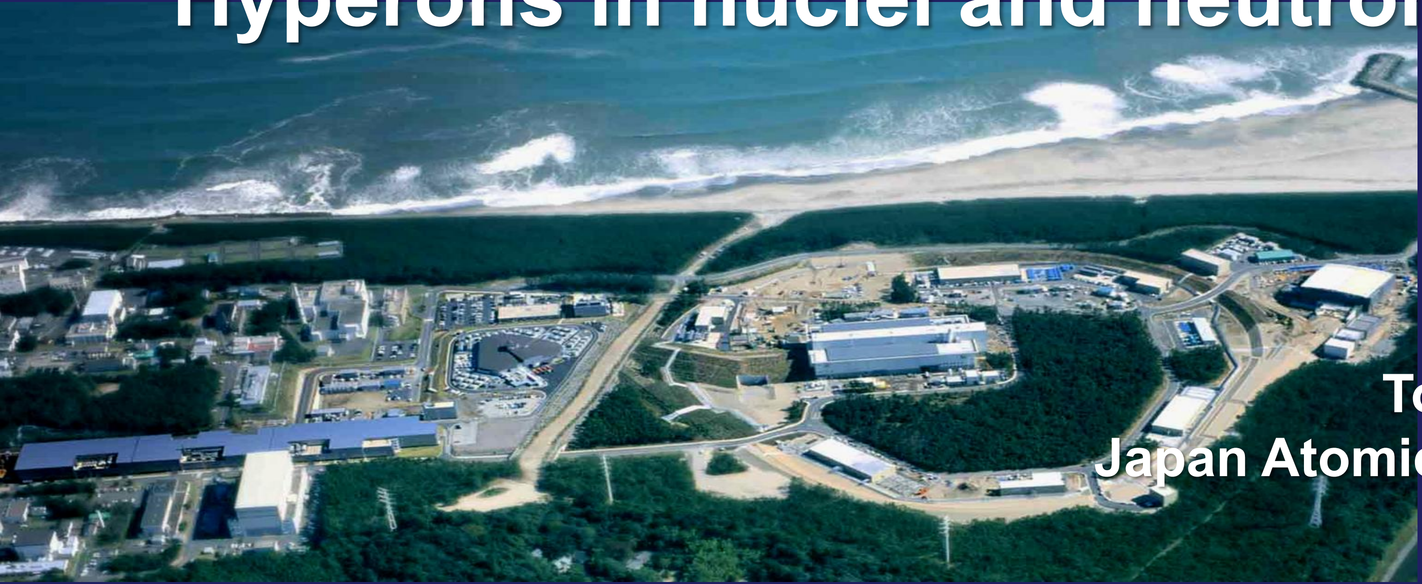
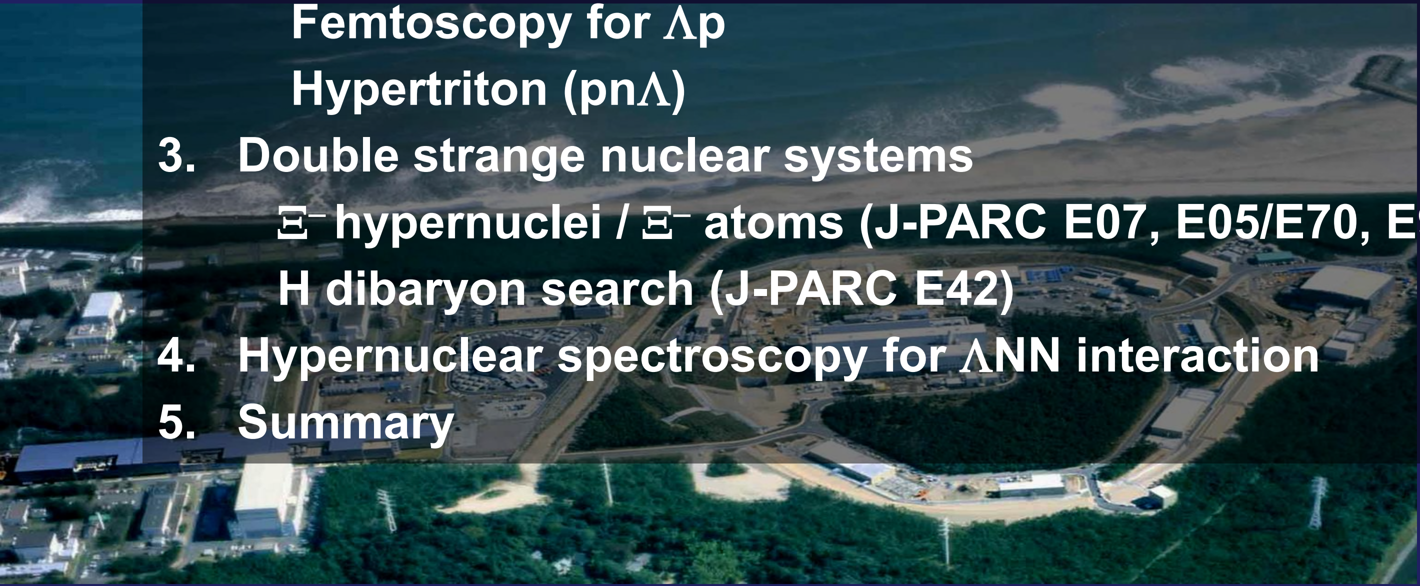
2025. 5. 29
INPC2025 @Daejeon

Hyperons in nuclei and neutron stars



H. Tamura
Tohoku University
Japan Atomic Energy Agency

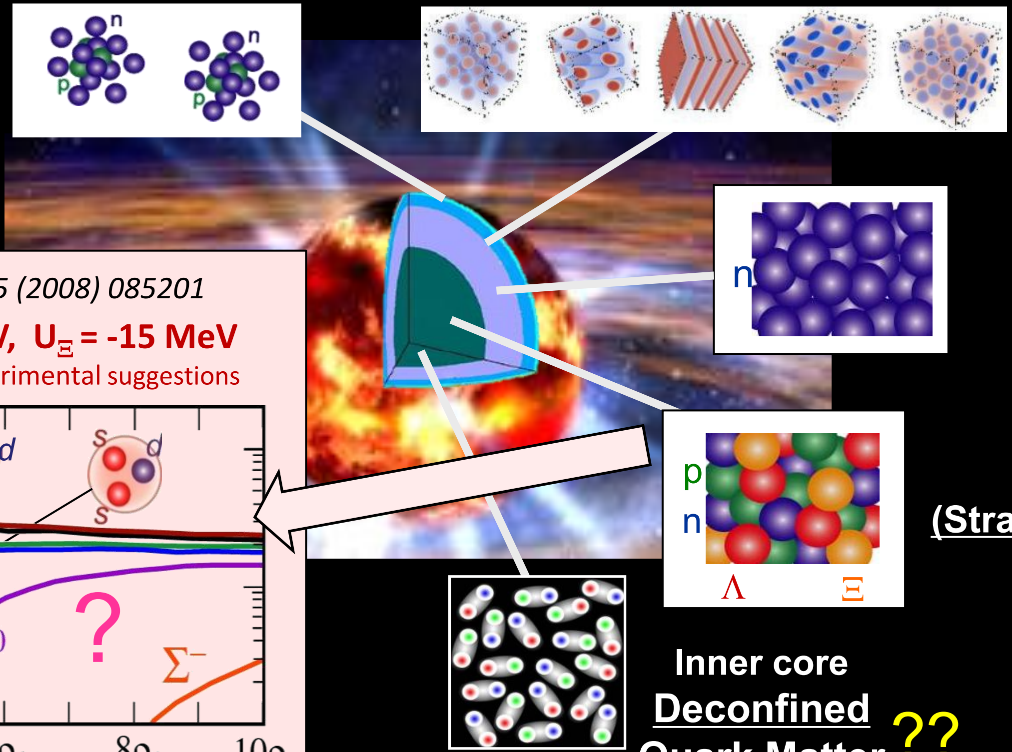
Contents



1. Introduction:
Hyperons in neutron stars?

Mystery of matter in neutron stars

Outer crust
Neutron-rich nuclei



Inner crust
Pasta nuclei

Outer core
(Almost pure) Neutron Matter

Inner core
Hyperon Matter (Strange Hadronic Matter)

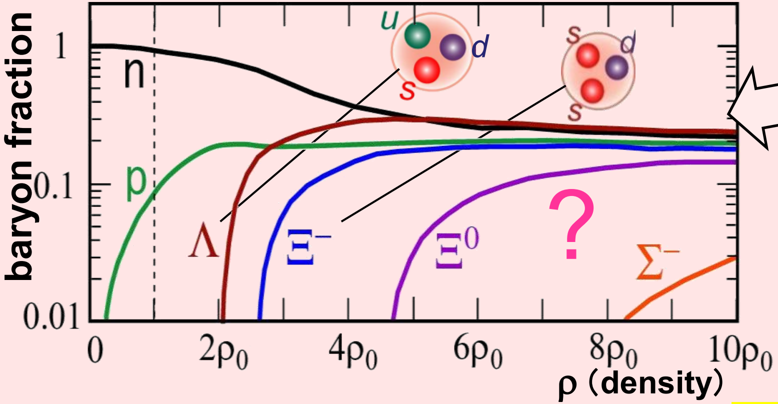
?

Inner core
Deconfined Quark Matter ??

C. Ishizuka et al., J.Phys.G 35 (2008) 085201

U_Λ = -30 MeV, U_Σ = +30 MeV, U_Ξ = -15 MeV

assumptions based on experimental suggestions



Sensitive to YN, YY interactions

Hyperons (Λ, Ξ^-) should appear at $\rho \sim$ 2-3 ρ_0

Hyperon Puzzle

EOS's with hyperons are too soft to support massive NS's of >1.5 M_{sun}.

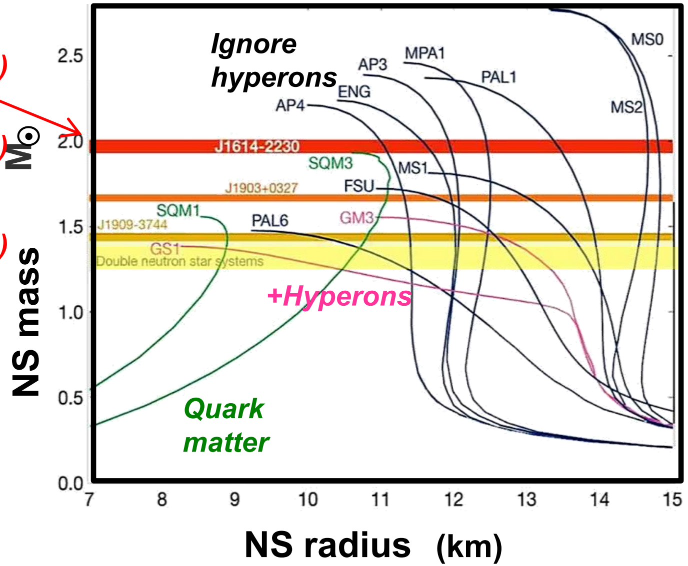
2.0 M_{sun} neutron stars are observed.

=> **Don't use U_Λ , U_Ξ , U_Σ at $\rho=\rho_0$!**

$1.97\pm0.04\ M_{sun}$ J1614-2230 (2010)

$2.01\pm0.04\ M_{sun}$ J0348-0432 (2013)

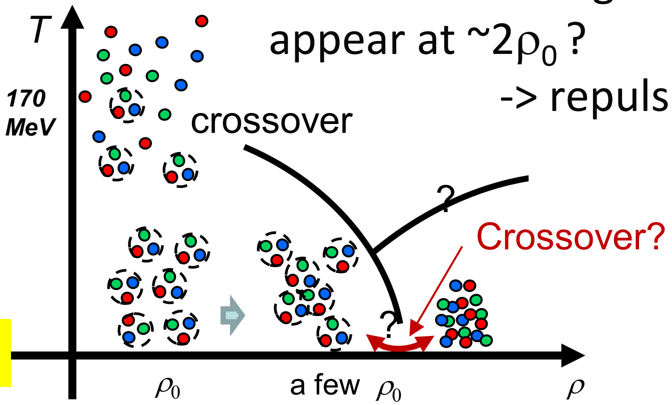
$2.14\pm0.10\ M_{sun}$ J0740-6620 (2020)



- **Repulsive three-body force in NNN.**
  Also in <u>YNN, YYN, YYY</u> ?
  but no clear experimental evidence
- **Deconfined quark matter?**

Quark matter begins to appear at ~2ρ_0 ?

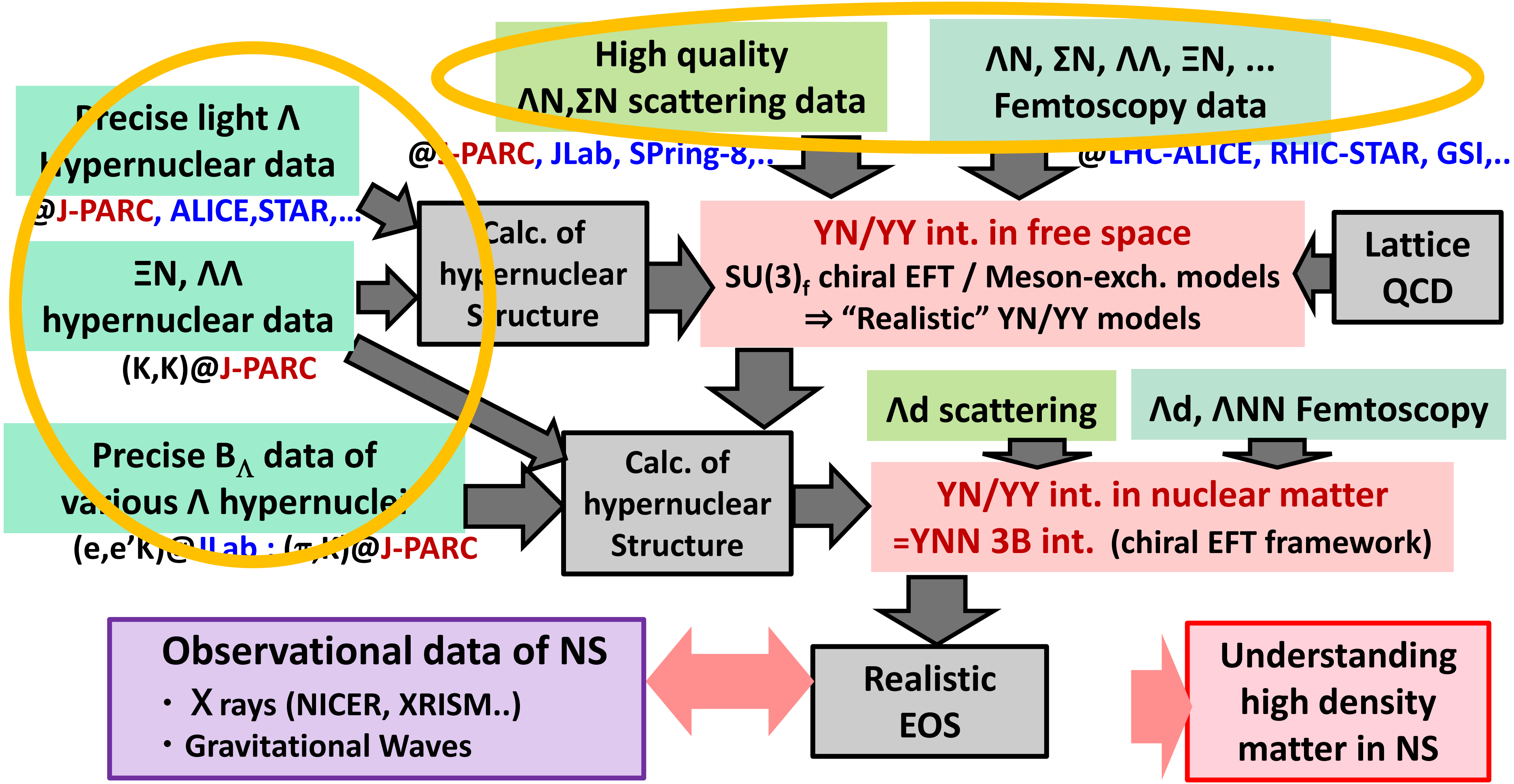
-> repulsive



Determine YNN 3BF

NS can be described in the hadron level or not

Strategy for solving the hyperon puzzle



2. YN interactions in free space

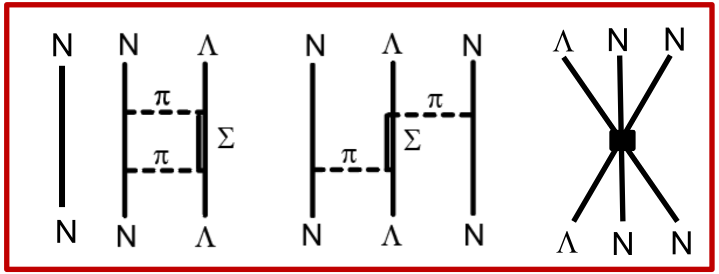
YN interaction

Λp, $\Sigma^{\pm}$p scattering with bubble chambers in (1960s)
<~ 0.30 GeV/c, poor quality, σ, no dσ/dΩ for Λp

Λ hypernuclei (+ Σ hypernuclei): B_Y + level scheme (1960-)

YN interaction Models (Nijmegen NSC, ESC)

But, YN int. in nuclei is significantly different from YN. Int in free space



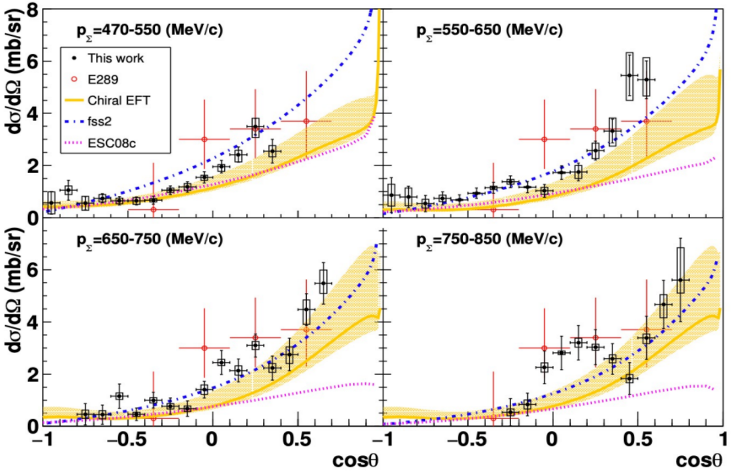
- **High quality YN scattering experiments**
  - $\Sigma^{\pm}$p 0.44-0.80 GeV/c dσ/dΩ (J-PARC E40)
  - Λp 0.9-2.0 GeV/c σ (JLab CLAS) *PRL 127, 272303 (2021)*
    - 0.3-0.65 GeV/c dσ/dΩ (SPring-8) -> started data taking
    - 0.4-0.8 GeV/c Pol.Λ -> dσ/dΩ, Analyzing Power, Depolarization (J-PARC E86, future)
- **Femtoscopy**
  - Λp <~ 0.3 GeV/c via pp coll. @√s=13 TeV (ALICE) -> (ALICE Run3)
- **Hypertriton (loose pnΛ system)** $B_\Lambda \leftrightarrow \tau$: inconsistent => being converged
  Precise data from STAR, ALICE, J-PARC, MAMI,…

$\Sigma^{\pm}p$ scattering at J-PARC

$\Sigma^- p$ elastic

$\Sigma^- p$ elastic scattering

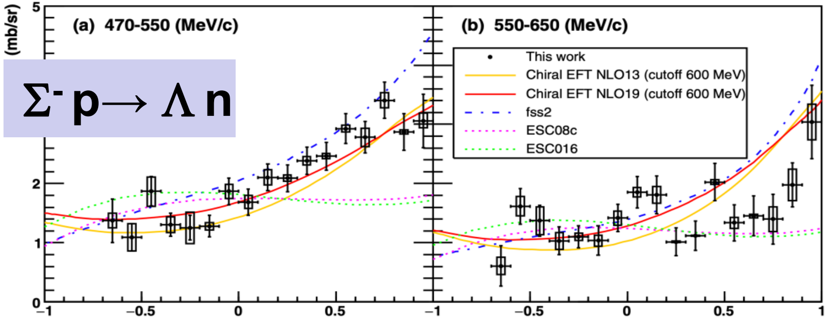
K. Miwa et al., PRC 104, 045204 (2021)



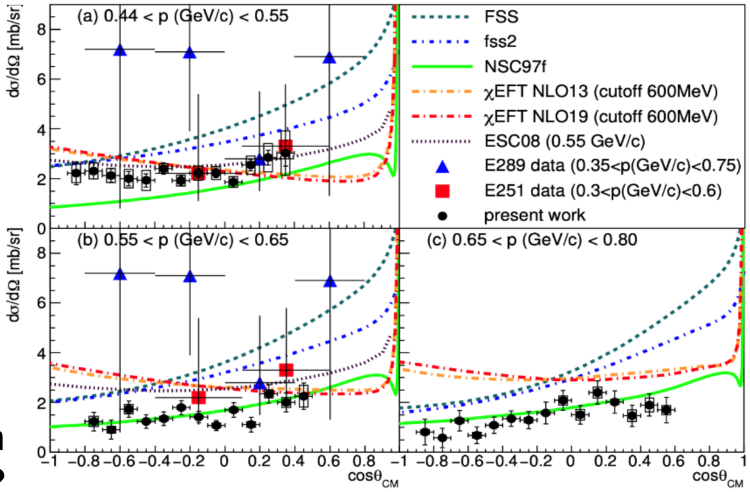
K. Miwa et al., PRL 128, 072501 (2022)

$\Sigma^- p \to \Lambda n$ inelastic scattering

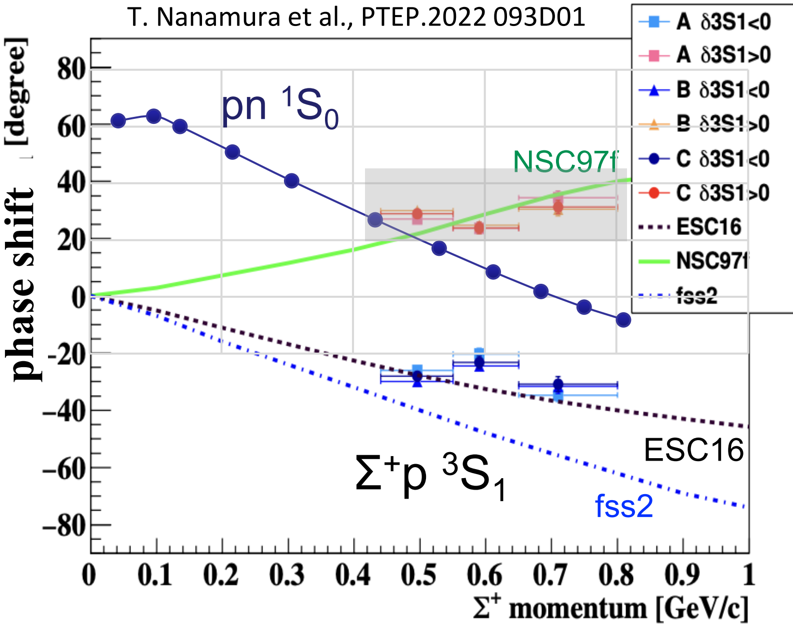
$\Sigma^- p \to \Lambda n$



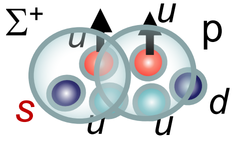
$\Sigma^+ p$ elastic



T. Nanamura et al., PTEP.2022 093D01



Σ^+-p (spin=1)

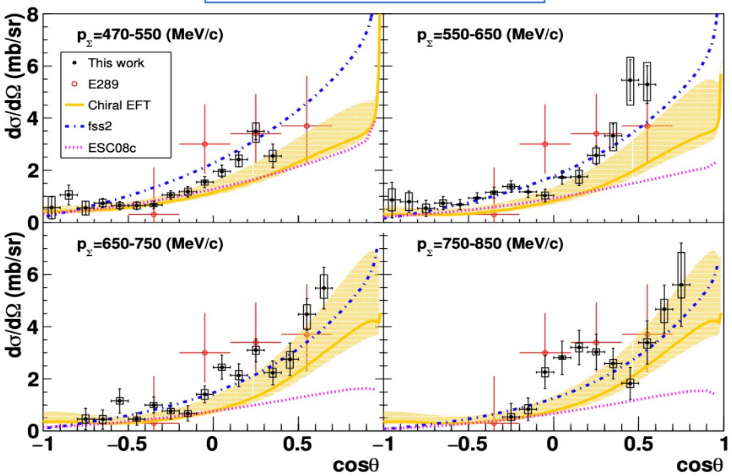


Strong repulsion by quark Pauli ??

$\Sigma^{\pm}p$ scattering at J-PARC

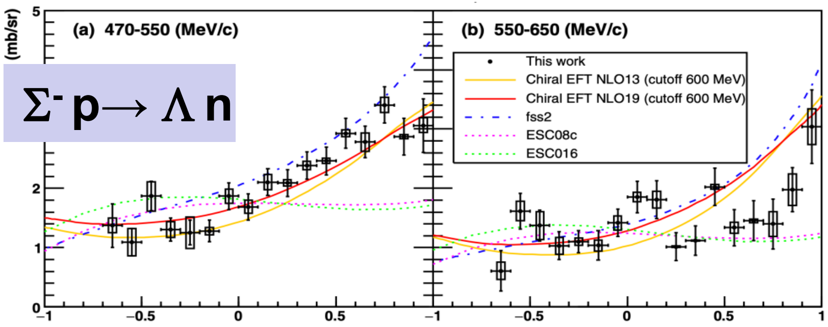
$\Sigma^- p$ elastic

$\Sigma^- p$ elastic scattering   K. Miwa et al., PRC 104, 045204 (2021)

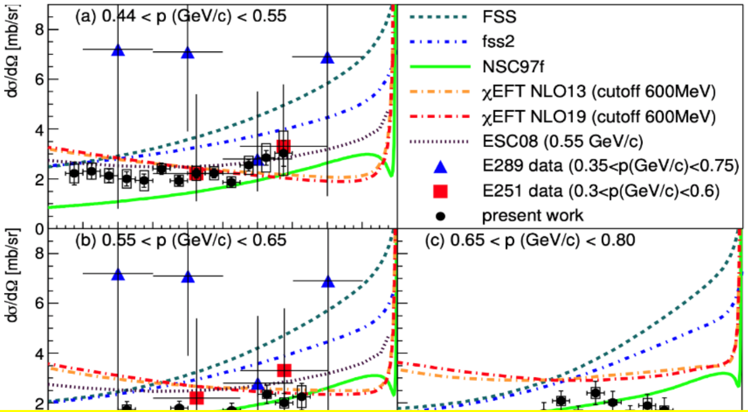


K. Miwa et al., PRL 128, 072501 (2022)

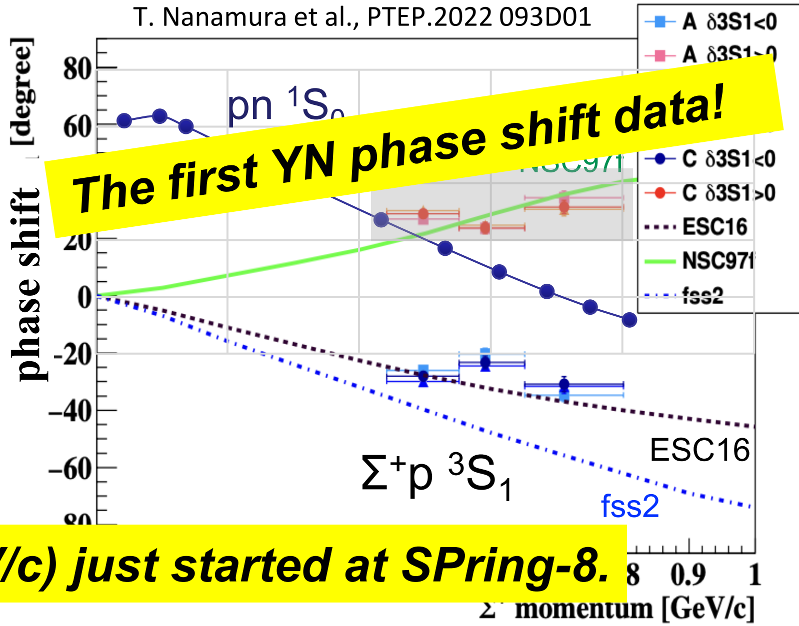
$\Sigma^- p \rightarrow \Lambda n$ inelastic scattering



$\Sigma^+ p$ elastic

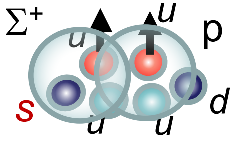


T. Nanamura et al., PTEP.2022 093D01



The first YN phase shift data!

Σ^+-p (spin=1)

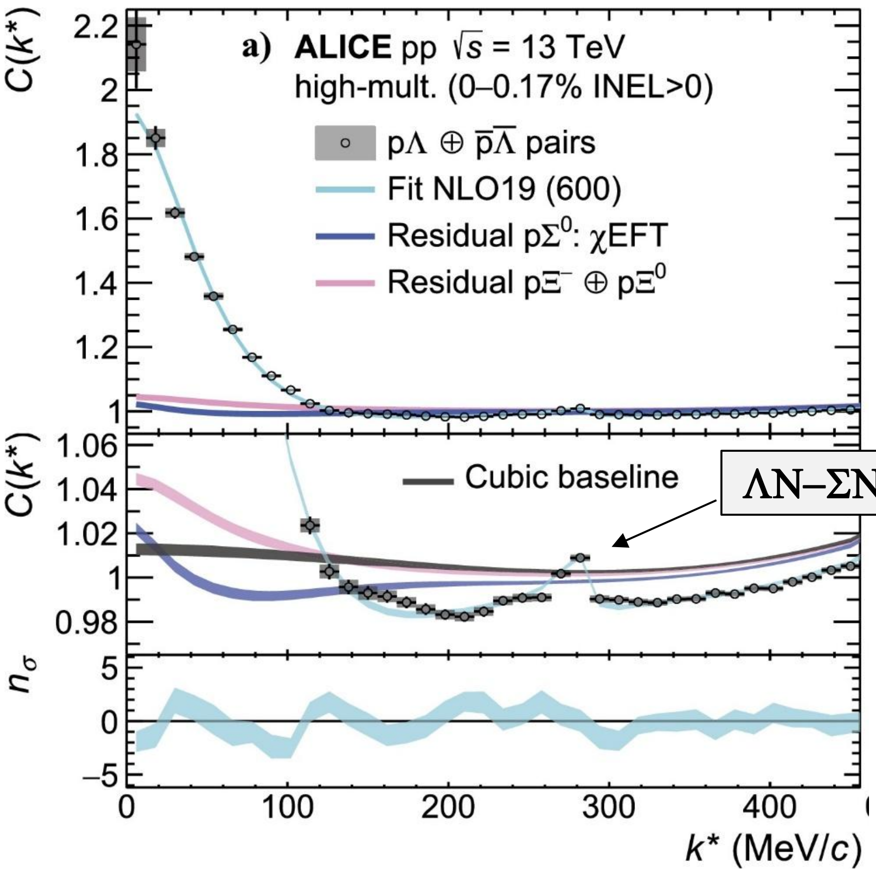


Stro... by qu...

A new exp. for Λp scattering (300-700 MeV/c) just started at SPring-8.

pΛ correlation (femtoscopy)

ALICE, PLB 833 (2022) 137272



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

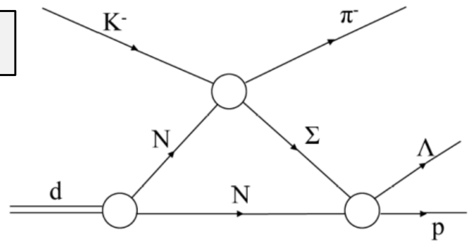
This data + Scattering data in 1960's are used to tune the chiral EFT force (NLO19)

PLB 850 (2024) 138550

=> U_Λ= -36 MeV

⇔ Hypernuclear data: U_Λ= -30 MeV

=> Suggesting a repulsive ΛNN 3BF



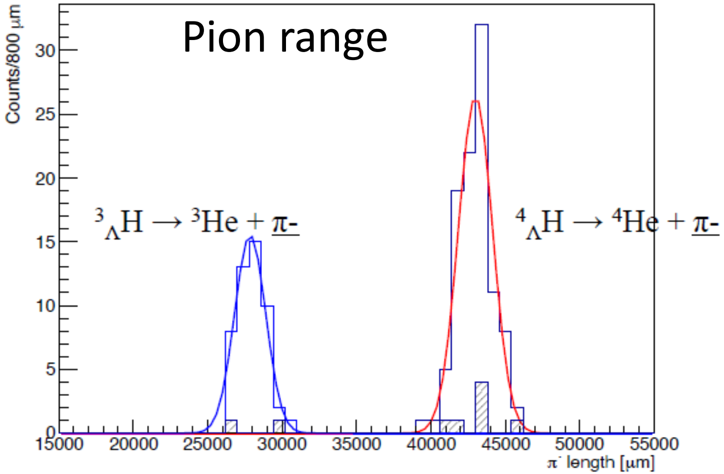
Measurement of ΛN–ΣN cusp via $K^- d \rightarrow \pi^- \Lambda p$ is planned.

=> ΣN scattering length (J-PARC E90)

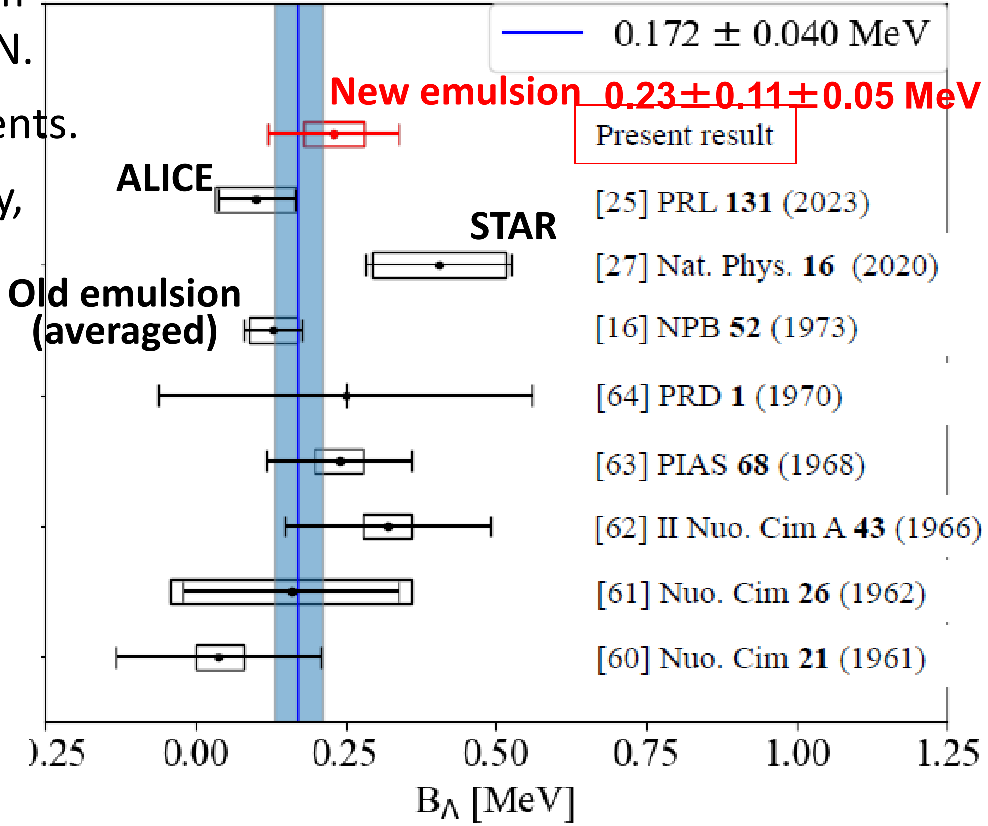
The benchmark, Hypertyriton (pnΛ)

A new B_Λ value from emulsion

- J-PARC E07 emulsion irradiated by K- beam was analyzed by T.R. Saito's group in RIKEN.
- Machine learning to find $^{3}_{\Lambda}H \rightarrow {}^{3}He\ \pi^{-}$ events.
- π^{-}'s range was converted to the π^{-} energy, where the systematic error was reduced down to 50 keV.



A. Kasagi et al., arXiv:2504.01601v2



Status of Hypertriton data

New data after 2018

Experiment	Reaction	Method	τ ($^{3}_{\Lambda}$H) ps	B_{Λ}($^{3}_{\Lambda}$H) MeV
STAR	HI (Au+Au) √s=3GeV	decay length inv. mass	221±15±19	0.41±0.12±0.11
ALICE	HI (Pb+Pb) √s=5TeV	decay length inv. mass	253±11±6	0.102±0.063 ±0.067
HADES	HI (Ag+Ag) √s=2.55GeV	decay length	256±22±36 (preliminary)	-
WASA-FRS	HI (^{6}Li+^{12}C) 2GeVA	decay length	under analysis	under analysis
J-PARC E73	^{3,4}He(K$^-$,π^0)	decay π^- timing	Under analysis	-
J-PARC E07	K$^-$ on emulsion	decay π^- range	-	0.23±0.11 ±0.05
MAMI	^{7}Li(e,K$^+$)	decay π^- momentum	**Kino (Thu)**	under analysis ΔM~±0.02

$^{3}_{\Lambda}$H -> ^{3}He π^-

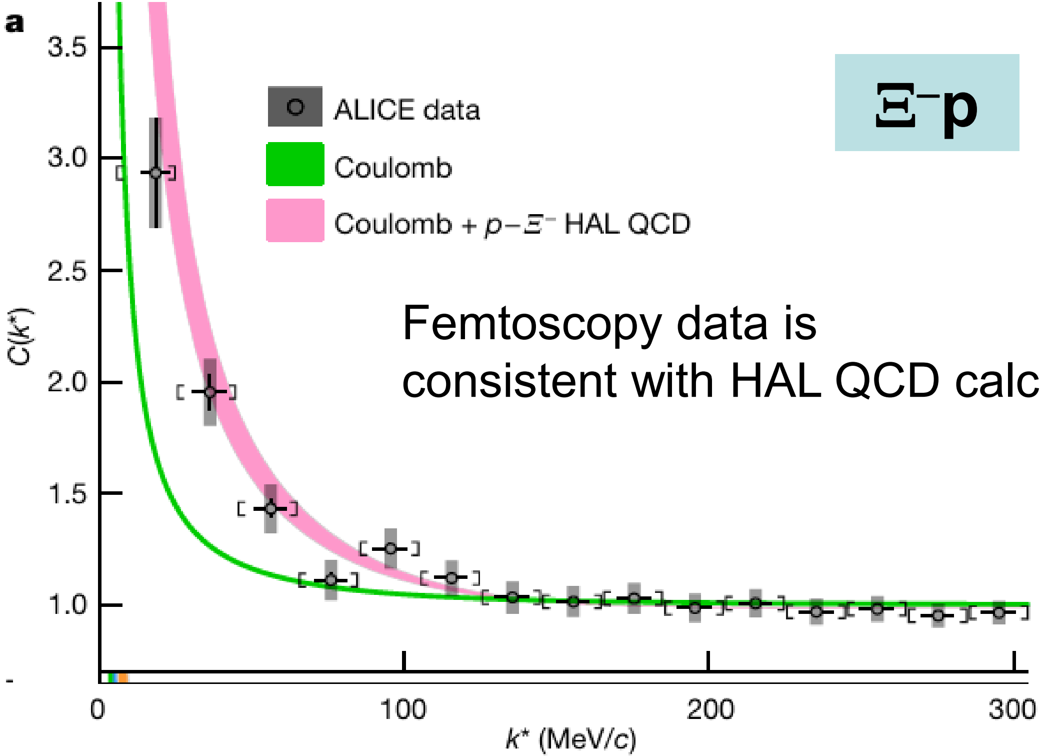
$^{3}_{\Lambda}$H -> ^{3}He π^-

Hypertriton is an excellent benchmark on ΛN interaction in free space but with a little effect of ΛNN 3BF.

3. Studies of Double strange systems at J-PARC

Ξ^-p from femtoscopy and lattice

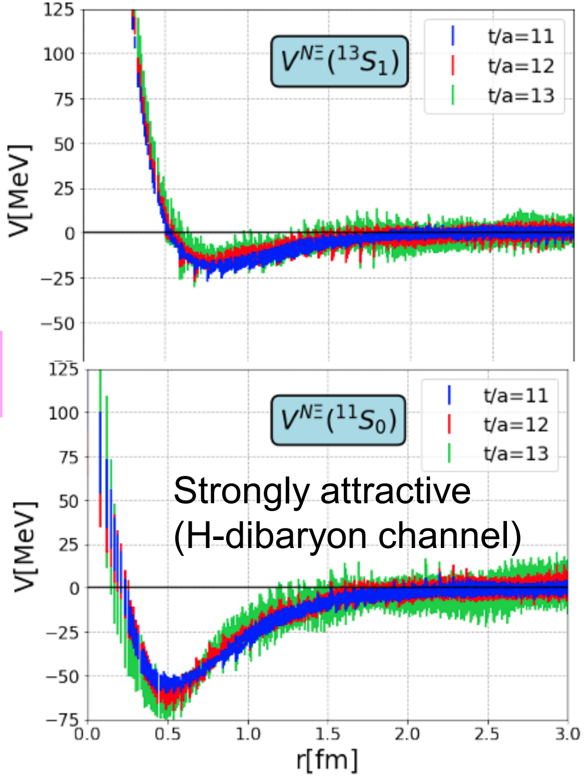
ALICE, Nature 588, 232 (2020)



Ξ^-p

Femtoscopy data is consistent with HAL QCD calc.

HAL QCD



K.Sasaki et al., Nucl.Phys.A 998 (2020) 121737

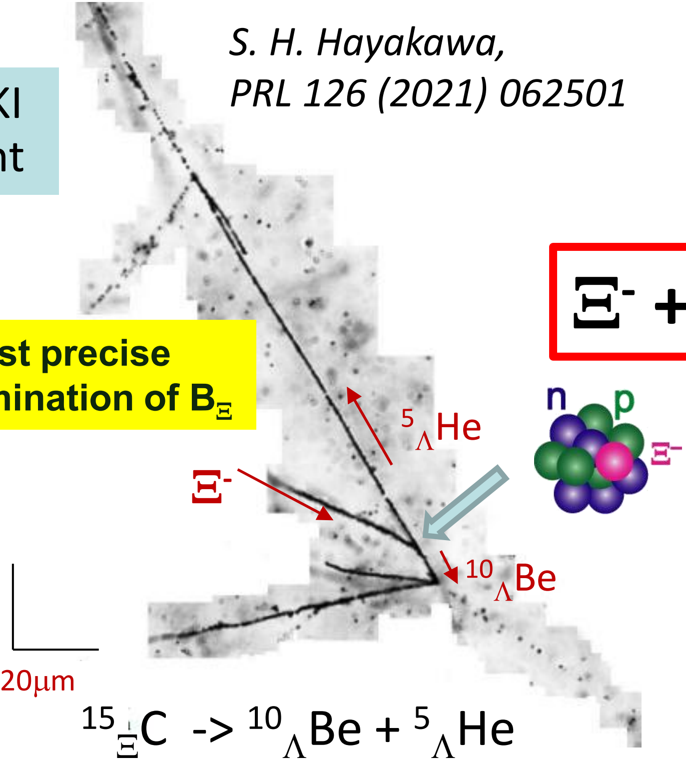
Ξ-hypernuclei in emulsion (J-PARC E07)

$K^- + \text{“}p\text{”} \rightarrow \Xi^- + K^+$, then Ξ^- is stopped in emulsion and captured by C, N, O nuclei.

IBUKI event

S. H. Hayakawa, PRL 126 (2021) 062501

First precise determination of B_Ξ



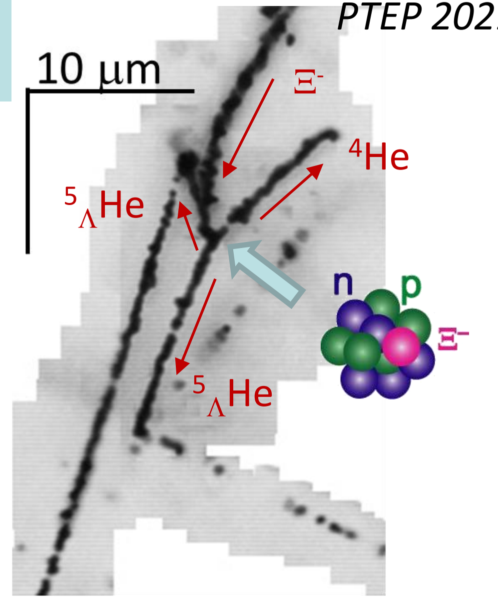
$^{15}_\Xi C \rightarrow {}^{10}_\Lambda Be + {}^5_\Lambda He$

$B_{\Xi^-} = 1.27 \pm 0.21$ MeV

$\Xi^- + {}^{14}N \rightarrow {}^{15}_\Xi C$

IRRAWADDY event

M. Yoshimoto et al., PTEP 2021, 073D02

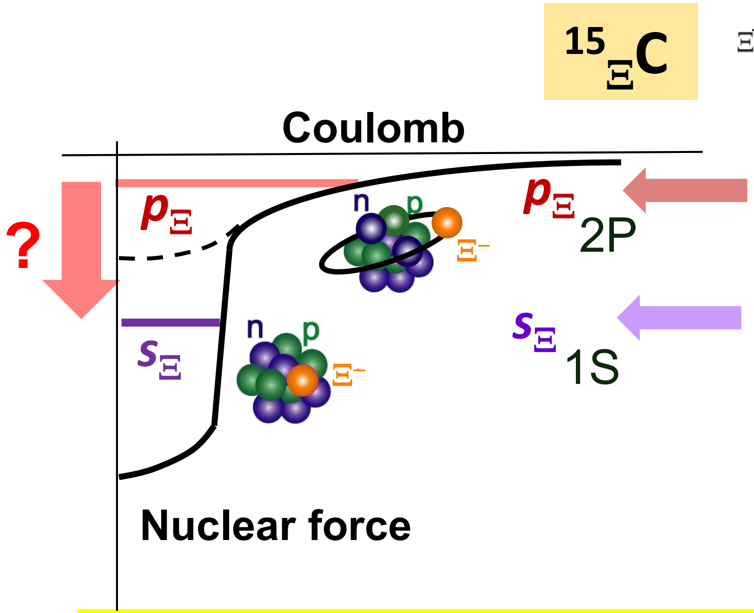


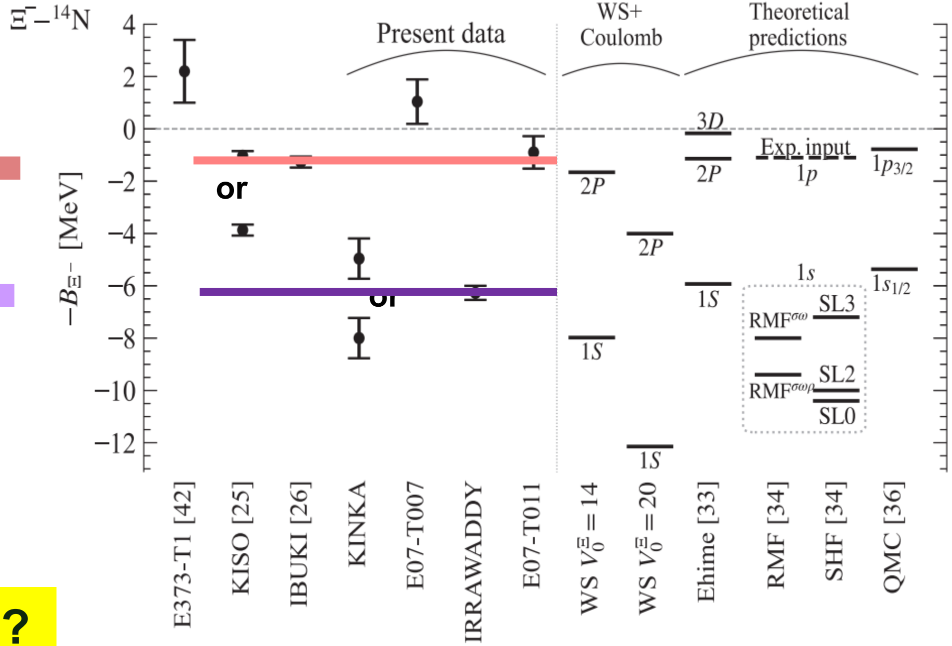
$^{15}_\Xi C \rightarrow {}^5_\Lambda He + {}^5_\Lambda He + {}^4He + n$

$B_{\Xi^-} = 6.27 \pm 0.27$ MeV

Observation of *p*- and *s*-state Ξ hypernuclei (?)

M. Yoshimoto et al., Prog. Theor. Exp. Phys. 2021, 073D02





ΞN→ΛΛ strength very small?

Nijmegen NSC: Ξ absorption mainly from 3D, 4%-0.3% from 2P orbit (T. Koike)

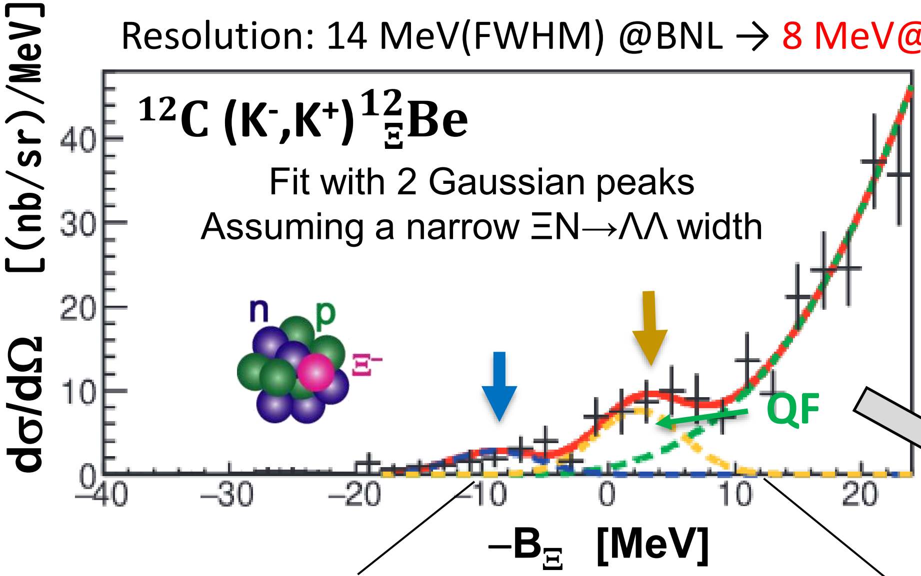
HAL QCD (~ 1/10 of NSC) -> 2P/3D absorption comparable, but 1S absorption still negligible

m(Ξ^-) - m(Ξ^0) = 6.9 MeV => p(Ξ^0) state via Ξ^-–Ξ^0mixing? (Gal-Friedman, *PLB 837 (2023) 137669)*

$^{12}C\,(K^-,K^+)\,^{12}_{\Xi}Be$ missing-mass spectroscopy

(J-PARC E05)

Resolution: 14 MeV(FWHM) @BNL → 8 MeV@J-PARC E05



Y. Ichikawa et al., *PTEP* 2024 (2024) 091D01

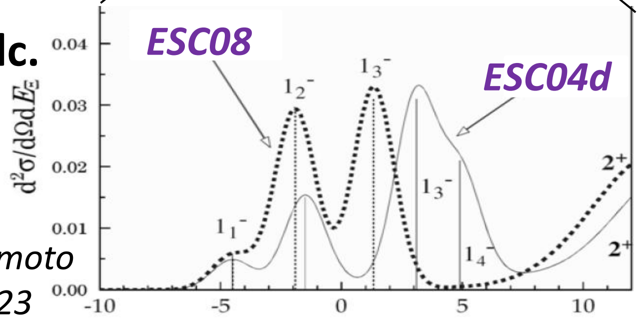
First observation of Ξ-hypernuclear peaks

B_Ξ values

$-2.4 \pm 1.3^{+2.8}_{-1.2}$ MeV

$8.9 \pm 1.4^{+3.8}_{-3.1}$ MeV

DWIA calc.

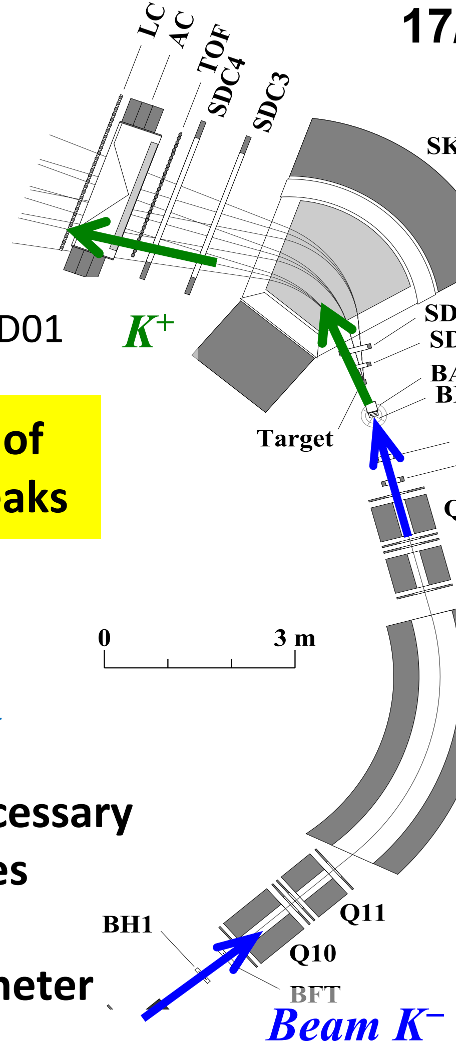


T.Motoba, S.Sugimoto NPA835 (2019) 223

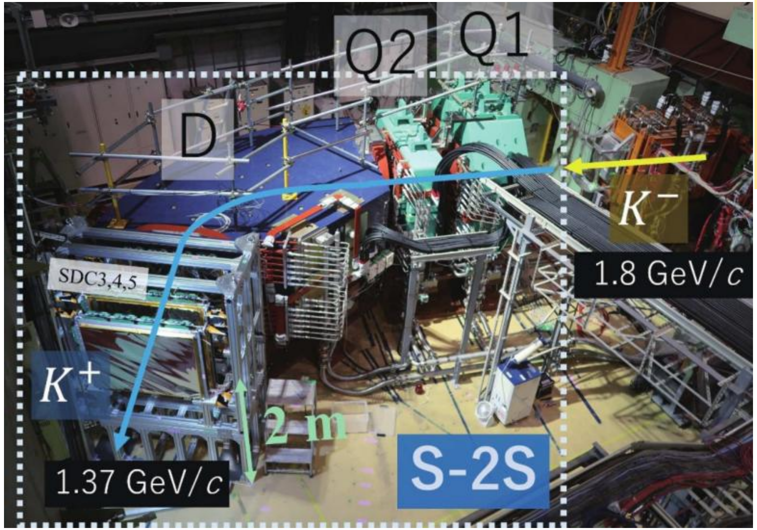
Better resolution necessary to identify states

➔ J-PARC E70

w/ a new spectrometer

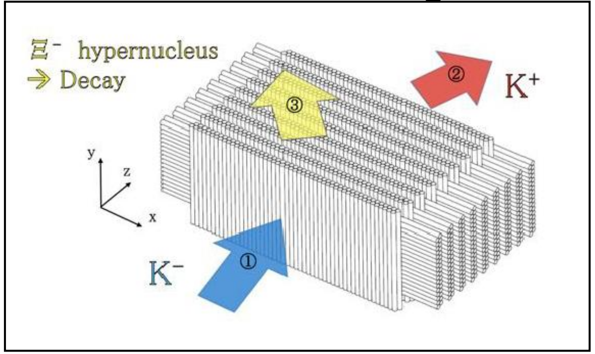


New experiments have been just finished



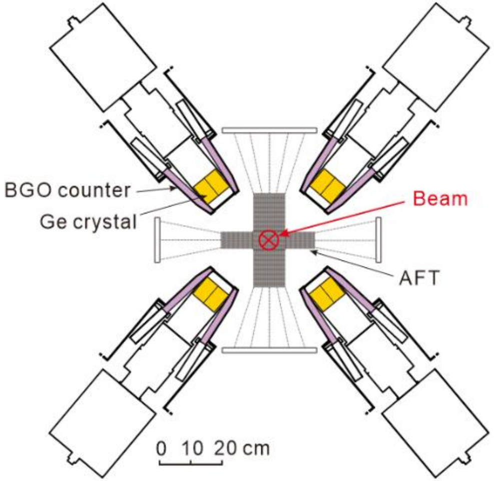
E70:
$^{12}C(K^-,K^+)^{12}{}_{\Xi}Be$
w/ a new spectrometer

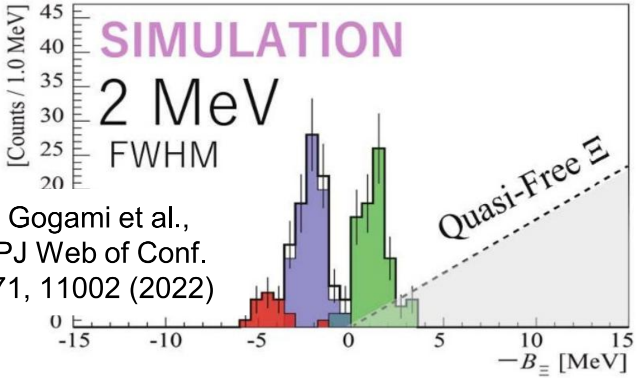
Active Fiber Target



Energy loss correction
Stopped Ξ selection

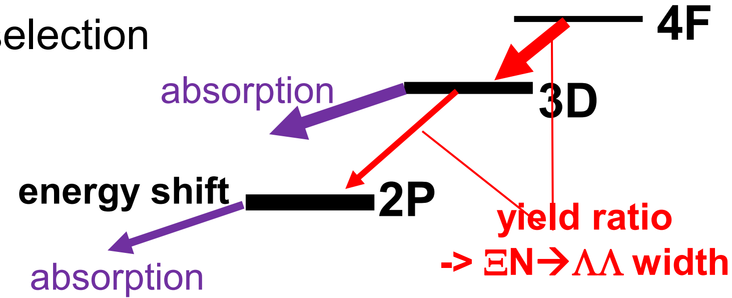
E96:
^{12}C Ξ atomic X-rays





T. Gogami et al.,
EPJ Web of Conf.
271, 11002 (2022)

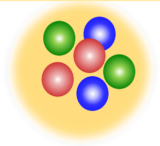
Data-taking just finished



H-dibaryon search and study of ΞN interaction

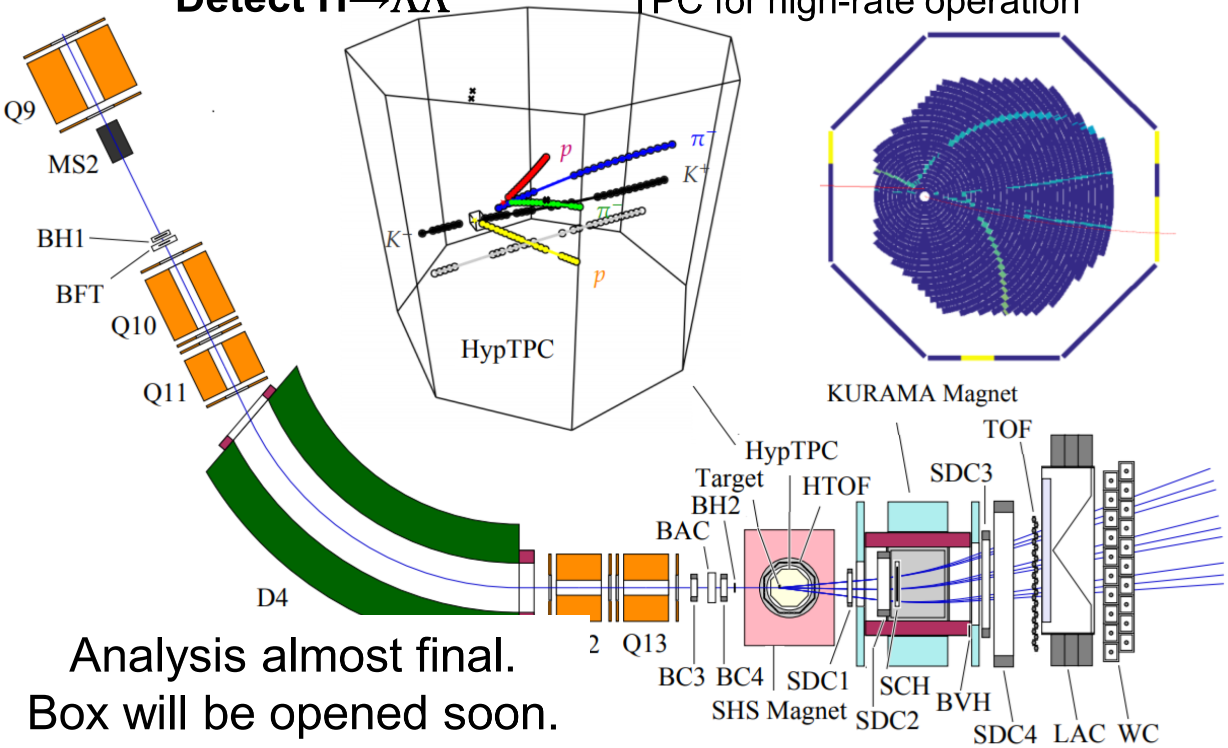
(J-PARC E42, J.K. Ahn et al.)

H dibaryon

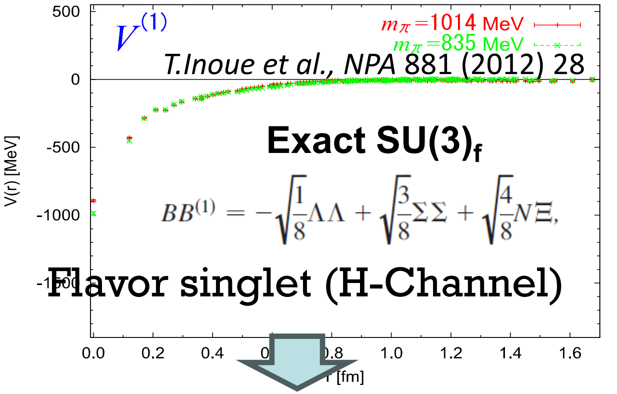


Above ΛΛ threshold
Detect H→ΛΛ

TPC for high-rate operation



Analysis almost final.
Box will be opened soon.

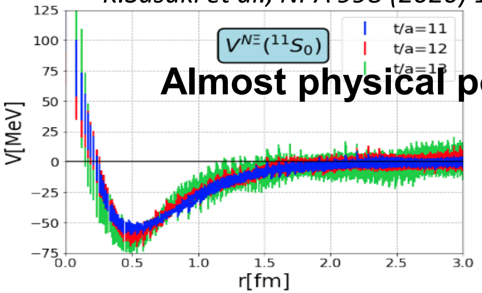


Exact SU(3)$_f$

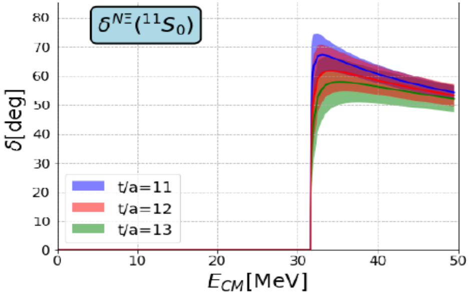
$$BB^{(1)} = -\sqrt{\frac{1}{8}}\Lambda\Lambda + \sqrt{\frac{3}{8}}\Sigma\Sigma + \sqrt{\frac{4}{8}}N\Xi,$$

Flavor singlet (H-Channel)

K.Sasaki et al., NPA 998 (2020) 121737



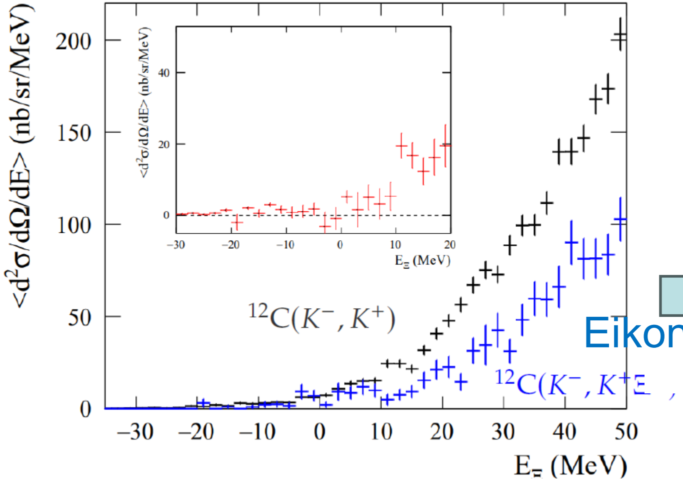
Almost physical point

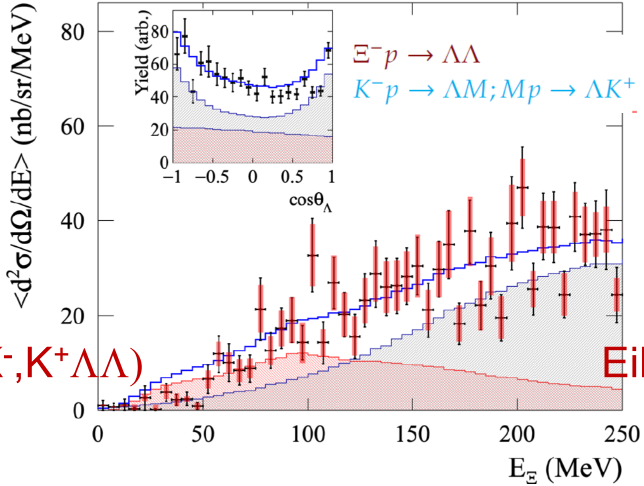


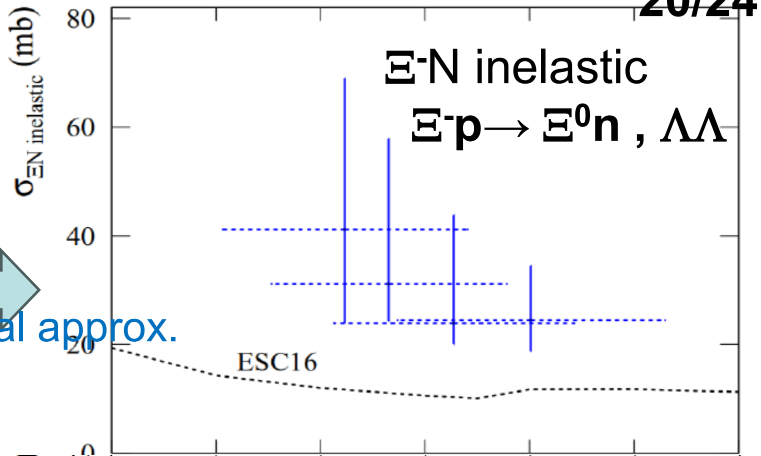
Resonance just above the threshold?

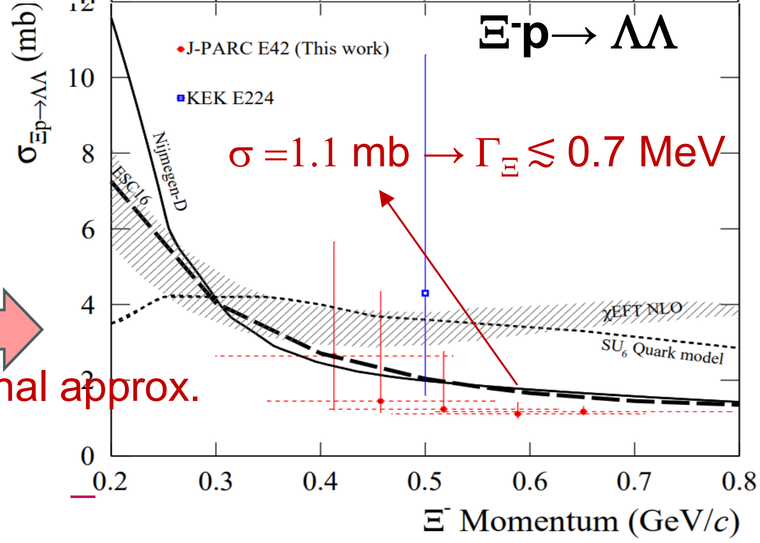
$^{12}C(K^-,K^+\Xi^-)$ and $^{12}C(K^-,K^+\Lambda\Lambda)$ Spectra

(J-PARC E42)









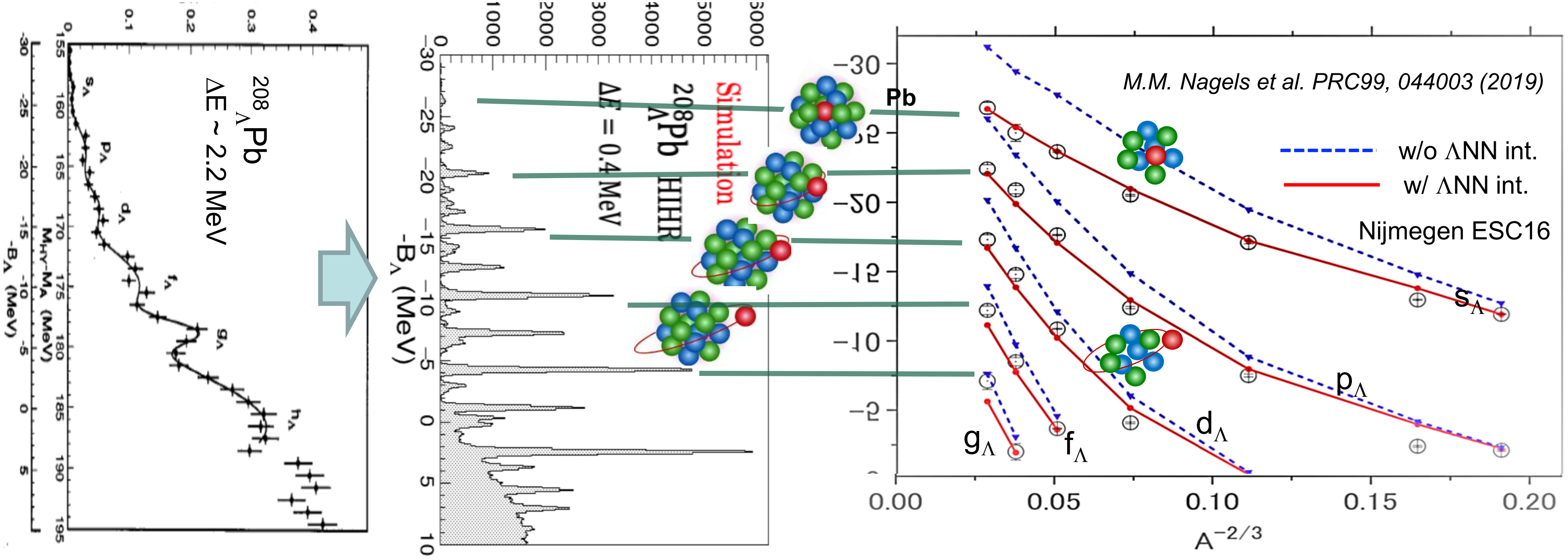
W.S. Jung et al., arXiv:2503.17614v2 [nucl-ex]

4. Hypernuclear spectroscopy for ΛNN interaction

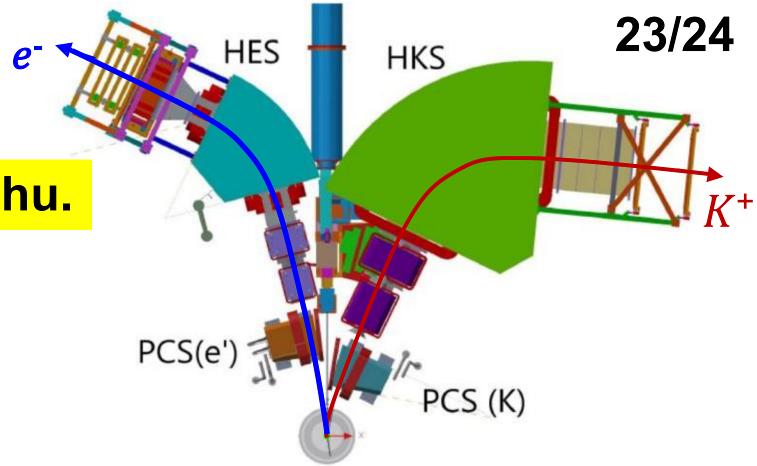
How can we extract YNN 3-body force effect ?

Single particle energies of Λ in hypernuclei => sensitive to ΛN density dep. (= ΛNN 3BF)

- Λ is distinguishable from nucleons. No Pauli from nucleons.
- We know the local density where the Λ is located.
- Different mass numbers, orbitals -> probe different densities



Experimental Plans



JLab @Hall C

Umeya, Thu.

E12-15-008: ^{40,48}Ca(e,e'K^+) $^{40,48}_{\Lambda}$K

E12-18-013: ^{208}Pb (e,e'K^+) $^{208}_{\Lambda}$Tl

T=1 ΛNN force => Λnn force in NS

J-PARC @HIHR line

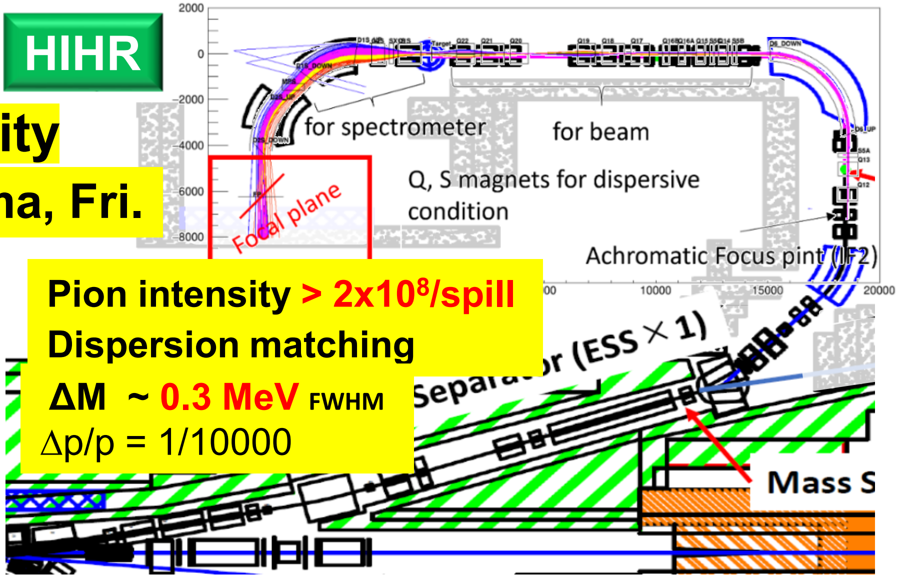
HIHR

at the extended Hadron Facility

Sakuma, Fri.

P84: (π^+,K^+) ...$^{12}_{\Lambda}$C, $^{28}_{\Lambda}$Si, $^{40}_{\Lambda}$Ca, $^{51}_{\Lambda}$V, $^{89}_{\Lambda}$Y, $^{139}_{\Lambda}$La, $^{208}_{\Lambda}$Pb

ΔM < 400 keV (FWHM)



Pion intensity > 2x10^8/spill
Dispersion matching
ΔM ~ 0.3 MeV FWHM
Δp/p = 1/10000

Together with ΛN scattering exp. (E86 @K1.1), those B_{Λ} values give info. on ΛNN strength.

Summary

1. In order to solve the hyperon puzzle of NS, we need YN/YY interactions both in free space and in nuclear matter to extract information on YNN 3BF.

2. High quality $\Sigma^{\pm}$p scattering data at J-PARC and high statistics Λp correlation data are being used to improve Hypertriton binding energy data from various experiments including J-PARC emulsion data will be also used.

3. Ξ hypernuclear data in emulsion and from (K^-,K^+) spectroscopy indicate an attractive Ξ-nucleus potential with a narrow ΞN-$\Lambda\Lambda$ width.

4. To investigate ΛNN interaction, precise Λ hypernuclear spectroscopy as are planned at Jlab and at the extended J-PARC Hadron Facility.