Current and future programs to investigate the ΛN interaction from scattering experiments

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

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

The 15th International Conference on Hypernuclear and Strange Particle Physics (HYP2025)

Sep. 29th – Oct. 3rd, 2025

TOHOKU UNIVERSITY

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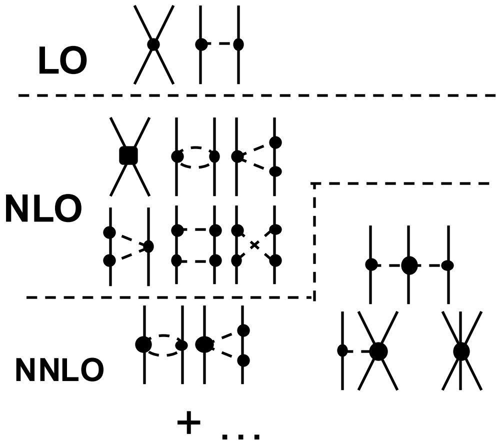
- Recent progress of baryon-baryon interaction study
- Brief summary of Σp scattering experiment (J-PARC E40)
- Collaborative research regarding the two-body ΛN, ΣN interactions
  - Scattering, Cusp, Lattice QCD
- New project of Λp scattering experiment at SPring-8
- Summary

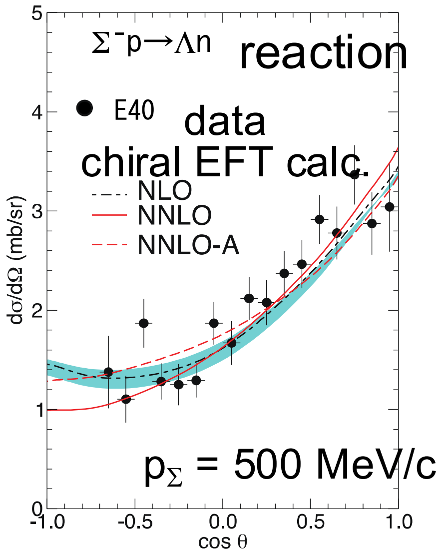
Progress of theory & experiment of BB int. study

Theoretical progress

Hyperon-Nucleon int. w/ chiral effective field theory
(J. Haidenbauer et al.)

2-body int. 3-body int.



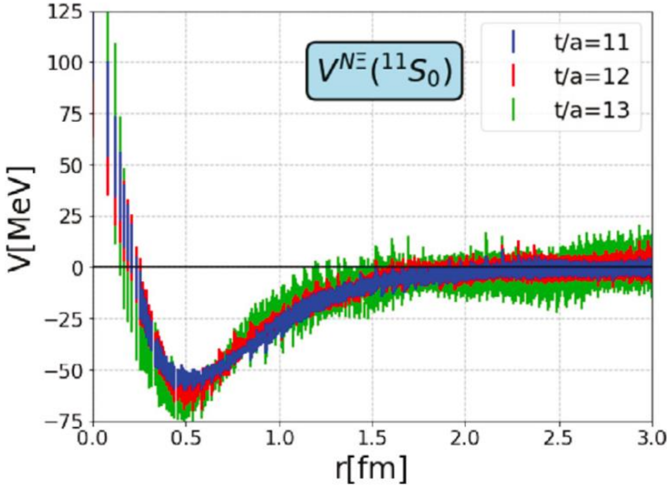


Improving accuracy w/ our new data

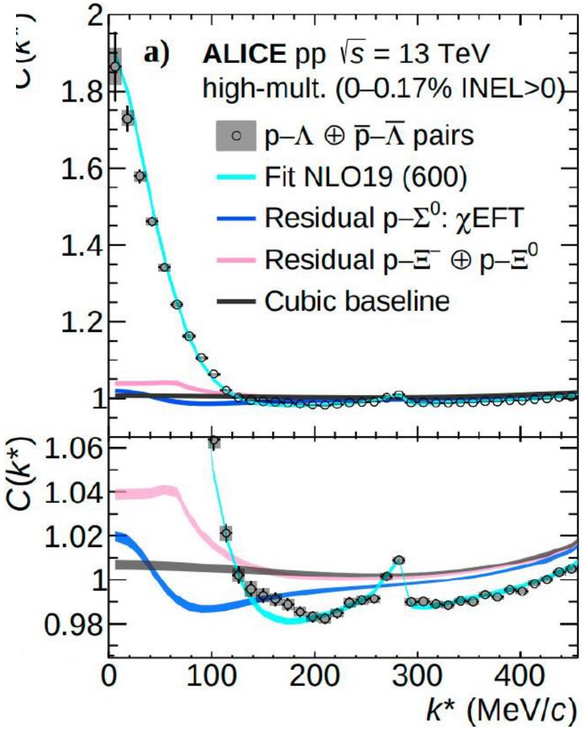
Hyperon potential by Lattice QCD

BB interaction at almost physical point for multi-strangeness sector

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

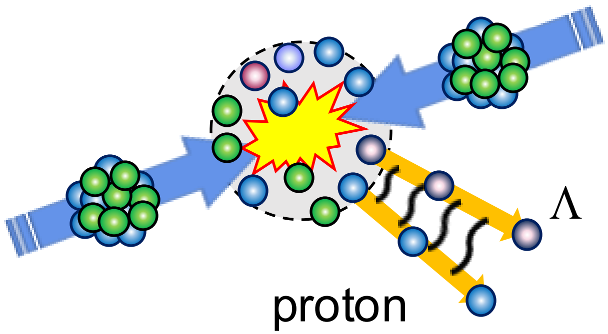


Particle correlation between Λ and p



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

Experimental progress



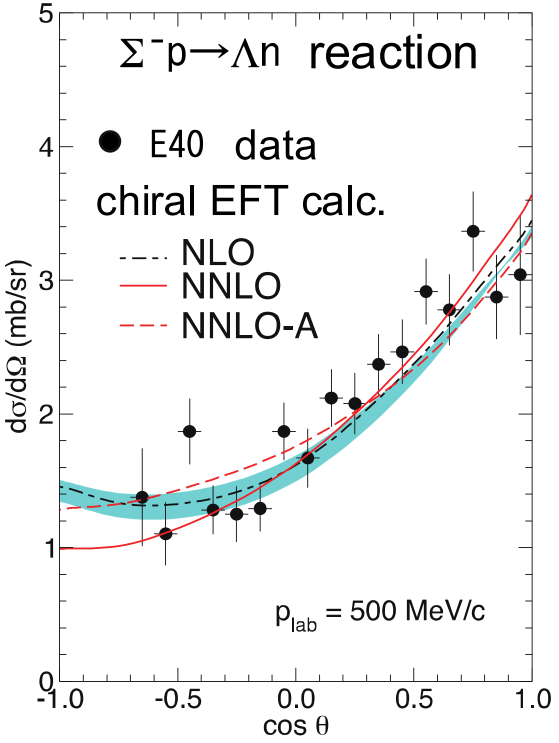
BB interaction from femtoscopy

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

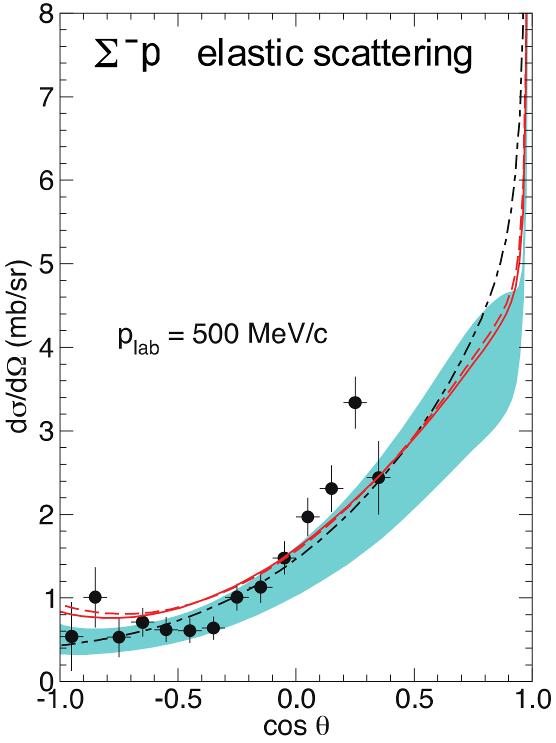
Fix source size(S(r*)) →
Study interaction from wave function ($\Psi(\vec{k^*},\vec{r^*})$)

New Σp scattering data at J-PARC

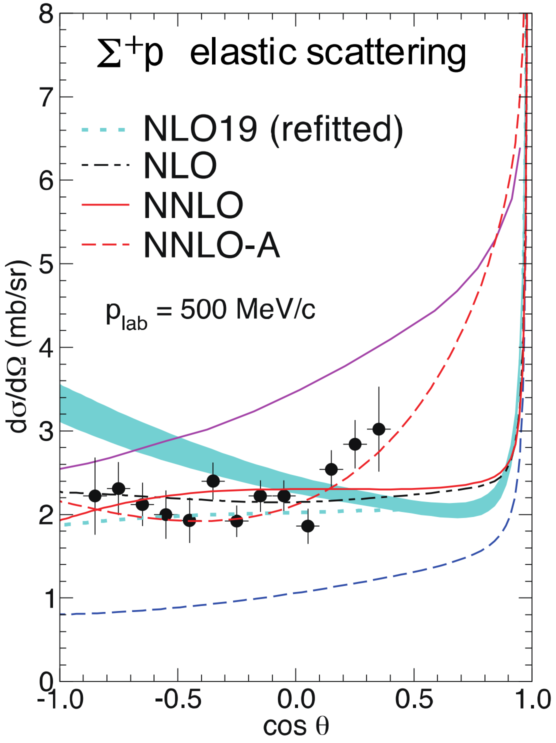
Accurate and systematic data of differential cross sections of Σp scattering



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

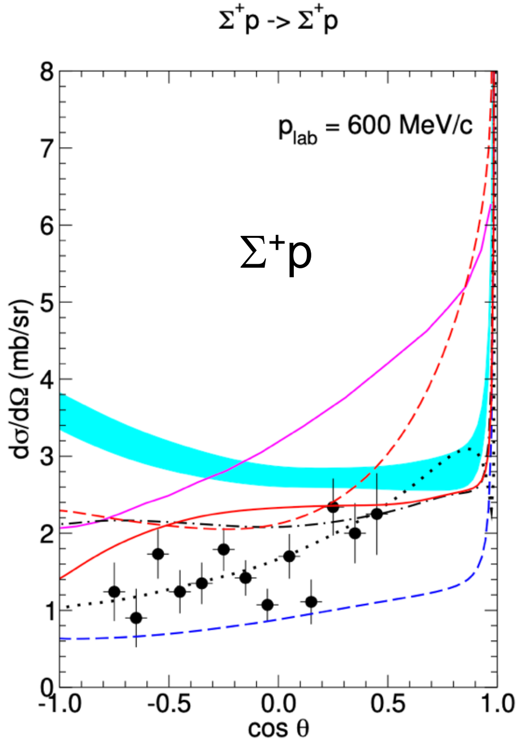


K. Miwa et al.,
PRC 104, 045204 (2021)



T. Nanamura et al., PTEP 2022 093D01

Difficulty at higher momentum

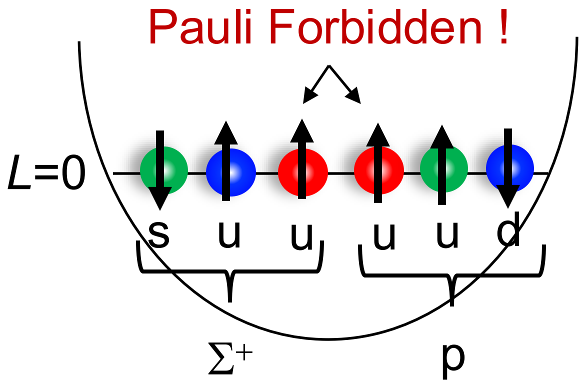


J. Haidenbauer et al.,
Eur.Phys.J.A 59 (2023) 3

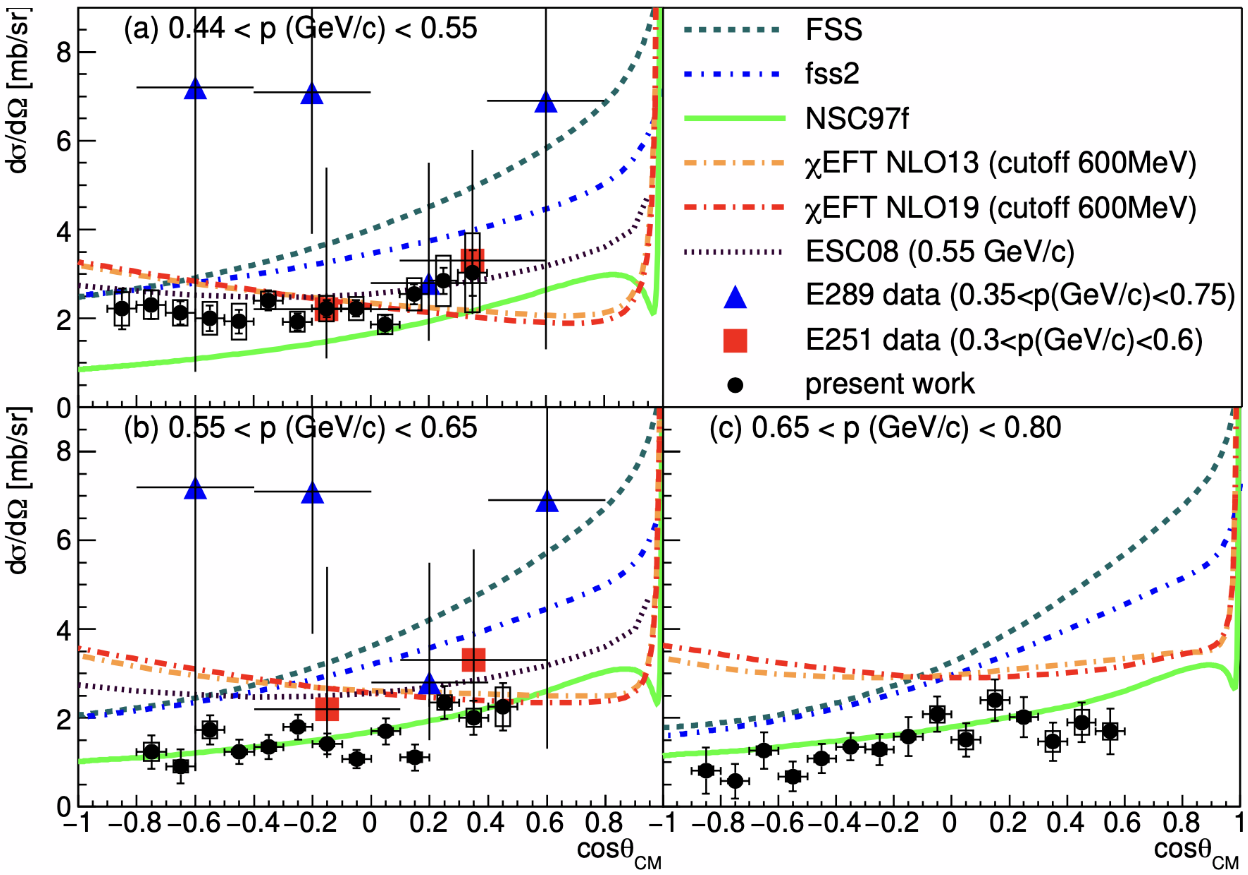
Development of Chiral EFT at NNLO have got started with E40 data

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

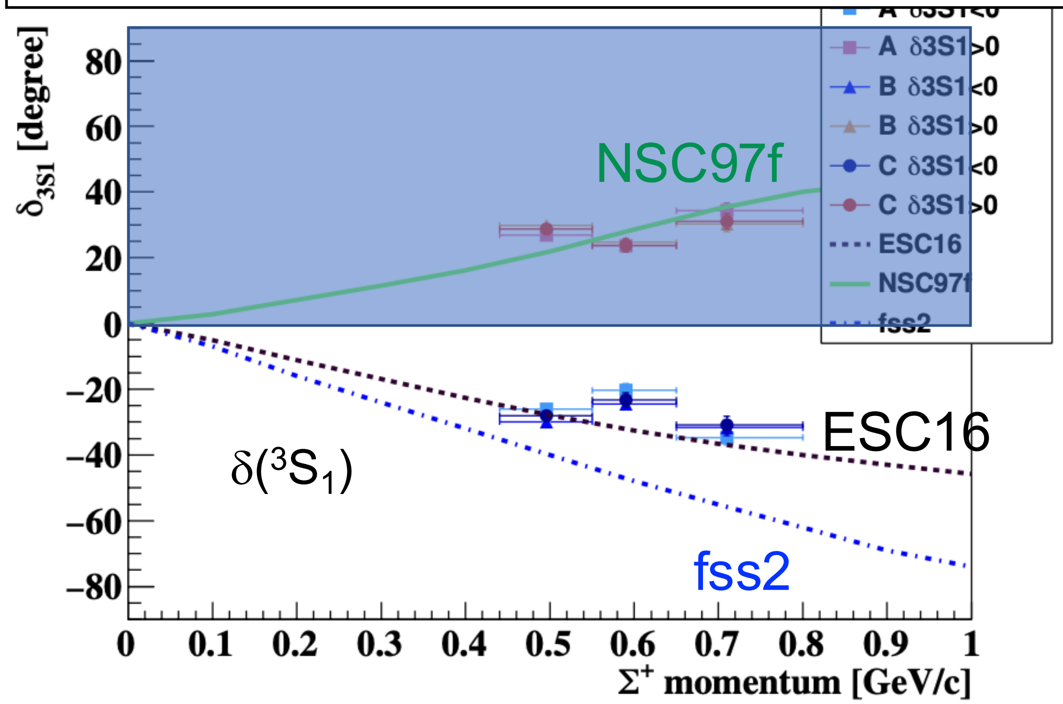
dσ/dΩ of $\Sigma^+ p$ elastic scattering



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



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

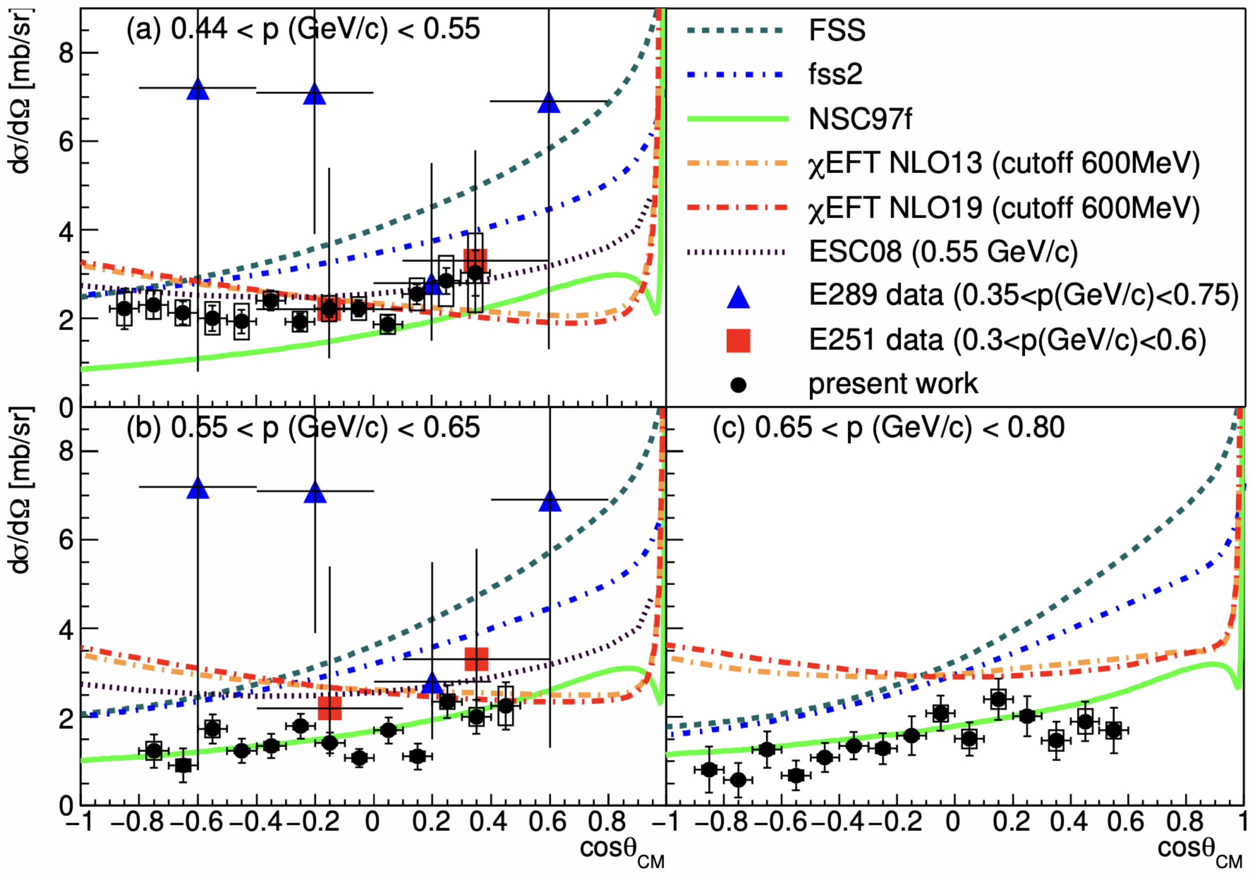


E40 data : much smaller than fss2 prediction and E289 results

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

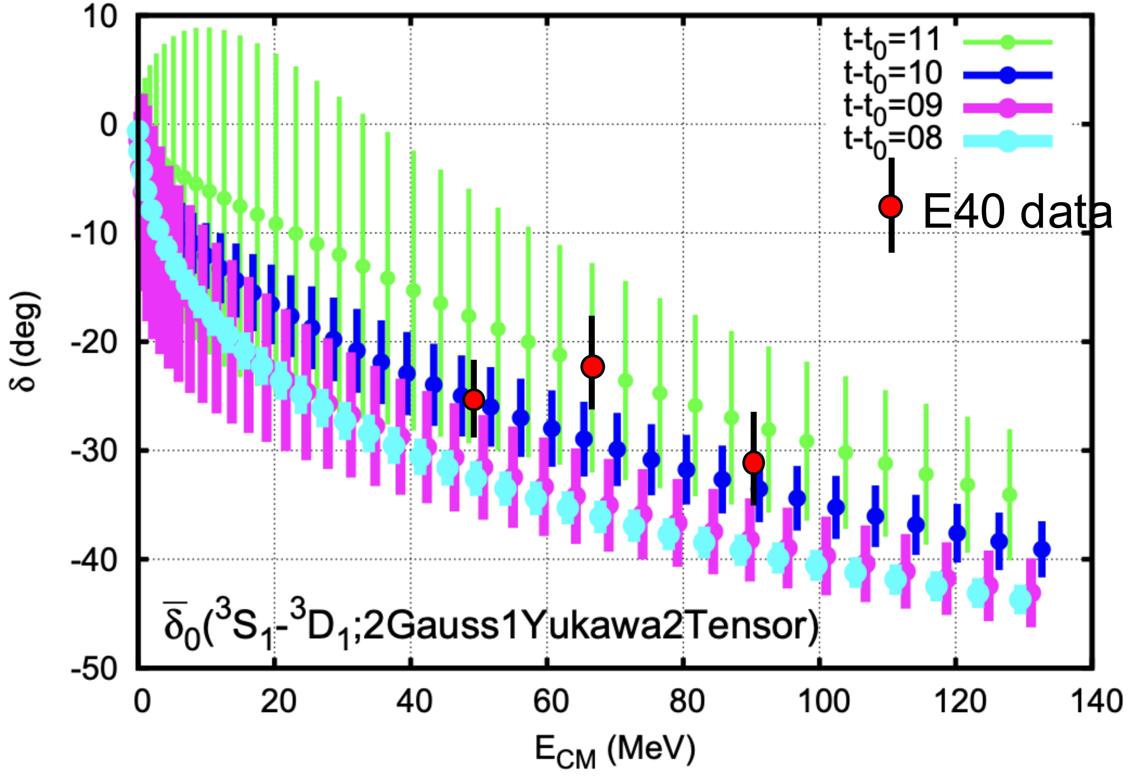
dσ/dΩ of Σ⁺p elastic scattering

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

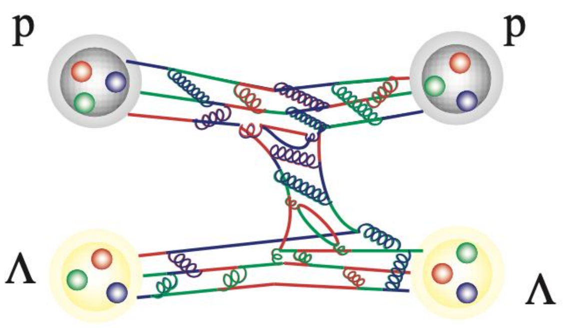


H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

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

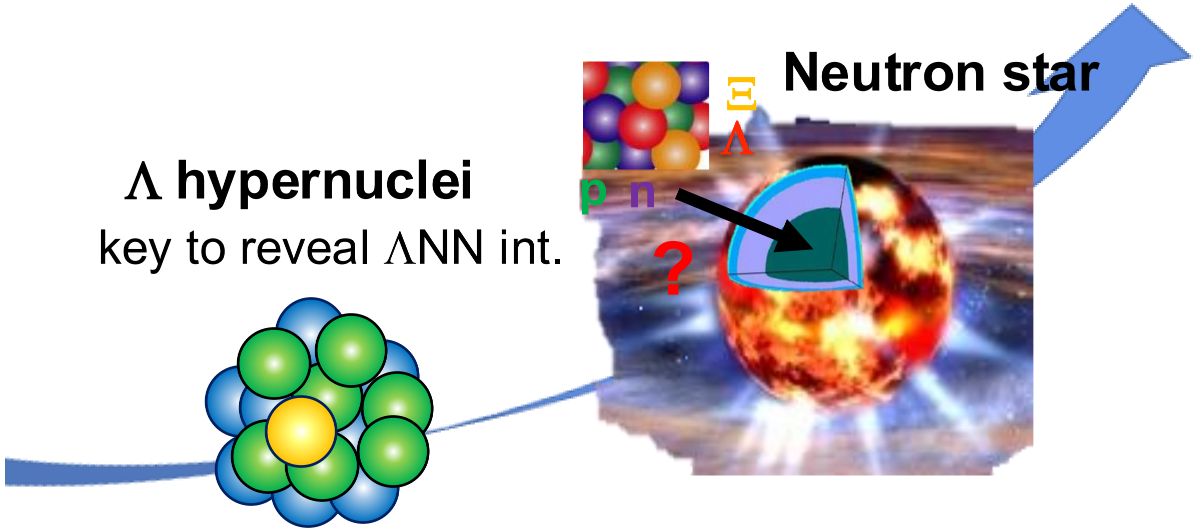
Toward Λp scattering

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

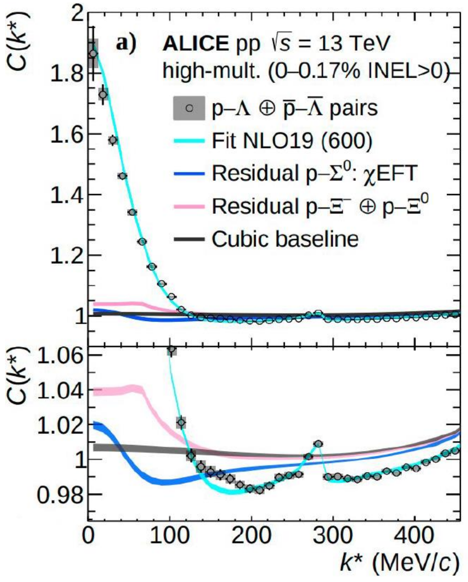


Λ hypernuclei
key to reveal ΛNN int.

Neutron star

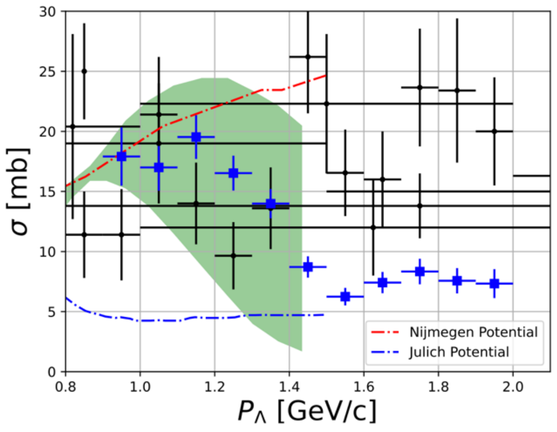


Femtoscopy from HIC



ALICE Collaboration, arXiv:2104.04427

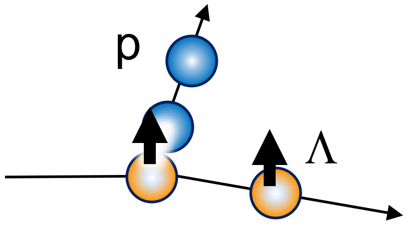
New cross section data
from Jlab CLAS



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

New project at SPring-8, J-PARC

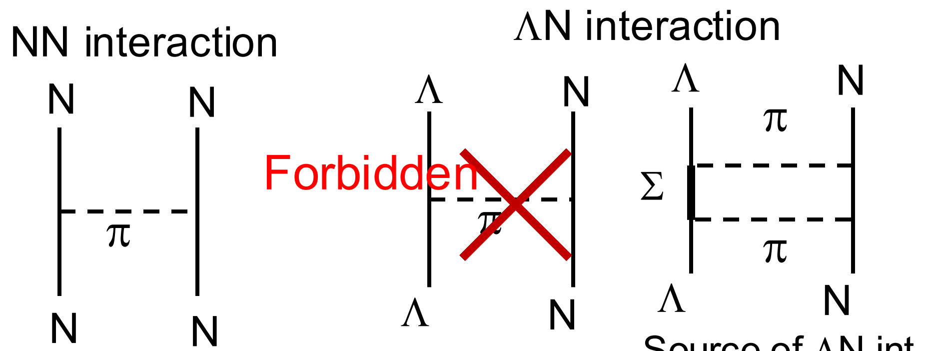
Λp scattering w/ (polarized) Λ



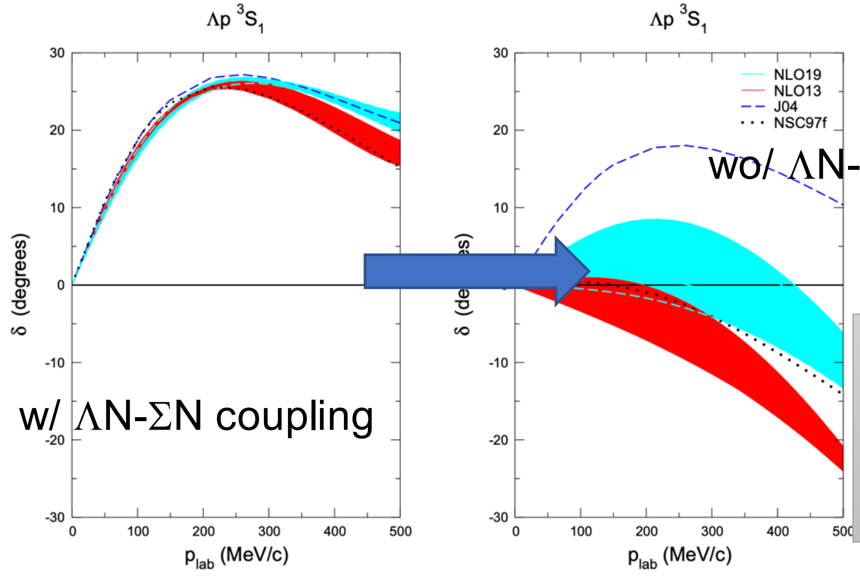
Origin of the density dependence of ΛN interaction

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

Interaction in free space

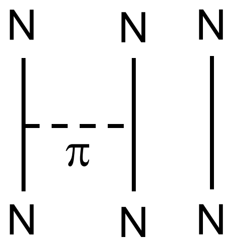


Source of ΛN int.



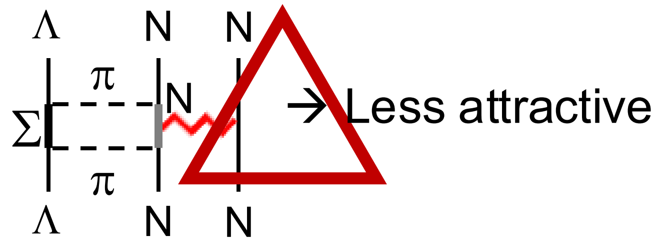
ΛN interaction becomes less attractive (repulsive) w/o ΛN-ΣN coupling

Interaction in nuclear medium



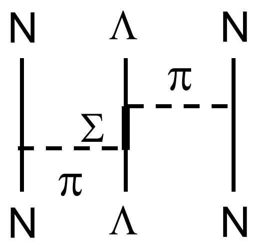
Two-body NN int. might not be affected very much by other nucleons

Suppression of two-body ΛN int.



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

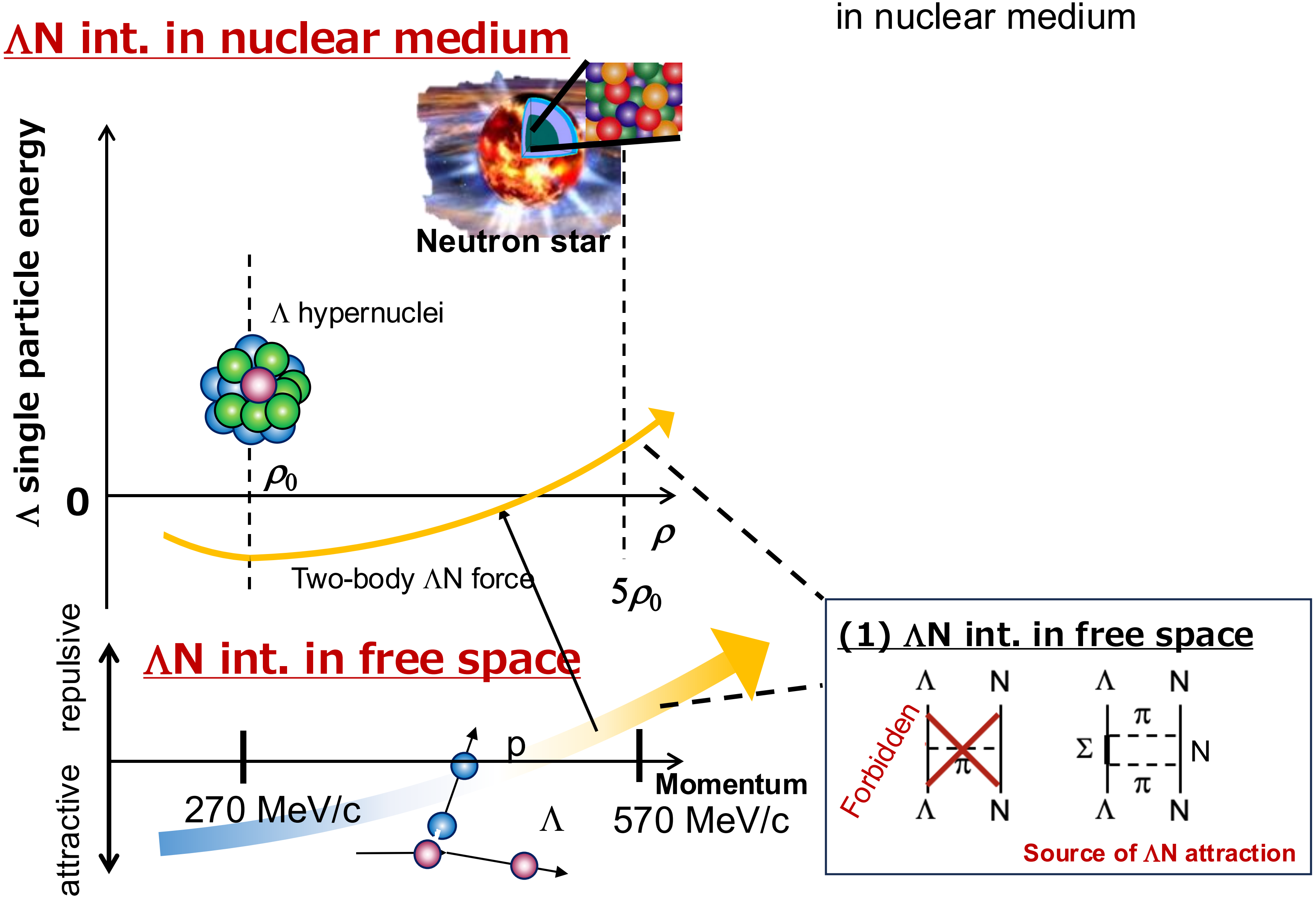
3 body int. mediated with Σ



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

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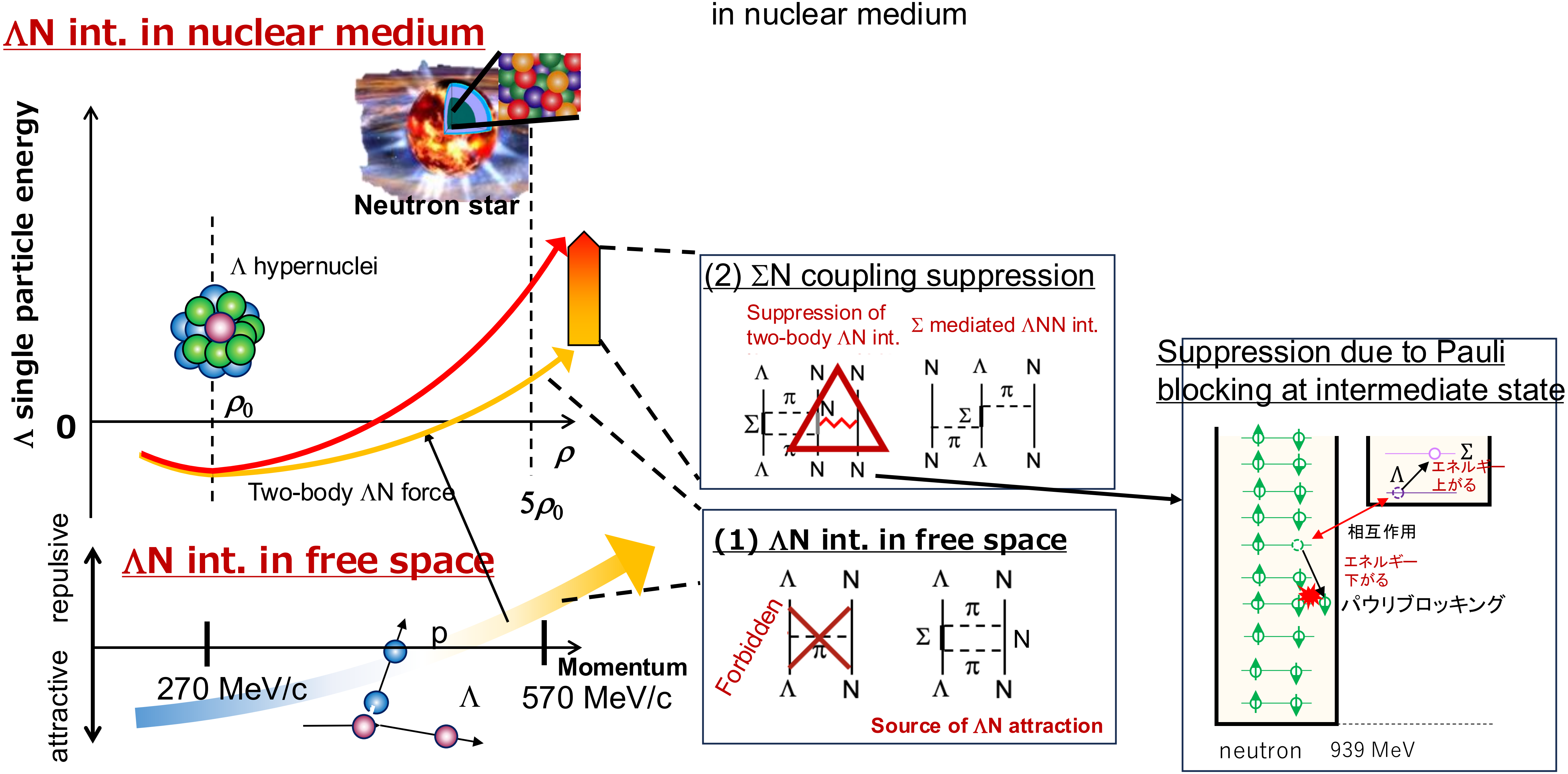
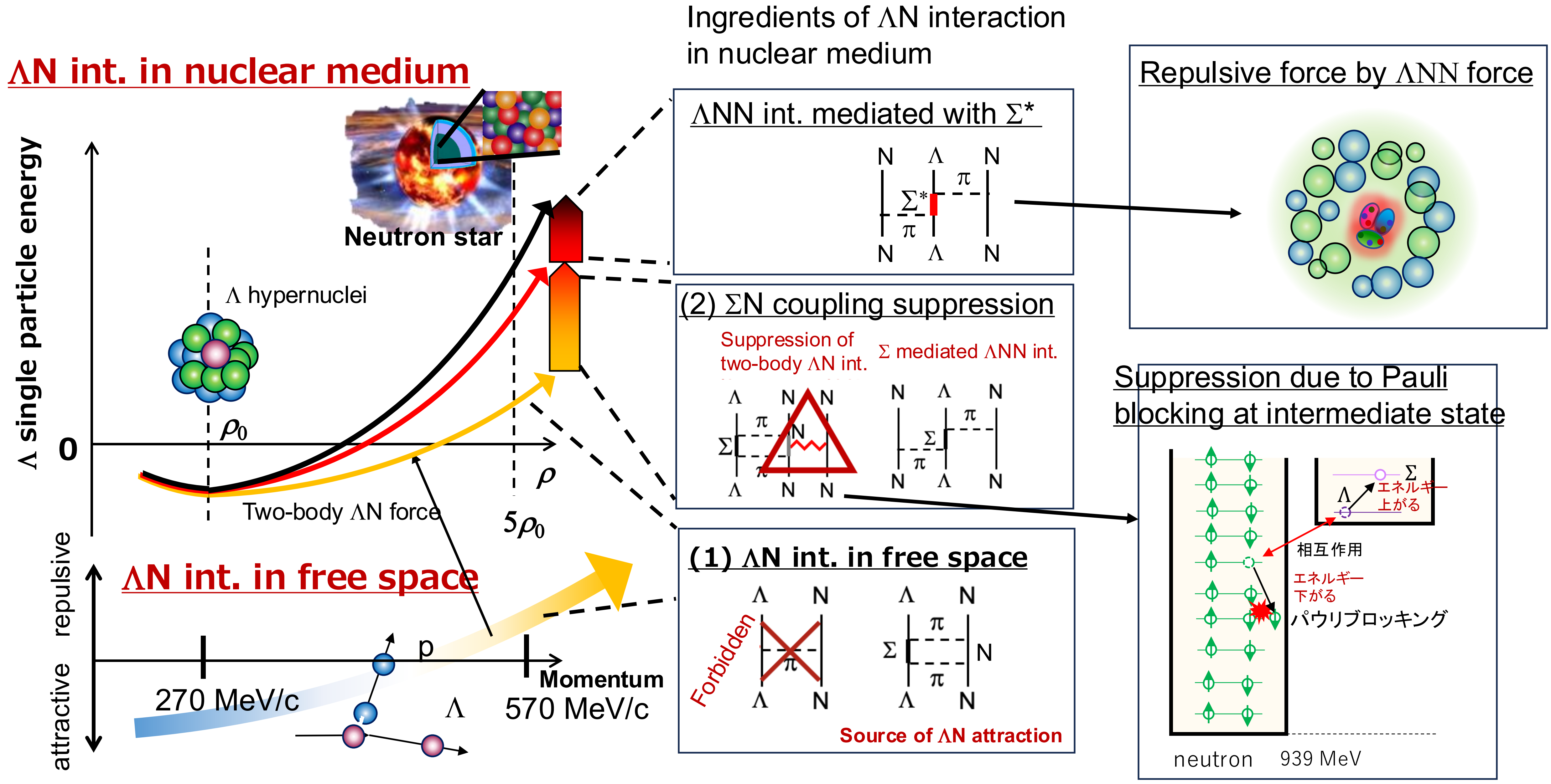
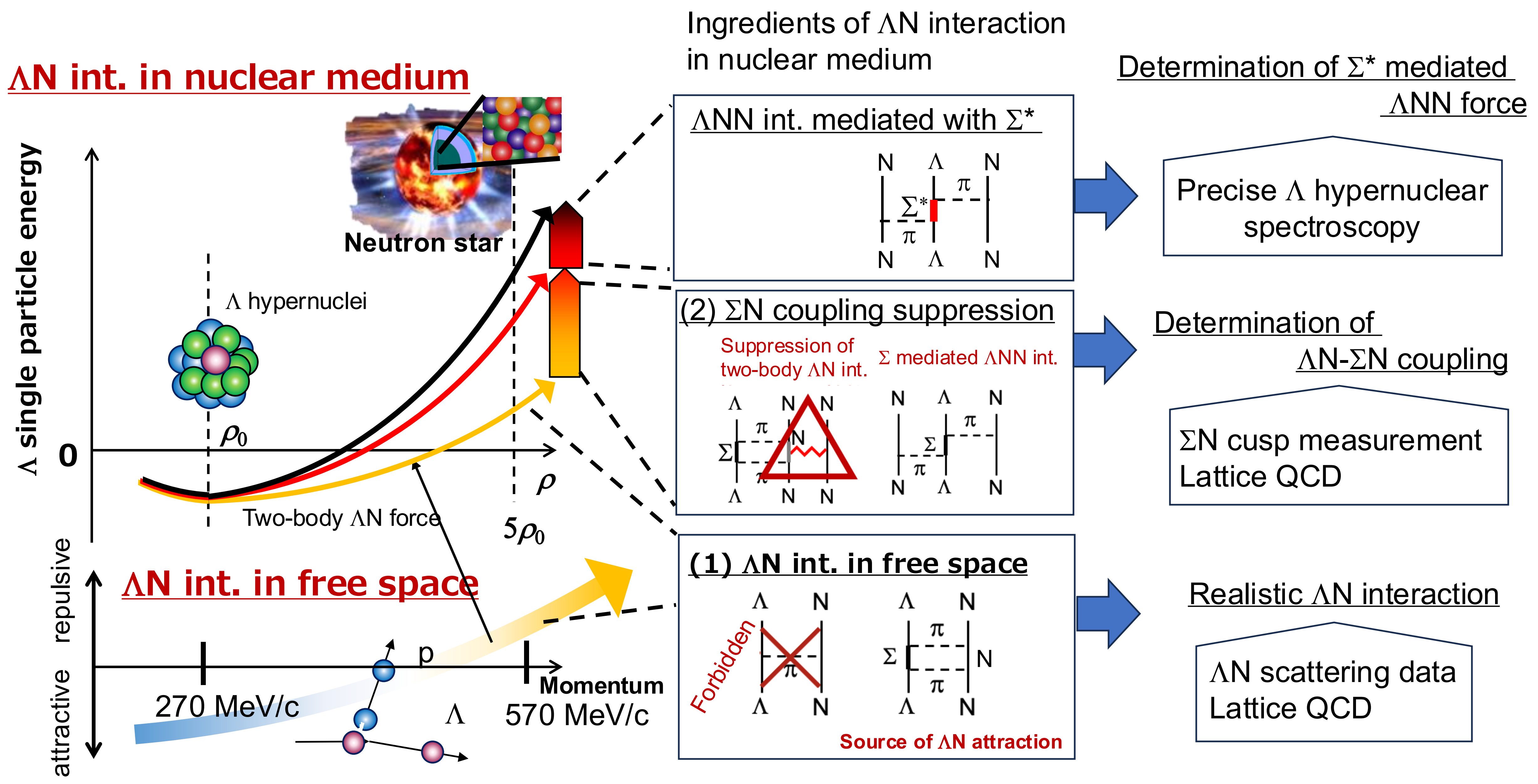


Toward the elucidation of the density dependence of the ΛN interaction

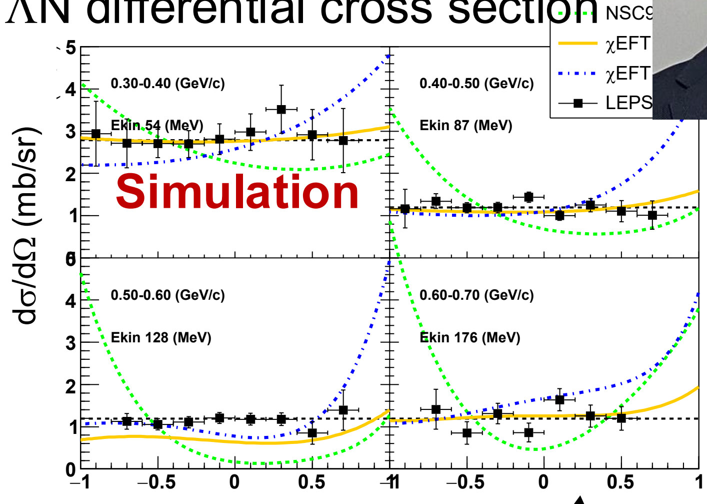


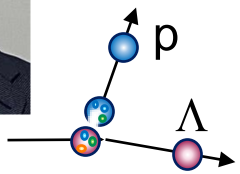
Toward the elucidation of the density dependence of the ΛN interaction



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

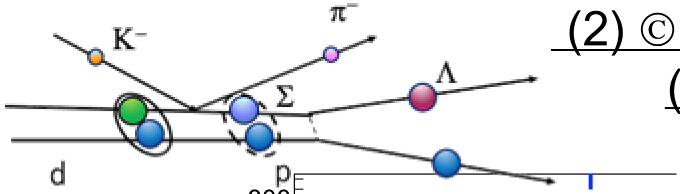
(1) Λp scattering experiment (Koji Miwa)

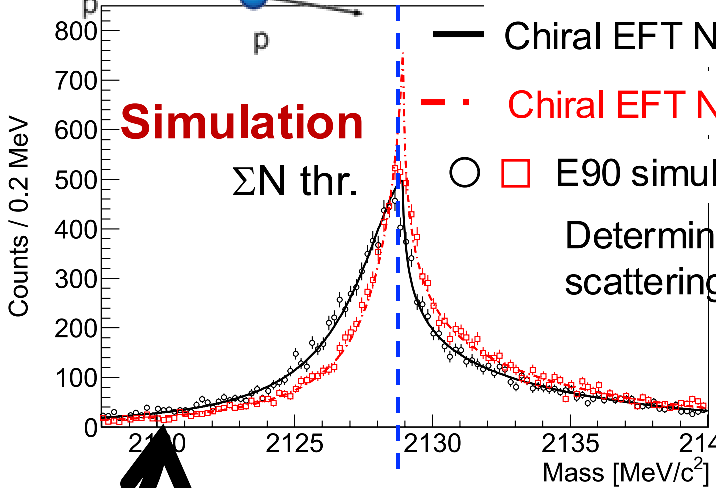




Consistency check between dσ/dΩ and ΛN-ΣN coupling

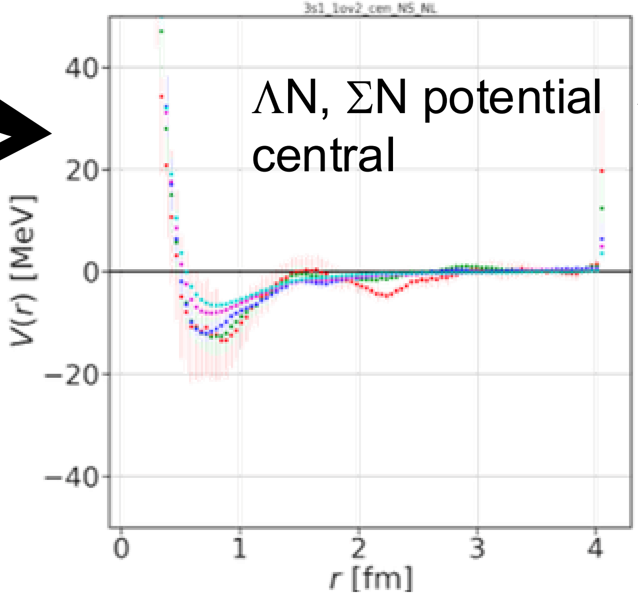
(2) ©N cusp measurement (Yudai Ichikawa)



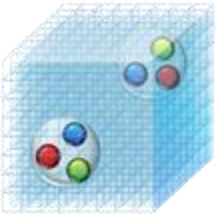


Determination of the ΣN (I=1/2, S=1) scattering length from the cusp shape

ΛN-ΣN coupling



Collaboration to separate ΛN $^3S_1$ and $^1S_0$ interaction



Independent determination of ΛN-ΣN coupling

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

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

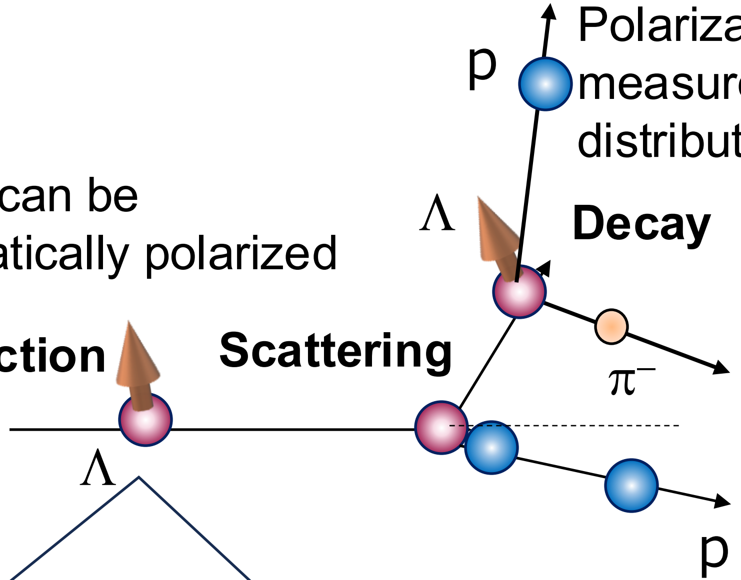
T. Doi, presentation at 3rd J-PARC HEF-ex WS

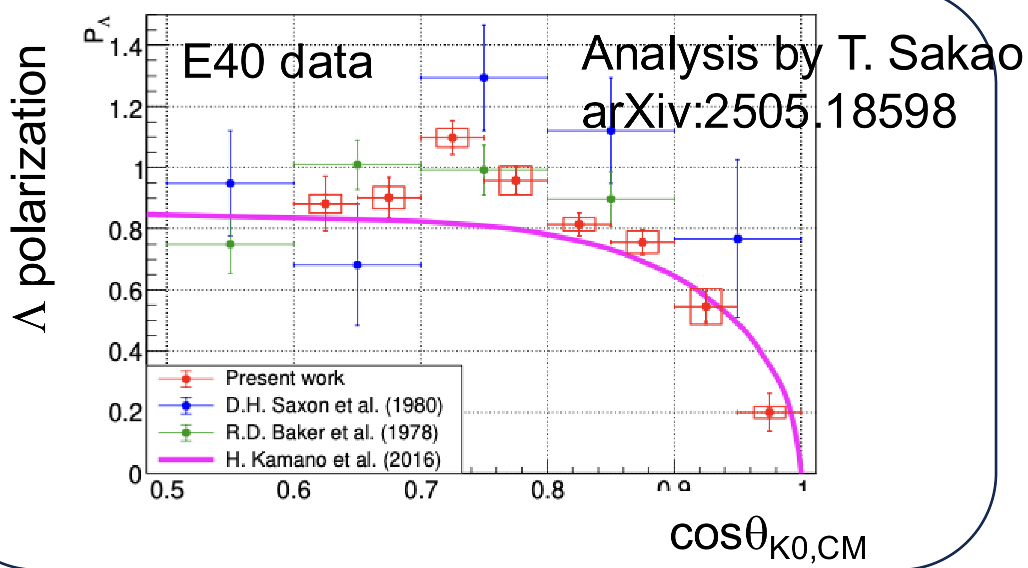
Λp scattering experiment with polarized Λ beam (J-PARC E86)

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

Λ spin can be automatically polarized

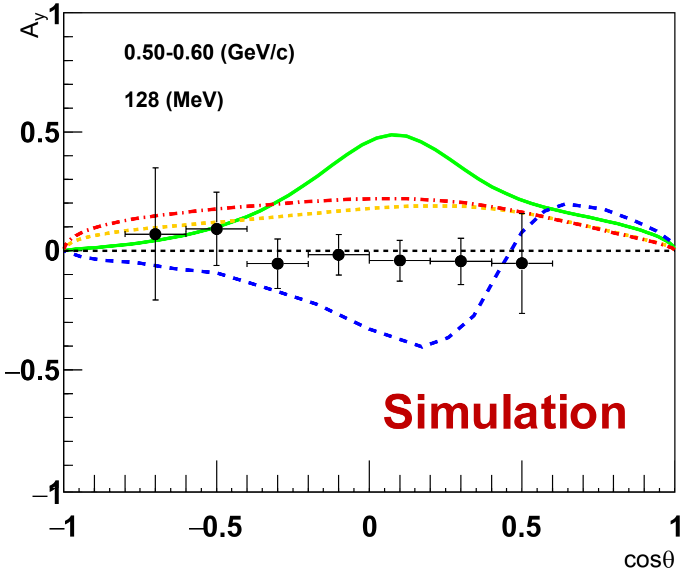
Polarization can be measured from angular distribution of p



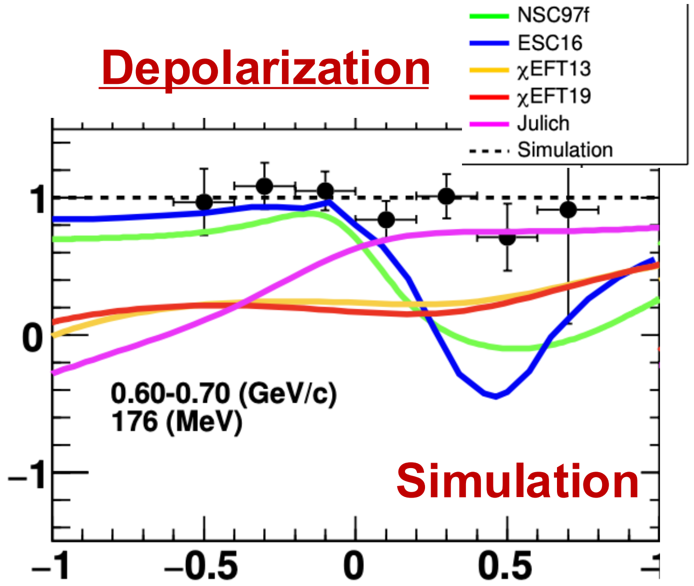


- Left-Right asymmetry of Λp scattering (Analyzing power)
  → spin-orbit interaction
- Polarization change before and after the scattering (Depolarization)
  → spin-spin interaction, tensor interaction

Analyzing power



Depolarization



Essential constraint to determine spin-dependent ΛN interaction

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

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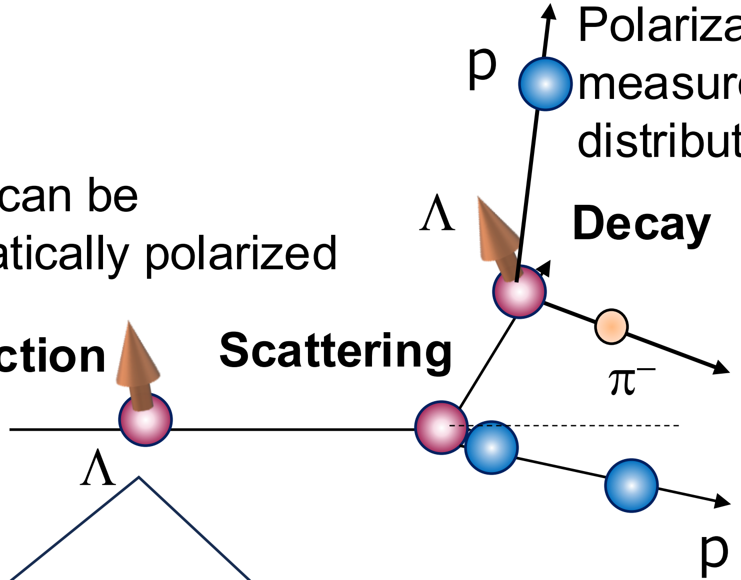

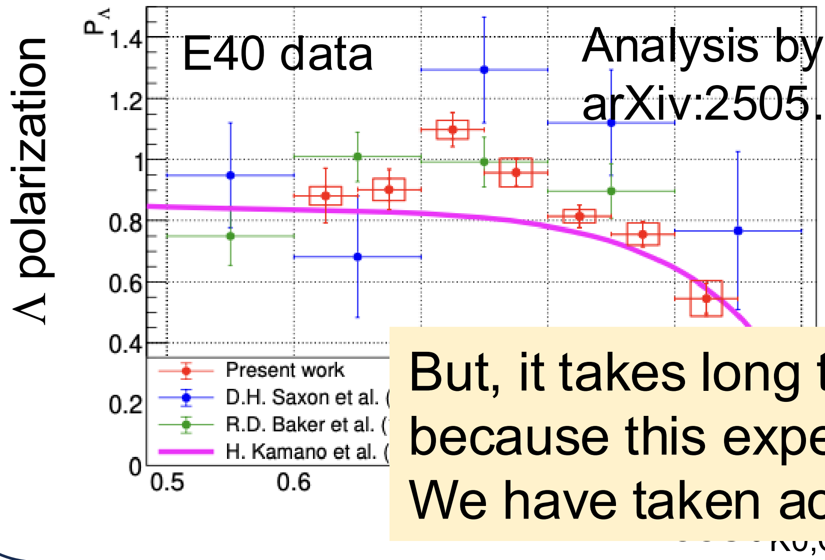

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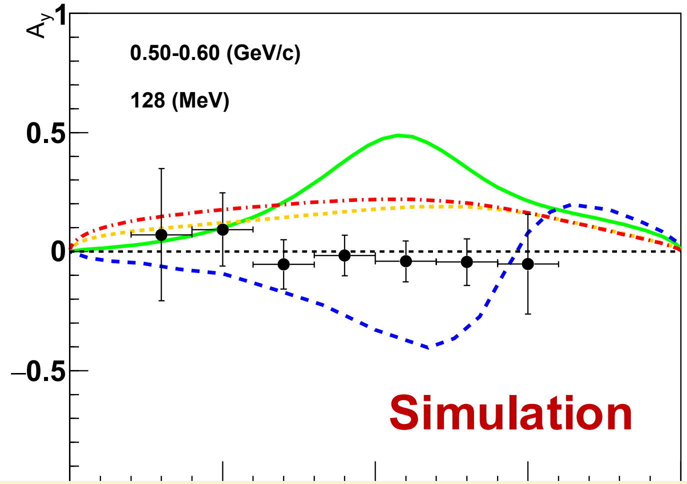
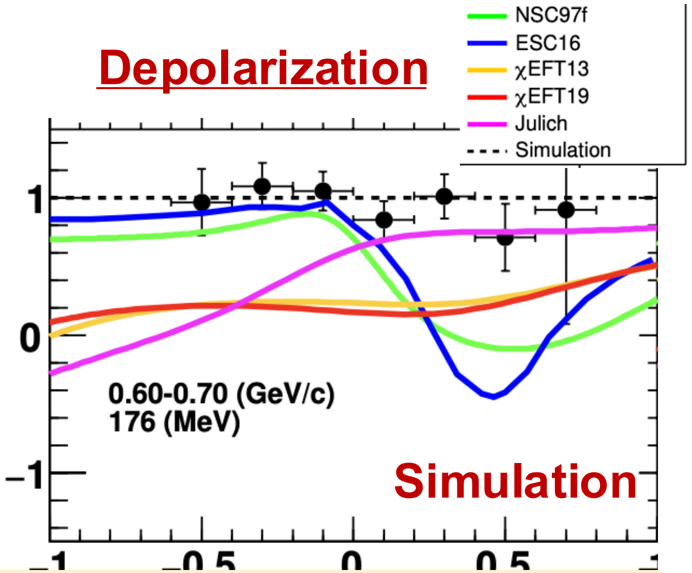
Analyzing power



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

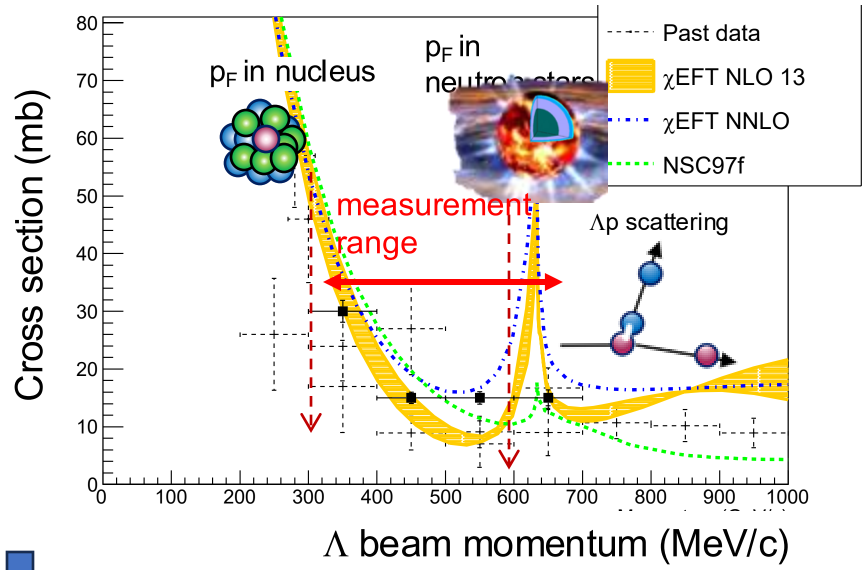
Purpose of research

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.

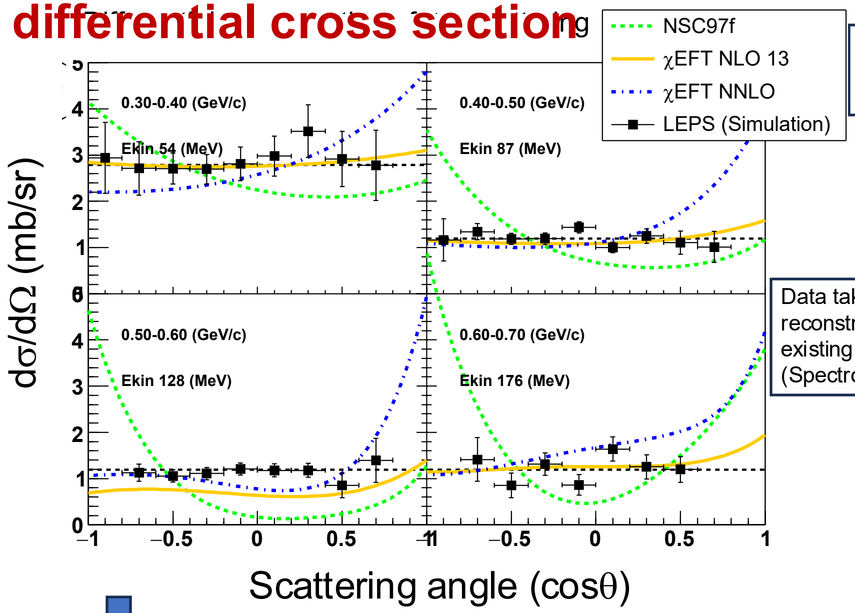
We plan to perform Λp scattering experiment at BL33LEP

Λp total cross section



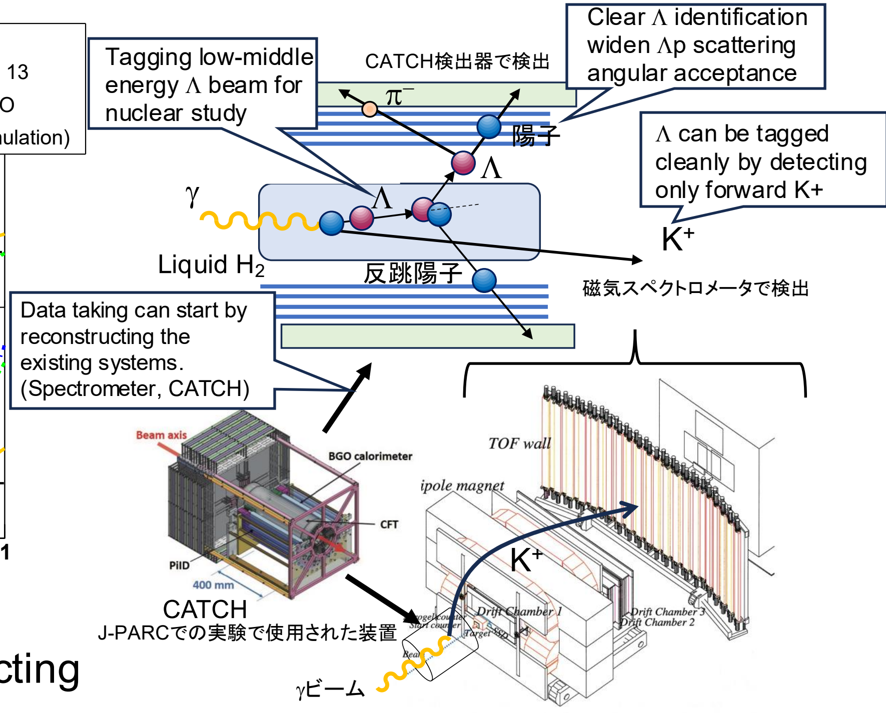
Density (radial) dependence of ΛN interaction

Λp differential cross section



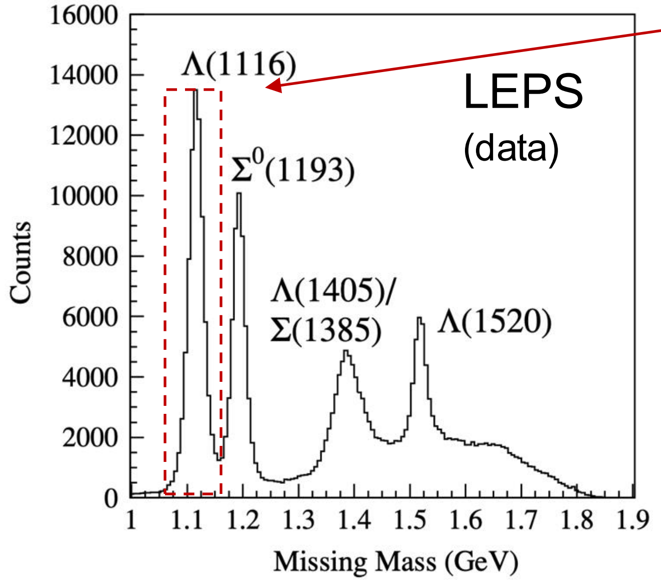
Essential input for constructing realistic ΛN interaction

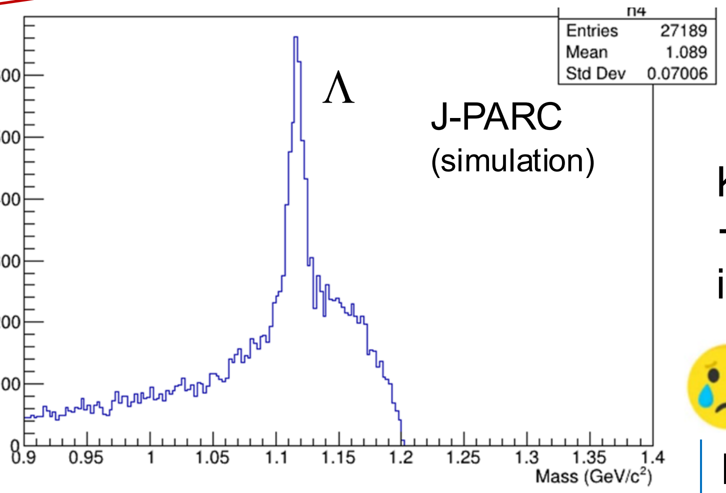
Advantage at BL33LEP



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

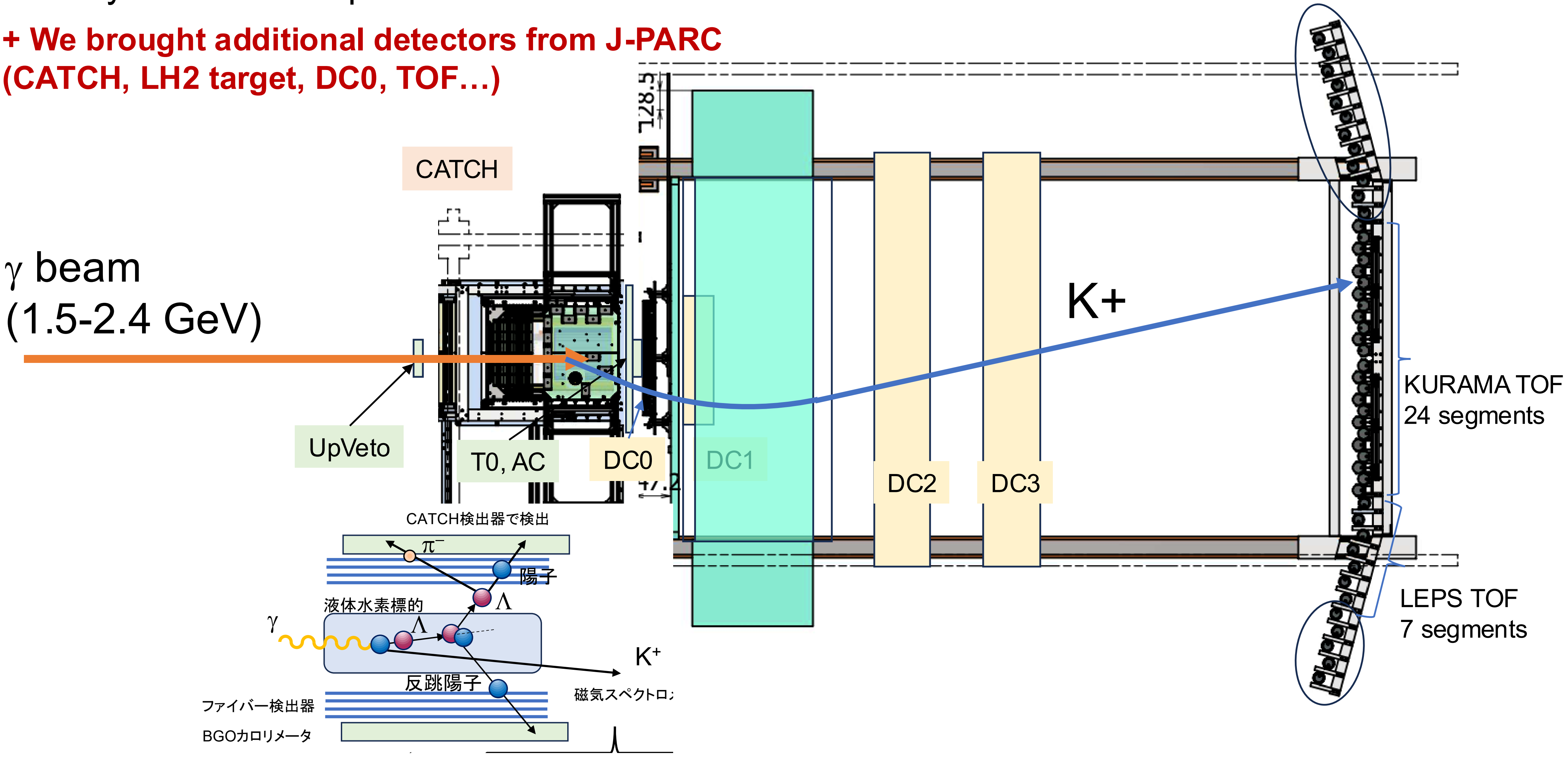
Advantage of backward Compton γ beam： A forward spectrometer can be placed, making it possible to tag low-energy Λ with small momentum transfer for the first time .

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

Detector setup

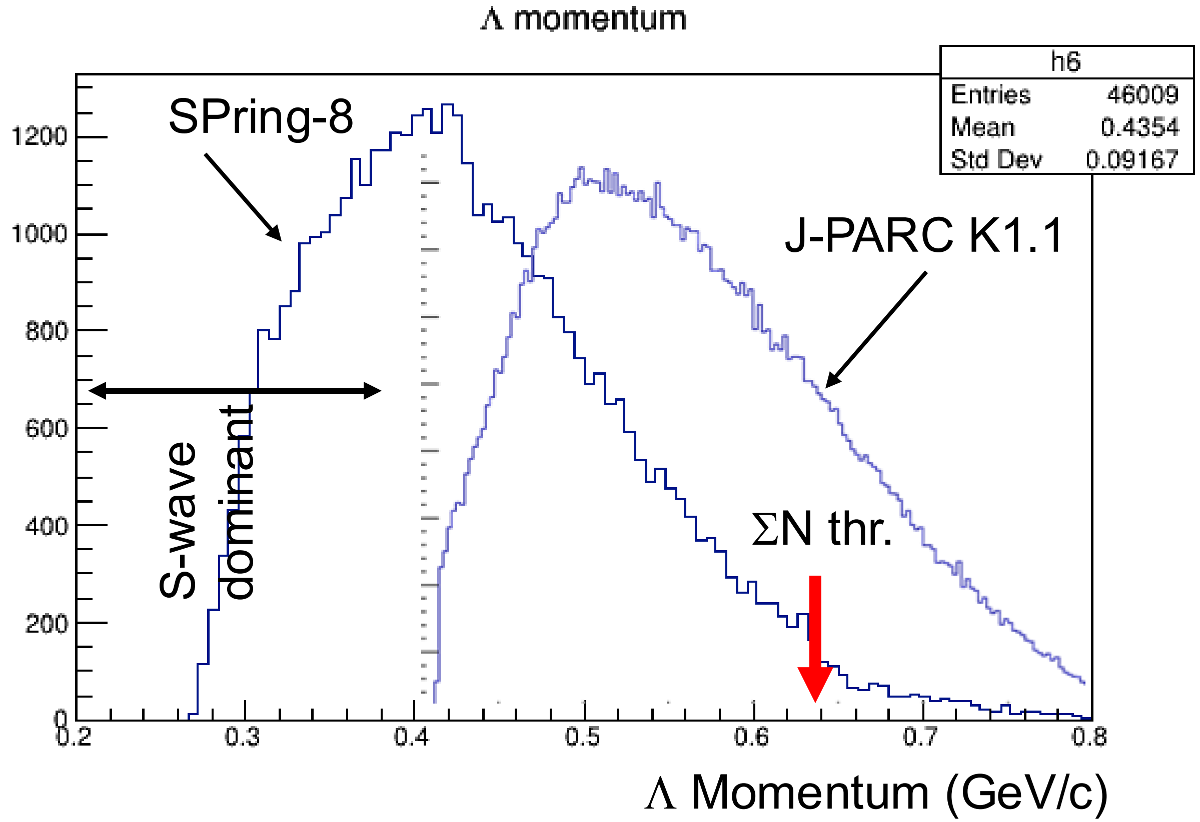
Base system : LEPS spectrometer

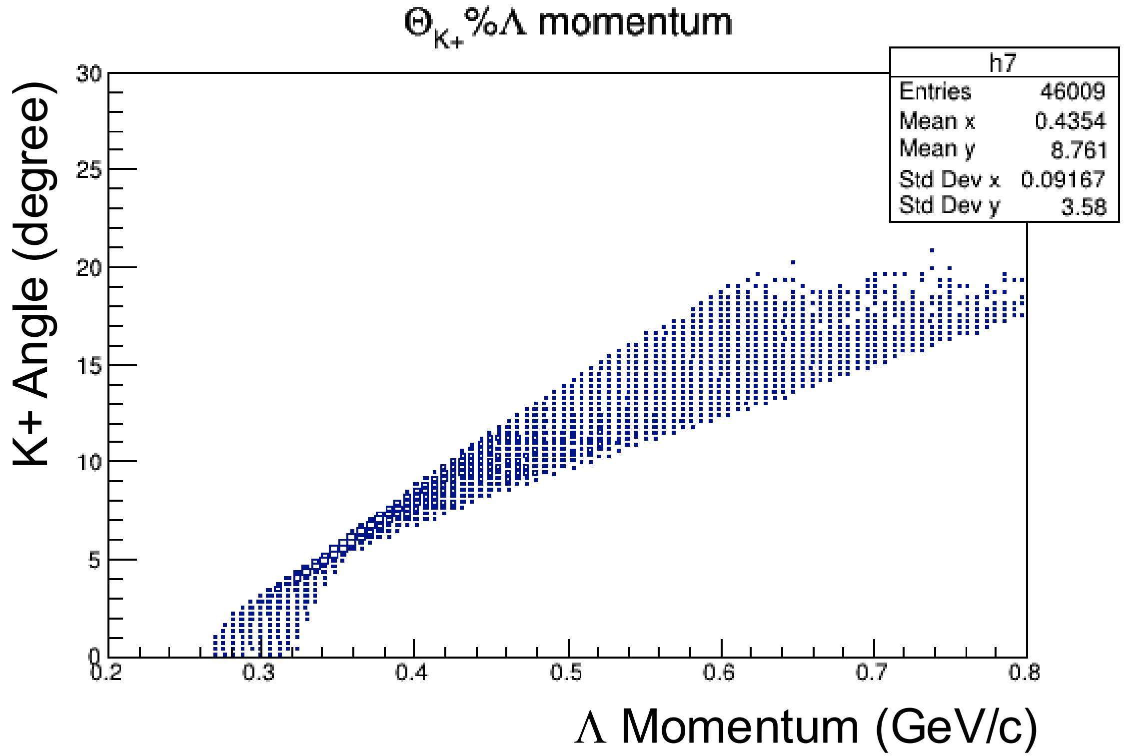
+ We brought additional detectors from J-PARC (CATCH, LH2 target, DC0, TOF…)



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:

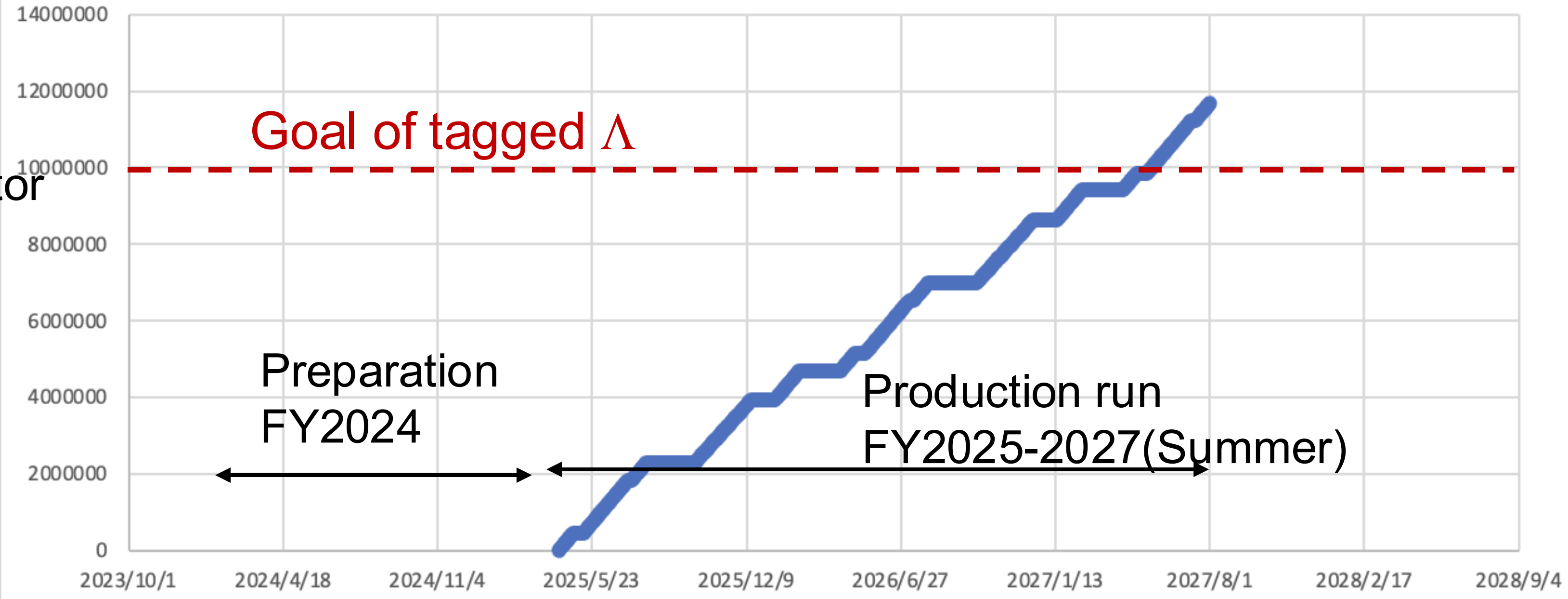
c.f. Σ^-p scattering (E40) 1.7 x 10^7 Σ^- beam

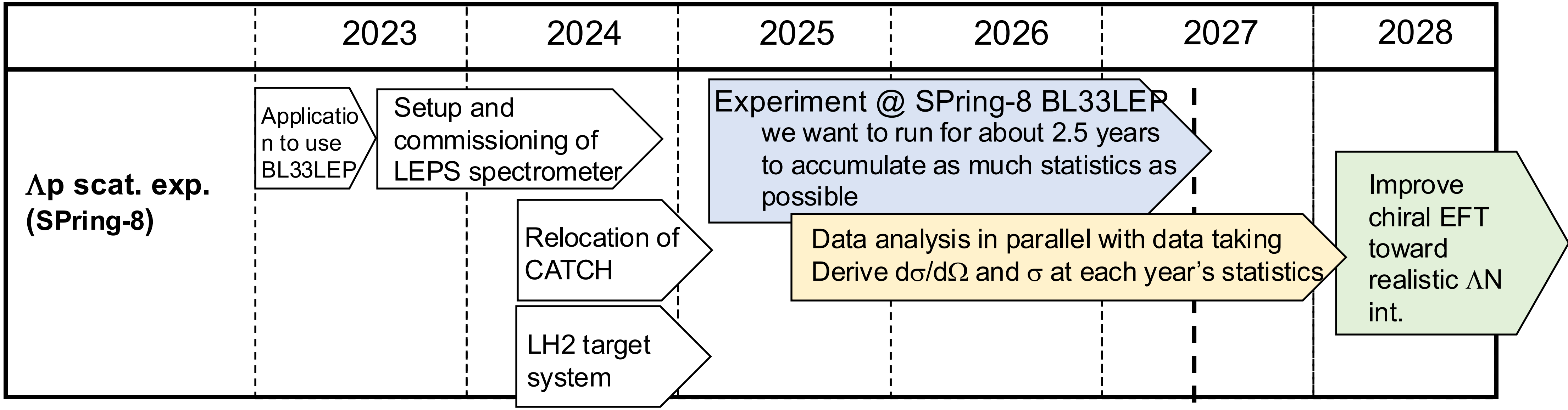
→ Beam time of ~400 days is necessary

Timeline

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

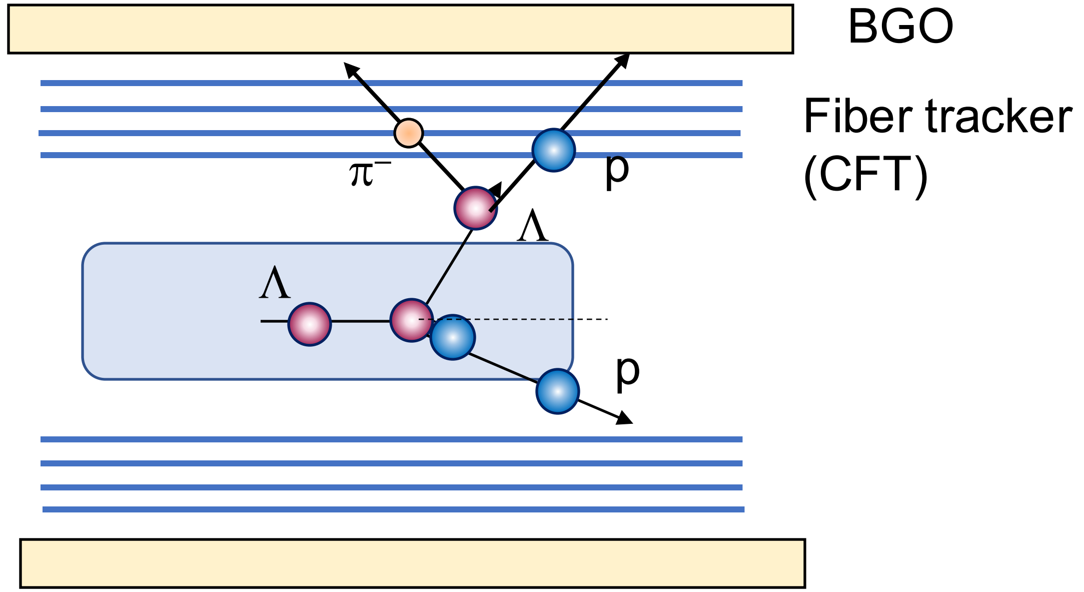
Yield estimation of tagged Λ

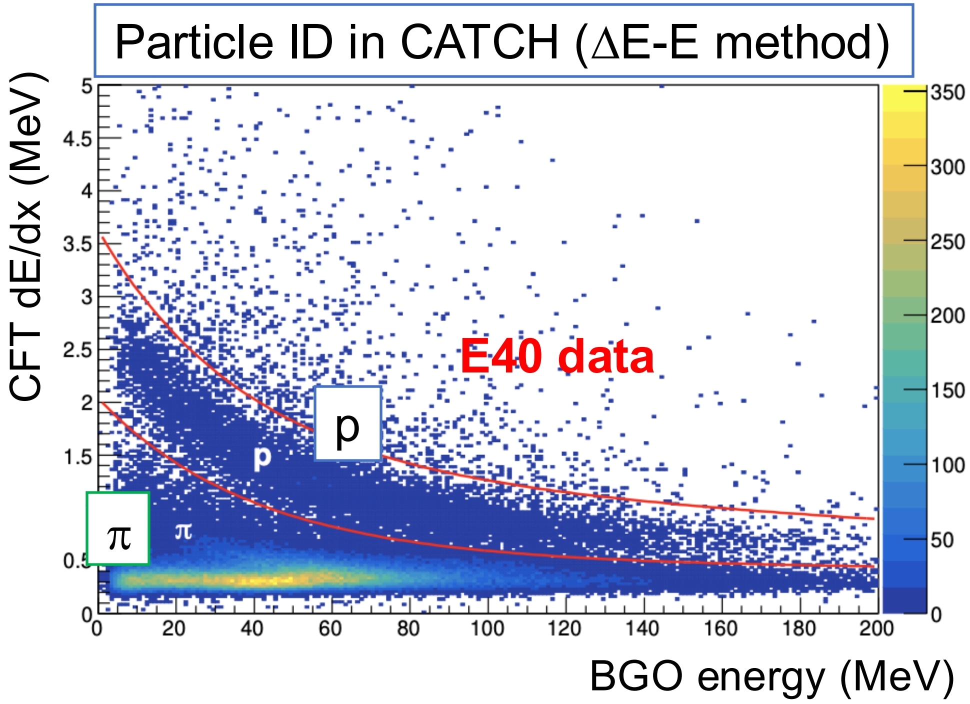


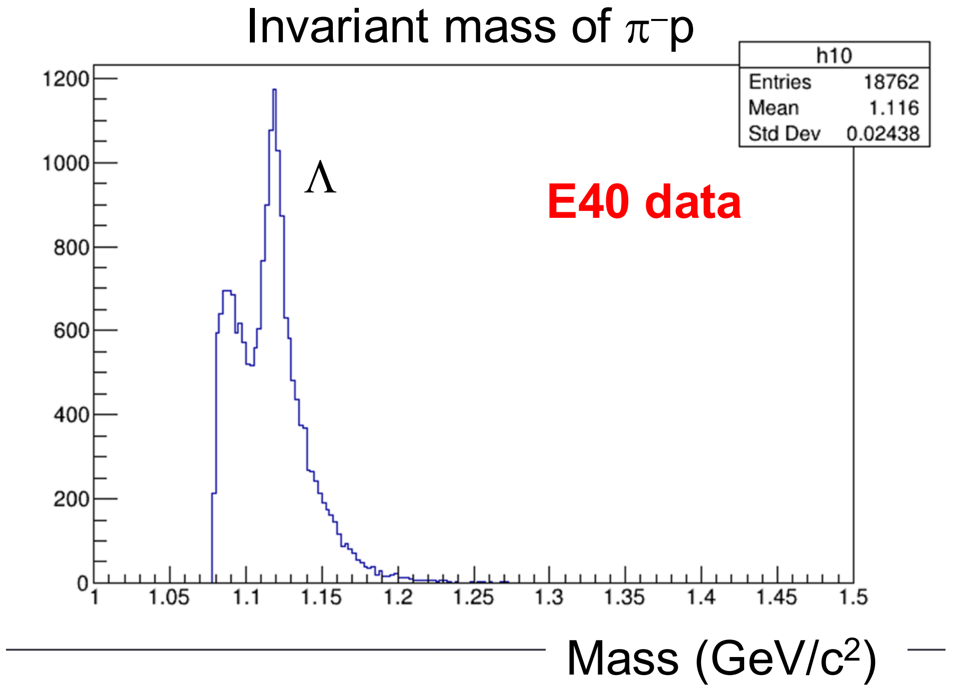


Beam stop at 2027 August ?

Λp scattering identification





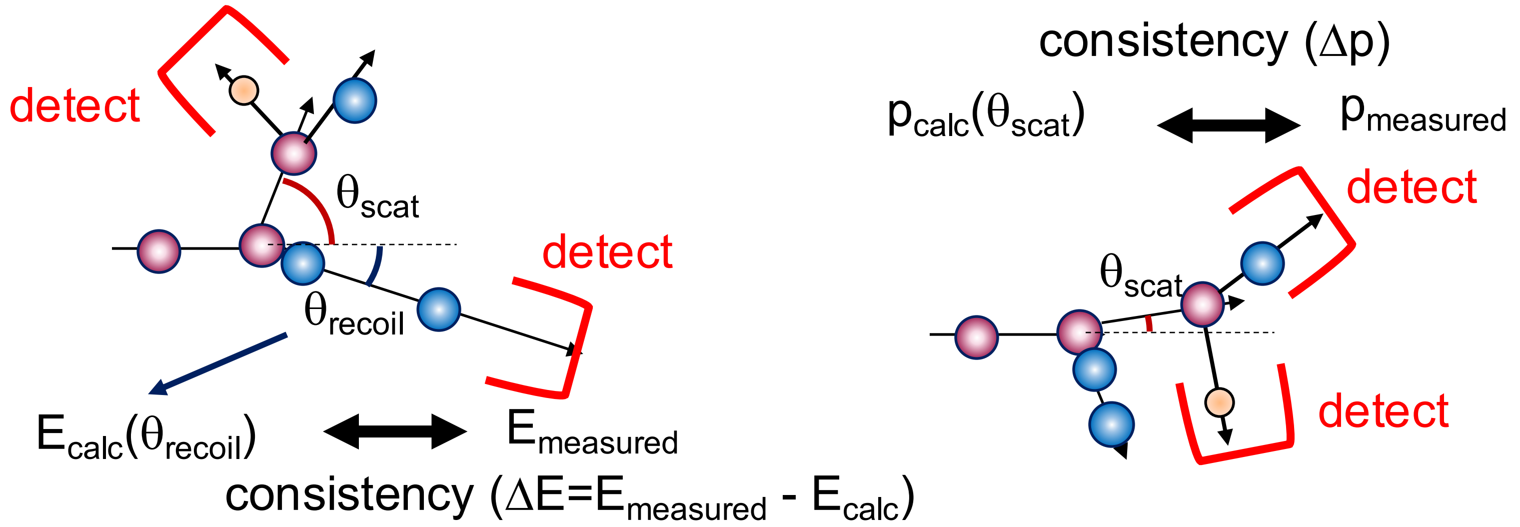


Proton can be stopped in BGO
→ Proton's direction and energy information
Pion cannot be stopped in BGO for many cases
→ Only direction information

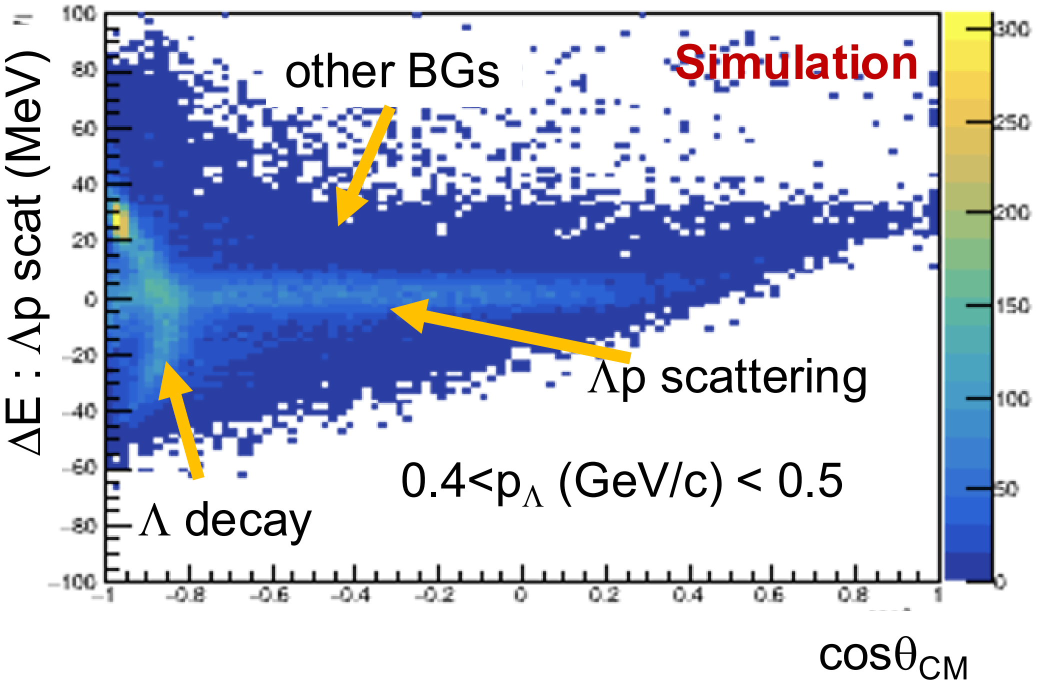
But, π^- from Λ decay has low momentum (~150 MeV/c)
→ many of π^- can be stopped (resolution is not so good)

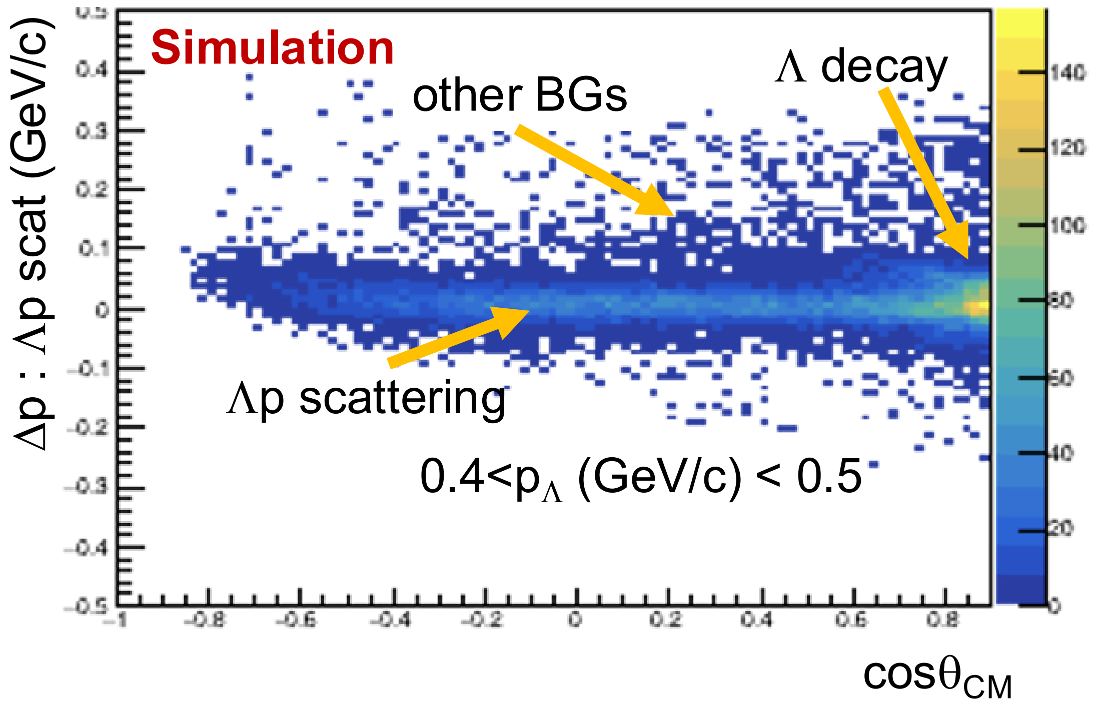
π^- energy is calculated from Λ's decay kinematics.

Angular acceptance of Λp scattering by CATCH



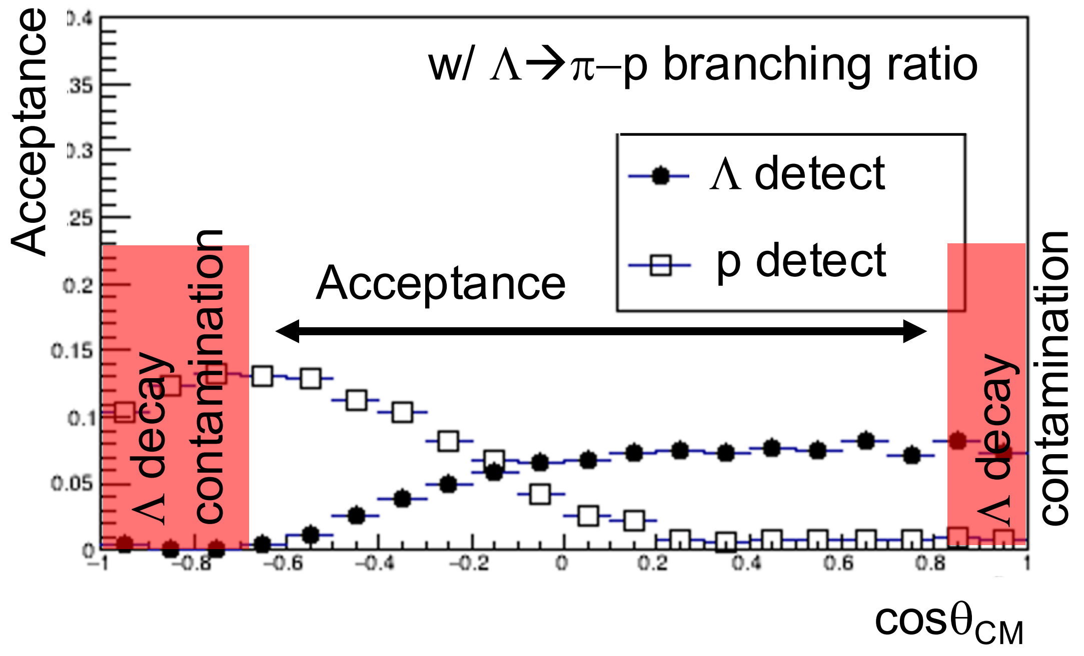
Λp cross section : 30 mb (assumed)
pp, π^{-}p : realistic cross section
Λ decay : 1/100



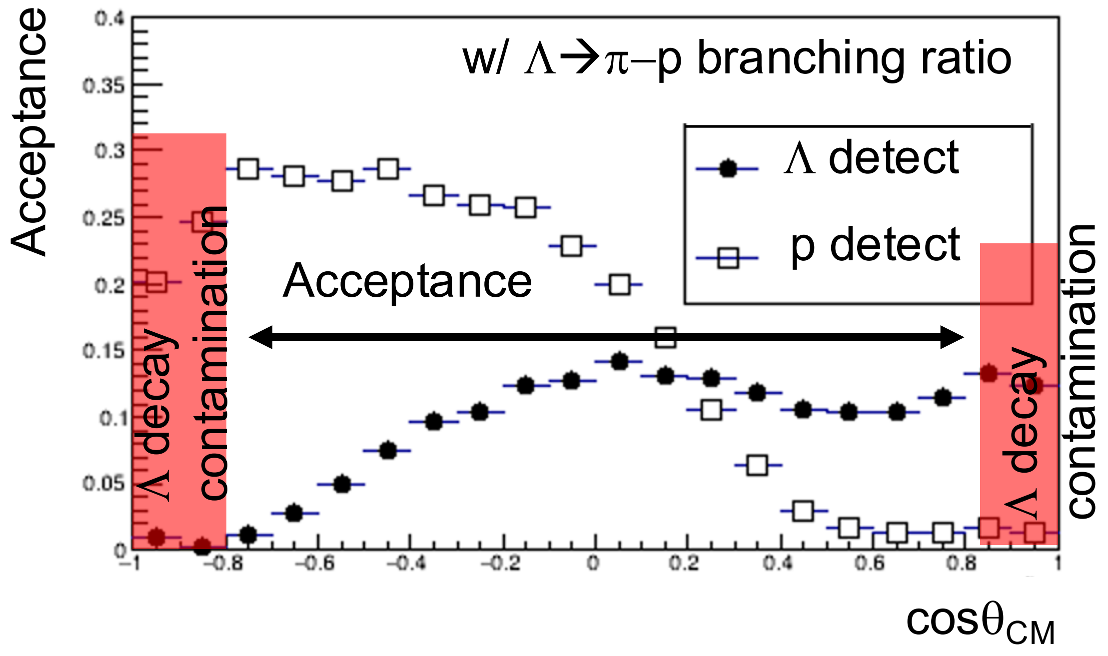


Angular acceptance of Λp scattering by CATCH

$0.3 < p_\Lambda$ (GeV/c) < 0.4



$0.4 < p_\Lambda$ (GeV/c) < 0.5

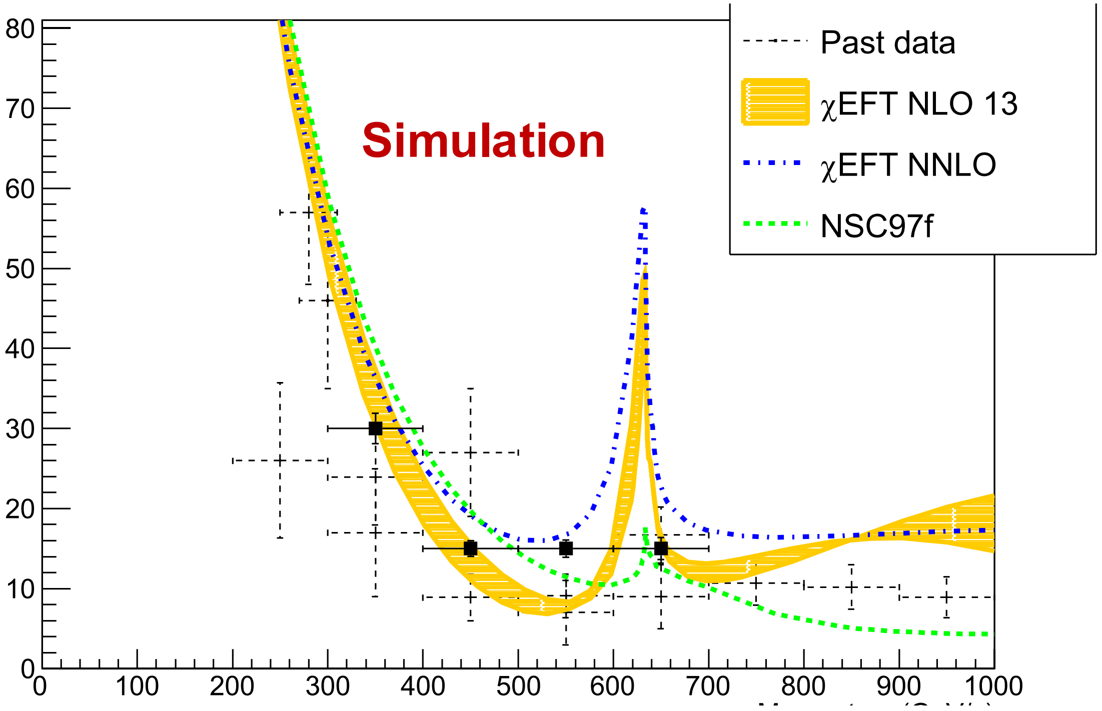


Forward scattering angle : covered by Λ detection
Backward scattering angle : covered by proton detection
But, very forward and very backward regions might be hard due to Λ decay contamination

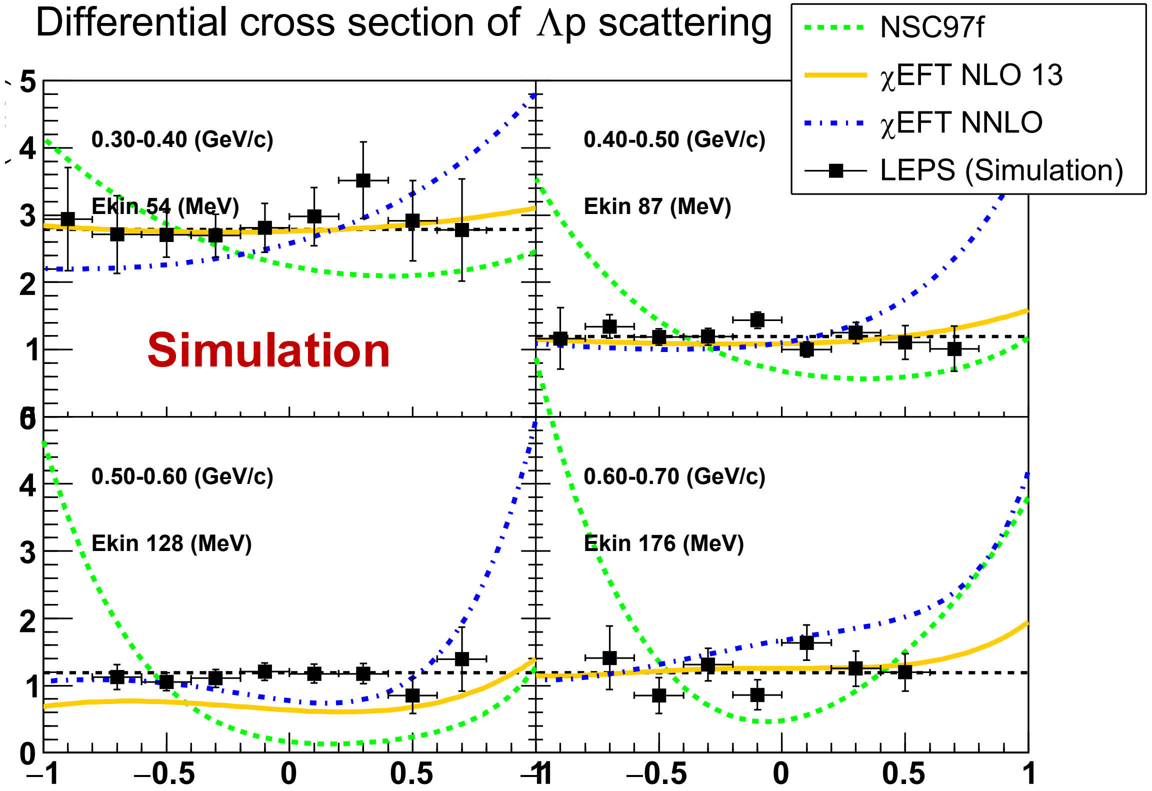
Even though, rather wide acceptance can be obtained.

Expected results

Momentum dependence of total cross section



Differential cross section of Λp scattering

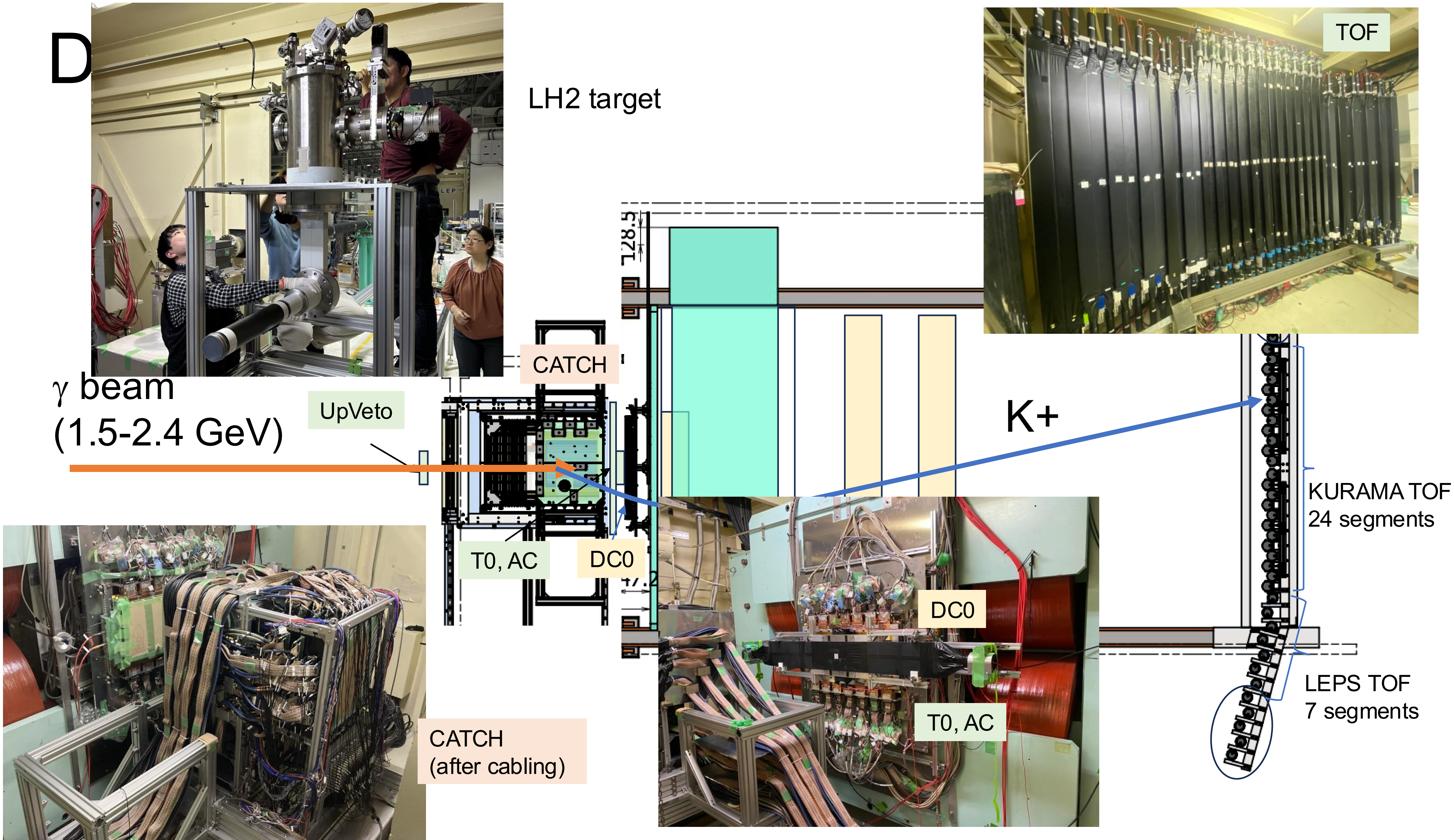


Accurate $d\sigma/d\Omega$ data and total cross section can put strong constraint on ΛN interaction theory.

Chiral NNLO ΛN interaction shows rather attractive nature

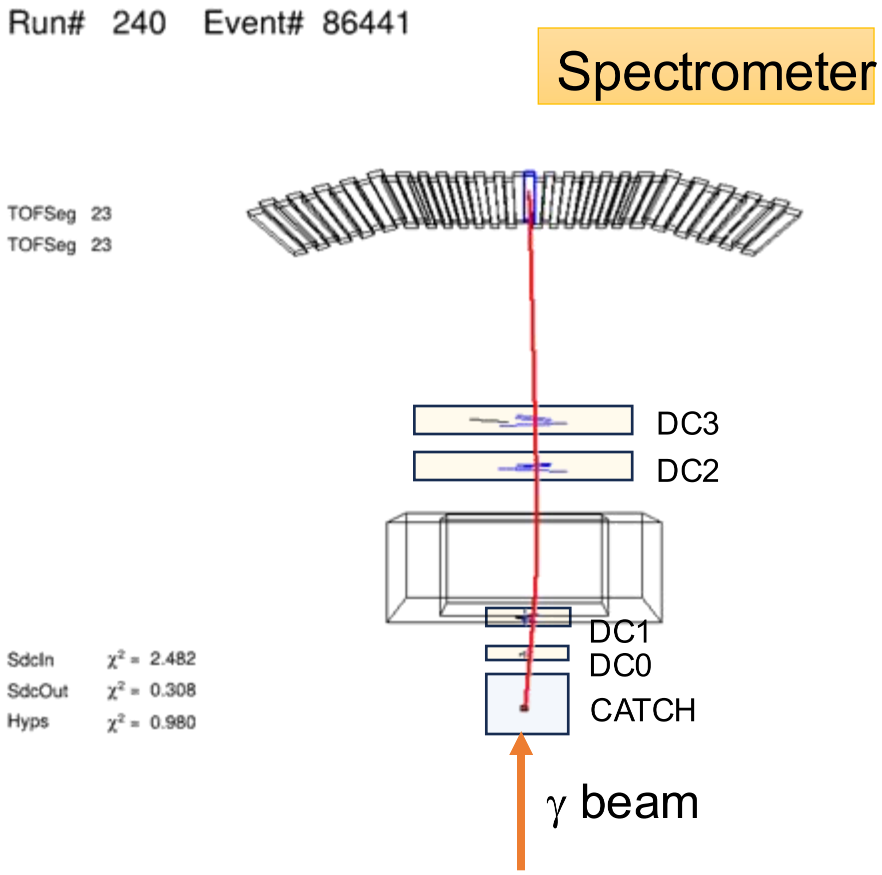
- Larger cross section around p_{Λ}~500 MeV/c
- Deeper U(Λ) potential (-35~-37 MeV)

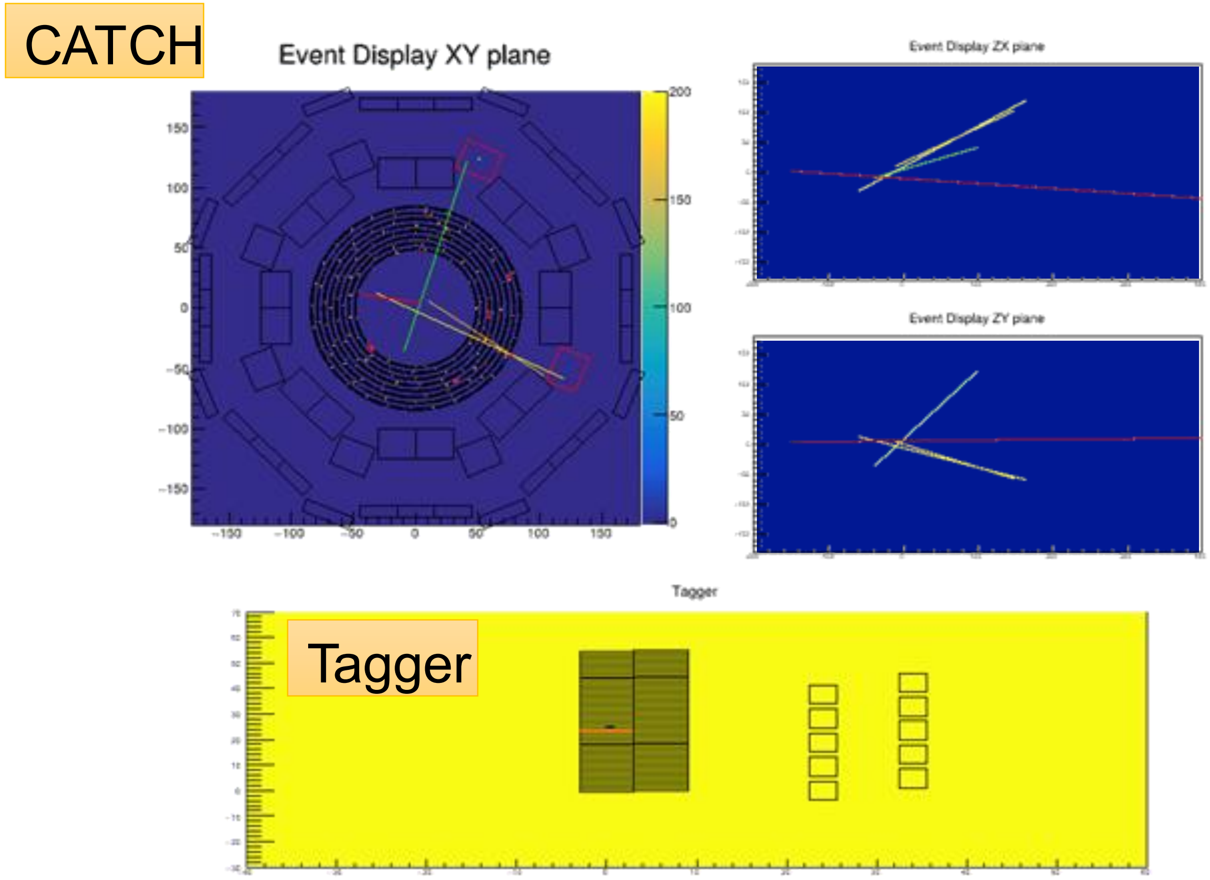
J. Haidenbauer et al.,
Eur.Phys.J.A 59 (2023) 3


D
LH2 target
TOF
CATCH
γ beam
(1.5-2.4 GeV)
UpVeto
K+
T0, AC
DC0
KURAMA TOF
24 segments
LEPS TOF
7 segments
CATCH
(after cabling)
DC0
T0, AC
128.5

Just started physics data taking

- We have just started physics data taking from 2025 April
- Detectors are working very well



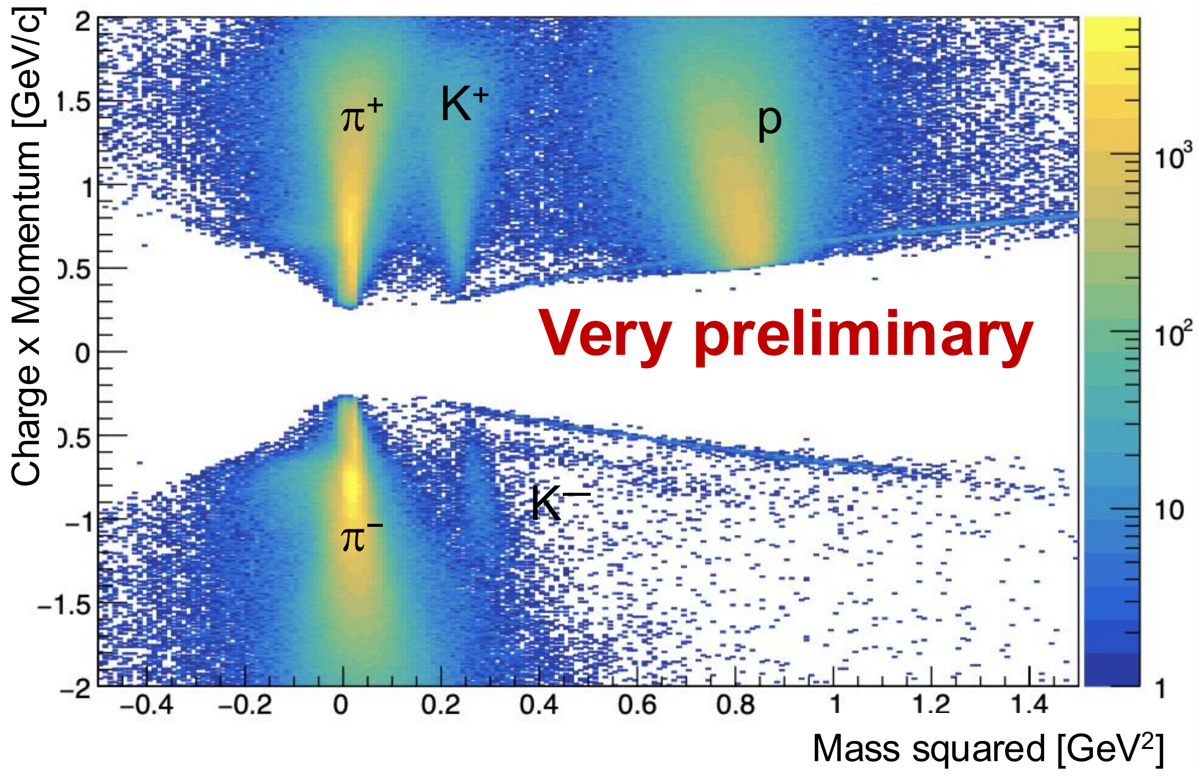


Magnetic spectrometer performance : A. Haratani (poster)

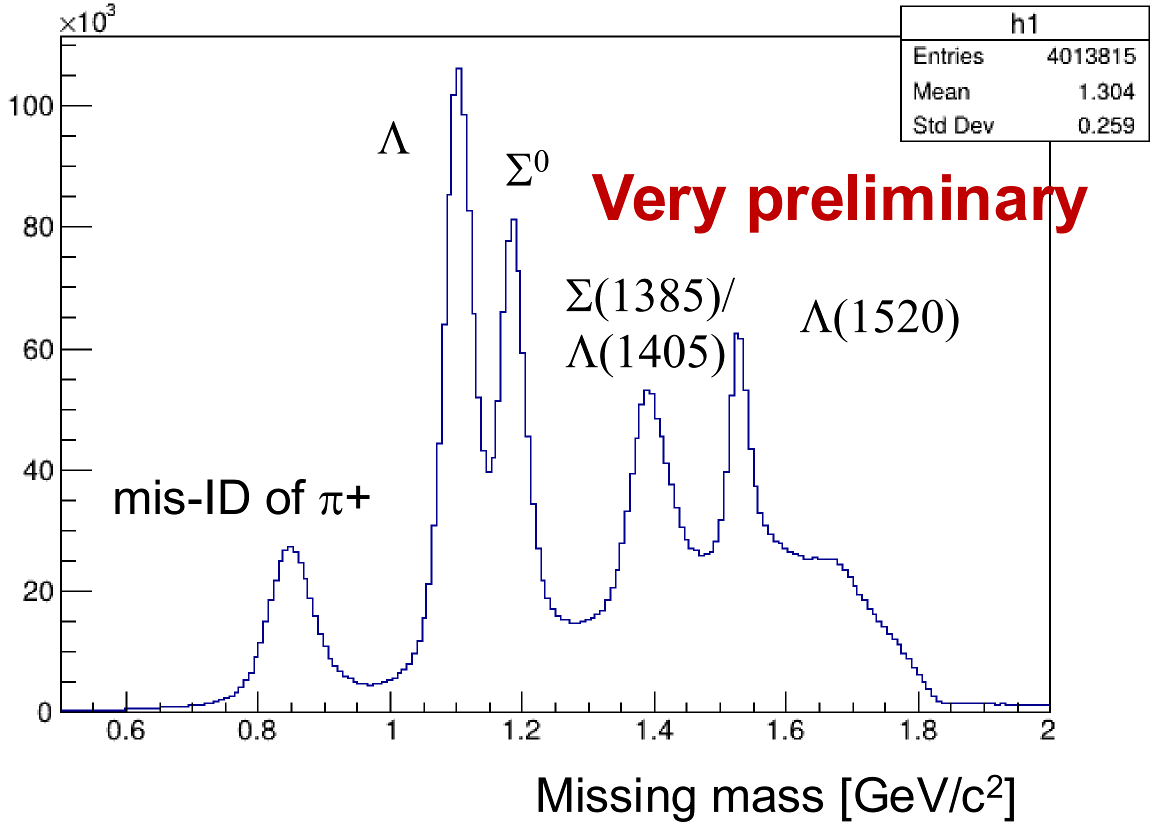
DAQ construction and performance : R. Kurata (poster)

Spectrometer analysis status

Scattered particle's identification

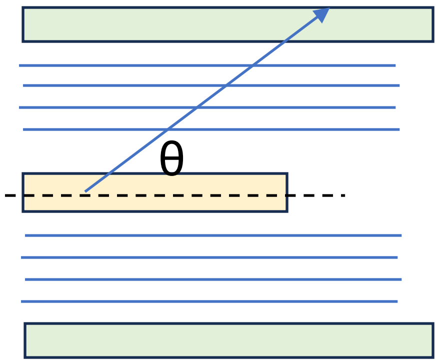


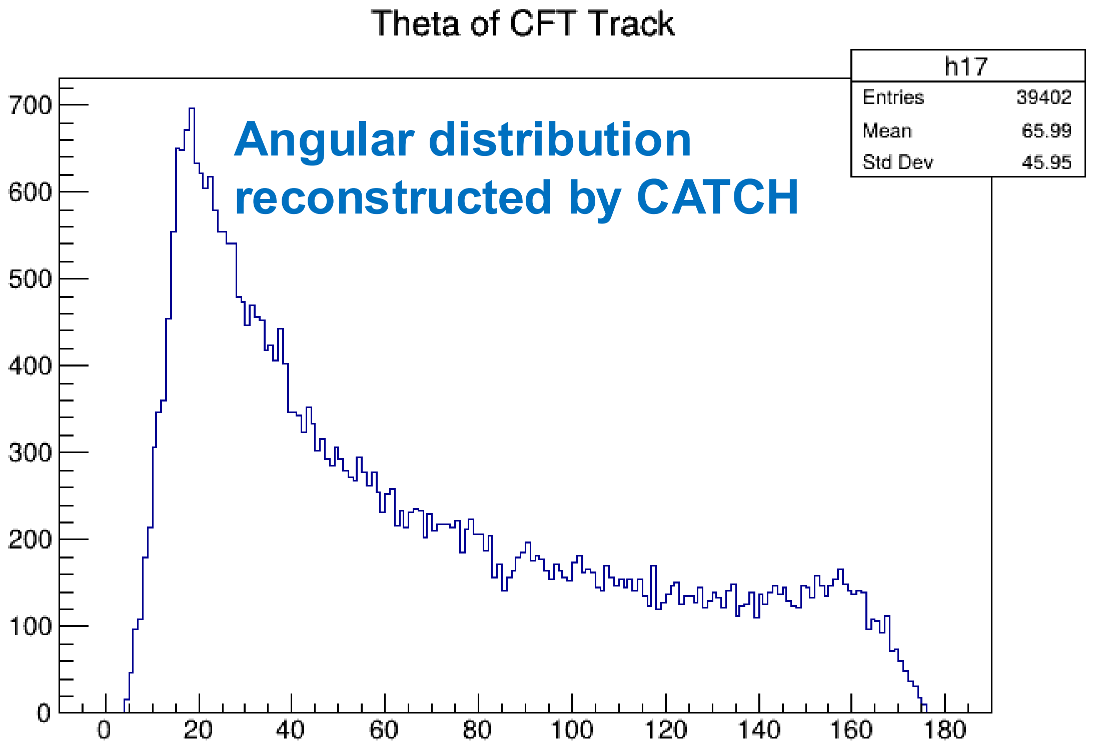
Missing mass spectrum of γp→K⁺X reaction

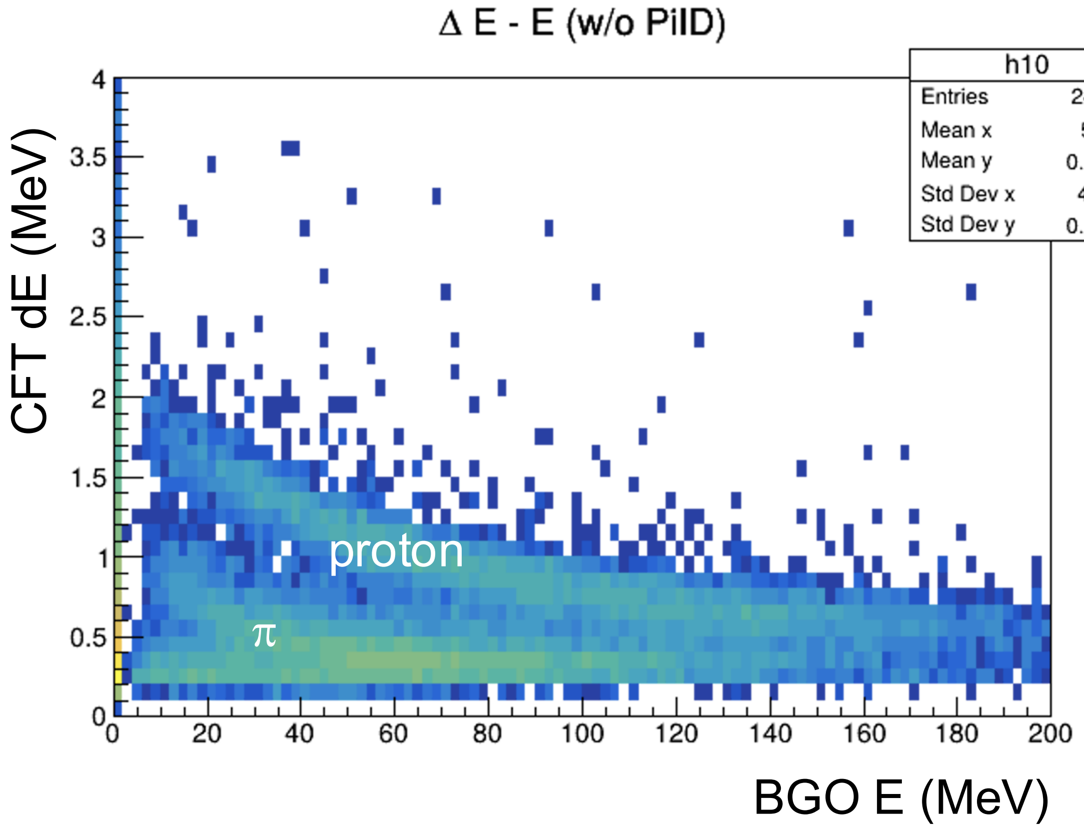


Detailed analysis status : T. Nanamura (Parallel session TODAY)

CATCH analysis status

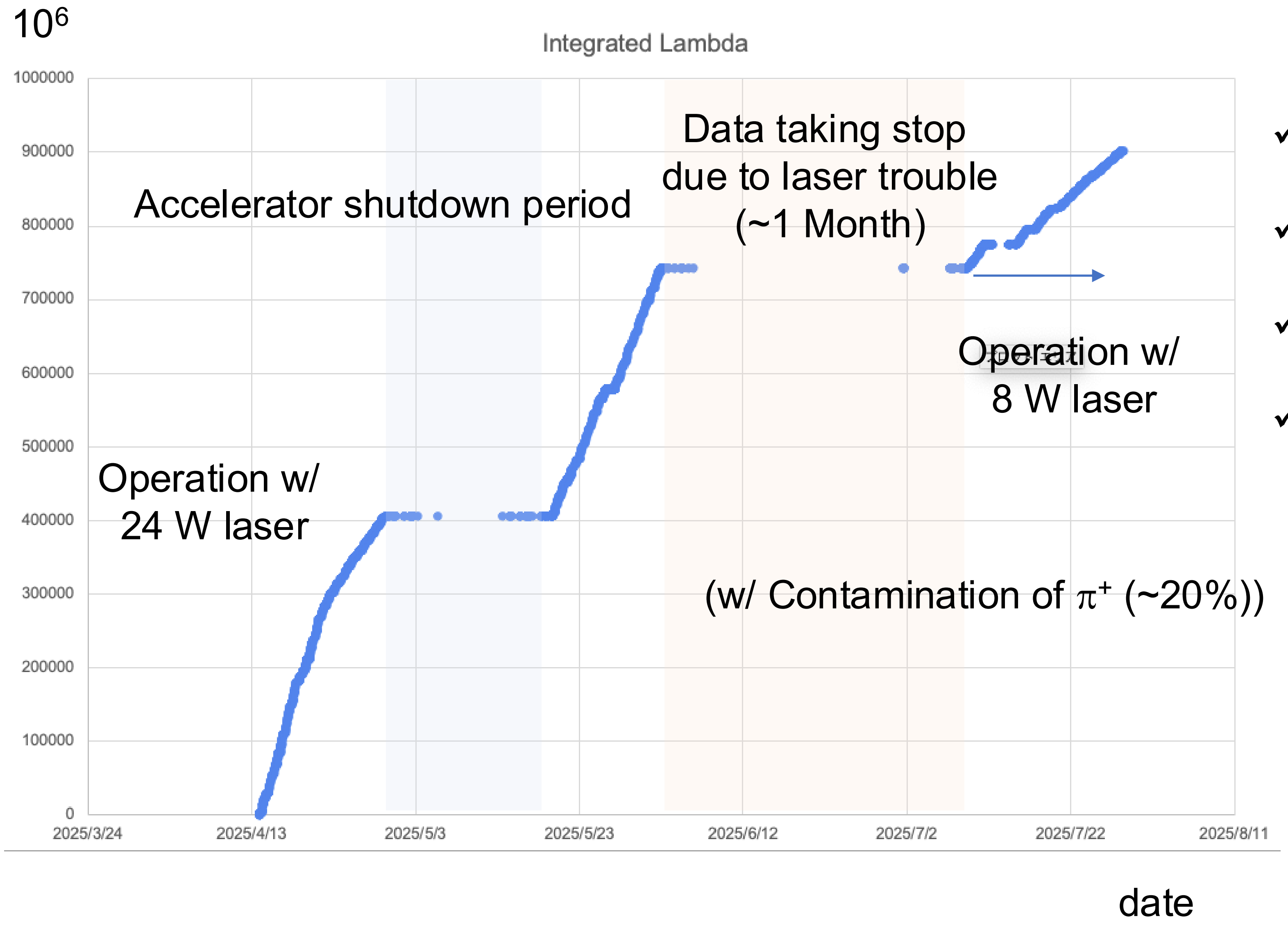






CATCH Analysis and calibration : M. Yoshida (poster)

Integrated Λ beam



- ✓ Λ yield with 24 W laser was as expected (or larger than expectation).
- ✓ Once data taking was suspended due to laser trouble.
- ✓ Anyway, we have accumulated ~10^6 Λ
- ✓ We will continue data taking until 2027 July to accumulate 10^7 Λ

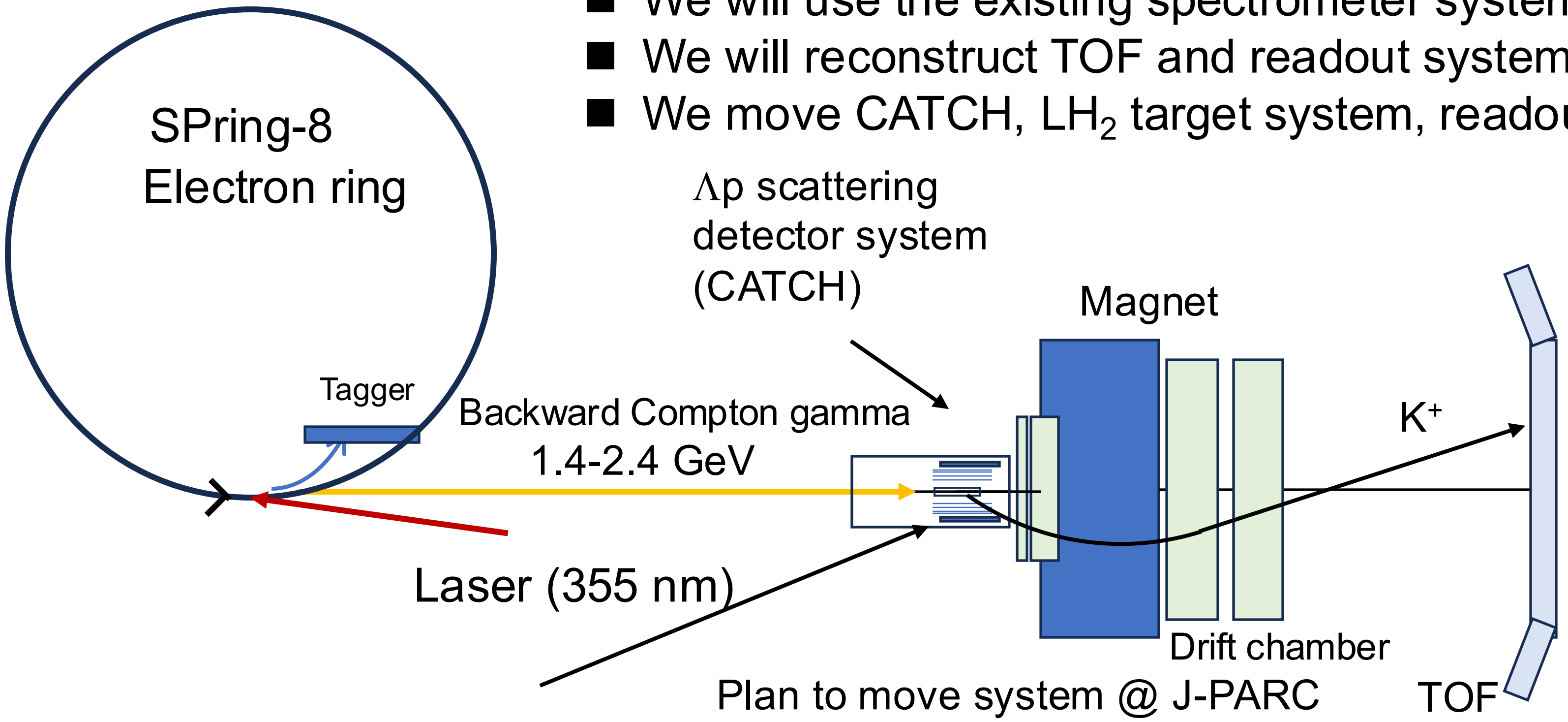
New Λp scattering data will be provided within a few years !

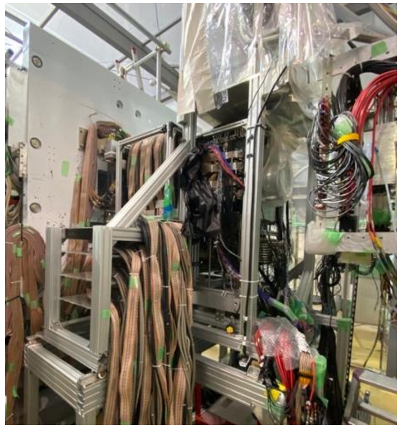
Summary

- 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 just started 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 is introduced.
  - Our goal
    - Total cross section measurement better than 10%
    - First derivation of the differential cross section for Λp elastic scattering

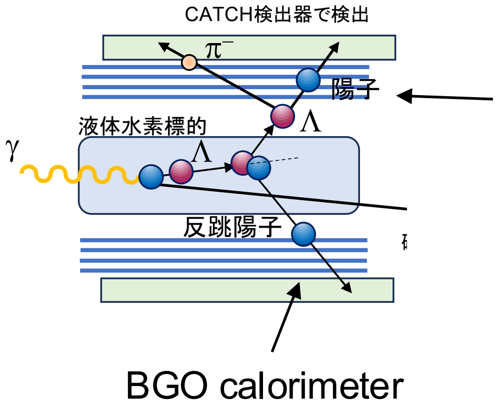
Experimental setup of Λp scattering experiment at BL33LEP

- 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

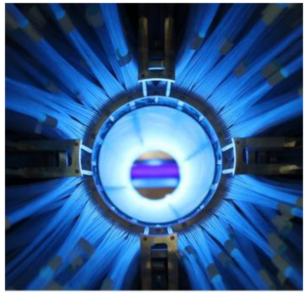




CATCH and LH2 target system



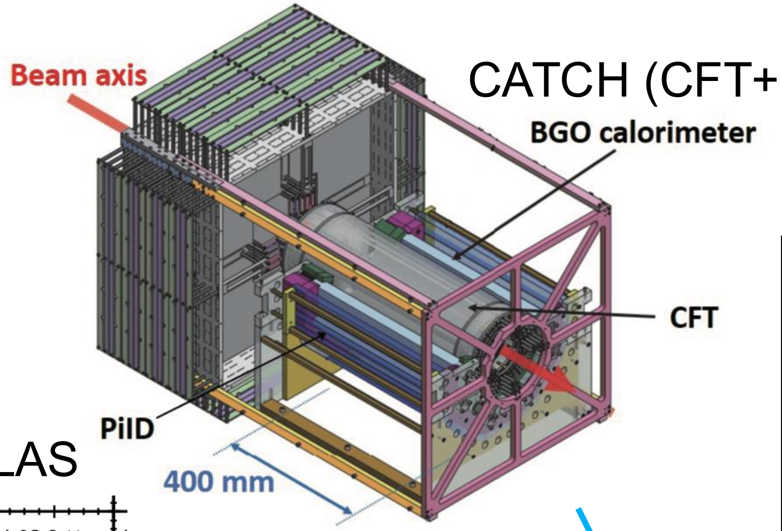
Cylindrical fiber tracker



Feasibility study at BL33LEP : Acceptance of Λ beam detection

We estimated essential parameters
w/ simulation study

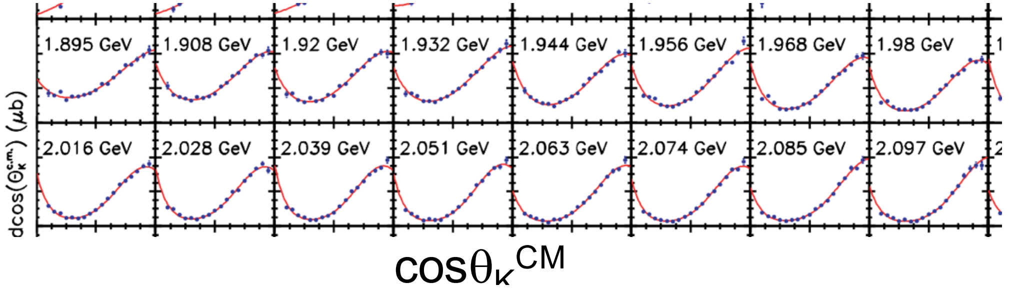
- Acceptance for K+
- Λ beam momentum distribution
- Λp scattering identification quality



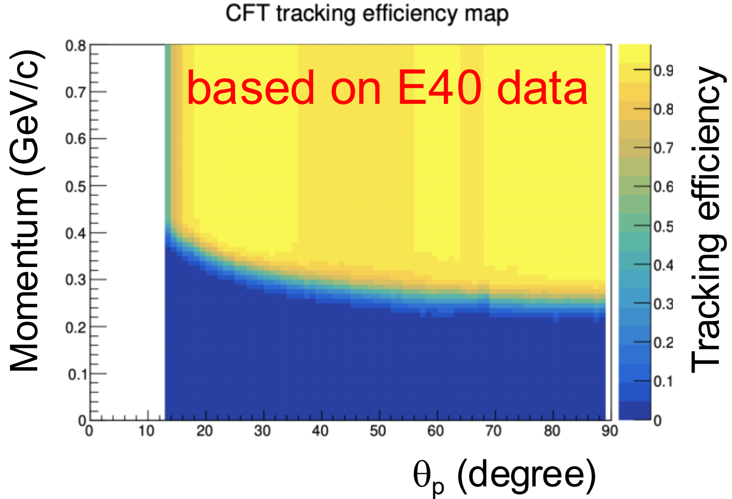
CATCH (CFT+BGO)

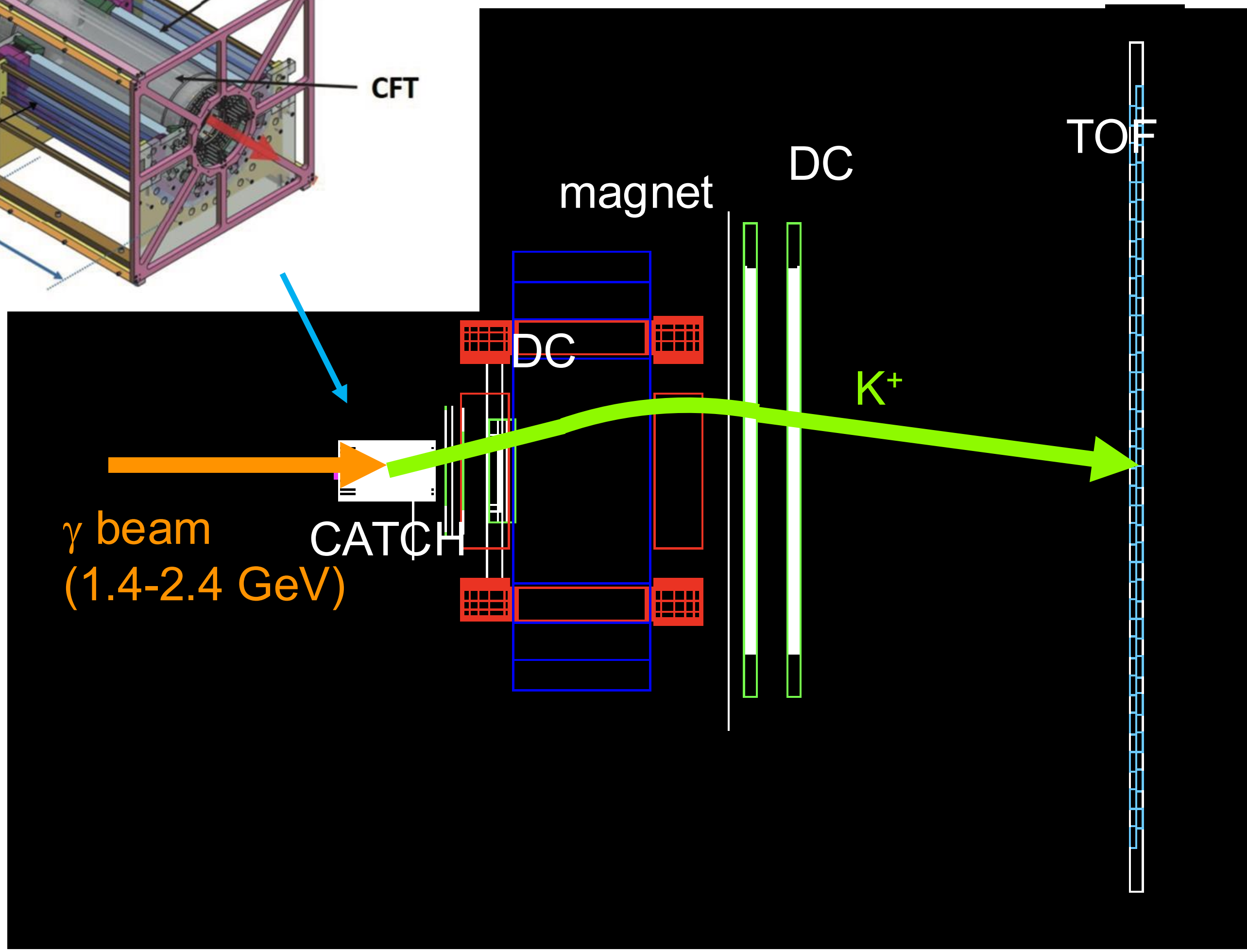
Input

Angular distribution of Λ production by CLAS



CATCH efficiency





Particle and Nuclear Physics at HEF

Comprehensive research on the origin and evolution of matter and the universe

- **the mystery of the matter-dominated universe,**
- **the evolution from quarks to hadrons (the smallest composite particles)**
- **neutron star as a giant atomic nucleus.**

Intensity frontier accelerator
providing intense and variety of secondary beams

K1.8BR
< 1.1 GeV/c
~5x10^5 K-/spill

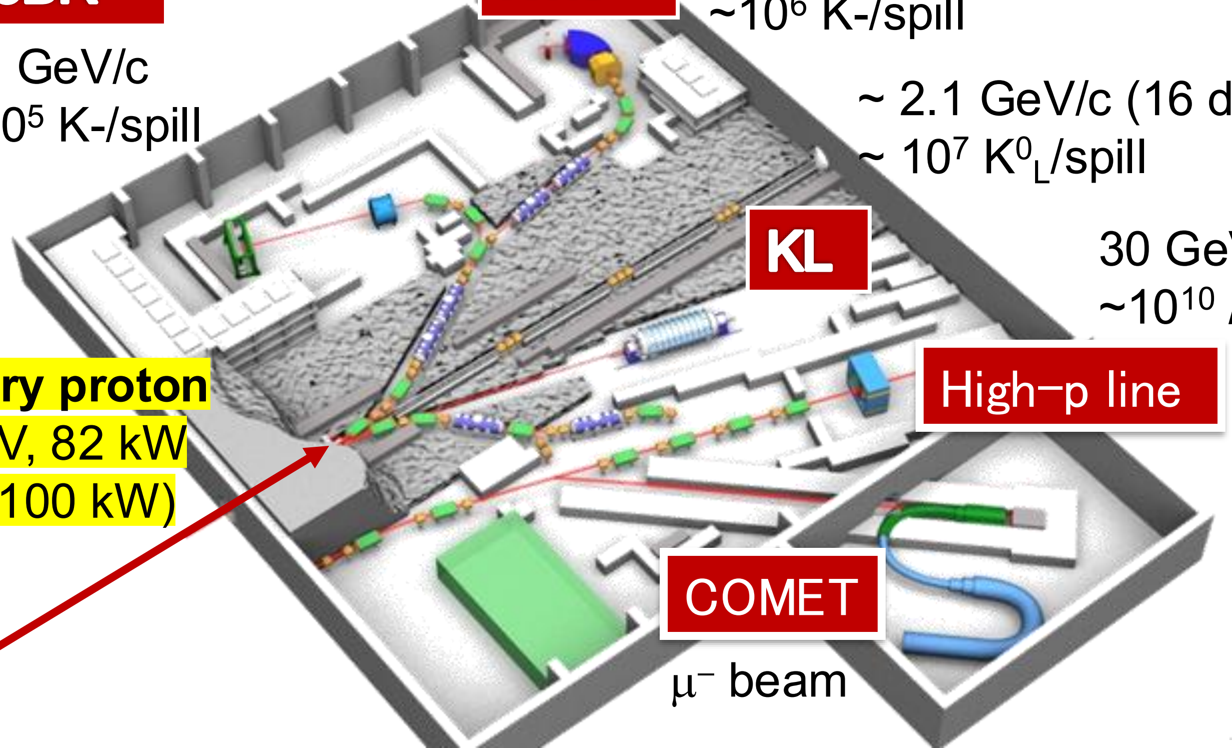
K1.8
< 2.0 GeV/c
~10^6 K-/spill

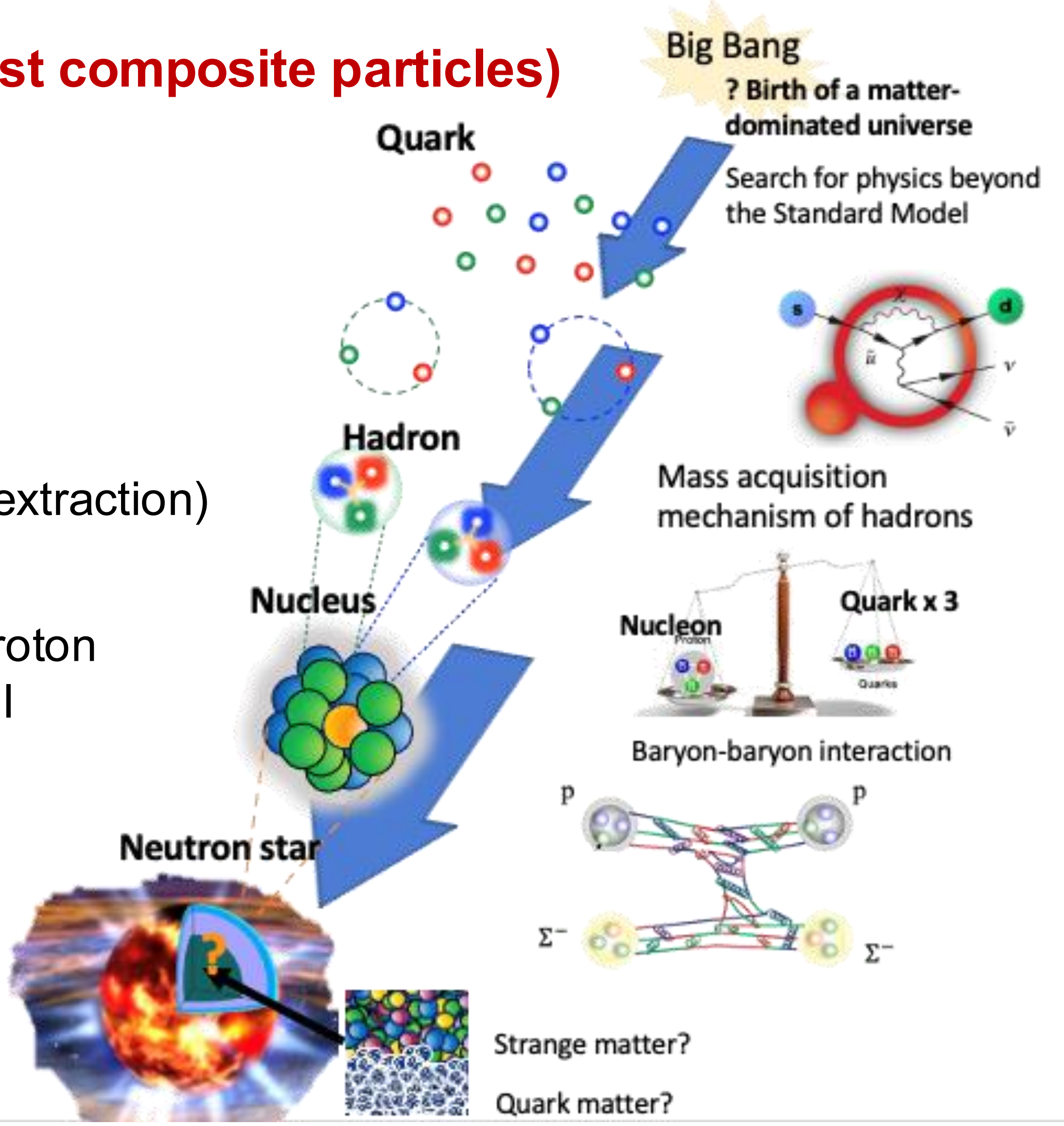
KL
~ 2.1 GeV/c (16 deg extraction)
~ 10^7 K^0_L/spill

High−p line
30 GeV proton
~10^{10} /spill

Primary proton
30 GeV, 82 kW
(Goal 100 kW)

COMET
μ^- beam





Particle and Nuclear Physics at HEF

Comprehensive research on the origin and evolution of matter and the universe

- **the mystery of the matter-dominated universe,**
- **the evolution from quarks to hadrons (the smallest composite particles)**
- **the neutron star as a giant atomic nucleus.**

μ→e conversion measurement

Search for charged lepton flavor violation

100 times improvement over present upper limits

Rare decay of neutral kaon

Search for CP violation beyond the standard model

The world's highest sensitivity exceeding the standard model

Mass modification of vector mesons in nuclei

Elucidation of the mass acquisition mechanism of hadrons

Vector meson in nuclei : 10 times more precision

Systematic study of Kaonic nuclei

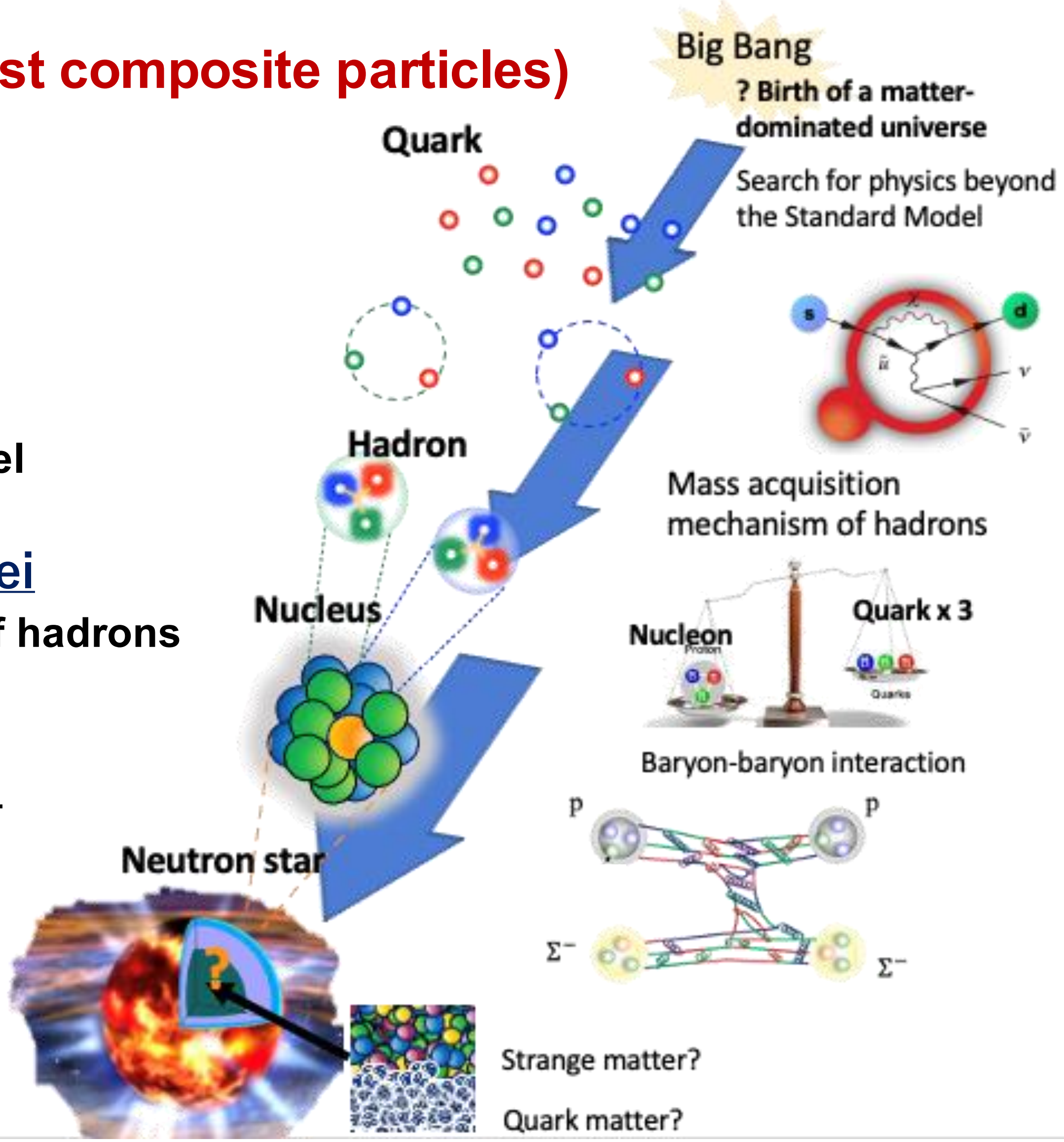
Study of exotic hadron bound system including K^-

Mass number dependence of kaonic nuclei

Spectroscopy of S=-1, -2 hypernuclei

Elucidation of the appearance mechanism of Ξ, Λ hyperons in dense matter

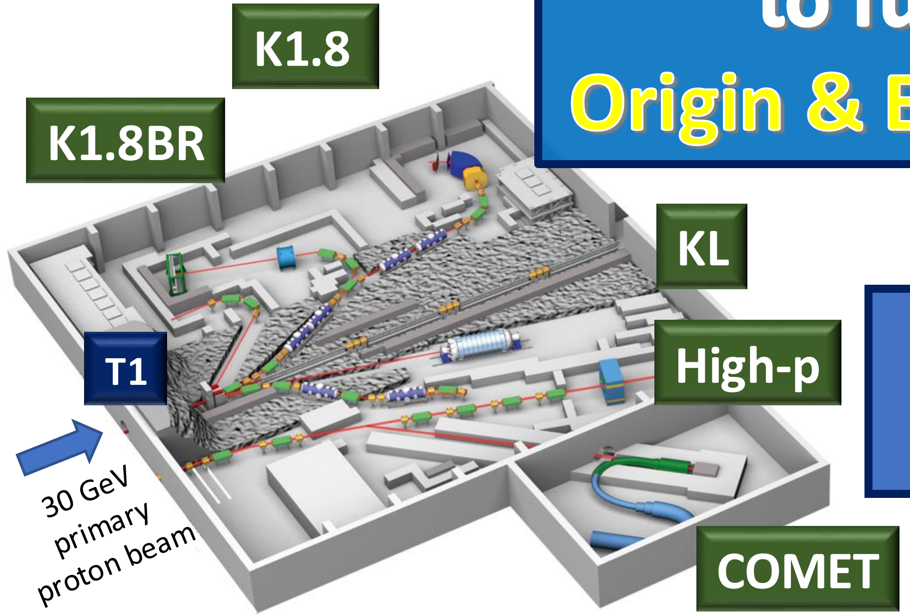
Excellent mass resolution of 2 MeV for Ξ hypernuclei



Hadron Experimental Facility extension (HEF-ex) Project

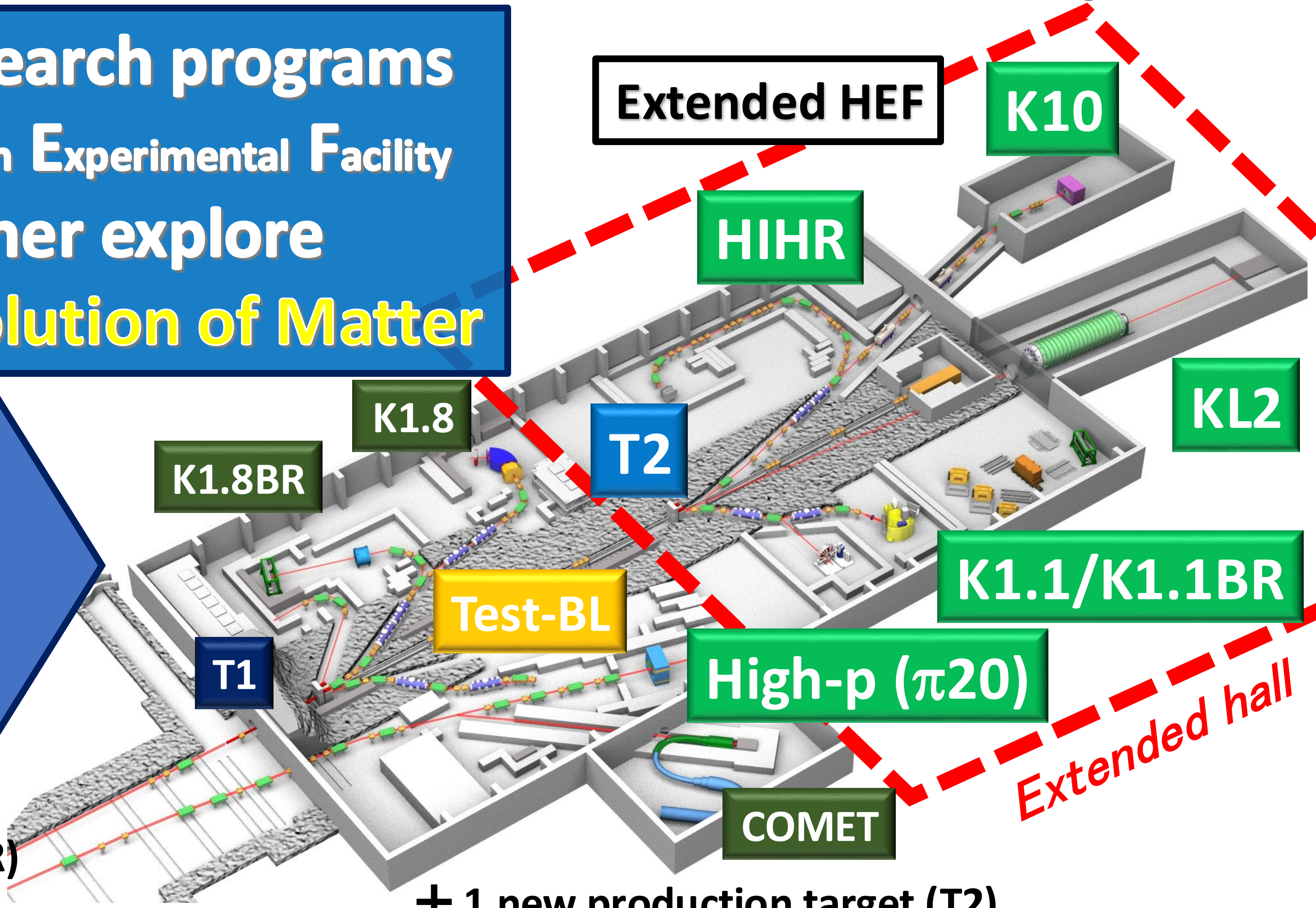
expand research programs at the Hadron Experimental Facility to further explore Origin & Evolution of Matter

Present HEF (2009～)



1 production target (T1)
1 secondary-charged beamline (K1.8/K1.8BR)
1 neutral beamline (KL)
1 primary beamline (High-p)
1 muon beamline (COMET)

Extended HEF



＋1 new production target (T2)
＋4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10)
＋ 2 updated beamlines (High-p (π20), Test-BL)

Expanded Research Programs

at the Extended Facility

Extract density dependent ΛN interaction

HIHR **Ultra-high-resolution Λ hypernuclear spectroscopy**

- intense dispersion matched π beam

K1.1 **Systematic ΛN scattering measurement**

- intense polarized Λ beam

Investigate diquarks in baryons

high-p (π20) **High-resolution charm baryon spectroscopy**

- intense high-momentum π beam

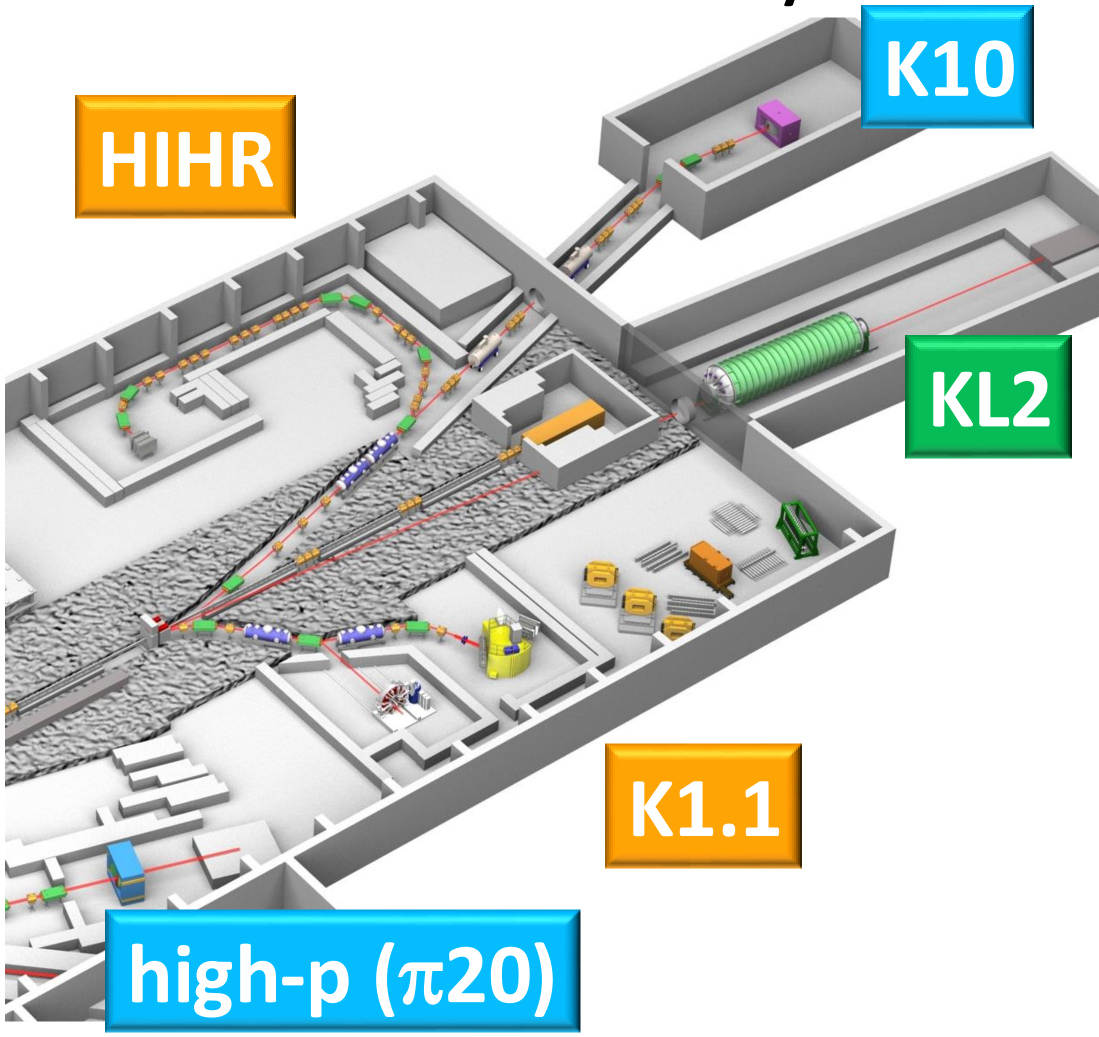
K10 **High-resolution multi-strange baryon spectroscopy**

- intense high-momentum separated K beam

Search for new physics beyond the SM

KL2 **Most sensitive $K_L^0 \to \pi^0 \nu\bar{\nu}$ measurement**

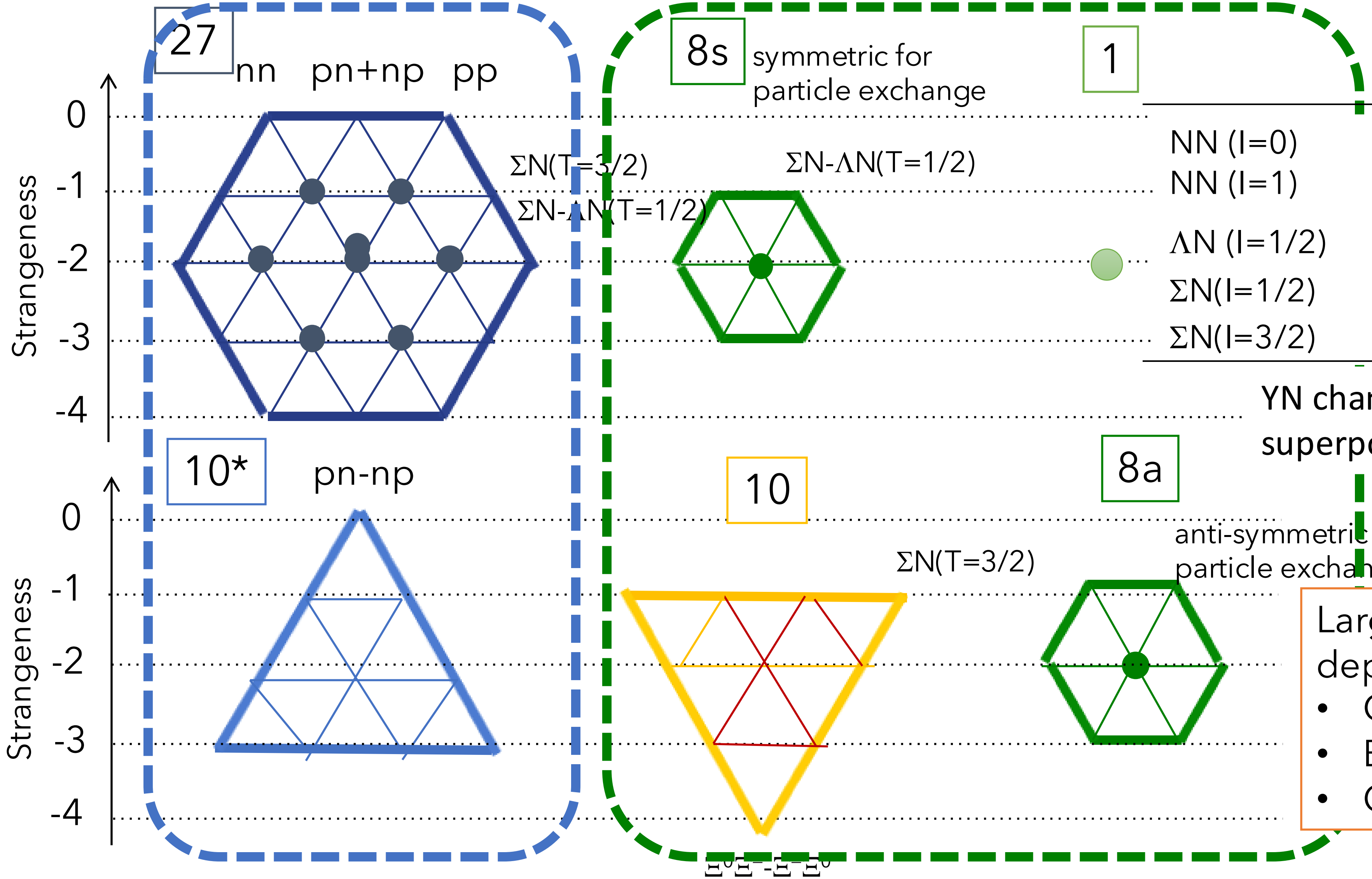
- intense neutral K beam



Baryon-Baryon interaction in $SU_F(3)$ symmetry

Same multiplet with NN interaction

Newly appeared interaction in BB(YN, YY) interaction



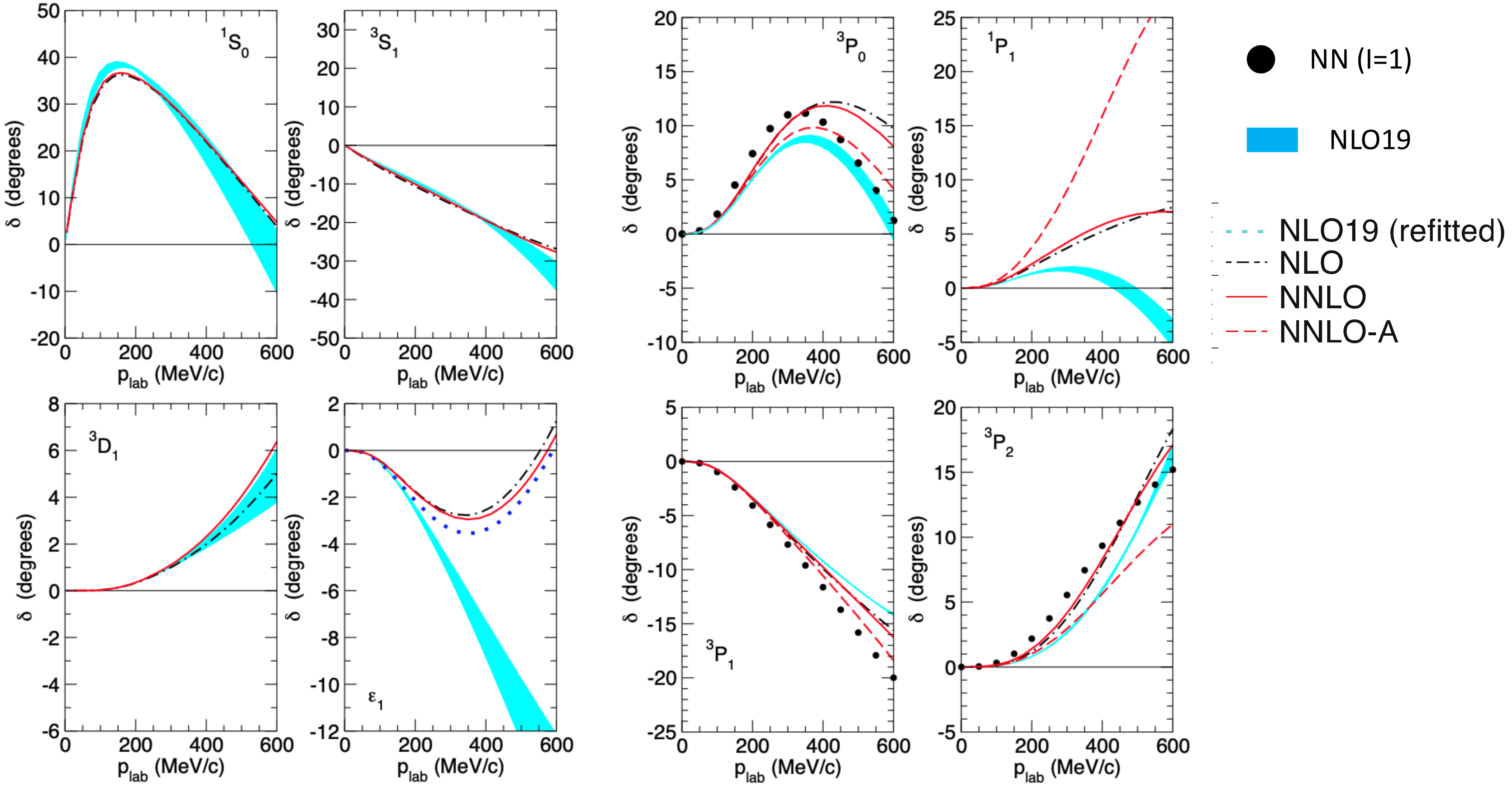
	^1E or ^3O	^3E or ^1O
NN (I=0)	------	(10*)
NN (I=1)	(27)	-----
ΛN (I=1/2)	$1/\sqrt{10}[(8_s) + 3(27)]$	$1/\sqrt{2}[-(8_a) + (10^*)]$
ΣN(I=1/2)	$1/\sqrt{10}[3(8_s) - (27)]$	$1/\sqrt{2}[(8_a) + (10^*)]$
ΣN(I=3/2)	(27)	(10)

YN channels ware represented as the superposition of these flavor multiplets.

Large difference in interaction models depending on physics picture

- Quark base model
- Boson exchange model
- Chiral effective field theory

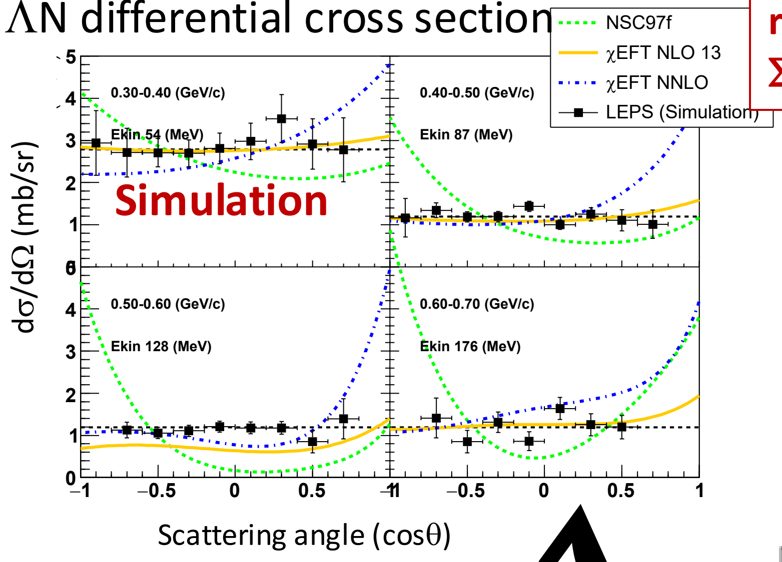
ΣN (I=3/2) phase shift in chiral EFT



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

(1) Λp scattering experiment
(Koji Miwa)

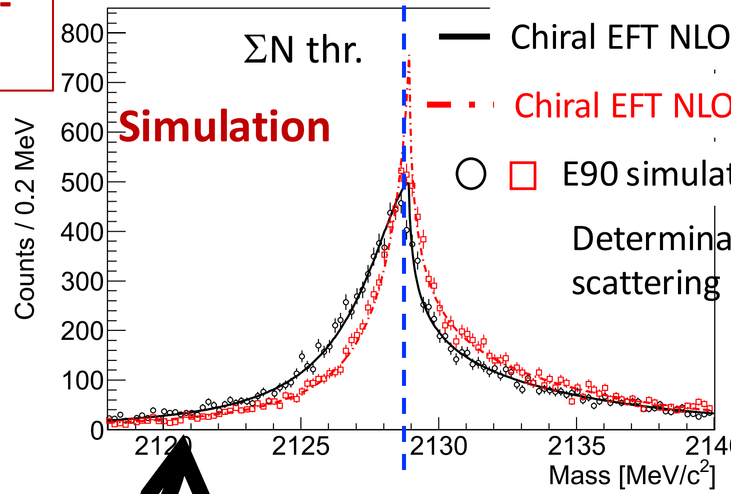
ΛN differential cross section



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

Momentum dependence of dσ/dΩ

(2) ©N cusp measurement
(Yudai Ichikawa)

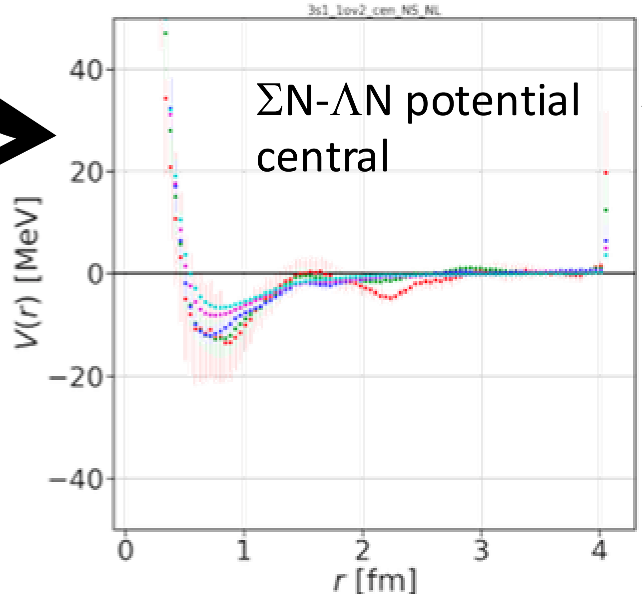


Determination of the ΣN (I=1/2, S=1) scattering length from the cusp shape

ΛN-ΣN coupling

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

Universal understanding of ΛN interaction from scattering and Lattice QCD



(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