Overview of Strangeness Nuclear Physics at J-PARC

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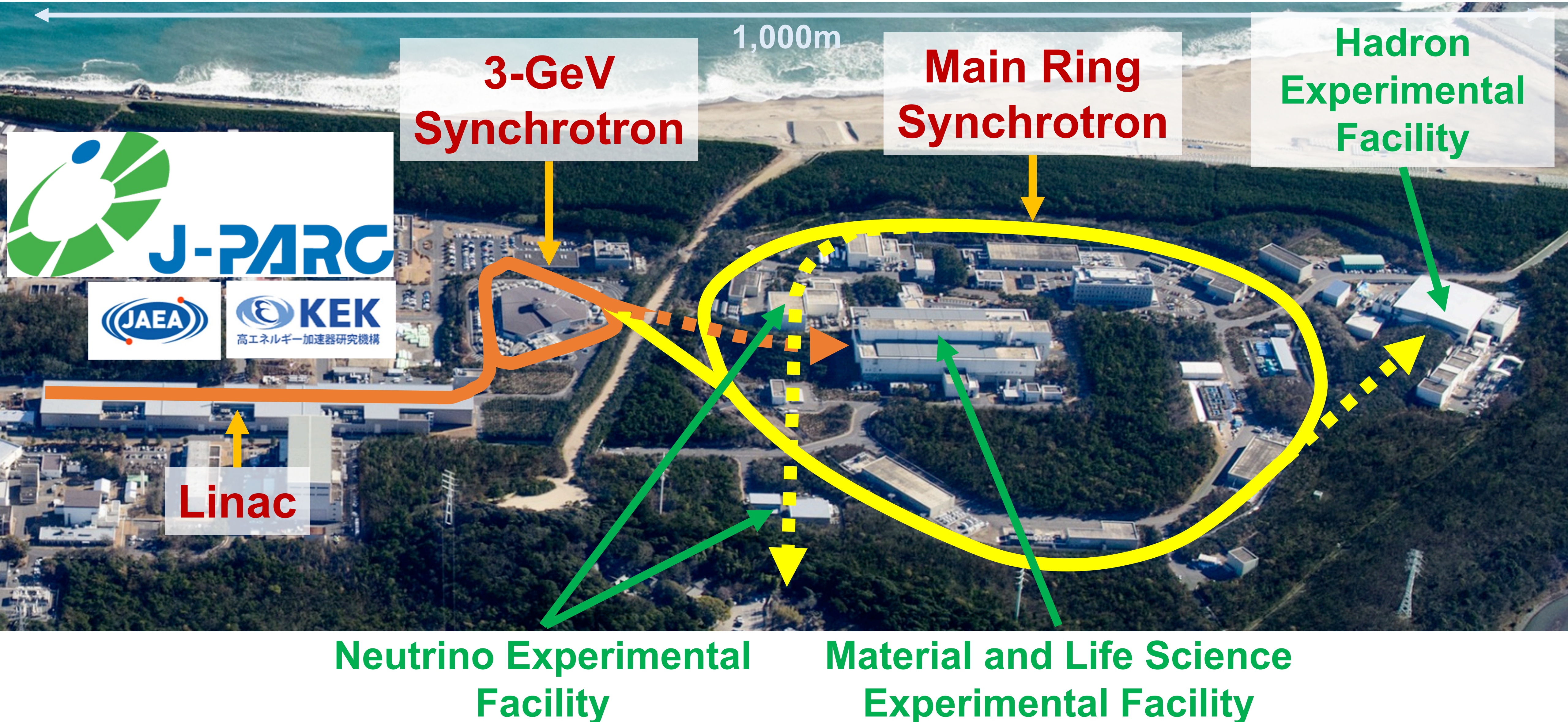
The 10th International Conference on Quarks and Nuclear Physics, July 8 – 12, 2024

TOHOKU UNIVERSITY

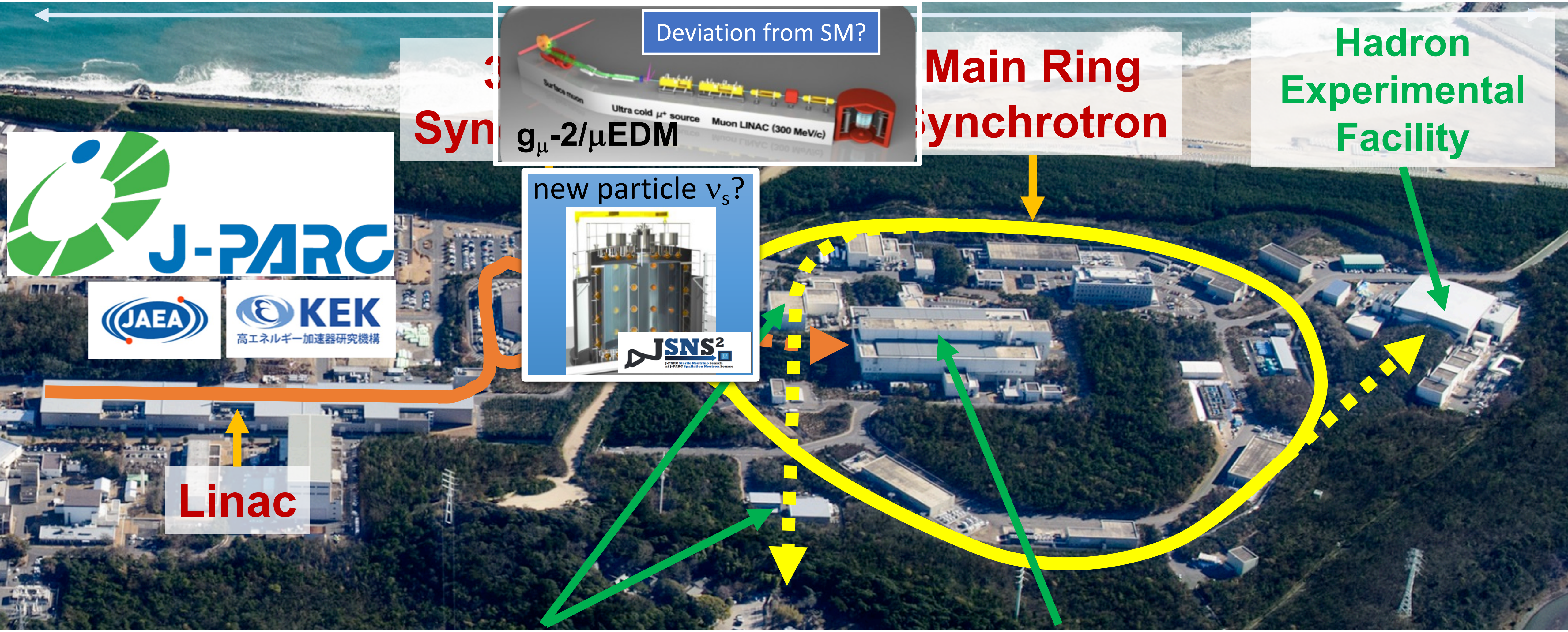
Contents

- Hyperon-Nucleon Interaction
- Few-body strangeness systems
- Exotic systems with strangeness
- Recent S=-2 studies
- Strangeness physics at extended hadron hall
- Summary

Particle and Nuclear Physics @ J-PARC



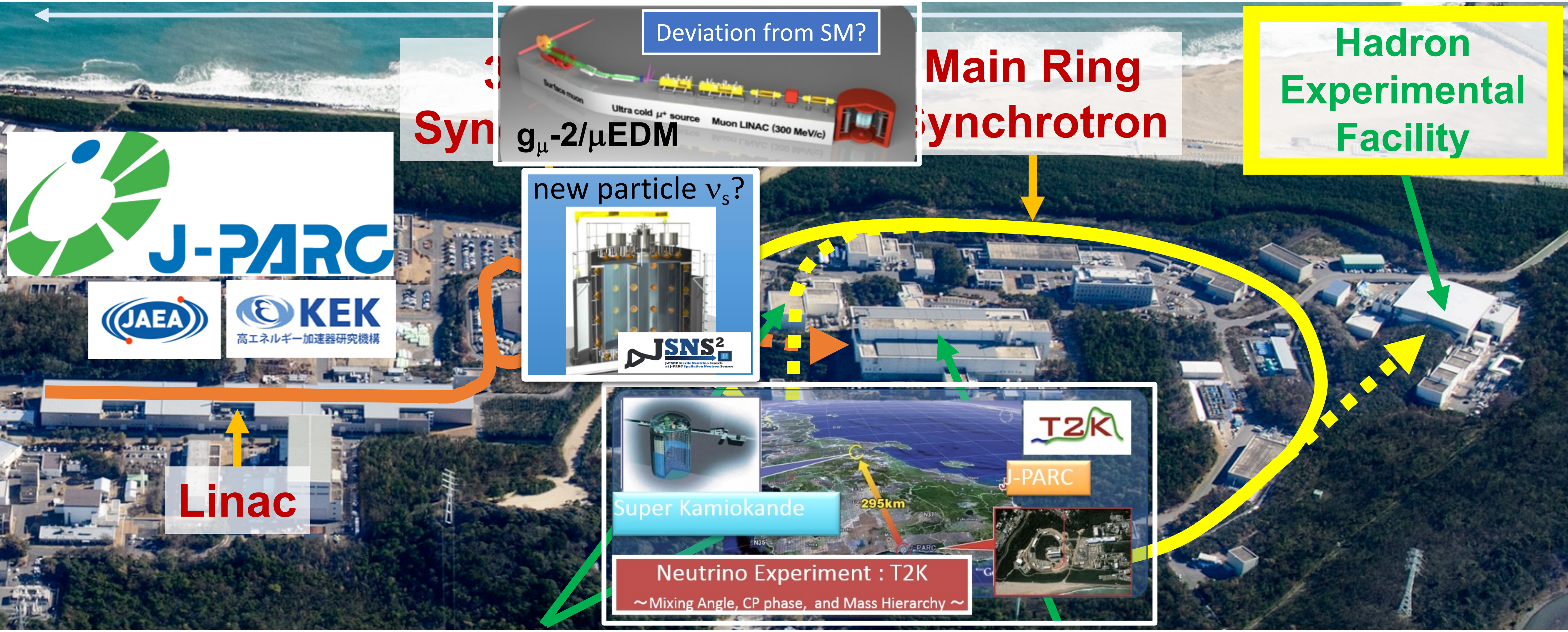
Particle and Nuclear Physics @ J-PARC



Neutrino Experimental Facility

Material and Life Science Experimental Facility

Particle and Nuclear Physics @ J-PARC



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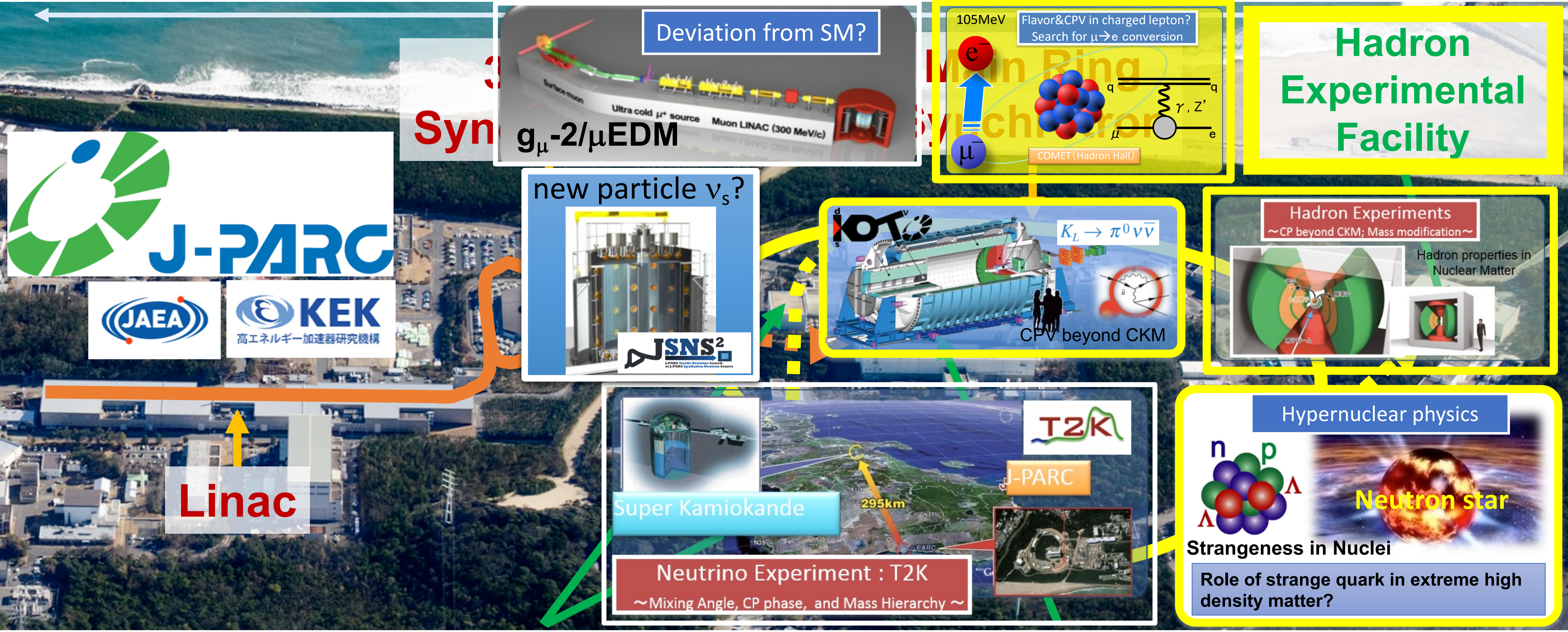


Neutrino Experimental Facility

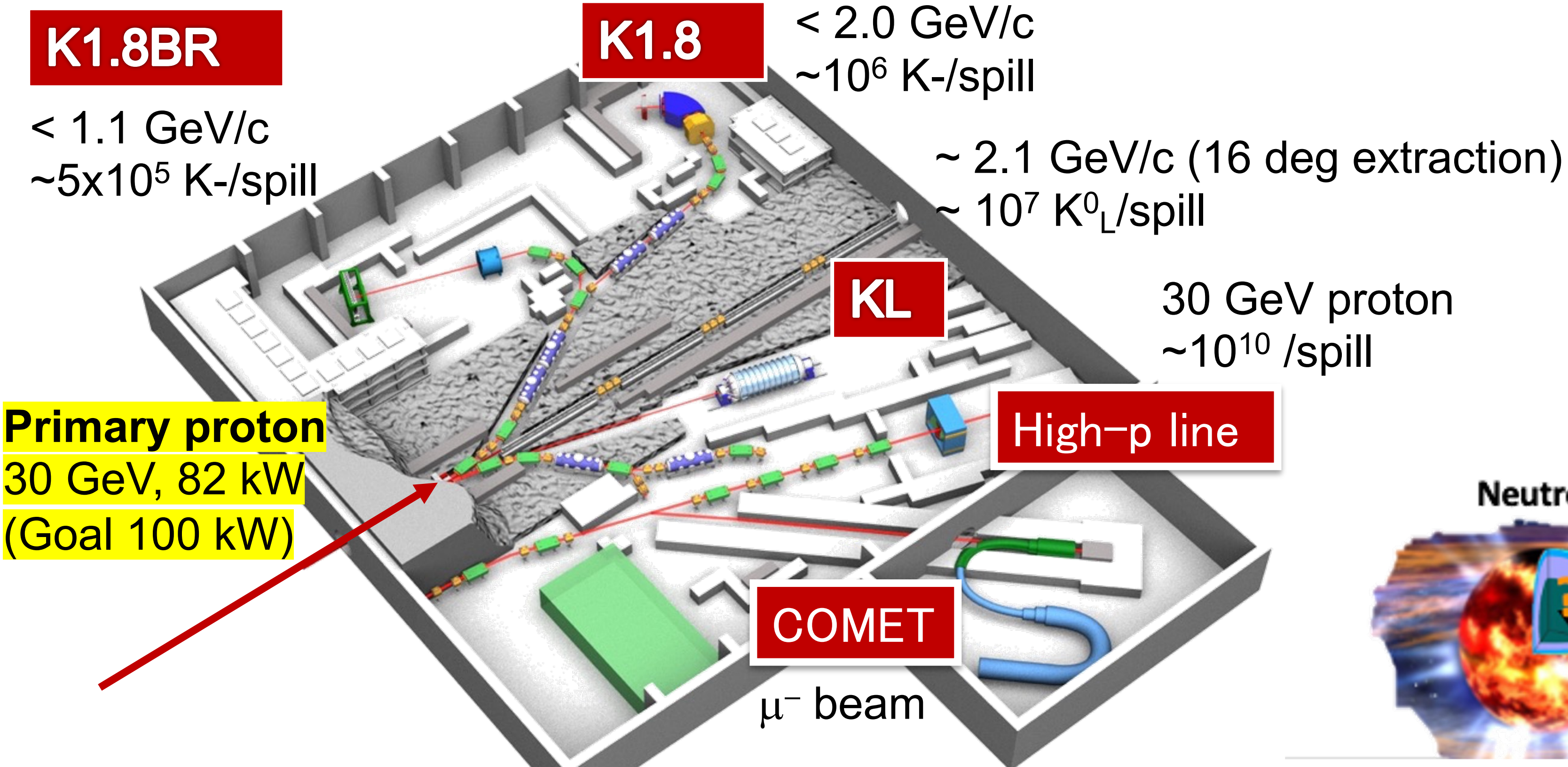
Material and Life Science Experimental Facility

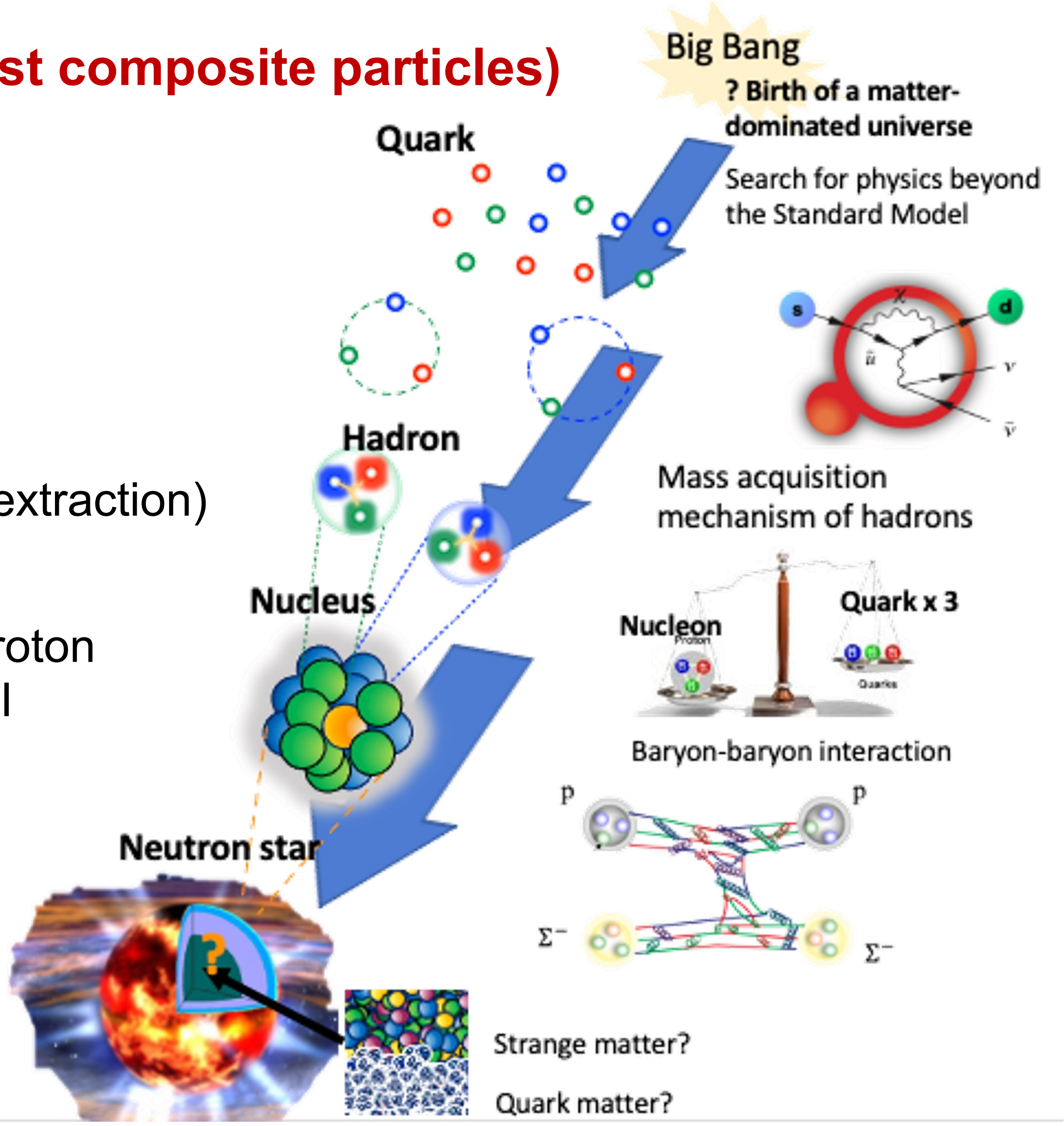
Particle and Nuclear Physics at HEF

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

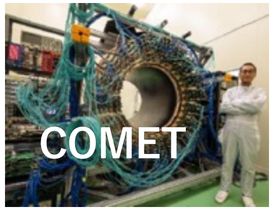




Particle and Nuclear Physics at HEF

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.**



μ→e conversion measurement

Search for charged lepton flavor violation

100 times improvement over present upper limits

Rare decay of neutral kaon

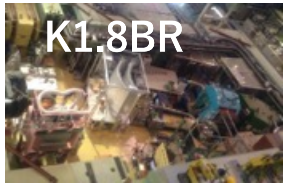
Search for CP violation beyond the standard model

The world's highest sensitivity exceeding the standard model

Mass modification of vector mesons in nuclei

Elucidation of the mass acquisition mechanism of hadrons

Vector meson in nuclei : 10 times more precision



Systematic study of Kaonic nuclei

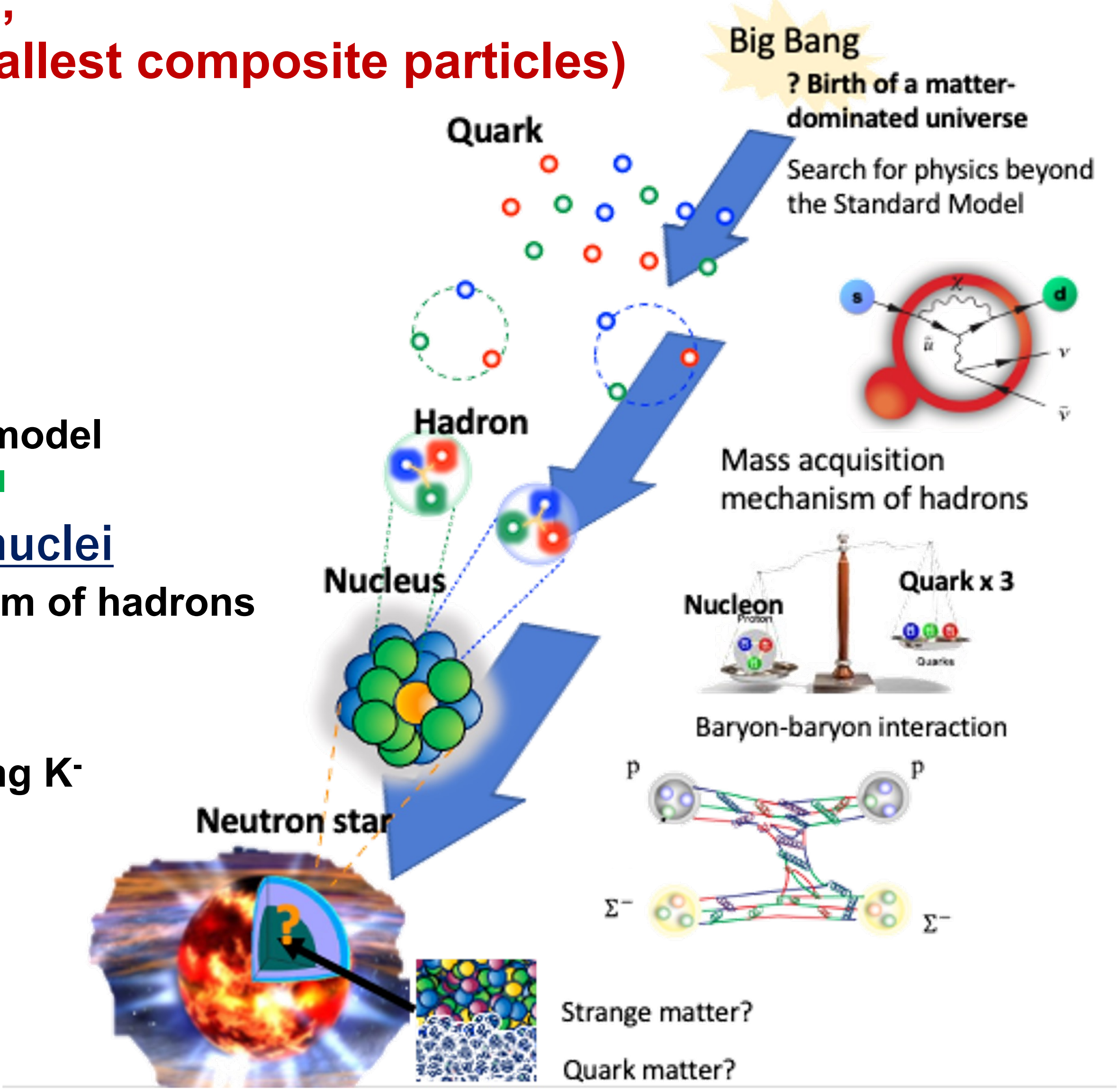
Study of exotic hadron bound system including K^-

Mass number dependence of kaonic nuclei

Spectroscopy of S=-1, -2 hypernuclei

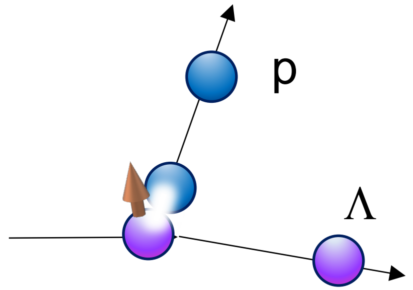
Elucidation of the appearance mechanism of Ξ, Λ hyperons in dense matter

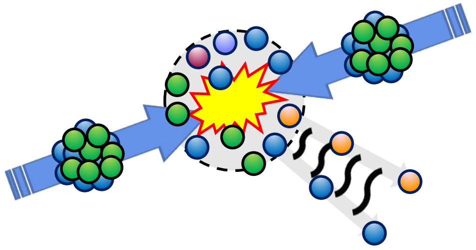
Excellent mass resolution of 2 MeV for Ξ hypernuclei

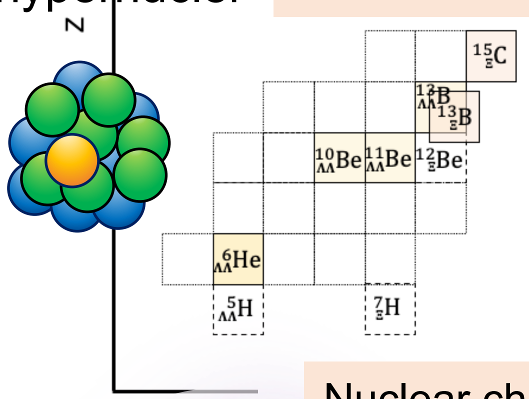


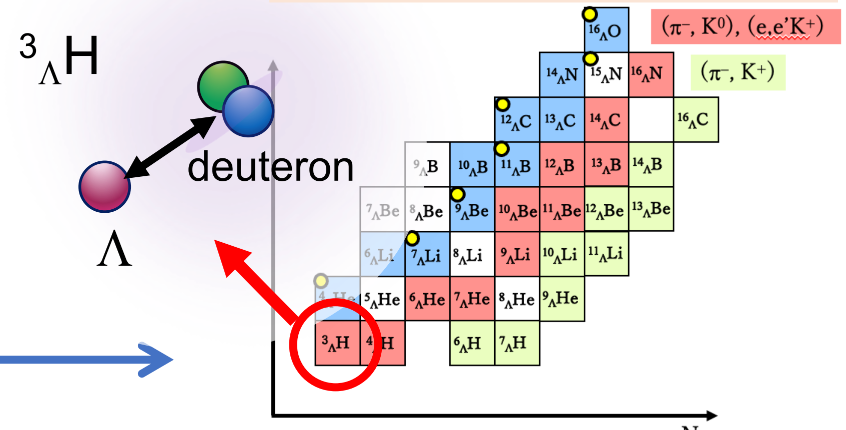
Hypernuclear physics

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



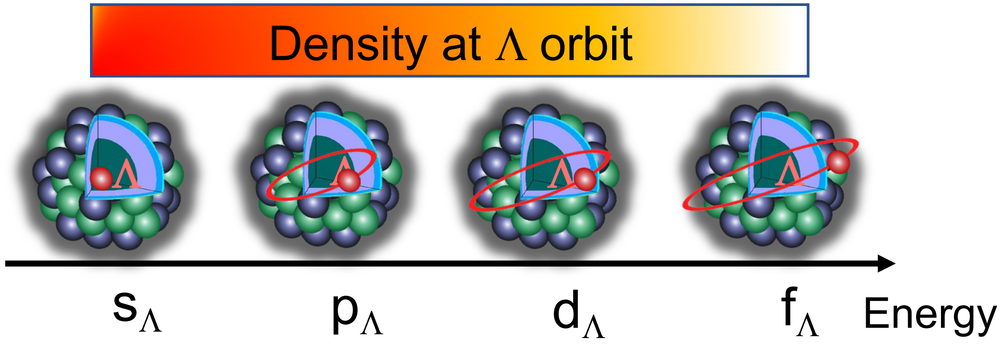


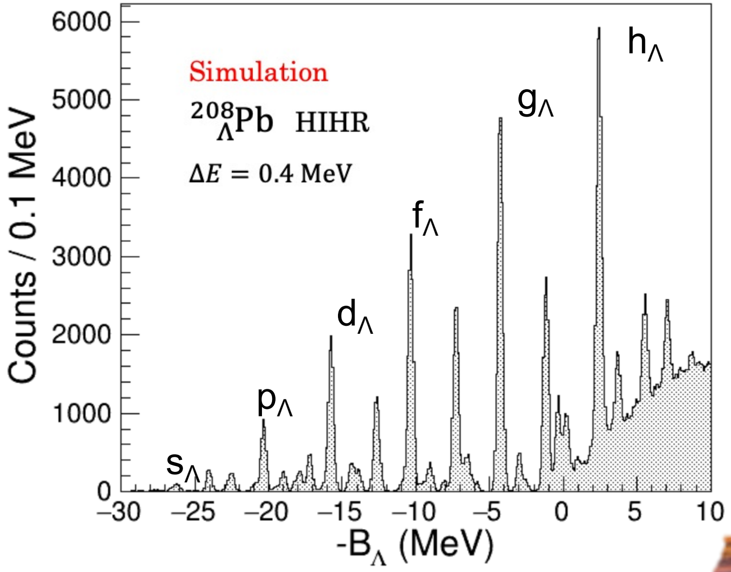




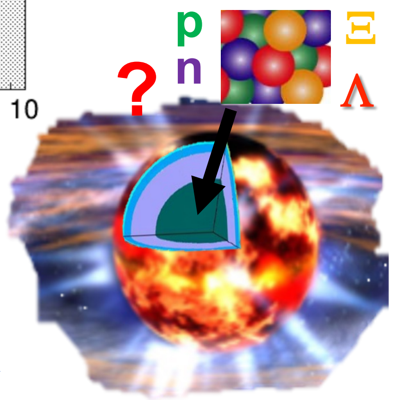
Two-body YN int.

ΛN-ΣN coupling, ΛNN int., ΛΛ, ΞN int.





Neutron star

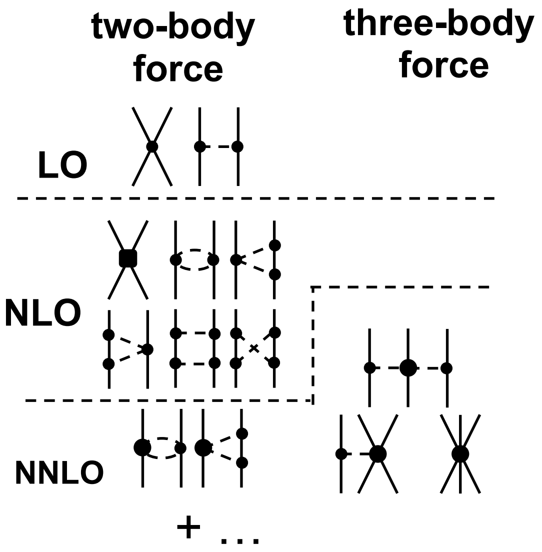


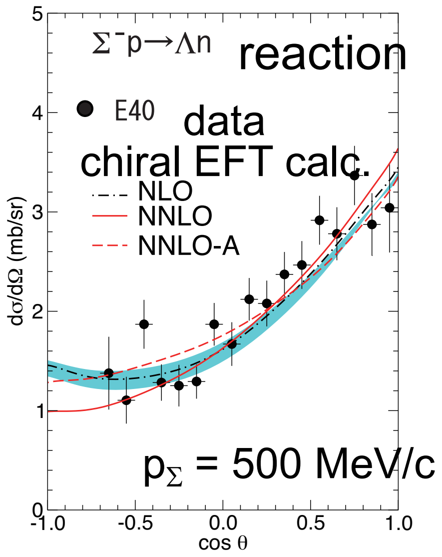
Density dependent ΛN int., ΛNN int.

Progress of theory & experiment of BB int. study

Theoretical progress

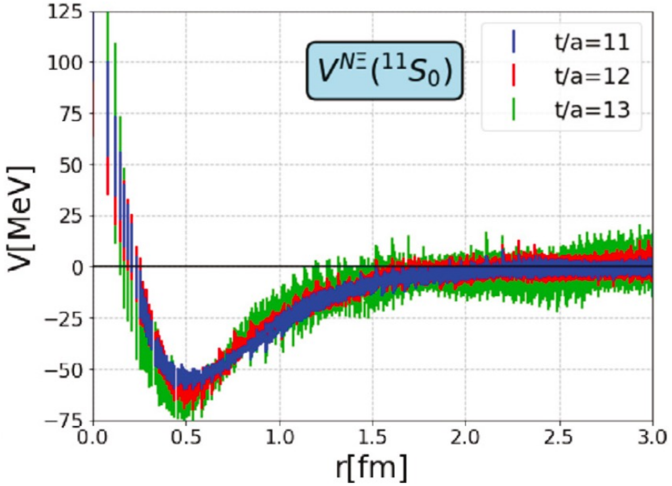
Hyperon-Nucleon int. w/ chiral effective field theory
(J. Haidenbauer et al.)





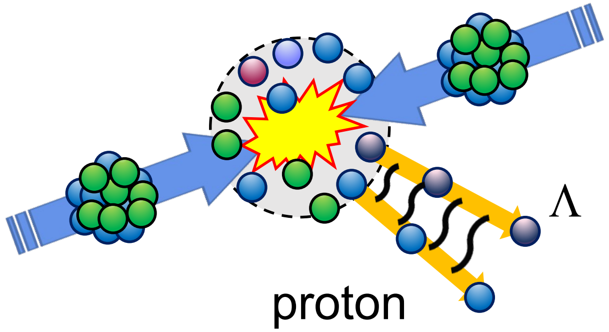
Improving accuracy w/ our new data

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

Experimental progress



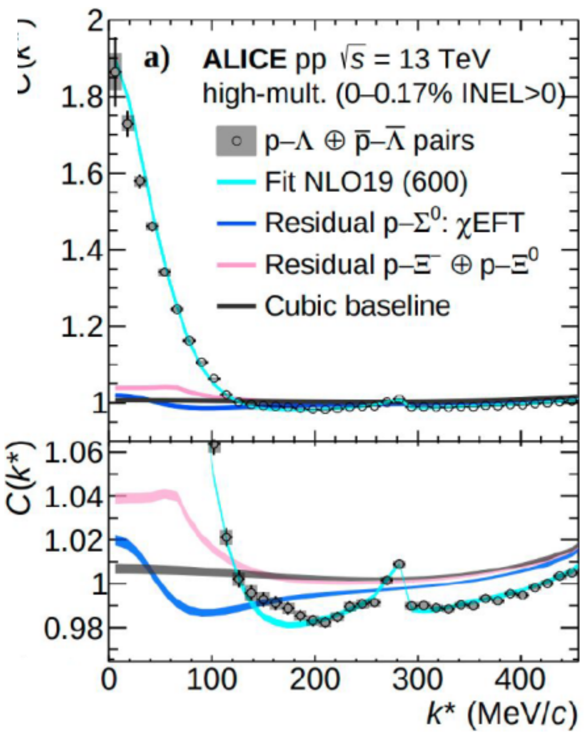
BB interaction by femtoscopy

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

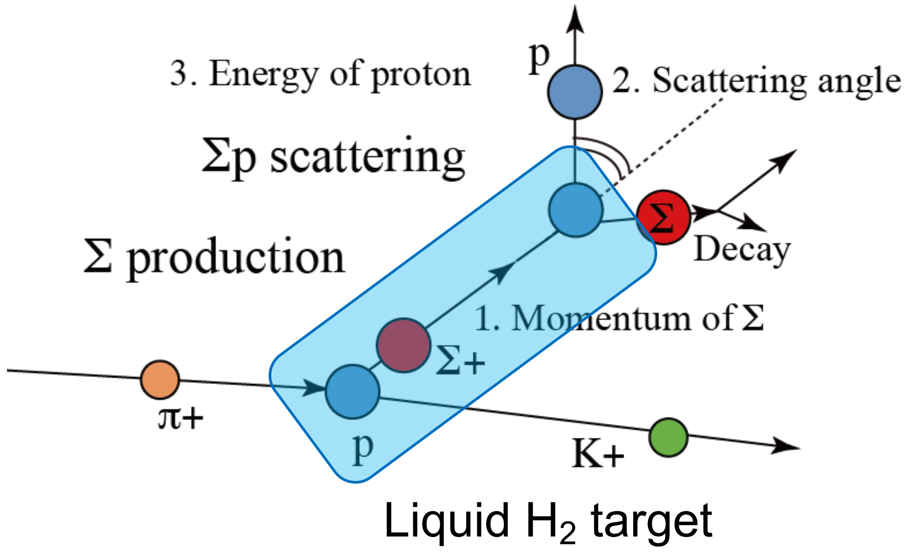
Fix source size(S(r*)) →
Study interaction from wave function $(\Psi(\vec{k^*},\vec{r^*}))$

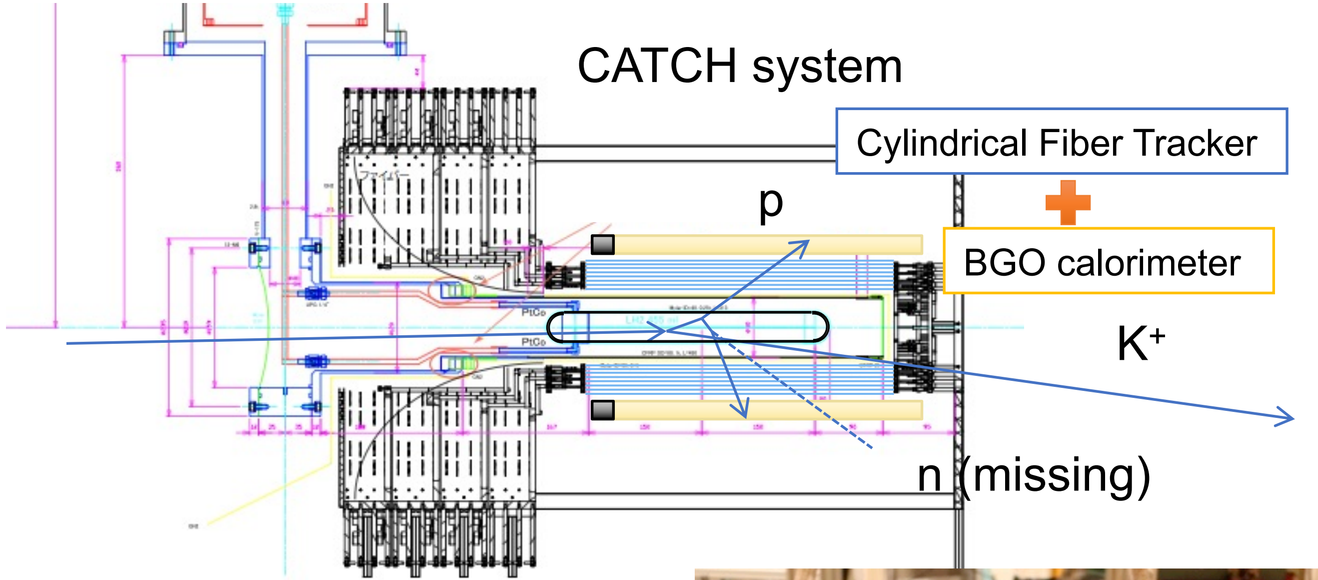
ALICE Collaboration, Phys. Lett. B 833 (2022) 137272

Particle correlation between Λ and p



Σp scattering experiment at J-PARC (E40)





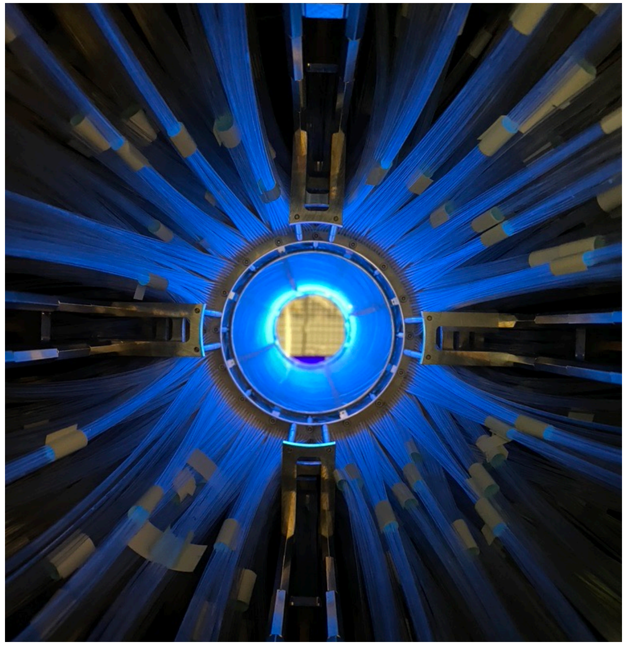
Many Σ hyperons are produced in LH_2 target

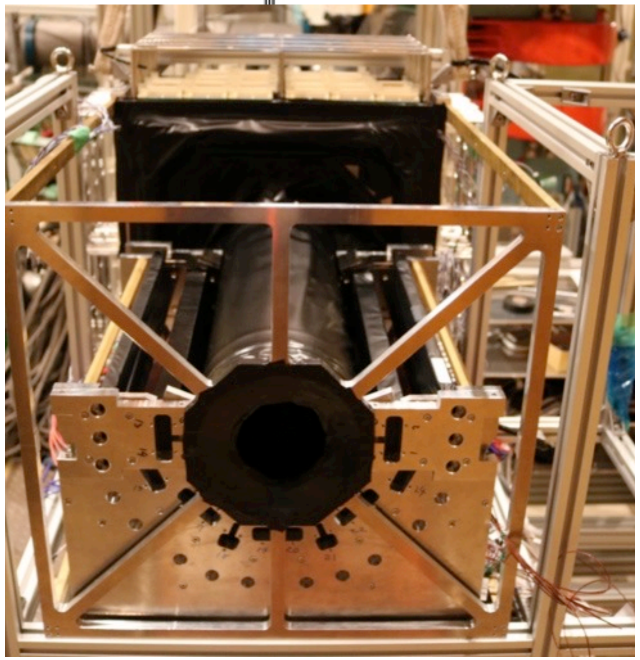
Σ are tagged by $\pi^{\pm}p \rightarrow K^{+}X$ reaction

- 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

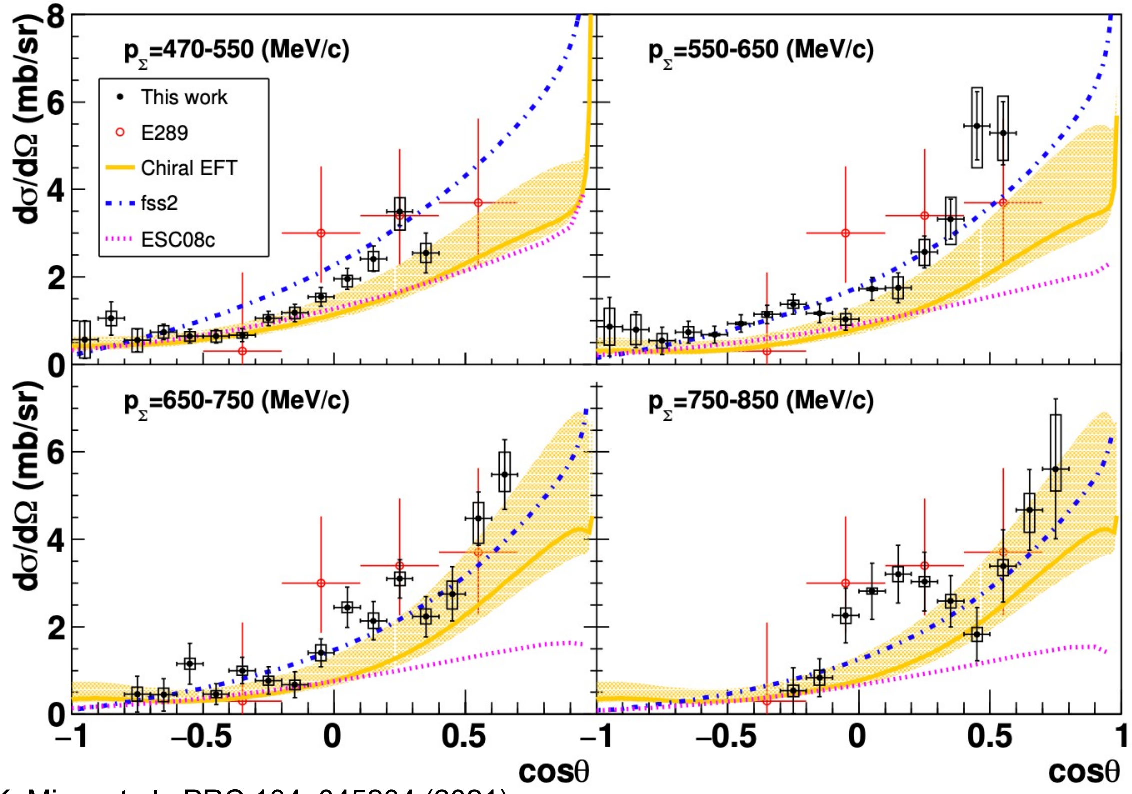




Systematic measurements of Σp dσ/dΩ

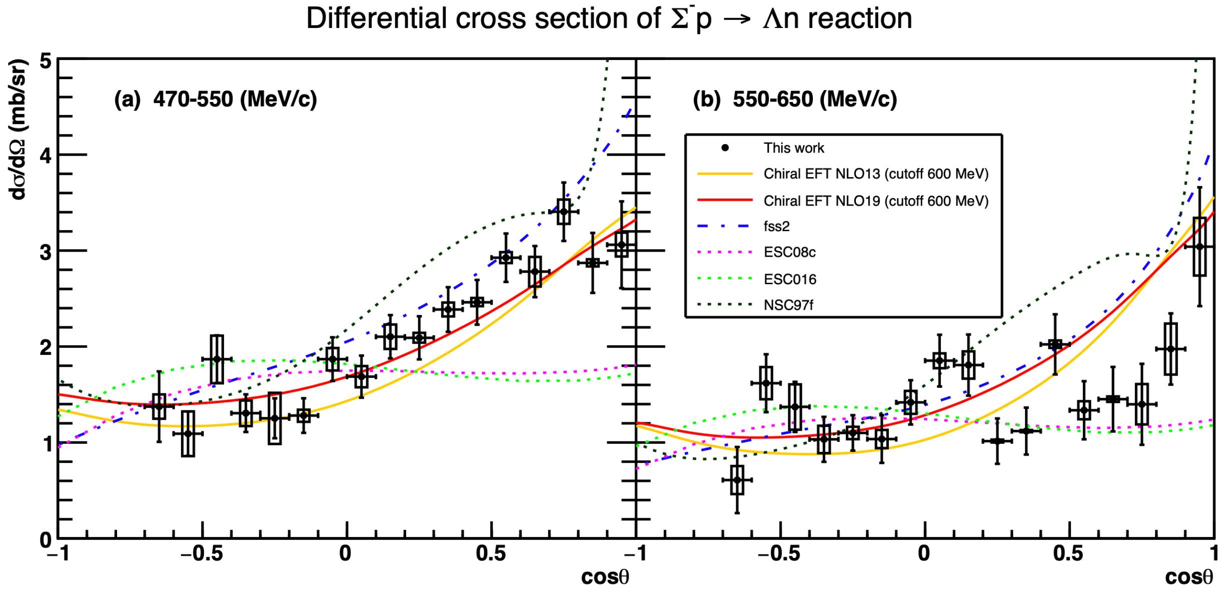
First accurate and systematic measurements of differential cross sections of Σ-proton channels

Σ^-p elastic scattering (0.47 < p (GeV/c) < 0.85)



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

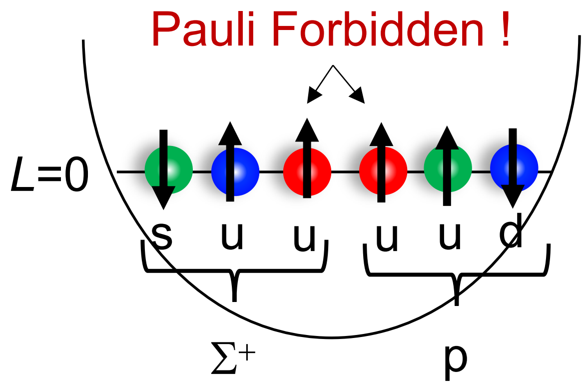
Σ^-p→Λn reaction (0.47 < p (GeV/c) < 0.65)



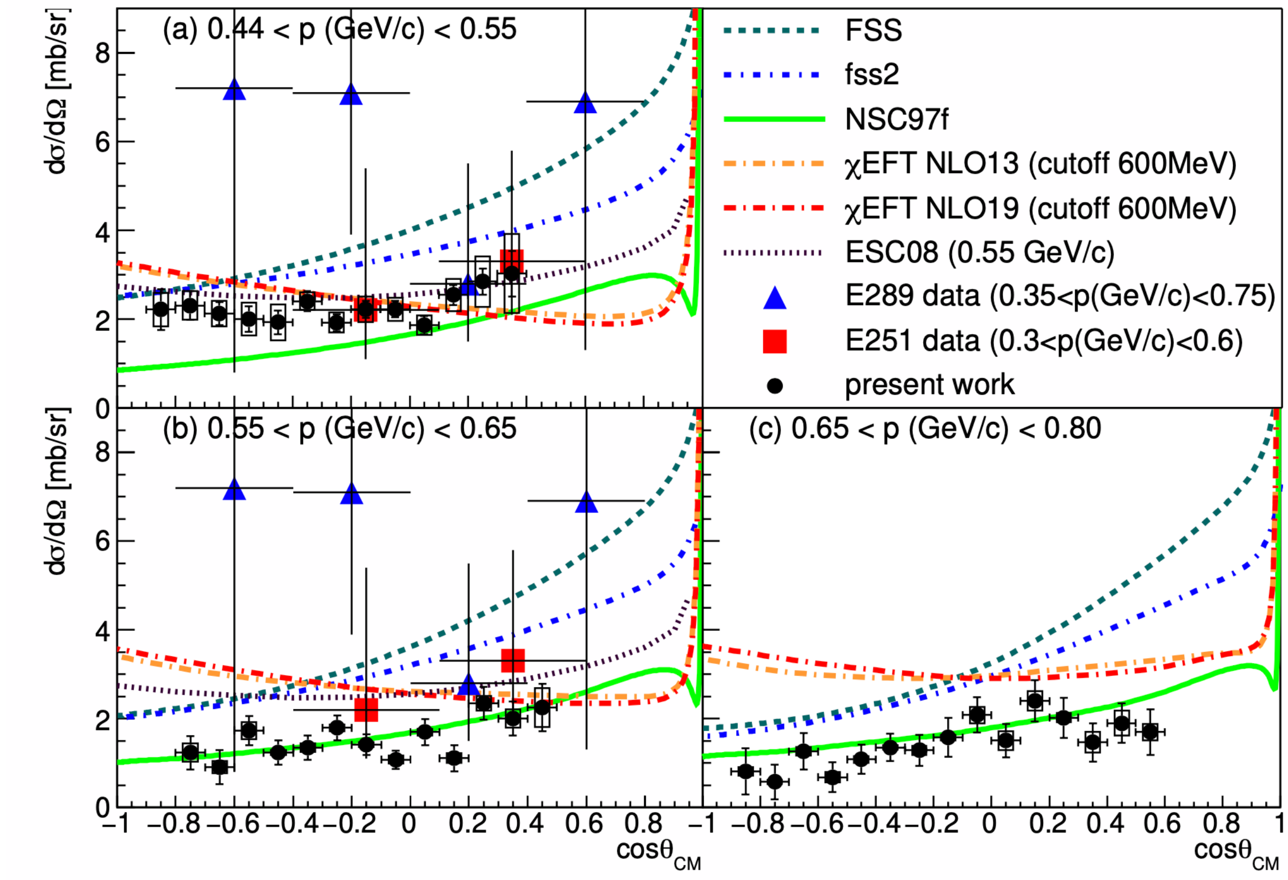
K. Miwa et al., PRL 128, 072501 (2022)

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

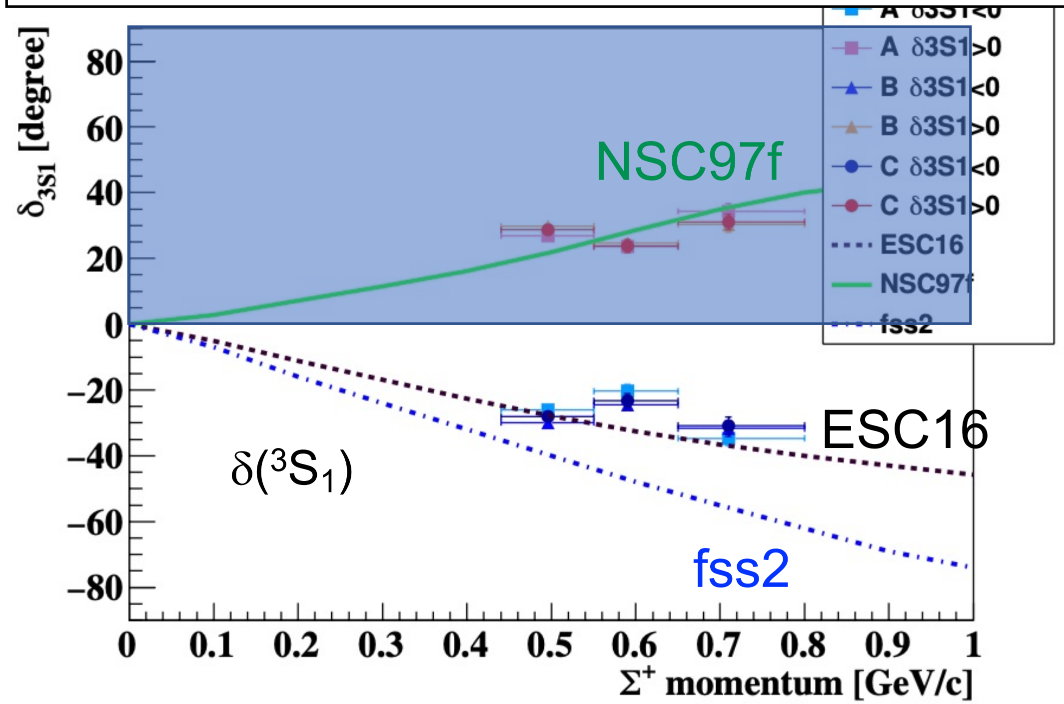
dσ/dΩ of Σ⁺p elastic scattering



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



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

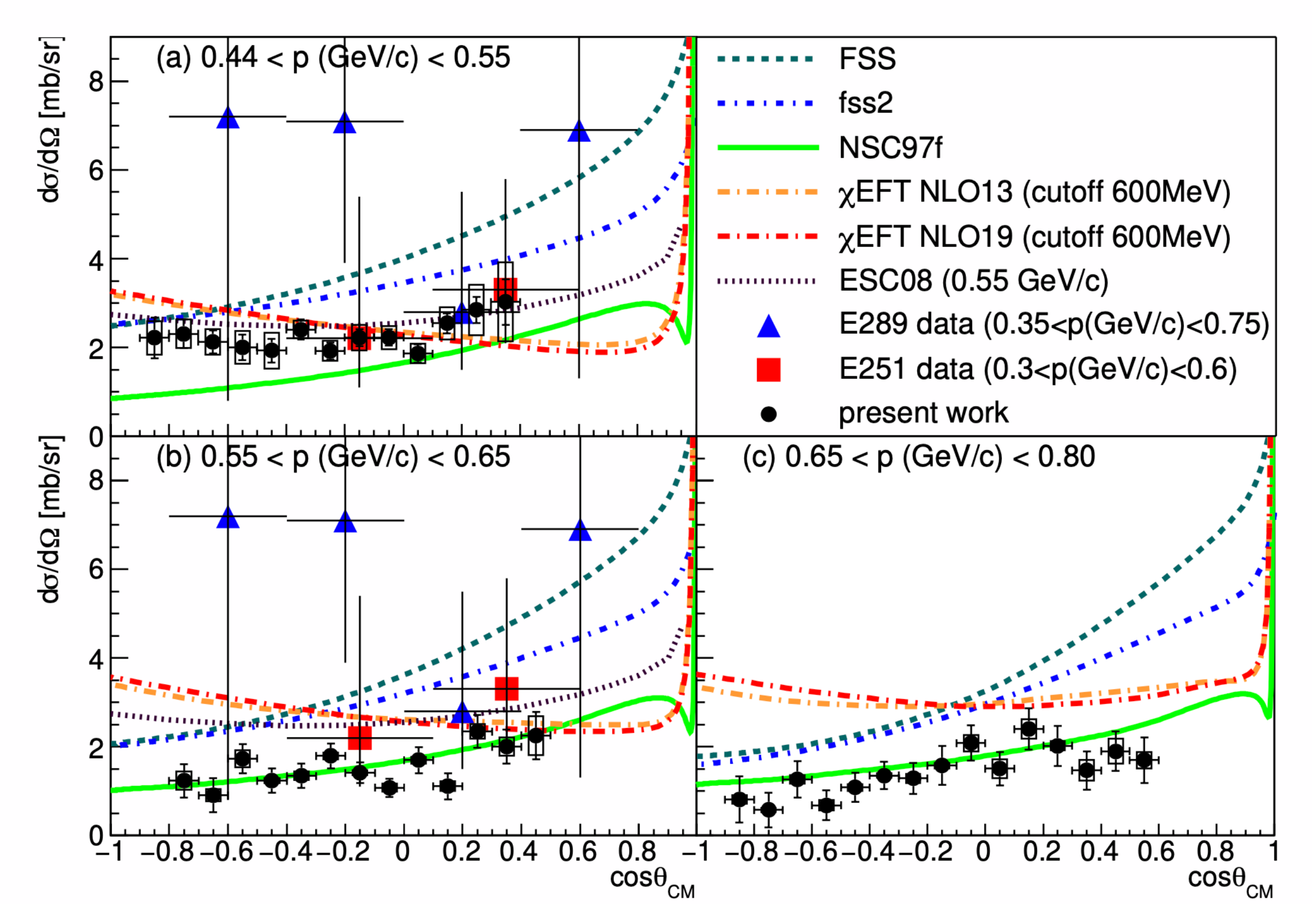


E40 data : much smaller than fss2 prediction and E289 results

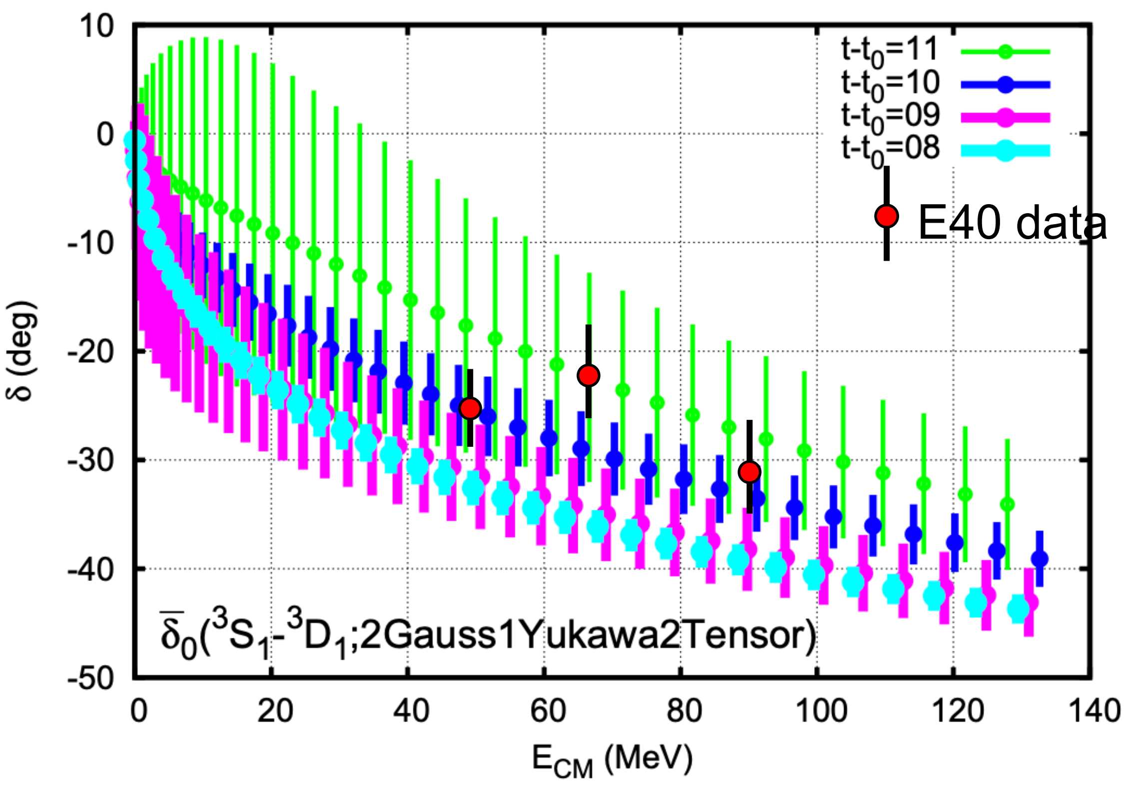
Derived phase shift suggests that **the $^3S_1$ interaction is moderately repulsive**.

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

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



Comparison with HAL QCD ΣN potential



E40 data : much smaller than fss2 prediction and E289 results

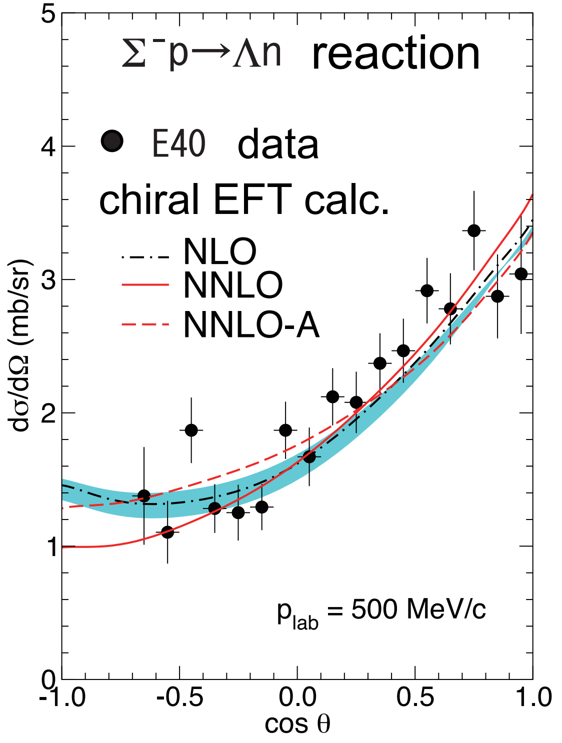
H. Nemura et al., EPJ Web of Conf., 175, 05030 (2018)

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

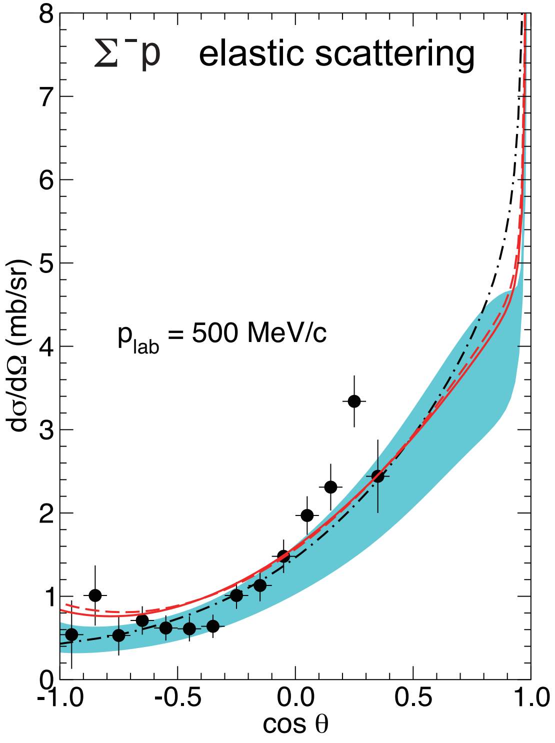
New Σp scattering data and progress of Chiral EFT

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

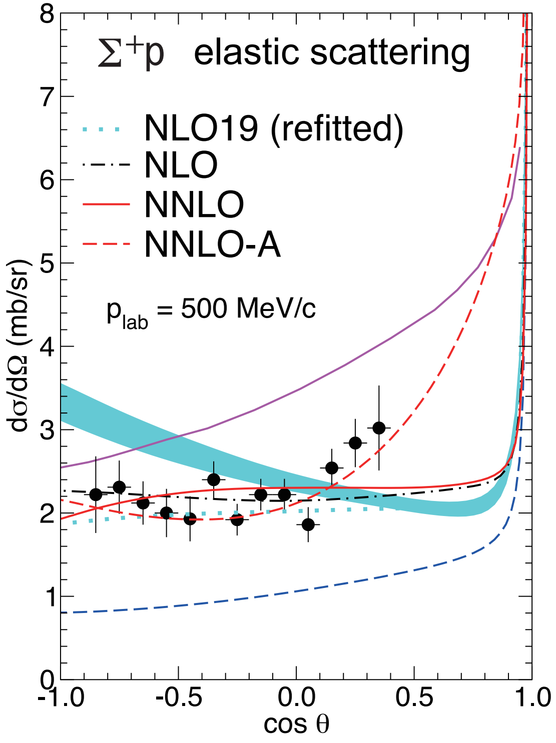
Difficulty at higher momentum



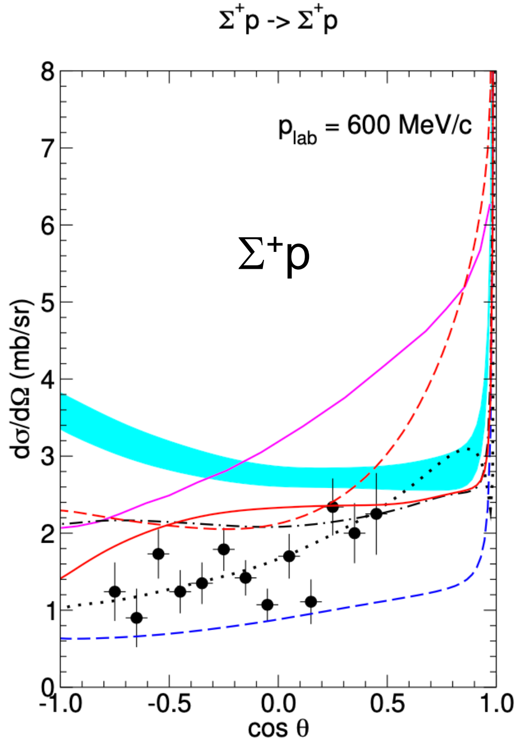
K. Miwa et al., PRL 128, 072501 (2022)



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



T. Nanamura et al., PTEP 2022 093D01

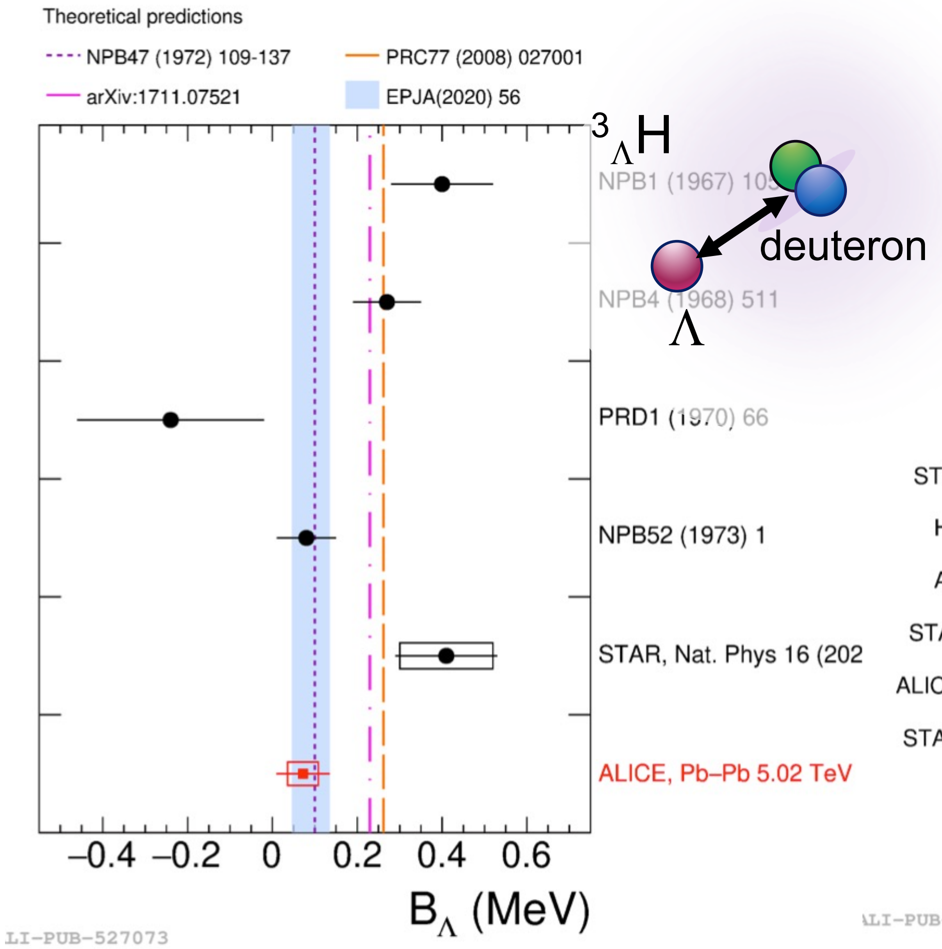


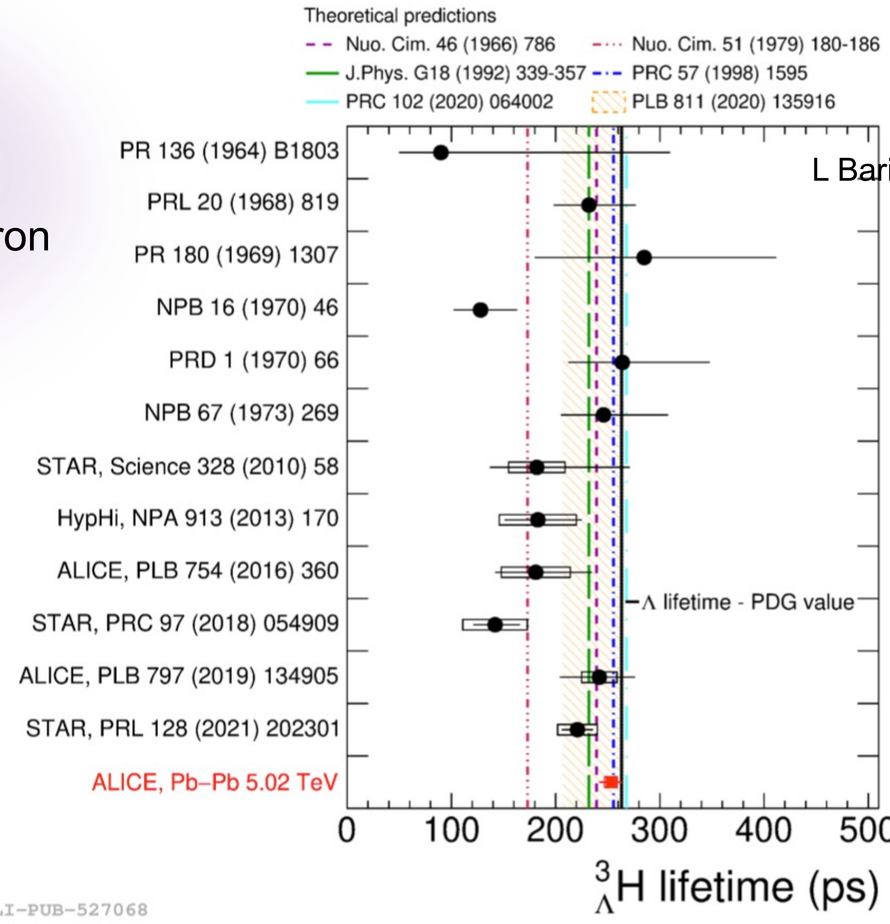
J. Haidenbauer et al., Eur.Phys.J.A 59 (2023) 3

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

Hypertriton puzzle

Heavy ion experimental results settle down ?





L Barioglio talk at EMMI Workshop 2023

HADES : Ag+Ag $\sqrt{s}$=2.55 GeV
$\tau = 256 \pm 22 \pm 36$ 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

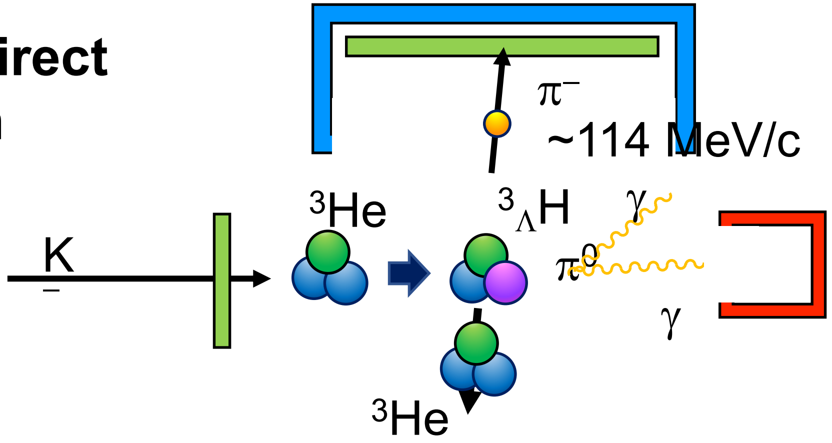
- MAMI : decay pion spectroscopy
- JLab : ^{3}He (e, e'K^{+}) missing mass spectroscopy
- J-PARC E07 : hyperfragment at K- interaction on emulsion

Lifetime measurement by direct time measurement

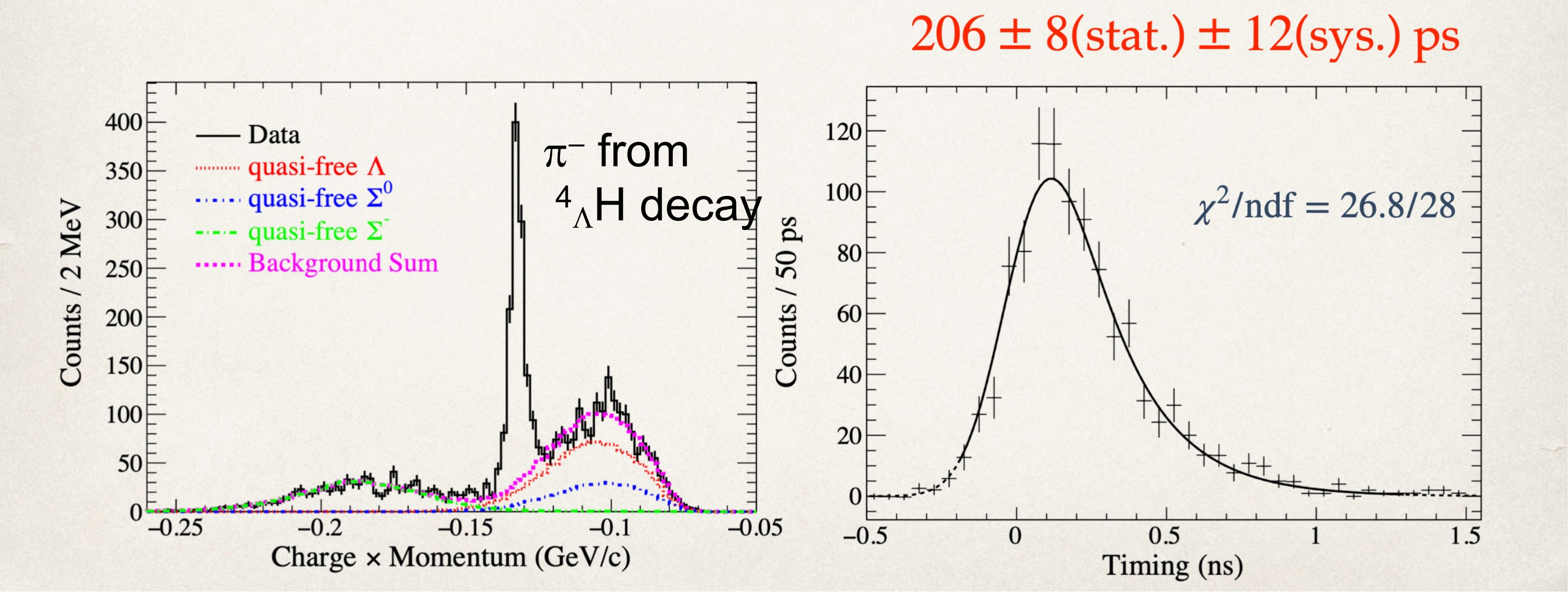
- ELPH : ^{3}He(γ, K^{+}) reaction
- J-PARC E73 : ^{3}He (K^{-}, π^{0}) reaction

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

Lifetime measurement by direct time measurement between production and decay



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



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

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

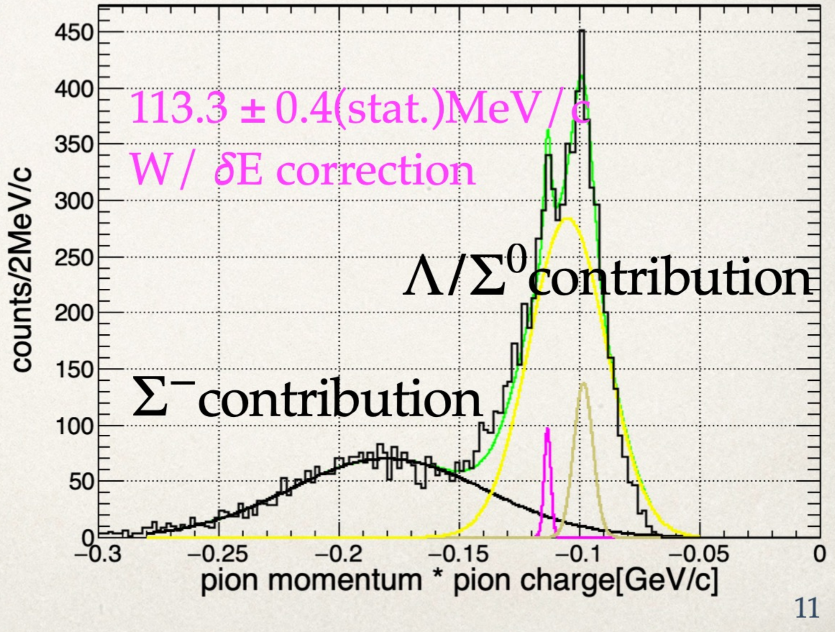
273kW*Day executed in May, 2021

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

slows down and decays at rest

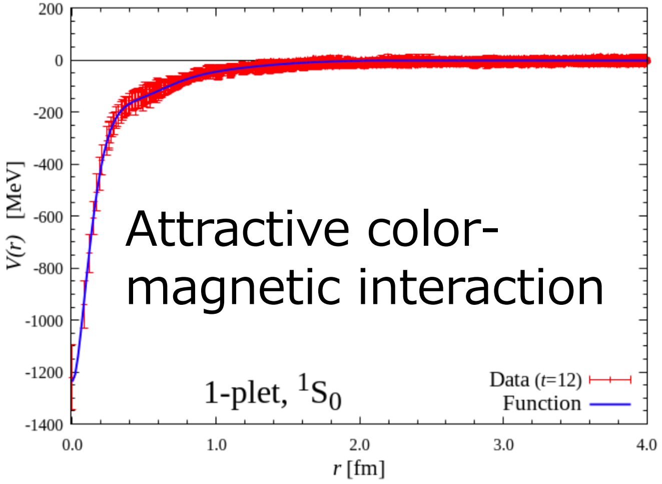
$${}^3_\Lambda H \rightarrow {}^3He + \pi^-$$

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

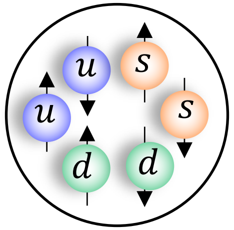


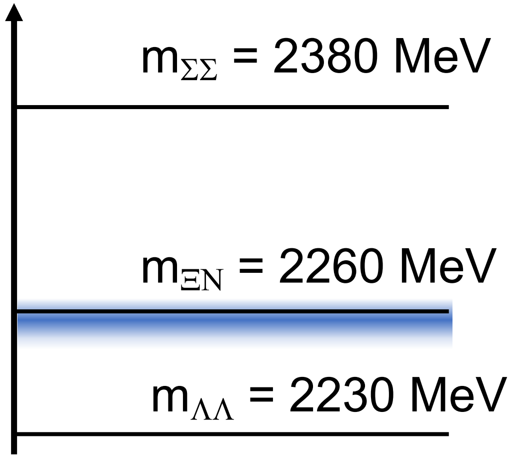
H dibaryon (SU(3) flavor singlet hexaquark state)

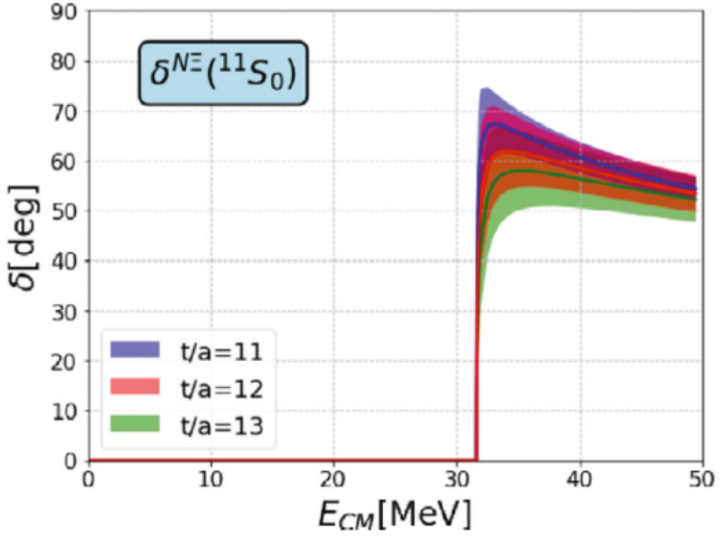
Theoretical progress on S=-2 system



H-dibaryon



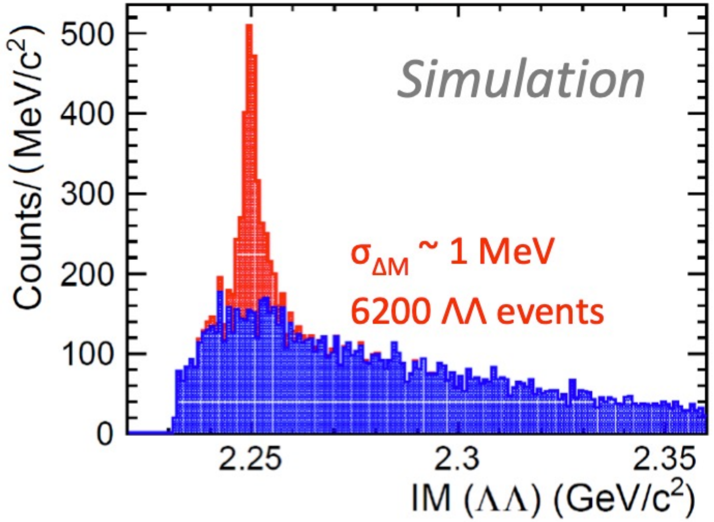




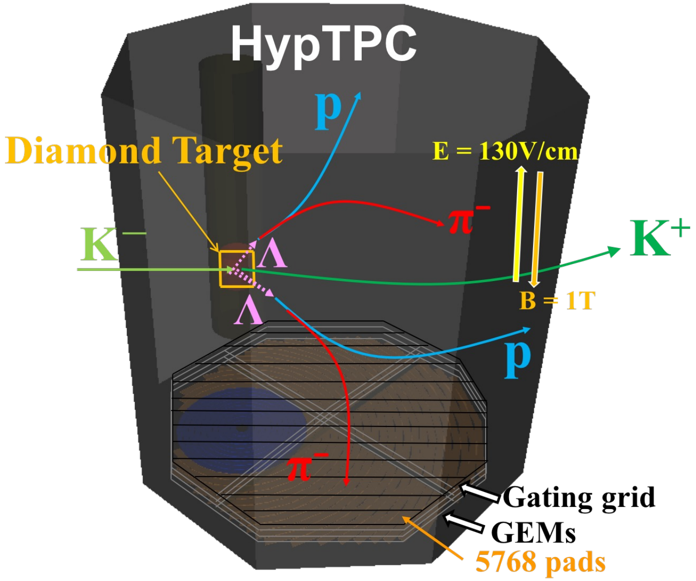
→ Definitive experimental confirmation is awaited

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

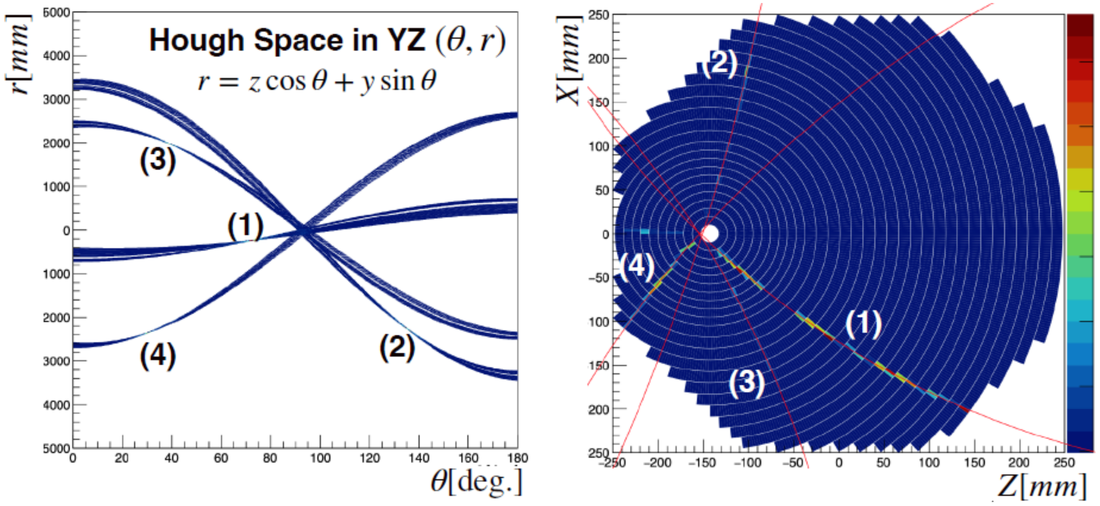
- Invariant mass measurement of ΛΛ and Ξ^-p system with HypTPC
- High resolution and high statistics measurement is realized



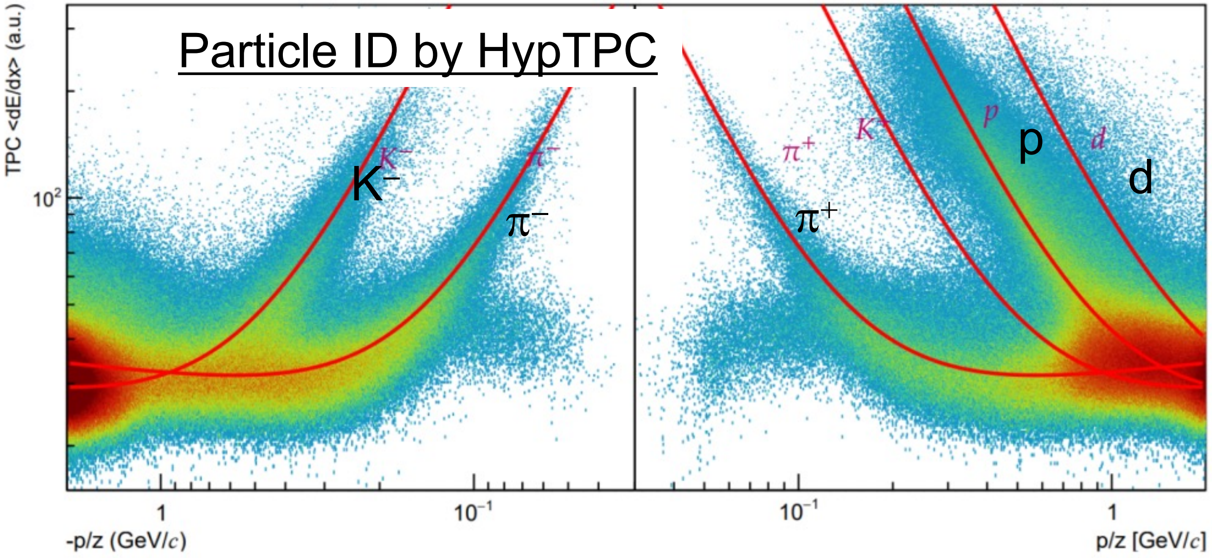
Progress on analysis of HypTPC



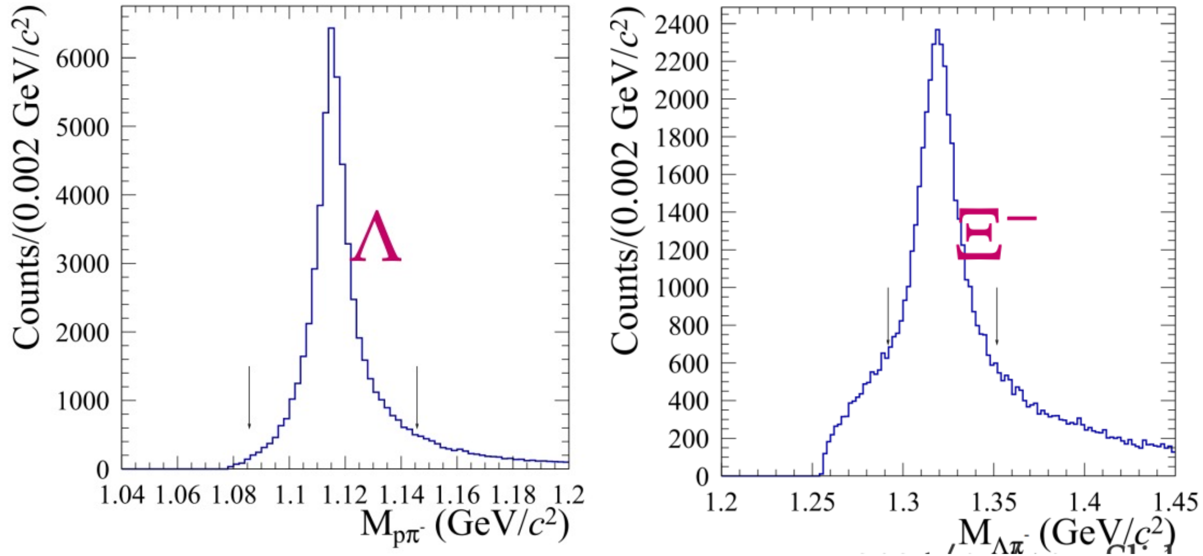
Development of track finding algorithm using Hough transformation



Particle ID by HypTPC



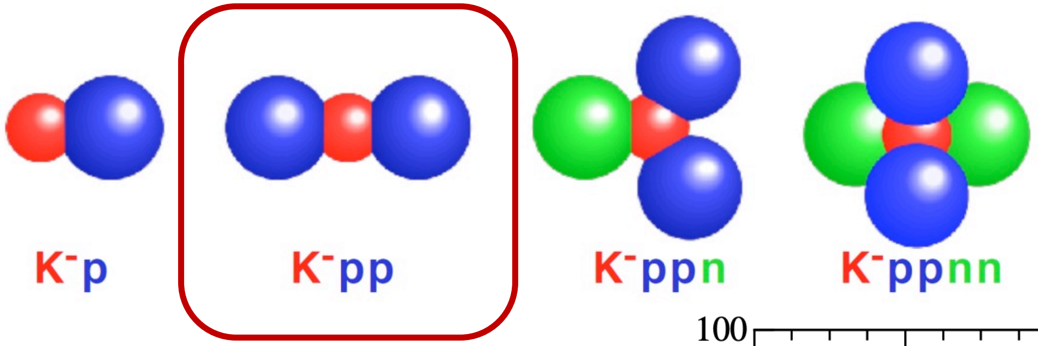
Invariant mass reconstruction by HypTPC



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

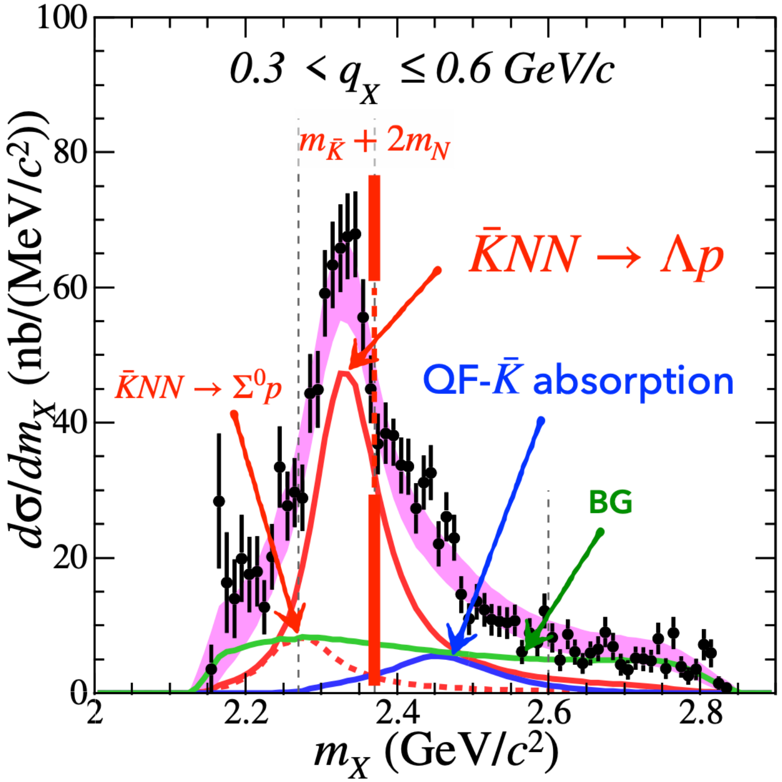
Strong attractive interaction between Kbar and N → Exotic hadronic system with Kbar meson

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

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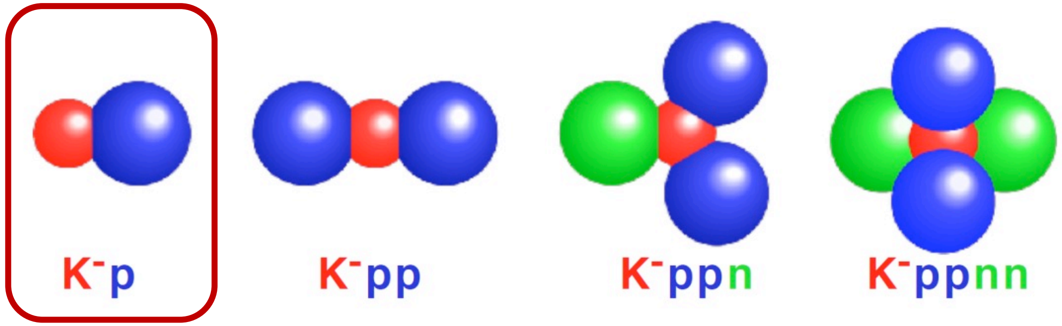
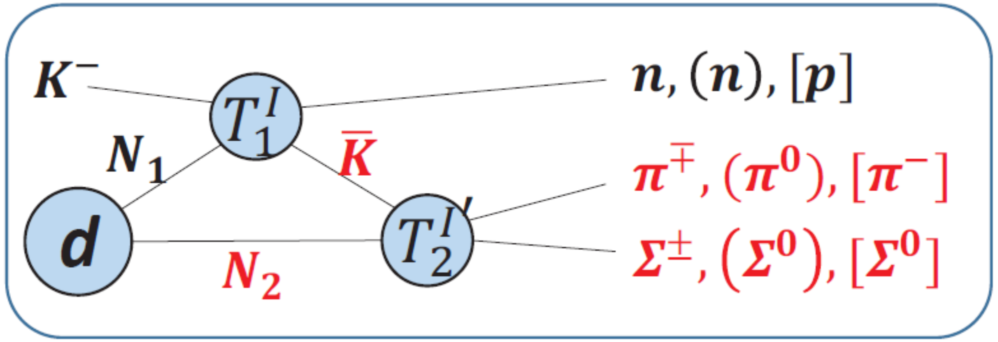


- Mass dependence of Kbar-nucleon system from K-p to K-ppnn
- Aiming to clarify the origin of QCD mass and the mysteries of high-density nuclear matter by measuring changes in the properties of K-mesons in nuclear matter.

J-PARC E31 @ K1.8BR

- First derivation of S-wave KbarN scattering amplitude in I=0 channel from 3 $\pi\Sigma$ decay modes.

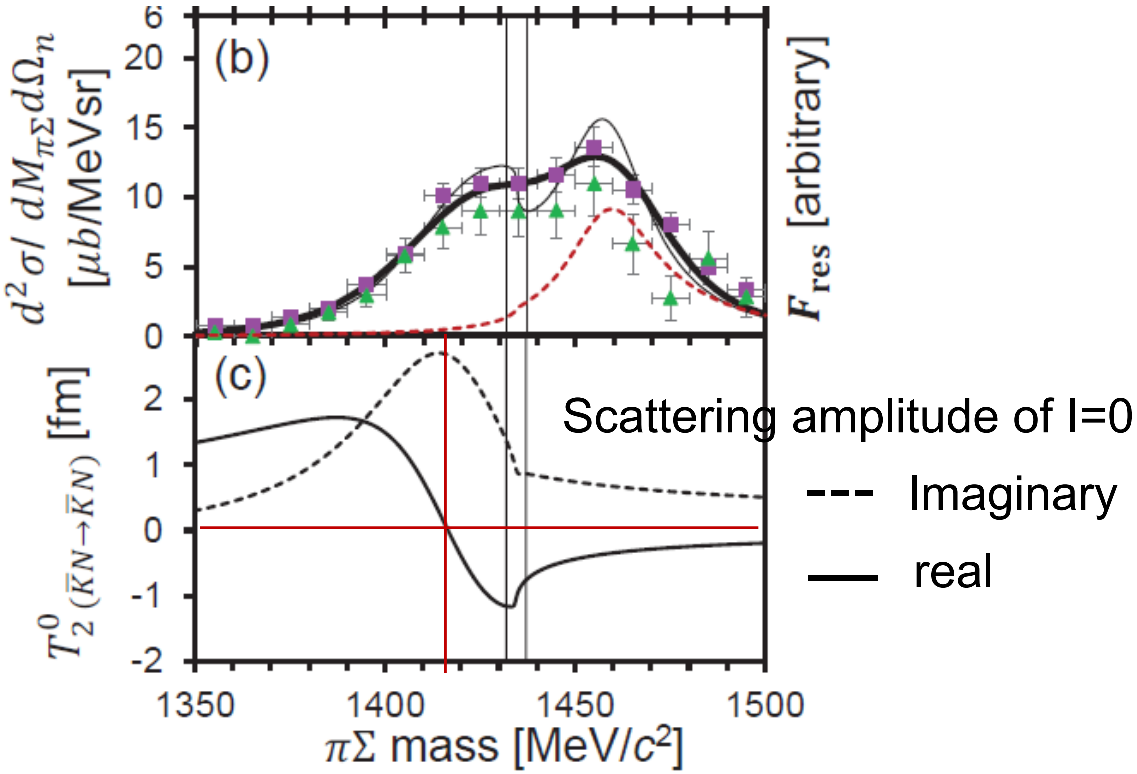


Resonance pole was found at

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

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

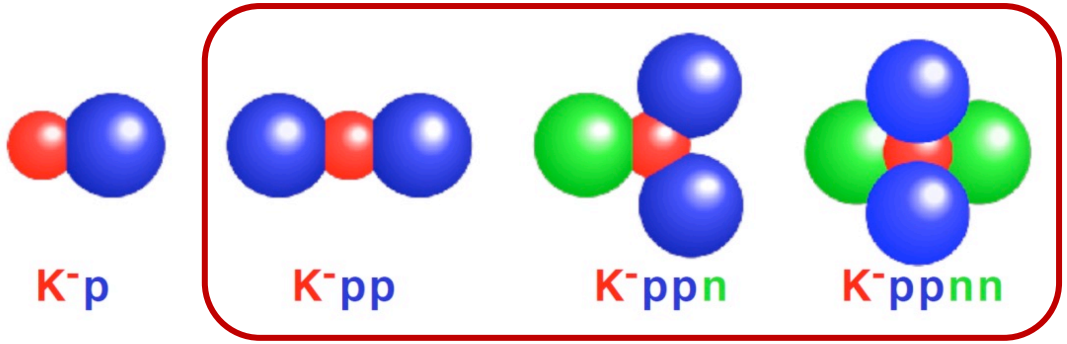
K^-p and K^0n mass thresholds



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

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

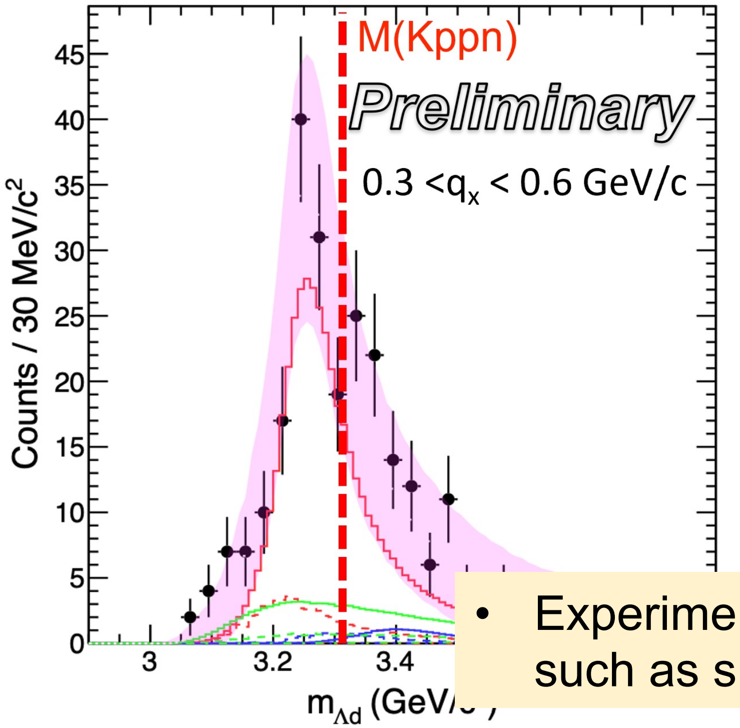


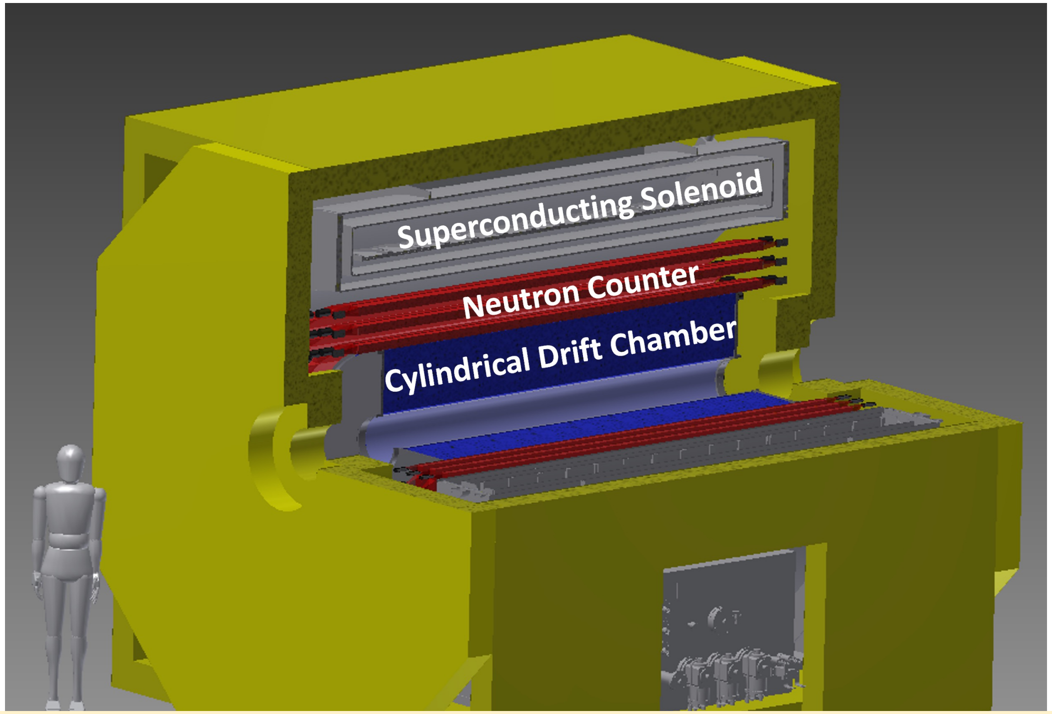
- Mass dependence of Kbar-nucleon system from K-p to K-ppnn
- Aiming to clarify the origin of QCD mass and the mysteries of high-density nuclear matter by measuring changes in the properties of K-mesons in nuclear matter.

J-PARC T77 @ K1.8BR

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

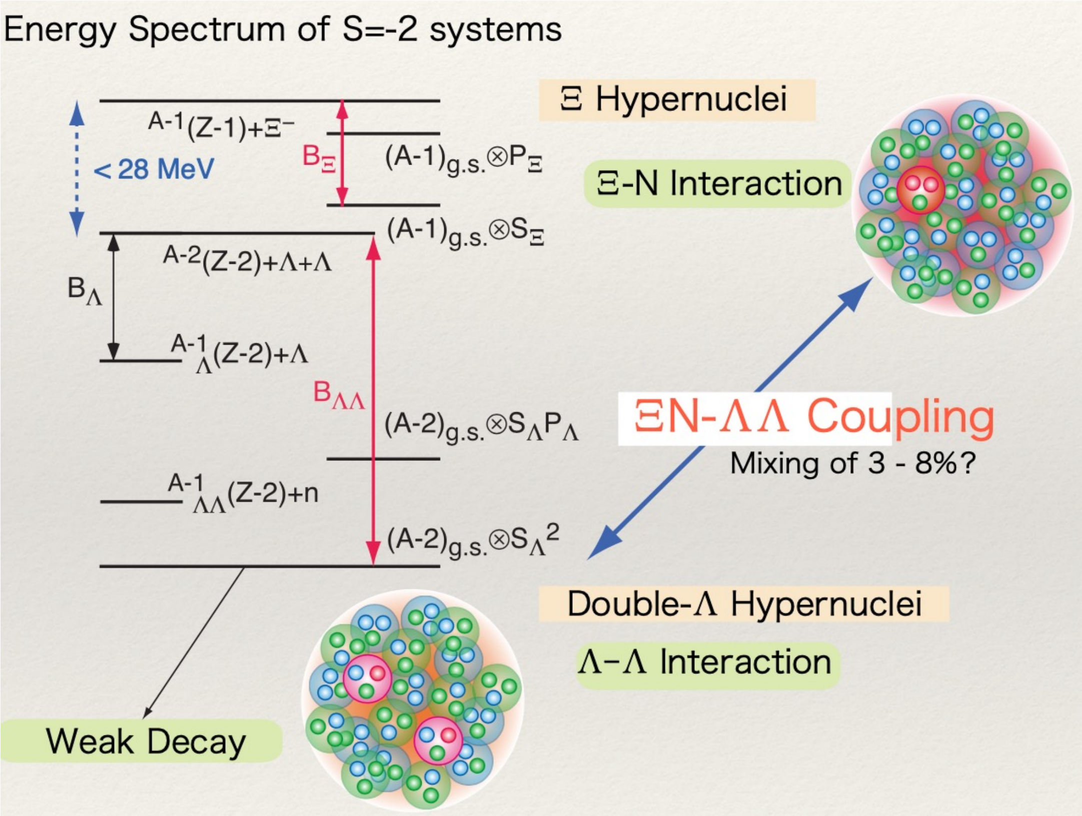
by T. Hashimoto @ HYP2022





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

Topics with S=–2 hypernuclei

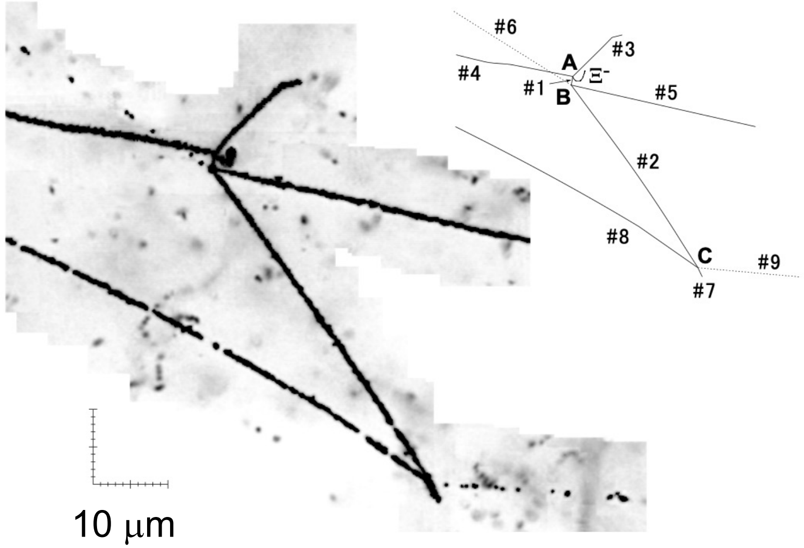


Performed experiment
Future experiment

- 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

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

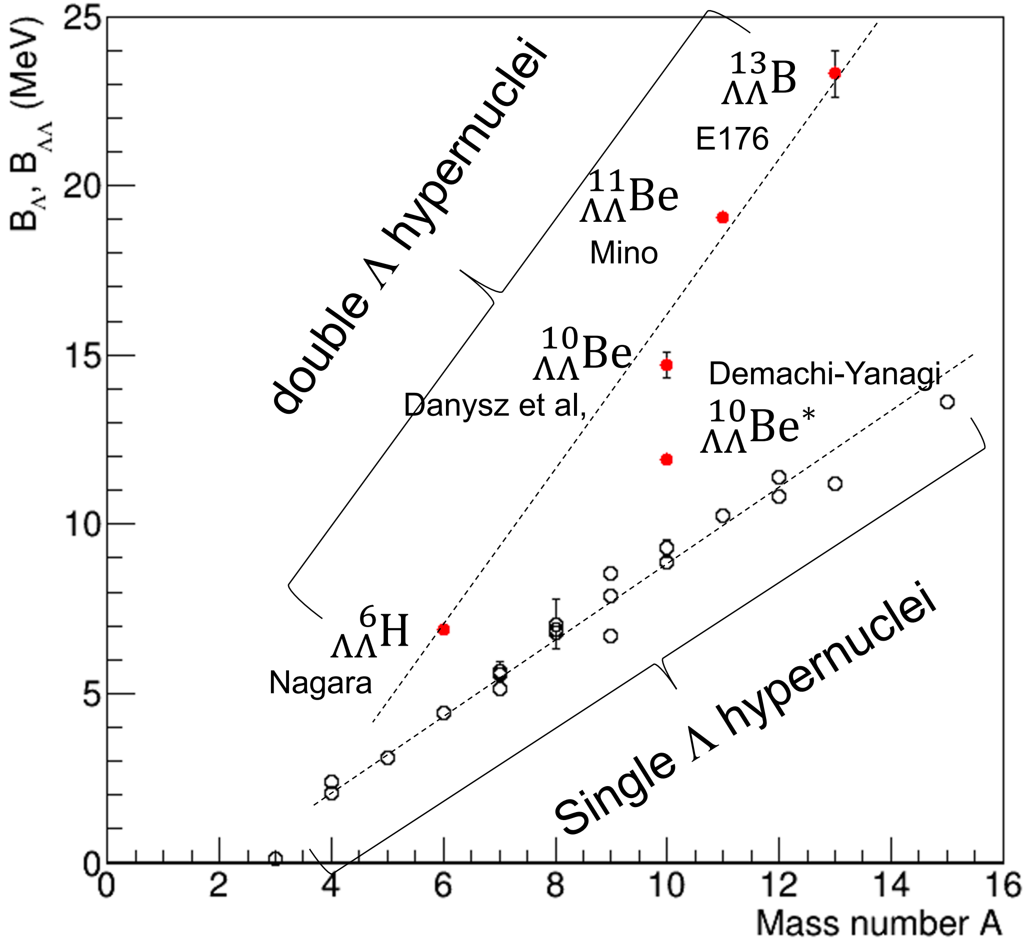
$$\hookrightarrow {}^5_{\Lambda}\mathrm{He} + (p, d, t) + p + xn,$$

$$\hookrightarrow {}^4\mathrm{He} + p + \pi^-.$$

$^{11}{}_{\Lambda\Lambda}$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 $B_{\Lambda\Lambda}$



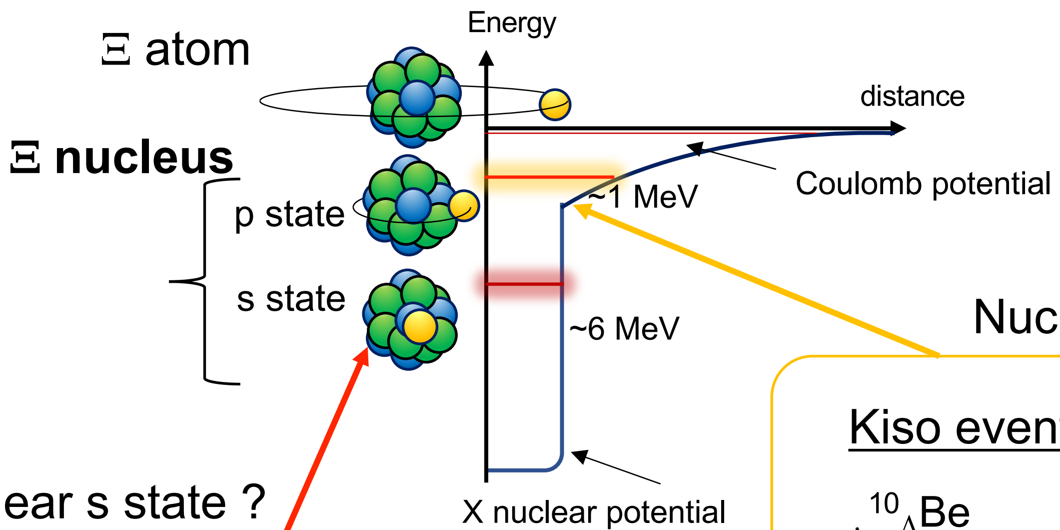
The value of $\Delta B_{\Lambda\Lambda}$ seems to be inconsistent with that of the NAGARA event

Ξ hypernuclei

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

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

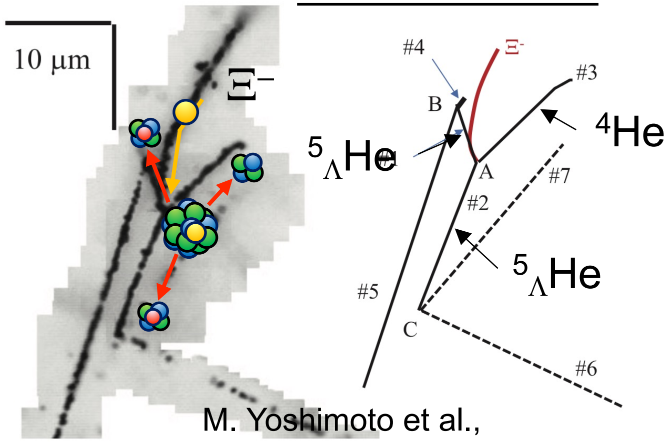
Two different energy levels
- BE ~1 MeV (p state)
- BE ~6 MeV (s state)



Nuclear p state

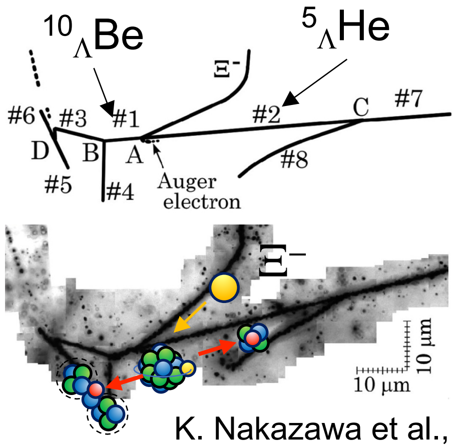
Nuclear s state ?

Irrawadi event



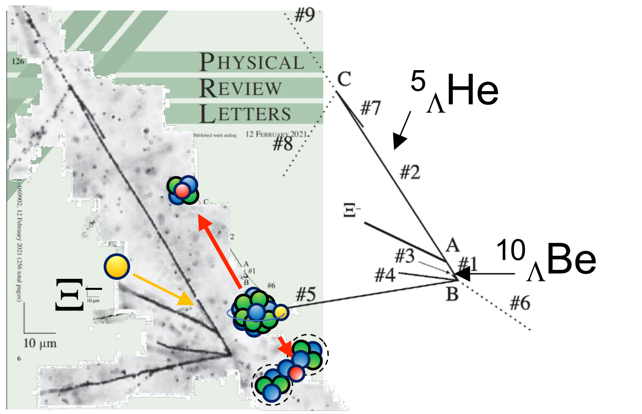
M. Yoshimoto et al., PTEP. 2021, 073D02

Kiso event



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

Ibuki event



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

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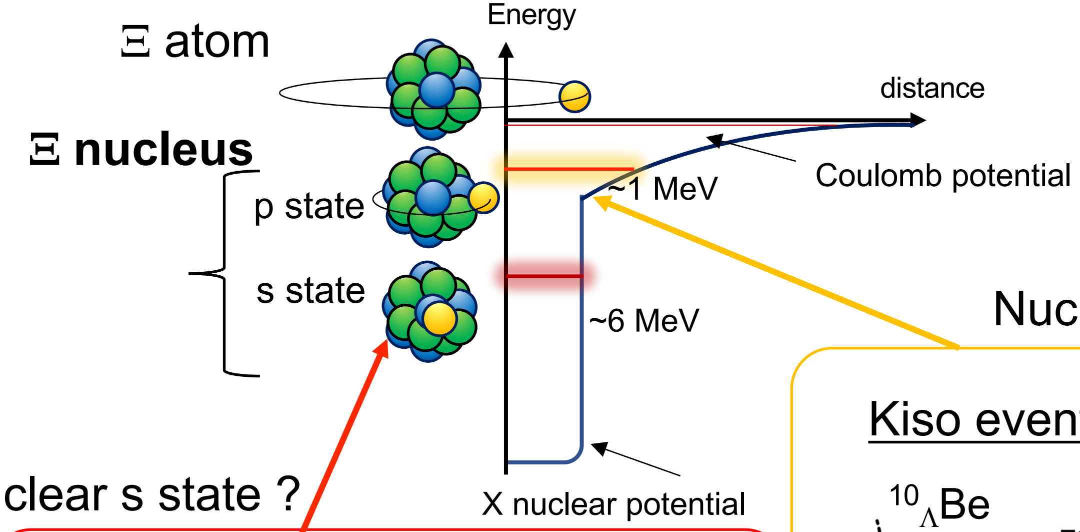
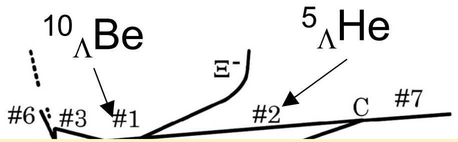
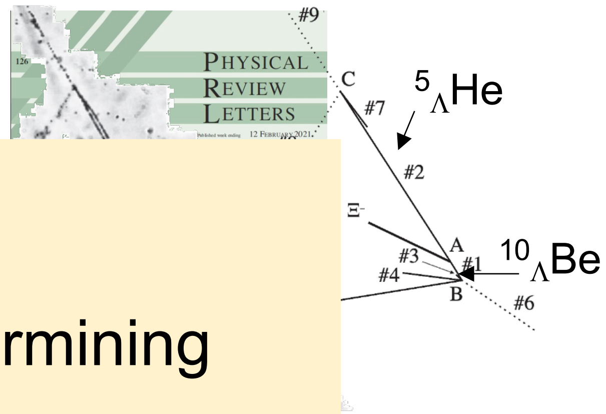


Nuclear p state

Kiso event



Ibuki event



l. 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.

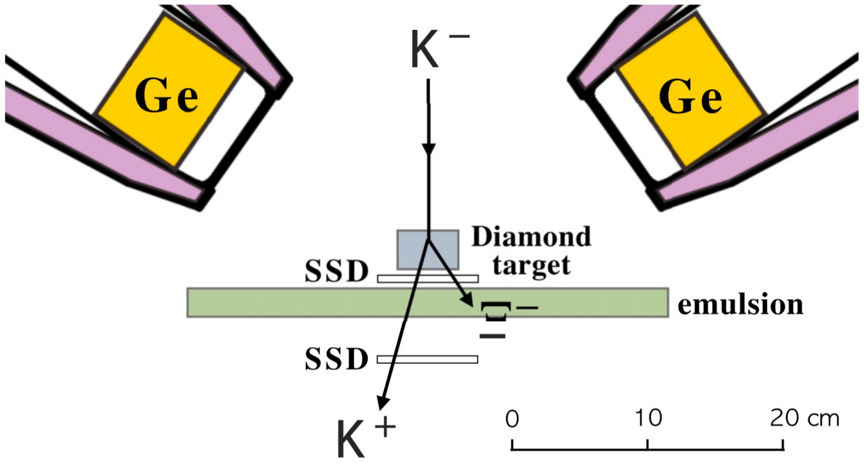
M. Yoshimoto et al.,
PTEP. 2021, 073D02

First attempt to measure Ξ Atomic X-ray in E07

Ξ-Ag/Br atomic X rays in emulsion

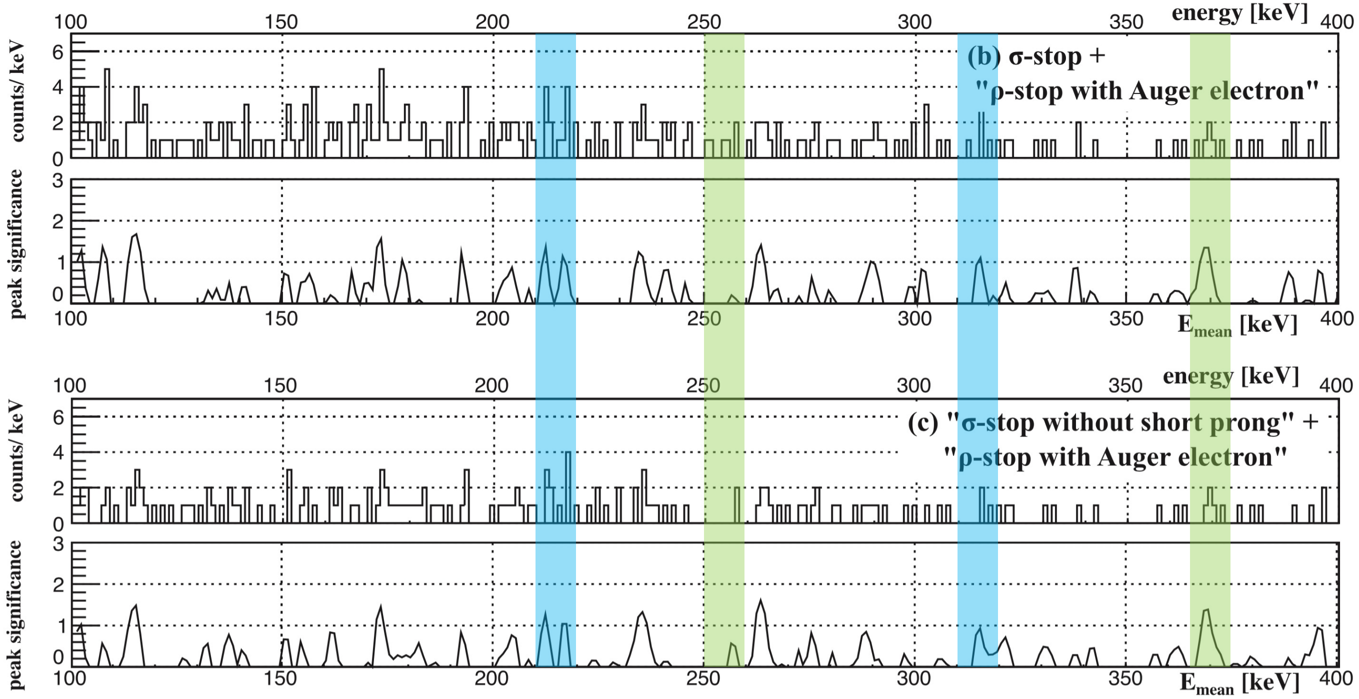
Triple-coincidence hybrid method

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



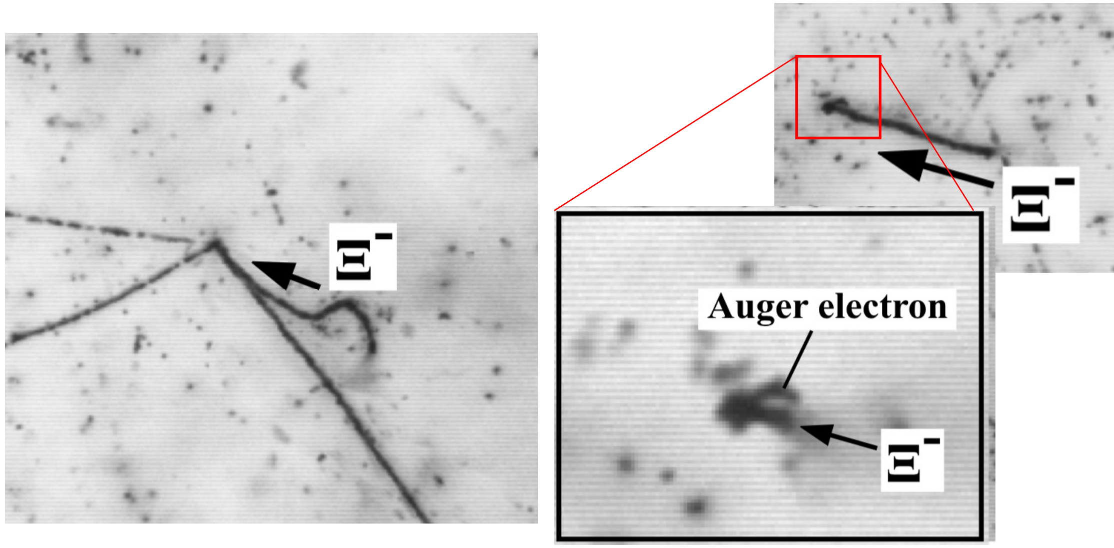
X-ray peaks were not observed due to lower emulsion and Ge detector efficiencies than expected

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

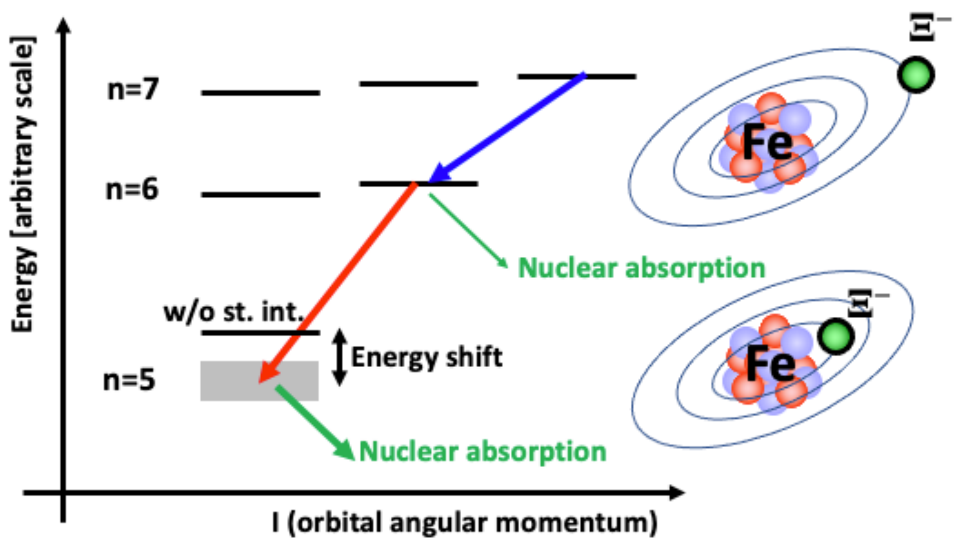


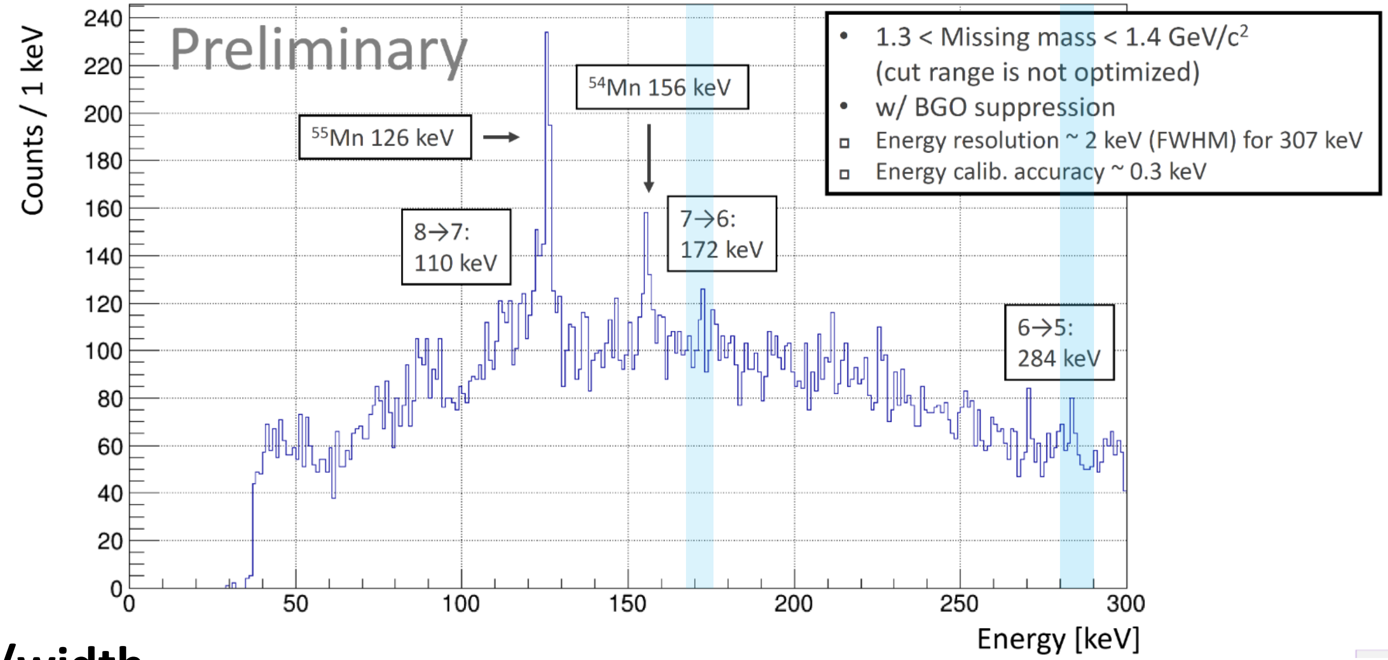
σ-stop (Nuclear fragment from Ξ⁻ stop)

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.

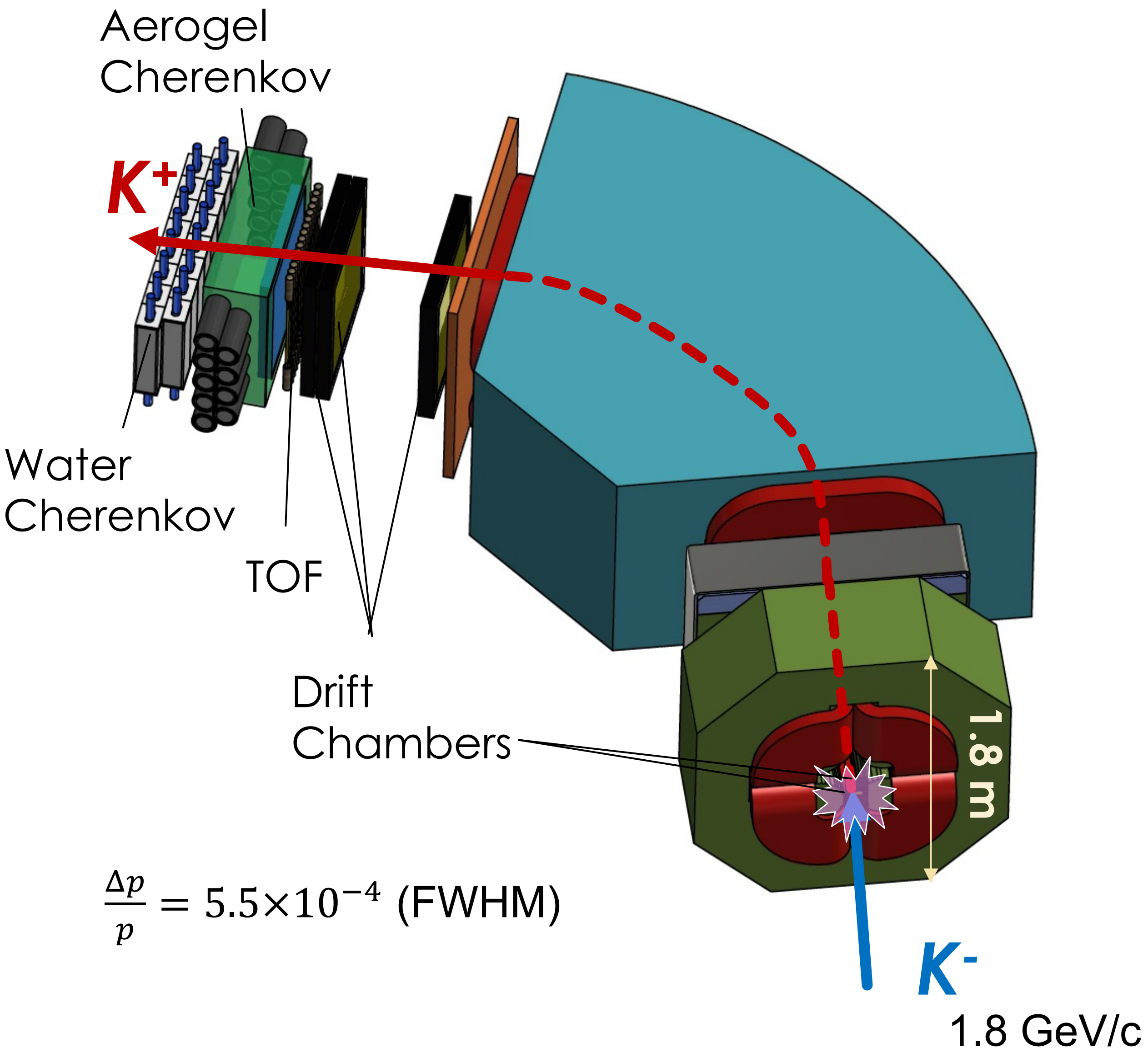
BG level is consistent with our expectation

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

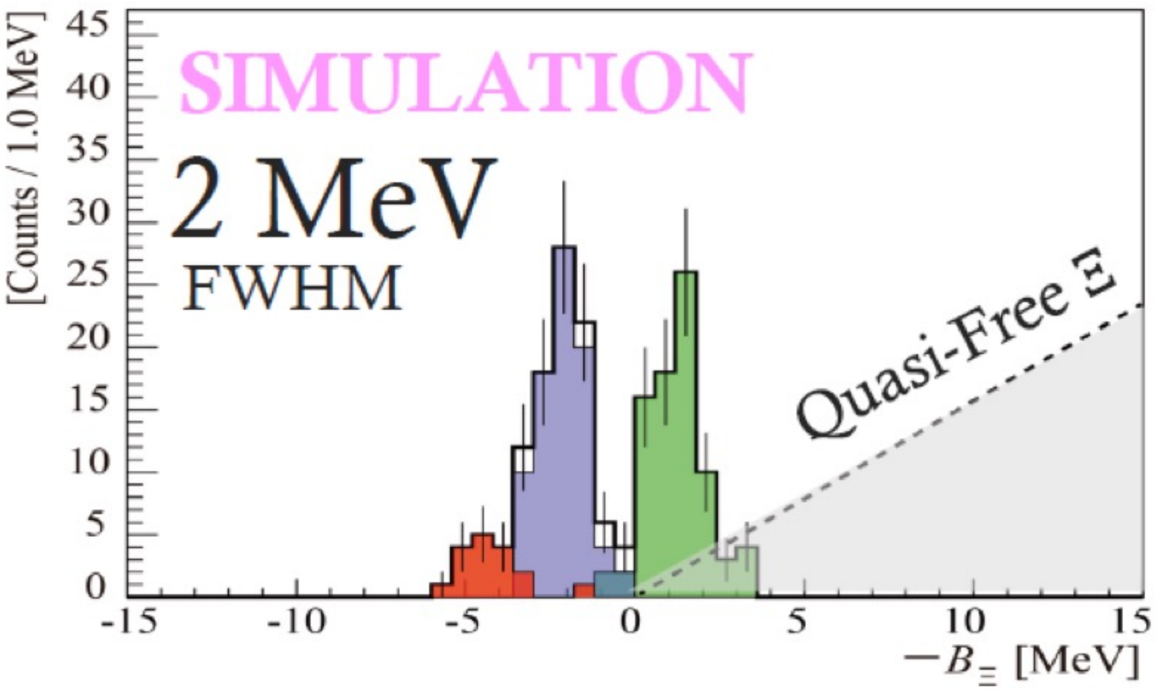
E70 experiment with S-2S spectrometer

Construction of S-2S has been completed!



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

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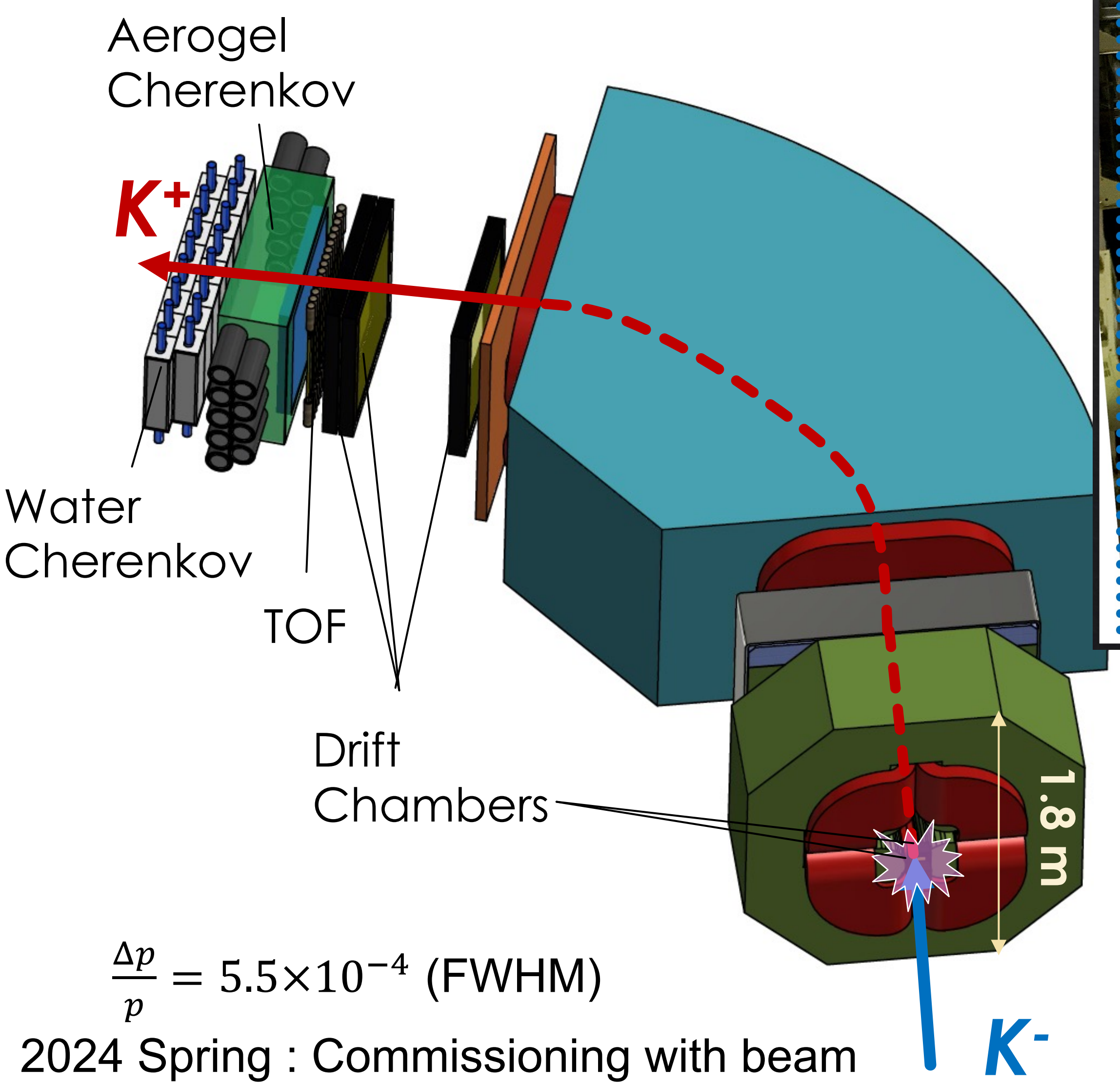

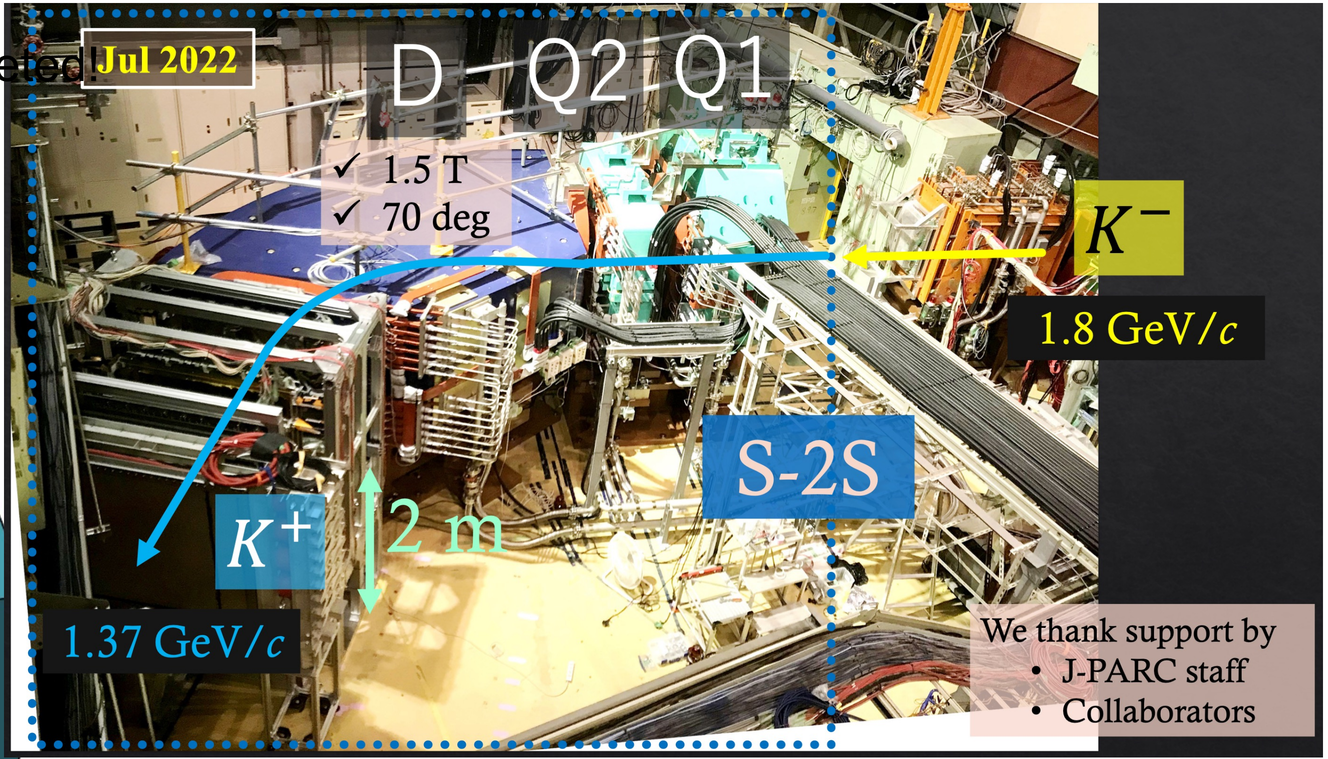

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2024 Spring : Commissioning with beam

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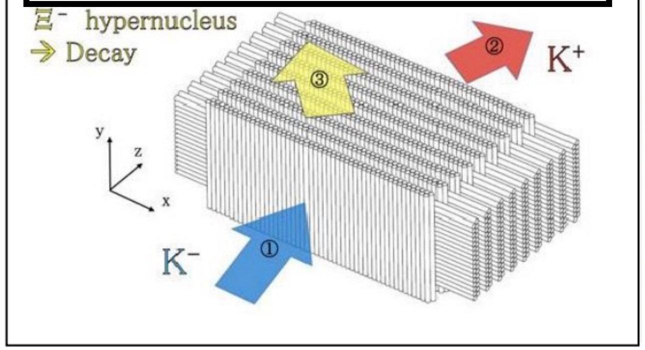
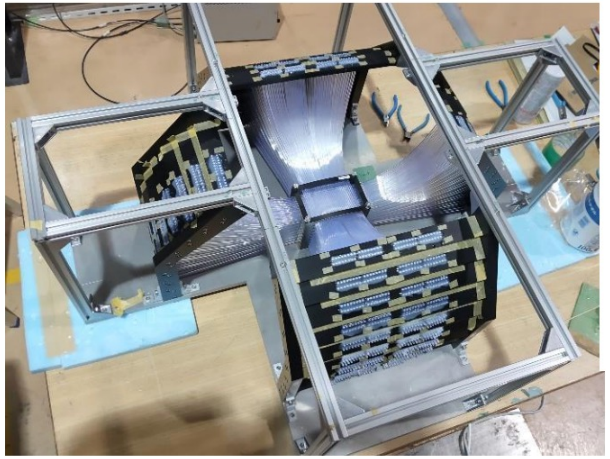
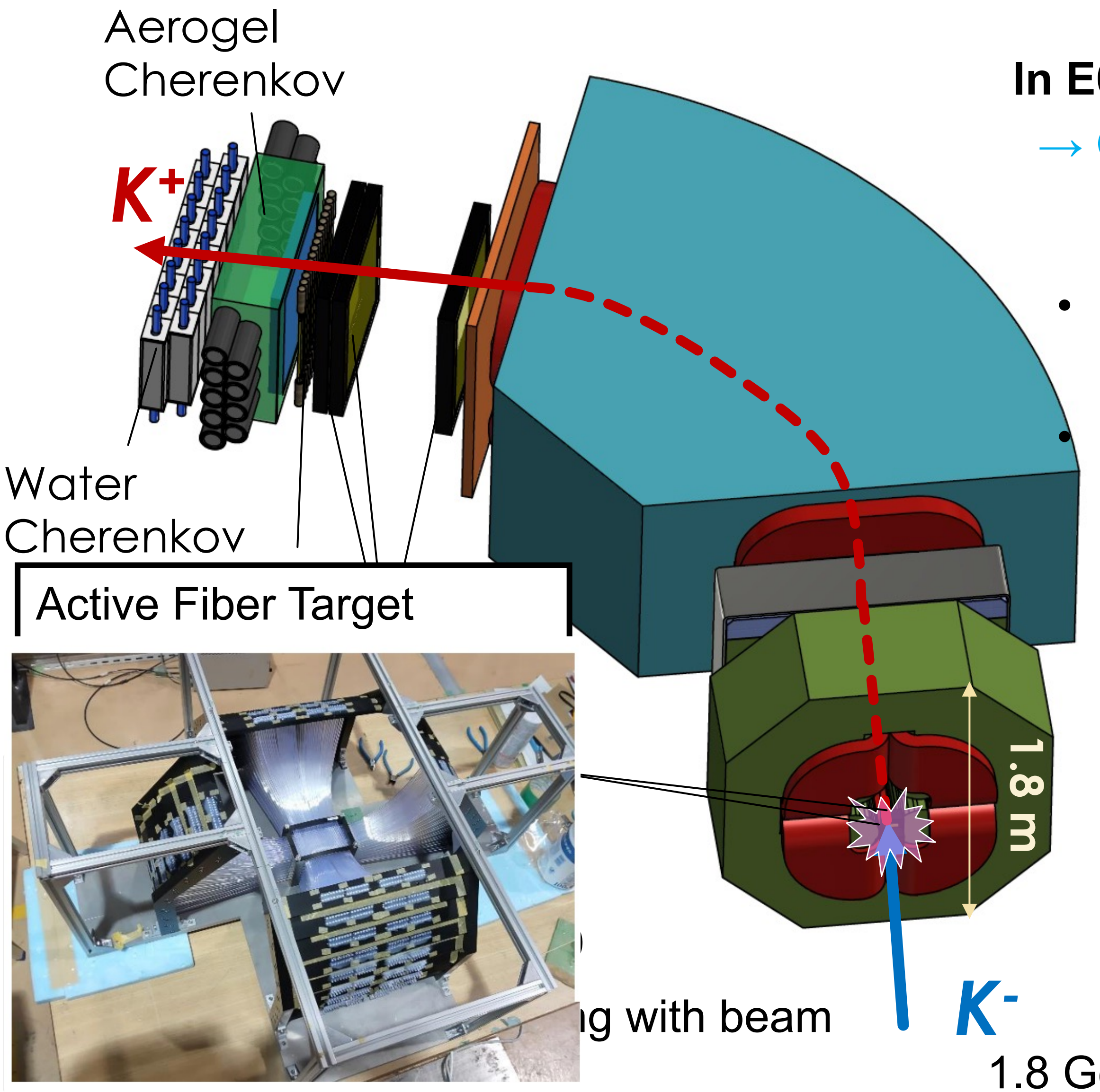
Active Fiber Target
for energy loss correction





Ξ^- ^{12}C X-ray measurement with AFT

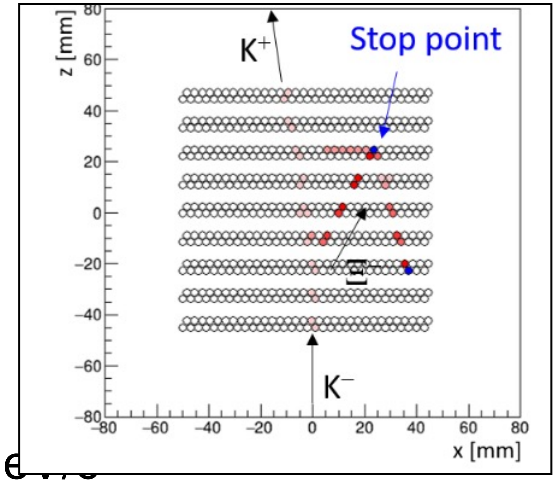
Construction of S-2S has been completed!

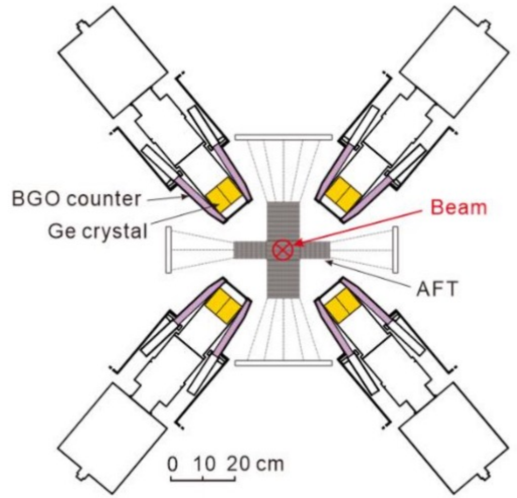


In E03, we found that X ray yields is smaller than expectation.

→ 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**

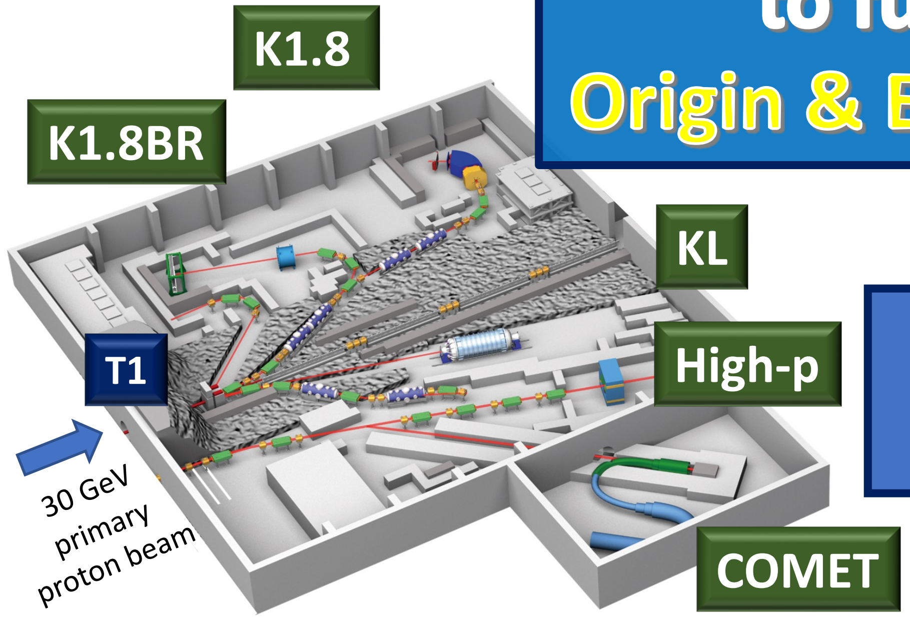




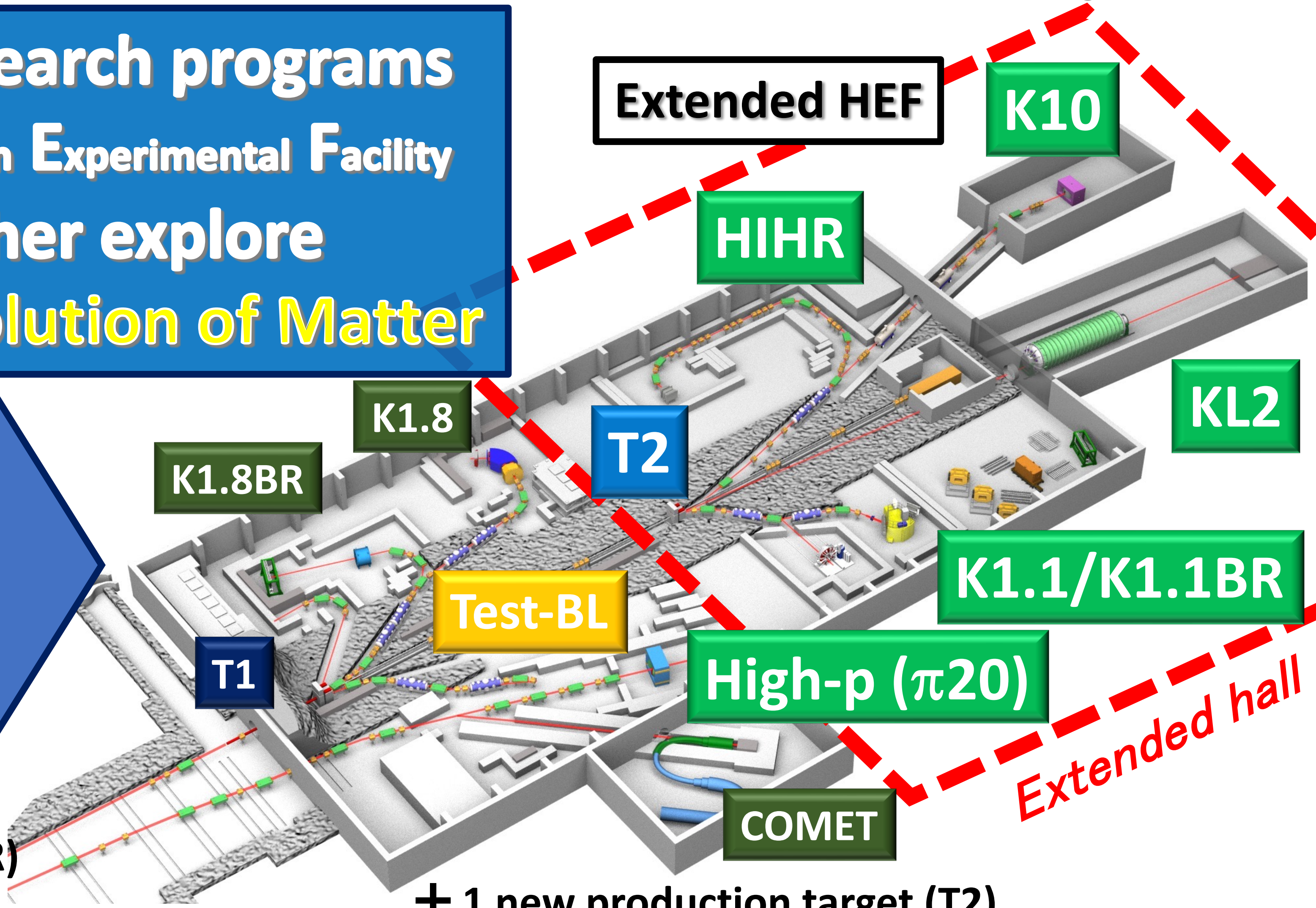
Hadron Experimental Facility eXtension (HEF-ex) Project

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

Present HEF (2009～)



Extended HEF



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 hypernuclear spectroscopy**
- intense dispersion matched π beam

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

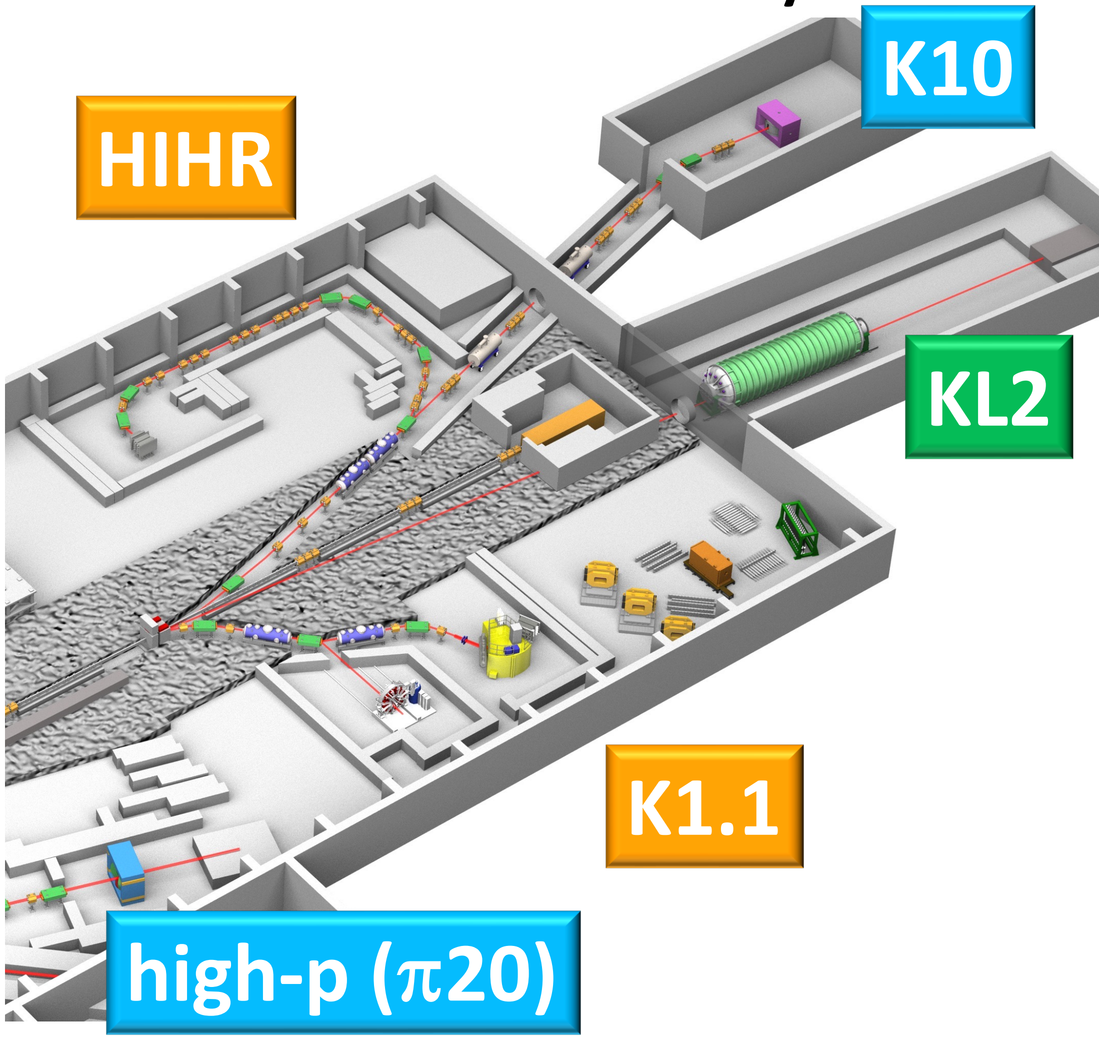
Investigate diquarks in baryons

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

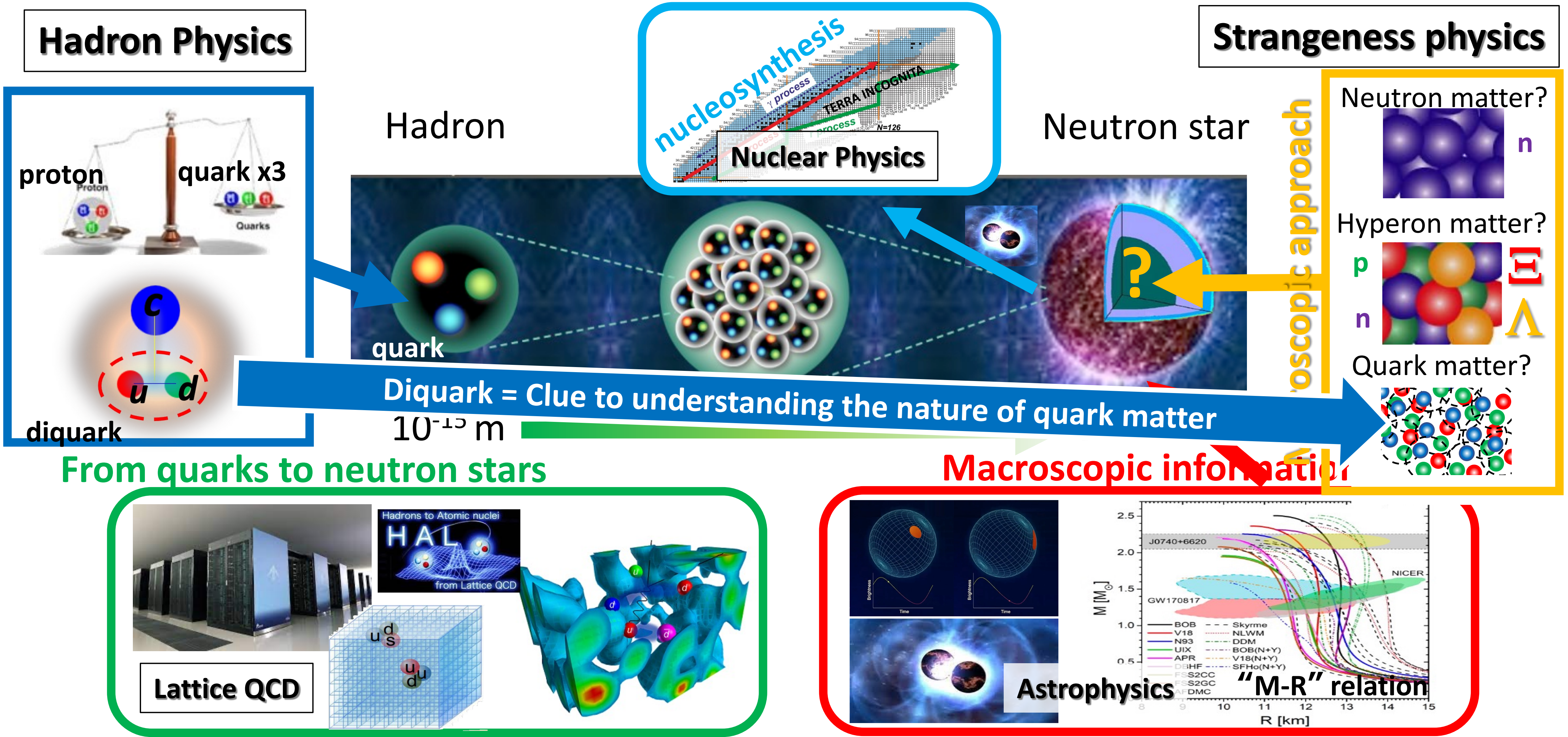
Search for new physics beyond the SM

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



From Quarks to Neutron stars

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

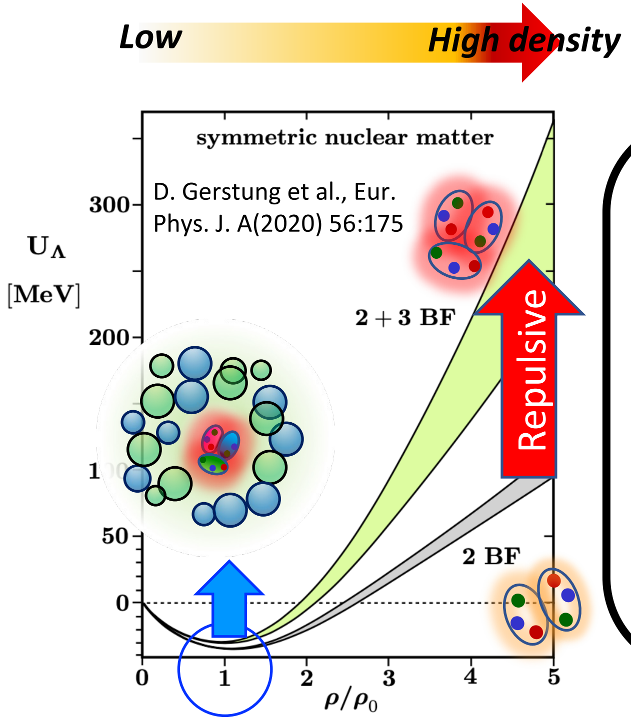


Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

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

ΛNN 3 Baryon Force is a key



heavy Λ-hypernuclei :

Λ binding energies (B_Λ)

→ density dependent ΛN interaction

→ We need precise measurements

We need to determine

a **tiny fraction of 3 Baryon Force effects**

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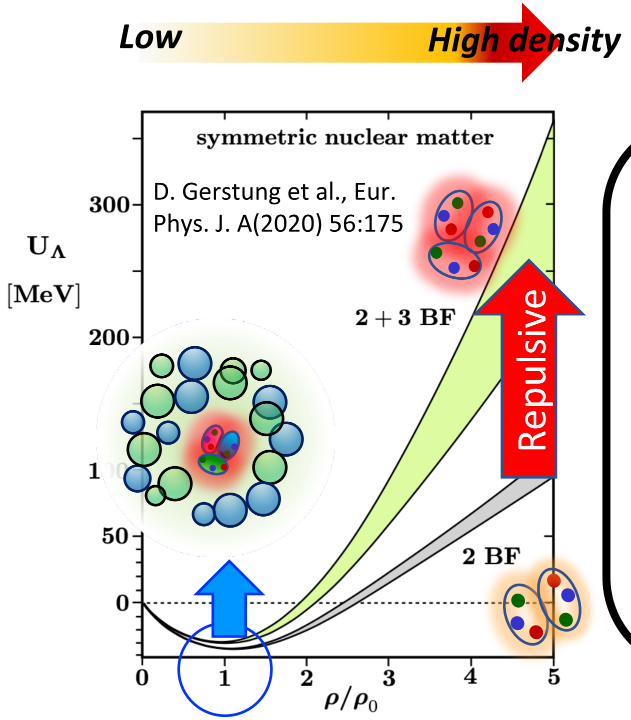

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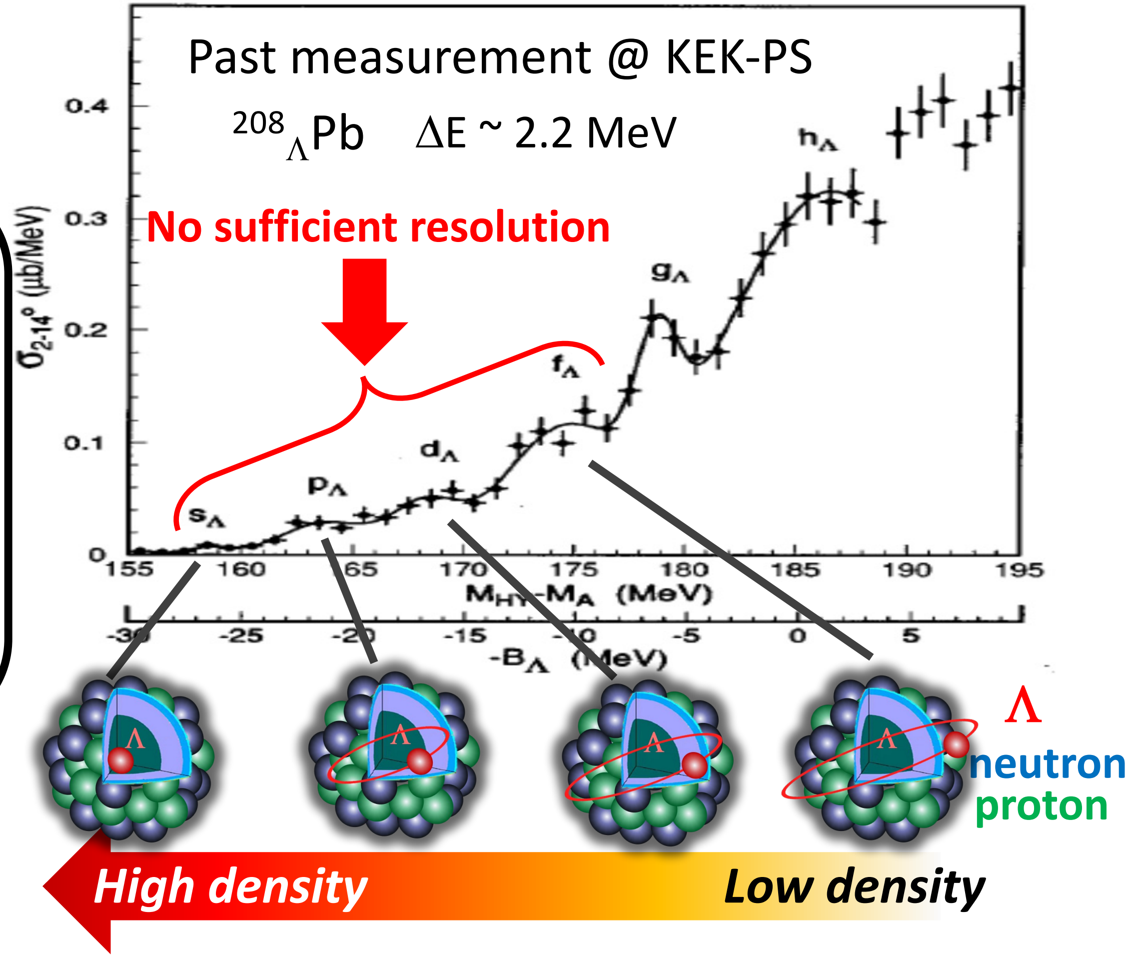

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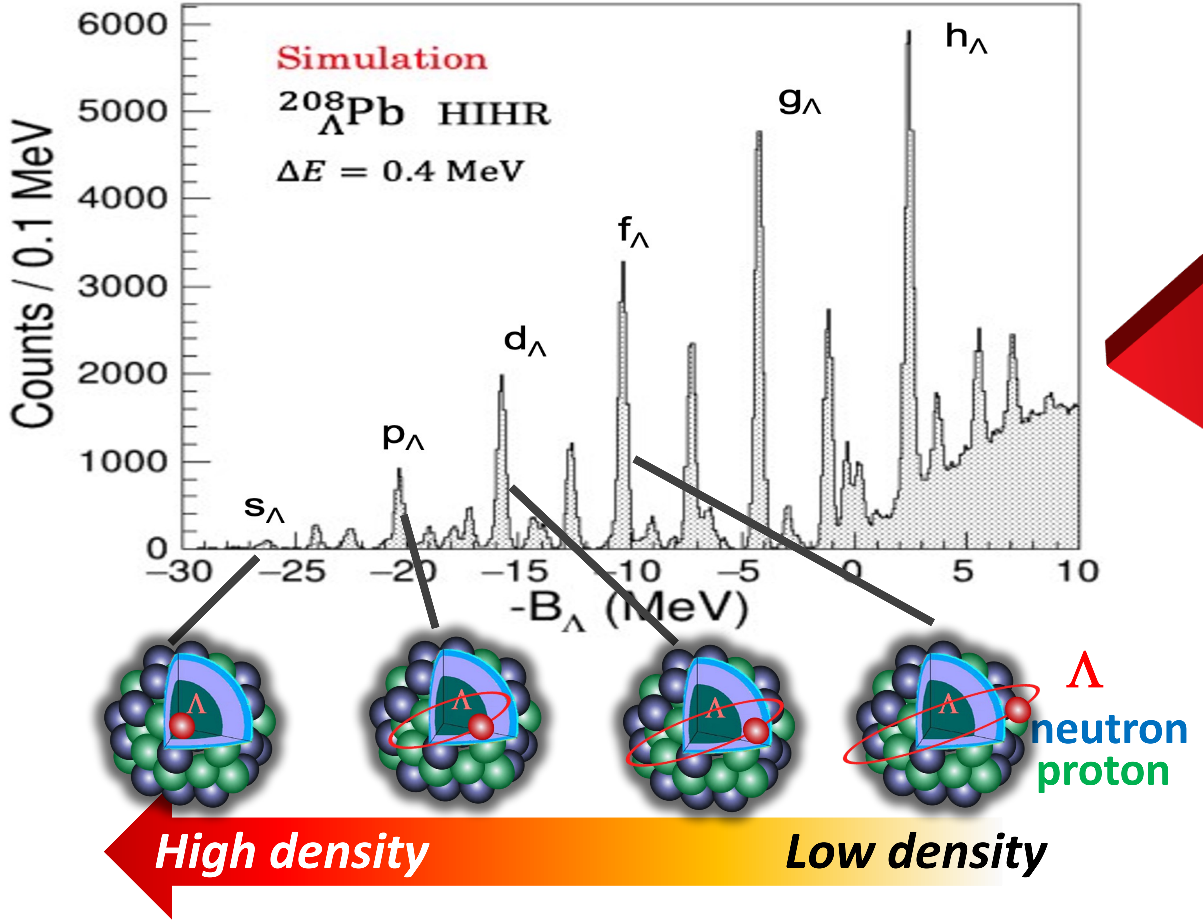
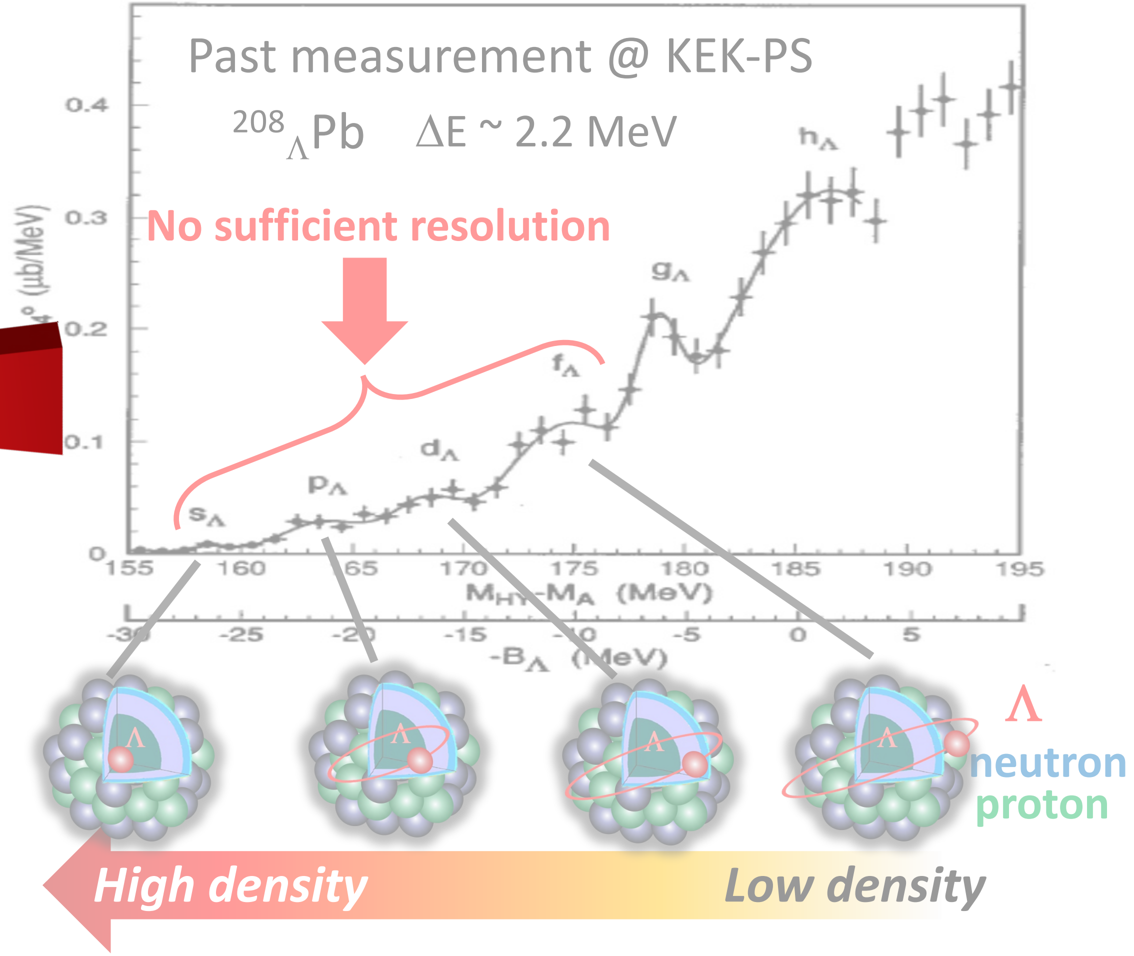
Need separation of each Λ orbital state





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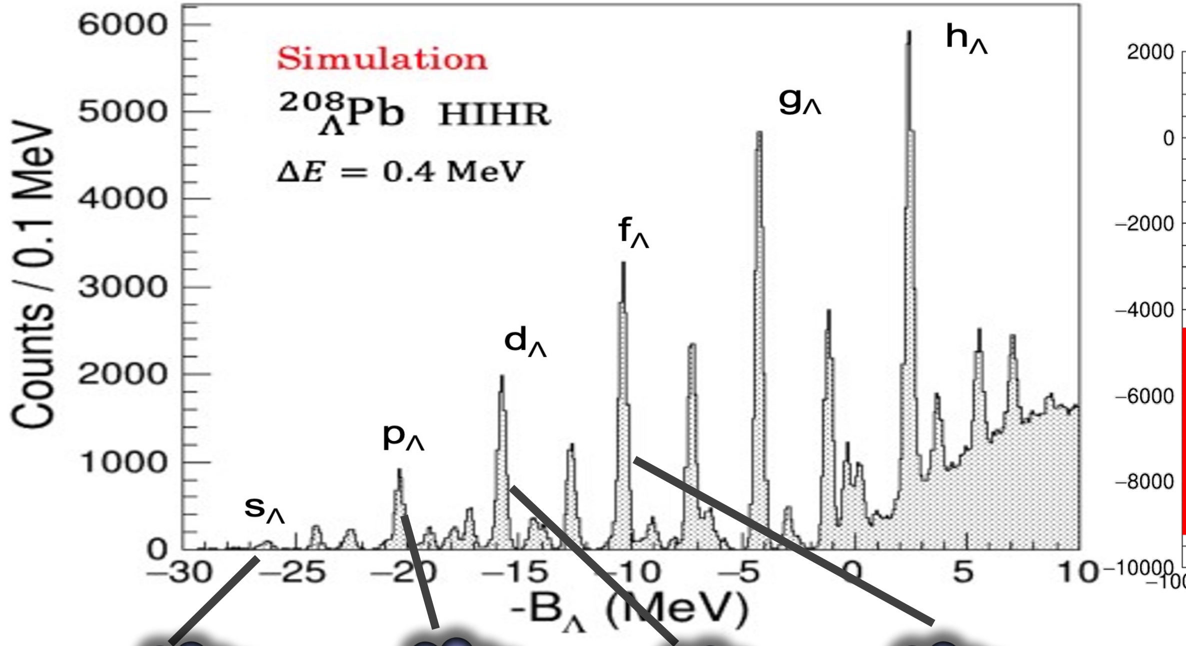
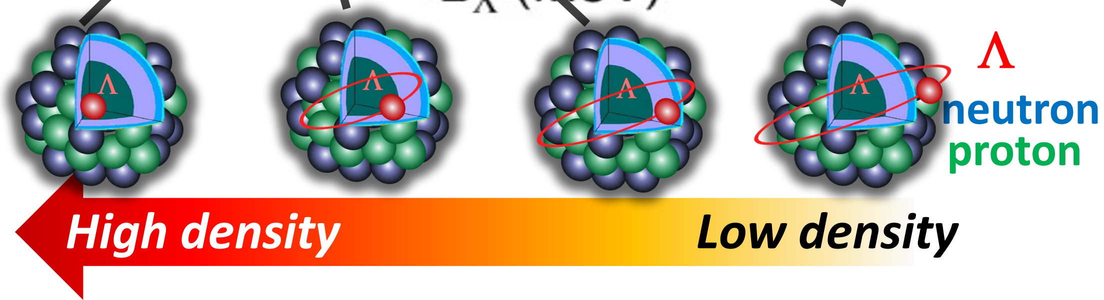
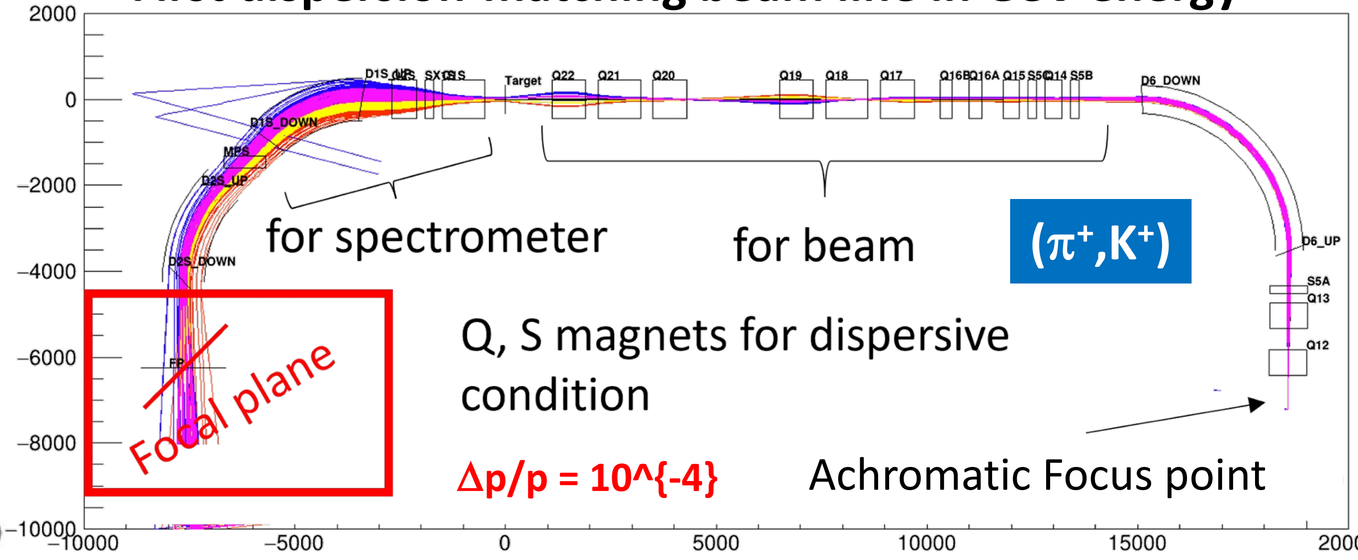
Ultra-high-resolution Λ-hyp. spectroscopy





HIHR beam line (High-Intensity High-Resolution)

First dispersion-matching beam line in GeV energy



up to 2 GeV/c

- 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

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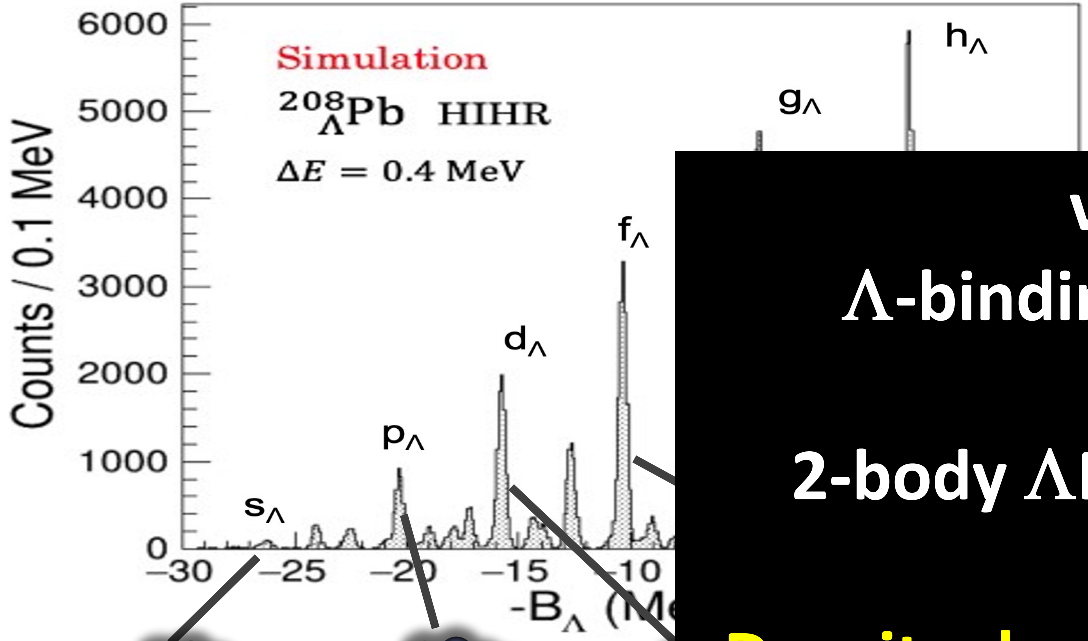

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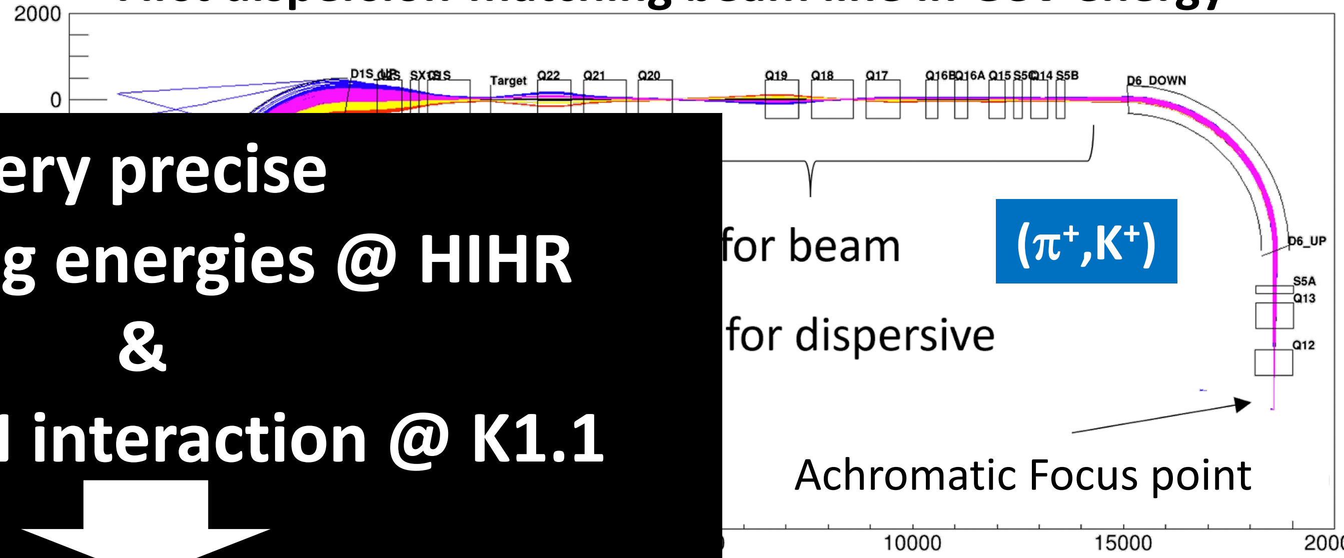
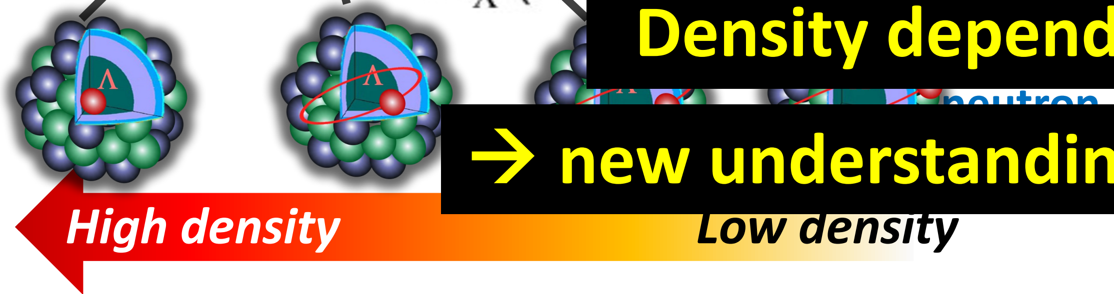


for beam

for dispersive

g

up to 2 GeV/c



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

Density dependent ΛN interaction

→ new understanding of neutron star matter

ion limit:

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

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
- Near future programs
  - Lifetime measurement of ${}^{3}_{\Lambda}H$
  - 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.