Λp scattering experiment with a polarized Λ beam at the K1.1 beam line --and K1.1 physics programs--

K. Miwa (Tohoku Univ.)
on behalf of the HIHR/K1.1 task force

Joint THEIA-STRONG2020 and JAEA/Mainz REIMEI Web-Seminar 2021/2022

Outline

- Physics goal at the J-PARC Hadron Experimental Facility
- Hyperon puzzle in neutron star
  - Strategy for understanding neutron star matter from HIHR/K1.1 experiments
- K1.1 physics programs
  - Λp scattering experiment
  - Hypernuclear γ-ray experiment
  - Weak decay experiment of hypernuclei
- Summary

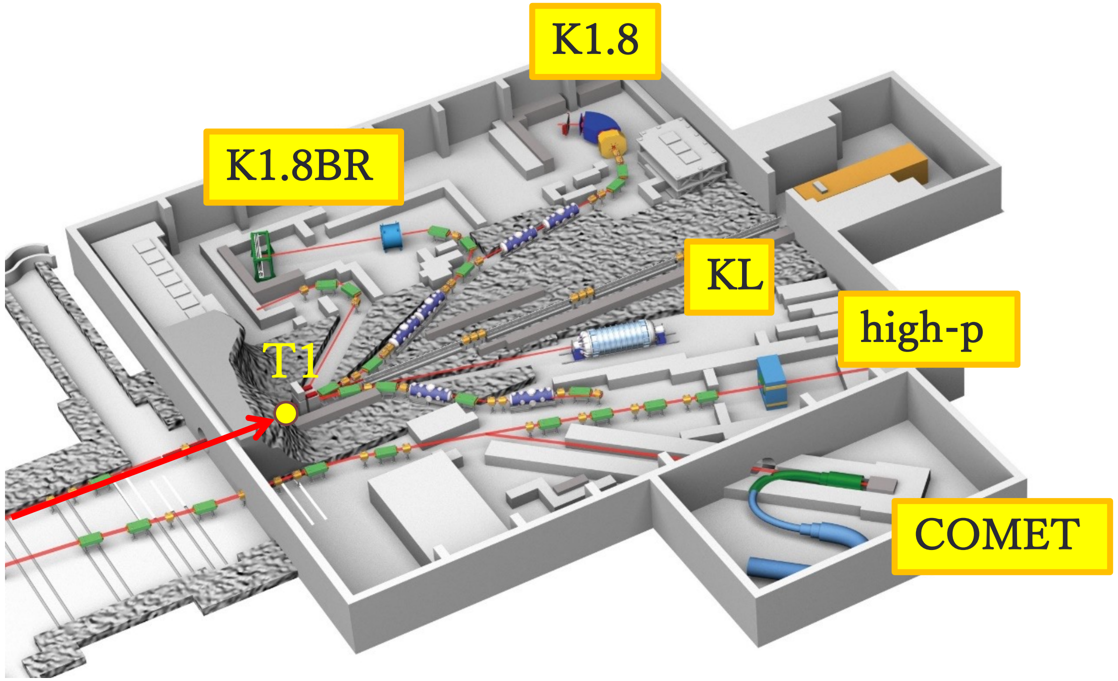
Hadron Experimental Facility Extension (HEF-EX) project

K1.8BR
(~1.0 GeV/c K^-)

K^{bar} N interaction

K1.8 (~1.8 GeV/c K^-)

BB interaction
(focusing on S=-2)



high-p (30GeV primary proton beam)
π20 (20GeV/c secondary beam)

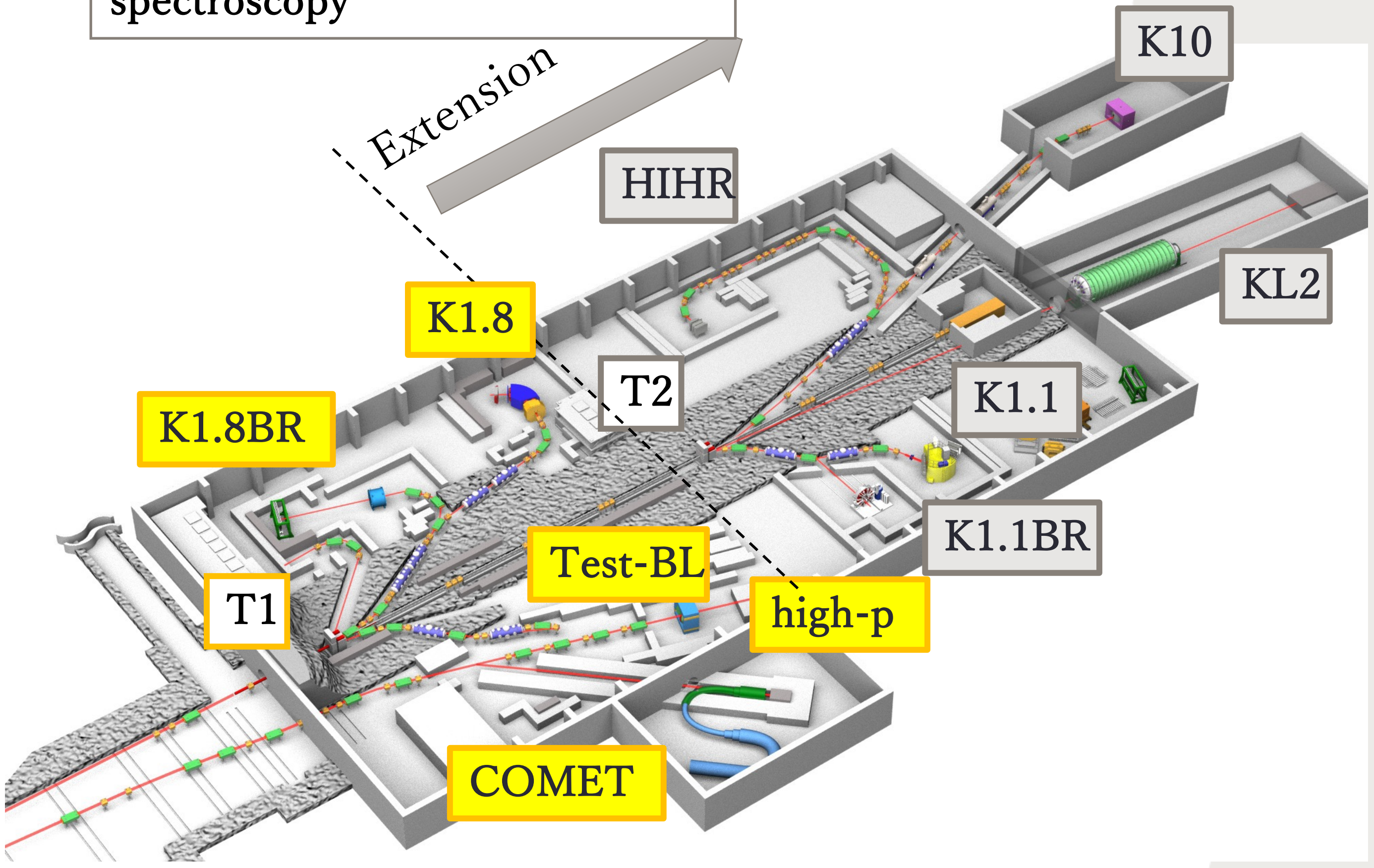
Hadron property in nuclear medium
Baryon spectroscopy

HIHR (~2 GeV/c π)

Ultra precise Λ hypernucler spectroscopy

K10 (~10 GeV/c K^-)

Ω baryon spectroscopy



K1.1BR (~0.8 GeV/c π/K)

Physics using a low energy Kaon

K1.1 (~1.2 GeV/c π/K)

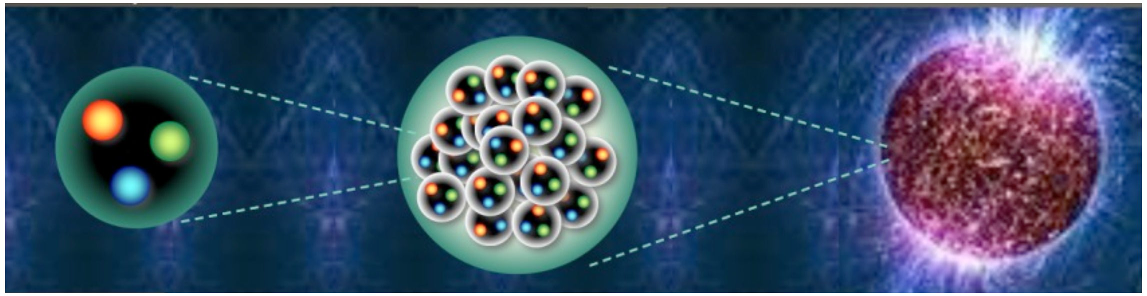
BB interaction
(focusing on S=-1)

Perform physics not accessible in the present hadron hall
Perform physics programs in parallel with twice more beam lines

From Quark to Neutron star

Understand quantum systems
governed by strong interaction
in a consistent way based on QCD

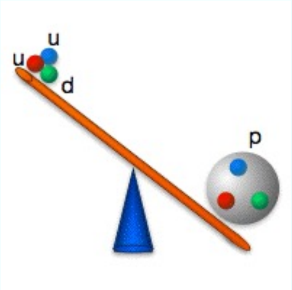
Baryon Nucleus Neutron star



From Quark to Hadron

Confinement of quark

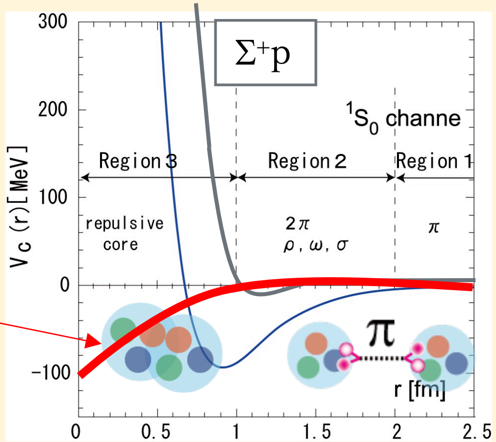
How to obtain hadron mass



From Hadron to Nuclei, Neutron star

Unified understanding
of **nuclear force** and
BB interaction

Flavor singlet

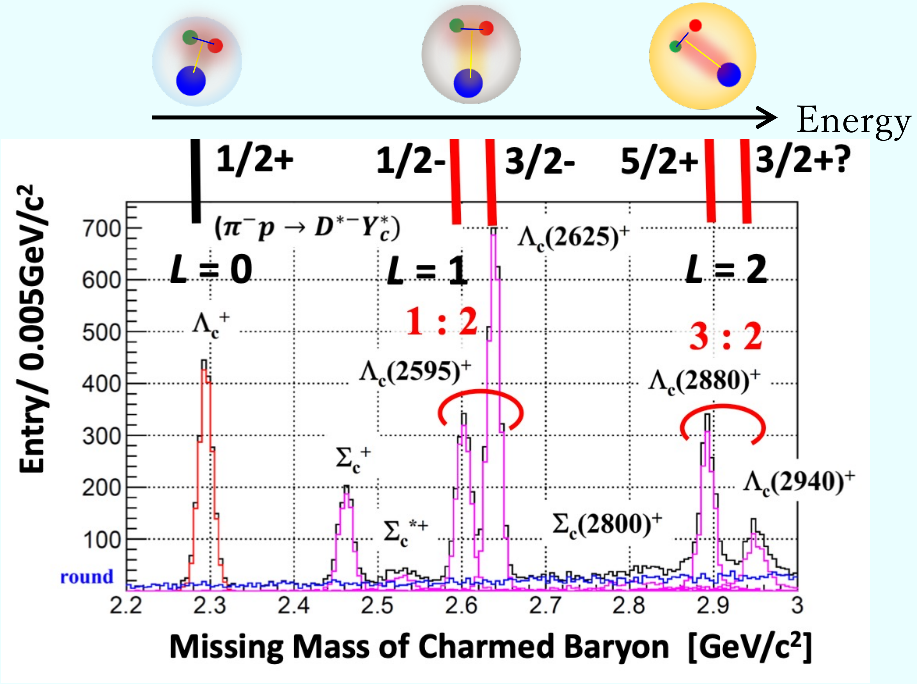


Based on the basic nature of main player of each hierarchy, we are going to investigate the dynamics of quantum many body system and bridge each hierarchy.

From Quark to Neutron star

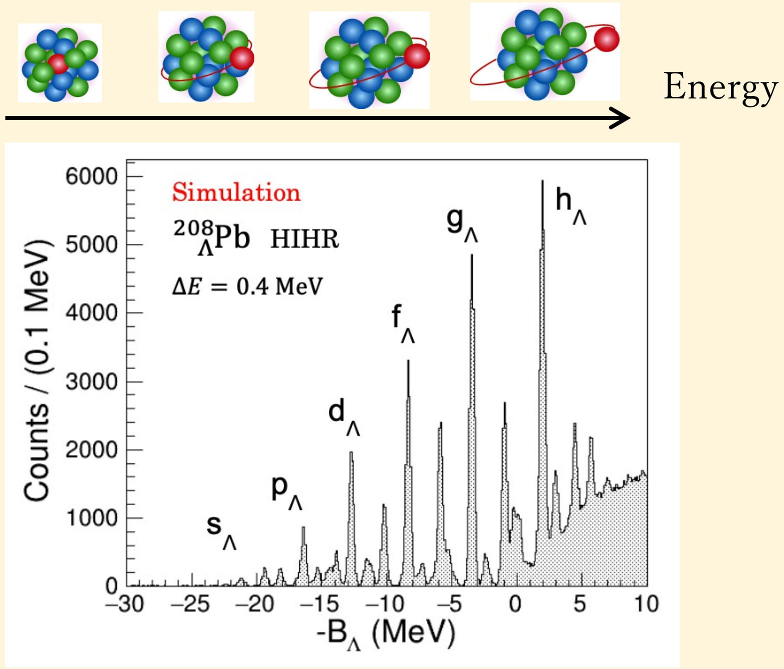
From quark to hadron

Charm and strange baryon spectroscopy



From Hadron to Nuclei, Neutron star

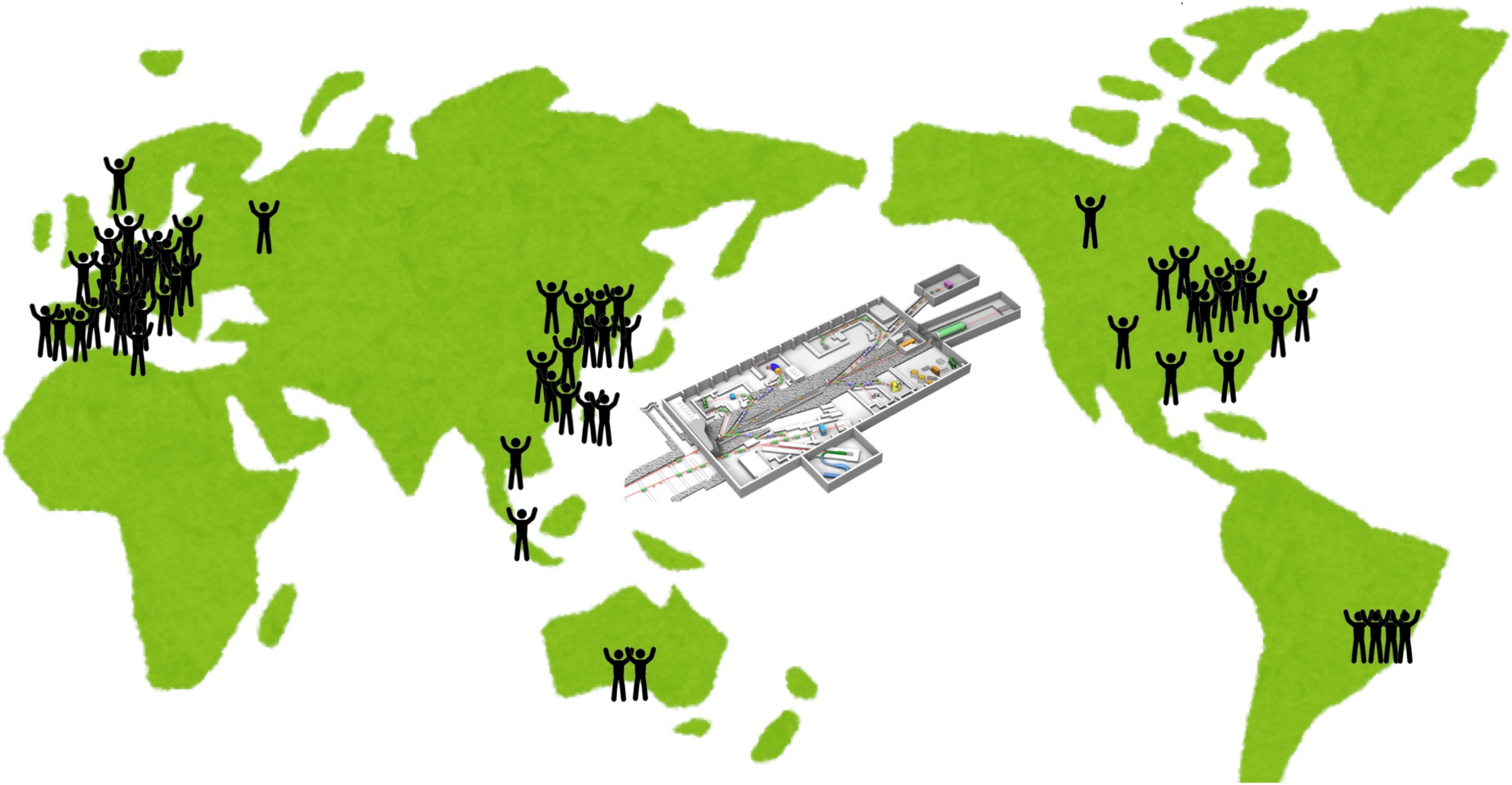
Hypernuclear spectroscopy



Based on the basic nature of main player of each hierarchy, we are going to investigate the dynamics of quantum many body system and bridge each hierarchy.

In J-PARC, we are going to investigate “Hadron nature, interactions between quarks” and “Nature of high-density nuclear matter” strategically using 2nd generation quarks (strange, charm).

Thank you for your support

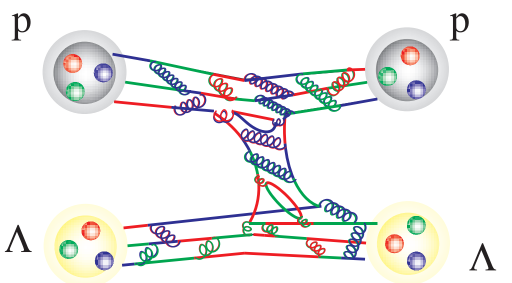


We received many support letters from many institutes all over the world.
We really appreciate your support.

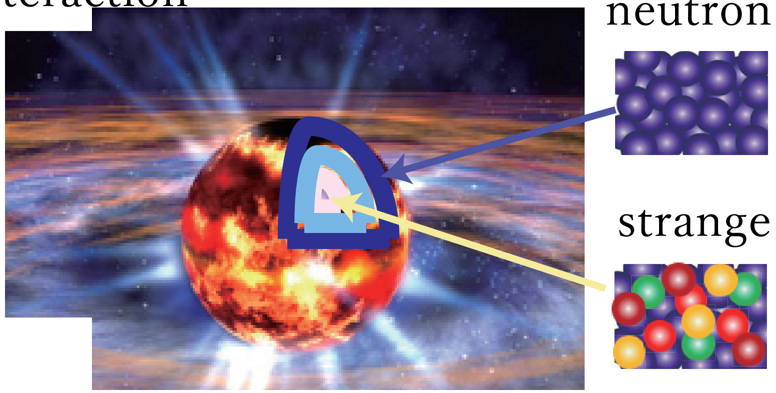
Matter in Extreme Conditions (Neutron star)

Baryon-baryon interaction and its density dependence play essential roles
- ✓ **to understand the composition at the inner core,**
- ✓ **to understand the mechanism to support the massive neutron star.**

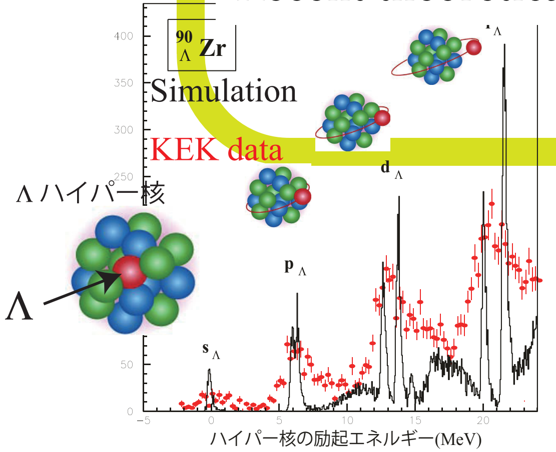
Hypernuclear physics based on Realistic YN interaction



YN scattering experiment
Lattice QCD
Recent theoretical framework

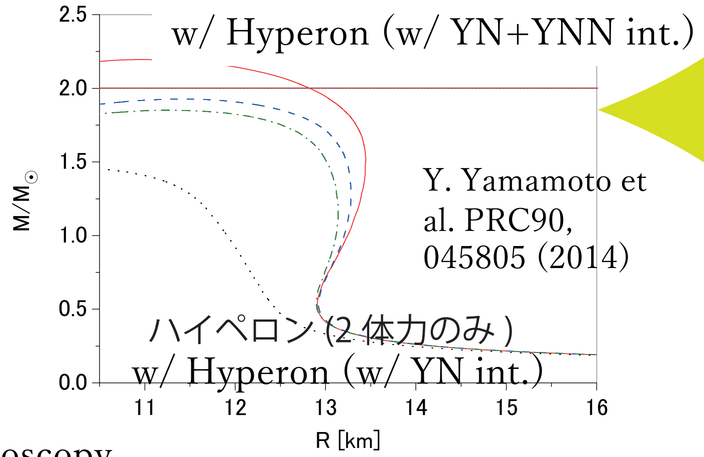


日本物理学会誌より
木内健太、関口雄一郎

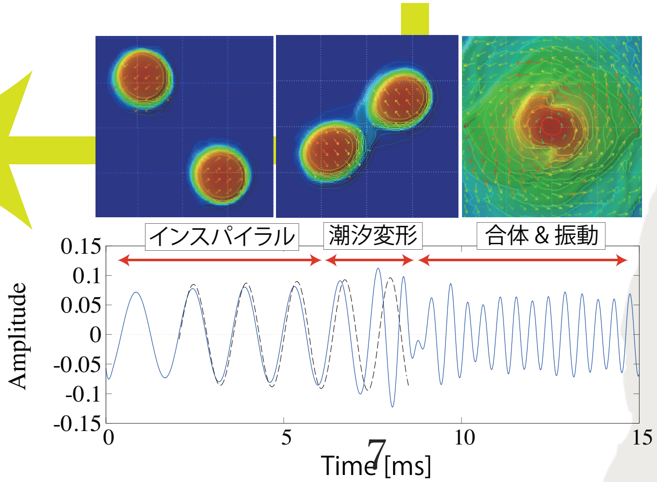


Ultra high-resolution Λ hypernuclear spectroscopy

EOS of neutron star



Gravitational wave from neutron star merger



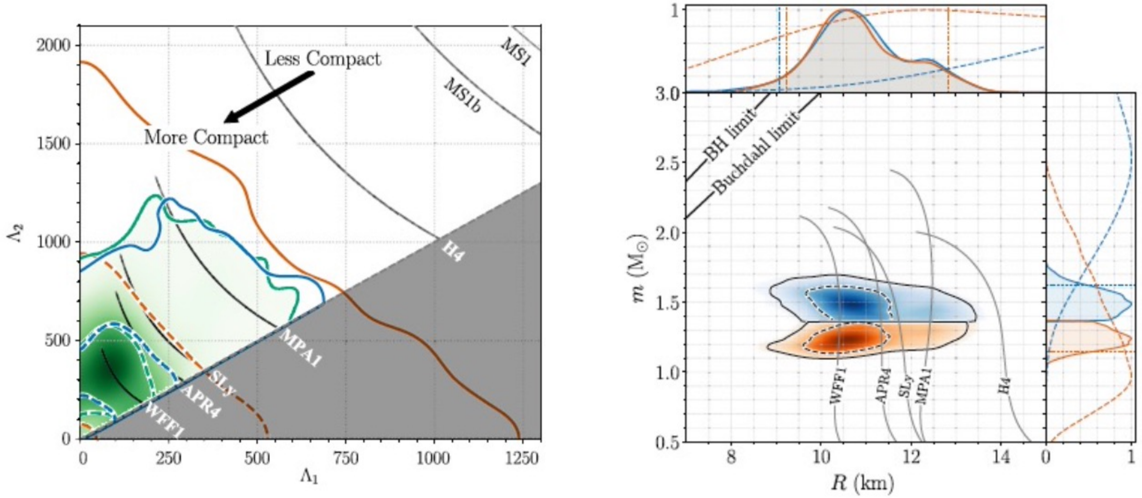
Astrophysical constraints (Mass, Radius)

$2M_\odot$ neutron stars

- PSR J1614–2230 ($M = 1.928 \pm 0.017\ M_\odot$)
- PSR J0348+0432 ($M = 2.01 \pm 0.04\ M_\odot$)
- PSR J0740+6620 ($M = 2.14^{+0.10}_{-0.09}\ M_\odot$)

GW detection from neutron star merger

Tidal deformability (Λ) → constraint on compactness (M/R)



B.P. Abbott et al., Phys. Rev. Lett. 121, 161101 (2018)

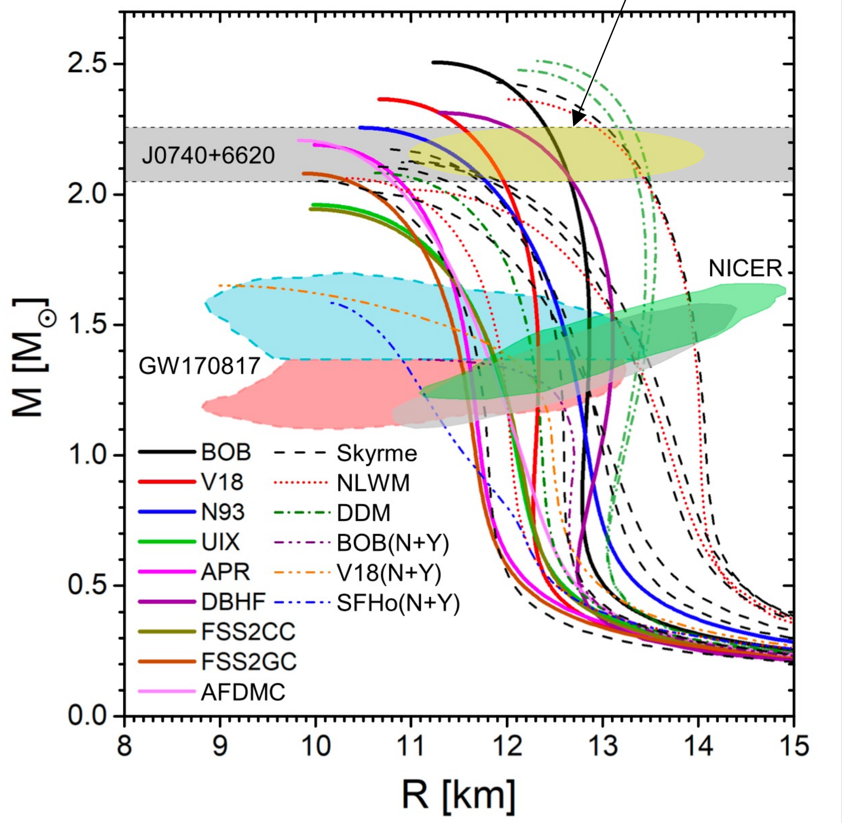
NICER

Hot spot information for neutron stars whose mass is well-measured.

→ constraint on compactness (M/R)

G.F. Burgio et al., Prog. Part. Nucl. Phys. 120, 103879 (2021).

T.E. Riley et al., arXiv:2105.06980



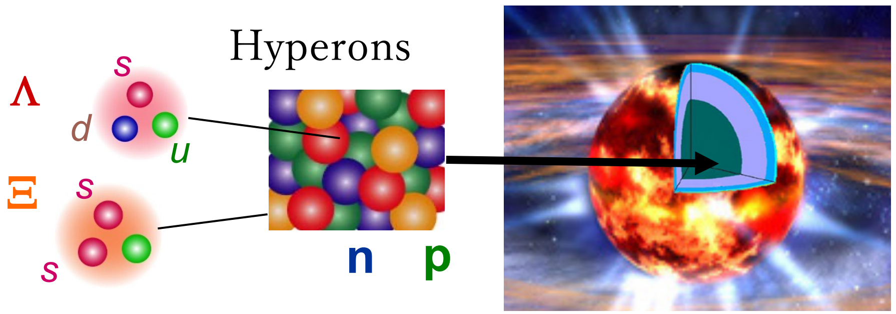
New constraints on M– R relation of NS

Essential "touchstone (試金石)" to judge the validity of equation of state

Hyperon puzzle in neutron star

Strange Hadronic Matter in neutron star ?

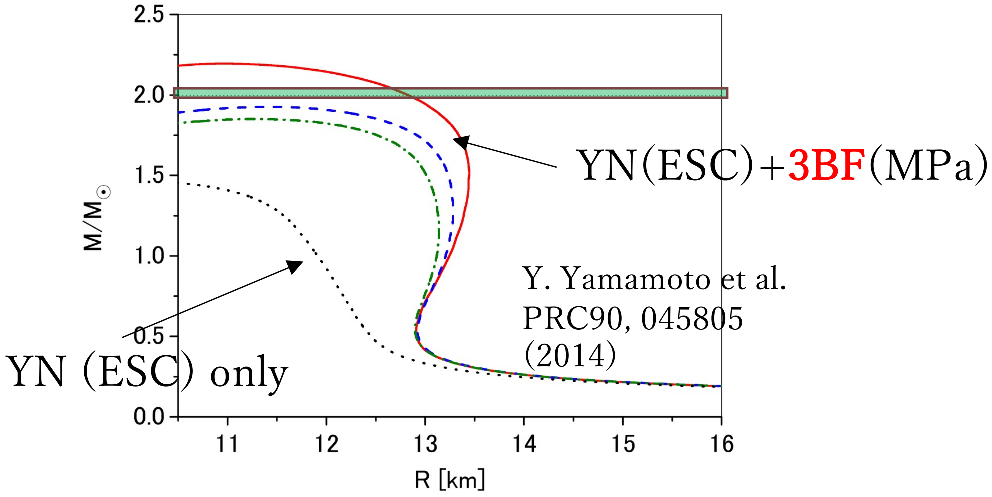
Hyperon's appearance is reasonable scenario because of the huge Fermi energy of neutrons in the inner core.



How can we reconcile ?

Hyperon appearance → **soften** EOS

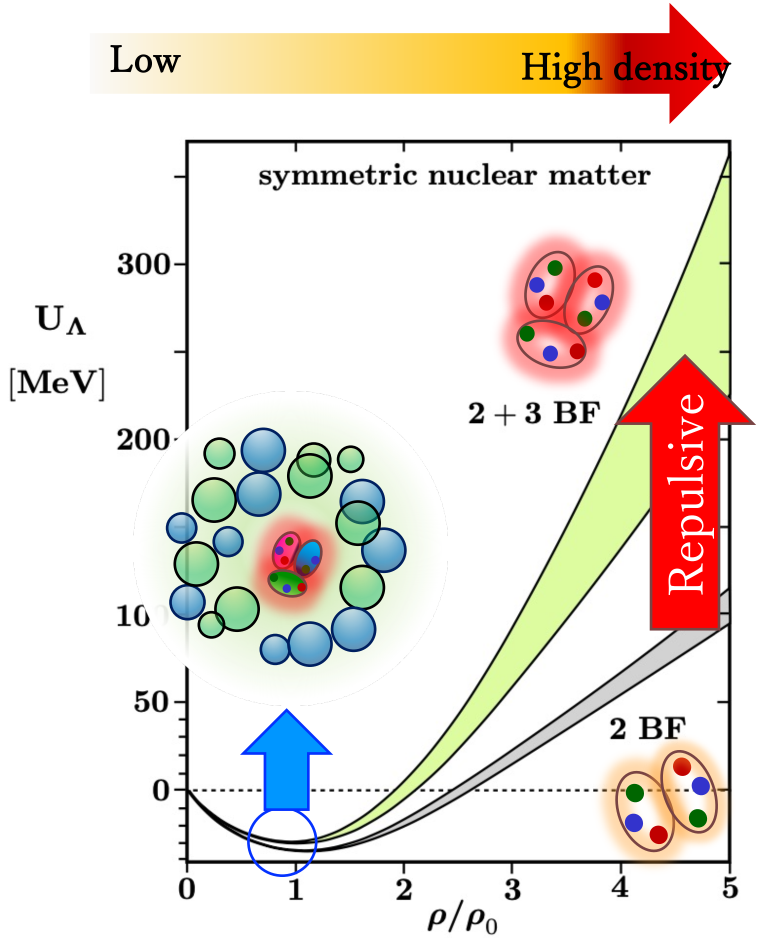
Two-solar-mass NS → require **stiff** EOS



Y. Yamamoto et al. PRC90, 045805 (2014)

3 Baryon Force (3BF):

Significant repulsive contribution at high density

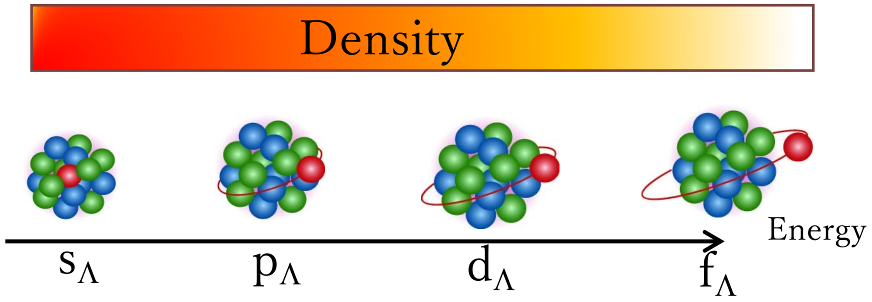


D. Gerstung et al., Eur. Phys. J. A(2020) 56:175

We have to understand the **density dependence of ΛN interaction** from **Λ binding energy data in hypernuclei.**
→ determine **the strength of the ΛNN force**

Λ binding energy measurement deep inside of nucleus : Unique for Λ hypernuclei

Nuclear density is different for each Λ orbital state



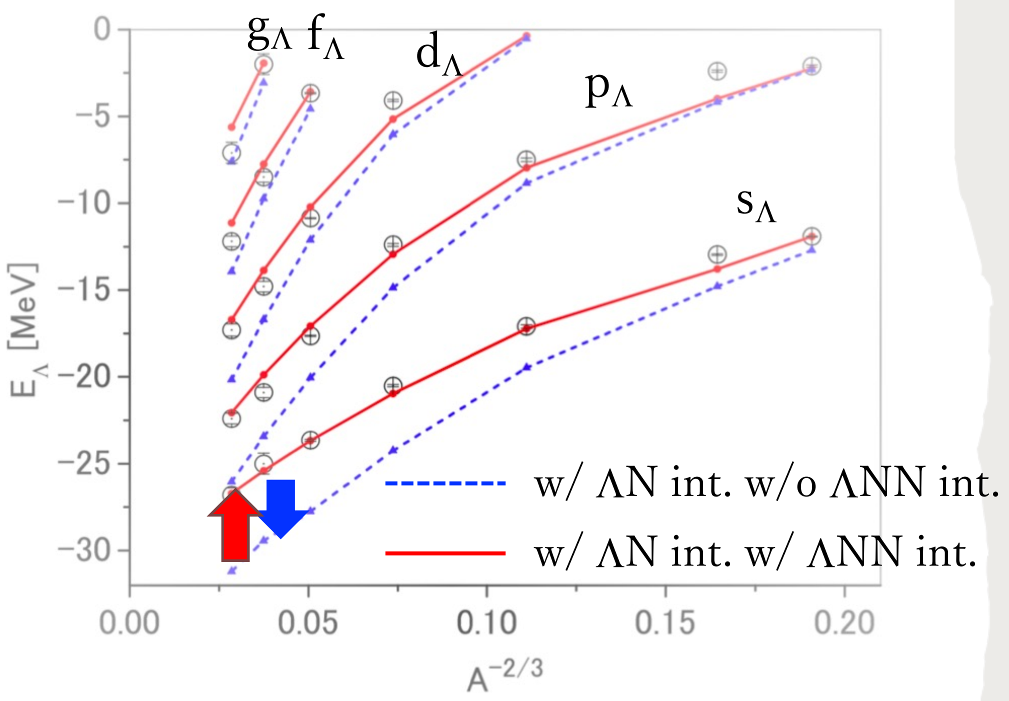
AMD calc. by M. Isaka

k_F from ADA

${}^{40}_{\Lambda}$K(s): k_F = 1.26 fm^{-1}
${}^{40}_{\Lambda}$K(p): k_F = 1.15 fm^{-1}
${}^{40}_{\Lambda}$K(d): k_F = 1.02 fm^{-1}

Energy spectra of ${}^{13}_{\Lambda}$C, ${}^{16}_{\Lambda}$O, ${}^{28}_{\Lambda}$Si, ${}^{51}_{\Lambda}$V, ${}^{89}_{\Lambda}$Y, ${}^{139}_{\Lambda}$La, ${}^{208}_{\Lambda}$Pb with Nijmegen ESC16 model

M.M. Nagels et al. Phys. Rev. C99, 044003 (2019)



Two directions for study of the density dependence of ΛN interaction

- Mass number dependence of B_Λ
- Λ orbital dependence of B_Λ

Accurate B_Λ measurement ⟷ Difference — Effect of **density dependence** of ΛN interaction

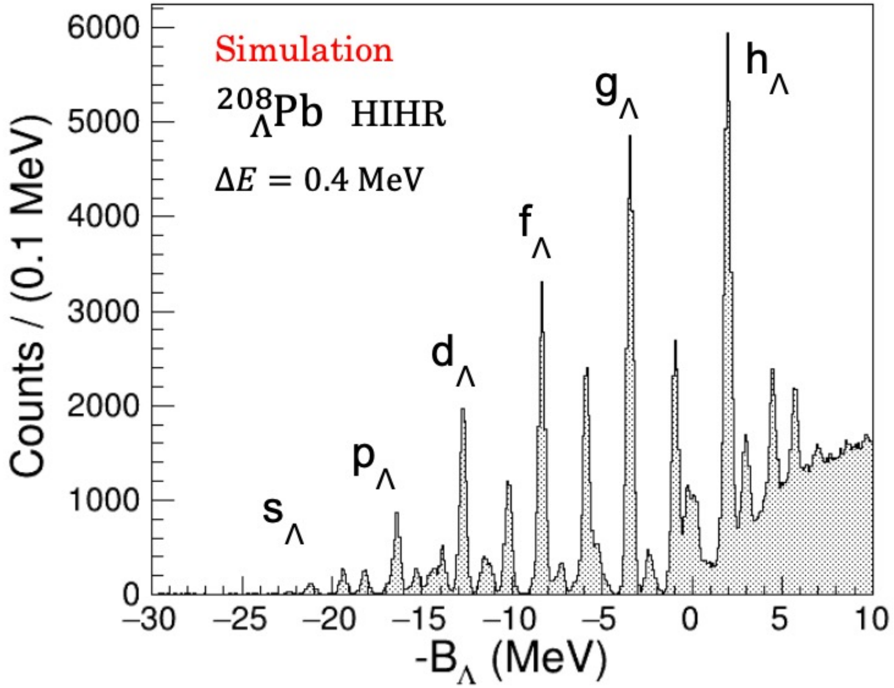
Calculation w/ only ΛN int : Over bound

ΛNN repulsive interaction is introduced to explain Λ hypernuclear binding energy

This density dependence should be explained from ΛNN force.
→ Predict ΛN int. in higher density nuclear matter.

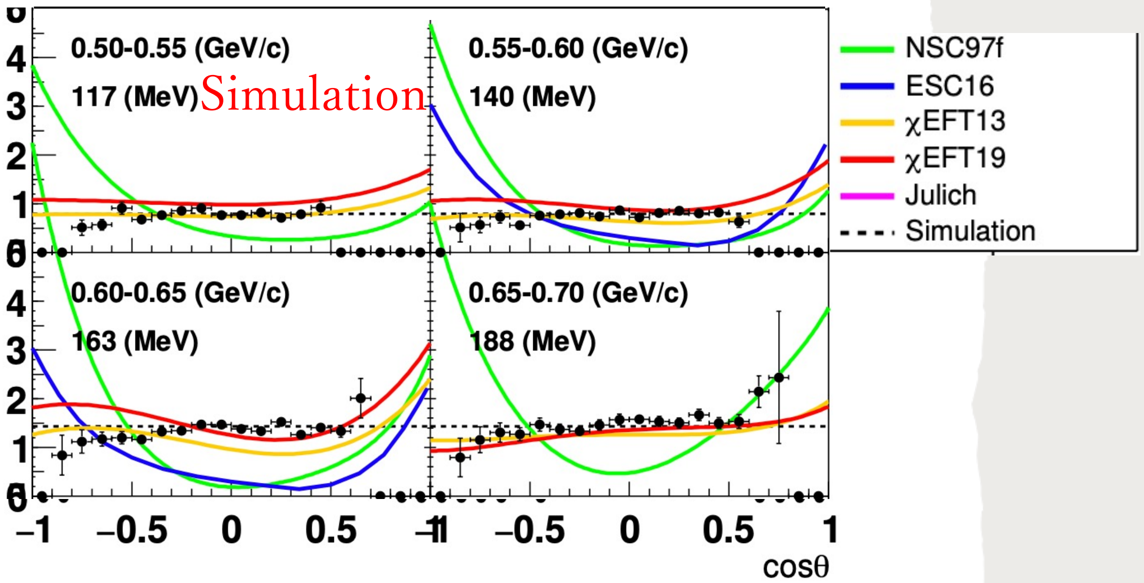
Λ binding energy measurement deep inside of nucleus : Unique for Λ hypernuclei

High-resolution Λ hypernuclear spectroscopy at HIHR



Realistic ΛN two-body interaction
by theoretical model based on ΛN scattering at K1.1

Differential cross section of Λp scattering



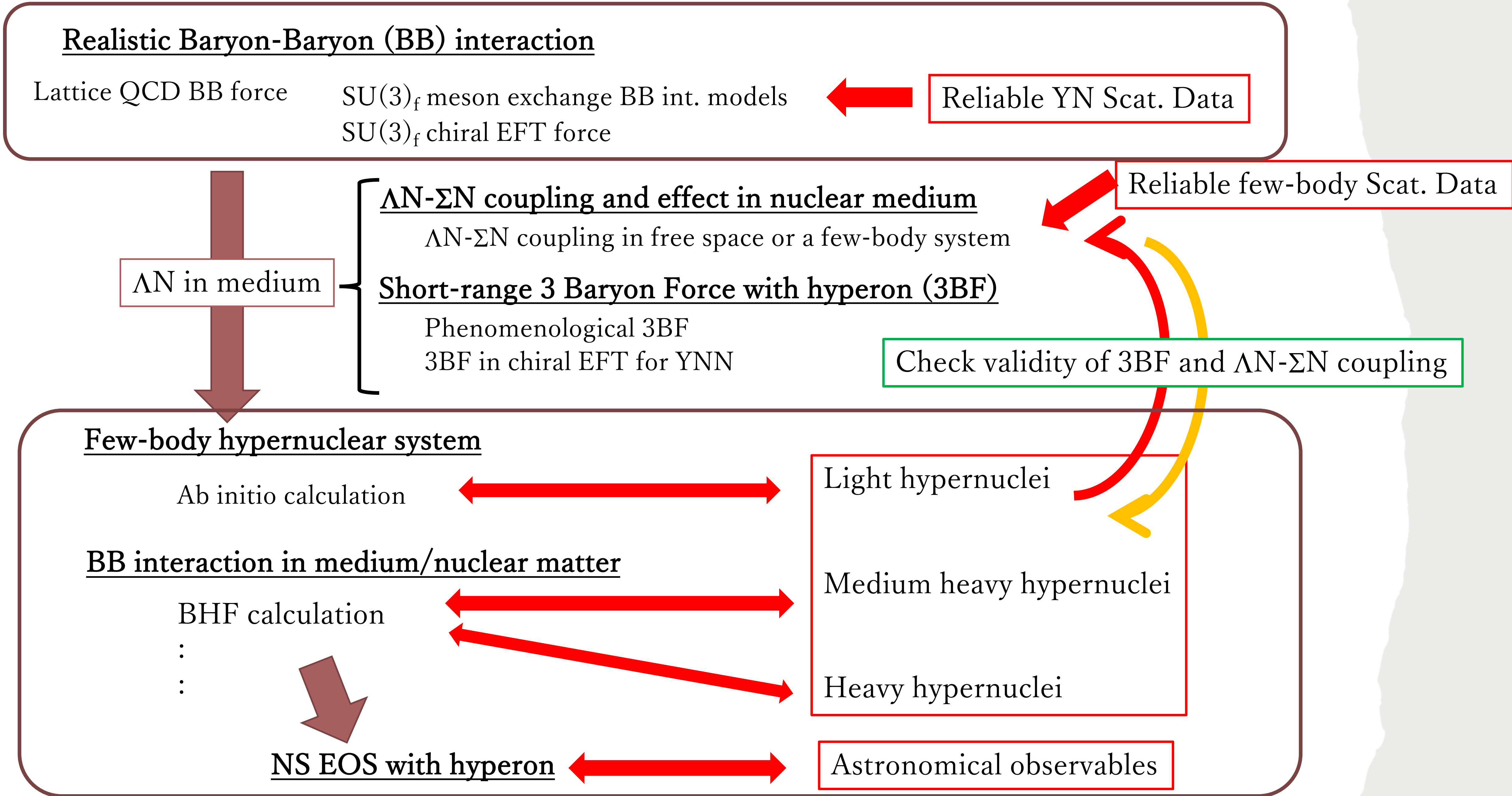
Accurate B_Λ measurement

Difference

Effect of **density dependence of ΛN interaction**

Calculation w/ realistic ΛN interaction

Understand hypernuclei and extend to neutron star



Realistic Baryon-Baryon (BB) interaction

Lattice QCD BB force

$SU(3)_f$ meson exchange BB int. models
$SU(3)_f$ chiral EFT force

Reliable YN Scat. Data

Reliable few-body Scat. Data

ΛN in medium

ΛN-ΣN coupling and effect in nuclear medium

ΛN-ΣN coupling in free space or a few-body system

Short-range 3 Baryon Force with hyperon (3BF)

Phenomenological 3BF
3BF in chiral EFT for YNN

Check validity of 3BF and ΛN-ΣN coupling

Few-body hypernuclear system

Ab initio calculation

BB interaction in medium/nuclear matter

BHF calculation
:
:

NS EOS with hyperon

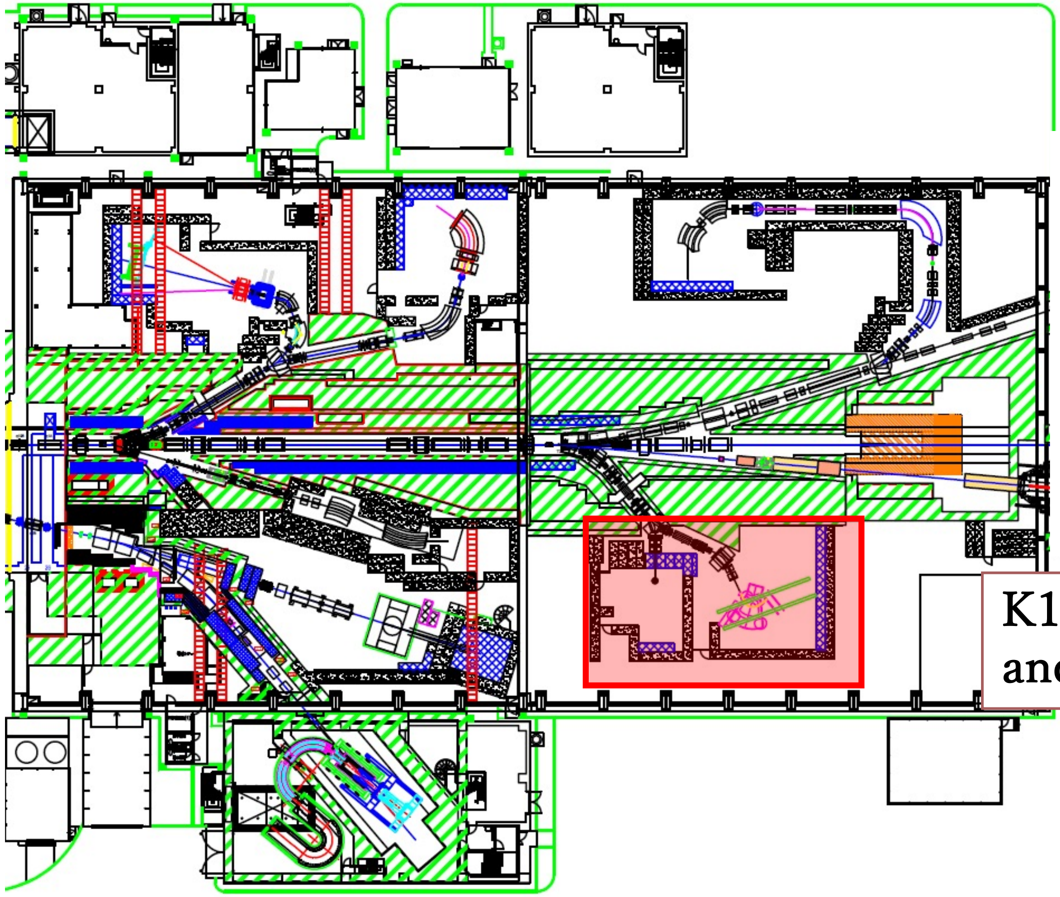
Light hypernuclei

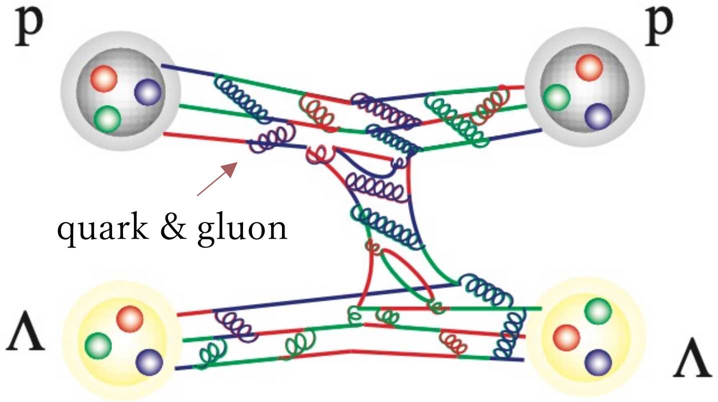
Medium heavy hypernuclei

Heavy hypernuclei

Astronomical observables

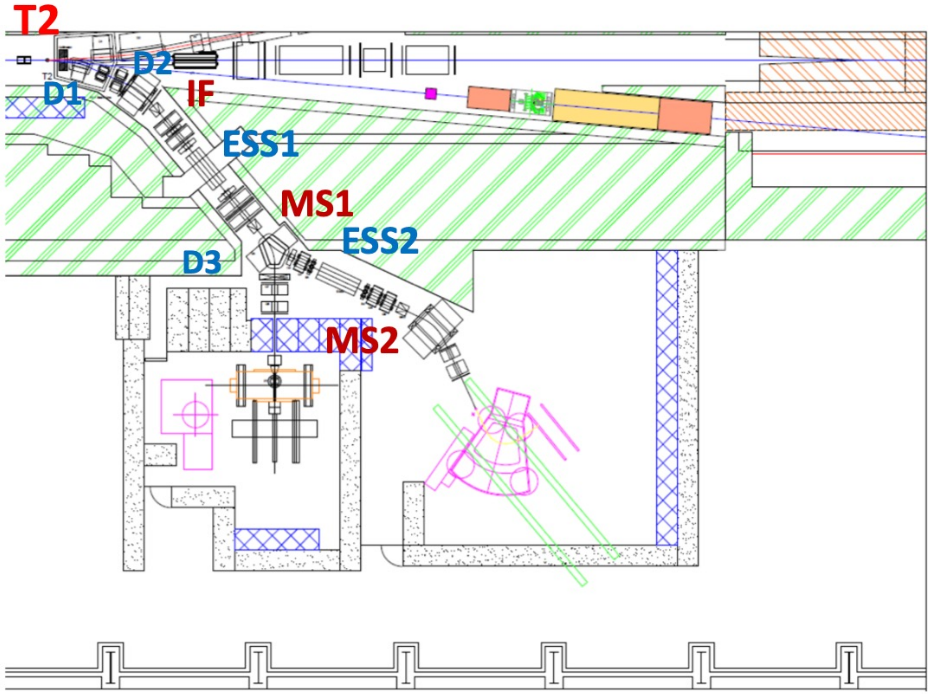
K1.1 programs



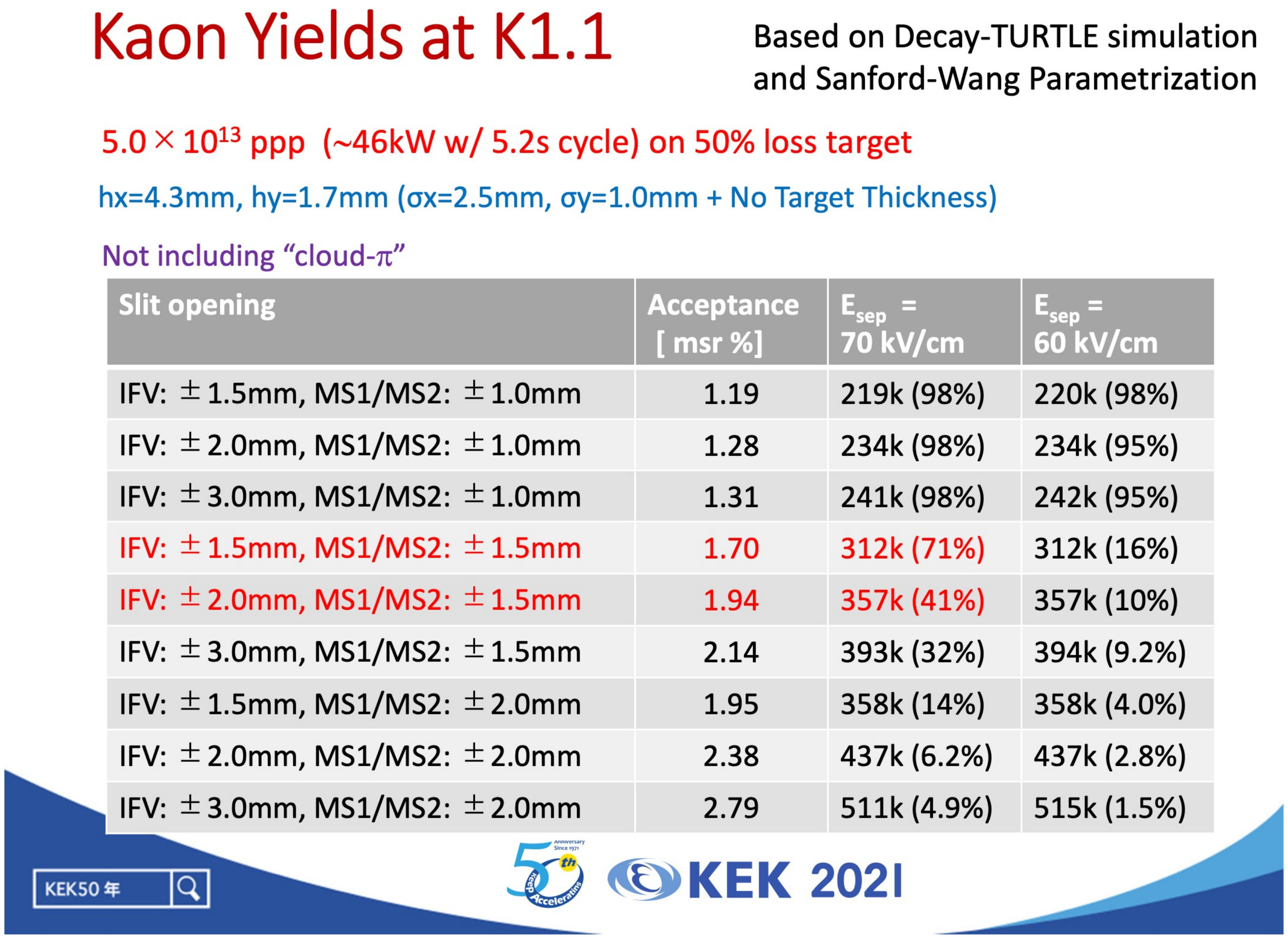


K1.1 beam line for high statistics YN scattering and S=-1 physics

K1.1/K1.1BR Beamline



Short length : 27.32 m (K1.1)
Double 2m long electric separators
SKS at K1.1



Kaon Yields at K1.1

Based on Decay-TURTLE simulation
and Sanford-Wang Parametrization

5.0×10^{13} ppp (~46kW w/ 5.2s cycle) on 50% loss target

hx=4.3mm, hy=1.7mm (σx=2.5mm, σy=1.0mm + No Target Thickness)

Not including "cloud-π"

Slit opening	Acceptance [msr %]	E_{sep} = 70 kV/cm	E_{sep} = 60 kV/cm
IFV: ±1.5mm, MS1/MS2: ±1.0mm	1.19	219k (98%)	220k (98%)
IFV: ±2.0mm, MS1/MS2: ±1.0mm	1.28	234k (98%)	234k (95%)
IFV: ±3.0mm, MS1/MS2: ±1.0mm	1.31	241k (98%)	242k (95%)
IFV: ±1.5mm, MS1/MS2: ±1.5mm	1.70	312k (71%)	312k (16%)
IFV: ±2.0mm, MS1/MS2: ±1.5mm	1.94	357k (41%)	357k (10%)
IFV: ±3.0mm, MS1/MS2: ±1.5mm	2.14	393k (32%)	394k (9.2%)
IFV: ±1.5mm, MS1/MS2: ±2.0mm	1.95	358k (14%)	358k (4.0%)
IFV: ±2.0mm, MS1/MS2: ±2.0mm	2.38	437k (6.2%)	437k (2.8%)
IFV: ±3.0mm, MS1/MS2: ±2.0mm	2.79	511k (4.9%)	515k (1.5%)

KEK50年

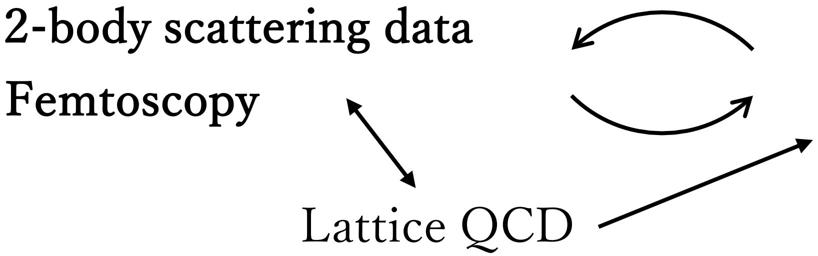
KEK 2021

High intensity pion beams can also be available

Experimental progress on two-body YN interactions

YN case

Link between here are connected



2-body scattering data

Femtoscopy

Lattice QCD

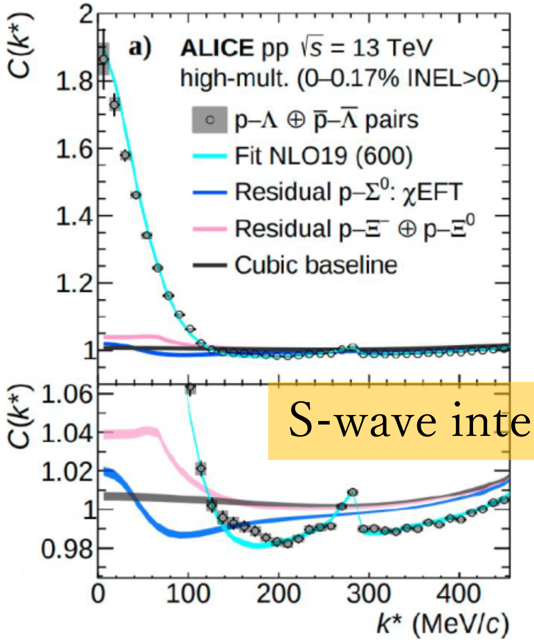
Base to improve to realistic two-body BB interaction is being constructed both theoretically and experimentally.

BB interaction model

- ☐ Meson exchange BB int. models
- ☐ Chiral EFT

Small relative-momentum region

ALICE Collaboration, arXiv:2104.04427

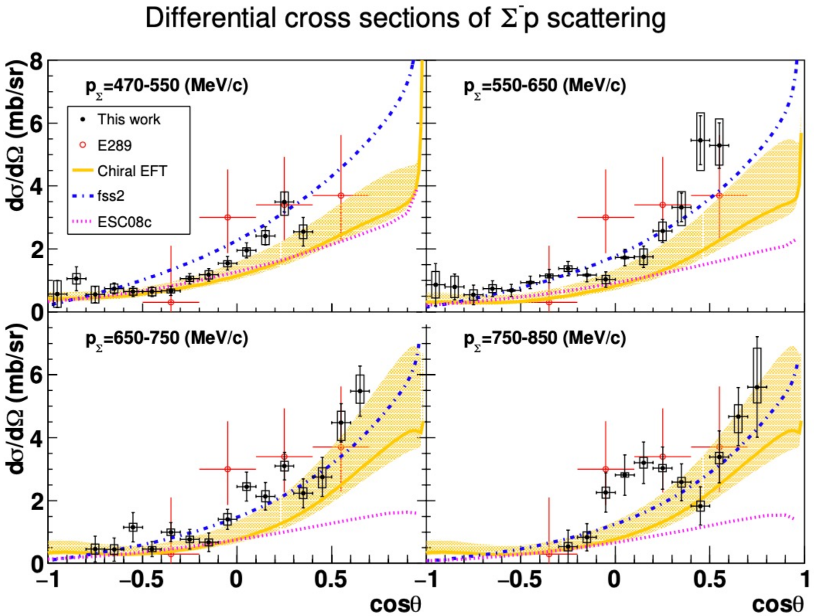


S-wave interaction

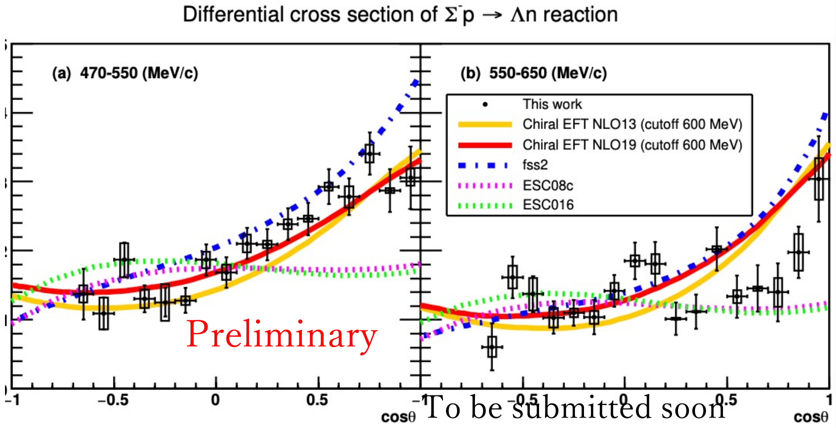
Femtoscopy from HIC

Intermediate energy region

K. Miwa et al. arXiv:2104.13608



P- and higher wave interaction



To be submitted soon

J-PARC E40 (K1.8 beam line)

Experimental method for YN scattering was established.

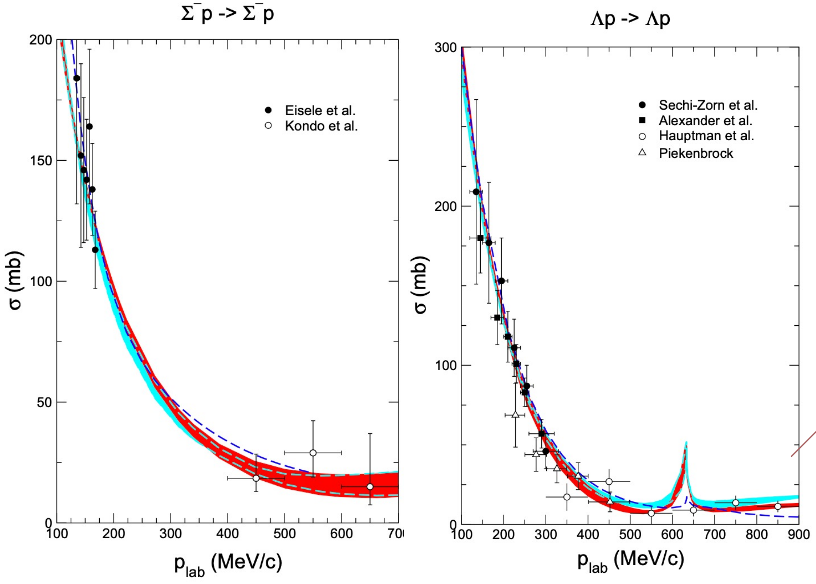
Chiral EFT

Underlying chiral symmetry in QCD

Power counting feature to improve calculation systematically by going to higher order

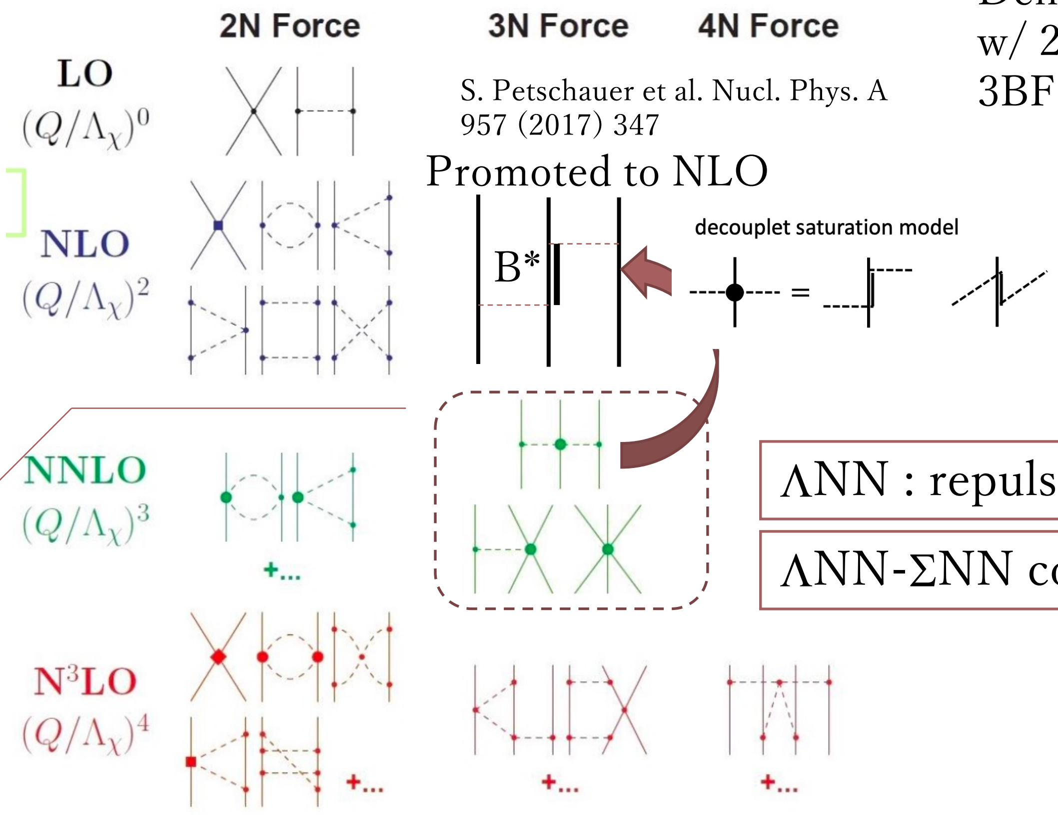
Multi baryon force appears naturally and automatically in a consistent implementation of the framework

YN interaction at NLO



J. Haidenbauer et al., Eur. Phys. J. A (2020) 56:91

J. Haidenbauer et al., Nucl. Phys. A 915 (2013) 24

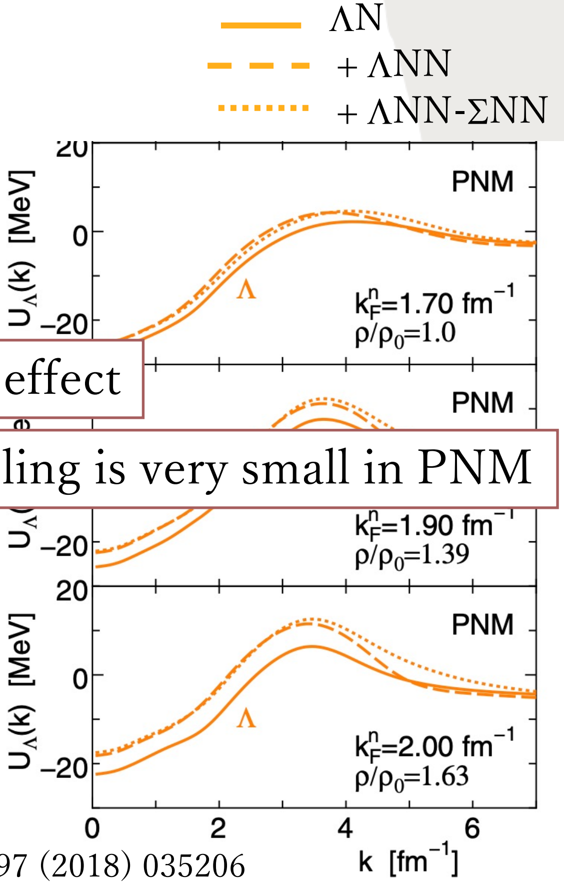


S. Petschauer et al. Nucl. Phys. A 957 (2017) 347

Promoted to NLO

From slide by M. Kohno

Density-dependent effective potential w/ 2π-exchange ΛNN and ΛNN-ΣNN 3BF

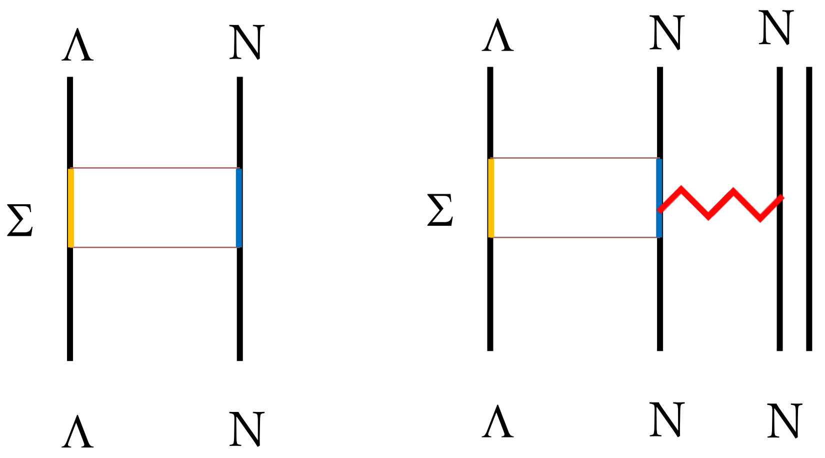


ΛNN : repulsive effect

ΛNN-ΣNN coupling is very small in PNM

M. Kohno, Phys. Rev. C 97 (2018) 035206

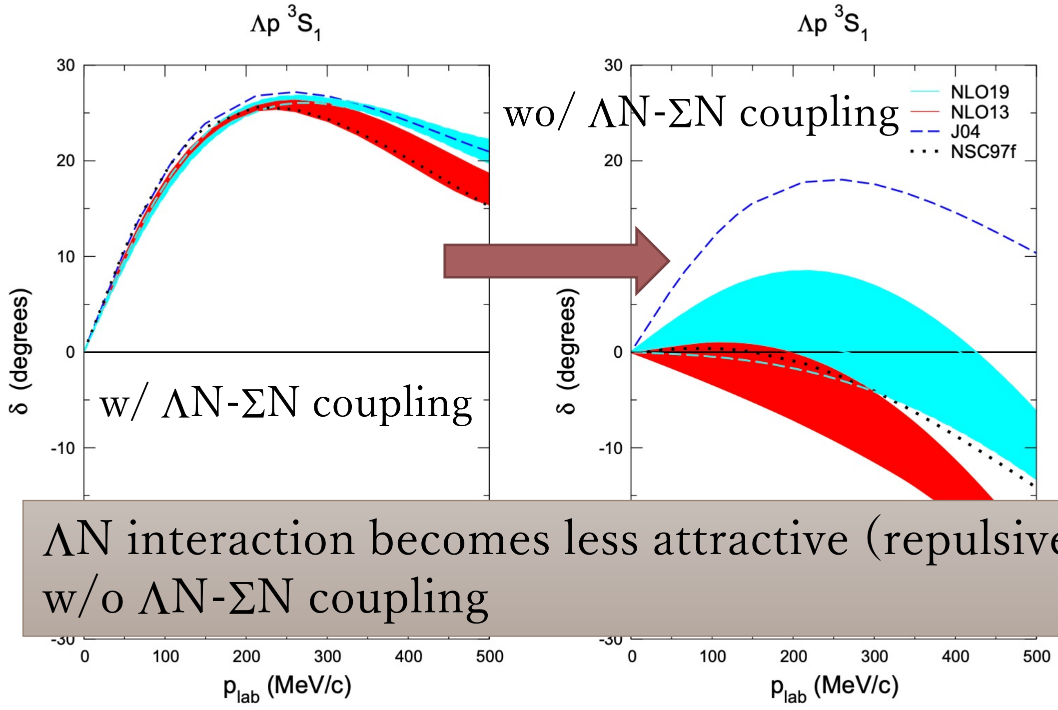
Source of attractive ΛN interaction ΛN-ΣN coupling



Pauli blocking

ΛN-ΣN coupling can be suppressed in nuclear medium due to the Pauli blocking at the intermediate N state

Artificially switch off ΛN-ΣN coupling potential



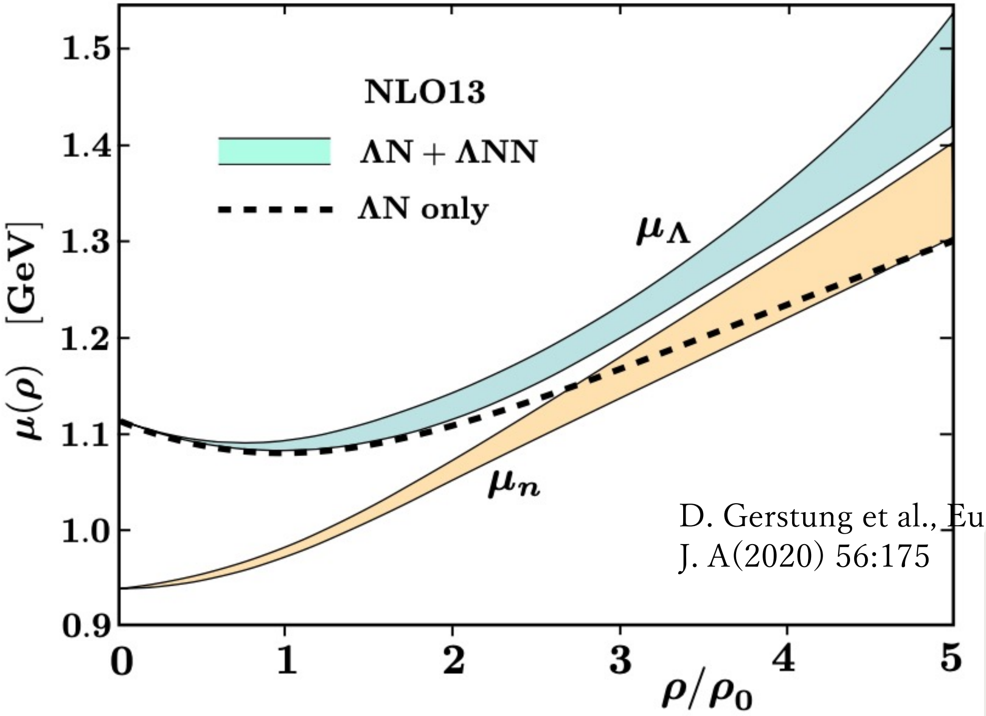
w/ ΛN-ΣN coupling

wo/ ΛN-ΣN coupling

ΛN interaction becomes less attractive (repulsive) w/o ΛN-ΣN coupling

J. Haidenbauer et al., Eur. Phys. J. A (2020) 56:91

w/ ΛN interaction with large ΛN-ΣN coupling
+ ΛNN three-repulsive force (LECs for ΛNN are adjusted)



D. Gerstung et al., Eur. Phys. J. A(2020) 56:175

Λ does not appear in neutron star ?

ΛN interaction and its uncertainty

Limited data

- Λp scattering data
- Λ binding energy of $^{3}_{\Lambda}\mathrm{H}$

$^{3}S_{1}$ and $^{1}S_{0}$ interactions ?

Scattering length of $^{1}S_{0}$ and $^{3}S_{1}$

Not sensitive to Λp total cross section

Sensitive to $^{3}_{\Lambda}\mathrm{H}$ binding energy

→ Precise information of $^{3}_{\Lambda}\mathrm{H}$ is essential

(emulsion, (e, e'K^{+}) experiment)

P-wave interaction ?

No Λp scattering data with differential information

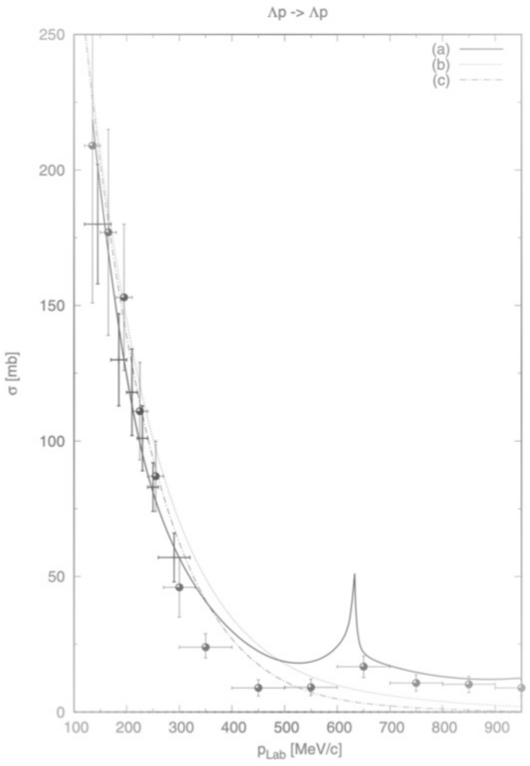
Difficult to fix YN contact terms in P waves

Total cross section might be similar for each model

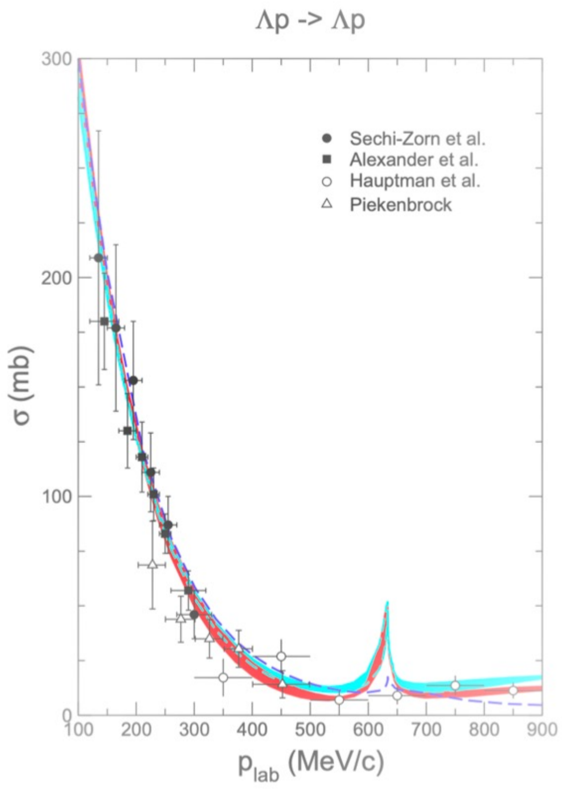
But, Large uncertainty in the P-wave interaction

→ Differential observables in Λp scattering

(1) ESC16 (Nijmegen)



(2) Chiral EFT



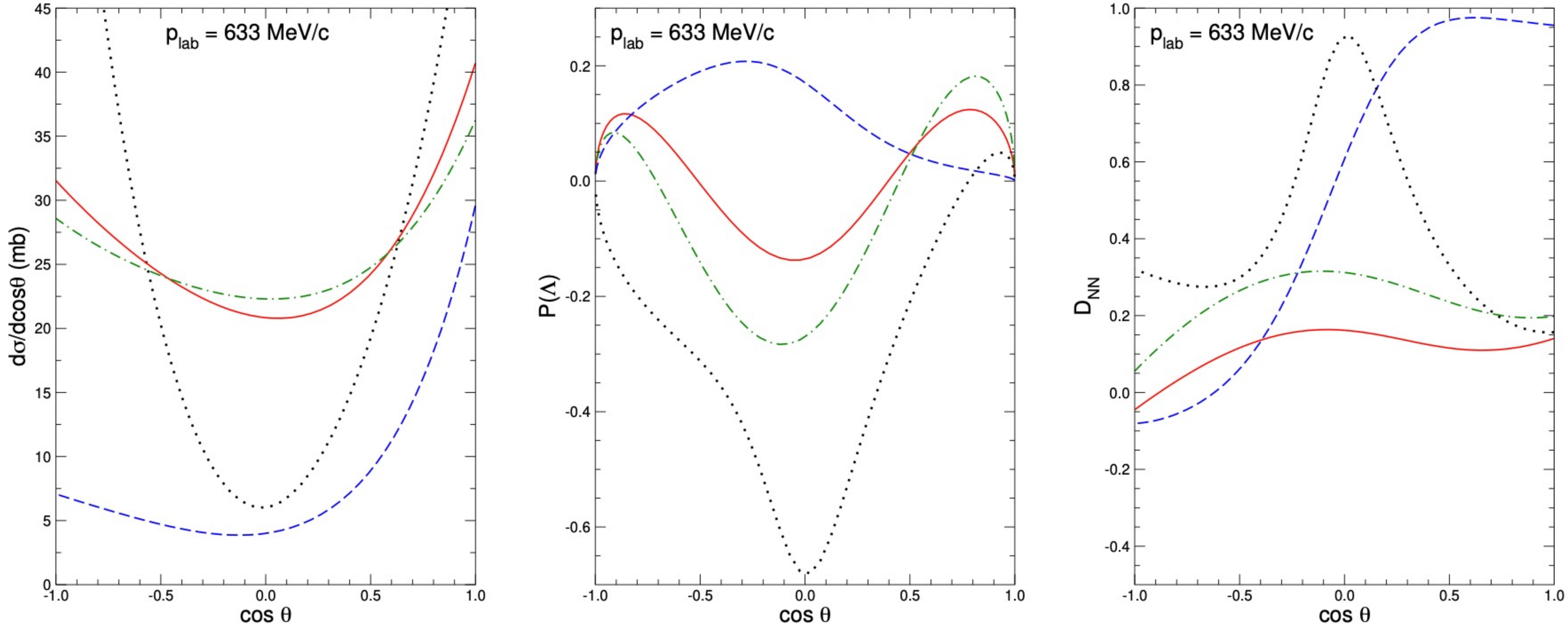
ΛN Differential information at ΣN threshold

- - - - NSC97f
— — — Julich 04
——— Chiral EFT(NLO13)
— · — · Chiral EFT(NLO19)

Differential cross section

Polarization (Λ)

Depolarization (D_{NN})



J. Haidenbauer, U.G. Meißner arXiv:2105.00836

Such a difference clearly appears in differential observables !
We should measure these differential cross sections and spin observables to constrain theoretical model strongly.

Spin-dependent YN interaction from scattering

From S. Ishikawa et al.
PRC 69, 034001 (2004)

dσ/dΩ and spin observables are essential to construct realistic YN interaction.

spin-independent spin-spin symmetric LS (ΔS=0) anti-symmetric LS (ΔS=1) Tensor

T matrix

$$\boldsymbol{M} = V_{\mathrm{c}} + V_{\sigma}(\boldsymbol{s}_a \cdot \boldsymbol{s}_b) + V_{\mathrm{SLS}}(\boldsymbol{s}_a + \boldsymbol{s}_b) \cdot \boldsymbol{L} + V_{\mathrm{ALS}}(\boldsymbol{s}_a - \boldsymbol{s}_b) \cdot \boldsymbol{L} + V_{\mathrm{T}}([\boldsymbol{s}_a \otimes \boldsymbol{s}_b]^{(2)} \cdot \boldsymbol{Y}_2(\hat{\boldsymbol{r}})),$$

Scalar amplitude

$$U_\alpha \equiv < \boldsymbol{k}_f | V_c | \boldsymbol{k}_i >, U_\beta \equiv < \boldsymbol{k}_f | V_\sigma | \boldsymbol{k}_i >$$

Vector amplitude

$$S_{ALS} \equiv < \boldsymbol{k}_f | V_{ALS} L_1 | \boldsymbol{k}_i >, S_{ALS} \equiv < \boldsymbol{k}_f | V_{SLS} L_1 | \boldsymbol{k}_i >$$

Tensor amplitude

$$T_j = \frac{1}{2} < \boldsymbol{k}_f | V_T Y_{2j-1} | \boldsymbol{k}_i >$$

We are going to measure following observables.

Differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right) = \frac{1}{4}\mathrm{Tr}(MM^\dagger) = |U_\alpha|^2 + \frac{3}{16}|U_\beta|^2 + \frac{1}{2}(|S_{SLS}|^2 + |S_{ALS}|^2) + \frac{1}{4}|T_1|^2 + \frac{1}{2}(|T_2|^2 + |T_3|^2).$$

Analyzing power
(Polarization)

$$A_y(Y) = -\frac{1}{\sqrt{2}\sigma(\theta)}\mathrm{Im}\left\{(U_\alpha + \frac{1}{4}U_\beta)^* S_{SLS} + (U_\alpha - \frac{1}{4}U_\beta)^* S_{ALS} - \frac{1}{2}T_\alpha^*(-S_{ALS} + S_{SLS})\right\},$$

Depolarization

$$D_y^y = \frac{1}{\sigma(\theta)}\mathrm{Re}\left\{\frac{1}{2\sqrt{3}}\left(U_0 + \frac{1}{\sqrt{3}}U_1\right)^* U_1 + \frac{1}{2}\left(U_0 - \frac{1}{\sqrt{3}}U_1\right)^* \left(\frac{1}{\sqrt{6}}T_1 + T_3\right) - S_1^* S_2 + \frac{1}{2}|S_3|^2 - \frac{1}{\sqrt{6}}T_1^*\left(\frac{1}{\sqrt{6}}T_1 - T_3\right) - \frac{1}{2}|T_2|^2\right\}.$$

Number of observables is still limited to determine each component separately.
But measurements of many observables contribute to impose constraints on YN theoretical models.

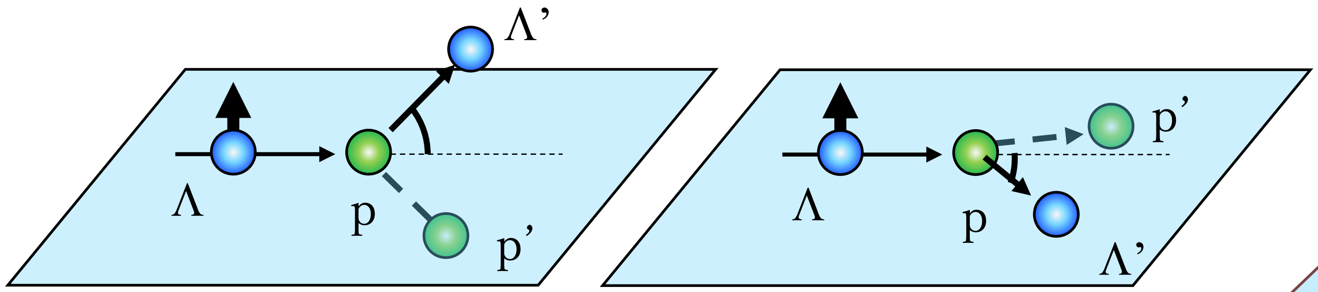
Spin-dependent YN interaction from scattering

Analyzing power

Left/Right asymmetry of Λp scattering

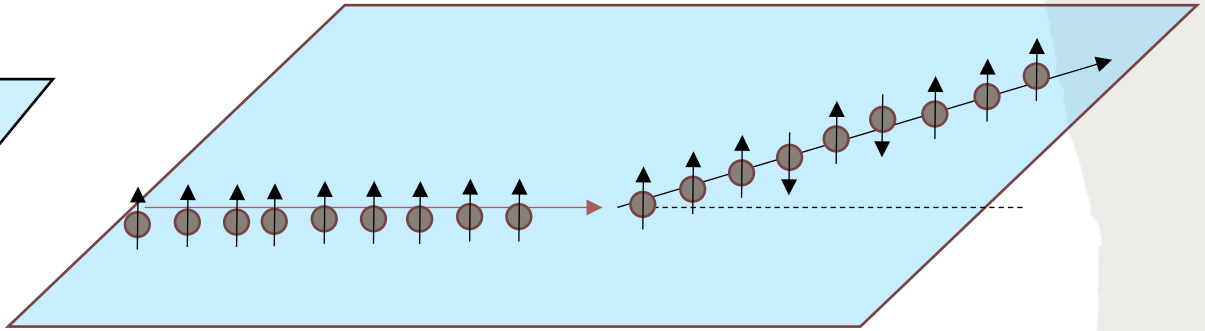
Left scattered event

Right scattered event



Depolarization ($D_y{}^y$)

Change the spin polarization after the Λp scattering



We are going to measure following observables.

Differential cross section

$$\left(\frac{d\sigma}{d\Omega}\right)=\frac{1}{4}\mathrm{Tr}(MM^\dagger)=|U_\alpha|^2+\frac{3}{16}|U_\beta|^2+\frac{1}{2}(|S_{SLS}|^2+|S_{ALS}|^2)+\frac{1}{4}|T_1|^2+\frac{1}{2}(|T_2|^2+|T_3|^2).$$

Analyzing power
(Polarization)

$$A_y(Y)=-\frac{1}{\sqrt{2}\sigma(\theta)}\mathrm{Im}\left\{(U_\alpha+\frac{1}{4}U_\beta)^*S_{SLS}+(U_\alpha-\frac{1}{4}U_\beta)^*S_{ALS}-\frac{1}{2}T_\alpha^*(-S_{ALS}+S_{SLS})\right\},$$

Depolarization

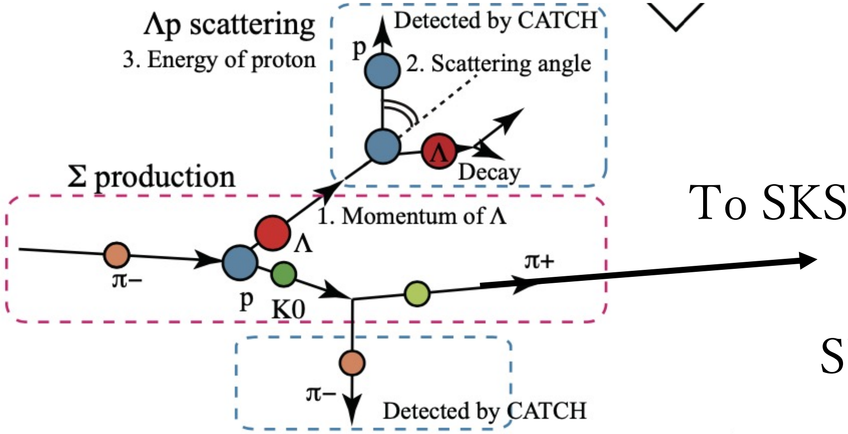
$$D_y^y=\frac{1}{\sigma(\theta)}\mathrm{Re}\left\{\frac{1}{2\sqrt{3}}\left(U_0+\frac{1}{\sqrt{3}}U_1\right)^*U_1+\frac{1}{2}\left(U_0-\frac{1}{\sqrt{3}}U_1\right)^*\left(\frac{1}{\sqrt{6}}T_1+T_3\right)-S_1^*S_2+\frac{1}{2}|S_3|^2-\frac{1}{\sqrt{6}}T_1^*\left(\frac{1}{\sqrt{6}}T_1-T_3\right)-\frac{1}{2}|T_2|^2\right\}.$$

Number of observables is still limited to determine each component separately.
But measurements of many observables contribute to impose constraints on YN theoretical models.

Λp scattering experiment at K1.1 beam line

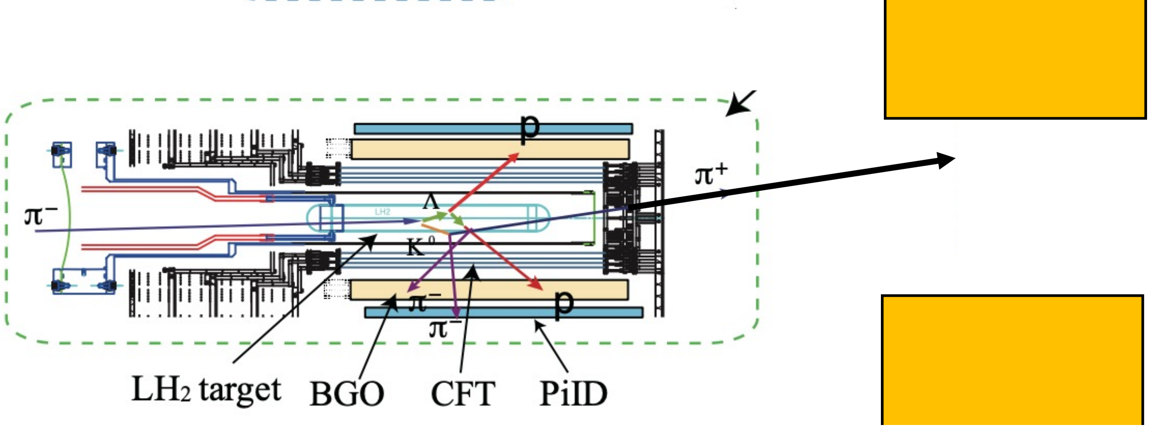
Λ beam identification

Tagged by $\pi^-p \rightarrow K^0\Lambda$ reaction at p=1.05 GeV/c



To SKS spectrometer

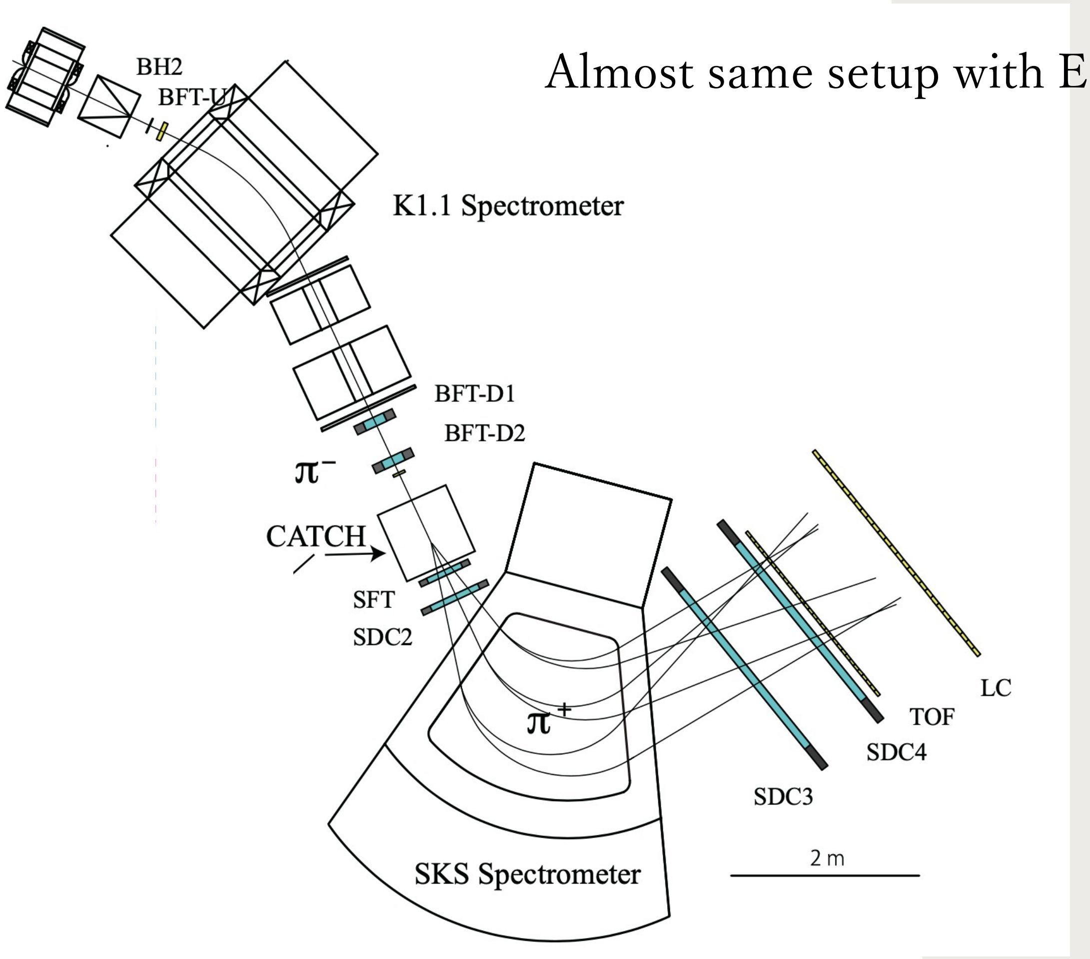
SKS spectrometer



Λp scattering identification

Detected by CATCH

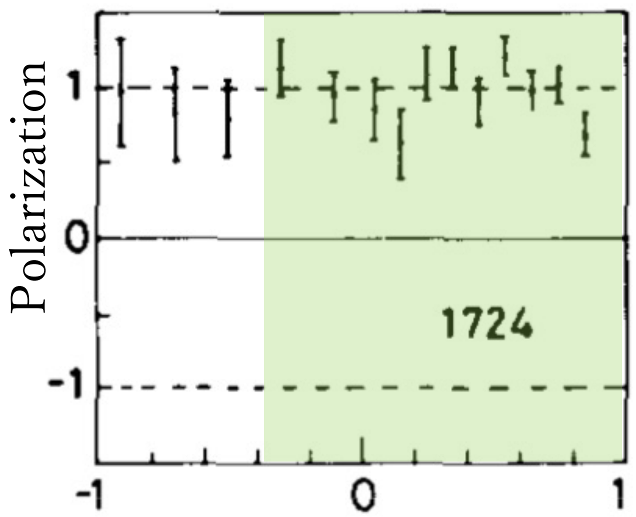
Almost same setup with E40



Polarized Λ beam

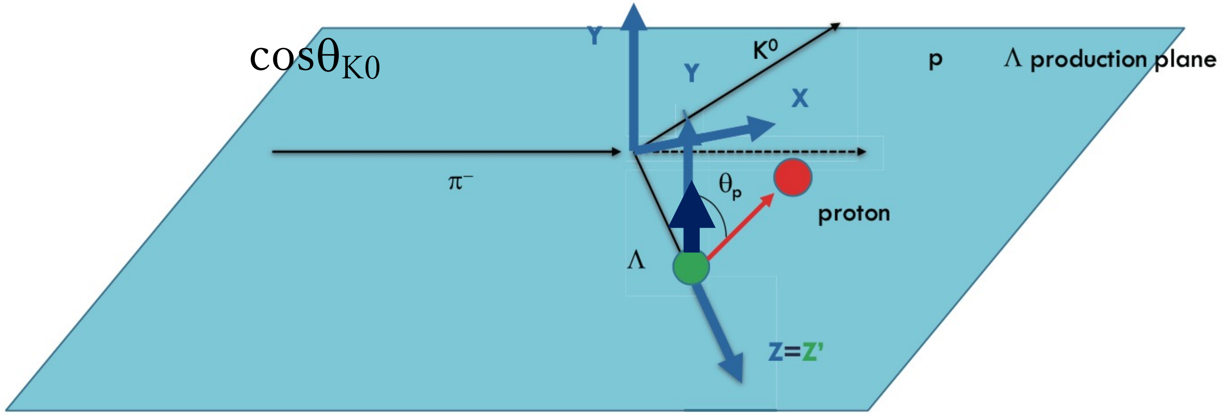
High spin polarization of Λ for Λ production plane

R.D. Baker et al. , Nucl. Phys. B141 (1978) 29

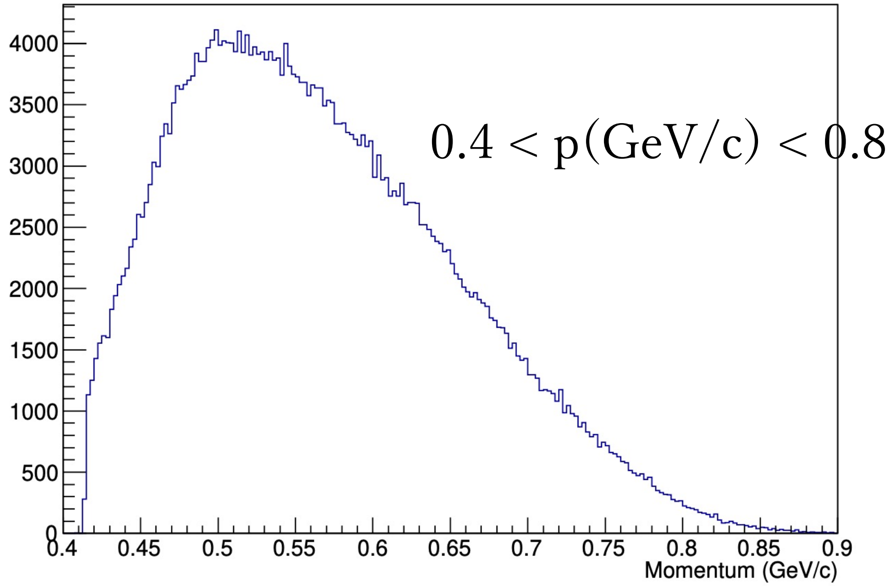


- ✓ Λ beam is automatically polarized with ~100% level

$\mathbf{Y} = \mathbf{P}_{\pi-} \times \mathbf{P}_{K0}$
$\mathbf{X} = \mathbf{Y} \times \mathbf{P}_{\Lambda}$
$\mathbf{Z} = \mathbf{P}_{\Lambda}$



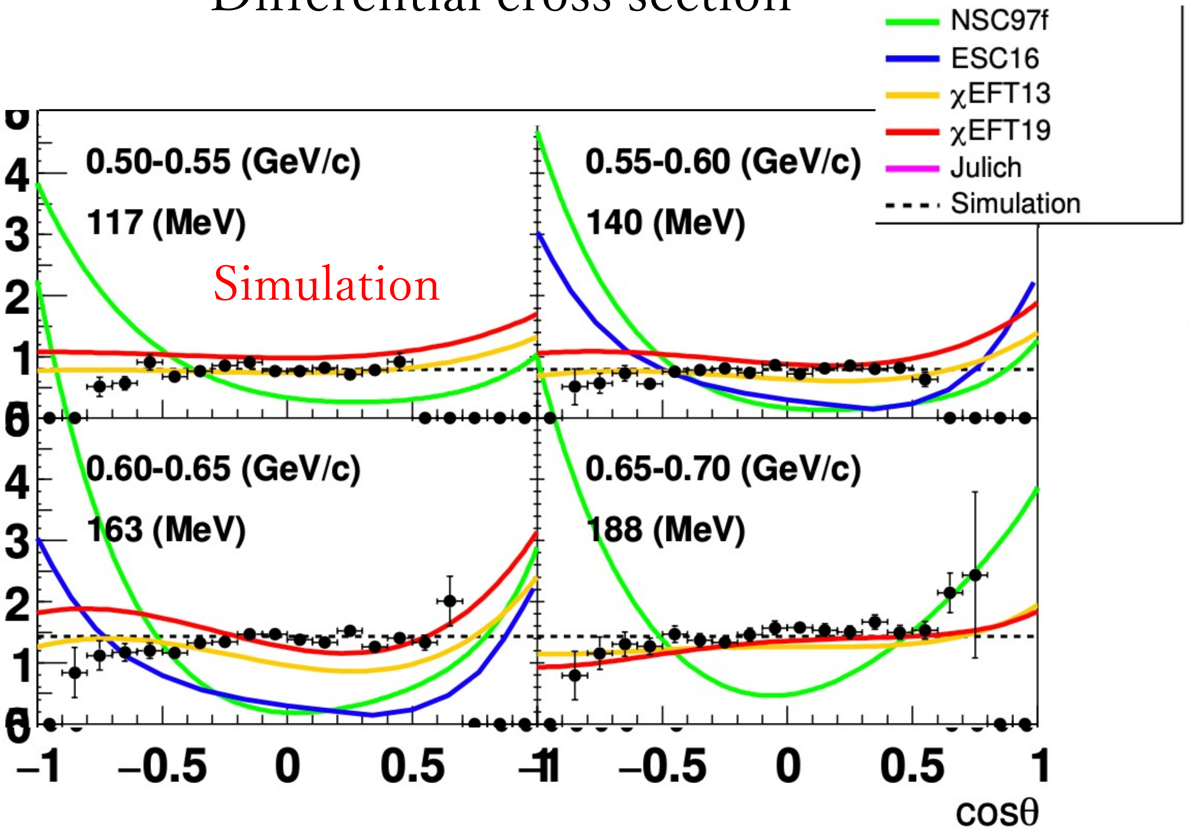
Momentum-tagged Λ beam


$0.4 < p(\mathrm{GeV}/c) < 0.8$

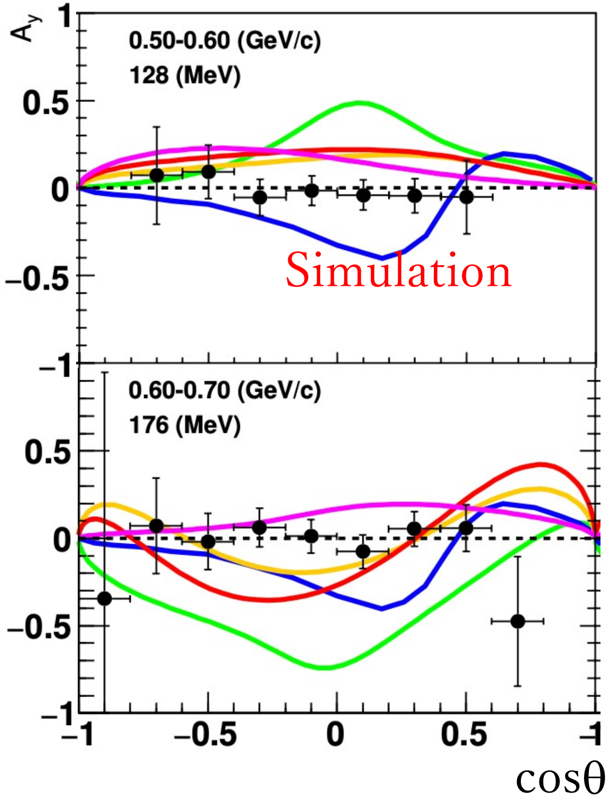
dσ/dΩ and Spin observables in Λp scattering

Simulated results w/ 100M Λ

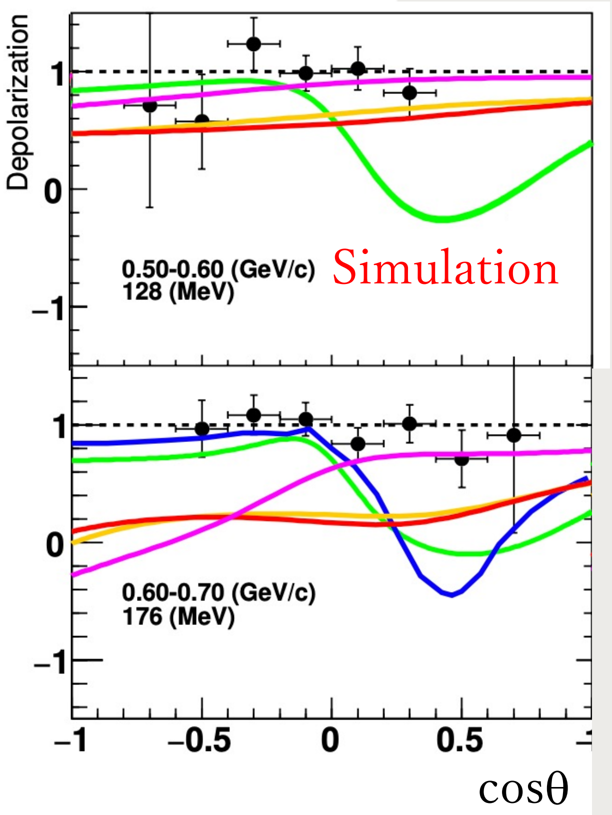
Differential cross section



Analyzing power



Depolarization (D_y^y)



No differential observables of Λp scattering in present.

--> Large uncertainty in P-wave and higher-wave interaction.

Theoretical prediction shows quite different angular dependence in dσ/dΩ, A_y and D_y^y

These new scattering data becomes essential constraint to determine spin-dependent ΛN interaction

Collaboration with Chiral EFT toward NNLO

Two body YN force

Num of LEC

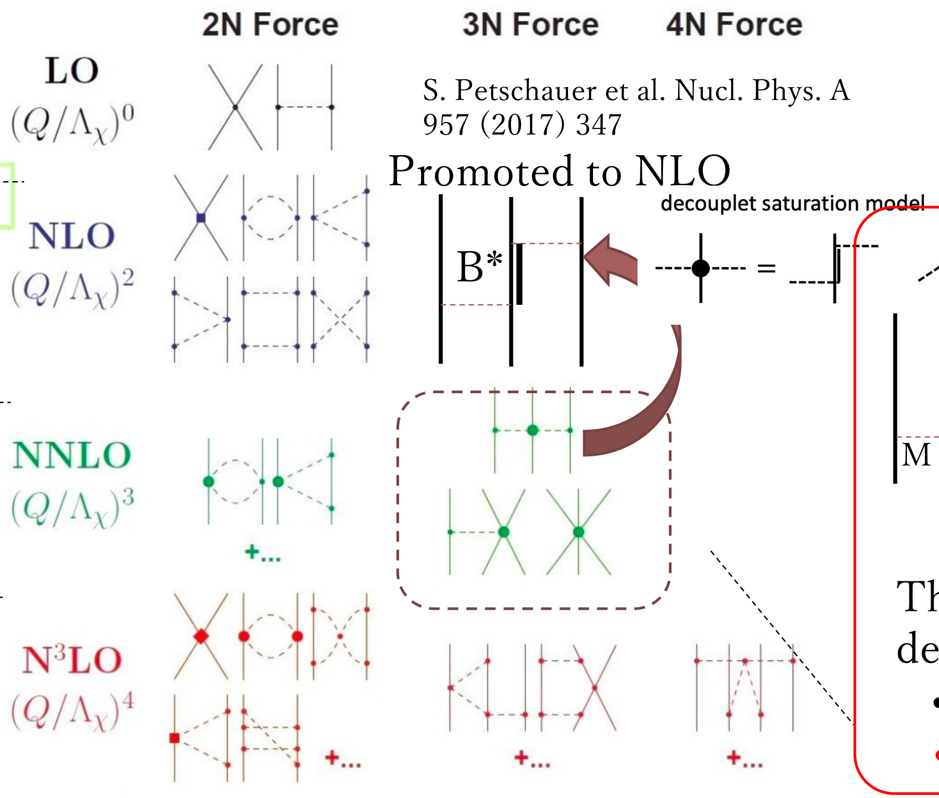
S wave : 5

S wave +
S-D transition : 8

P wave : 10

NO LEC

NNLO can be realized
with J-PARC data

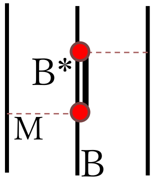


S. Petschauer et al. Nucl. Phys. A
957 (2017) 347

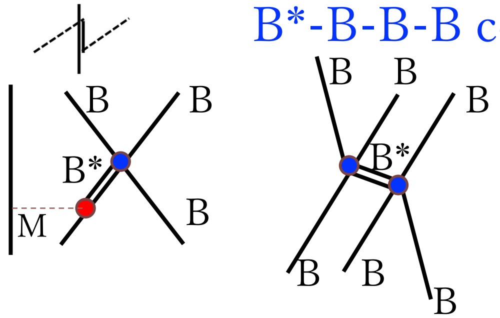
Promoted to NLO

Three body YNN force

Num of LEC in decuplet saturation model



B*-B-M coupling : 2
can be determined theoretically.
2π-exchange ΛNN force is
already studied.



B*-B-B-B coupling : 2

These two LECs should be
determined from experiment from

- binding energy ${}^{4}_{\Lambda}$He (0^+ and 1^+ states)
- **Λd scattering**

As a next step at K1.1, Λd scattering experiment can be performed using a liquid deuterium target with almost the same setup

Hypernucler γ-ray spectroscopy at K1.1

Slide from T.O. Yamamoto

J-PARC K1.1 beam line

0.8-1.1 GeV/c (K^-, π^-) reaction

- Large production cross-section
- Small Doppler broadening
  (also good for hyperfragments)

1.05 GeV/c (π^-, K^0) reaction (to be established)

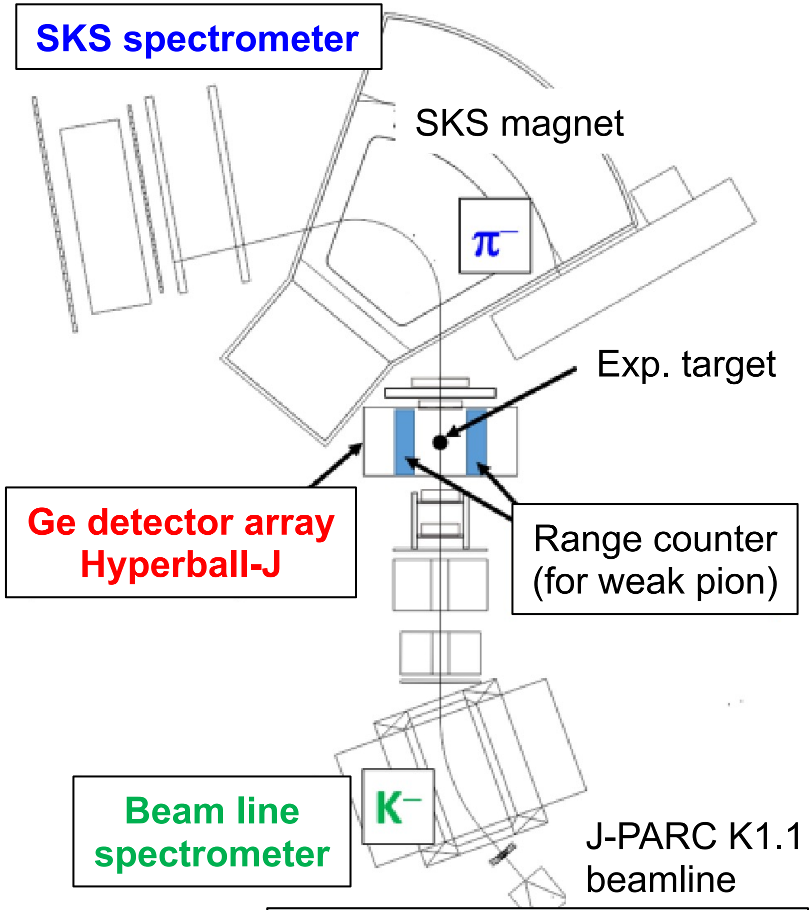
- Study of neutron-rich hypernuclei

reaction-γ coincidence experiment

- **Tag hypernuclear production**
  - **Beam line spectrometer**
  - **SksMinus spectrometer**
- **Detect γ–ray**
  - **Hyperball-J**
- **Tag weak decay π^-**
  - **Range counter**

Used for gamma–ray peak identification

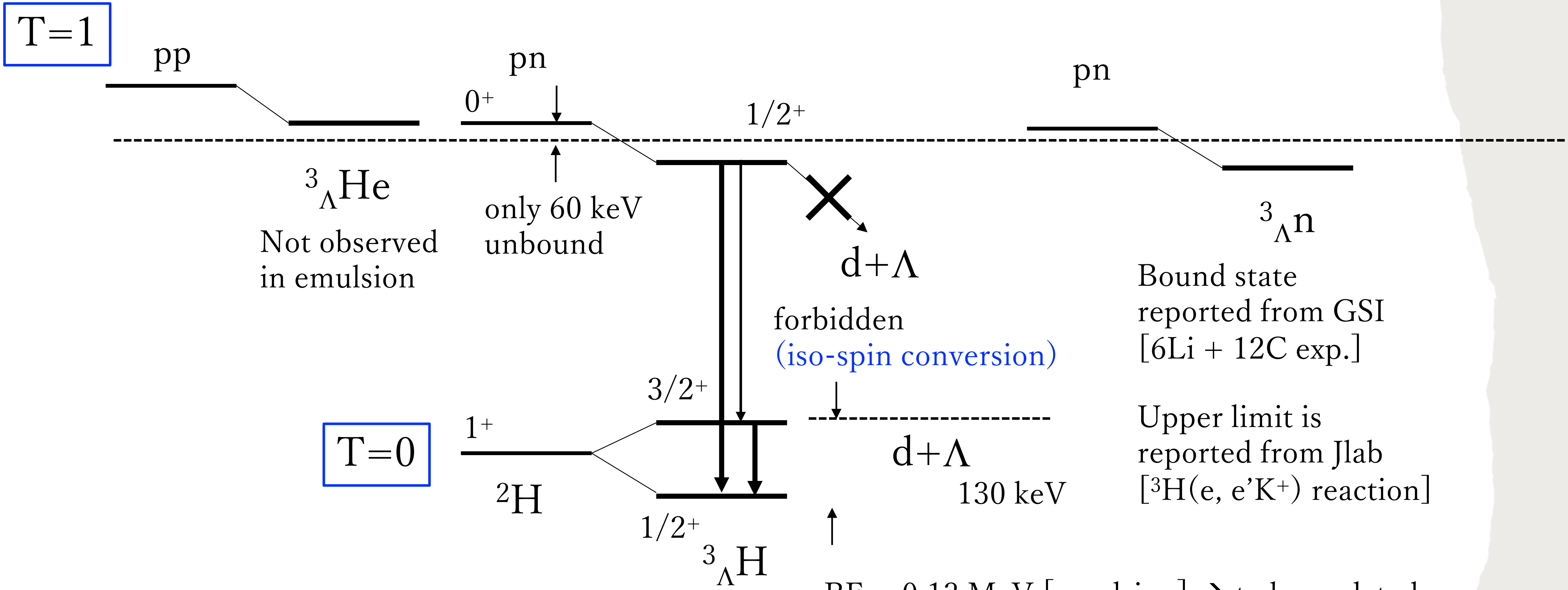
Experimental setup



1 month beamtime
→ ~400 γ counts
(~40 π-γ coincidence)

Slide from T.O. Yamamoto

Search for ${}^{3}_{\Lambda}$H spin-doublet by γ-ray measurement



Not observed in emulsion

only 60 keV unbound

forbidden (iso-spin conversion)

Bound state reported from GSI [6Li + 12C exp.]

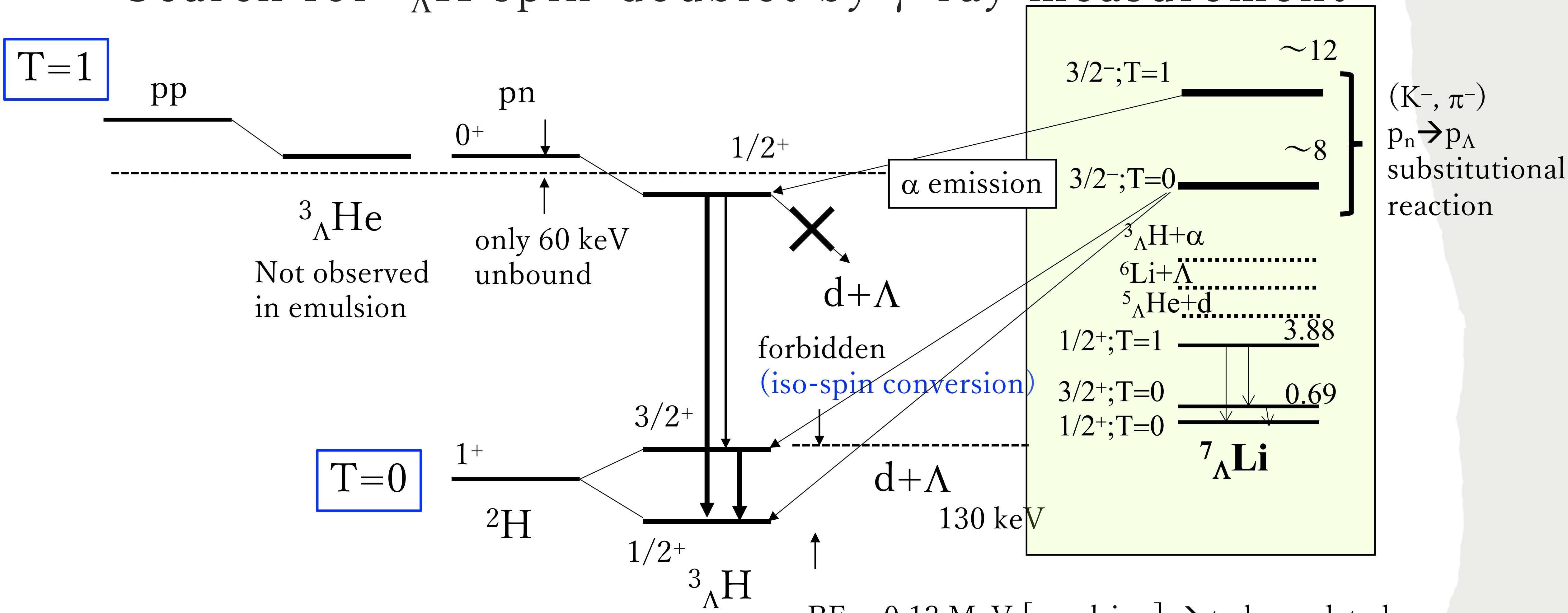
Upper limit is reported from Jlab [^{3}H(e, e'K^+) reaction]

Precise measurement of spin doublet of ${}^{3}_{\Lambda}$H
- ΛN ${}^{1}S_0$ channel information
- ΛN ${}^{3}S_1$ channel w/ ΛN-ΣN mixing effect

BE = 0.13 MeV [emulsion] → to be updated using general scanning method

BE = 0.41 MeV [STAR, 2019]

Search for $^{3}_{\Lambda}H$ spin-doublet by γ-ray measurement



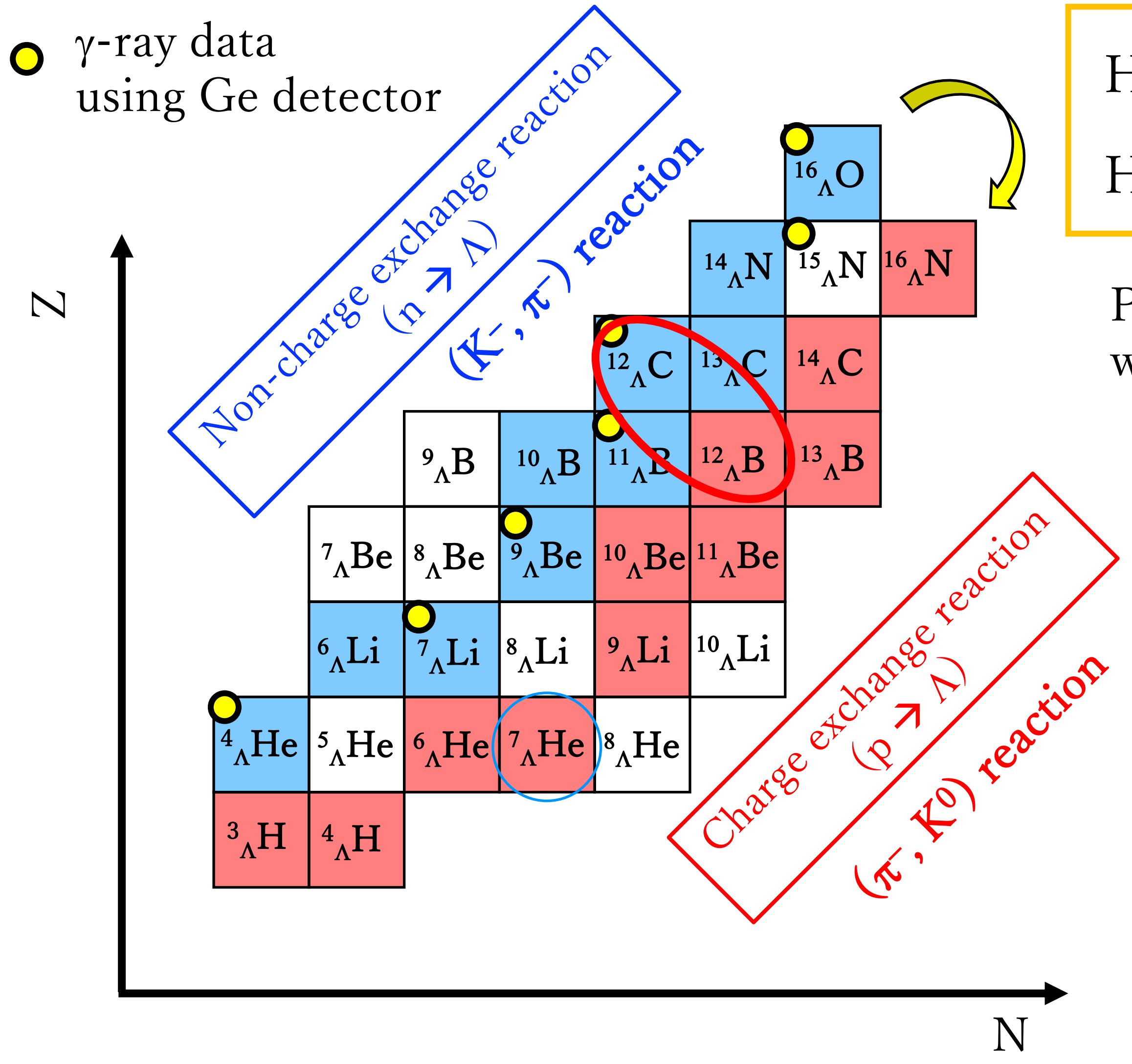
Precise measurement of spin doublet of $^{3}_{\Lambda}H$
- ΛN $^{1}S_{0}$ channel information
- ΛN $^{3}S_{1}$ channel w/ ΛN-ΣN mixing effect

BE = 0.13 MeV [emulsion] → to be updated using general scanning method

BE = 0.41 MeV [STAR, 2019]

Slide from T.O. Yamamoto

γ-ray spectroscopy of neutron-rich hypernuclei



How strongly CSB effect appears in A>4 hypernuclei ?

How large ΛNN force in neutron rich Λ hypernuclei ?

Precise energy-spacing determination by γ-ray spectroscopy will play critical role

Precise data for proton-rich side produced by “n → Λ” reaction

⇩

Need to approach mirror pair (neutron rich) hypernuclei by introducing “p → Λ” reaction

Level structure of mirror hypernuclei
→ Study for CSB effect

Neutron-rich hypernuclei can be accessed
→ Help for study of ΛNN force with ΛΣ mixing effect

Reaction and γ-ray spectroscopy of medium-heavy hypernuclei

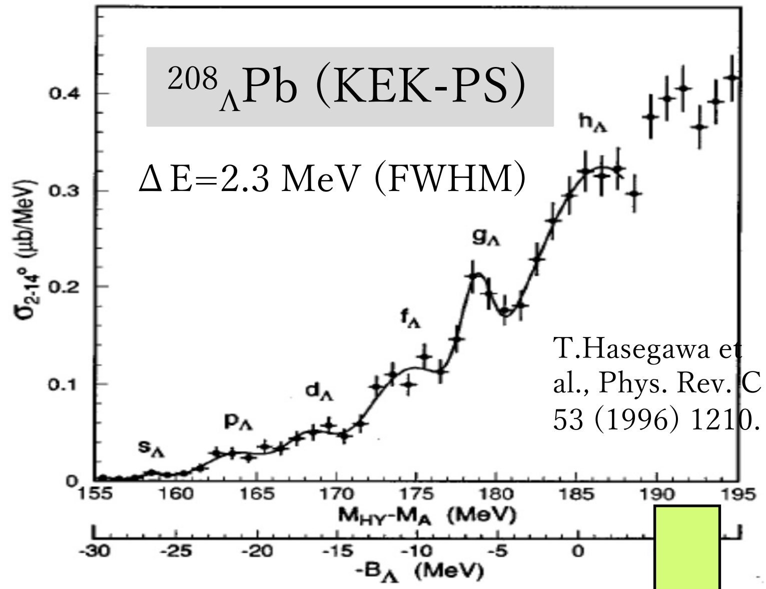
High-resolution reaction spectroscopy at HIHR
[w/ B.E. accuracy better than 0.1 MeV]

Wide-mass Λ hypernuclei for study of density dependence of ΛN interaction

Gamma-ray data for the same hypernuclei

$^{28}{}_{\Lambda}$Si, $^{40}{}_{\Lambda}$Ca, $^{51}{}_{\Lambda}$V, $^{89}{}_{\Lambda}$Y, $^{139}{}_{\Lambda}$La, $^{208}{}_{\Lambda}$Pb

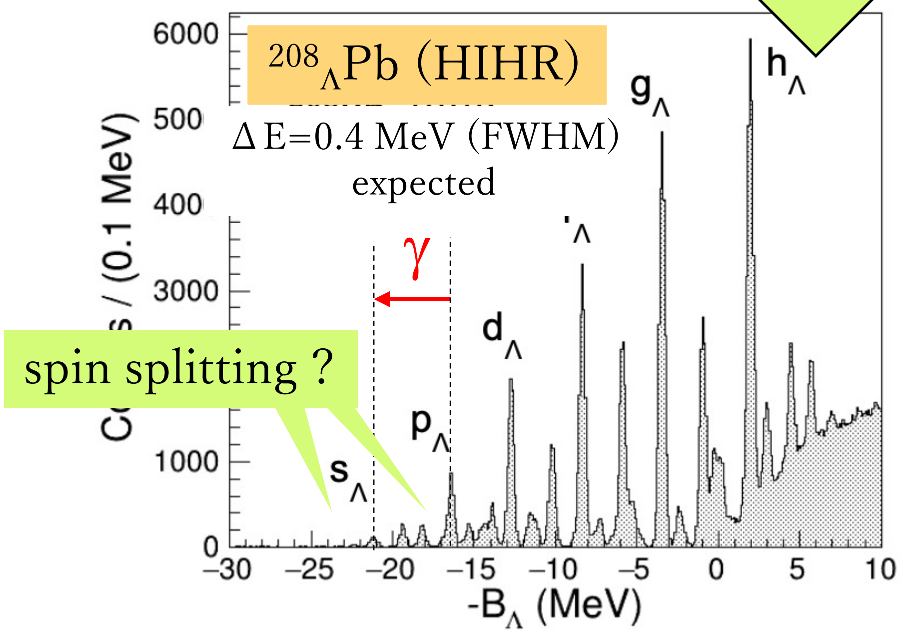
- Spin splitting measurement (for both s_Λ- and p_Λ-states)
  → Reaction data to spin-averaged B.E. data
  Support reaction spectroscopy data
- E1 γ transition energy
  → "Another barometer" for density dependence



$^{208}{}_{\Lambda}$Pb (KEK-PS)

ΔE=2.3 MeV (FWHM)

T.Hasegawa et al., Phys. Rev. C 53 (1996) 1210.



$^{208}{}_{\Lambda}$Pb (HIHR)

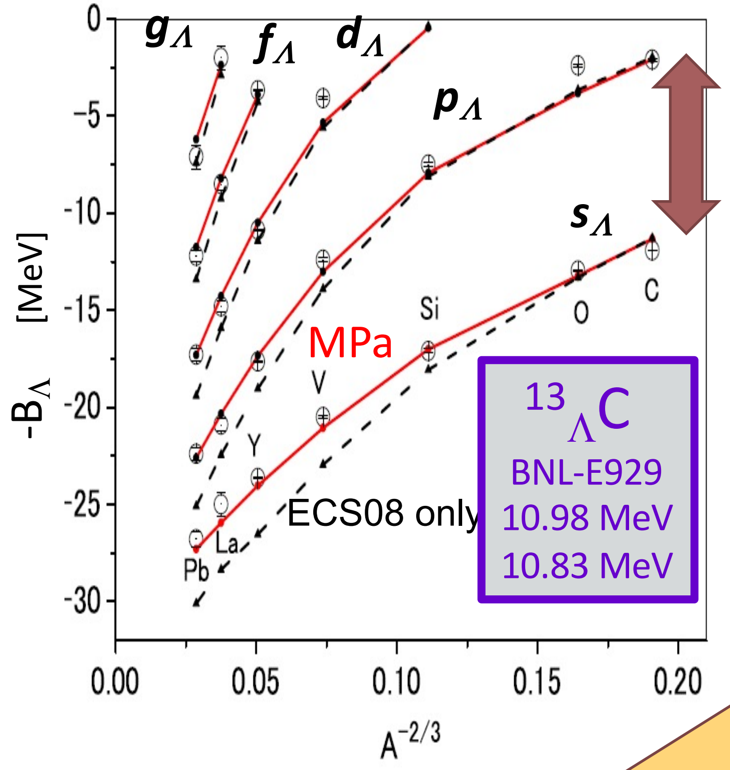
ΔE=0.4 MeV (FWHM)
expected

spin splitting ?

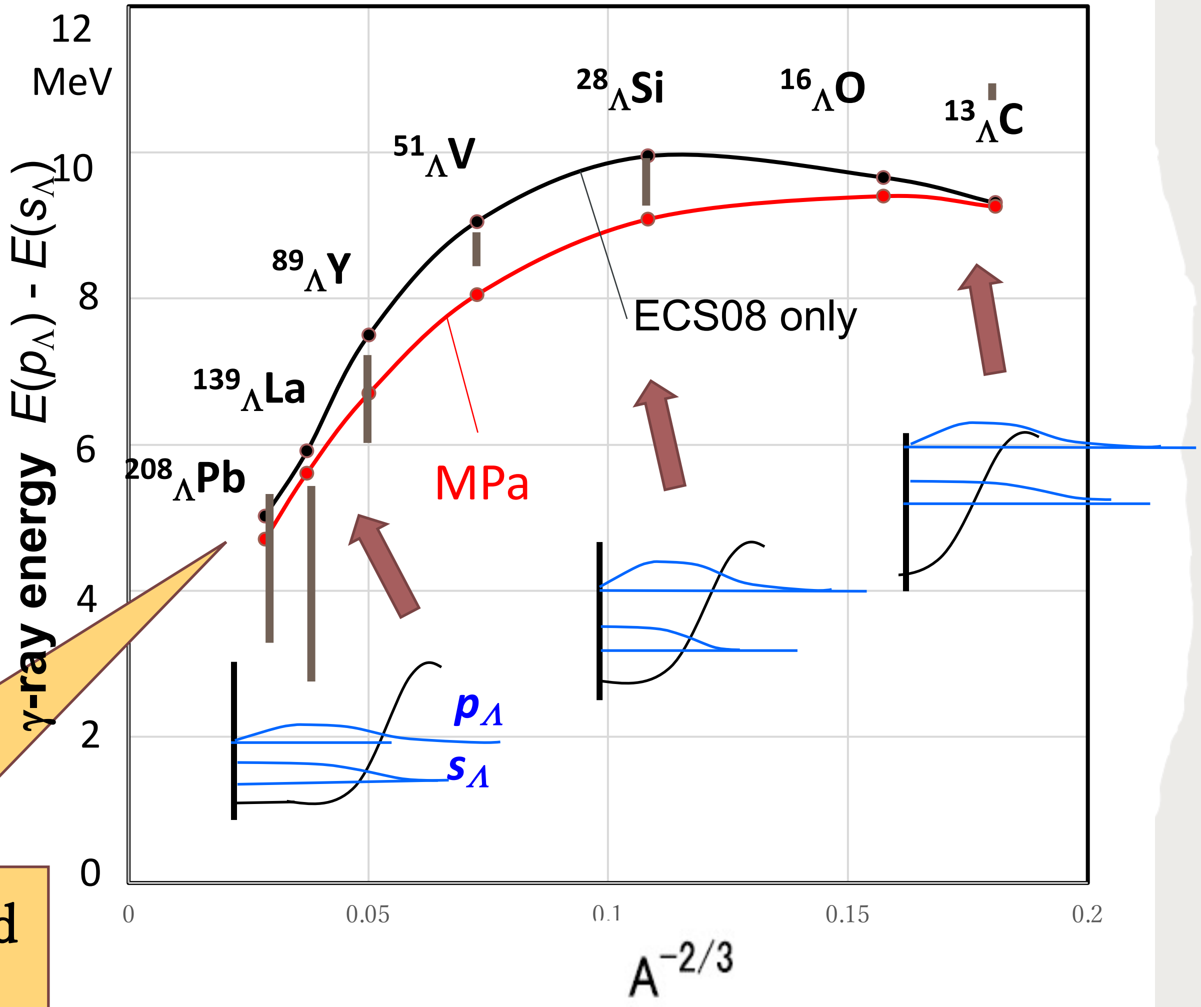
Study of density dependence from p_Λ-s_Λ energy spacing measurement

A dependence of BE
[rection spectroscopy]

M.M.Nagel, et. al. Phys. Rev. C99 044003



A dependence of p_Λ-s_Λ energy spacing



A few keV data can be obtained
from E1 γ measurement

Weak decays of Λ hypernuclei

- Three-body non-mesonic weak decay, $\Lambda NN \rightarrow NNN$ (E18)
- Mesonic and non-mesonic weak decays via (π^-, K^0) and (π^+, K^+) reactions

Test of $\Delta I=1/2$ rule in NMWD for ${}^4_\Lambda$H and ${}^4_\Lambda$He

p-induced NMWD rate (Γ_p) in ${}^4_\Lambda$H
n-induced NMWD rate (Γ_n) in ${}^4_\Lambda$He

Weak decay studies of various hypernuclei (${}^3_\Lambda$H, ${}^4_\Lambda$H and neutron-rich p-shell hypernuclei)

- Beta decay of Λ hypernuclei

Weak decay of Λ in a nucleus is a unique probe to investigate possible modification of baryon structure in nuclear medium

Λ's beta decay $(\Lambda \rightarrow pe^-\bar{\nu})$ branching ratio of ${}^5_\Lambda$He

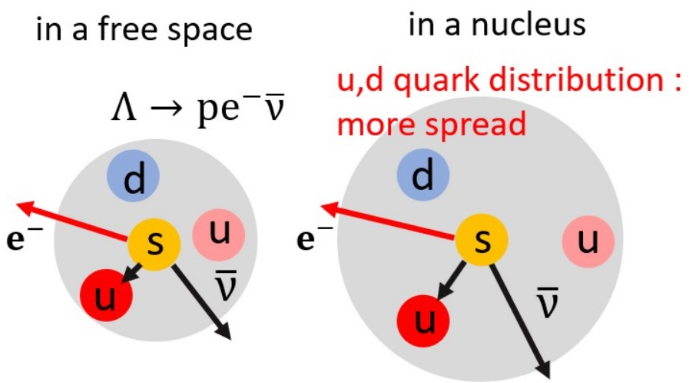


Fig 1: Λ beta decay

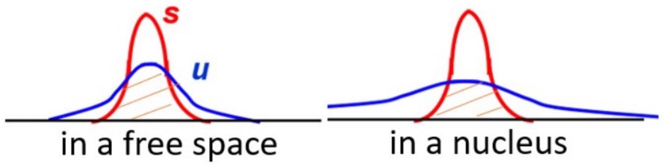


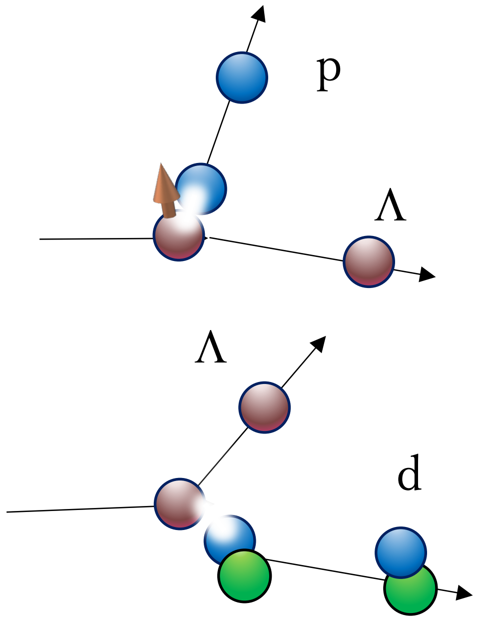
Fig 2: Wave function

Summary

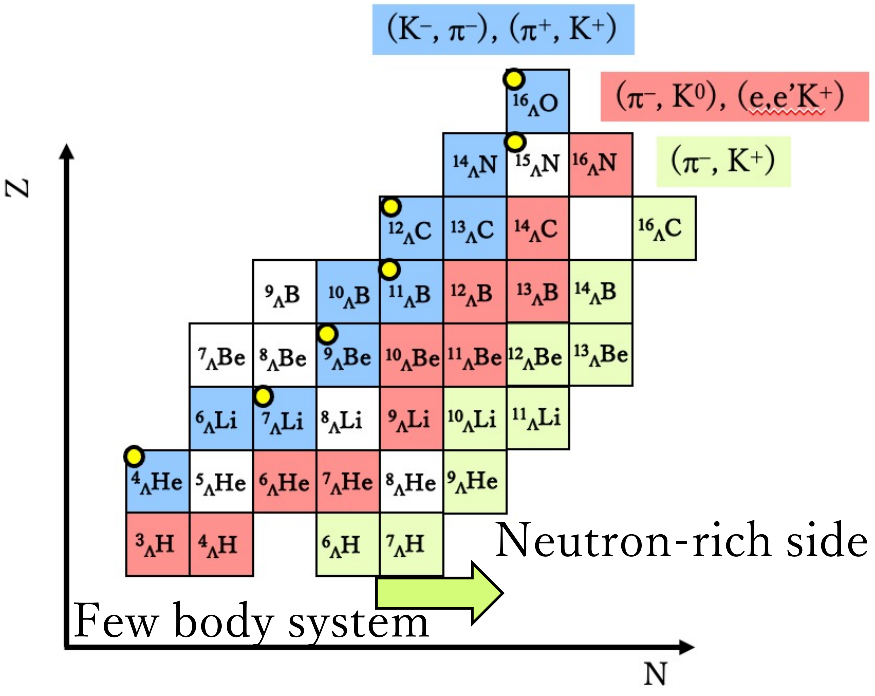
We are going to attack hyperon puzzle by gathering experimental programs at J-PARC

Density dependent ΛN interaction is key issue and it should be represented from ΛNN three-body force.

Hyperon-proton scattering



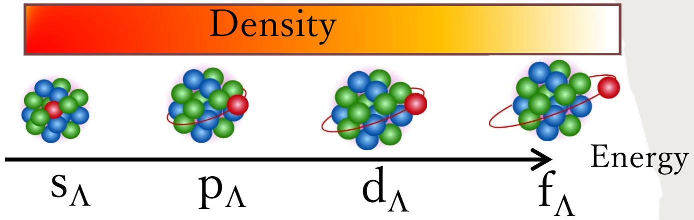
Precise study of light hypernuclei

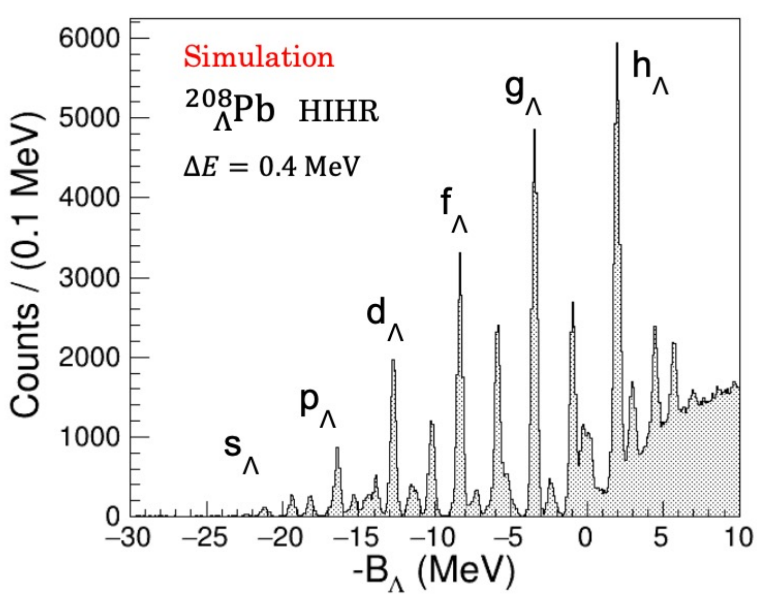


Neutron-rich side

Few body system

Precise B_Λ measurement for medium and heavy hypernuclei





Two-body YN int.

ΛN-ΣN coupling, ΛNN int.

Density dependent ΛN int., ΛNN int.