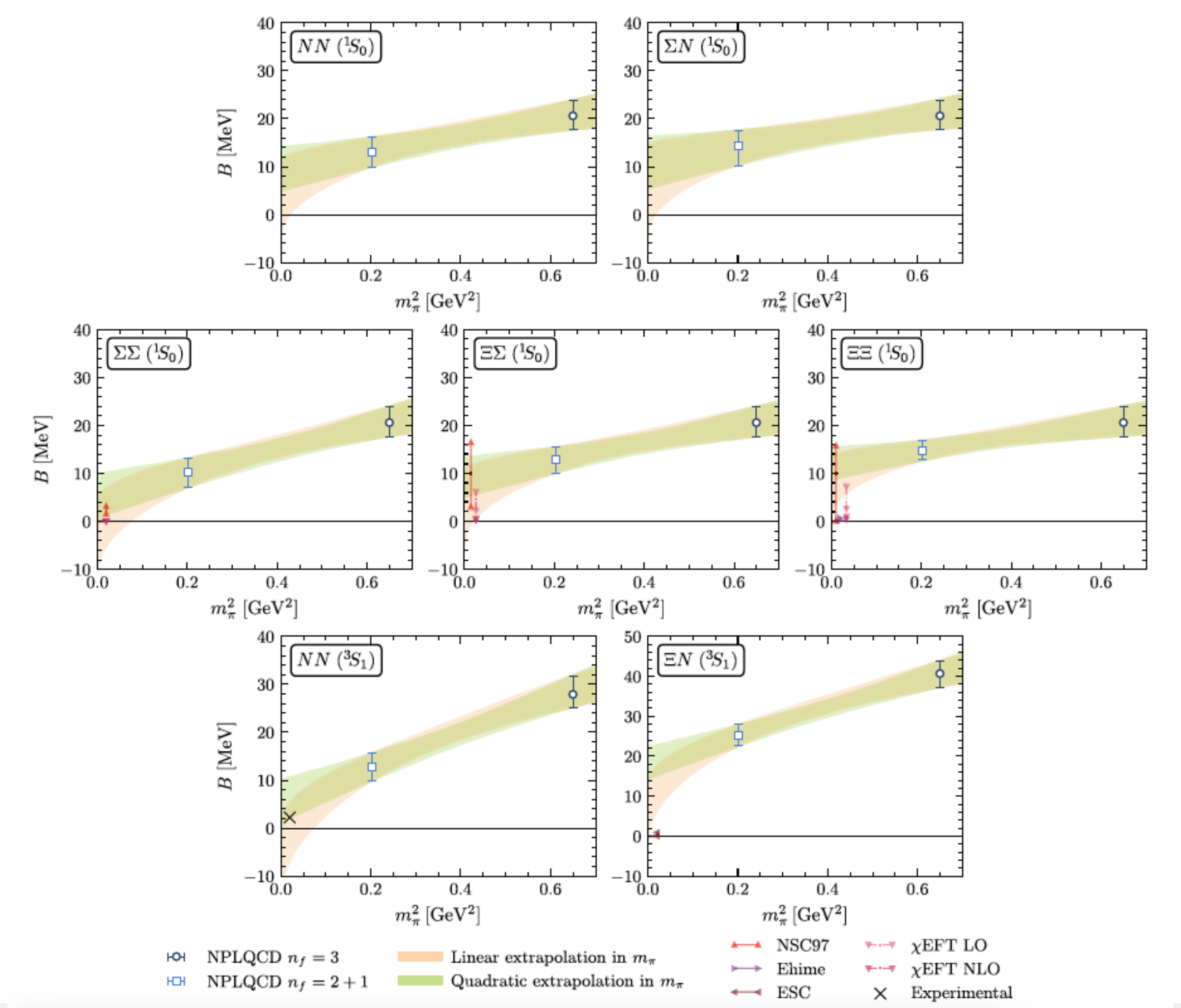
BB strangeness ranging from 0 to -4

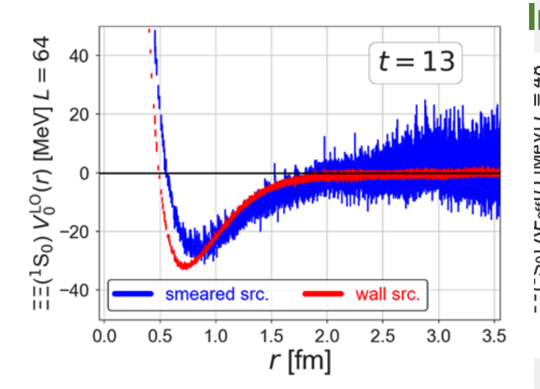
NPLQCD

Sasaki, NPA (2020)

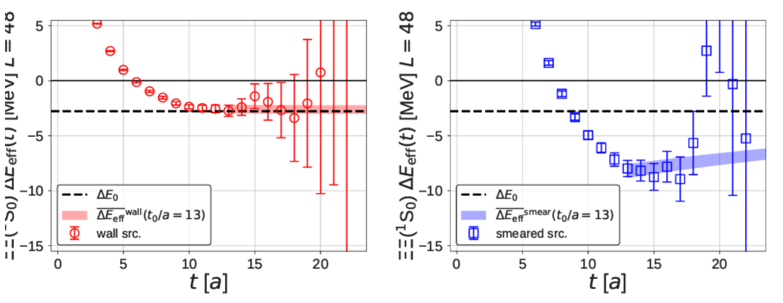


Illa, PRD (2021)





Iritani, JHEP (2019), PRD (2019)

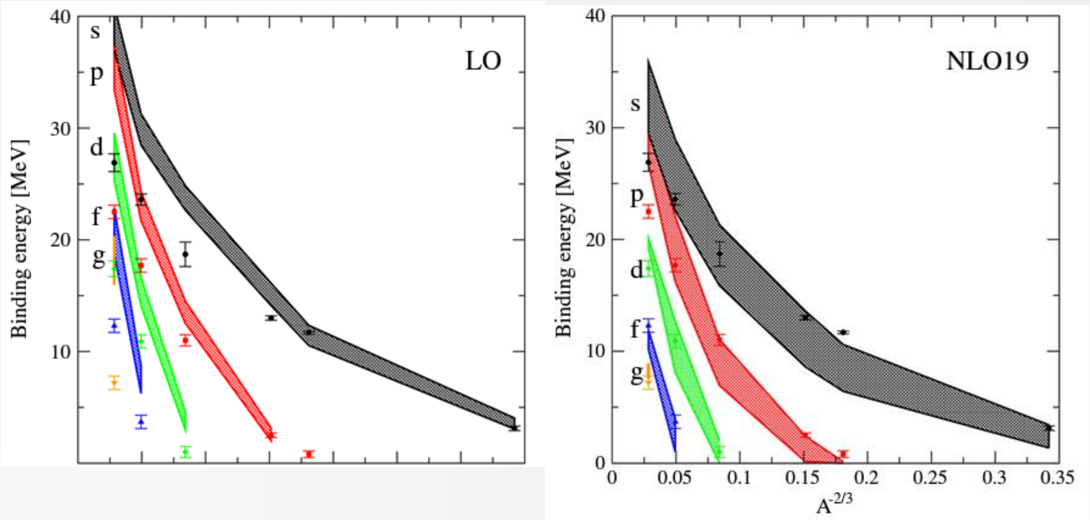


Lyu, PRD (2022)

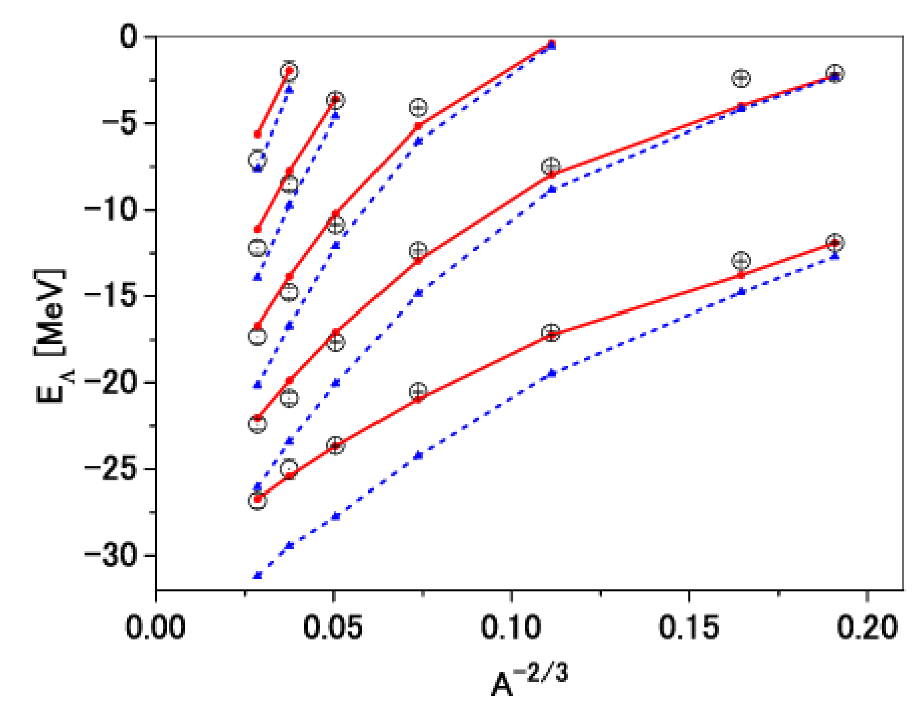
Testing (and constraining) YN, YY interactions with hypernuclei

(mean-field Y-potentials obtained from in-medium modified G-matrix interactions)

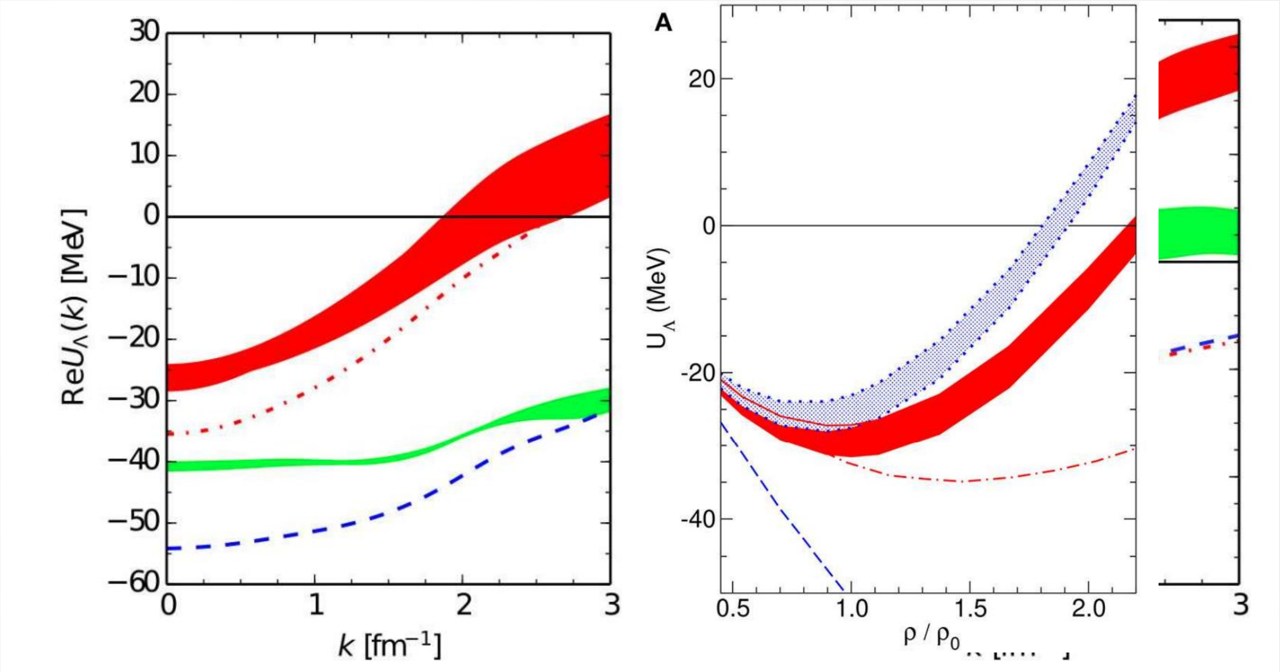
Haidenbauer , Vidaña, EPJA (2020)



Nagels, Rijken, Yamamoto, PRC (2019)



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



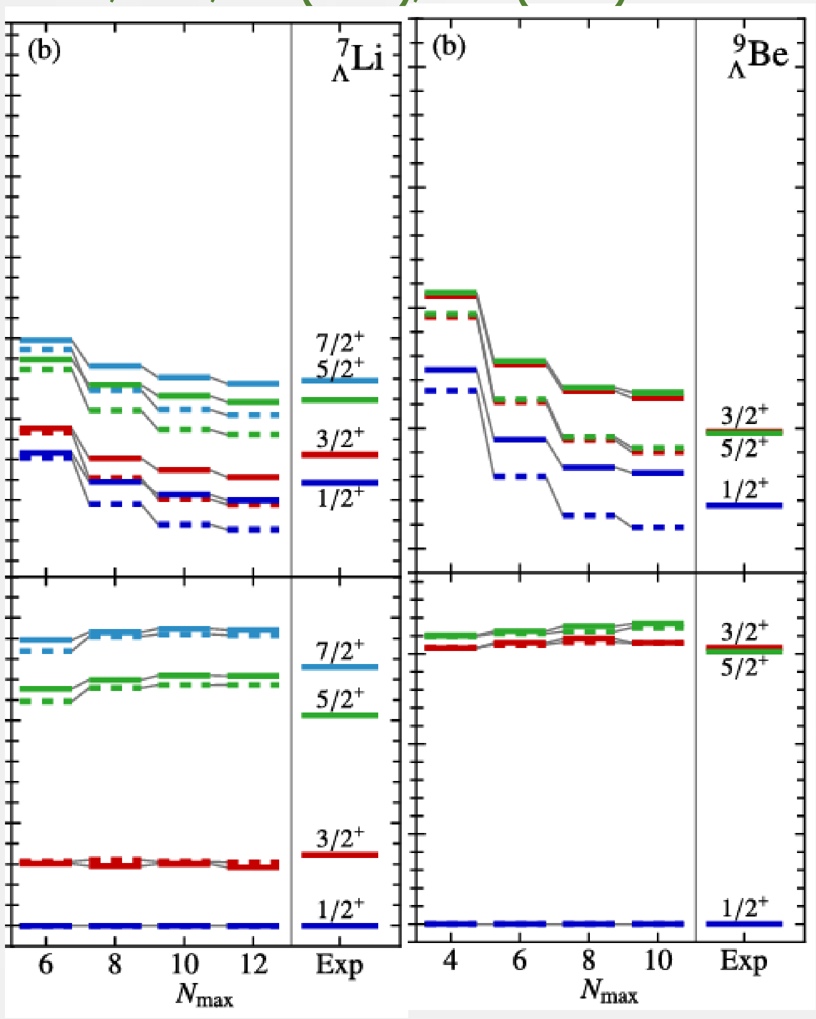
Testing (and constraining) YN, YY interactions with hypernuclei

(*ab-initio* No Core Shell Model calculations)

Slater determinant basis of HO states

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

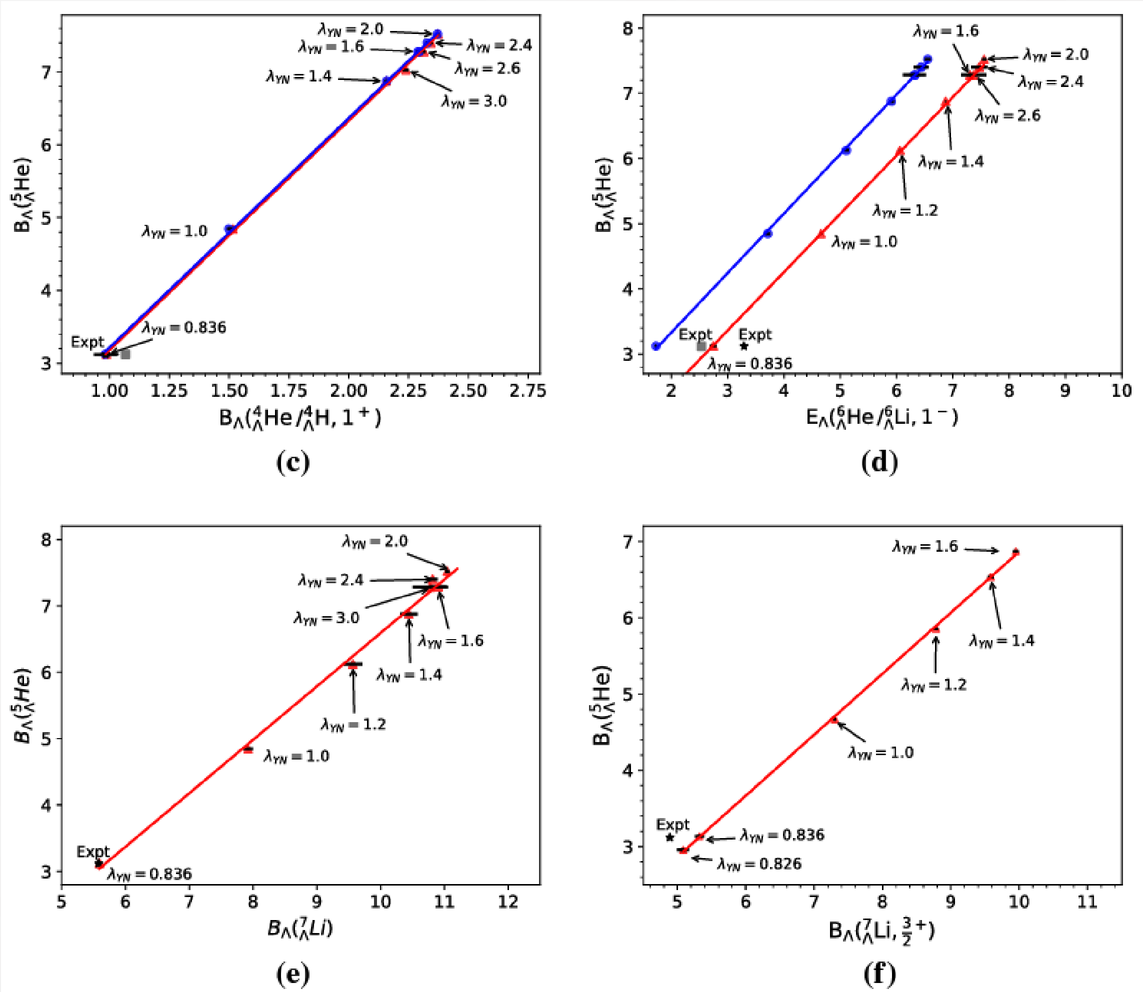
Wirth, Roth, PLB (2018); PRC (2019)



Jacobi coordinates and symmetry-adapted basis

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

ΛΛ hypernuclei: EPJA (2021)



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

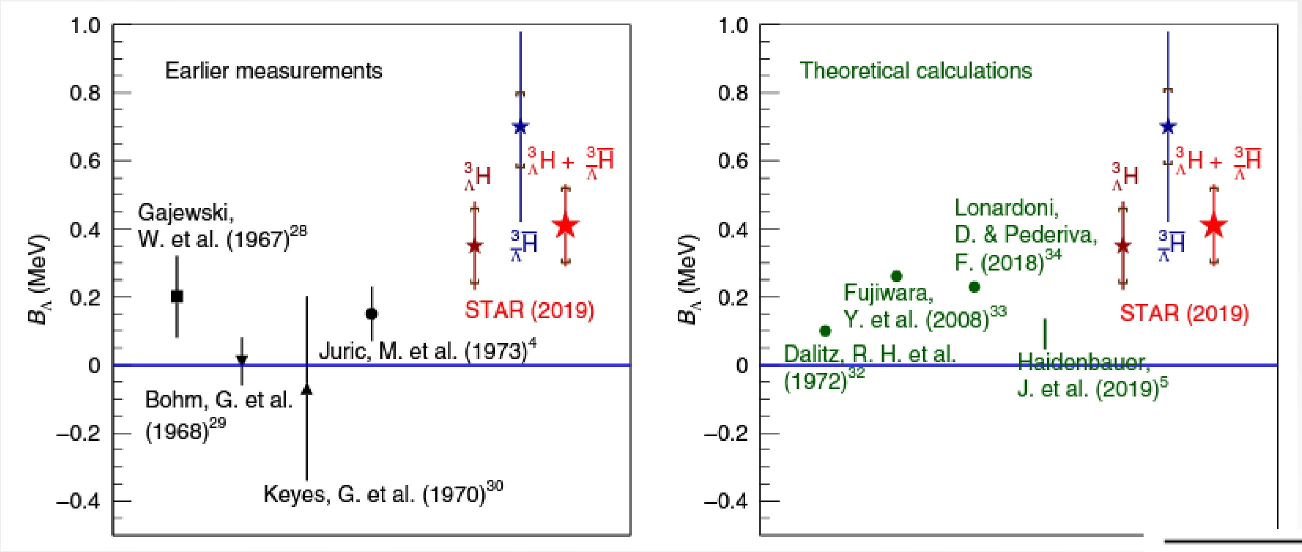
(→ "exact" wavefunction is known)

the best benchmark for testing the YN interaction and understand a few puzzles:

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

- **Hypertriton B_Λ (is it larger than before?)**

Adam (STAR), Nature Phys. (2020)



average value: $B_\Lambda = 0.13 \pm 0.05$ MeV

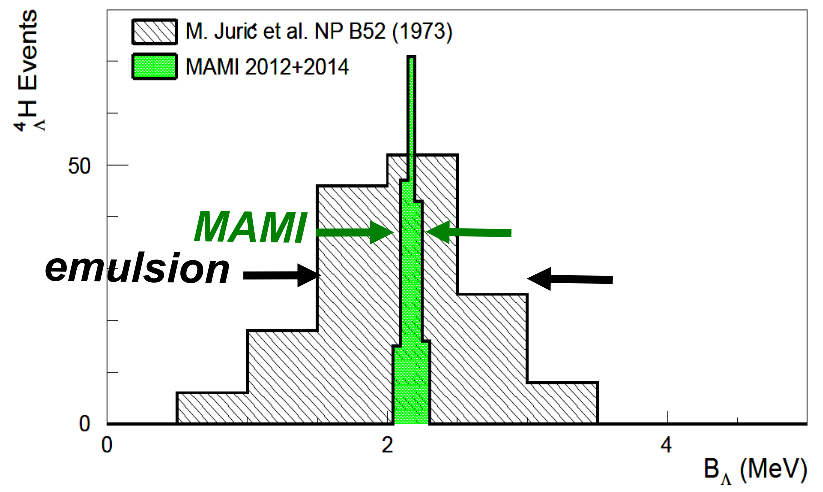
STAR measurement: $B_\Lambda = 0.41 \pm 0.12$ MeV

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

(the new value used to constrain the relative weigth of the singlet/tripet ΛN interaction)

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

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

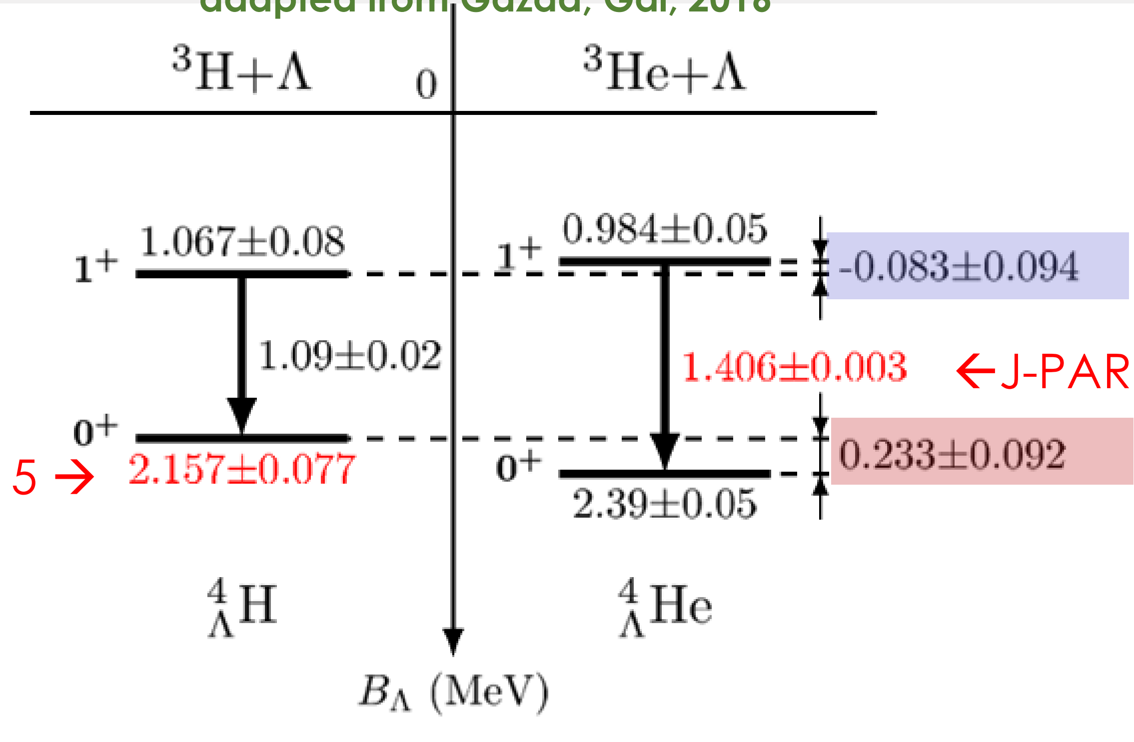


New measurement **@MAMI** coming soon!

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

- **Charge Symmetry Breaking (CSB) in hypernuclei**

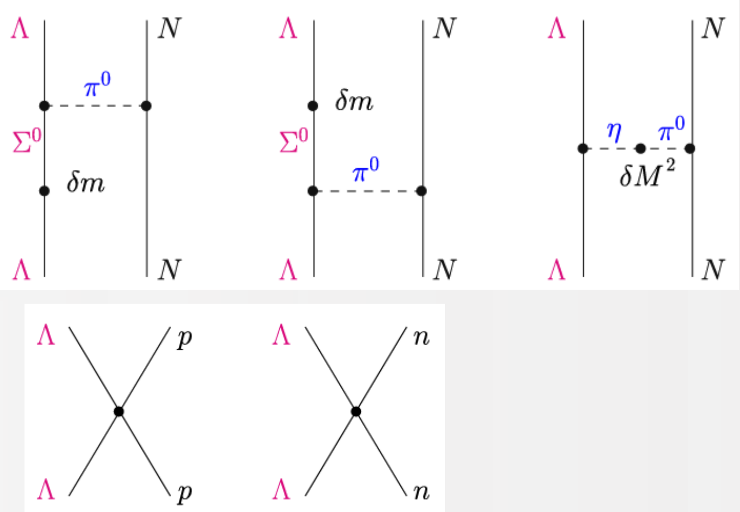
adapted from Gazda, Gal, 2016

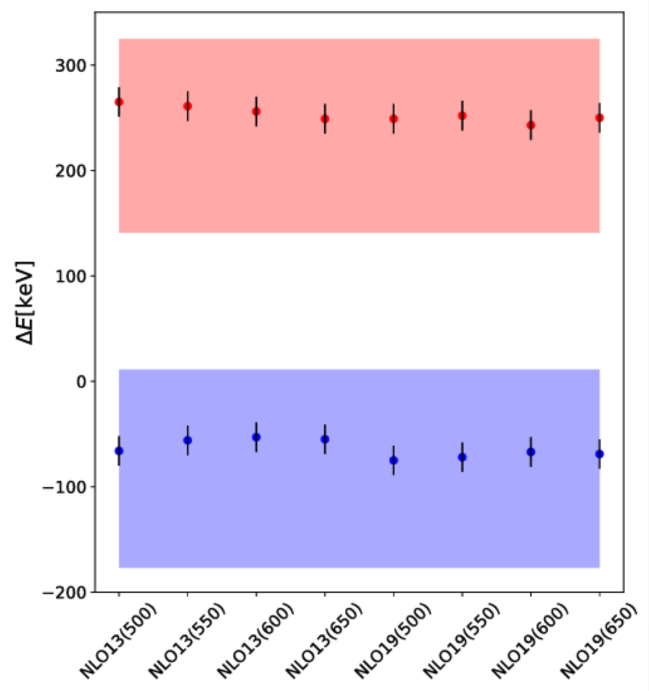


← J-PARC, 2015

MAMI, 2015 →

Haidenbauer, Meißner, Nogga, 2021





J-PARC E63 experiment:

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

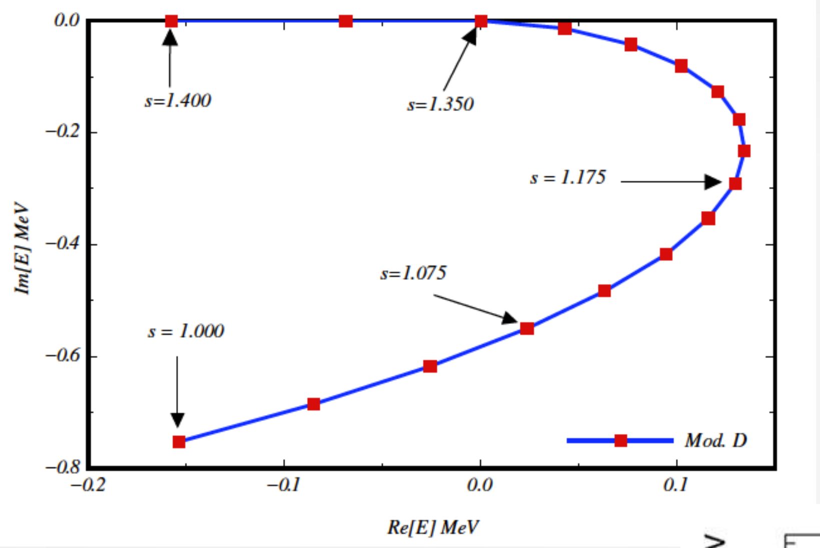
(a triple coincidence measurement with the in-flight (K−, π−) reaction, gamma-ray, and weak decay)

- **Is there a Λnn resonant state? (and a Σ^0nn one?)** (HypHI Collaboration, 2013)

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

Gibson, Afnan SciPost, 2020

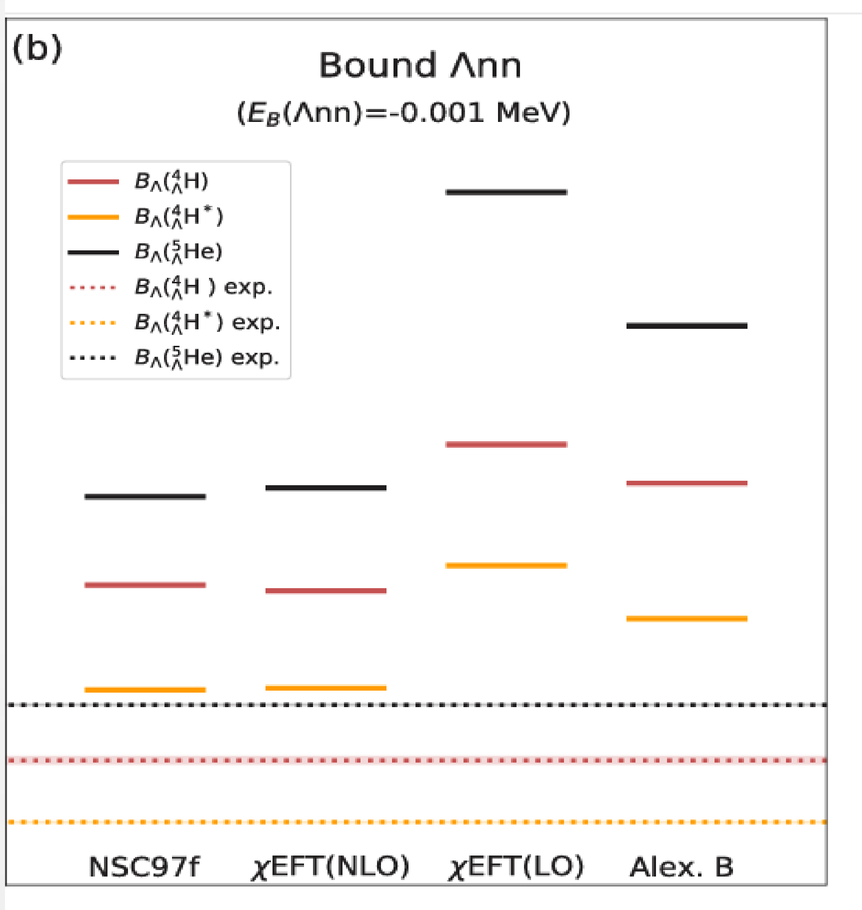
Nijmegen D



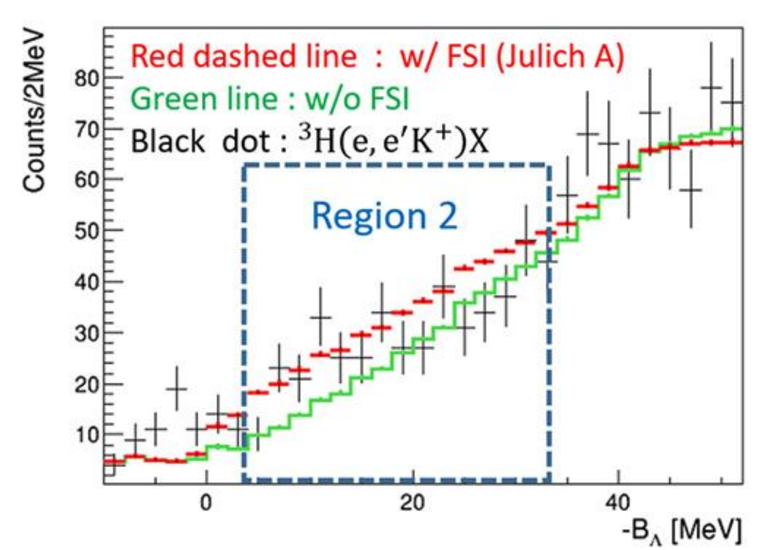
Schäfer, Bazak, Barnea, Mareš, PLB 2020, PRC2021

LO pionless EFT + 2- and 3-body contact terms

(strength of 3-body force varied)



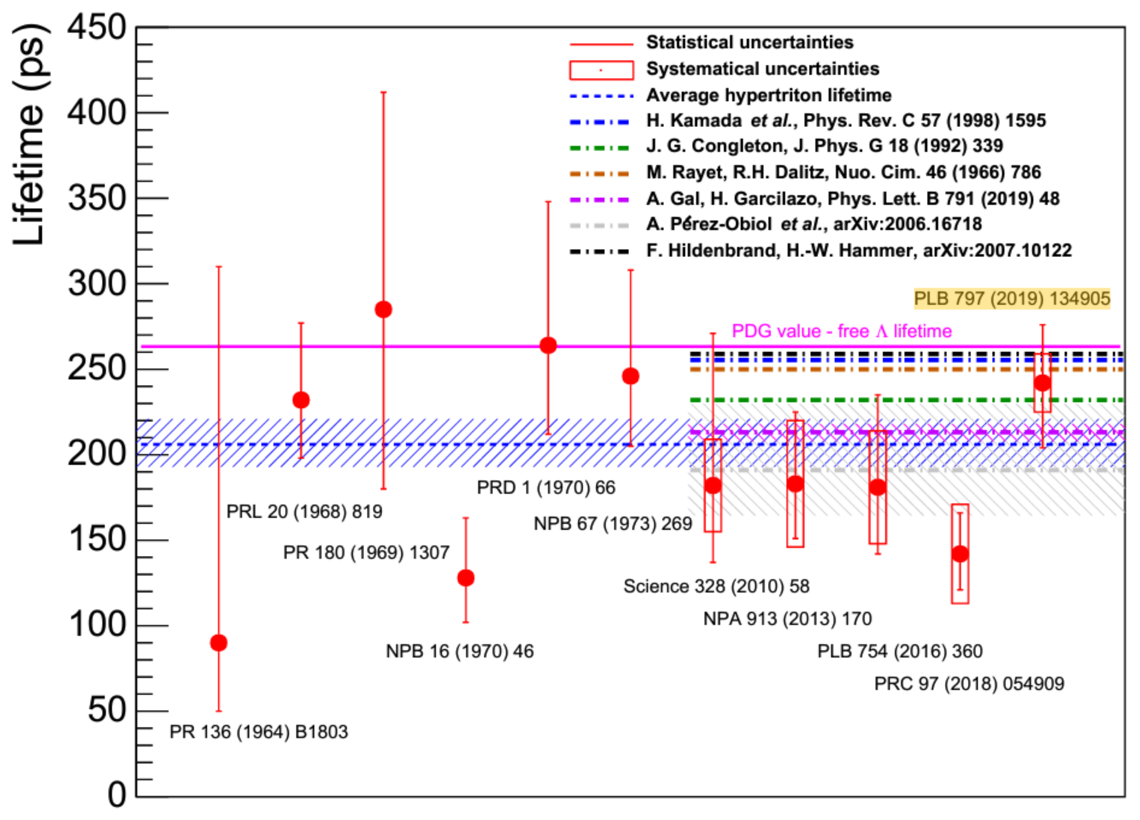
E12-17-003 in Hall A@J-lab:
(enhancements seen)
➔ a possible Λnn resonance
and a pair of ΣNN states ?



Suzuki et al (E12-17-003), PTEP (2022)

- **Lifetime of the hypertriton (short 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 π^- - ^{3}He FSI

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

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

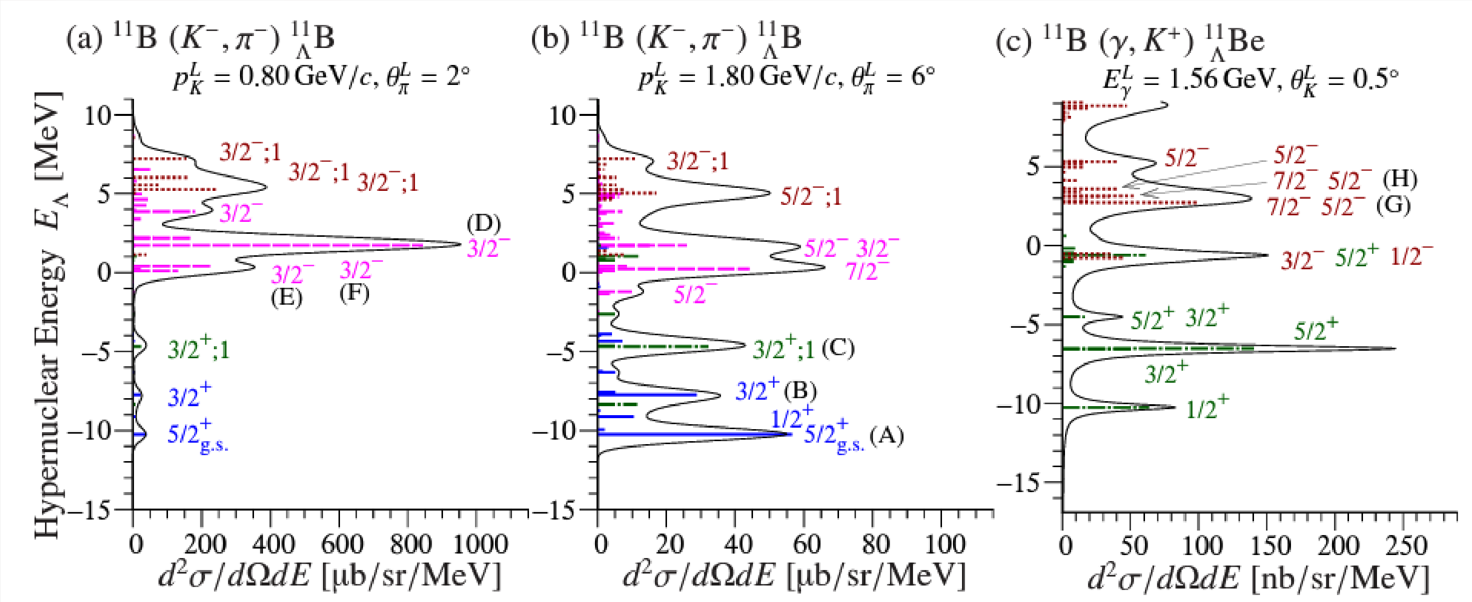
Lifetime and decay branching ratios in pionless EFT

Hildenbrand, Hammer, PRC (2020)

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

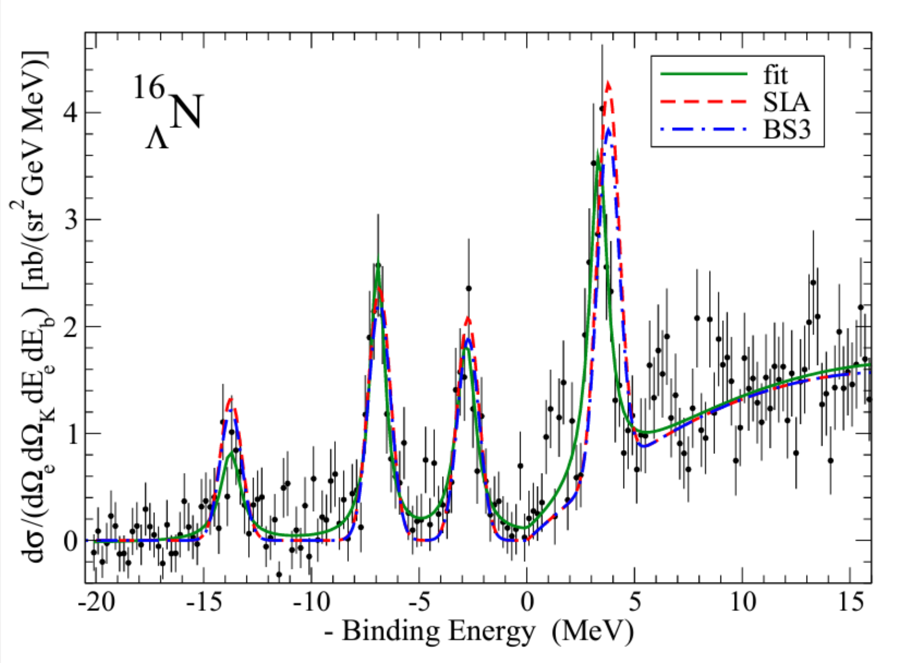
HYPERNUCLEAR SPECTROSCOPY

DWIA x-sections of (K⁻, π⁻), (π⁺,K⁺), and (γ,K+) reactions
(within the extended model space) **Umeya, Motoba, Itonaga,**



(e,eK⁺) reactions

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



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

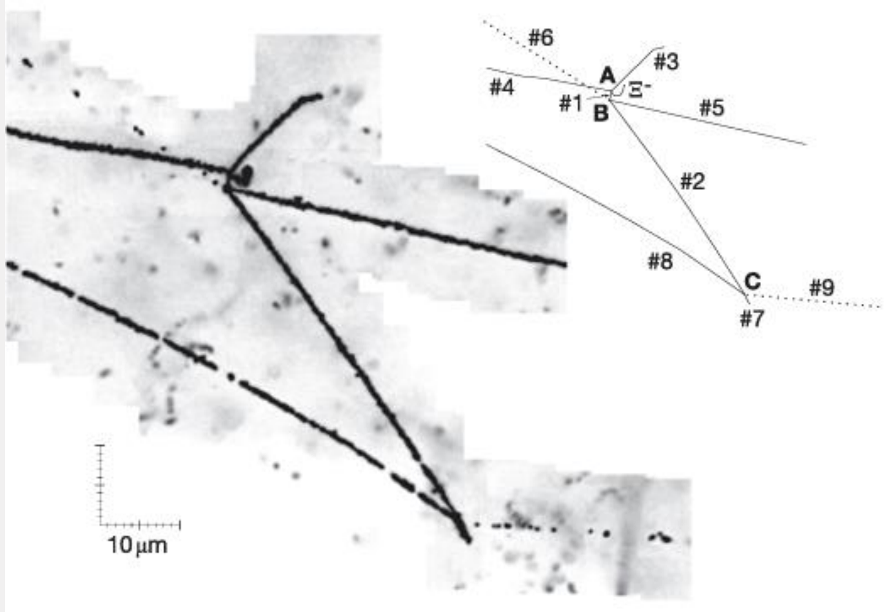
Beam line **HIHR at JPARC**:
supra-precision (π,K⁺) Λ-hypernuclei spectroscopy

S=-2

ΛΛ – hypernuclei / Ξ hypernuclei / Ξ^- - atoms

Observation of a new ΛΛ hypernucleus (MINO event)

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



$$^{16}\mathrm{O} + \Xi^- \rightarrow {}^{10}_{\Lambda\Lambda}\mathrm{Be} + {}^4\mathrm{He} + t,$$

$$^{16}\mathrm{O} + \Xi^- \rightarrow {}^{11}_{\Lambda\Lambda}\mathrm{Be} + {}^4\mathrm{He} + d,$$ ← most probable

$$^{16}\mathrm{O} + \Xi^- \rightarrow {}^{12}_{\Lambda\Lambda}\mathrm{Be}^* + {}^4\mathrm{He} + p.$$

↓

$B_{\Lambda\Lambda} = 19.07 \pm 0.11\,\mathrm{MeV}$

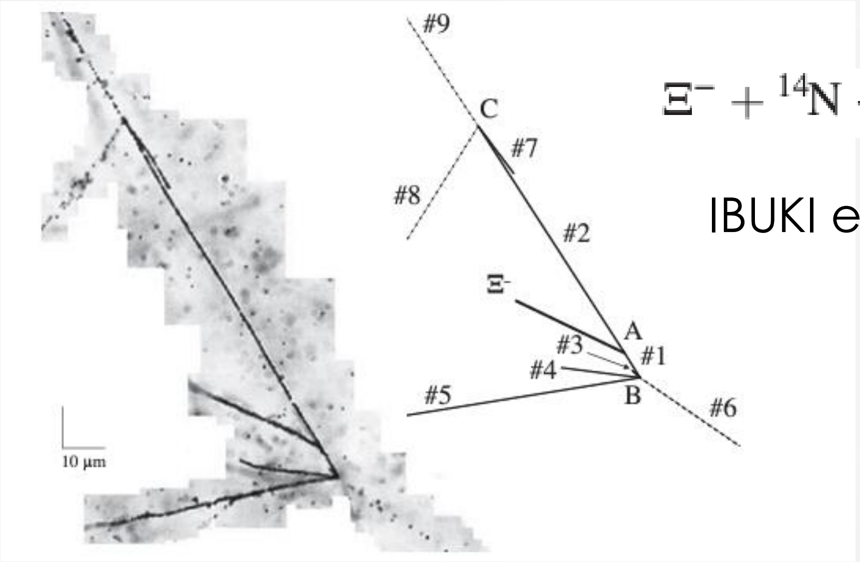
$\Delta B_{\Lambda\Lambda} = 1.87 \pm 0.37\,\mathrm{MeV}$

Ξ^-–Nuclear Bound States

KEK E373 and **J-PARC E07** experiments

Coulomb-Assisted Ξ^-–^{14}N $1p_{\Xi}$- nuclear bound state

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



$\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{10}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He}$

IBUKI event

Yoshimoto, PTEP (2021)

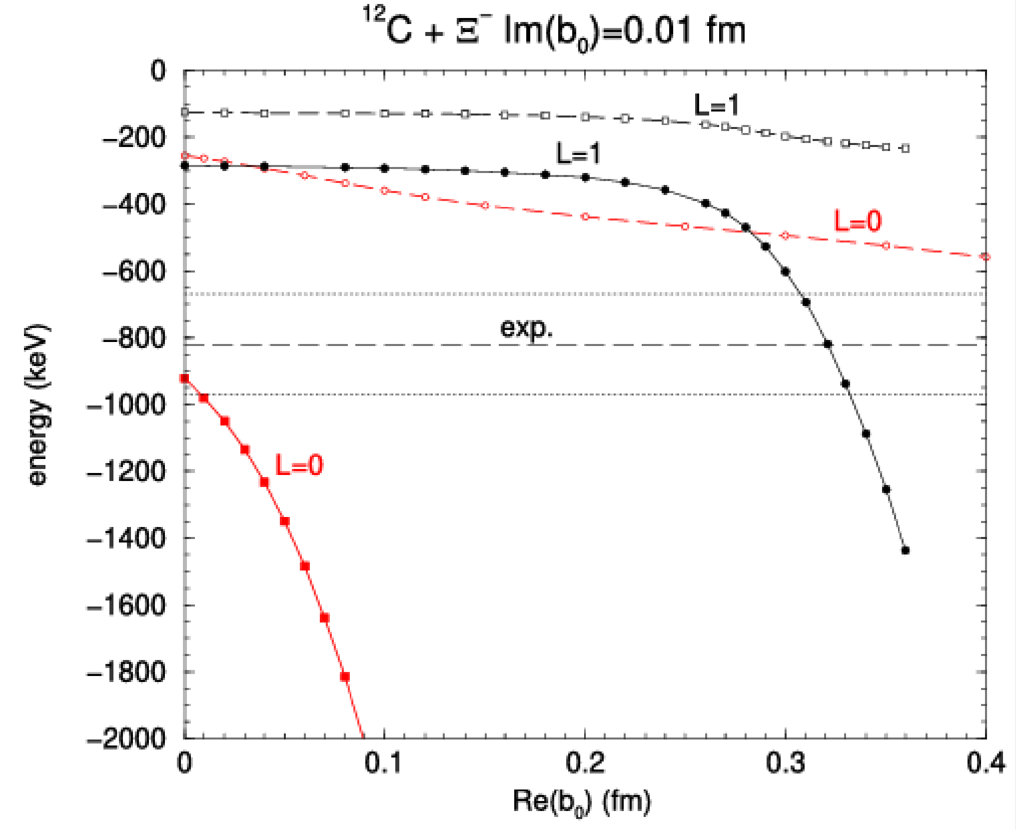
KINKA (E373) $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{9}_{\Lambda}\mathrm{Be} + {}^{5}_{\Lambda}\mathrm{He} + n$

IRRAVADDY (E07) $\Xi^- + {}^{14}\mathrm{N} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + {}^{5}_{\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + n$

→ $1s_{\Xi}$- nuclear state

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

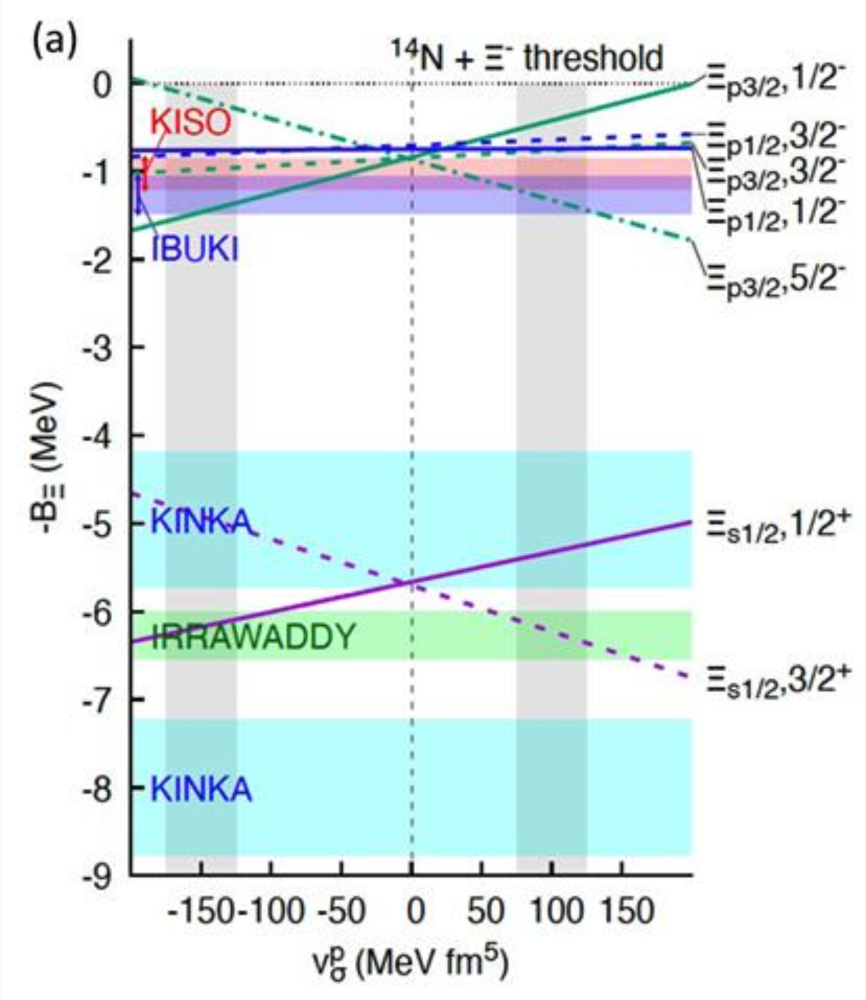
Friedman ,Gal, Phys.Lett.B (2021)



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

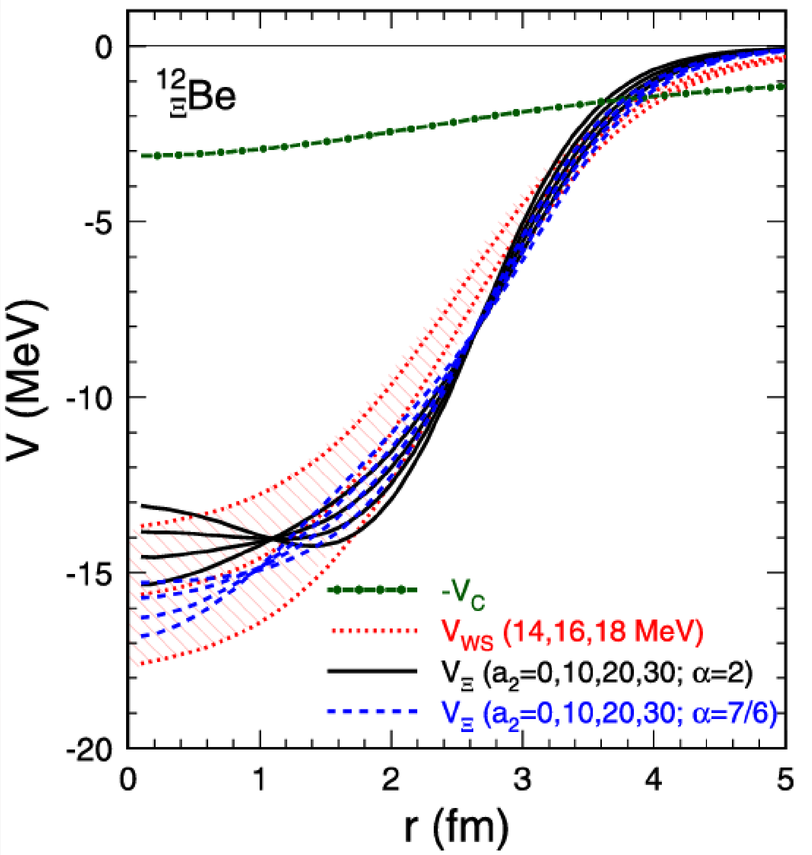
Energy spectra of Ξ⁻ hypernuclei within a RMF model (constrained to the new observations)

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)

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)	···	···

→ the NNNΞ system (T =0, J^{π} = 1^{+}) appears to be bound

Chiral NN and ΞN interactions

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

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

Planned:

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

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

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

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

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

K̄N 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

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

Piscicchia (AMADEUS@DAFNE) (2019)

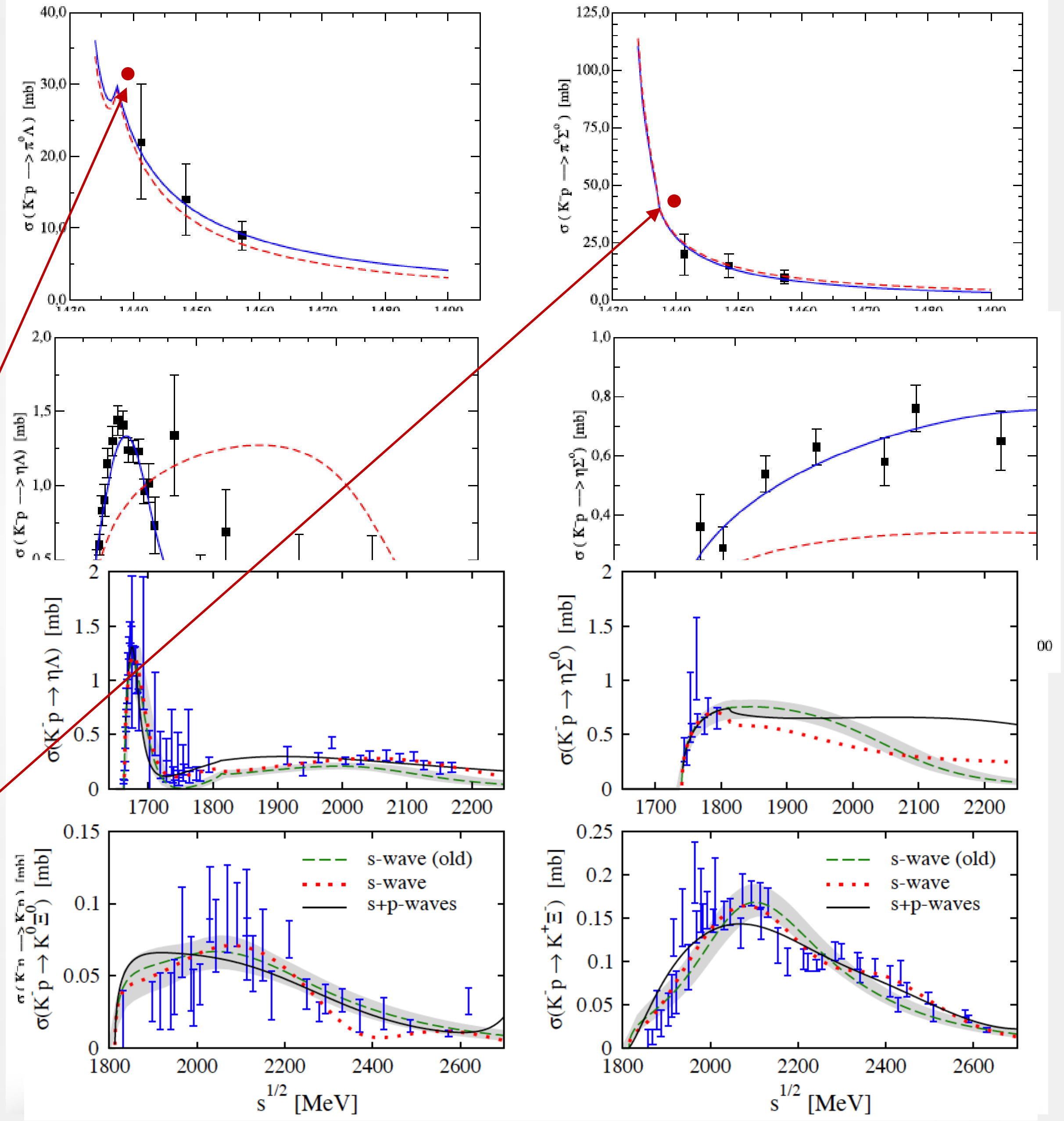
$$|A_{K^-n\rightarrow\Lambda\pi^-}| = (0.334 \pm 0.018\,\mathrm{stat}^{+0.034}_{-0.058}\,\mathrm{syst})\ \mathrm{fm}.$$

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

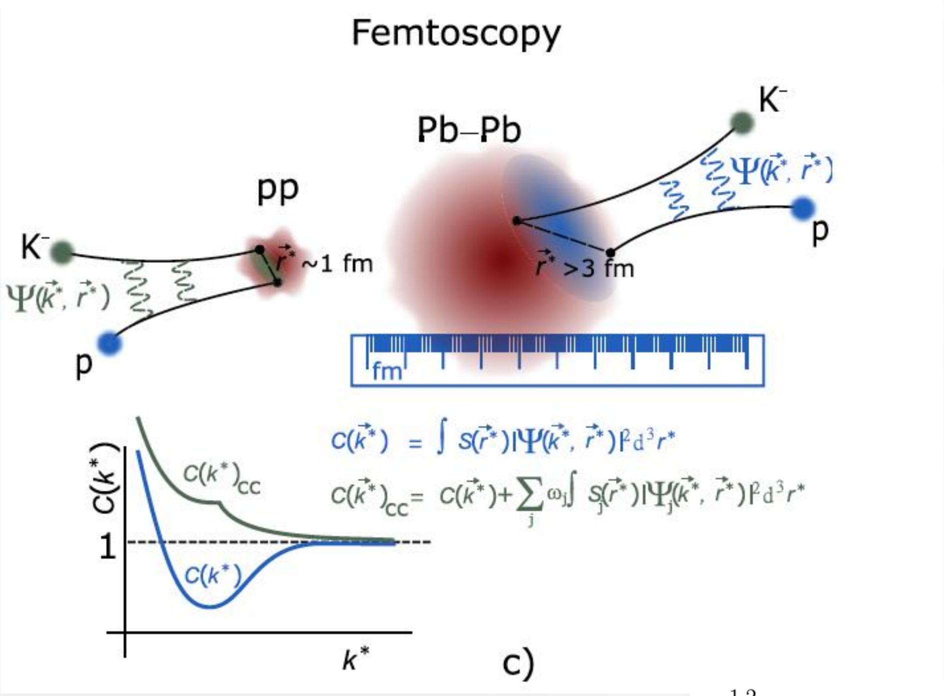
Piscicchia (AMADEUS@DAFNE) (2022)

$$\sigma_{K^-p\rightarrow\Lambda\pi^0} = 31.0\pm0.5(stat.)^{+1.2}_{-1.2}(syst.)\ \mathrm{mb}$$

$$\sigma_{K^-p\rightarrow\Sigma^0\pi^0} = 42.8\pm1.5(stat.)^{+2.4}_{-2.0}(syst.)\ \mathrm{mb}$$



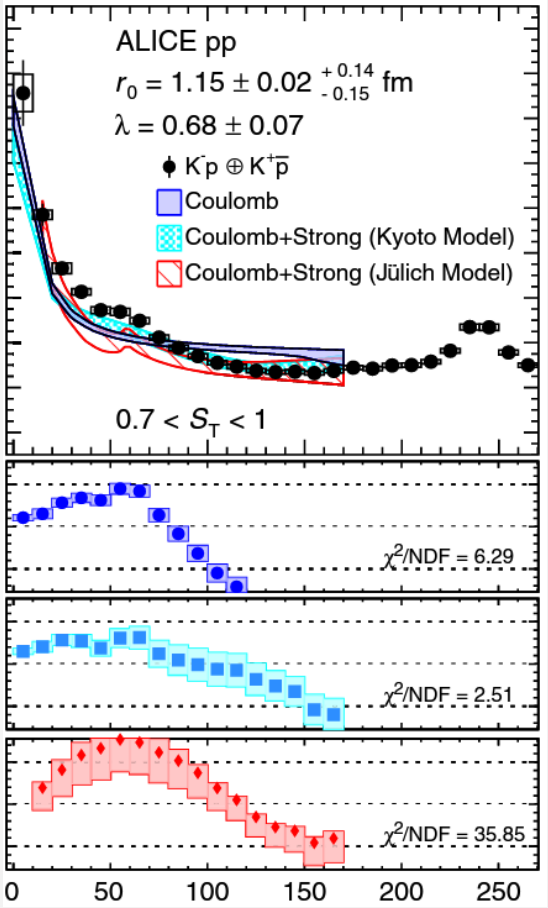
(adapted from Phys. Lett. B822 (2021) 136708)



Femtoscpoy ALICE@LHC

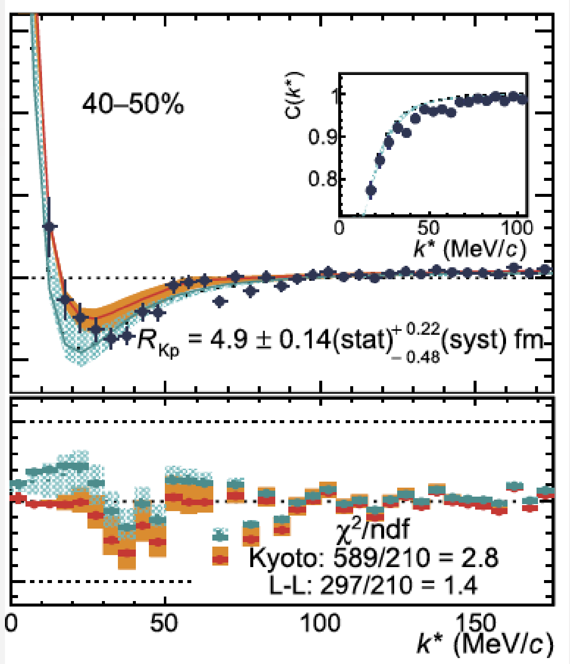
pp collisions

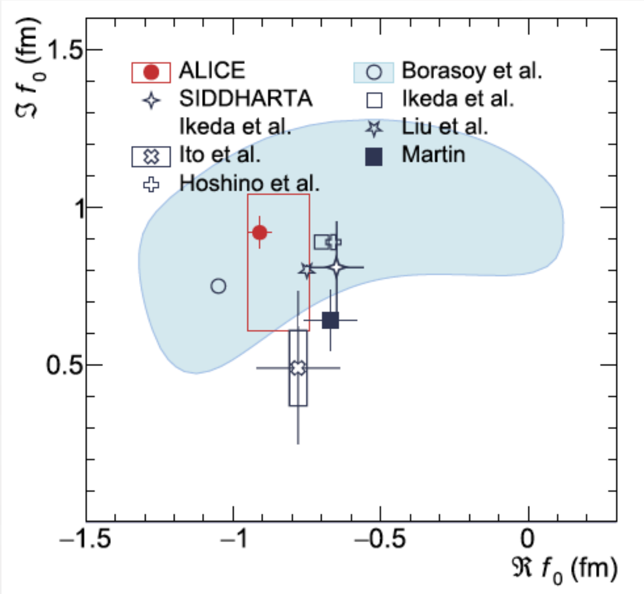
Acharya (ALICE), PRL (2020)



Pb Pb collisions

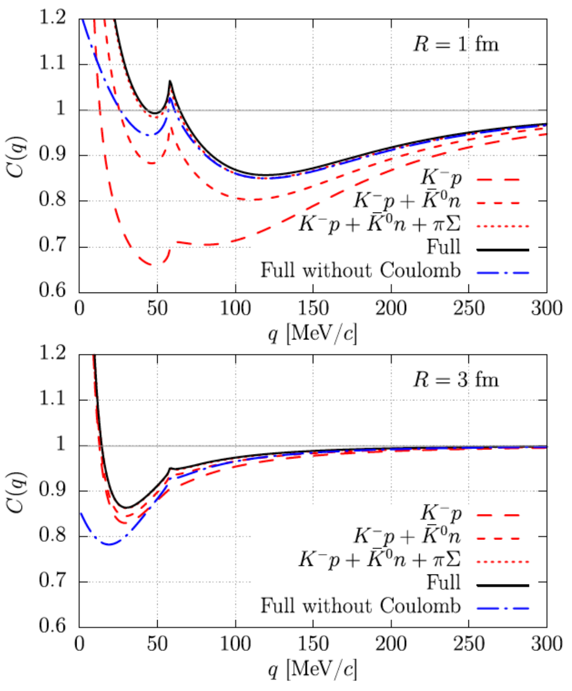
Acharya (ALICE), PLB 2021



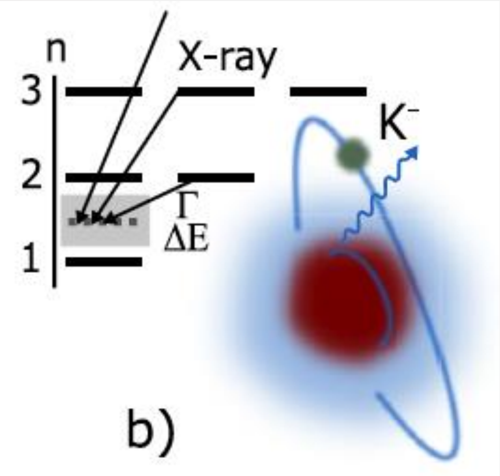


Importance of coupled channels (K^-p – K^0n) and dependence on source size R

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

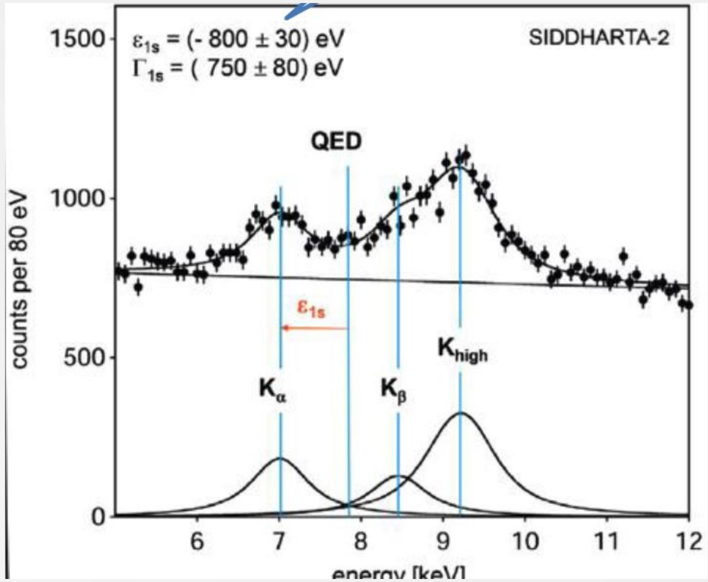


Light kaonic atoms



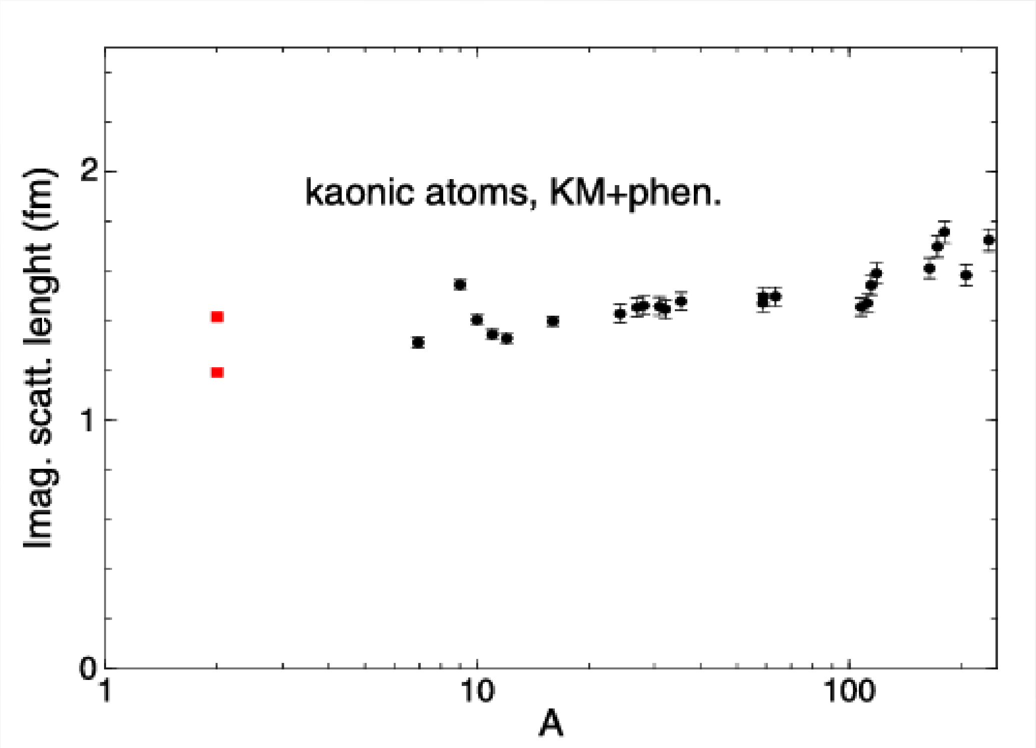
The **K^-n** interaction will be pinned down from the measurement of the energy shift and width of the **kaonic deuterium** ground state (data being taken now at **SIDDHARTA2@DAFNE**)

(and planned at J-PARC)



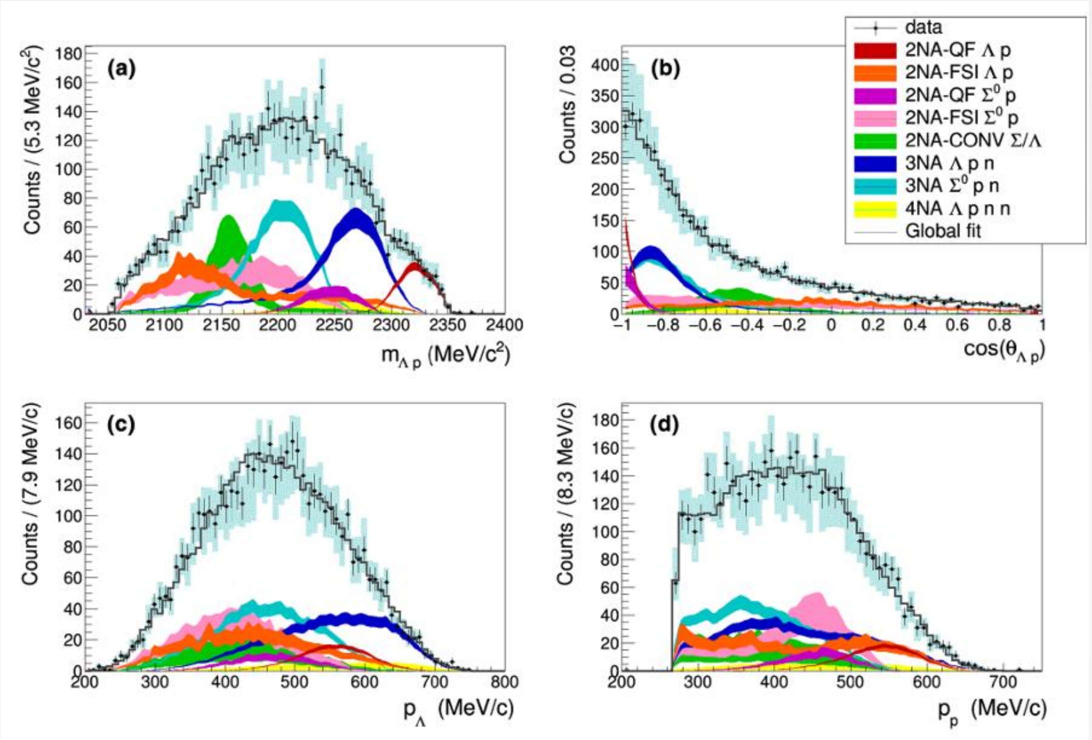
Connecting heavy kaonic atom fits with kaonic deuterium

Barnea, Friedman, Gal, NPA (2021)



K⁻ multi-nucleon absorption in ^{12}C

Del Grande (AMADEUS), EPJC (2019)



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

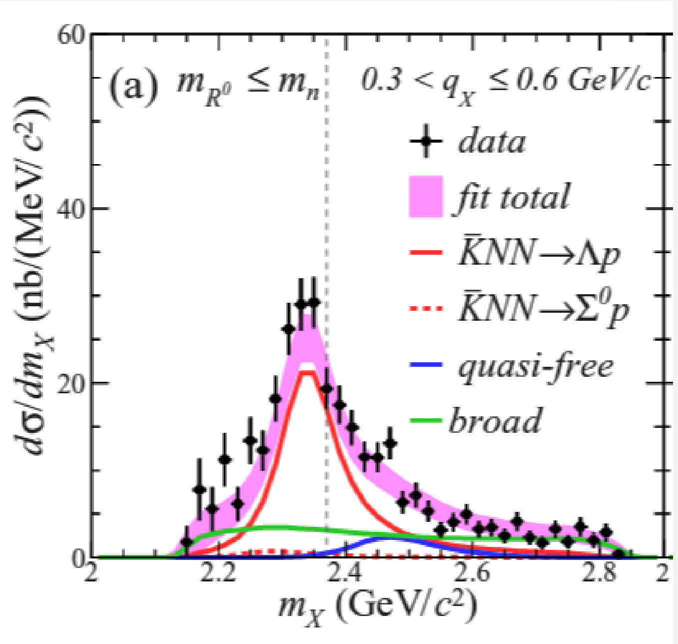
Hrtánkova, Ramos, PRC (2020)

K⁻pp bound state

$$K^{-3}\mathrm{He} \rightarrow \Lambda pn$$

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

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



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

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

$$^3\mathrm{He}(K^-, p)\Lambda n$$

$$^4\mathrm{He}(K^-, n)$$

Schevchenko, FBS (2021)

Kanada-En'yo, EPJA (2021)

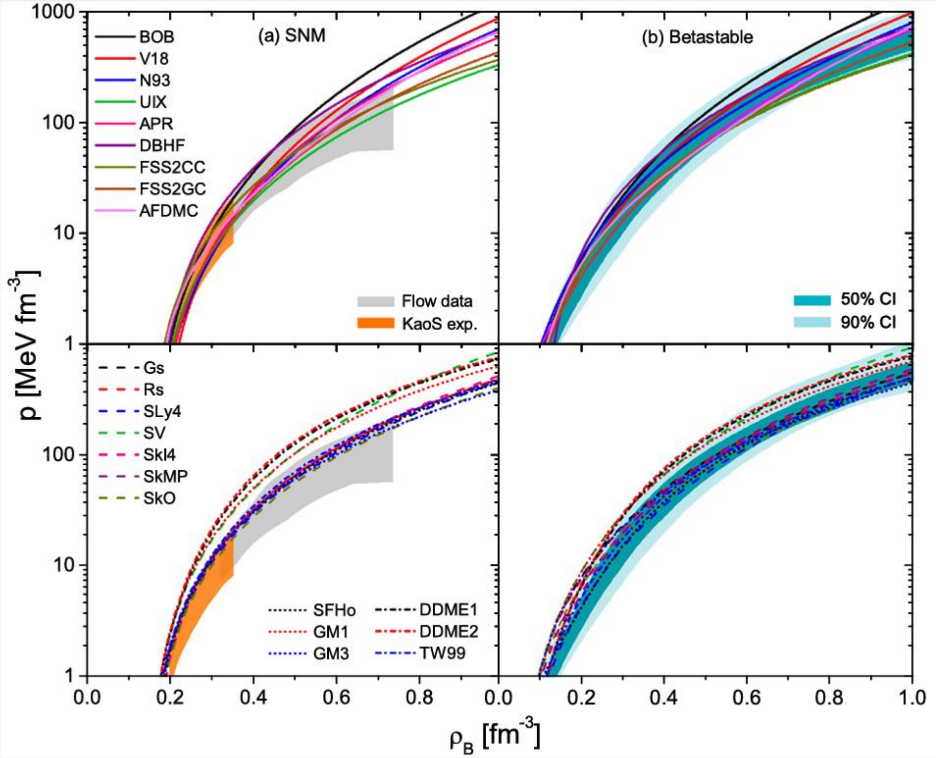
Strangeness in matter and in neutron stars

Laura Tolos, Laura Fabbietti
Prog.Part.Nucl.Phys. 112 (2020) 103770

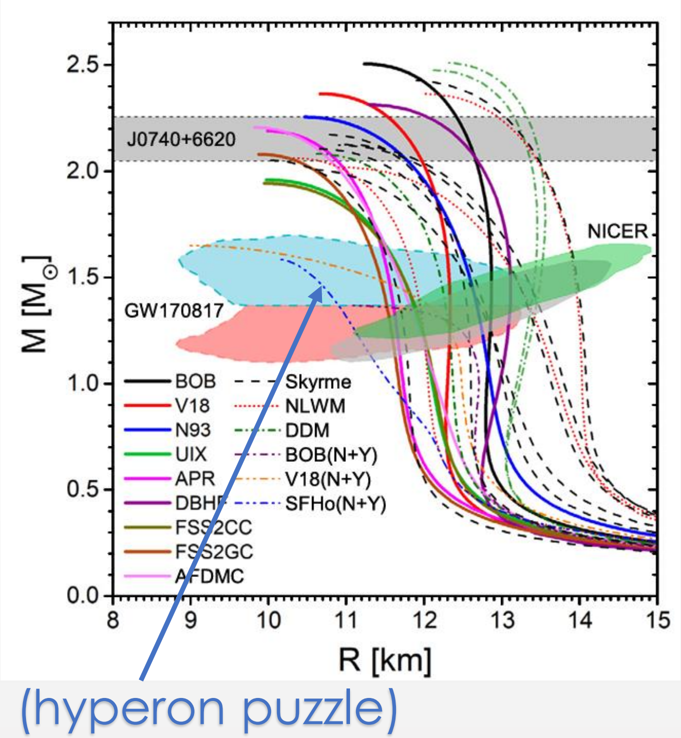
G.F. Burgio, H.-J. Schulze,I. Vidana, J.-B. Wei,
Prog.Part.Nucl.Phys. 120 (2021) 103879

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

EoS

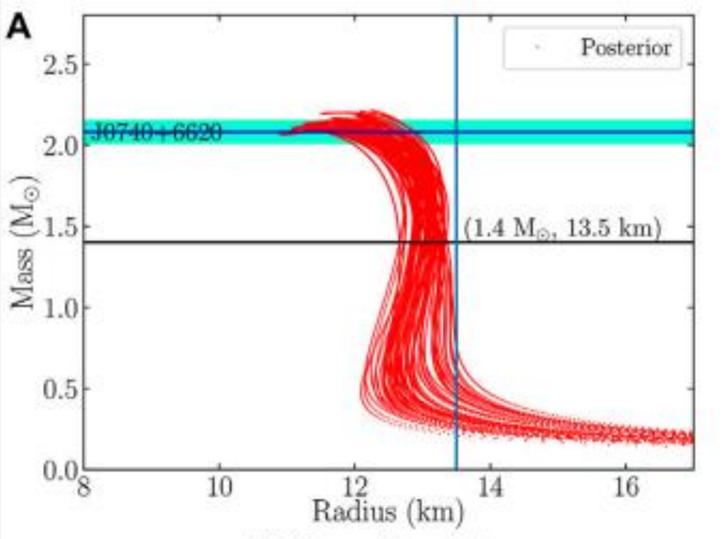


M-R relationship



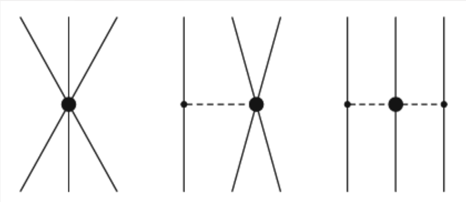
Multi-Physics Constraints in Hyperonic Neutron Stars (RMF)

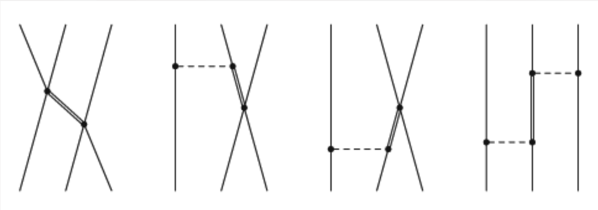
Ghosh, Pradhan, Chatterjee, Schaffner-Bielich Front.Astron.Space (2022)



(A) Mass-radius relation

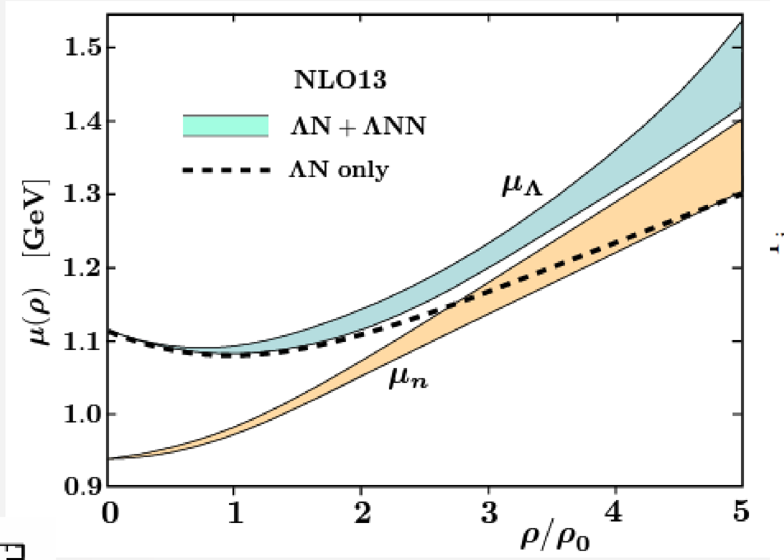
YNN force? Hyperon–nucleon three-body forces and strangeness in neutron stars





YNN prevents the appearance of hyperons

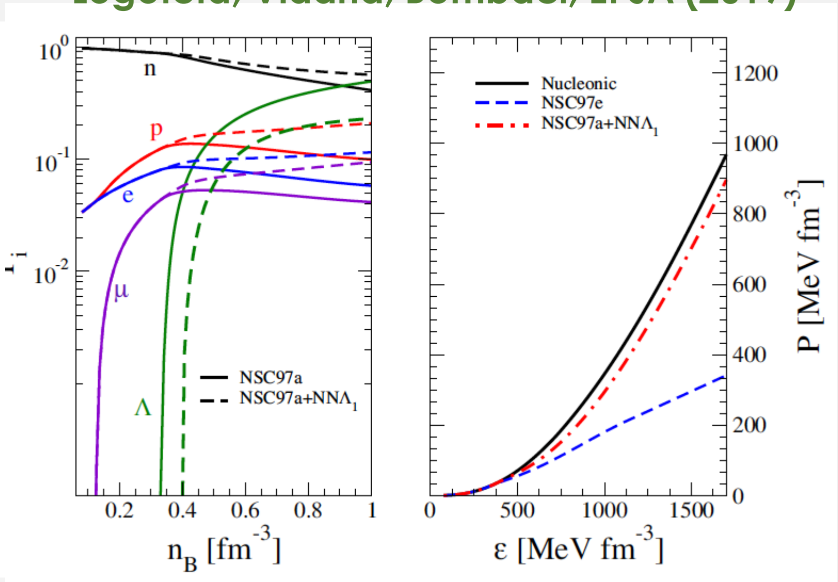
Gerstung, Kaiser, Weise EPJA (2020)

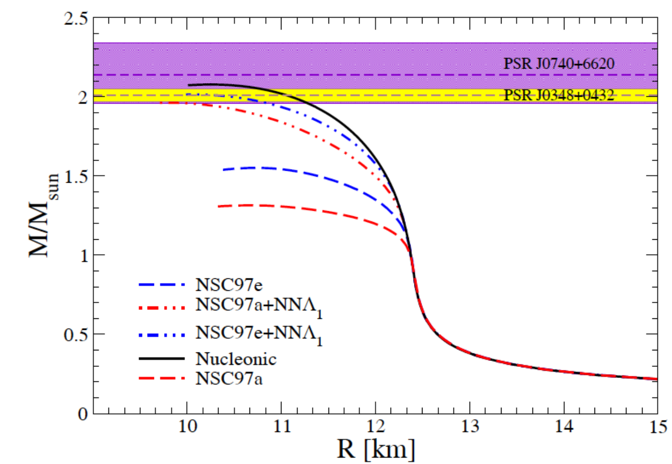


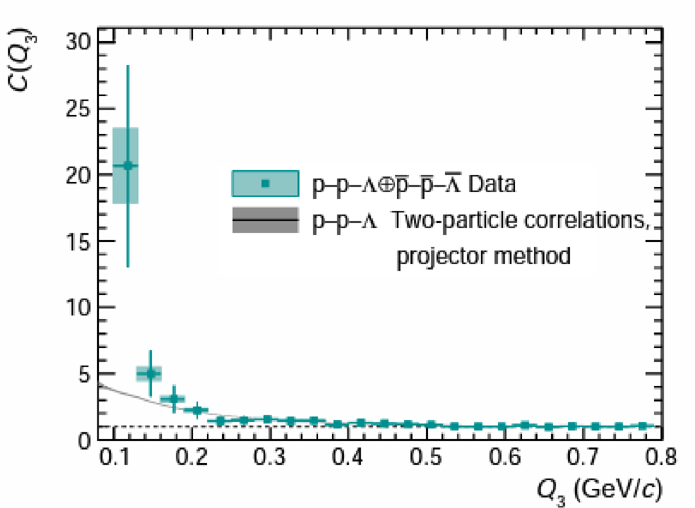
Hyperons appear in the core even with YNN

$2M_\odot$ maximum mass reproduced

Logoteta, Vidaña, Bombaci, EPJA (2019)







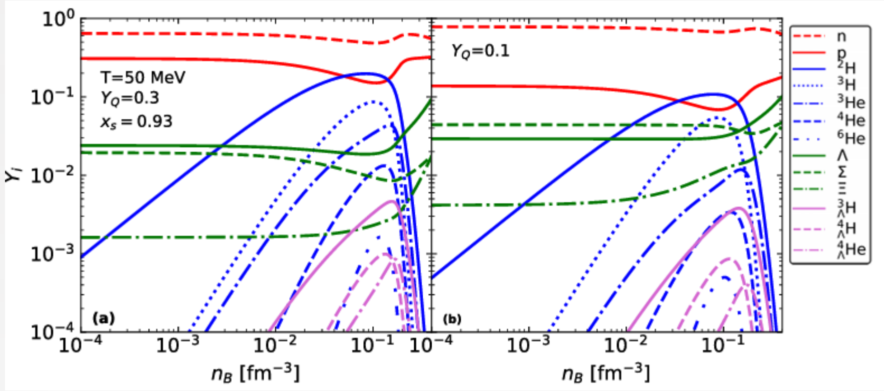
ppΛ correlations **(ALICE)**

arXiv:2206.03344v1

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

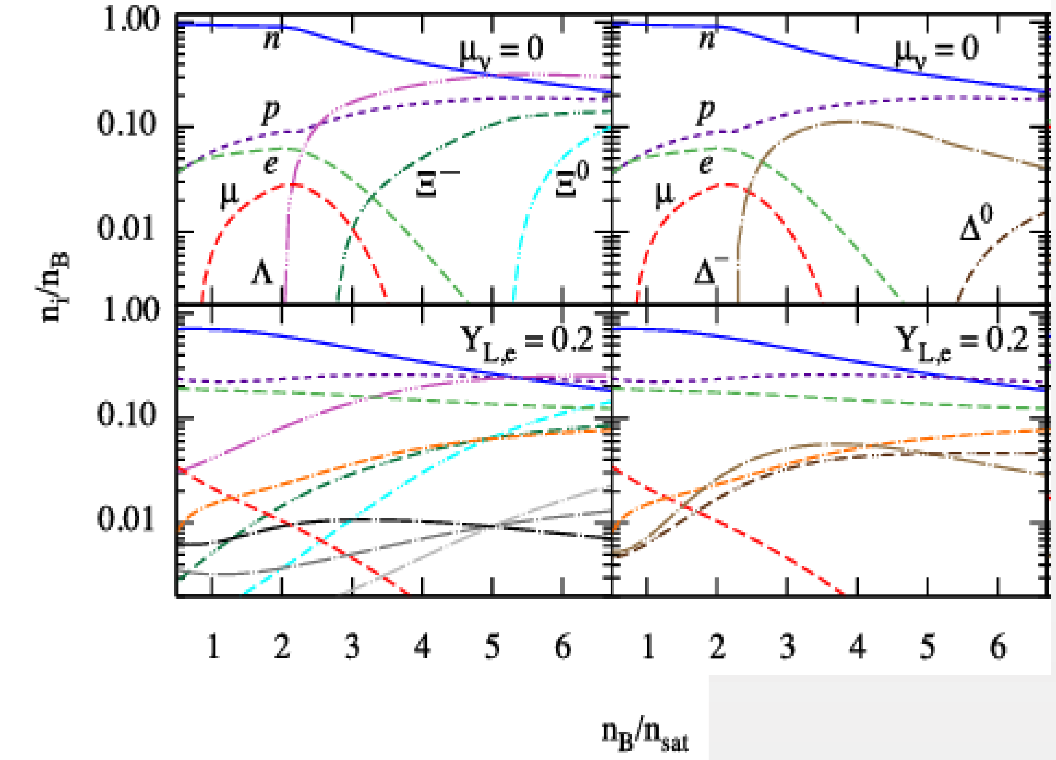
Light nuclei and hypernuclei are present in the **crust**

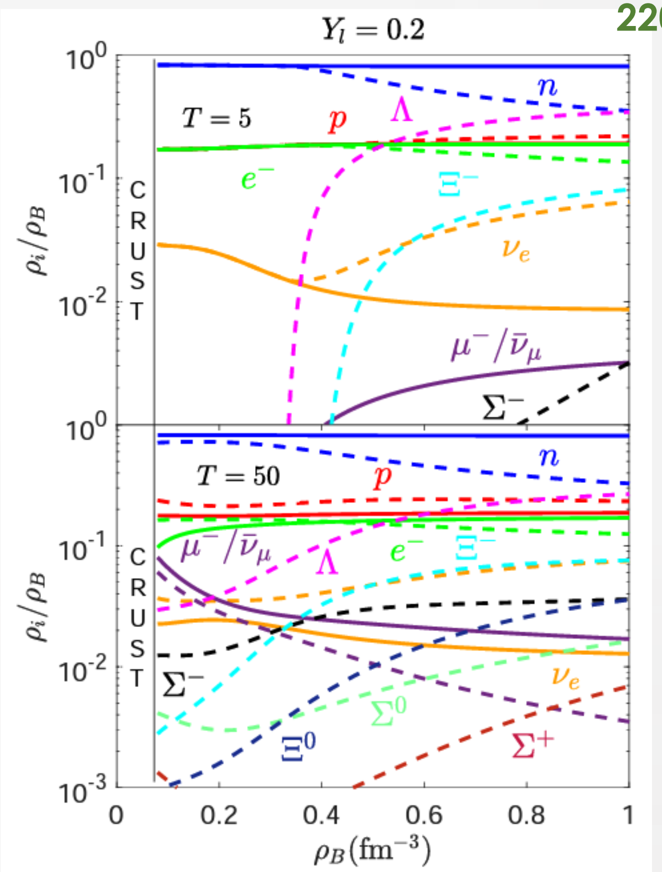
Custódio, Pais, Providência, PRC (2021)



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

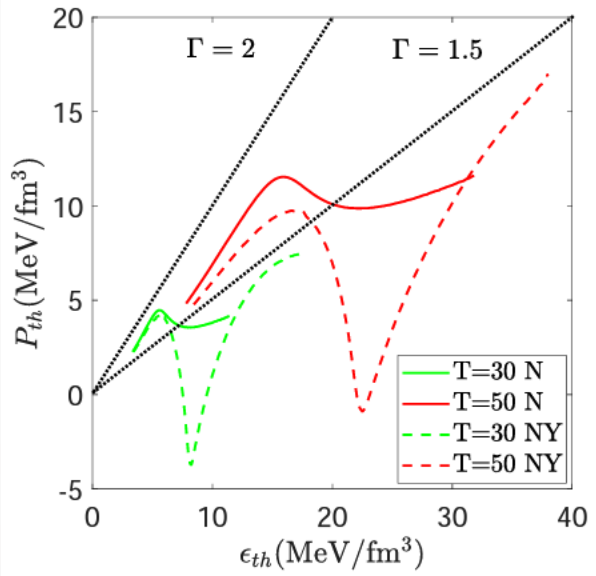
Sedrakian, Harutyunyan, 2202.12083 [nucl-th]





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

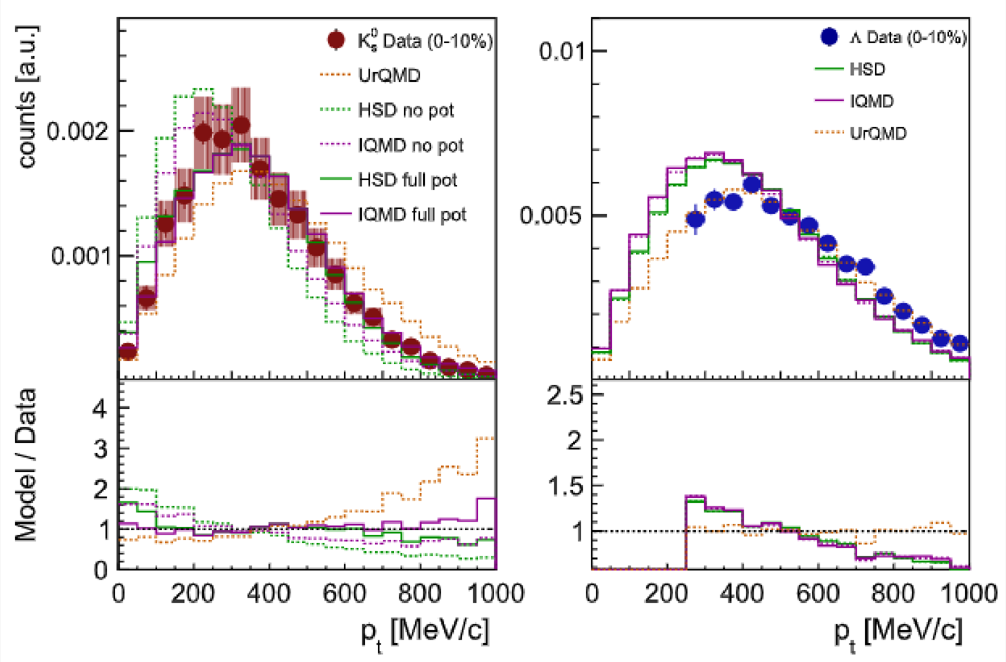
Hyperons affect strongly the P_{th}- ε_{th} relation



In-medium properties of **strange particles** from **heavy-ion collisio**n experiments

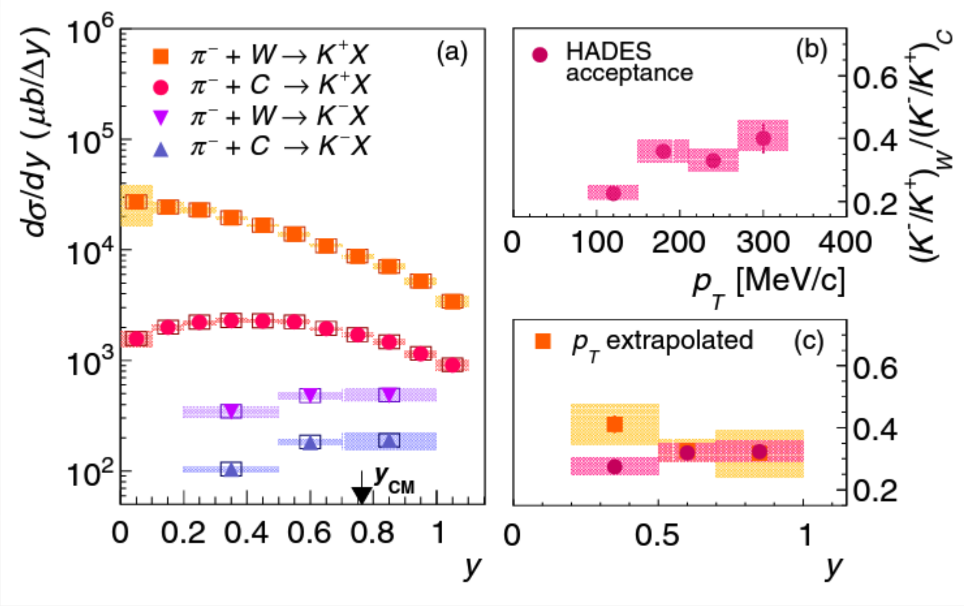
Sub-threshold production of $\mathbf{K^0_s}$ and $\mathbf{\Lambda}$ in Au+Au collisions at $\sqrt{s_{NN}}$ = 2.4 GeV with HADES

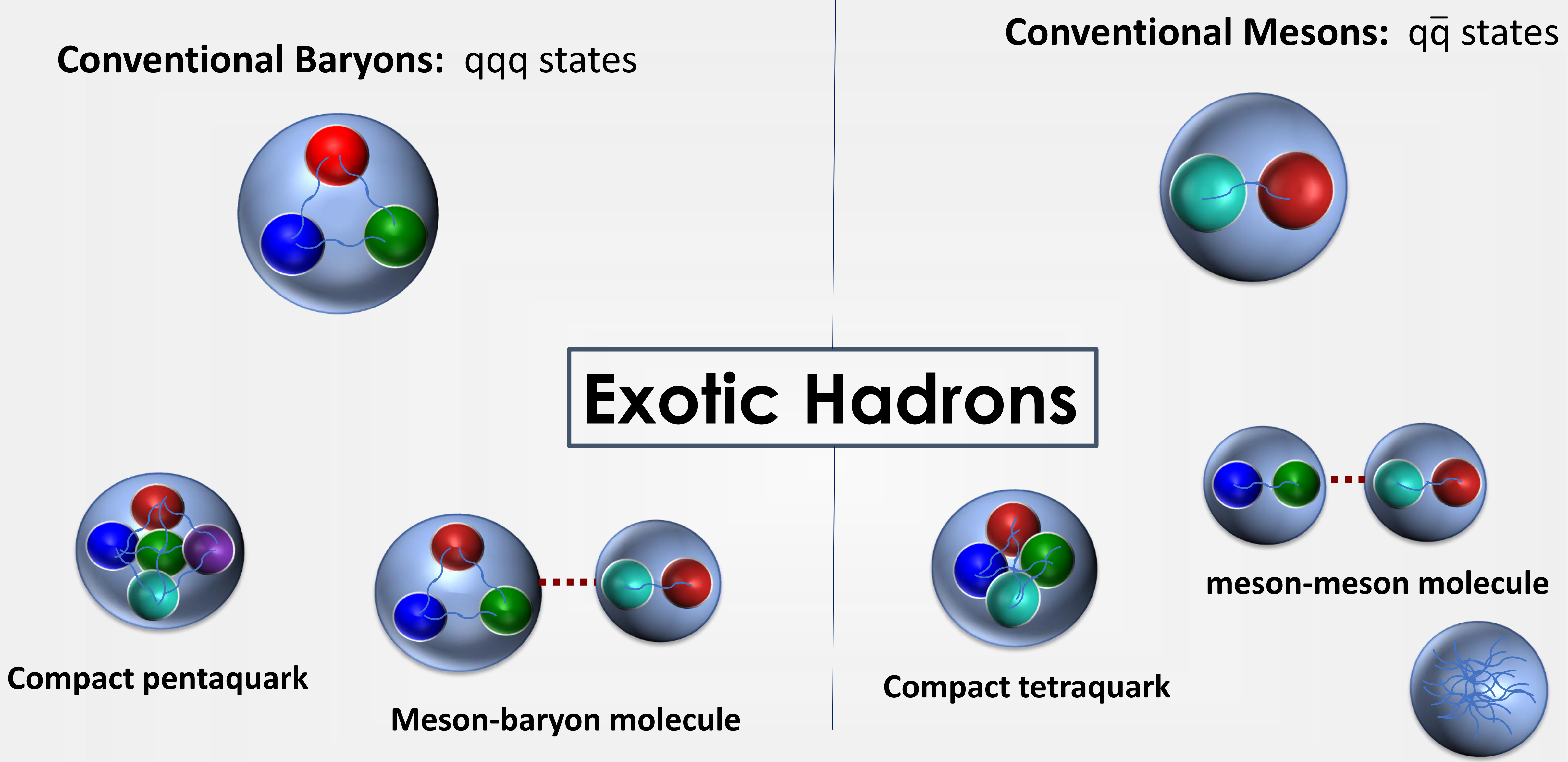
Leifels (HADES PLB (2019)



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)





F.K. Guo et al., Rev. Mod. Phys. 90 (2018) 015004

Hua-Xing Chen, Wei Chen, Xiang Liu, Yan-Rui Liu, Shi-Lin Zhu, e-Print: 2204.02649

Tetsuo Hyodo, Masayuki Niiyama, Prog.Part.Nucl.Phys. 120 (2021) 103868

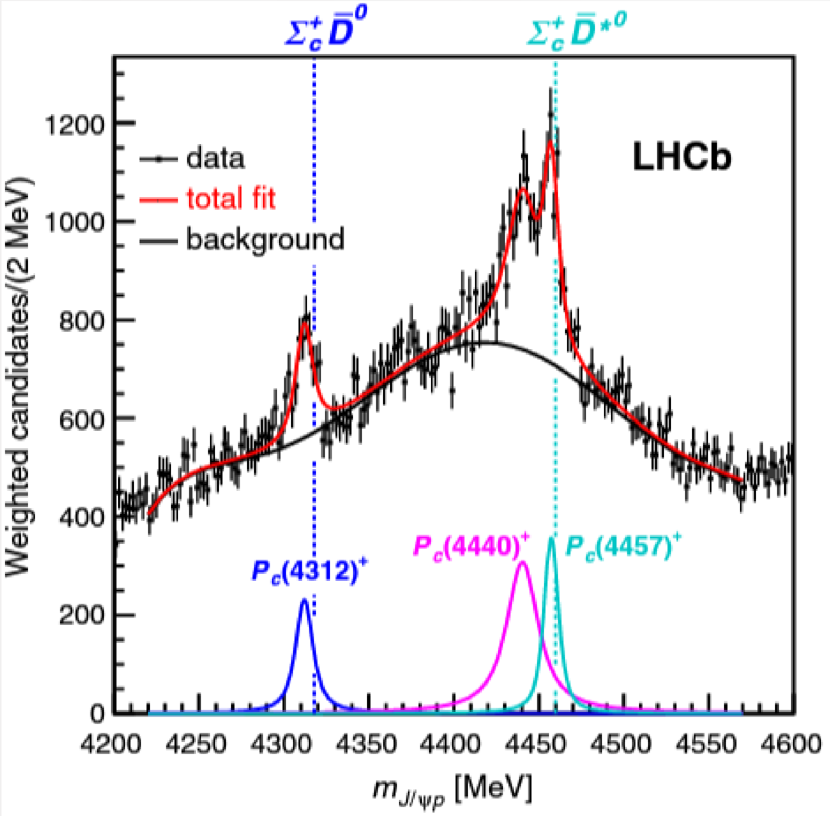
Nora Brambilla et al. Phys.Rept. 873 (2020) 1-154

Pentaquarks

S=0

LHCb, PRL (2015)

revisted: LHCb, PRL (2019)



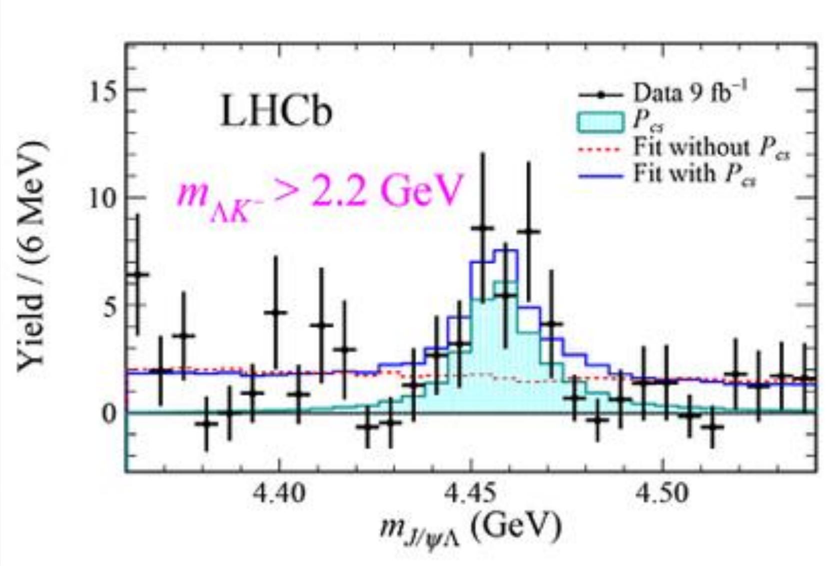
a narrow $P_c(4380)$?

Du, Baru, Guo,Hanhart, Meissner, PRL (2020)

S=-1

P_{cs} mass:~4459 MeV

LHCb, Science Bulletin (2021)



S=-3?

Ω_c^* D_s state with J^P=3/2-

Wang, Yang, Chen, Liu, PRD (2021)

S=-2?

OBE phenomenological

Wang, Chen, Liu, PRD (2021)

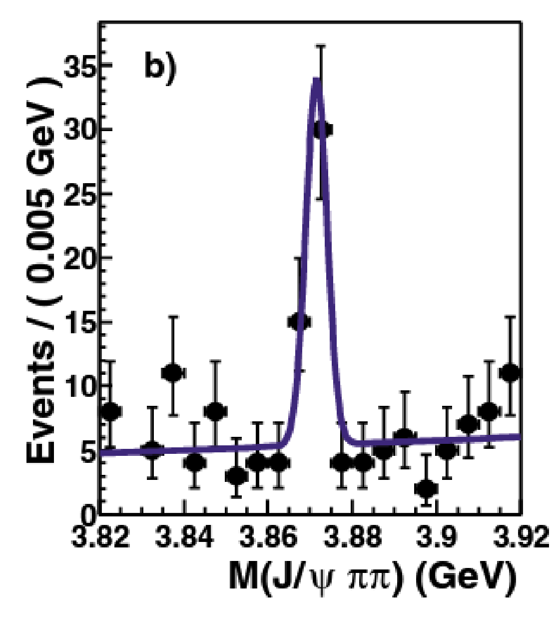
Aparently absent in unitary models based on t-channel vector-meson exchange...
(stay tuned)

Marse, Magas, Ramos (2022)

Exotics in the meson sector

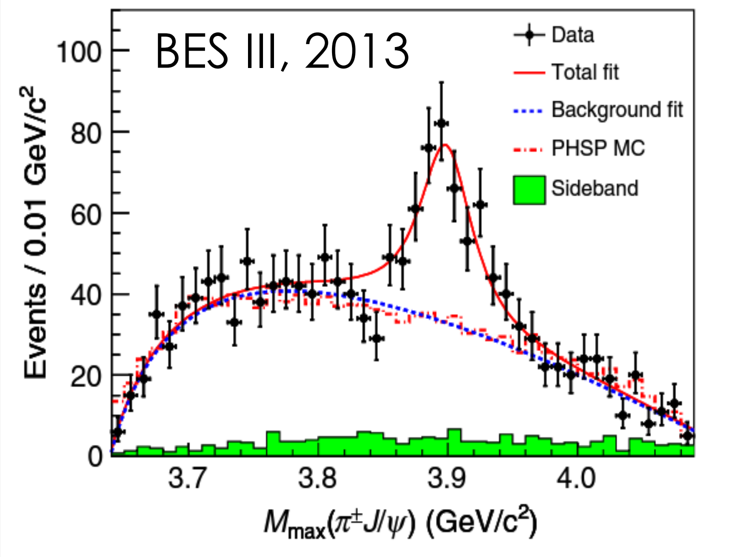
χc1(3872)

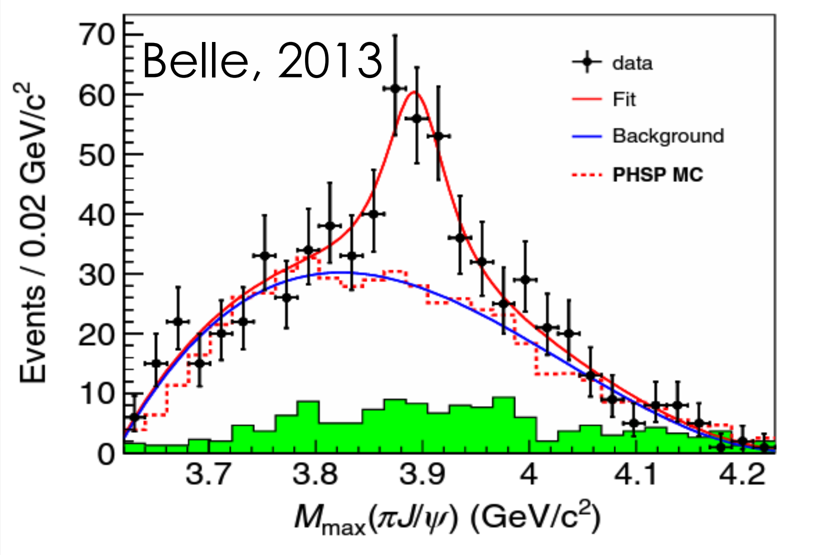
Formerly X(3872), Discovered in 2003 (Belle)



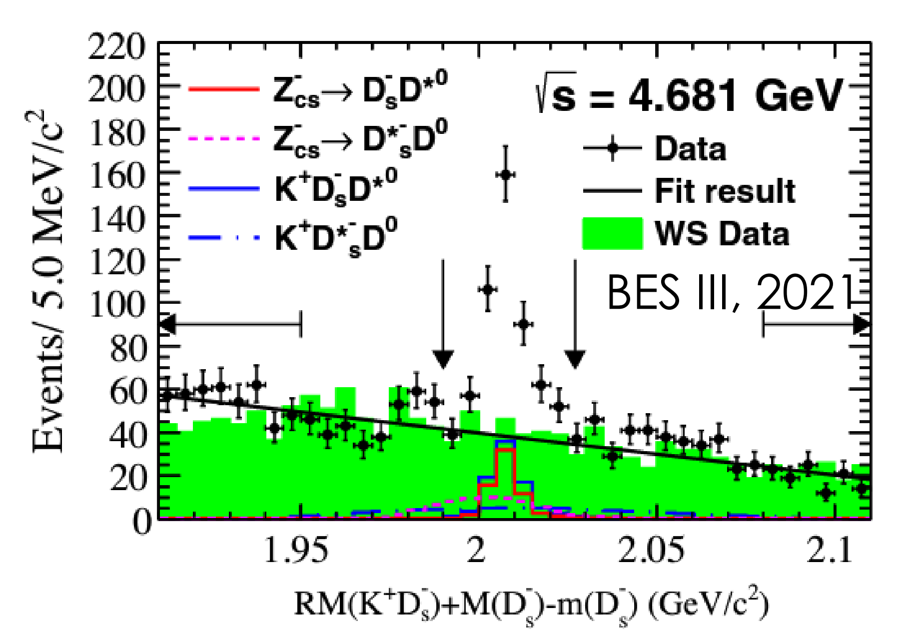
Extensively studied (Belle, BESIII, LHCb): lineshape, decay channels etc

charged $Z_c(3900)^{\pm}$





charged hidden-charm tetraquark with strangeness $Z_{cs}(3985)^{-}$



Molecular states

Cao, Guo, Nieves, Pavon-Valderrama, PRD (2021)

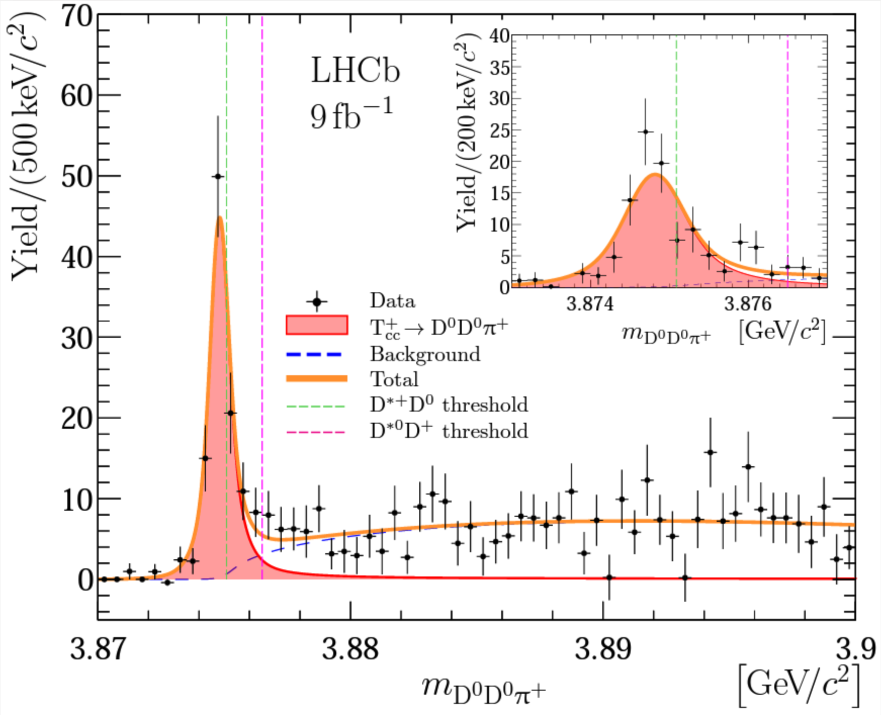
Z.H. Guo, Oller, PRD (2021)

Du, Albaladejo, Guo, PRD (2022)

Baru, Epelbaum, Filin, Hanhart, Nefediev, PRD (2022)

The T_{cc} state ($cc\bar{u}\bar{d}$)

LHCb, 2019

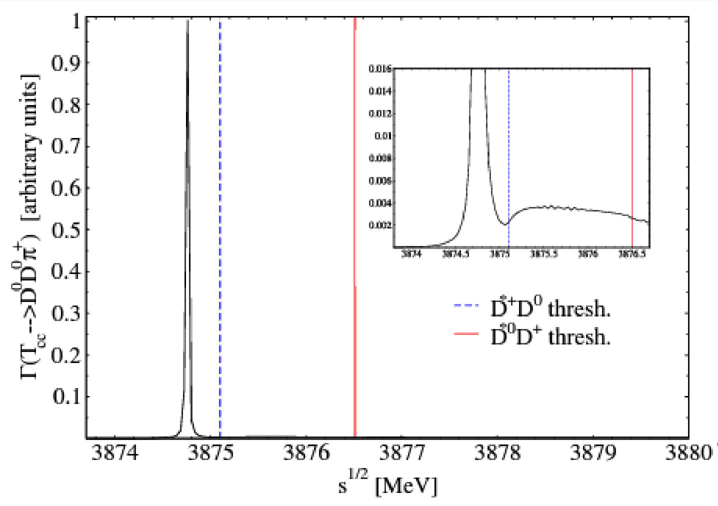


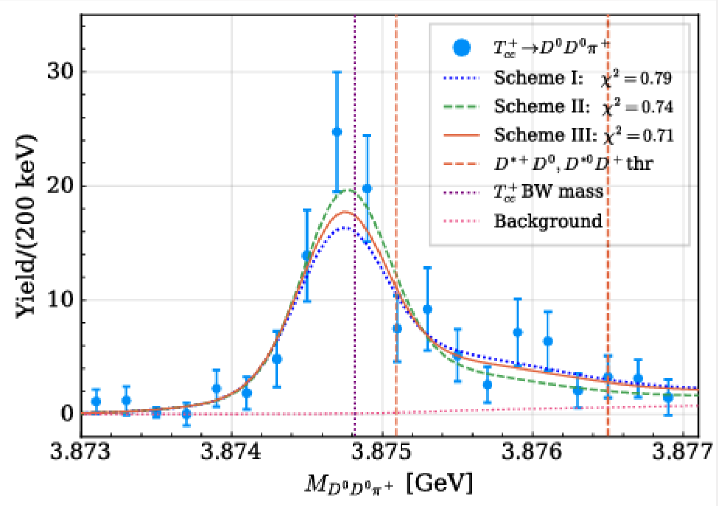
$$\delta m_{BW} = -273 \pm 61 \pm 5\,^{+11}_{-14}\ \mathrm{keV}/c^2\,,$$
$$\Gamma_{BW} = 410 \pm 165 \pm 43\,^{+18}_{-38}\ \mathrm{keV}\,,$$

$D^{*+}D^0$, $D^{*0}D^+$ (in a I=0 configuration)

Feijoo, Liang, Oset, PRD (2021)

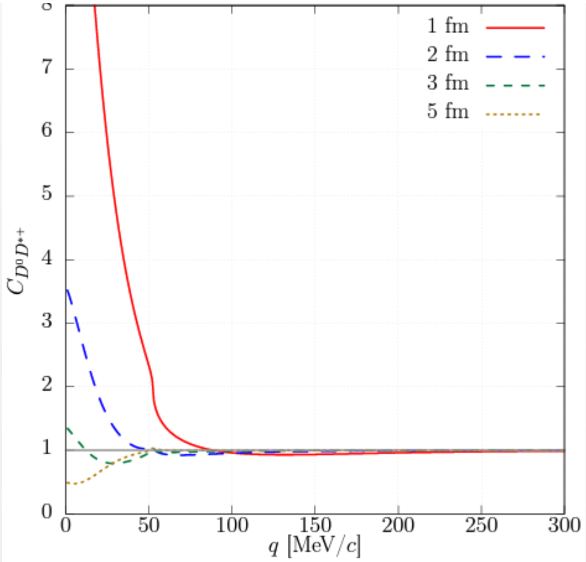
Du,Baru,Dong,Filin, Guo,Hanhart, Nefediev, Nieves, Wang, PRD (2022)





Femtoscopy study of the interaction

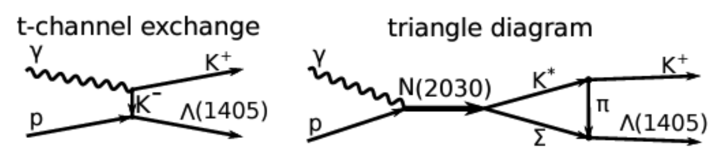
Kamiya, Hyodo, Ohnishi
e-Print: 2203.13814 [hep-ph]

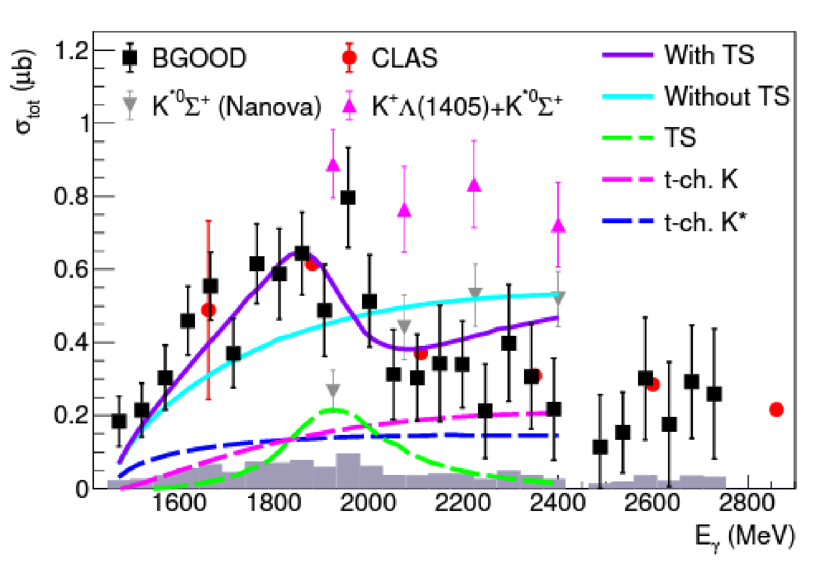


Let's not forget that the $\Lambda(1405)$ was in fact the first exotic baryon (a meson-baryon molecule)!

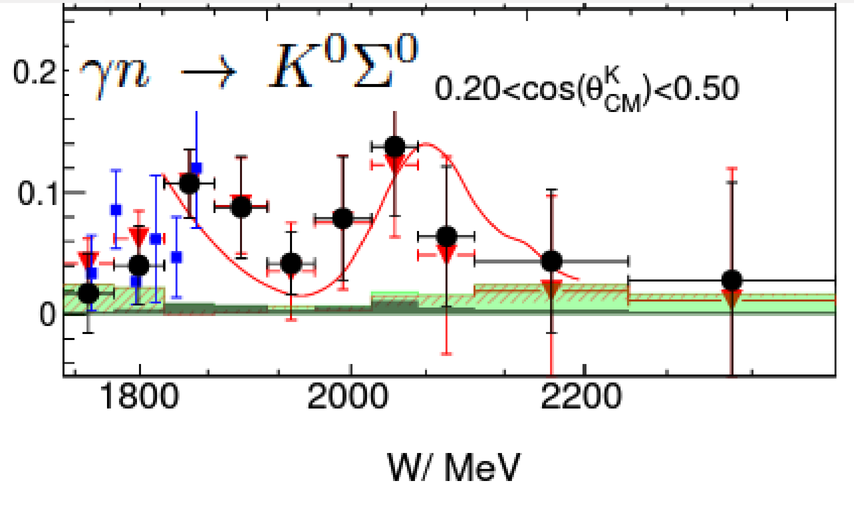
BGOOD@ELSA, arXiv:2108.12235

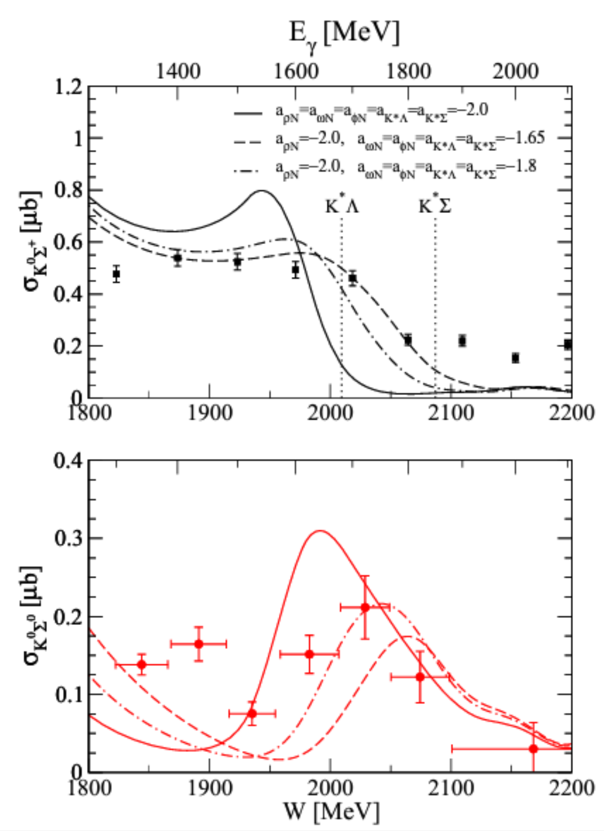
$$\gamma p \rightarrow K^{+}\Lambda(1405)(\rightarrow \pi^{0}\Sigma^{0})$$





BGOOD@ELSA, PLB2021



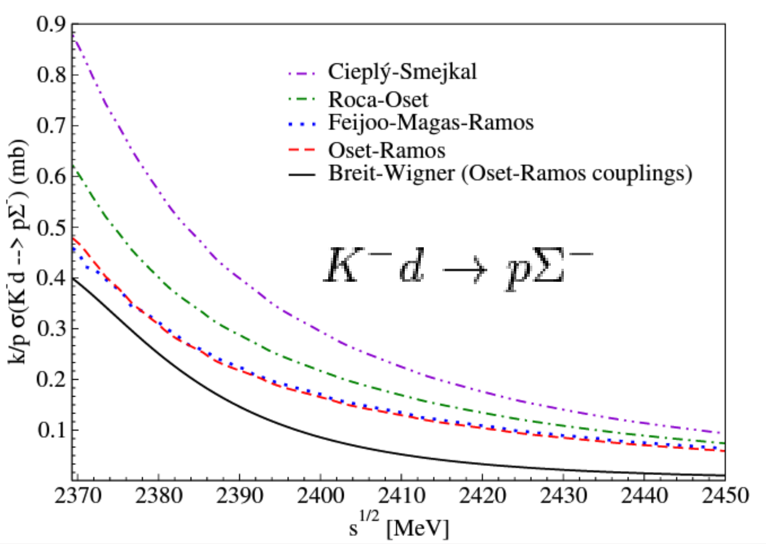


N*(2030) ($K^{*}\Sigma$ state),

Ramos et al. FBS 2020

Triangle singularity, involving the $\Lambda(1405)$

Feijoo,Molina,Oset, arXiv:2105.09654v1



GLUEX@Jlab

E_γ=8.2–8.8 GeV

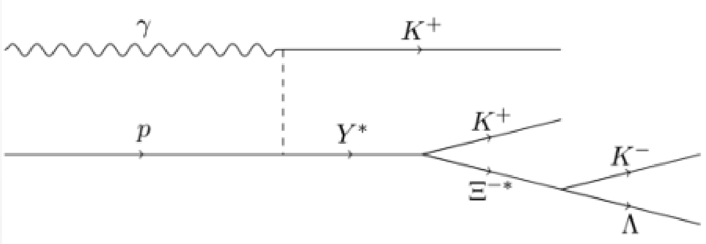
$\gamma p \rightarrow \Lambda(1520)K^+$ PRC 2022

$\vec{\gamma} p \rightarrow K^+\Sigma^0(1193)$ PRC 2020

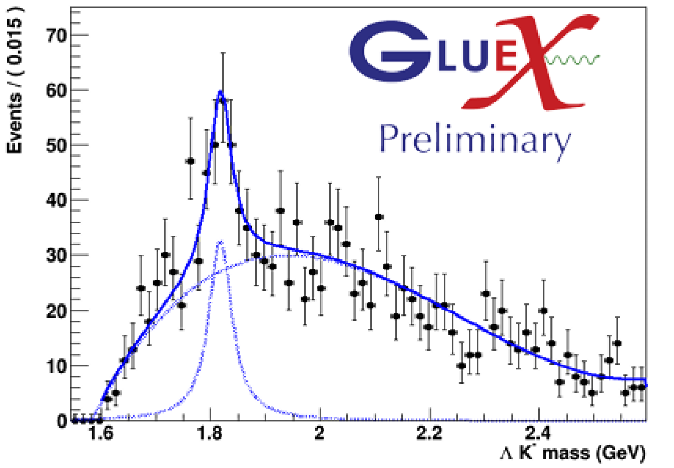
lineshape of the $\Lambda(1405)$
(in progress)

$\gamma p \rightarrow K^+\Lambda(1405)(\rightarrow \pi^0\Sigma^0)$

Photoproducion of $\Xi^{(*)}$



(a) Production model



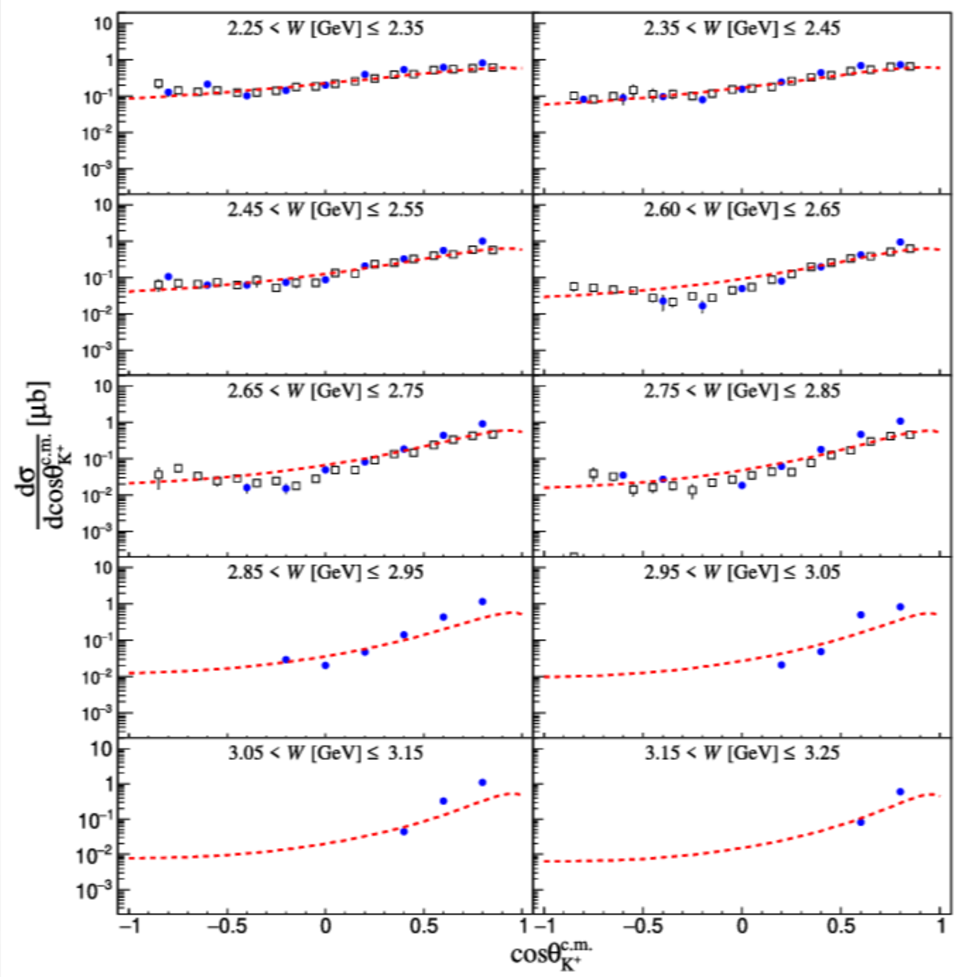
(b) ΛK^- invariant mass

Clas@Jlab

$\gamma p \to K^+\Lambda(1520)$

differential x-sections

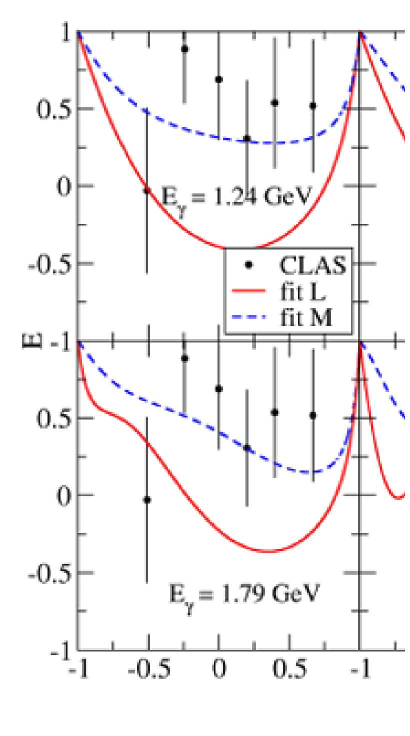
PRC (2021)

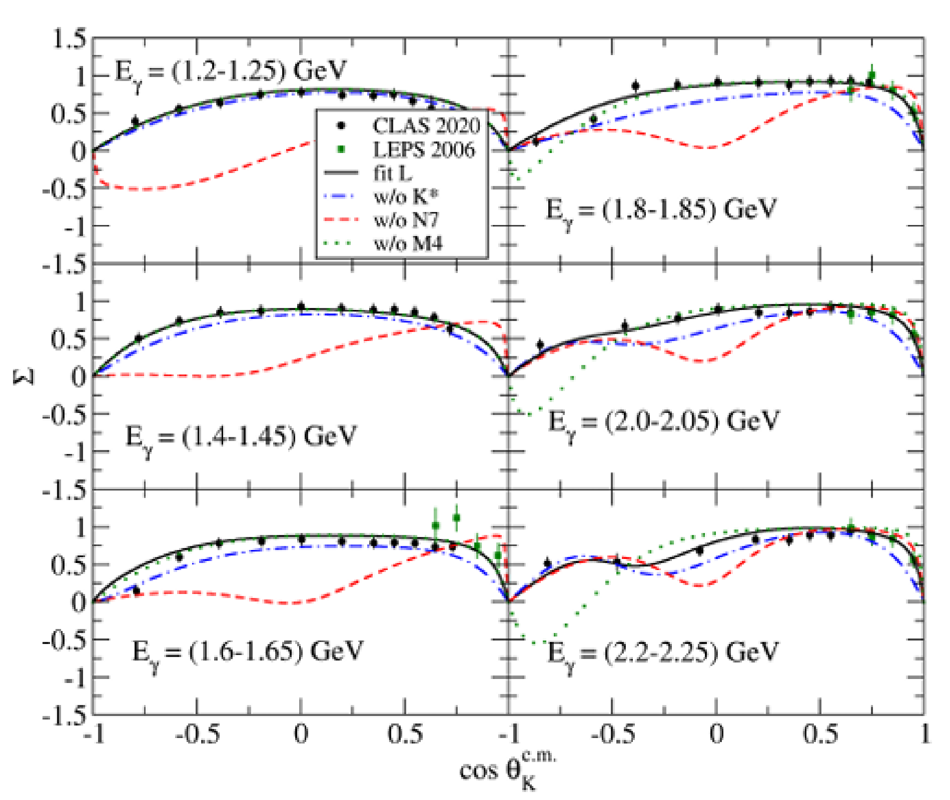


CLAS:

Beam–target helicity asymmetry in $\vec{\gamma}\vec{n} \to K^+\Sigma^-$ PLB (2020)

Beam spin asymmetry in $\vec{\gamma}n \to K^+\Sigma^-$ PLB (2022)





Isobar Model:

Bydžovský , Cieplý Petrellis, Skoupil, Zachariou, PRC (2021)

CLAS12 (elecroproduction):

beam-recoil transferred polarizations in

$p(e,e'K^+)\Lambda$ $p(e,e'K^+)\Sigma^0$ PRC (2022)

Longitudinal Spin Transfer to Λ Hyperons

arXiv:2201.06480

A lot of good work has been done in the 2018-2022 period

(the field has kept alive in spite of the difficult circumstances)

Congratulations!