J-PARC

Japan Proton Accelerator Research Complex

J-PARC and its hadron hall extension overview

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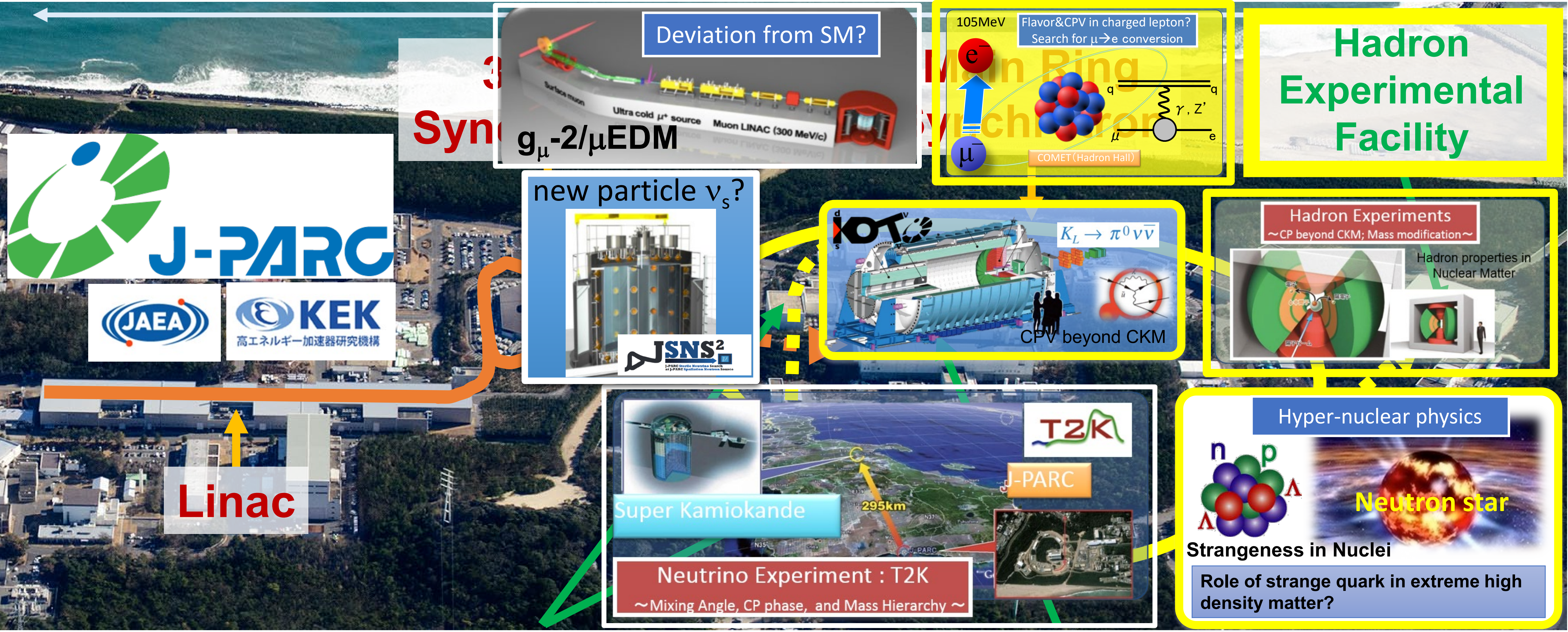
Particle and Nuclear Physics @ J-PARC



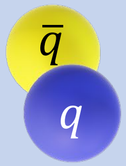
Neutrino Experimental Facility

Material and Life Science Experimental Facility

Origin & Evolution of Matter

Matter-Antimatter Symmetry

matter dominated universe



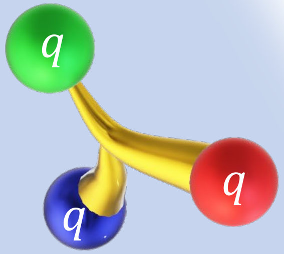
Flavor Physics

CP violation
weak interaction
→ new physics

Kaon rare decays
$\mu \to e$ conversion

Origin of Matter Creation

formation of hadrons from quarks



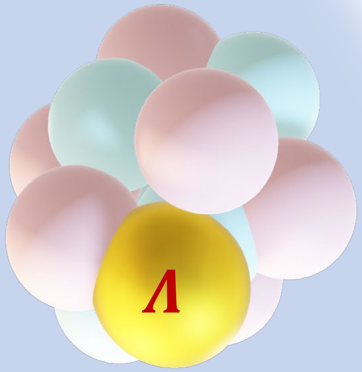
Hadron Physics

quark interactions
hadron mass-generation mechanism

Hadron spectroscopy
Meson in nuclei

Matter in Extreme Conditions

dense matter in neutron stars



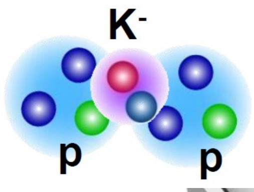
Strangeness Nuclear Physics

hadron interactions
hadronic many-body systems

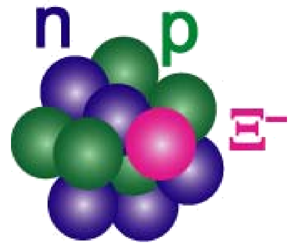
Hyperon-Nucleon scattering
Hypernuclear spectroscopy

Present Hadron Experimental Facility (HEF)

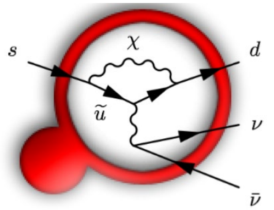
- < 1.1 GeV/c
- ~ 5x10^5 K$^-$/spill
- **Kaon in nuclei**

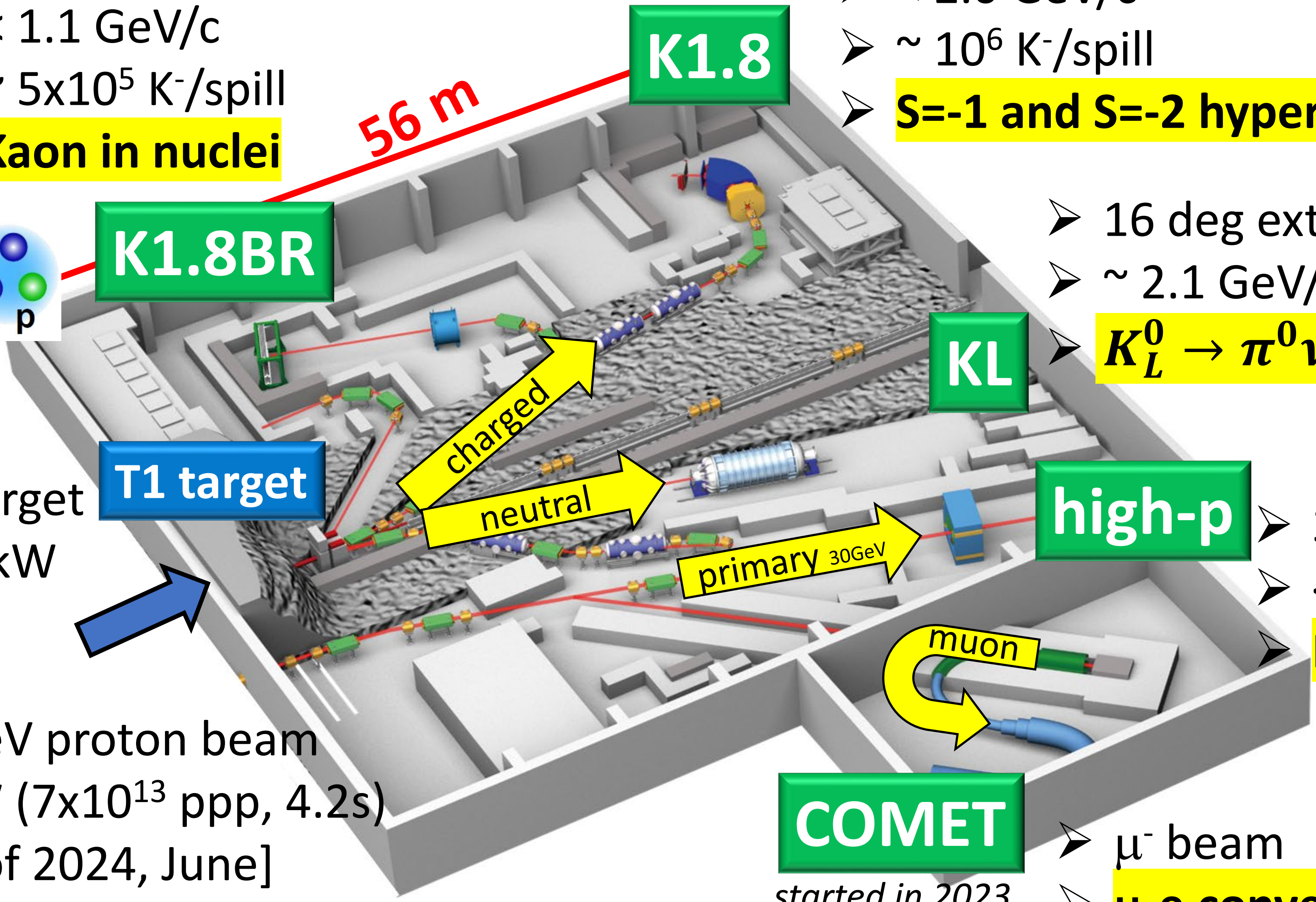


- < 2.0 GeV/c
- ~ 10^6 K$^-$/spill
- **S=-1 and S=-2 hypernuclei**



- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- $K_L^0 \to \pi^0 \nu \bar{\nu}$

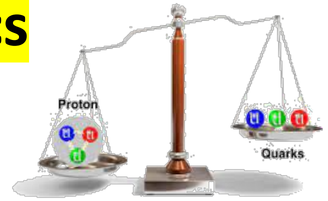




- Au Target
- < 95 kW

launched in 2020

- 30 GeV proton ~ 10^{10}
- < 31 GeV/c unsepa. π ~ 10^7
- **Hadron physics**



- 30 GeV proton beam
- 82kW (7x10^{13} ppp, 4.2s)

  [as of 2024, June]

started in 2023

- μ$^-$ beam
- **μ-e conversion**

Achievements in research at the Hadron Experimental Facility

Flavor Physics

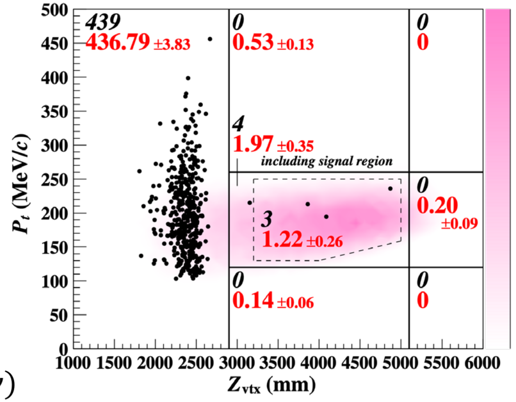
$K_L^0 \to \pi^0 \nu\bar{\nu}$ search @ KOTO

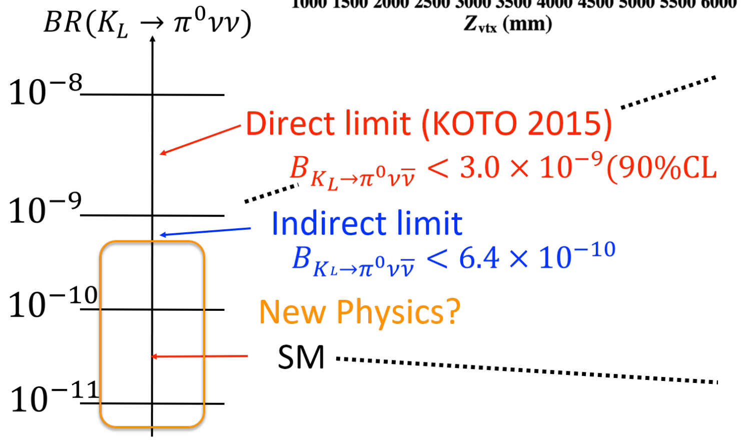
→ **Approaching the SM sensitivity for CP violation**

KOTO 2015

Single Event Sensitivity = 3×10^{-9}

KOTO 2016-18



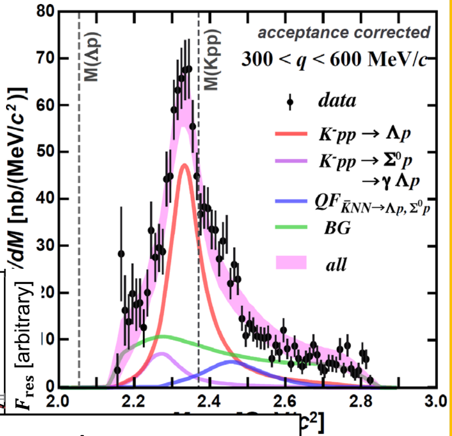


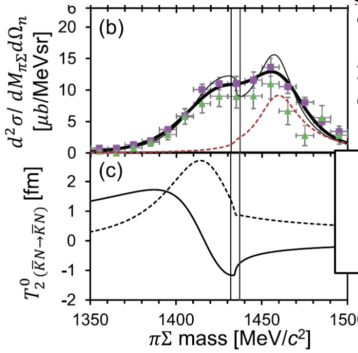
Hadron Physics

Observation of an exotic hadron bound system including K⁻ meson

→ **Established a new direction to understand meson-baryon int.**

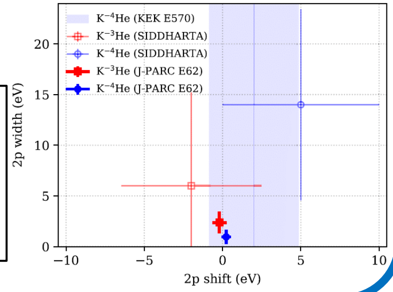
Kaonic nuclear state, "K-pp"





Pole position of Λ(1405)

Ultra-precise measurement of kaonic atoms

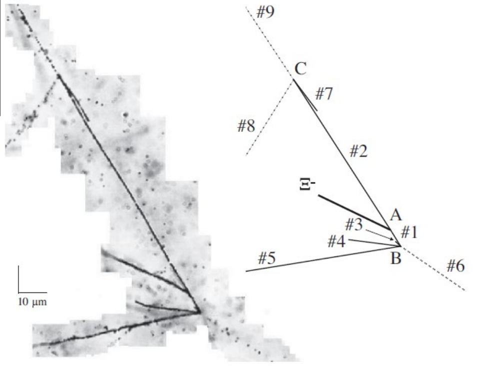


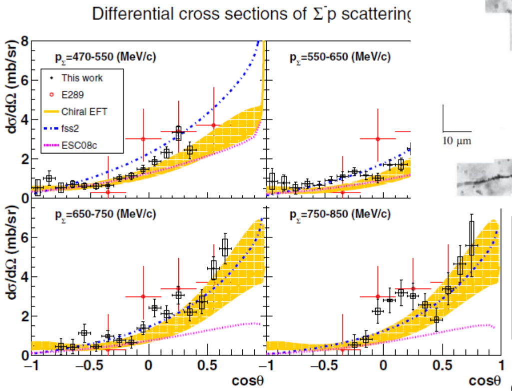
Strangeness Nuclear Physics

A lot of progress in hypernuclear research

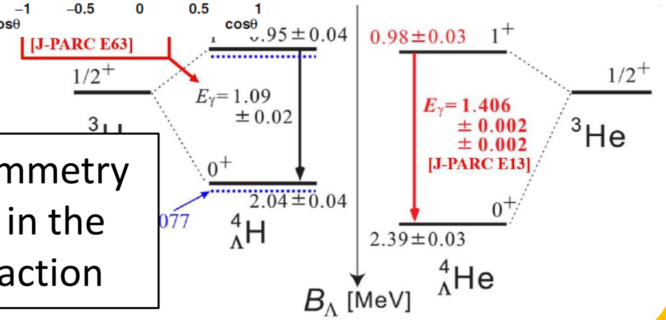
→ **Clarified attractive S=–2 ΞN interaction and deepened S=–1 ΛN, ΣN interactions**

Observation of Ξ hypernuclei





First precise ΣN scattering



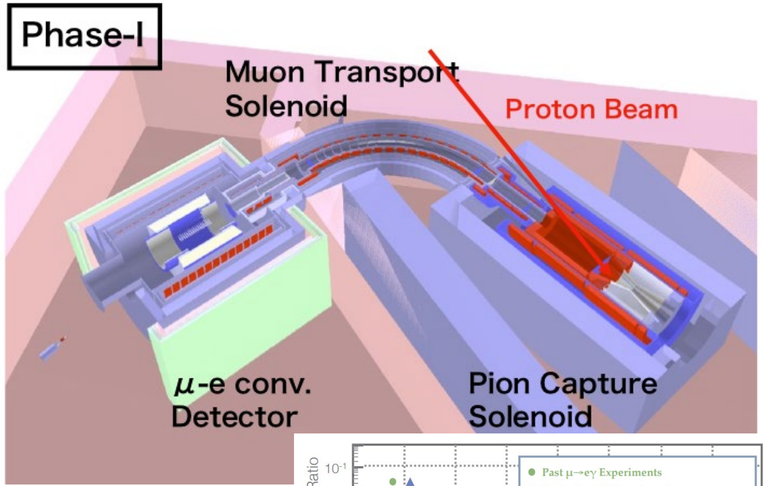
Charge-symmetry breaking in the ΛN interaction

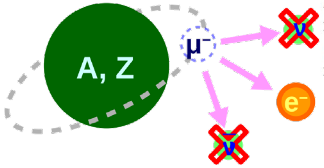
Further research directions at the Hadron Experimental Facility

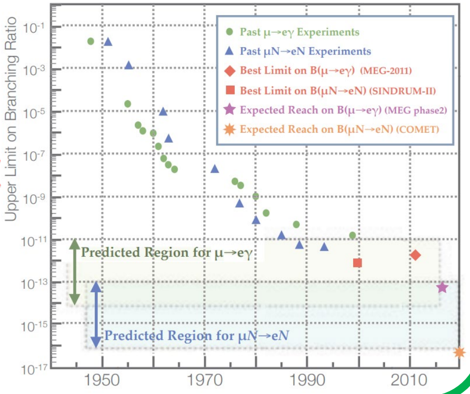
Flavor Physics

Search for μ→e conversion @ COMET (2023~)

→ Search for charged lepton flavor violation



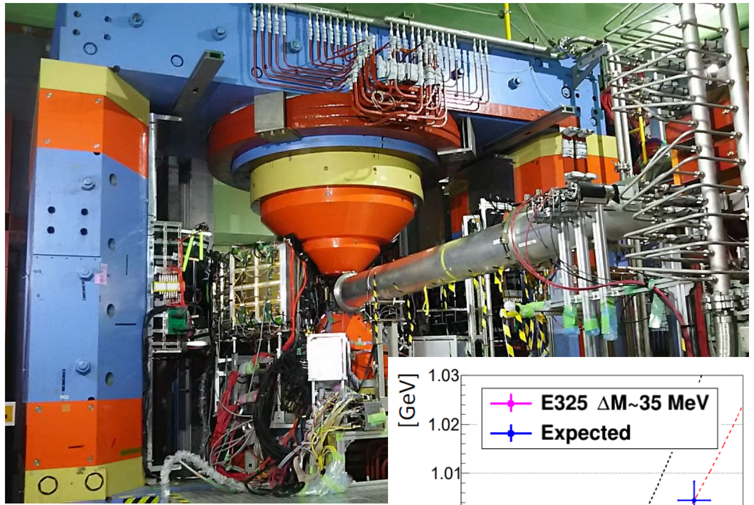


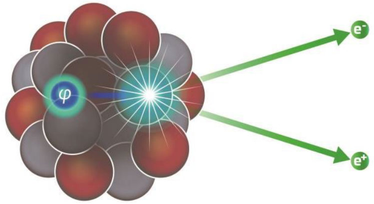


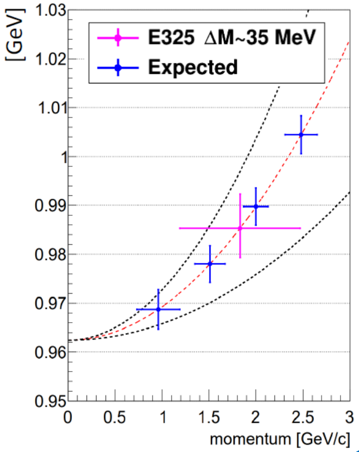
Hadron Physics

Measurement of spectral modification of ϕ meson in nuclei (2020~)

→ Attack mass-generation mechanism of hadrons



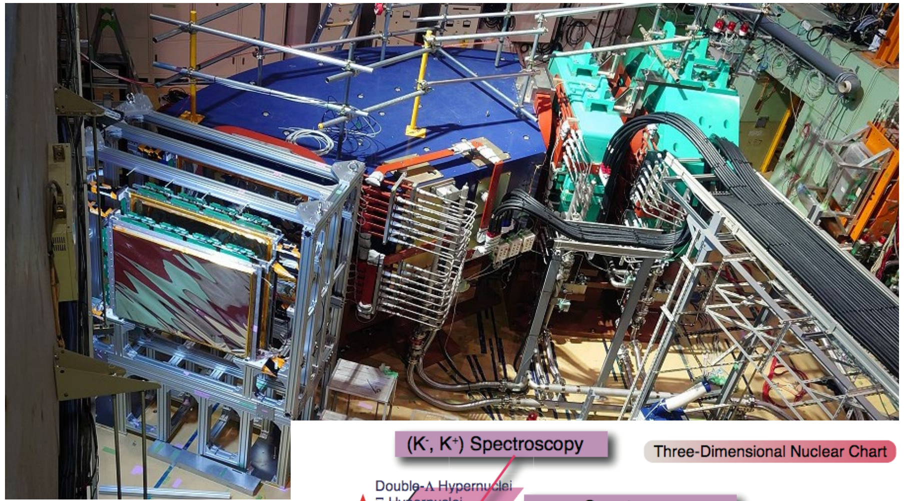


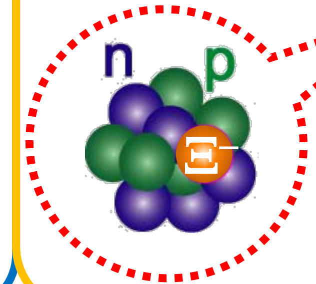


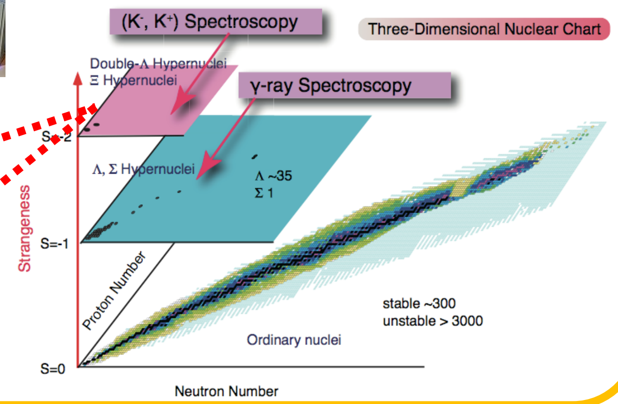
Strangeness Nuclear Physics

High-resolution spectroscopic study of S=–2 Ξ-hypernuclei (2023~)

→ Provide accurate and systematic information on ΞN, ΛΛ interactions



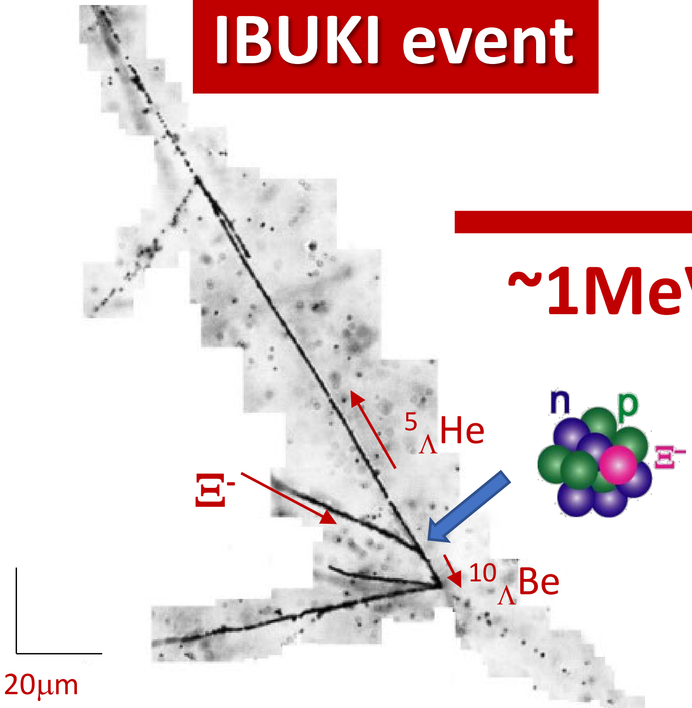




Highlights of the intense K⁻ beam experiments (1) Ξ-hypernuclei

- Attractive Ξ-nuclear potential was confirmed from observation of Ξ-hypernuclei in emulsion at J-PARC (E05)

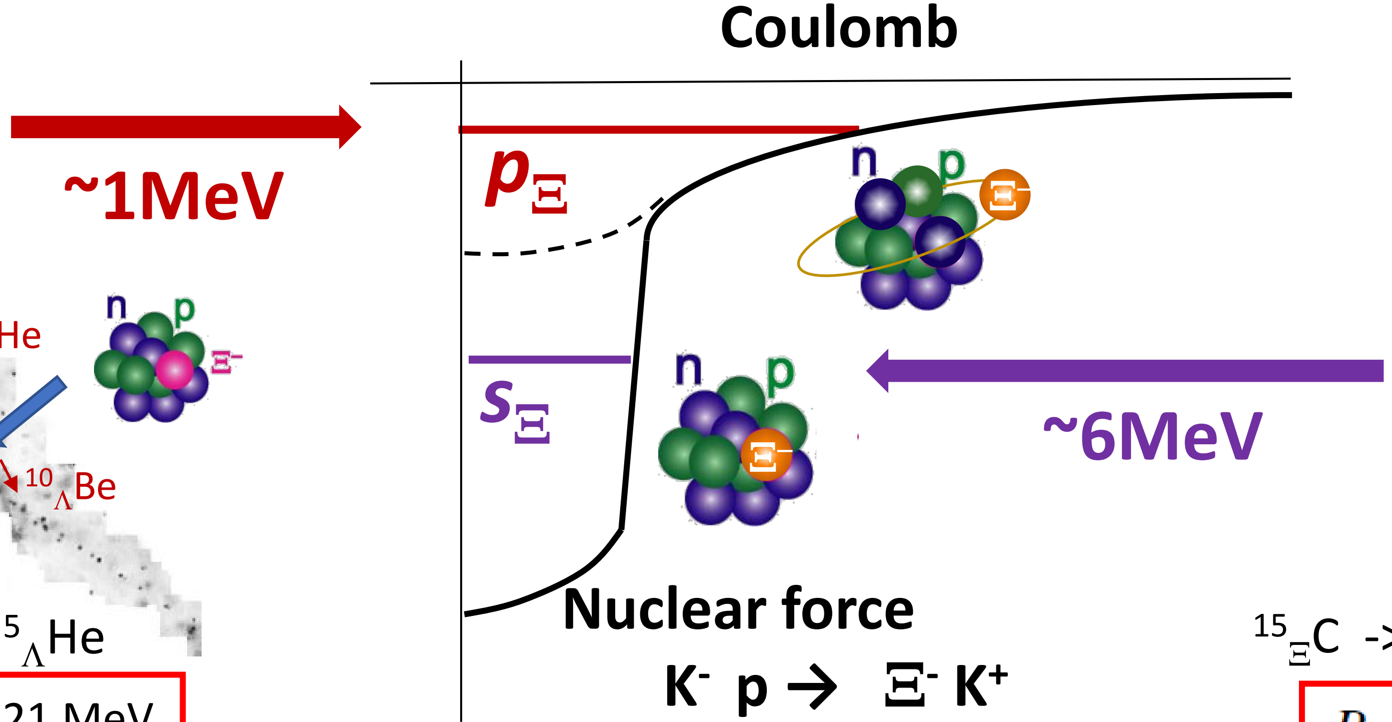
IBUKI event



$^{15}_{\Xi}$C -> $^{10}_{\Lambda}$Be + $^{5}_{\Lambda}$He

B_{Ξ^-} = 1.27 ± 0.21 MeV

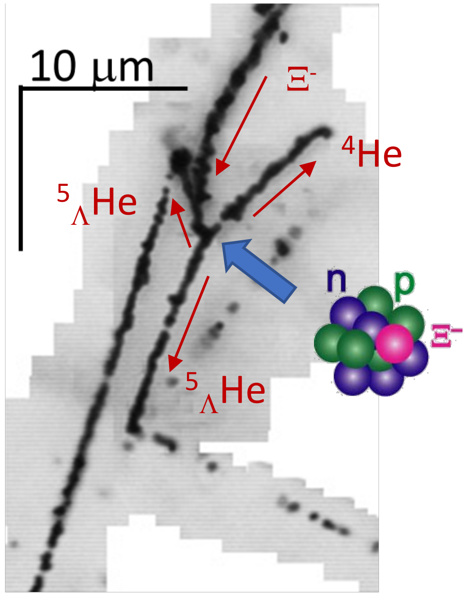
S. H. Hayakawa et al., PRL 126 (2021) 062501



$K^- \; p \rightarrow \; \Xi^- K^+$

$\Xi^- + {}^{14}N \rightarrow {}^{15}_{\Xi}C$

IRRAWADDY event



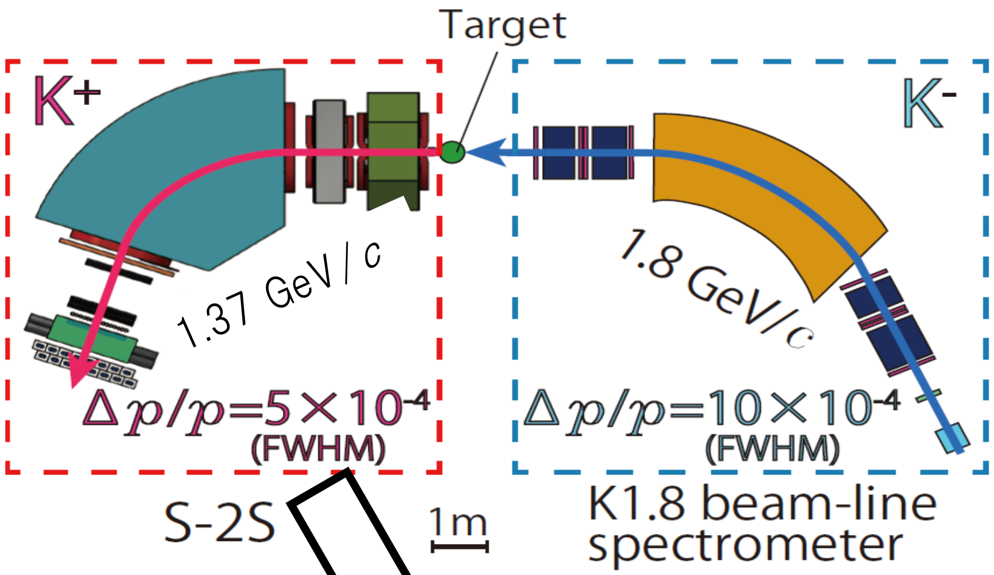
$^{15}_{\Xi}$C -> $^{5}_{\Lambda}$He + $^{5}_{\Lambda}$He + ^{4}He + n

B_{Ξ^-} = 6.27 ± 0.27 MeV

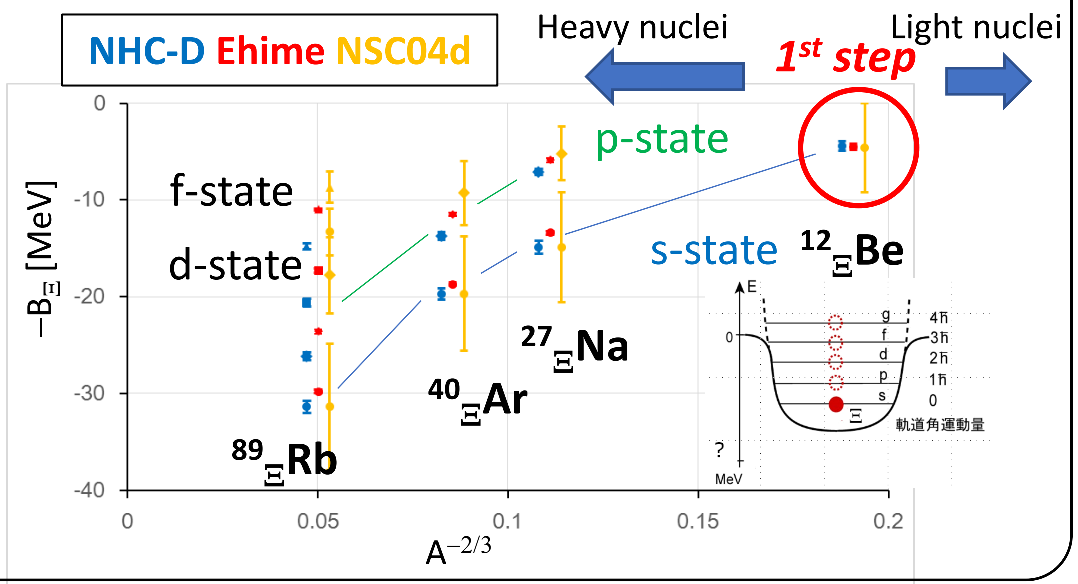
M. Yoshimoto et al., PTEP 2021, 073D02

Highlights of the intense K^- beam experiments (1)
Ξ-hypernuclei

- The first Ξ-hypernucleus spectroscopy
  - Ξ potential – both Re(V_Ξ) and Im(V_Ξ)
  - isospin dependence ($\propto 1/A$)
  - ΞN-ΛΛ conversion
- Systematic measurements will be strongly promoted at J-PARC

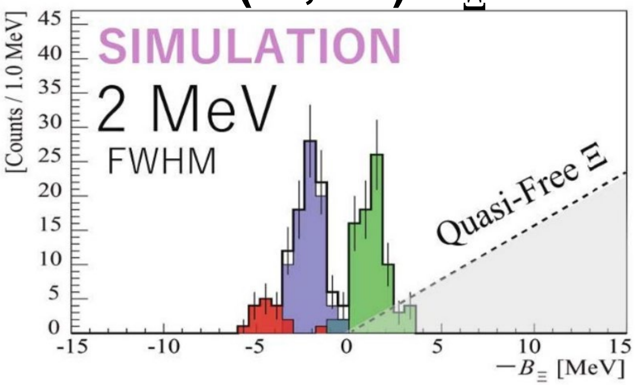


Calculated Ξ binding energy (and width)

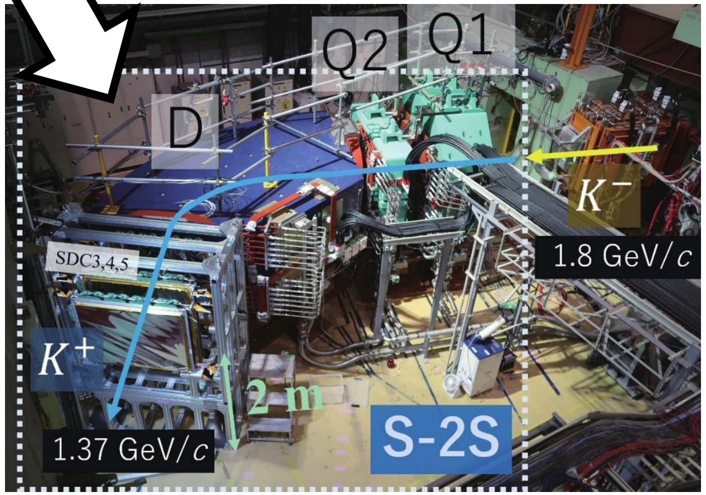


1st step is ongoing

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



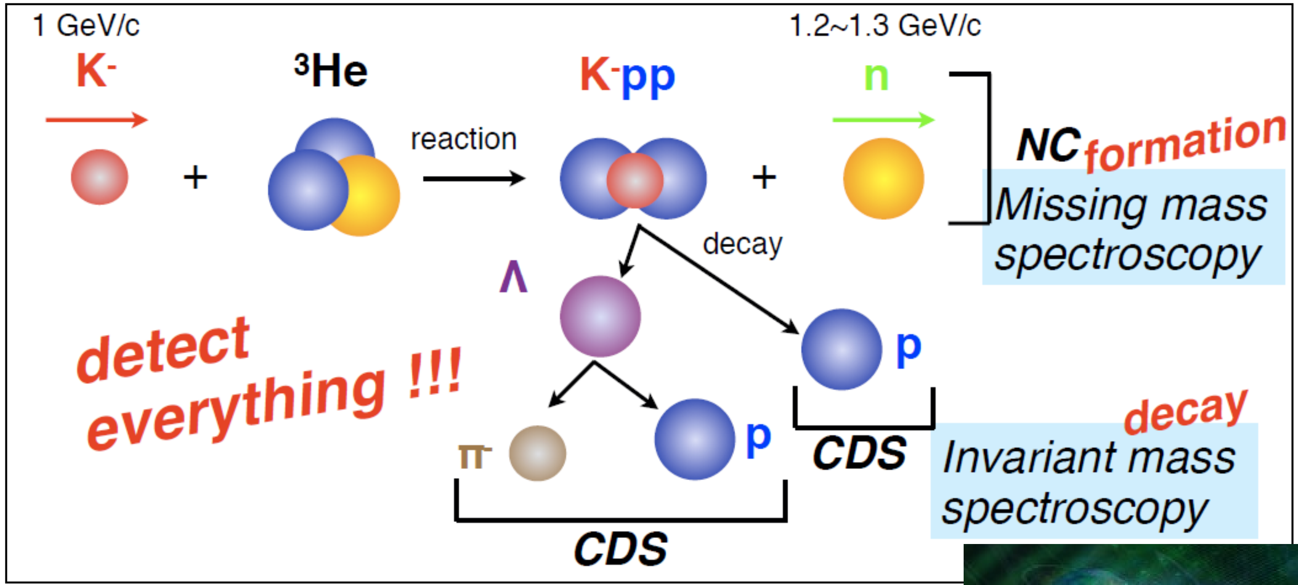
T. Gogami et al., EPJ Web of Conf. 271, 11002 (2022)

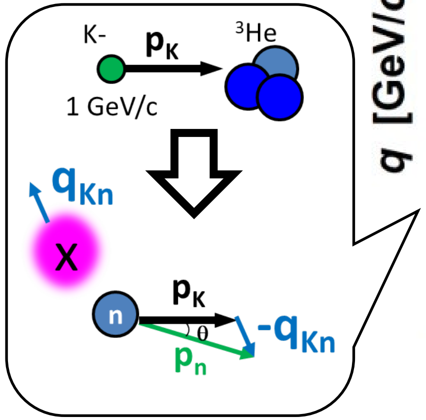


Results coming soon

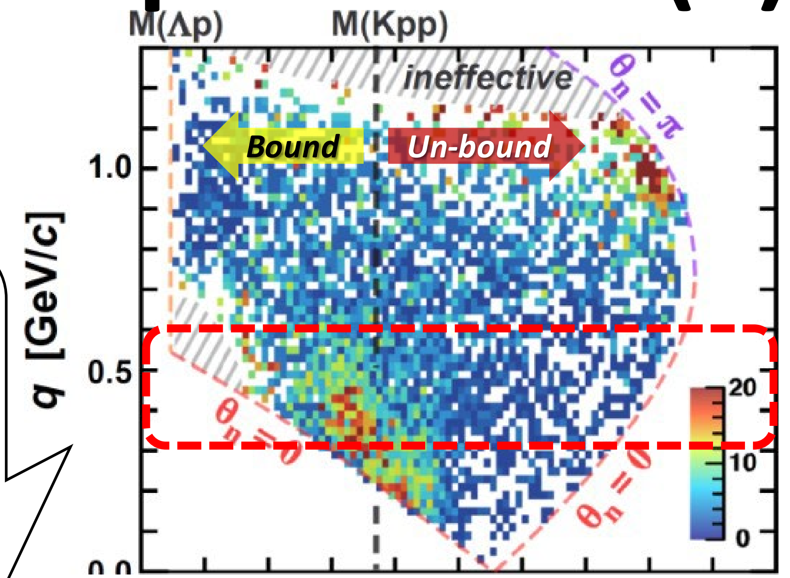
Highlights of the intense K⁻ beam experiments (2)
Kaonic nuclei

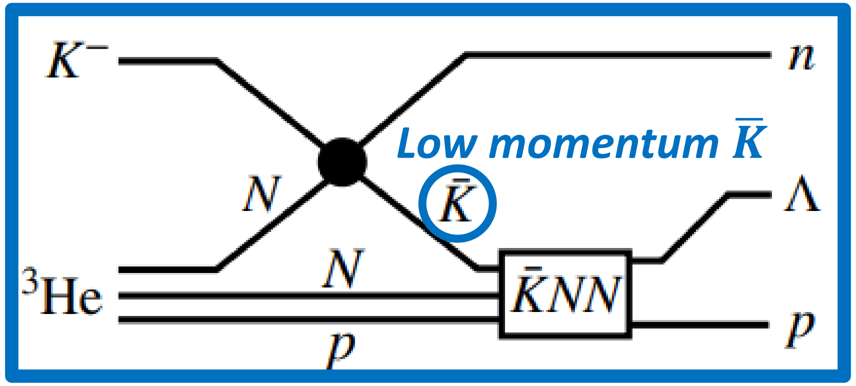
- “K⁻pp” bound state was observed in ^{3}He(K⁻,n)Λp at J-PARC (E15)

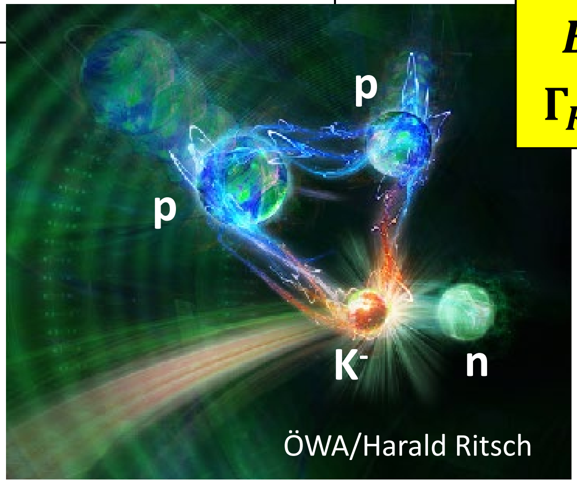




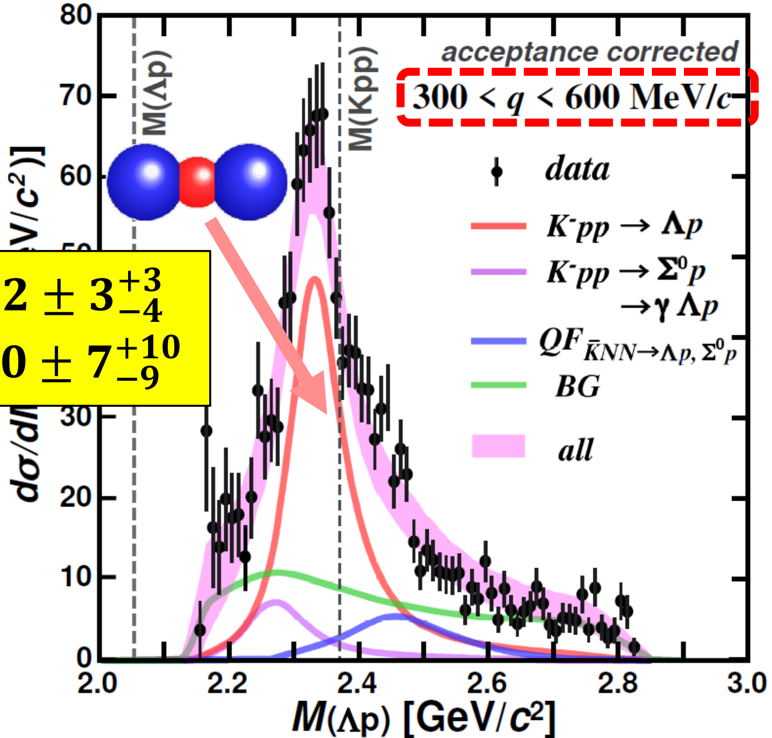
PLB789(2019)620., PRC102(2020)044002.







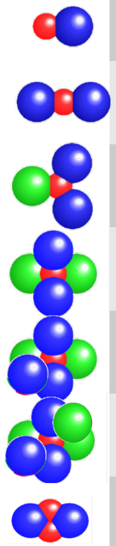
$$B_{Kpp} = 42 \pm 3^{+3}_{-4}$$
$$\Gamma_{Kpp} = 100 \pm 7^{+10}_{-9}$$



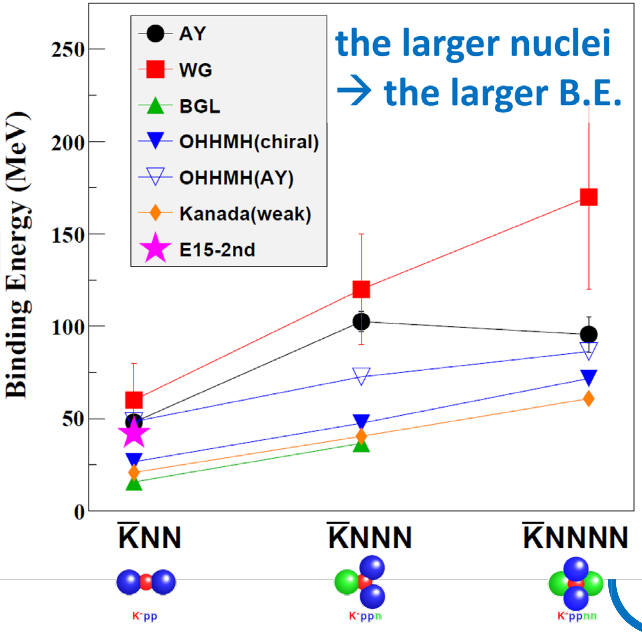
Highlights of the intense K⁻ beam experiments (2)

Kaonic nuclei

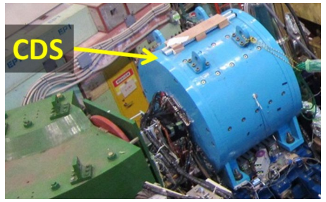
- Systematic measurement of kaonic nuclei will be promoted at J-PARC
  - Mass number dependence
    - Binding energy, Branching ratio, *q* dependence, ..
  - Spin/parity determination
  - Internal structure extracted with theoretical investigations



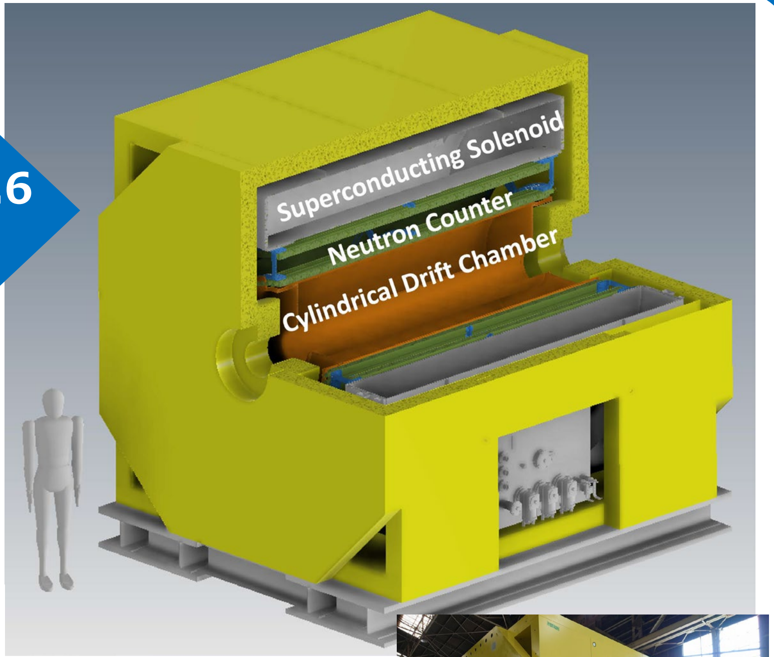
	Reaction	Decays
$\bar{K}N$	d(K⁻,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$
$\bar{K}NN$	^{3}He(K⁻,N)	Λp/Λn
$\bar{K}NNN$	^{4}He(K⁻,N)	Λd/Λpn ← first step
$\bar{K}NNNN$	^{6}Li(K⁻,d)	Λt/Λdn
$\bar{K}NNNNN$	^{6}Li(K⁻,N)	Λα/Λdd/Λdpn
$\bar{K}NNNNNN$	^{7}Li(K⁻,N)	Λαn/Λddn
$\bar{K}\bar{K}NN$	$\bar{p}$ + ^{3}He	ΛΛ

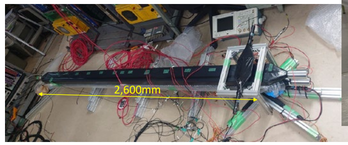


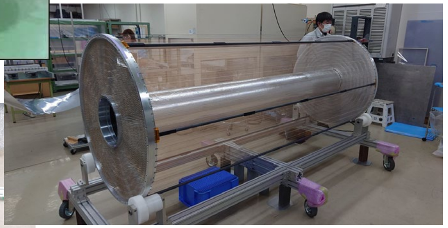
the larger nuclei
→ the larger B.E.



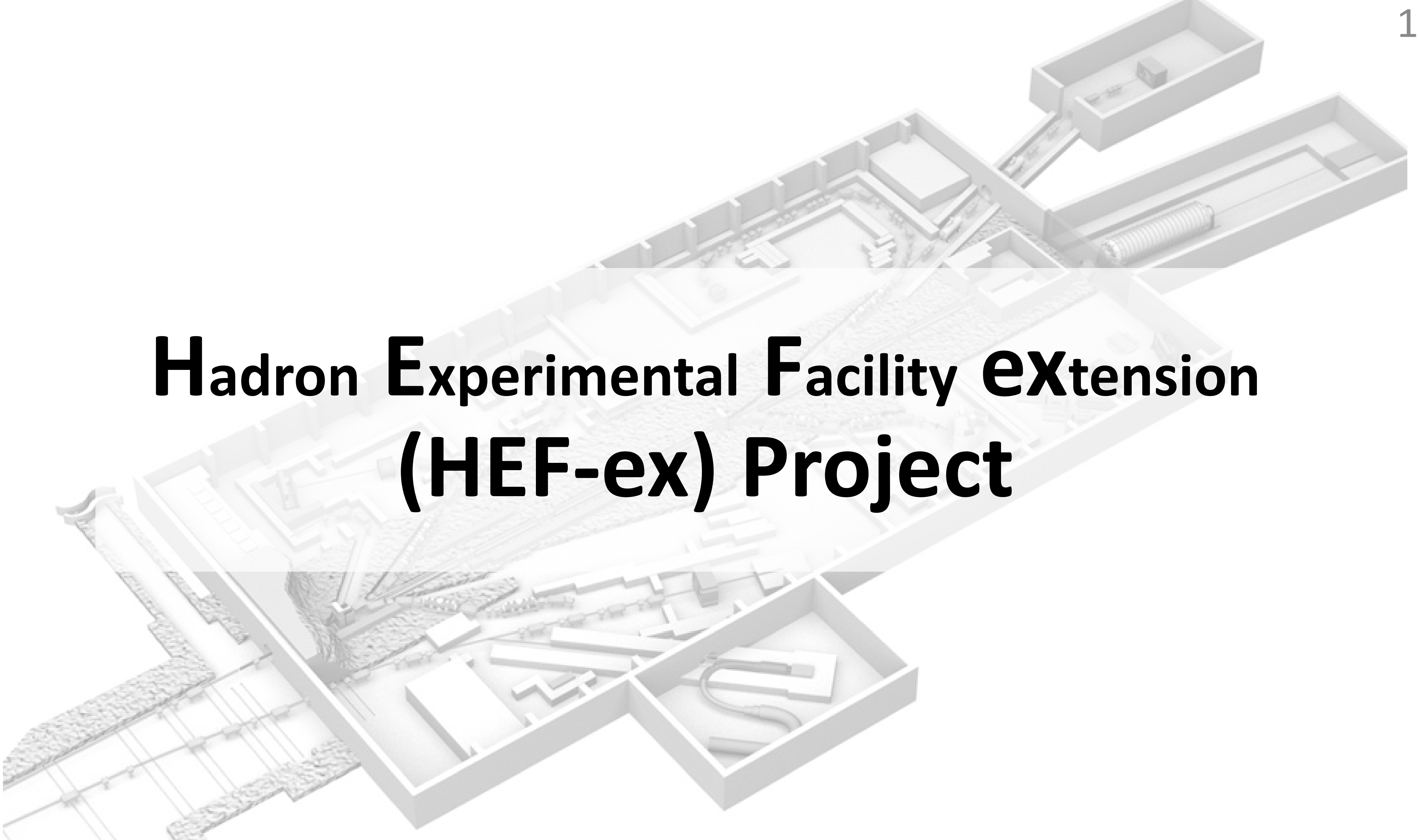
✓Solid angle: x1.6
✓Neutron eff.: x7







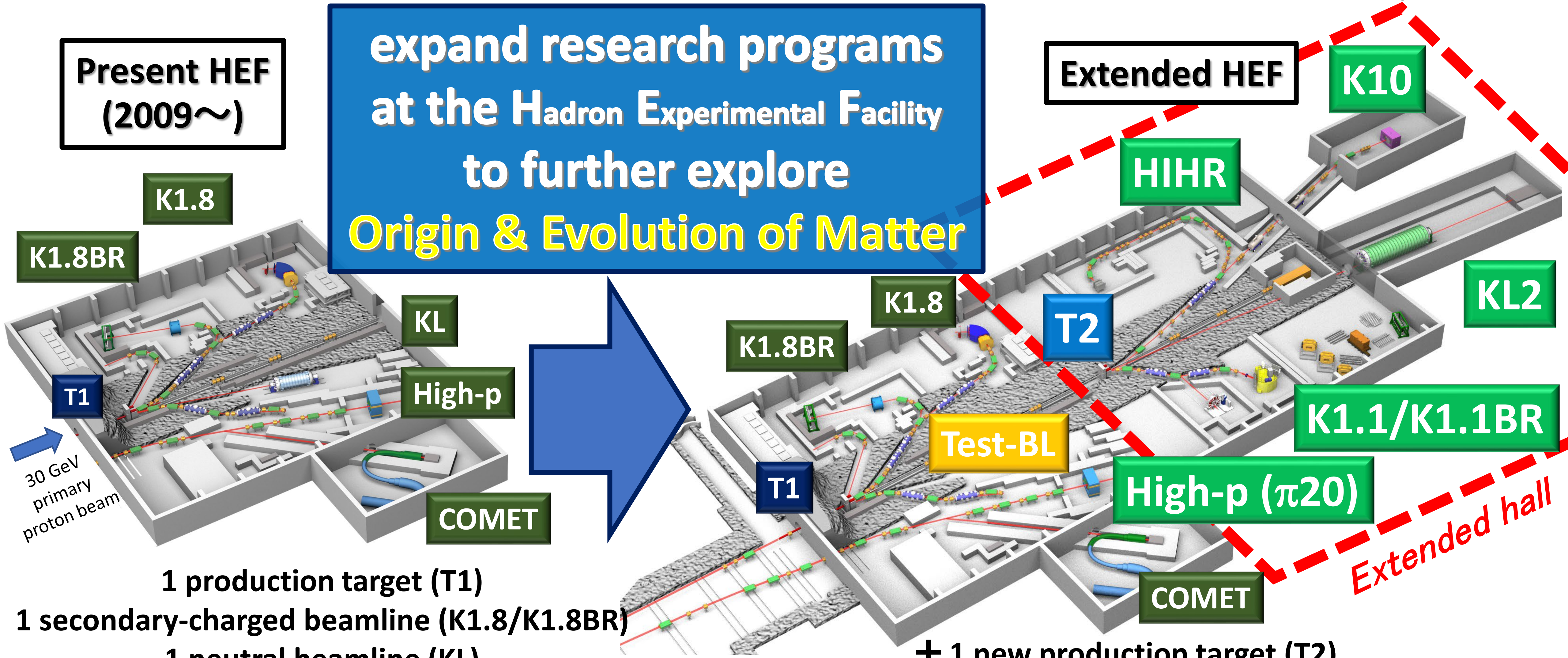
Will start in FY2026-27



Hadron Experimental Facility eXtension (HEF-ex) Project

Hadron Experimental Facility extension (HEF-ex) Project

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



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

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

Expanded Research Programs

at the Extended Facility

Extract density dependent ΛN interaction

HIHR **Ultra-high-resolution Λ hypernuclei spectroscopy**
- intense dispersion matched π beam

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

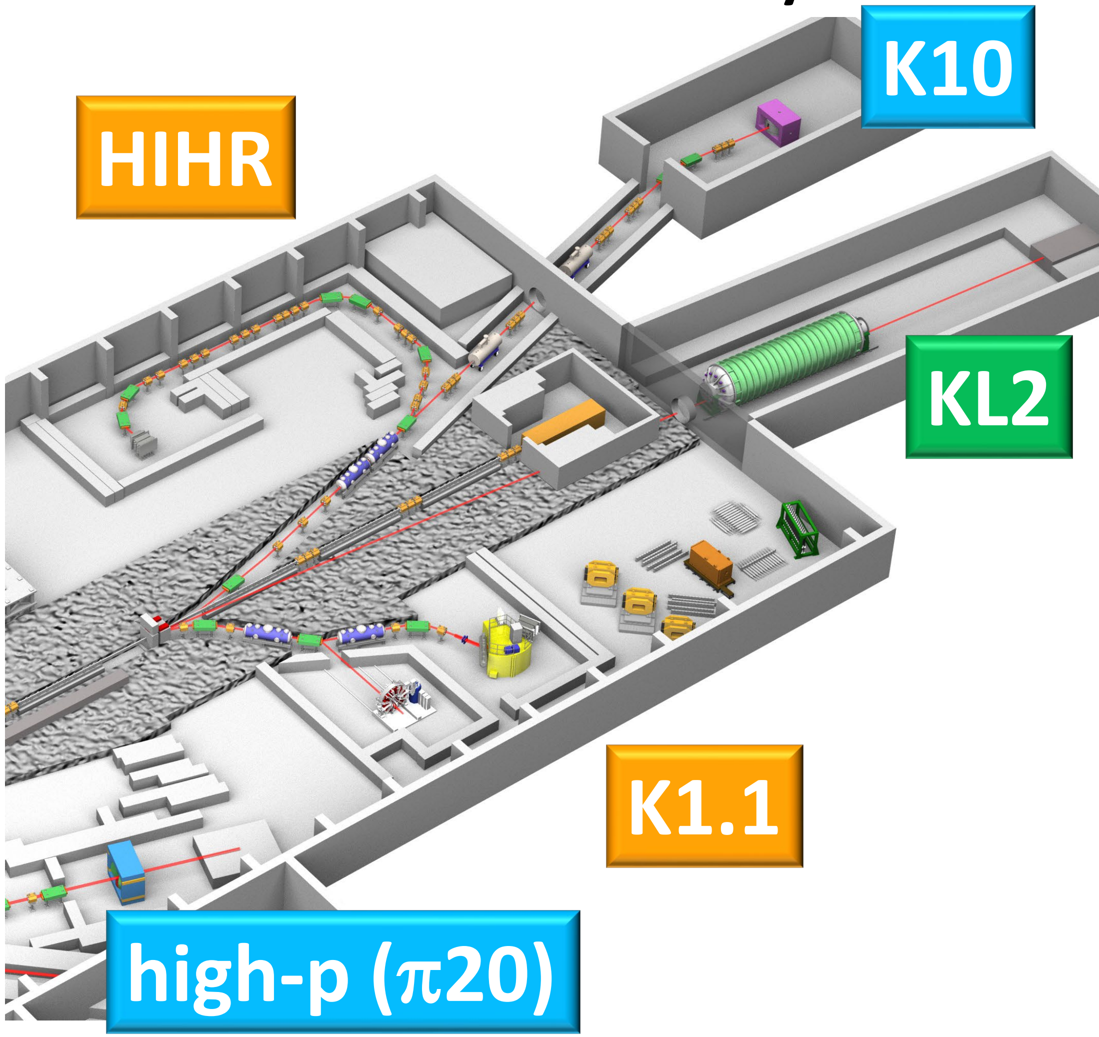
Investigate diquarks in baryons

high-p (π20) **High-resolution charm baryon spectroscopy**
- intense high-momentum π beam

K10 **High-resolution multi-strange baryon spectroscopy**
- intense high-momentum separated K beam

Search for new physics beyond the SM

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



Expanded Research Programs

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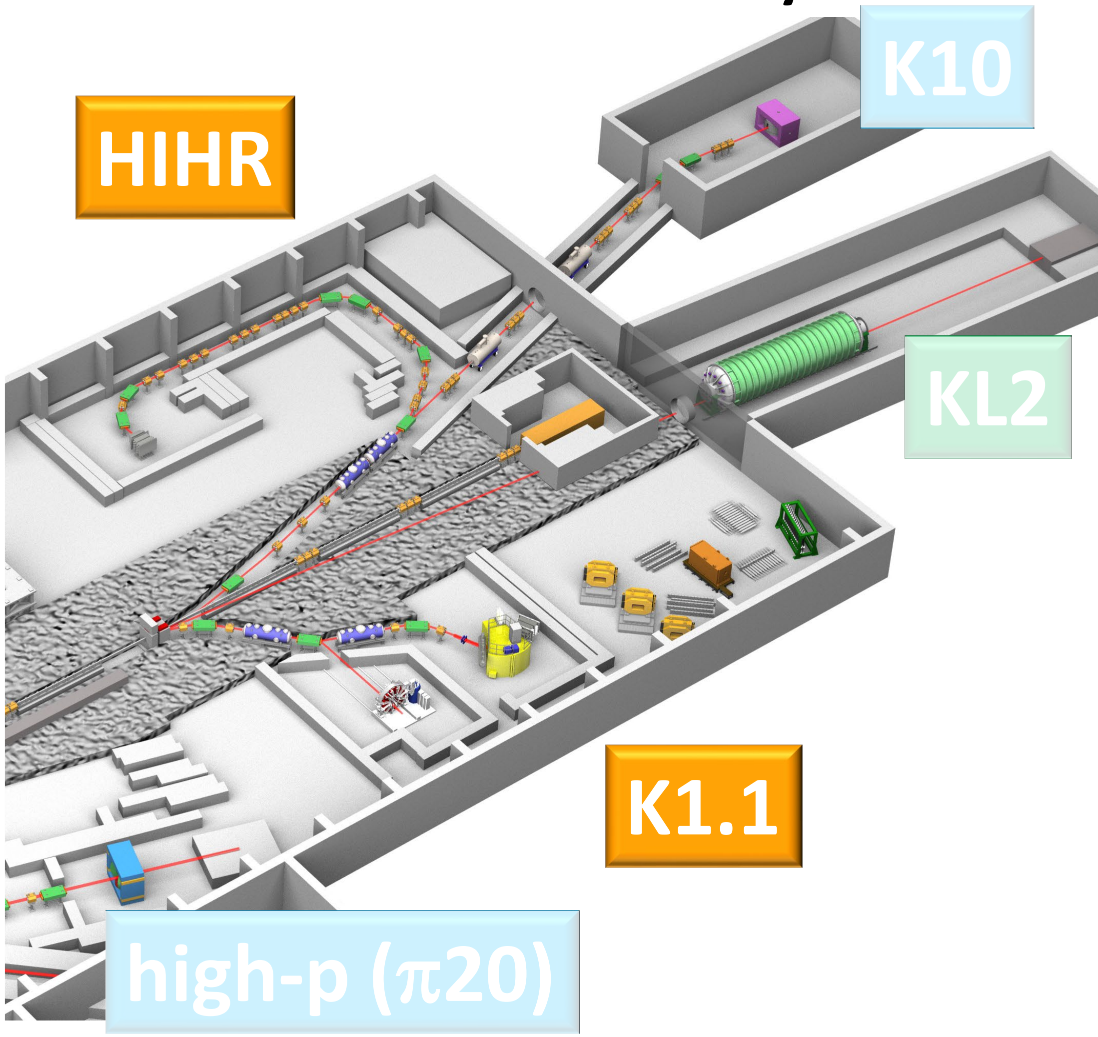
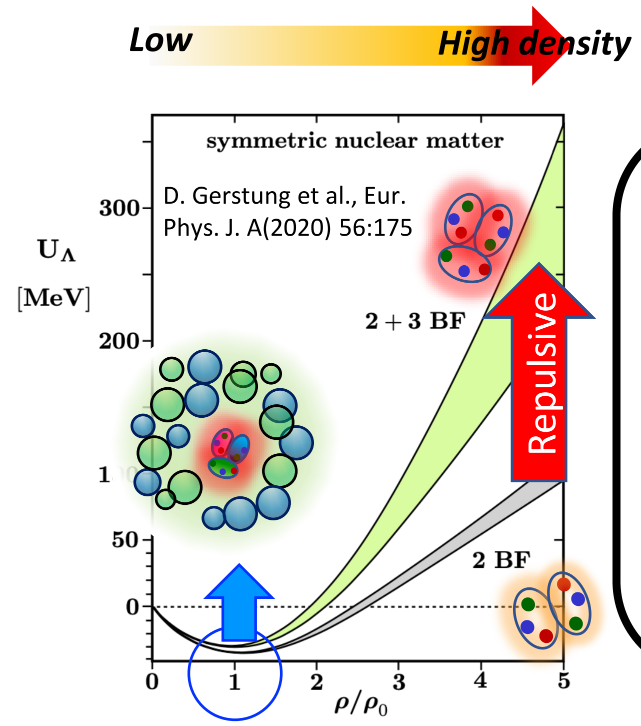


Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

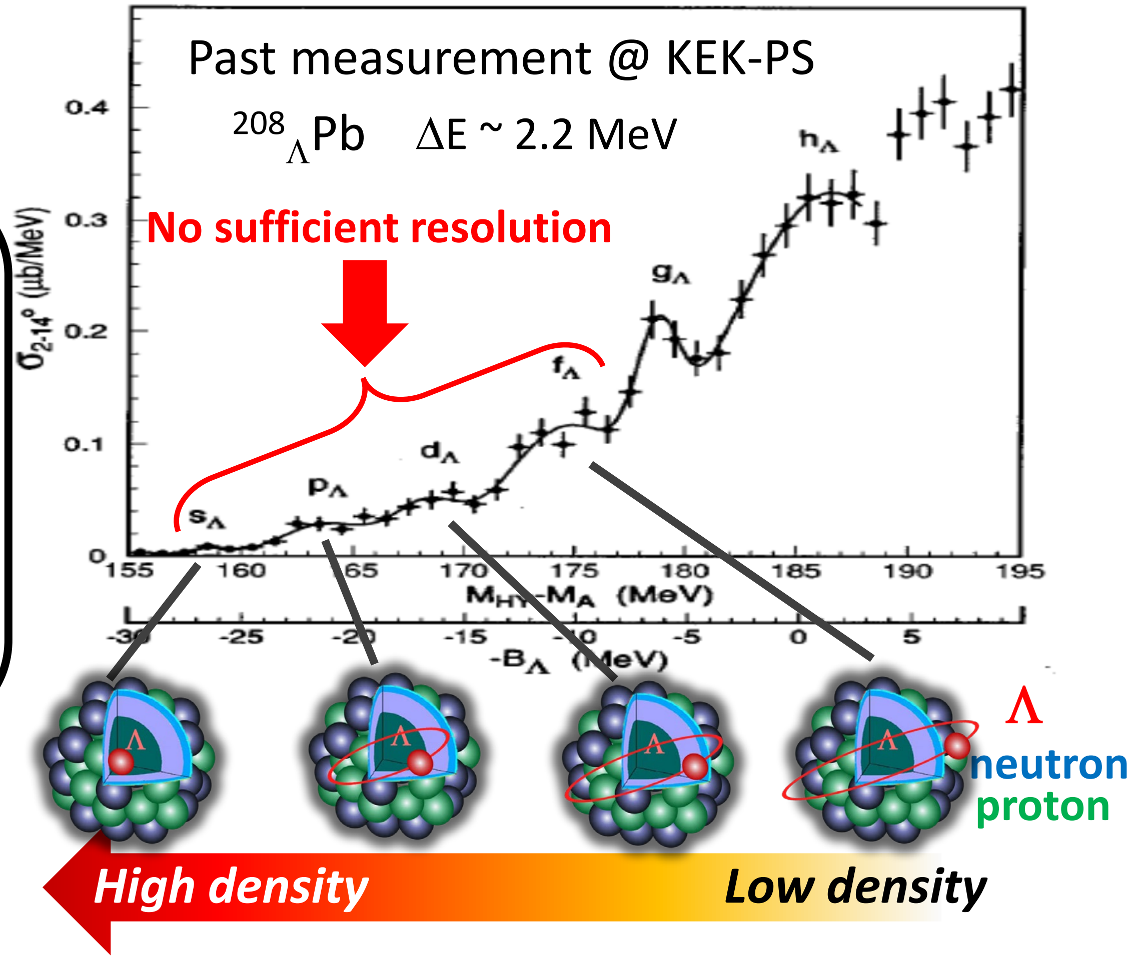
➢ **Hyperons (Λ, Ξ, ...) emerge in dense neutron star matter?**

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

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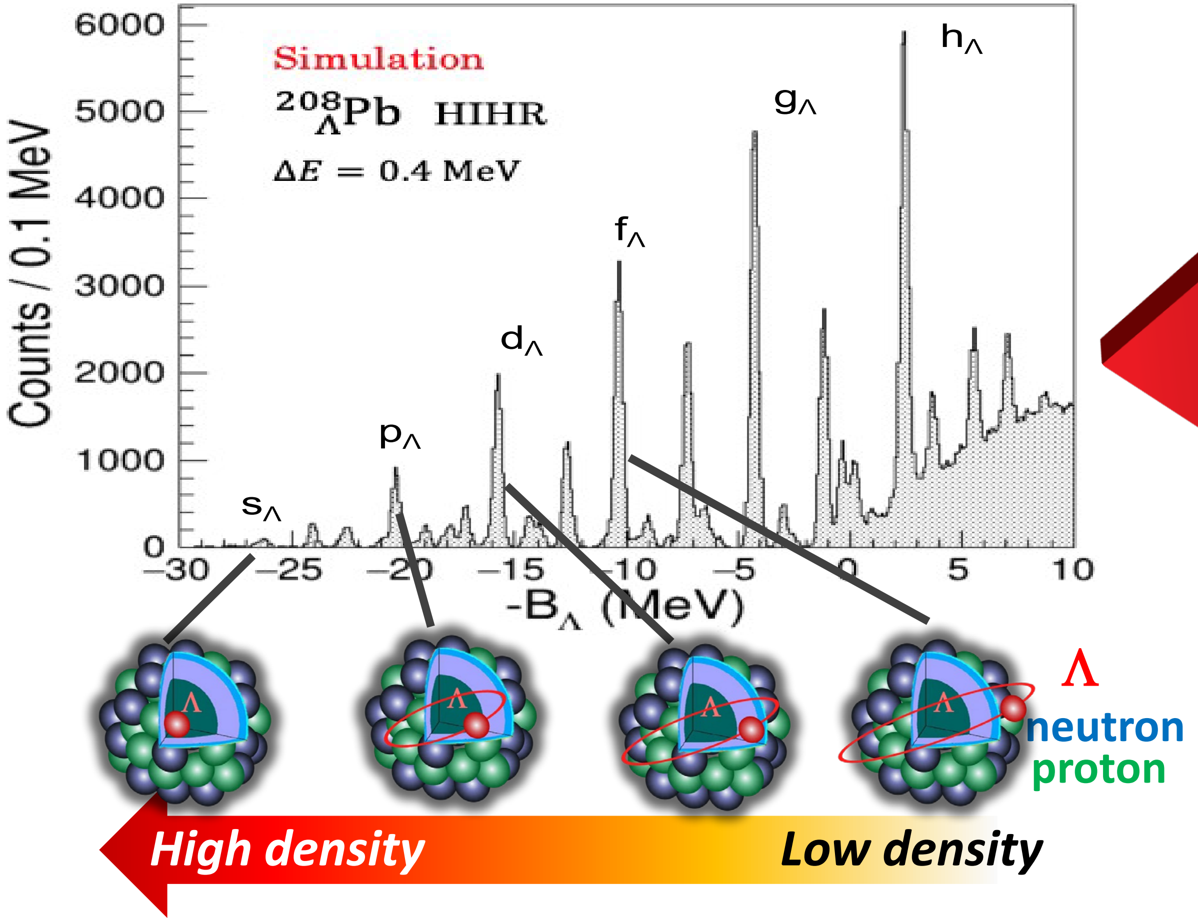
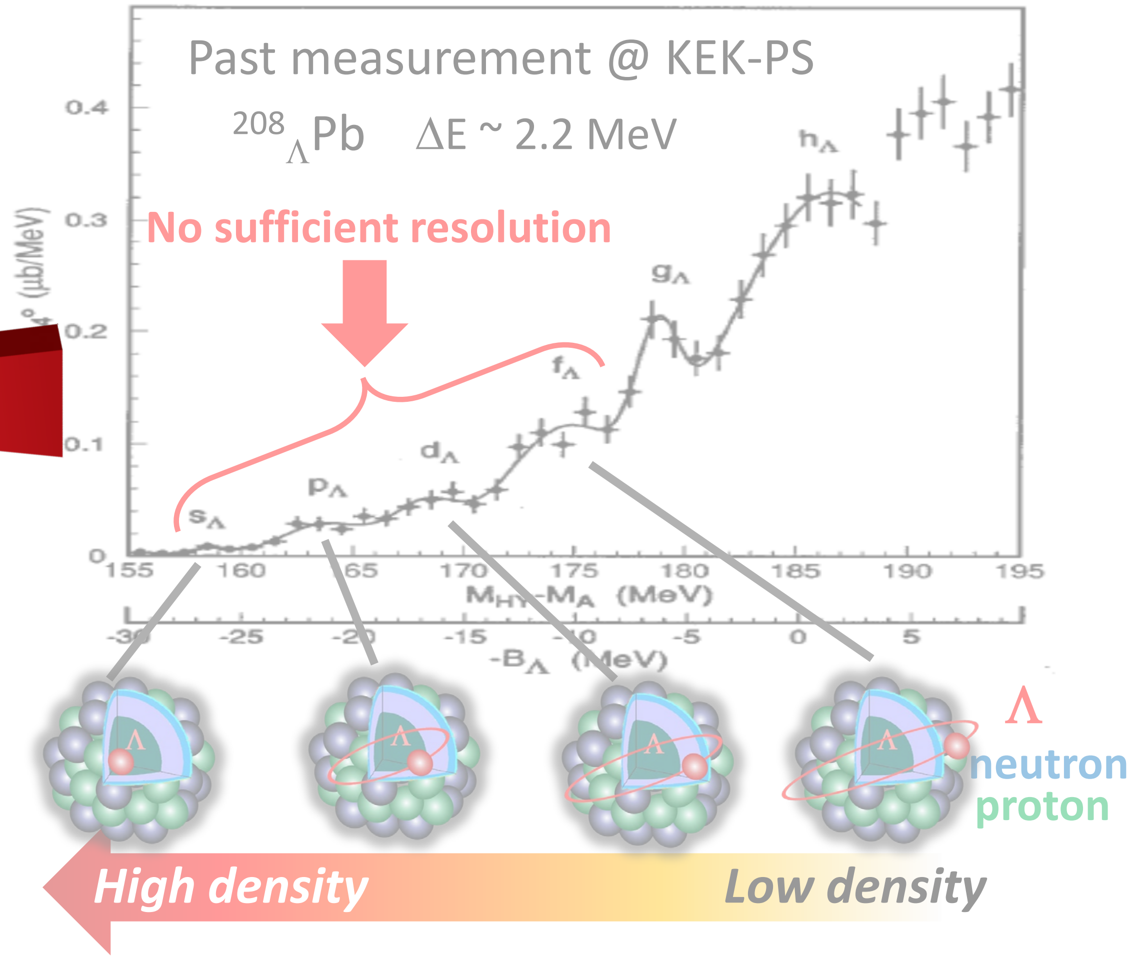
Need separation of each Λ orbital state





Strangeness Nuclear Physics: Hyperon in Dense Environment

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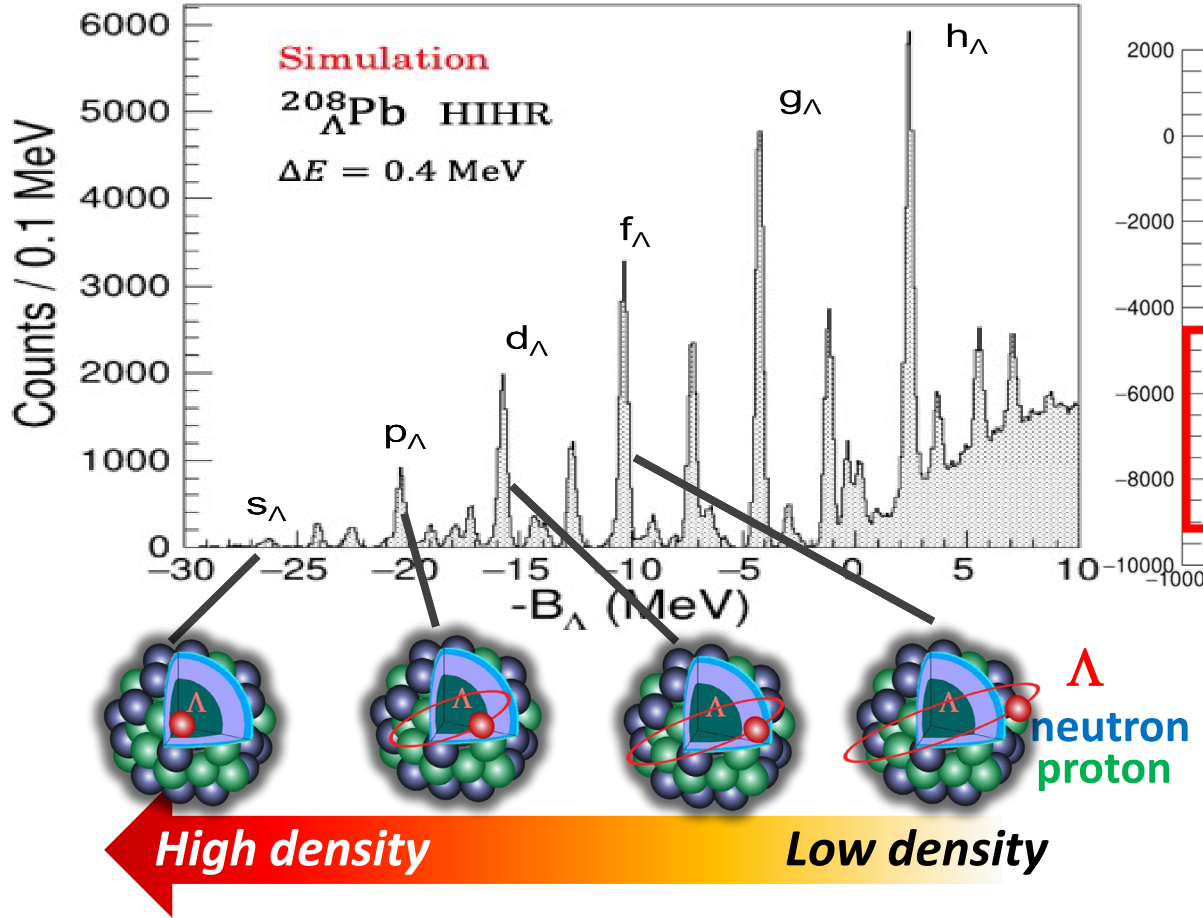
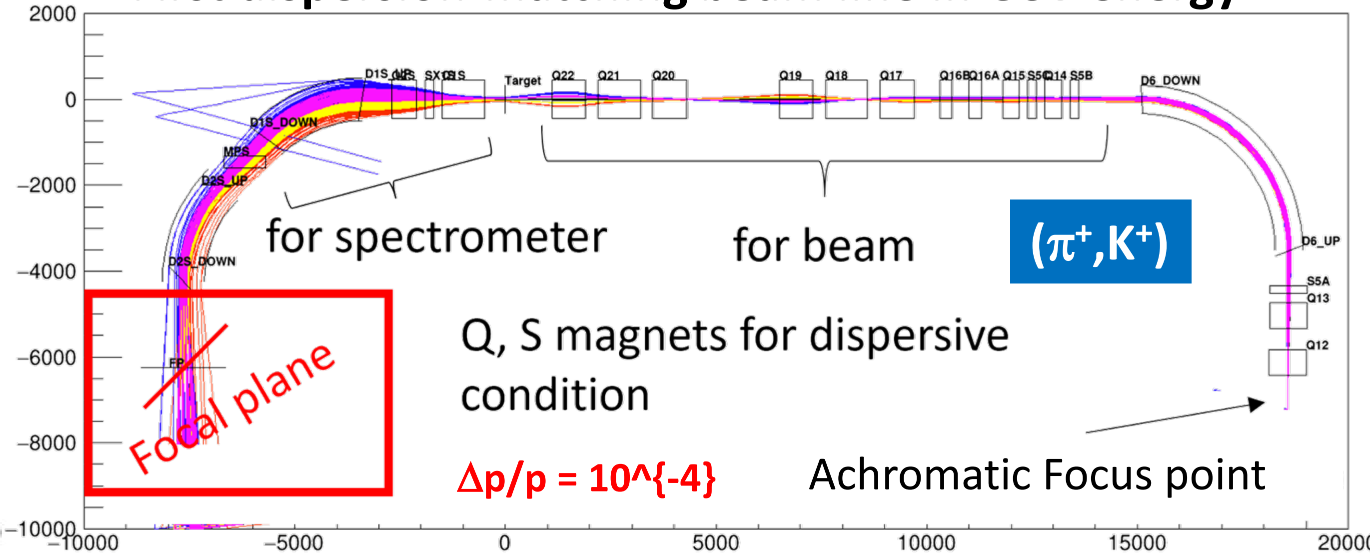
Ultra-high-resolution Λ-hyp. spectroscopy



HIHR beam line (High-Intensity High-Resolution)

First dispersion-matching beam line in GeV energy



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

● **Break through the resolution limit:**

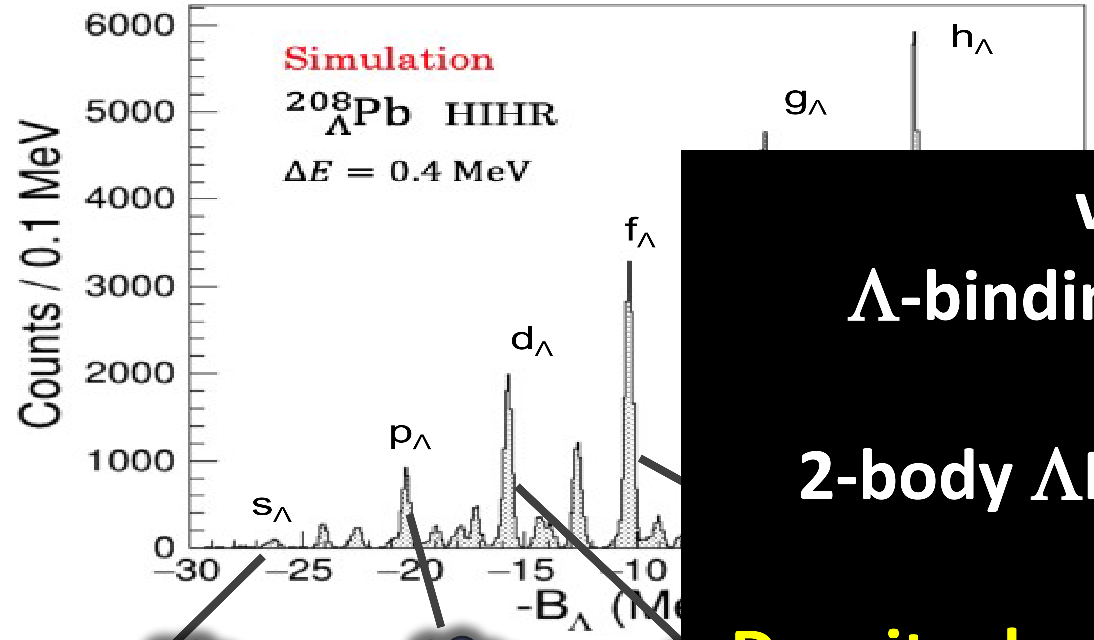
~2.2 MeV → better than ~0.4 MeV (FWHM)

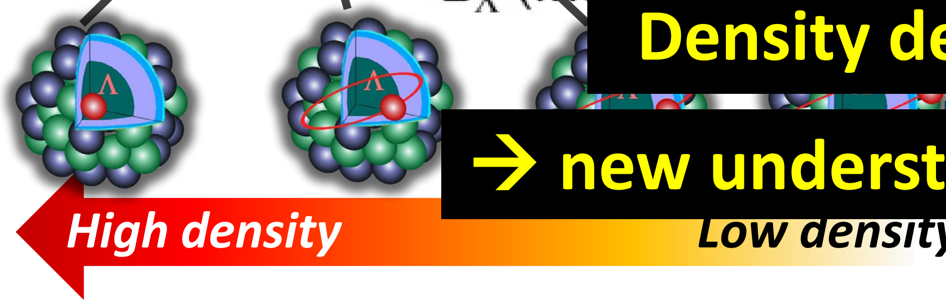
Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

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

Ultra-high-resolution Λ-hyp. spectroscopy





HIHR beam line (High-Intensity High-Resolution)

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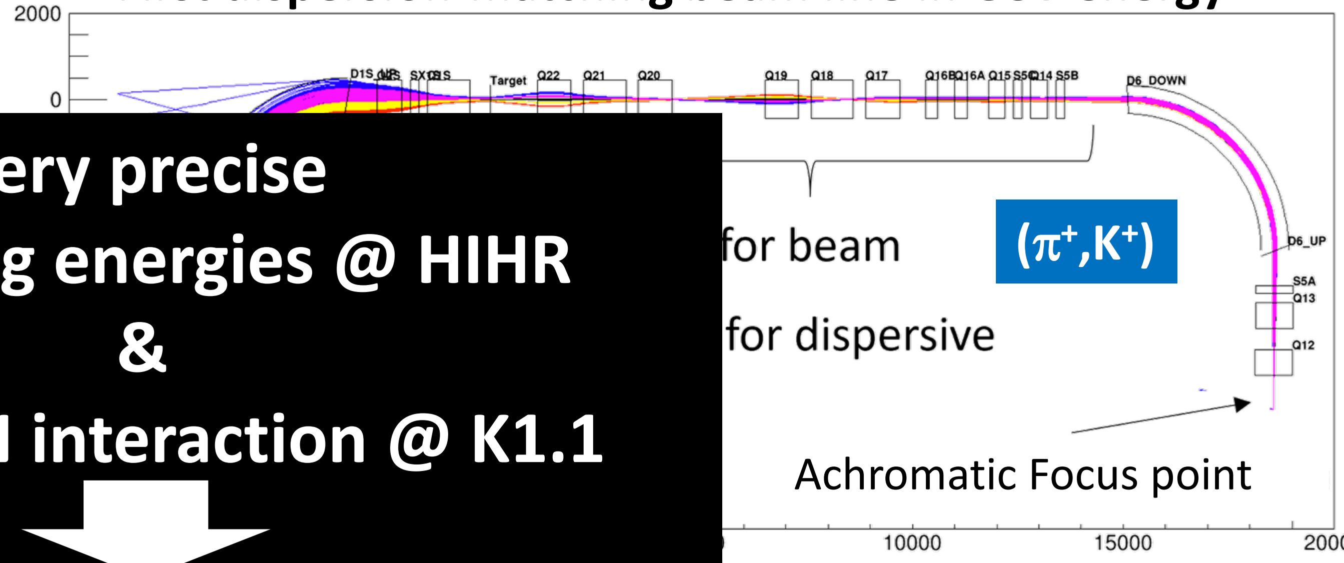


up to 2 GeV/c

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)

Expanded Research Programs

at the Extended Facility

Extract density dependent ΛN interaction

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

- intense dispersion matched π beam

K1.1 **Systematic ΛN scattering measurement**

- intense polarized Λ beam

Investigate diquarks in baryons

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

- intense high-momentum π beam

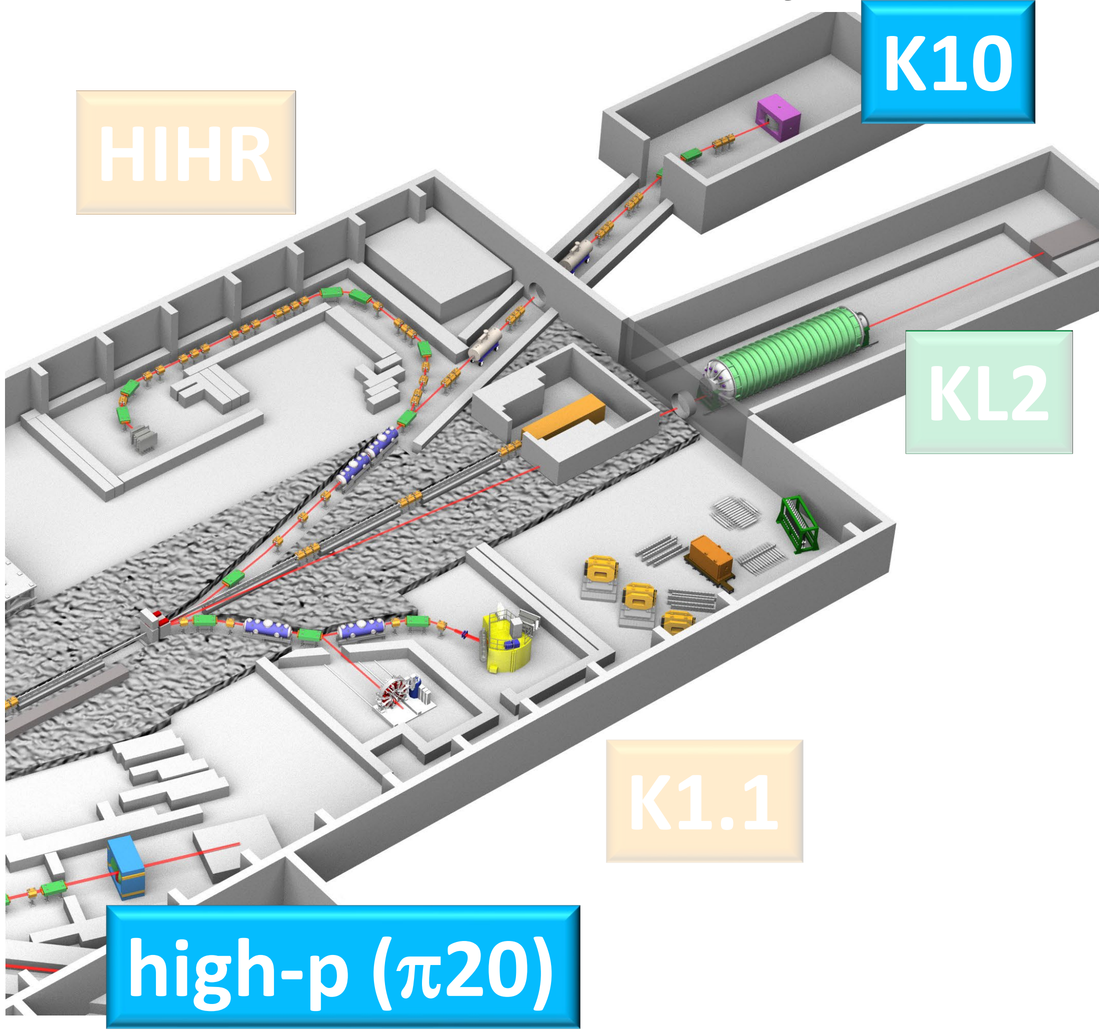
K10 **High-resolution multi-strange baryon spectroscopy**

- intense high-momentum separated K beam

Search for new physics beyond the SM

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

- intense neutral K beam



Behaver of non-perturbative QCD in low energy regime

Hadron Physics: Diquarks in Baryons

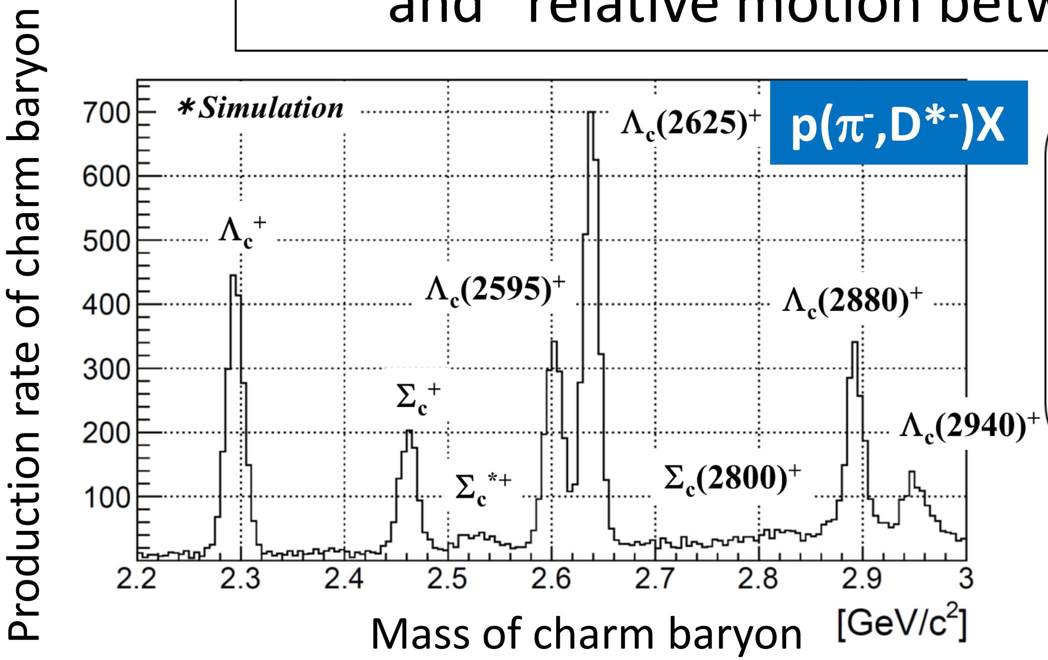
How quarks build hadrons?

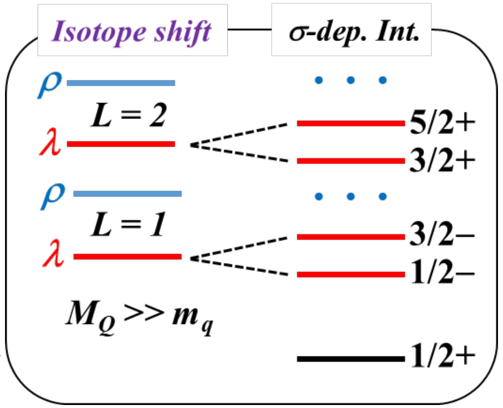
- Investigate **diquarks** in baryons **toward** understanding of **dense quark matter**

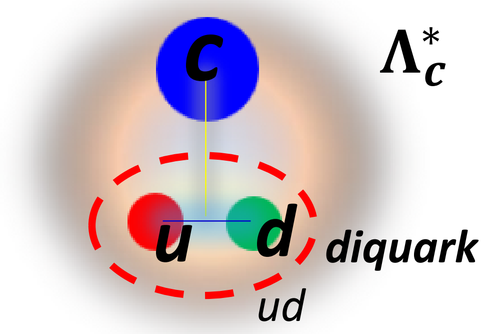
- **Charm Baryon Spectroscopy**
  using intense high-momentum π beam @ High-p (π20)

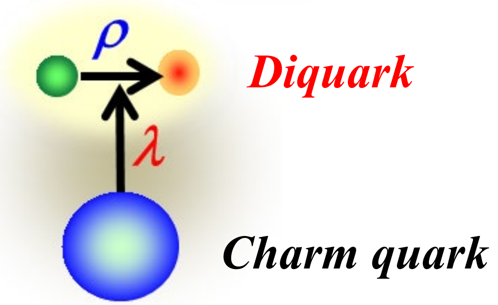
Establish a diquark (*ud*)

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









"production rate" and "decay rate" will give us information about diquark

Behaver of non-perturbative QCD in low energy regime

Hadron Physics: Diquarks in Baryons

How quarks build hadrons?

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

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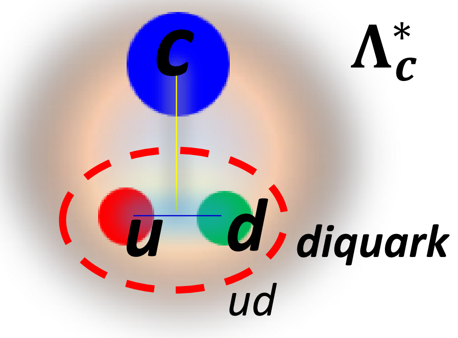


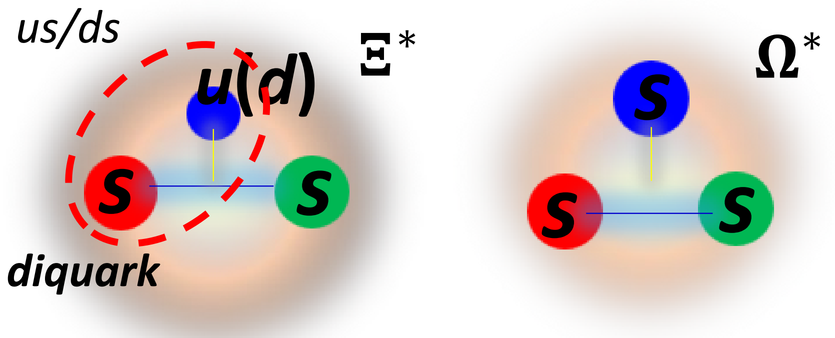
- **Multi-Strange Baryon Spectroscopy**
  using intense high-momentum K beam @ K10

Diquarks in different systems

Ξ^*: *us/ds* diquark

Ω^*: the simplest *sss* system

→ diquark is expected to be suppressed



Systematic measurements will reveal the internal structure of baryons through the diquarks

Expanded Research Programs

at the Extended Facility

Extract density dependent ΛN interaction

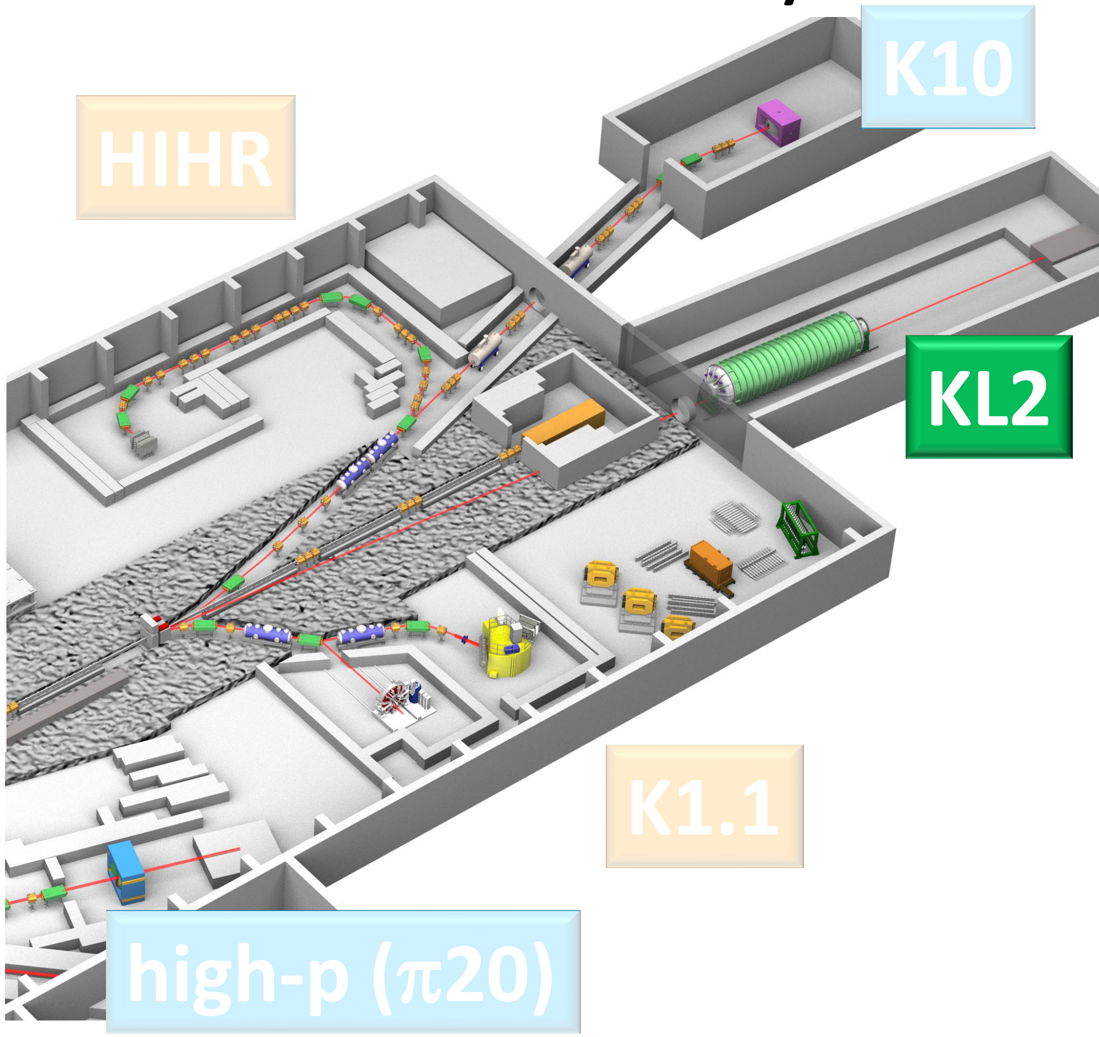
- HIHR — Ultra-high-resolution Λ hypernuclei spectroscopy
  - intense dispersion matched π beam
- K1.1 — Systematic ΛN scattering measurement
  - intense polarized Λ beam

Investigate diquarks in baryons

- high-p (π20) — High-resolution charm baryon spectroscopy
  - intense high-momentum π beam
- K10 — High-resolution multi-strange baryon spectroscopy
  - intense high-momentum separated K beam

Search for new physics beyond the SM

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



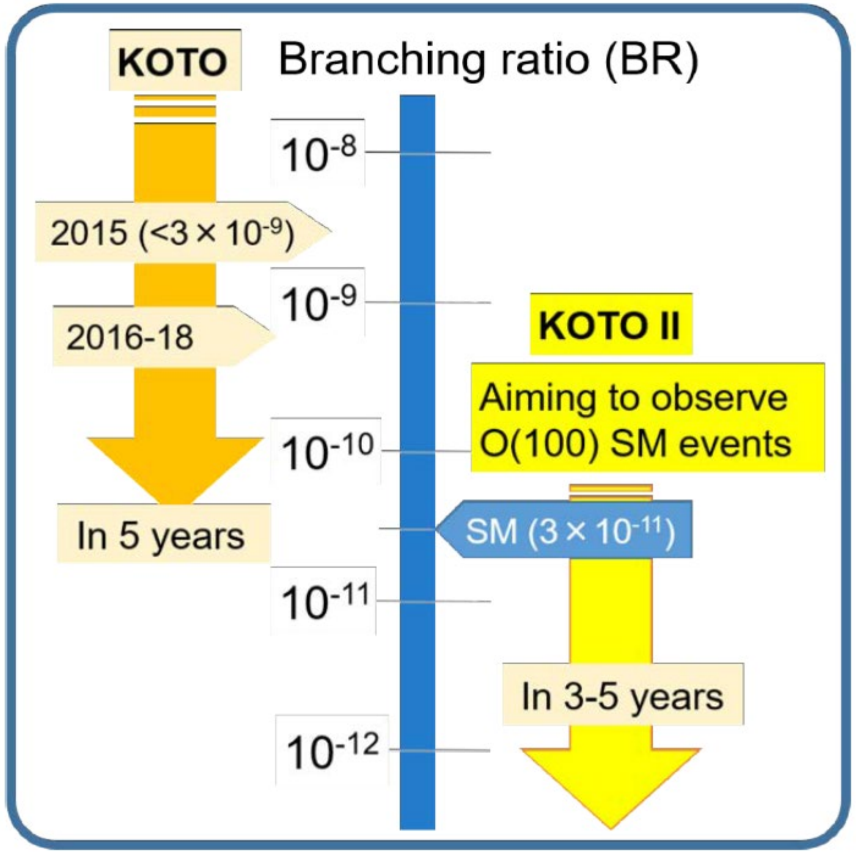
Flavor Physics: New Physics Search at KOTO Step-2

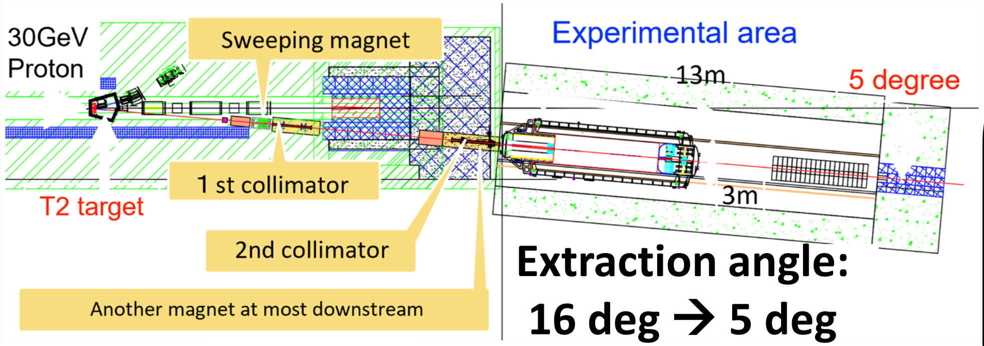
Is there new physics beyond the Standard Model?

Rare kaon decay: $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

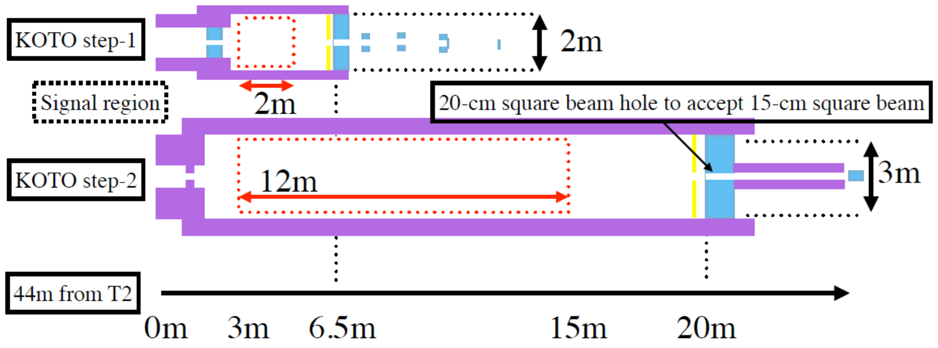
One of the best probes for new physics searches

- Directly break CP symmetry
- Suppressed in the SM → Branching ratio ～ 3×10^{-11}
- Small theoretical uncertainties (～2%)





Intense neutral kaon beam @KL2 (~x2.6)



Ultra-high sensitivity detector (~x70)

KOTO Step-2

New physics search with world's highest sensitivity more than 100 times

- Discover the $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ signal with 5σ
- Measure the branching ratio with 30% accuracy

Indicate new physics, if deviation form the SM > 40%

Current Status of the Extension Project

listed as a candidate for government funding:

- **MEXT Roadmap 2020** (2012, 2014)
- **S**cience **C**ouncil of **J**apan **Master Plan 2020** (2011, 2014, 2017)

The project was selected as **the top-priority project** to be budgeted in <u>the KEK mid-term plan (FY2022-26)</u> at KEK-PIP2022 (Project Implementation Plan)

KEK Inter-University Research Institute Corporation High Energy Accelerator Research Organization
About KEK News International Research Education Public Relations

Home > KEK Science Advisory Committee・KEK Roadmap・KEK-PIP

https://www.kek.jp/en/roadmap-en/

KEK Science Advisory Committee・KEK Roadmap・KEK-PIP

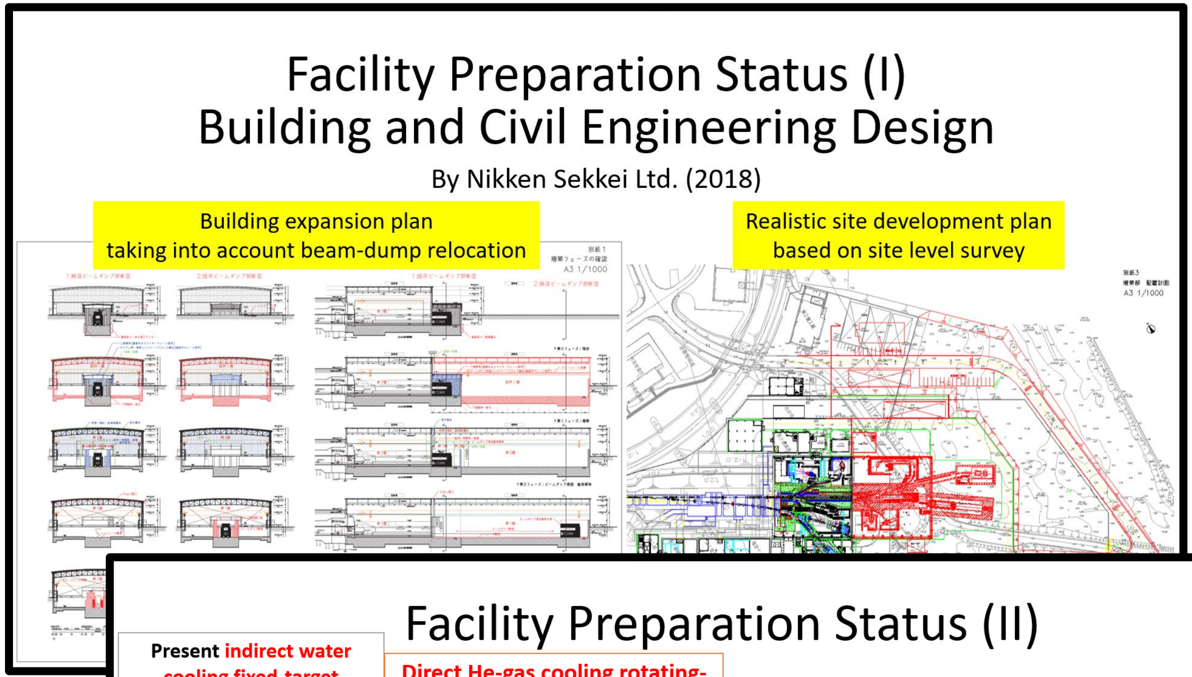
2022/06/24

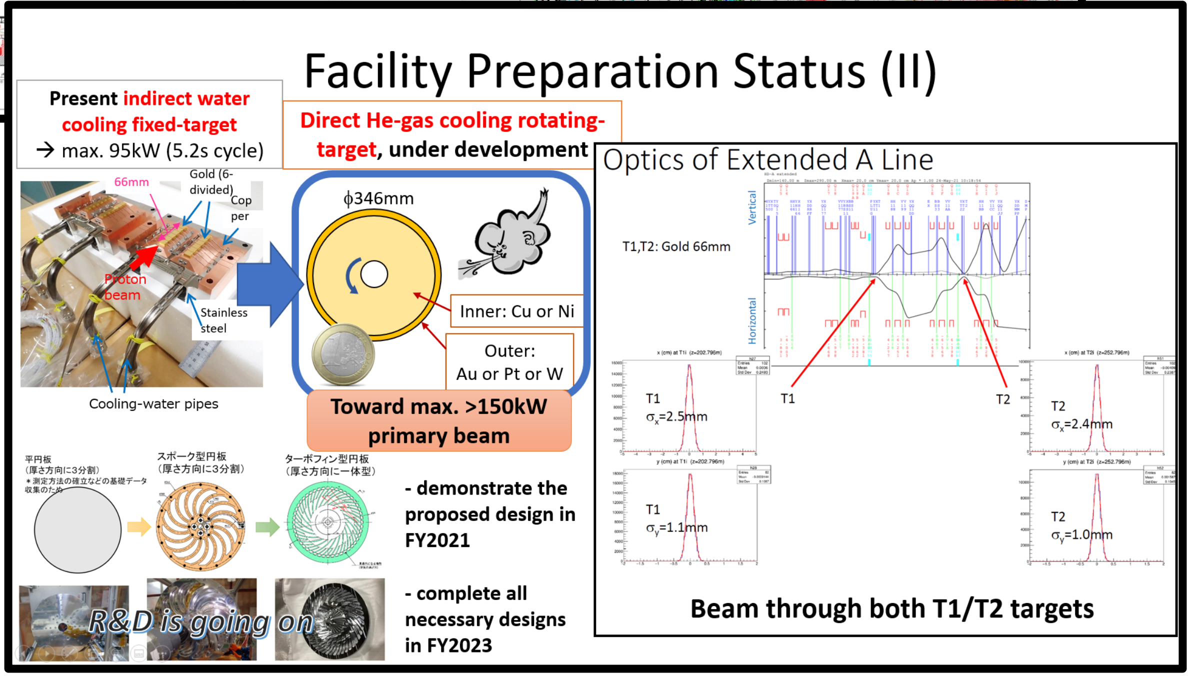
KEK Science Advisory Committee

1.Report:The 4th Meeting of The KEK Science Advisory Committee (English, March 15, 2023)

About KEK

What is KEK
Mission
Organization
Corporatedevelopment

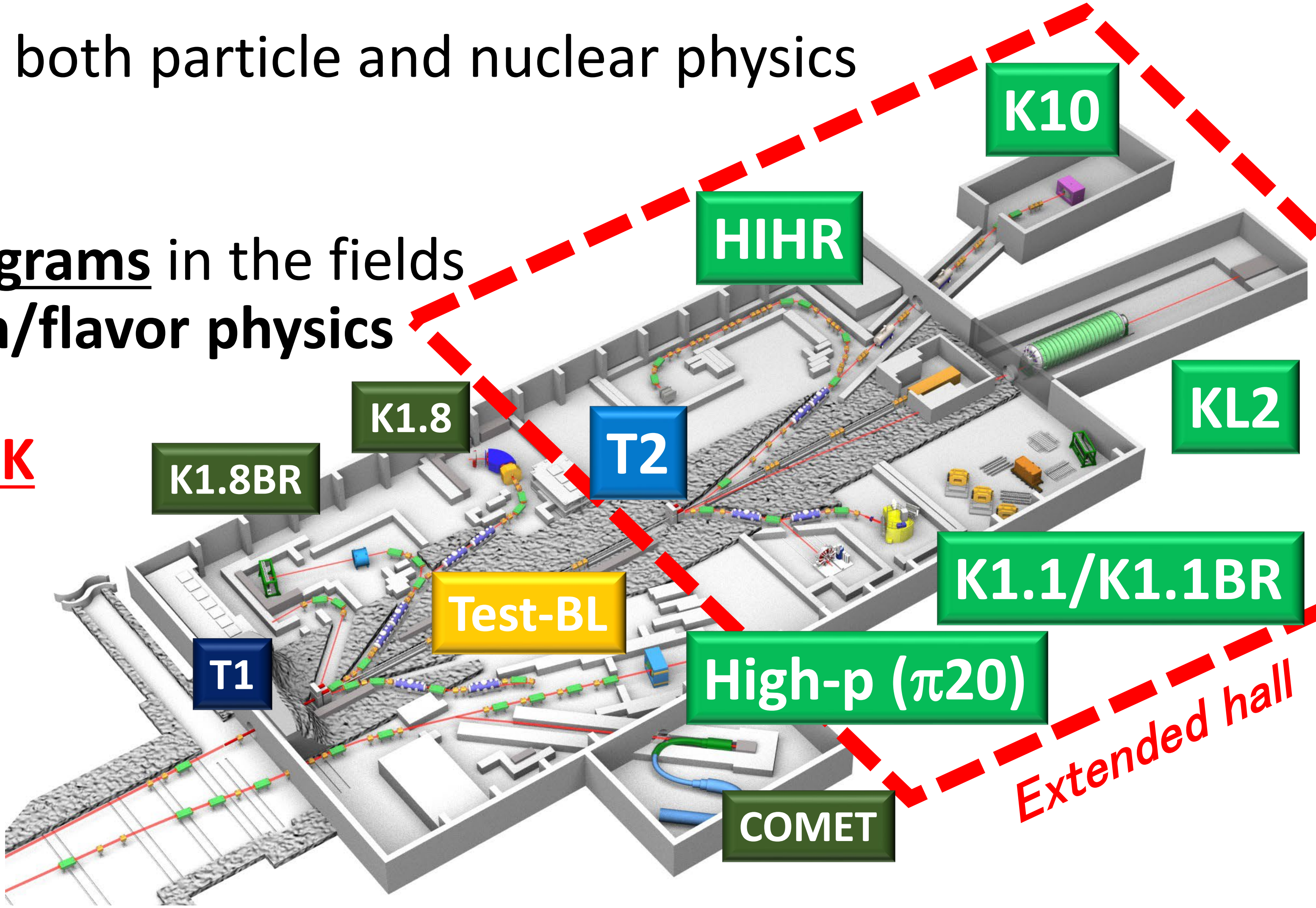




Summary of the Extension Project of the J-PARC Hadron Experimental Facility

- **Unique research programs** in both particle and nuclear physics at high-intensity frontier
- **World's leading research programs** in the fields of **strangeness-nuclear/hadron/flavor physics**
- **Top-priority project in the KEK mid-term plan (FY2022-26)** /
  → Project is now ready to start

Stay tuned!



HUA Thank you for your attention!

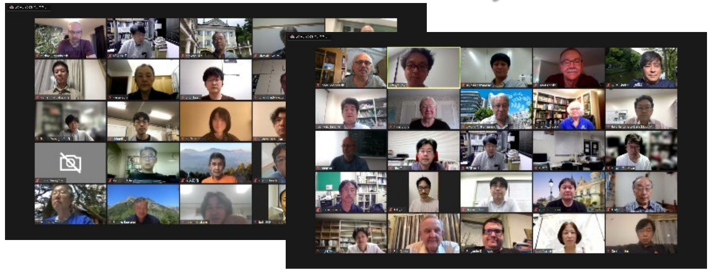
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html


First-Beam WS at the J-PARC Hadron Experimental Hall
25-26 March 2009, IQBRC, Tokai


International WS on physics
at the extended hadron experimental facility of J-PARC
5-6 March 2016, KEK Tokai Campus


International WS on the project for
the extended hadron experimental facility of J-PARC
26-28 March 2018, KEK Tokai Campus

1st J-PARC HEF-ex WS, 7-9 July 2021, online



2nd J-PARC HEF-ex WS, Feb.16-18 2022, online


3rd J-PARC HEF-ex WS, Mar.14-16 2023, J-PARC


HEF-ex 2024, 19-21 February 2024, J-PARC