Future prospects of Lambda-proton scattering experiment

Koji Miwa (Tohoku Univ., KEK IPNS, RIKEN)

on behalf of J-PARC E40, E86, HYPS collaboration

Workshop on Strange hadrron as a Precision tool for strongly interacting systems
May. 13rd – 17th, 2024

TOHOKU
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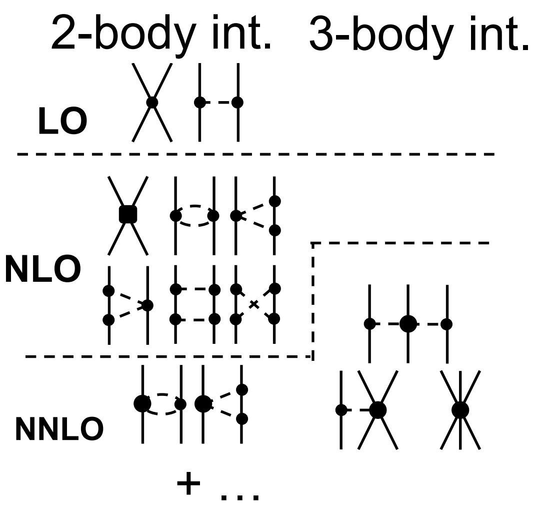
- Brief summary of Σp scattering experiment (J-PARC E40)
- New project of Λp scattering experiment at SPring-8
- Summary

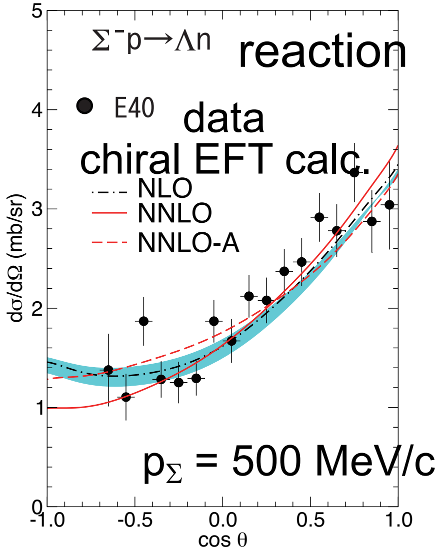
Progress of theory & experiment of BB int. study

Theoretical progress

Hyperon-Nucleon int. w/ chiral effective field theory

(J. Haidenbauer et al.)



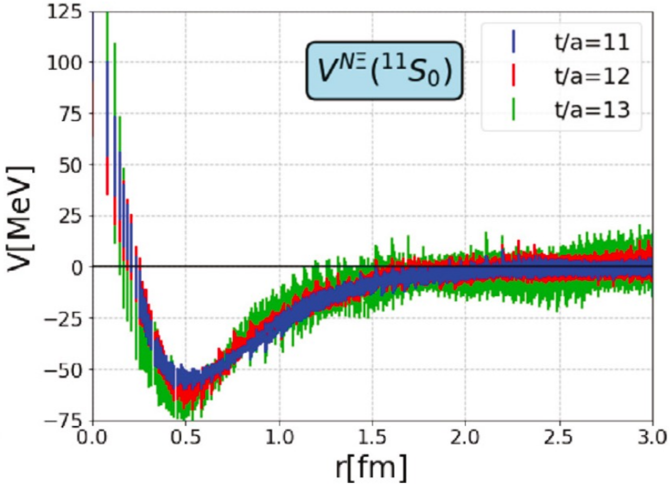


Improving accuracy w/ our new data

Hyperon potential by Lattice QCD

BB interaction at almost physical point for multi-strangeness sector

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

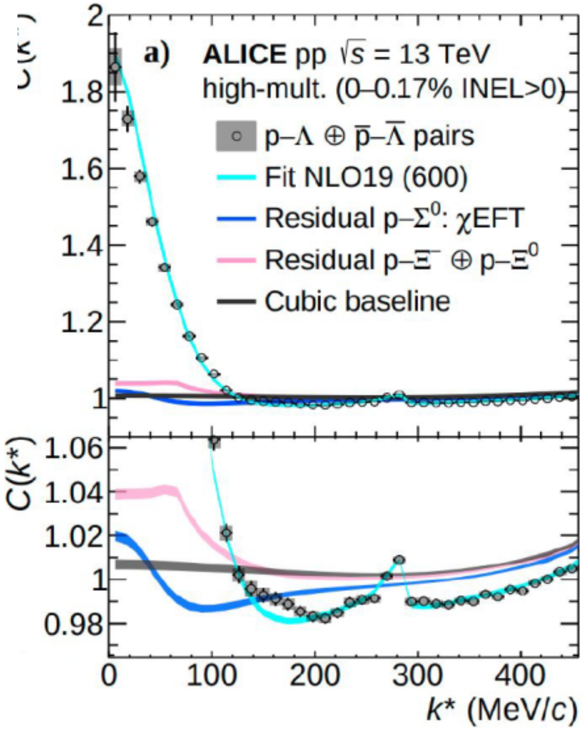


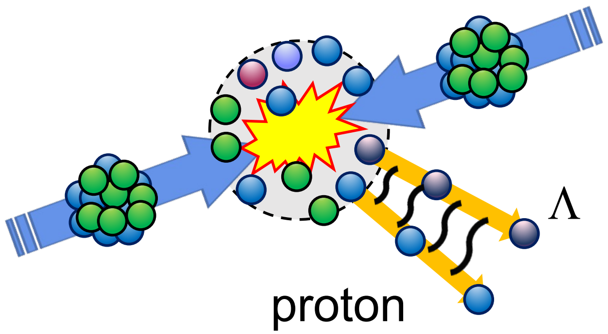
Experimental progress

BB interaction from femtoscopy

ALICE Collaboration,
Phys. Lett. B 833
(2022) 137272

Particle correlation between Λ and p





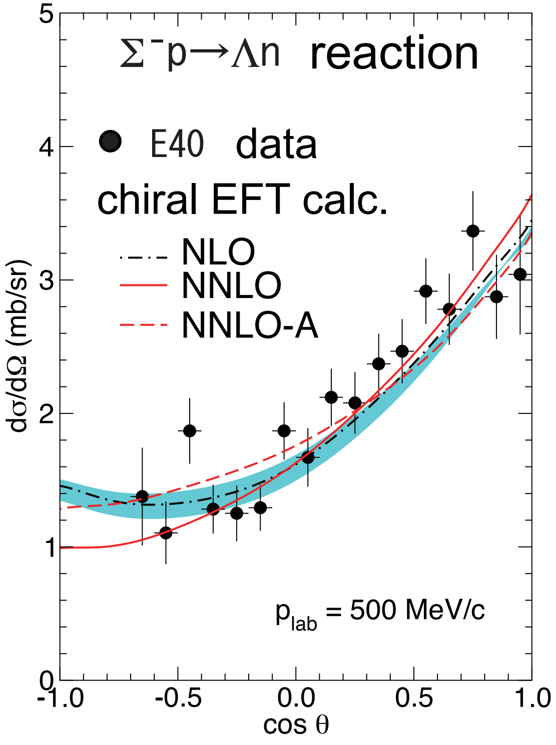
$$c(k^*) = \int S(r^*)\left|\Psi(\overrightarrow{k^*},\overrightarrow{r^*})\right|^2 d^3r^*$$

Fix source size(S(r*)) →

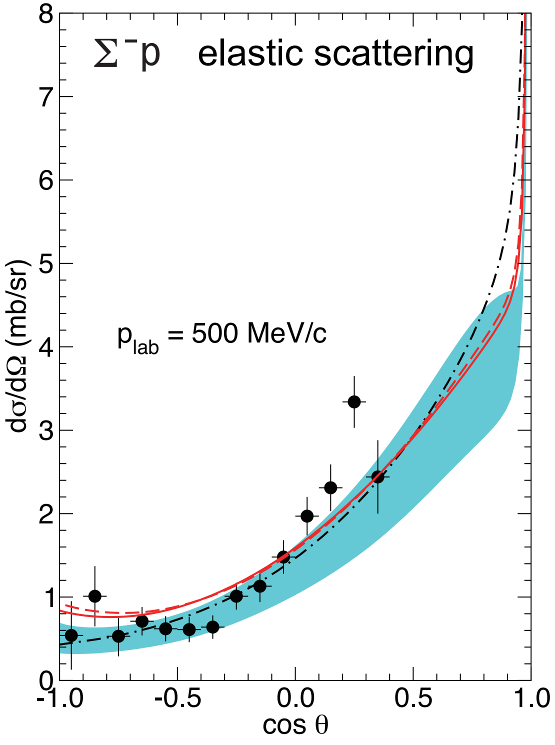
Study interaction from wave function ($\Psi(\overrightarrow{k^*},\overrightarrow{r^*})$)

New Σp scattering data at J-PARC

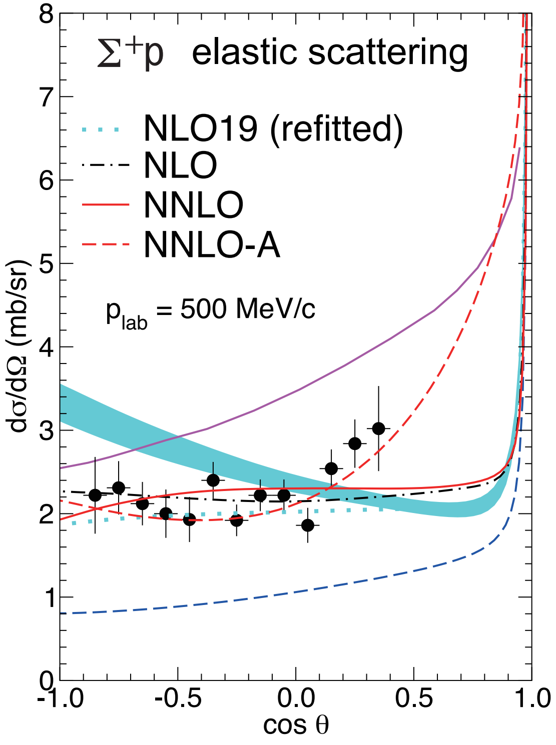
Accurate and systematic data of differential cross sections of Σp scattering



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

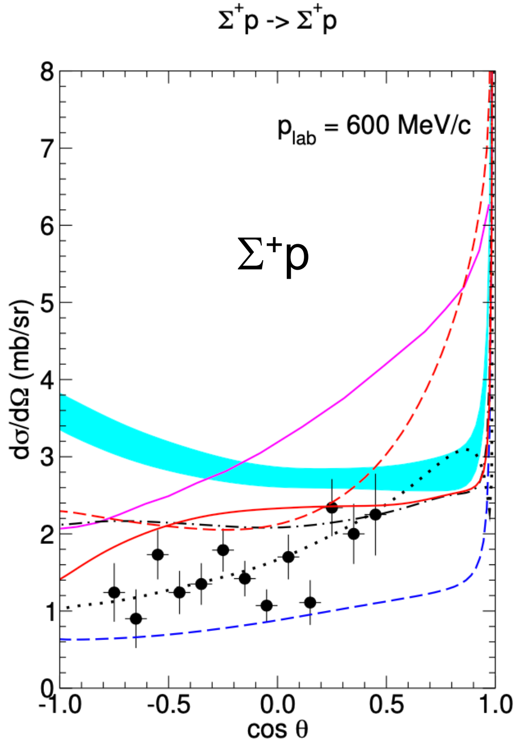


K. Miwa et al.,
PRC 104, 045204 (2021)



T. Nanamura et al., PTEP 2022 093D01

Difficulty at higher momentum

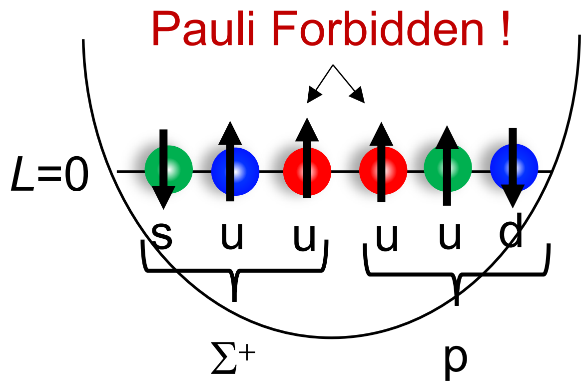


J. Haidenbauer et al.,
Eur.Phys.J.A 59 (2023) 3

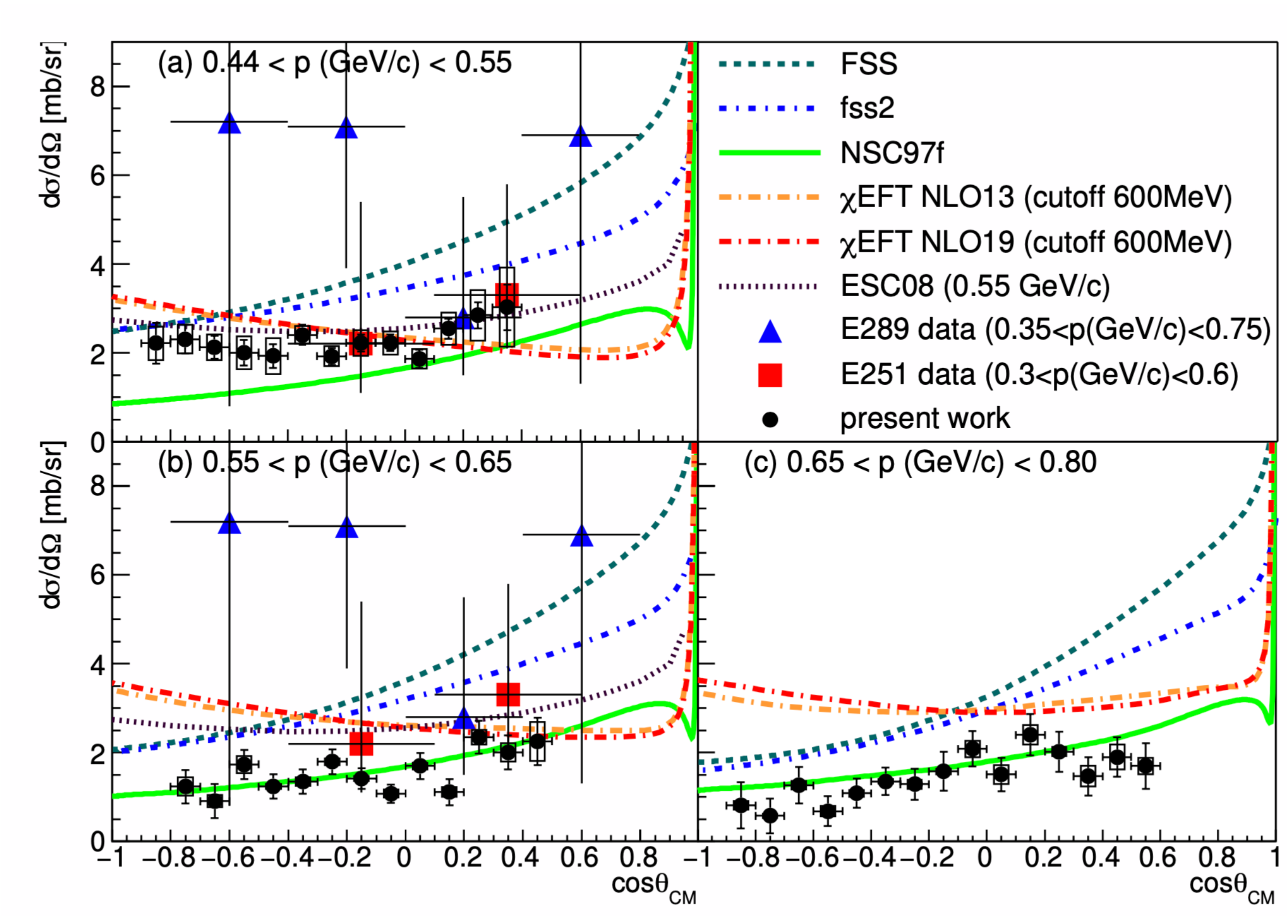
Development of Chiral EFT at NNLO have got started with E40 data

But, the interactions are not uniquely determined yet.
We need more data from additional channels (Λp, …) and additional differential observables (polarizations, …)

$d\sigma/d\Omega$ of Σ^+p elastic scattering

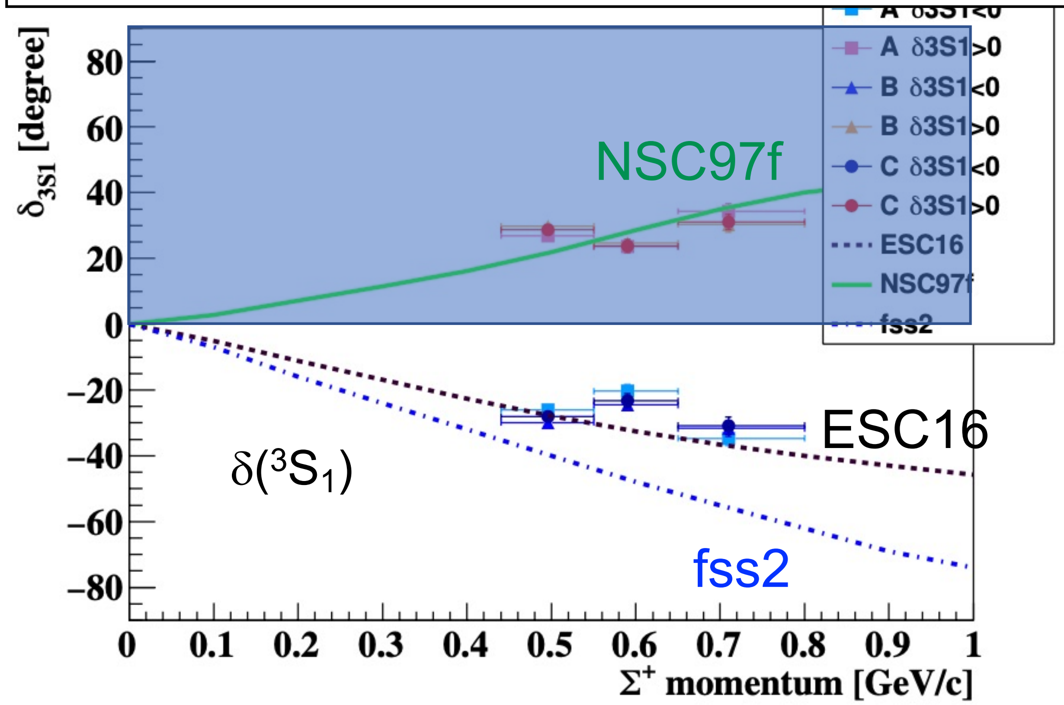


T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01



E40 data : much smaller than fss2 prediction and E289 results

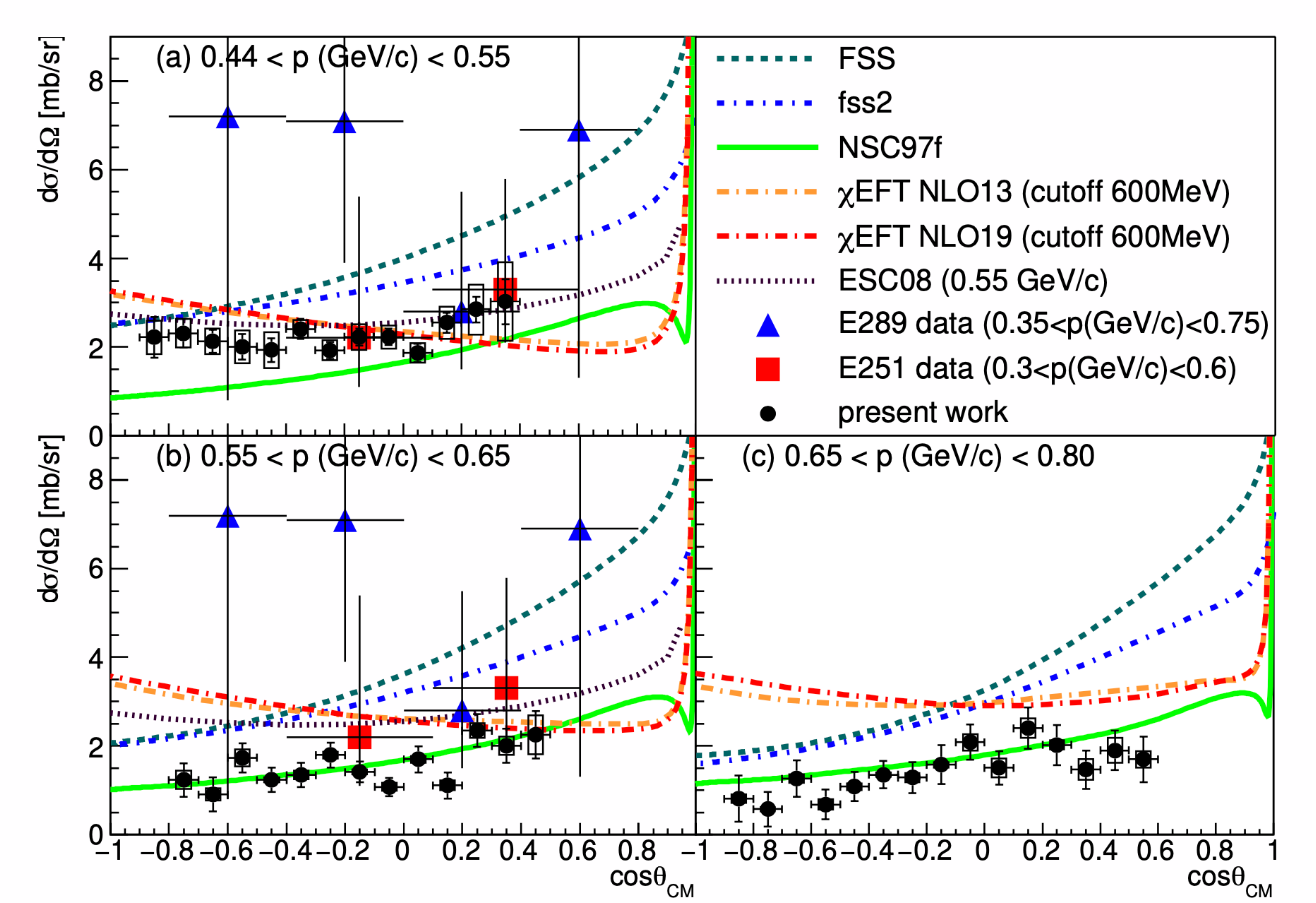
First experimental derivation of phase shift of $^3S_1$



Derived phase shift suggests that **the $^3S_1$ interaction is moderately repulsive**.

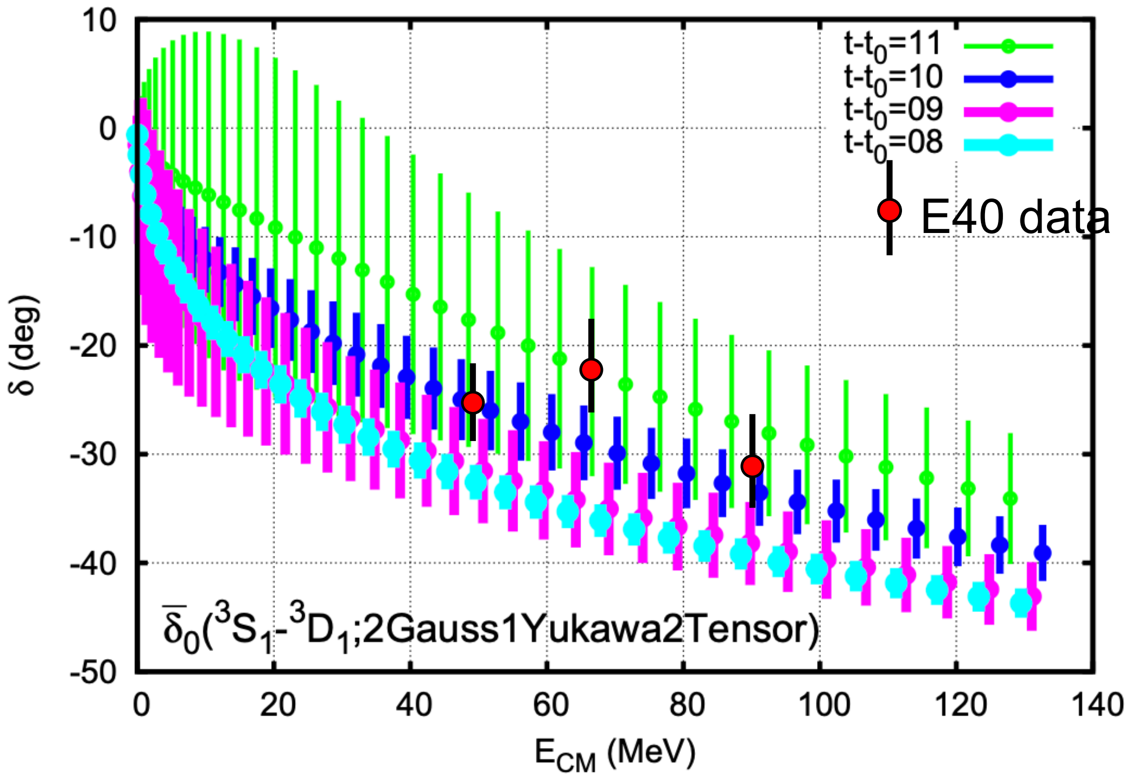
dσ/dΩ of Σ^+p elastic scattering

T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01



E40 data : much smaller than fss2 prediction and E289 results

Comparison with HAL QCD ΣN potential

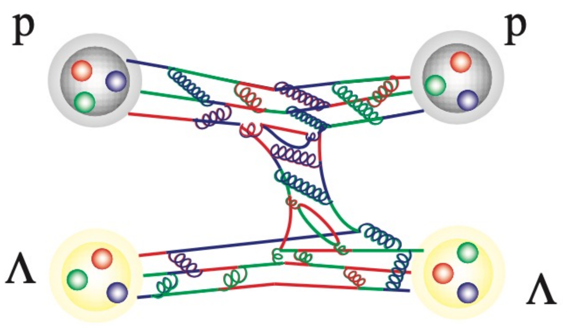


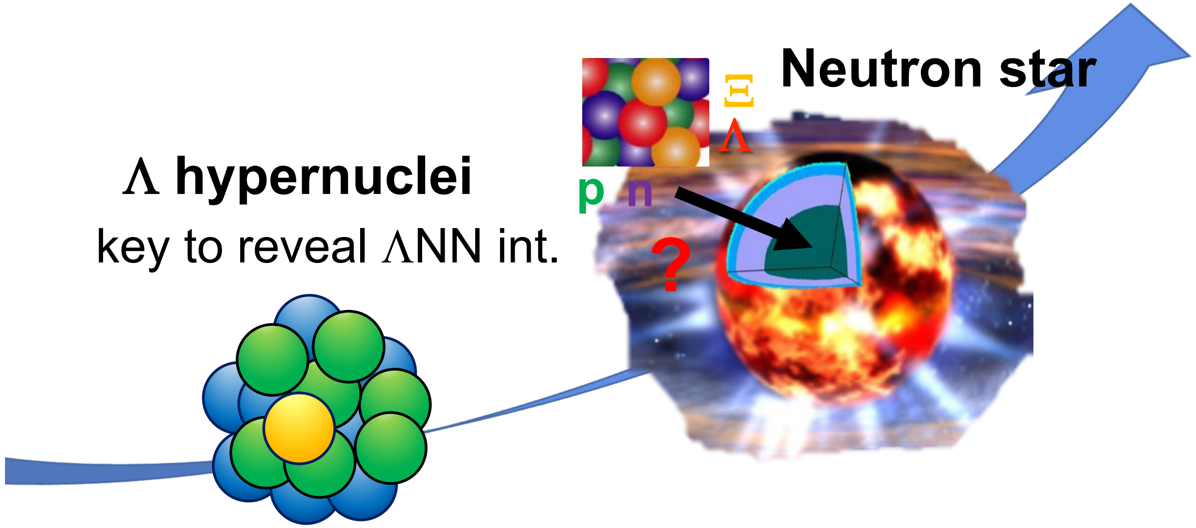
H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

Derived phase shift suggest that **the $^3S_1$ interaction is moderately repulsive**.

Toward Λp scattering

Reliable ΛN two-body interaction :
key to deepen Λ hypernuclear physics

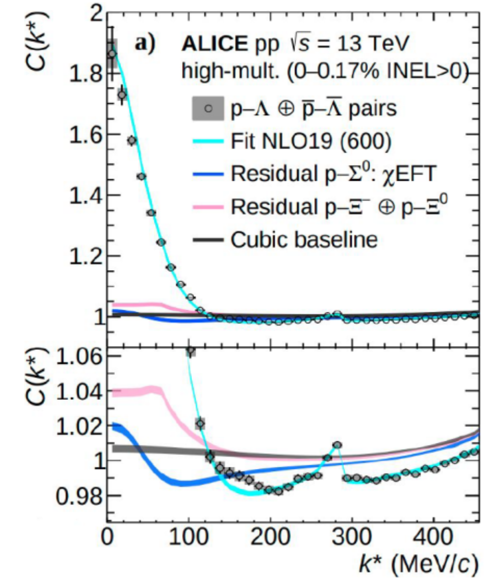




Neutron star

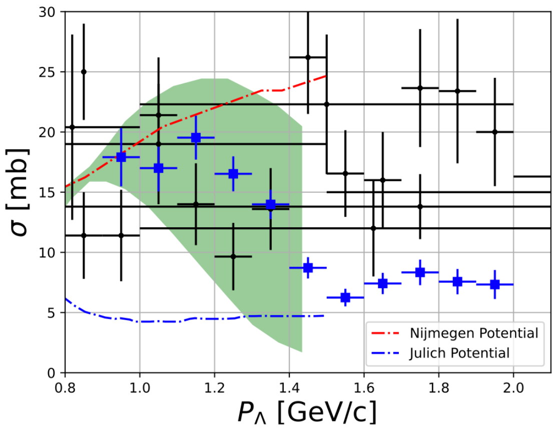
Λ hypernuclei
key to reveal ΛNN int.

Femtoscopy from HIC



ALICE Collaboration, arXiv:2104.04427

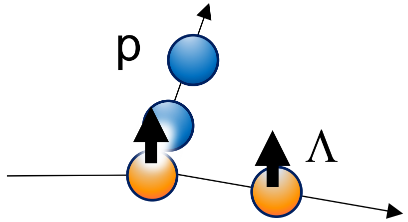
New cross section data
from Jlab CLAS



J. Rowley et al. (CLAS), Phys. Rev. Lett. 127 (2021) 272303

New project at SPring-8, J-PARC

Λp scattering w/ (polarized) Λ

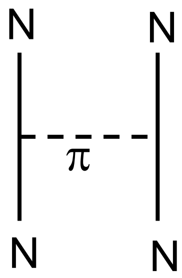


Origin of the density dependence of ΛN interaction

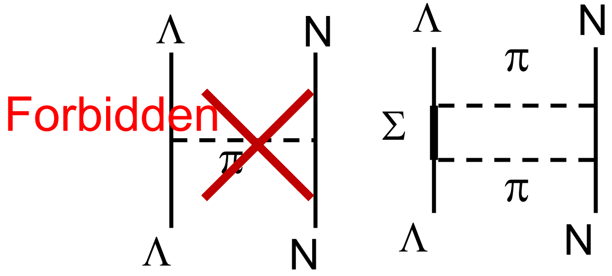
Λ is the only isospin 0 baryon that makes up matter → One-pion exchange is forbidden

Interaction in free space

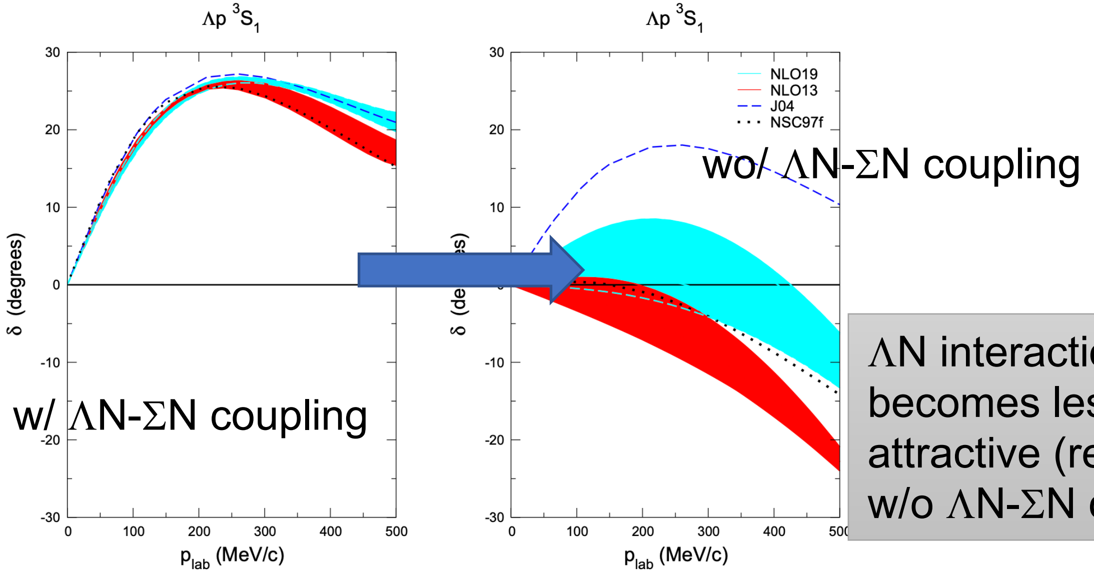
NN interaction



ΛN interaction

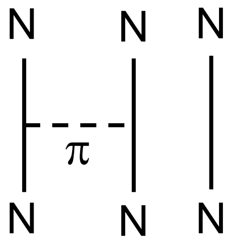


Source of ΛN int.



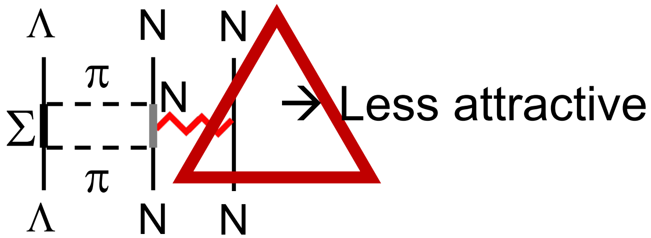
ΛN interaction becomes less attractive (repulsive) w/o ΛN-ΣN coupling

Interaction in nuclear medium



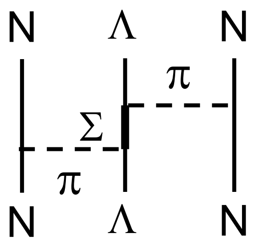
Two-body NN int. might not be affected very much by other nucleons

Suppression of two-body ΛN int.



Due to the Pauli blocking for the intermediate nucleon, ΛN-ΣN coupling can be very suppressed

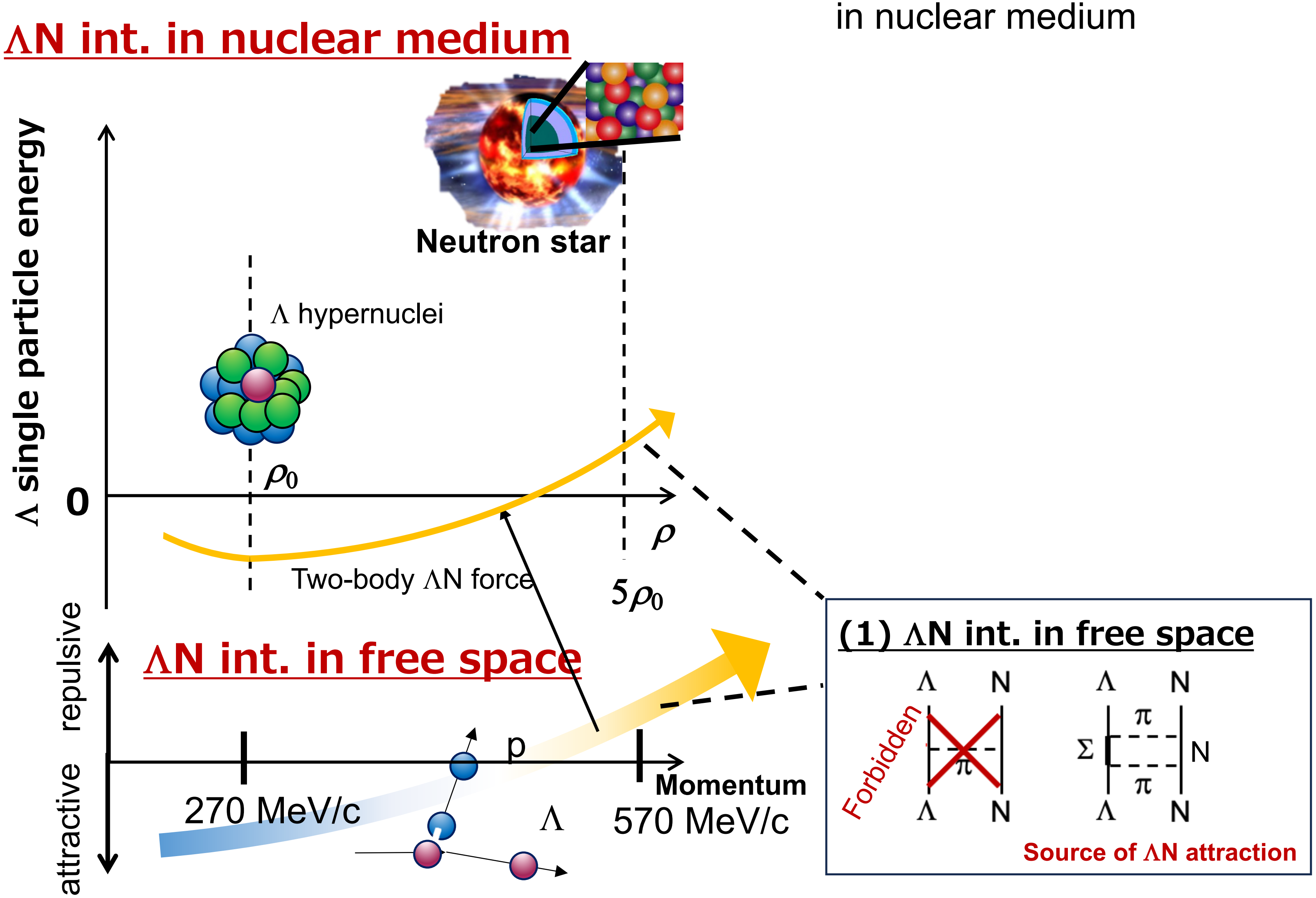
3 body int. mediated with Σ



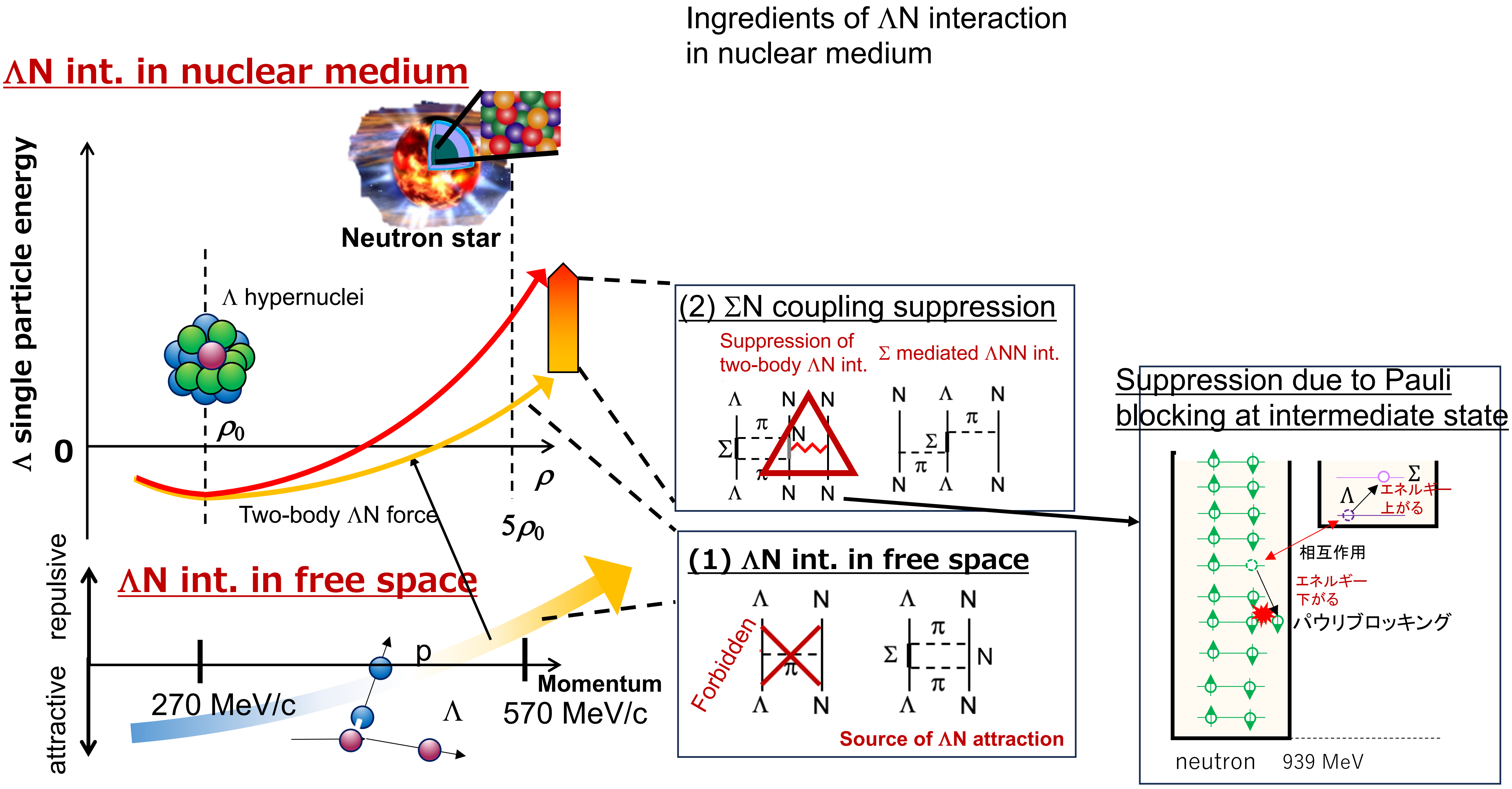
Additional three-body interaction, which does not appear in NN interaction.
What is the density dependence of this 3-body int. ?

Toward the elucidation of the density dependence of the ΛN interaction

Ingredients of ΛN interaction
in nuclear medium



Toward the elucidation of the density dependence of the ΛN interaction



Ingredients of ΛN interaction
in nuclear medium

ΛN int. in nuclear medium

ΛN int. in free space

(2) ΣN coupling suppression

Suppression of two-body ΛN int.

Σ mediated ΛNN int.

(1) ΛN int. in free space

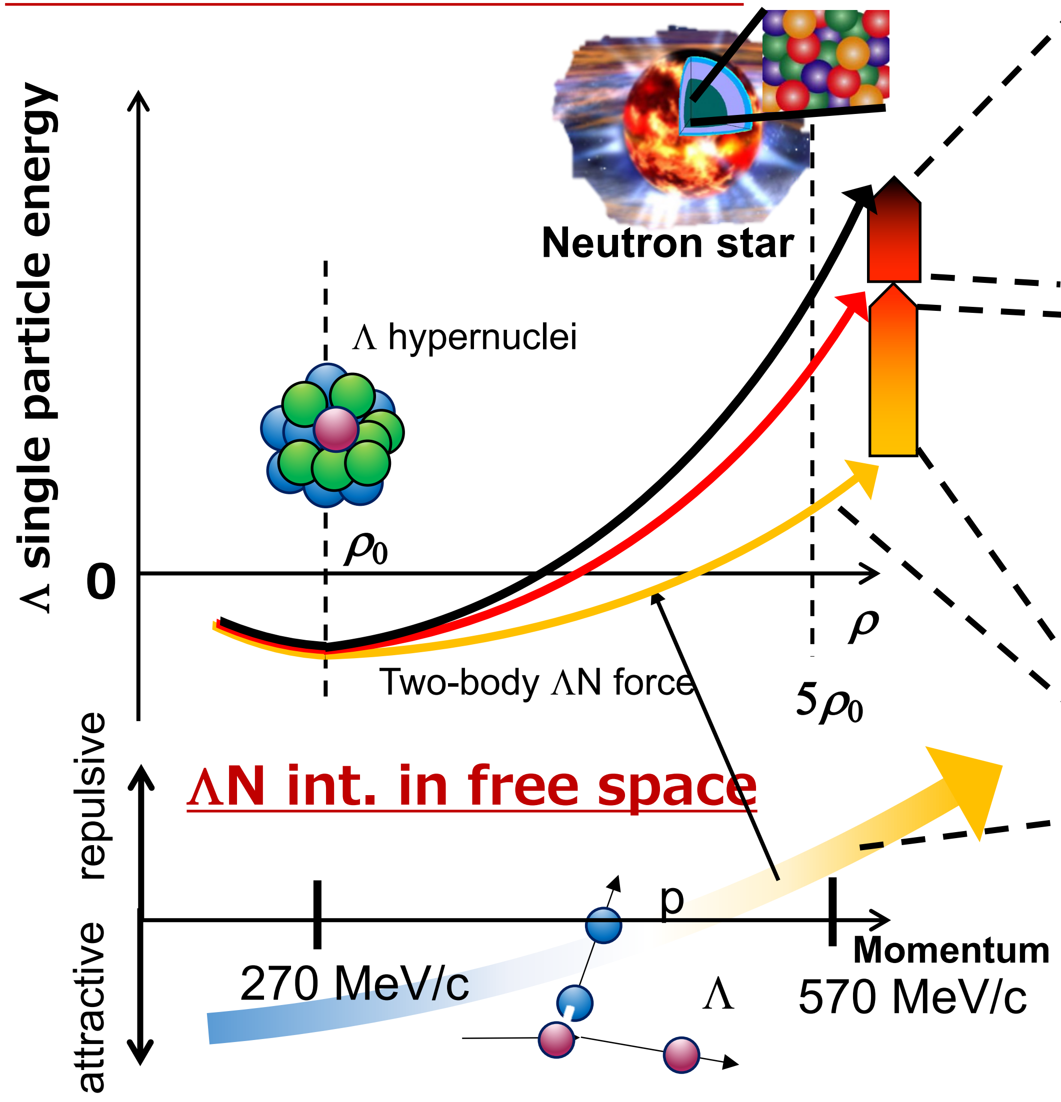
Forbidden

Source of ΛN attraction

Suppression due to Pauli blocking at intermediate state

Toward the elucidation of the density dependence of the ΛN interaction

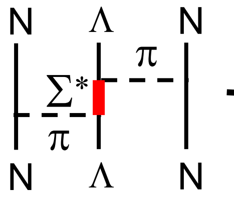
ΛN int. in nuclear medium



ΛN int. in free space

Ingredients of ΛN interaction in nuclear medium

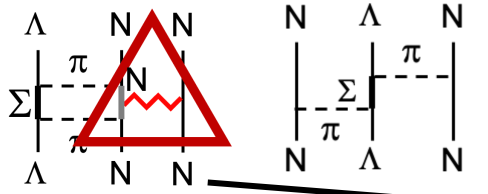
ΛNN int. mediated with Σ*



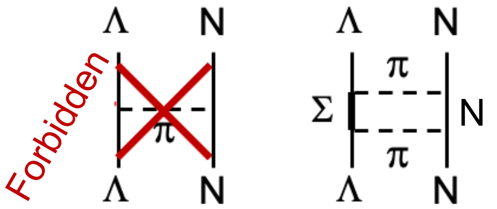
(2) ΣN coupling suppression

Suppression of two-body ΛN int.

Σ mediated ΛNN int.

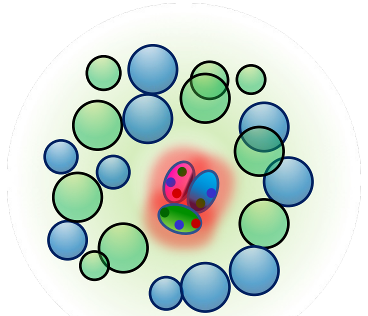


(1) ΛN int. in free space

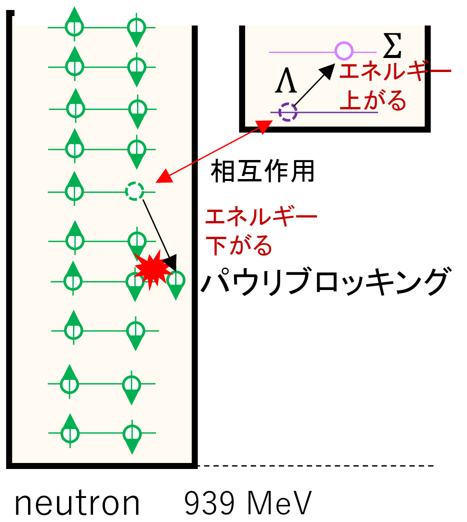


Source of ΛN attraction

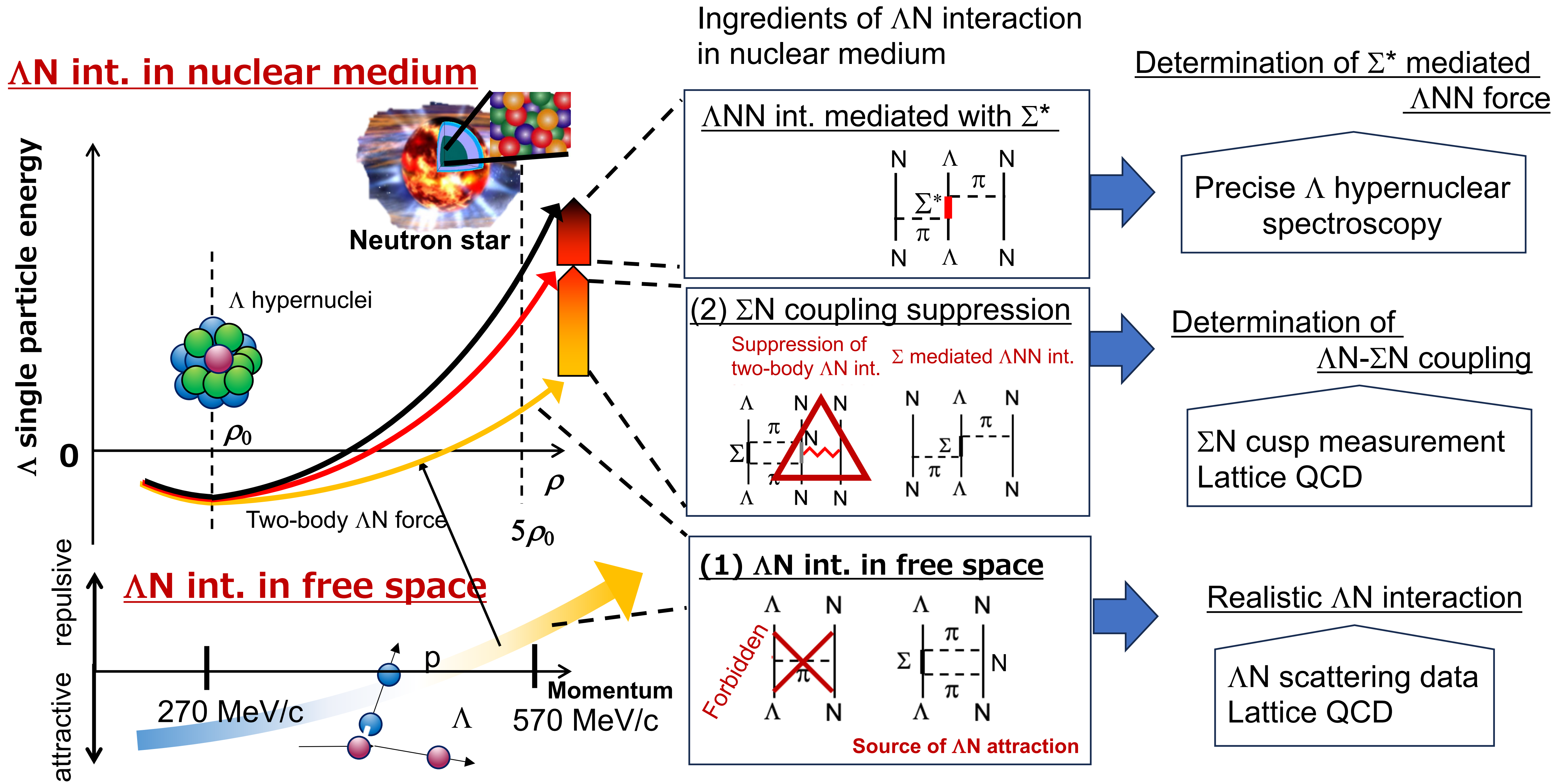
Replsive force by ΛNN force



Suppression due to Pauli blocking at intermediate state



Toward the elucidation of the density dependence of the ΛN interaction



ΛN int. in nuclear medium

ΛN int. in free space

270 MeV/c

570 MeV/c

Ingredients of ΛN interaction in nuclear medium

ΛNN int. mediated with Σ*

(2) ΣN coupling suppression

Suppression of two-body ΛN int.

Σ mediated ΛNN int.

(1) ΛN int. in free space

Source of ΛN attraction

Determination of Σ* mediated ΛNN force

Precise Λ hypernuclear spectroscopy

Determination of ΛN-ΣN coupling

ΣN cusp measurement
Lattice QCD

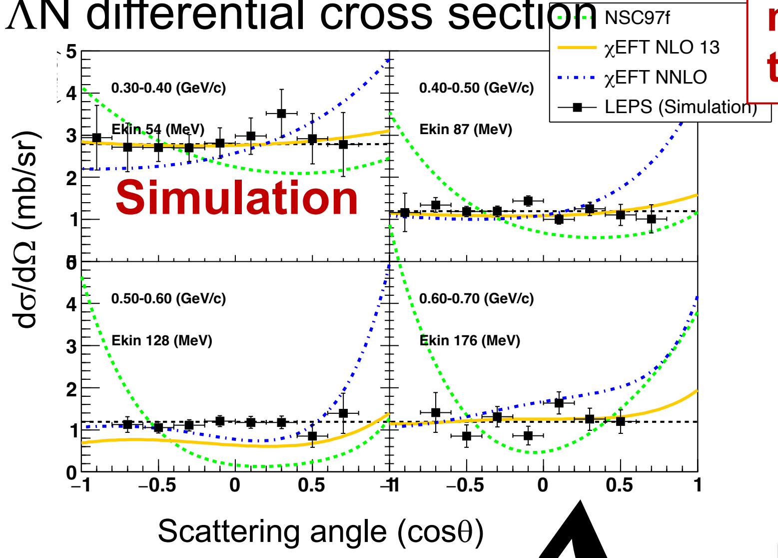
Realistic ΛN interaction

ΛN scattering data
Lattice QCD

Collaborative research regarding the two-body ΛN, ΣN int.

(1) Λp scattering experiment
(Koji Miwa)

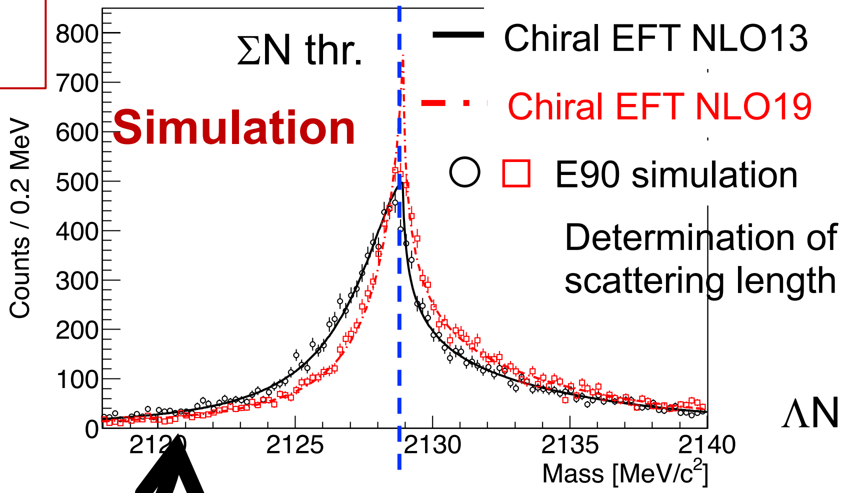
ΛN differential cross section



The differential cross section and cusp structure must be represented with the same ΛN-ΣN coupling

Momentum dependence of dσ/dΩ

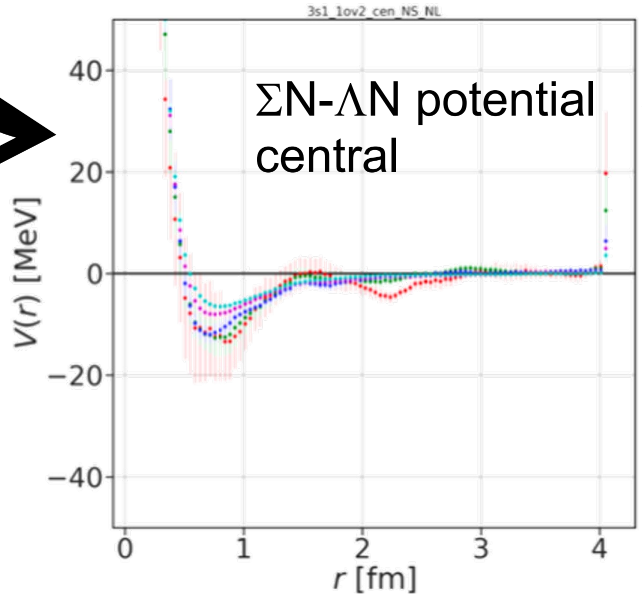
(2) ΣN cusp measurement
(Yudai Ichikawa)



Determination of the ΣN (I=1/2, S=1) scattering length from the cusp shape

ΛN-ΣN coupling

Universal understanding of ΛN interaction from scattering and Lattice QCD



Independent determinations of ΛN-ΣN coupling through the scattering length measurement

(3) ΛN, ΣN Lattice QCD potential
(Takahiro Doi)

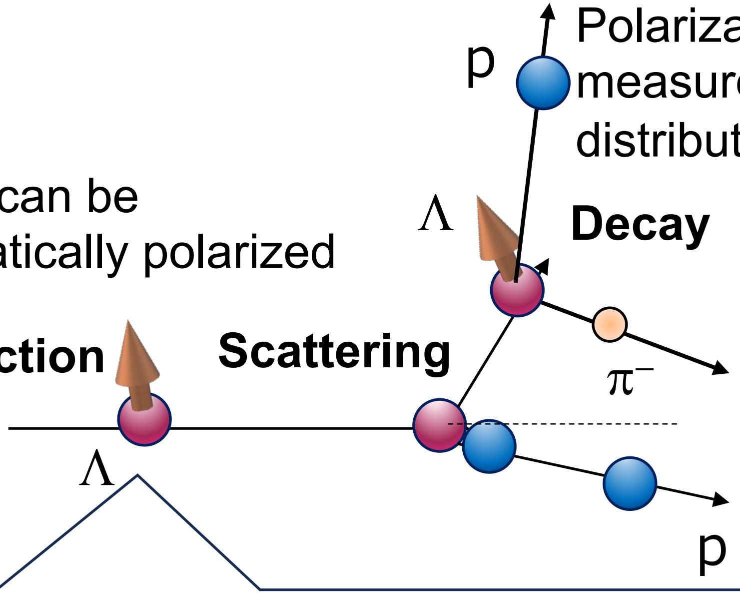
ΛN, ΣN and ΛN-ΣN coupling potentials by HAL QCD

ΛN-ΣN coupling

T. Doi, presentation at 3rd J-PARC HEF-ex WS

Λp scattering experiment with polarized Λ beam (J-PARC E86)

Advantage of scattering experiment: Spin observables can be measured thanks to self polarimeter of hyperon



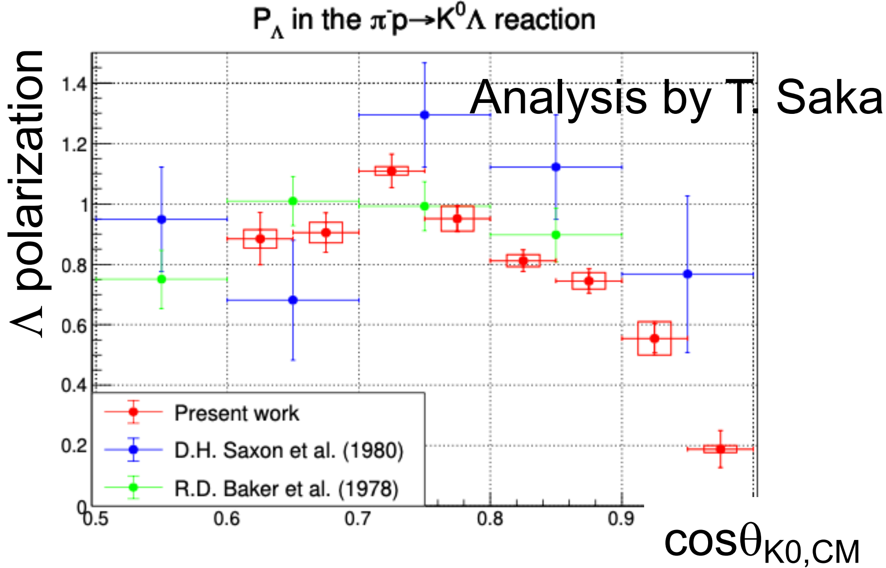
Polarization can be measured from angular distribution of p

Λ spin can be automatically polarized

Production

Scattering

Decay



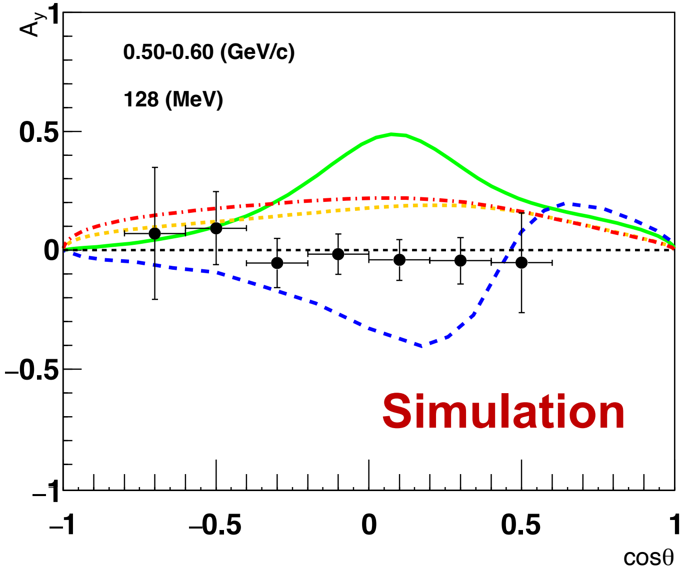
Analysis by T. Sakao

- Left-Right asymmetry of Λp scattering (Analyzing power)

  → spin-orbit interaction
- Polarization change before and after the scattering (Depolarization)

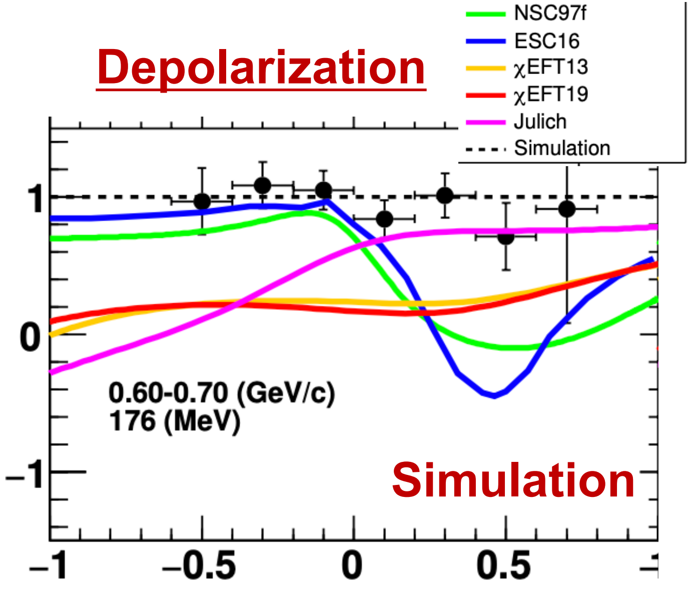
  → spin-spin interaction, tensor interaction

Analyzing power



Simulation

Depolarization

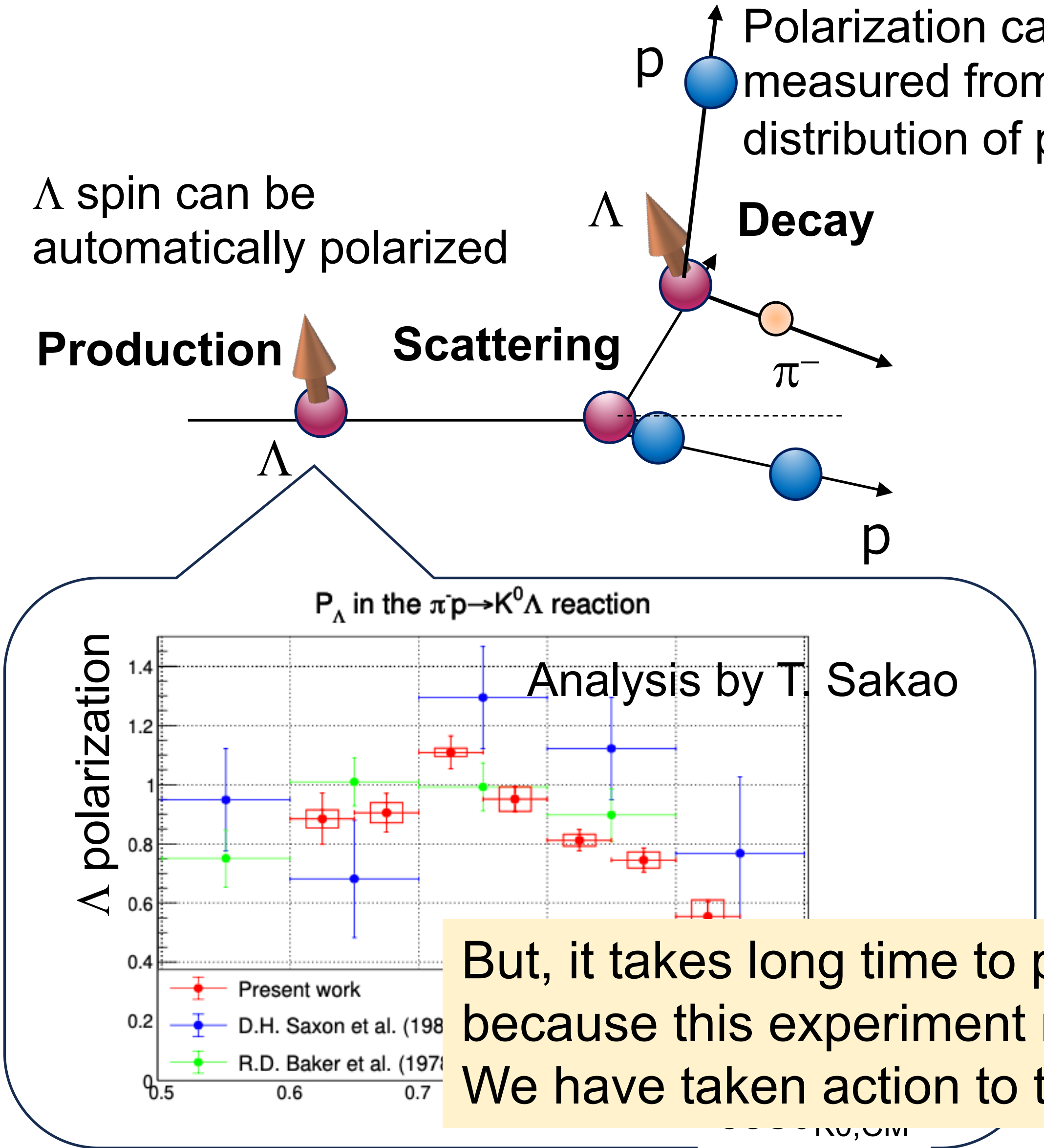


Simulation

Essential constraint to determine spin-dependent ΛN interaction

Λp scattering experiment with polarized Λ beam (J-PARC E86)

Advantage of scattering experiment: Spin observables can be measured thanks to self polarimeter of hyperon



Polarization can be measured from angular distribution of p

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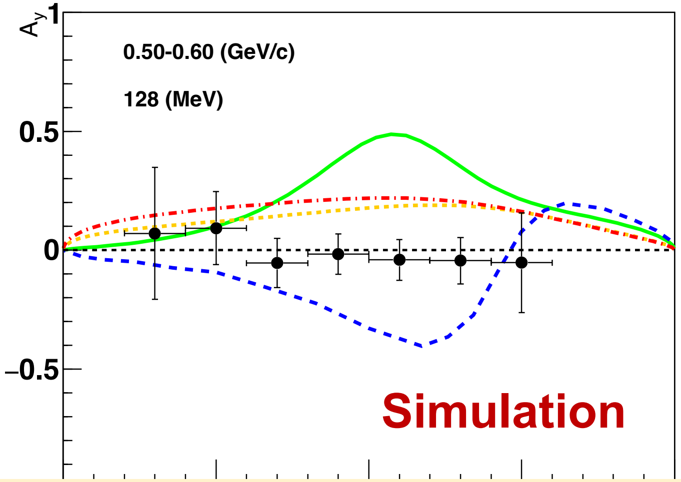
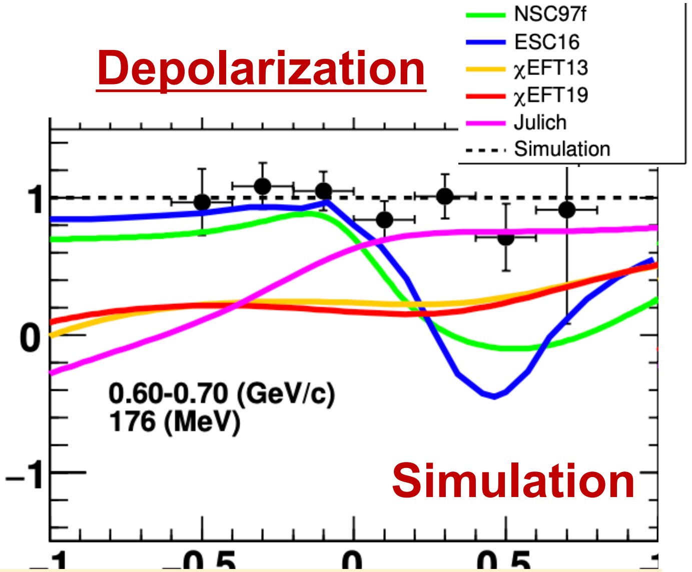
Analyzing power



Depolarization



But, it takes long time to perform this experiment,
because this experiment needs a construction of new K1.1 beam line.
We have taken action to take data using photon beam at SPring-8 to measure dσ/dΩ.

Λp scattering experiment using photo-produced Λ at SPring-8 (HYPS project)

This project is performed as RIKEN-TOHOKU project

Building ΛN interaction from ΛN scattering experiment using photo-produced Λ

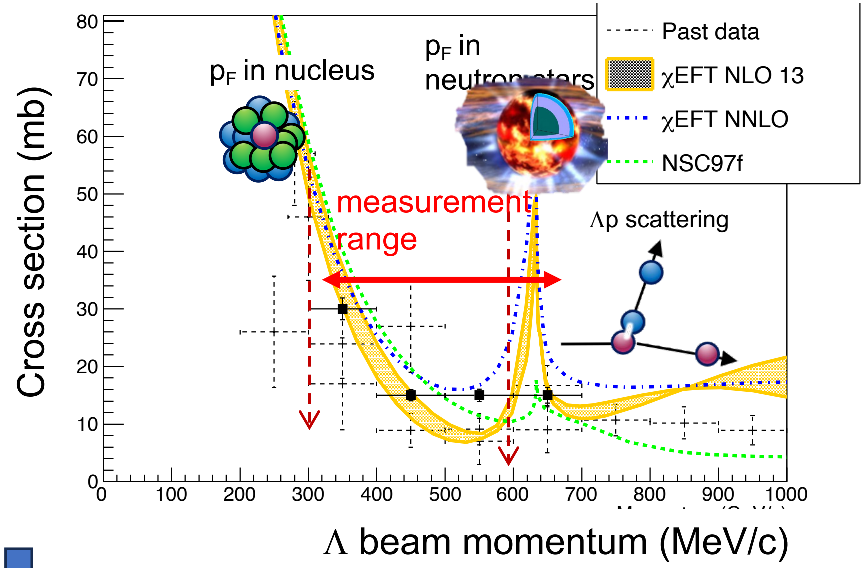
Purpose of research

Building the realistic ΛN interaction by providing ΛN scattering data to chiral EFT theory

ΛN interaction is still uncertain due to lack of scattering data, although the interaction is essential to describe many-body system with Λ such as hypernuclei and neutron stars.

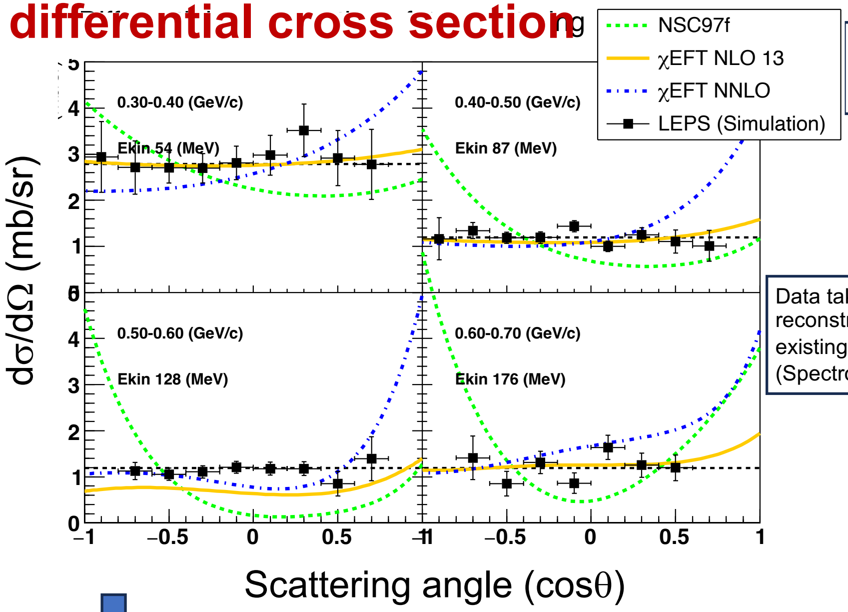
We plan to perform Λp scattering experiment at BL33LEP

Λp total cross section



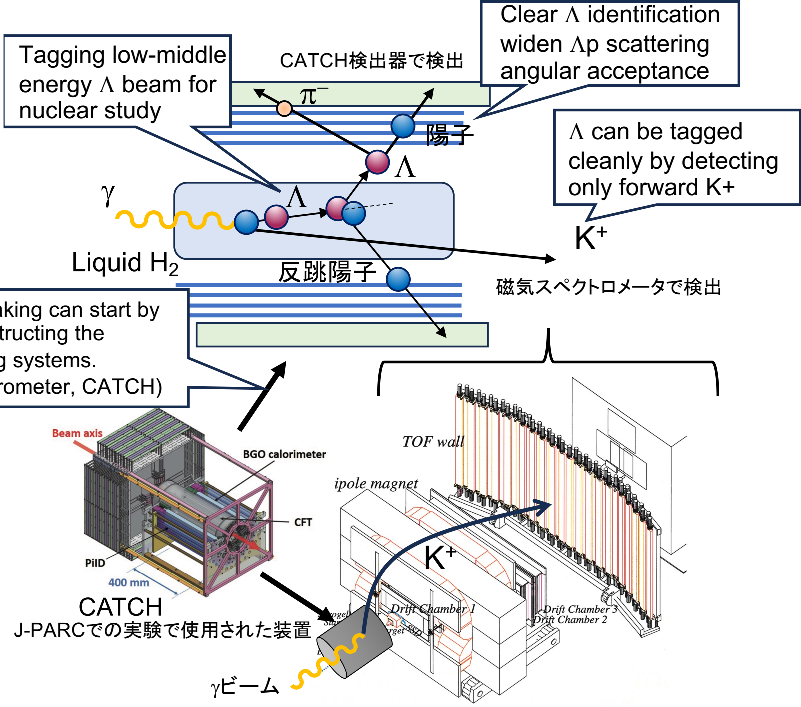
Density (radial) dependence of ΛN interaction

Λp differential cross section



Essential input for constructing realistic ΛN interaction

Advantage at BL33LEP



Tagging low-middle energy Λ beam for nuclear study

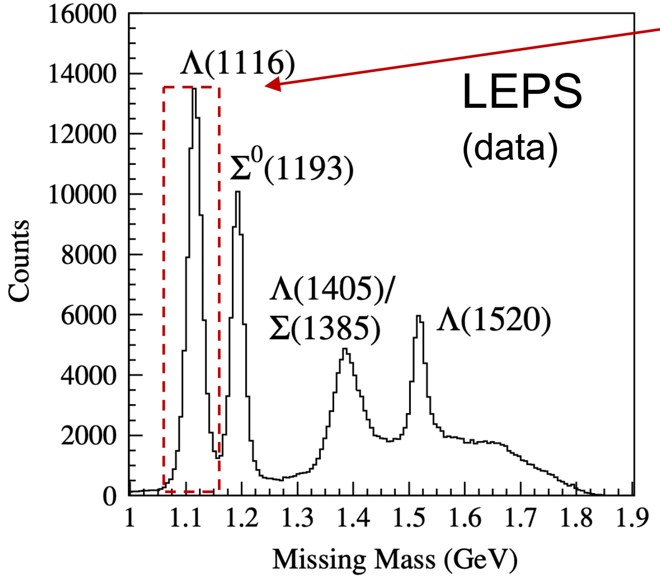
Clear Λ identification widen Λp scattering angular acceptance

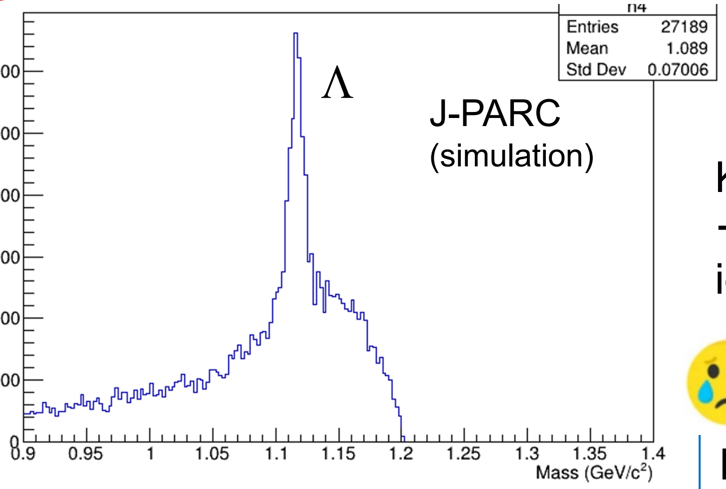
Λ can be tagged cleanly by detecting only forward K+

Data taking can start by reconstructing the existing systems. (Spectrometer, CATCH)

Why BL33LEP?

Advantage of γ beam: Λ production can be identified most clearly by detecting K+





K^0 identification
→Some background remains due to identification method

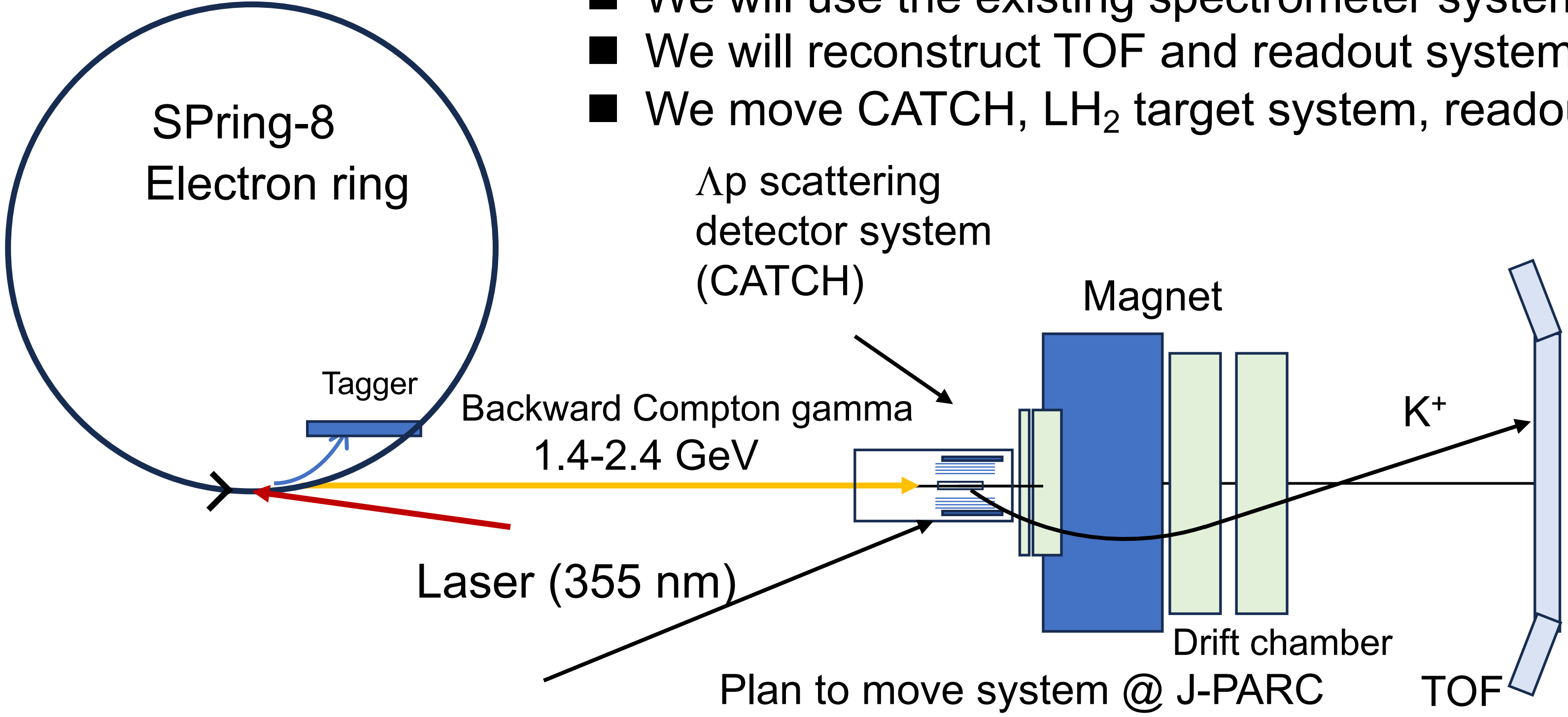
In the scattering analysis, we need to require two protons. This limits angular acceptance of Λp scattering

Advantage of backward Compton γ beam: A forward spectrometer can be placed, making it possible to tag low-energy Λ with small momentum transfer for the first time .

We can get Λ beam from 0.3 GeV/c (for nuclear study) to 0.6 GeV/c (for neutron star)

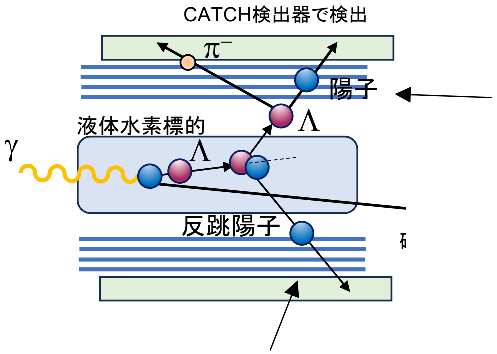
Experimental setup of Λp scattering experiment at BL33LEP

- We will use the existing spectrometer system.
- We will reconstruct TOF and readout systems
- We move CATCH, LH_2 target system, readout system to SPring-8 from J-PARC



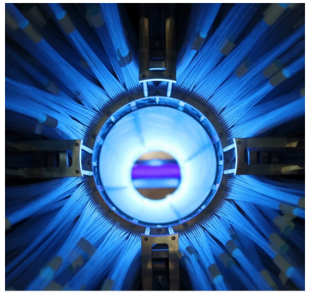
Plan to move system @ J-PARC

CATCH and LH2 target system



BGO calorimeter

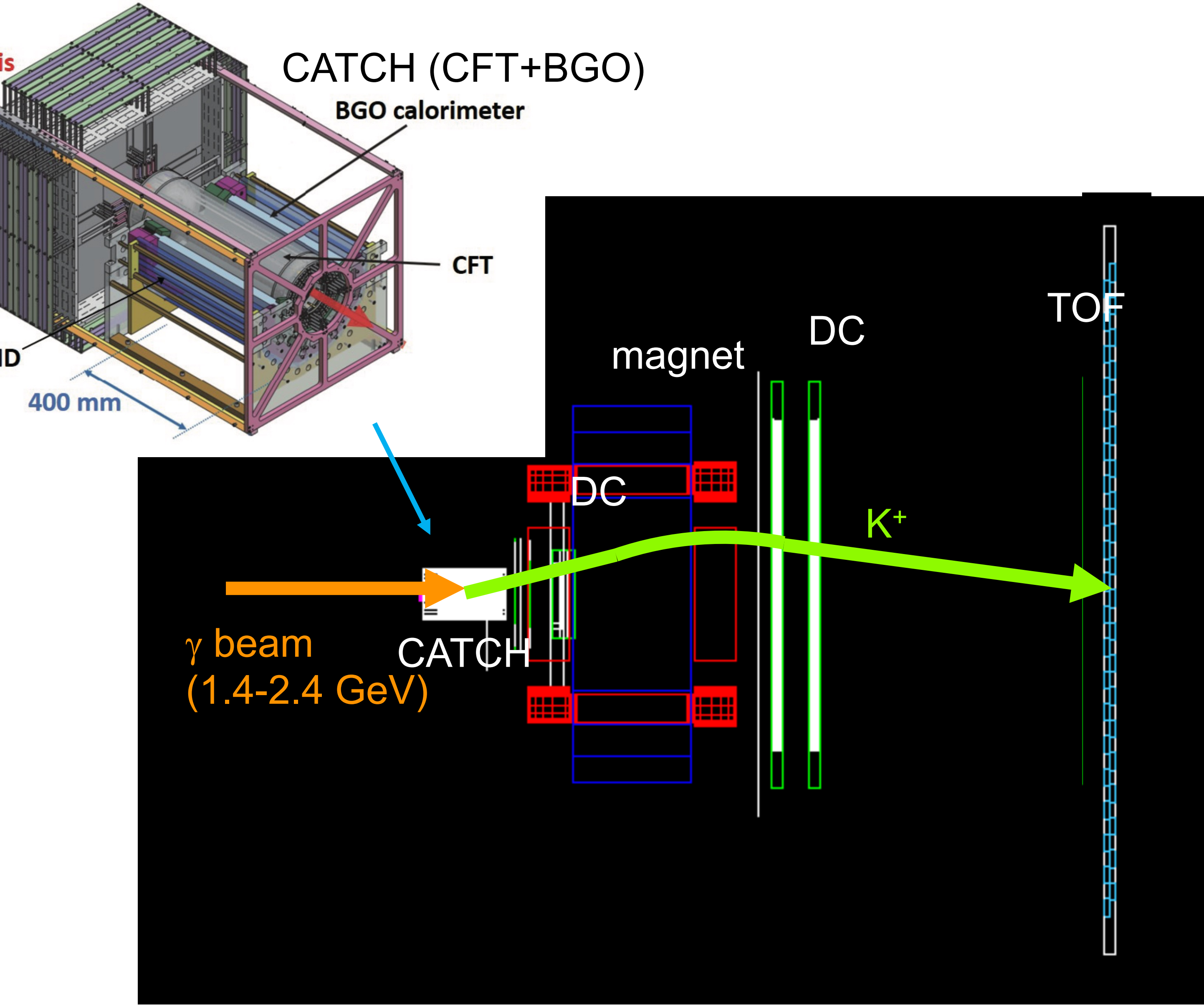
Cylindrical fiber tracker



Feasibility study at BL33LEP : Acceptance of Λ beam detection

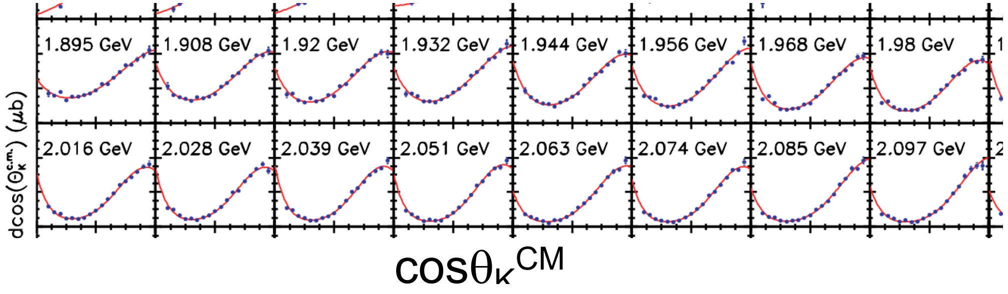
We estimated essential parameters
w/ simulation study

- Acceptance for K+
- Λ beam momentum distribution
- Λp scattering identification quality

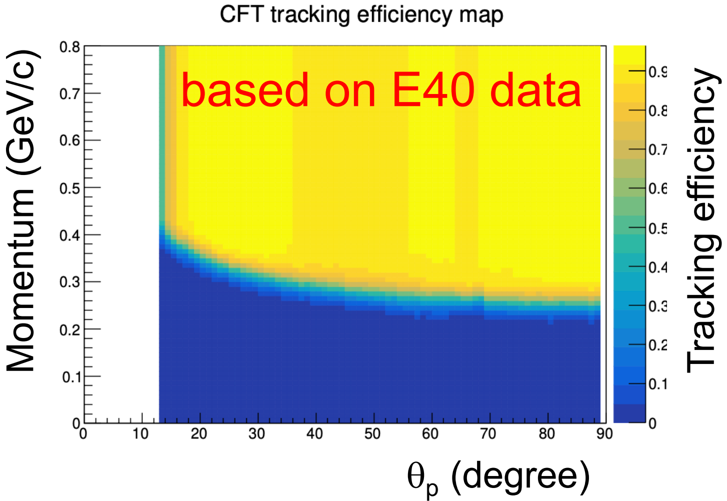


Input

Angular distribution of Λ production by CLAS

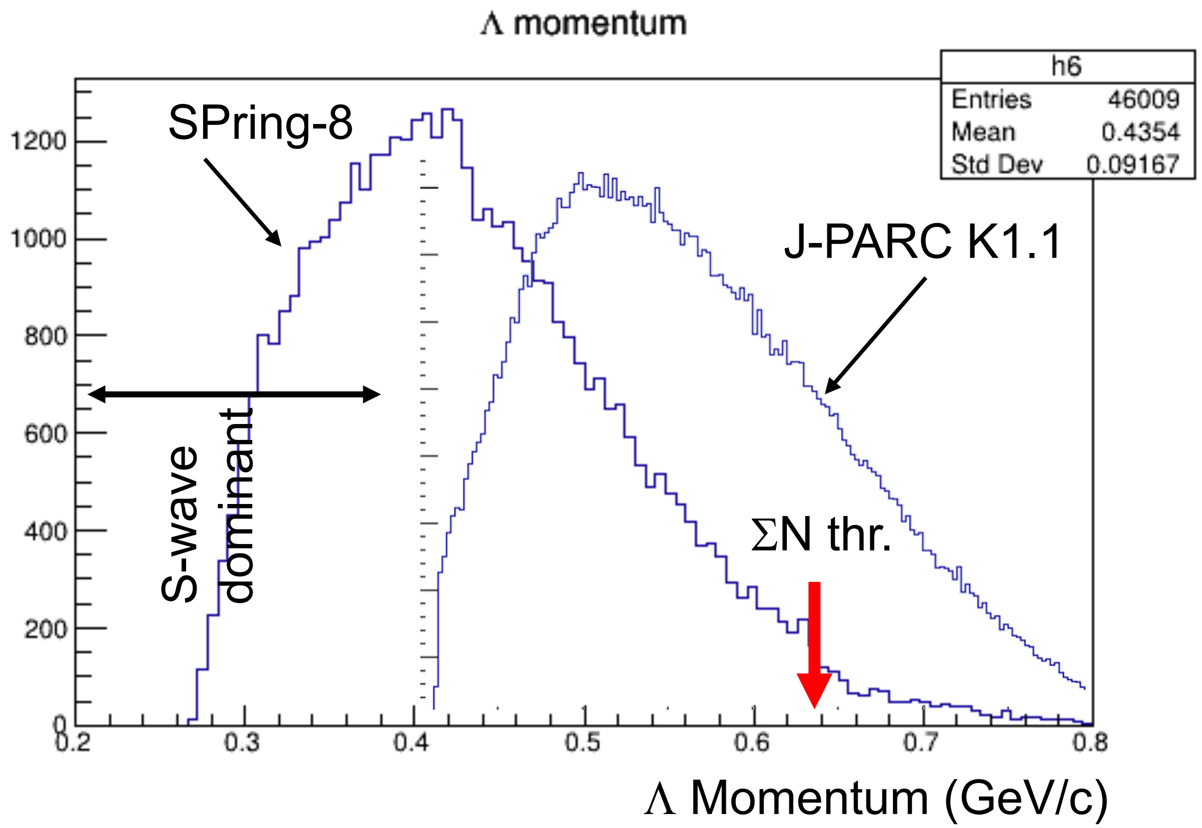


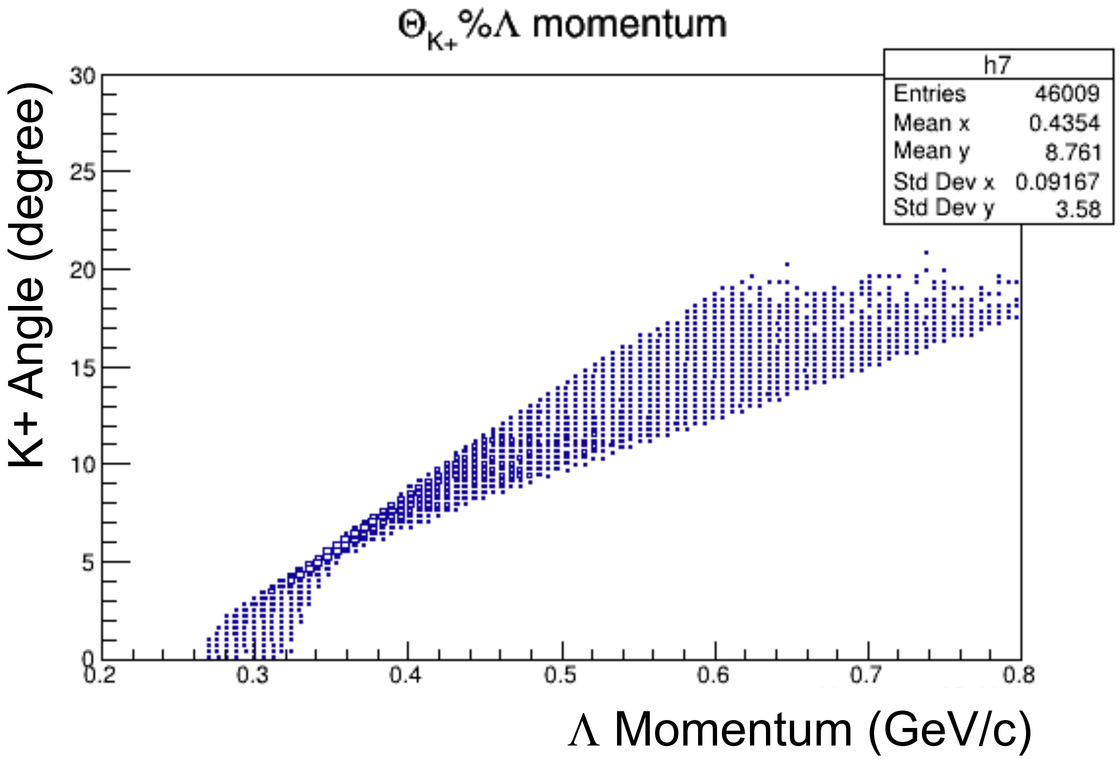
CATCH efficiency



Λ beam identification (Acceptance, Momentum)

- Acceptance for mimicked setup for HYPS : ~10%
  - Corresponding K+ momentum : 1 ~ 2 GeV/c
- Λ momentum range : 0.3 ~ 0.55 GeV/c
  - Cover lower momentum region. Close relationship with hypernuclear physics.
  - Good complementary with K1.1





Λ beam yield estimation

Items	**Estimated values**
γ beam intensity	2 MHz
Λ production cross section	1.5 μb
Liquid H_2 target thickness, number	30 cm → 12.7 x 10^{23} [1/cm^2]
K+ acceptance	0.11
K+ survival rate	0.69 (for p_{K+}=1.5 GeV/c, L=3.7 m)
DAQ, analysis efficiency	0.9 (assumption)
Tagged Λ yield per second	0.281 [1/s]
Tagged Λ yield per day	2.42 x 10^4 [1/day]

We need to accumulate 10^7 Λ beams for 10% order accuracy:

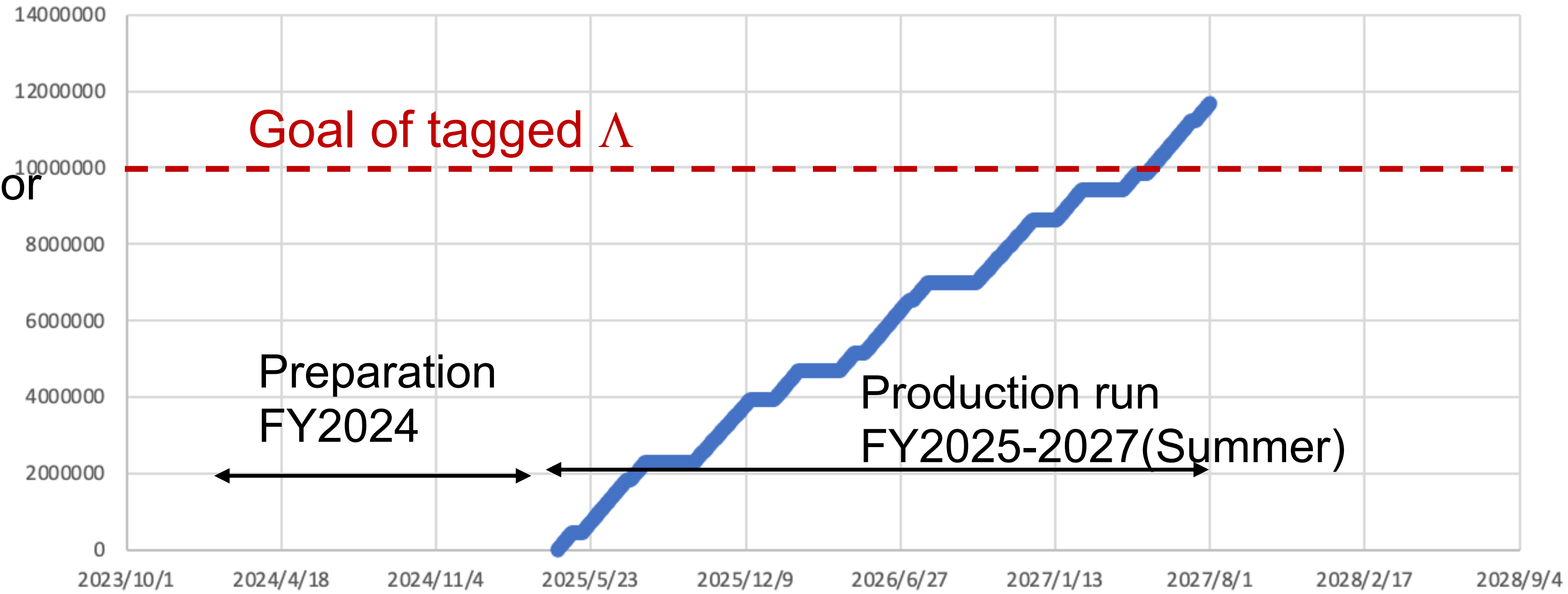
c.f. Σ^-p scattering (E40) 1.7 x 10^7 Σ^- beam

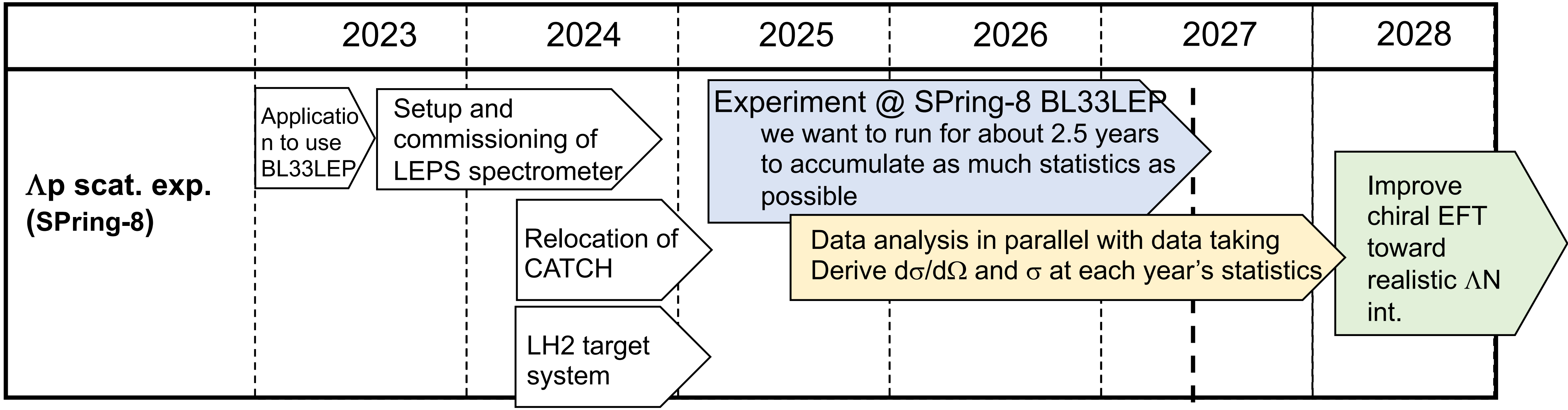
→ Beam time of ~400 days is necessary

Timeline

FY2024 : Commissioning of detector
FY2025: Start data taking
until Aug. 2027

Yield estimation of tagged Λ





Λp scat. exp. (SPring-8)

Application to use BL33LEP

Setup and commissioning of LEPS spectrometer

Relocation of CATCH

LH2 target system

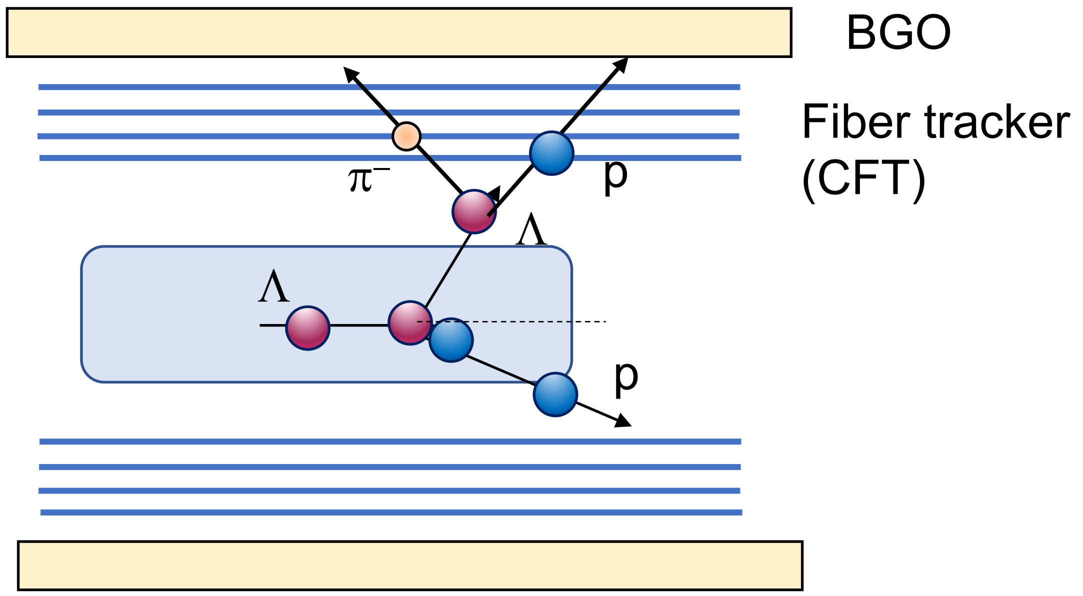
Experiment @ SPring-8 BL33LEP
we want to run for about 2.5 years to accumulate as much statistics as possible

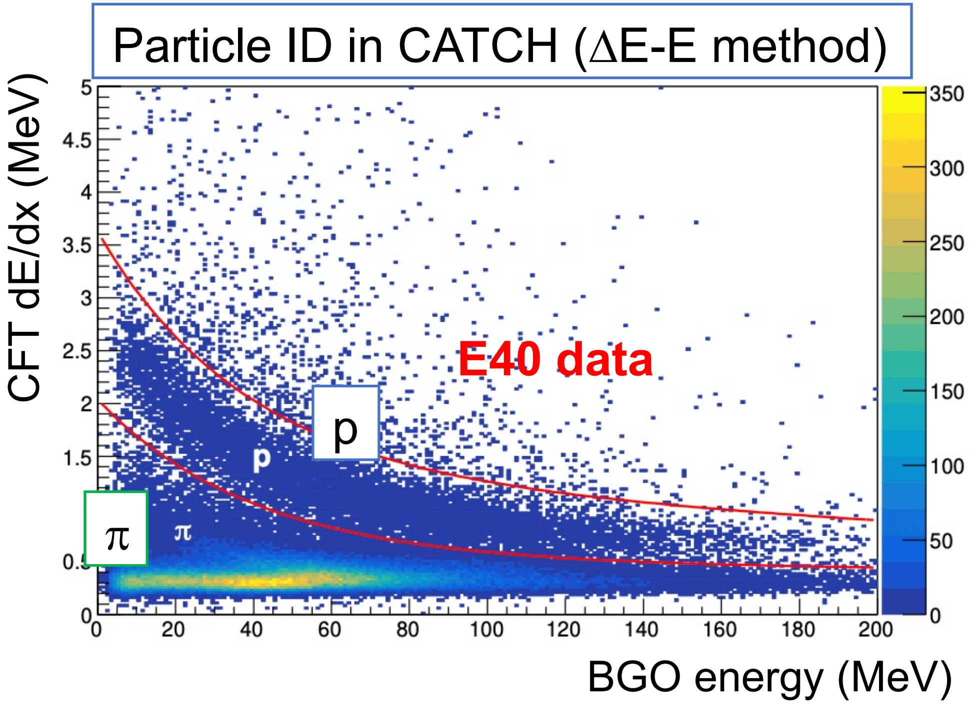
Data analysis in parallel with data taking
Derive $d\sigma/d\Omega$ and σ at each year's statistics

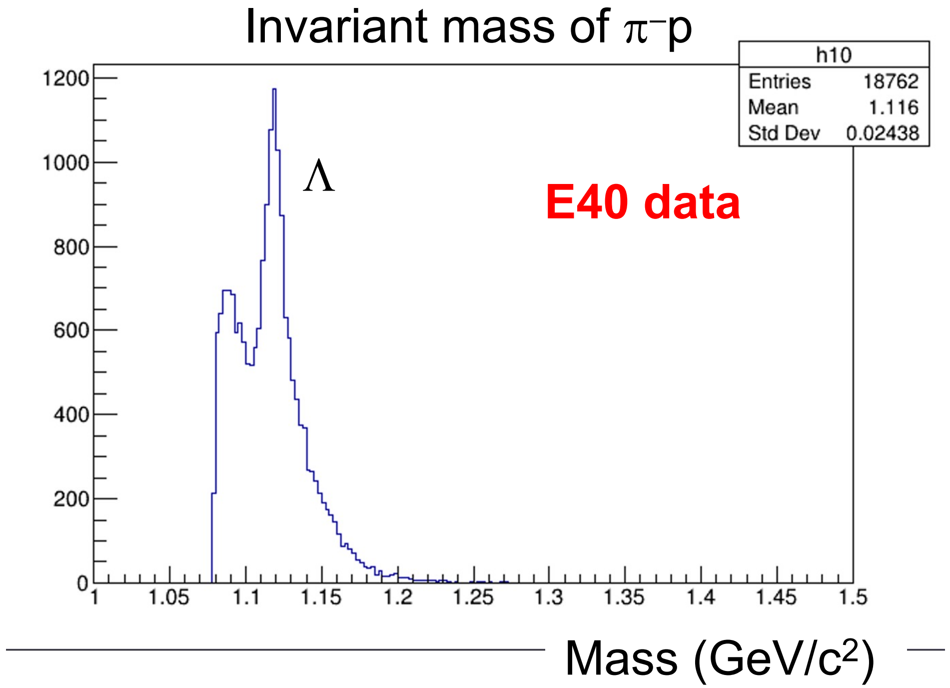
Improve chiral EFT toward realistic ΛN int.

Beam stop at 2027 August ?

Λp scattering identification





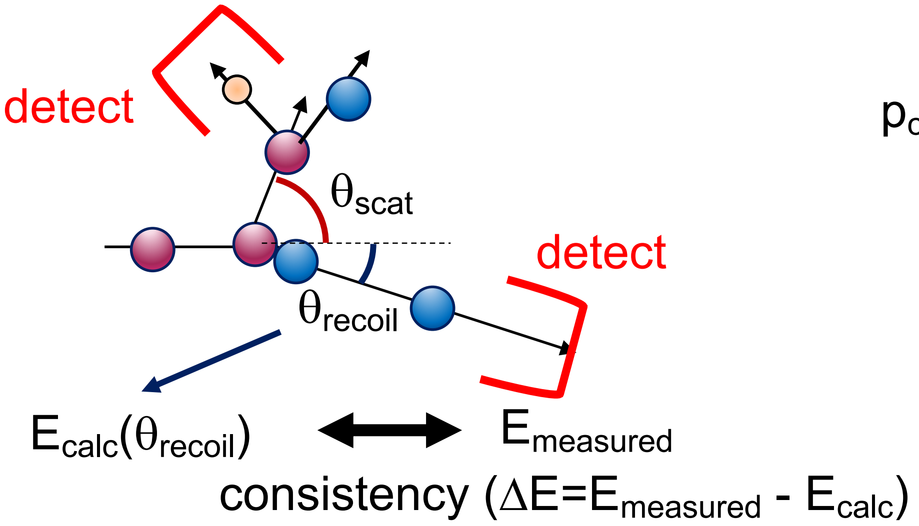


Proton can be stopped in BGO
→ Proton's direction and energy information
Pion cannot be stopped in BGO for many cases
→ Only direction information

But, π^- from Λ decay has low momentum (~150 MeV/c)
→ many of π^- can be stopped (resolution is not so good)

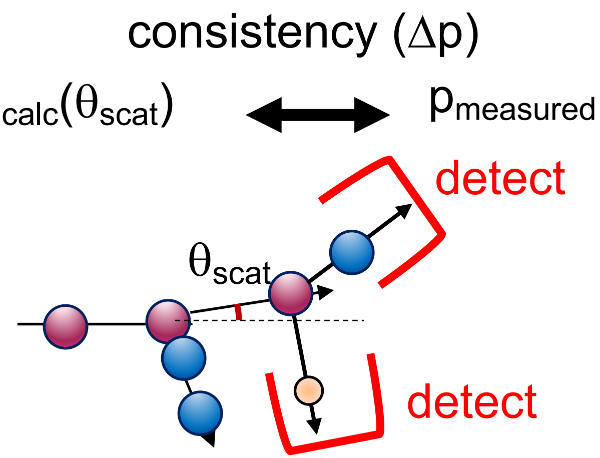
π^- energy is calculated from Λ's decay kinematics.

Angular acceptance of Λp scattering by CATCH



$E_{calc}(\theta_{recoil})$ ⟷ $E_{measured}$

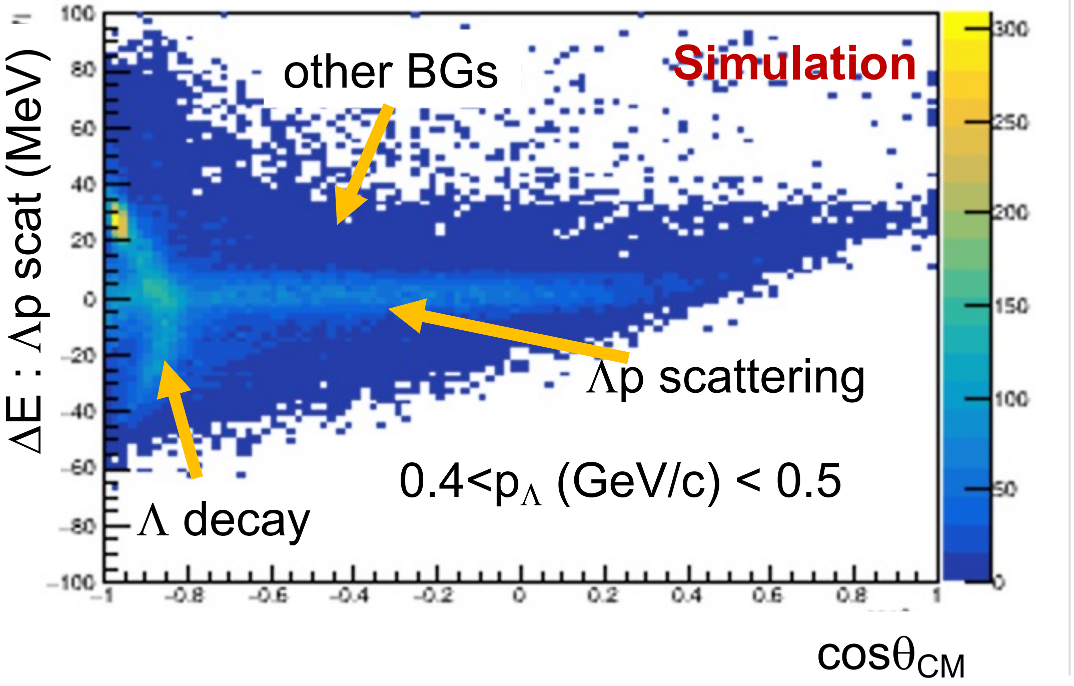
consistency ($\Delta E = E_{measured} - E_{calc}$)

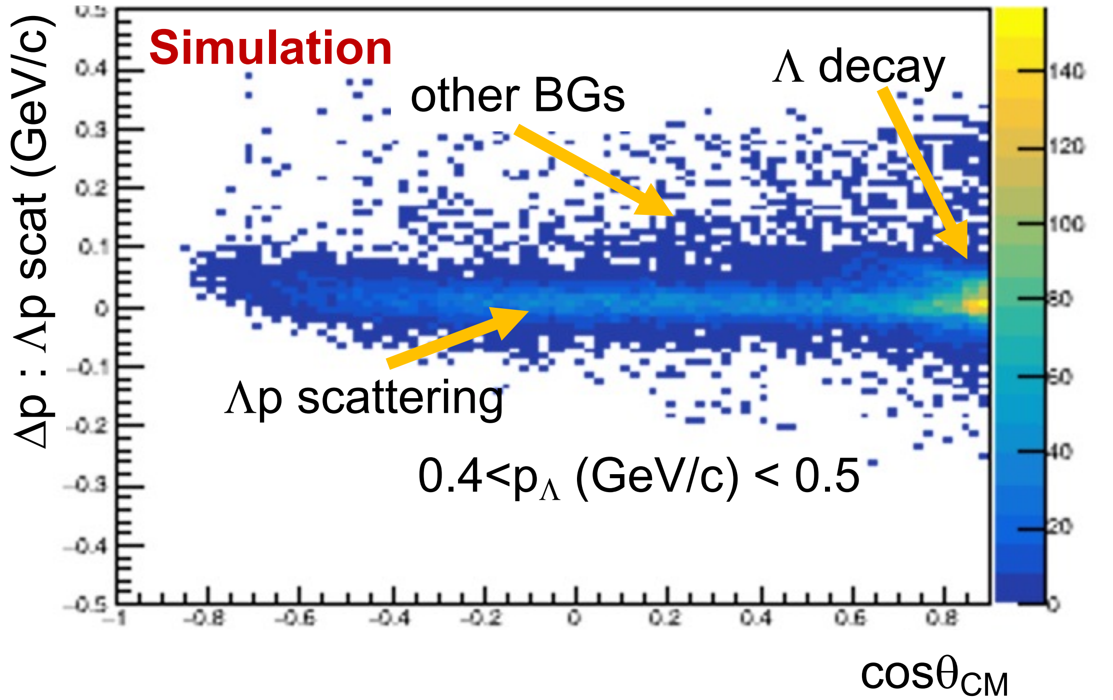


consistency (Δp)

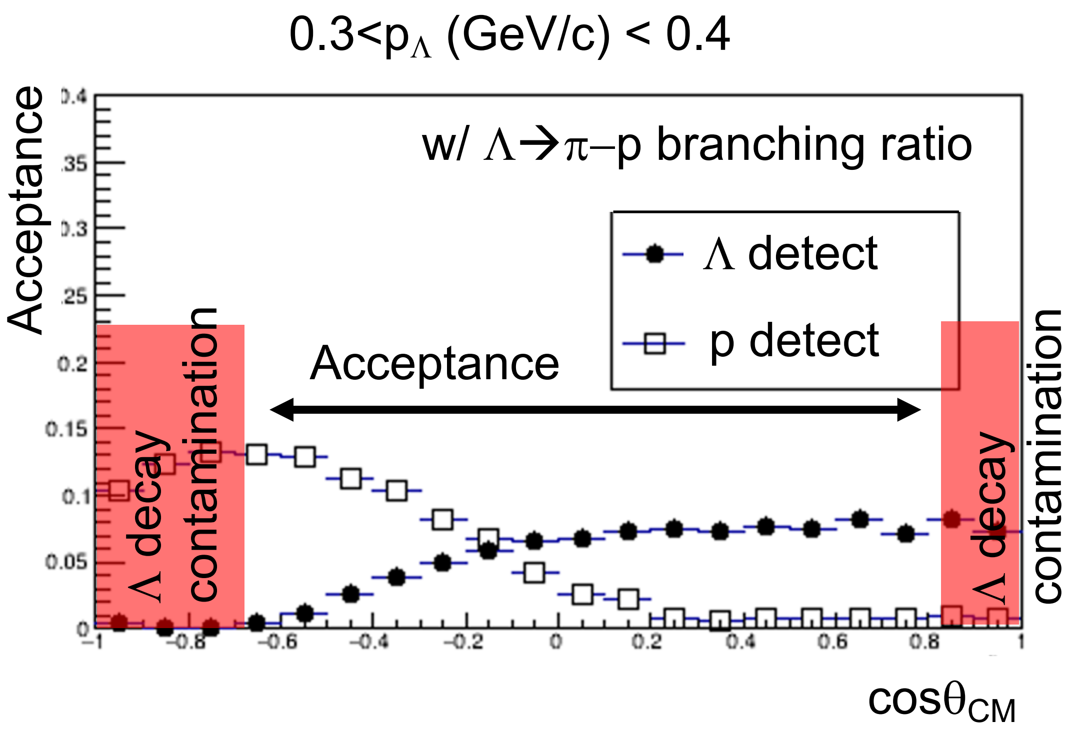
$p_{calc}(\theta_{scat})$ ⟷ $p_{measured}$

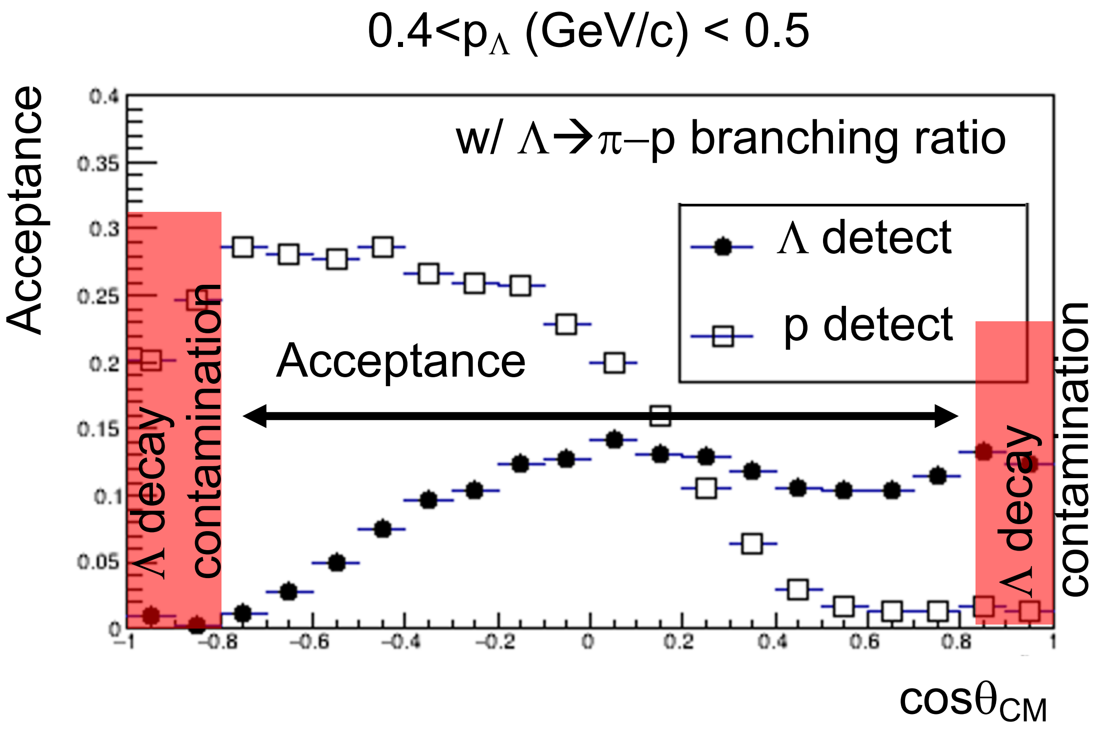
Λp cross section : 30 mb (assumed)
pp, π^-p : realistic cross section
Λ decay : 1/100





Angular acceptance of Λp scattering by CATCH


0.3<p_Λ (GeV/c) < 0.4

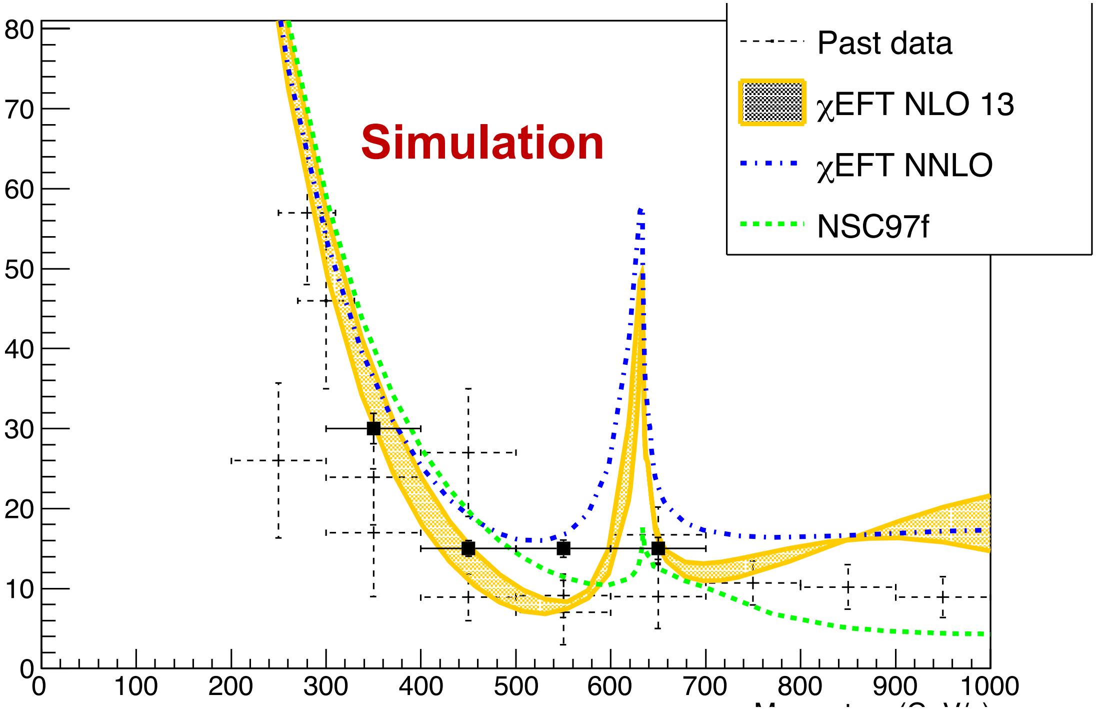

0.4<p_Λ (GeV/c) < 0.5

Forward scattering angle : covered by Λ detection
Backward scattering angle : covered by proton detection
But, very forward and very backward regions might be hard due to Λ decay contamination

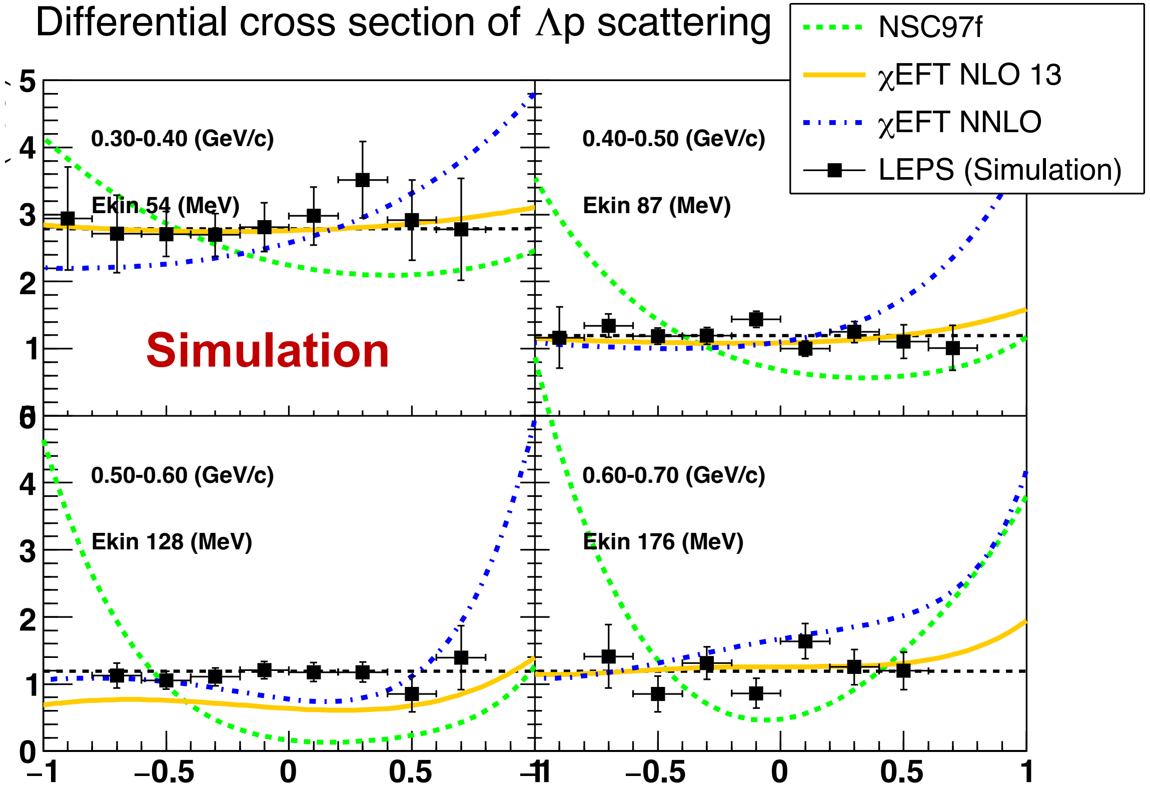
Even though, rather wide acceptance can be obtained.

Expected results

Momentum dependence of total cross section



Differential cross section of Λp scattering



Accurate dσ/dΩ data and total cross section can put strong constraint on ΛN interaction theory.

Chiral NNLO ΛN interaction shows rather attractive nature

- Larger cross section around p_{Λ}~500 MeV/c
- Deeper U(Λ) potential (-35~-37 MeV)

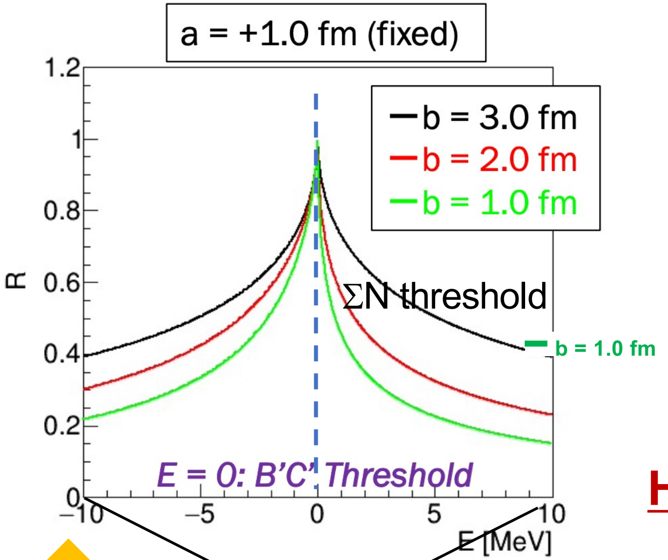
J. Haidenbauer et al.,
Eur.Phys.J.A 59 (2023) 3

Summary

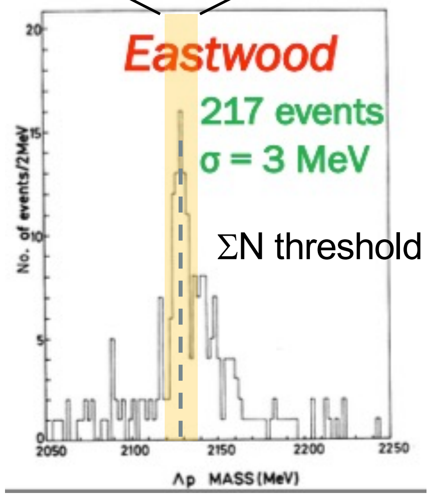
- Many progresses have been obtained in the BB interactions study.
  - Lattice QCD, Chiral EFT, …
  - Femtoscopy is successfully used for the hadron-hadron interaction study.
  - YN scattering experiment gets possible!
- New collaborative project regarding the two-body ΛN, ΣN interactions
  - Λp scattering experiment with photo-produced Λ
  - Precise measurement of ΣN cusp shape with S-2S
  - Lattice QCD potential of ΛN, ΣN, ΛN-ΣN potentials
- New experimental project will begin at SPring-8 to measure Λp scattering cross section
  - Λ particle ($300<p_\Lambda<600$ MeV/c)can be identified cleanly by $\gamma p \rightarrow K^+\Lambda$ reaction.
  - Experimental technology developed at J-PARC will be introduced.
  - Our goal
    - Total cross section measurement better than 10%
    - First derivation of the differential cross section for Λp elastic scattering

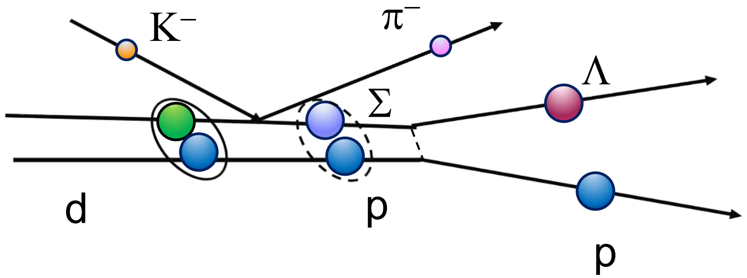
Precise ΣN cusp measurement with K⁻d →Λpπ⁻ reaction (J-PARC E90)

ΛN-ΣN Coupling dependence of cusp shape



Past measurement

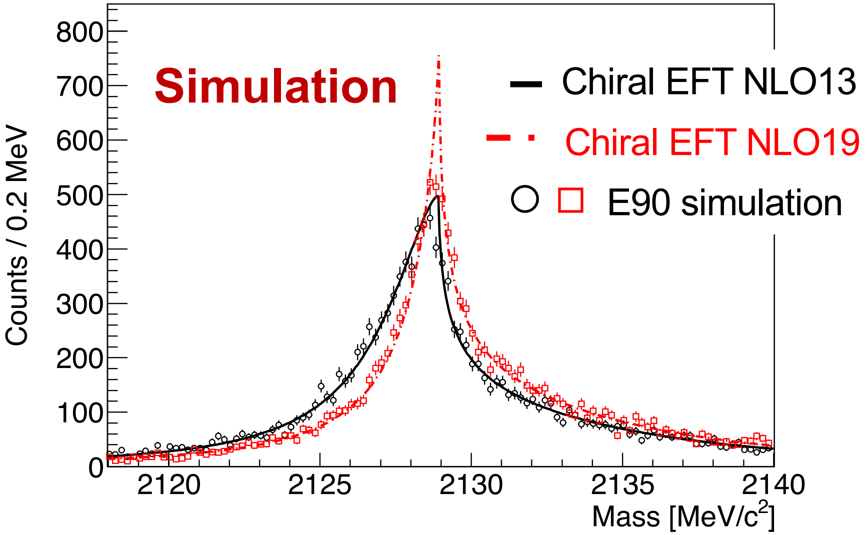




The cusp shape is represented by the scattering length A=a + ib of ΣN (I=1/2, S=1) channel

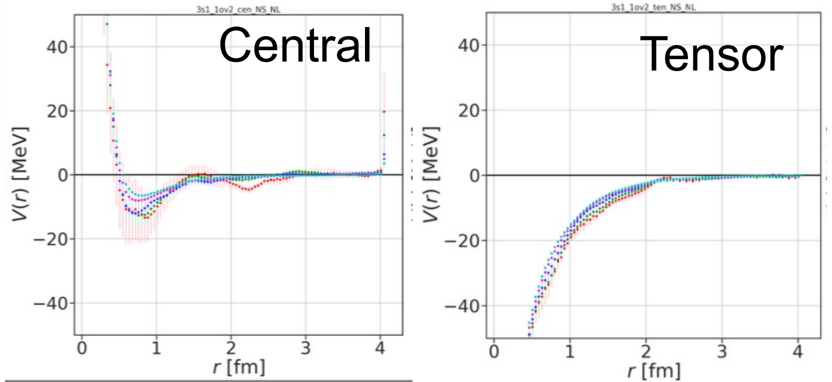
- **Real part a : Attraction of the ΣN interaction at low energy**
- **Imaginary part b : ΛN-ΣN coupling**

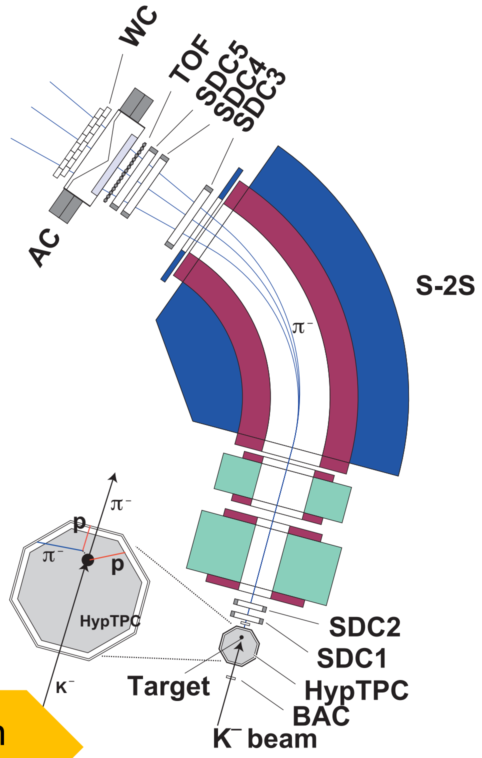
High resolution cusp measurement of σ=0.4 MeV w/ S-2S



Direct comparison by scattering length

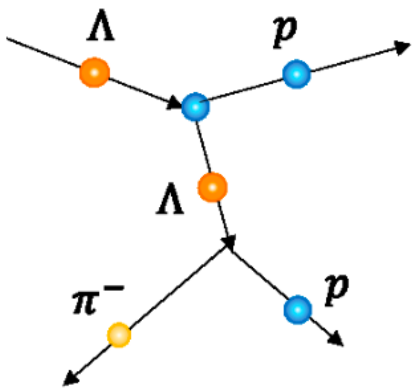
ΛN-ΣN potential from Lattice QCD



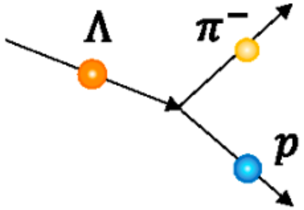


Background of Λp scattering

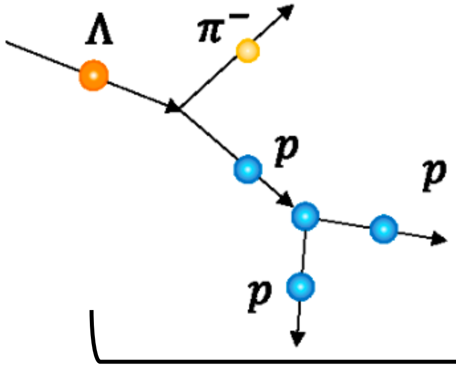
Λp scattering



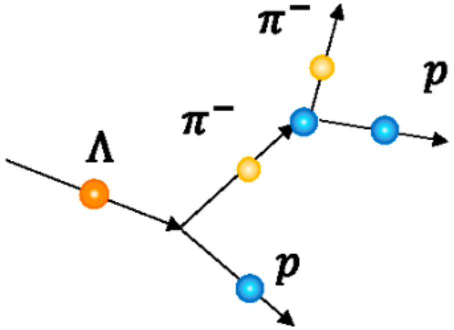
Λ decay



pp scattering from Λ decay



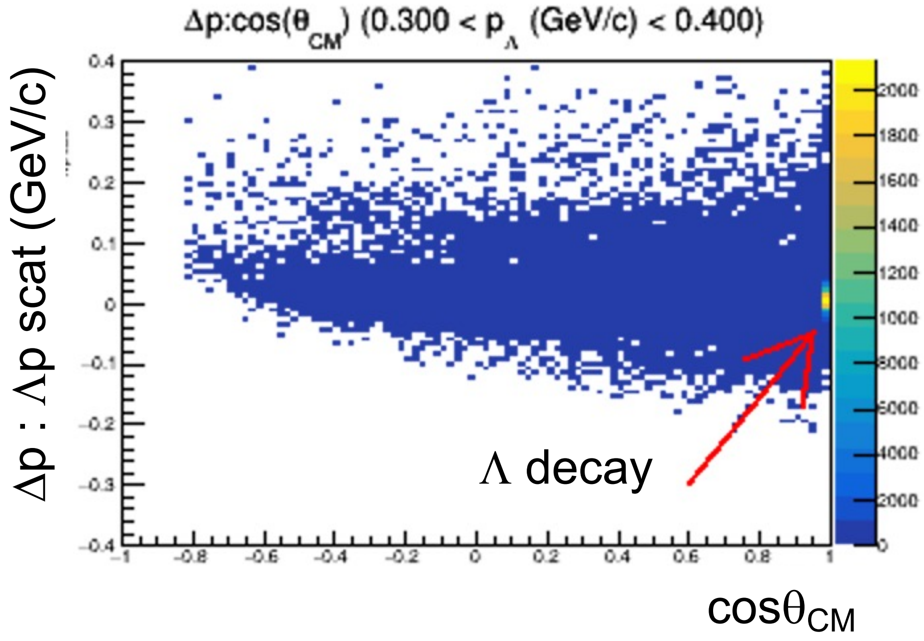
π⁻p scattering from Λ decay



To suppress background,

- one proton and one π⁻
- two protons

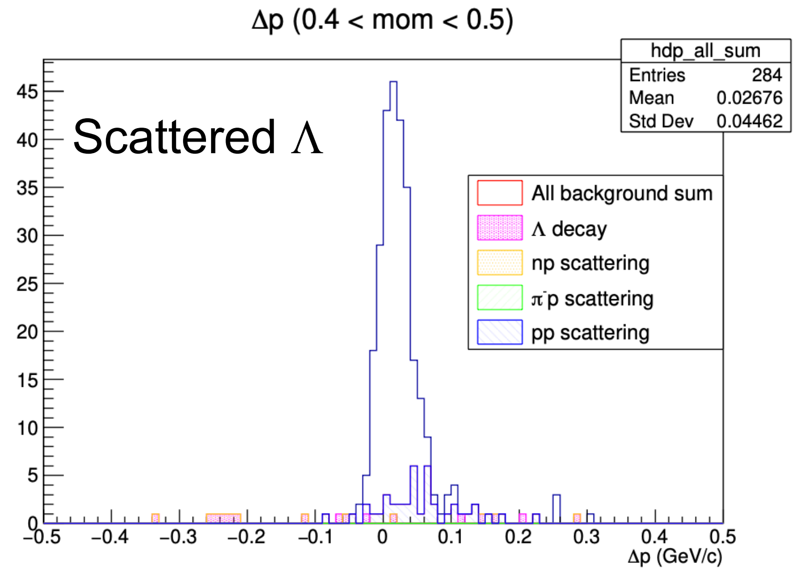
are essential

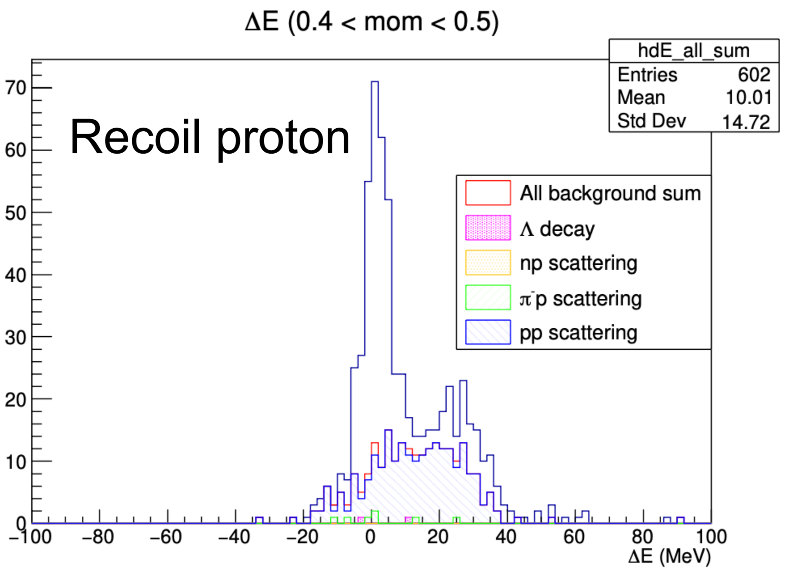


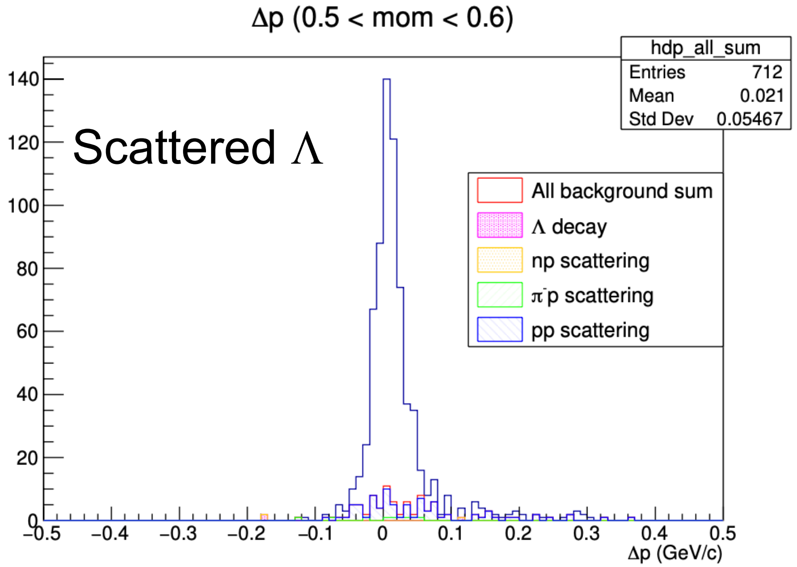
These rescattering events after Λ decay can be partially rejected kinematically

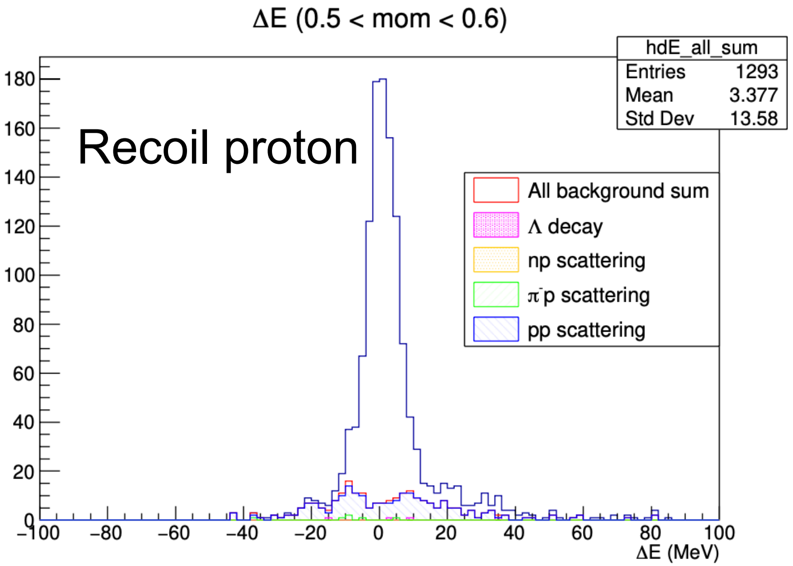
Λ decay can be identified as scattering at 0 degree

Event ID for 10^7 Λ



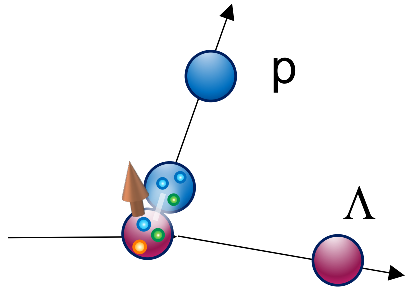


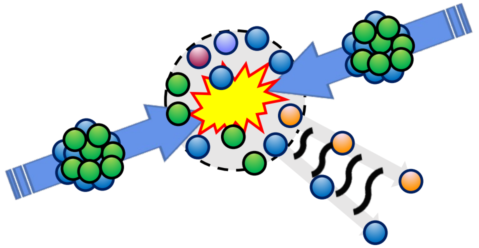


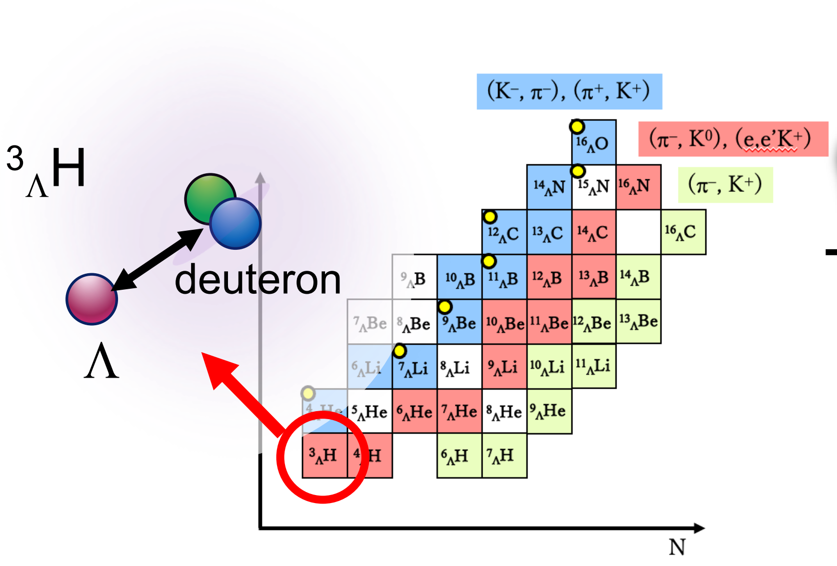


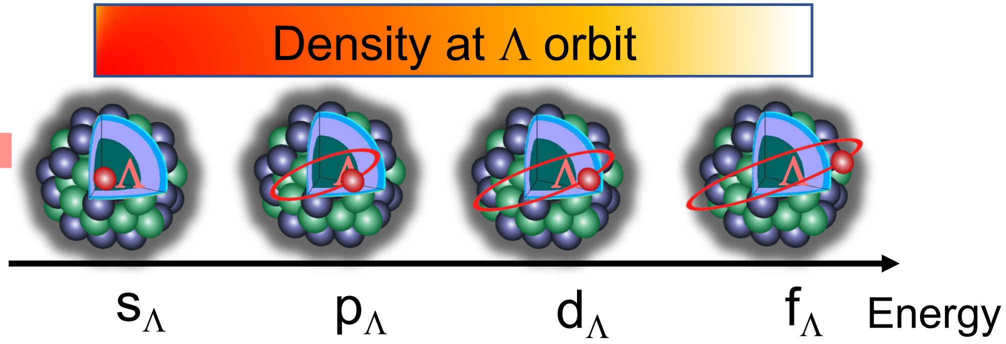
Hypernuclear physics

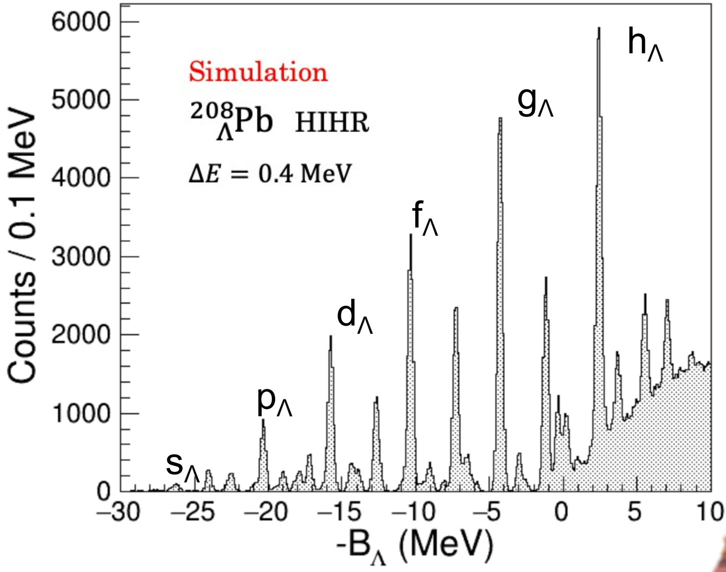
Baryon-Baryon interaction **Study of light Λ, Ξ hypernuclei** **Spectroscopy of heavy hypernuclei**





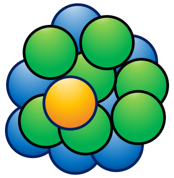




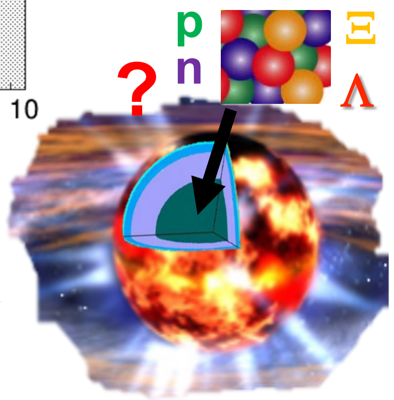


Two-body YN int.

Ξ hypernuclei



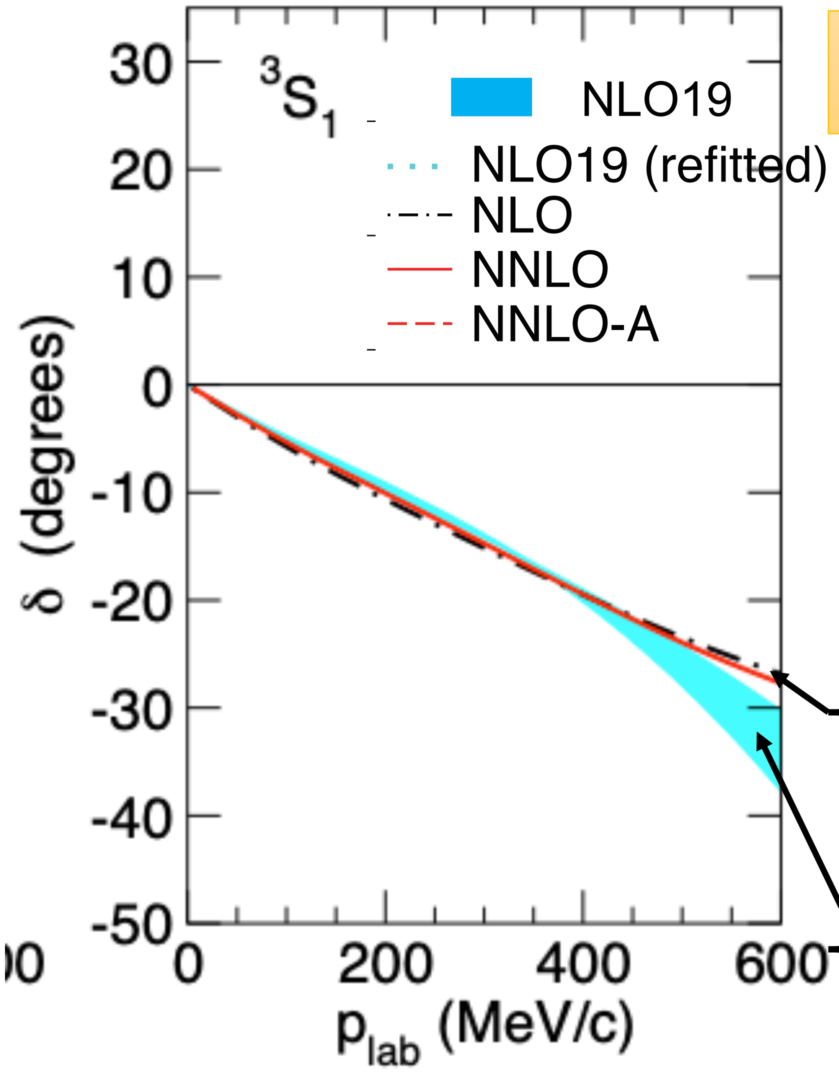
Neutron star



ΛN-ΣN coupling, ΛNN int., ΛΛ, ΞN int.

Density dependent ΛN int., ΛNN int.

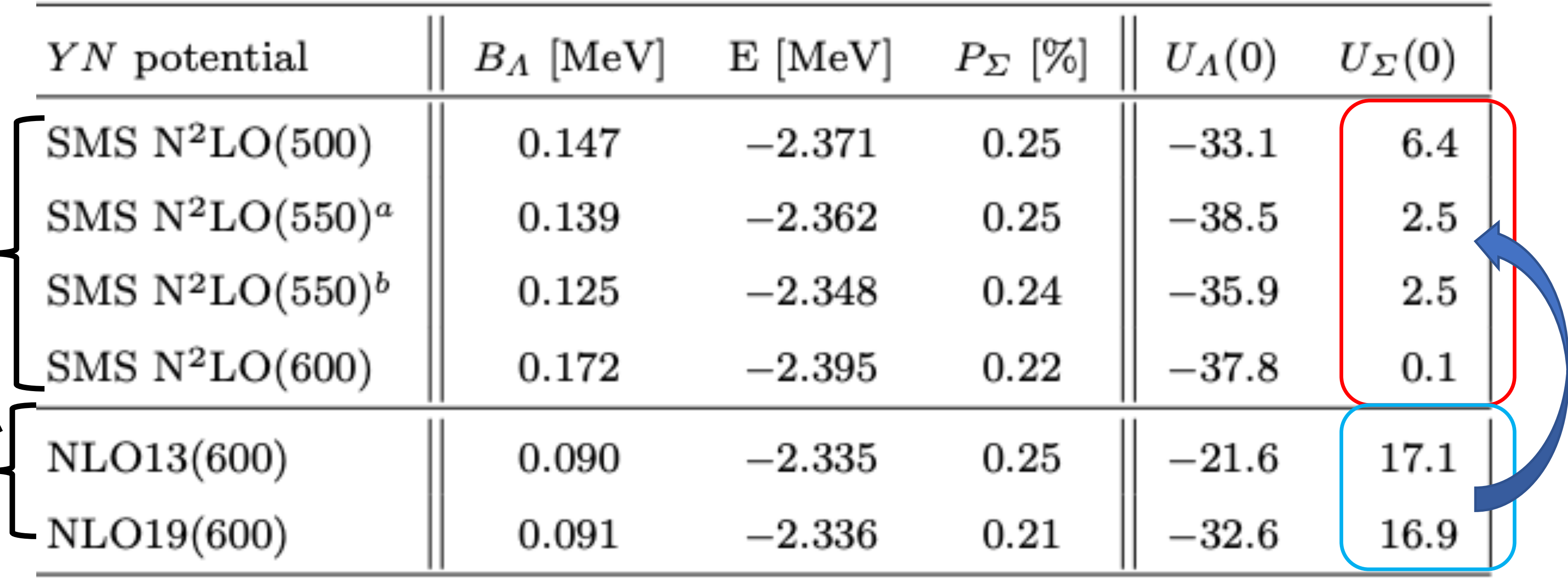
Phase shift in Chiral EFT NNLO and U_Σ



J. Haidenbauer et al., arXiv:2301.00722

Based on the E40 Σ^+p phase shift, U_Σ becomes less repulsive.

$^3_\Lambda H$



YN potential	B_Λ [MeV]	E [MeV]	P_Σ [%]	$U_\Lambda(0)$	$U_\Sigma(0)$
SMS N²LO(500)	0.147	−2.371	0.25	−33.1	6.4
SMS N²LO(550)[a]	0.139	−2.362	0.25	−38.5	2.5
SMS N²LO(550)[b]	0.125	−2.348	0.24	−35.9	2.5
SMS N²LO(600)	0.172	−2.395	0.22	−37.8	0.1
NLO13(600)	0.090	−2.335	0.25	−21.6	17.1
NLO19(600)	0.091	−2.336	0.21	−32.6	16.9

ΣN (I=3/2) phase shift in chiral EFT