Recent progress of hyperon-nucleon scattering experiment and future programs at J-PARC

Koji Miwa (Tohoku Univ./KEK)

2nd Workshop on Hadron Interactions, Hyper-Nuclei and Exotic Hadron productions at High-Energy Experiments, May 24, 2023

TOHOKU UNIVERSITY

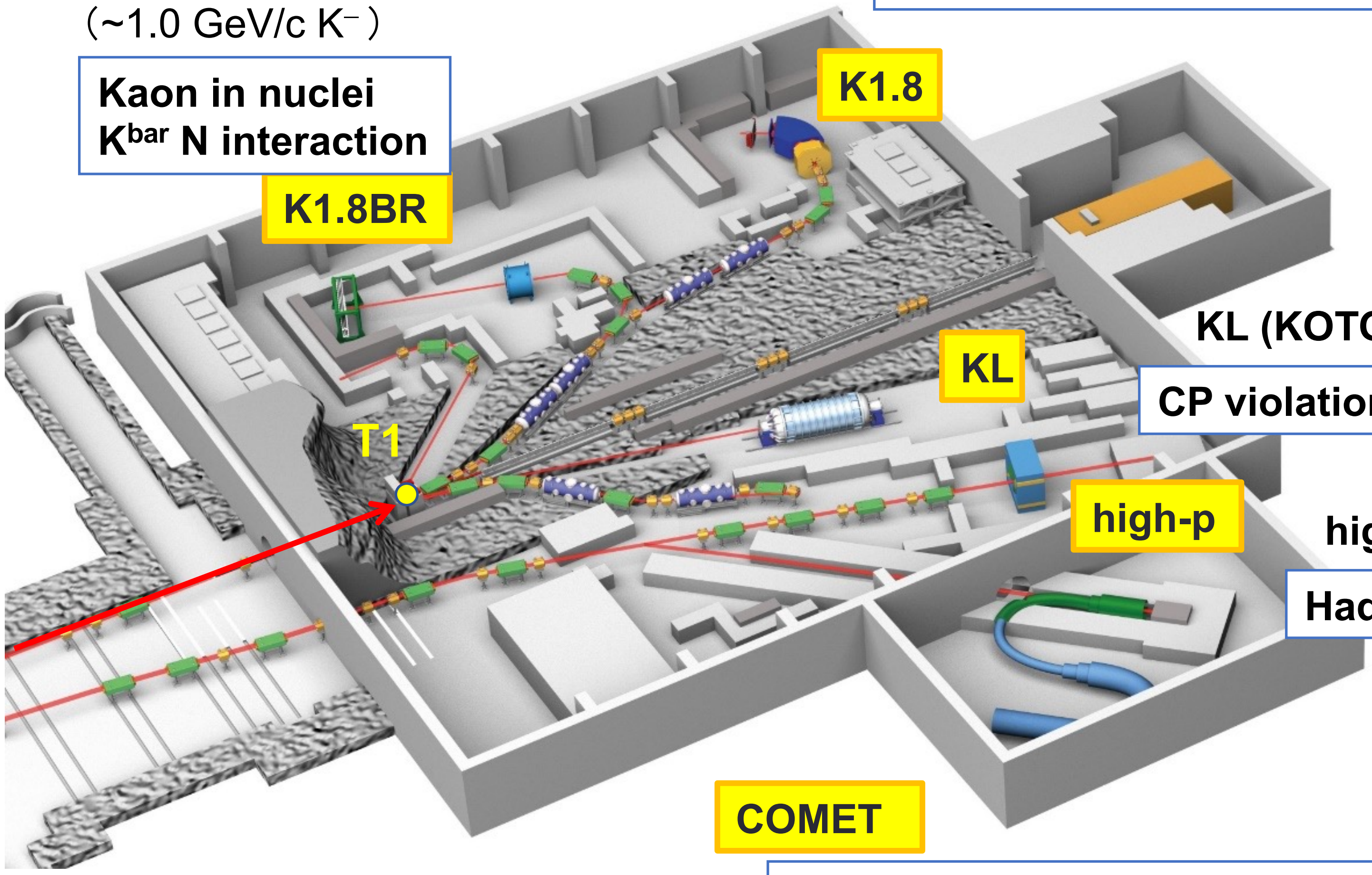
Present Hadron Experimental Facility

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

Kaon in nuclei
K^{bar} N interaction

K1.8（~1.8 GeV/c K^-）

S=-1, -2 hypernuclei
Baryon-Baryon interaction



KL (KOTO)

CP violation in K^0_L decay

high-p（30GeV primary proton beam）

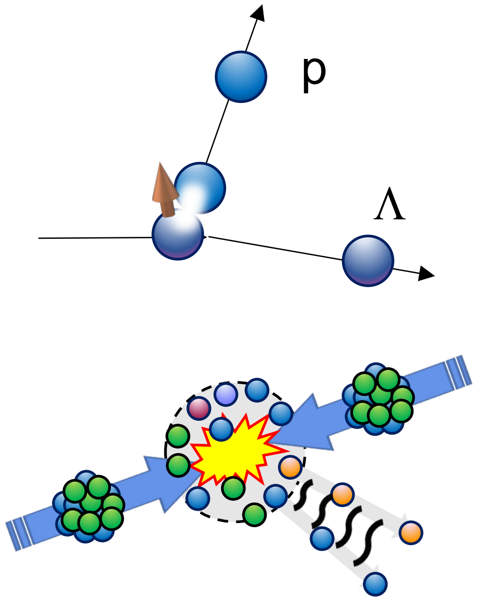
Hadron property in nuclear medium

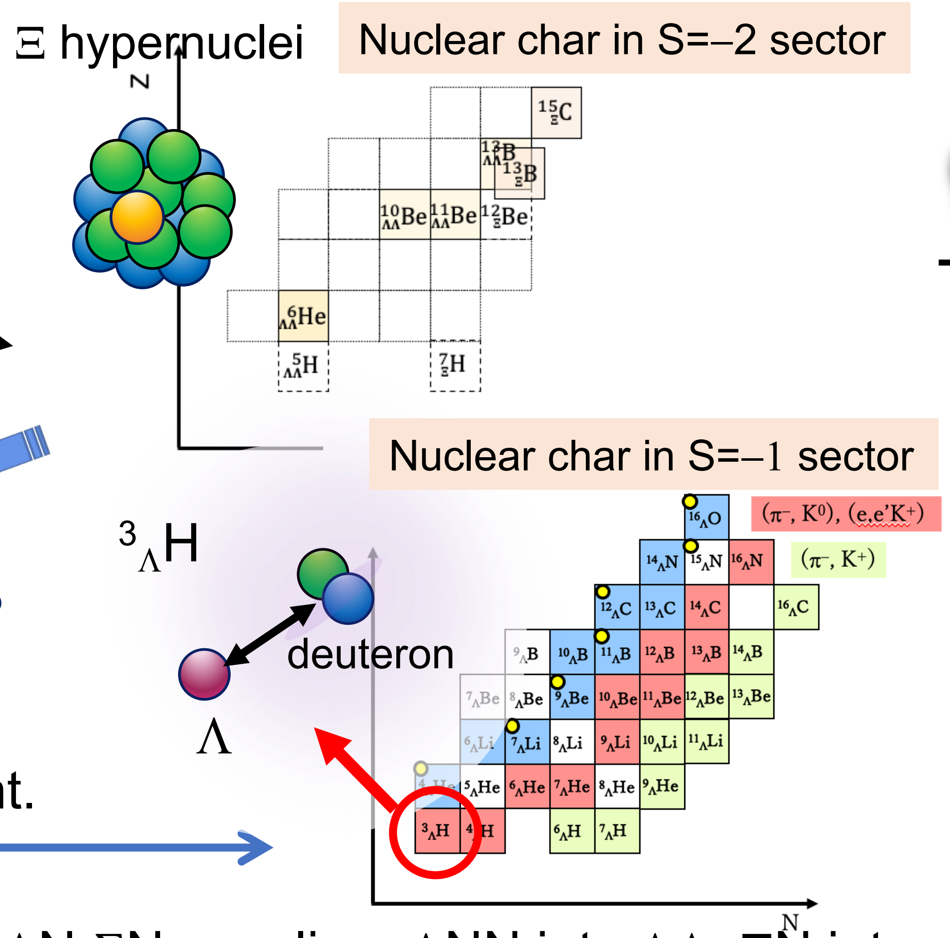
Measurement of μ→e conversion
(2023~)

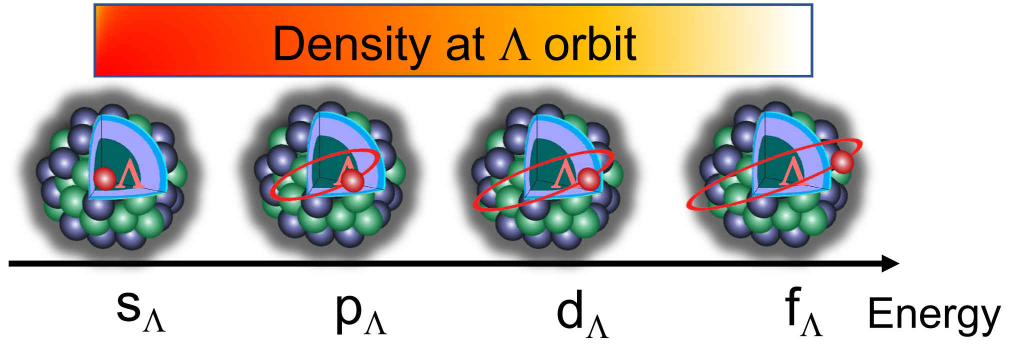
Contents

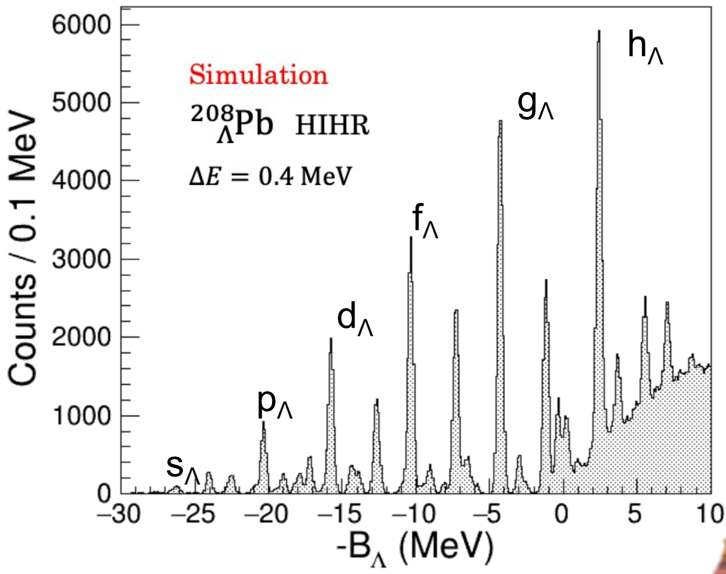
Hypernuclear physics

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

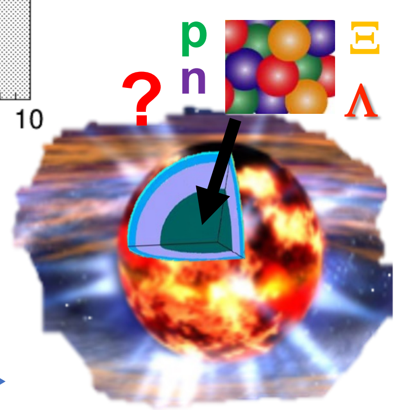








Neutron star



Two-body YN int.

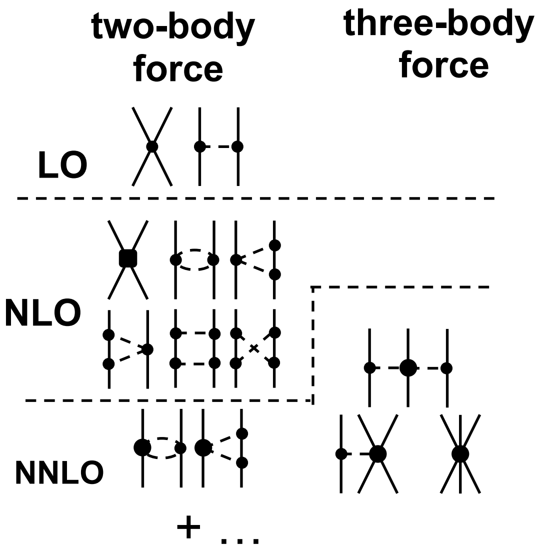
ΛN-ΣN coupling, ΛNN int., ΛΛ, ΞN int.

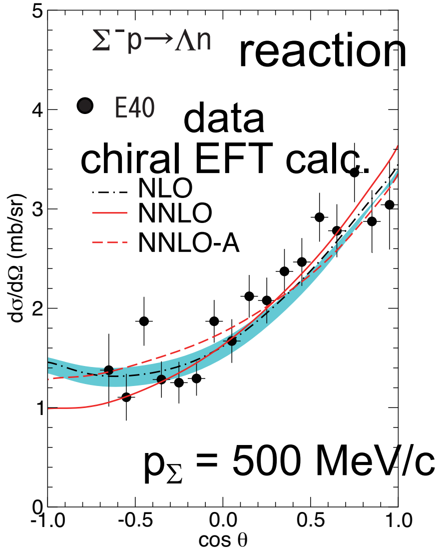
Density dependent ΛN int., ΛNN int.

Progress of theory & experiment of BB int. study

Theoretical progress

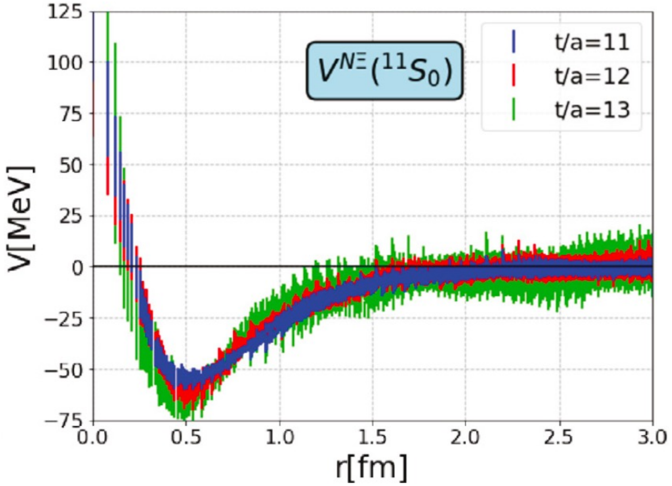
Hyperon-Nucleon int. w/ chiral effective field theory
(J. Haidenbauer et al.)





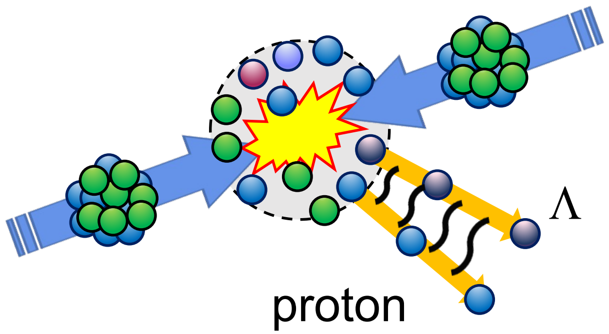
Improving accuracy w/ our new data

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

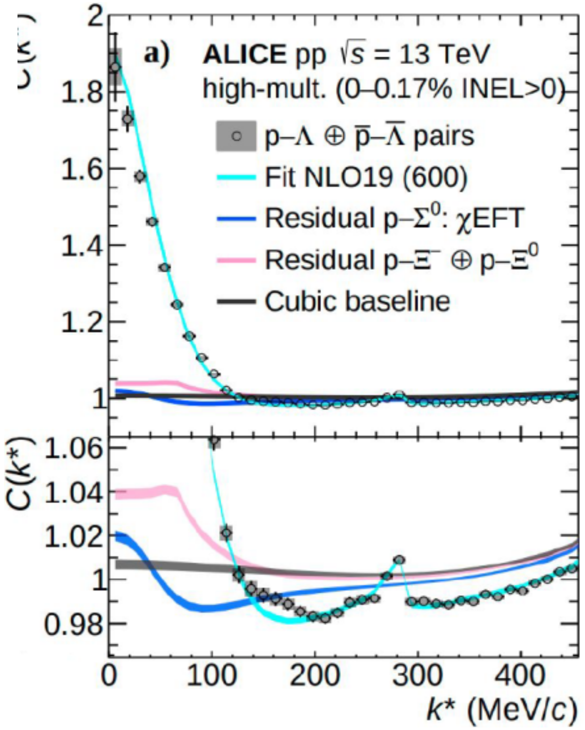


BB interaction by femtoscopy

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

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

Particle correlation between Λ and p

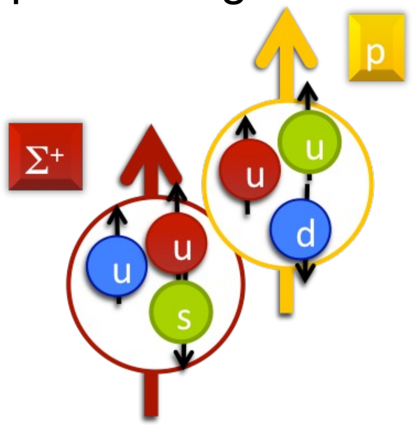


ALICE Collaboration, Phys. Lett. B 833 (2022) 137272

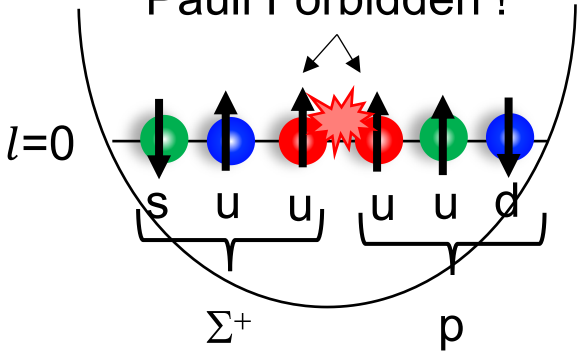
J-PARC E40 : Measurement of dσ/dΩ of Σp scatterings

Verification of quark Pauli repulsion

Σ^+p scatterng

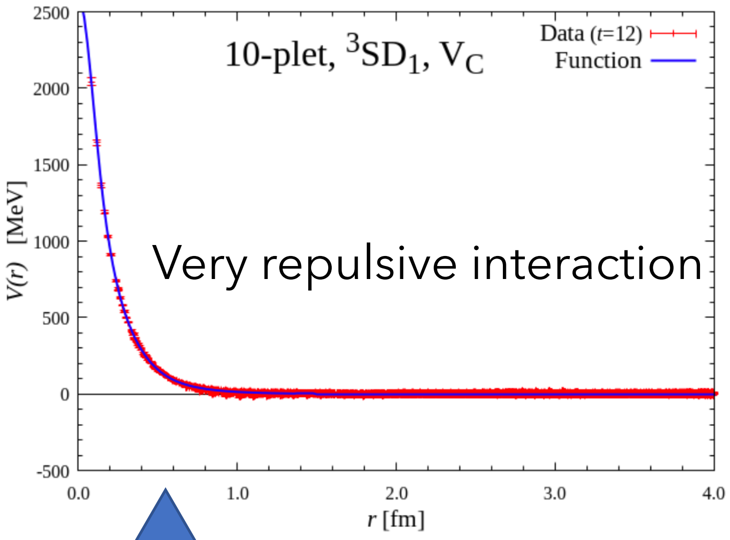


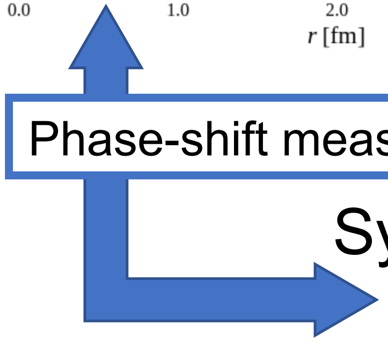
6 quarks can stay in s state in normal case



Lattice QCD calculation

T. Inoue, AIP Conf. Proc. 2130, 020002 (2019)

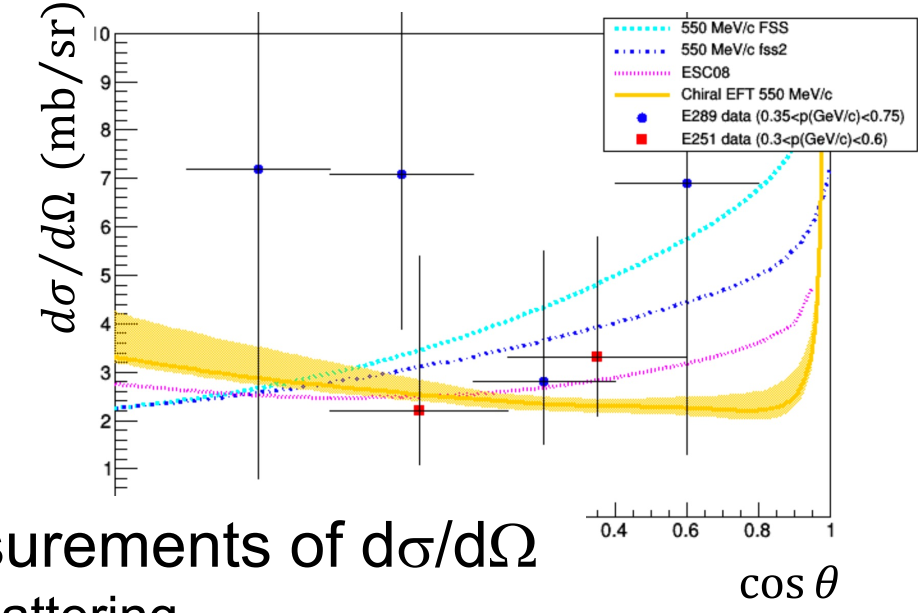




Constraint for BB int. theories

- Quark Cluster model (FSS, fss2)
- Nijmegen model
- Chiral EFT (NLO)

Σ^+p (0.5 < p (GeV/c) < 0.6)

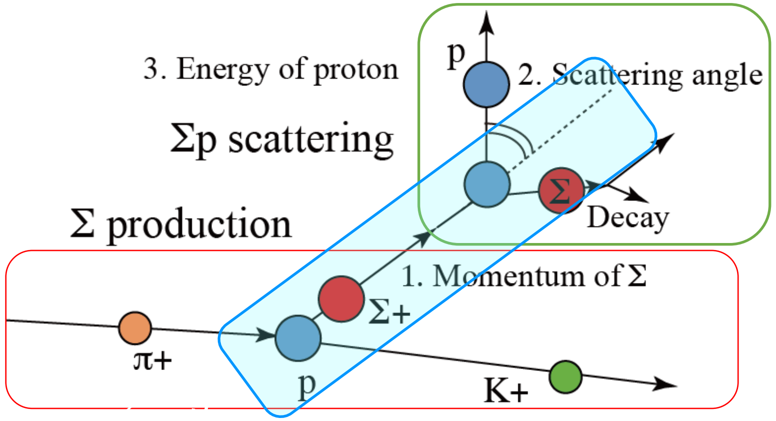


Systematic measurements of dσ/dΩ

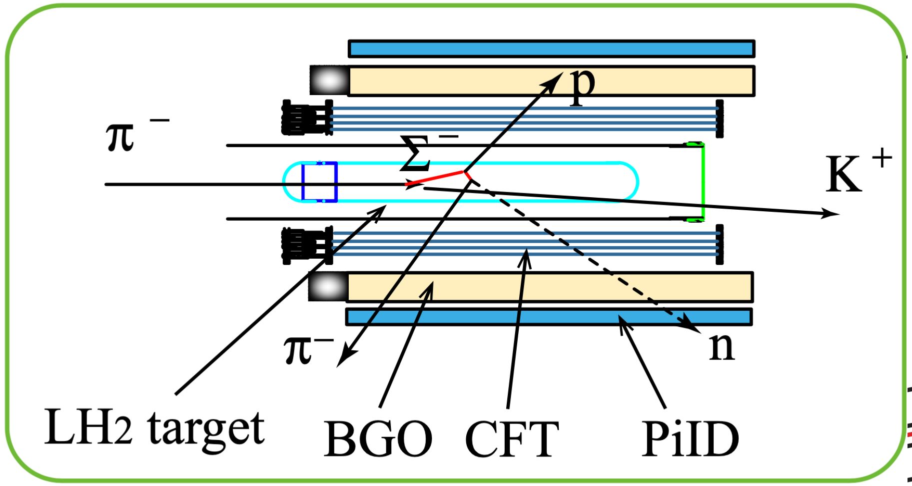
- Σ^+p elastic scattering
- Σ^-p elastic scattering
- $\Sigma^-p \rightarrow \Lambda n$ inelastic scattering

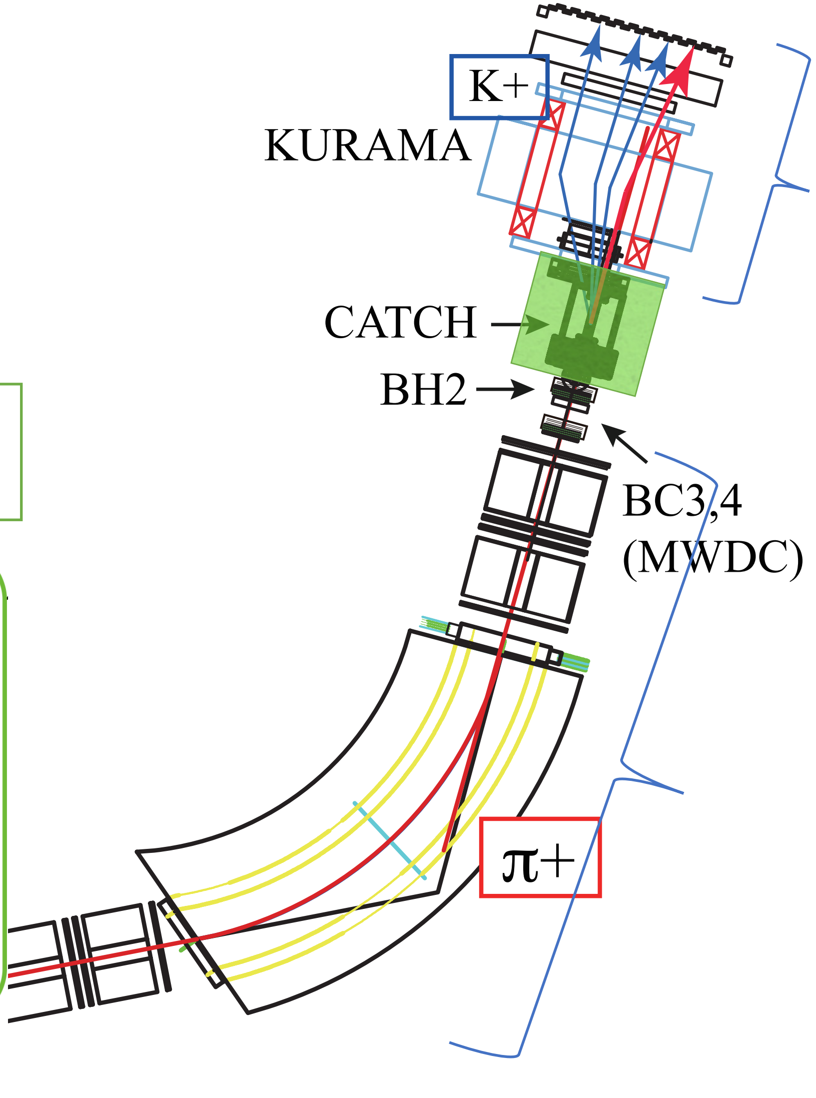
J-PARC E40 experimental setup

Two successive two-body reactions



Detection of Σp scattering event by CATCH detector





KURAMA spectrometer

- Identification of K^+
- Momentum analysis

Momentum tagging of Σ beam

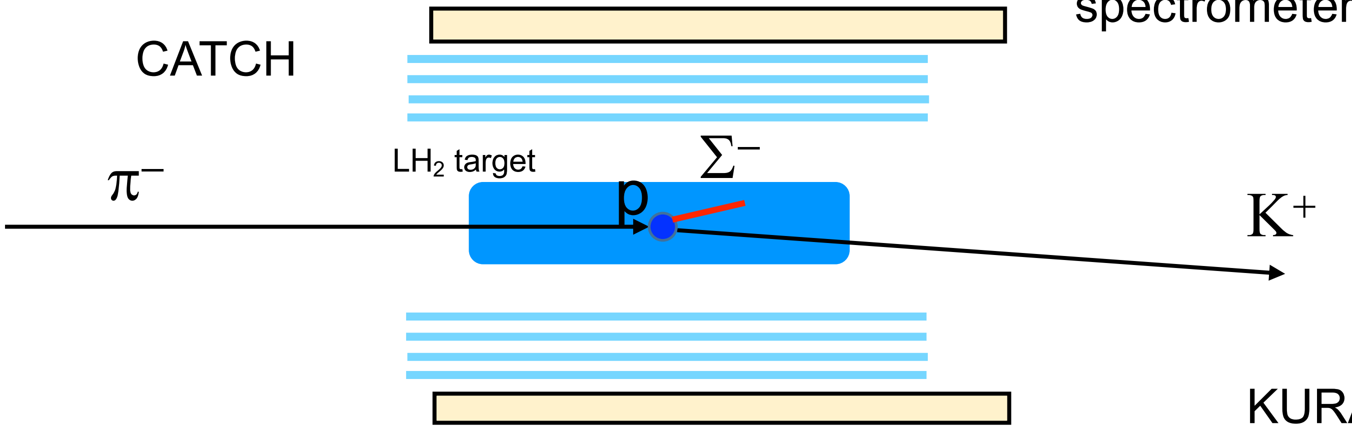
Beam-line spectrometer

- Momentum analysis of π beam

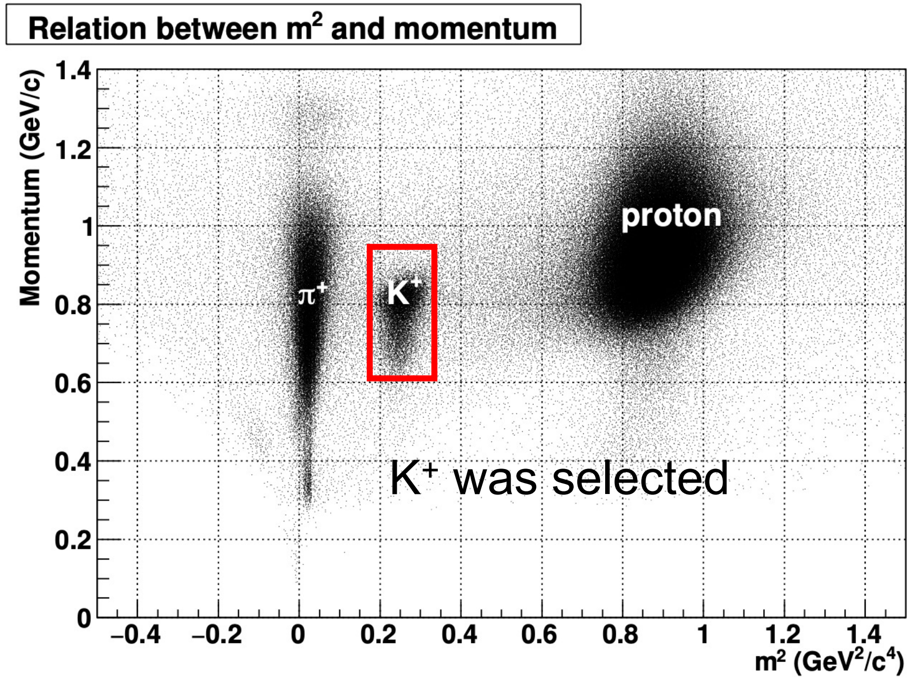
J-PARC K1.8 beam line

Σ beam identification

Σ beam in LH_2 target is tagged by the magnetic spectrometers

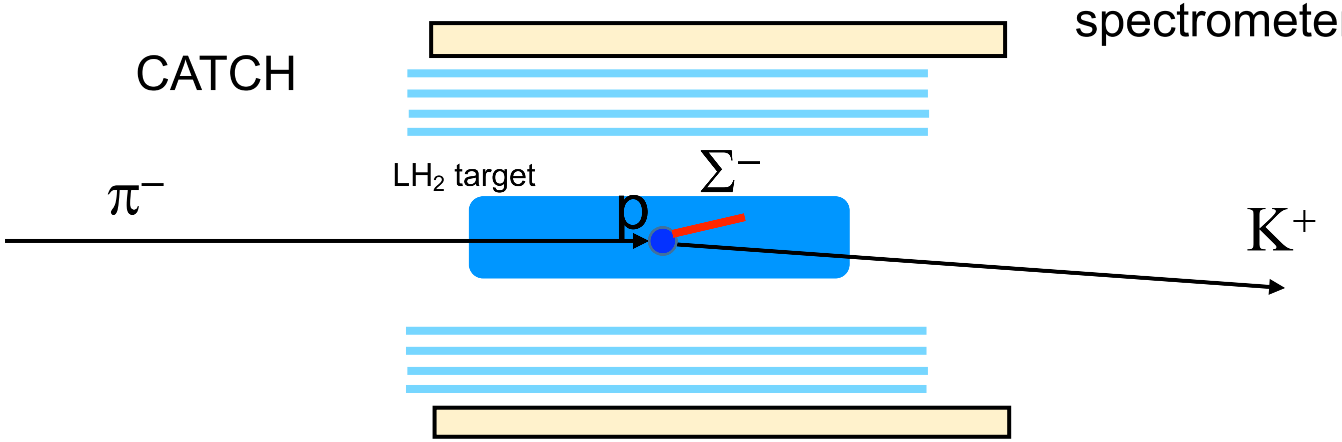


KURAMA spectrometer analysis

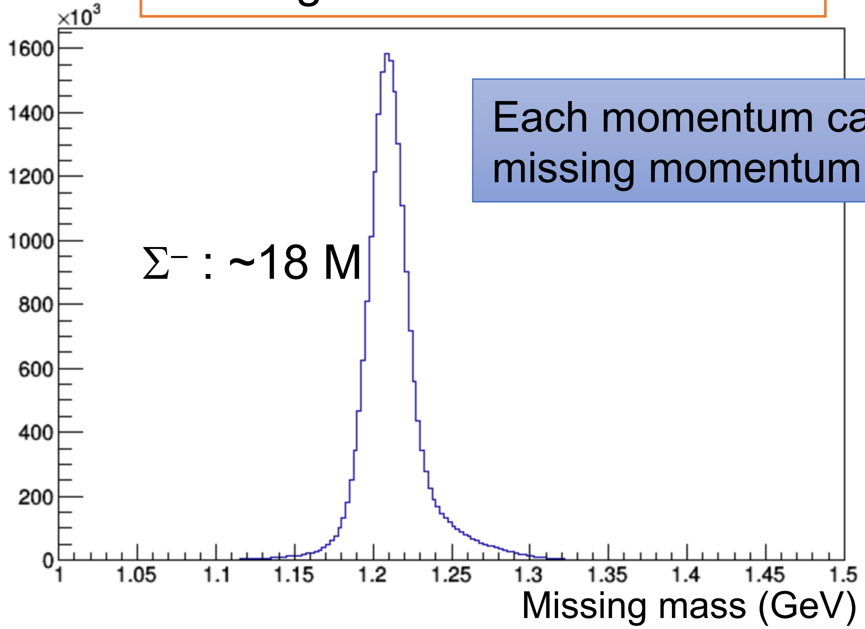


Σ beam identification

Σ beam in LH_2 target is tagged by the magnetic spectrometers



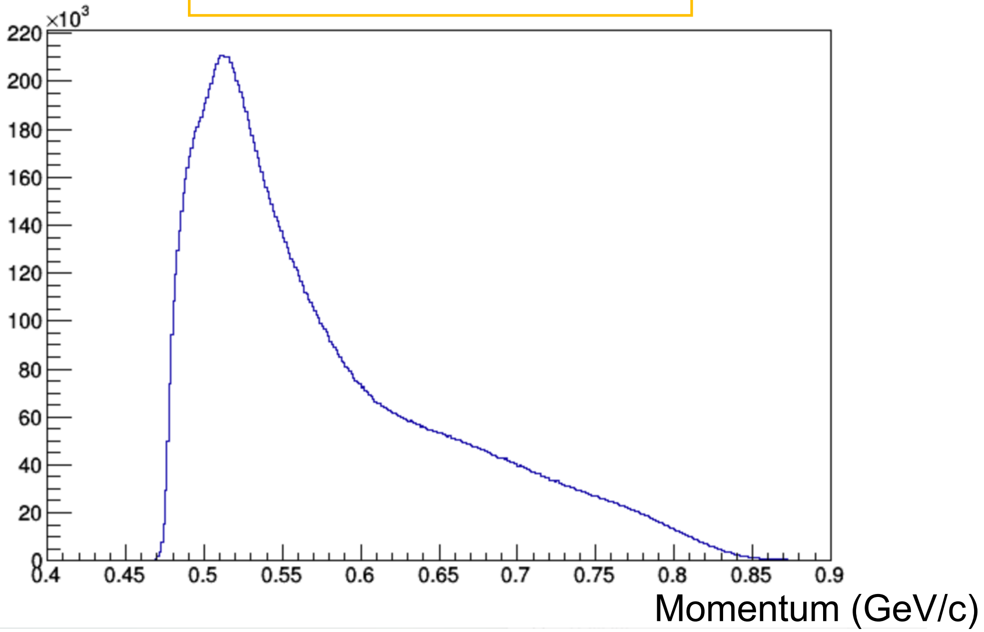
Missing mass from π^- and K^+



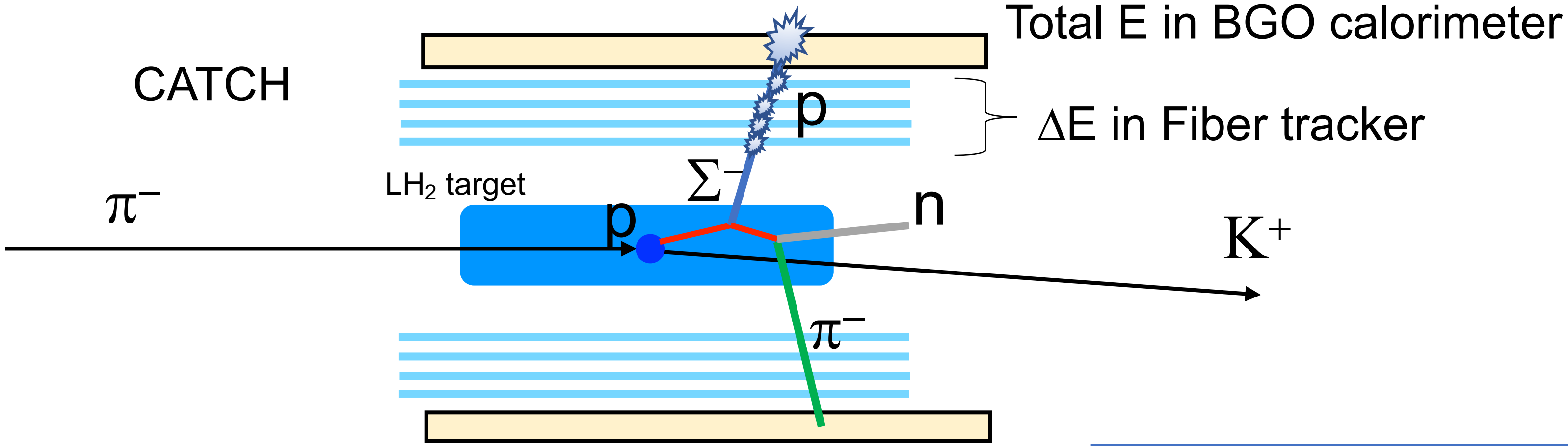
Σ^- : ~18 M

Each momentum can be reconstructed from missing momentum

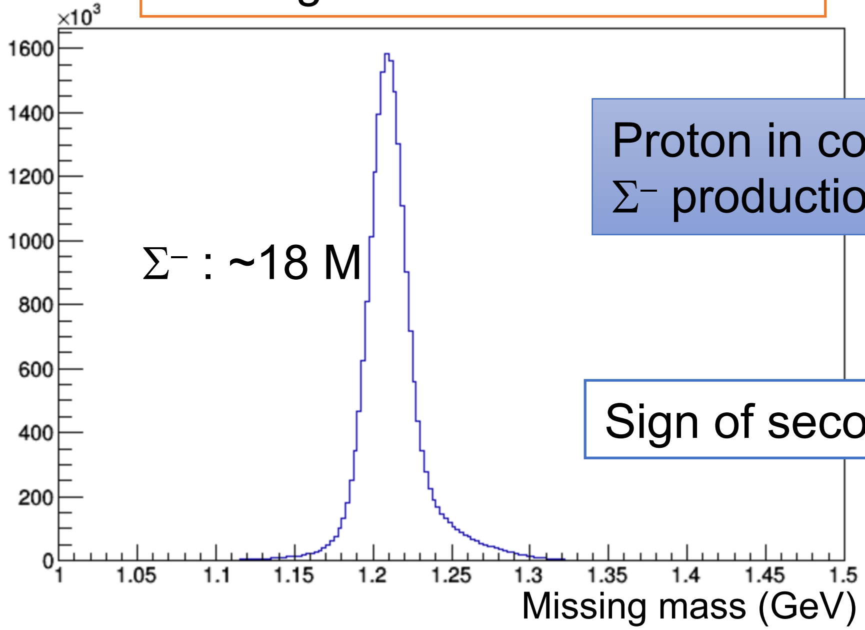
Σ^- beam momentum



Recoil proton identification



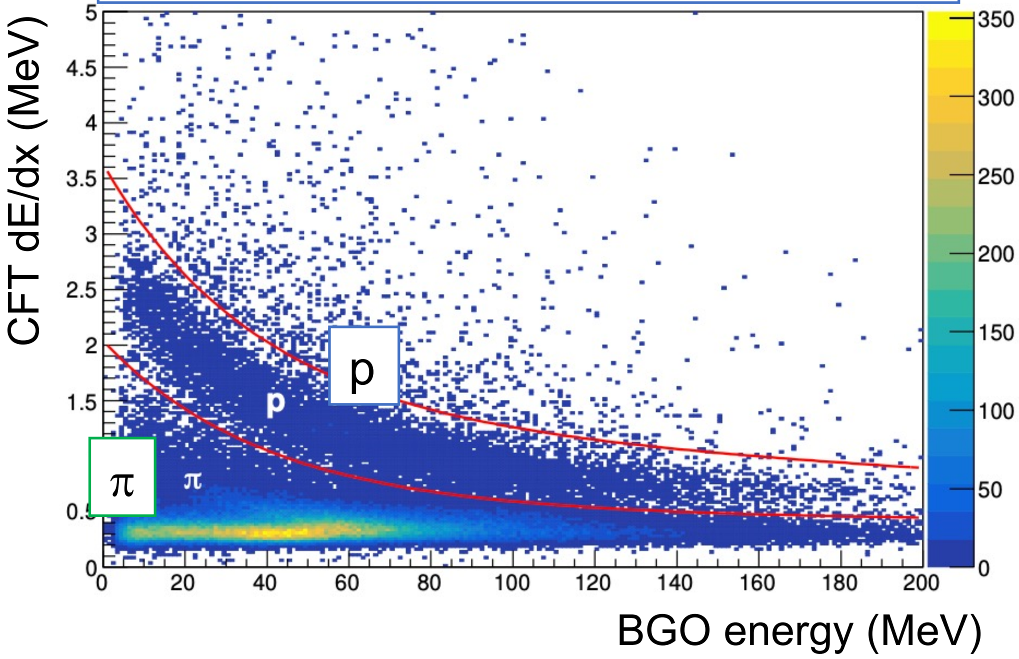
Missing mass from π⁻ and K⁺



Proton in coincidence with Σ⁻ production

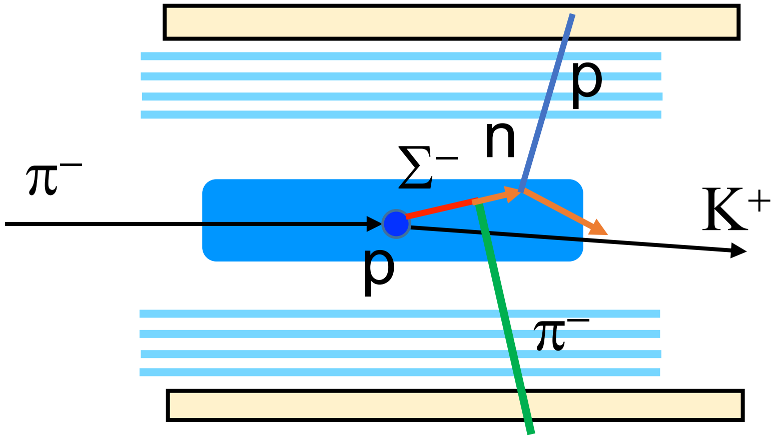
Sign of secondary reactions

Particle ID in CATCH (ΔE-E method)



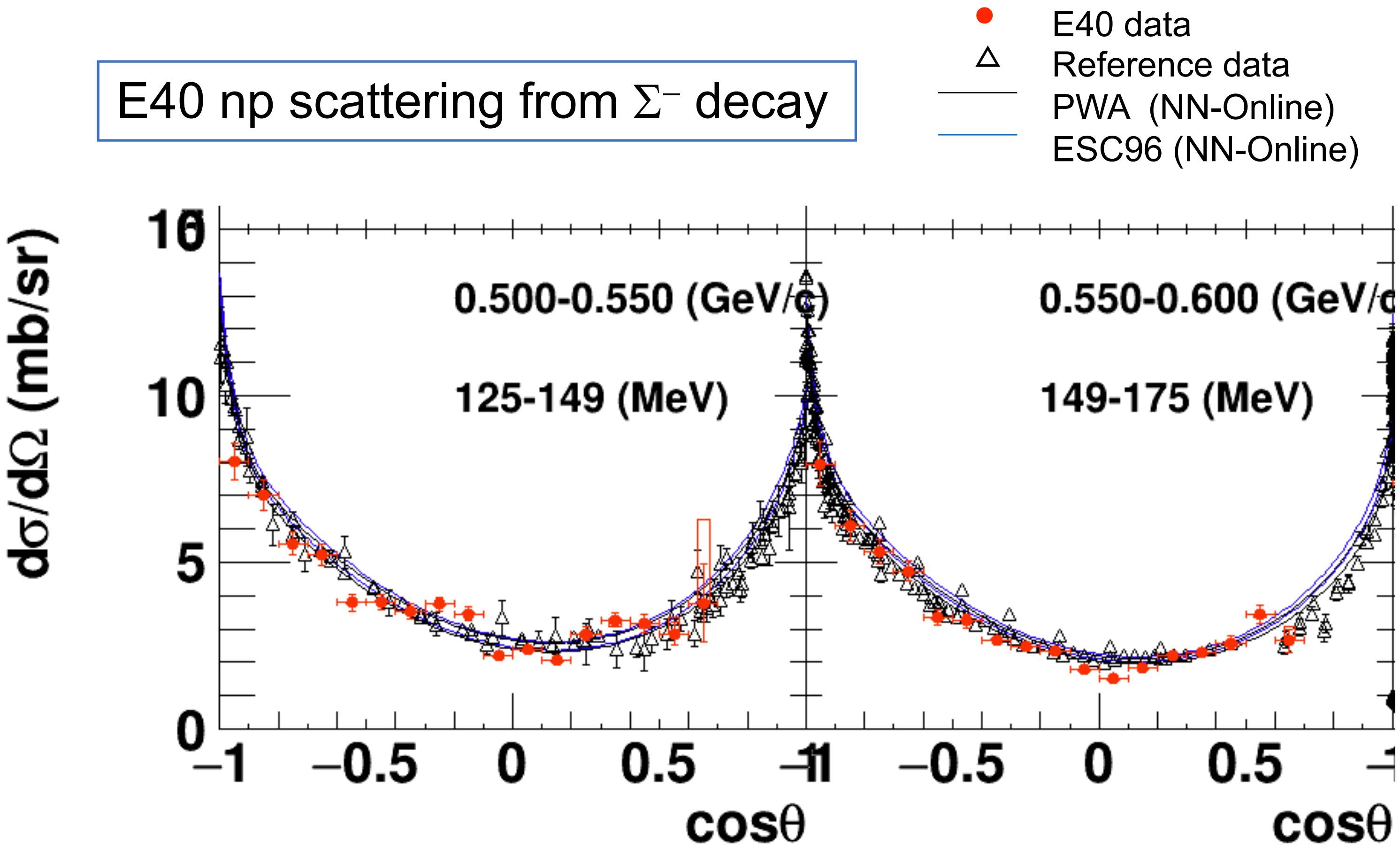
dσ/dΩ of np scattering from Σ^- decay

np scattering



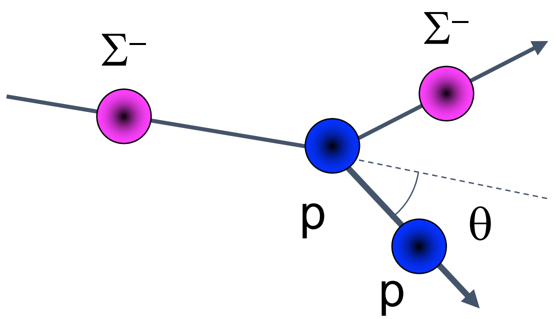
Good reaction to understand our systematics of the dσ/dΩ measuremer

E40 np scattering from Σ^- decay



The derived dσ/dΩ of np scattering are consistent with past measurements.

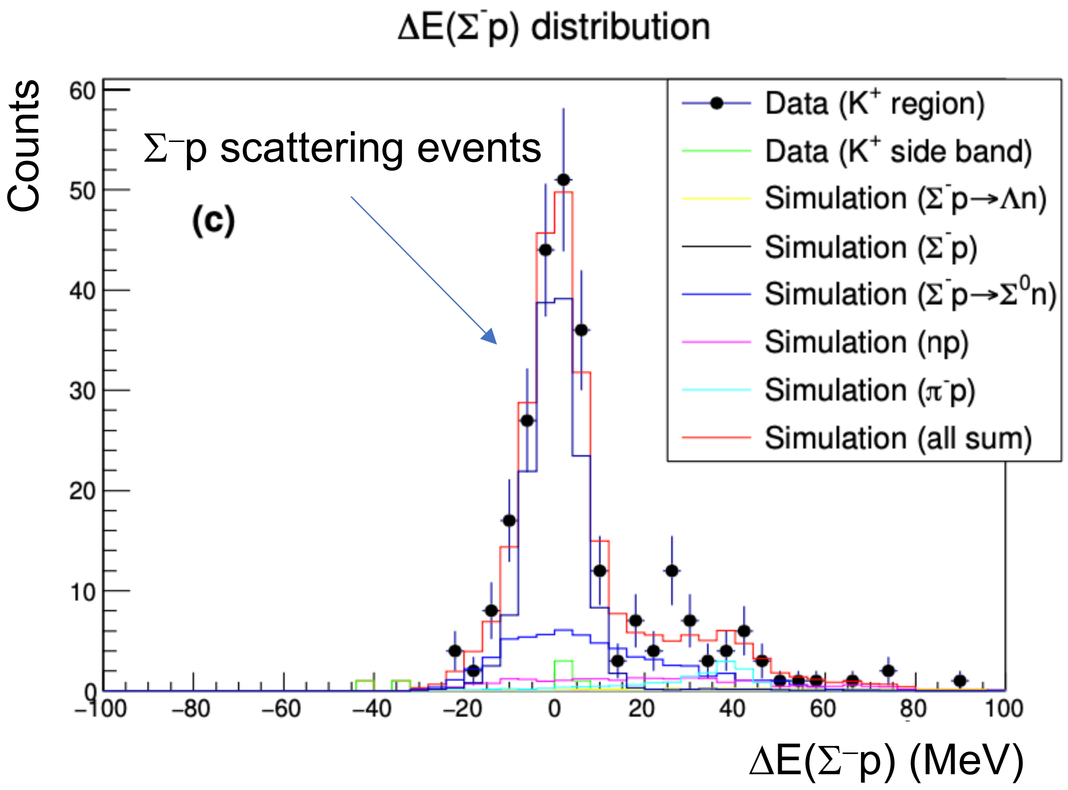
Kinematical identification of $\Sigma^{-}p$ scatterings

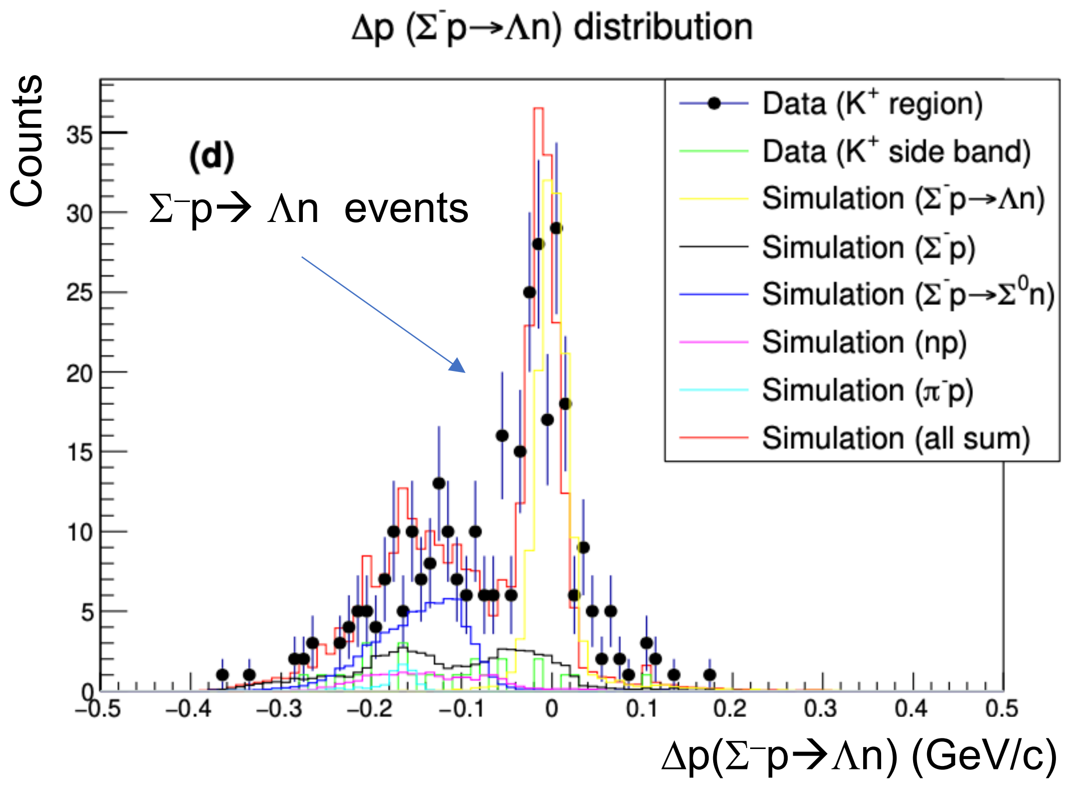


Check kinetic energy difference between

- $E_{measured}$: measured energy
- E_{calc} : calculated energy from scattering angle based on $\Sigma^{-}p$ elastic scattering kinematics

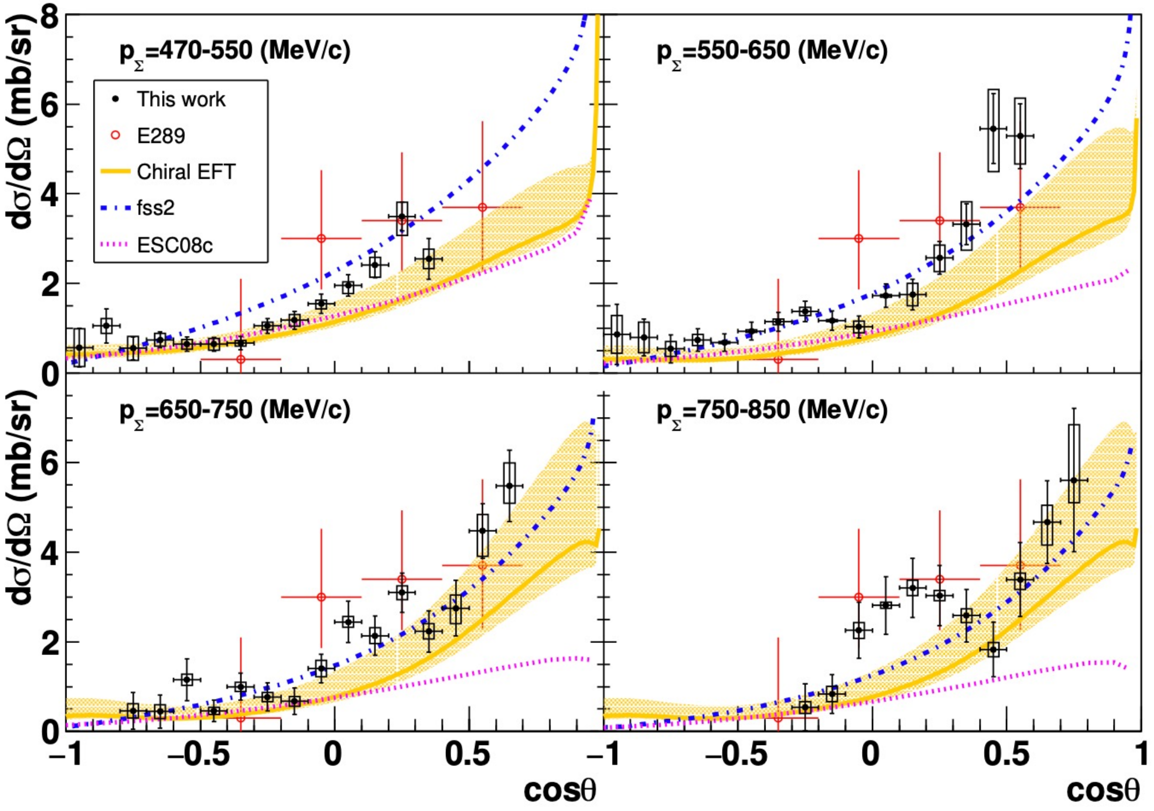
$$\Delta E(\Sigma^{-}p) = E_{measured} - E_{calc}$$





dσ/dΩ of the $\Sigma^{-}p$ channels

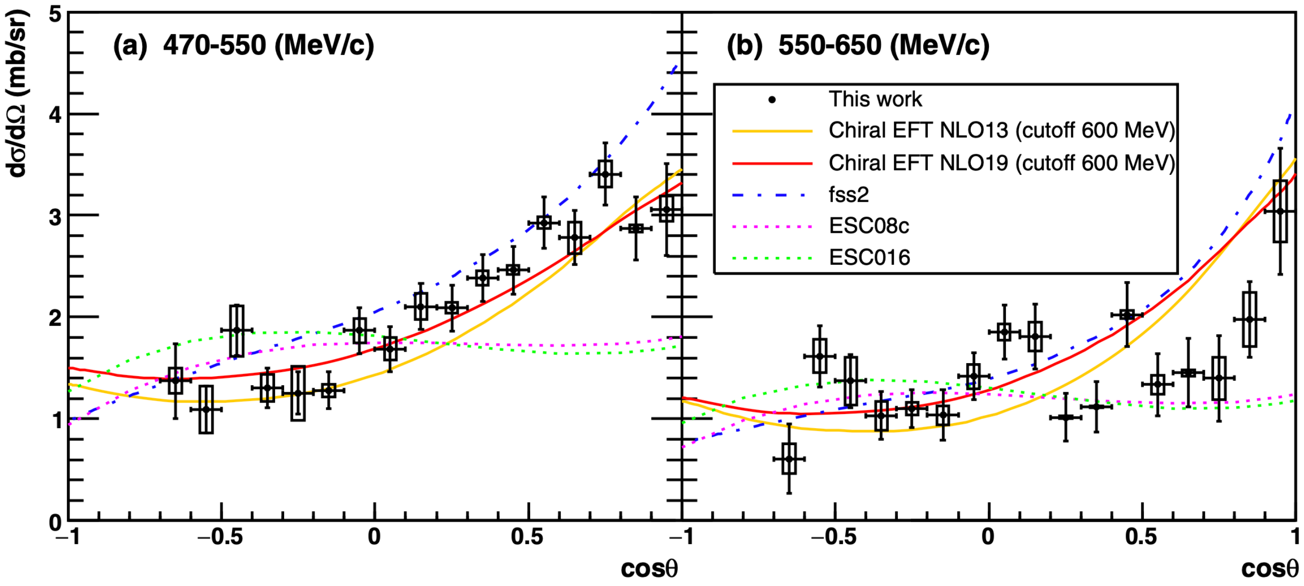
$\Sigma^{-}p$ elastic scattering K. Miwa et al., PRC 104, 045204 (2021)



Clear forward peaking angular dependence

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

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



Moderate forward peaking dependence

<u>Comparison with theories</u>

- fss2, Chiral EFT show a reasonable angular dependence.
- Nijmegen ESC models clearly underestimate the forward angle.

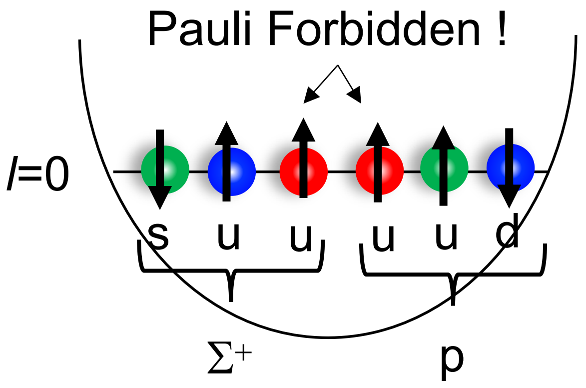
These channels CAN be understood within extended SU(3) flavor symmetry based on NN interaction.

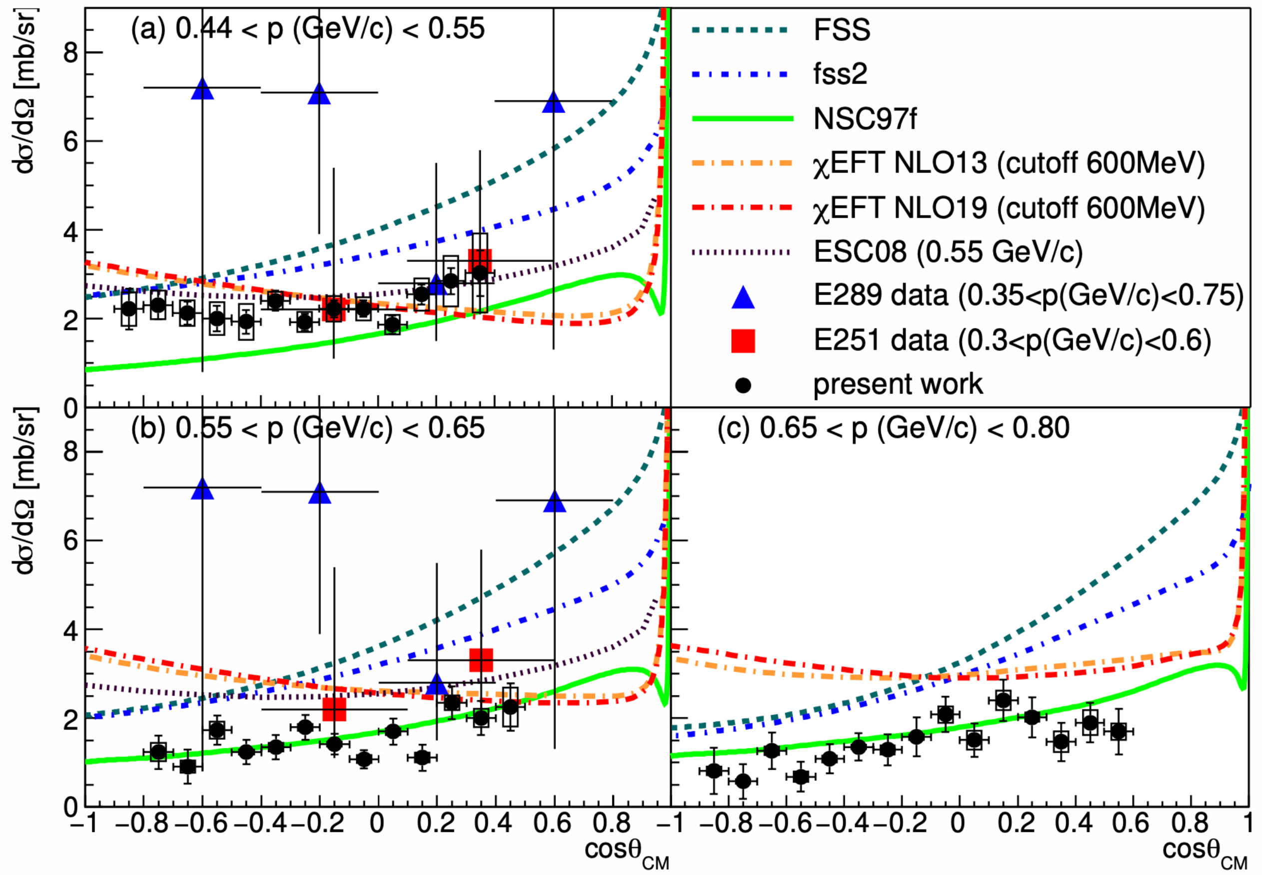
dσ/dΩ of Σ^+p elastic scattering

T. Nanamura et al., arXiv:2203.08393
Talk in June 30th

Σ^+p scatterng

6 quarks can stay in s state in normal case





The more repulsive potential in $^3S_1$

→ The larger dσ/dΩ (like fss2)

E40 data : much smaller than fss2 prediction and E289 results

Comparison with theories

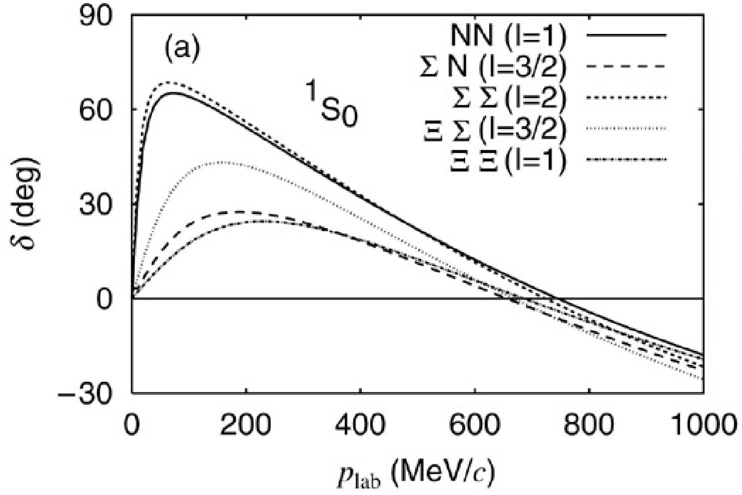
- fss2, FSS (quark model) are too large compared to data
- Chiral EFT's momentum dependence does not match with data
- Nijmegen (ESC) models are rather consistent.

Phase shift analysis

T. Nanamura et al., arXiv:2203.08393
Talk in June 30th

strangeness	BB channel (I)	^{1}Even or ^{3}Odd	^{3}Even or ^{1}Odd
0	NN($I=0$)	–	**(10*)**
	NN($I=1$)	**(27)**	–
	$\Sigma N(I=\frac{3}{2})$	**(27)**	**(10)**

- Constrained from NN (I=1) channel
- Smaller uncertainty

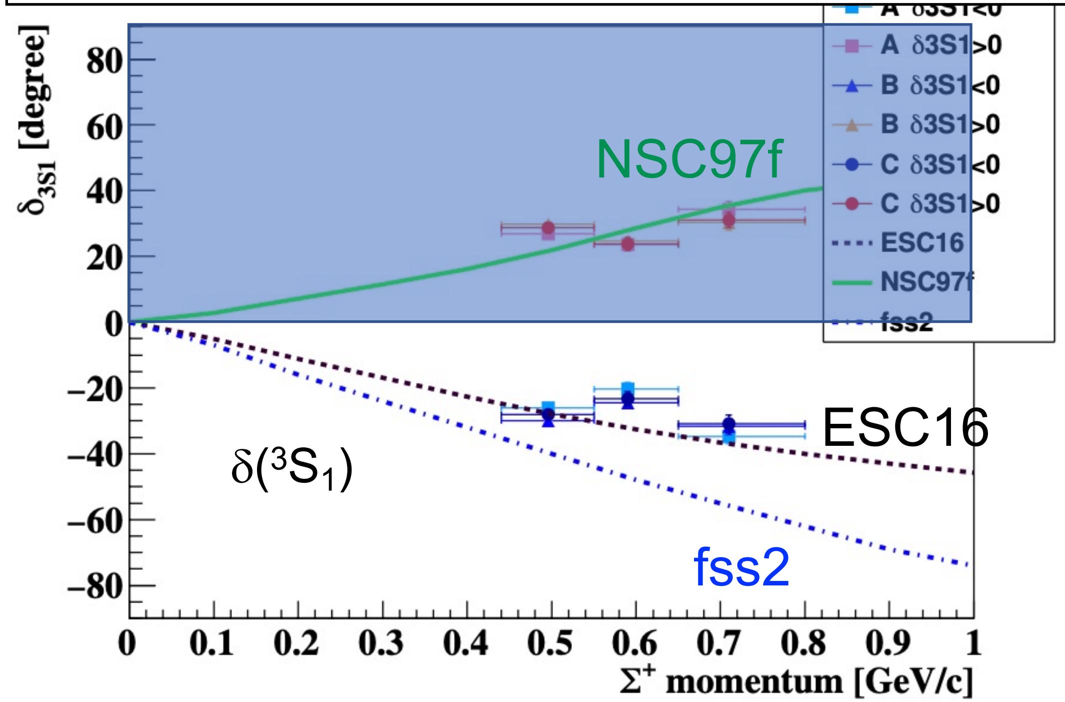


Phase shift analysis for $\Sigma^+ p$ $d\sigma/d\Omega$

- Two parameters : $\delta(^3S_1)$, $\delta(^1P_1)$
- Other phase shifts up to D wave :

fixed on NSC97f, ESC16, pp scat

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

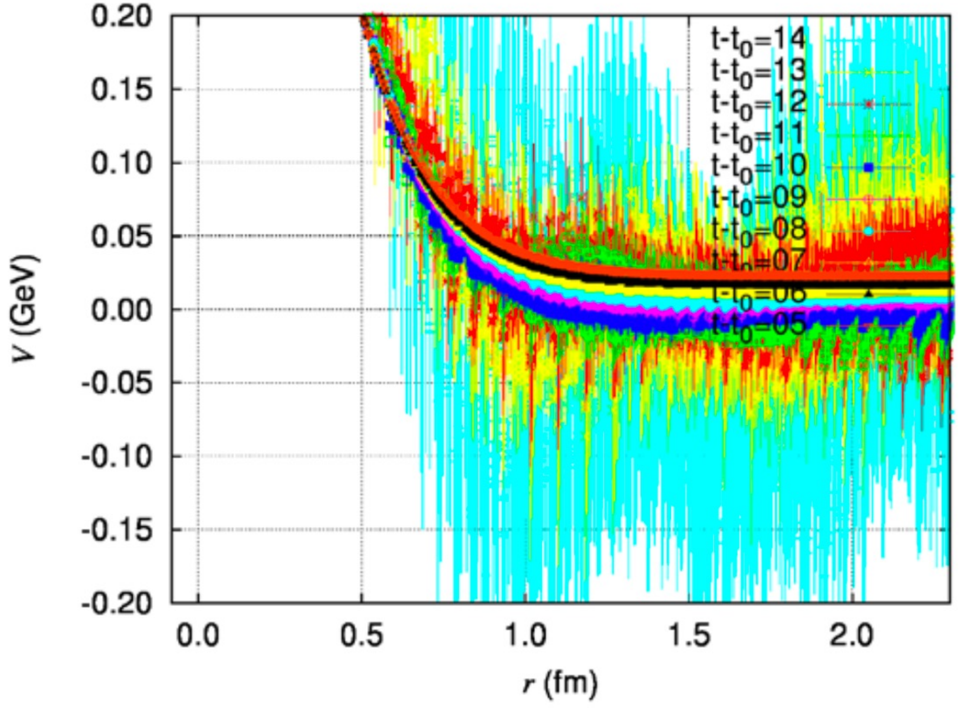


Derived phase shift suggest that **the $^3S_1$ interaction is moderately repulsive**.

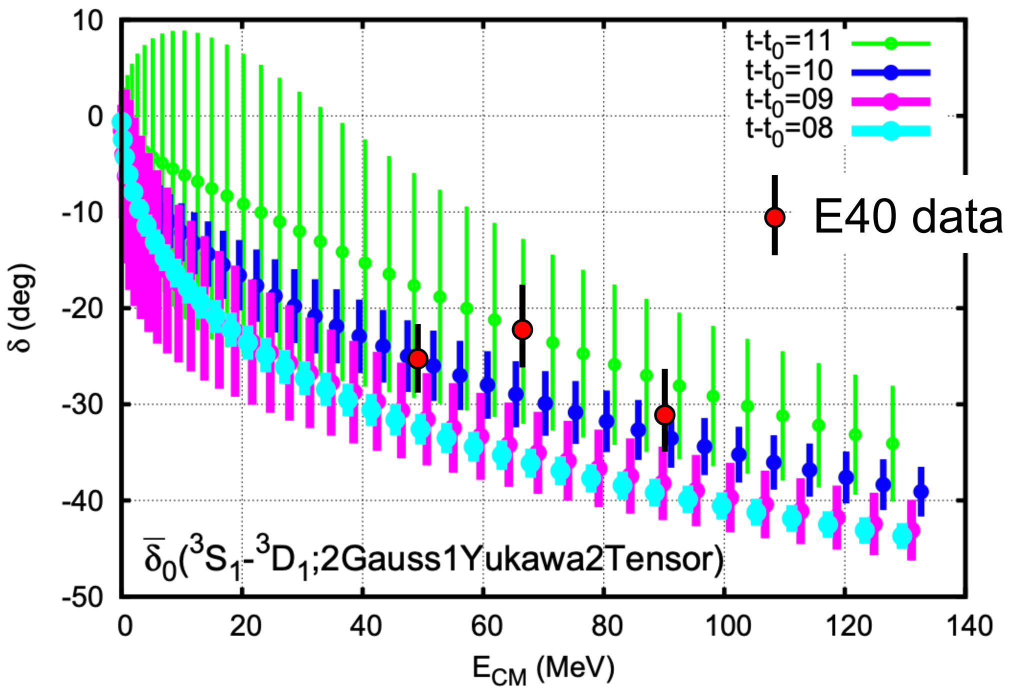
Comparison with HAL QCD

Our phase shift values are consistent with HAL QCD's prediction.

Potential of Σ^+p $^3S_1$ channel



Phase shift of Σ^+p $^3S_1$ channel

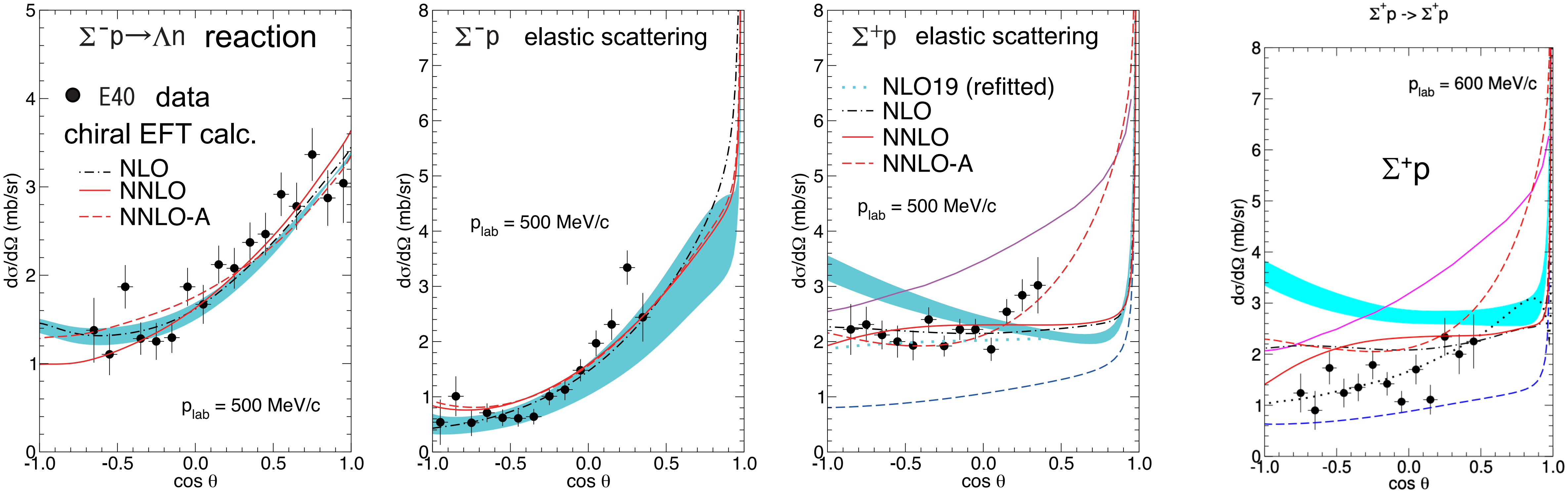


H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

New Σp scattering data and progress of Chiral EFT

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

Difficulty at higher momentum



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

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

T. Nanamura et al., PTEP 2022 093D01

J. Haidenbauer et al., arXiv:2301.00722

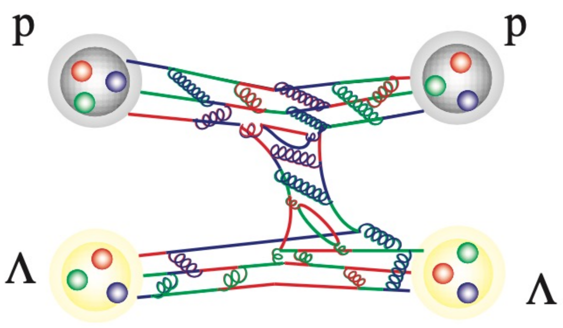
But, the interactions are not uniquely determined yet.
We need more data from additional channels (Λp, …) and additional differential observables (polarizations, …)

→ **Future Λp scattering experiment w/ polarized Λ in the extension project.**

Toward Λp scattering

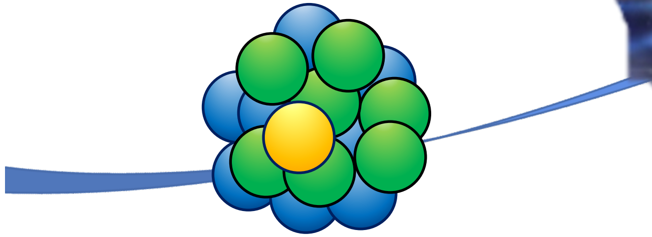
Reliable ΛN two-body interaction :

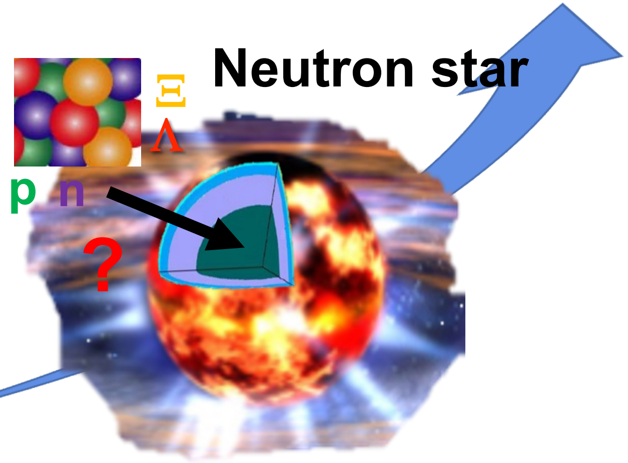
key to deepen Λ hypernuclear physics



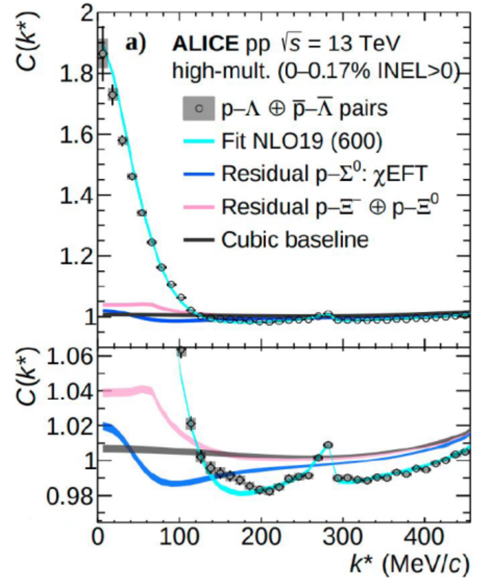
Λ hypernuclei

key to reveal ΛNN int.



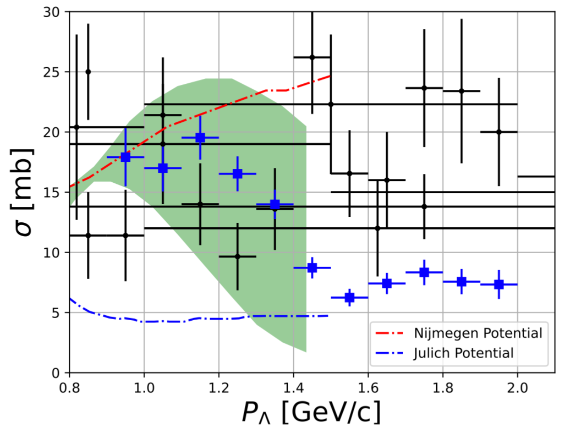


Femtoscopy from HIC



ALICE Collaboration, arXiv:2104.04427

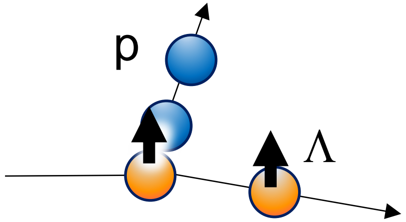
New cross section data from Jlab CLAS



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

New project at J-PARC

Λp scattering w/ polarized Λ

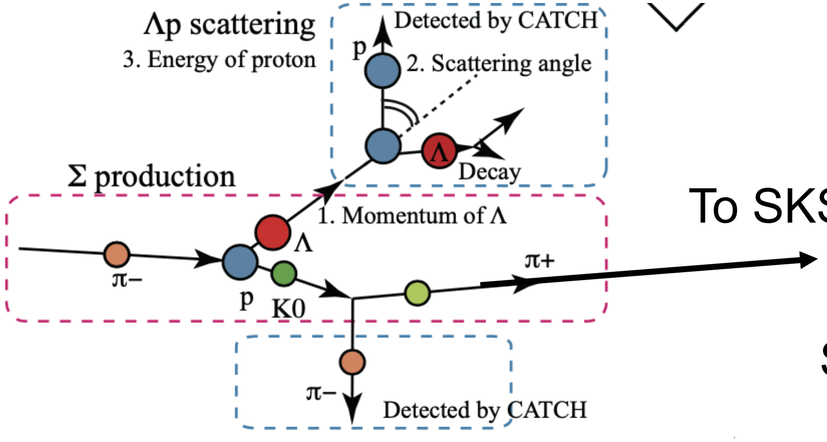


- Feasibility test w/ E40 data
- Expected results in new experiment

Λp scattering experiment with polarized Λ beam

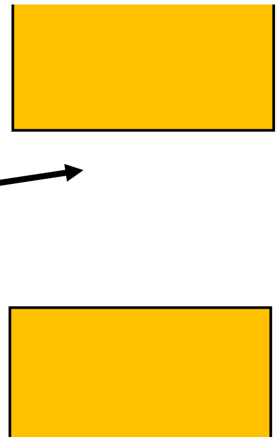
Λ beam identification

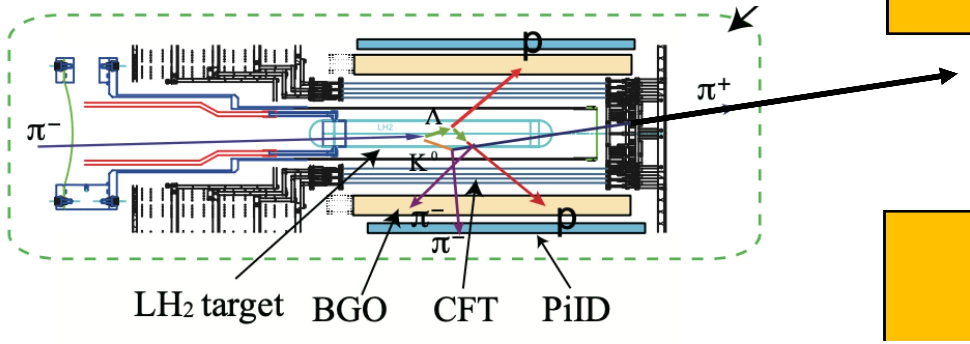
Tagged by $\pi^{-}p \rightarrow K^{0}\Lambda$ reaction at p=1.05 GeV/c



To SKS spectrometer

SKS spectrometer



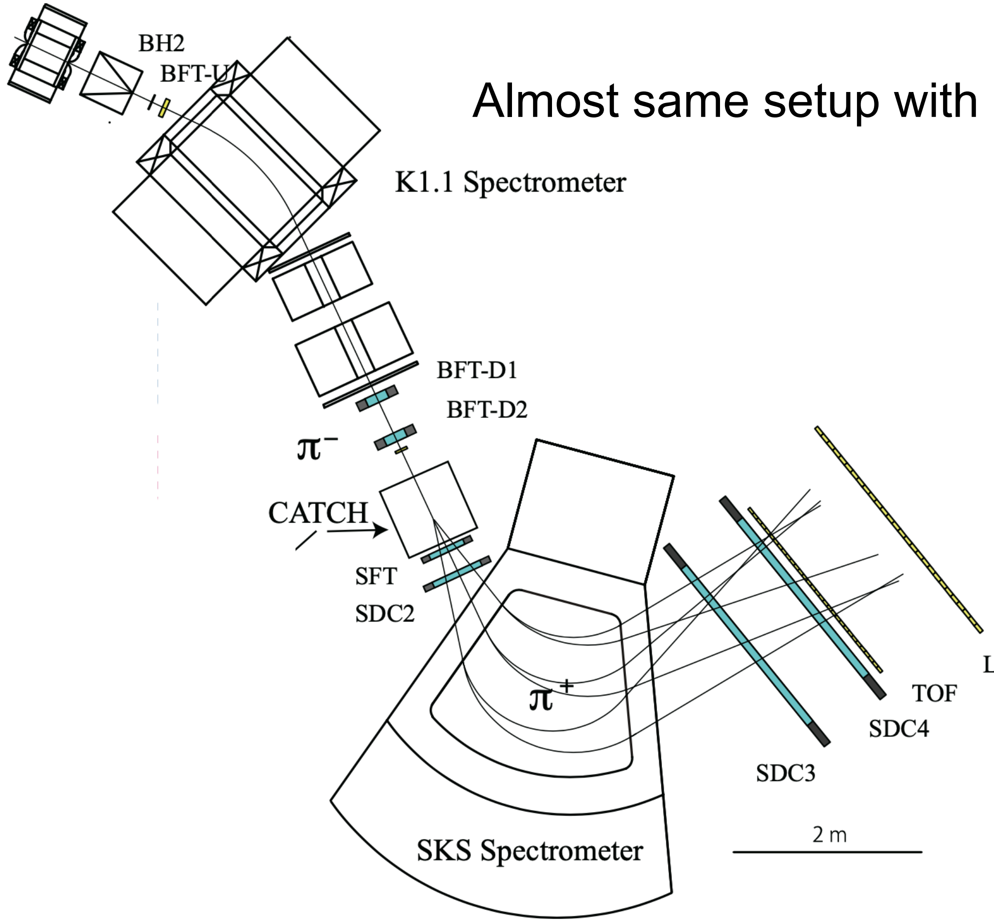


Λp scattering identification

Detected by CATCH

J-PARC P86 (J-PARC EX project)
at K1.1 beam line

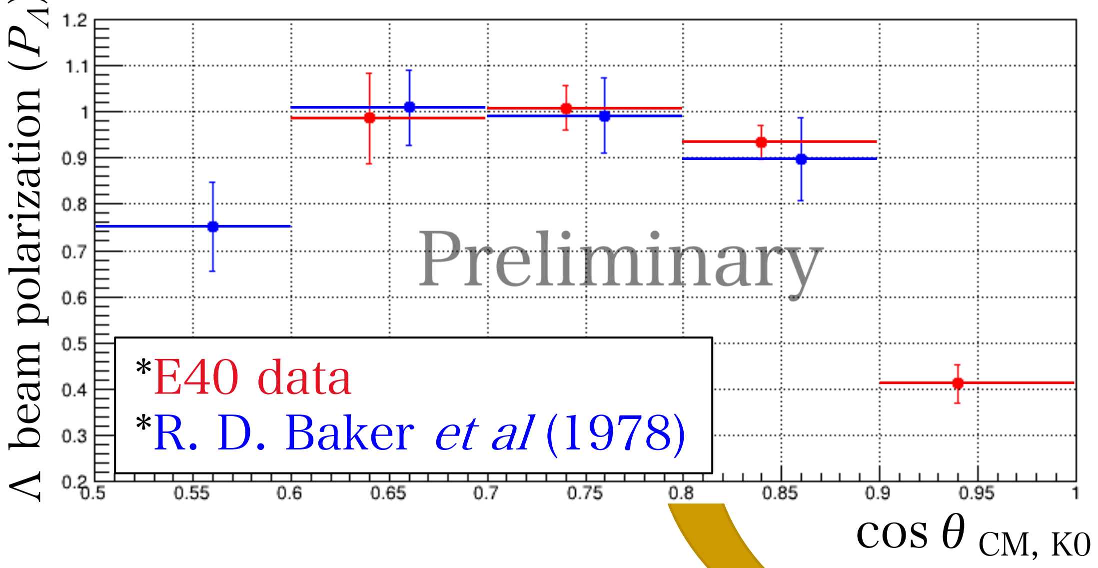
Almost same setup with E40



Λp scattering experiment with polarized Λ beam

High spin polarization of Λ

Λ polarization in the $\pi^- p \to K^0 \Lambda$ reaction

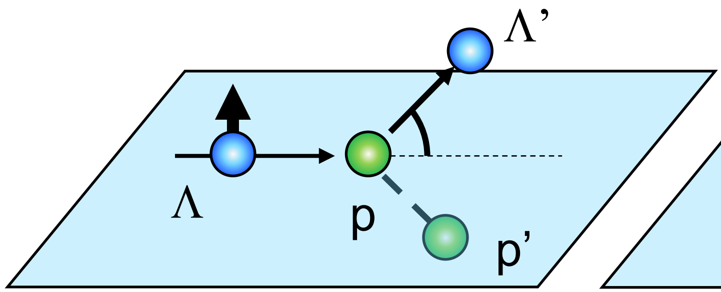


Realize spin observable measurement

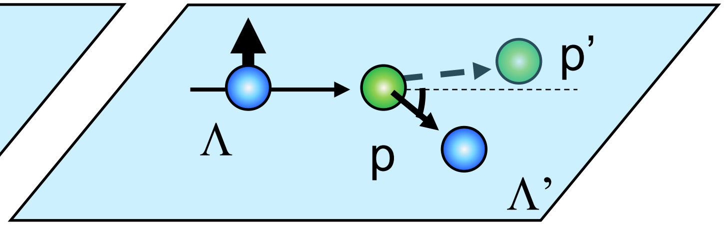
Analyzing power

Left/Right asymmetry of Λp scattering

Left scattered event

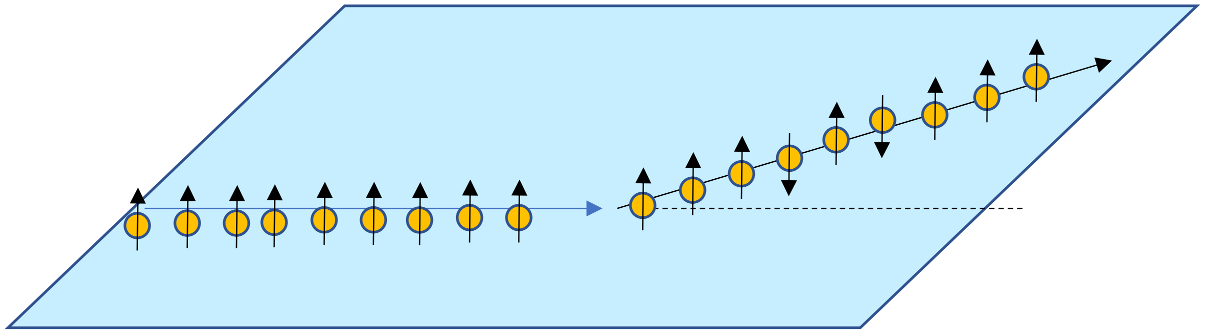


Right scattered event



Depolarization (D_y^y)

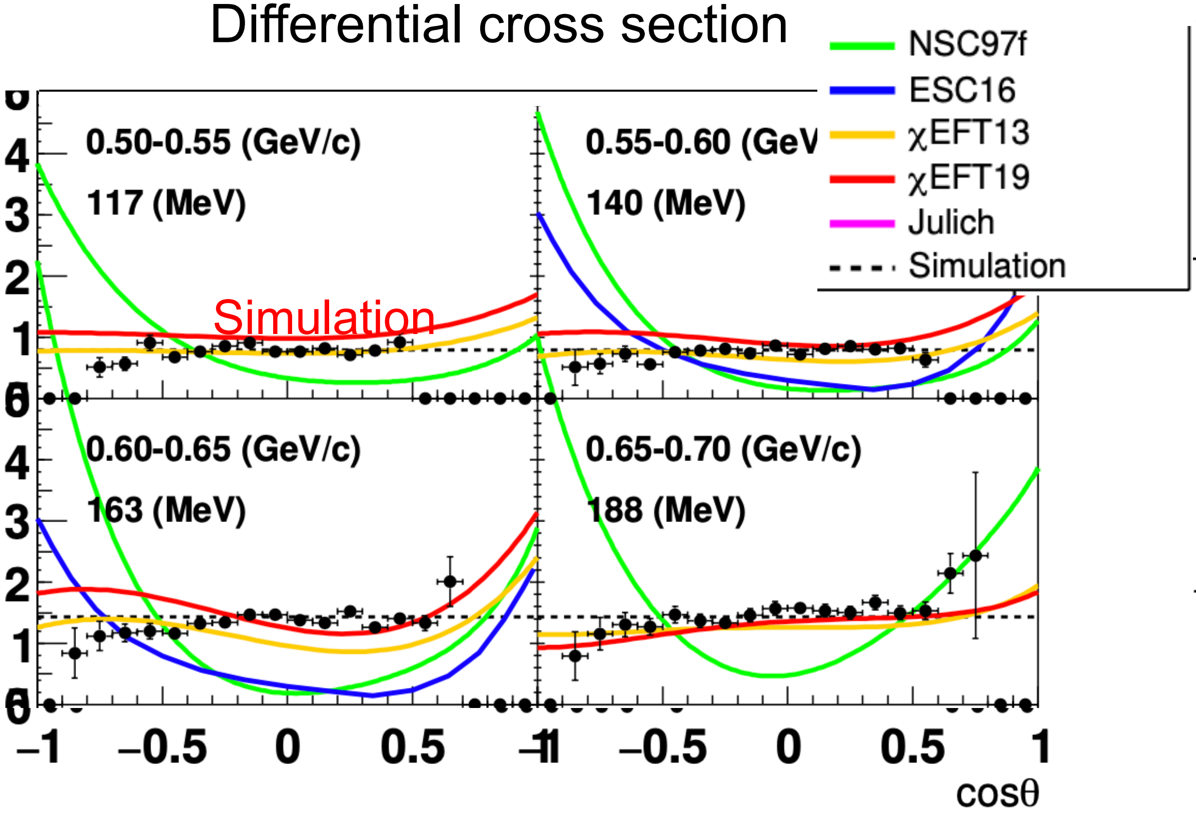
Change the spin polarization after the Λp scattering



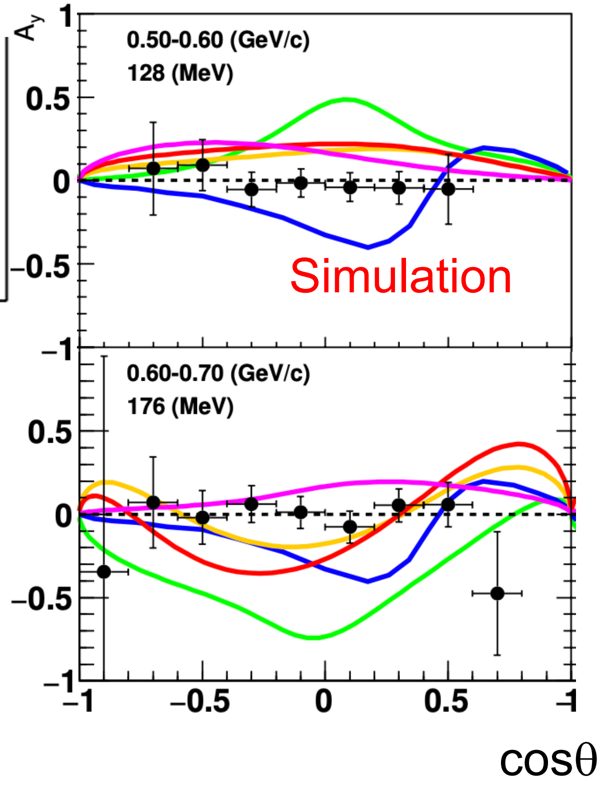
dσ/dΩ and Spin observables in Λp scattering

J-PARC P86 (J-PARC EX project) at K1.1 beam line

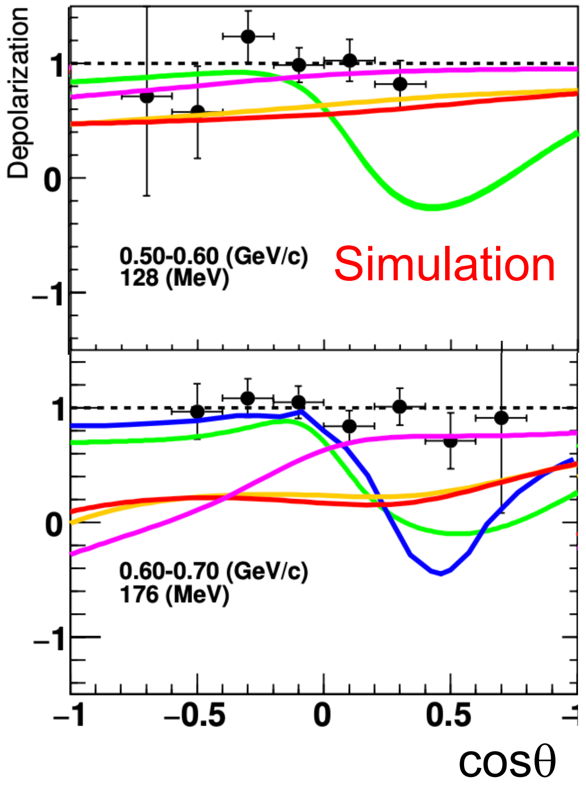
Differential cross section



Analyzing power



Depolarization (D_y^y)



Simulated results w/ 10^8 Λ

No differential observables of Λp scattering SO FAR

--> 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

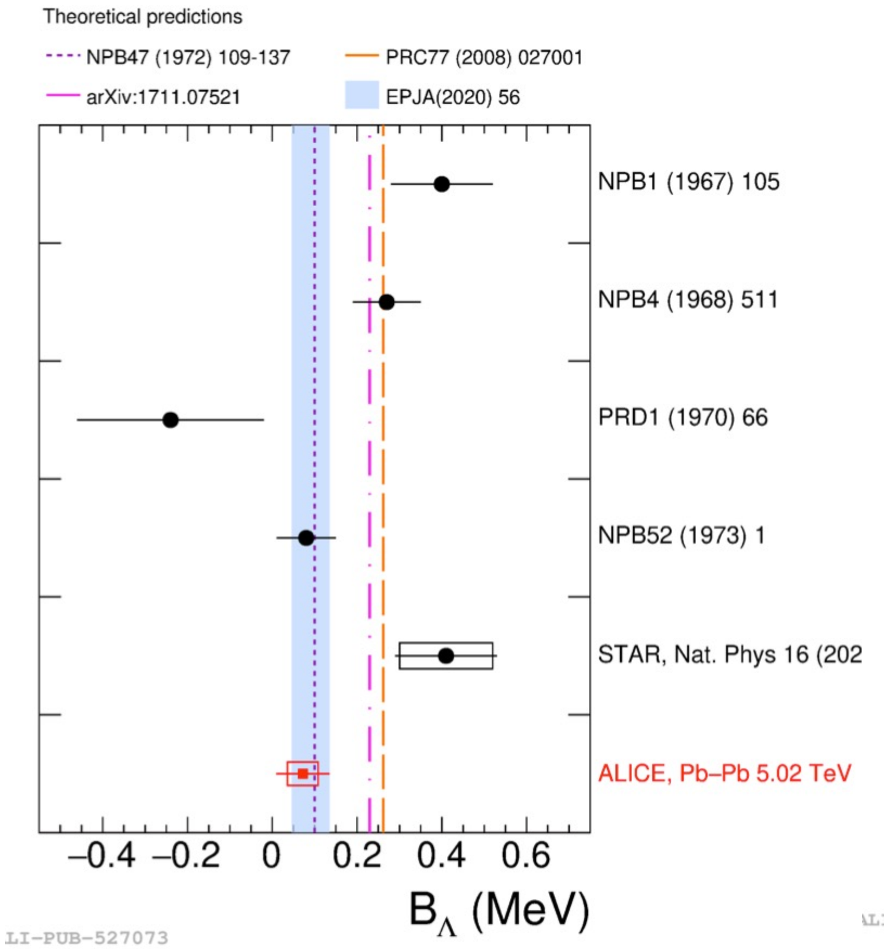
These new scattering data become essential constraint to determine spin-dependent ΛN interaction

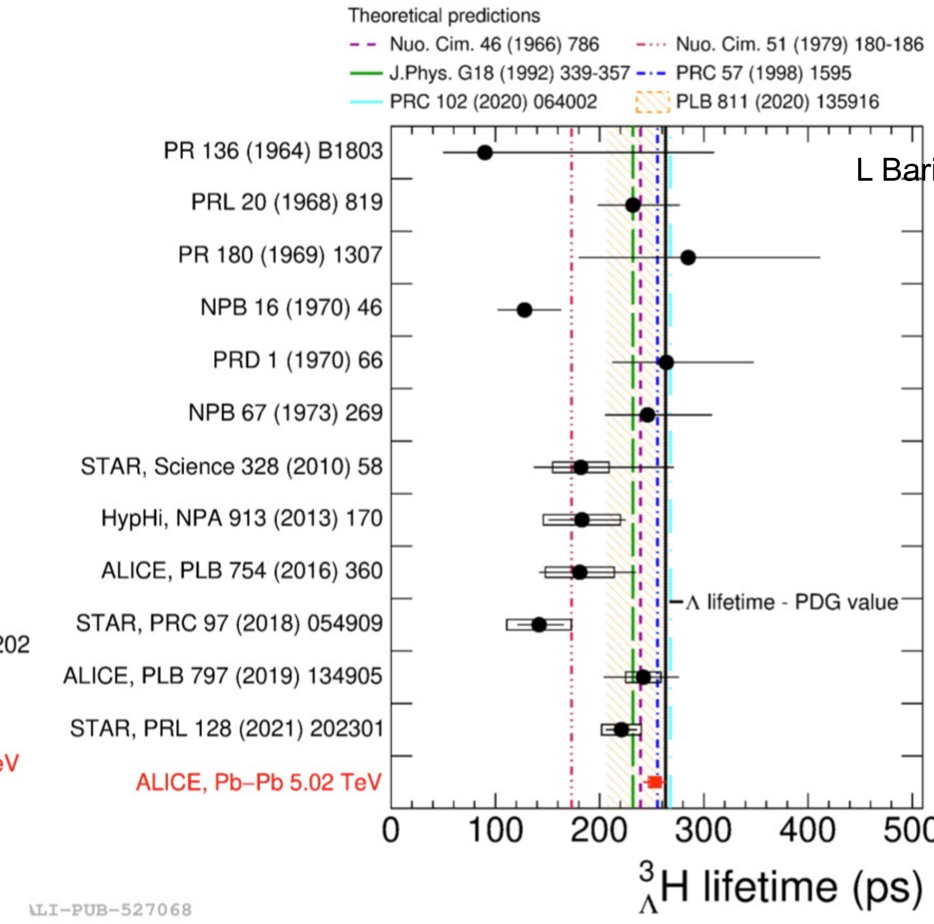
Contents

- Recent progress of hyperon-nucleon scattering experiment
  - Σp scattering experiment at J-PARC
- Current programs at J-PARC
  - Few-body strangeness systems
  - Exotic systems with strangeness
  - Recent S=-2 studies
- Physics programs at extended hadron hall
- Summary

Hypertriton puzzle

Heavy ion experimental results settle down ?





L Barioglio talk at EMMI Workshop 2023

HADES : Ag+Ag $\sqrt{s}$=2.55 GeV
τ=256±22±36 ps
(M. Lorentz talk at EMMI Workshop 2023)

WASA-FRS : ^{6}Li+^{12}C 2 GeV/A
τ, B_Λ : under analysis
→ Ekawa's talk

B_Λ measurement

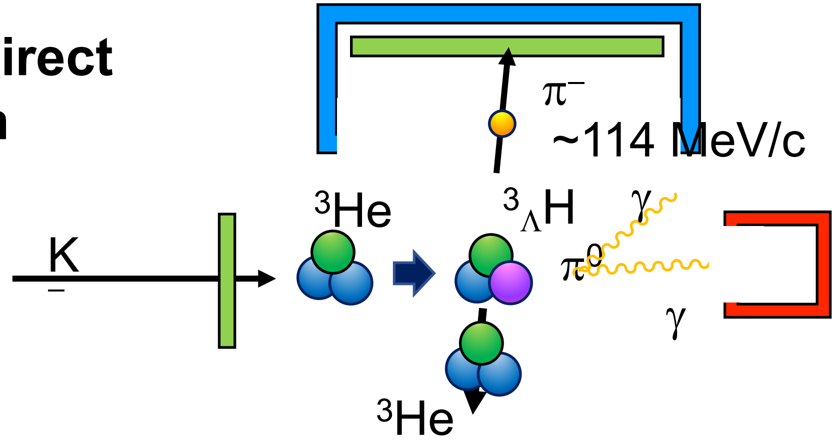
- MAMI : decay pion spectroscopy
- JLab : 3He (e, e'K$^+$) missing mass spectroscopy
- J-PARC E07 : hyperfragment at K- interaction on emulsion
  → Nakagawa's talk

Lifetime measurement by direct time measurement

- ELPH : ^{3}He(γ, K$^+$) reaction
- J-PARC E73 : ^{3}He (K$^-$, π^0) reaction

E73 is ready for data taking of $^{3}_{\Lambda}$H run

Lifetime measurement by direct time measurement between production and decay



$^3{}_\Lambda$H production was confirmed from the decay π^-'s momentum

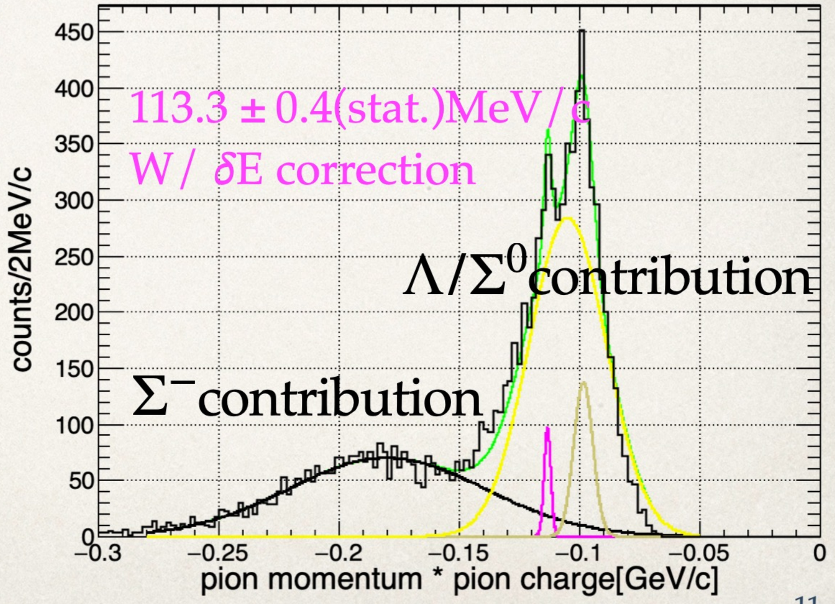
273kW*Day executed in May, 2021

$$K^- + {}^3He \rightarrow {}^3_\Lambda H + \pi^0$$

slows down and decays at rest

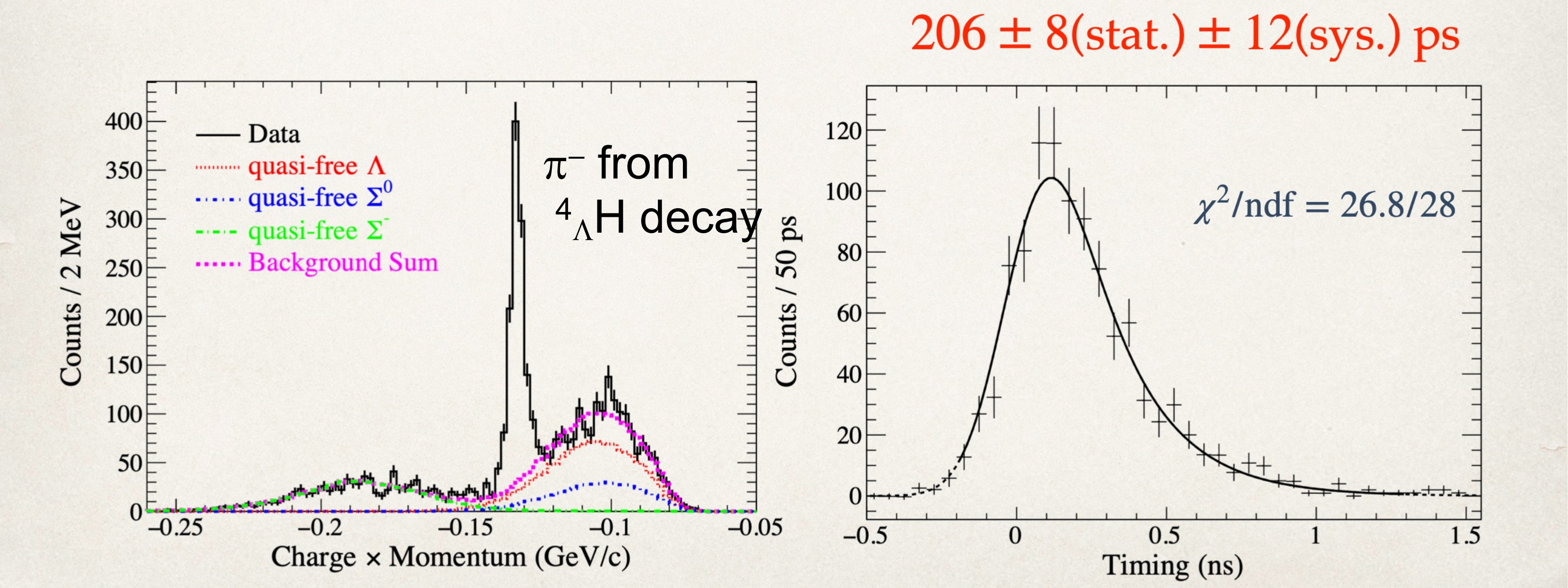
$${}^3_\Lambda H \rightarrow {}^3He + \pi^-$$

$${}^3_\Lambda H \rightarrow {}^2H + p + \pi^-$$



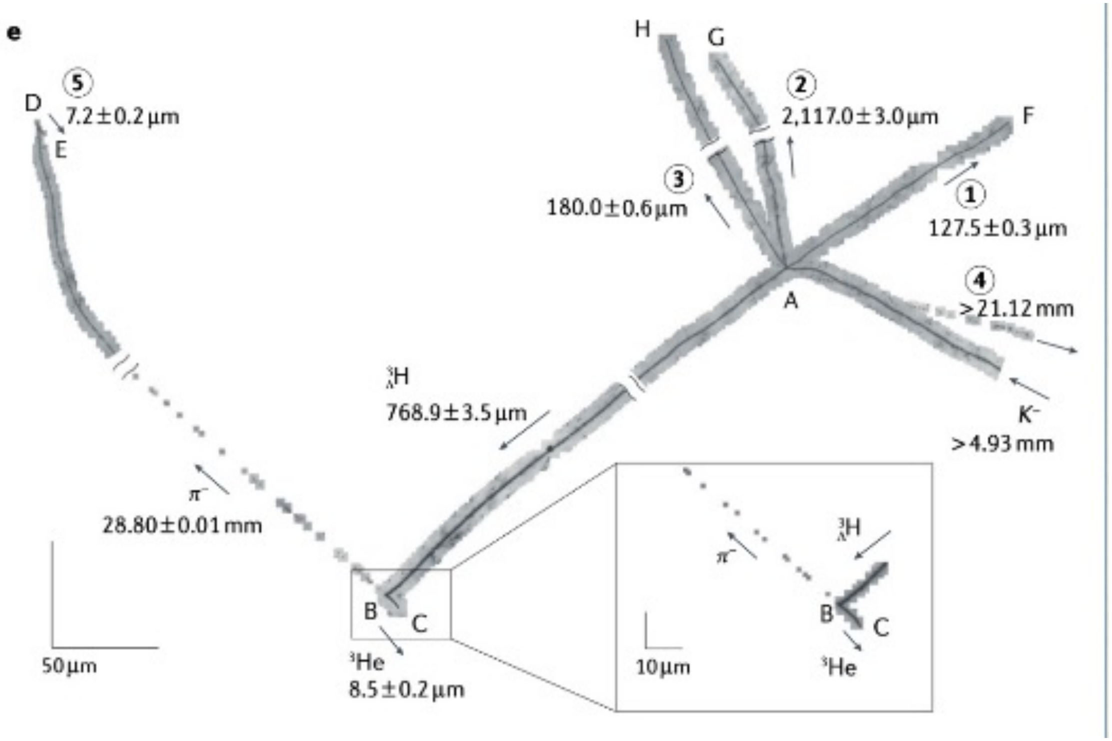
11

Pilot run for $^4{}_\Lambda$H lifetime measurement was successful



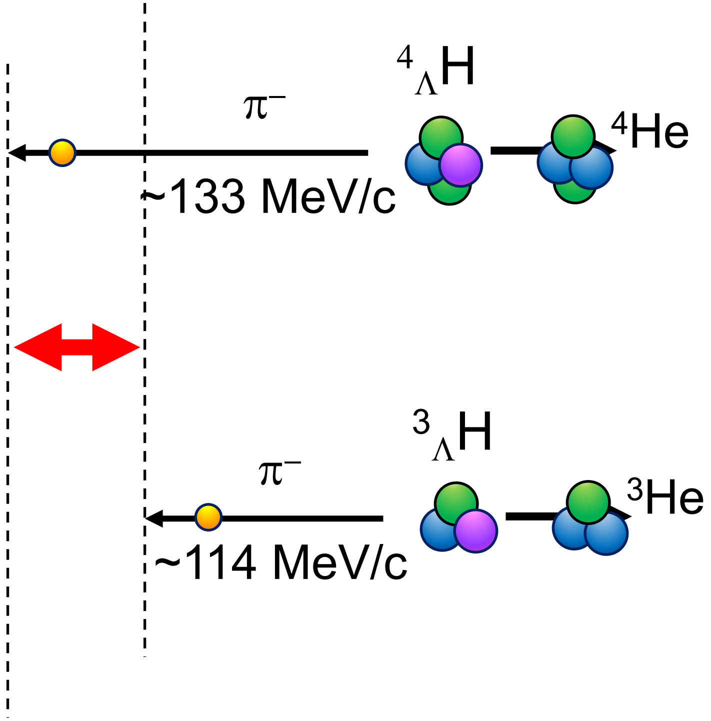
Hyperfragment at K- interaction on emulsion

Succeeded in finding hypertriton w/ Machine Learning in the E07 nuclear emulsion (RIKEN, Gifu Univ. + α)



T. R. Saito et al., Nature Review Physics 3, 803 (2021)

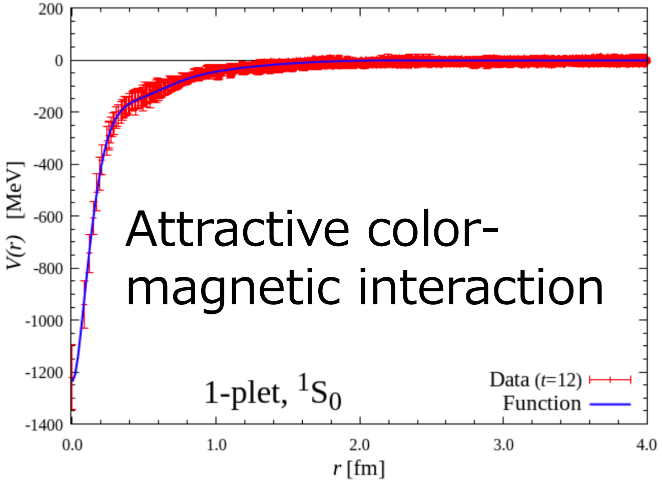
$^{4}{}_{\Lambda}$H and $^{3}{}_{\Lambda}$H can be separated clearly from the π^{-}'s range information



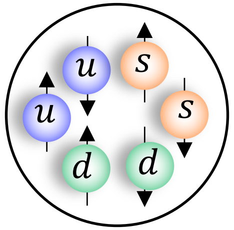
B_{Λ} measurements of $^{4}{}_{\Lambda}$H and $^{3}{}_{\Lambda}$H are ongoing
→ Nakagawa's talk in detail

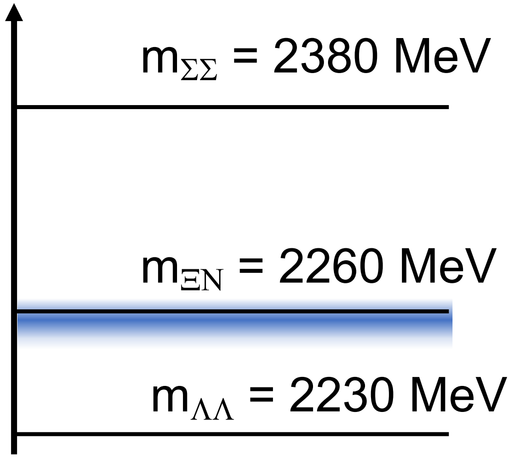
H dibaryon (SU(3) flavor singlet hexaquark state)

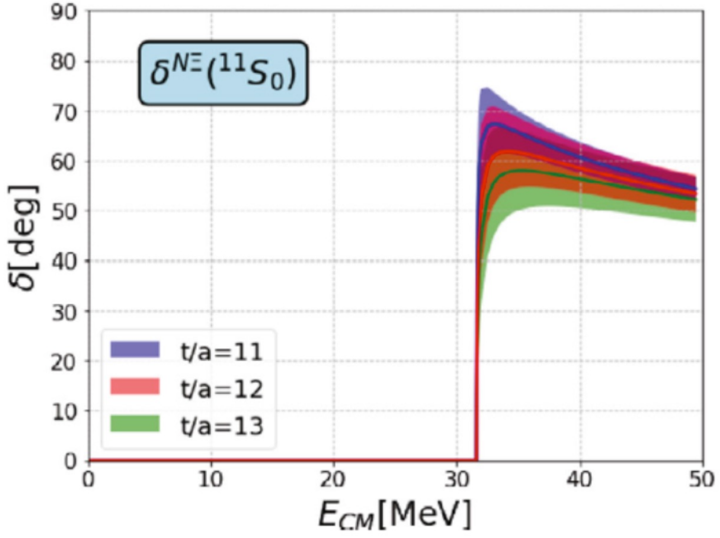
Theoretical progress on S=-2 system



H-dibaryon



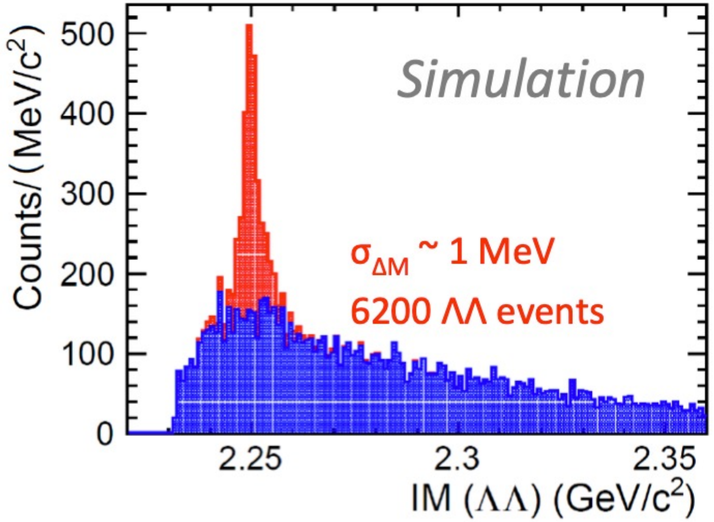




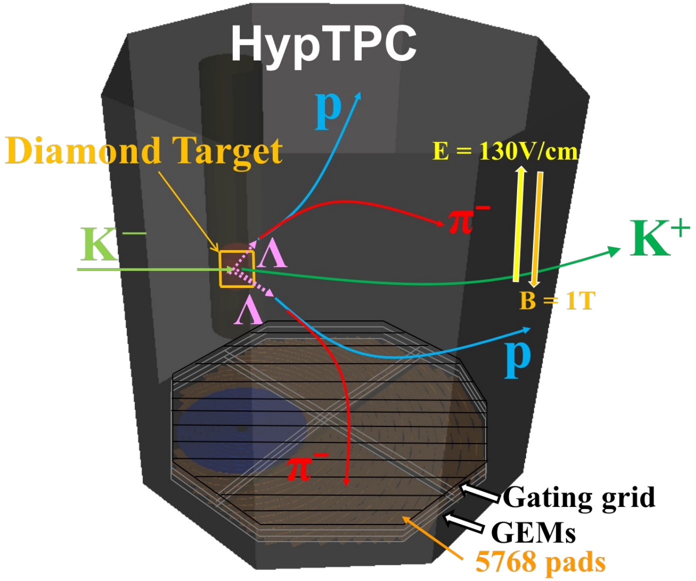
Definitive experimental confirmation is awaited

Search for H-dibaryon via $^{12}C(K^-, K^+)$ reaction : E42

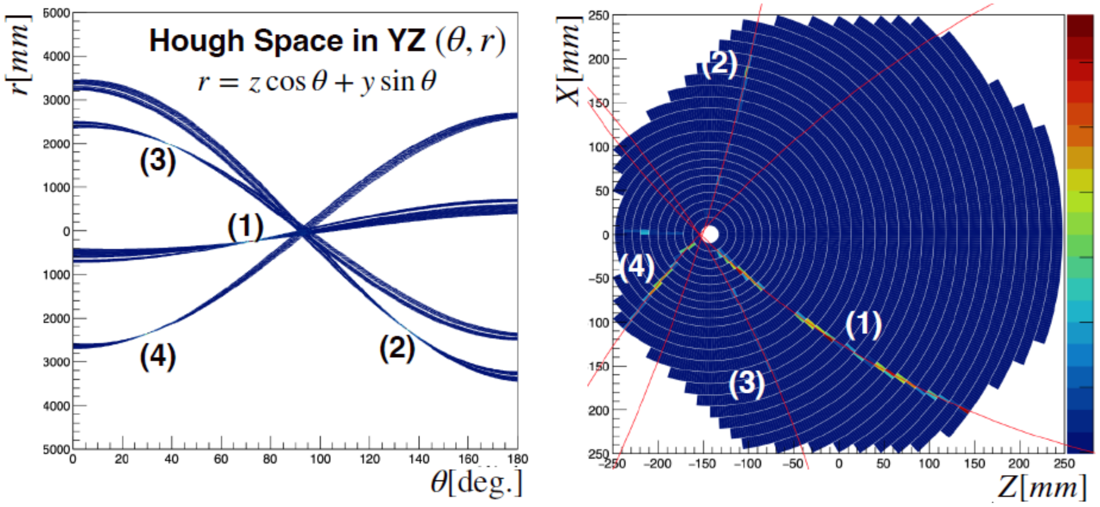
- Invariant mass measurement of ΛΛ and Ξ^-p system with HypTPC
- High resolution and high statistics measurement is realized



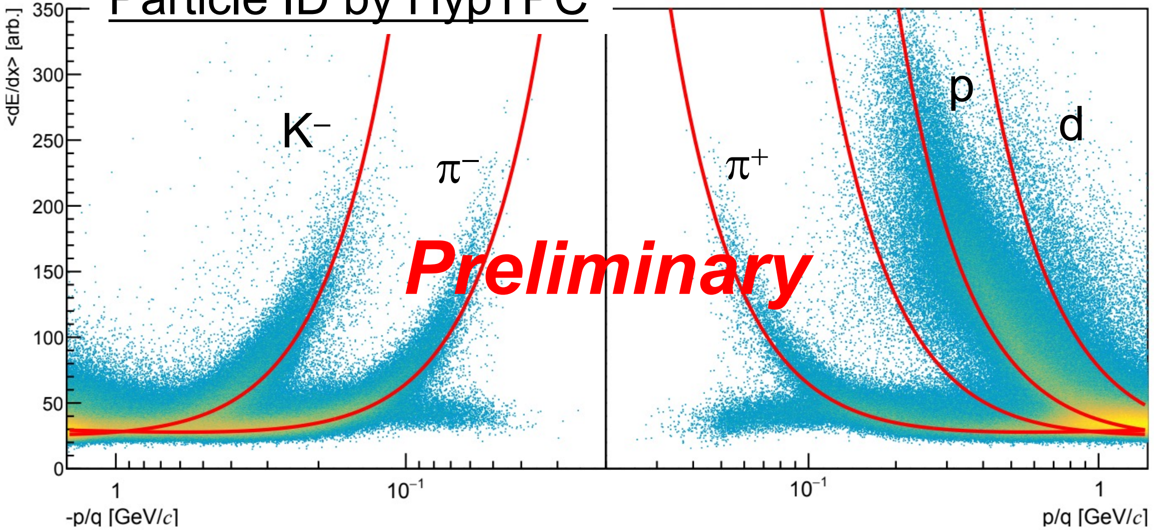
Progress on analysis of HypTPC



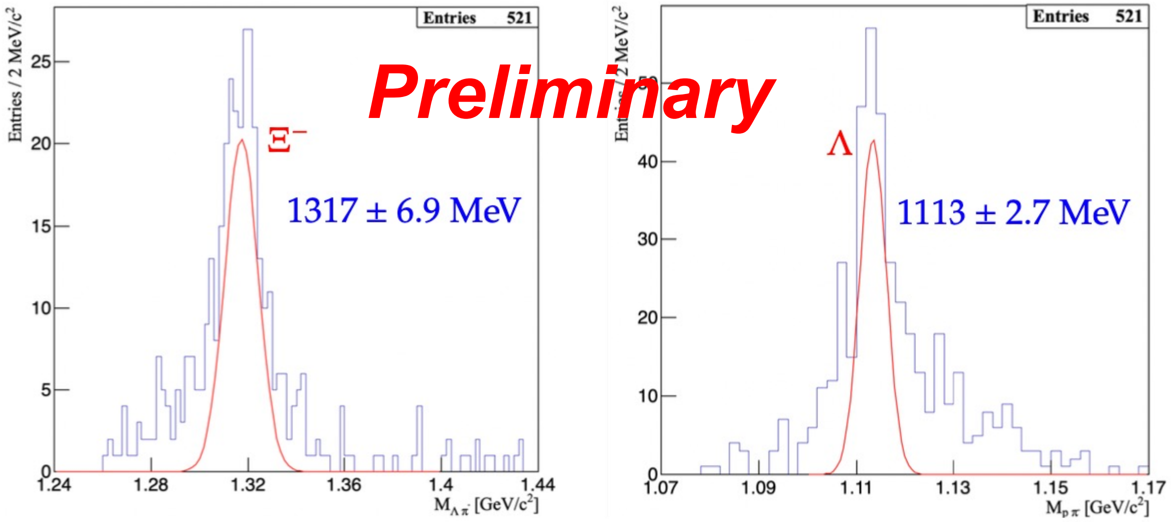
Development of track finding algorithm using Hough transformation



Particle ID by HypTPC



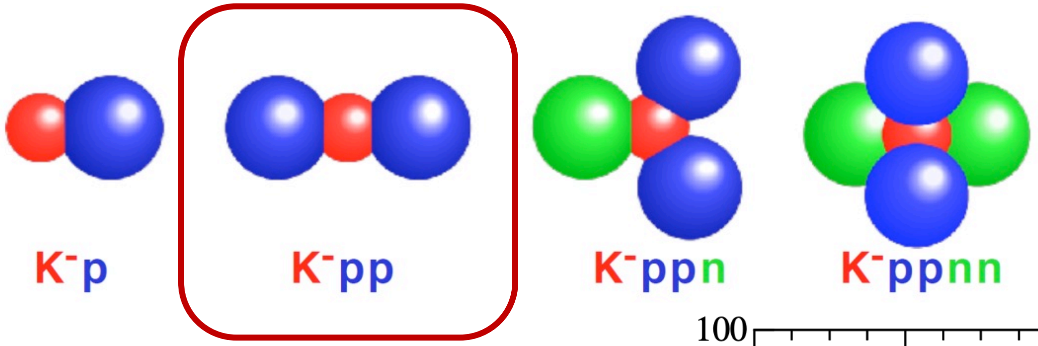
Invariant mass reconstruction by HypTPC



Observation of an exotic hadron bound system including K⁻ meson

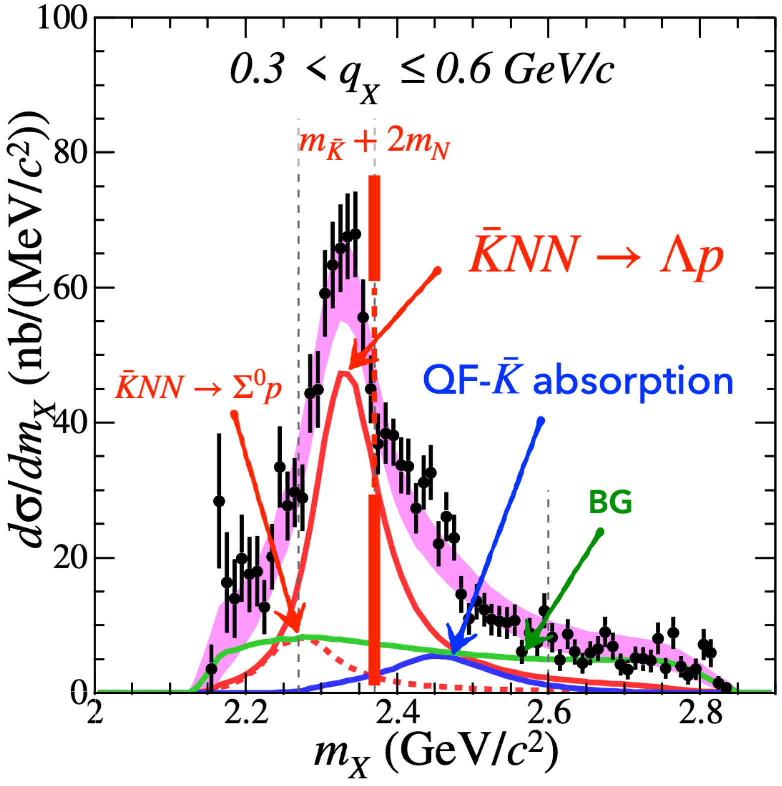
Strong attractive interaction between Kbar and N → Exotic hadronic system with Kbar meson

New development of detailed systematic investigation of novel nuclei containing K-mesons



- Mass dependence of Kbar-nucleon system from K-p to K-ppnn
- Aiming to clarify the origin of QCD mass and the mysteries of high-density nuclear matter by measuring changes in the properties of K-mesons in nuclear matter.

E15 at K1.8BR
Clear observation of K⁻pp system



The peak position is below the $M_{\bar{K}NN}$.
→ *We interpreted it as $\bar{K}NN$ signal.*

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

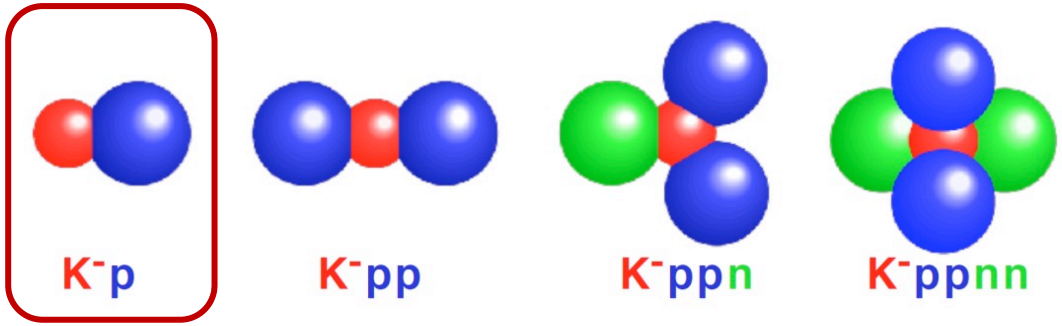
$$\Gamma = 100 \pm 7\ (\text{stat.})\ ^{+19}_{-9}\ (\text{syst.})\ \text{MeV}$$

* obtained as peak position & width of simple Breit-Wigner

Observation of an exotic hadron bound system including K^- meson

Strong attractive interaction between Kbar and N → Exotic hadronic system with Kbar meson

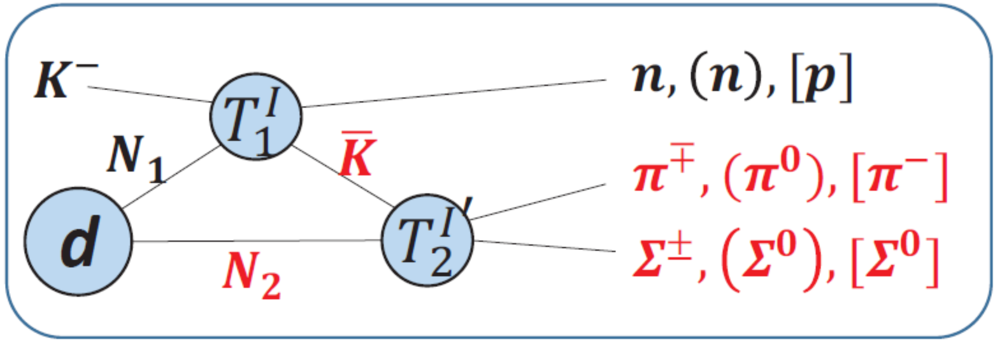
New development of detailed systematic investigation of novel nuclei containing K-mesons



- Mass dependence of Kbar-nucleon system from K-p to K-ppnn
- Aiming to clarify the origin of QCD mass and the mysteries of high-density nuclear matter by measuring changes in the properties of K-mesons in nuclear matter.

J-PARC E31 @ K1.8BR

- First derivation of S-wave KbarN scattering amplitude in I=0 channel from 3 πΣ decay modes.

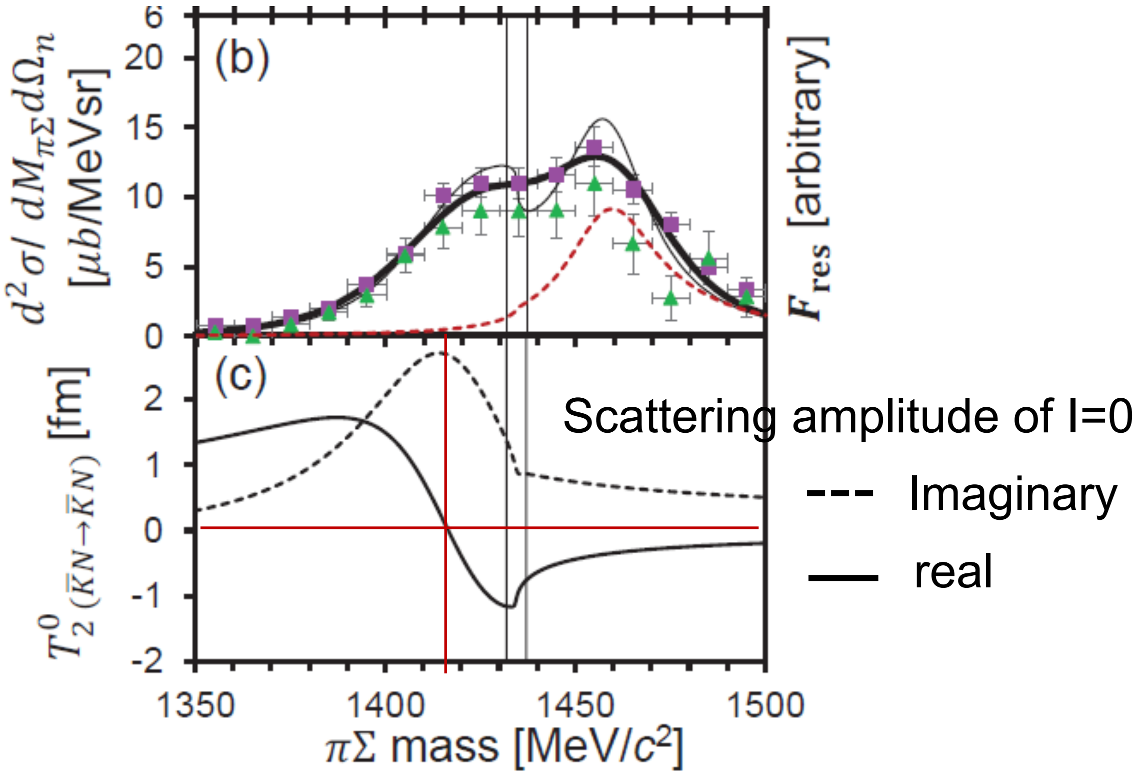


Resonance pole was found at

$$1417.7^{+6.0}_{-7.4}\ {}^{+1.1}_{-1.0} + \left[-26.1^{+6.0}_{-7.9}\ {}^{+1.7}_{-2.0}\right] i\ \mathrm{MeV}/c^2$$

S. Aikawa et al., Phys. Lett. B 837 (2023) 137637

K^-p and K^0n mass thresholds



Observation of an exotic hadron bound system including K⁻ meson

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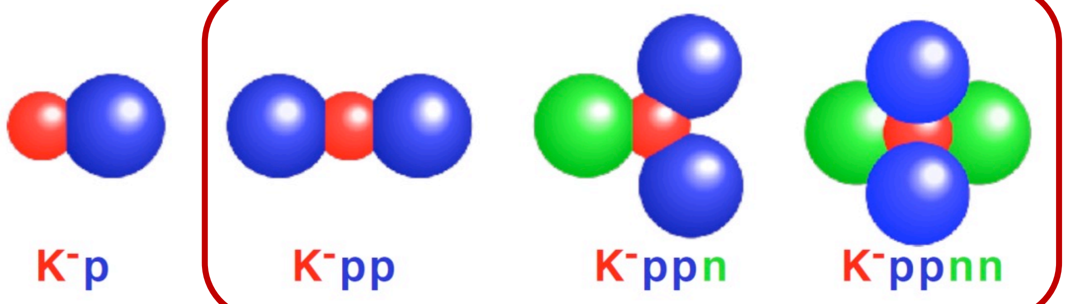
New development of detailed systematic investigation of novel nuclei containing K-mesons

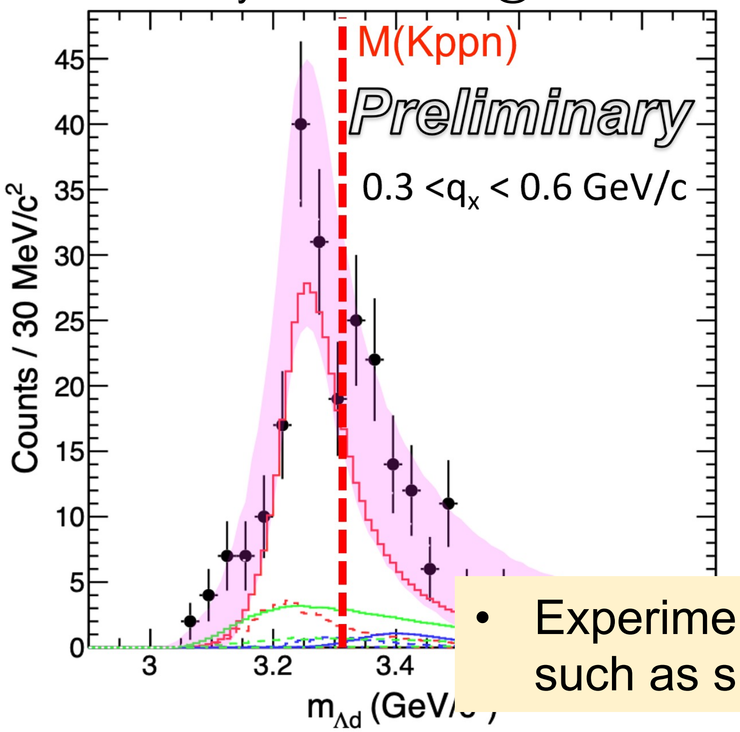


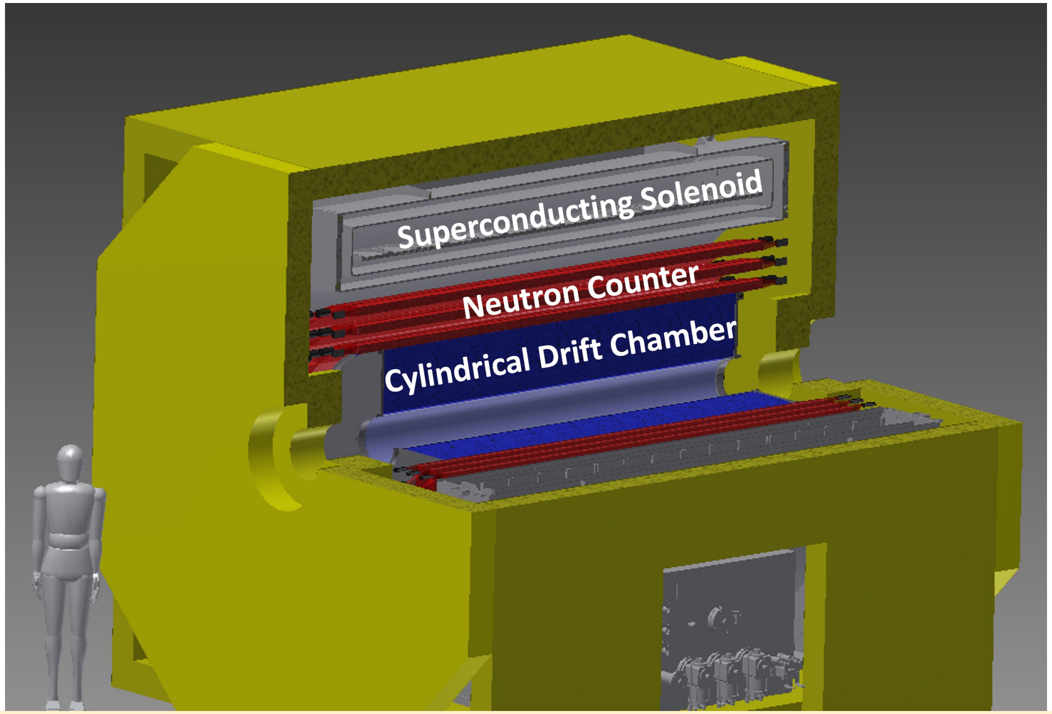
- Mass dependence of Kbar-nucleon system from K-p to K-ppnn
- Aiming to clarify the origin of QCD mass and the mysteries of high-density nuclear matter by measuring changes in the properties of K-mesons in nuclear matter.

J-PARC T77 @ K1.8BR

Invariant mass of Λd system shows enhancement below the Kppn threshold.

by T. Hashimoto @ HYP2022





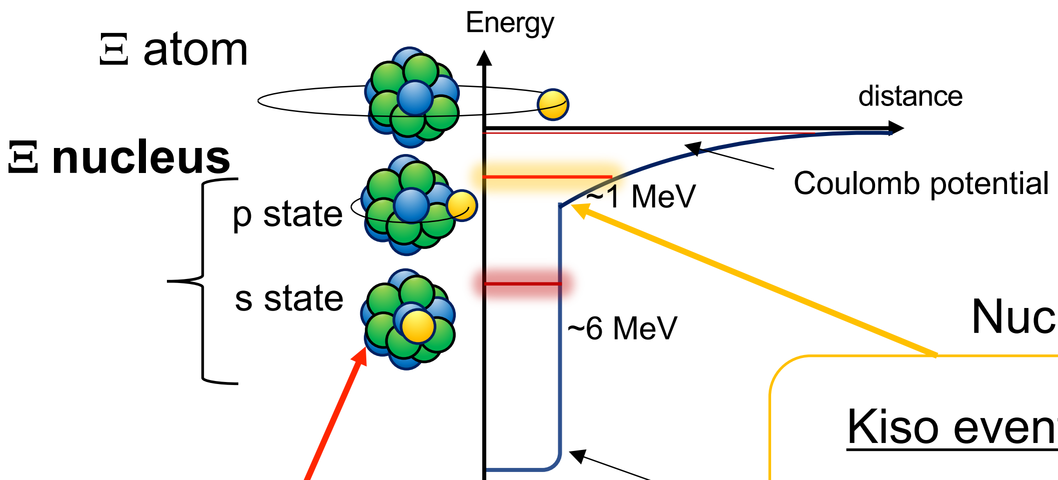
- Experimental measurement of internal quantum numbers such as spin parity to establish a novel atomic nucleus

Ξ hypernuclei

Confirm the attractive Ξ-nuclear potential from observation of Ξ hypernuclei in emulsion

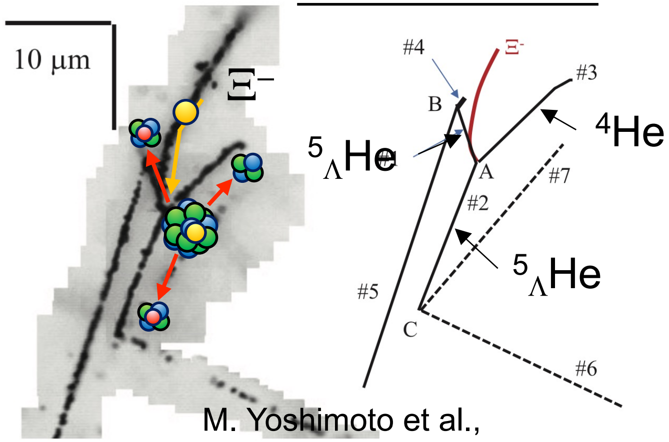
Measure the mass of Ξ nuclei produced by absorption of Ξ⁻ into ^{14}N nucleus in emulsion.

Two different energy levels
- BE ~1 MeV (p state)
- BE ~6 MeV (s state)



Nuclear s state

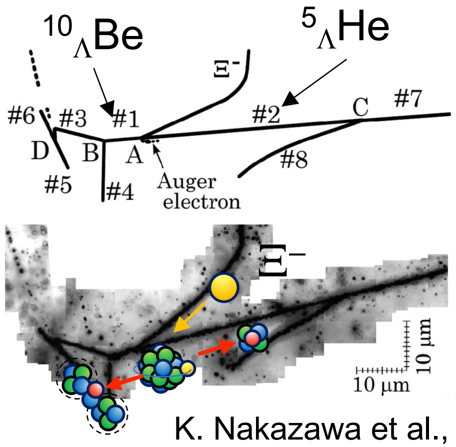
Irrawadi event



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

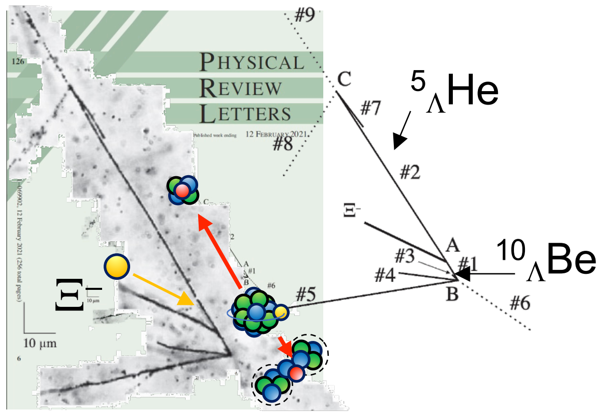
Nuclear p state

Kiso event



K. Nakazawa et al., PTEP. 2015, 033D02

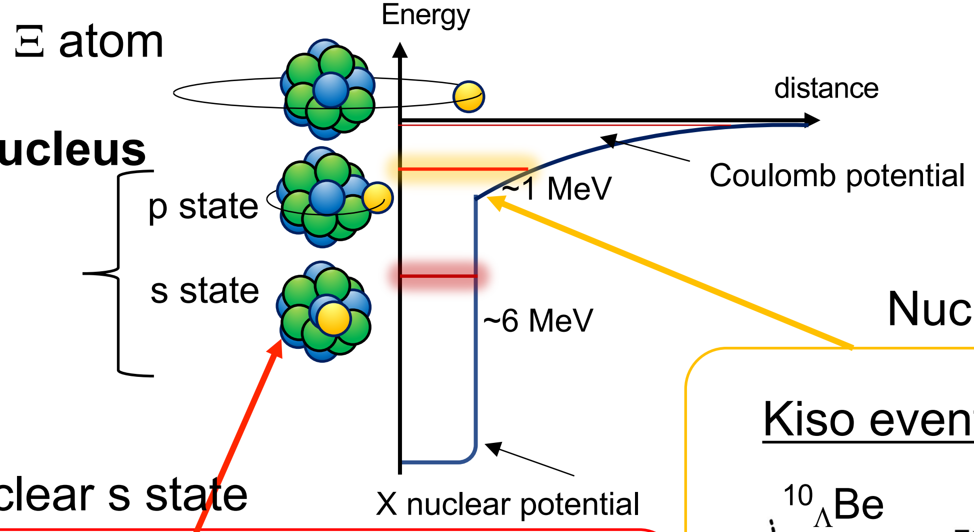
Ibuki event



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

Ξ hypernuclei

Confirm the attractive Ξ-nuclear potential from observation of Ξ hypernuclei in emulsion



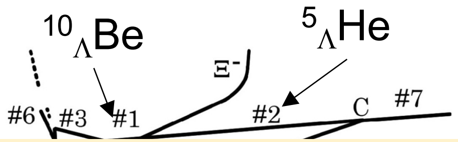
Measure the mass of Ξ nuclei produced by absorption of Ξ⁻ into ^{14}N nucleus in emulsion.

Two different energy levels

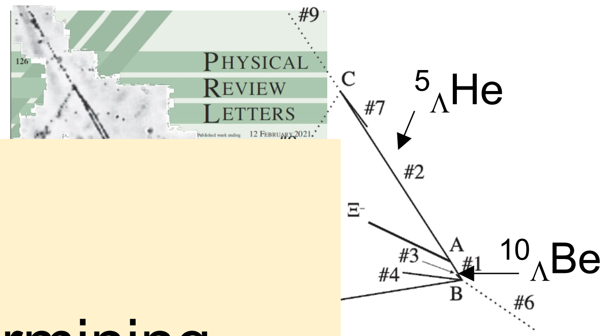
- BE ~1 MeV (p state)
- BE ~6 MeV (s state)

Nuclear p state

Kiso event



Ibuki event



...I. Hayakawa et al., ..., 126, 062501 (2021)

Nuclear s state

Irrawadi event

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

Observation of deeply bounded Ξ state is big surprise

Ξ atomic X-ray measurement plays essential role in determining

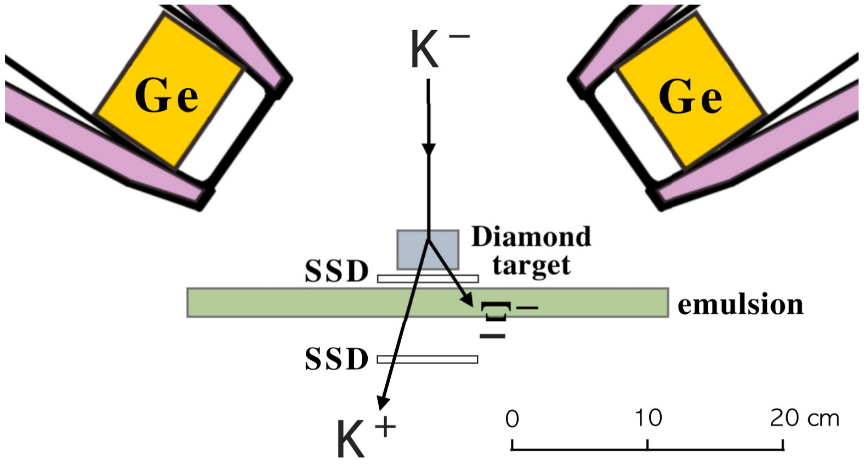
- the probability of arriving at each nuclear state and
- ΞA potential around nuclear surface.

First attempt to measure Ξ Atomic X-ray in E07

Ξ-Ag/Br atomic X rays in emulsion

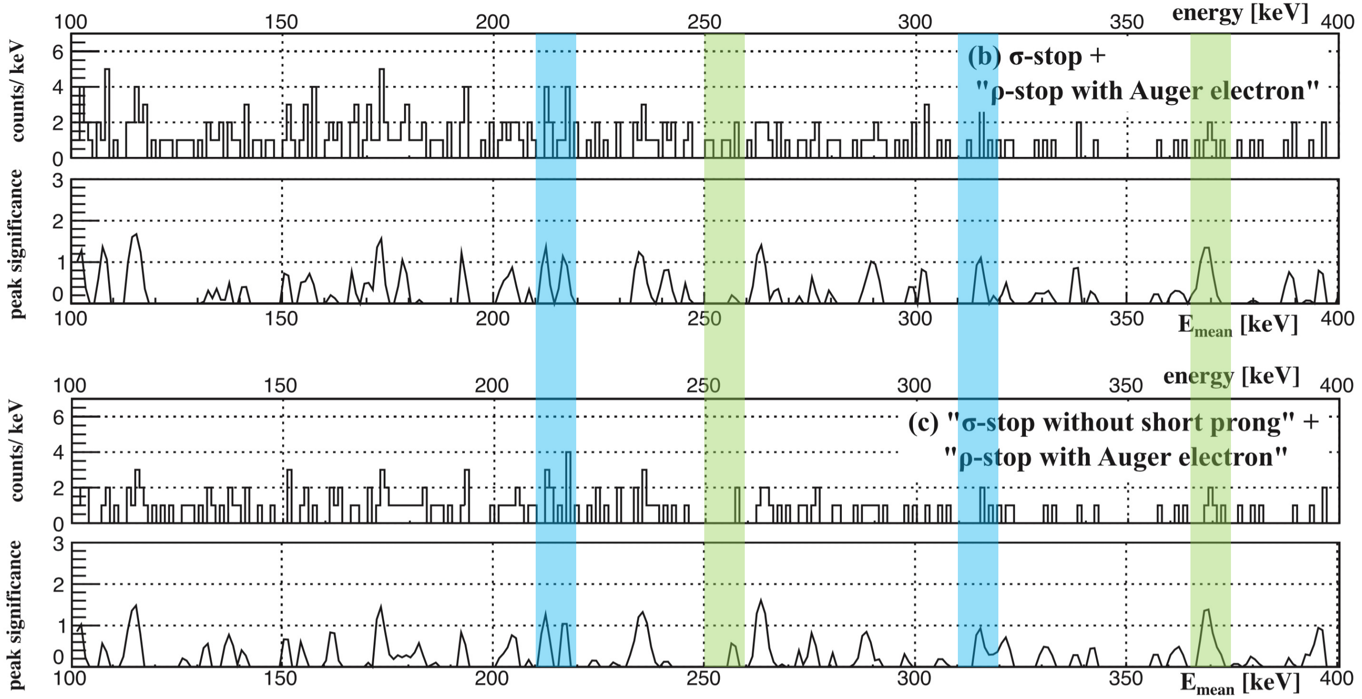
Triple-coincidence hybrid method

1. Ξ production by spectrometers
2. Ξ stop ID by emulsion
3. X-ray measurement with Ge detectors

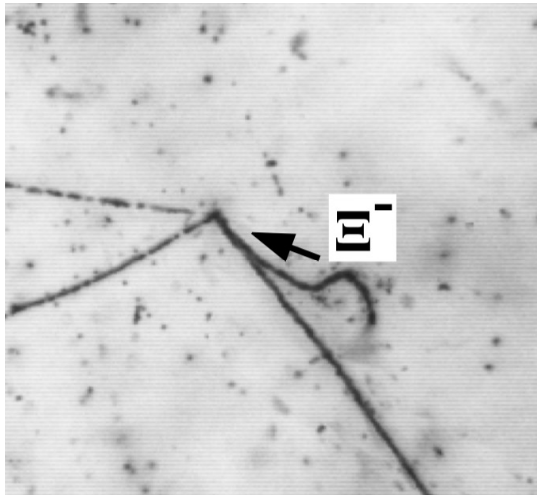


X-ray peaks were not observed due to lower emulsion and Ge detector efficiencies than expected

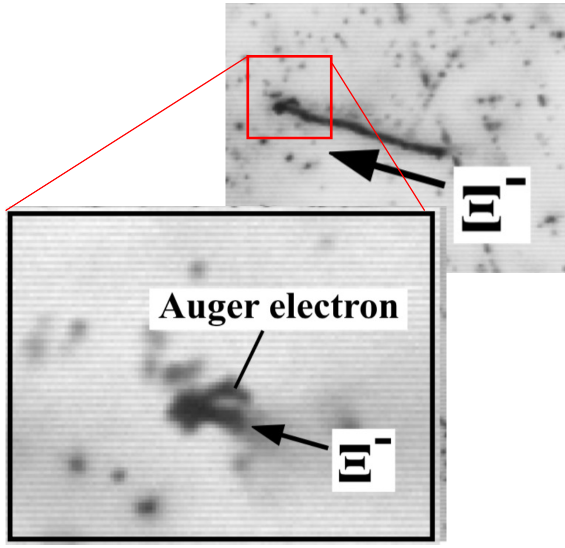
Br (8J→7I) 206 keV | Ag (9K→8J) 255 keV | Br (7I→6H) 316 keV | Ag (8J→7I) 370 keV



σ-stop
(Nuclear fragment from Ξ⁻ stop)

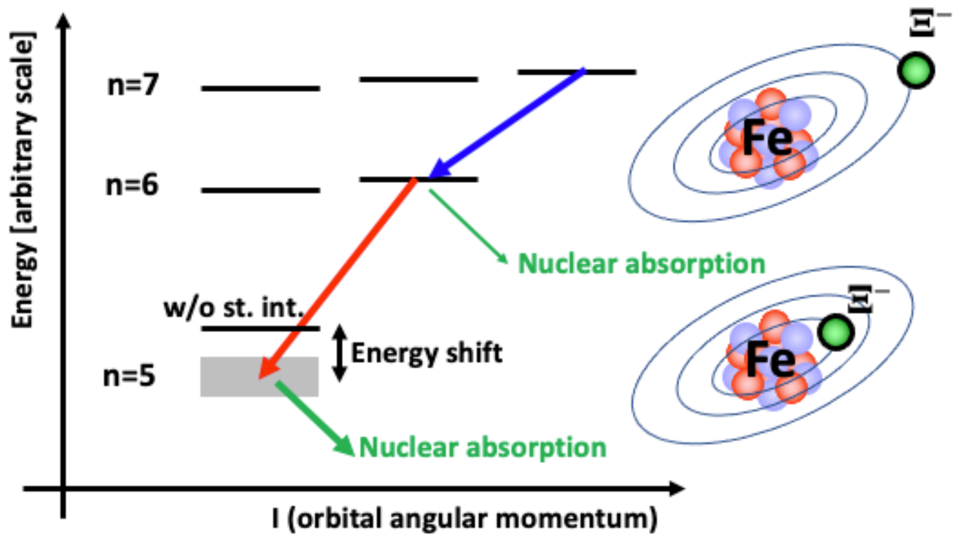


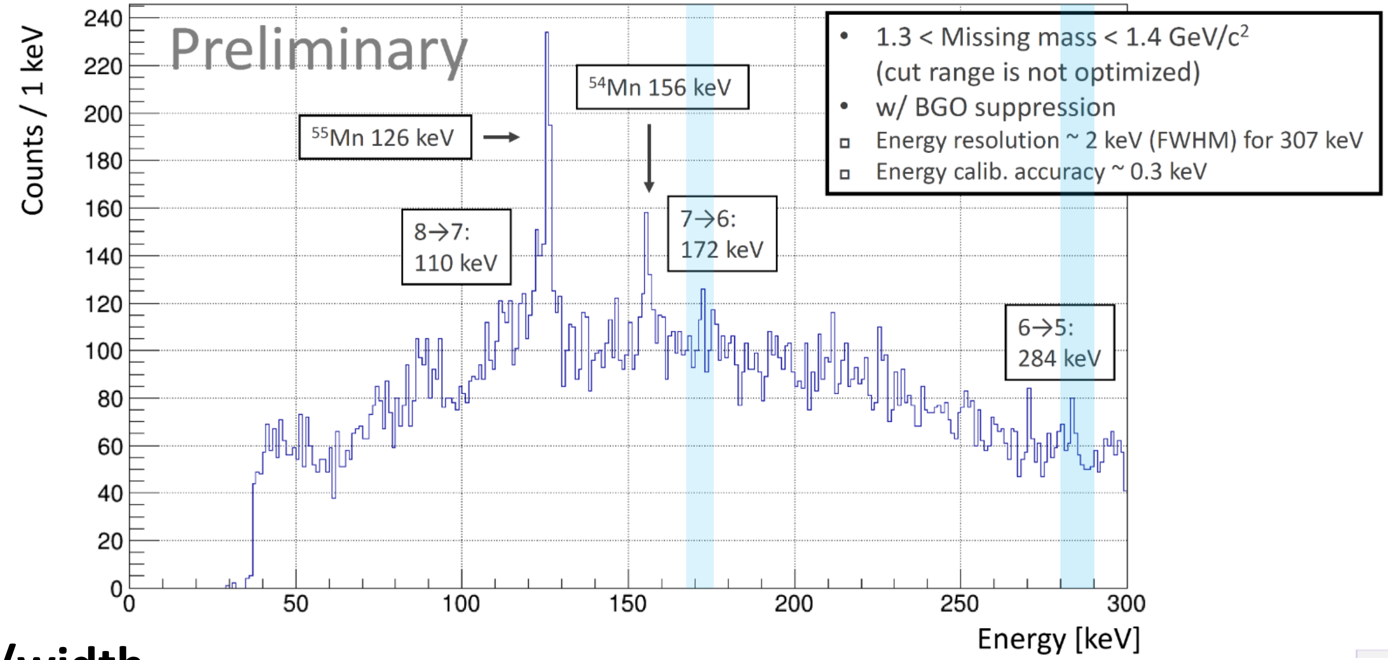
ρ-stop with Auger electron
(Absorption by heavy elements)



M. Fujita et al., PTEP 2022 123D01

Ξ⁻ Fe atomic X-ray (E03)





n=7→6 : X-ray energy = 172 keV ← **small shift/width**

n=6→5 : X-ray energy = ~286 keV ← **finite shift/width due to ΞN interaction**

expected shift ~ 4keV, width(Γ) ~ 4keV

No clear peak structures are found at present.

GOOD! **BG level is consistent with our expectation**

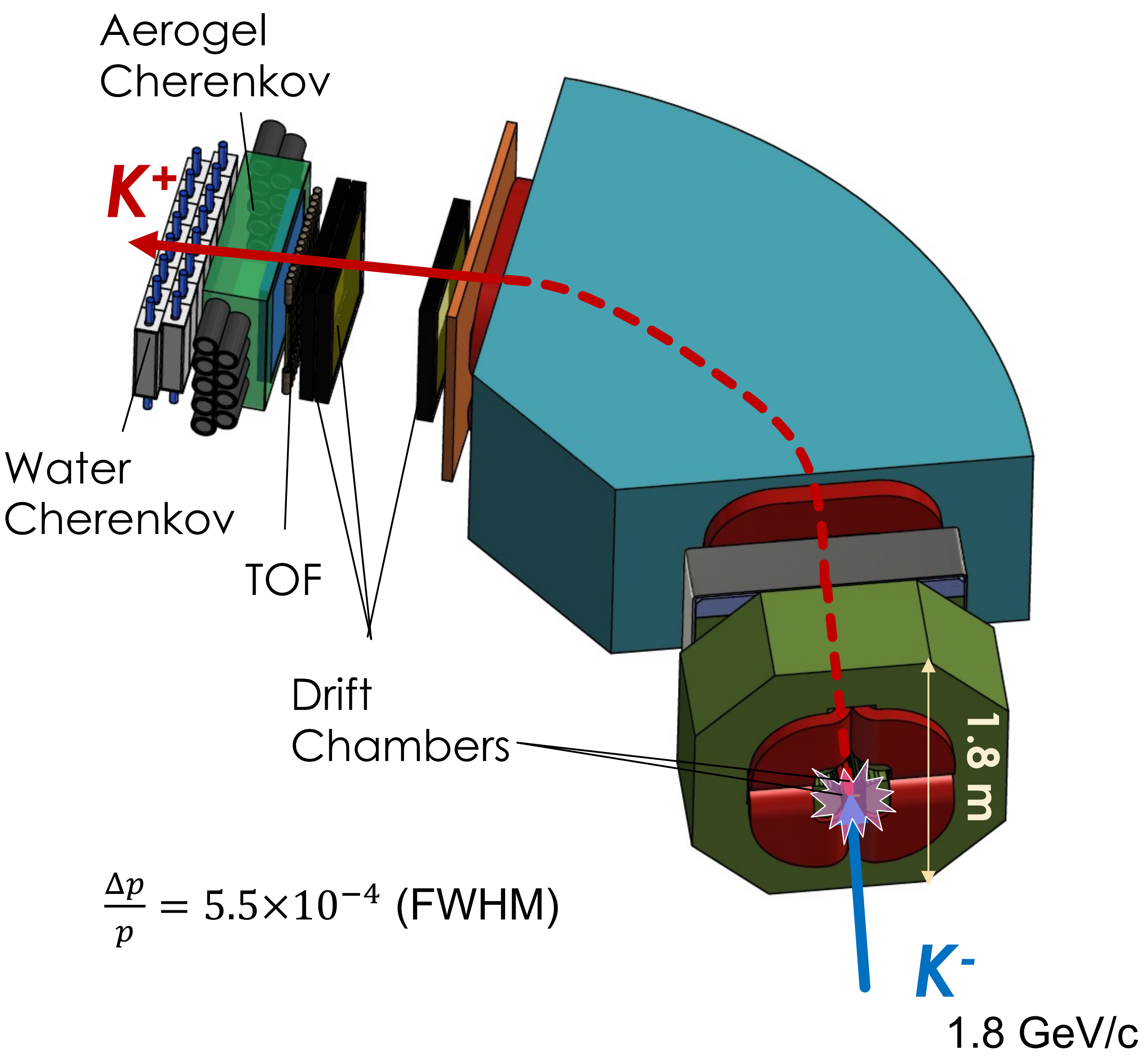
BAD! **X ray yields are found to be smaller than expectation?**

→ **Good S/N measurement may have advantage than high statistics measurement.**

Future measurement w/ Ξ stop identification using active target

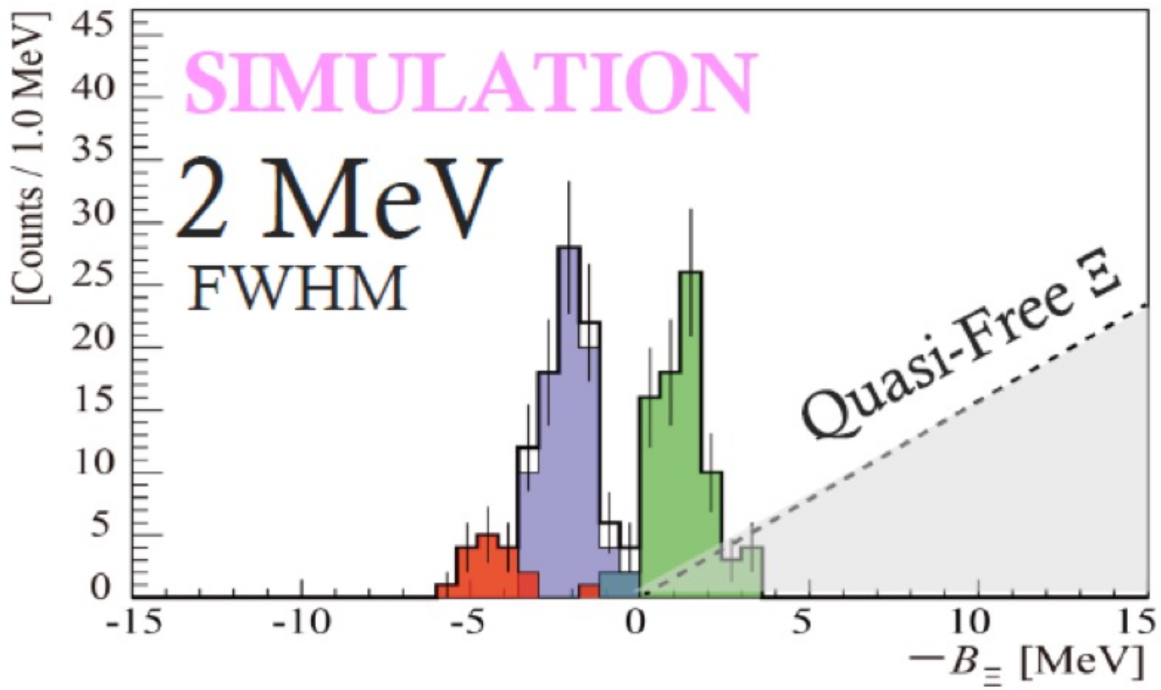
E70 experiment with S-2S spectrometer

Construction of S-2S has been completed!



$\frac{\Delta p}{p} = 5.5 \times 10^{-4}$ (FWHM)

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

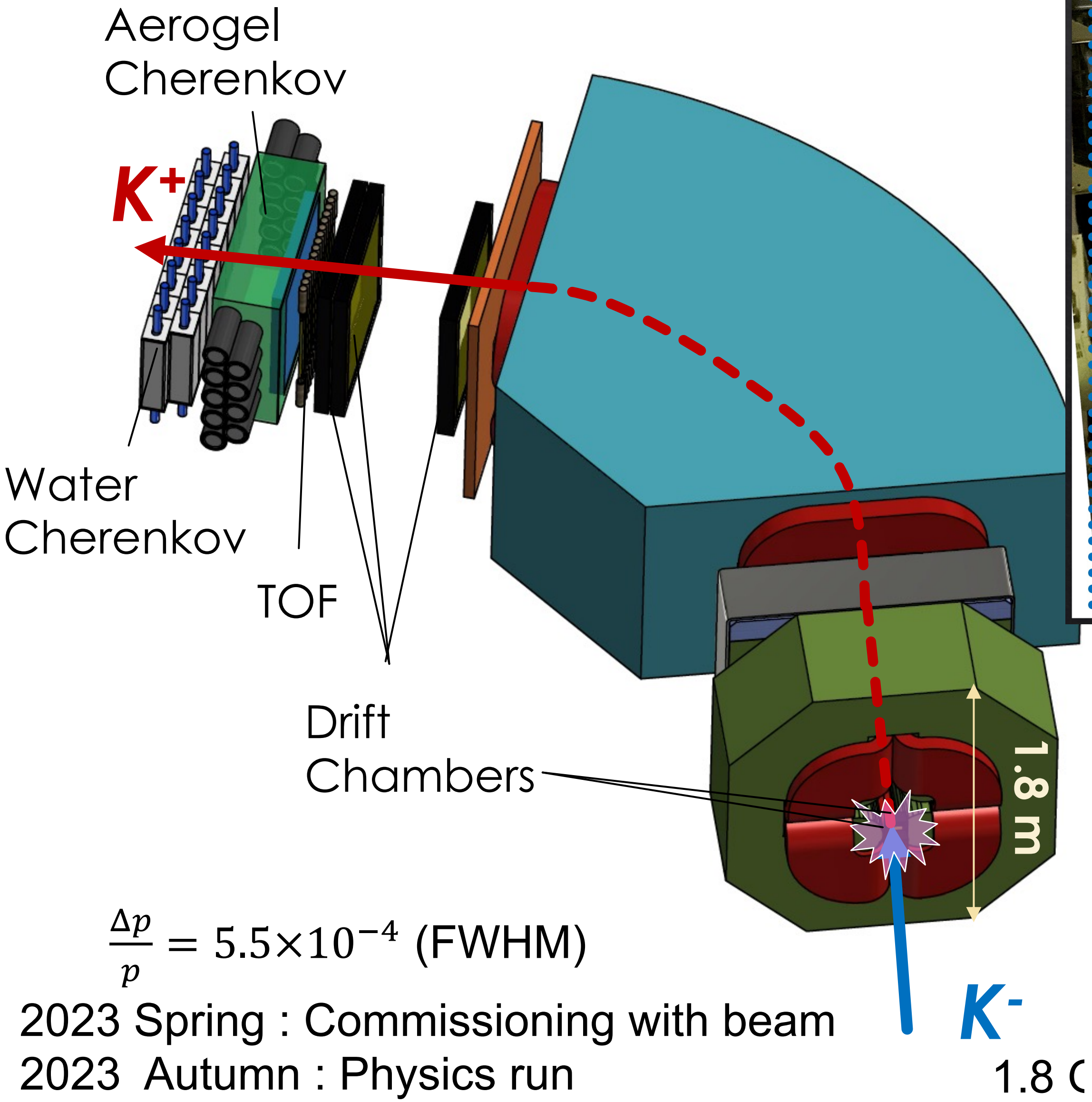


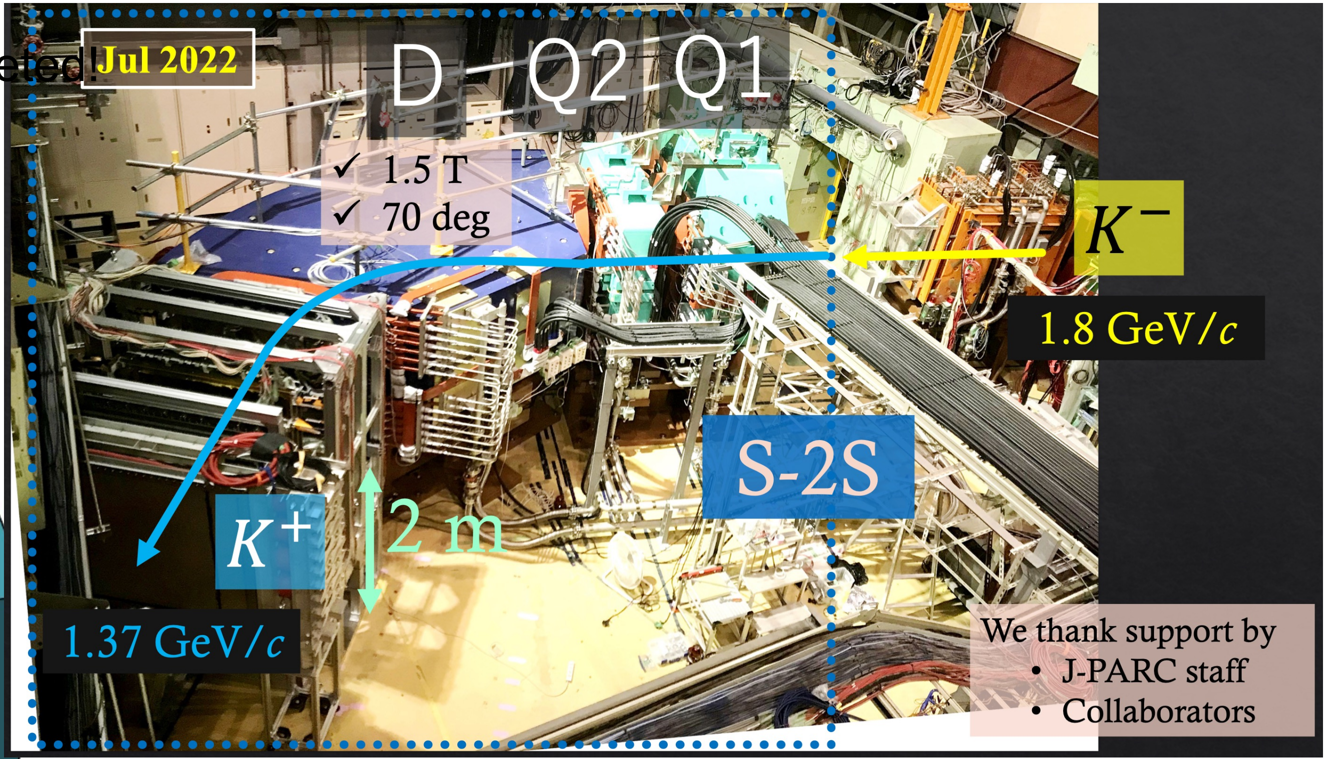
Missing Mass resolution 2 MeV (FWHM)

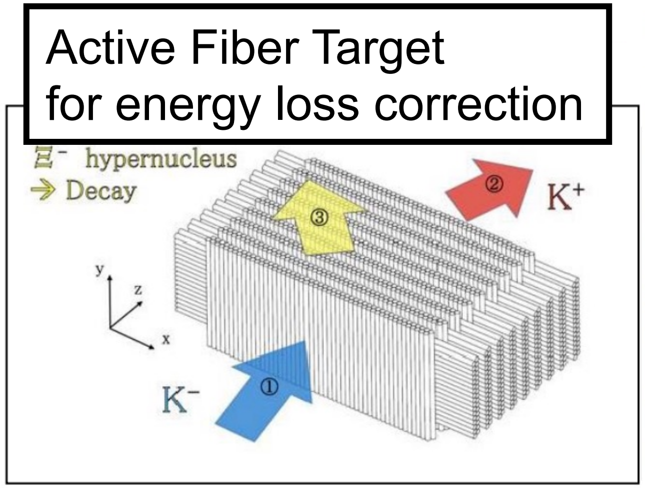
2023 Spring : Commissioning with beam
2023 Autumn : Physics run

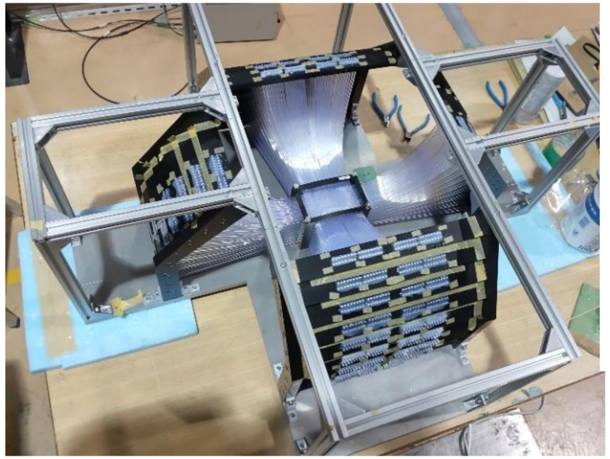
E70 experiment with S-2S spectrometer

Construction of S-2S has been completed!







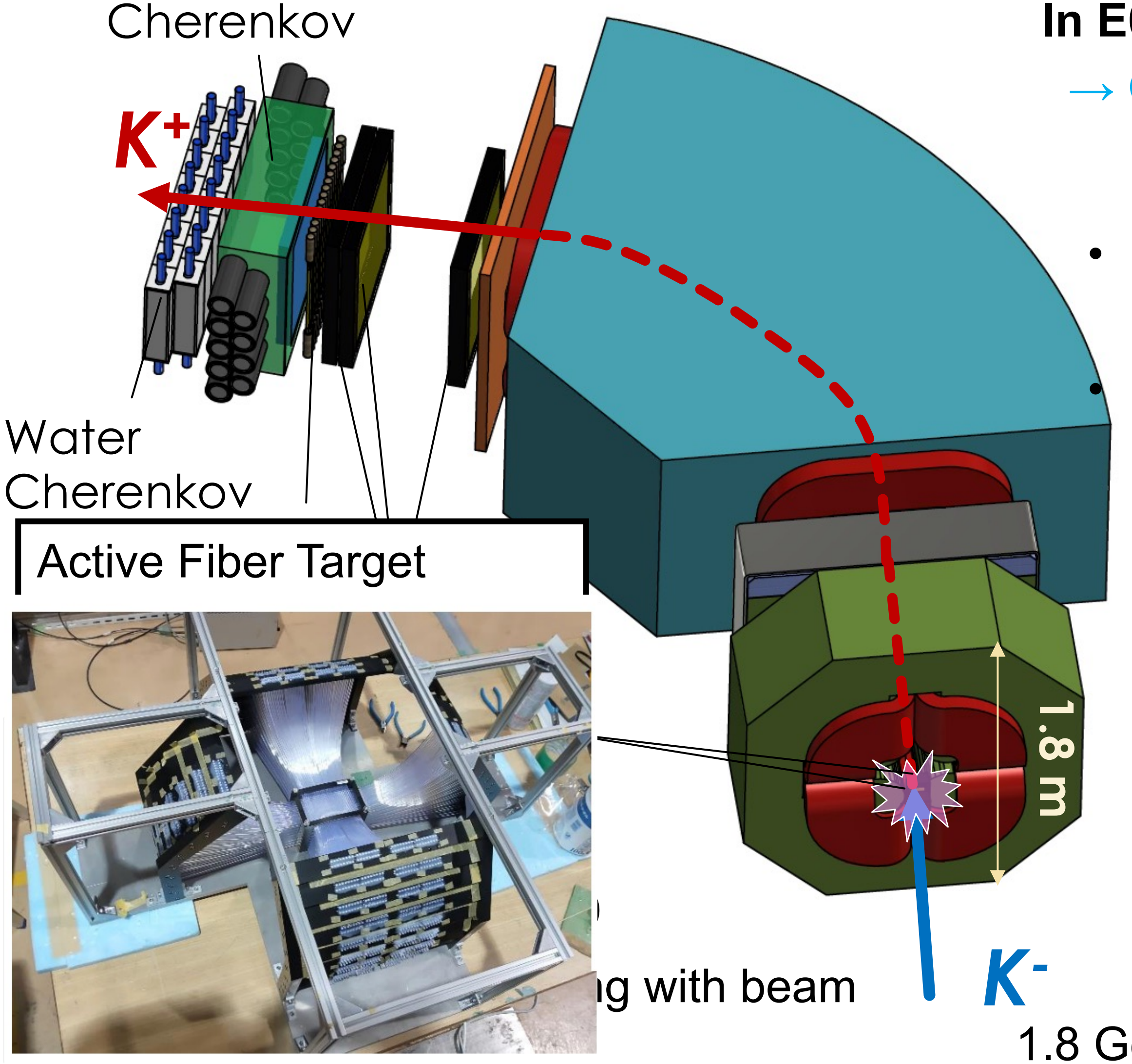


$\frac{\Delta p}{p} = 5.5\times10^{-4}$ (FWHM)

2023 Spring : Commissioning with beam
2023 Autumn : Physics run

Ξ^- ^{12}C X-ray measurement with AFT

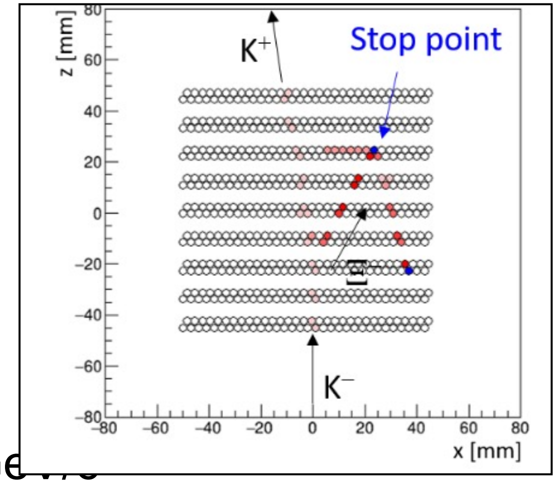
Construction of S-2S has been completed!

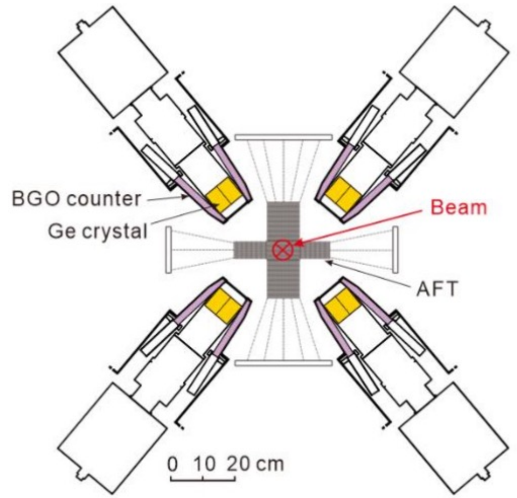


In E03, we found that X ray yields is smaller than expectation.

→ Good S/N measurement may have advantage than high statistics measurement.

- **Ξ^- stop ID w/ Active Fiber Target**
  95% background reduction! (w/ 70% survival ratio)
- **We have chance to take X-ray data in parallel with E70 (Ξ hypernuclear spectroscopy w/ S-2S) physics data-taking**





Light Ξ hypernuclear systems

The spin, isospin averaged ΞN interaction was confirmed to be attractive by E07 experiment.
→ Study of spin, isospin dependence of ΞN interaction is essential

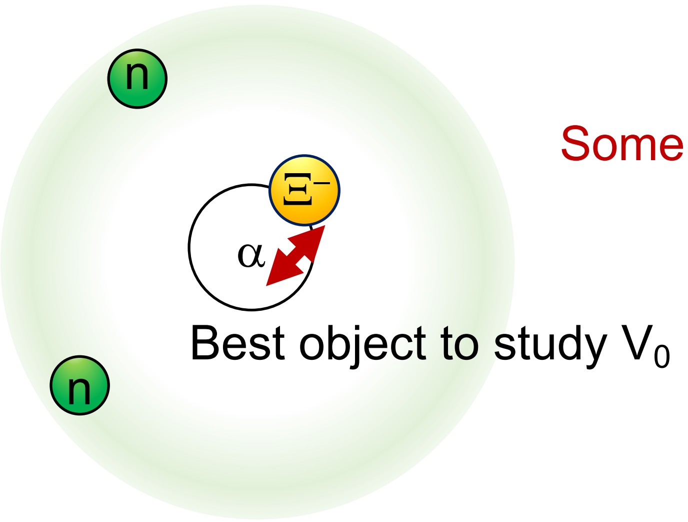
$$V_{\Xi N} = V_0 + \sigma\cdot\sigma V_{\sigma\cdot\sigma} + \tau\cdot\tau V_{\tau\cdot\tau} + (\sigma\cdot\sigma)(\tau\cdot\tau)V_{\sigma\cdot\sigma\,\tau\cdot\tau}$$

After E75

1) spin-isospin independent term
^{7}Li (K^-, K^+) $^7_\Xi$H is suitable

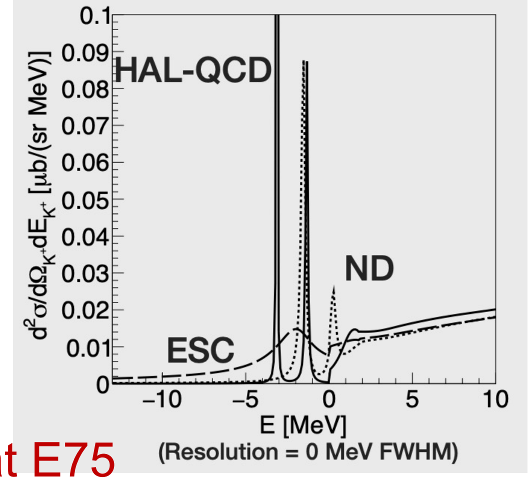
^{6}He : neutron halo nucleus
2 neutrons are far away from Ξ^-+α

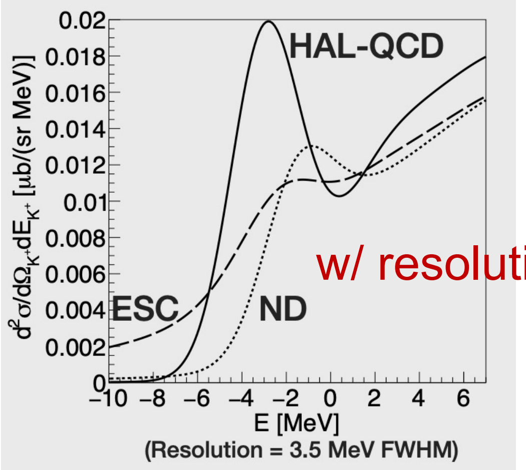
E. Hiyama et al., PRC78,054316(2008).



$^7_\Xi$H

Some hints at E75



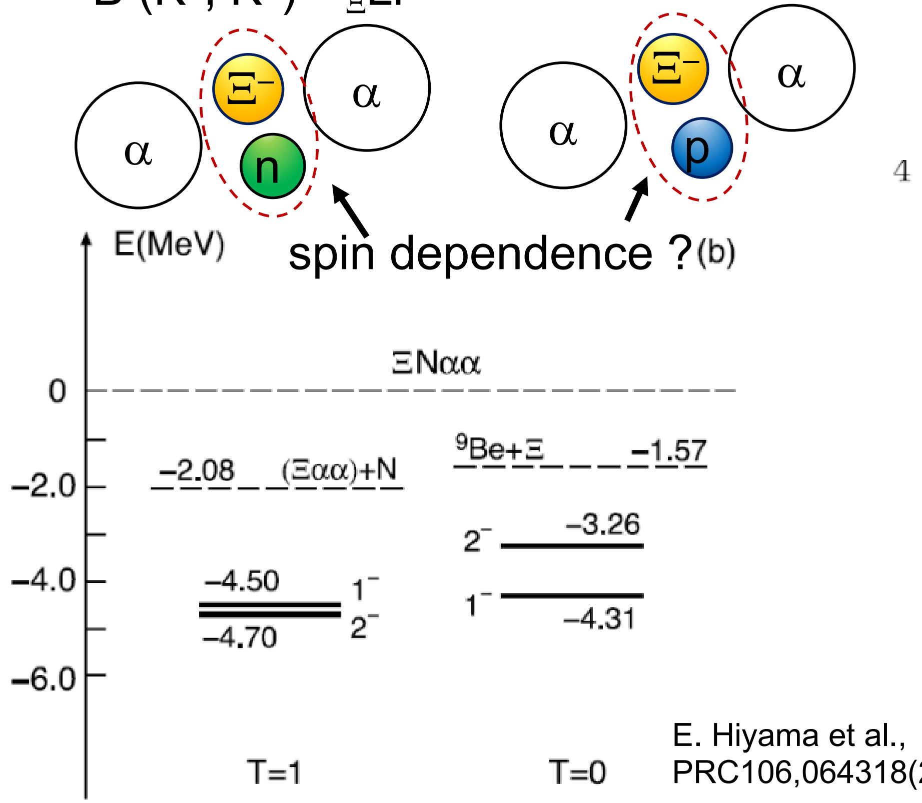


w/ resolution

2) spin-isospin dependent term
ΞNαα system is important

^{10}B (K^-, K^+) $^{10}_\Xi$Li

^{10}B (K^-, K^0) $^{10}_\Xi$Be



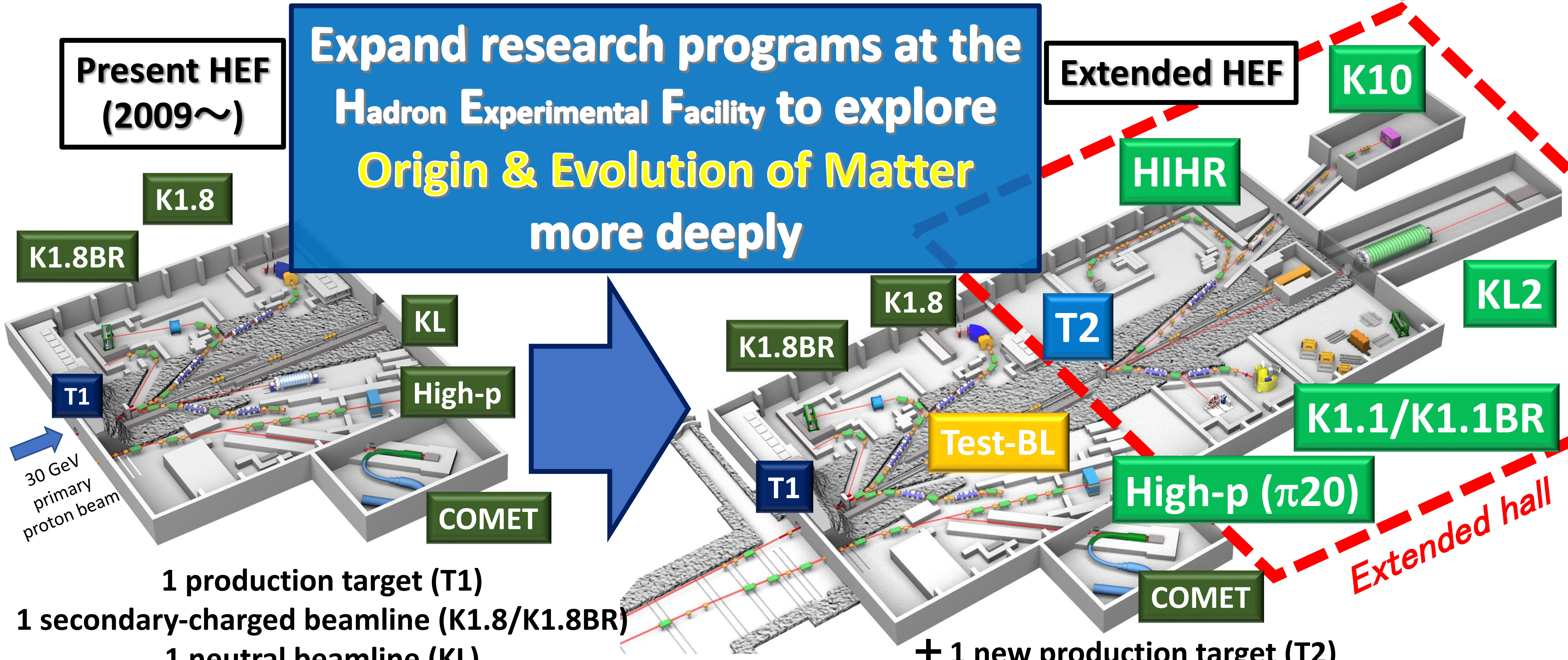
E. Hiyama et al., PRC106,064318(2022).

Contents

- Recent progress of hyperon-nucleon scattering experiment
  - Σp scattering experiment at J-PARC
- Current programs at J-PARC
  - Few-body strangeness systems
  - Exotic systems with strangeness
  - Recent S=-2 studies
- Physics programs at extended hadron hall
- Summary

Hadron Experimental Facility eXtension (HEF-ex) Project

Expand research programs at the Hadron Experimental Facility to explore Origin & Evolution of Matter more deeply



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)

＋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 hypernuclei spectroscopy**
- intense dispersion matched π beam

K1.1 **Systematic ΛN scattering measurement**
- intense polarized Λ beam

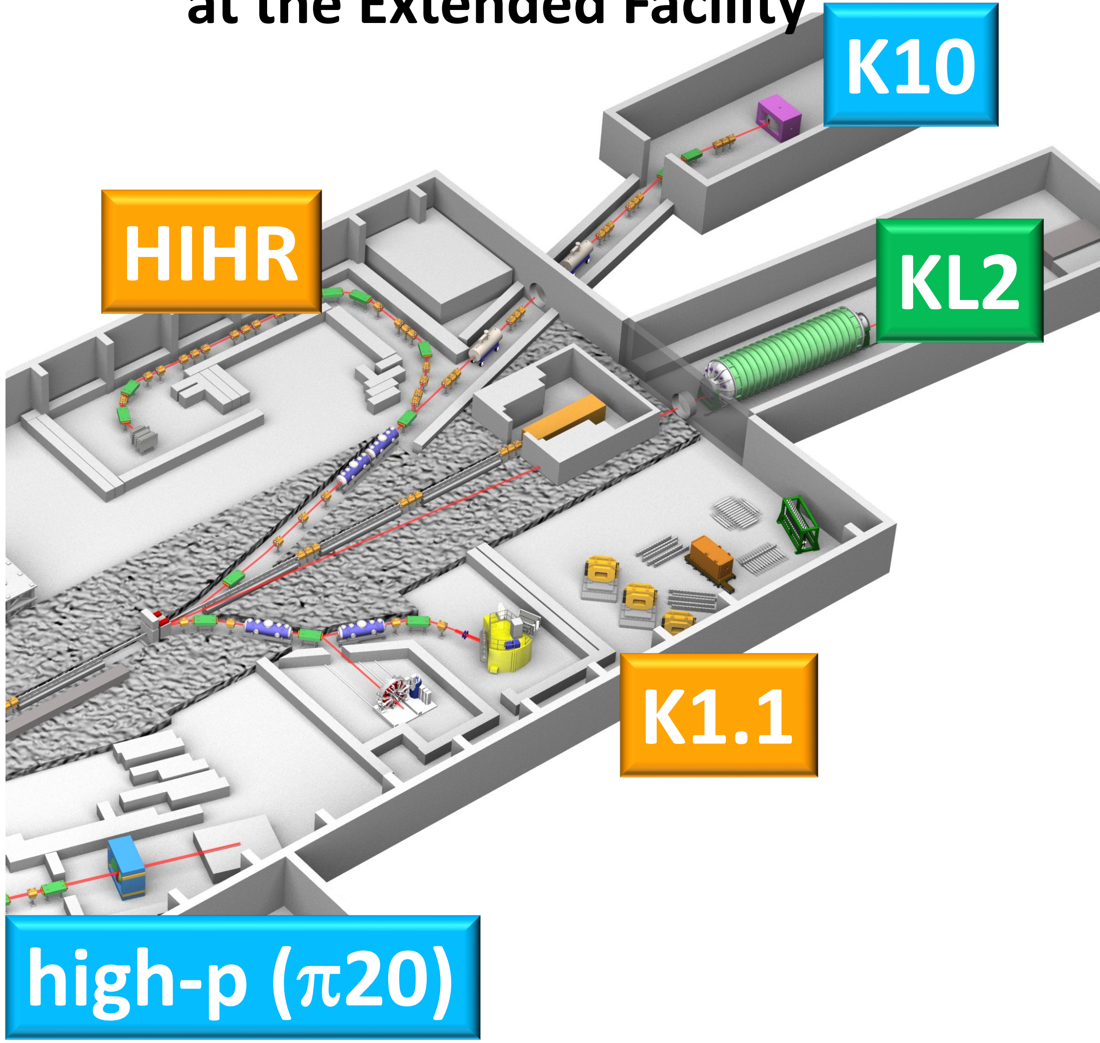
Investigate diquarks in baryons

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 **Highest-sensitive $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ measurement**
- intense neutral K beam



Slide by F. Sakuma

Hadron Physics: Diquarks in Baryons

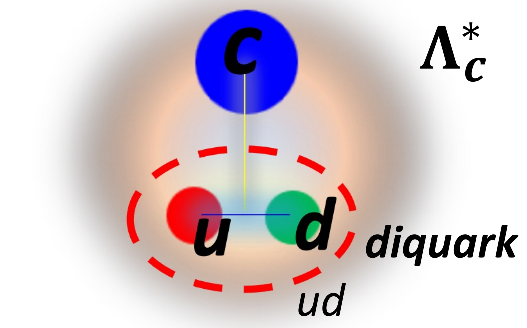
How quarks build hadrons?

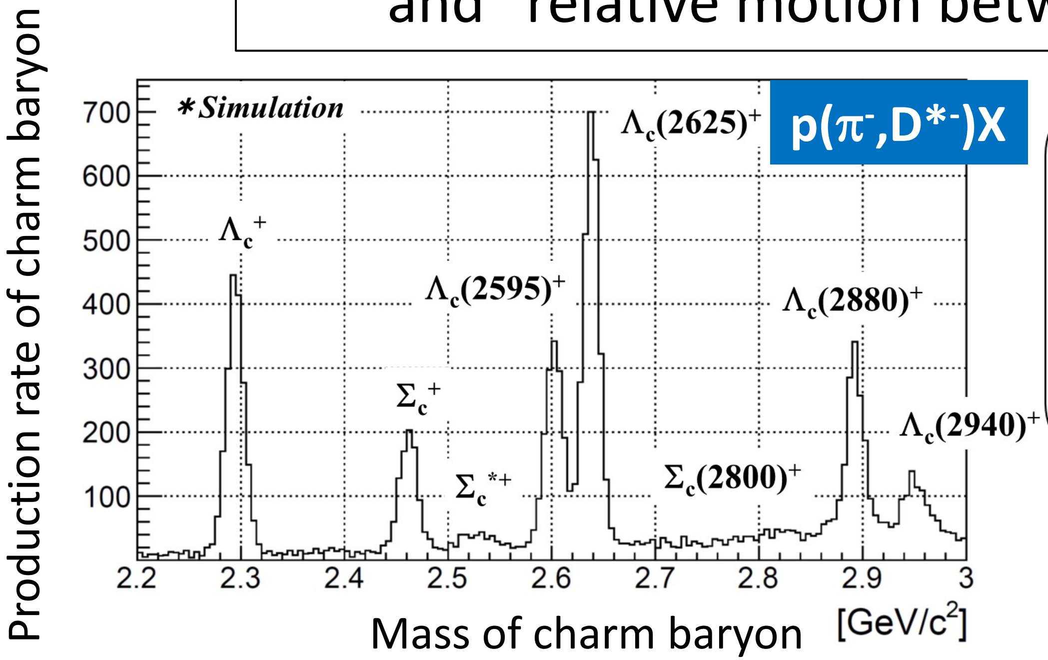
- Investigate **diquarks** in baryons **toward** understanding of **dense quark matter**

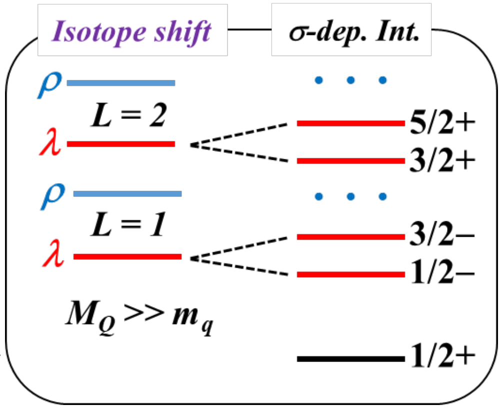
- **Charm Baryon Spectroscopy**
  with intense high-momentum π beam @ High-p (π20)

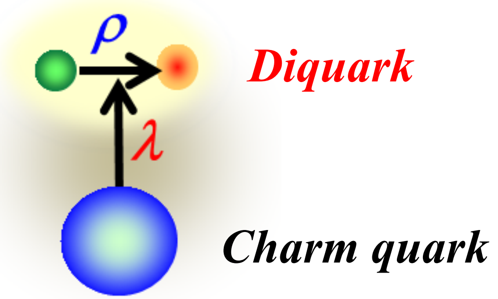
Establish a diquark (*ud*)

Λ_c^*: Disentangle "collective motion of *ud*" and "relative motion between *u* and *d*"









"production rate" and "decay rate" will provide us information on diquark

Hadron Physics: Diquarks in Baryons

How quarks build hadrons?

- Investigate **diquarks** in baryons **toward** understanding of **dense quark matter**

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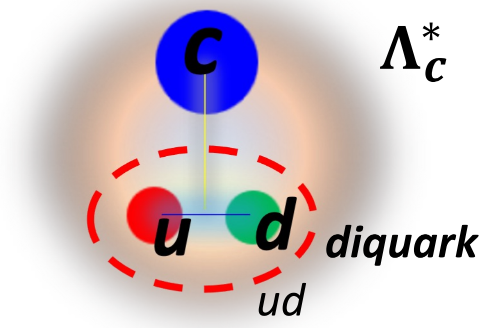


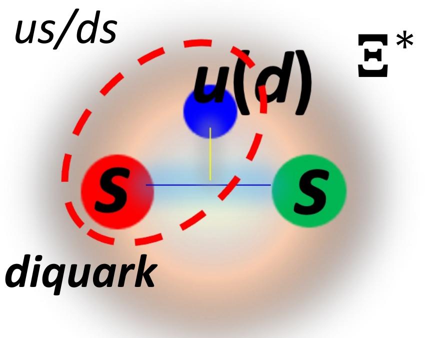
- **Multi-Strange Baryon Spectroscopy**
  with intense high-momentum K beam @ K10

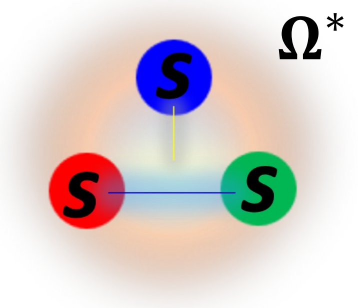
Diquarks in different systems

Ξ^*: *us/ds* diquark

Ω^*: the simplest *sss* system

→ diquark is expected to be suppressed



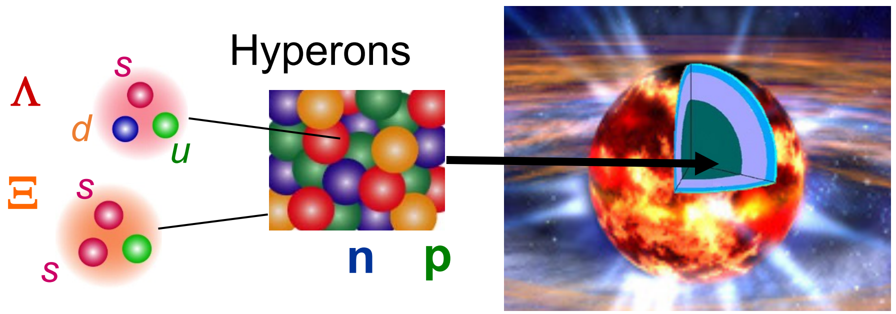


Systematic measurements of charm and multi-strange baryons will reveal the internal structure of baryons through the diquarks

Hyperon puzzle in neutron star

Strange Hadronic Matter in neutron star ?

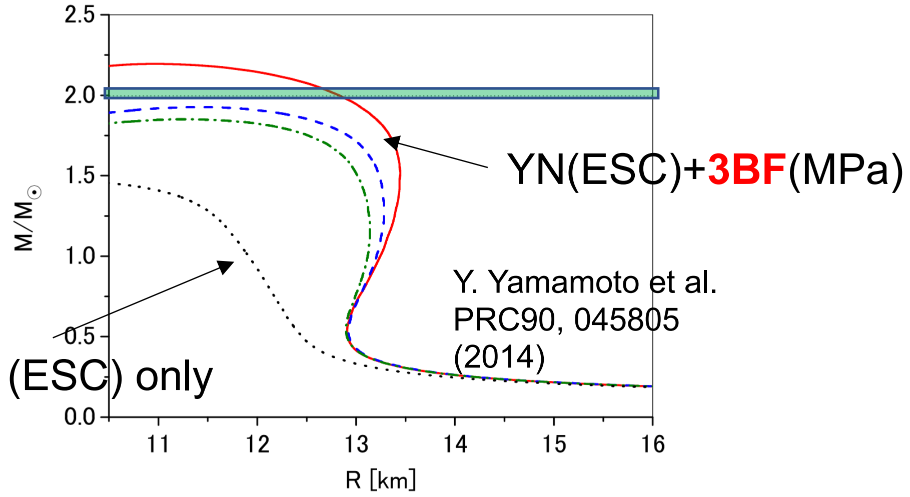
Hyperon's appearance is reasonable scenario because of the huge Fermi energy of neutrons in the inner core.



How can we reconcile ?

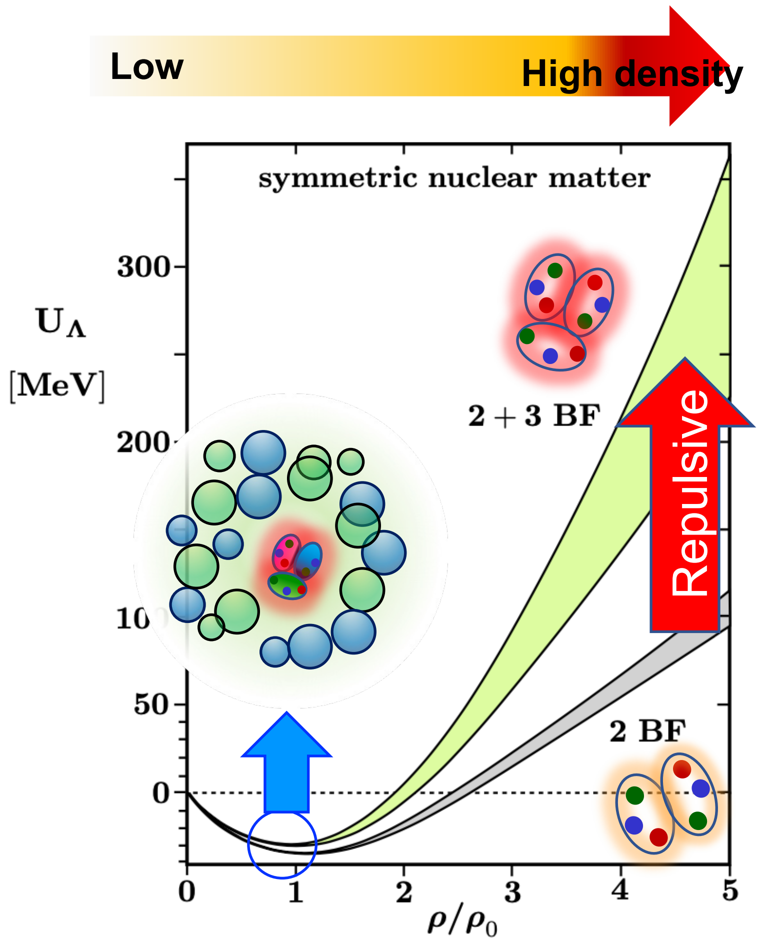
Hyperon appearance → **soften** EOS

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



3 Baryon Force (3BF):

Significant repulsive contribution at high density



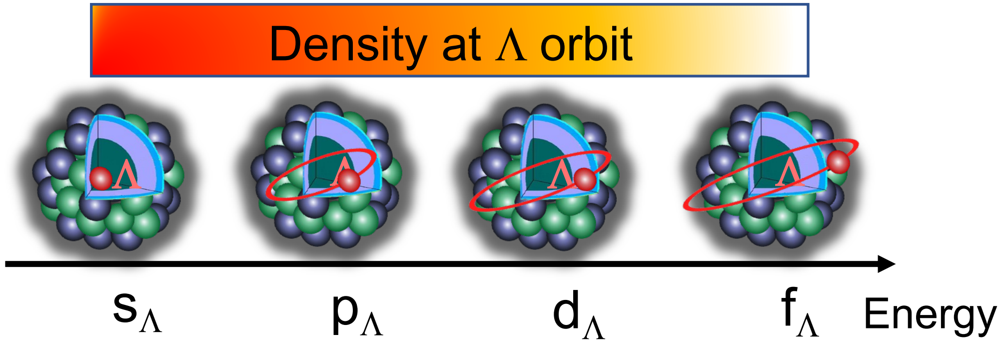
D. Gerstung et al., Eur. Phys. J. A(2020) 56:175

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



Two directions for study of the density dependence of ΛN interaction

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

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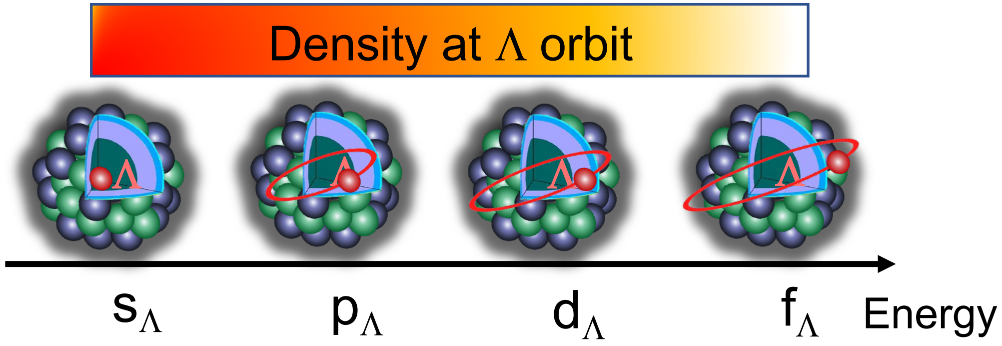

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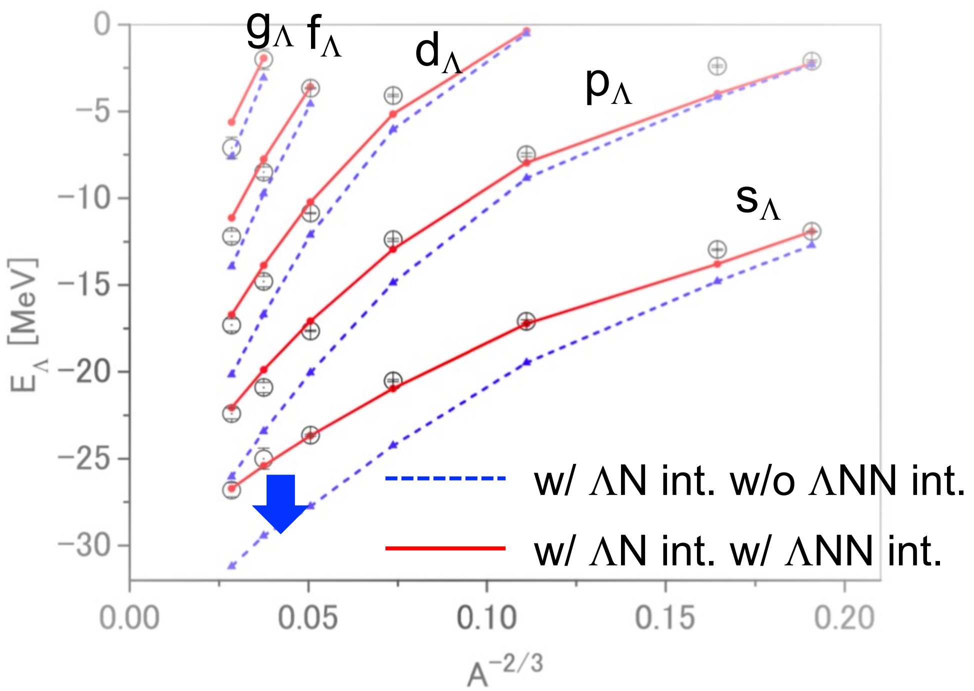
M.M. Nagels et al. Phys. Rev. C99, 044003 (2019)



Calculation w/ only ΛN int : Over bound

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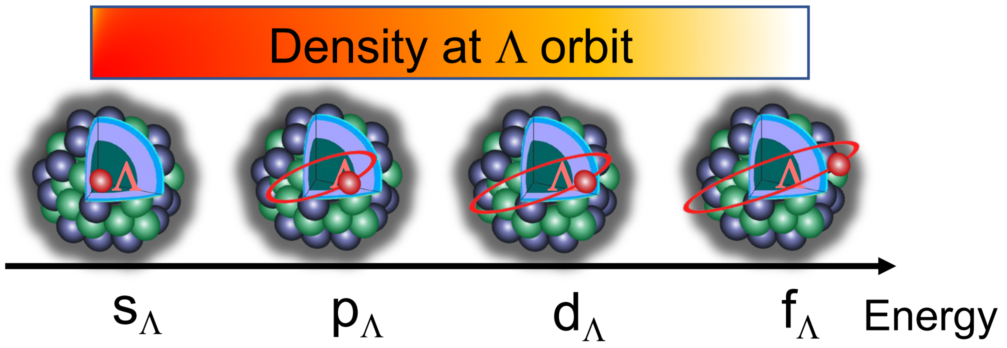

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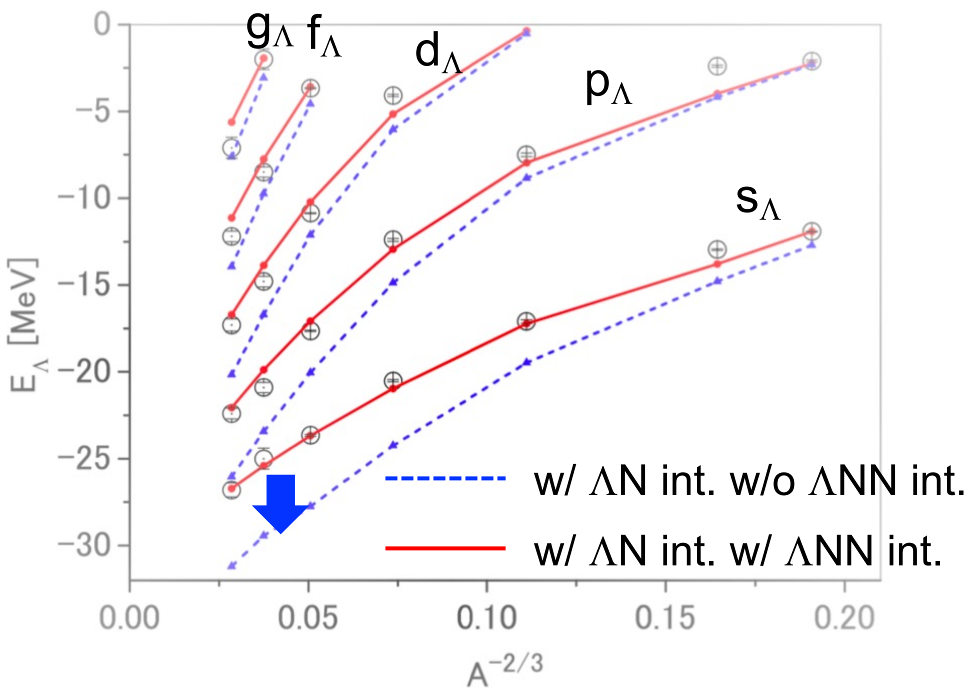

Accurate B_Λ measurement ⟷ **Difference** ⟷ **Calculation w/ only ΛN int : Over bound**

Effect of **density dependence of ΛN interaction**

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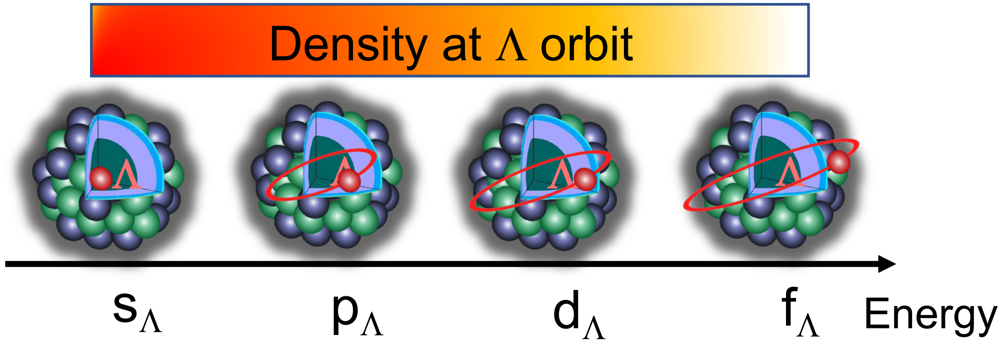

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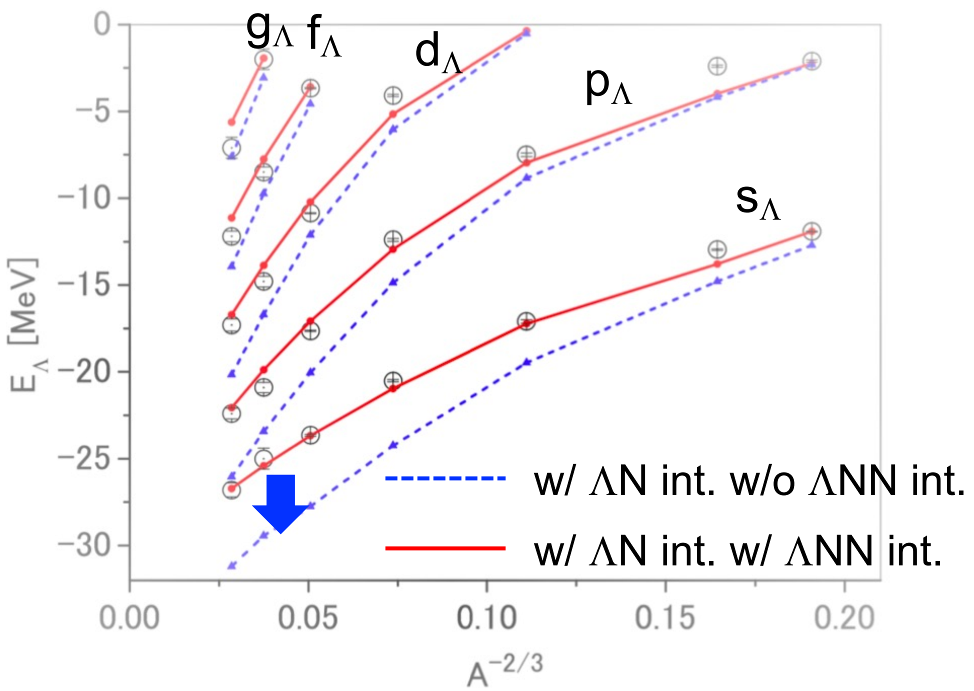

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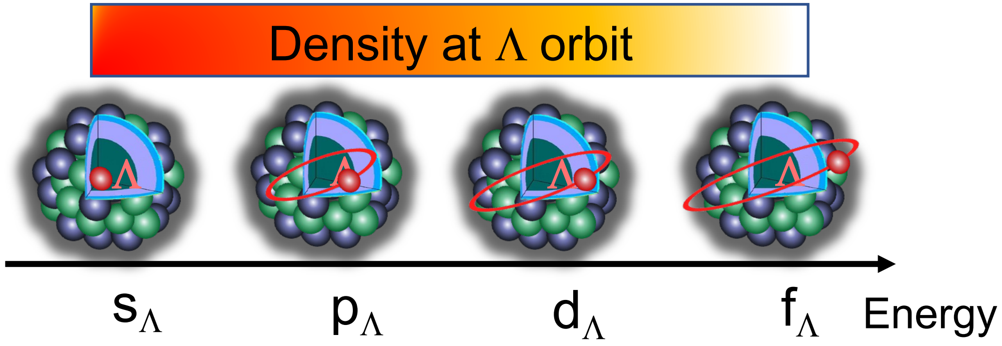
Effect of **density dependence of ΛN interaction**

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

Nuclear density is different for each Λ orbital state



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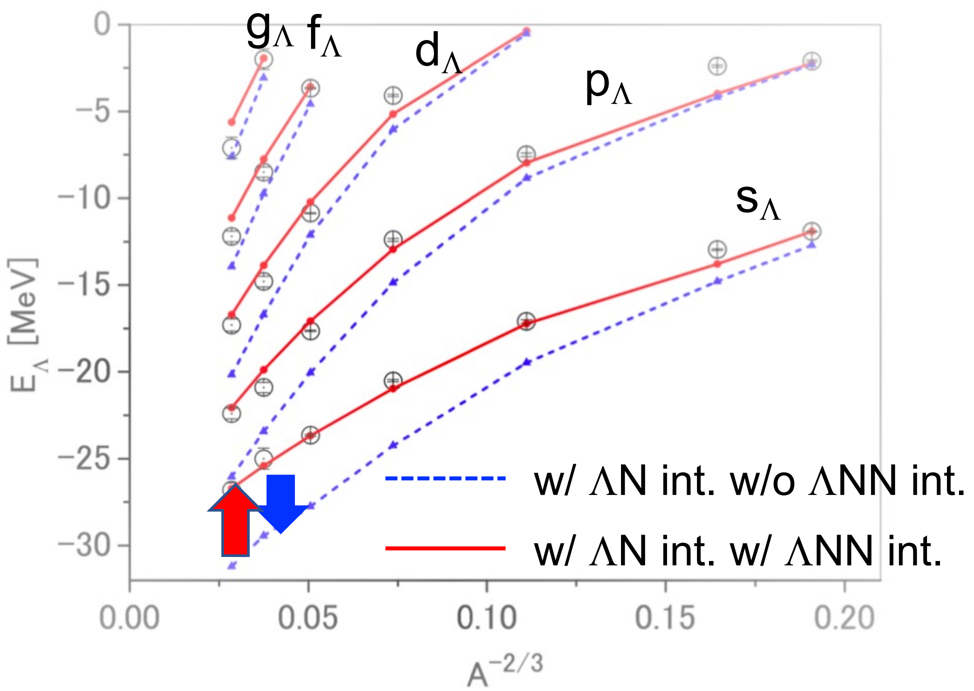


Accurate B_Λ measurement ⟷ **Difference** ⟷ **Calculation w/ only ΛN int : Over bound**

Effect of **density dependence of ΛN interaction**

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.

High-resolution Λ hypernuclear spectroscopy at HIHR

HIHR : Dispersion-matching beam line

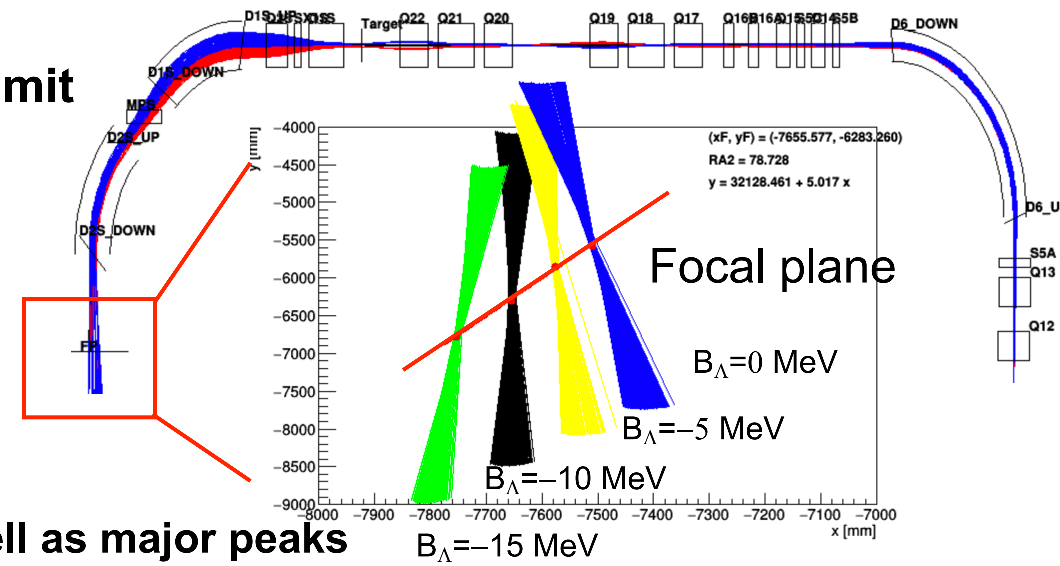
→ Realize **high-resolution** spectroscopy **without beam intensity limit**

High intensity π beam of **> 10^8 /pulse**

(**~100 times stronger** than KEK-PS)

- Thin target can be used

→ High resolution and various target options

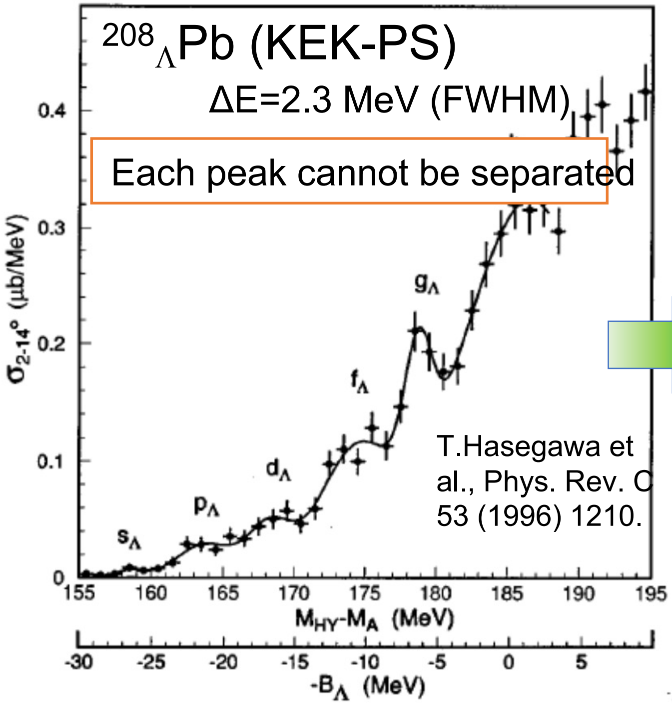


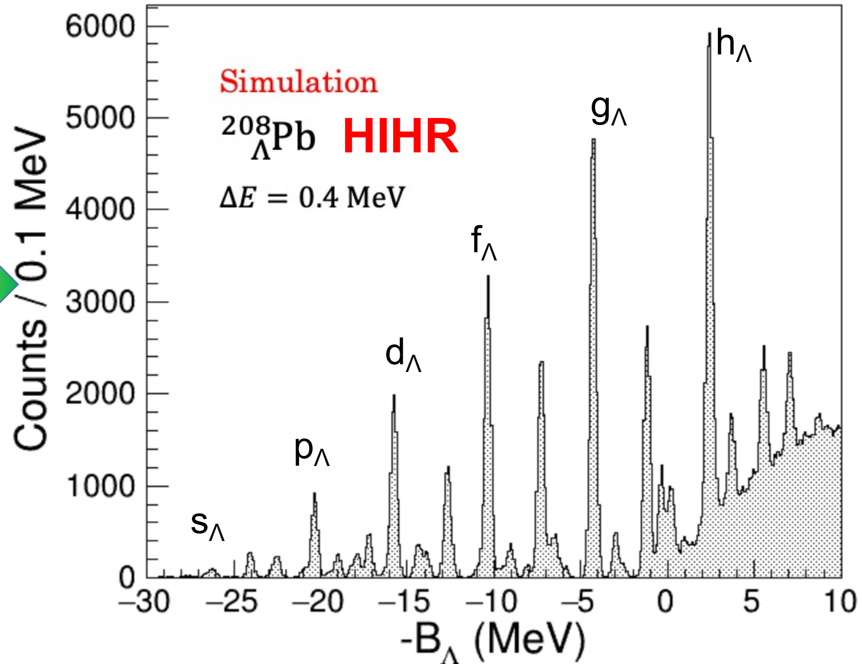
Impossible to separate peaks with a few MeV resolution

0.4 MeV (FWHM) resolution

⇩

Clear separation of sub-major as well as major peaks





Precise Λ binding energies for wide-mass range

⇩

Density dependence of ΛN interaction (ΛNN interaction)

⇩

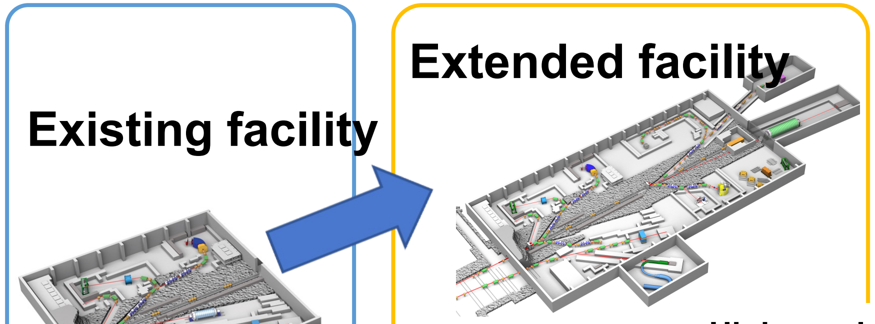
Calculate U_Λ at high density region

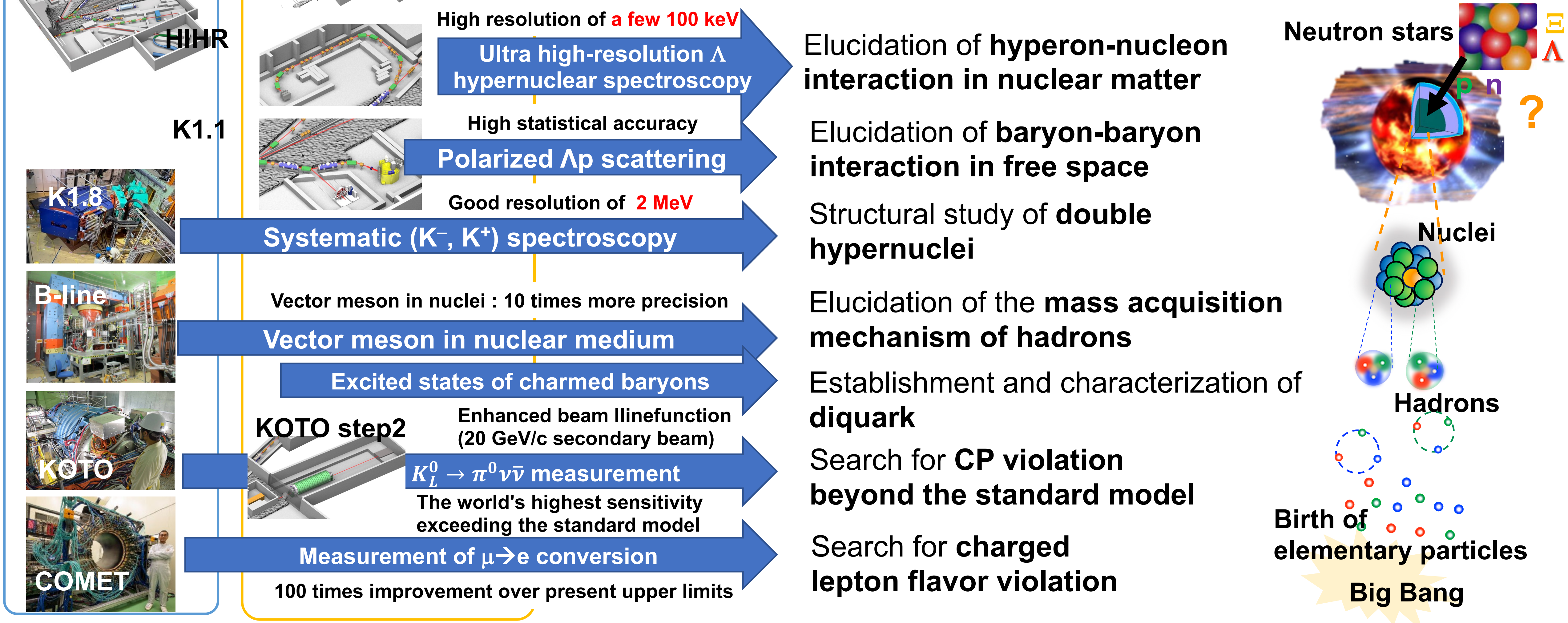
Untangle hyperon puzzle in neutron star

Physics at Hadron Experimental Facility

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

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





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!
- Systematic measurements of Σp scattering at J-PARC
  - $d\sigma/d\Omega$ for Σ^+p, Σ^-p, Σ^-p→Λn scatterings with ~10% level accuracy for fine angular pitch ($d\cos\theta$=0.1)
  - Momentum dependence of Σ^+p $\delta(^3S_1)$ channel was derived (–20 ~ −35 degrees)
- Future project : Λp scattering w/ polarized Λ beam
  - $d\sigma/d\Omega$ and spin observables (analyzing power, depolarization)
  - → reinforce the current ΛN interaction for deepening hypernuclear physics.
- Current strangeness nuclear physics programs at J-PARC
  - Hypertriton, H-dibaryon, Kaonic nuclei, X hypernuclear spectroscopy, X atimic X-ray measurement
- High-resolution spectroscopy up to medium and heavy Λ hypernuclei
  - New HIHR beam line with dispersion-matching technique will open new era of unprecedent resolution of 400 keV (FWHM)
  - By using this high resolution, the ΛNN 3body interaction will be examined.