Recent highlights and future prospects of hypernuclear physics at J-PARC

Koji Miwa (Tohoku Univ.)

Hadrons and Hadron Interactions in QCD 2024 (HHIQCD 2024), Oct 22, 2024

TOHOKU UNIVERSITY

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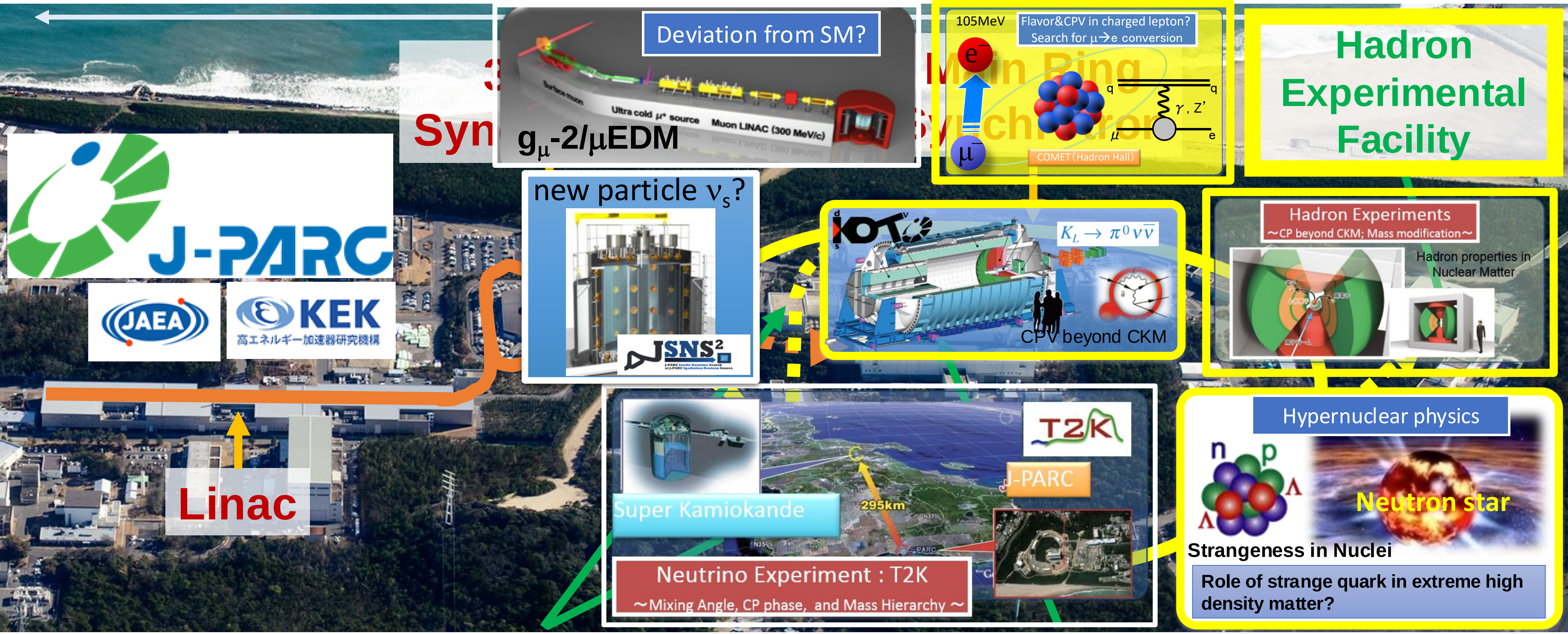
Particle and Nuclear Physics @ J-PARC



Neutrino Experimental Facility

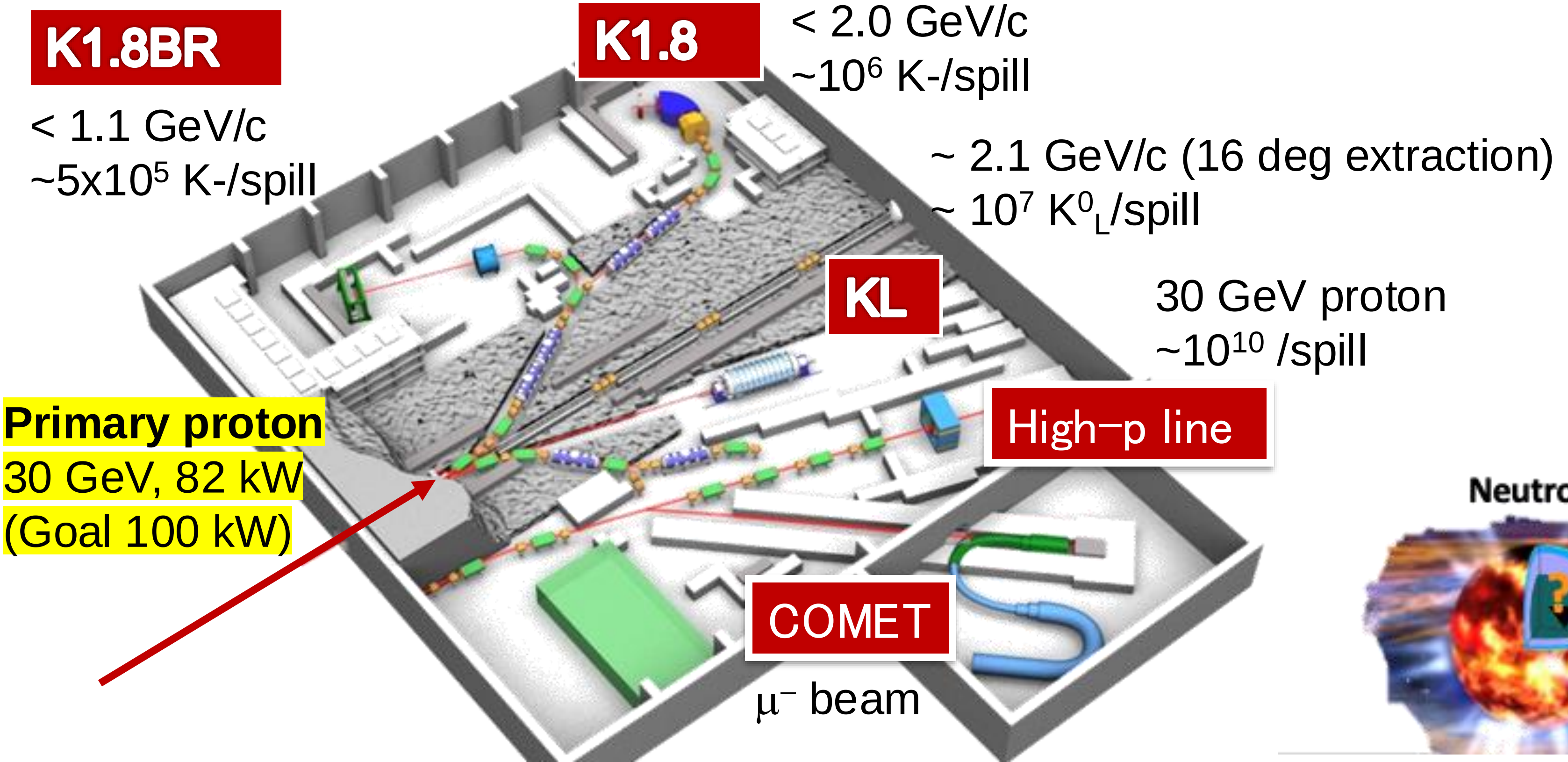
Material and Life Science Experimental Facility

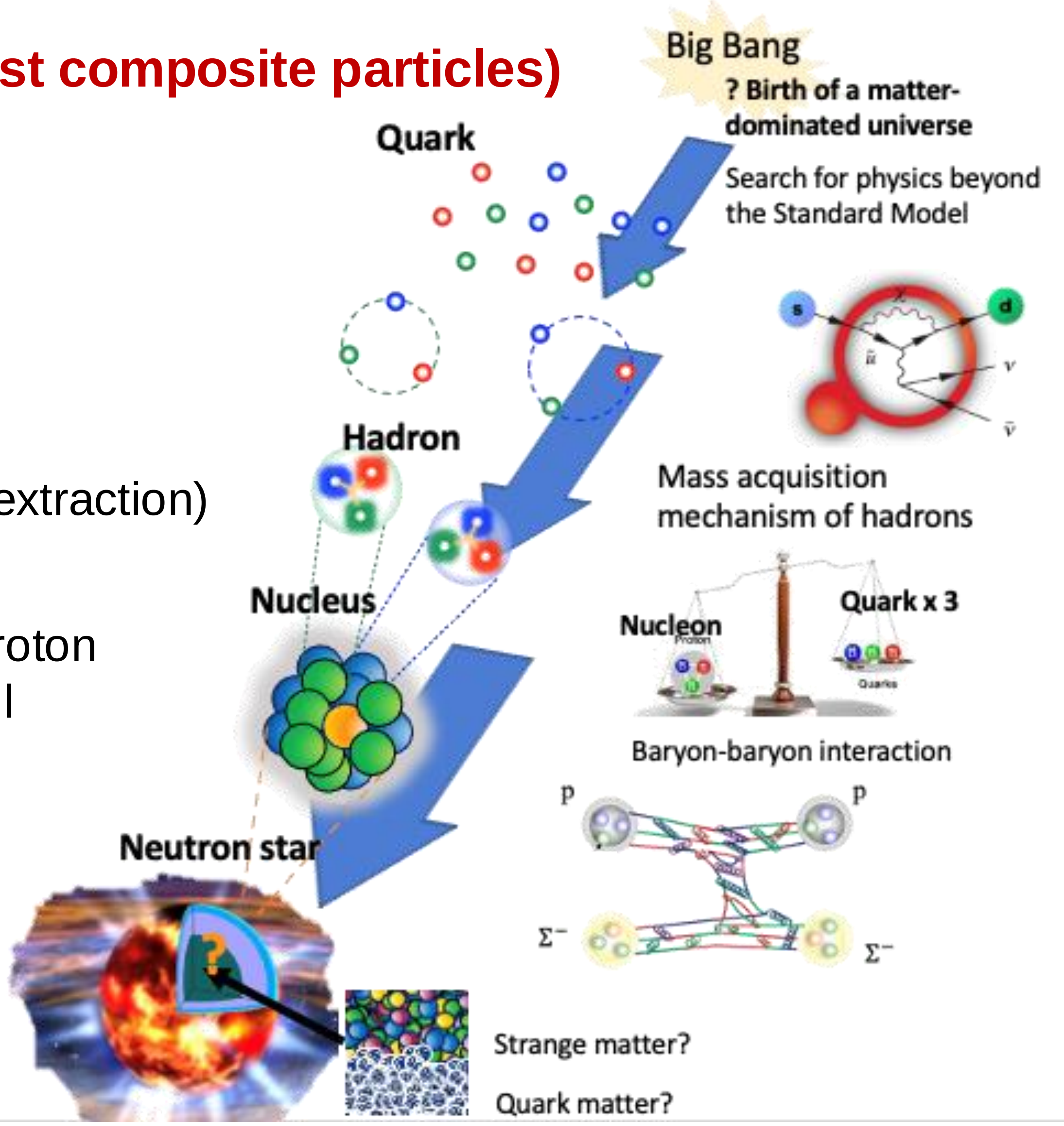
Particle and Nuclear Physics at HEF

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





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.**

$\mu \rightarrow e$ 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

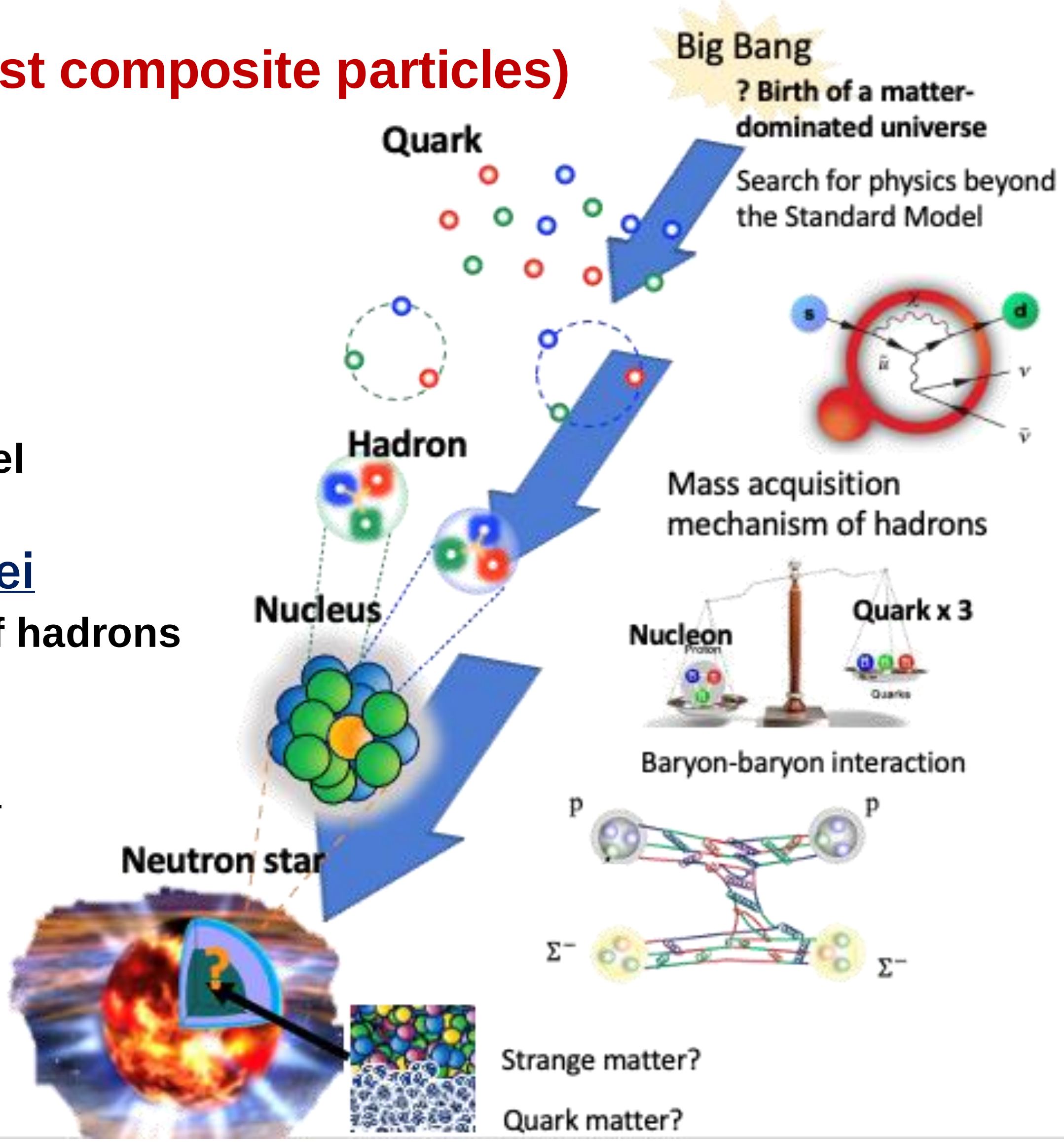
Study of exotic hadron bound system including K^-

Mass number dependence of kaonic nuclei

Spectroscopy of S=-1, -2 hypernuclei

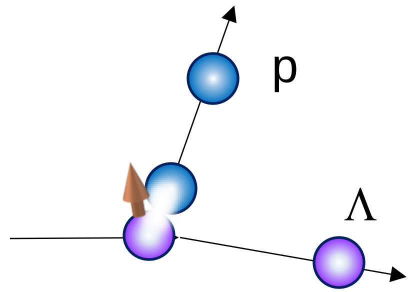
Elucidation of the appearance mechanism of Ξ, Λ hyperons in dense matter

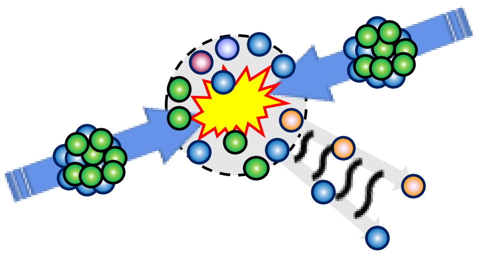
Excellent mass resolution of 2 MeV for Ξ hypernuclei



Hypernuclear physics

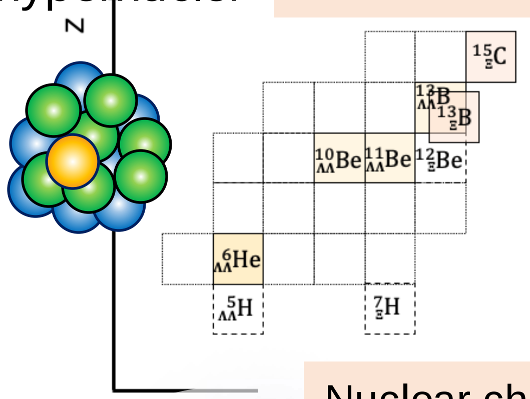
Baryon-Baryon interaction | **Study of light Λ, Ξ hypernuclei** | **Spectroscopy of heavy hypernuclei**



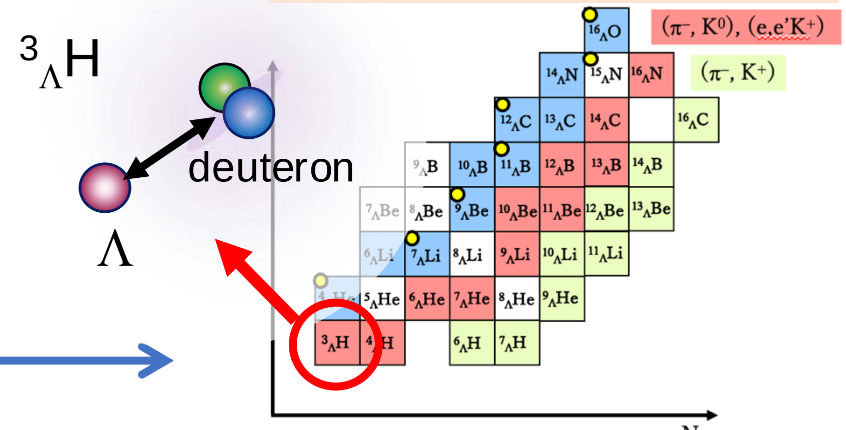


Ξ hypernuclei

Nuclear char in S=–2 sector



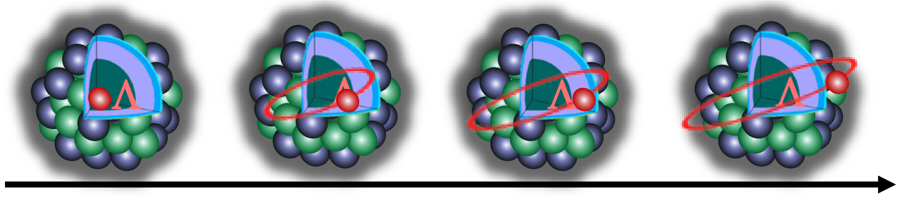
Nuclear char in S=–1 sector

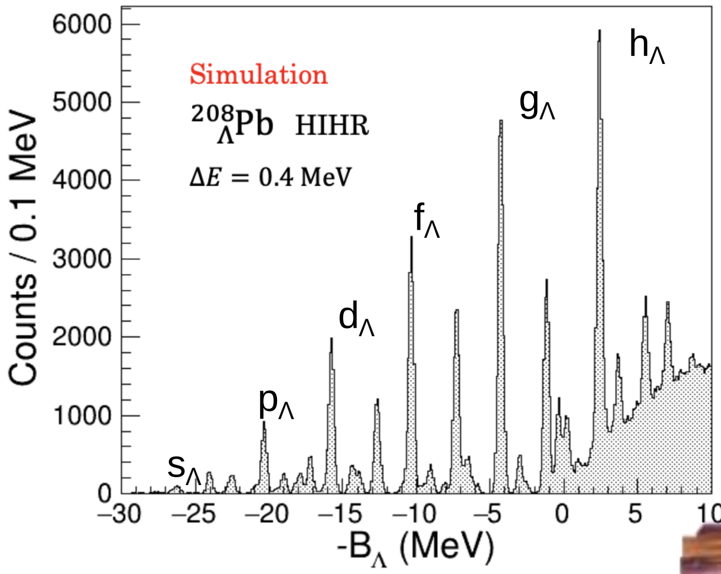


Two-body YN int.

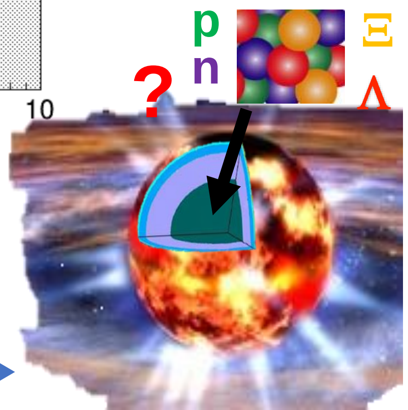
ΛN-ΣN coupling, ΛNN int., ΛΛ, ΞN int.

Density at Λ orbit





Neutron star

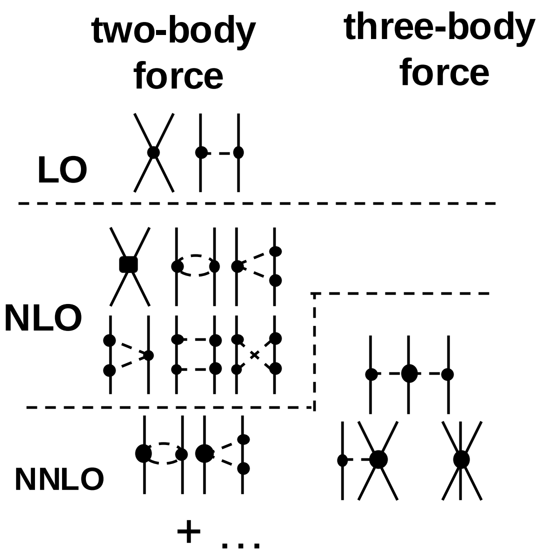


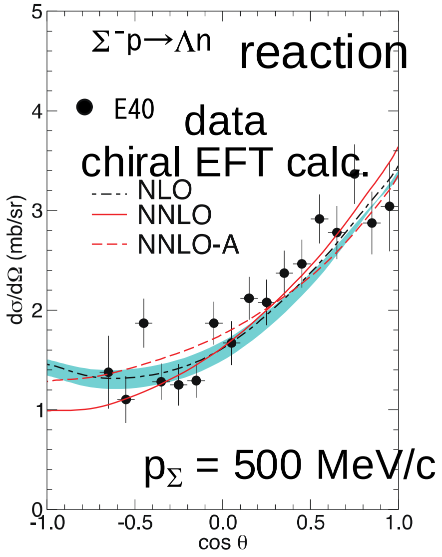
Density dependent ΛN int., ΛNN int.

Progress of theory & experiment of BB int. study

Theoretical progress

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

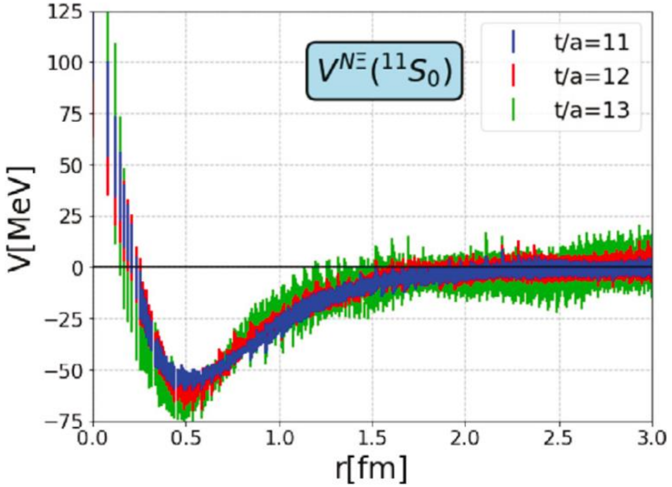




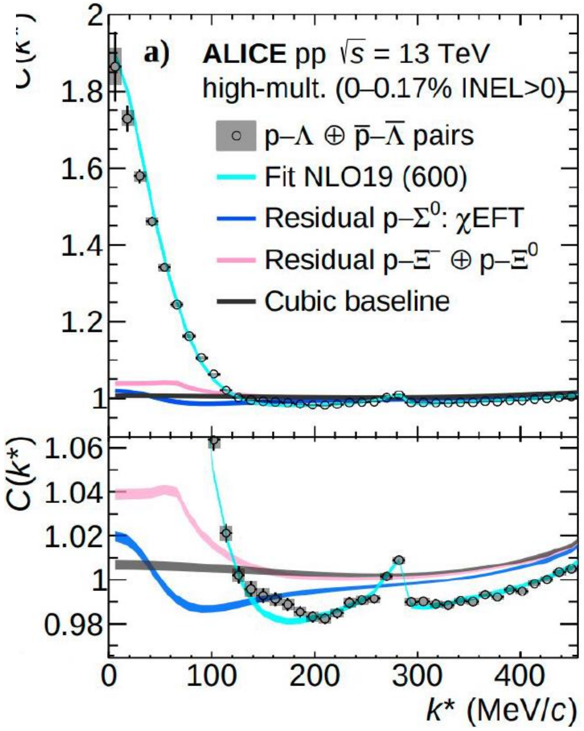
Improving accuracy w/ our new data

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



Particle correlation between Λ and p

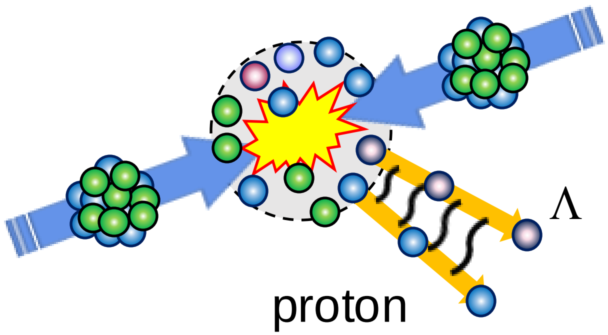


Experimental progress

BB interaction by femtoscopy

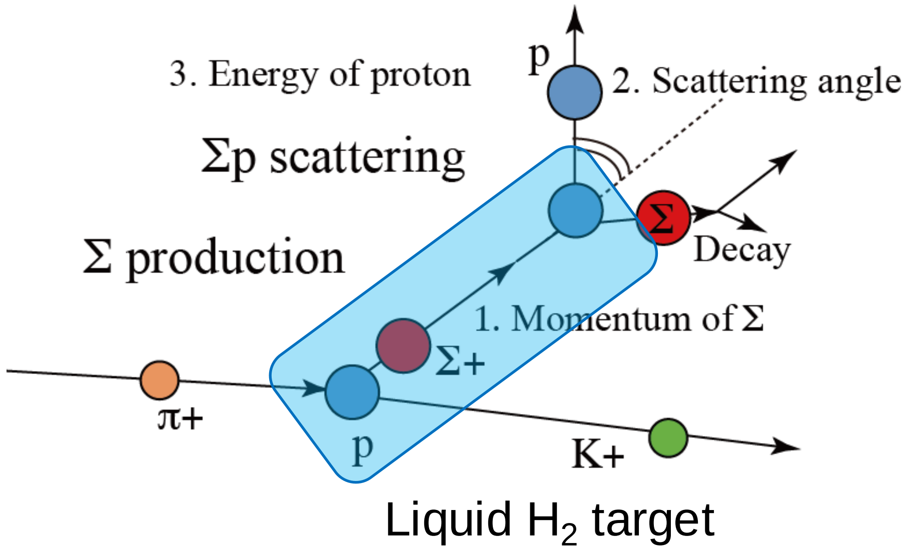
ALICE Collaboration, Phys. Lett. B 833 (2022) 137272

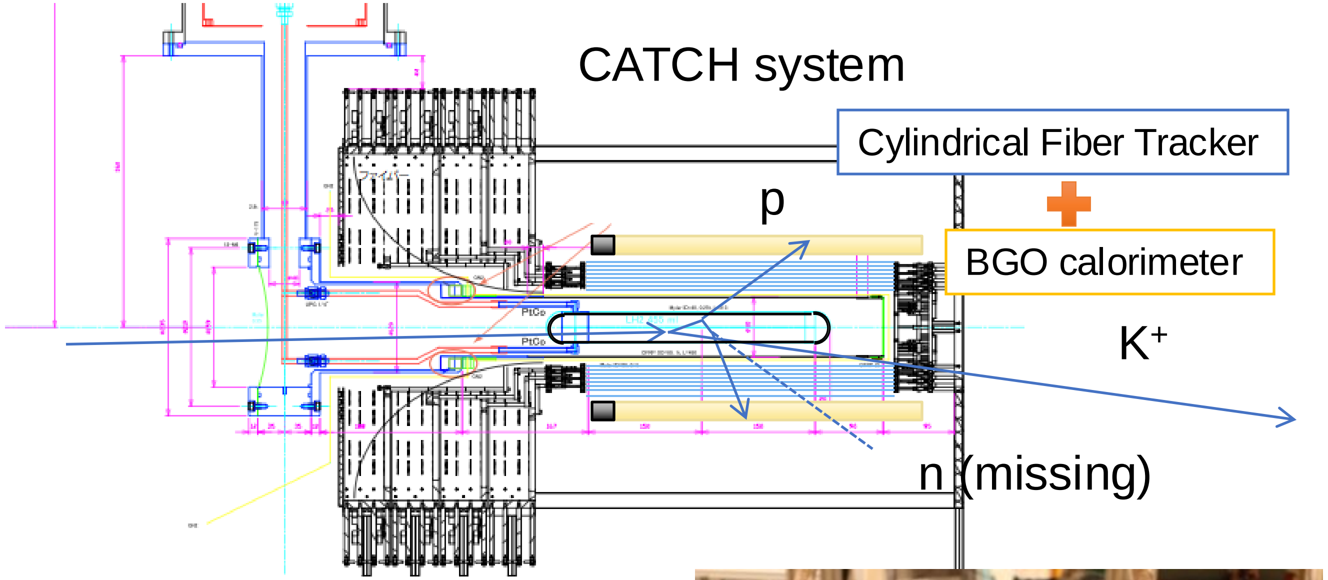
$$c(k^*) = \int S(r^*)\left|\Psi(\vec{k^*},\vec{r^*})\right|^2 d^3r^*$$



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

Σp scattering experiment at J-PARC (E40)





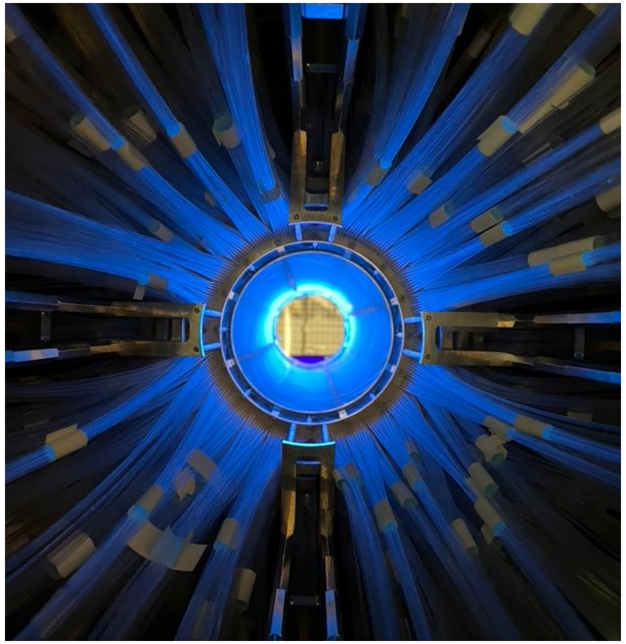
Many Σ hyperons are produced in LH_2 target

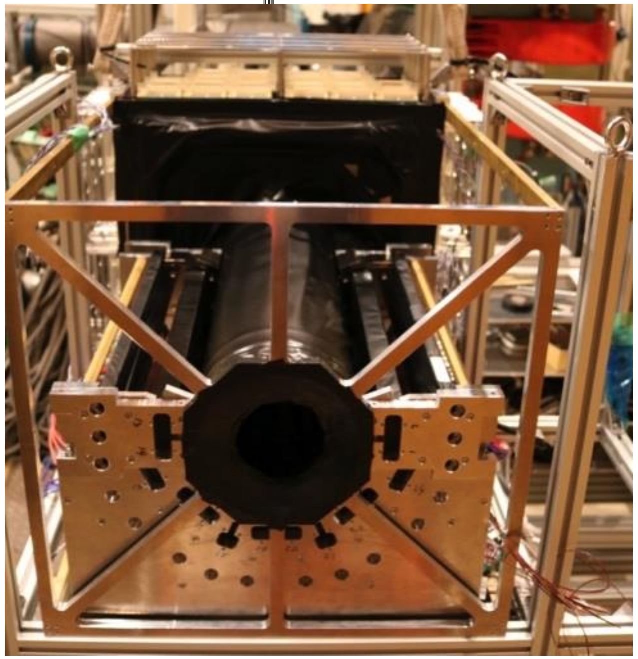
Σ are tagged by $\pi^{\pm}p \rightarrow K^{+}X$ reaction

- Σ^{-} beam : 17 M
- Σ^{+} beam : ~65 M

Secondary Σp scattering events are detected by surrounding detectors

- $\Sigma^{-}p$ elastic scattering
- $\Sigma^{-}p \rightarrow \Lambda n$ reaction
- $\Sigma^{+}p$ elastic scattering

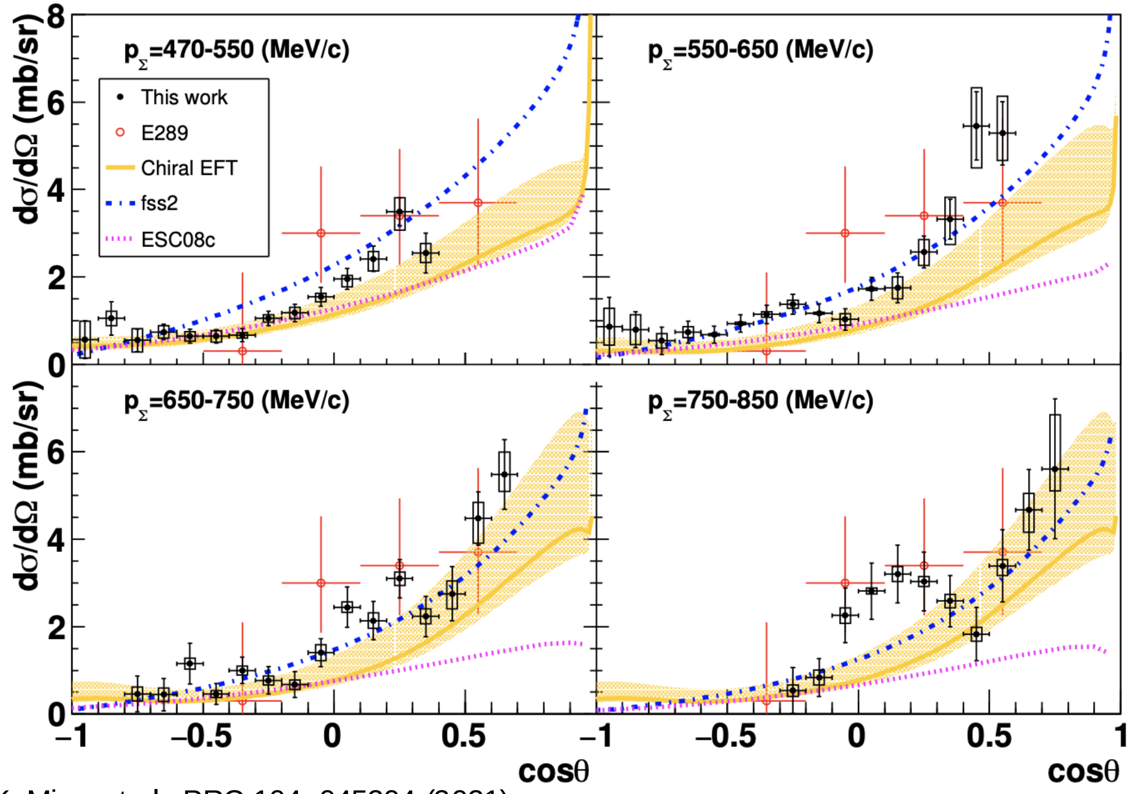




Systematic measurements of Σp dσ/dΩ

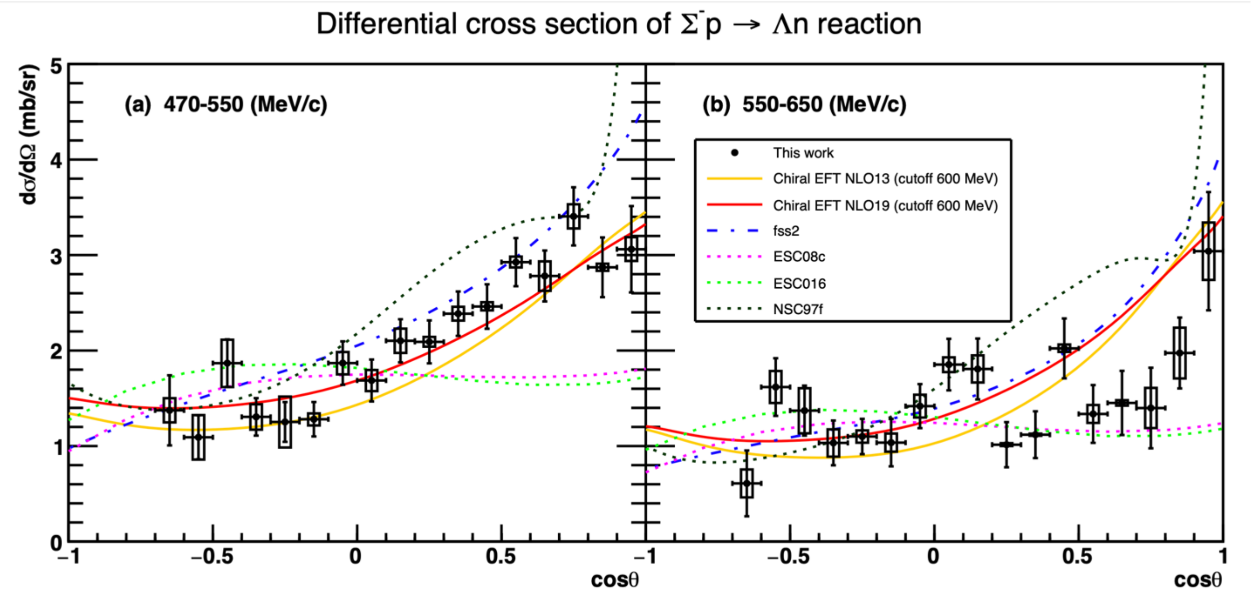
First accurate and systematic measurements of differential cross sections of Σ-proton channels

$\Sigma^- p$ elastic scattering (0.47 < p (GeV/c) < 0.85)



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

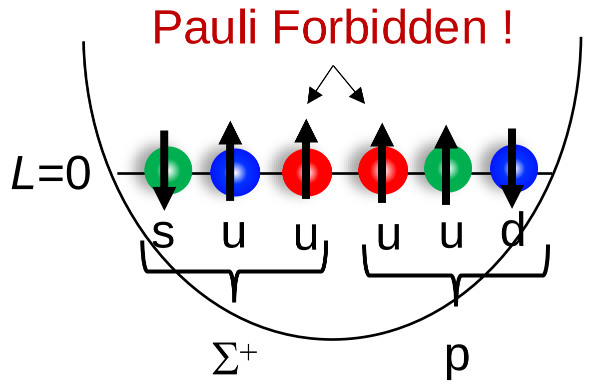
$\Sigma^- p \rightarrow \Lambda n$ reaction (0.47 < p (GeV/c) < 0.65)



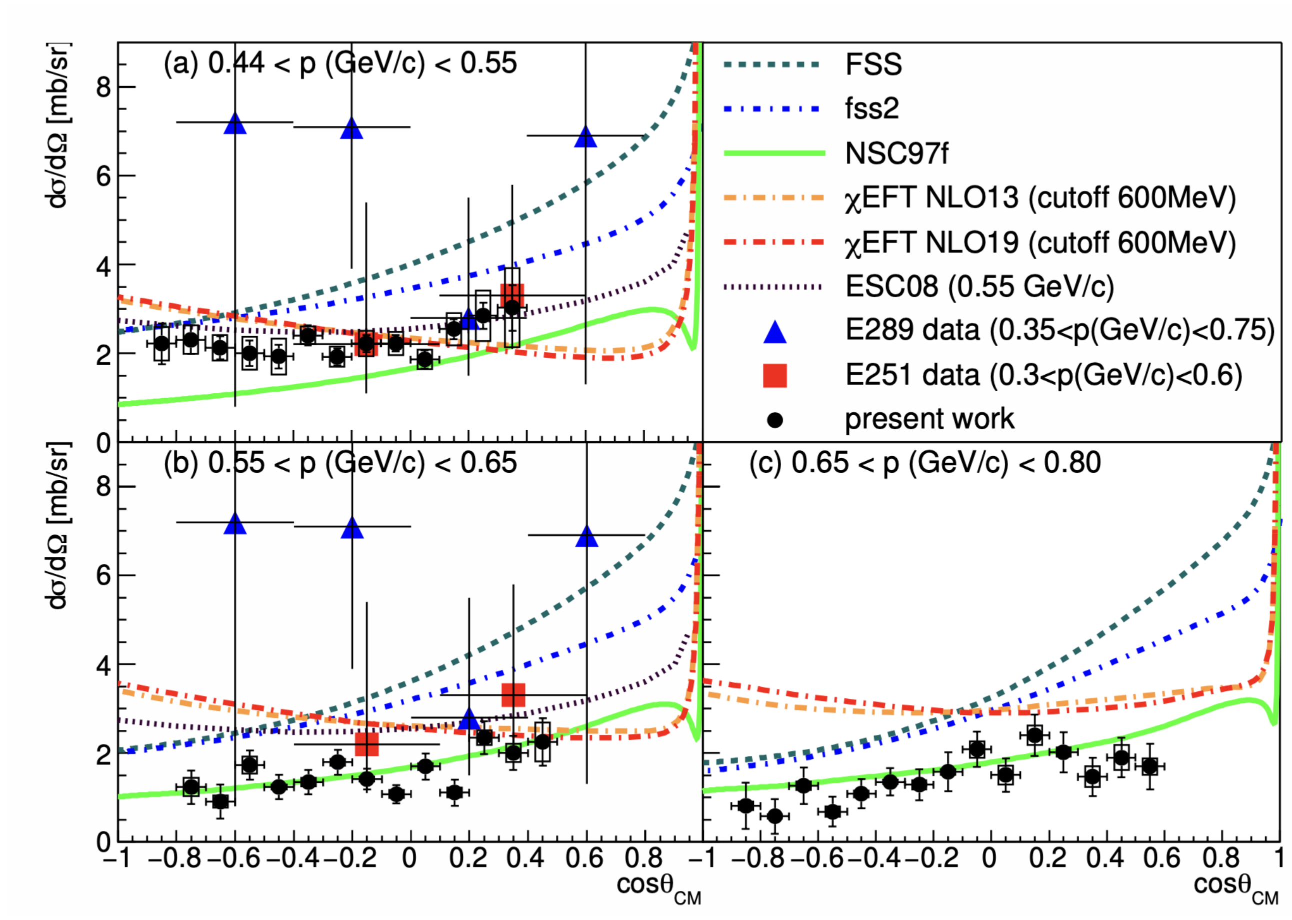
K. Miwa et al., PRL 128, 072501 (2022)

Quark model (fss2) and chiral EFT seem to be rather consistent with data, whereas Nijmegen (ESC) models is inconsistent at the forward angles.

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

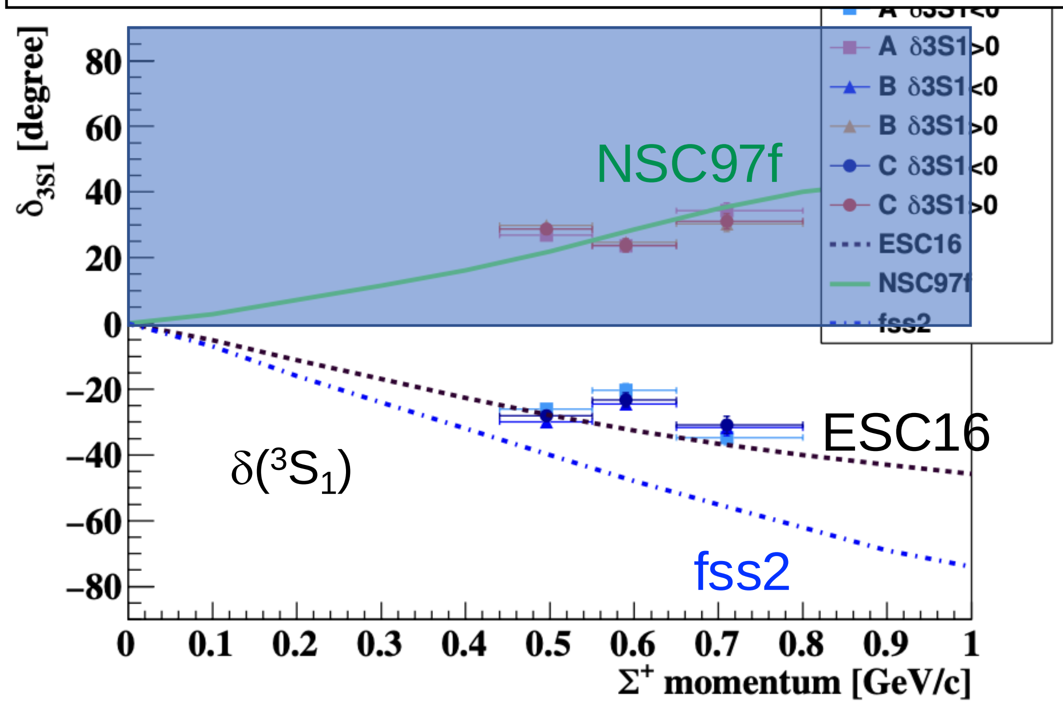


T. Nanamura et al., Prog. Theor. Exp. Phys. **2022** 093D01



E40 data : much smaller than fss2 prediction and E289 results

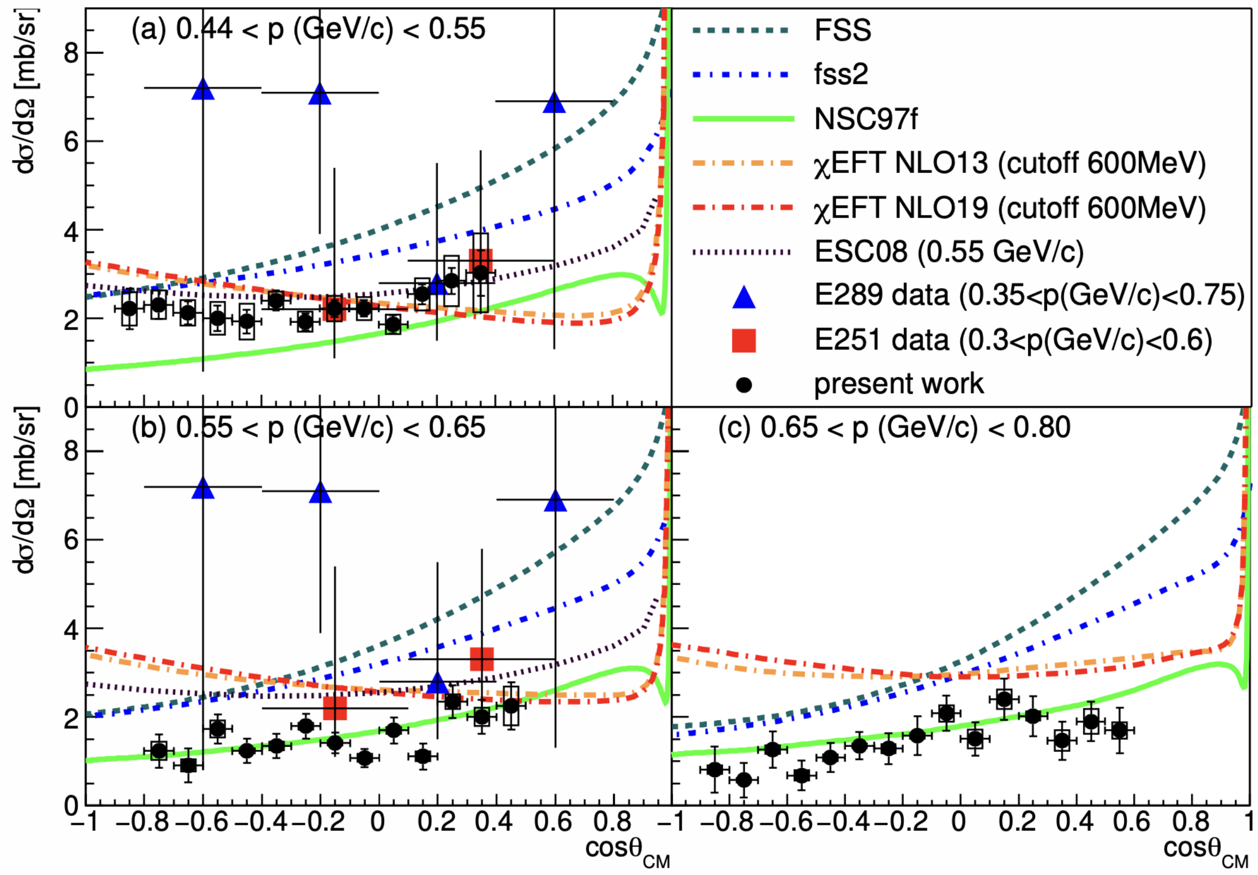
First experimental derivation of phase shift of $^3S_1$



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

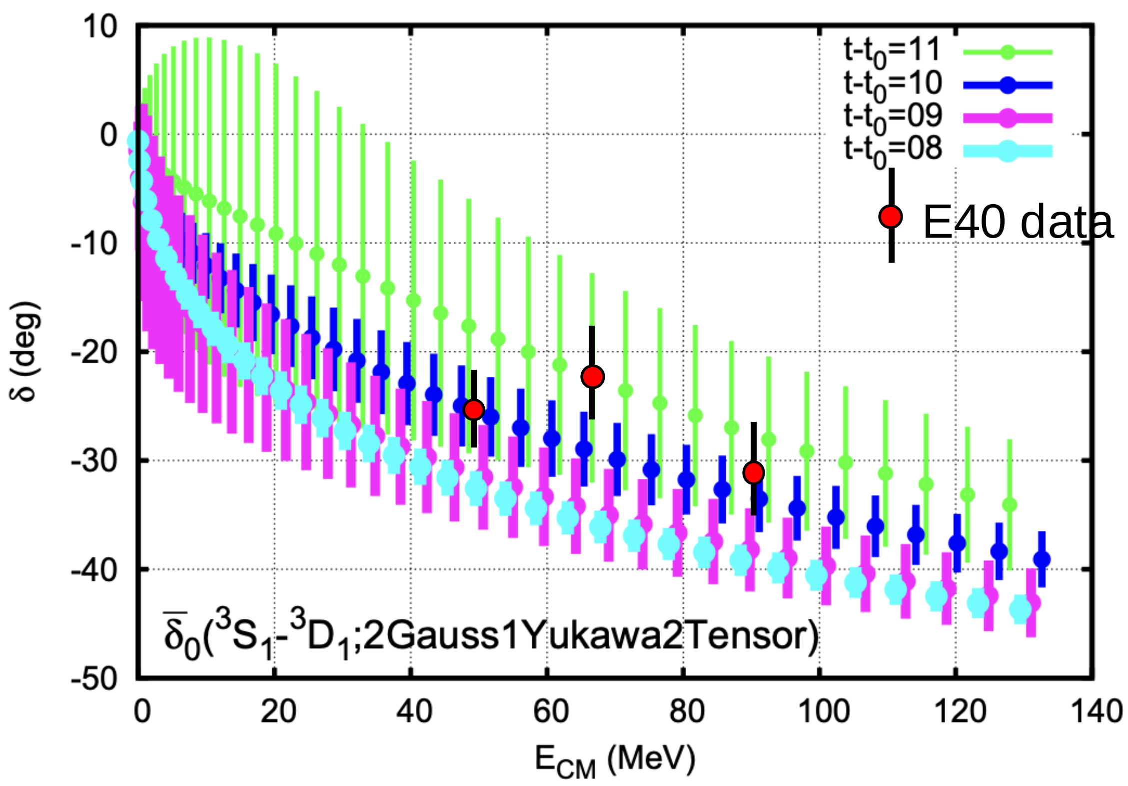
dσ/dΩ of Σ⁺p elastic scattering

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



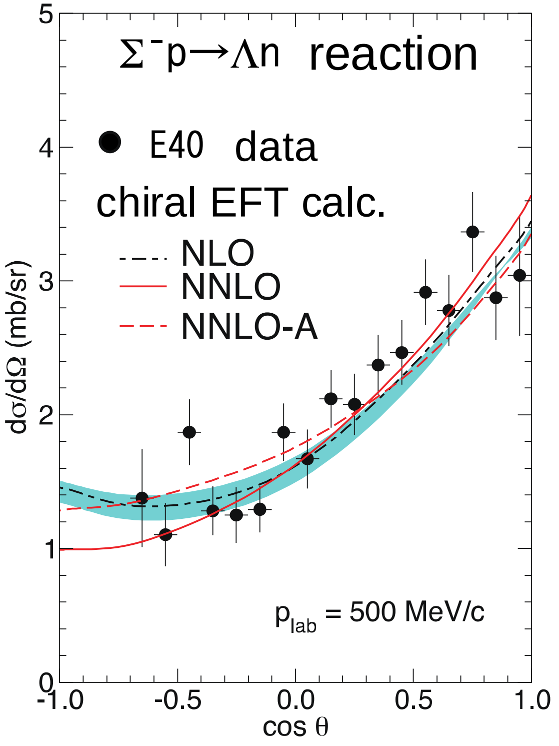
H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

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

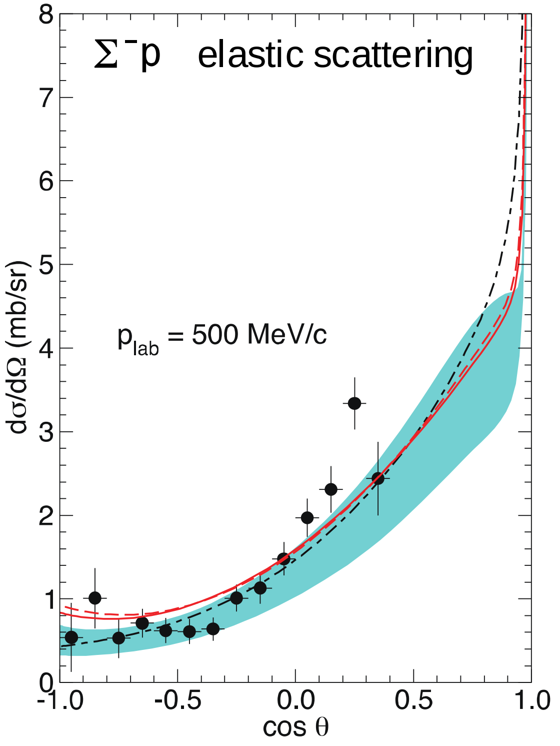
New Σp scattering data and progress of Chiral EFT

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

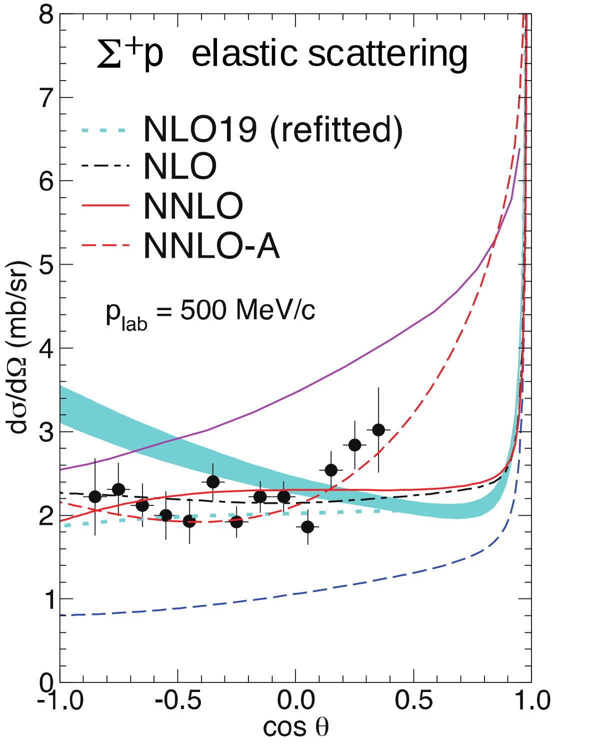
Difficulty at higher momentum



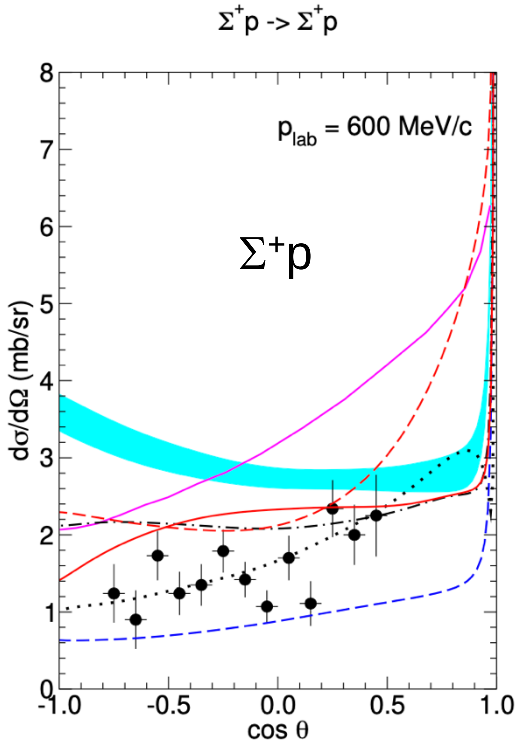
K. Miwa et al.,
PRL 128, 072501 (2022)



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



T. Nanamura et al., PTEP 2022 093D01



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

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

Updated ΛN, ΣN chiral interaction

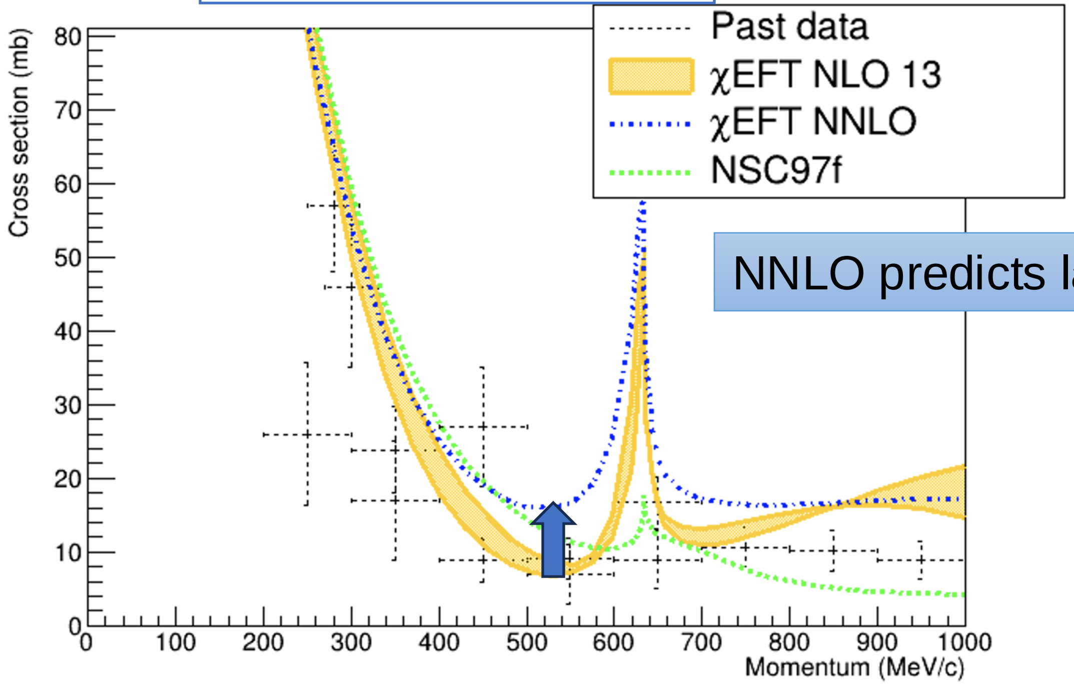
YN potential	B_Λ [MeV]	E [MeV]	P_Σ [%]	$U_\Lambda(0)$	$U_\Sigma(0)$
SMS N^{2}LO(500)	0.147	−2.371	0.25	−33.1	6.4
SMS N^{2}LO(550)^a	0.139	−2.362	0.25	−38.5	2.5
SMS N^{2}LO(550)^b	0.125	−2.348	0.24	−35.9	2.5
SMS N^{2}LO(600)	0.172	−2.395	0.22	−37.8	0.1
NLO13(600)	0.090	−2.335	0.25	−21.6	17.1
NLO19(600)	0.091	−2.336	0.21	−32.6	16.9

J. Haidenbauer et al., Eur. Phys. J. A 59 (2023) 63

Based on the E40 Σp scattering data,
U_Σ becomes less repulsive and
U_Λ becomes more attractive.

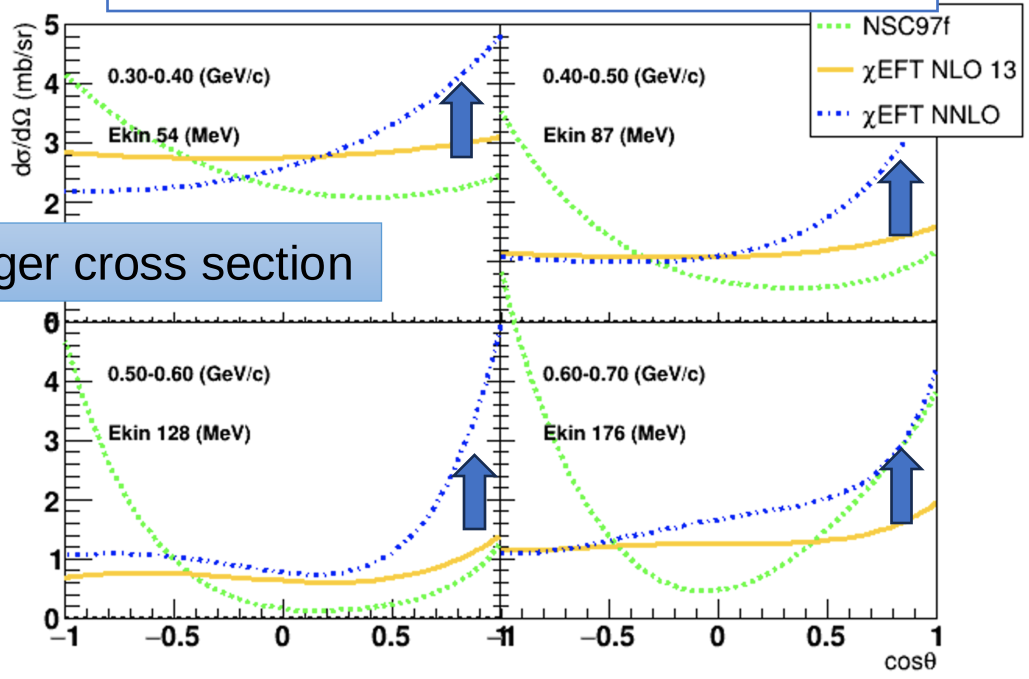
Calculation by J. Haidenbauer

Λp cross section



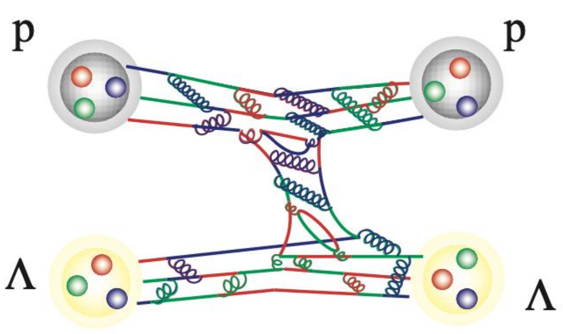
NNLO predicts larger cross section

Λp differential cross section

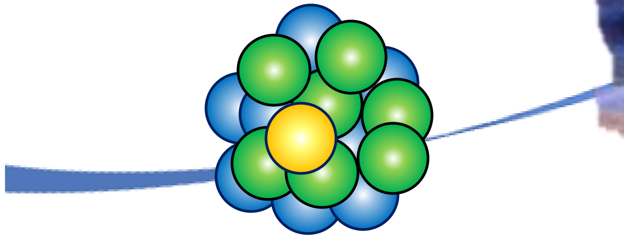


Toward Λp scattering

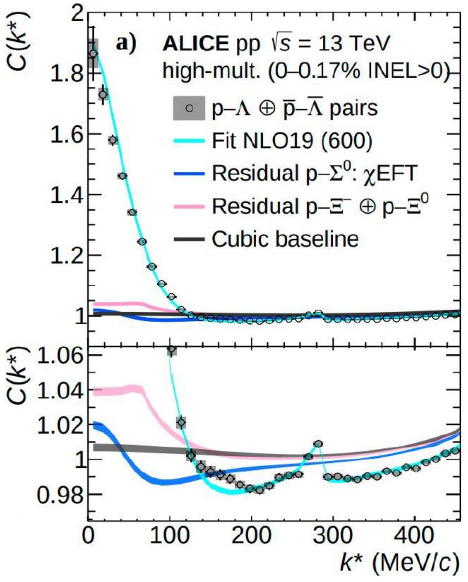
<u>Reliable ΛN two-body interaction :</u>
key to deepen Λ hypernuclear physics



Λ hypernuclei
key to reveal ΛNN int.

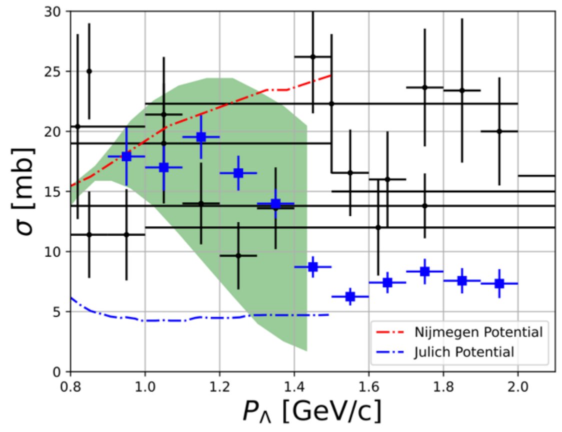


Femtoscopy from HIC



ALICE Collaboration, arXiv:2104.04427

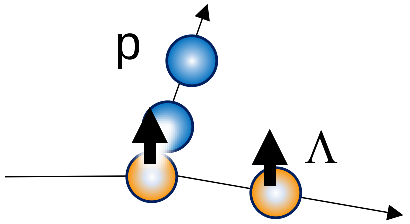
New cross section data
from Jlab CLAS



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

New project at SPring-8, J-PARC

Λp scattering w/ (polarized) Λ



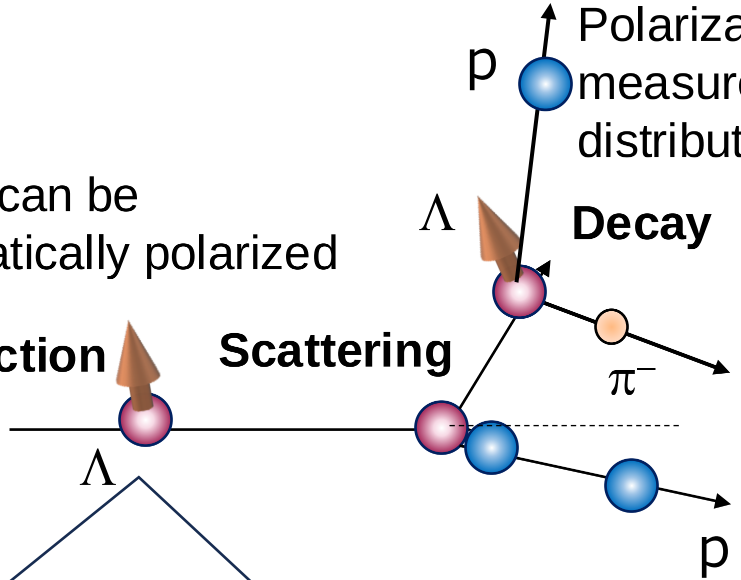
Λp scattering experiment with polarized Λ beam (J-PARC E86)

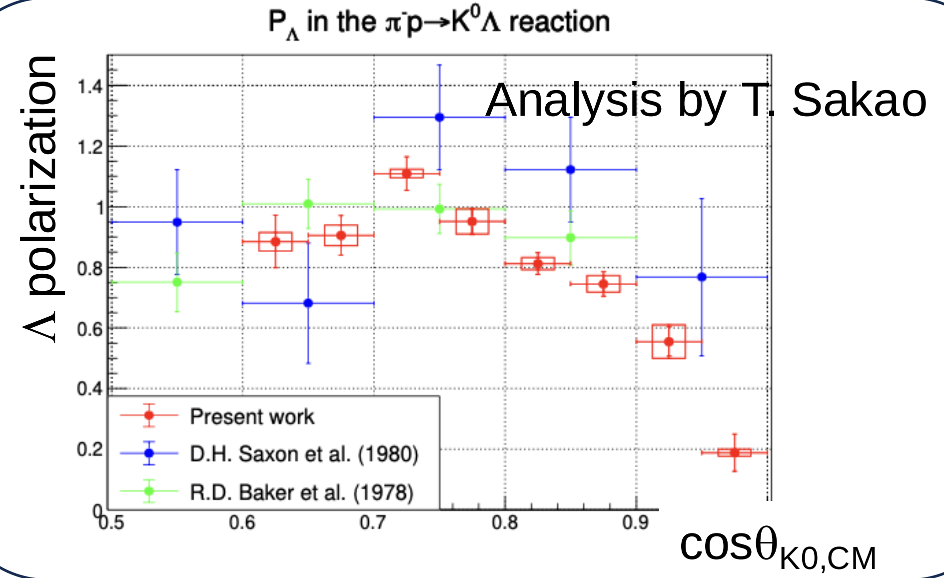
Advantage of scattering experiment: Spin observables can be measured thanks to self polarimeter of hyperon

Polarization can be measured from angular distribution of p

Λ spin can be automatically polarized

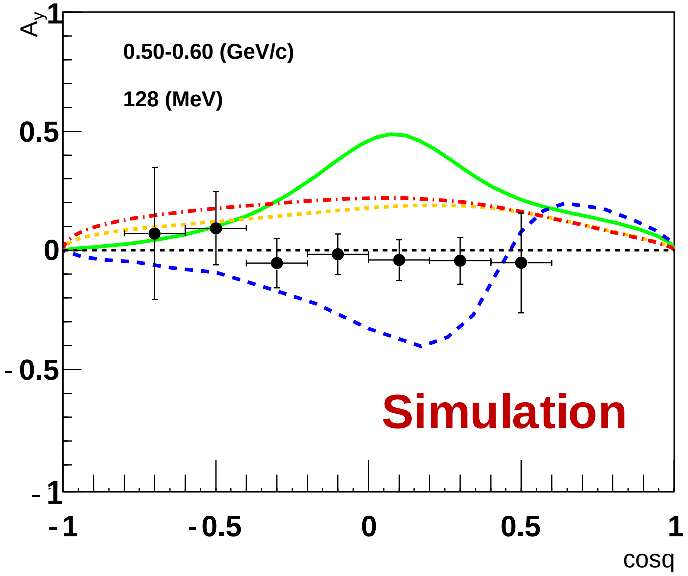
Production



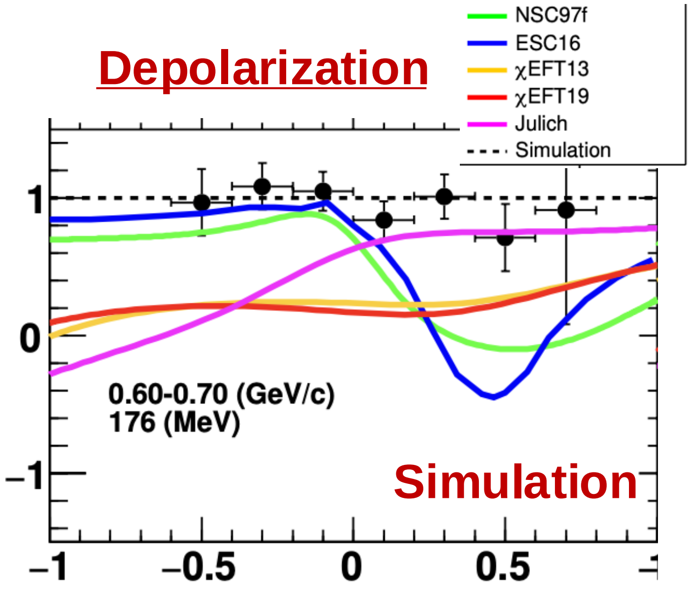


- Left-Right asymmetry of Λp scattering (Analyzing power)
  → spin-orbit interaction
- Polarization change before and after the scattering (Depolarization)
  → spin-spin interaction, tensor interaction

Analyzing power



Depolarization



Essential constraint to determine spin-dependent ΛN interaction

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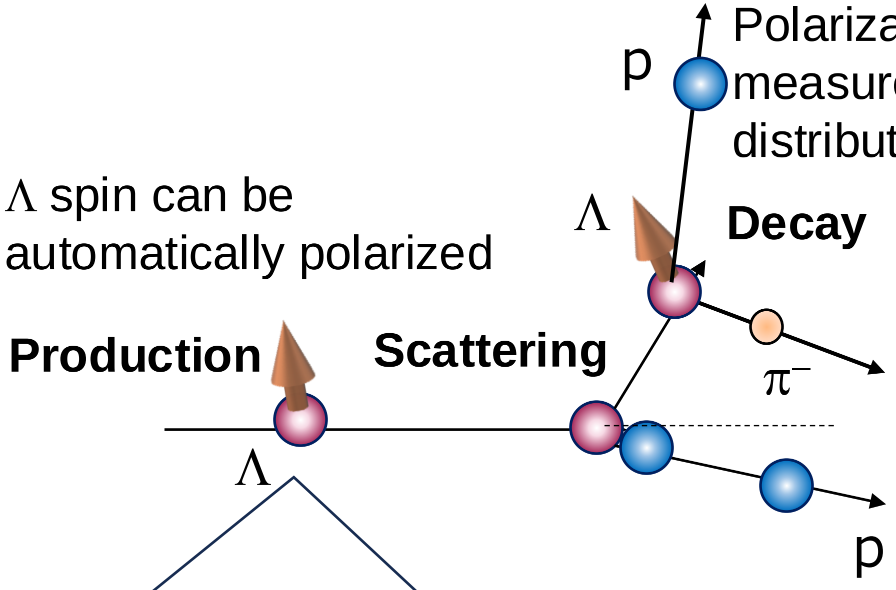

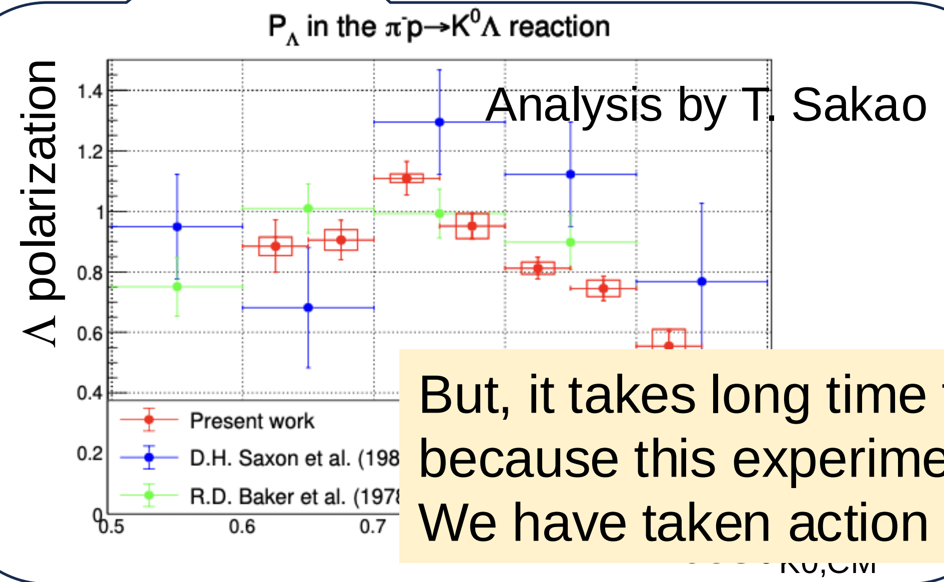

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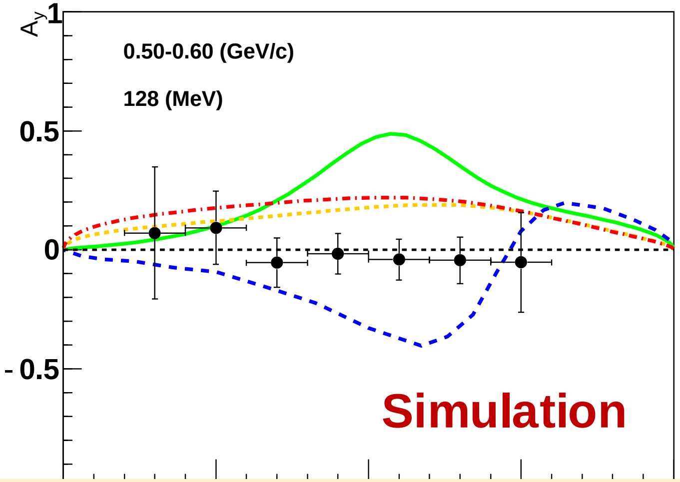
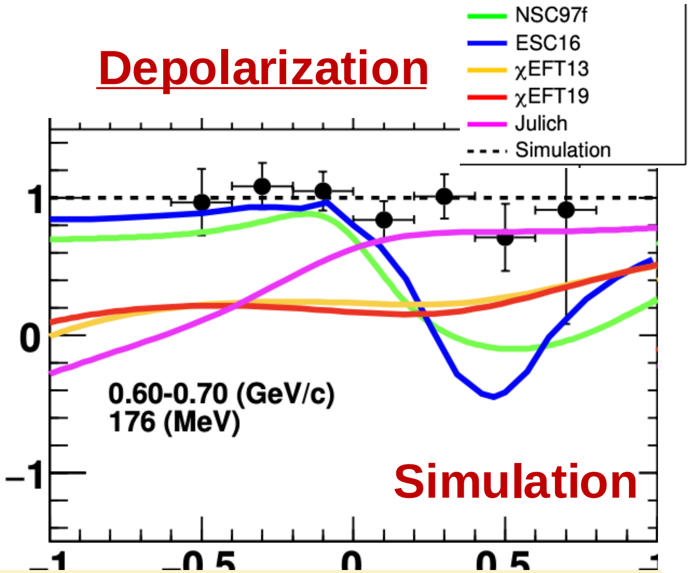
Analyzing power



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 $d\sigma/d\Omega$.

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

Activity at SPring-8

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

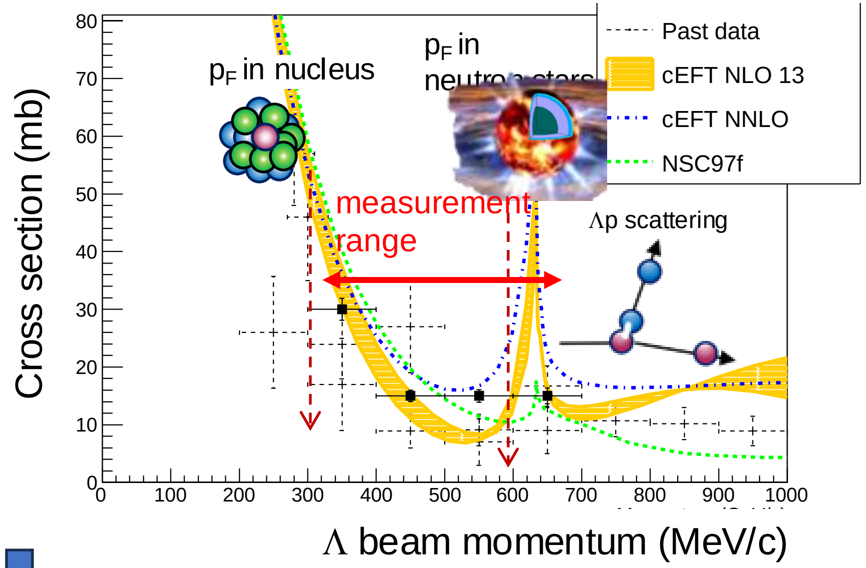
We plan to perform Λp scattering experiment at BL33LEP

Momentum tagged Λ particle produced γp→K^+Λ reaction

+

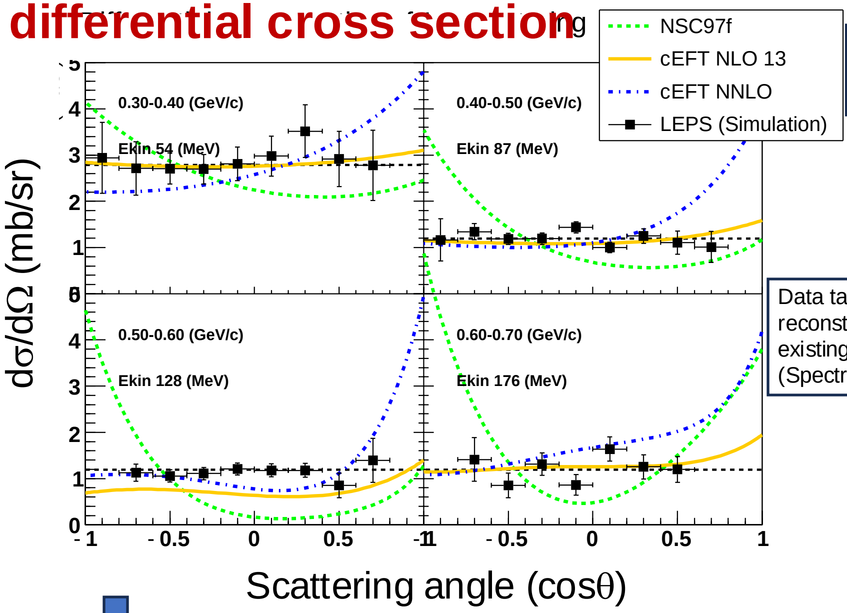
Existing YN scattering detector system (CATCH)

Λp total cross section



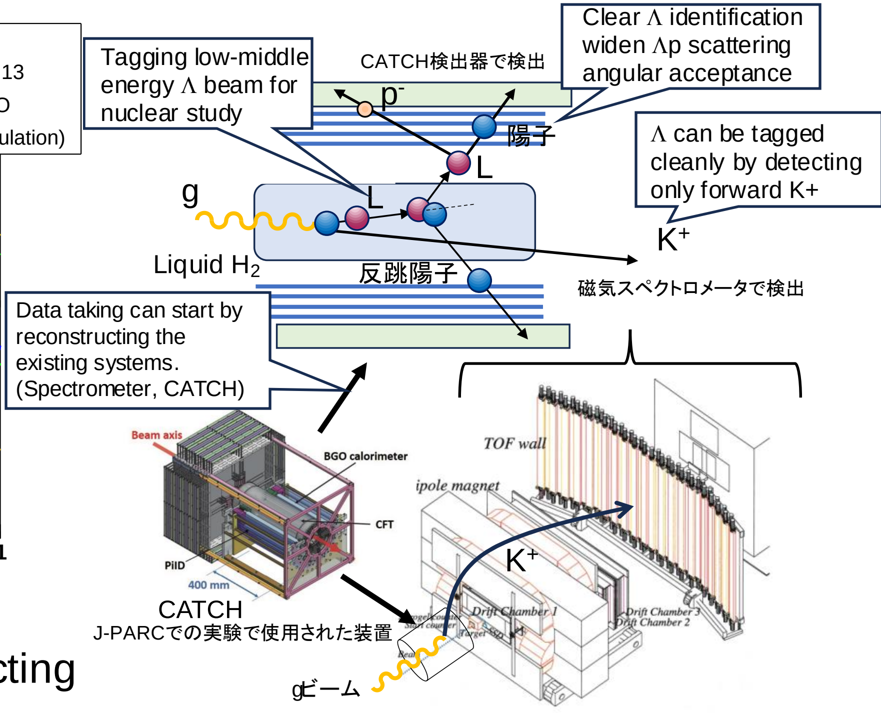
Density (radial) dependence of ΛN interaction

Λp differential cross section



Essential input for constructing realistic ΛN interaction

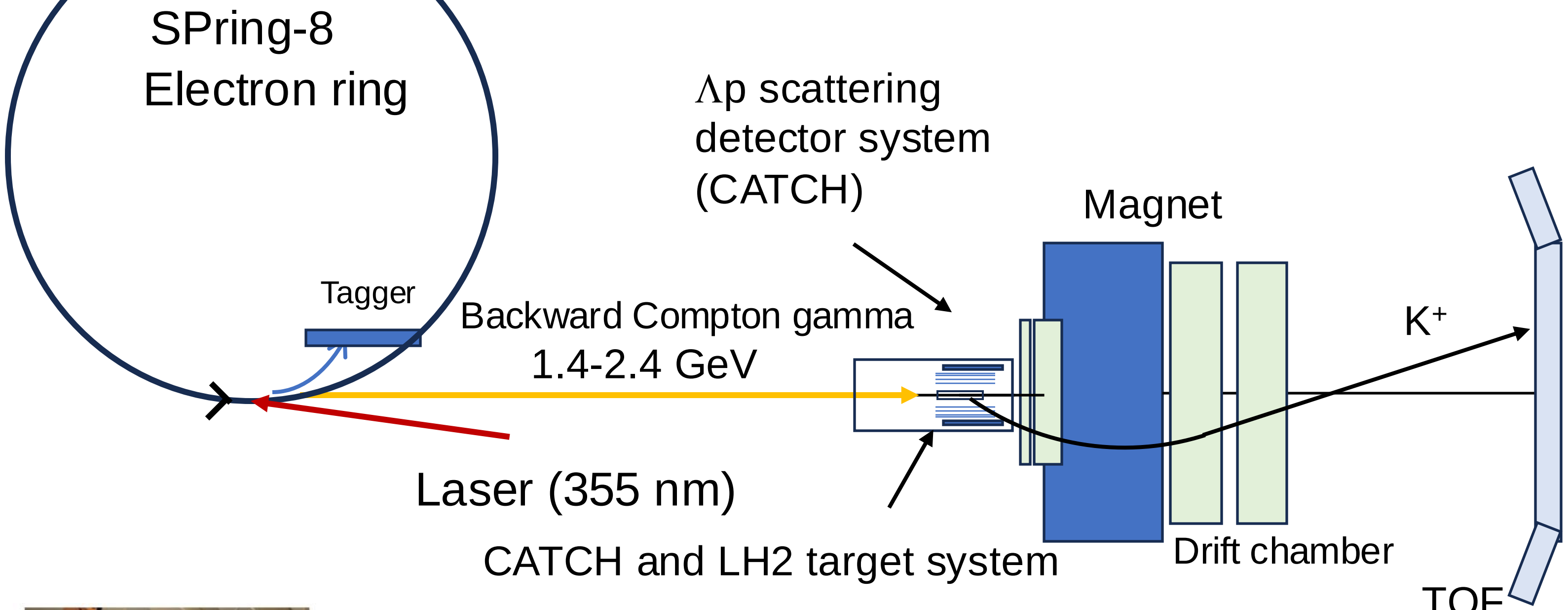
Advantage at BL33LEP

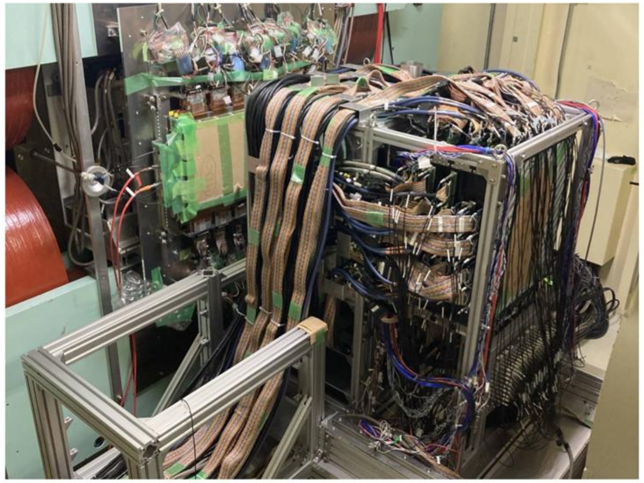


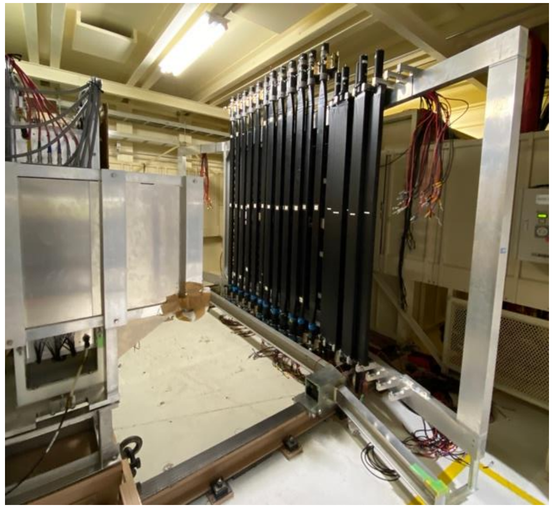
Experimental setup of Λp scattering experiment at SPring-8

We are preparing the experiment at SPring-8
to start data taking from next April.

Activity at
SPring-8



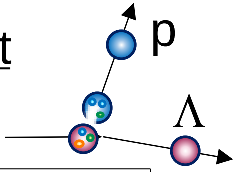




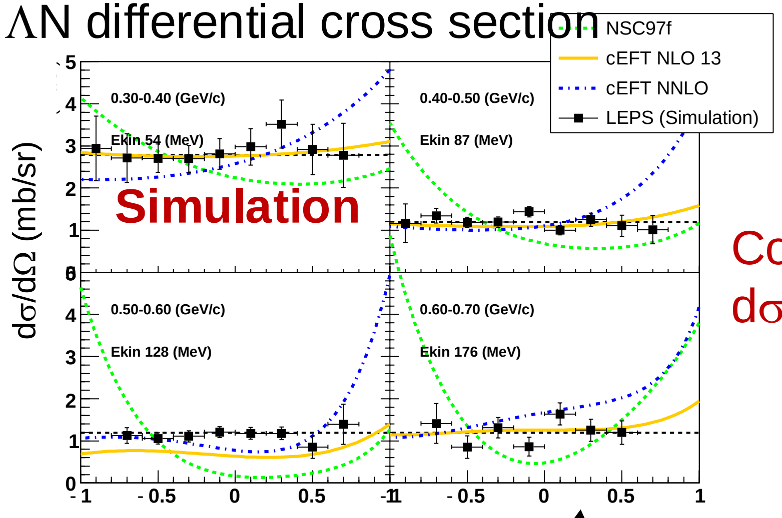
Transported detectors from J-PARC
to SPring-8

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

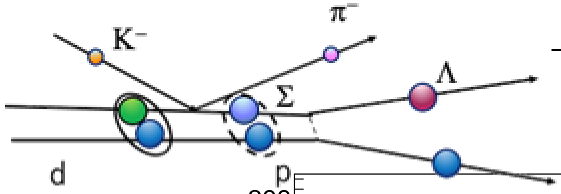
(1) Λp scattering experiment
(Koji Miwa)

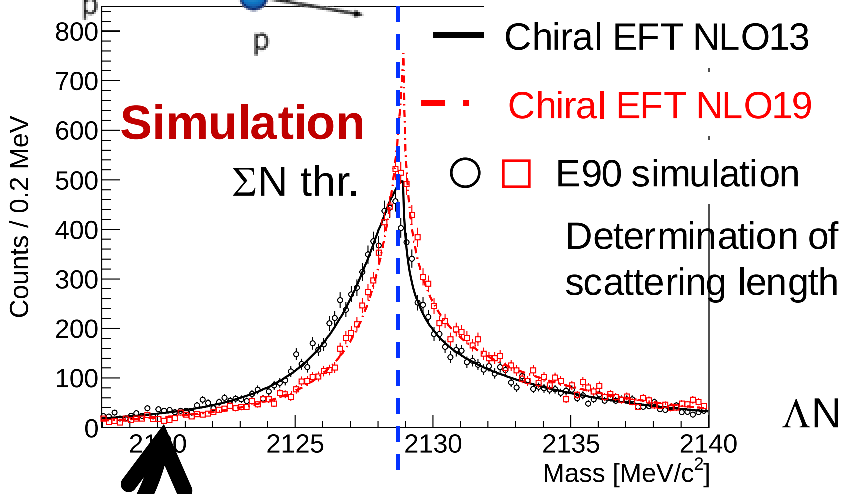


ΛN differential cross section



(2) ©N cusp measurement
(Yudai Ichikawa)



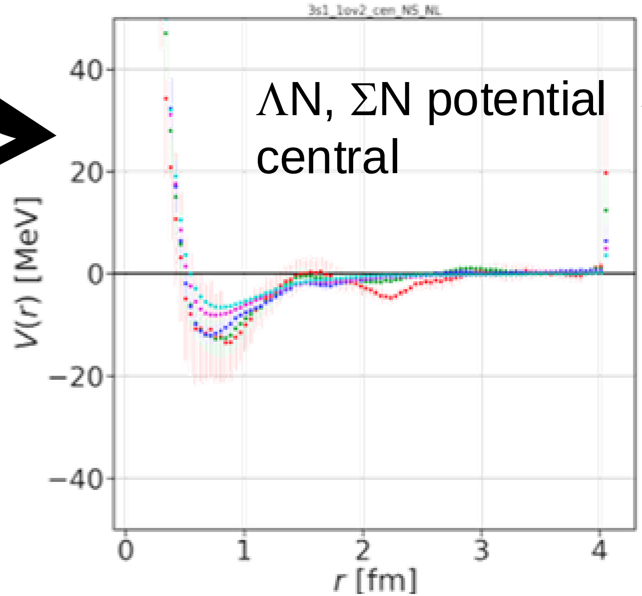


Consistency check between
dσ/dΩ and ΛN-ΣN coupling

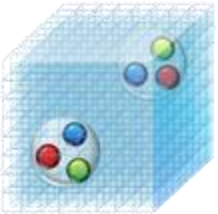
Determination of the ΣN (I=1/2, S=1)
scattering length from the cusp shape

ΛN-ΣN coupling

Independent determination of
ΛN-ΣN coupling



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

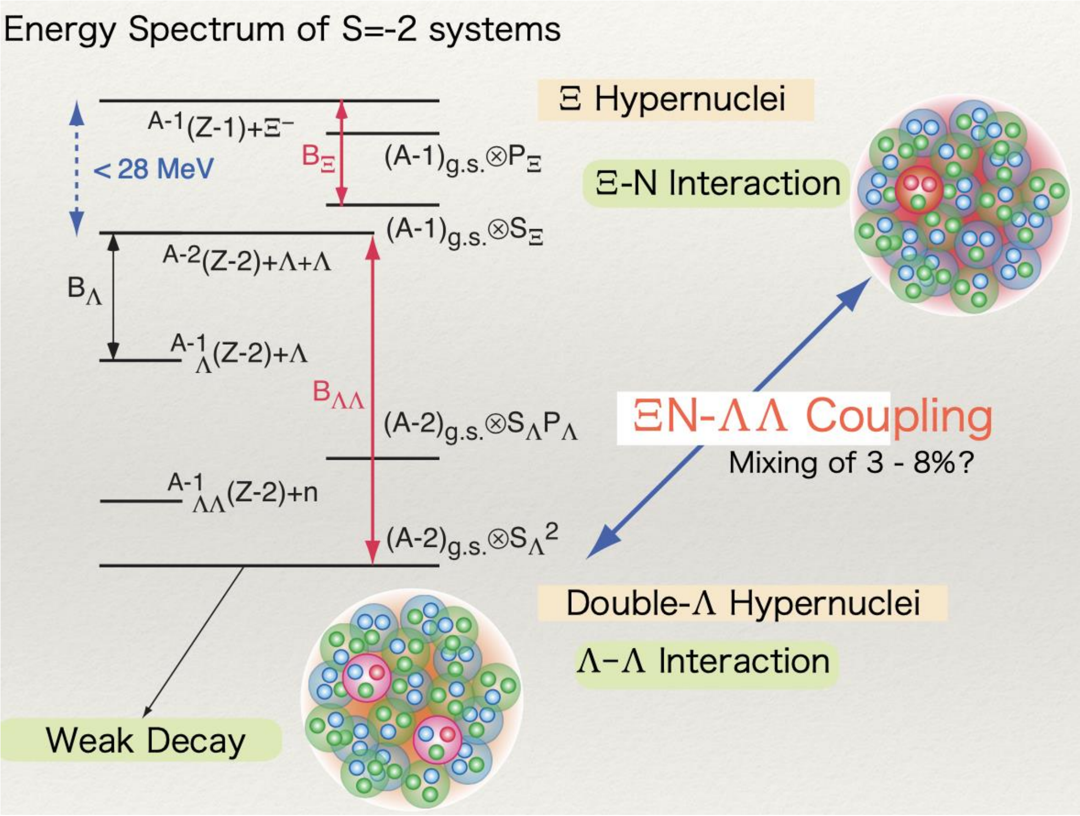


(3) ΛN, ΣN Lattice QCD potential
(Takahiro Doi)

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

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

Topics with S=–2 hypernuclei

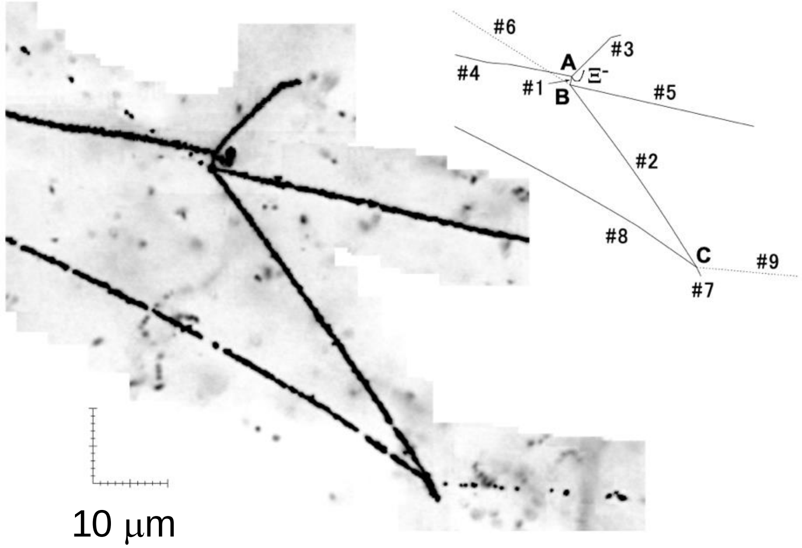


Performed experiment
Future experiment

- s-shell ΛΛ hypernuclei
  - $^{5}_{\Lambda\Lambda}$H : Possible lightest ΛΛ hypernucleus (E75)
- A=6~17 ΛΛ hypernuclei
  - Confirmation of ΛΛ interaction and nuclear structure effect such as shrinkage due to Λ (E07)
- Ξ hypernuclei
  - Emulsion (E07) & spectroscopy (E70)
- ΞN interaction with X-ray from Ξ-atoms (E03, E07)
  - ΞN interaction at nuclear surface
- ΛΛ p-wave interaction
  - excited ΛΛ hypernuclear state with one Λ hyperon in p-orbit
  - Direct production of ΛΛ hypernuclei via (K^-, K^+) reaction (E70 ?)
- Search for H-dibaryon state (E42)
  - Sharp resonance just below ΞN threshold is predicted by LQCD

Double Λ hypernuclei at J-PARC and KEK

H. Ekawa et al.,
Prog. Theor. Exp. Phys. 2019, 021D02 (2019)



Nuclide	$B_{\Lambda\Lambda}$ [MeV]
$_{\Lambda\Lambda}{}^{10}$Be	15.05 +- 0.11
$_{\Lambda\Lambda}{}^{11}$Be	19.07 +- 0.11
$_{\Lambda\Lambda}{}^{12}$Be	13.68 +- 0.11

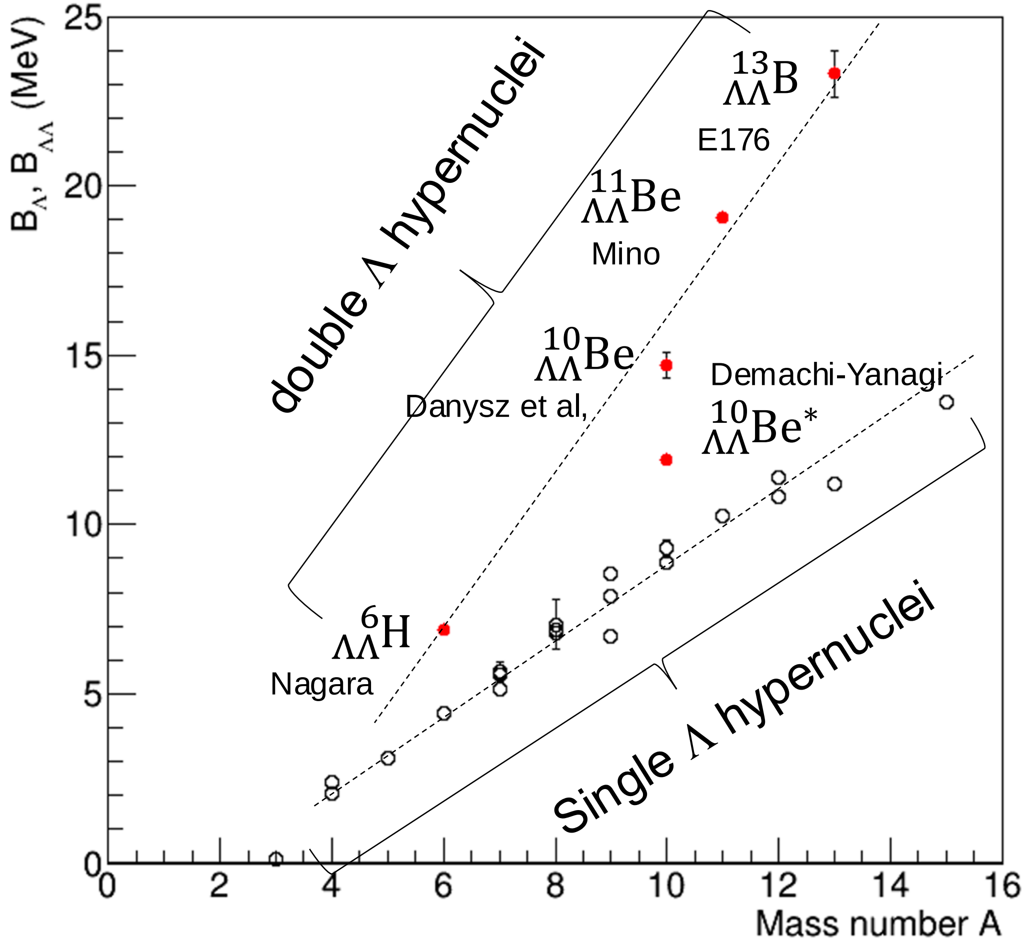
Where, B_{Ξ^-} = 0.23 MeV

$$^{16}\mathrm{O} + \Xi^- \to ({}^{10}_{\Lambda\Lambda}\mathrm{Be},\ {}^{11}_{\Lambda\Lambda}\mathrm{Be},\ {}^{12}_{\Lambda\Lambda}\mathrm{Be}) + {}^4\mathrm{He} + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_\Lambda\mathrm{He} + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$

$^{11}{}_{\Lambda\Lambda}$Be is the most kinematically plausible
(in the assumption of capture on atomic 3D state)

→ $B_{\Lambda\Lambda}$ ($\Delta B_{\Lambda\Lambda}$) = 19.07 ± 0.11 (1.87 ± 0.37) MeV

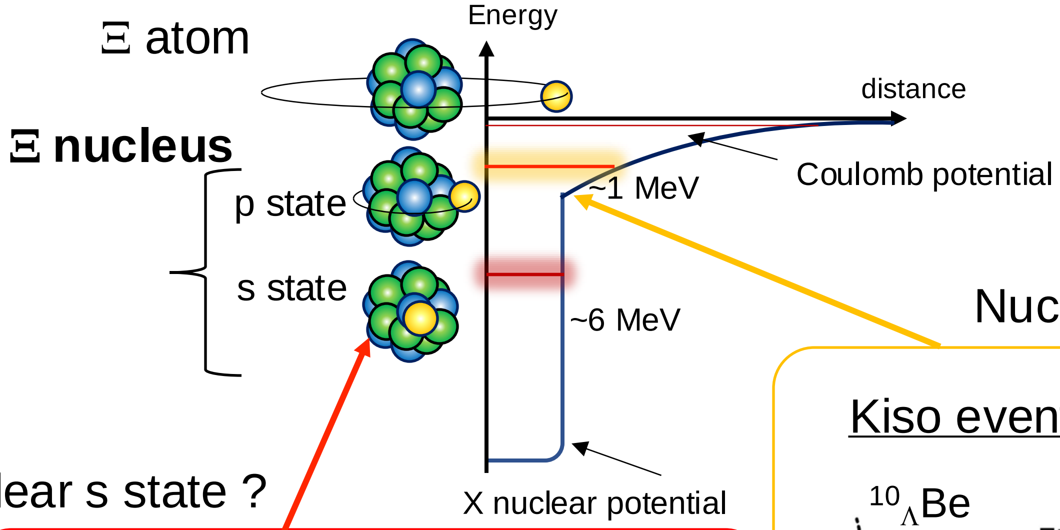
Mass number dependence for $B_{\Lambda\Lambda}$



The value of $\Delta B_{\Lambda\Lambda}$ seems to be inconsistent with that of the NAGARA event

Ξ hypernuclei

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



Nuclear s state ?

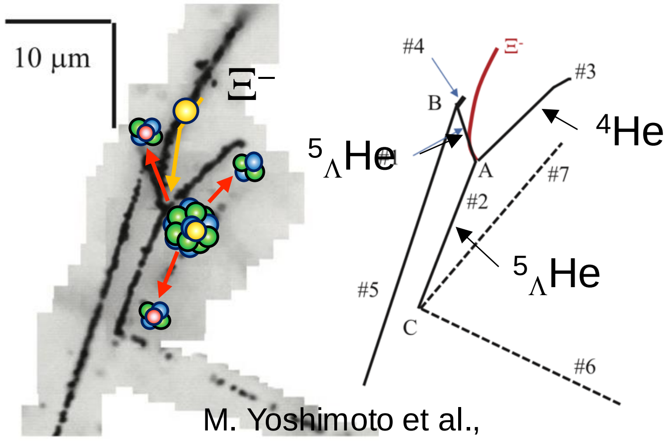
Measure the mass of Ξ nuclei produced by absorption of Ξ^- into ^{14}N nucleus in emulsion.

Two different energy levels

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

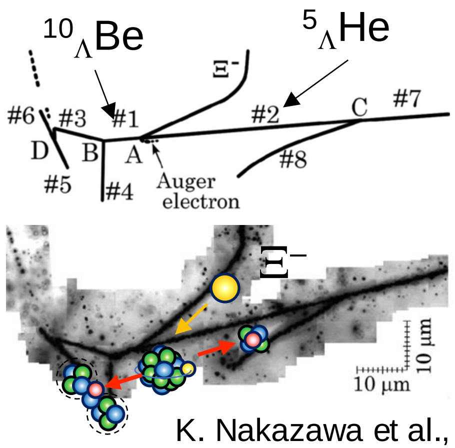
Nuclear p state

Irrawadi event



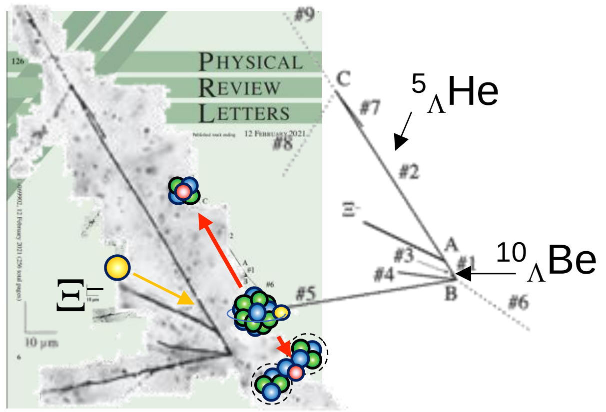
M. Yoshimoto et al., PTEP. 2021, 073D02

Kiso event



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

Ibuki event



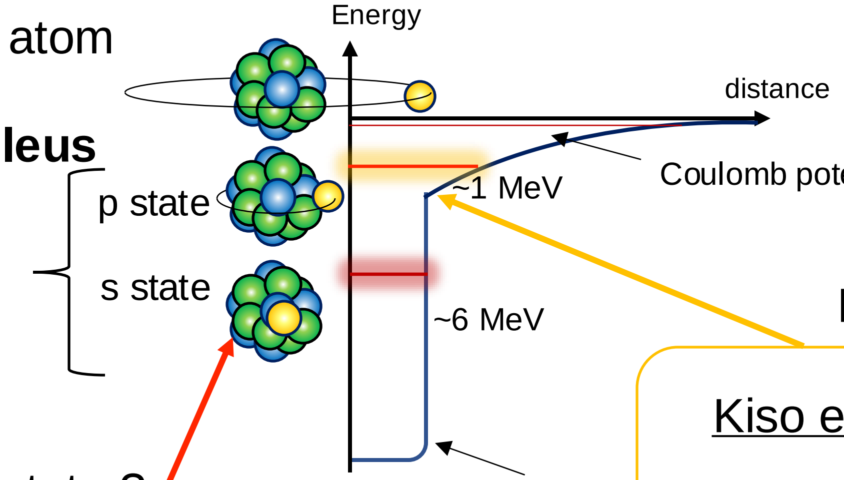
S. H. Hayakawa et al., PRL, 126, 062501 (2021)

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.

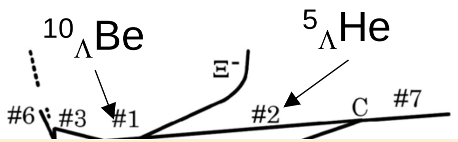
Two different energy levels
- BE ~1 MeV (p state)
- BE ~6 MeV (s state)



Nuclear s state ?

Nuclear p state

Kiso event



Ibuki event

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

Irrawadi event

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.

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

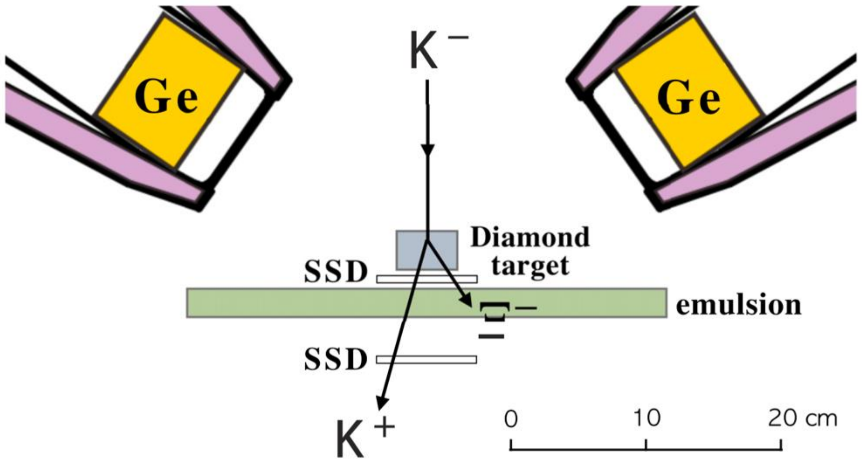
First attempt to measure Ξ Atomic X-ray in E07

Ξ-Ag/Br atomic X rays in emulsion

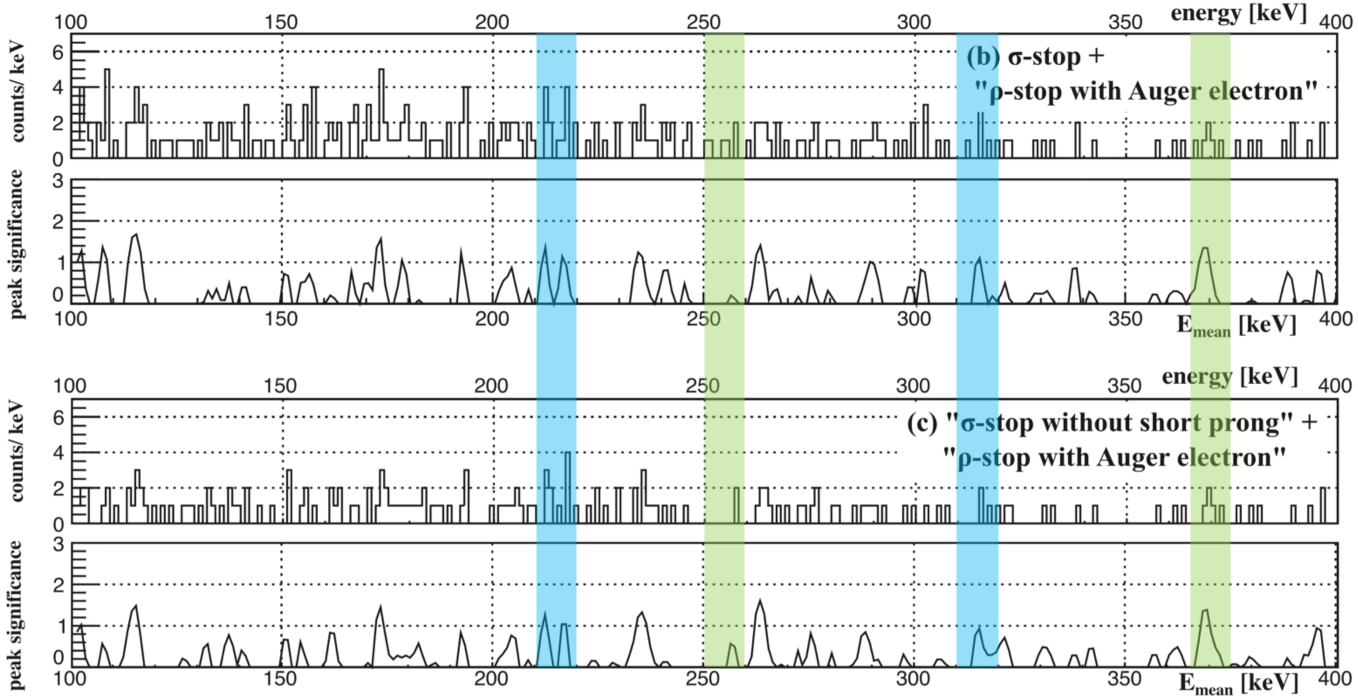
Triple-coincidence hybrid method

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

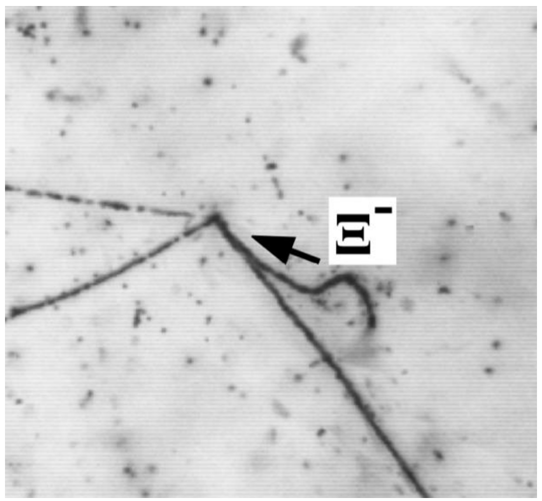
X-ray peaks were not observed due to lower emulsion and Ge detector efficiencies than expected



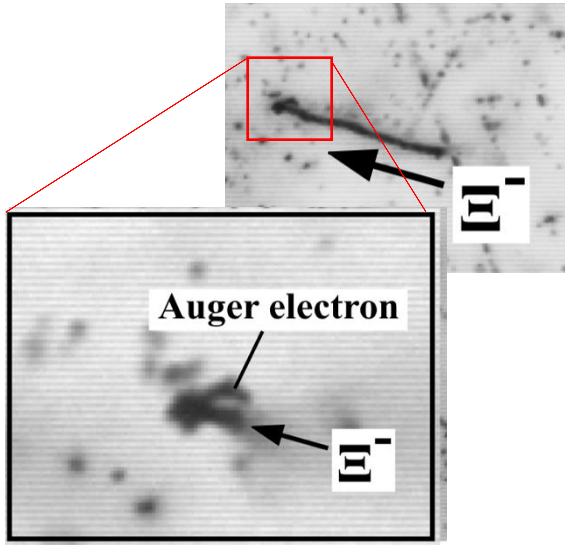
Br (8J→7I) 206 keV | Ag (9K→8J) 255 keV | Br (7I→6H) 316 keV | Ag (8J→7I) 370 keV



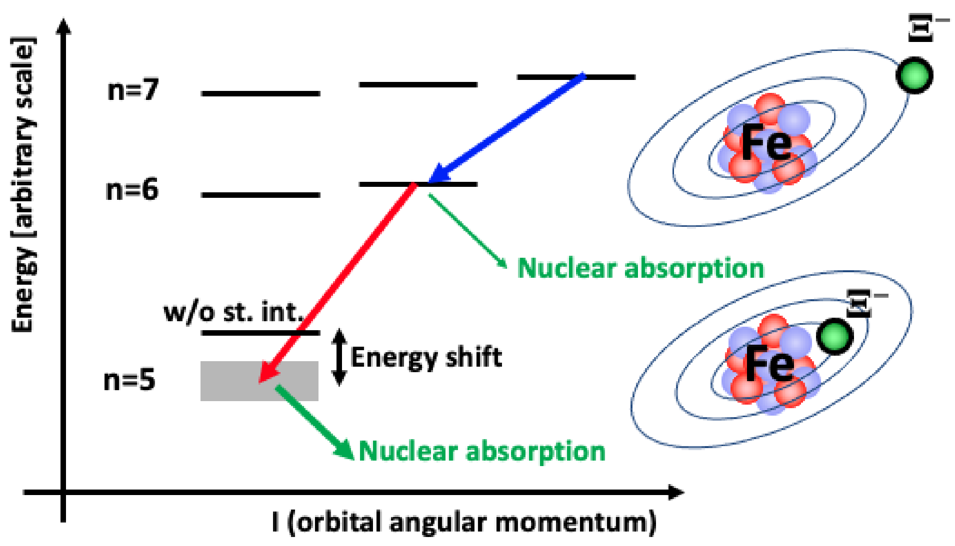
σ-stop
(Nuclear fragment from Ξ^- stop)

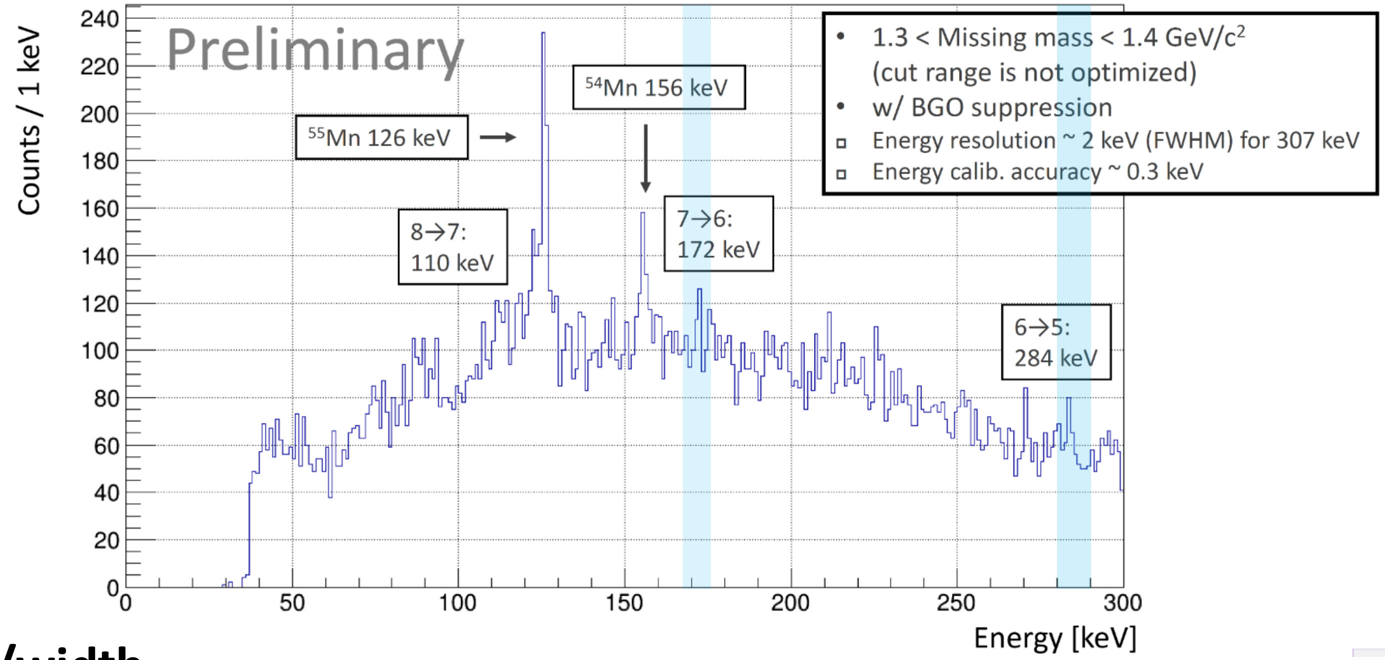


ρ-stop with Auger electron
(Absorption by heavy elements)



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?**

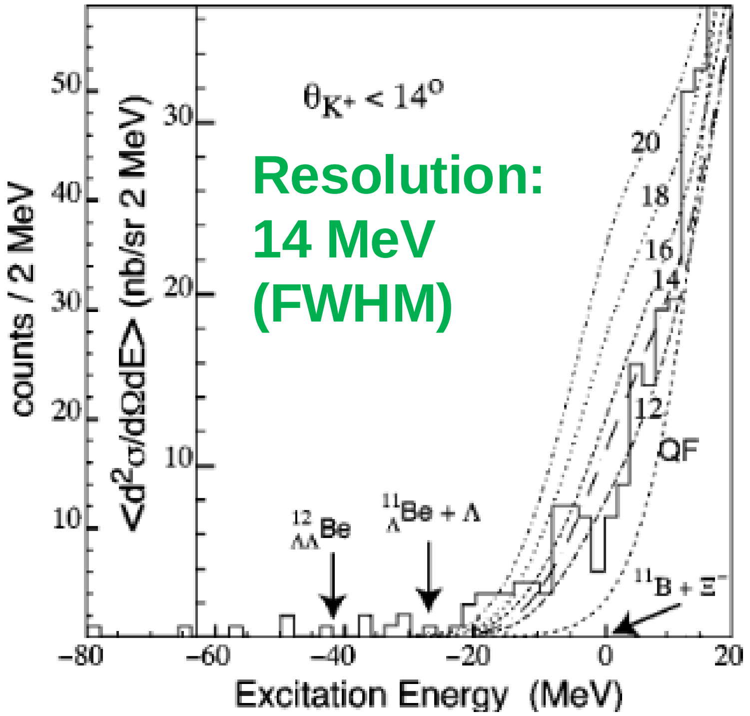
→ **Good S/N measurement may have advantage than high statistics measurement.**

⇒ **Future measurement w/ Ξ stop identification using active target**

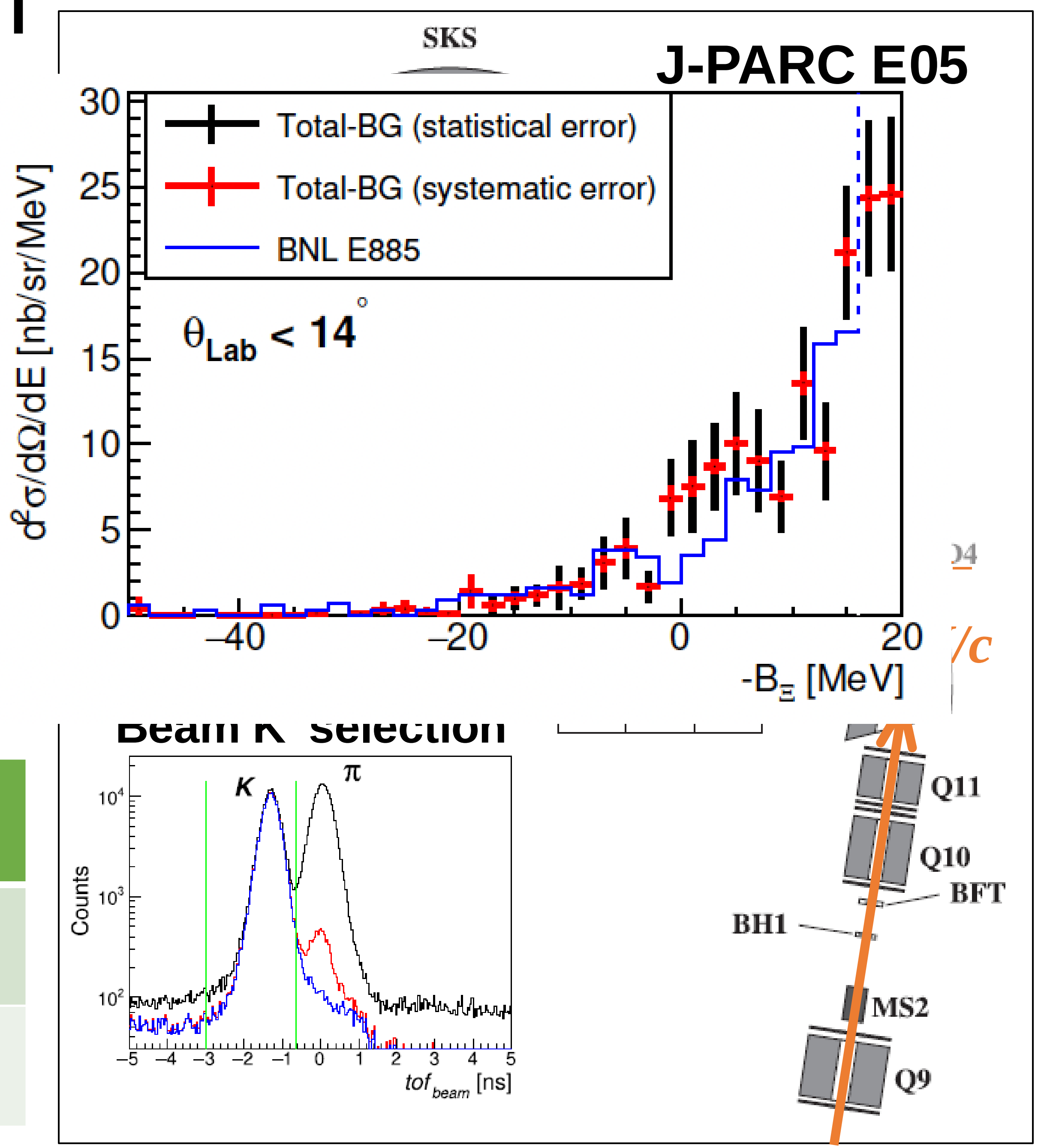
New $^{12}C(K^-, K^+)$ spectrum

Y. Ichikawa *et al.*, *PTEP* 2024 (2024) 9, 091D01

BNL E885



P. Khaustov et al.,
PRC **61** 054603(2000).

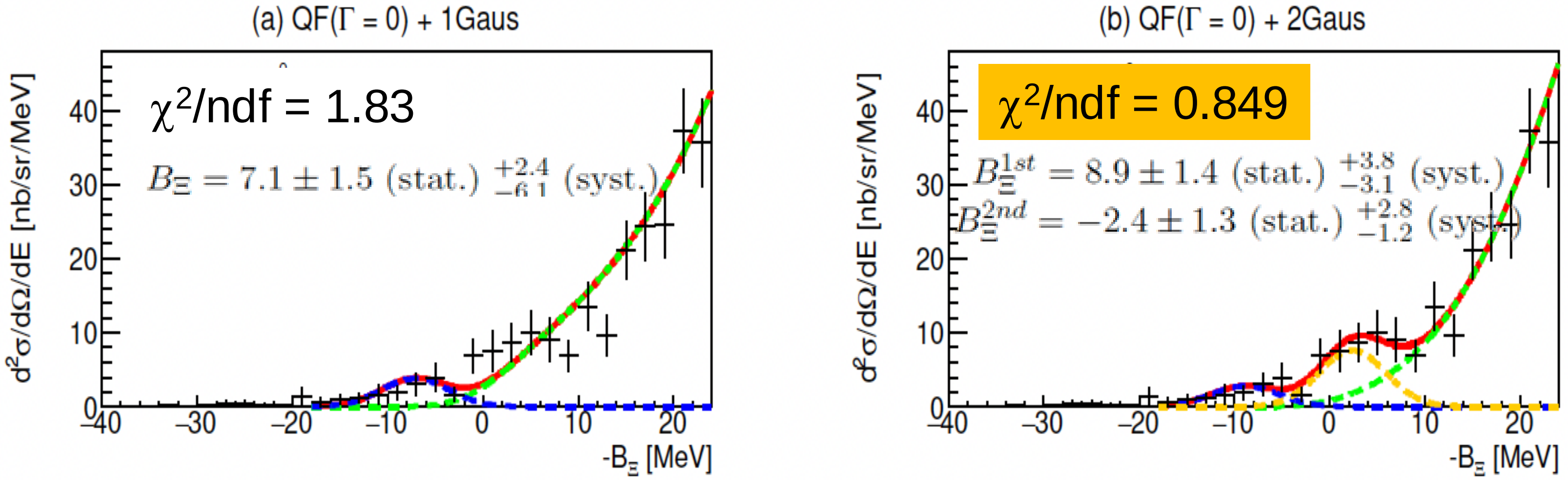


Experiment	BNL E885	J-PARC E05	J-PARC E70
Resolution FWHM (MeV)	14	8	2
Momentum range (GeV/c)	0.8 - 1.4	0.8 - 2.2	1.2 - 1.5

Spectrum Fitting

Not decisive data but some hints

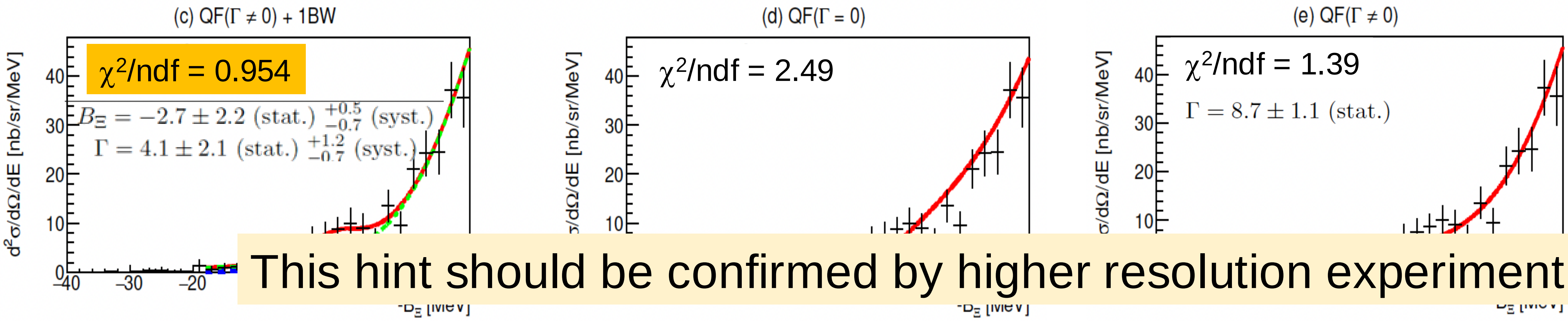
Y. Ichikawa *et al.*, *PTEP* 2024 (2024) 9, 091D01



QF function

$$h(B'_\Xi) = C\sqrt{B'_\Xi}\exp(\alpha B'_\Xi + \beta B'^2_\Xi)$$

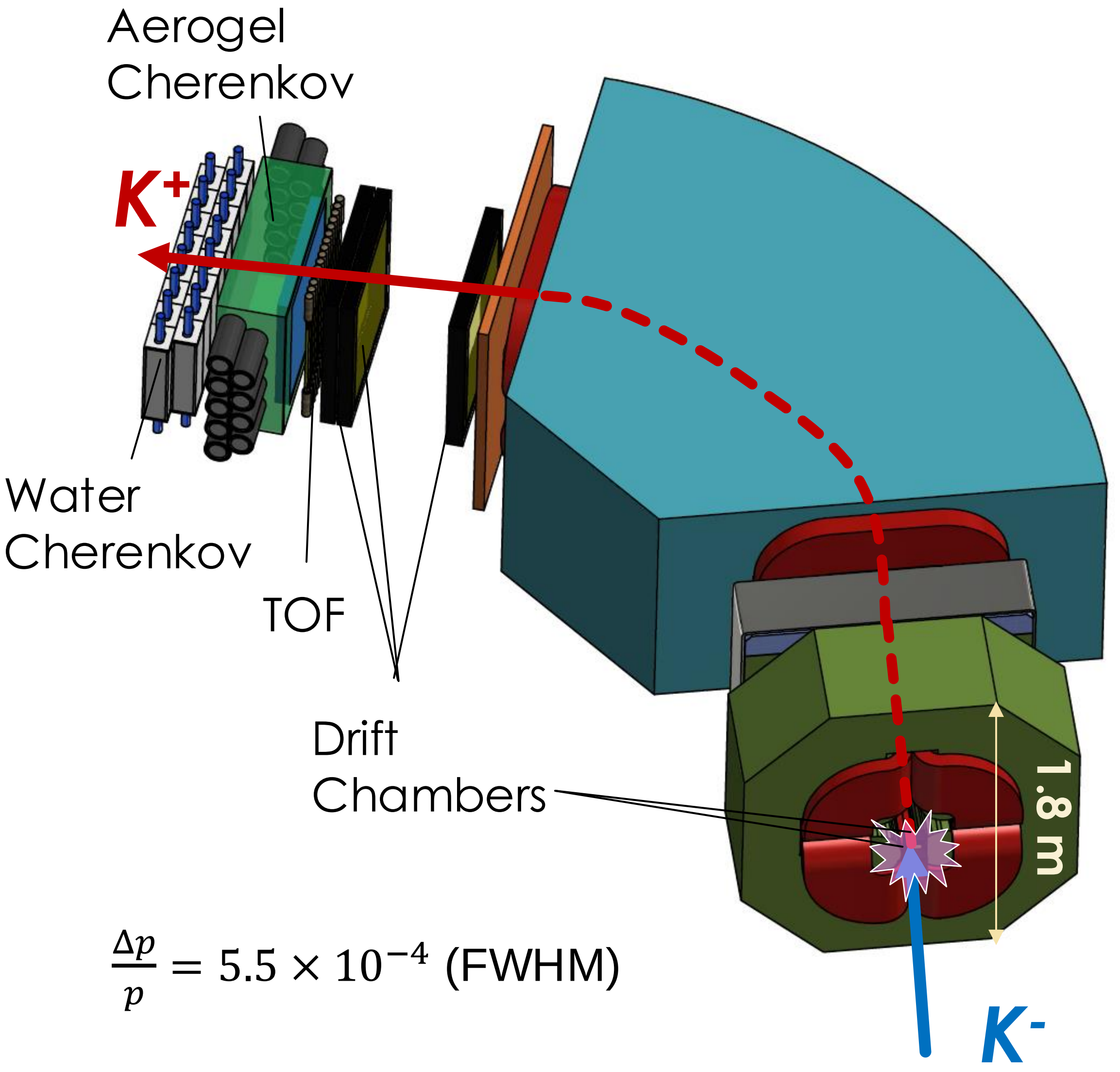
Convoluted by Gaus (Γ = 0)
Convoluted by Voigt (Γ ≠ 0)



This hint should be confirmed by higher resolution experiment

E70 experiment with S-2S spectrometer

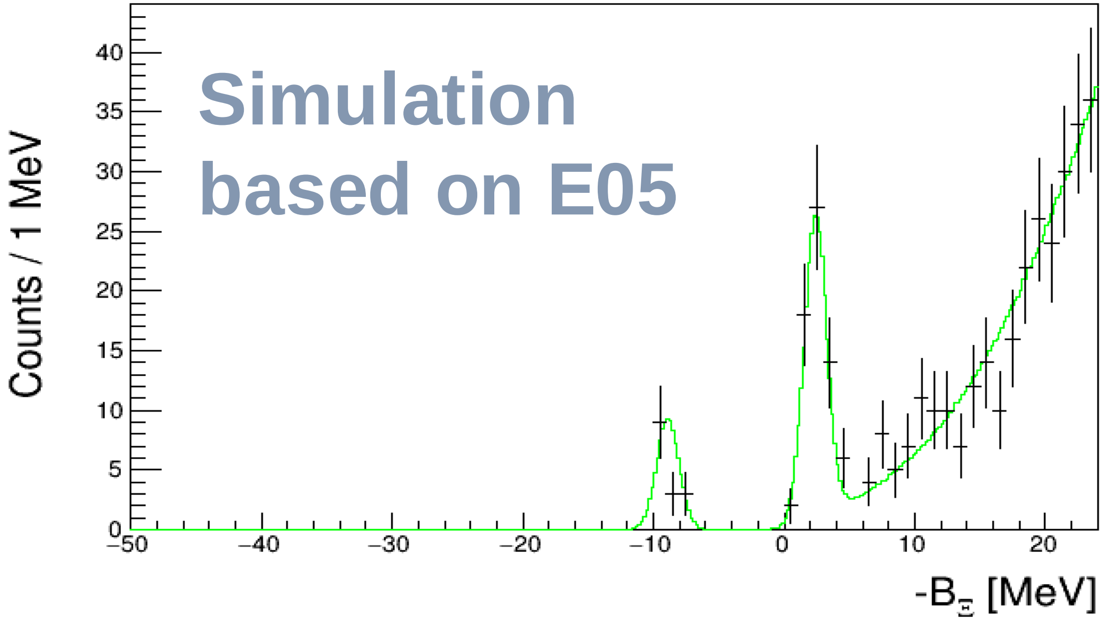
Construction of S-2S has been completed!



1.8 GeV/c

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

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

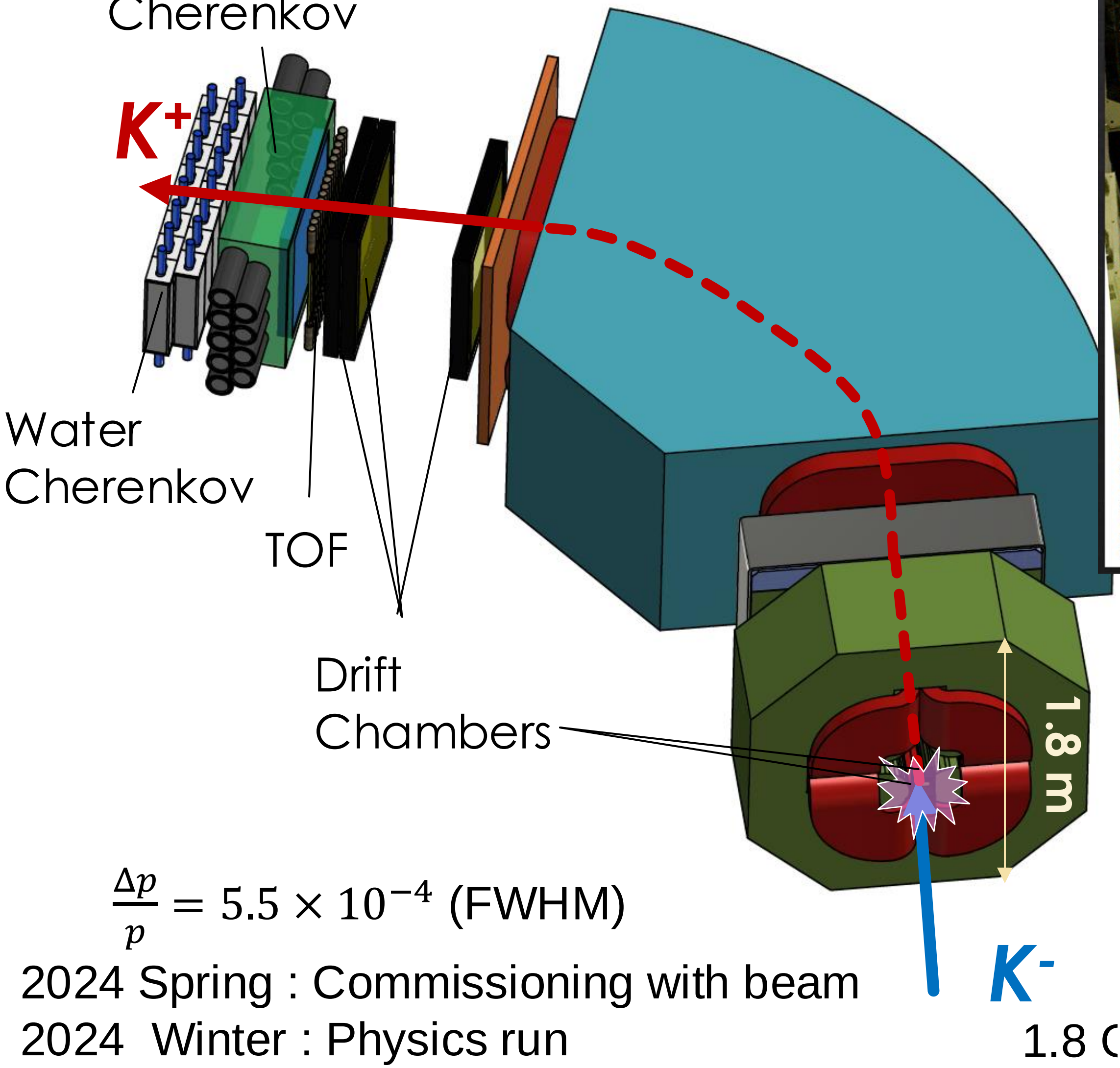


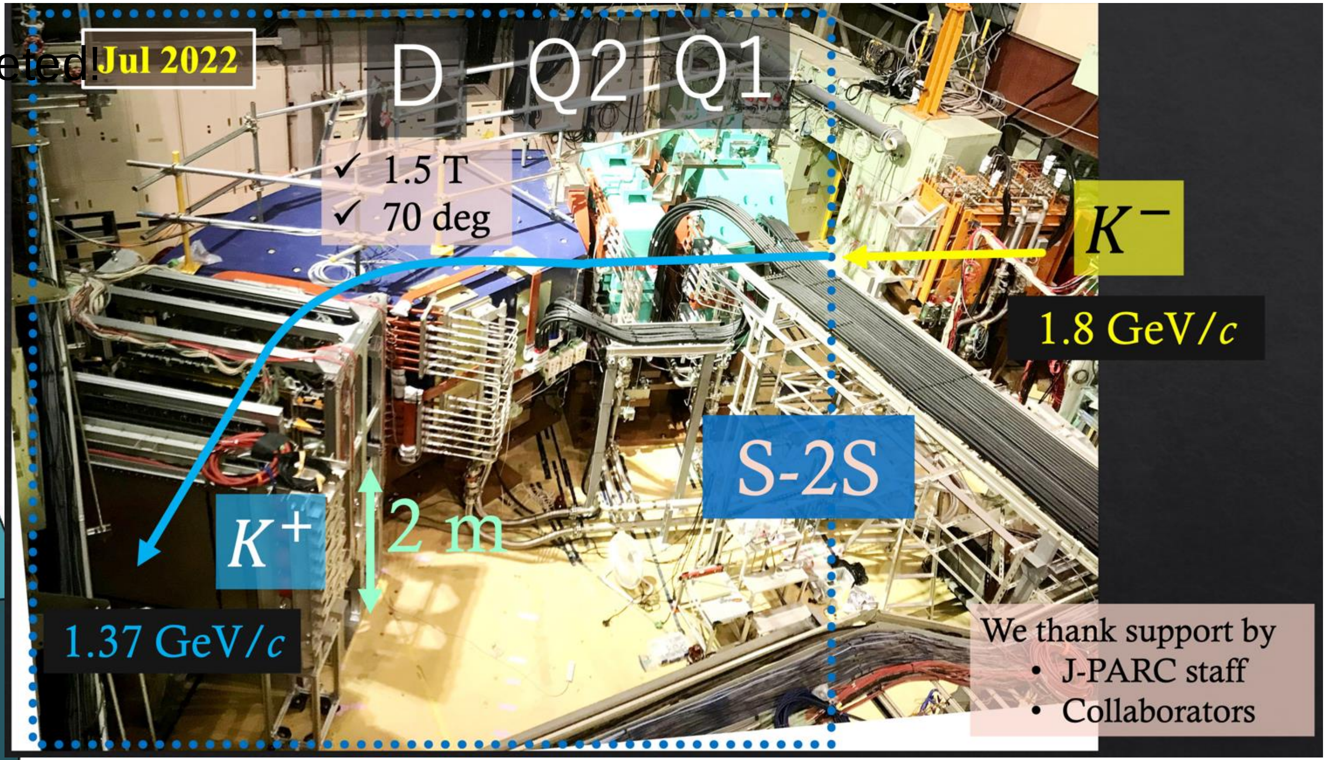
Missing Mass resolution 2 MeV (FWHM)

2024 Spring : Commissioning with beam
2024 Winter : Physics run

E70 experiment with S-2S spectrometer

Construction of S-2S has been completed!



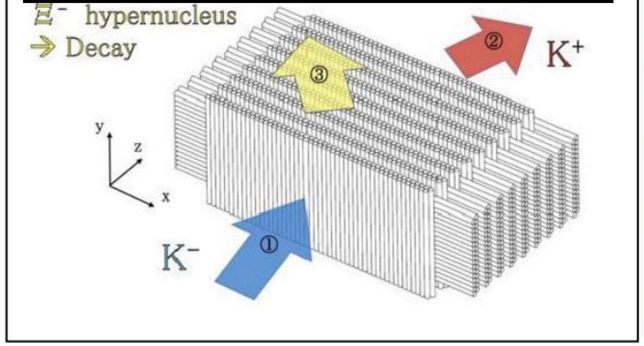


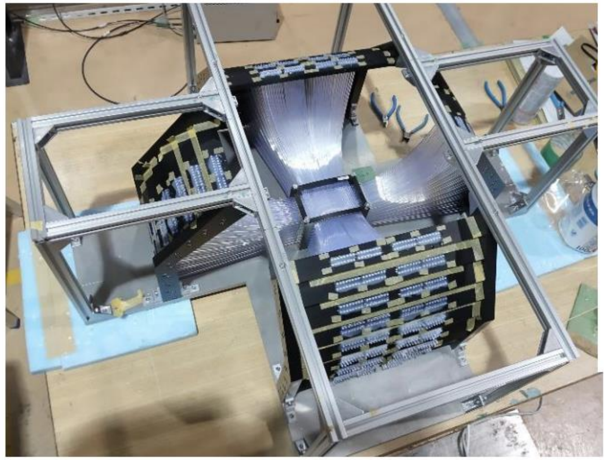
$\frac{\Delta p}{p} = 5.5 \times 10^{-4}$ (FWHM)

2024 Spring : Commissioning with beam

2024 Winter : Physics run

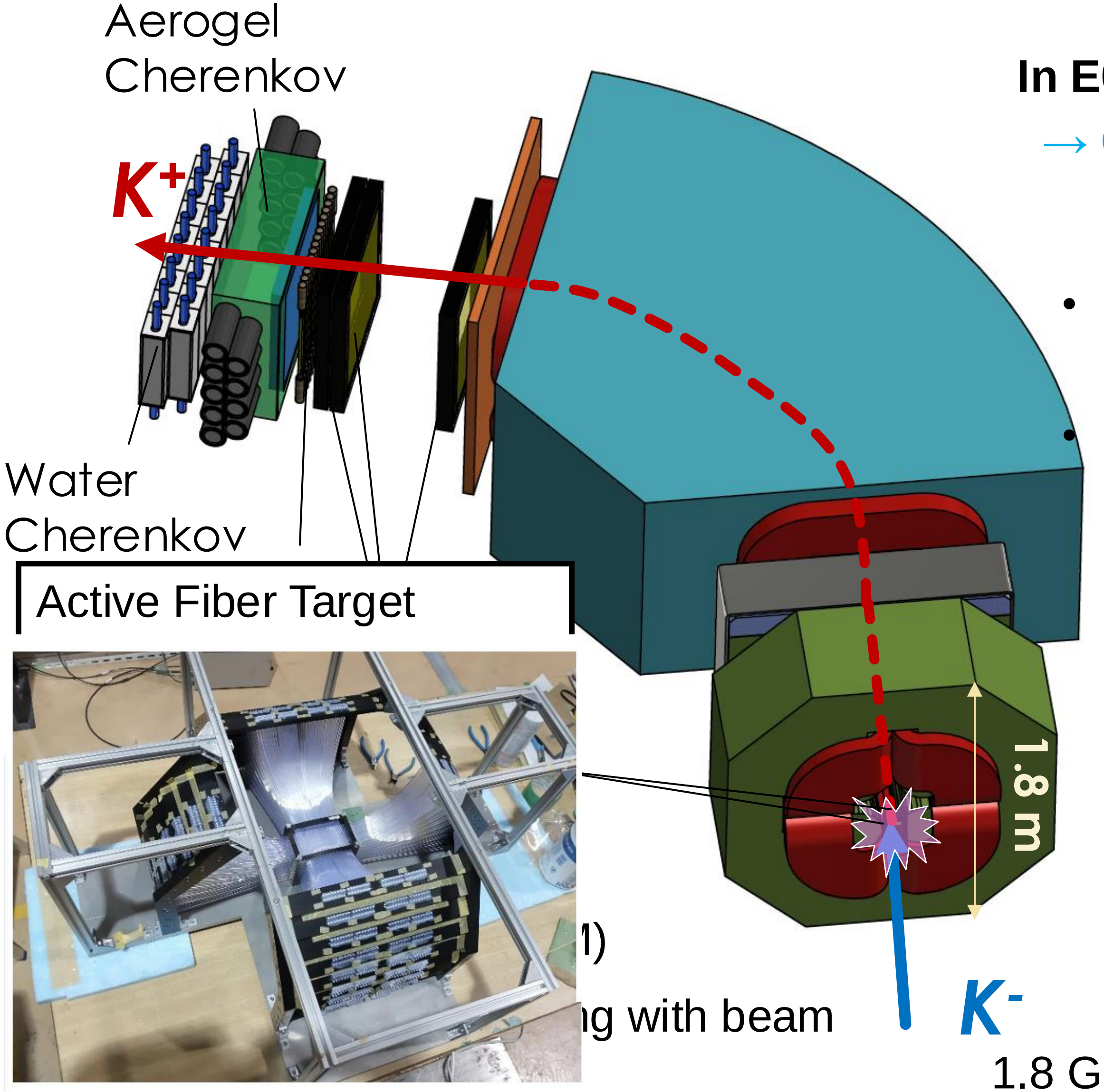
Active Fiber Target
for energy loss correction





Ξ^- ^{12}C X-ray measurement with AFT

Construction of S-2S has been completed!



l)

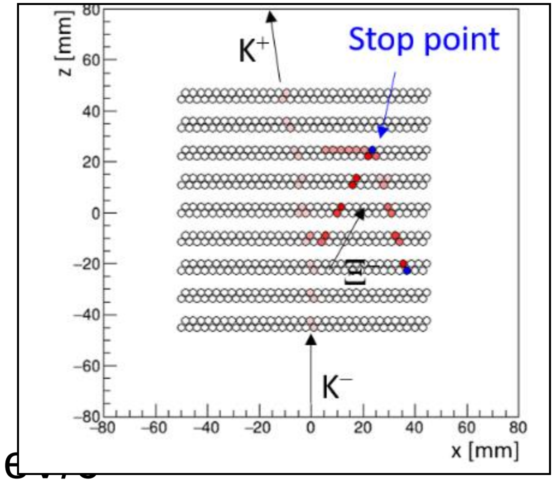
ng with beam

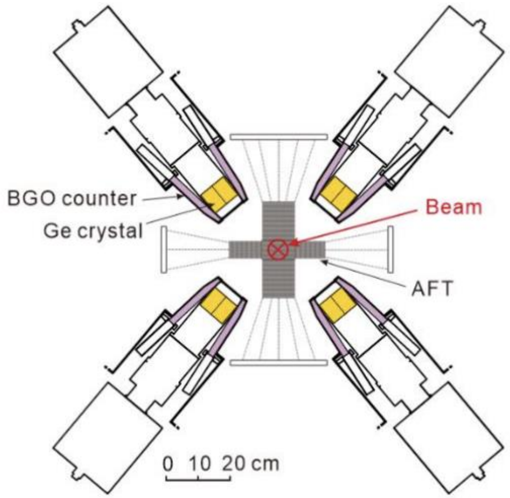
1.8 Ge

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**

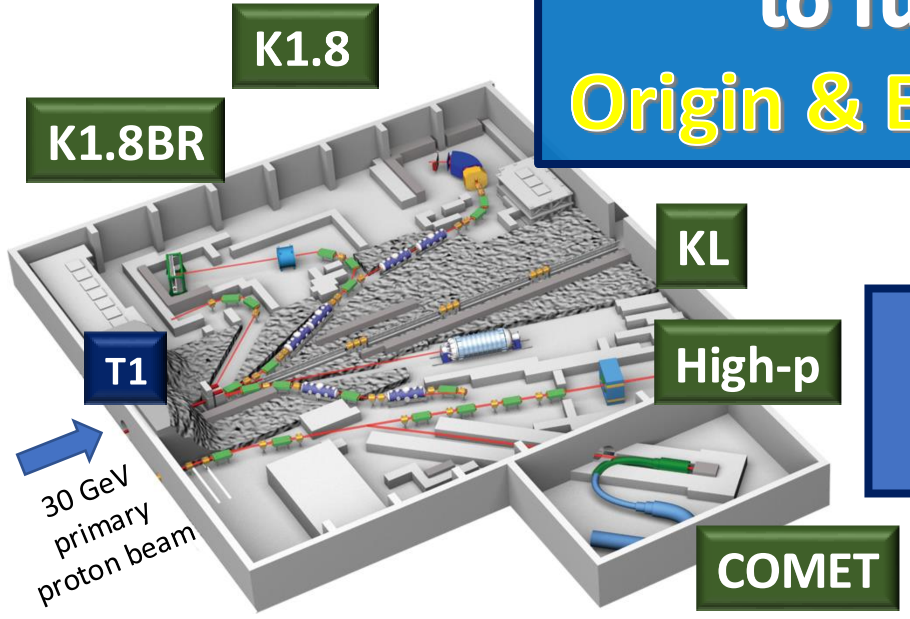




Hadron Experimental Facility extension (HEF-ex) Project

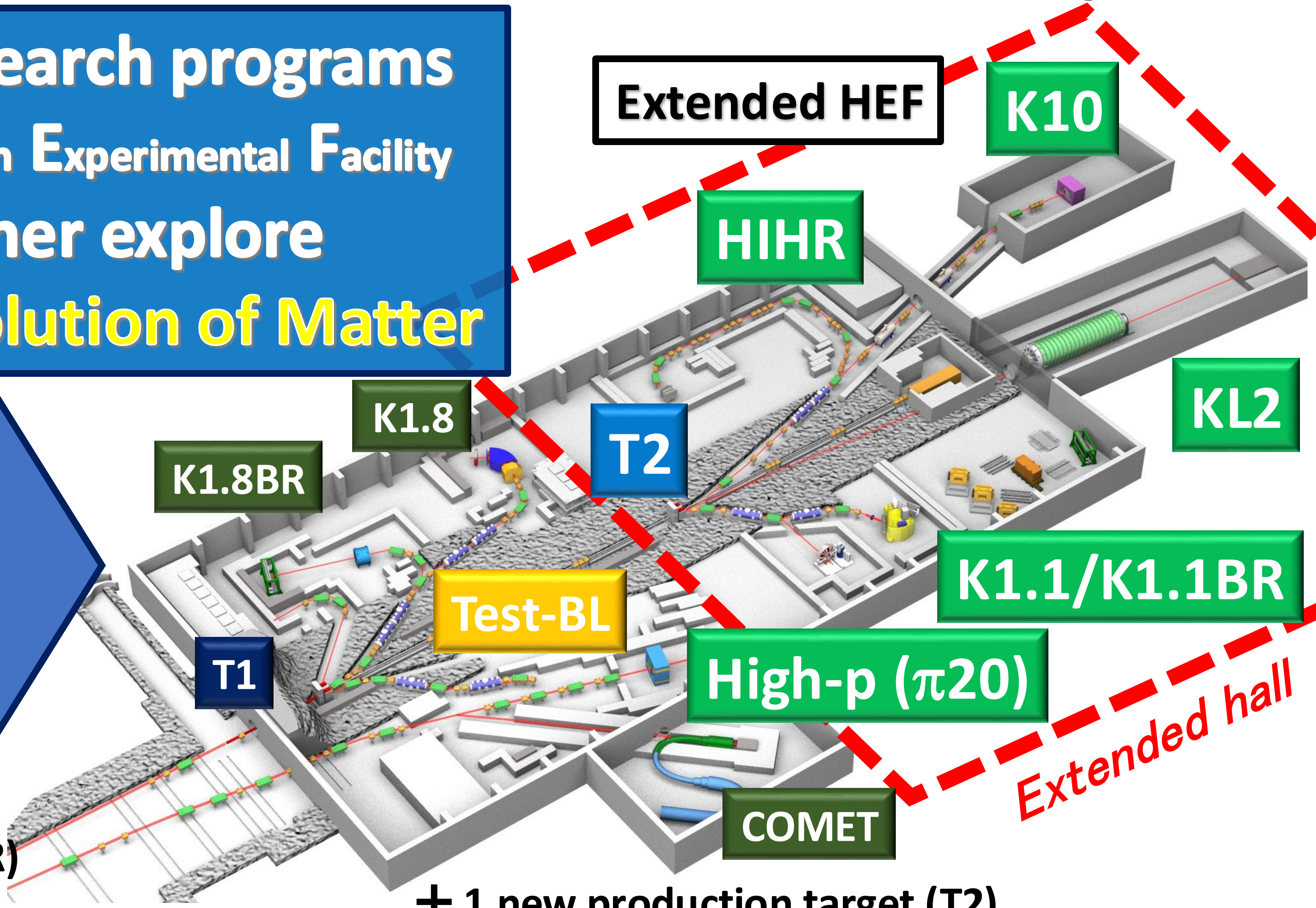
expand research programs at the Hadron Experimental Facility to further explore Origin & Evolution of Matter

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

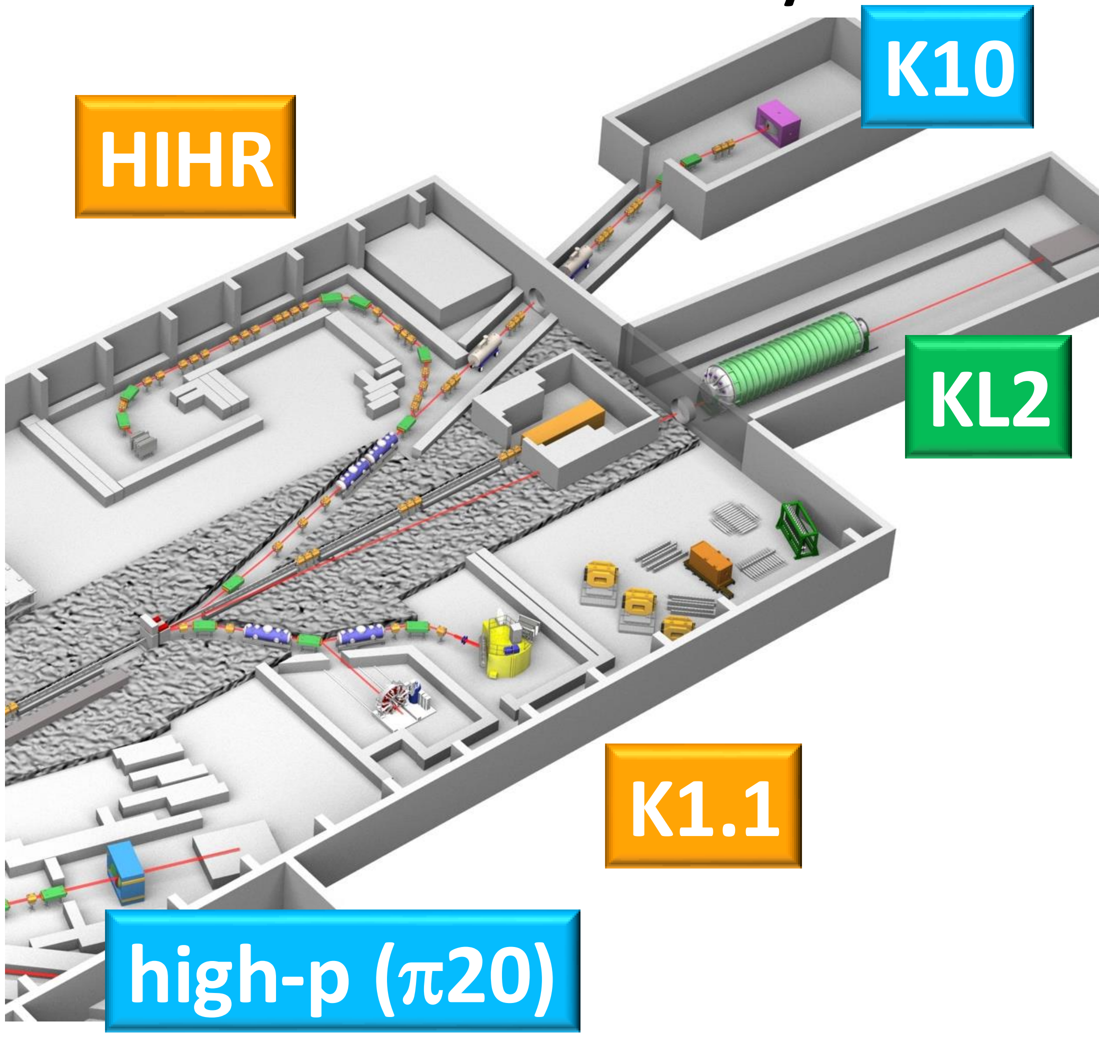
Investigate diquarks in baryons

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

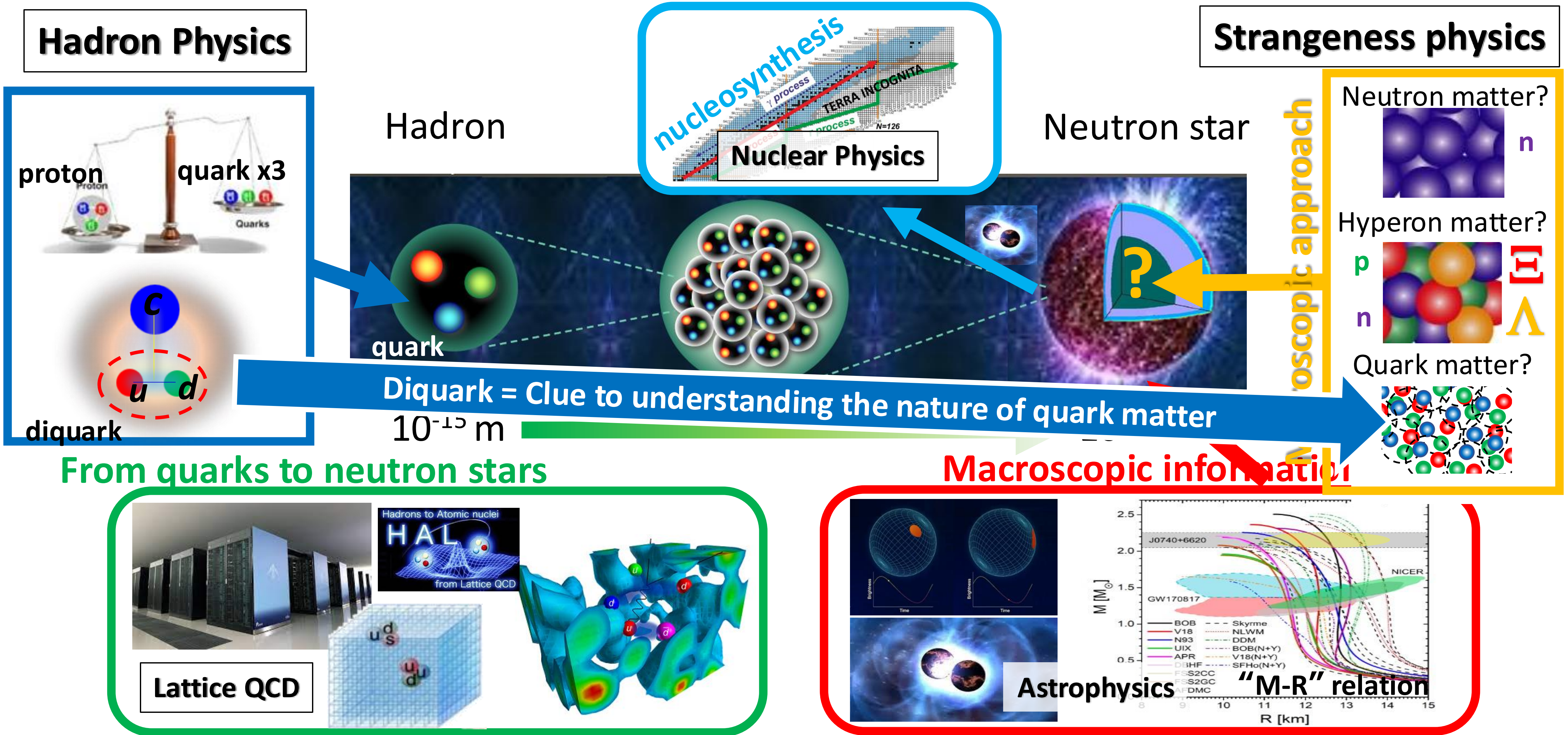
Search for new physics beyond the SM

KL2 — **Most sensitive $K_L^0 \to \pi^0 \nu \bar{\nu}$ measurement**
- intense neutral K beam



From Quarks to Neutron stars

towards unified understanding of strongly interacting systems over 10^{19} scale difference

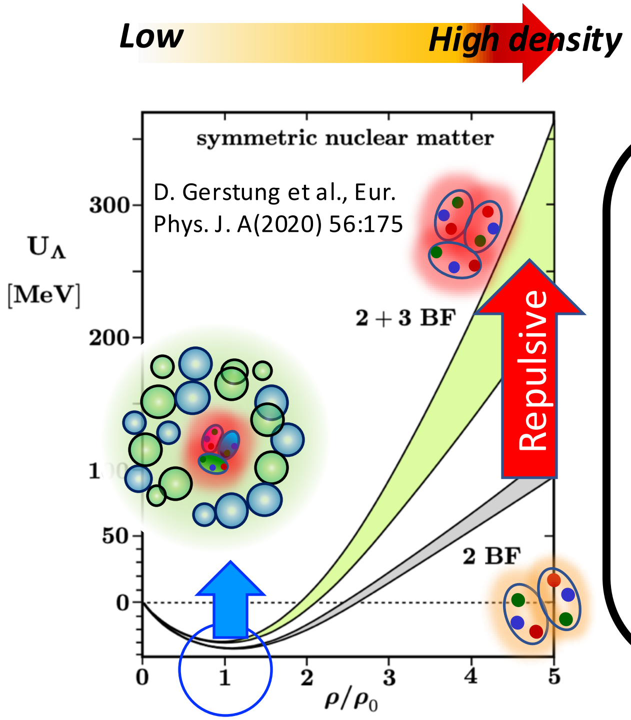


Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

➢ **Hyperons (Λ, Ξ, ...) emerge in dense neutron star matter?**

ΛNN 3 Baryon Force is a key



We need to determine

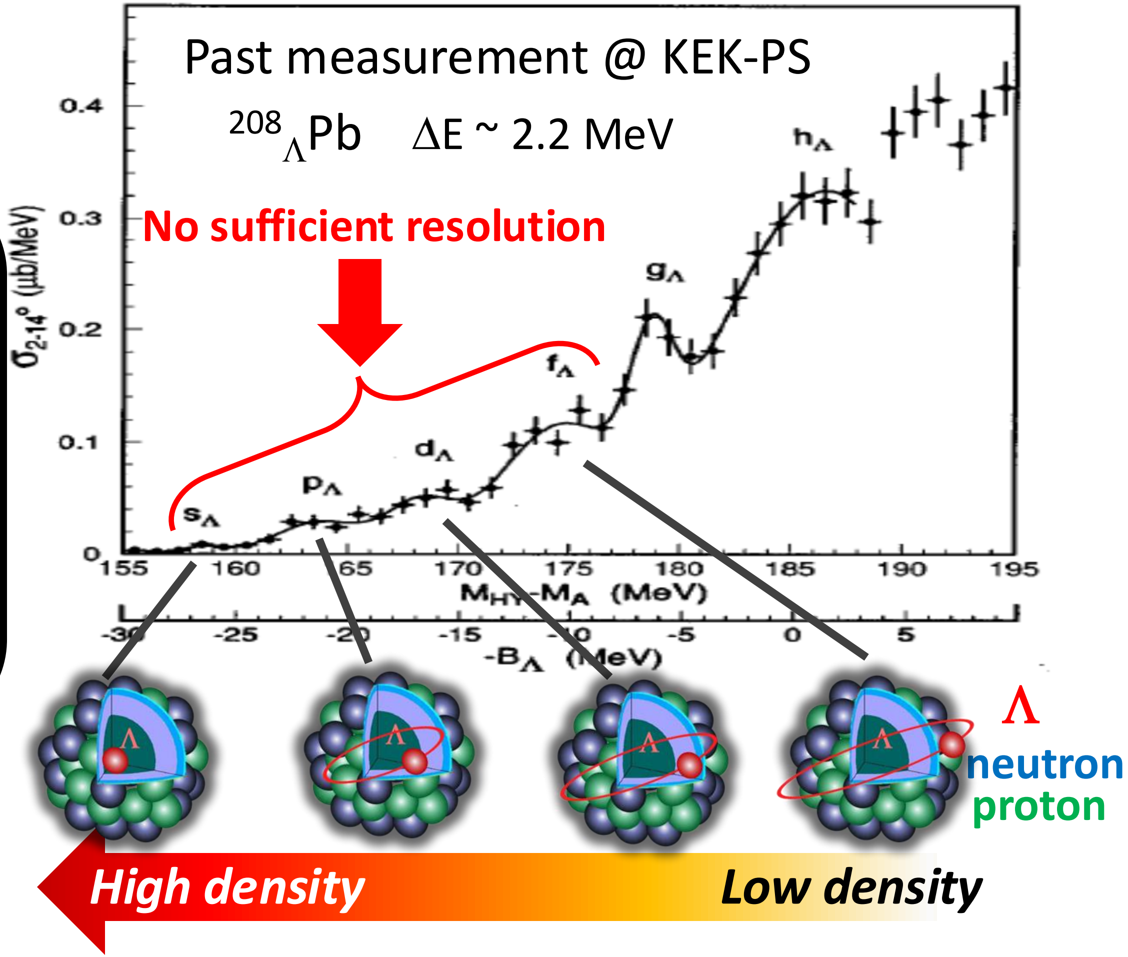
a tiny fraction of 3 Baryon Force effects

heavy Λ-hypernuclei :

Λ binding energies (B_Λ)

→ density dependent ΛN interaction

→ We need precise measurements

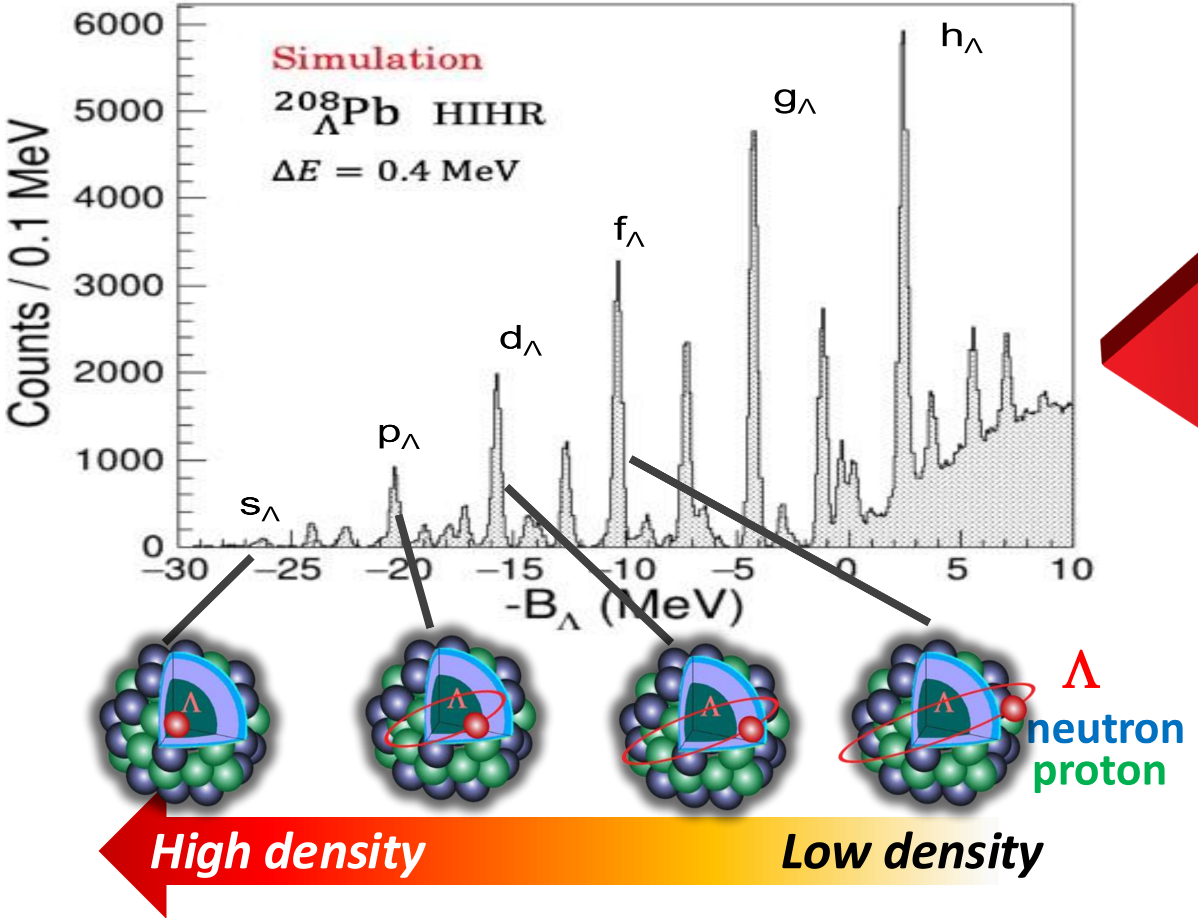


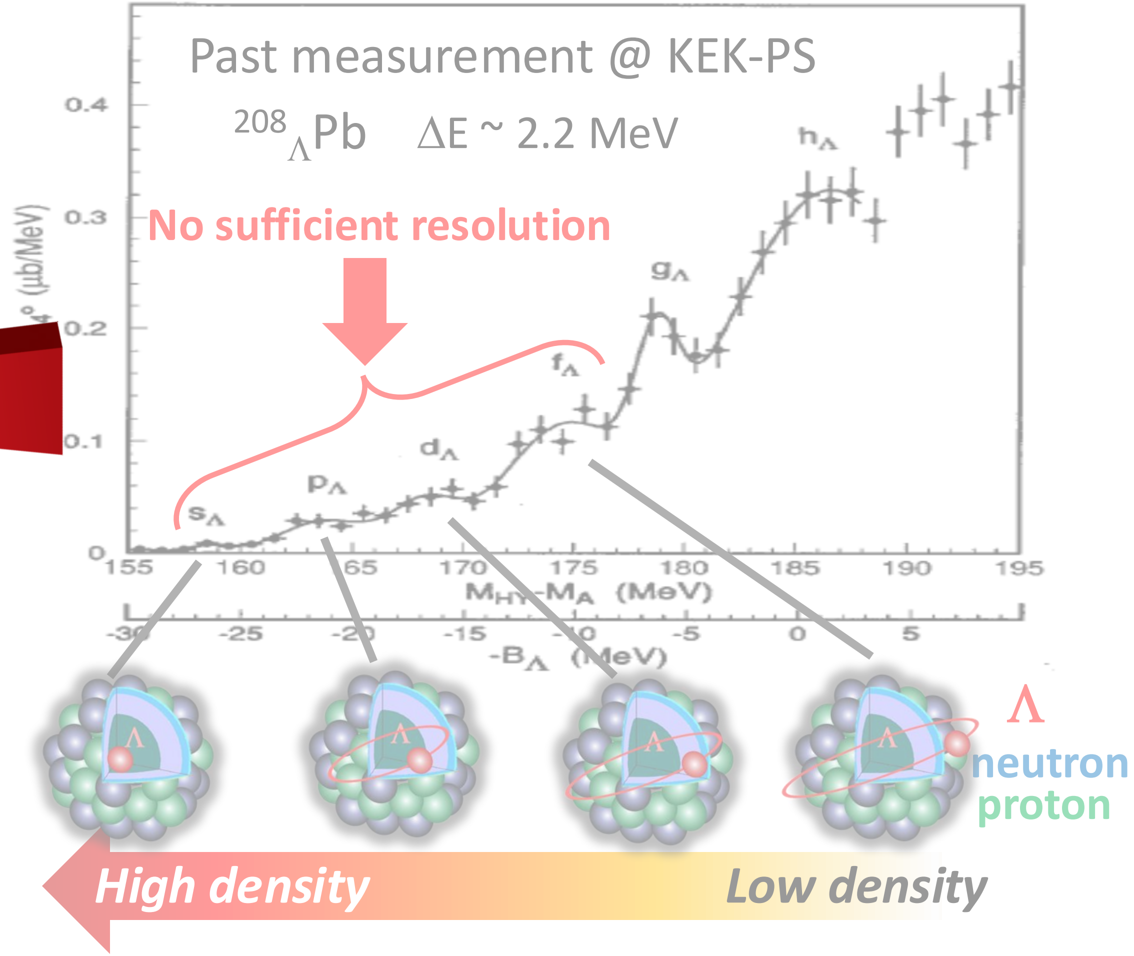
Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

- **Hyperons (Λ, Ξ, ...) emerge in dense neutron star matter?**

Need separation of each Λ orbital state





Strangeness Nuclear Physics: Hyperon in Dense Environment

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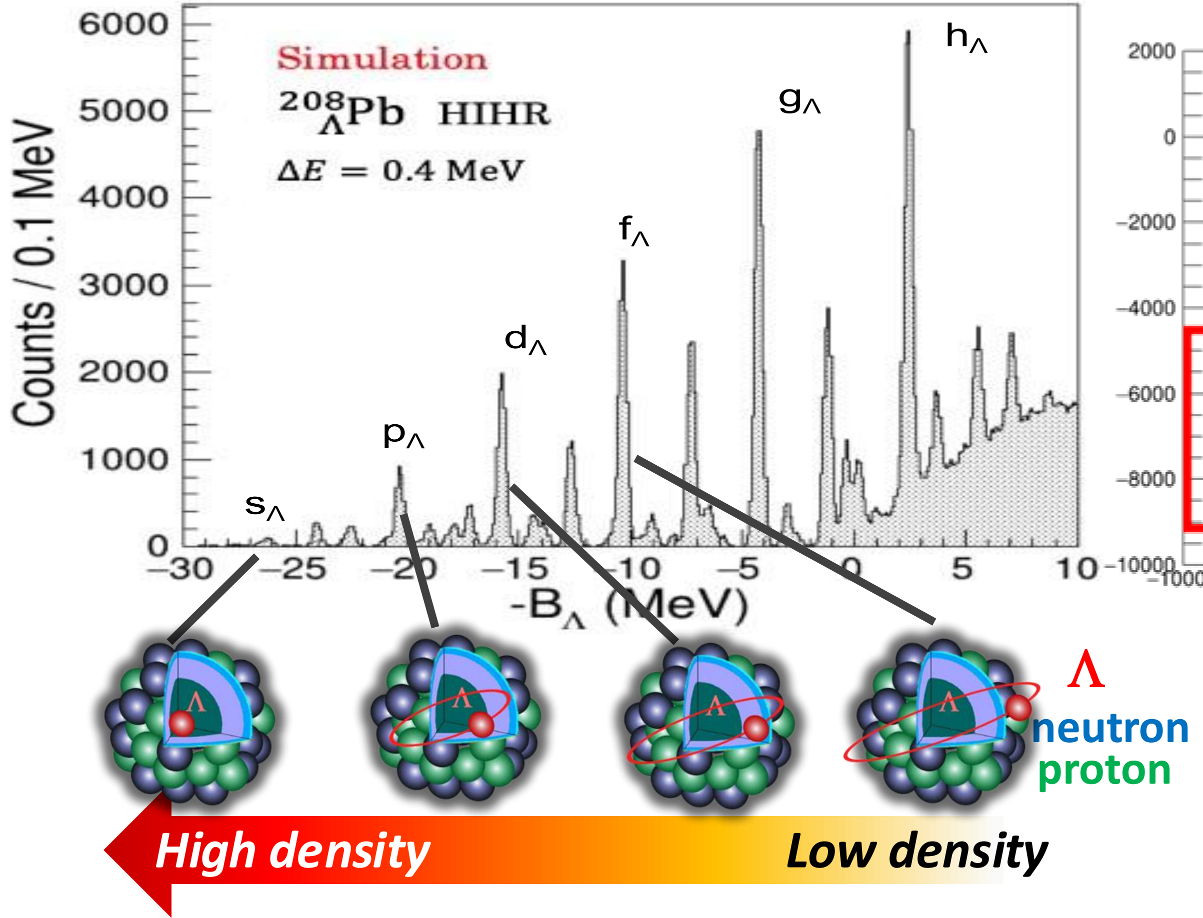
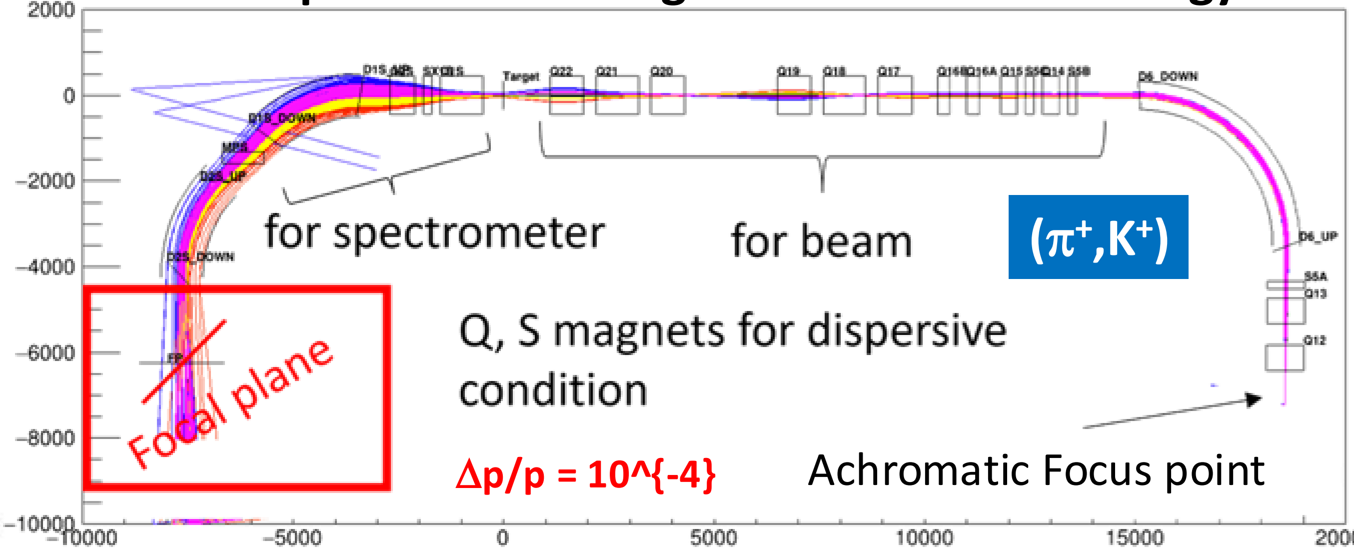
➢ **Hyperons (Λ, Ξ, ...) emerge in dense neutron star matter?**

Ultra-high-resolution Λ-hyp. spectroscopy



HIHR beam line (High-Intensity High-Resolution)

First dispersion-matching beam line in GeV energy



- No need for beam tracking
- Intense π beam of > 10^8 /pulse

● **Break through the resolution limit:**

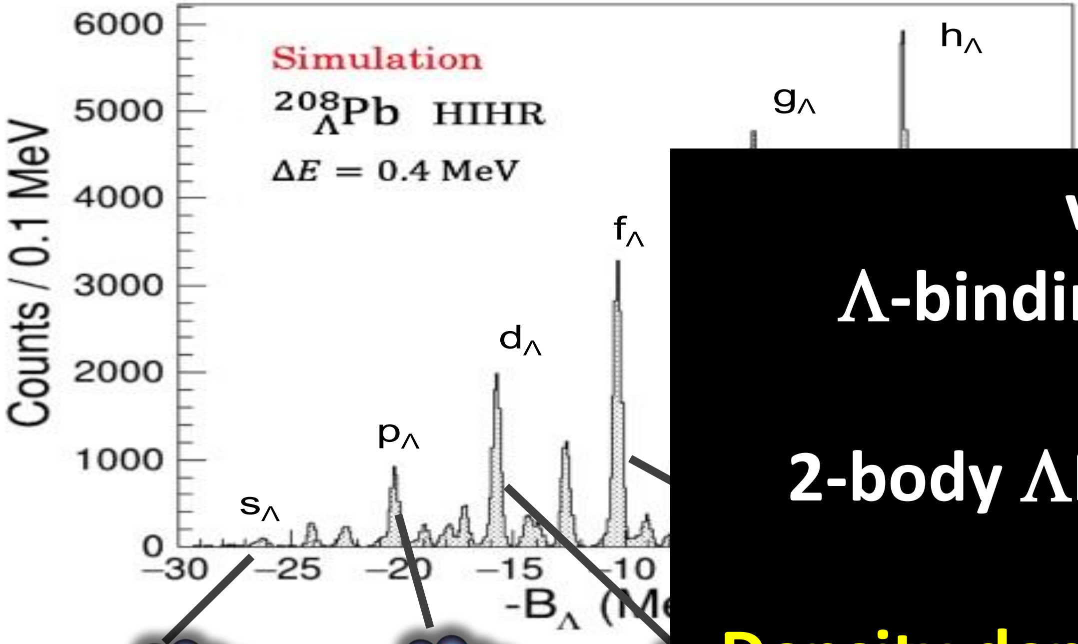
～2.2 MeV → better than ～0.4 MeV (FWHM)

Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

➢ **Hyperons (Λ, Ξ, ...) emerge in dense neutron star matter?**

Ultra-high-resolution Λ-hyp. spectroscopy

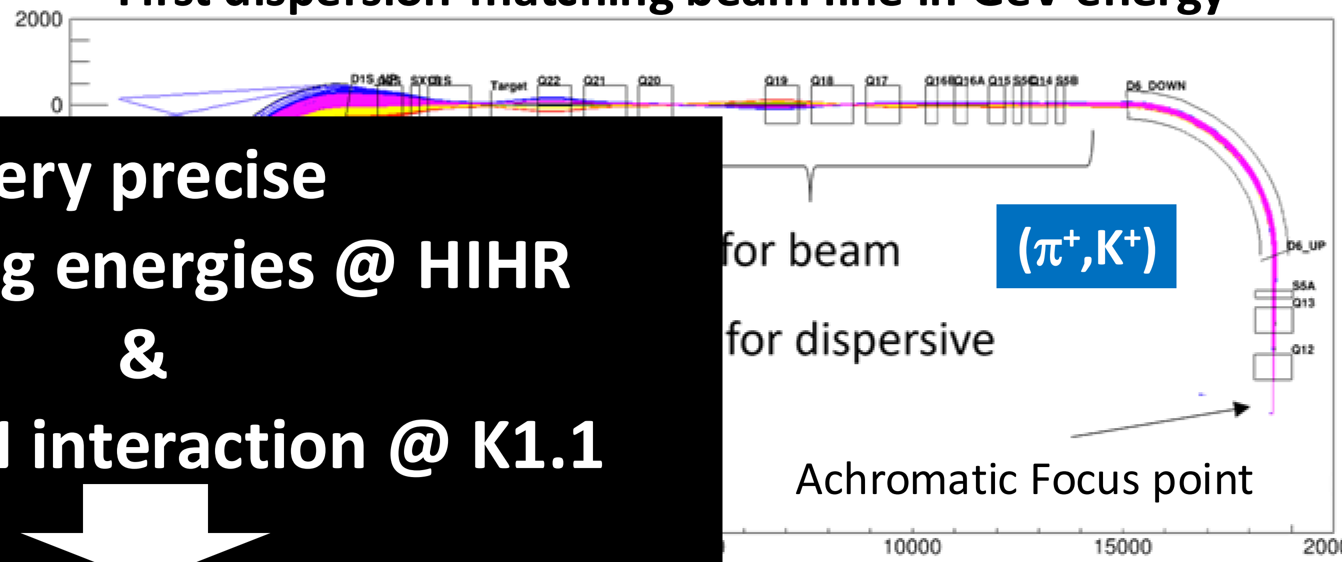


High density

Low density

HIHR beam line (High-Intensity High-Resolution)

First dispersion-matching beam line in GeV energy



up to 2 GeV/c

g

• Intense π beam of > 10⁸ /pulse

ion limit:

~2.2 MeV → better than ~0.4 MeV (FWHM)

very precise
Λ-binding energies @ HIHR
&
2-body ΛN interaction @ K1.1

⇩

Density dependent ΛN interaction

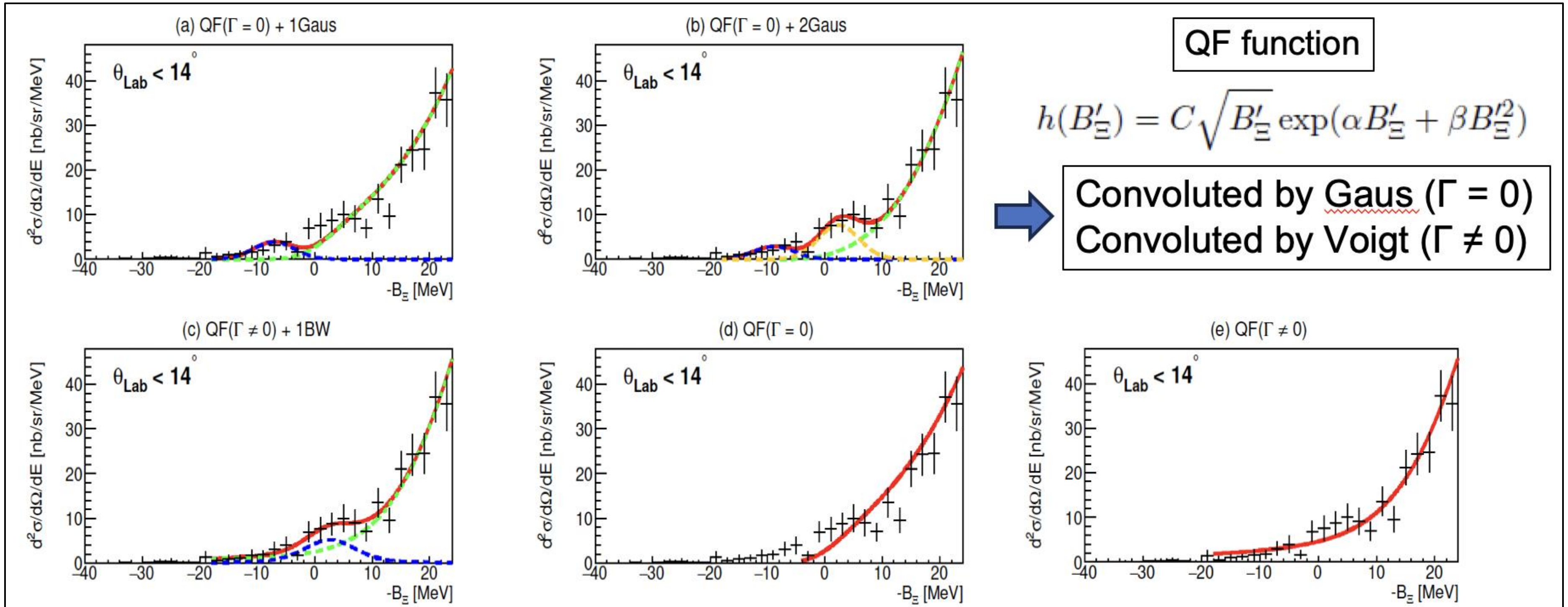
→ new understanding of neutron star matter

Summary

- J-PARC is a powerful accelerator facility for particle and nuclear physics.
    - A lot of hadron and strangeness nuclear physics programs
- Recent highlights
    - Accurate measurement of Σp scattering cross sections
    - Clear observation of kaonic nuclear system
    - Systematic compiling of double Λ hypernuclei from KEK to J-PARC
    - Clear identification of Ξ hypernucler states
    - New data of $^{12}C(K^-, K^+)$ spectrum to search for $^{12}_{\Xi}Be$
- Near future programs
    - Ξ hypernuclear spectroscopy with S-2S spectrometer and Ξ atomic X-ray measurement.
- Facility upgrade
    - Hadron extension project is under consideration
    - Ultra high-resolution hypernuclear spectroscopy with dispersion matching method at HIHR.

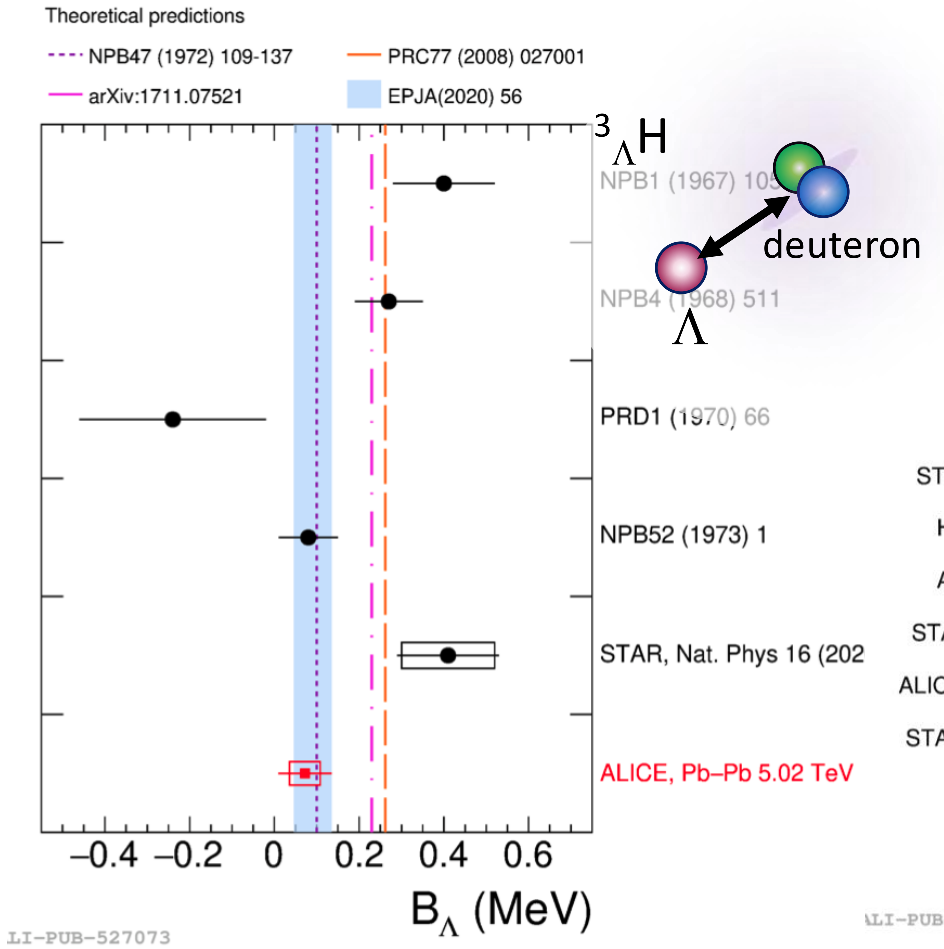
Result of the Spectrum Fitting

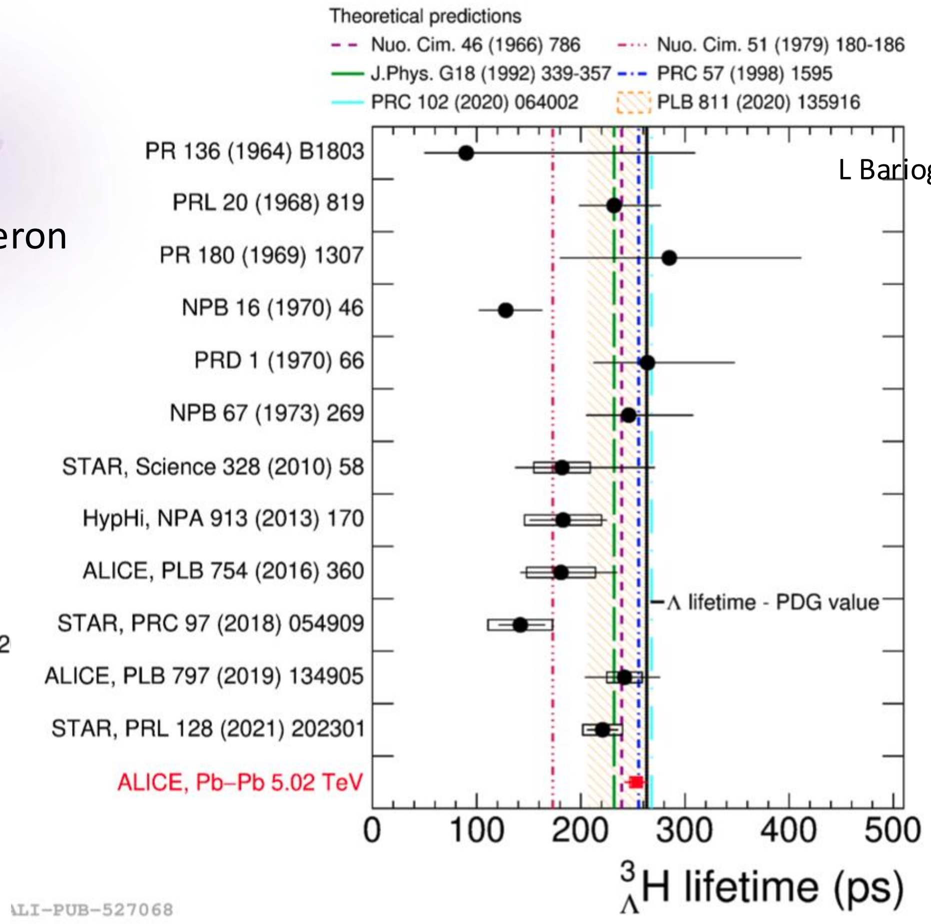
Function	χ^2/ndf (ndf)	P-value	Fitting parameters (MeV)
(a) QF($\Gamma = 0$) + 1Gaus	1.83 (23)	0.00896	$B_\Xi = 7.1 \pm 1.5$ (stat.) $^{+2.4}_{-6.1}$ (syst.)
(b) QF($\Gamma = 0$) + 2Gaus	0.849 (22)	0.665	$B_\Xi^{1st} = 8.9 \pm 1.4$ (stat.) $^{+3.8}_{-3.1}$ (syst.) $B_\Xi^{2nd} = -2.4 \pm 1.3$ (stat.) $^{+2.8}_{-1.2}$ (syst.)
(c) QF($\Gamma \neq 0$) + 1BW	0.954 (23)	0.524	$B_\Xi = -2.7 \pm 2.2$ (stat.) $^{+0.5}_{-0.7}$ (syst.) $\Gamma = 4.1 \pm 2.1$ (stat.) $^{+1.2}_{-0.7}$ (syst.)
(d) QF($\Gamma = 0$)	2.49 (19)	0.000332	
(e) QF($\Gamma \neq 0$)	1.39 (25)	0.0914	$\Gamma = 8.7 \pm 1.1$ (stat.)



Hypertriton puzzle

Heavy ion experimental results settle down ?





L Barioglio talk at EMMI Workshop 2023

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

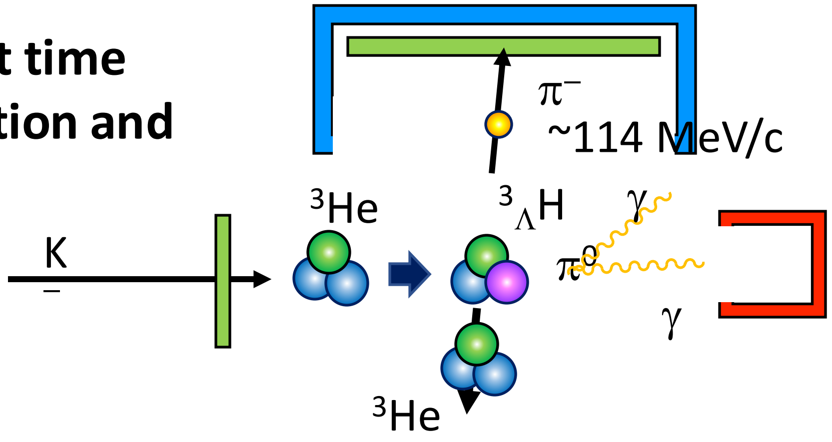
WASA-FRS : ^{6}Li+^{12}C 2 GeV/A
τ, B_Λ : under analysis

B_Λ measurement
- MAMI : decay pion spectroscopy
- JLab : ^{3}He (e, e'K^{+}) missing mass spectroscopy
- J-PARC E07 : hyperfragment at K- interaction on emulsion

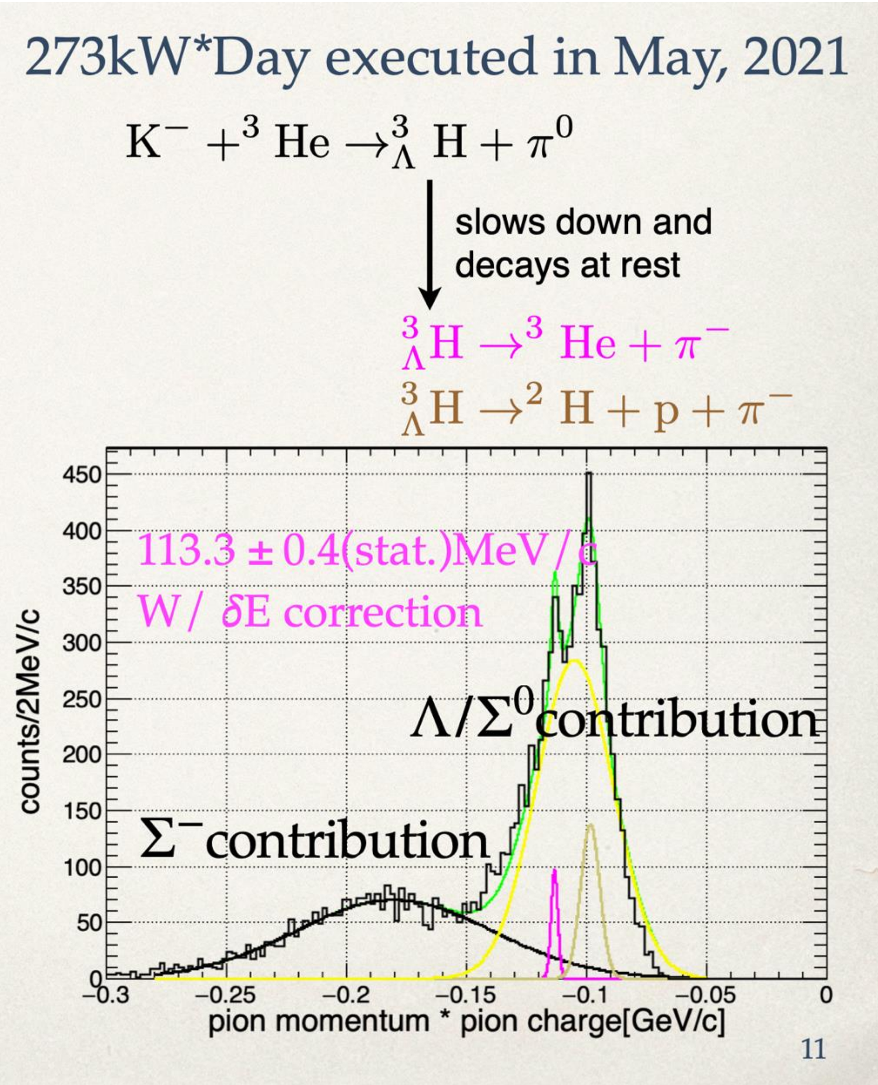
Lifetime measurement by direct time measurement
- ELPH : ^{3}He(γ, K^{+}) reaction
- J-PARC E73 : ^{3}He (K^{-}, π^{0}) reaction

E73 has stated data taking of $^{3}_{\Lambda}H$ run

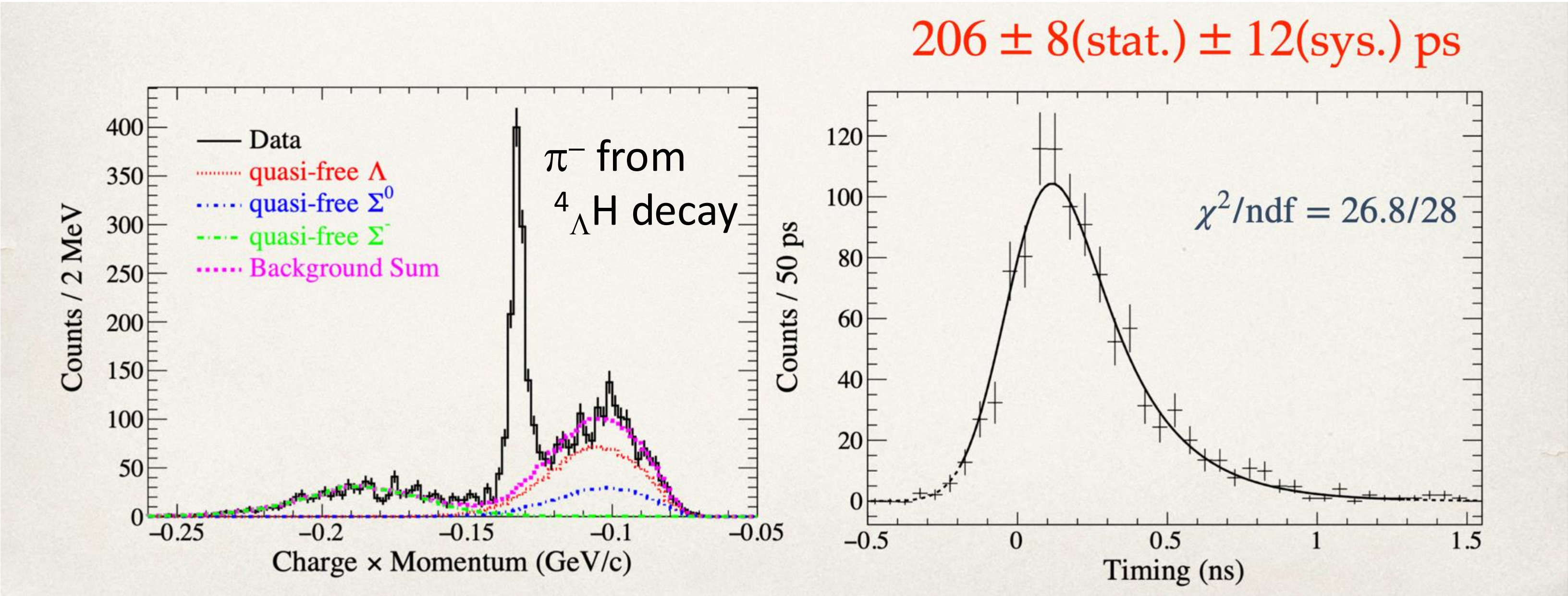
Lifetime measurement by direct time measurement between production and decay



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



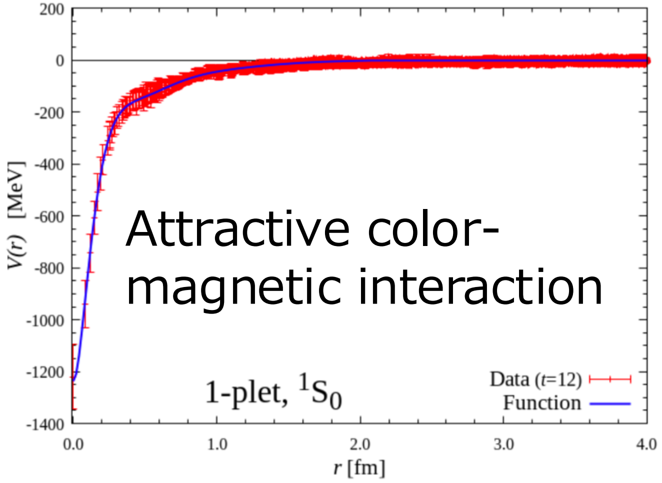
Pilot run for $^{4}_{\Lambda}H$ lifetime measurement was successful



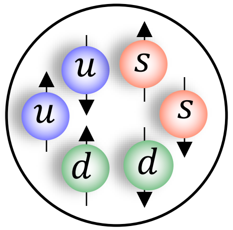
T. Akaishi et al., PLB 845 (2023) 138128

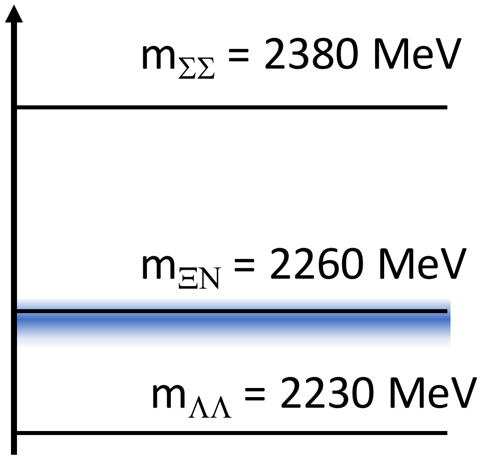
H dibaryon (SU(3) flavor singlet hexaquark state)

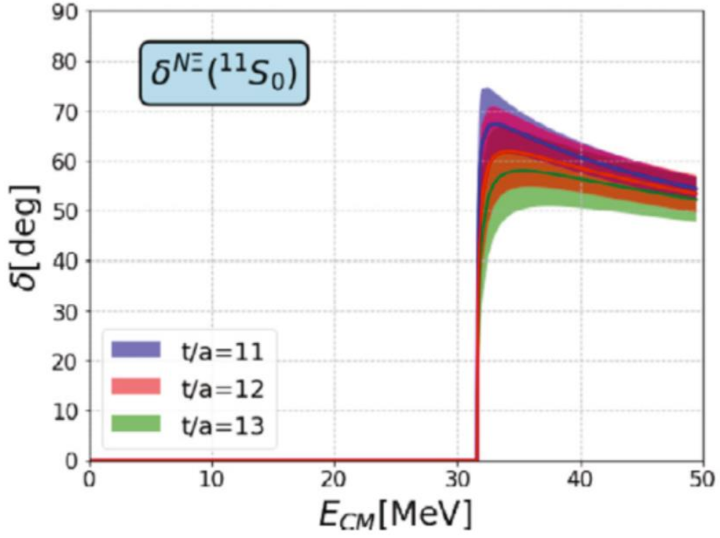
Theoretical progress on S=-2 system



H-dibaryon



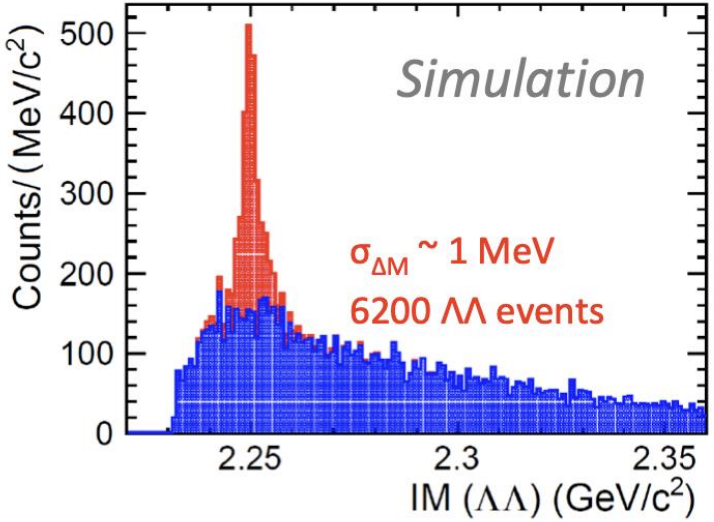




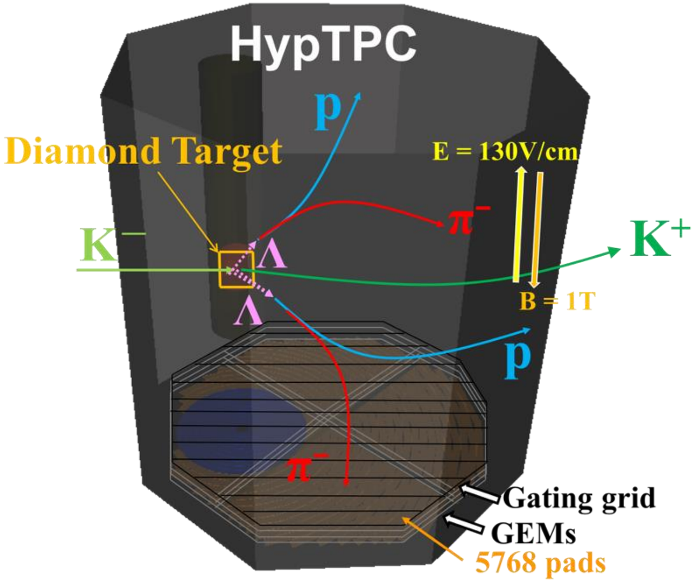
→ Definitive experimental confirmation is awaited

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

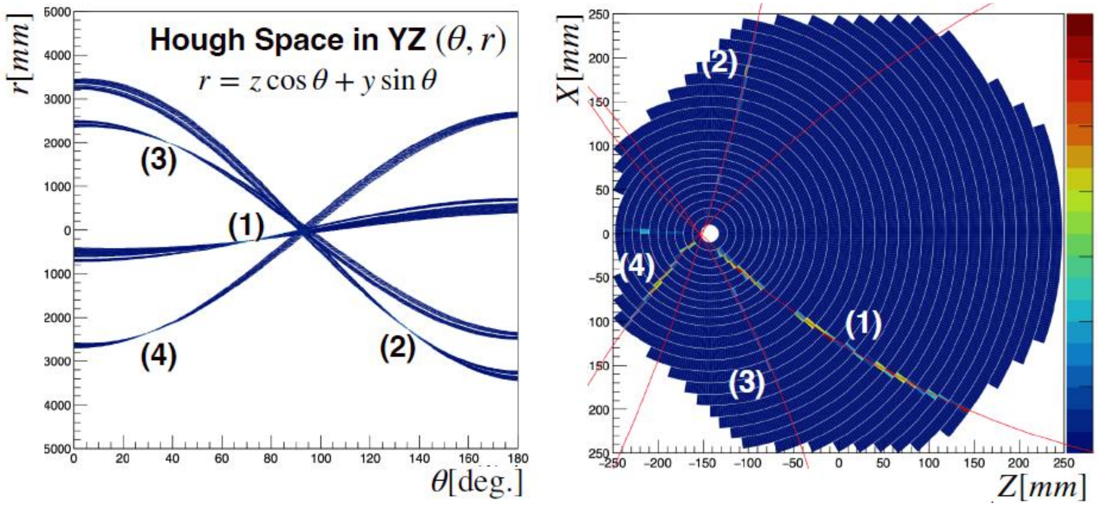
- Invariant mass measurement of $\Lambda\Lambda$ and Ξ^-p system with HypTPC
- High resolution and high statistics measurement is realized



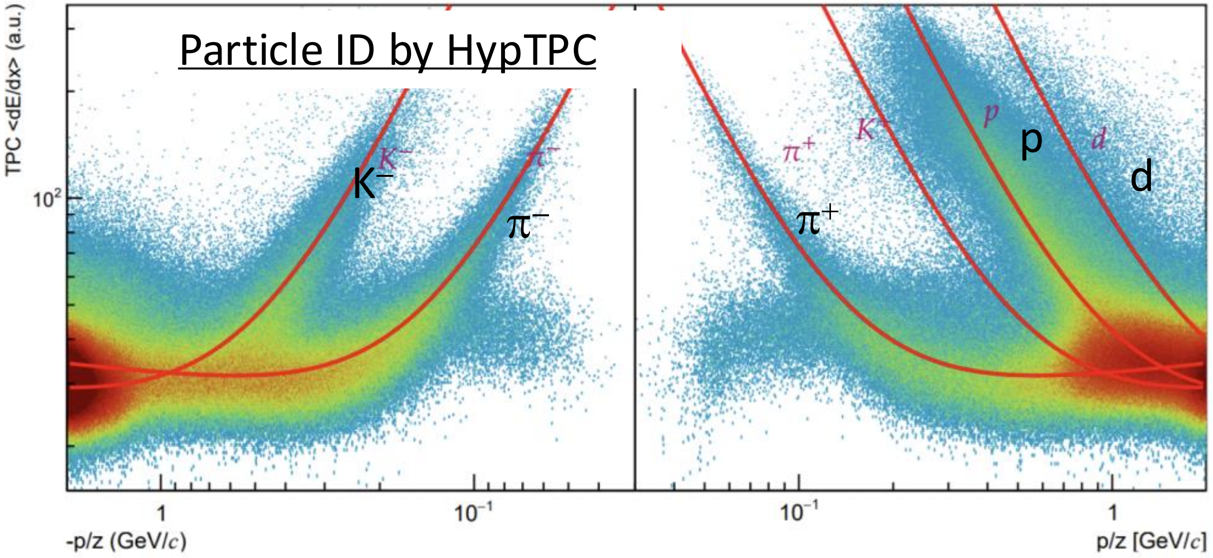
Progress on analysis of HypTPC



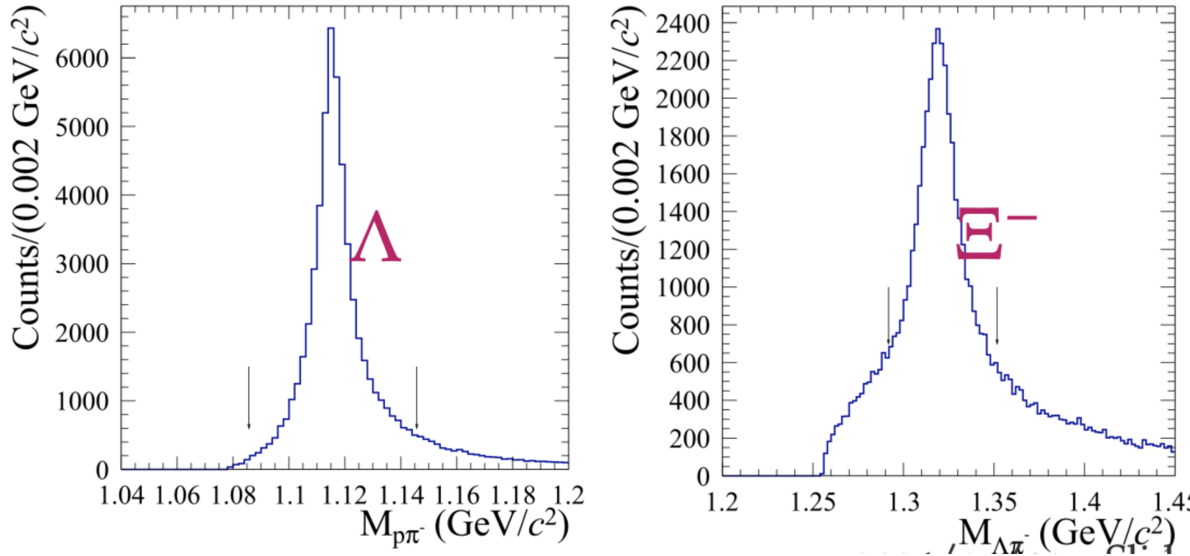
Development of track finding algorithm using Hough transformation



Particle ID by HypTPC



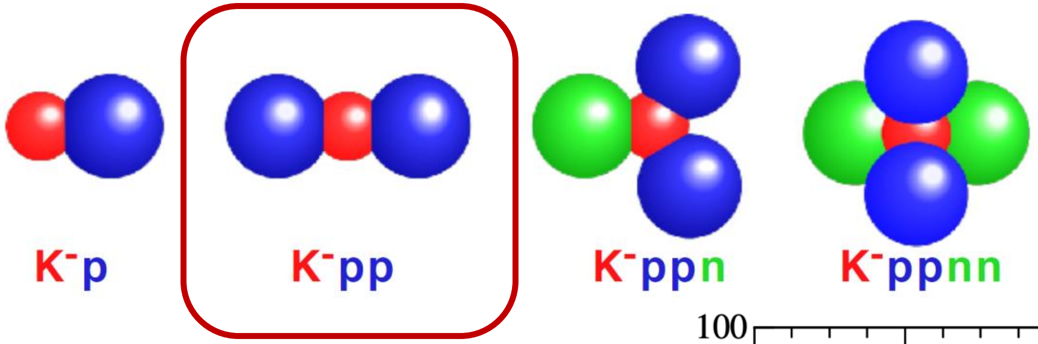
Invariant mass reconstruction by HypTPC



Observation of an exotic hadron bound system including K⁻ meson

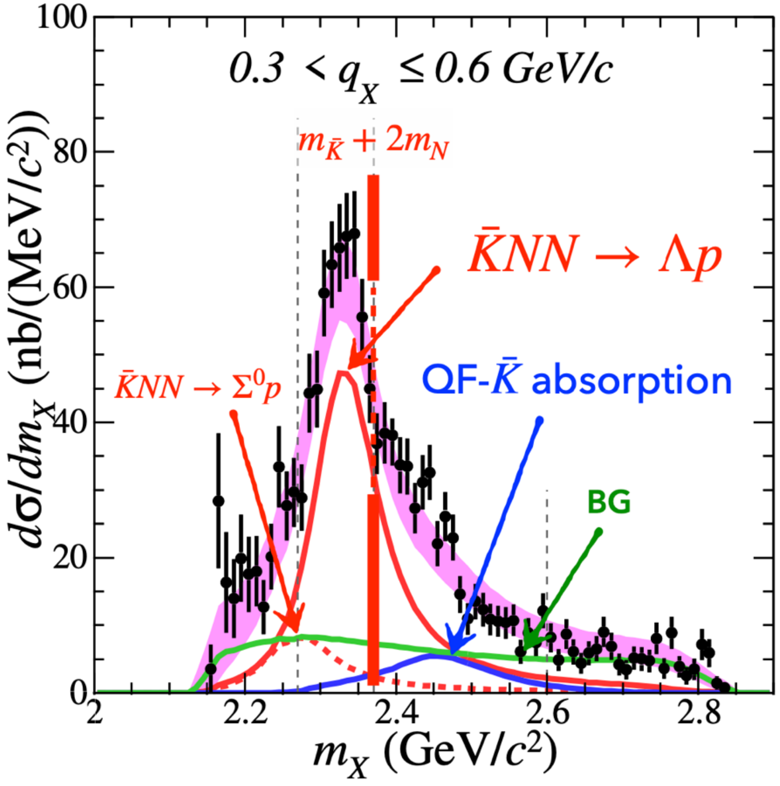
Strong attractive interaction between Kbar and N → Exotic hadronic system with Kbar meson

<u>New development of detailed systematic investigation of novel nuclei containing K-mesons</u>



- 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

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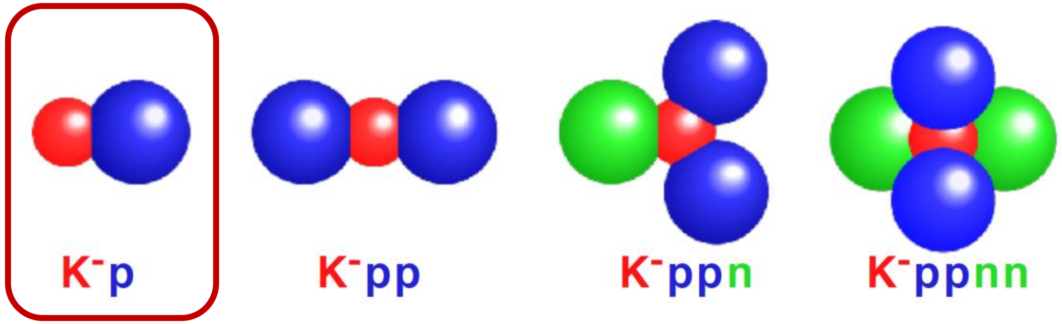
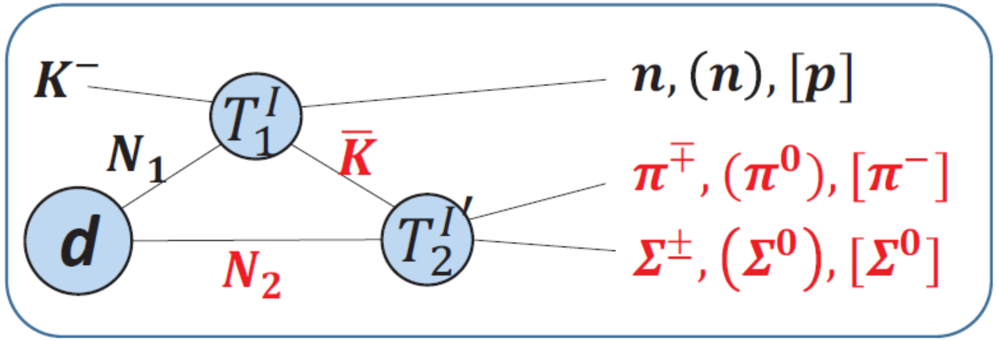


- Mass dependence of Kbar-nucleon system from K-p to K-ppnn
- Aiming to clarify the origin of QCD mass and the mysteries of high-density nuclear matter by measuring changes in the properties of K-mesons in nuclear matter.

J-PARC E31 @ K1.8BR

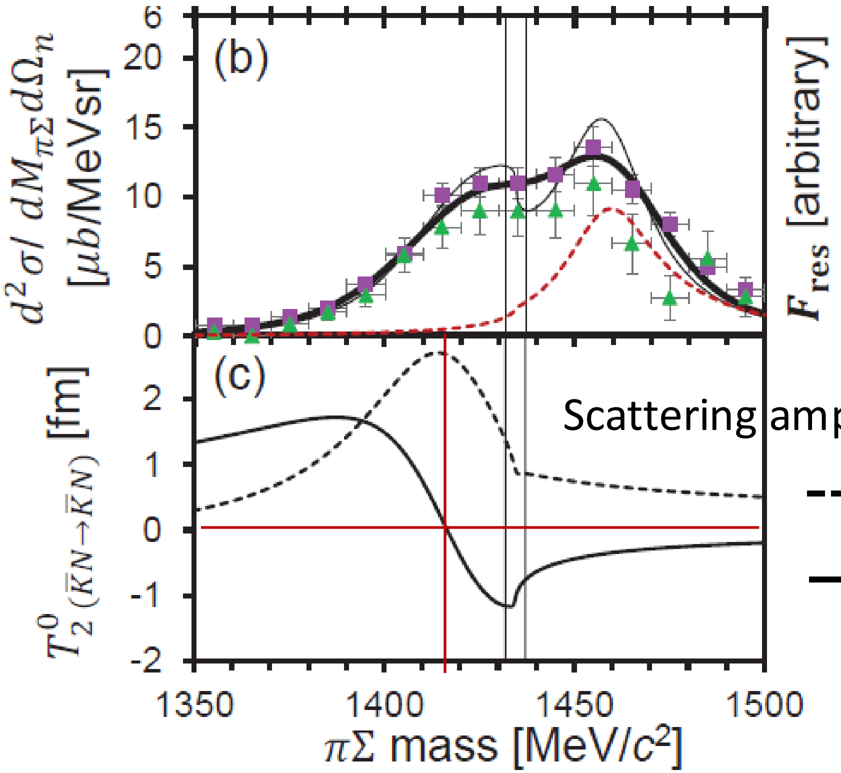
- First derivation of S-wave KbarN scattering amplitude in I=0 channel from 3 πΣ decay modes.



Resonance pole was found at

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

K⁻p and K⁰n mass thresholds

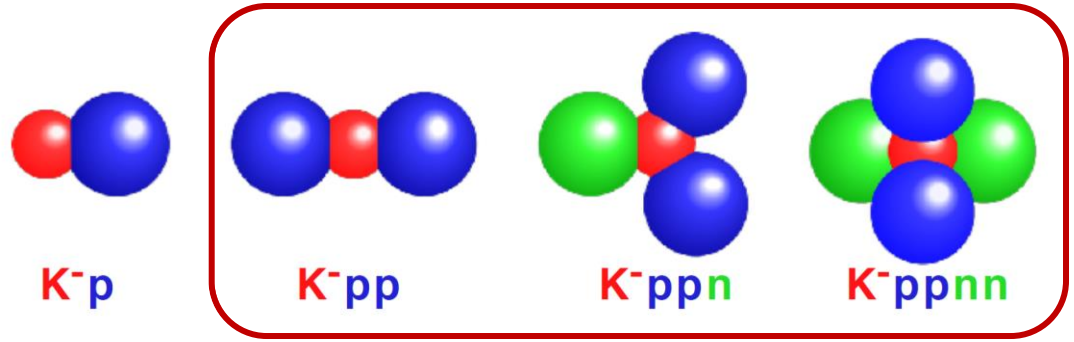


S. Aikawa et al., Phys. Lett. B 837 (2023) 137637

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

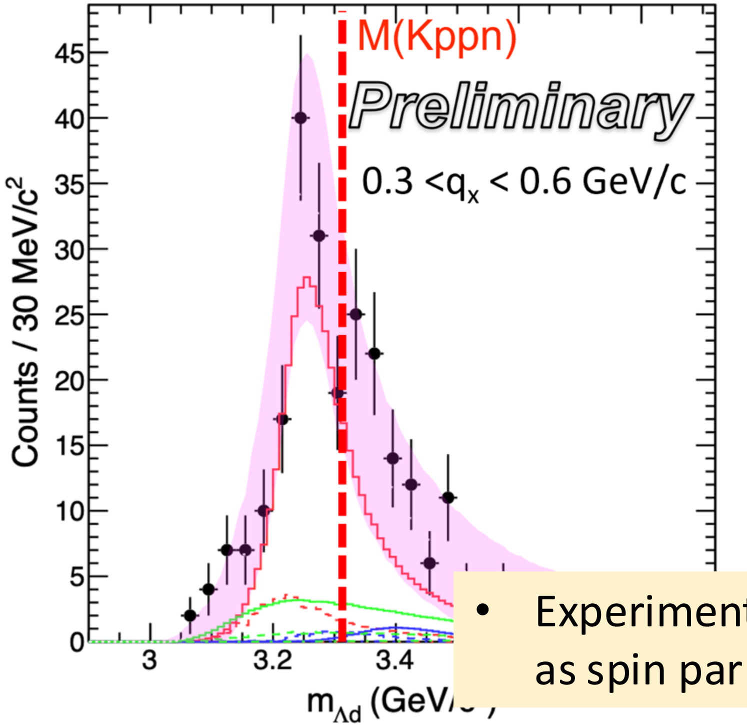


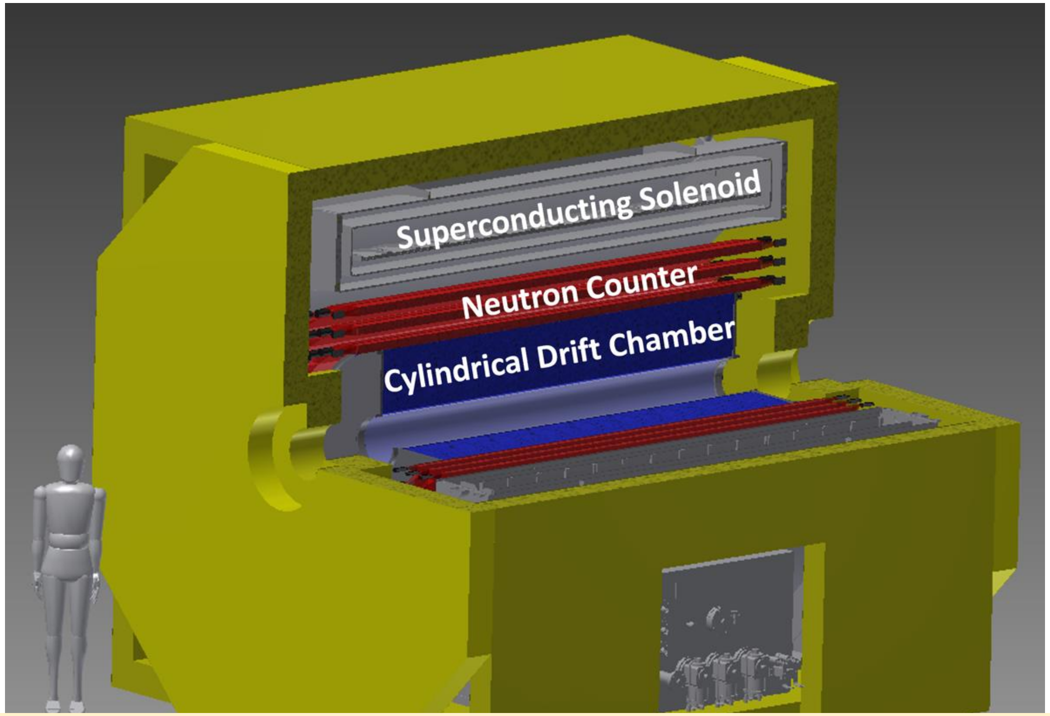
- Mass dependence of Kbar-nucleon system from K-p to K-ppnn
- Aiming to clarify the origin of QCD mass and the mysteries of high-density nuclear matter by measuring changes in the properties of K-mesons in nuclear matter.

J-PARC T77 @ K1.8BR

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

by T. Hashimoto @ HYP2022



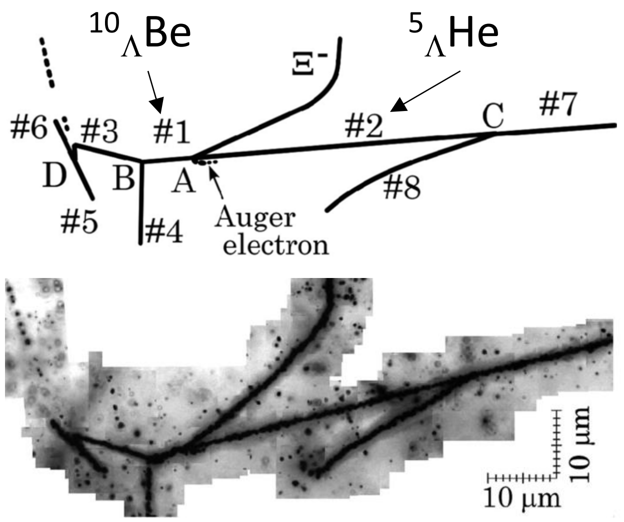


- Experimental measurement of internal quantum numbers such as spin parity to establish a novel atomic nucleus

$\Xi^{-}+^{14}N$ hypernucleus

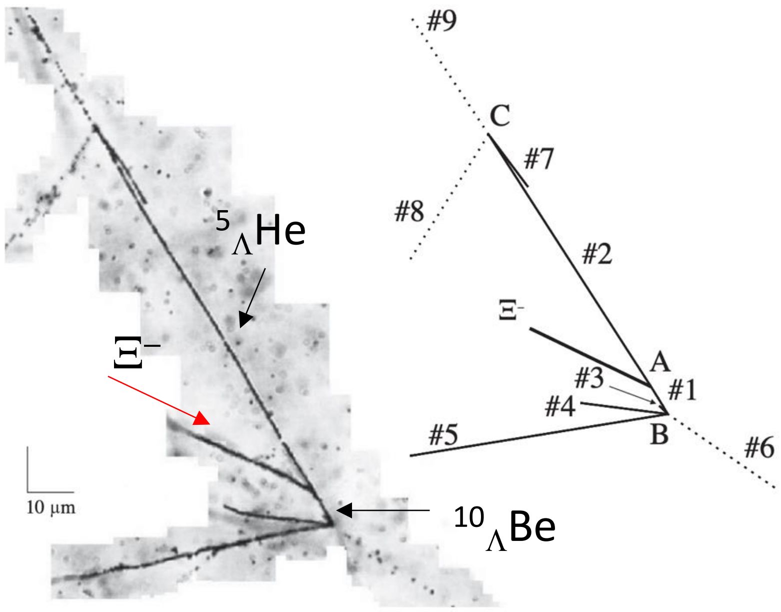
$\Xi^{-} + ^{14}N \rightarrow ^{5}_{\Lambda}He + ^{5}_{\Lambda}He + ^{4}He + n$

KISO event



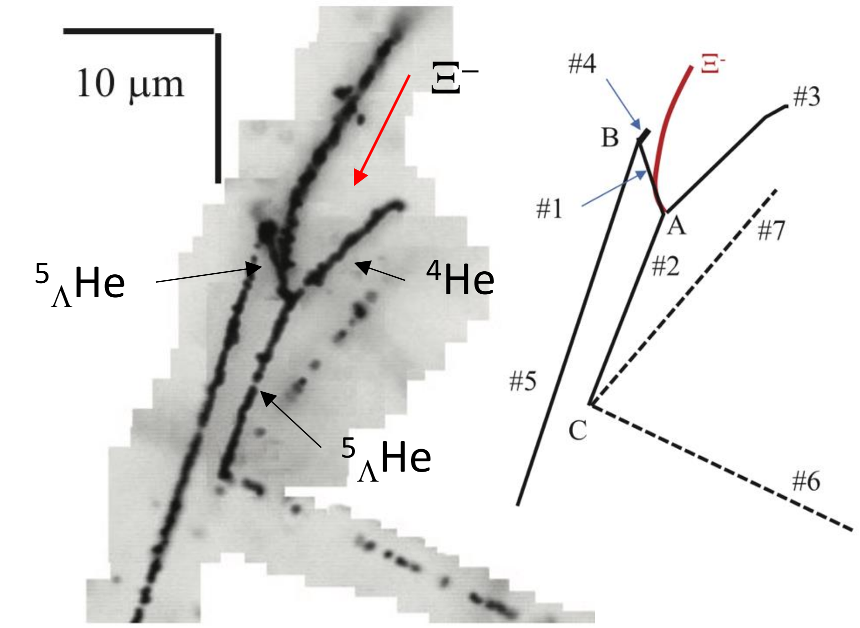
K. Nakazawa et al., PTEP. 2015, 033D02

IBUKI event



S. H. Hayakawa et al.,
Physical Review Letters, 126, 062501 (2021)

IRRAWADDY event



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

1st discovery of clear Ξ nuclear state

Two possibilities of B_{Ξ^-} depending on $^{10}_{\Lambda}Be$ state

- B_{Ξ^-} ($^{10}_{\Lambda}Be_{g.s.}$) = 3.87 ± 0.21 MeV
- B_{Ξ^-} ($^{10}_{\Lambda}Be_{1st.\ Ex.}$) = 1.03 ± 0.18 MeV

1st uniquely identified Ξ nuclear state

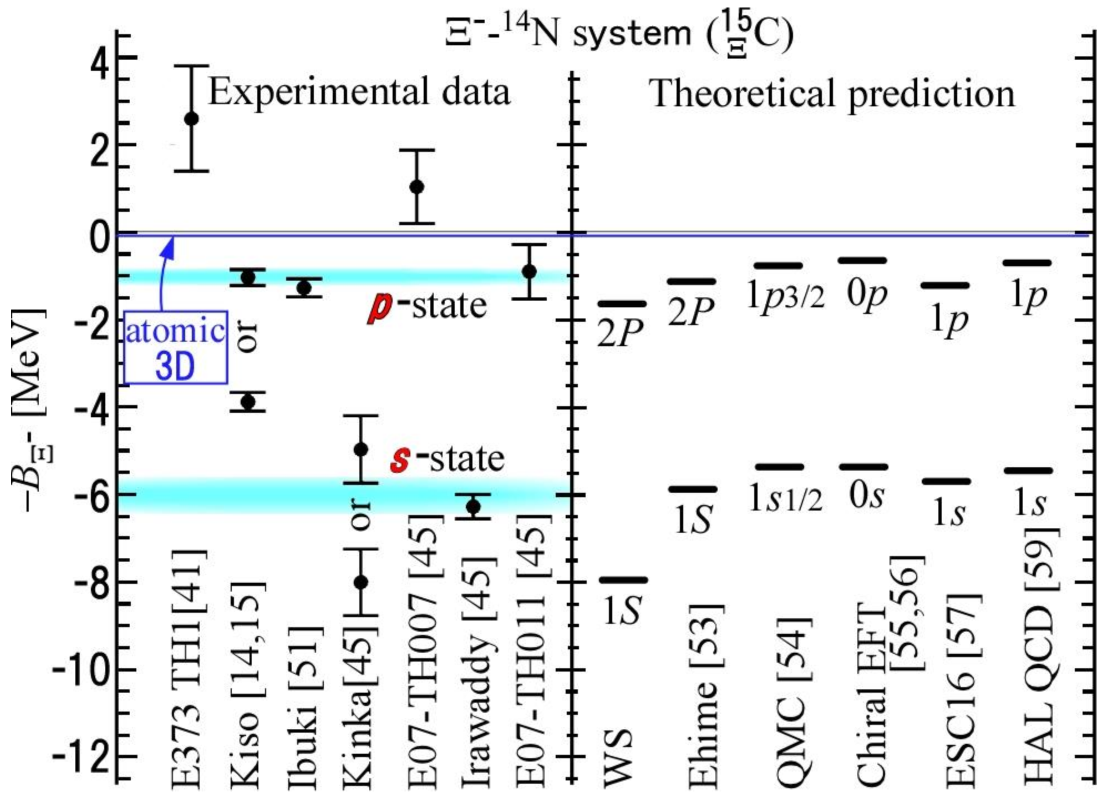
One reaction process satisfied kinematical consistency.

- B_{Ξ^-} = 1.27 ± 0.21 MeV

1st observation of nuclear s-sate of Ξ hypernucleus

- B_{Ξ^-} = 6.27 ± 0.27 MeV

Level scheme of Ξ hypernucleus ($\Xi^{-}+^{14}N$)



Number of Ξ^{-} captured by ^{14}N ~ 300

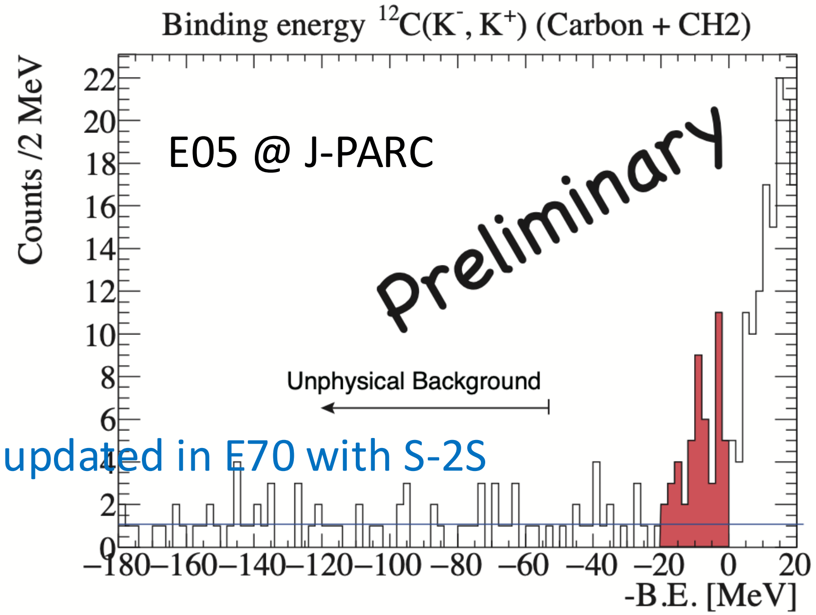
IRRAWADDY event is assumed to be s state

→ Ξ^{-} capture probability in s orbit ~ 0.33%

Much larger than theoretical calculations

- 0.0001%-0.02% w/ W_0^{Ξ} = 0.5-8 MeV (T. Koike)
- 0.00% - 0.03% (Zhu et al.)

T. Nagae et al., AIP conf. proc., 2030, 020015 (2019)



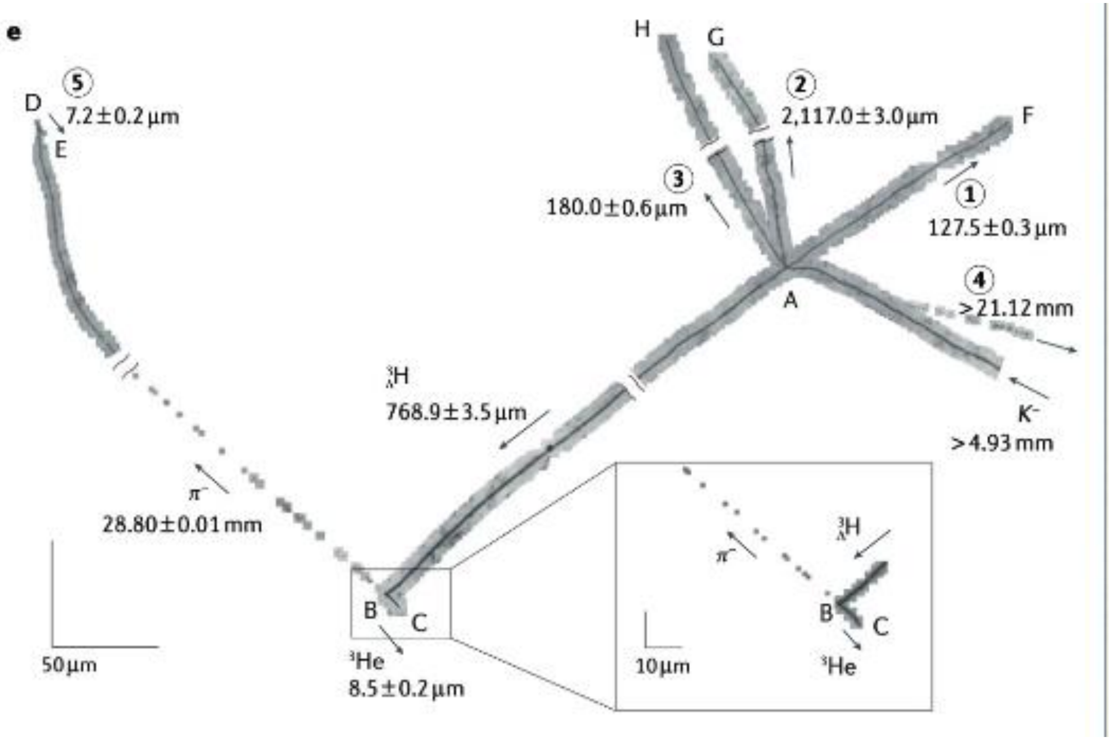
→ To be updated in E70 with S-2S

Ξ hypernuclear spectroscopic studies are highly important to spin-dep. ΞN interaction.

Support weak ΞN-ΛΛ coupling predicted by HAL QCD

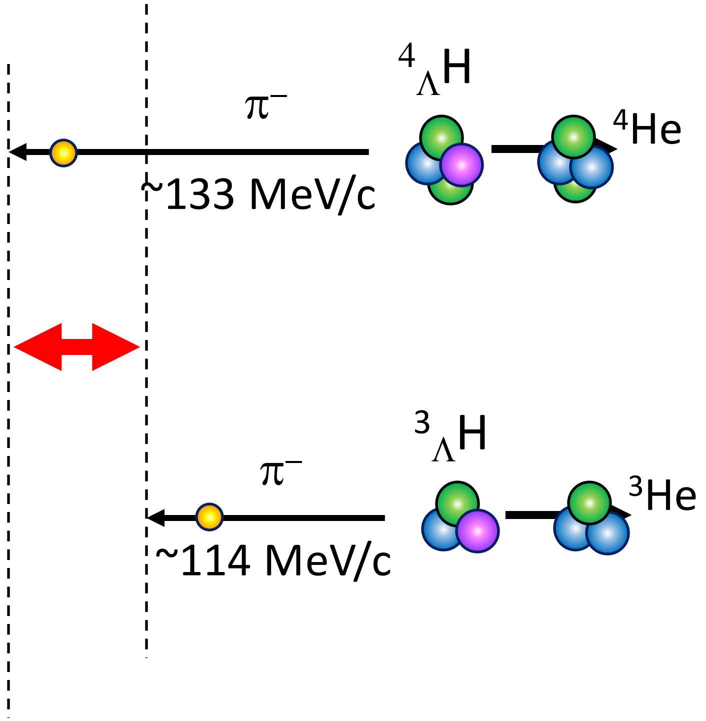
Hyperfragment at K- interaction on emulsion

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

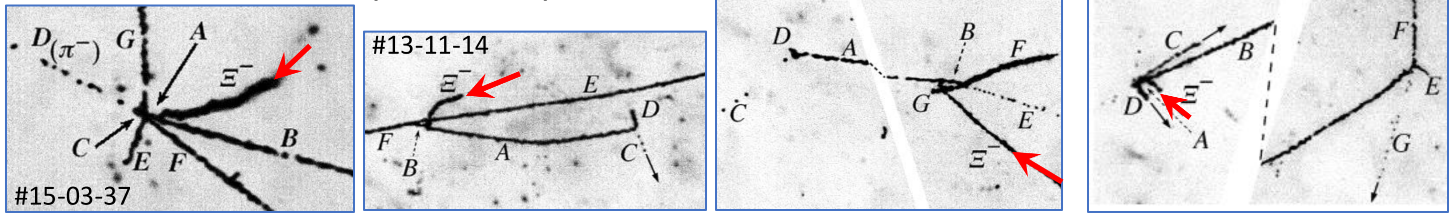
→ Nakagawa's talk in detail

Evolution of experiments with hybrid emulsion method for S=-2

Slide from J. Yoshida

KEK-PS E176 (1988-89)

Nuclear Physics A 828 (2009) 191–232

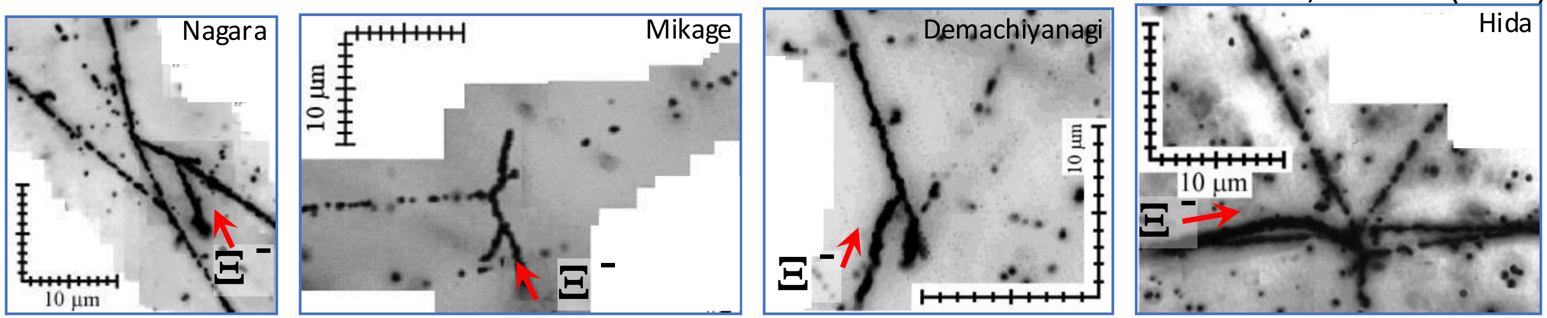


* ~80 Ξ^- stop events
* Existence of double Lambda hypernucleus

X10 statistics

KEK-PS E373 (1998-2000)

PHYSICAL REVIEW C 88, 014003 (2013)



* At least ~650 Ξ^- stop events; Prog. Theor. Exp. Phys. 2019, 021D01
* NAGARA, KISO

X10 statistics

J-PARC E07 (2016-17)

* ~10k Ξ^- stop events

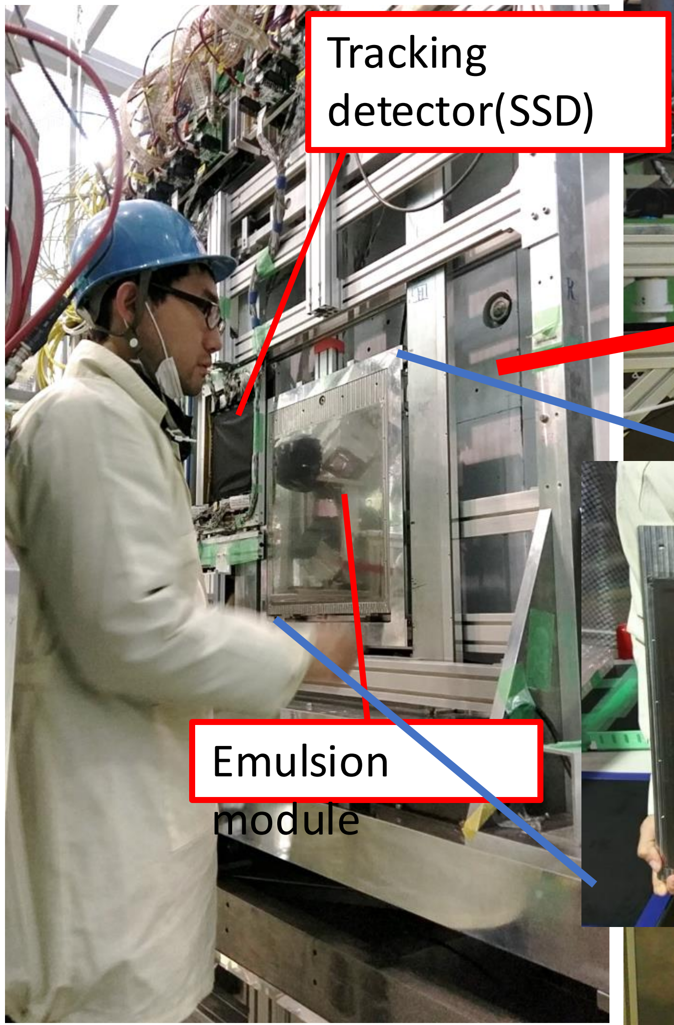
	Emulsion gel	K^- purity	Beam intensity
KEK-PS E373	0.8 tons	25%	$1*10^4$/spill
J-PARC E07	2.1 tons	~82%	$3*10^5$/spill

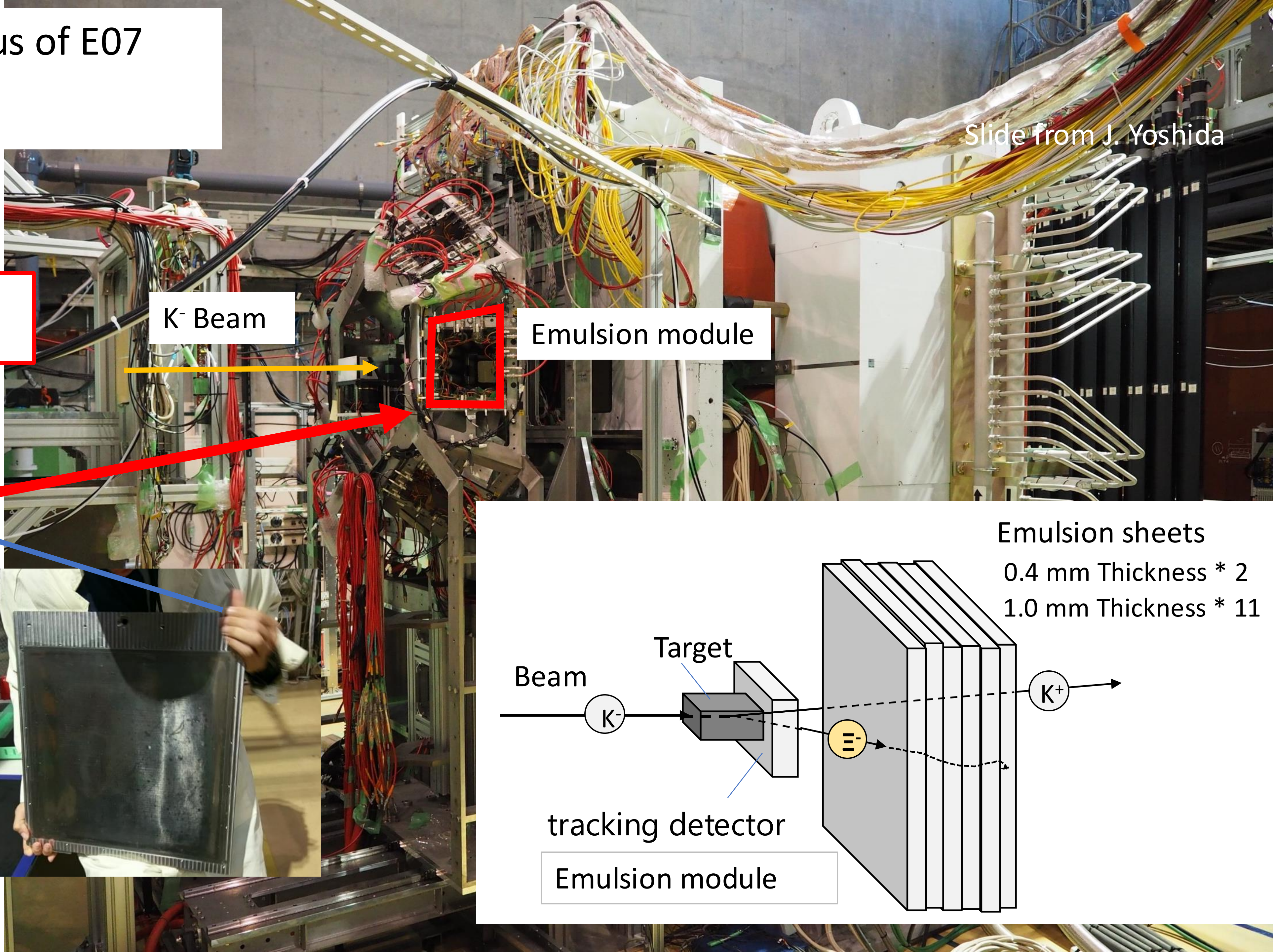
Experimental apparatus of E07

2016-2017

J-PARC, Ibaraki, Japan

Emulsion module

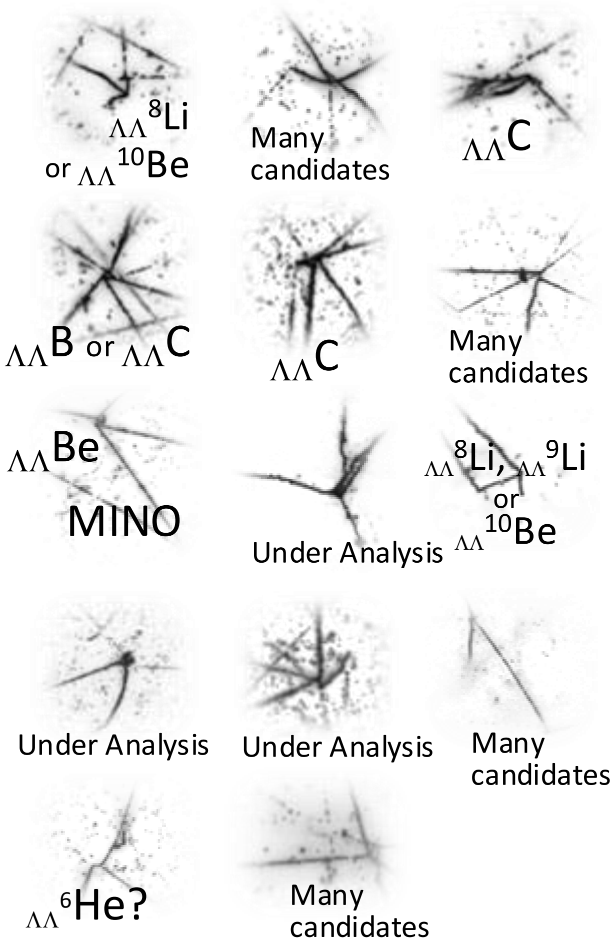




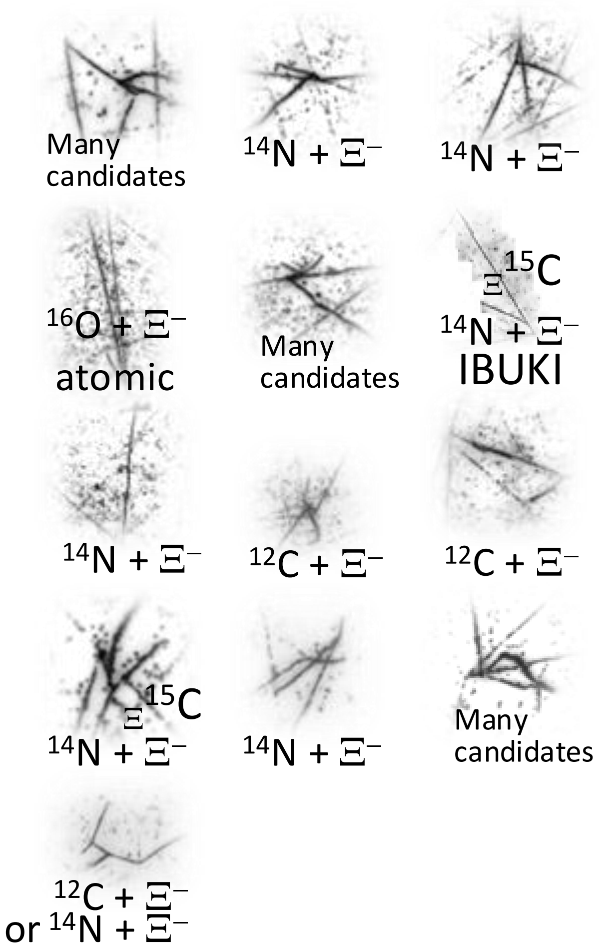
List of detected DBL HY in E07 (Apr., 2020)

	KEK-PS E373	J-PARC E07
Searching period	~7 years	2 years (Apr., 2018 ~)
S=-2 system	9	33

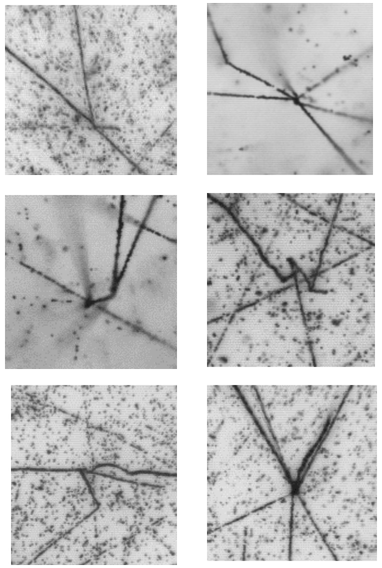
14 double-Λ events



13 twin-hyper events

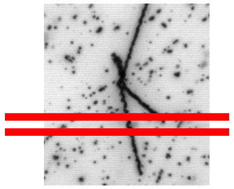


7 confused



Developing X-ray microscope

7 → 6



New events are being accumulated successfully and rapidly.

Slide from K. Nakazawa

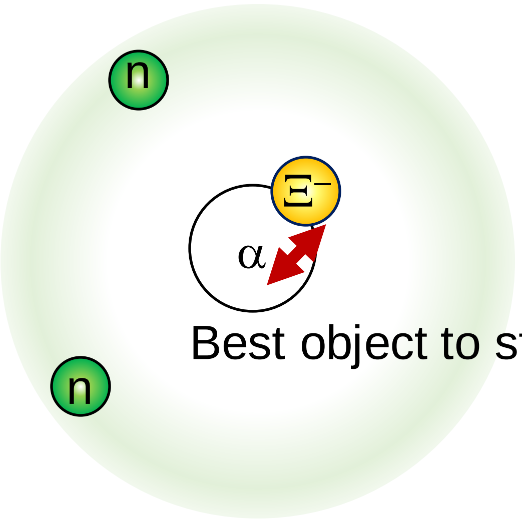
Light Ξ hypernuclear systems

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

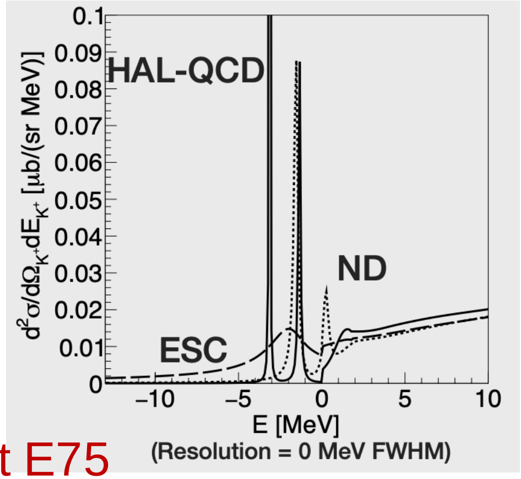
1) spin-isospin independent term
^{7}Li (K^-, K^+) $^{7}_{\Xi}$H is suitable
^{6}He : neutron halo nucleus
2 neutrons are far away from Ξ^-+α
E. Hiyama et al., PRC78,054316(2008).

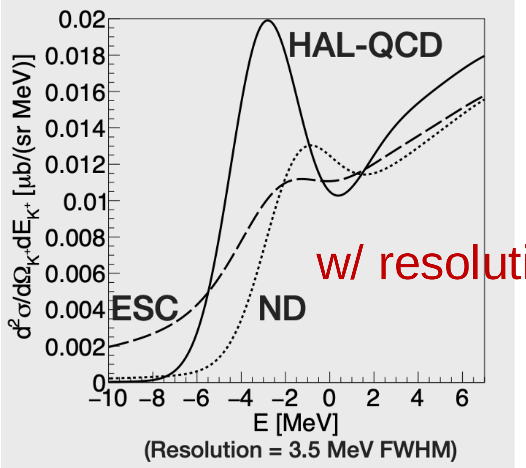


Best object to study V_0

$^{7}_{\Xi}$H

Some hints at E75



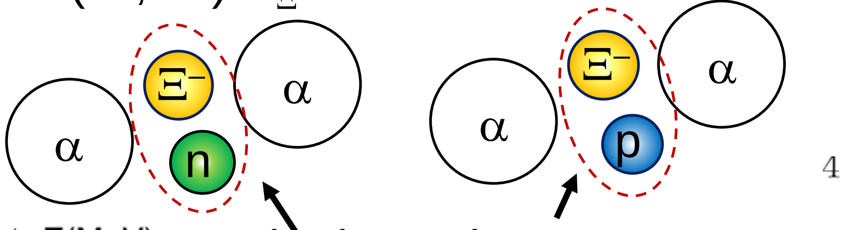


w/ resolution

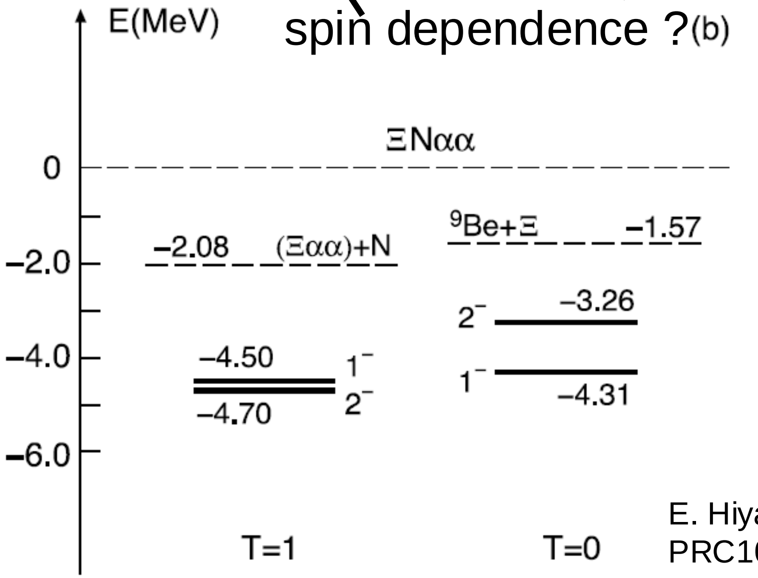
2) spin-isospin dependent term
ΞNαα system is important

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

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



spin dependence ?



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

Future programs

- $^{5}_{\Lambda\Lambda}$H from $^{7}_{\Xi}$H decay (E75) — K1.8
  - Study of lightest $\Lambda\Lambda$ nuclei
- ΛN-ΣN cusp measurement (E90)
  - Low-energy ΣN (S=1, T=0) interaction, ΛN-ΣN coupling
- High resolution (π^+, K^+) spectroscopy for light Λ hypernuclei (E94)
  - Confirmation of energy calibration point by 7_{Λ}Li for (π^+, K^+) spectroscopy
- Nucleon resonance by π induced reaction (E45)
  - Missing resonance
- New Λ^* resonance study by $\Lambda\eta$ decay (E72) — K1.8BR
  - P or D-wave resonance state just above the threshold
- Kaonic deuterium X-ray measurement (E73)
  - Isospin dependence of KbarN interaction
- γ-ray spectroscopy of Λ hypernuclei (E63) — K1.1
  - Modification Λ property in nuclear medium, CSB study for $^{4}_{\Lambda}$H

Hadron Experimental Facility Extension (HEF-EX) project

K1.8BR (~1.0 GeV/c K⁻)

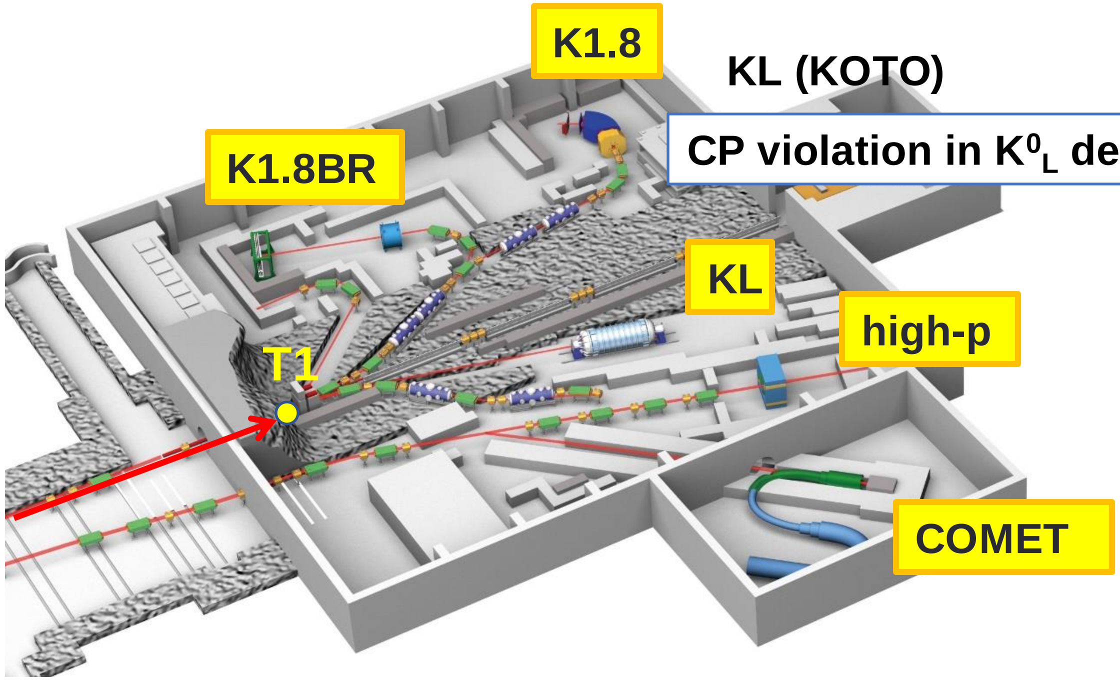
K^{bar} N interaction

K1.8 (~1.8 GeV/c K⁻)

BB interaction (focusing on S=-2)

KL (KOTO)

CP violation in K^0_L decay



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

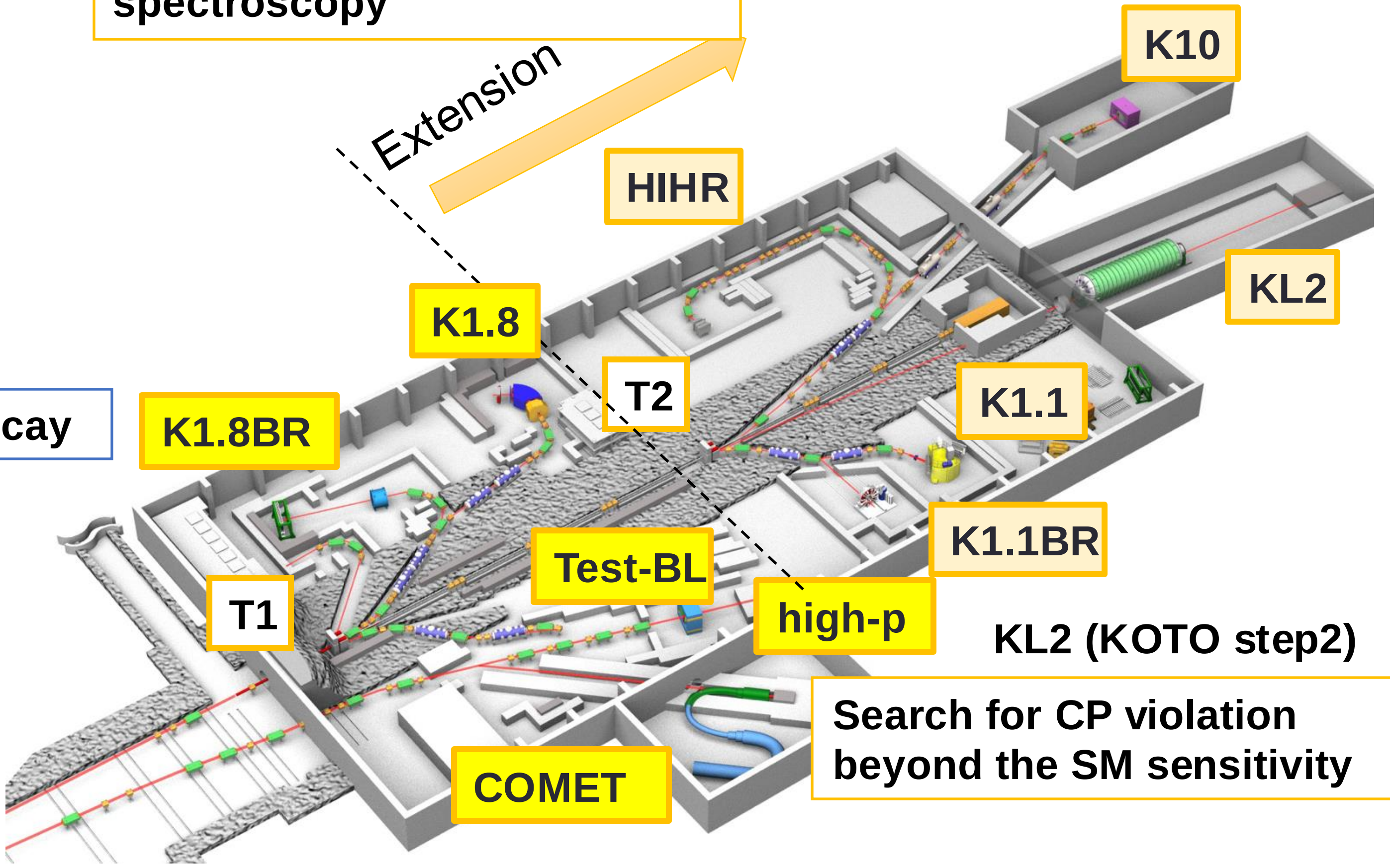
Hadron property in nuclear medium
Baryon spectroscopy

HIHR (~2 GeV/c π)

Ultra precise Λ hypernucler spectroscopy

K10 (~10 GeV/c K⁻)

Ω baryon spectroscopy



KL2 (KOTO step2)

Search for CP violation beyond the SM sensitivity

K1.1BR (~0.8 GeV/c π/K)

Physics using a low energy Kaon

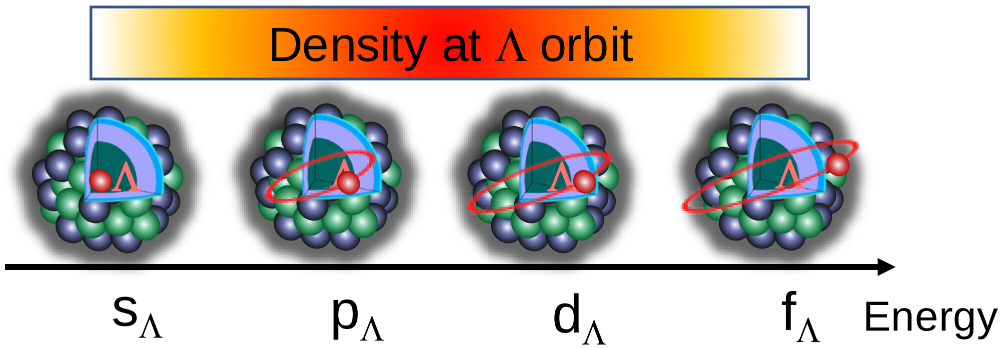
K1.1 (~1.2 GeV/c π/K)

BB interaction (focusing on S=-1)

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

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

Nuclear density is different for each Λ orbital state

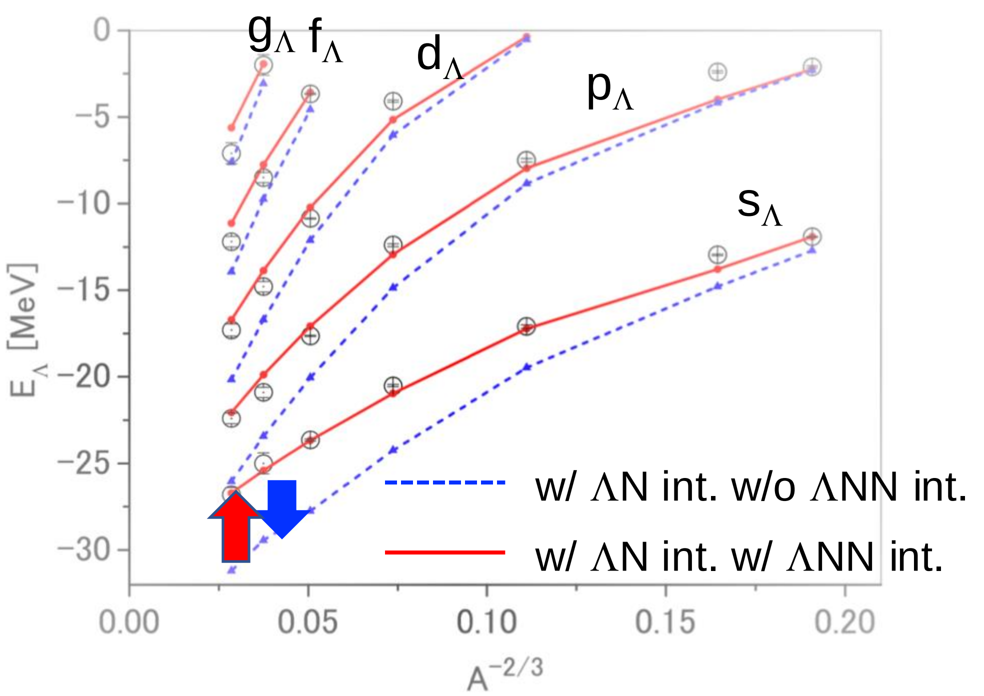


Two directions for study of the density dependence of ΛN interaction

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

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

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



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

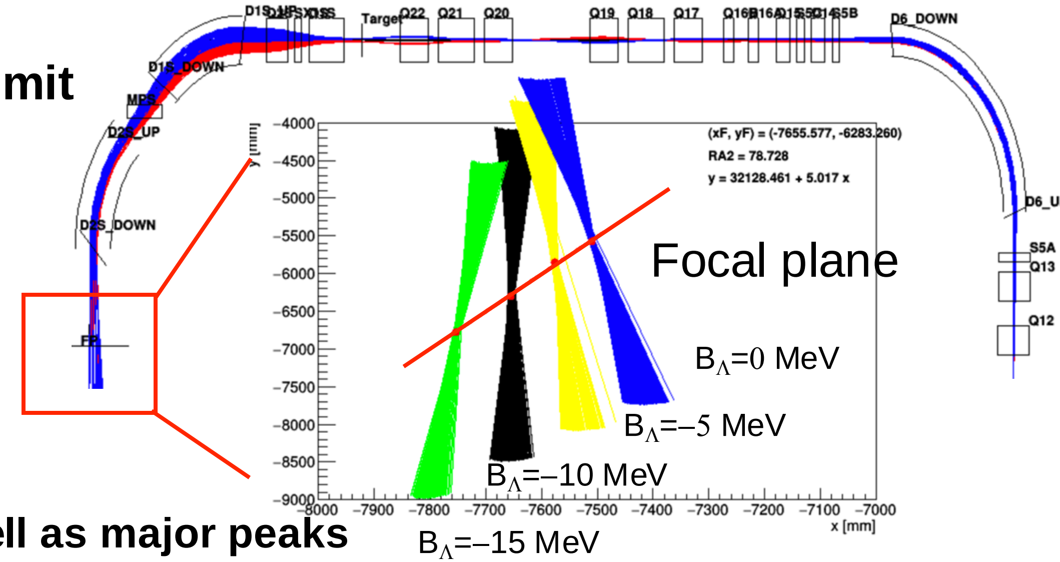
→ Realize **high-resolution** spectroscopy **without beam intensity limit**

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

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

- Thin target can be used

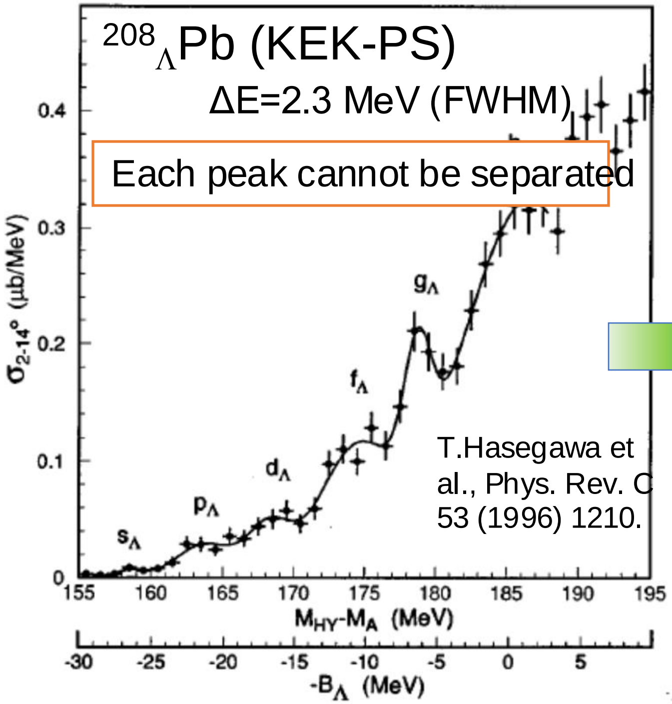
→ High resolution and various target options

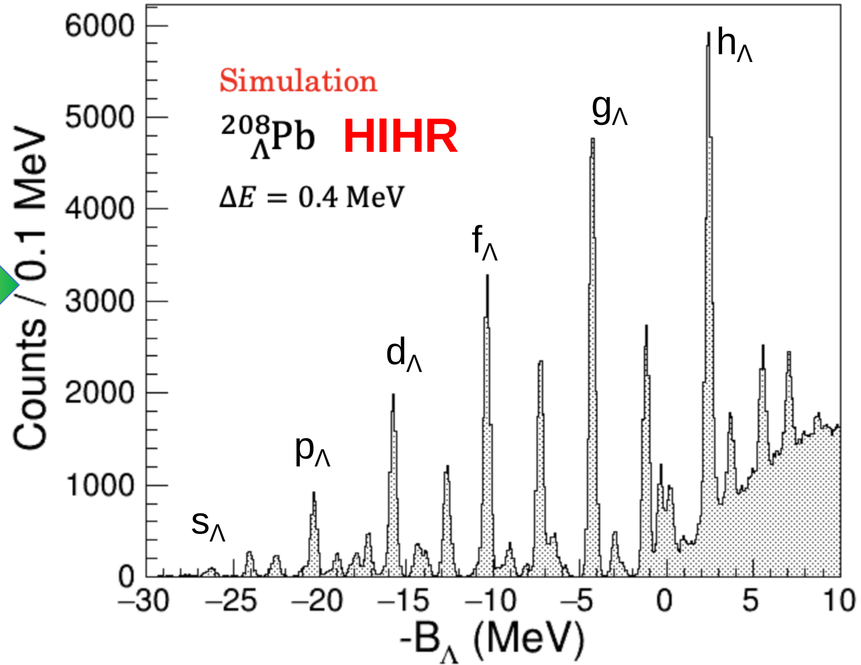


Impossible to separate peaks with a few MeV resolution

0.4 MeV (FWHM) resolution

Clear separation of sub-major as well as major peaks





Precise Λ binding energies for wide-mass range

⇩

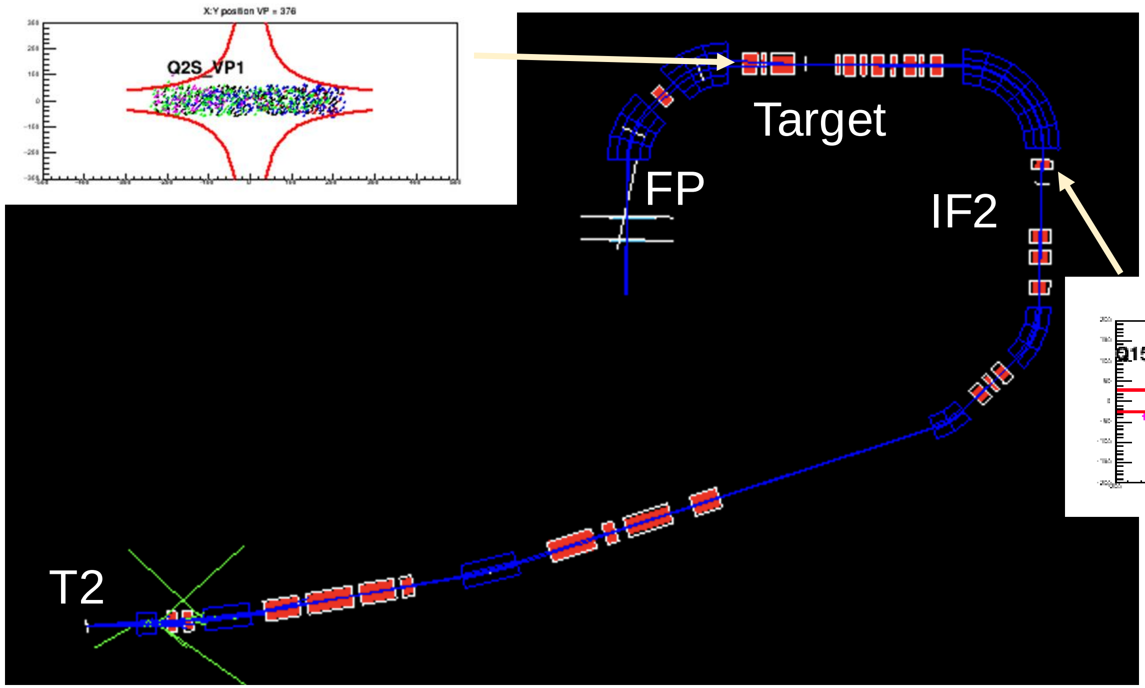
Density dependence of ΛN interaction (ΛNN interaction)

⇩

Calculate U_Λ at high density region

Untangle hyperon puzzle in neutron star

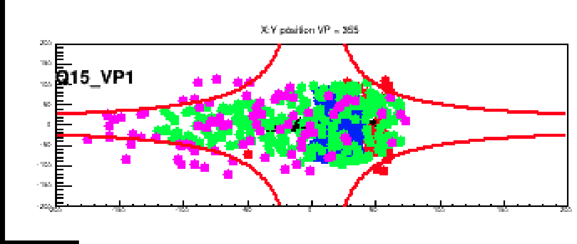
HIHR Study with Geant4 is ongoing

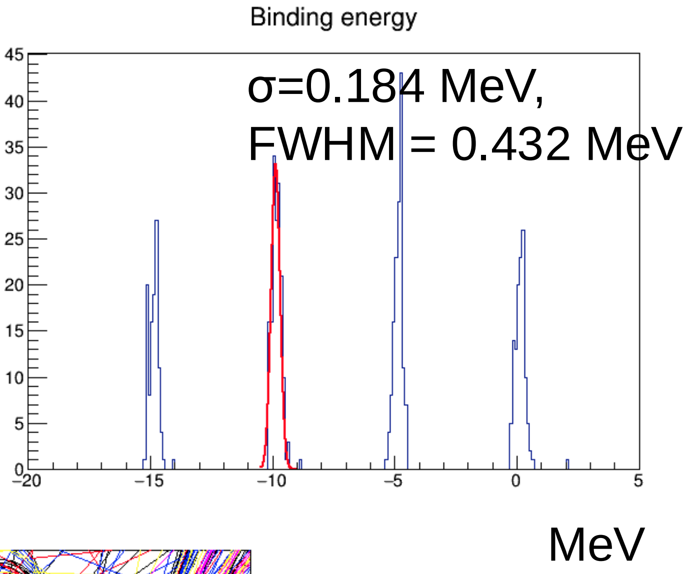


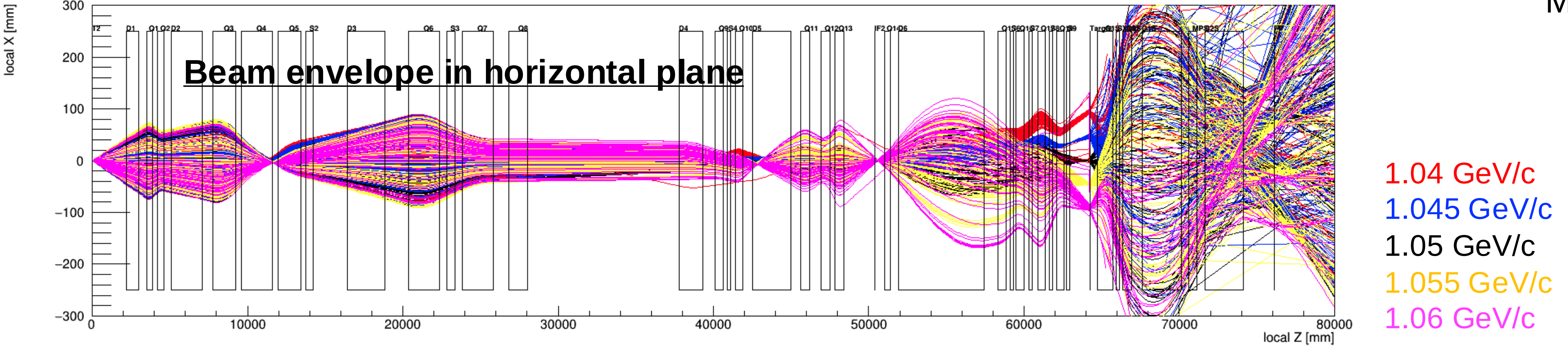
New beam line configuration w/ minimum number of magnet

Geant4 program from T2 target was constructed

- Beam size at each component
- Mass resolution

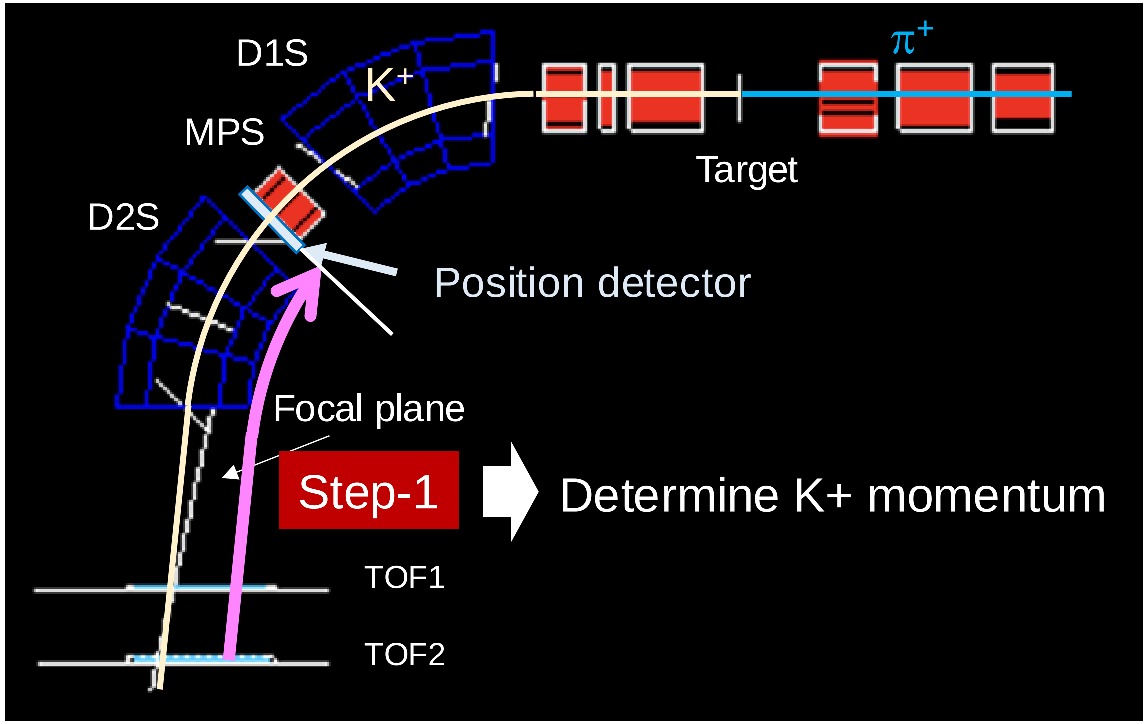






K^+ momentum measurement option at HIHR

HIHR dose NOT need to measure K+ momentum for mass measurement thanks to dispersion matching.
But, K^+ momentum information would help us with the initial commissioning and widen physics cases.



Idea to install position detector downstream MPS

Step-1

Focal plane info. (x_{FP}, y_{FP}, θ_{FP}, ϕ_{FP})

+ Matix (FP → position detector) + position info.

→ Determination of K+ momentum (δ)

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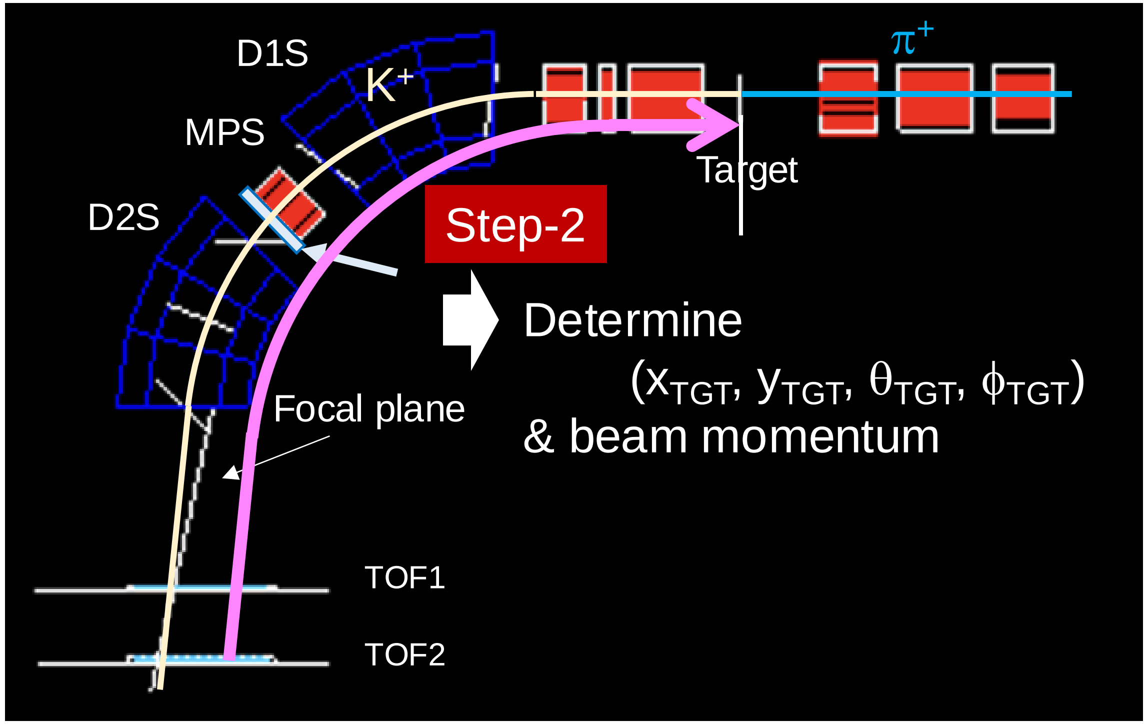

Idea to install position detector downstream MPS

Step-1

Focal plane info. $(x_{FP}, y_{FP}, \theta_{FP}, \phi_{FP})$

+ Matix (FP → position detector) + position info.
→ Determination of K+ momentum (δ)

Step-2

Updated focal plane info. $(x_{FP}, y_{FP}, \theta_{FP}, \phi_{FP}, \delta)$

+ Matix (FP → target) + position info.
→ Determination of reaction information at target $(x_{TGT}, y_{TGT}, \theta_{TGT}, \phi_{TGT})$
→ Dispersive relation at target
x_{TGT} → determination of beam momentum

Missing mass can be calculated

K^+ momentum measurement option at HIHR

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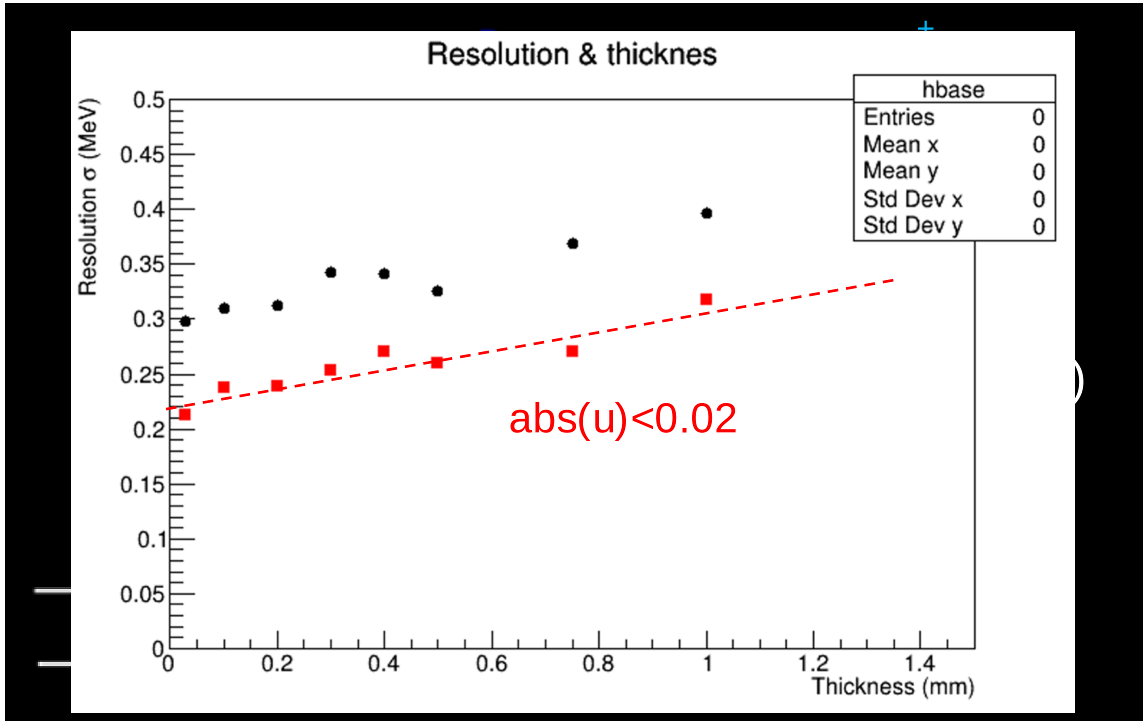
But, K^+ momentum information would help the initial commissioning and widen physics cases.



By using thin detector,
reasonable resolution can be obtained.

Idea to install position detector downstream MPS

Step-1

Focal plane info. (x_{FP}, y_{FP}, θ_{FP}, ϕ_{FP})

+ Matix (FP → position detector) + position info.
→ Determination of K+ momentum (δ)

Step-2

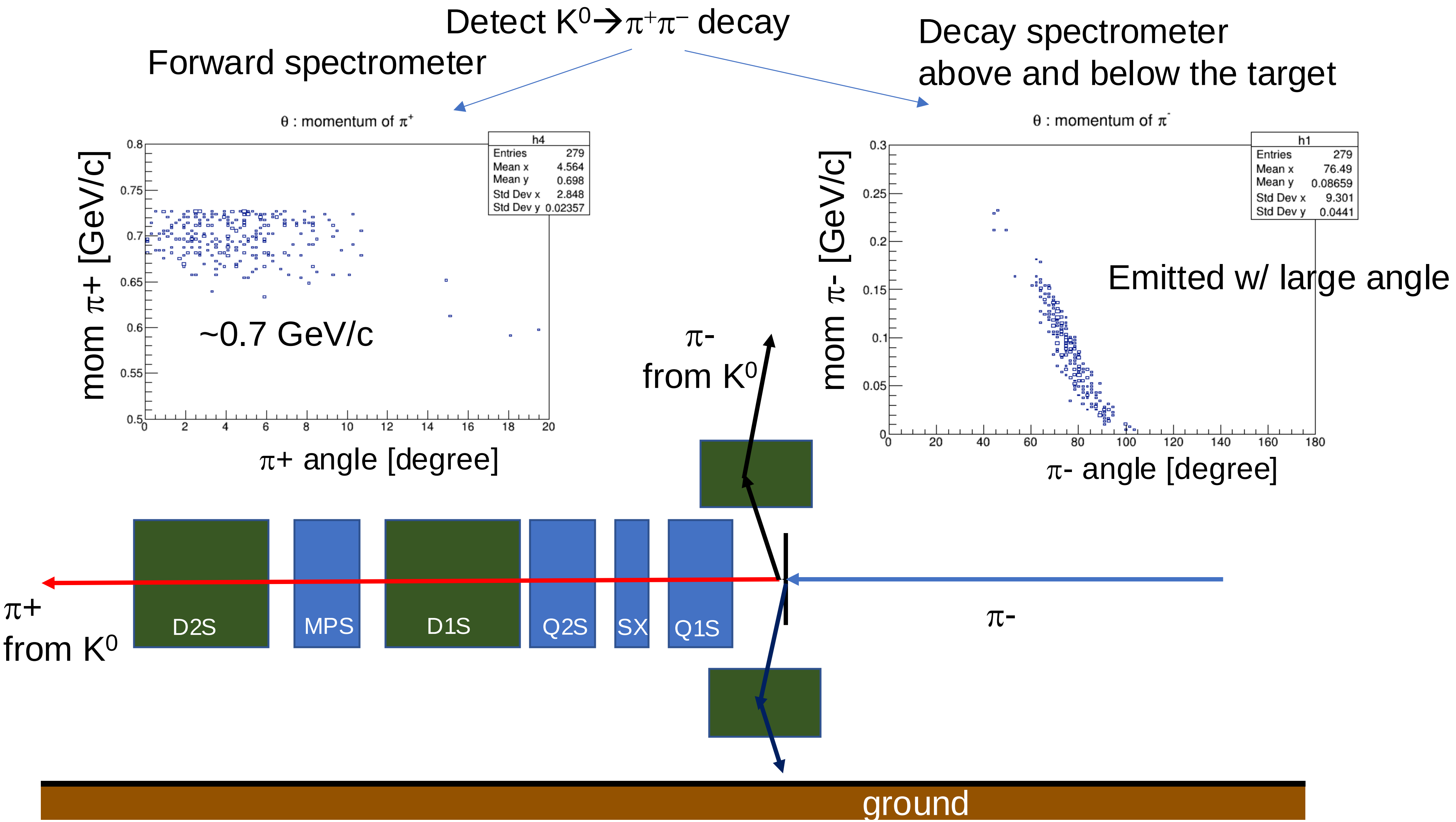
Updated focal plane info. (x_{FP}, y_{FP}, θ_{FP}, ϕ_{FP}, δ)

+ Matix (FP → target) + position info.
→ Determination of reaction information at target
(x_{TGT}, y_{TGT}, θ_{TGT}, ϕ_{TGT})
→ Dispersive relation at target
x_{TGT} → determination of beam momentum

Missing mass can be calculated

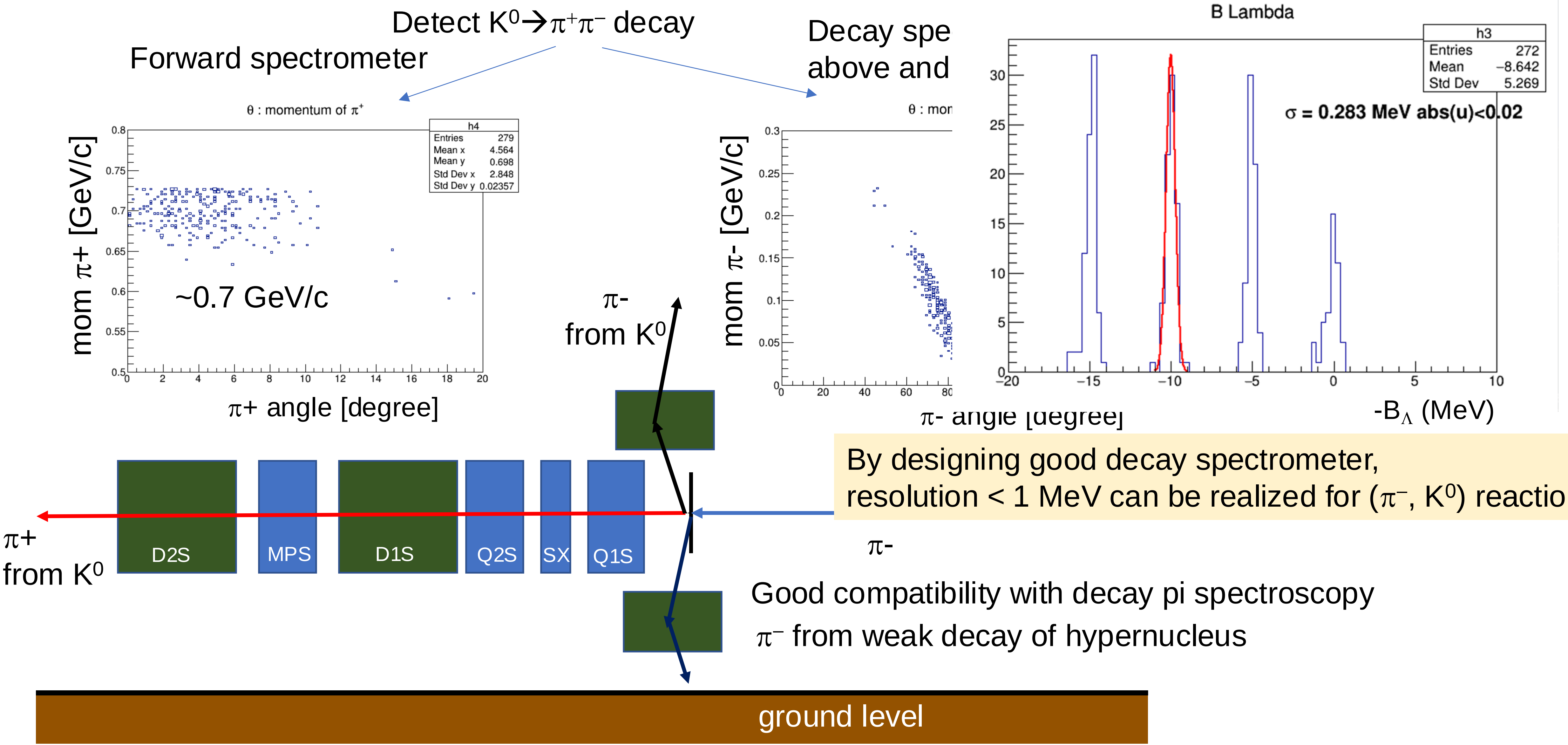
(π^-, K^0) spectroscopy at HIHR

Combination of HIHR and additional spectrometers will open the (π^-, K^0) spectroscopy at HIHR



(π^-, K^0) spectroscopy at HIHR

Combination of HIHR and additional spectrometers will open the (π^-, K^0) spectroscopy at HIHR

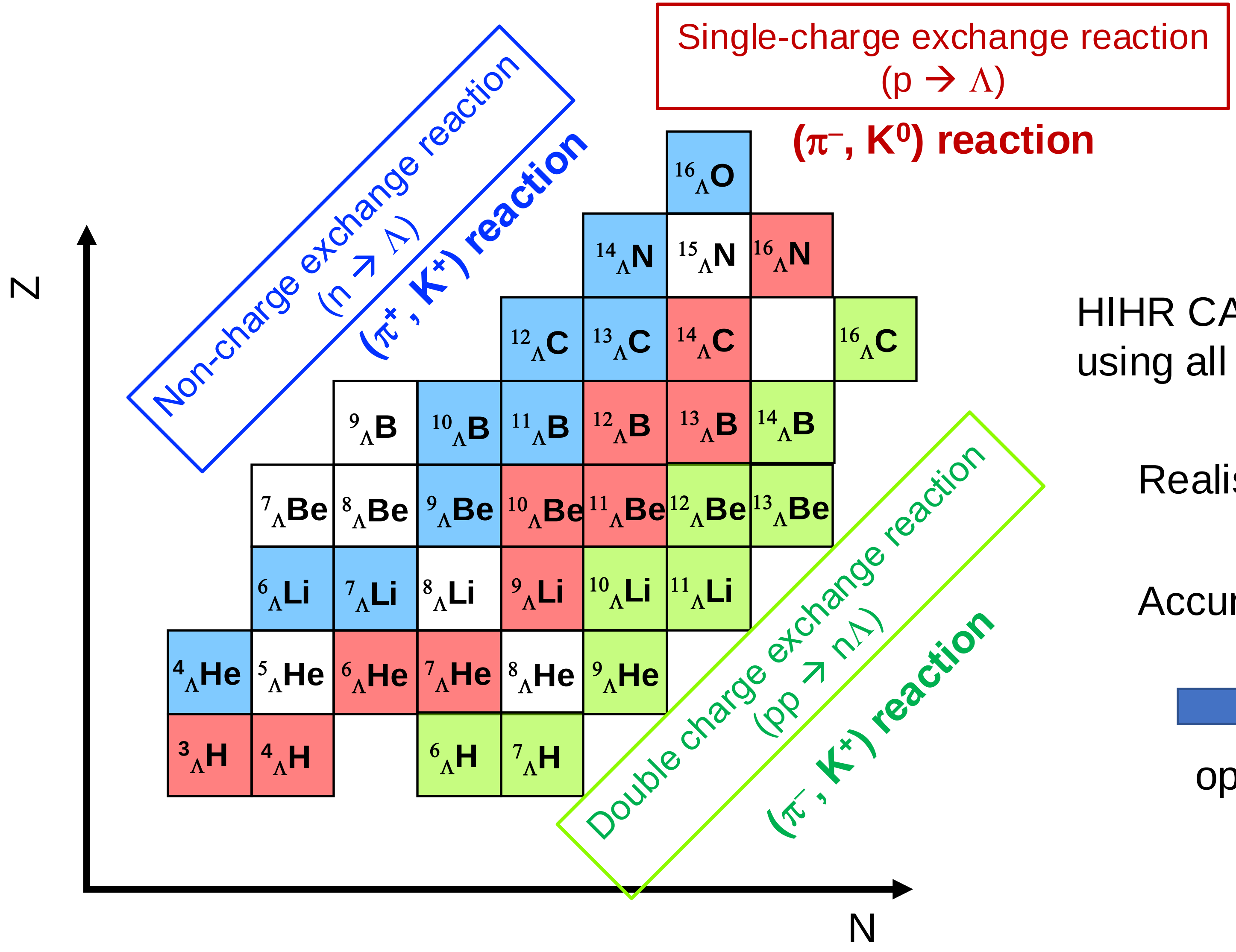


By designing good decay spectrometer, resolution < 1 MeV can be realized for (π^-, K^0) reaction

Good compatibility with decay pi spectroscopy

π^- from weak decay of hypernucleus

HIHR as hypernuclear factory



HIHR CAN explore various hypernucler species using all possible reactions with high resolution.

Realistic YN interaction

+

Accurate and systematic data of hypernuclei

→

open new era of hypernuclear physics