J-PARC

Japan Proton Accelerator Research Complex

The hadron experimental facility extension at J-PARC

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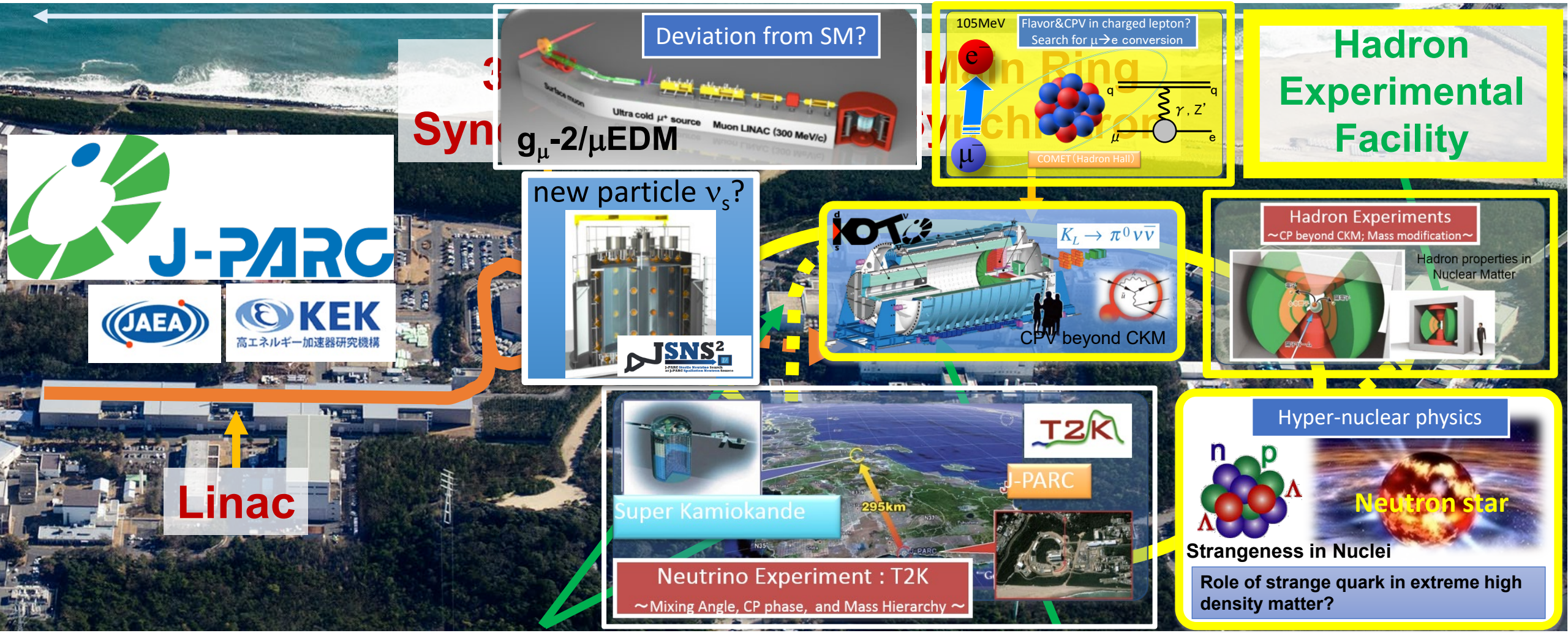
MESON2023, Jun.22-27, 2023

Particle and Nuclear Physics @ J-PARC



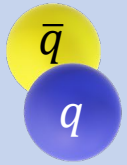
Neutrino Experimental Facility

Material and Life Science Experimental Facility

Origin & Evolution of Matter

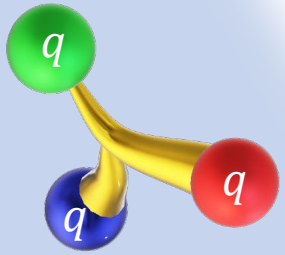
Matter-Antimatter Symmetry

matter dominated universe



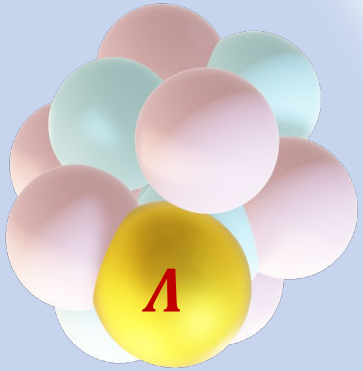
Origin of Matter Creation

formation of hadrons from quarks



Matter in Extreme Conditions

dense matter in neutron stars



Flavor Physics

CP violation
weak interaction
→ new physics

Kaon rare decays
μ→e conversion

Hadron Physics

quark interactions
hadron mass-generation mechanism

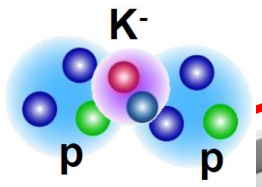
Hadron spectroscopy
Meson in nuclei

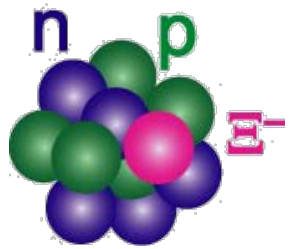
Strangeness Nuclear Physics

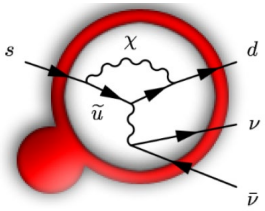
hadron interactions
hadronic many-body systems

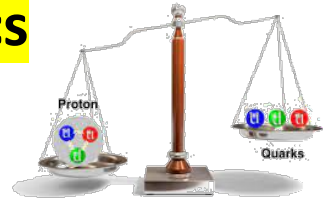
Hyperon-Nucleon scattering
Hypernuclear spectroscopy

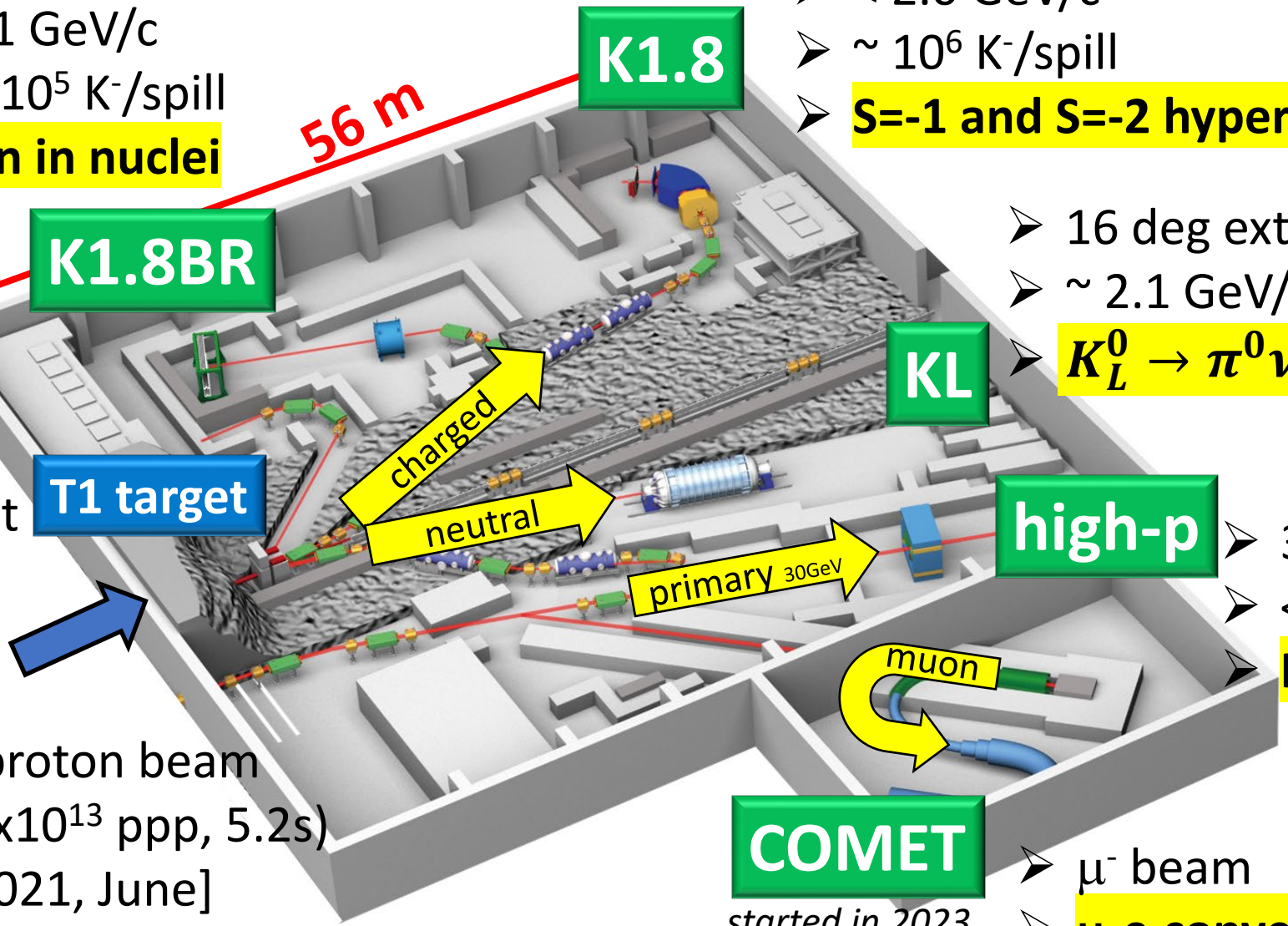
Present Hadron Experimental Facility (HEF)











- < 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
- 65kW (7x10^{13} 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

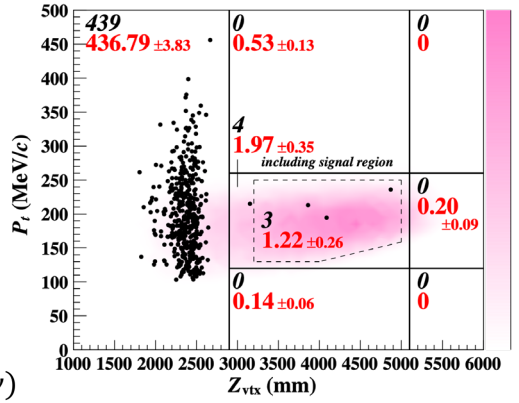
$K_L^0 \to \pi^0\nu\bar{\nu}$ search @ KOTO

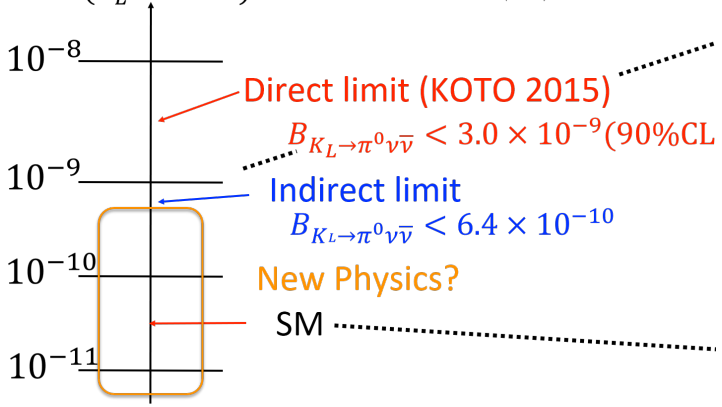
→ Approaching the SM sensitivity for CP violation

KOTO 2015

Single Event Sensitivity = 3×10^{-9}

KOTO 2016-18



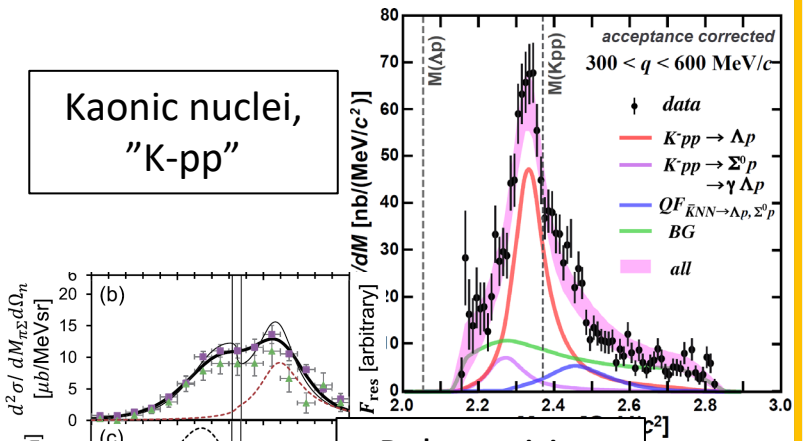


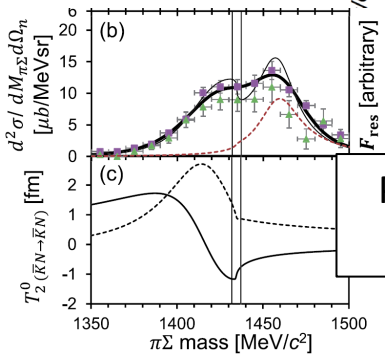
Hadron Physics

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

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

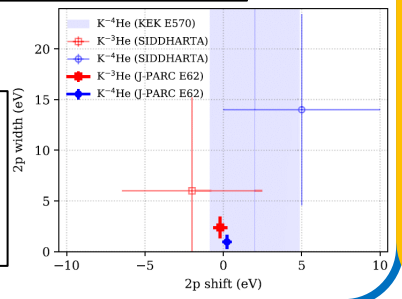
Kaonic nuclei, "K-pp"





Pole position of Λ(1405)

Ultra-precise measurement of kaonic atoms

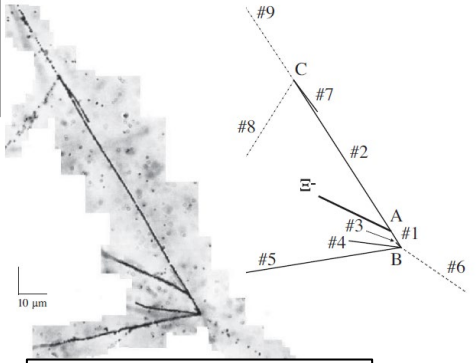


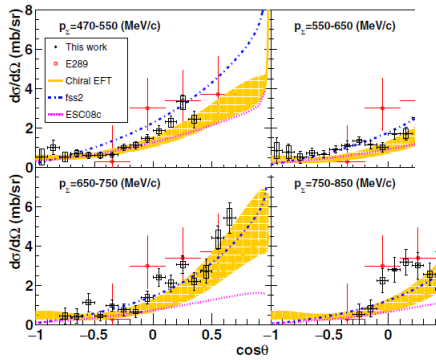
Strangeness Nuclear Physics

A lot of progress in hypernuclear research

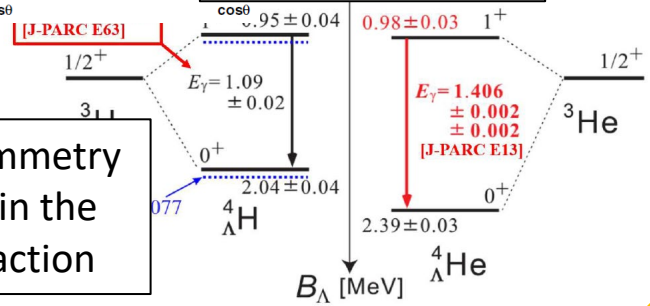
→ Clarified attractive S=–2 ΞN interaction and deepened S=–1 ΛN, ΣN interactions

Observation of Ξ hypernuclei





First precise hyperon-nucleon scattering



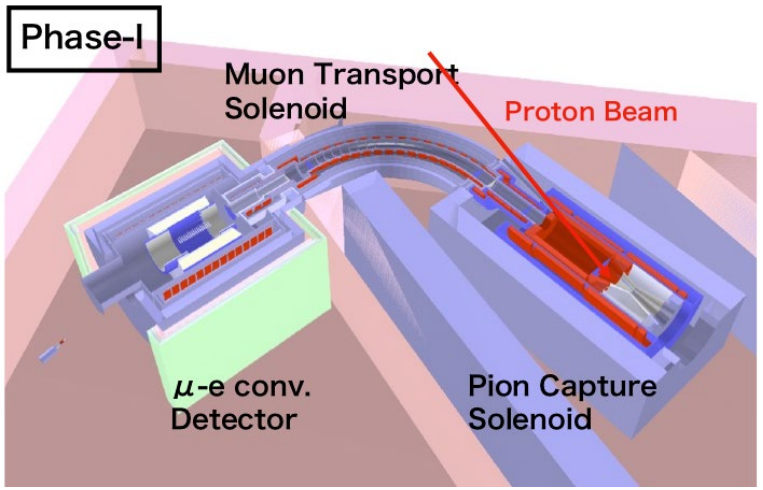
Charge-symmetry breaking in the ΛN interaction

Further research directions at the Hadron Experimental Facility

Flavor Physics

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

→ **Search for charged lepton flavor violation**



Futher research

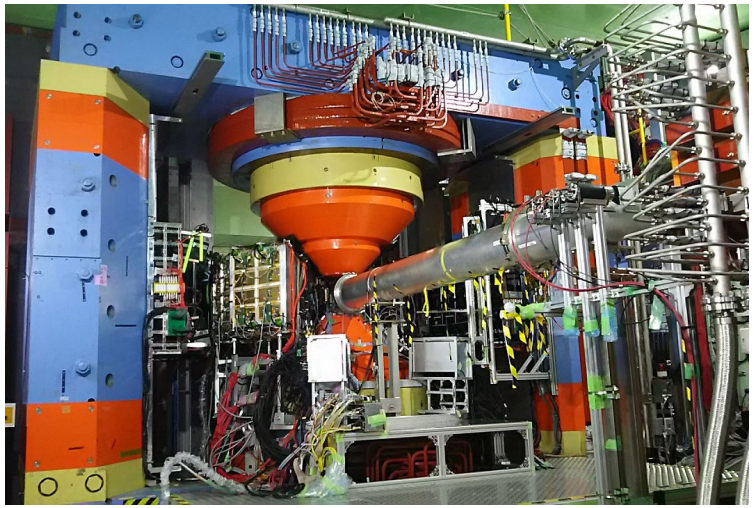
$K_L^0 \to \pi^0 \nu\bar{\nu}$ search with further sensitivity

→ **Explore beyond the SM sensitivity**

Hadron Physics

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

→ **Attack mass-generation mechanism of hadrons**



Futher research

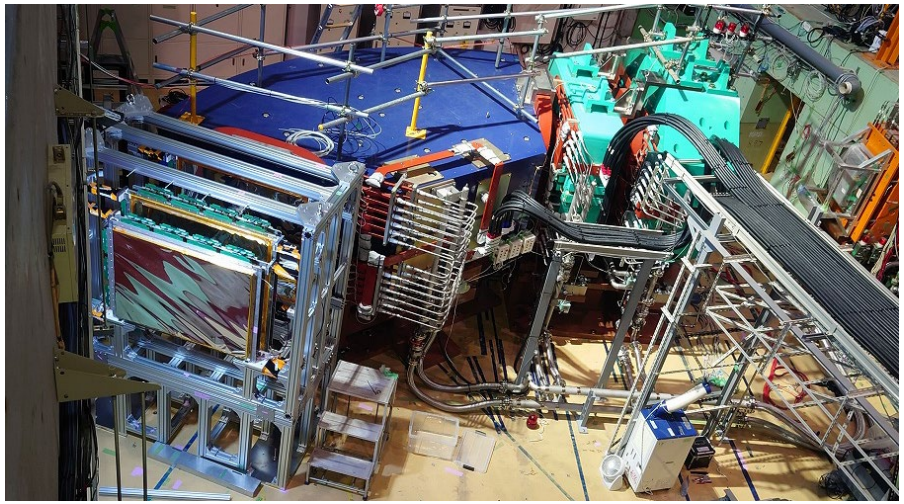
Charmed and muti-strange baryon spectroscopies

→ **Establish diquark in baryon**

Strangeness Nuclear Physics

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

→ **Provide accurate and systematic information on ΞN, ΛΛ interactions**



Futher research

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

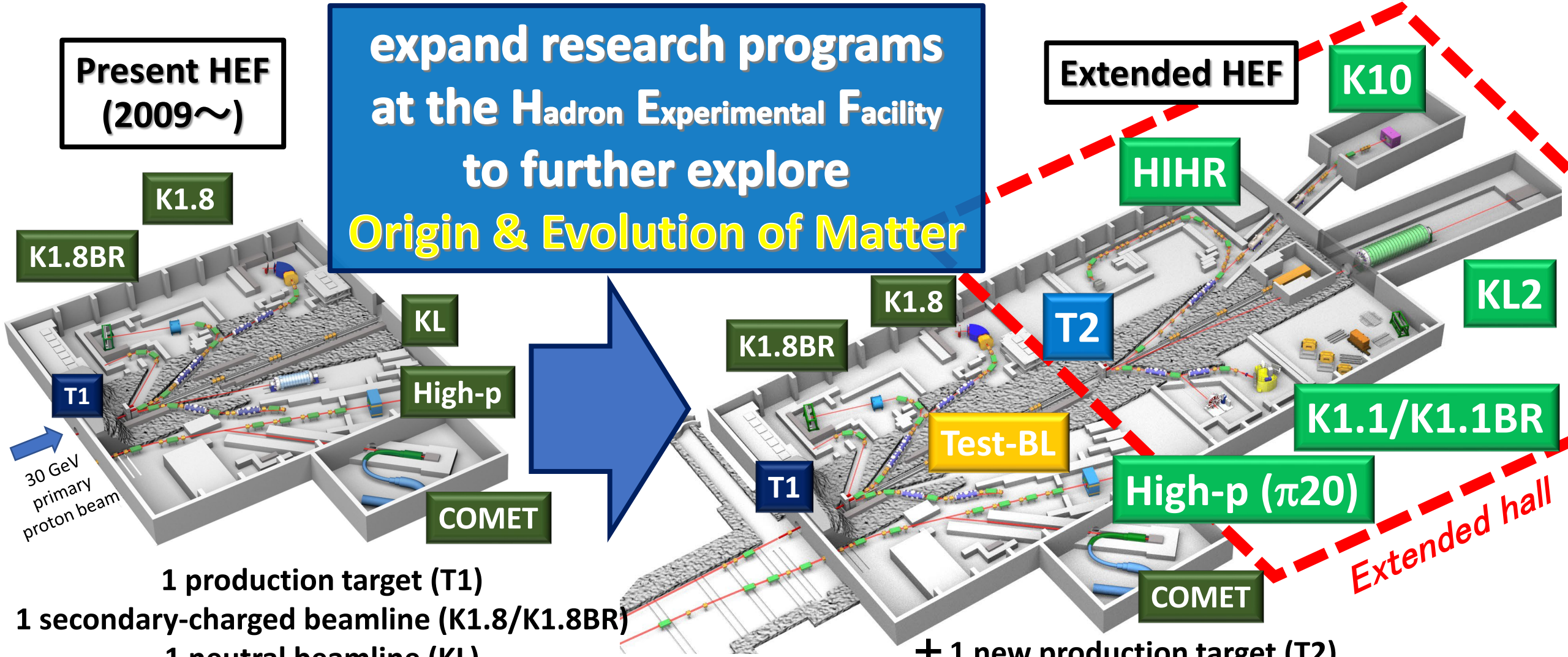
→ **Extract density dependence of ΛN int.**

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)

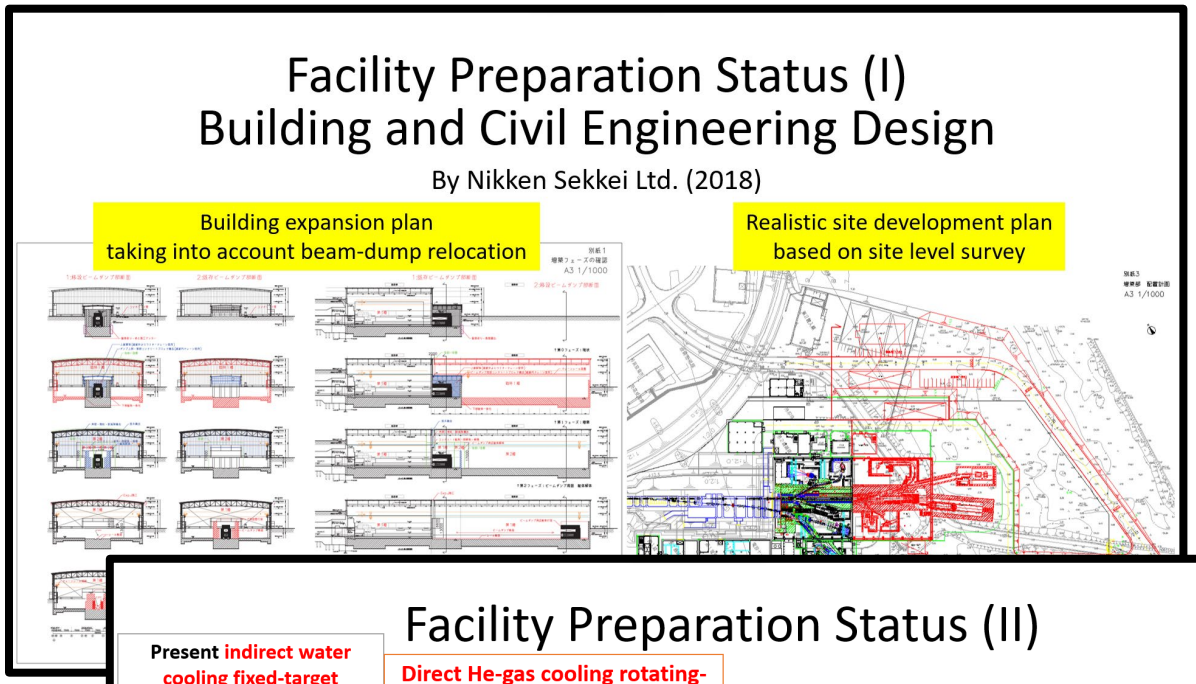
＋1 new production target (T2)
＋4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10)
＋ 2 updated beamlines (High-p (π20), Test-BL)

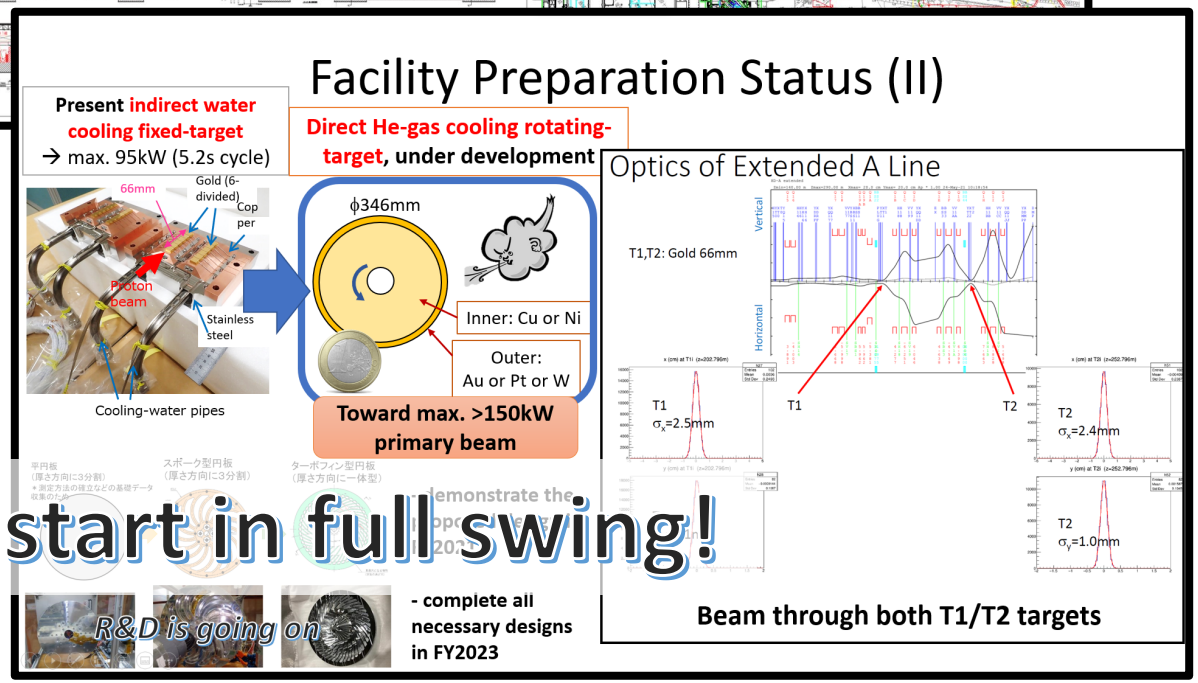
Present Status of the Extension Project

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)





The project will soon start in full swing!

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

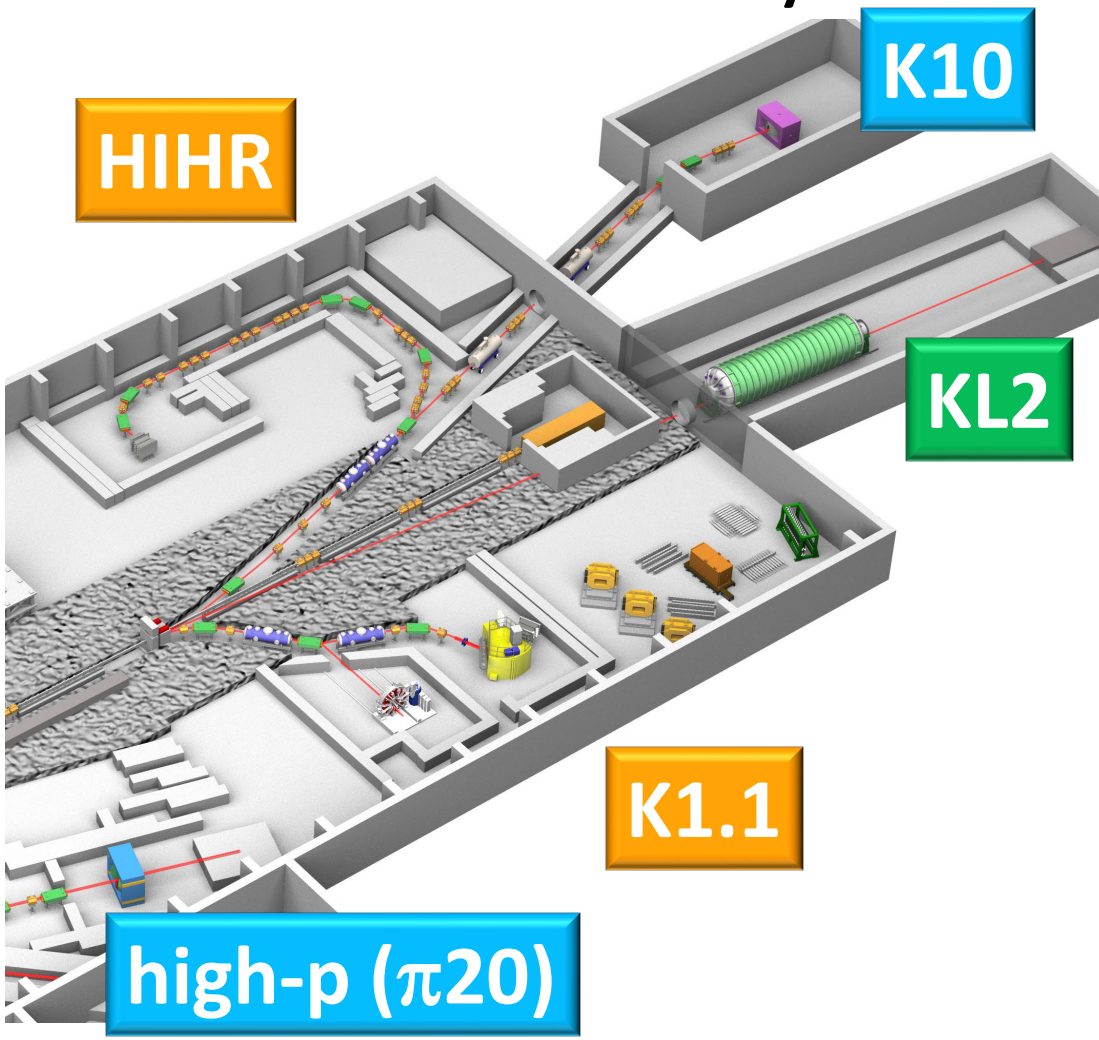
Investigate diquarks in baryons

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



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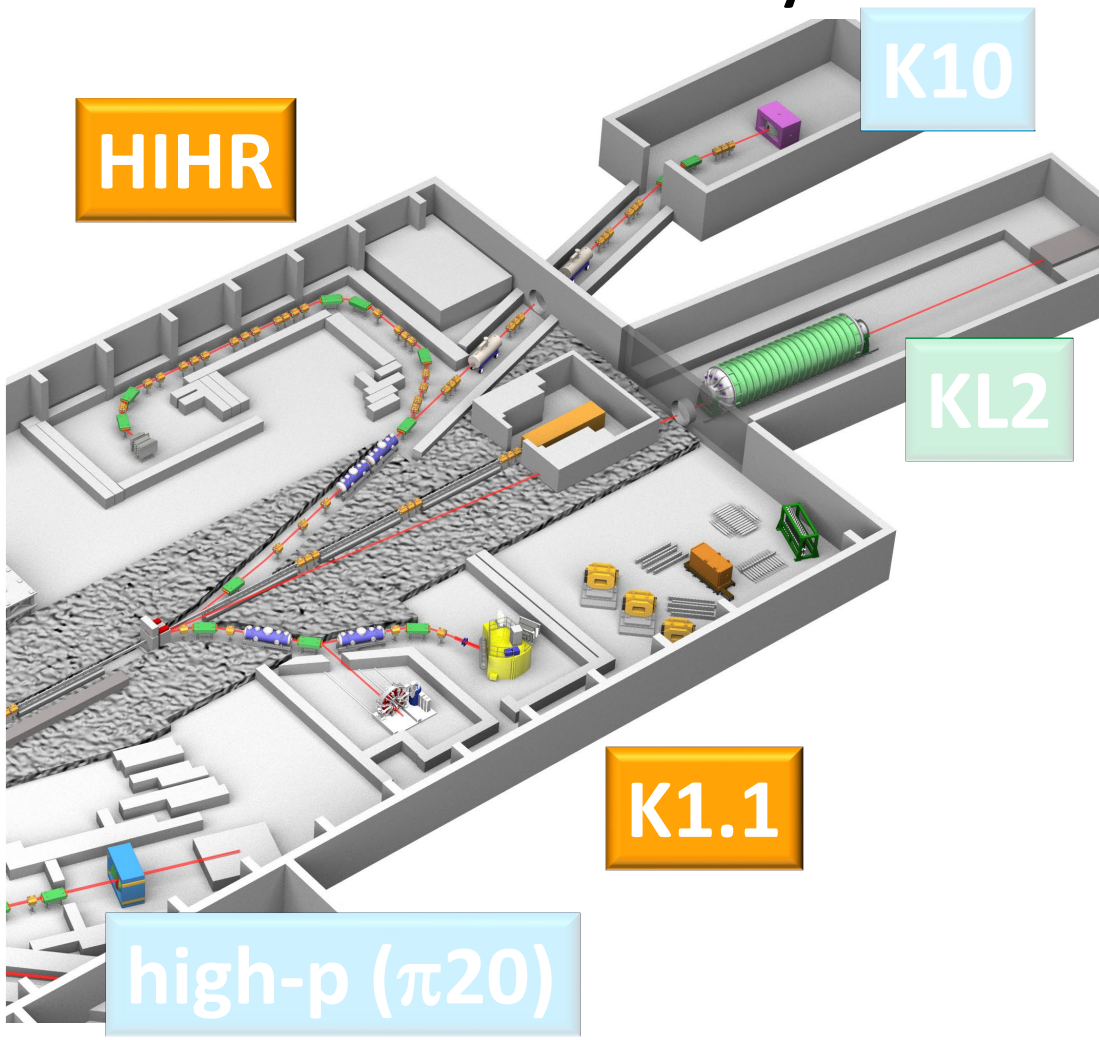
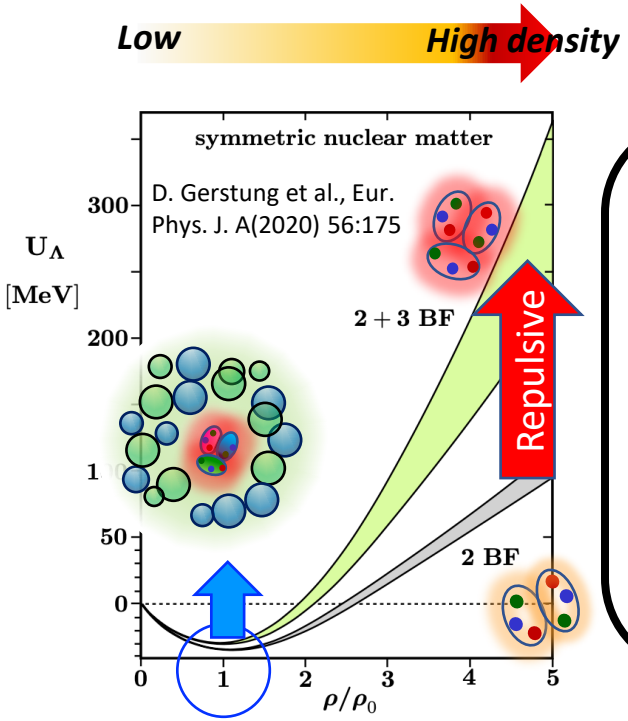


Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

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

ΛNN 3 Baryon Force is a key

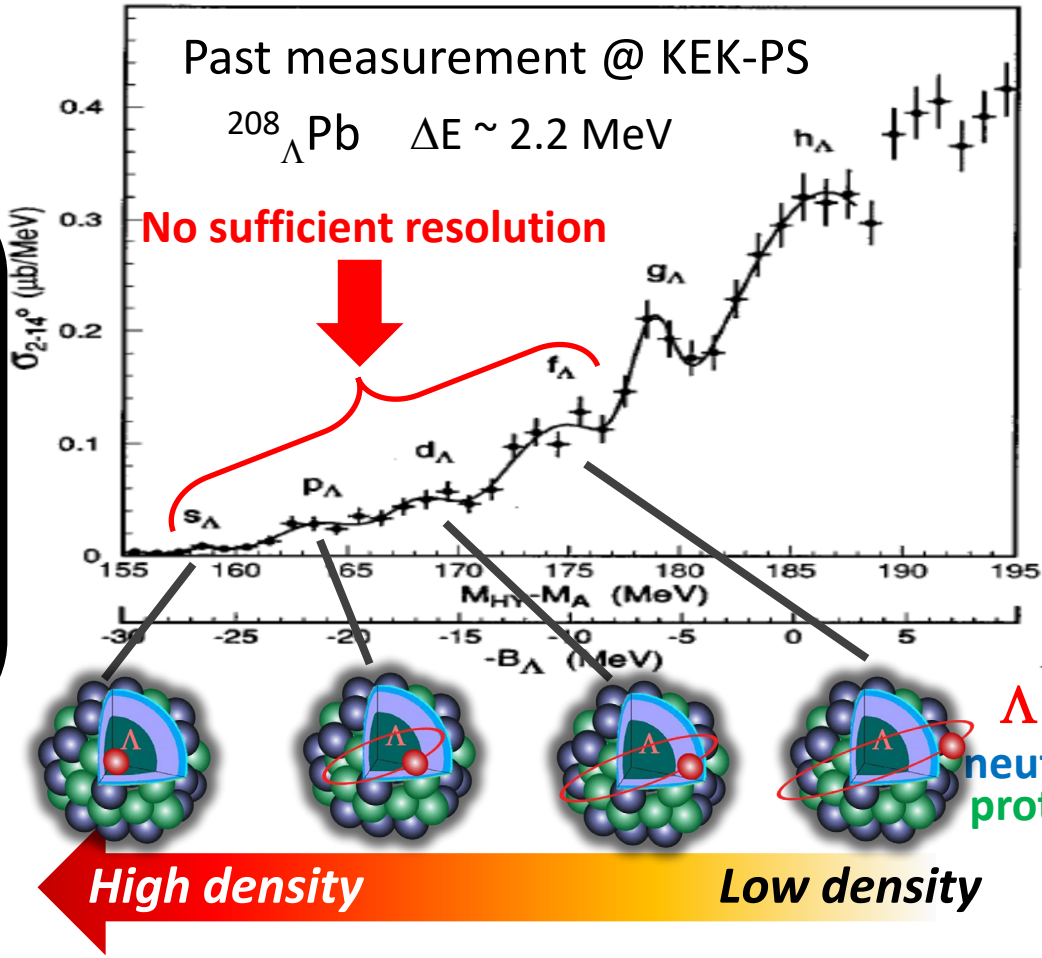


heavy Λ-hypernuclei :

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**

Strangeness Nuclear Physics: Hyperon in Dense Environment

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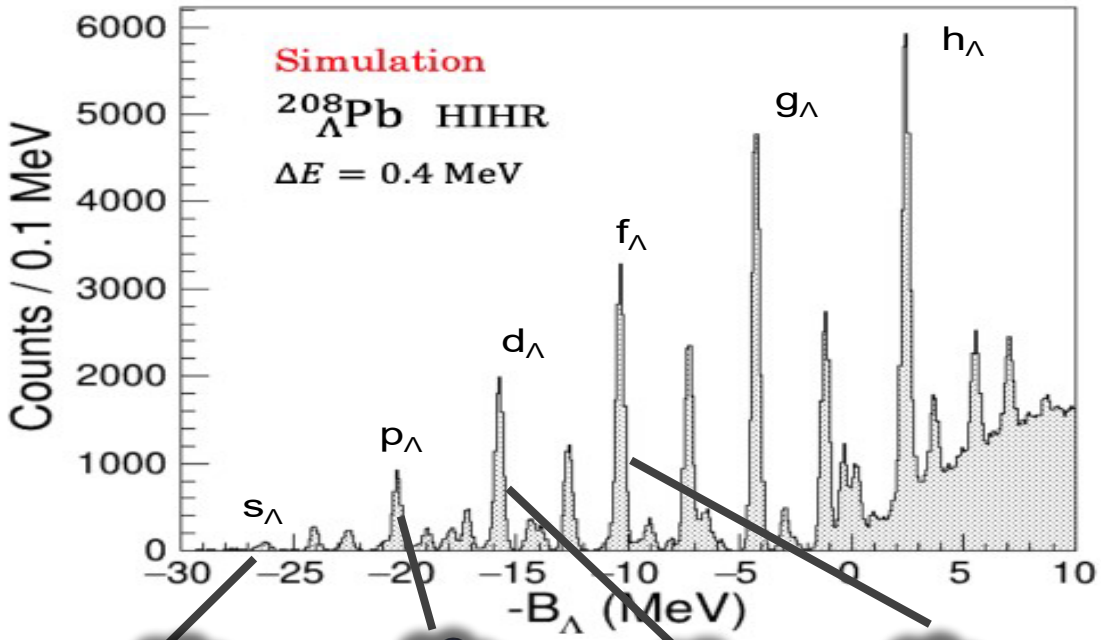
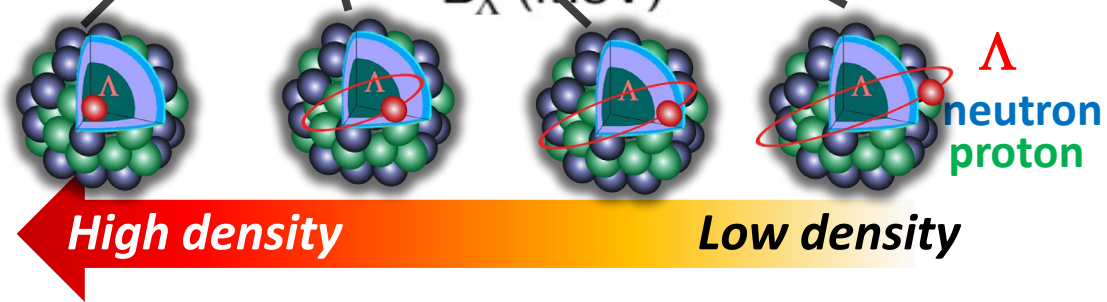
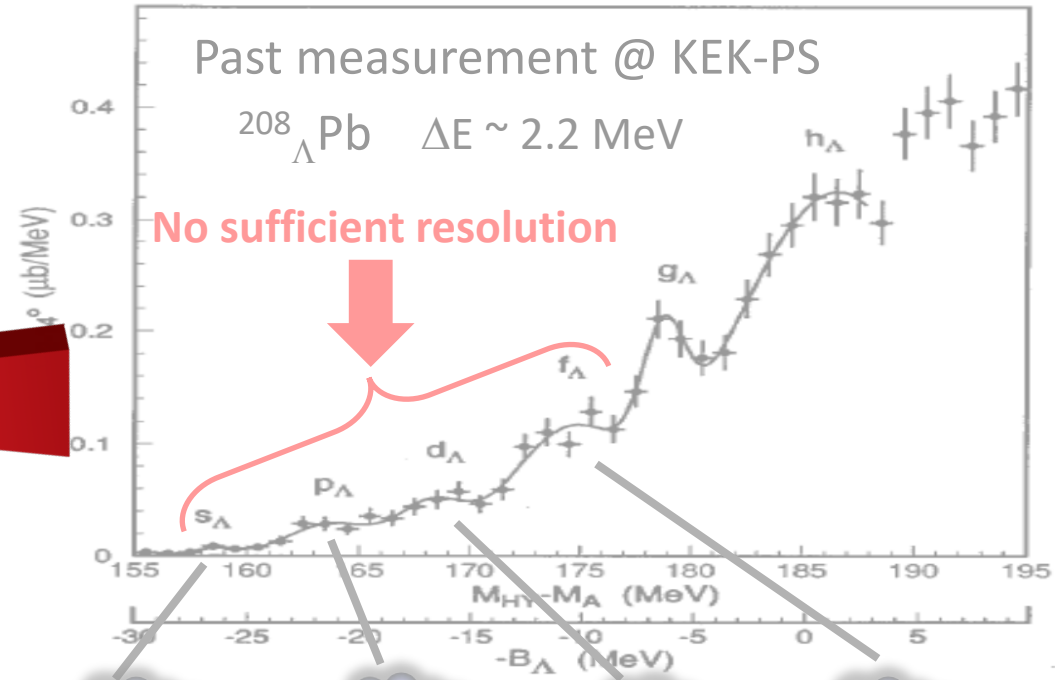
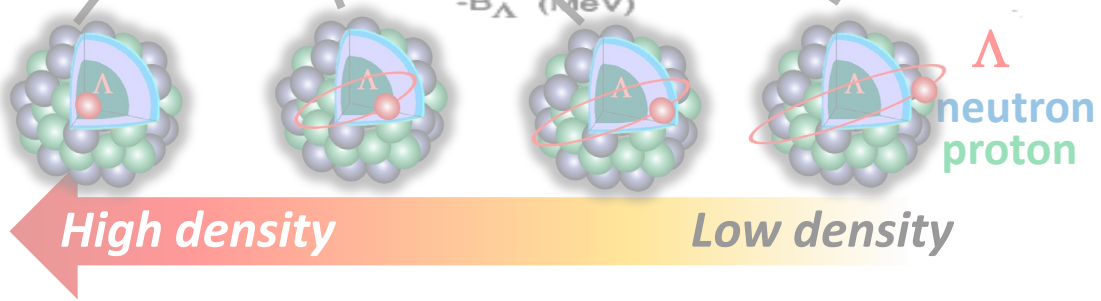
➢ **Hyperons (Λ, Ξ, …) emerge in dense neutron star matter?**

Need separation of each Λ orbital state







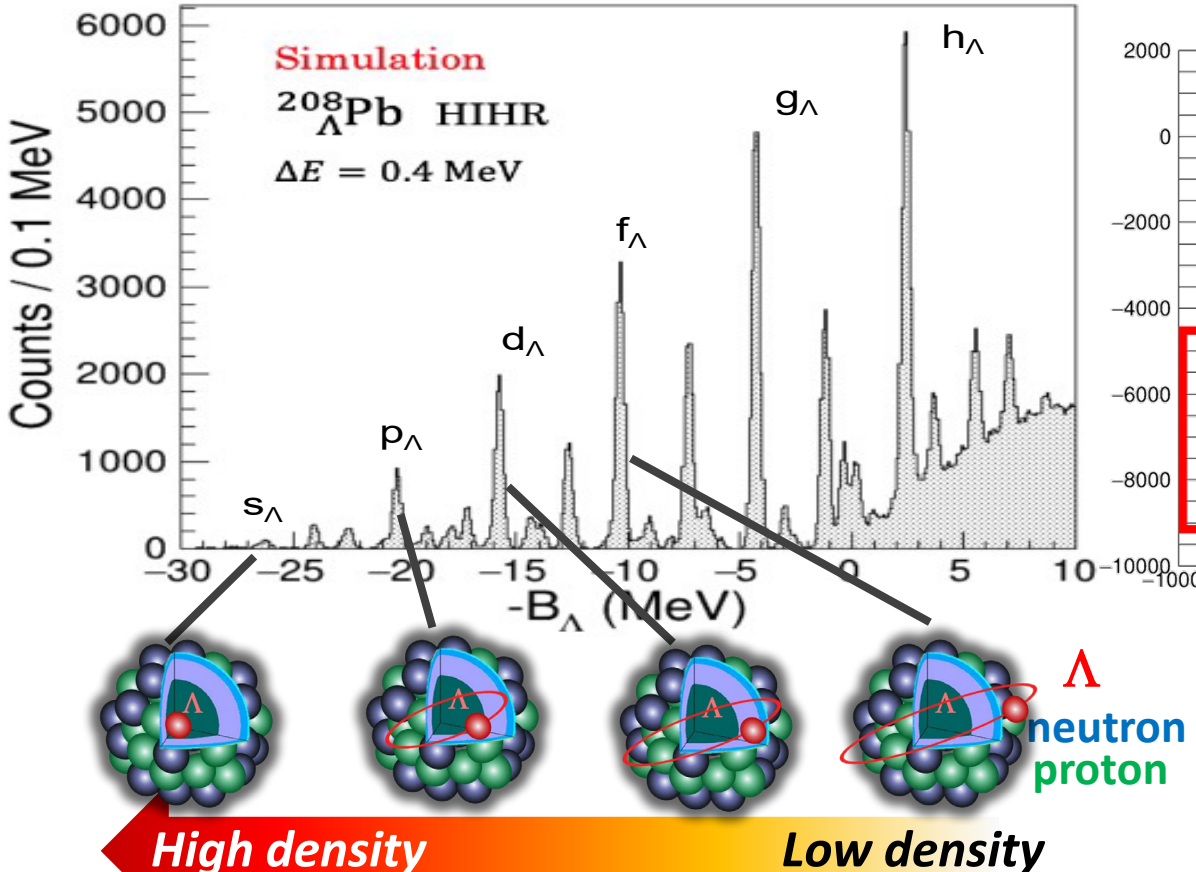


Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

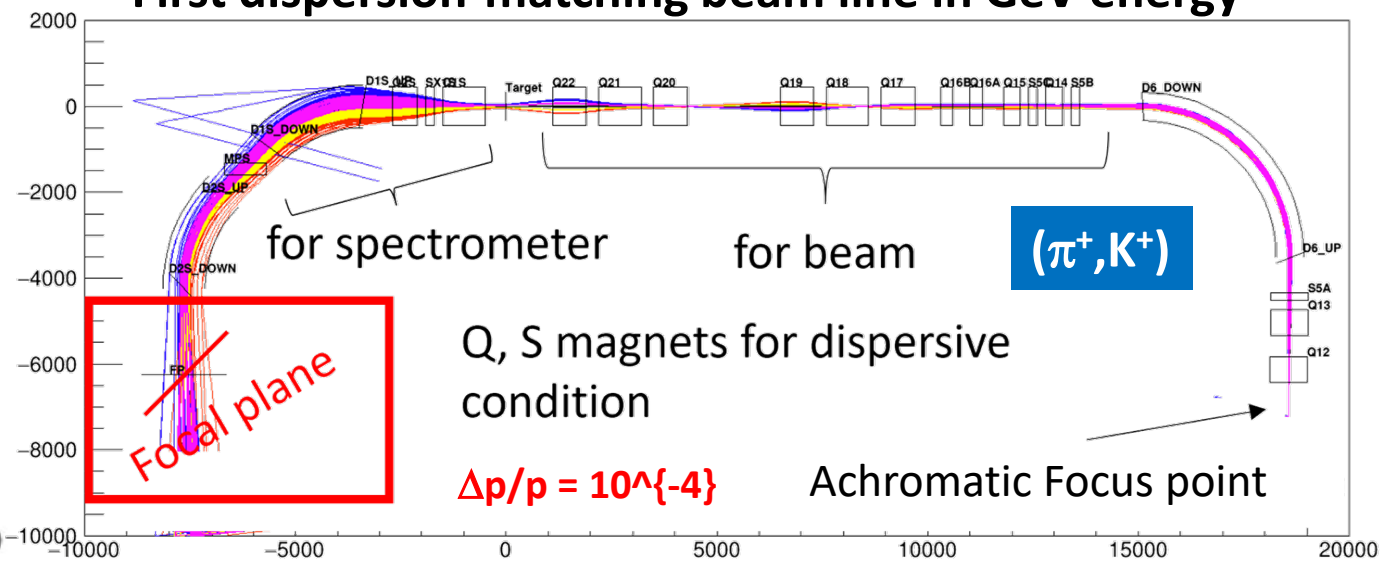
➢ **Hyperons (Λ, Ξ, …) emerge in dense neutron star matter?**

Ultra-high-resolution Λ-hyp. spectroscopy



HIHR beam line (High-Intensity High-Resolution)

First dispersion-matching beam line in GeV energy



- 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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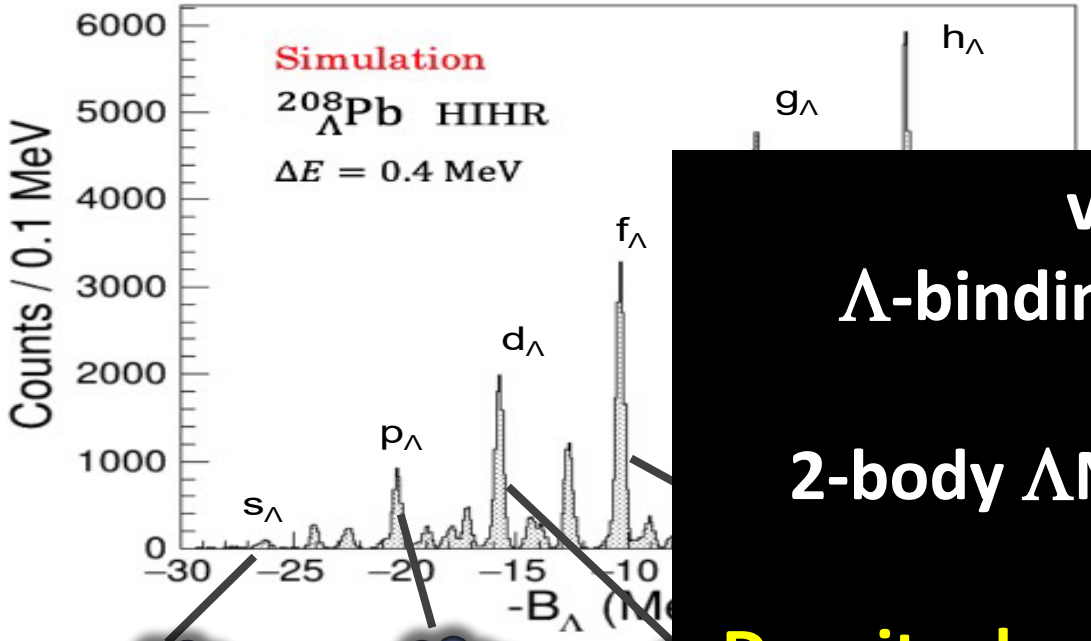


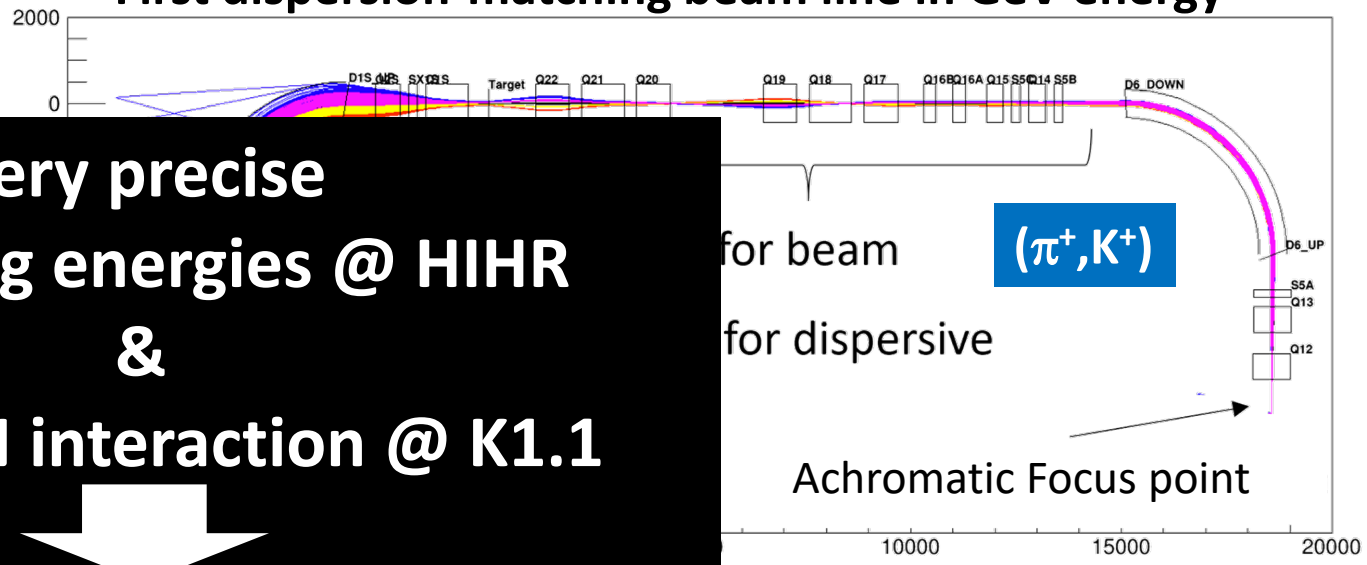
very precise
Λ-binding energies @ HIHR
&
2-body ΛN interaction @ K1.1

Density dependent ΛN interaction

→ new understanding of neutron star matter

HIHR beam line (**H**igh-**I**ntensity **H**igh-**R**esolution)

First dispersion-matching beam line in GeV energy



up to 2 GeV/c

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

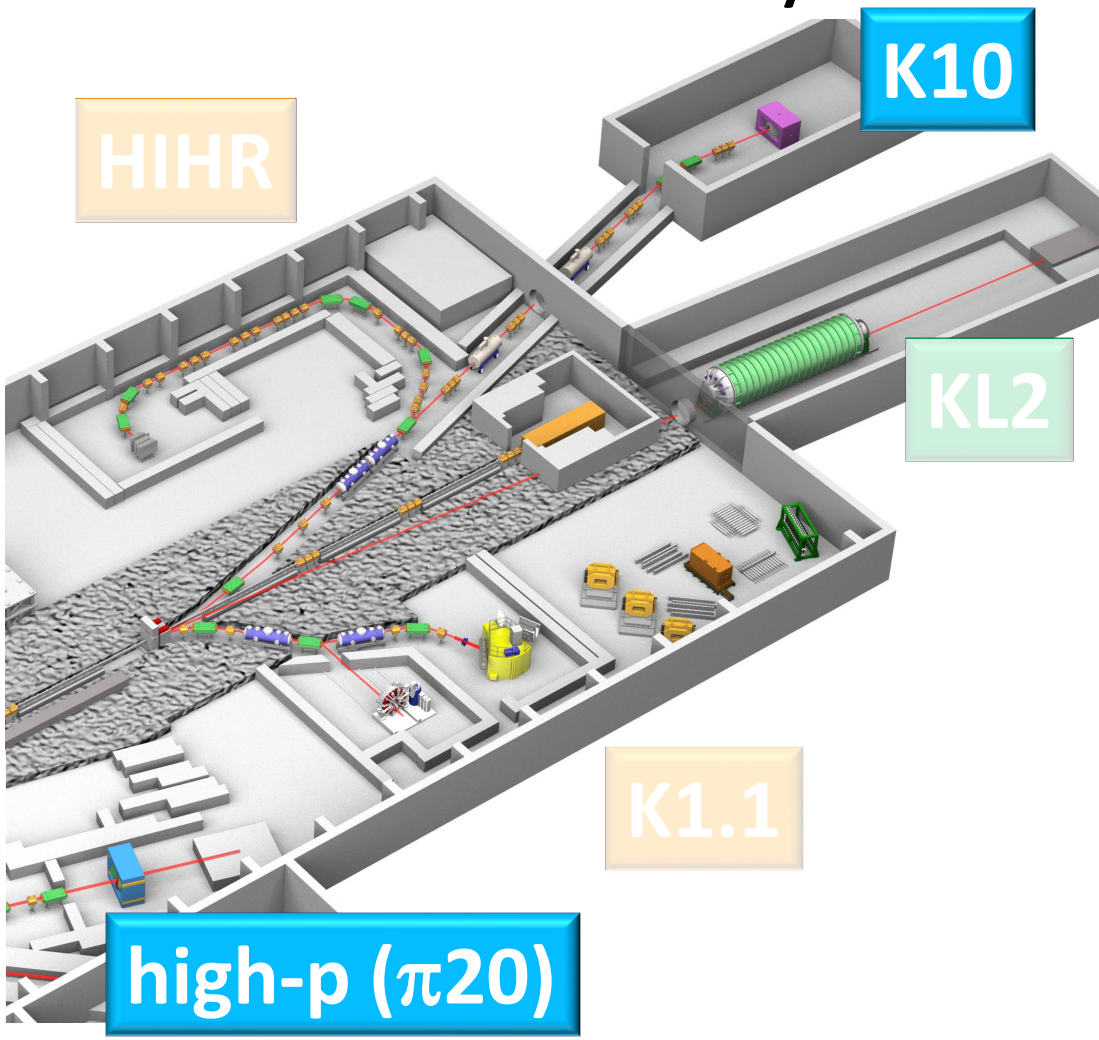
Investigate diquarks in baryons

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



Hadron Physics: Diquarks in Baryons

How quarks build hadrons?

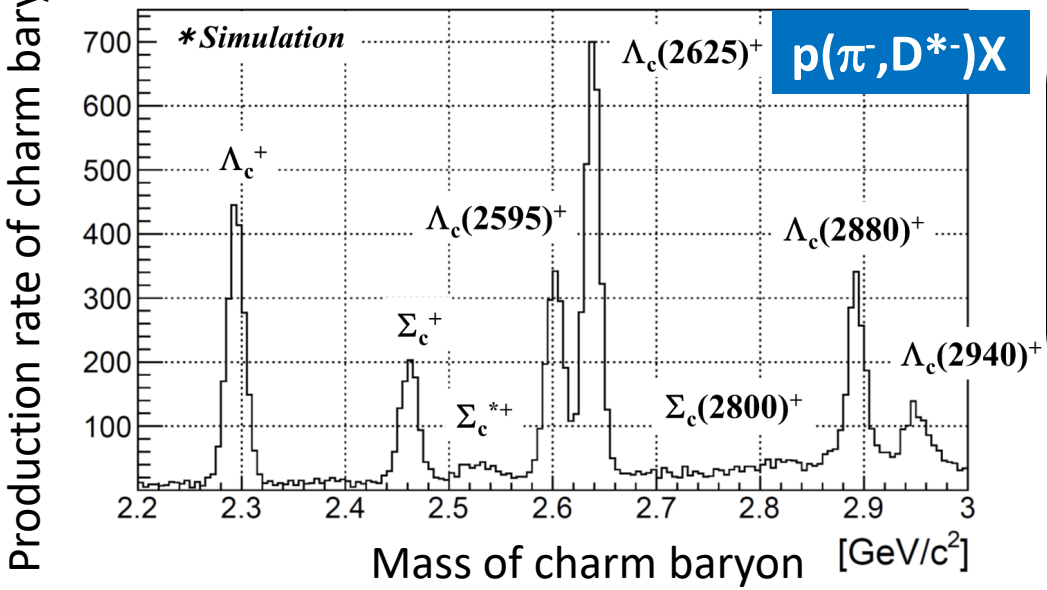
➢ Investigate **diquarks** in baryons **toward** understanding of **dense quark matter**

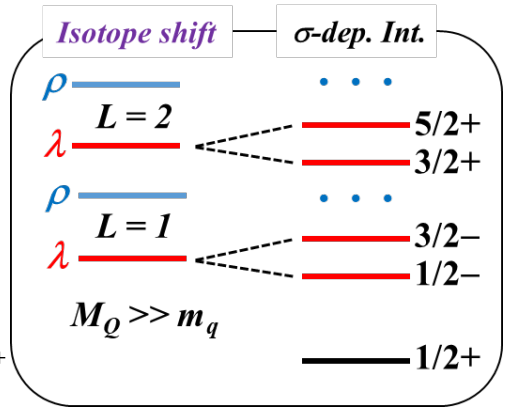
➢ Charm Baryon Spectroscopy

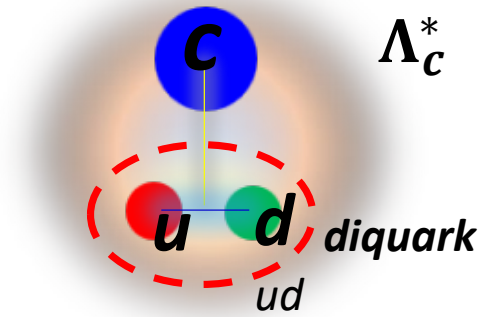
using intense high-momentum π beam @ High-p (π20)

Establish a diquark (*ud*)

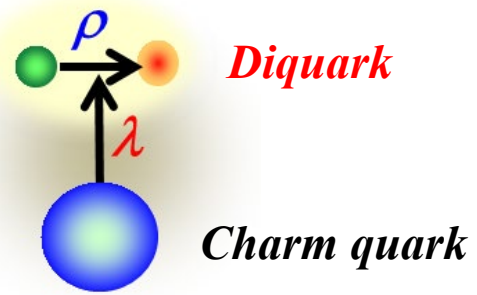
Λ_c^*: Disentangle "collective motion of *ud*"
and "relative motion between *u* and *d*"







Λ_c^*



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

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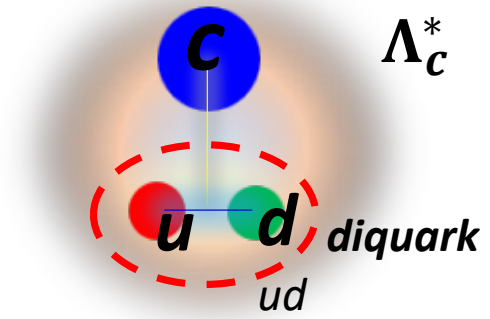


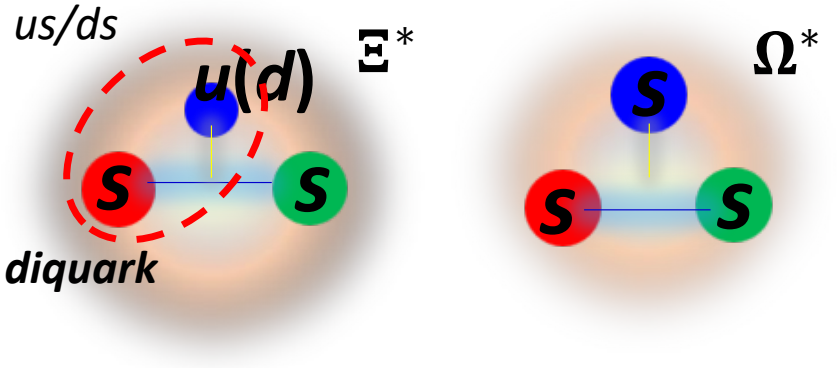
➢ **Multi-Strange Baryon Spectroscopy**

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

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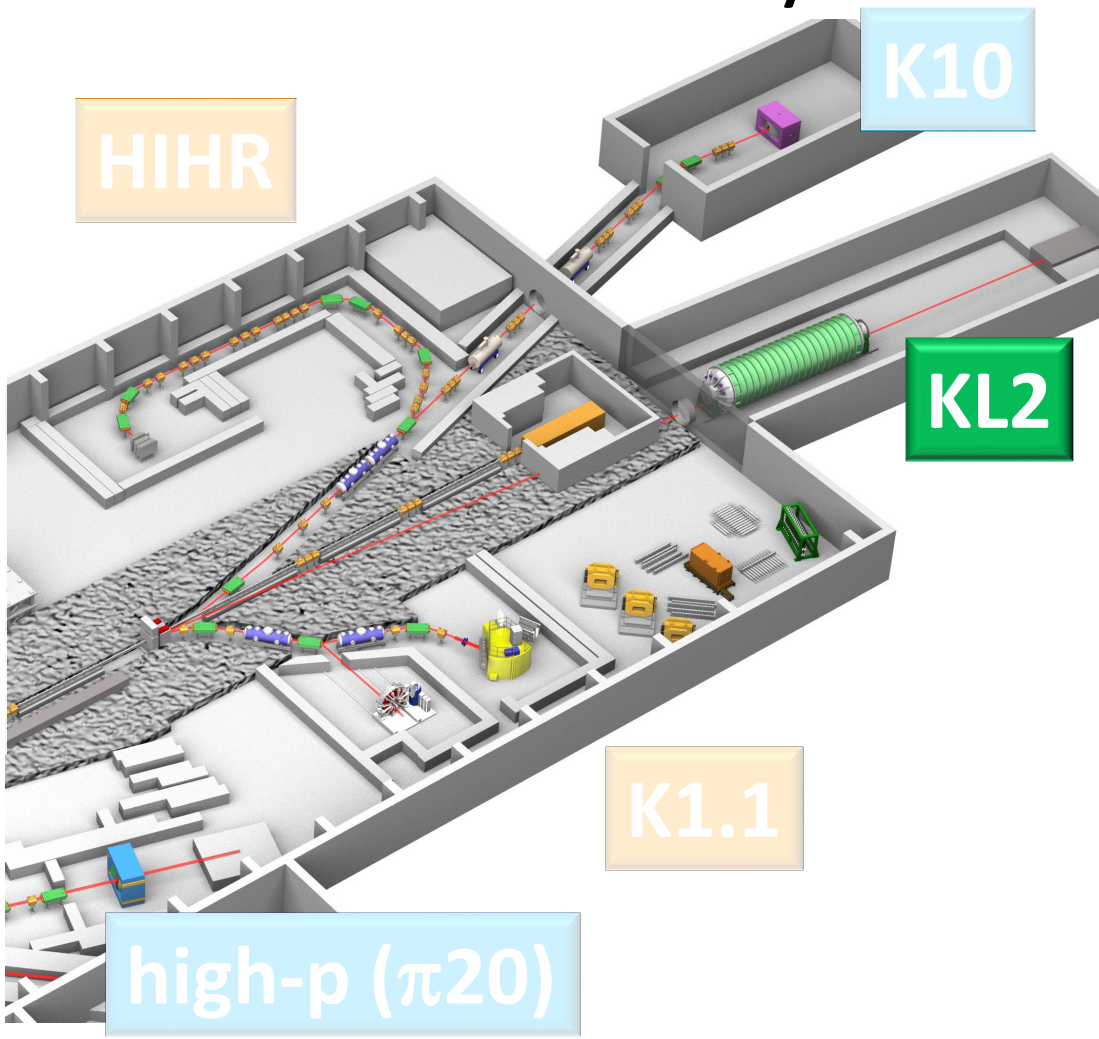
- intense high-momentum separated K beam

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

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

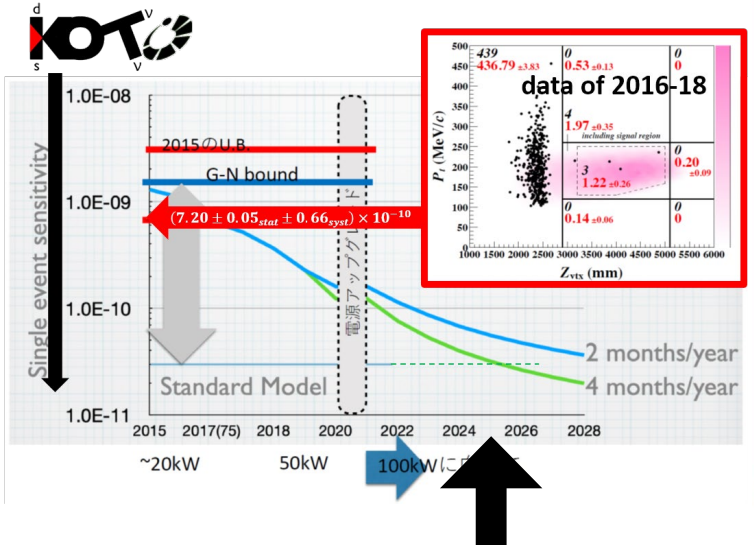
One of the best probes of new physics search

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

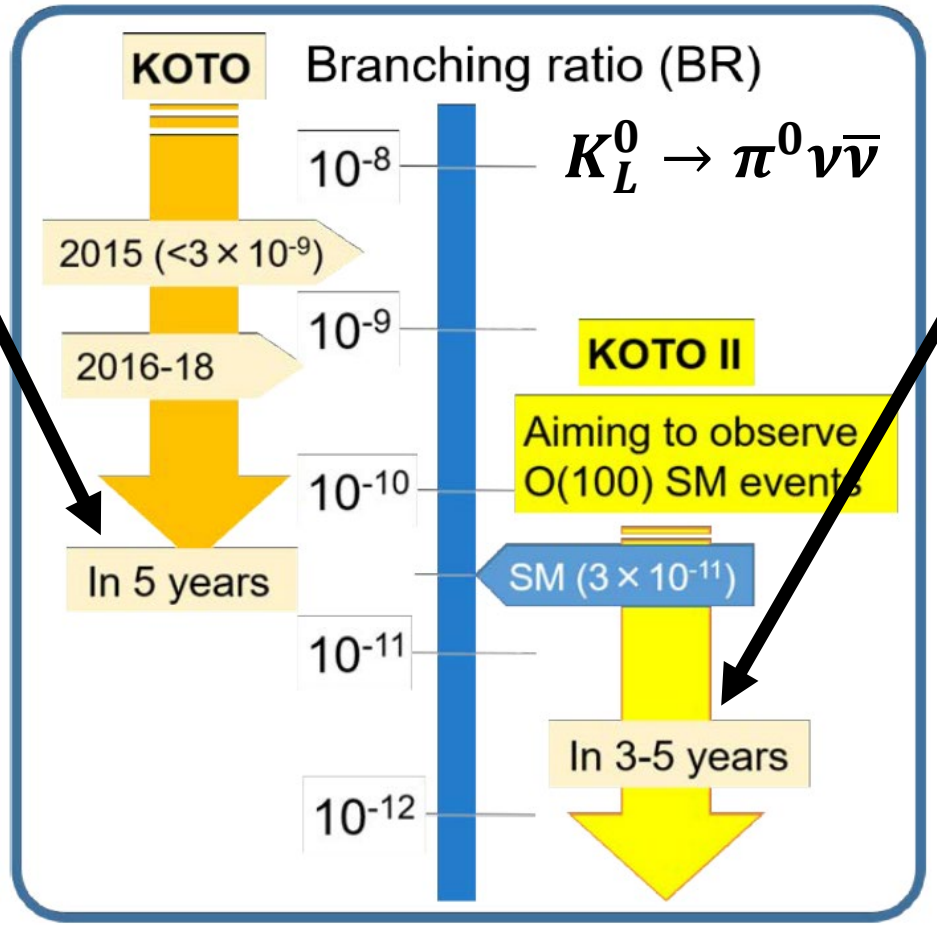
Present HEF

KOTO:

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



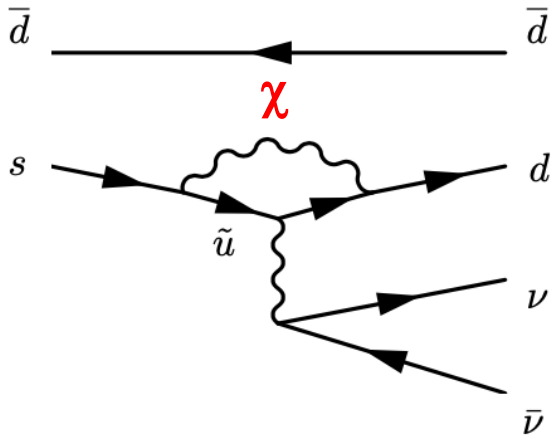
Sensitive to ~$O(100)$ TeV physics



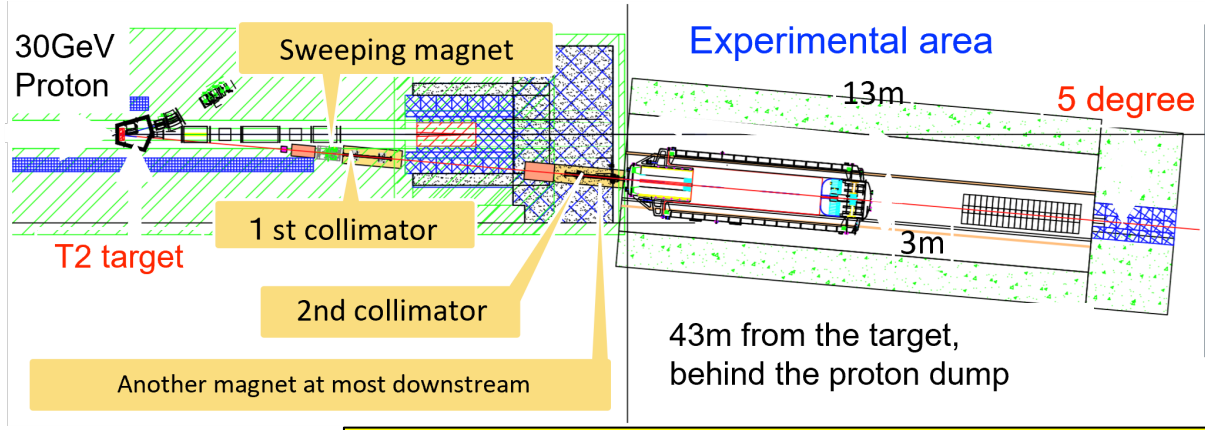
Extended HEF

KOTO Step-2:

- Will explore the region beyond the SM sensitivity

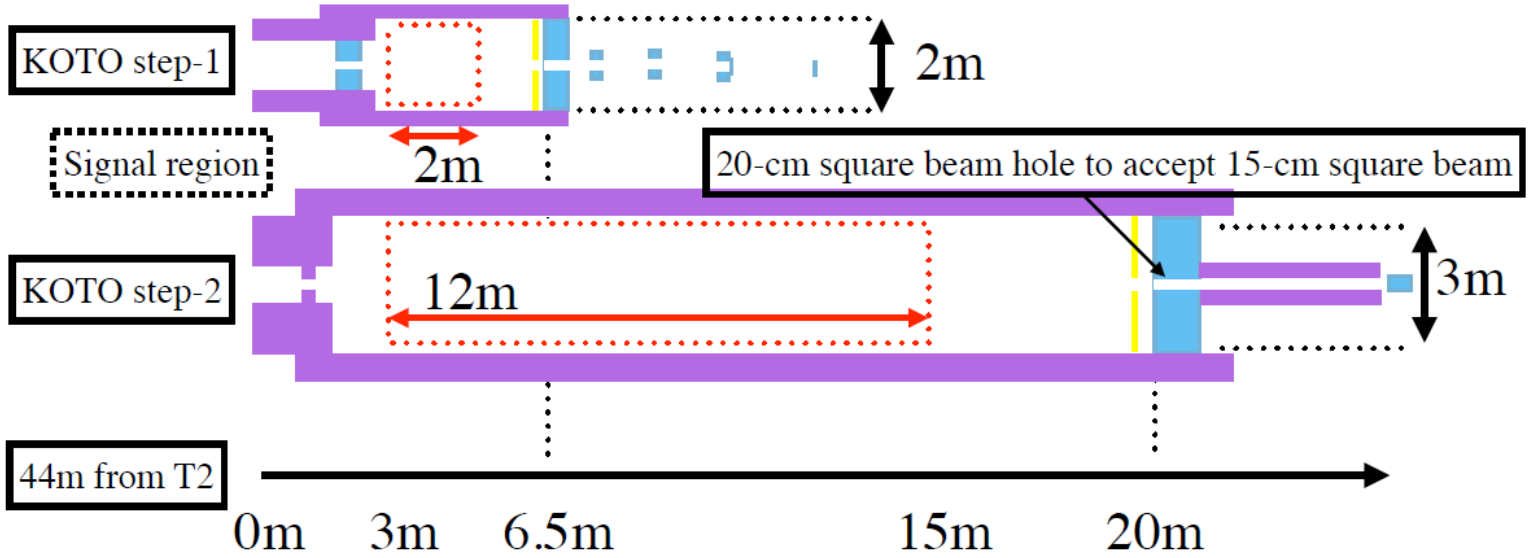


Flavor Physics: New Physics Search at KOTO



	Step1	Step2	Gain for KL yield
Production angle	16°	5°	x 5
Beam line length	20m	43m	x 0.8
Solid angle (μsr)	7.8	4.8	x 0.6
			= 2.6

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

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

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

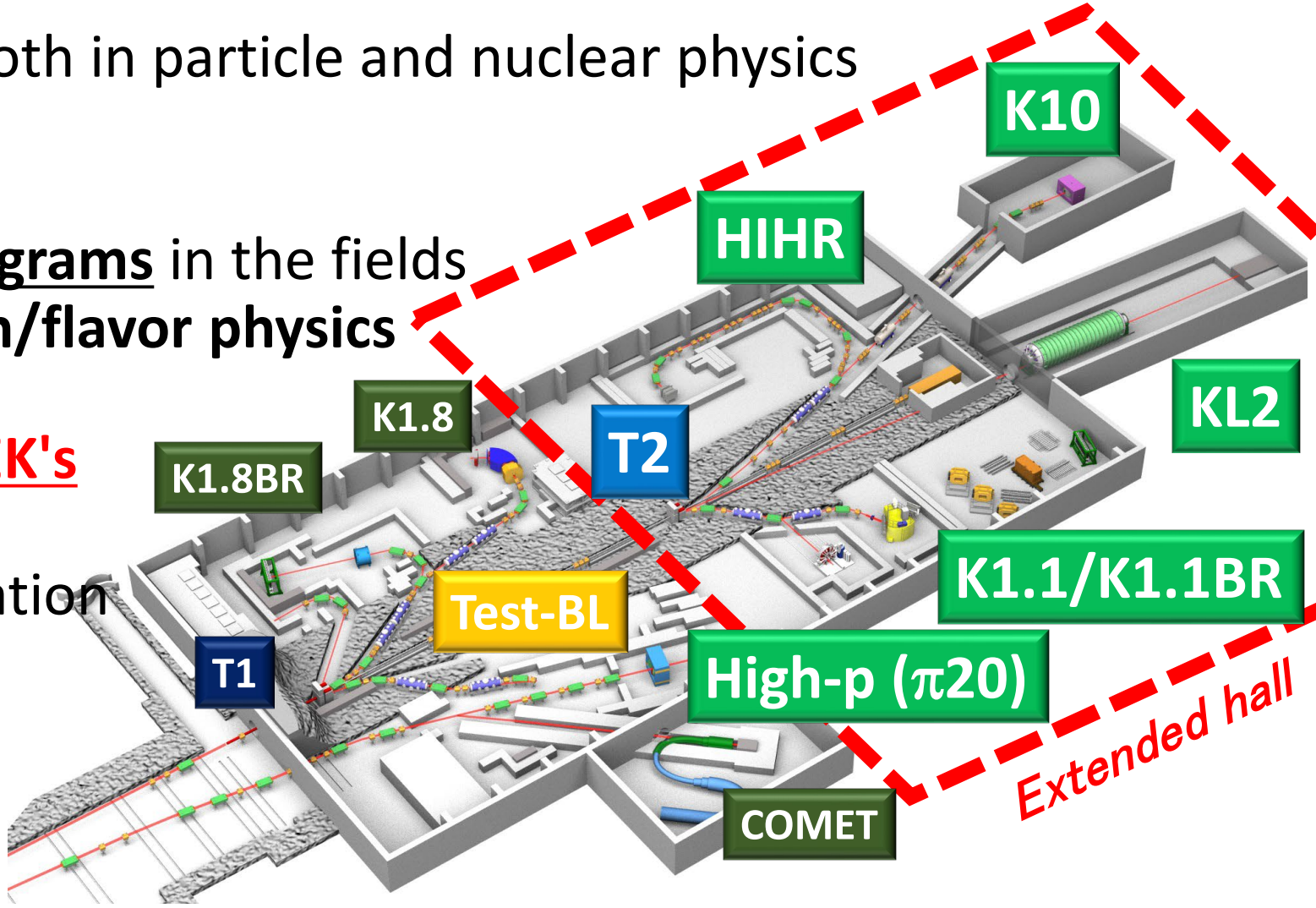
- **Unique research programs** both in particle and nuclear physics at high-intensity frontier

- **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

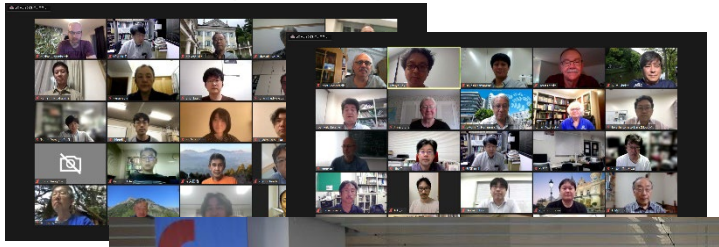
Stay tuned!



Thank you for your attention!

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

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

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

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