

J-PARC

Japan Proton Accelerator Research Complex

The hadron experimental facility extension at J-PARC



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Main Ring Synchrotron

Hadron Experimental Facility

Linac

Neutrino Experimental Facility

Material and Life Science Experimental Facility

1,000m

Particle and Nuclear Physics @ J-PARC

J-PARC
 JAEA KEK
 高エネルギー加速器研究機構

Linac

Synchrotron

Hadron Experimental Facility

Neutrino Experimental Facility

Material and Life Science Experimental Facility

Deviations from SM?
 $g_\mu - 2/\mu$ EDM
 Ultra cold μ^+ source
 Muon LINAC (300 MeV/c)

105MeV
 Flavor&CPV in charged lepton?
 Search for $\mu \rightarrow e$ conversion
 COMET (Hadron Hall)

new particle ν_s ?
 JSNS²

Hadron Experiments
 ~CP beyond CKM; Mass modification~
 Hadron properties in Nuclear Matter

Hyper-nuclear physics
 Neutron star
 Strangeness in Nuclei
 Role of strange quark in extreme high density matter?

Super Kamiokande
 Neutrino Experiment : T2K
 ~Mixing Angle, CP phase, and Mass Hierarchy~

T2K
 J-PARC

CPV beyond CKM
 $K_L \rightarrow \pi^0 \nu \bar{\nu}$

Neutrino Experimental Facility

Material and Life Science Experimental Facility

Origin & Evolution of Matter

Matter-Antimatter Symmetry

matter dominated universe



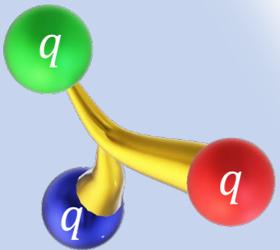
Flavor Physics

CP violation
weak interaction
→ new physics

Kaon rare decays
 $\mu \rightarrow e$ 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

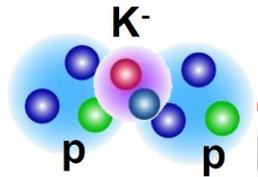


Strangeness Nuclear Physics

hadron interactions
hadronic many-body systems
Hyperon-Nucleon scattering
Hypernuclear spectroscopy

Present Hadron Experimental Facility (HEF)

- < 1.1 GeV/c
- ~ 5x10⁵ K⁻/spill
- **Kaon in nuclei**

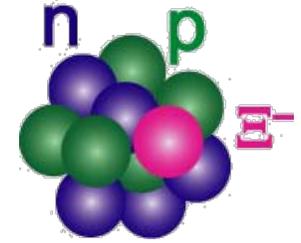


K1.8BR

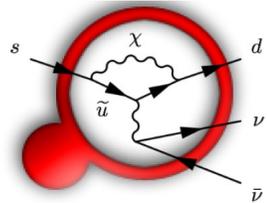
56 m

K1.8

- < 2.0 GeV/c
- ~ 10⁶ K⁻/spill
- **S=-1 and S=-2 hypernuclei**



- 16 deg extraction
- ~ 2.1 GeV/c ~ 10⁷ K_L⁰/spill
- **K_L⁰ → π⁰νν̄**



KL

T1 target

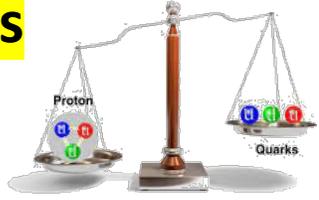
- Au Target
- < 95 kW

charged
neutral

primary 30GeV

high-p

- launched in 2020
- 30 GeV proton ~ 10¹⁰
- < 31 GeV/c unsepa. π ~ 10⁷
- **Hadron physics**



muon

COMET

- 30 GeV proton beam
- 65kW (7x10¹³ ppp, 5.2s)
- [as of 2021, June]

started in 2023

- μ⁻ beam
- **μ-e conversion**



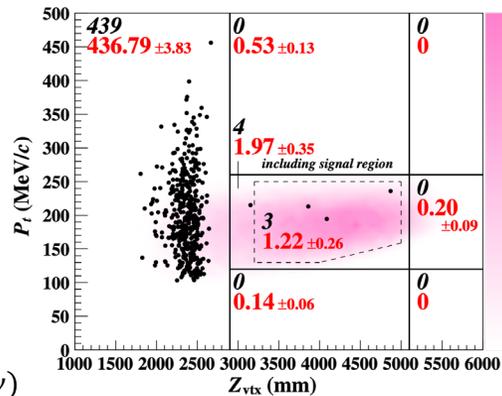
Achievements in research at the Hadron Experimental Facility

Flavor Physics

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

→ Approaching the SM sensitivity for CP violation

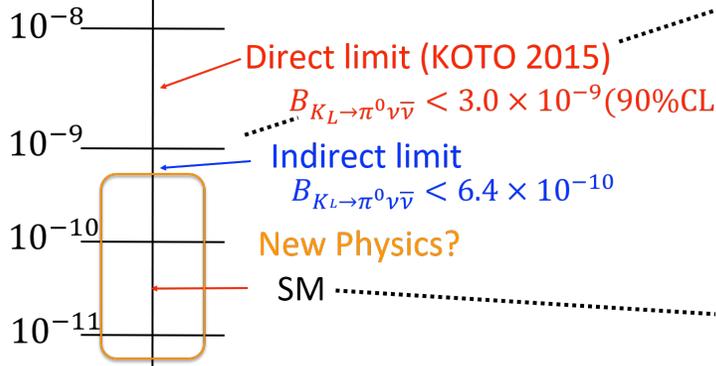
KOTO 2016-18



KOTO 2015

Single Event Sensitivity = 3×10^{-9}

$BR(K_L \rightarrow \pi^0 \nu \bar{\nu})$



Direct limit (KOTO 2015)

$B_{K_L \rightarrow \pi^0 \nu \bar{\nu}} < 3.0 \times 10^{-9}$ (90%CL)

Indirect limit

$B_{K_L \rightarrow \pi^0 \nu \bar{\nu}} < 6.4 \times 10^{-10}$

New Physics?

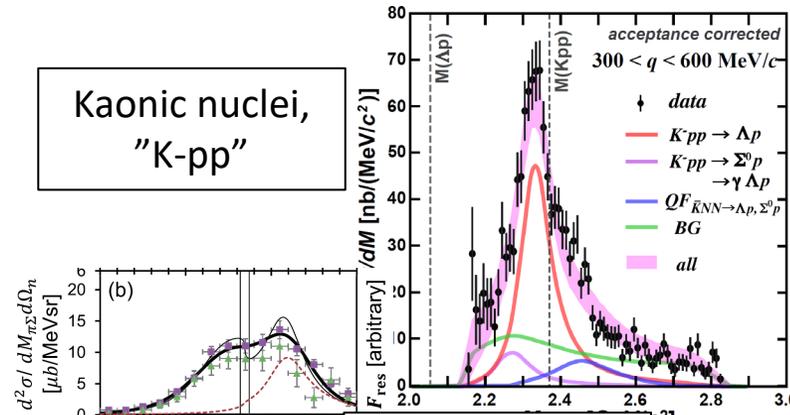
SM

Hadron Physics

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

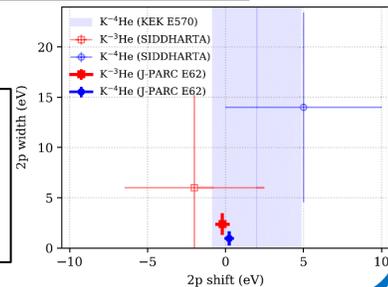
→ Established a new direction to understand meson-baryon int.

Kaonic nuclei, "K-pp"



Pole position of $\Lambda(1405)$

Ultra-precise measurement of kaonic atoms

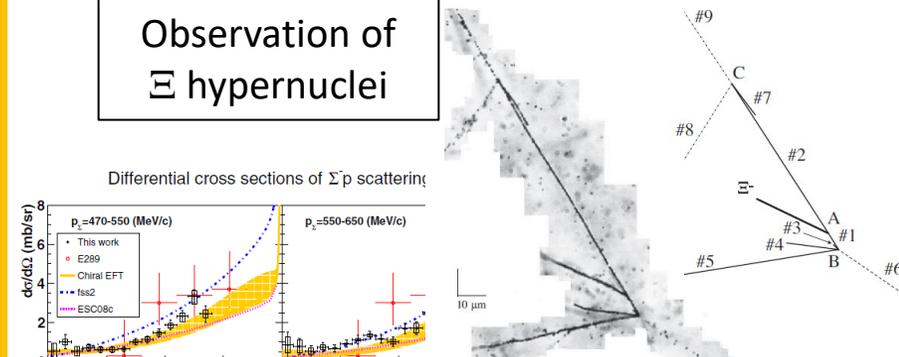


Strangeness Nuclear Physics

A lot of progress in hypernuclear research

→ Clarified attractive $S=-2$ ΞN interaction and deepened $S=-1$ $\Lambda N, \Sigma N$ interactions

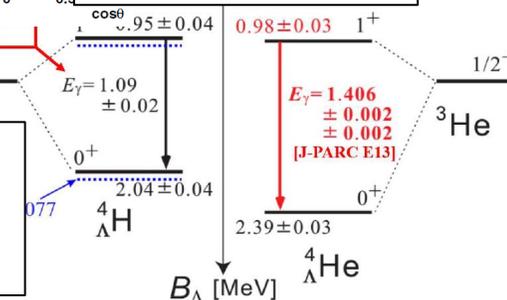
Observation of Ξ hypernuclei



Differential cross sections of $\Sigma^+ p$ scattering

First precise hyperon-nucleon scattering

Charge-symmetry breaking in the ΛN interaction



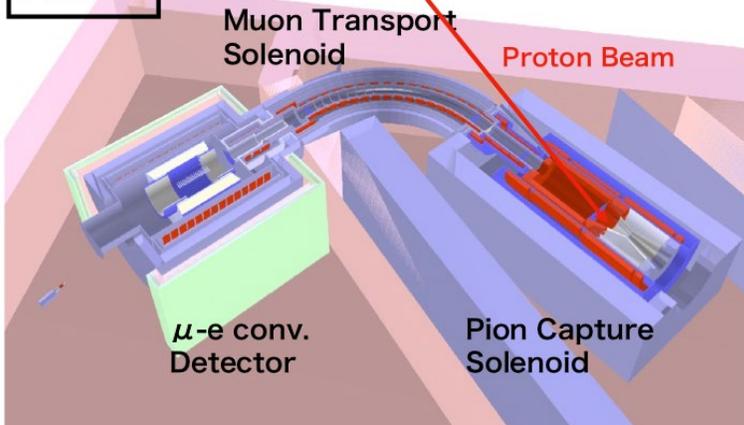
Further research directions at the Hadron Experimental Facility

Flavor Physics

Search for $\mu \rightarrow e$ conversion @ COMET (2023~)

→ Search for charged lepton flavor violation

Phase-I



Further research

$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ search with further sensitivity

→ Explore beyond the SM sensitivity

Hadron Physics

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

→ Attack mass-generation mechanism of hadrons



Further research

Charmed and multi-strange baryon spectroscopies

→ Establish diquark in baryon

Strangeness Nuclear Physics

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

→ Provide accurate and systematic information on ΞN , $\Lambda\Lambda$ interactions



Further research

Ultra-precise spectroscopy of $S=-1$ hypernuclei with a state-of-the-art spectrometer

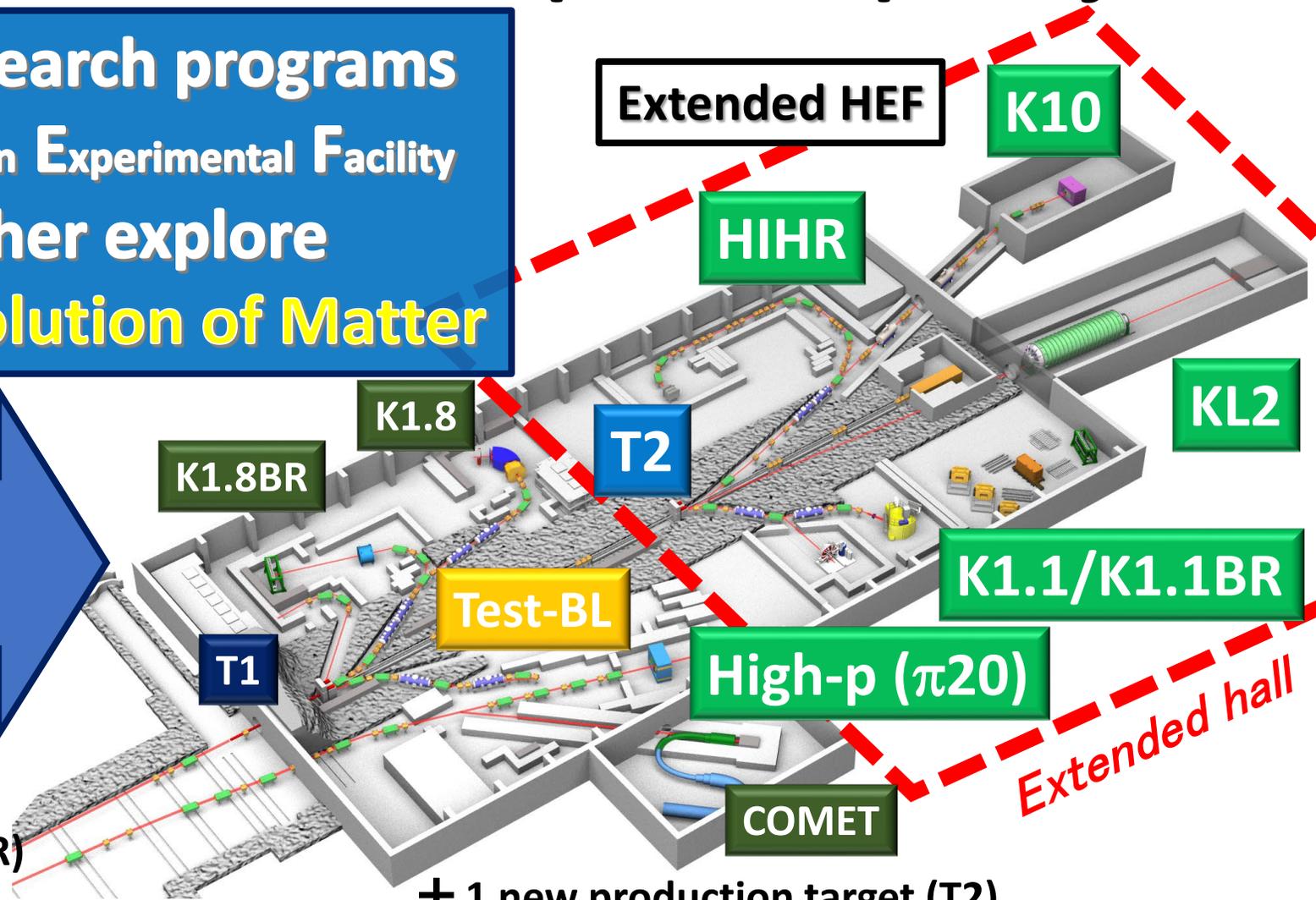
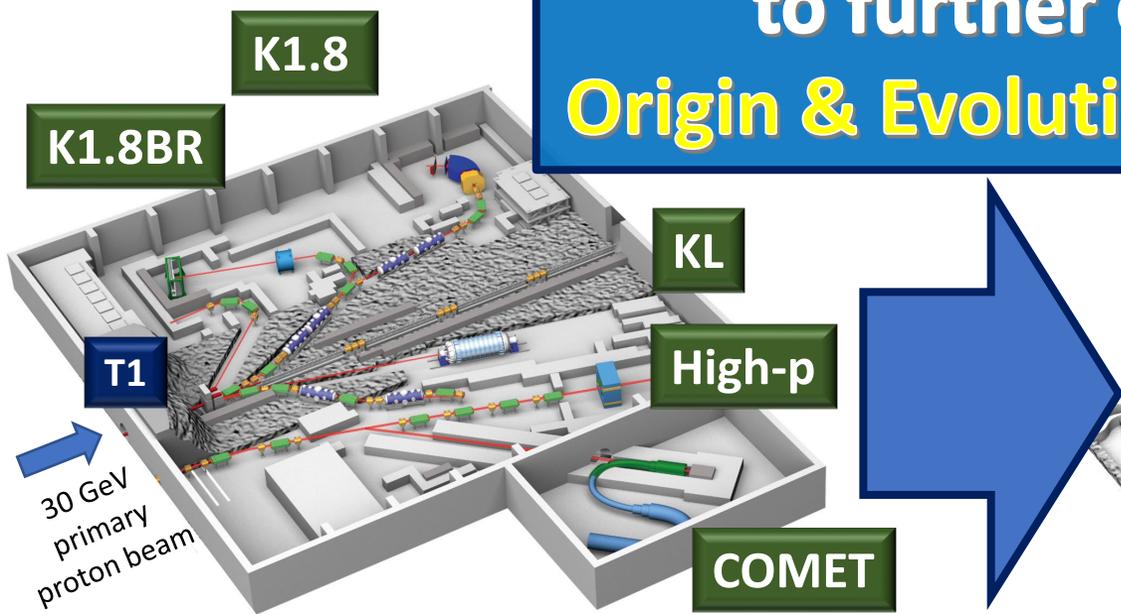
→ Extract density dependence of ΛN int.

Hadron Experimental Facility eXtension (HEF-ex) Project

Present HEF
(2009~)

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

Extended HEF



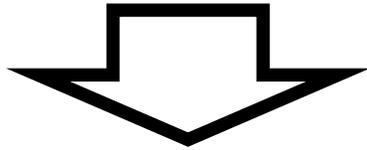
- 1 production target (T1)
- 1 secondary-charged beamline (K1.8/K1.8BR)
- 1 neutral beamline (KL)
- 1 primary beamline (High-p)
- 1 muon beamline (COMET)

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

Present Status of the Extension Project

listed as a candidate for government funding:

- **MEXT Roadmap 2020** ^{2012, 2014}
- **Science Council of Japan Master Plan 2020** ^{2011, 2014, 2017}



The project was selected as **the top-priority project** to be budgeted in the KEK's mid-term plan (FY2022-26) 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

About KEK

2022/06/2
Mission

Organization

Corporatedevelopment

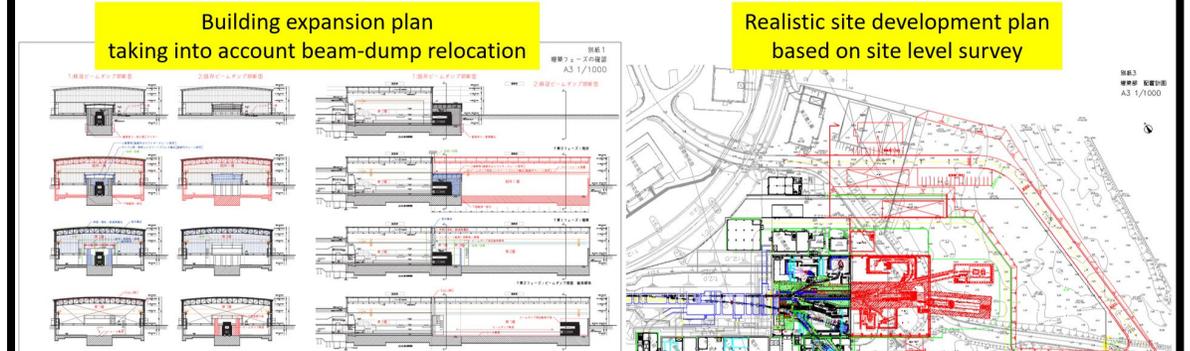
KEK Science Advisory Committee

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

The project will soon start in full swing!

Facility Preparation Status (I) Building and Civil Engineering Design

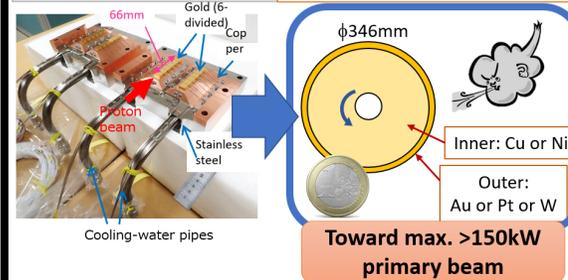
By Nikken Sekkei Ltd. (2018)



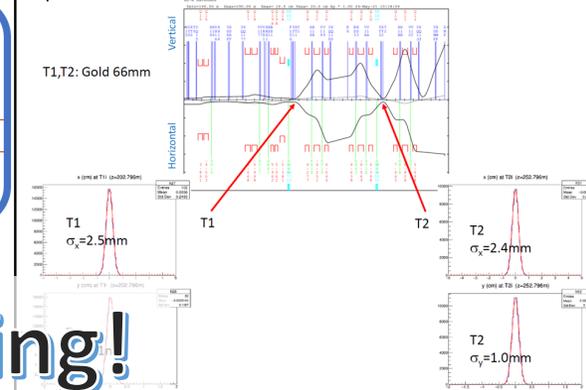
Facility Preparation Status (II)

Present **indirect water cooling fixed-target**
→ max. 95kW (5.2s cycle)

Direct He-gas cooling rotating-target, under development



Optics of Extended A Line



Beam through both T1/T2 targets

emonstrate the
2023

R&D is going on

- complete all necessary designs in FY2023

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
($\pi 20$)

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

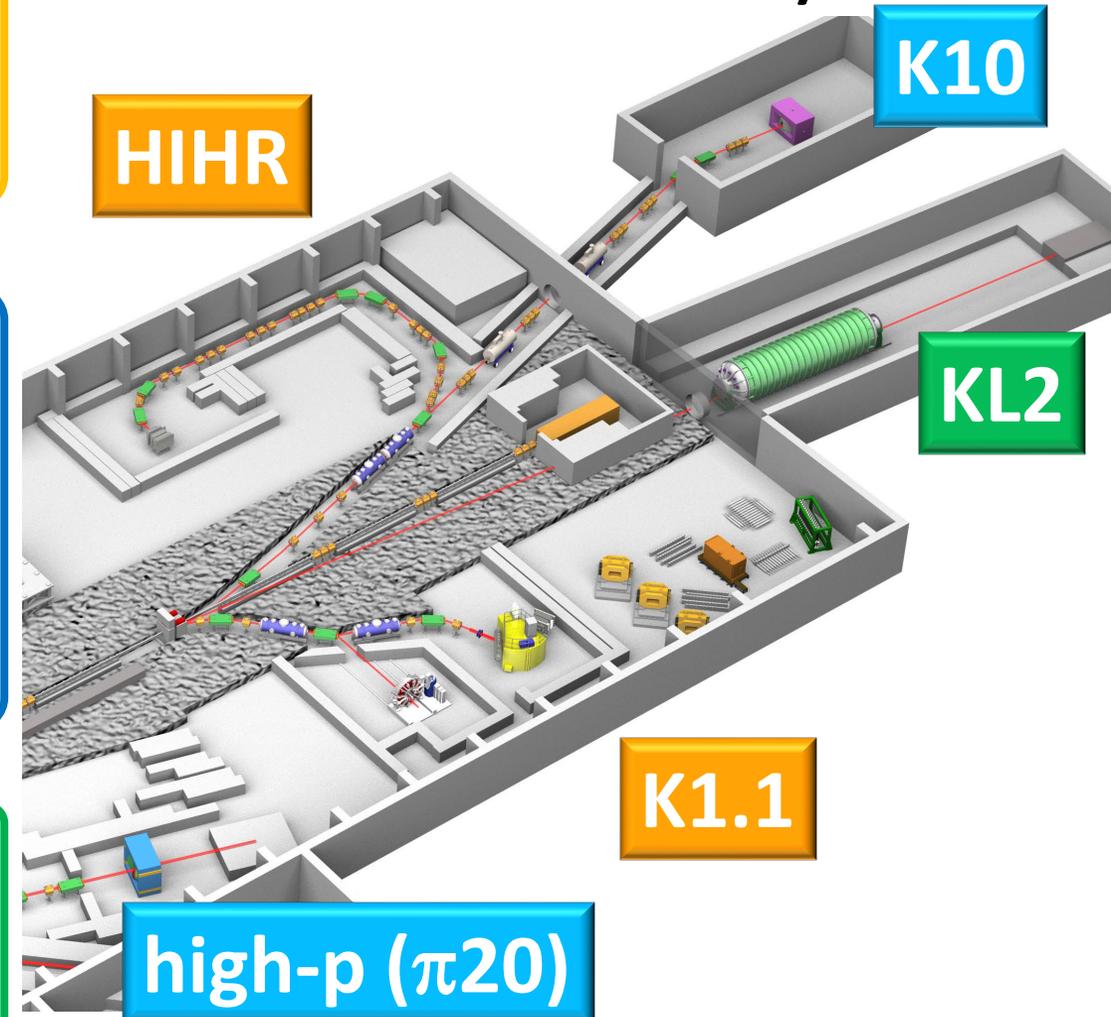
KL2

Most sensitive $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ measurement

- intense neutral K beam

Expanded Research Programs

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

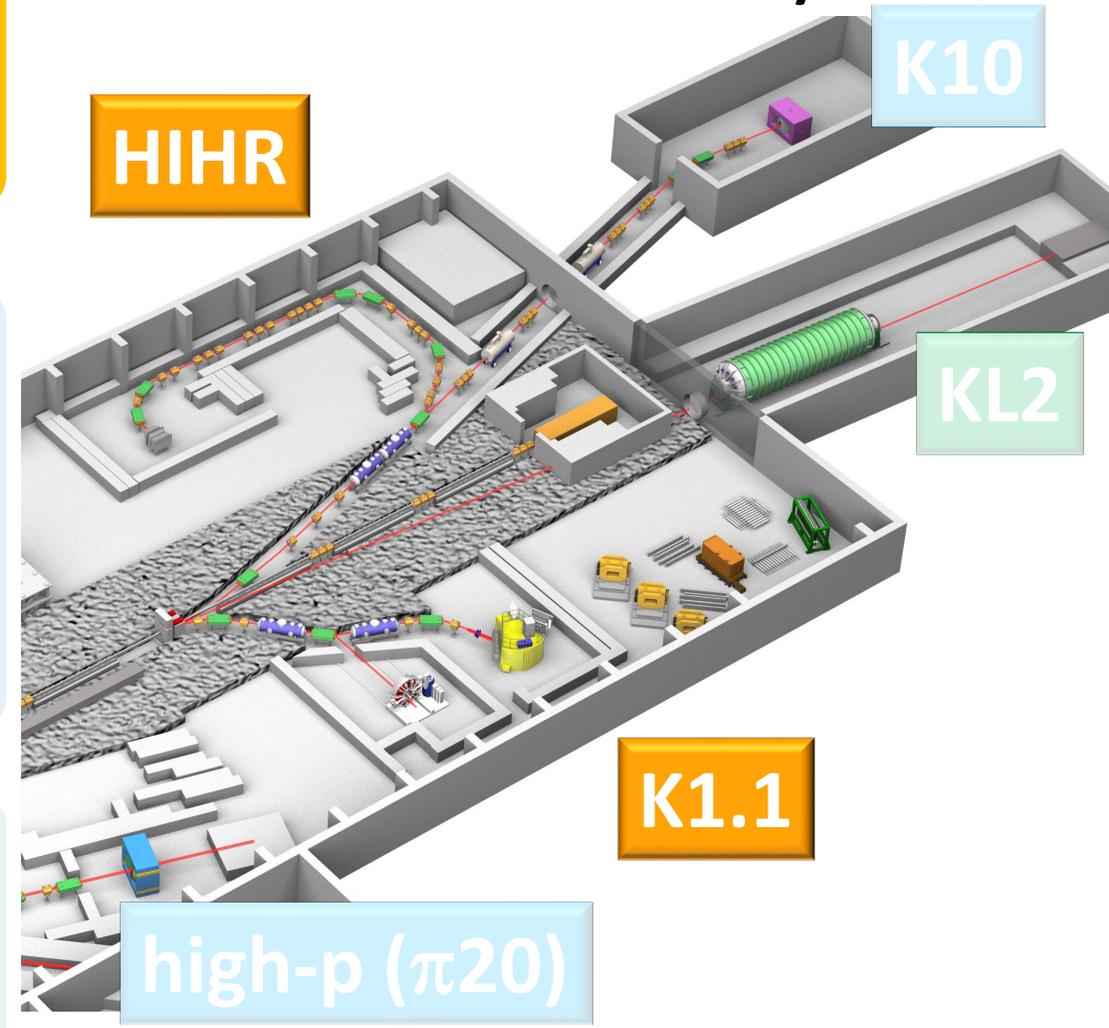
Investigate diquarks in baryons

- high-p ($\pi 20$)** High-resolution charm baryon spectroscopy
 - intense high-momentum π beam
- K10** High-resolution multi-strange baryon spectroscopy
 - intense high-momentum separated K beam

Search for new physics beyond the SM

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

Expanded Research Programs at the Extended Facility

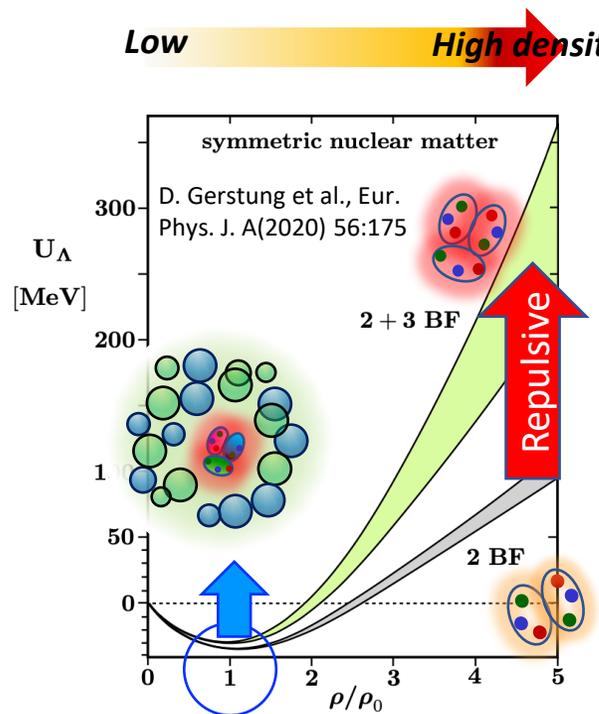


Strangeness Nuclear Physics: Hyperon in Dense Environment

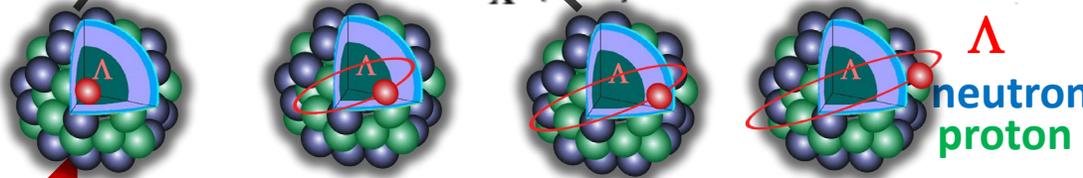
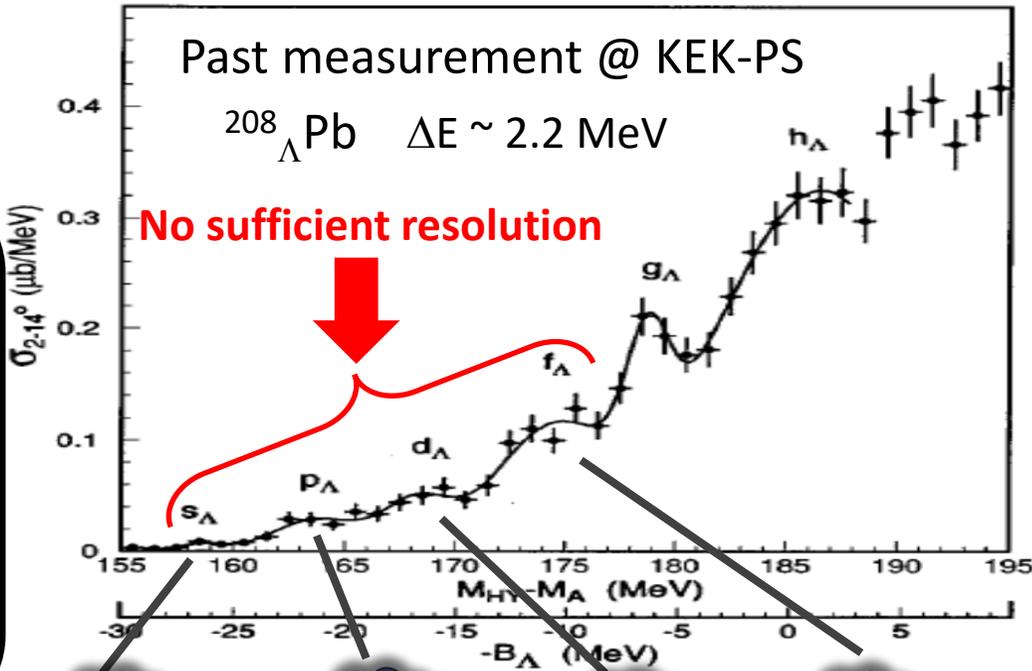
Why can heavy neutron stars exist?

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

Λ NN 3 Baryon Force is a key



heavy Λ -hypernuclei :
 Λ binding energies (B_Λ)
 → density dependent
 Λ N interaction
 → We need precise measurements



We need to determine

a tiny fraction of 3 Baryon Force effects

High density

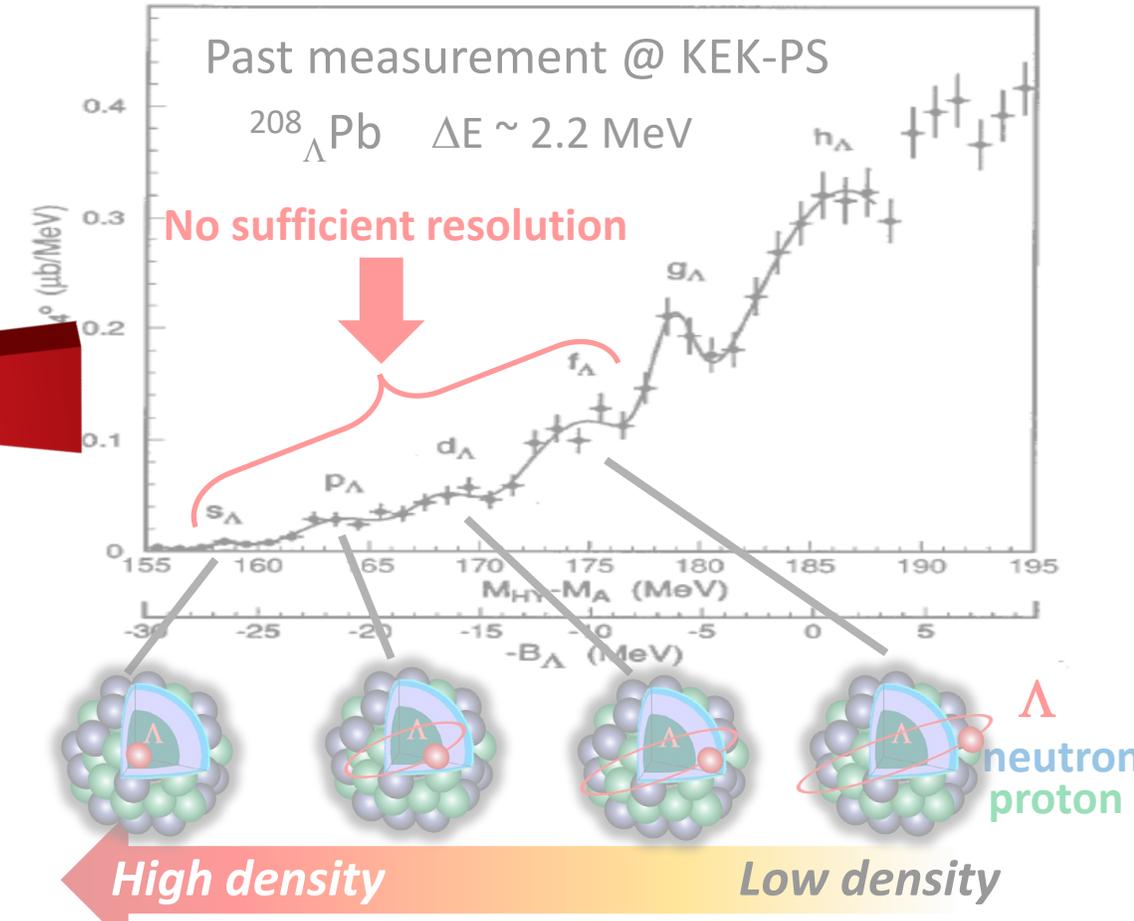
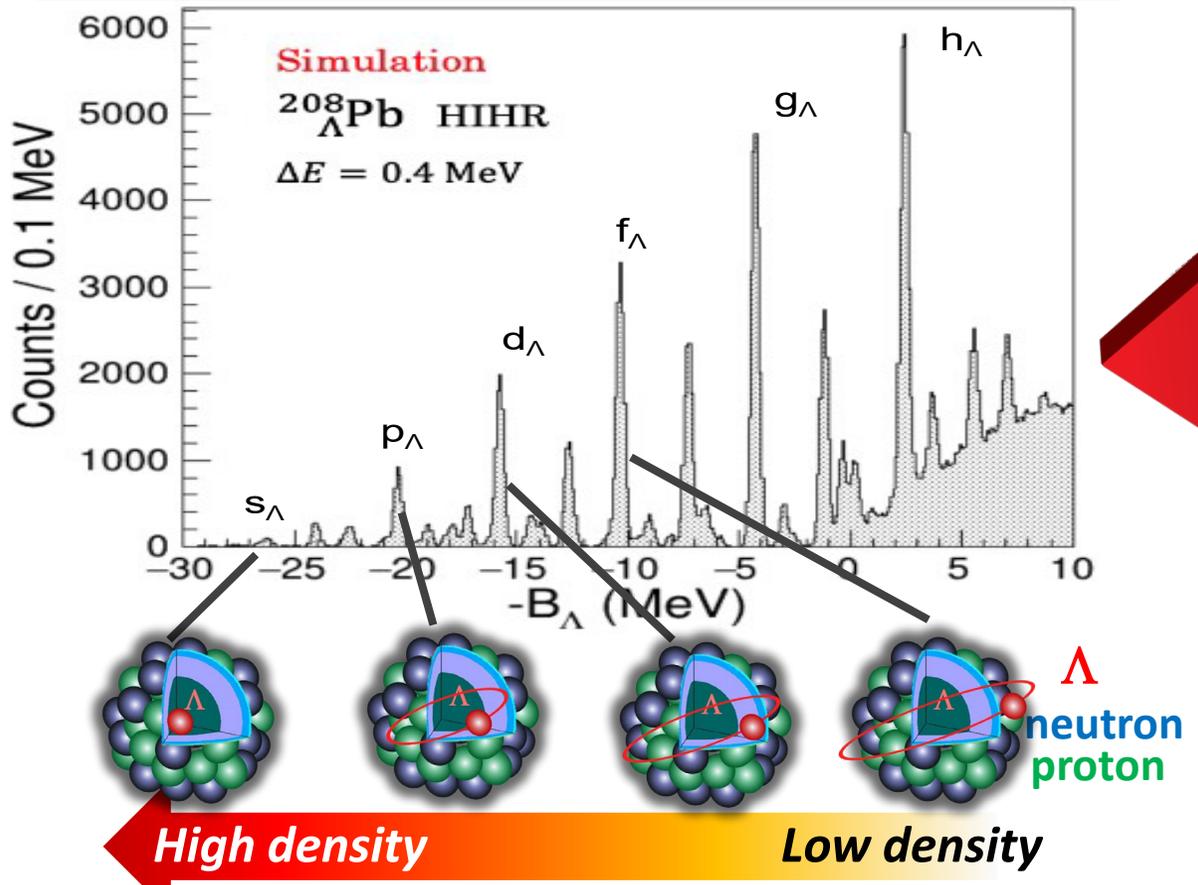
Low density

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

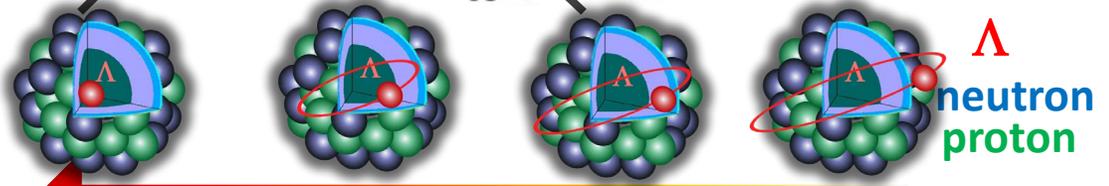
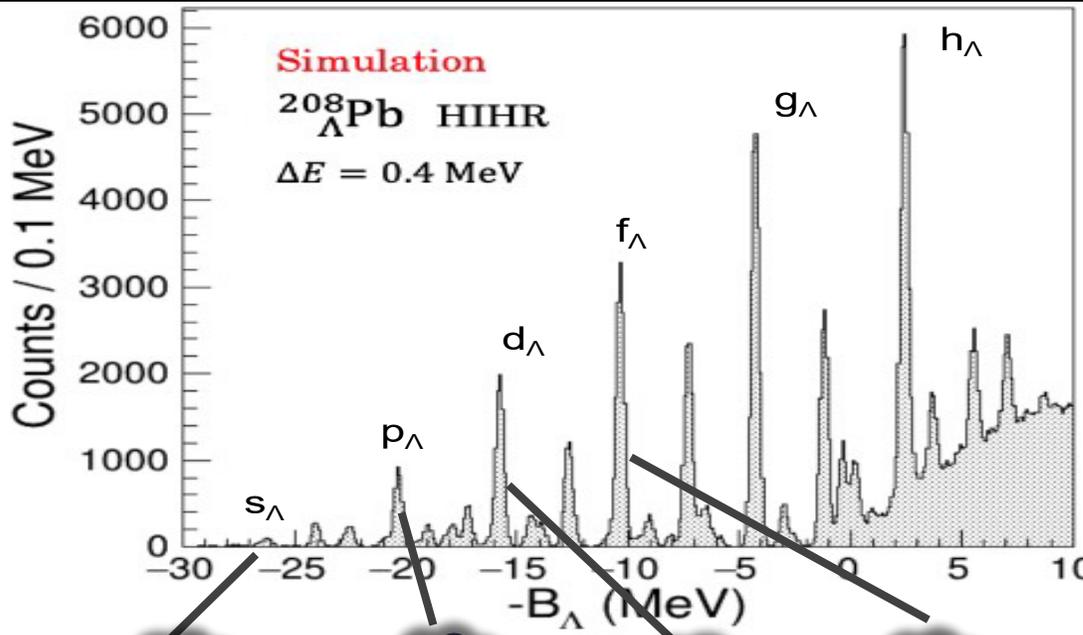


Strangeness Nuclear Physics: Hyperon in Dense Environment

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Ultra-high-resolution Λ -hyp. spectroscopy

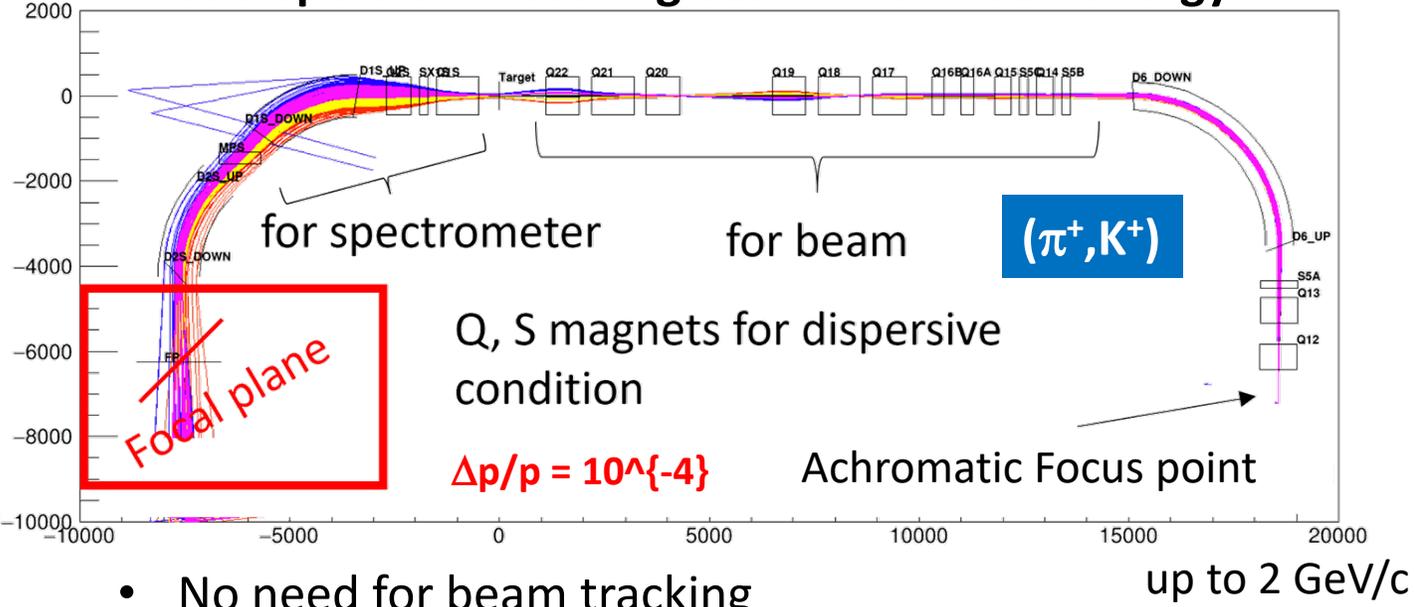


High density

Low density

HIHR beam line (High-Intensity High-Resolution)

First dispersion-matching beam line in GeV energy



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

● Break through the resolution limit:

~ 2.2 MeV \rightarrow better than ~ 0.4 MeV (FWHM)

Strangeness Nuclear Physics: Hyperon in Dense Environment

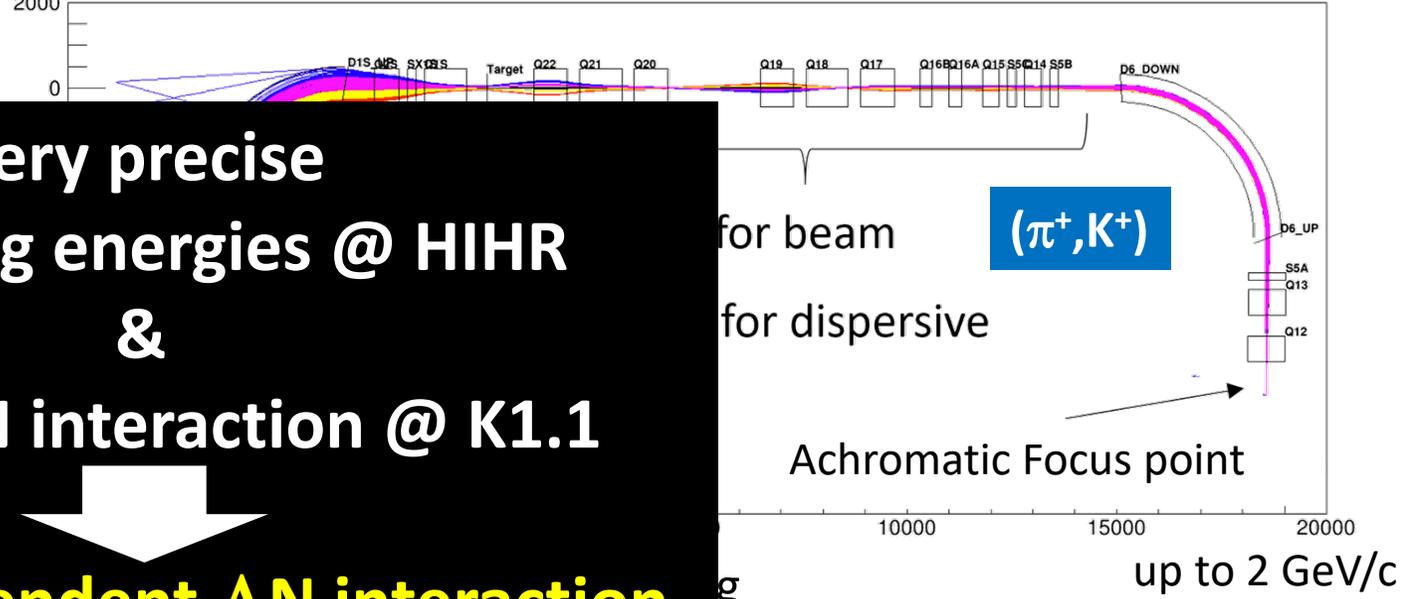
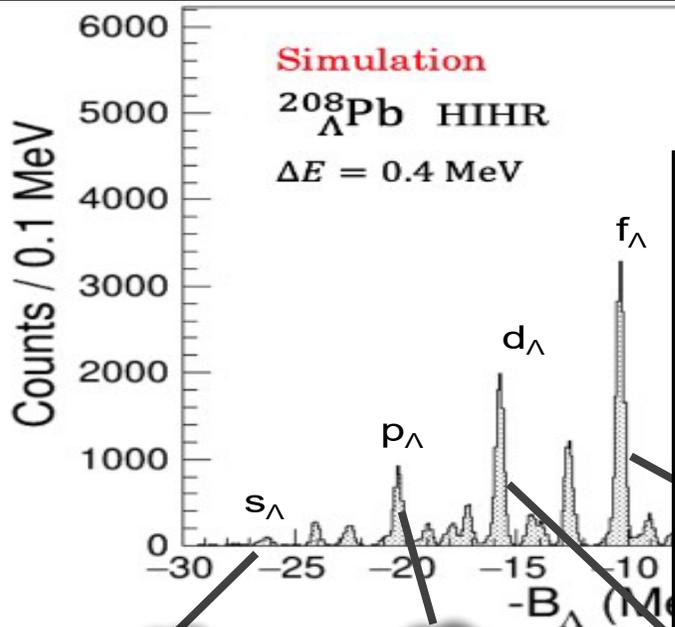
Why can heavy neutron stars exist?

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

Ultra-high-resolution Λ -hyp. spectroscopy

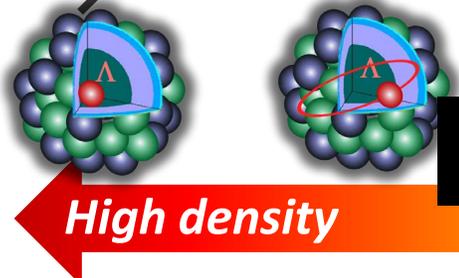
HIHR beam line (High-Intensity High-Resolution)

First dispersion-matching beam line in GeV energy



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

→ new understanding of neutron star matter



ion limit:

$\sim 2.2 \text{ MeV} \rightarrow$ better than $\sim 0.4 \text{ MeV}$ (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
($\pi 20$)

High-resolution charm baryon spectroscopy

- intense high-momentum π beam

K10

High-resolution multi-strange baryon spectroscopy

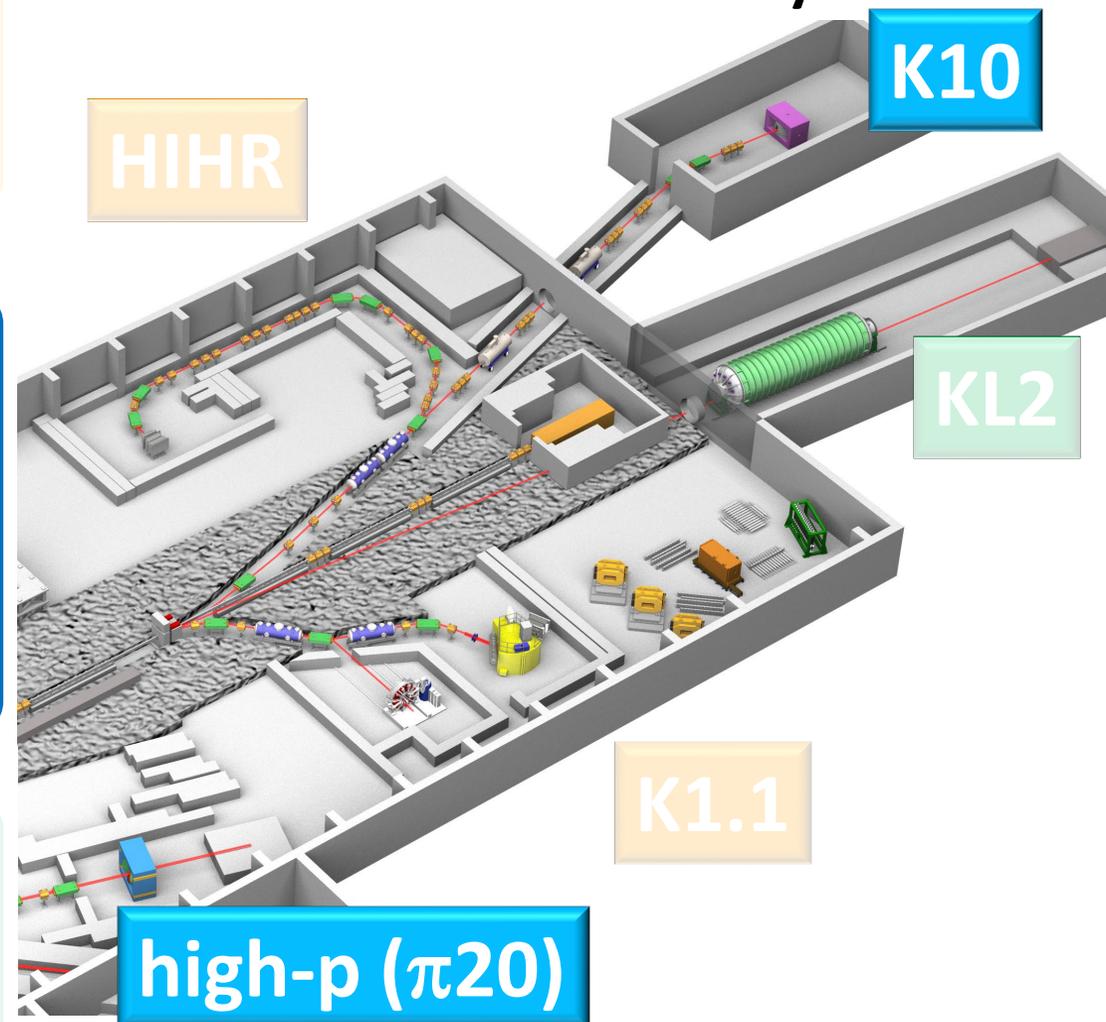
- intense high-momentum separated K beam

Search for new physics beyond the SM

KL2

Highest-sensitive $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ measurement

- intense neutral K beam



Hadron Physics: Diquarks in Baryons

How quarks build hadrons?

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

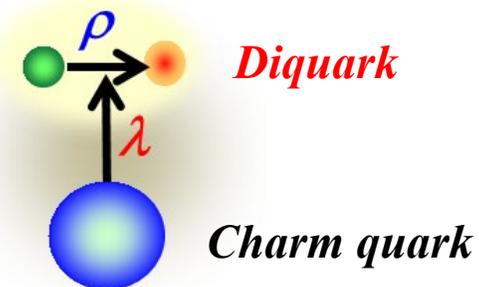
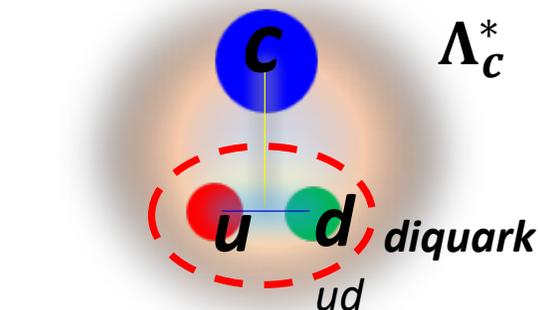
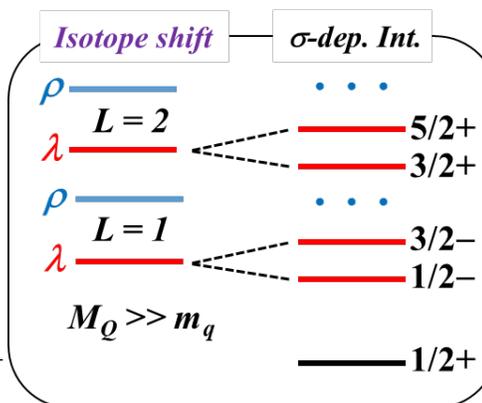
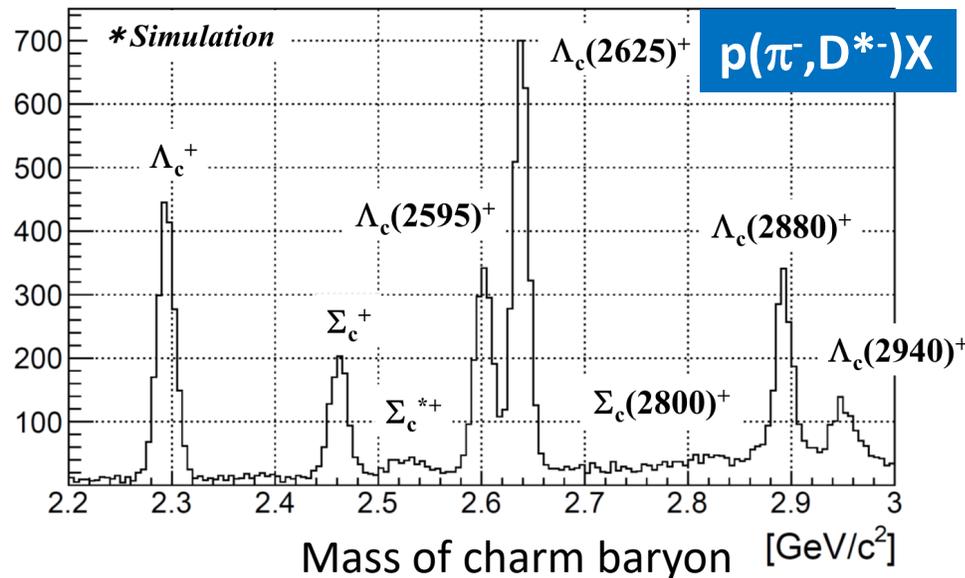
➤ Charm Baryon Spectroscopy

using intense high-momentum π beam @ High-p ($\pi 20$)

Establish a diquark (ud)

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

Production rate of charm baryon



➔ “production rate” and “decay rate”
will give us information about diquark

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 ($\pi 20$)

Establish a diquark (ud)

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

➤ Multi-Strange Baryon Spectroscopy

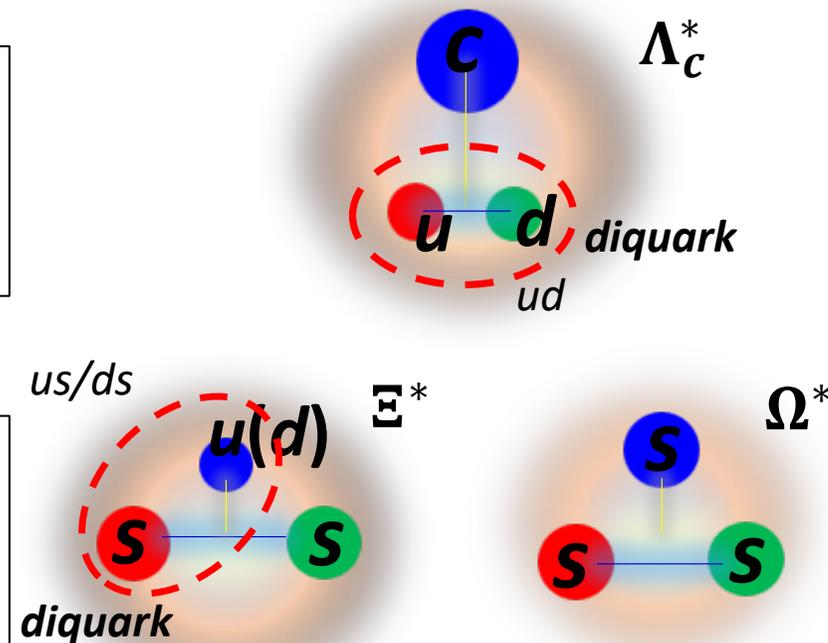
using intense high-momentum K beam @ K10

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
($\pi 20$)

High-resolution charm baryon spectroscopy

- intense high-momentum π beam

K10

High-resolution multi-strange baryon spectroscopy

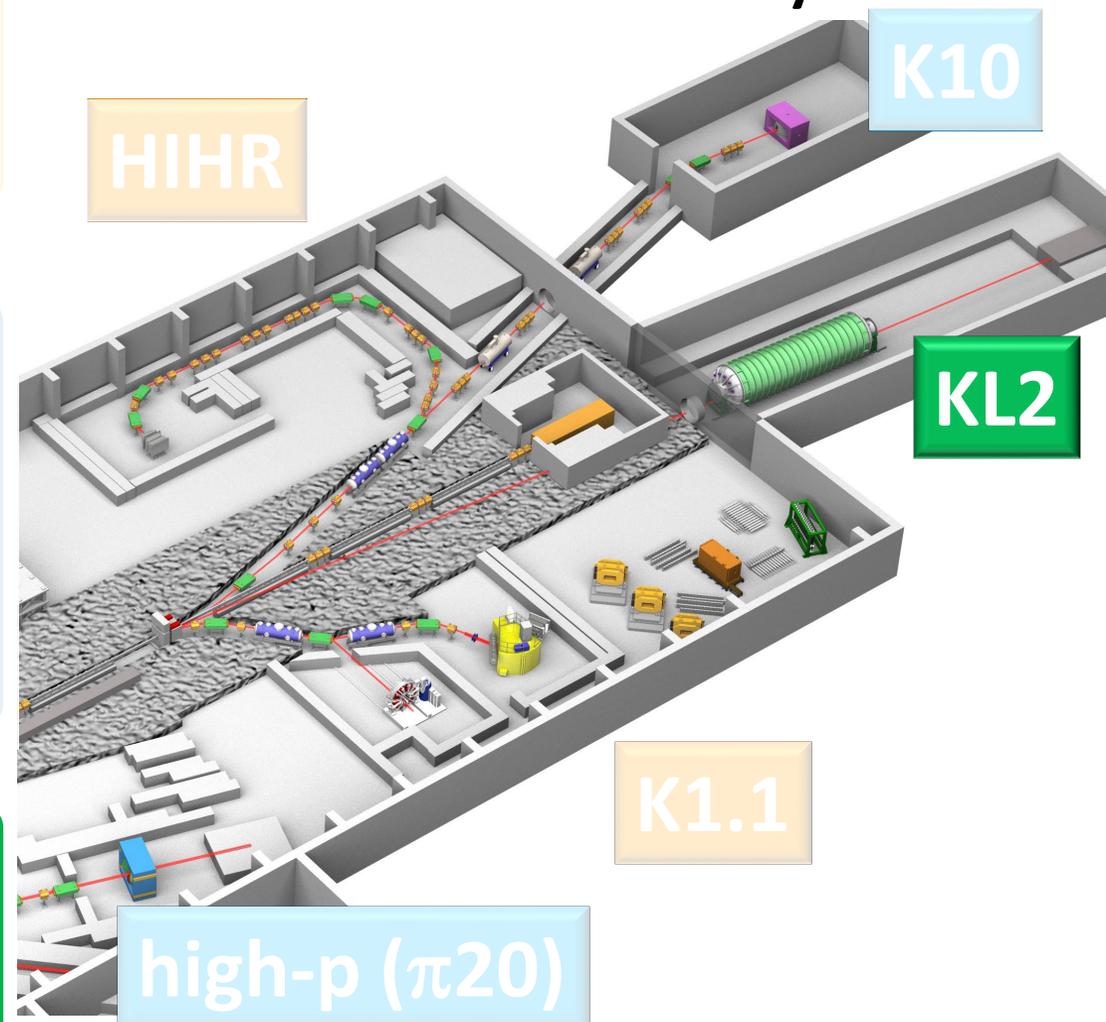
- intense high-momentum separated K beam

Search for new physics beyond the SM

KL2

Highest-sensitive $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ measurement

- intense neutral K beam



Flavor Physics: New Physics Search at KOTO

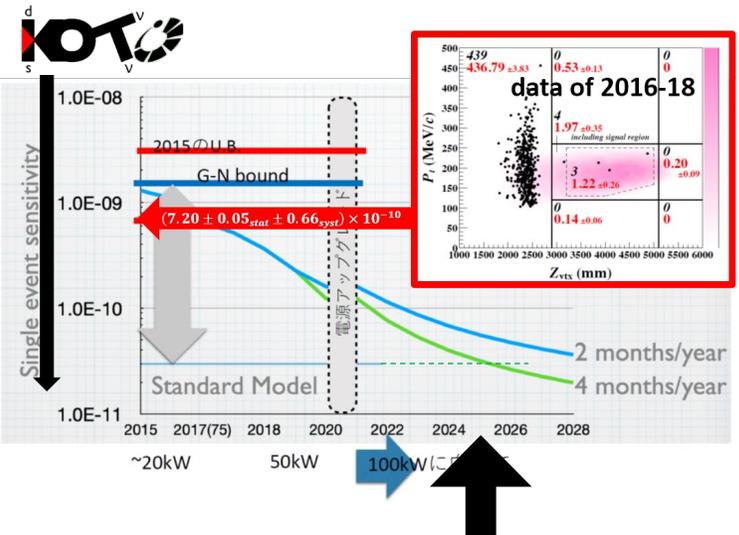
Rare kaon decay: $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$
 One of the best probes of new physics search

- Directly break CP symmetry
- Suppressed in the SM \rightarrow Branching ratio $\sim 3 \times 10^{-11}$
- Small theoretical uncertainties ($\sim 2\%$)

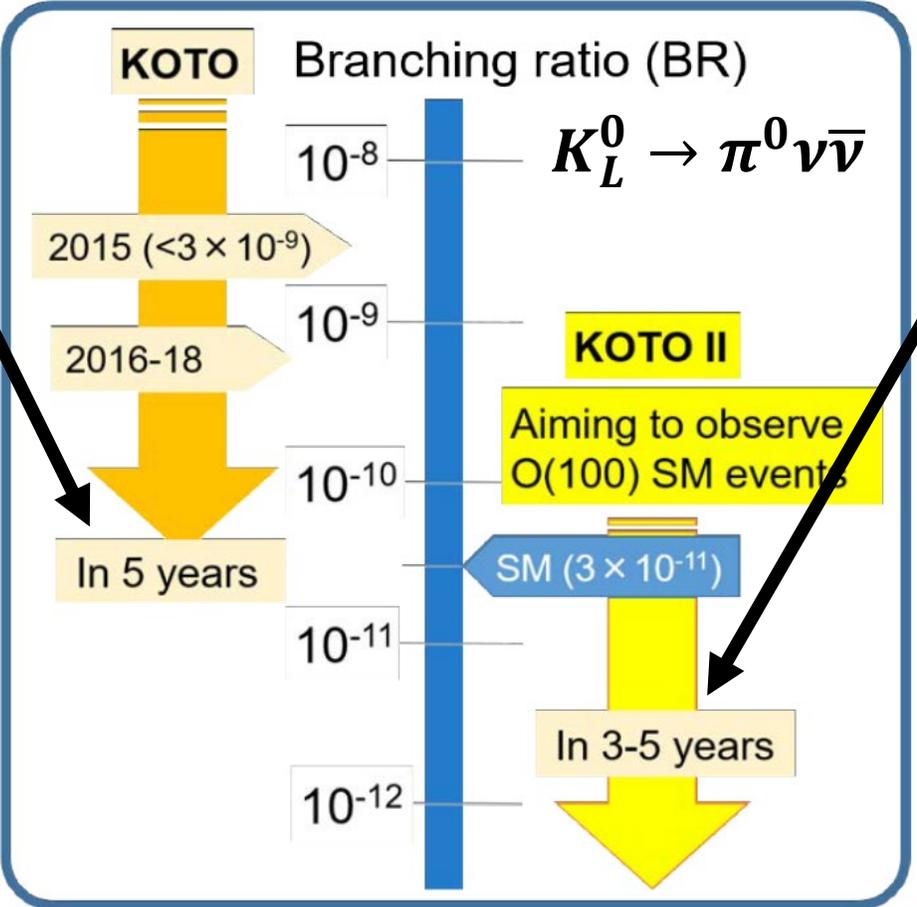
Present HEF

KOTO:

- Will reach the SM sensitivity of $<O(10^{-10})$ around FY2025



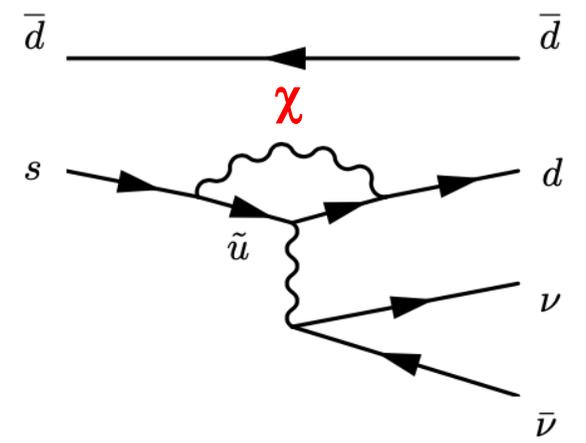
Sensitive to $\sim O(100)$ TeV physics



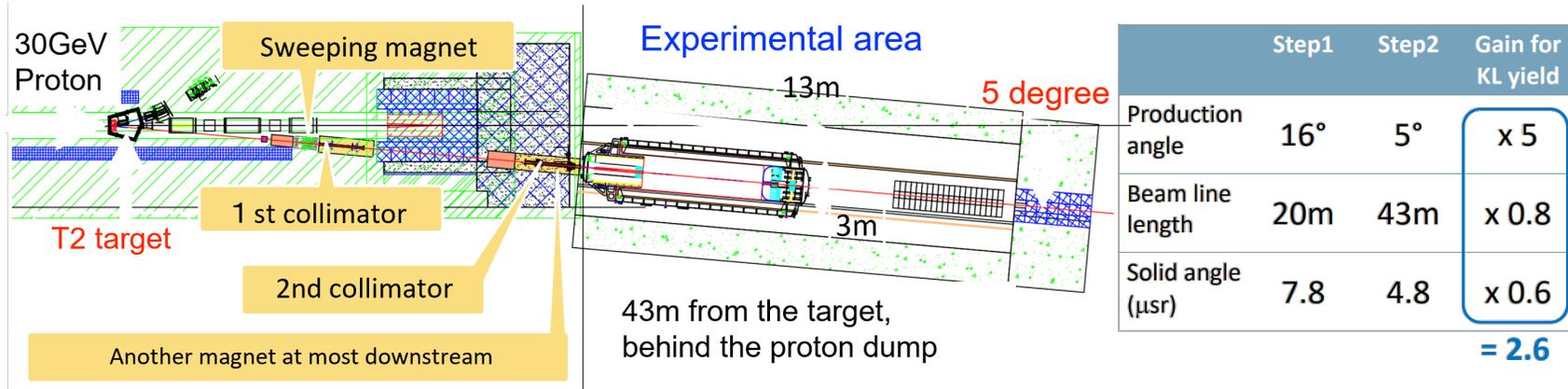
Extended HEF

KOTO Step-2:

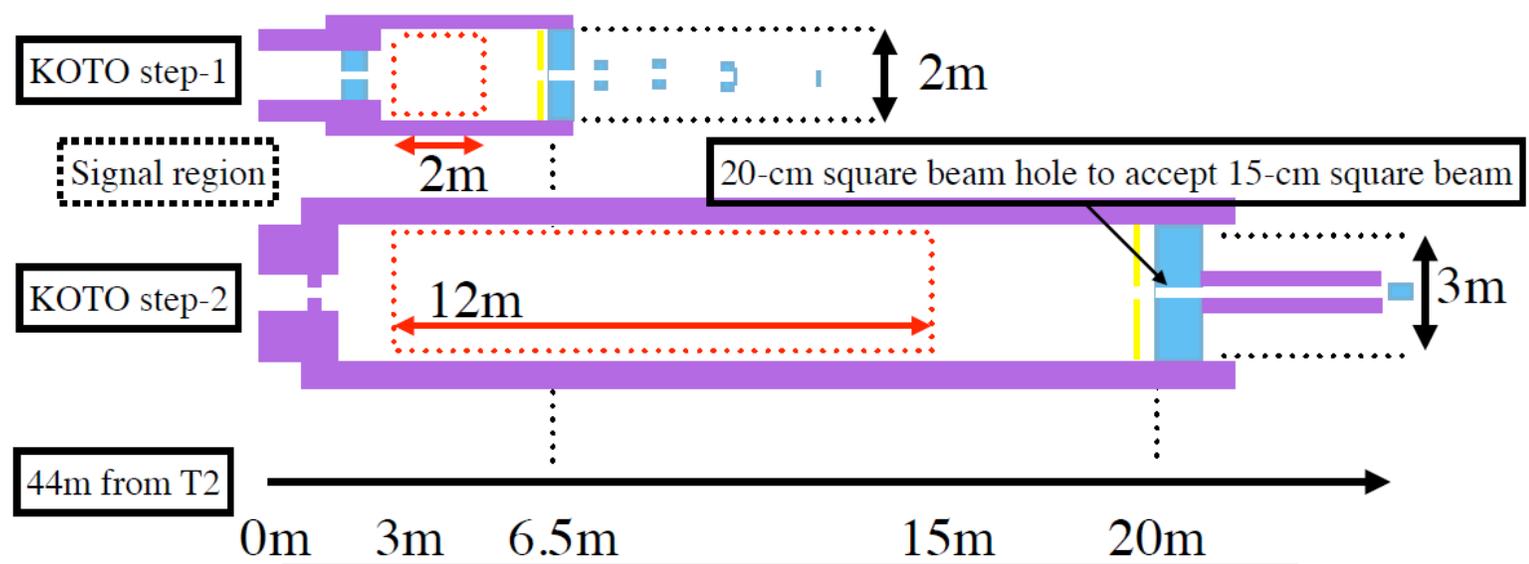
- Will explore the region beyond the SM sensitivity



Flavor Physics: New Physics Search at KOTO



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

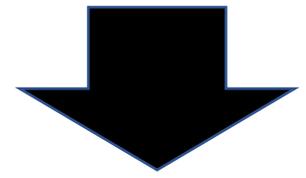


Ultra-high sensitivity detector (~x70)



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

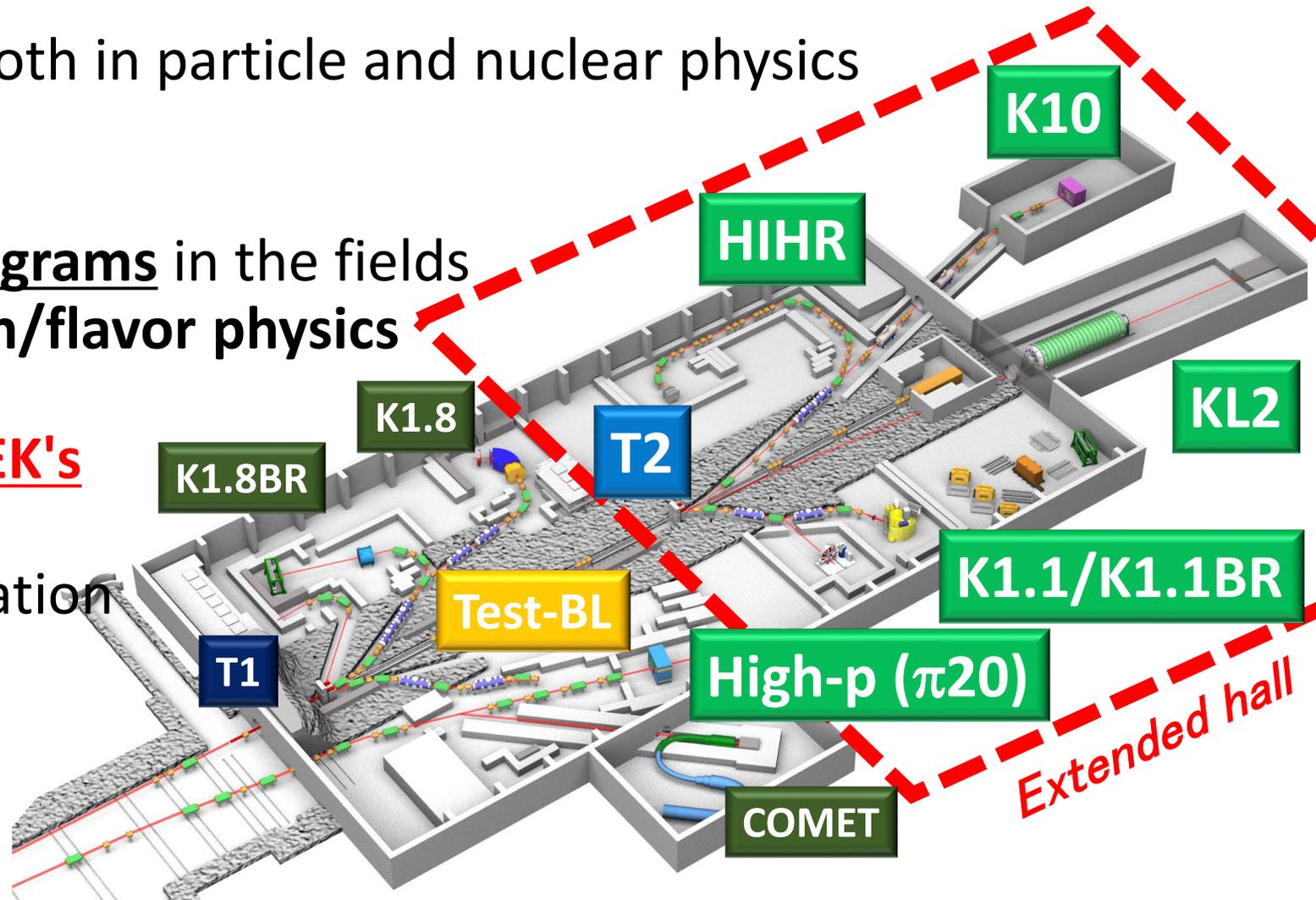


Indicate new physics, if deviation from the SM > 40%

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

- Unique research programs both in 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's mid-term plan (FY2022-26) / Progress in facility-side preparation
→ The project will start soon

Stay tuned!





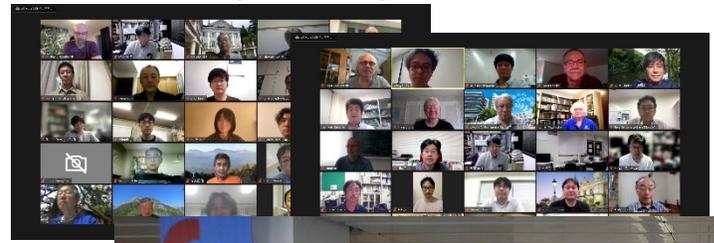
Thank you for your attention!

<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
First-Beam Workshop at the J-PARC Hadron Experimental Hall, March 25-26, 2009, Tokai, Japan

International WS on the Extension Project for the J-PARC Hadron Experimental Facility (J-PARC HEF-ex WS), 7-9 July 2021, online



2nd International WS on the Extension Project for the J-PARC Hadron Experimental Facility (2nd J-PARC HEF-ex WS), Feb.16-18 2022, online



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

3rd International WS on the Extension Project for the J-PARC Hadron Experimental Facility (3rd J-PARC HEF-ex WS), Mar.14-16 2023, J-PARC



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

We are planning the 4th WS on Feb. 19-21, 2024