J-PARC

Japan Proton Accelerator Research Complex

J-PARC Hadron Hall Extension Project

F.Sakuma, RIKEN

on behalf of HEF-ex TF

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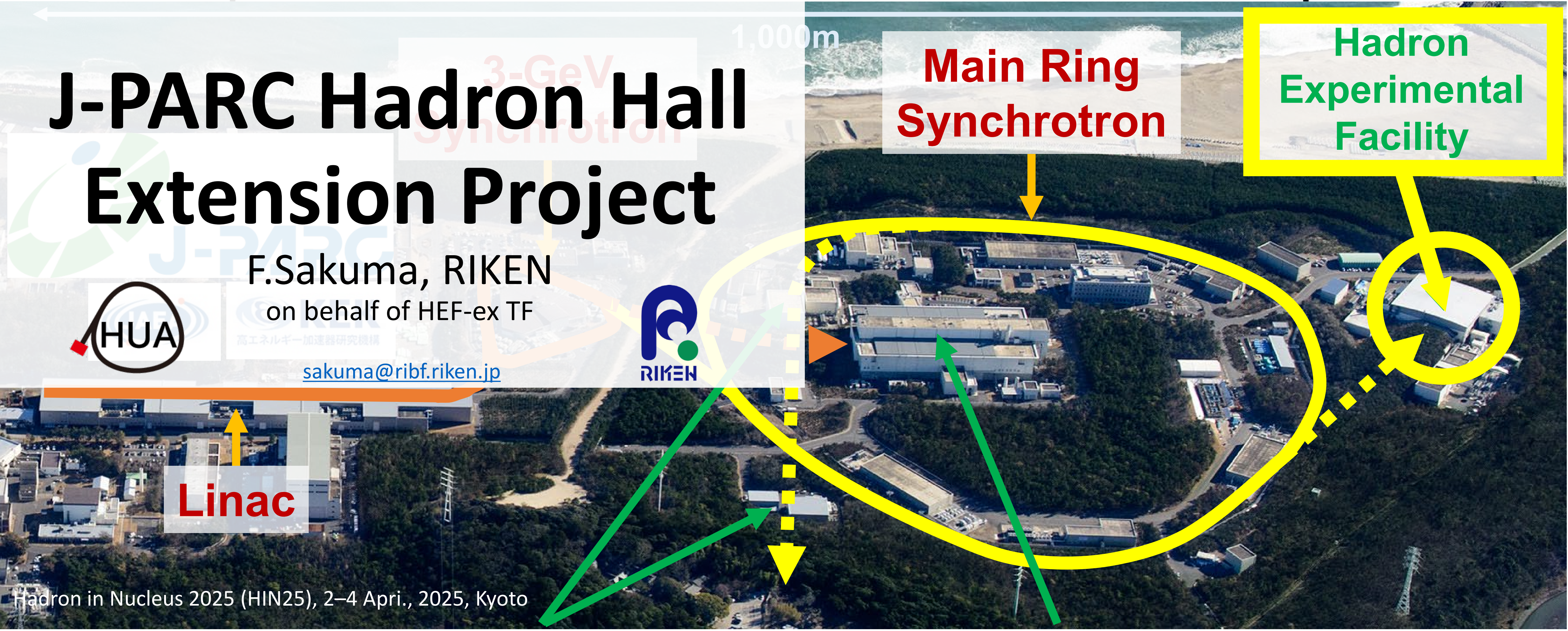
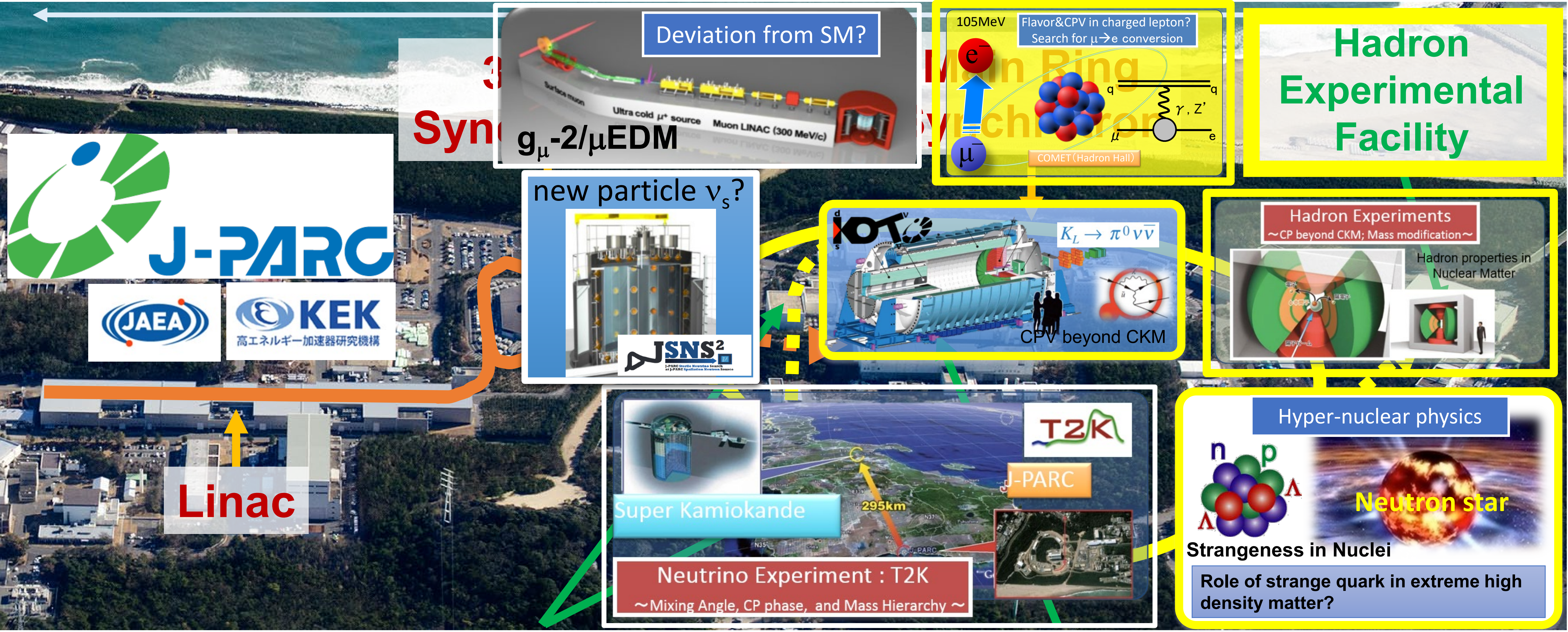
Hadron in Nucleus 2025 (HIN25), 2–4 Apri., 2025, Kyoto



Particle and Nuclear Physics @ J-PARC



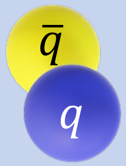
Neutrino Experimental Facility

Material and Life Science Experimental Facility

Origin & Evolution of Matter

Matter-Antimatter Symmetry

matter dominated universe



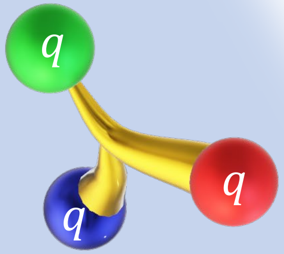
Flavor Physics

CP violation
weak interaction
→ new physics

Kaon rare decays
μ→e conversion

Origin of Matter Creation

formation of hadrons from quarks



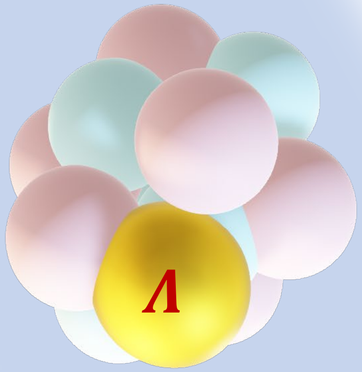
Hadron Physics

quark interactions
hadron mass-generation mechanism

Hadron spectroscopy
Meson in nuclei

Matter in Extreme Conditions

dense matter in neutron stars



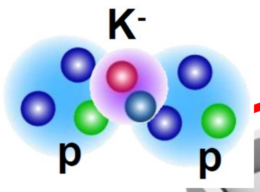
Strangeness Nuclear Physics

hadron interactions
hadronic many-body systems

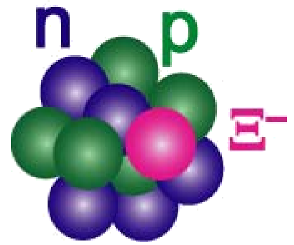
Hyperon-Nucleon scattering
Hypernuclear spectroscopy

Present Hadron Experimental Facility (HEF)

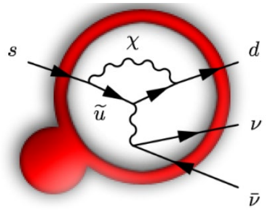
- < 1.1 GeV/c
- ~ 5x10^{5} K^{-}/spill
- **Kaon in nuclei**

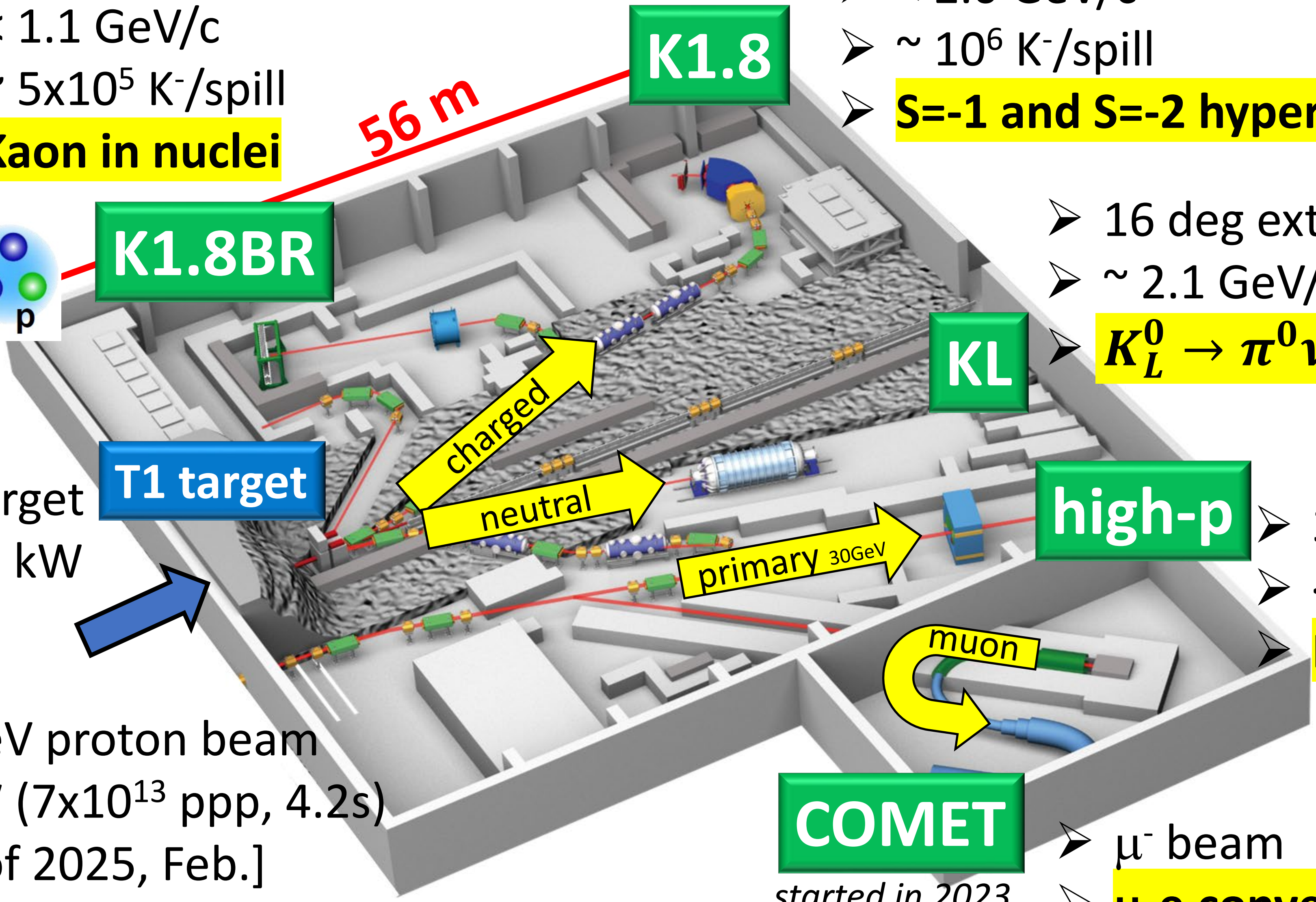


- < 2.0 GeV/c
- ~ 10^{6} K^{-}/spill
- **S=-1 and S=-2 hypernuclei**



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

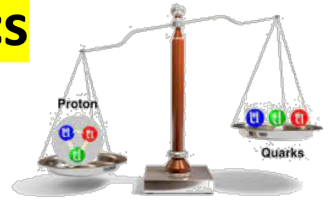




- Au Target
- < 115 kW

launched in 2020

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



- 30 GeV proton beam
- 84kW (7x10^{13} ppp, 4.2s)
  [as of 2025, Feb.]

started in 2023

- μ^{-} beam
- **μ-e conversion**

Achievements in research at the Hadron Experimental Facility

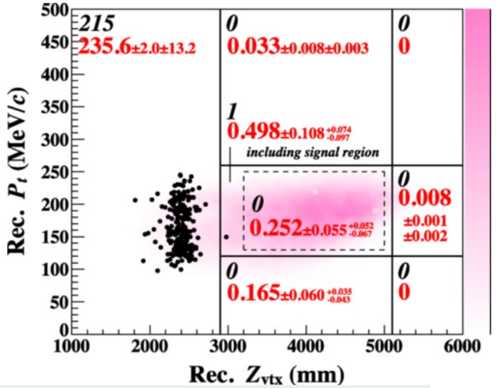
Flavor Physics

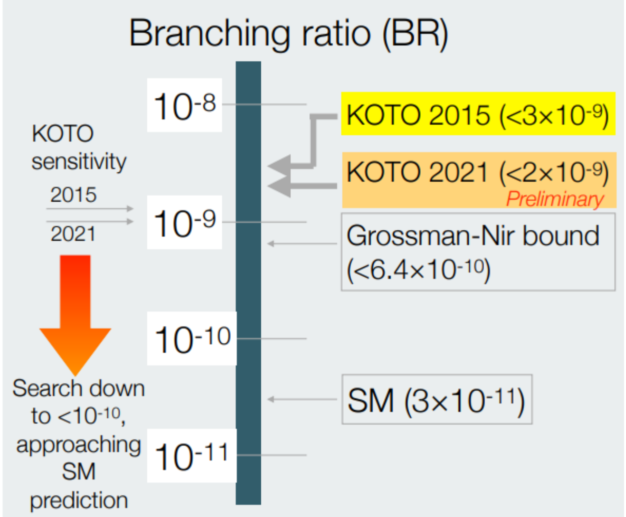
$K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$ search @ KOTO

→ Approaching the SM sensitivity for CP violation

KOTO 2021

Single Event Sensitivity = 9×10^{-10}



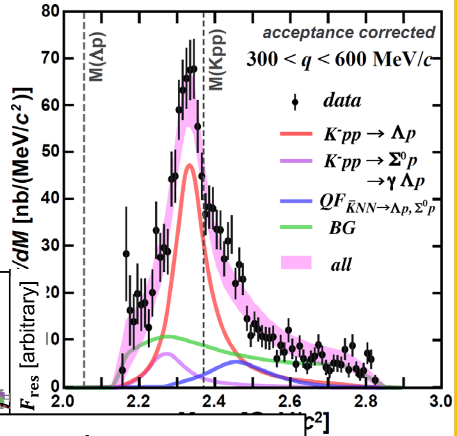


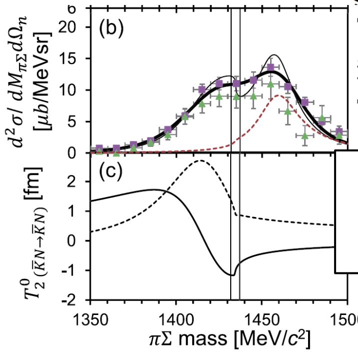
Hadron Physics

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

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

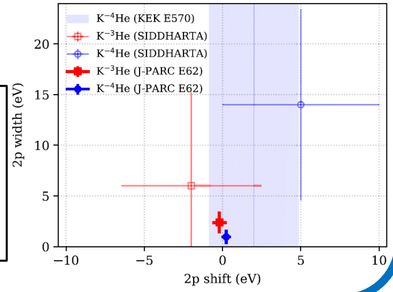
Kaonic nuclear state, "K-pp"





Pole position of $\Lambda(1405)$

Ultra-precise measurement of kaonic atoms

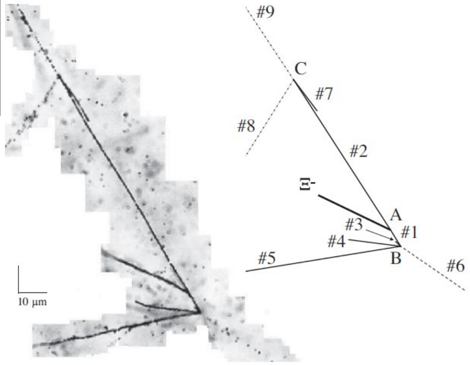


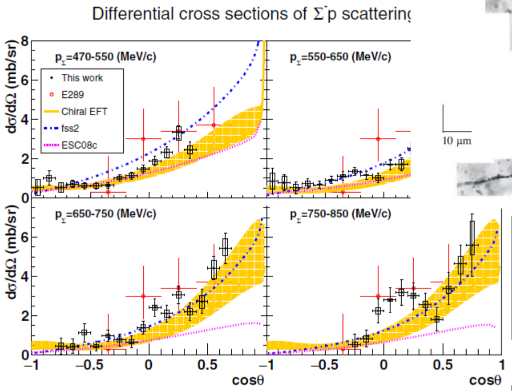
Strangeness Nuclear Physics

A lot of progress in hypernuclear research

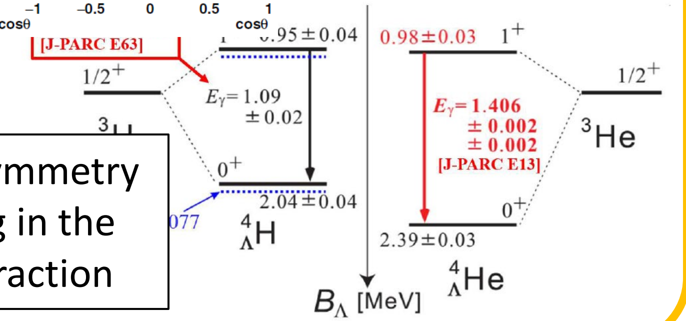
→ Clarified attractive S=–2 ΞN interaction and deepened S=–1 ΛN, ΣN interactions

Observation of Ξ hypernuclei





First precise ΣN scattering



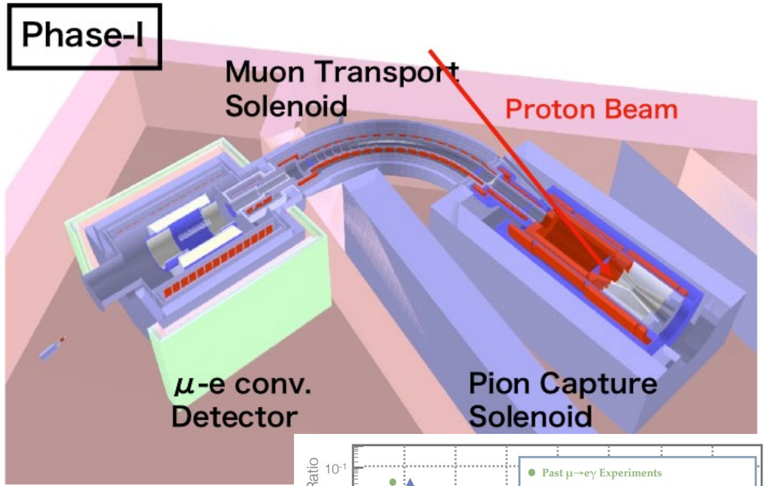
Charge-symmetry breaking in the ΛN interaction

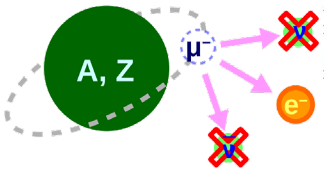
Further research directions at the Hadron Experimental Facility

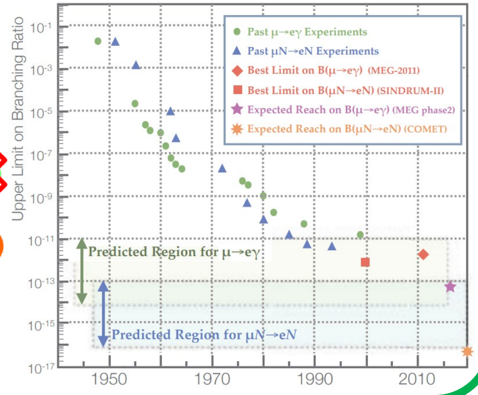
Flavor Physics

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

→ Search for charged lepton flavor violation



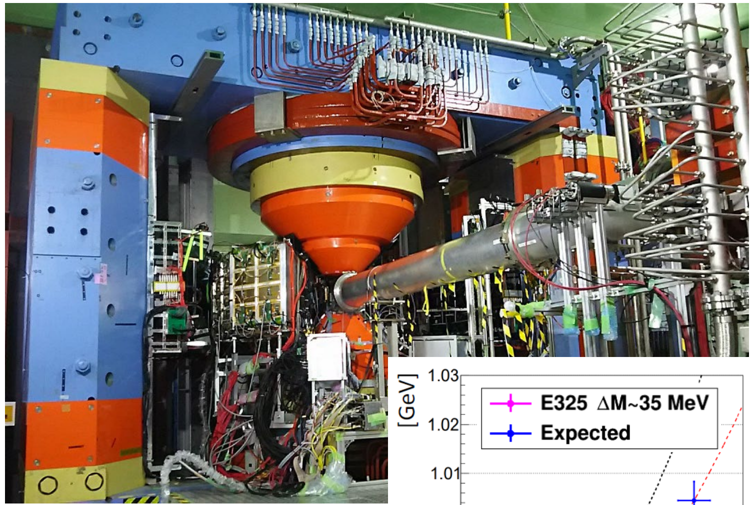


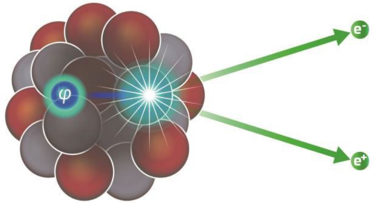


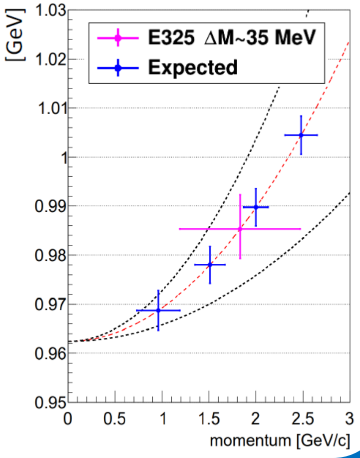
Hadron Physics

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

→ Attack mass-generation mechanism of hadrons



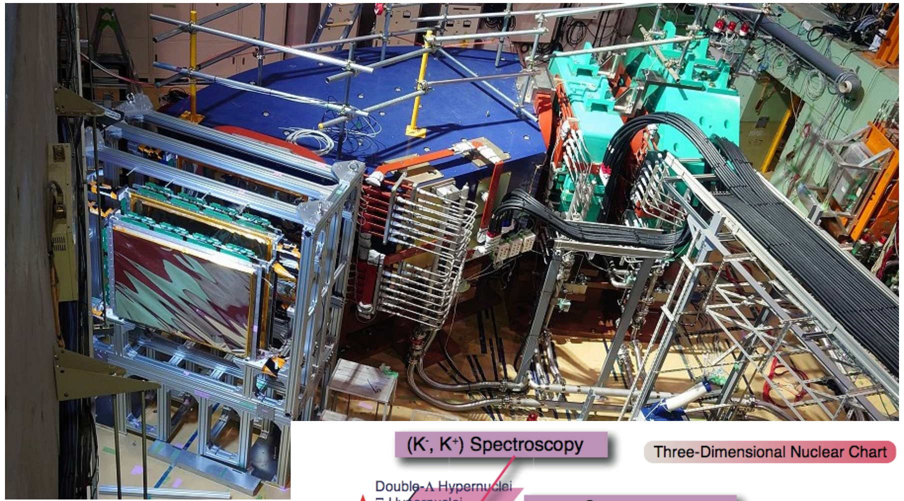


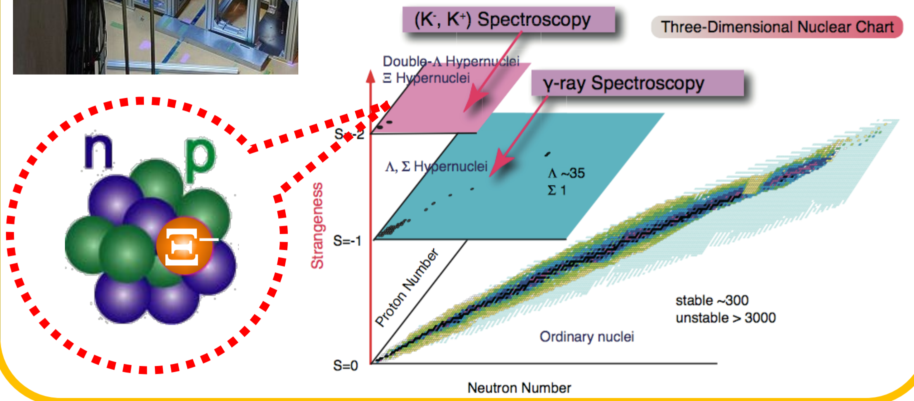


Strangeness Nuclear Physics

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

→ Provide accurate and systematic information on ΞN, ΛΛ interactions



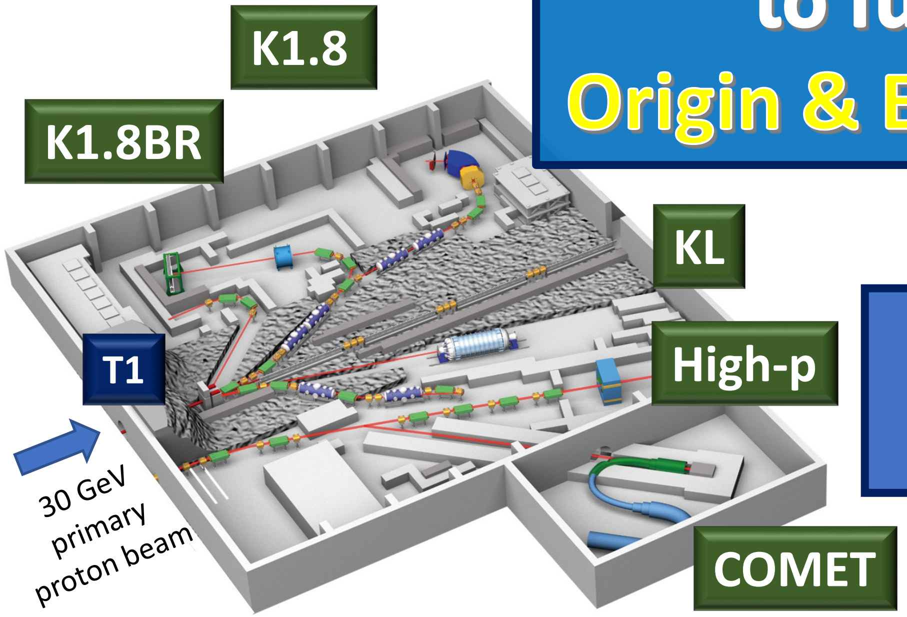


Hadron Experimental Facility extension (HEF-ex) Project

Hadron Experimental Facility extension (HEF-ex) Project

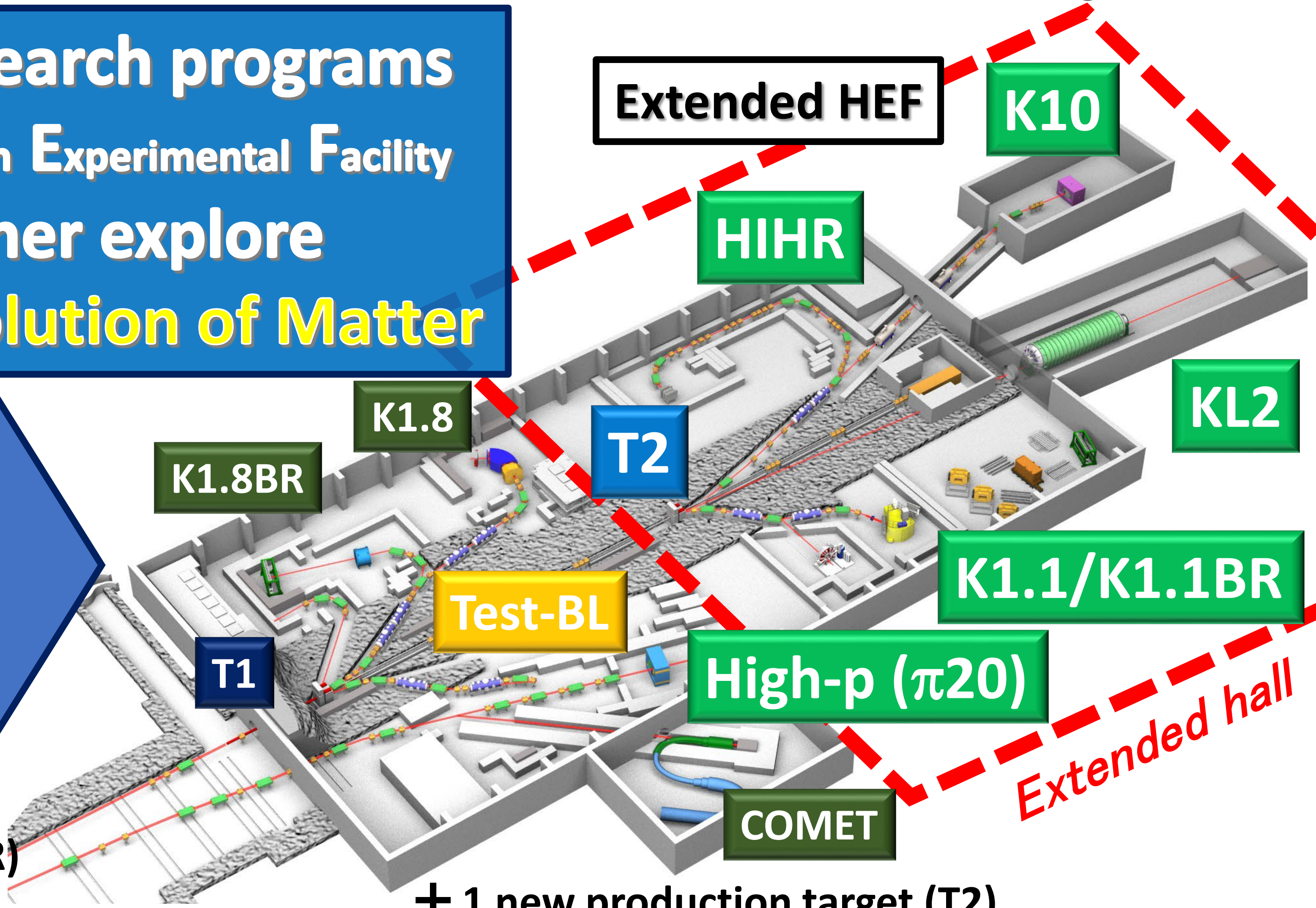
Present HEF (2009～)

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



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

Extended HEF



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

Expanded Research Programs

at the Extended Facility

Extract density dependent ΛN interaction

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

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

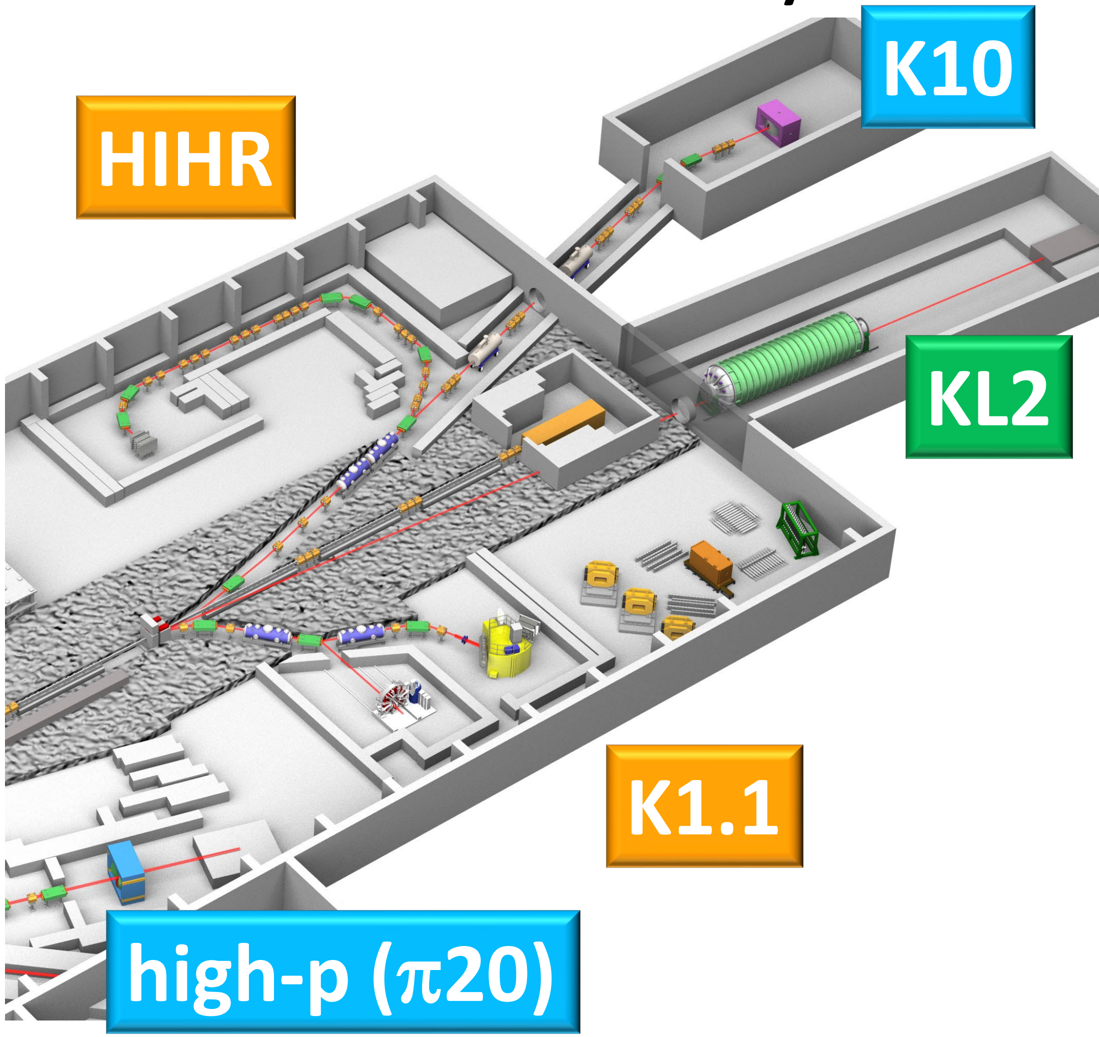
Investigate diquarks in baryons

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



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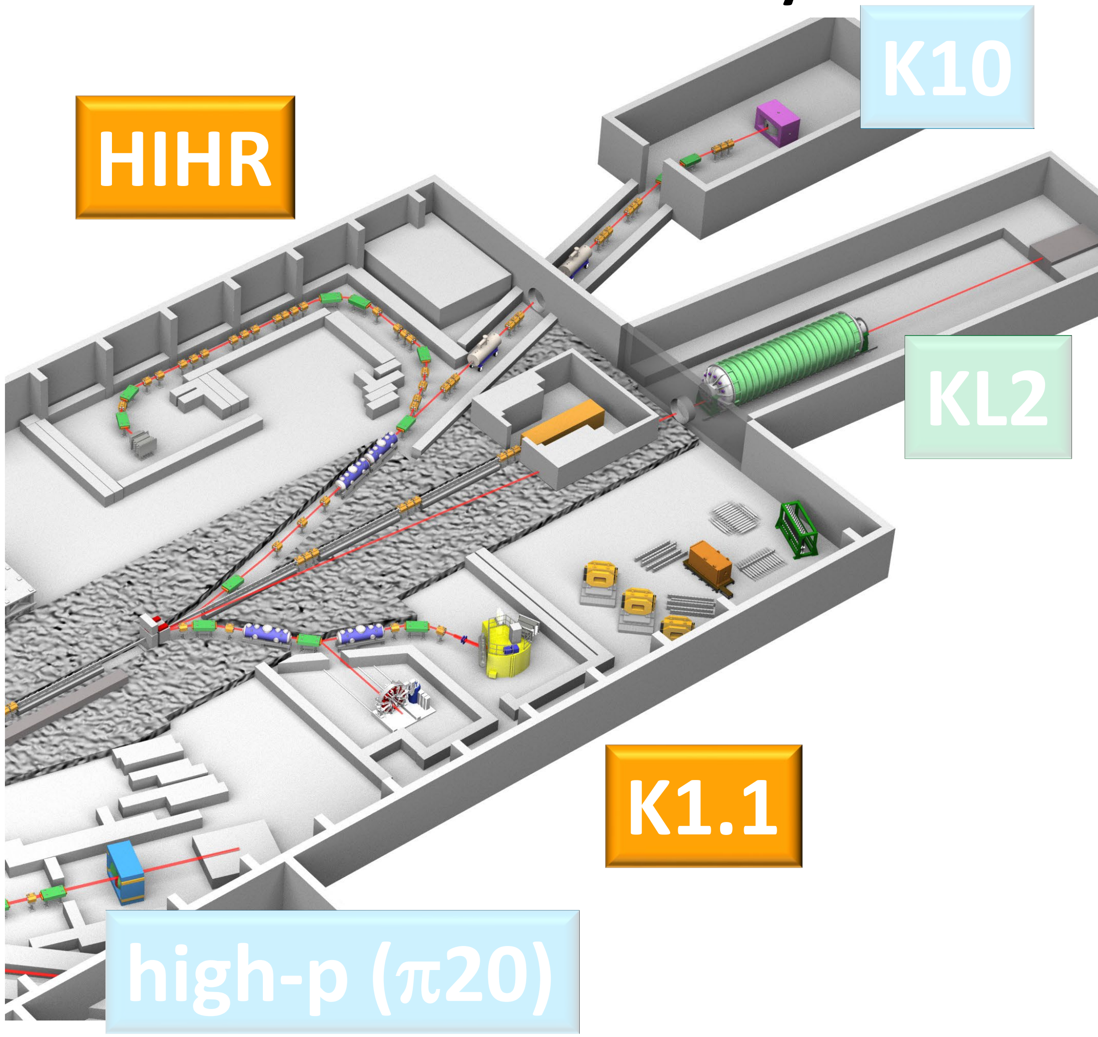
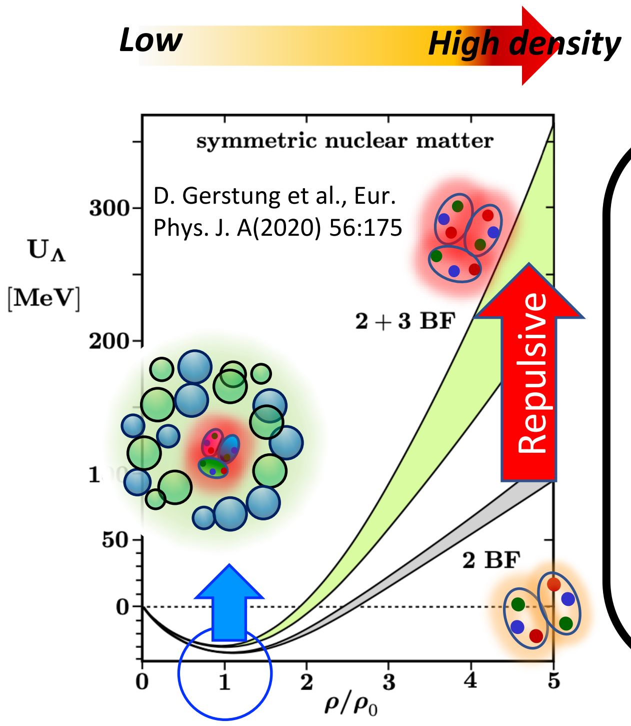


Strangeness Nuclear Physics: Hyperon in Dense Environment

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

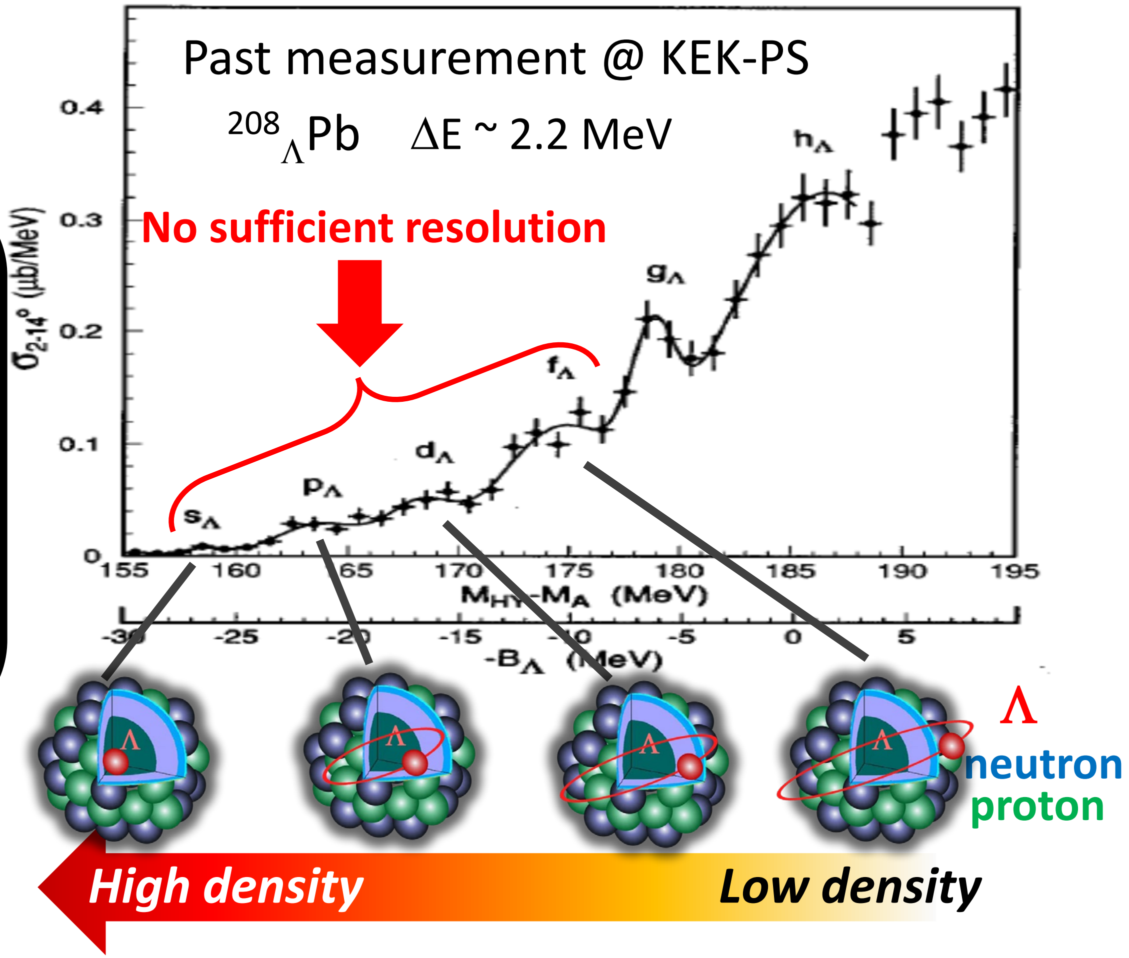
a tiny fraction of 3 Baryon Force effects

heavy Λ-hypernuclei :

Λ binding energies (B_Λ)

→ density dependent ΛN interaction

→ We need precise measurements

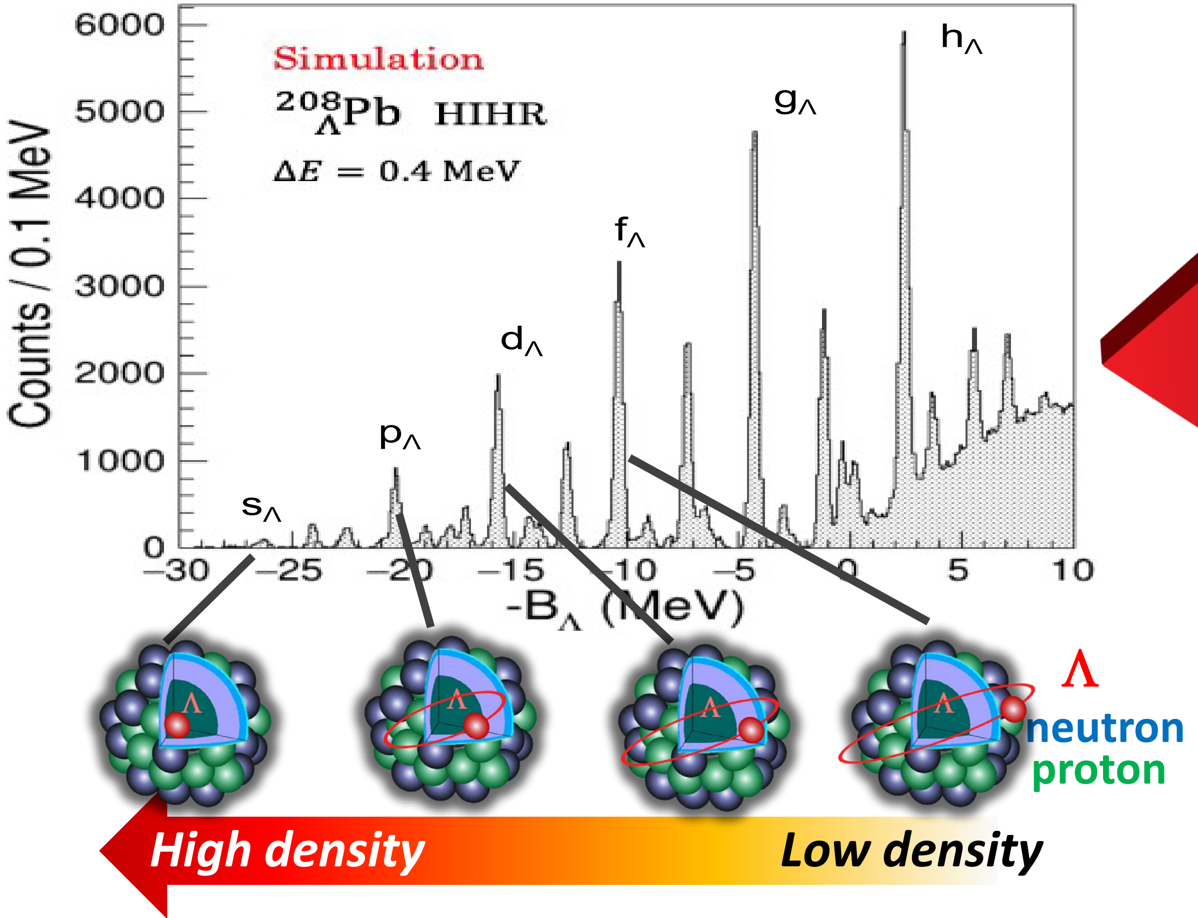


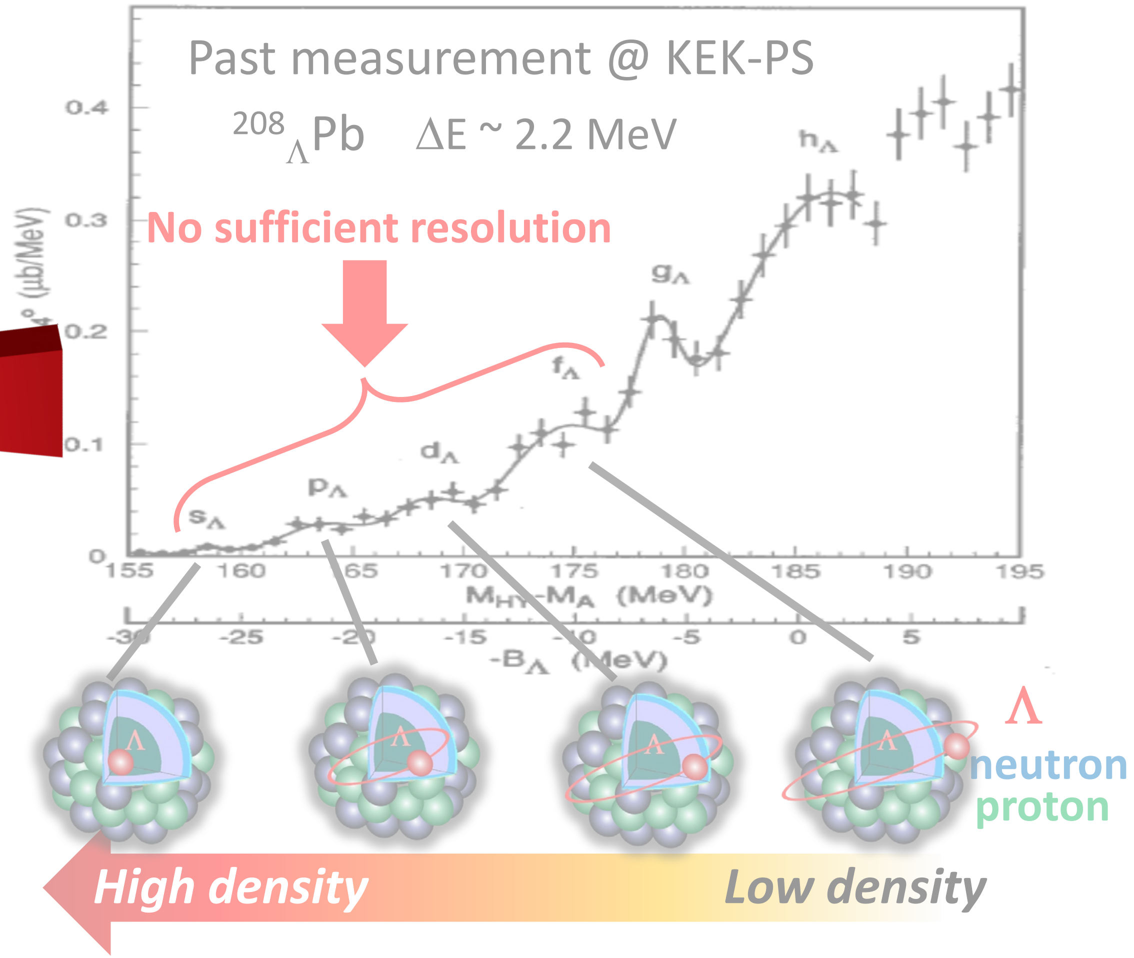
Strangeness Nuclear Physics: Hyperon in Dense Environment

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

Why can heavy neutron stars exist?

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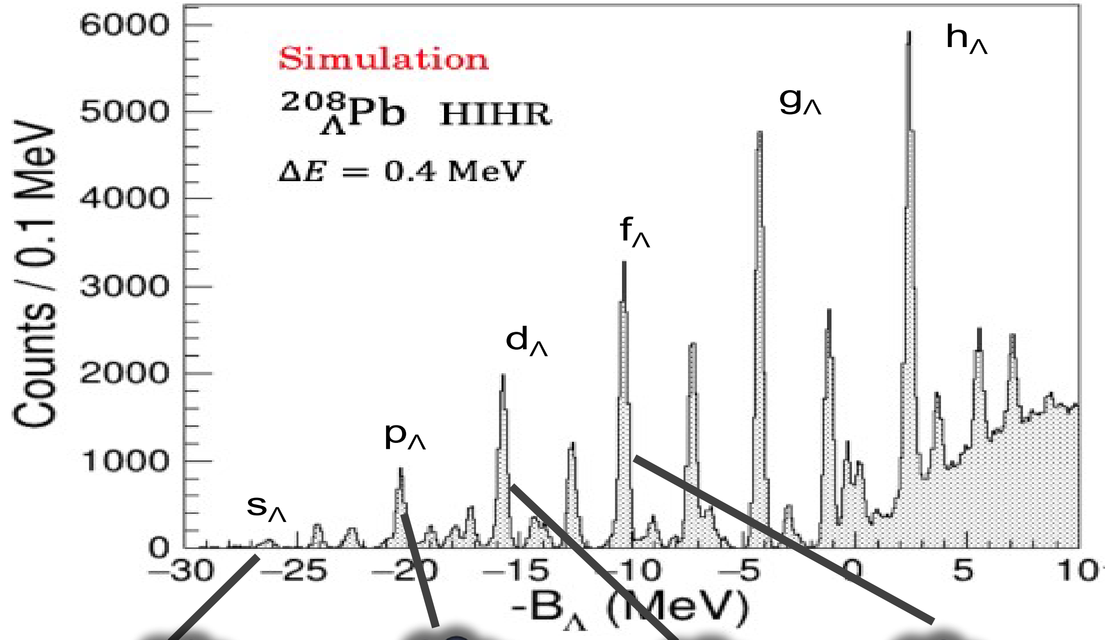
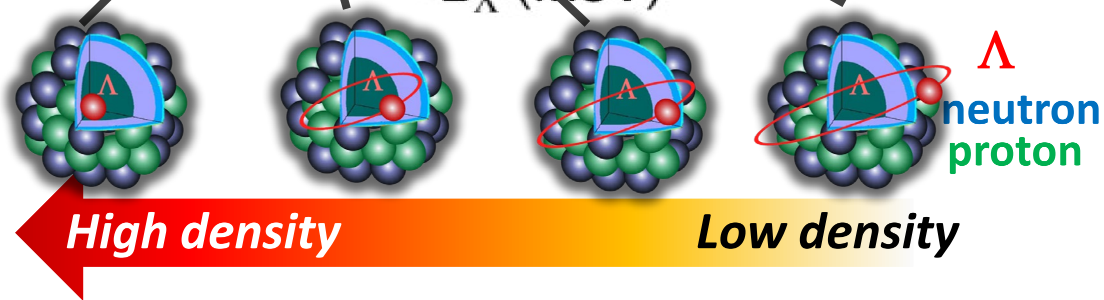
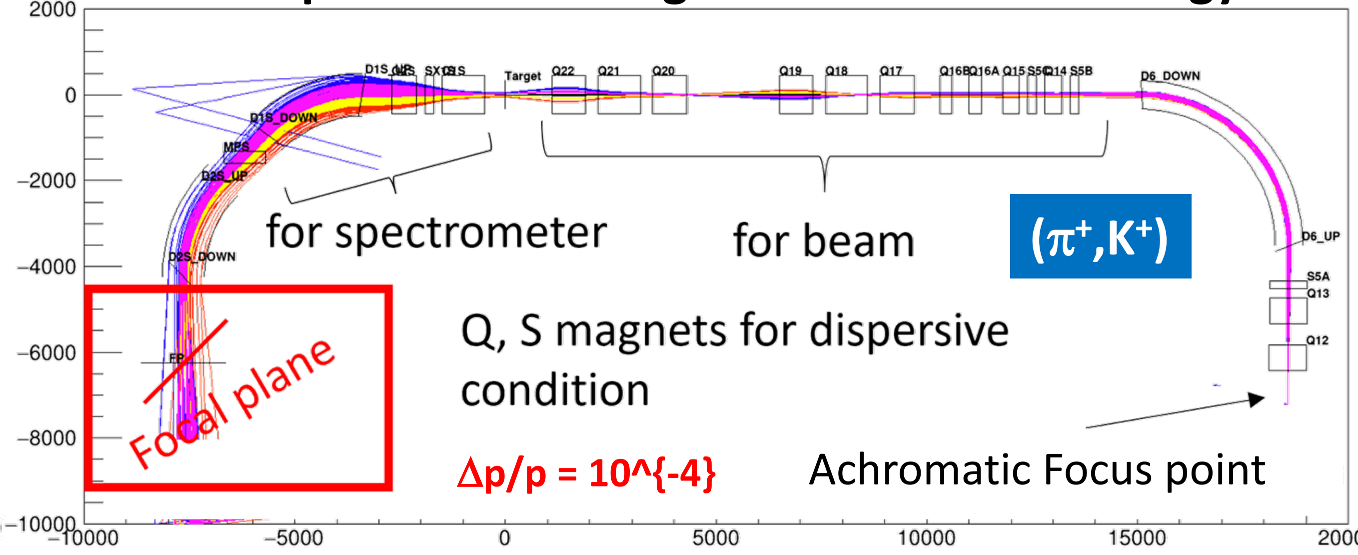
Ultra-high-resolution Λ-hyp. spectroscopy





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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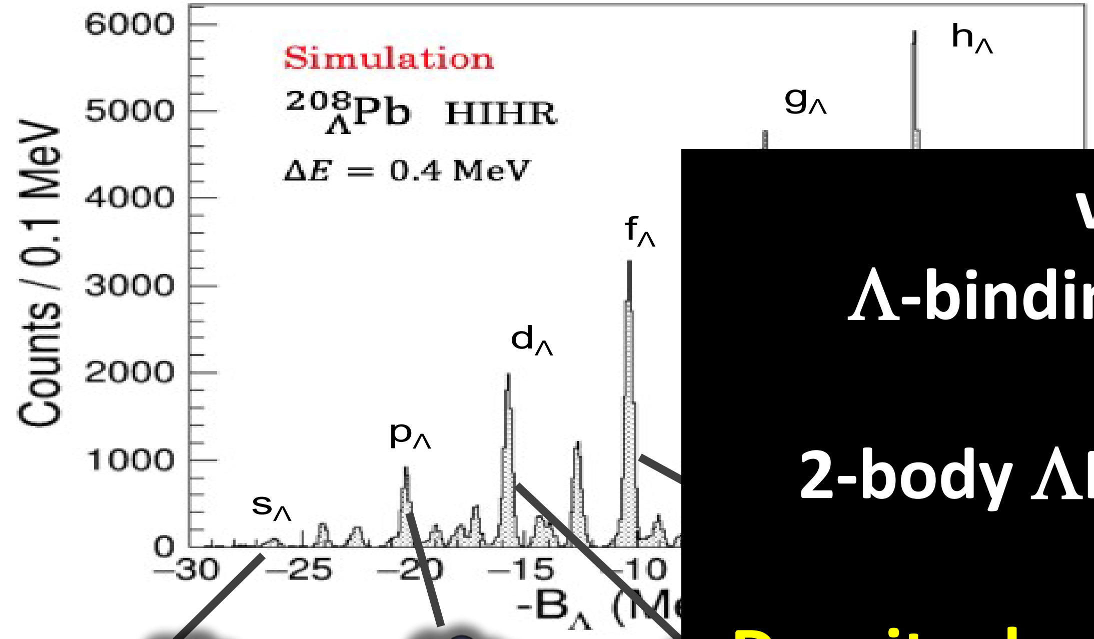
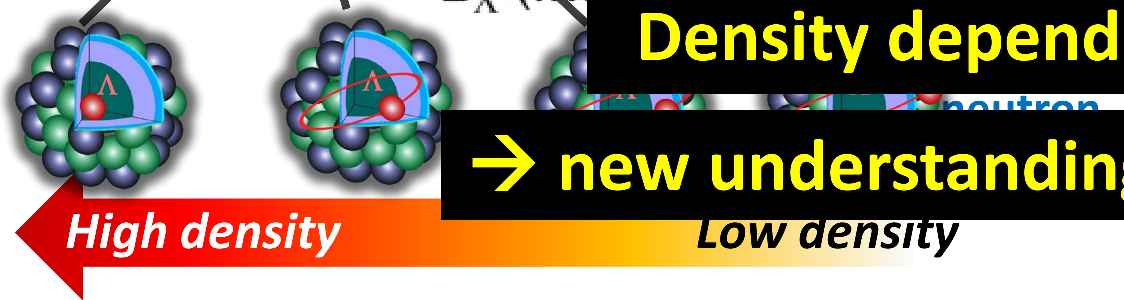
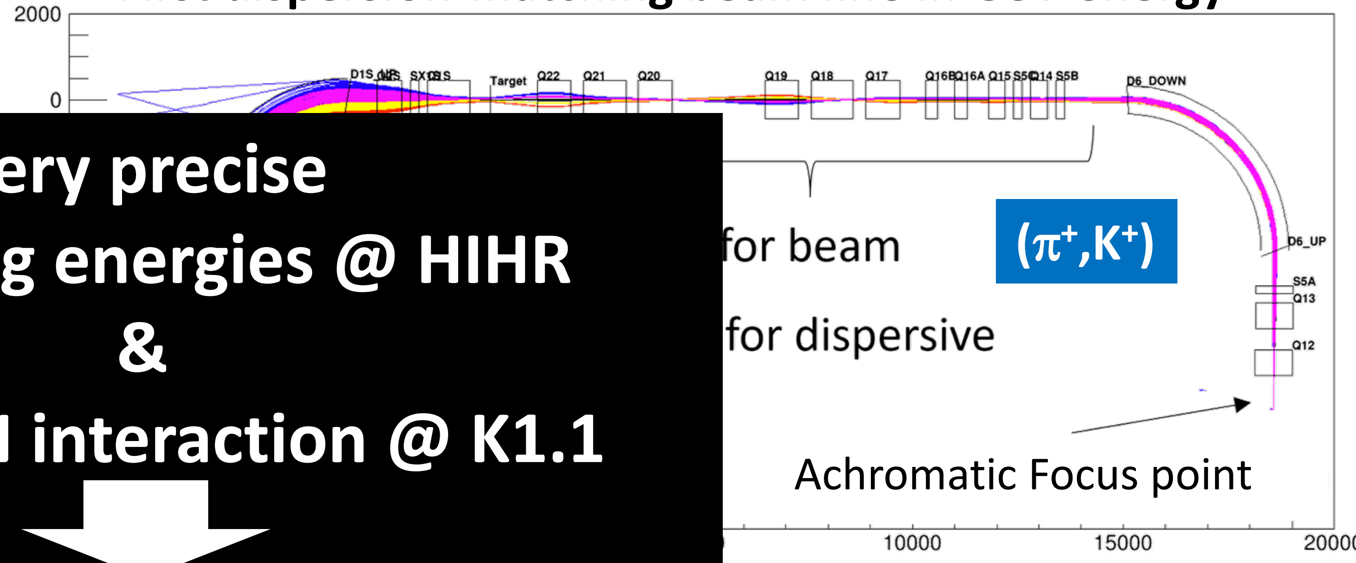




HIHR beam line (**H**igh-**I**ntensity **H**igh-**R**esolution)

First dispersion-matching beam line in GeV energy



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

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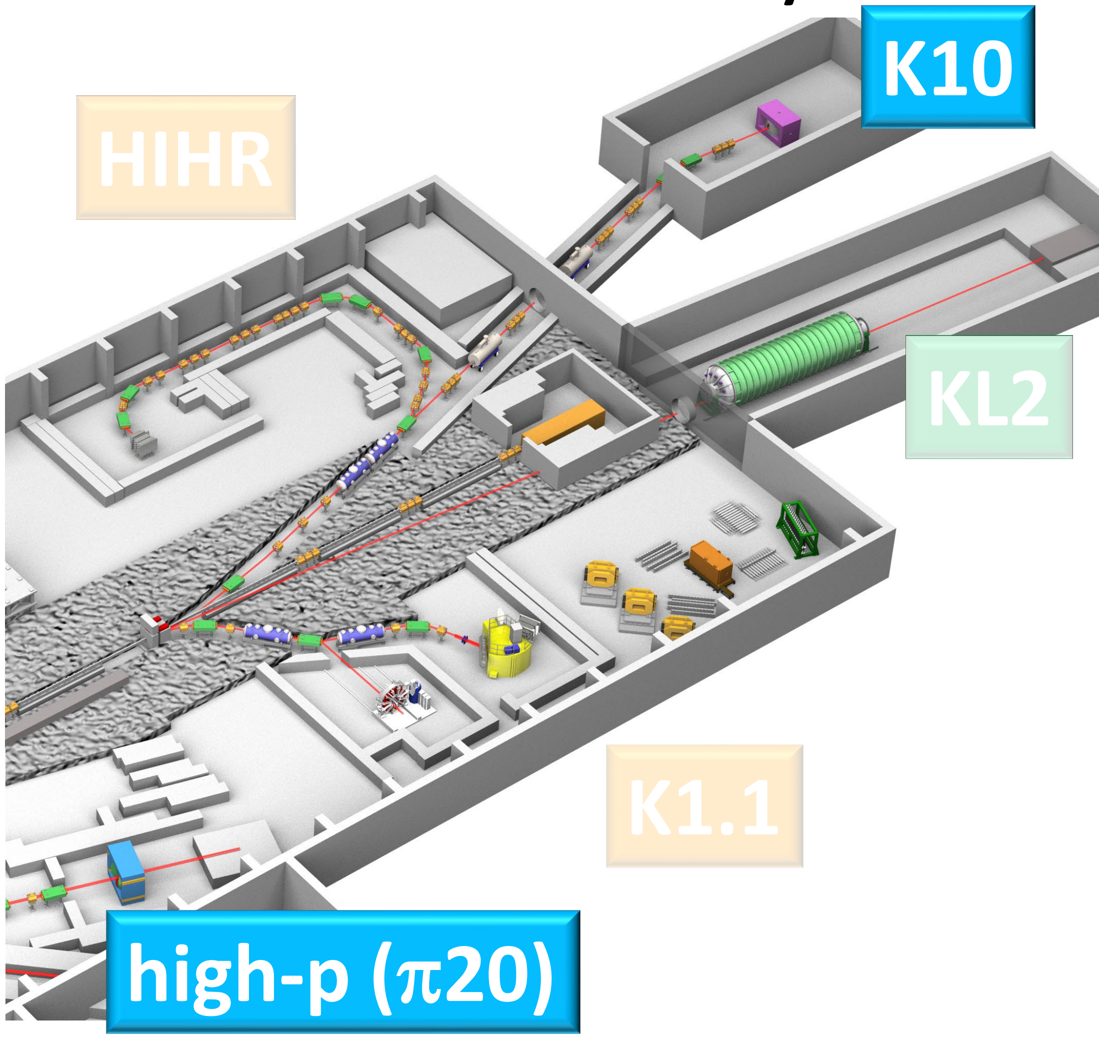


Behaver of non-perturbative QCD in low energy regime

Hadron Physics: Diquarks in Baryons

How quarks build hadrons?

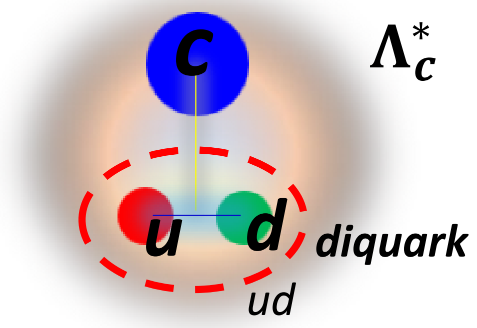
- Investigate **diquarks** in baryons **toward** understanding of **dense quark matter**

- **Charm Baryon Spectroscopy**

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

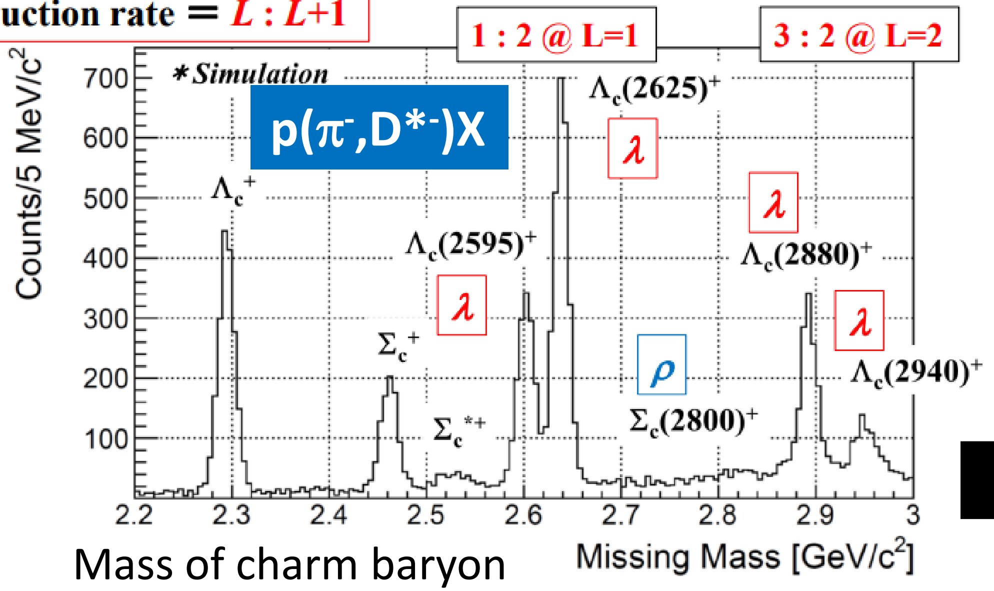
Establish a diquark (*ud*)

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

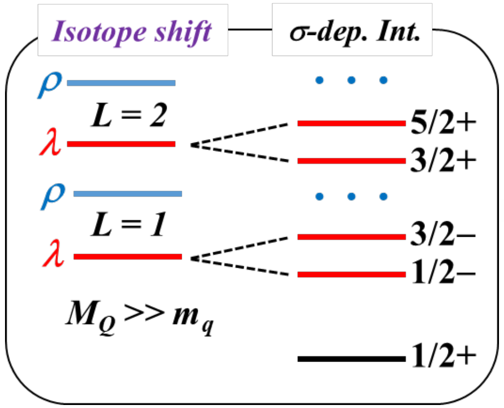


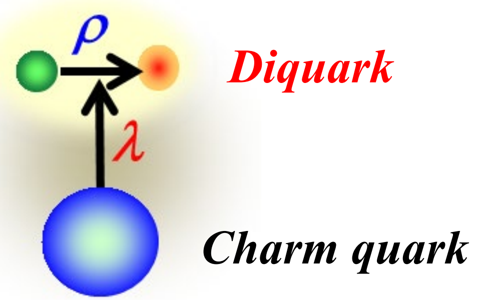
Production rate of charm baryon

∗ Production rate = *L* : *L*+1



Mass of charm baryon





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

Behaver of non-perturbative QCD in low energy regime

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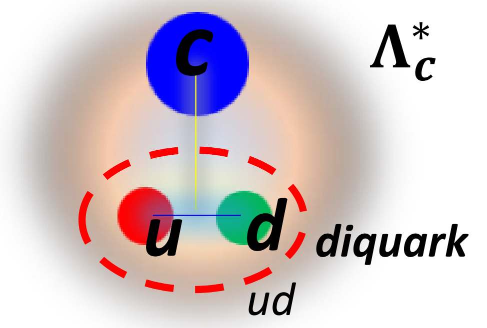


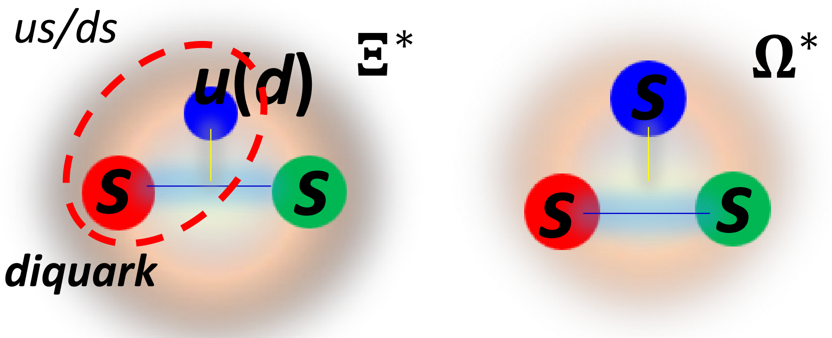
- **Multi-Strange Baryon Spectroscopy**
  using intense high-momentum K beam @ K10

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

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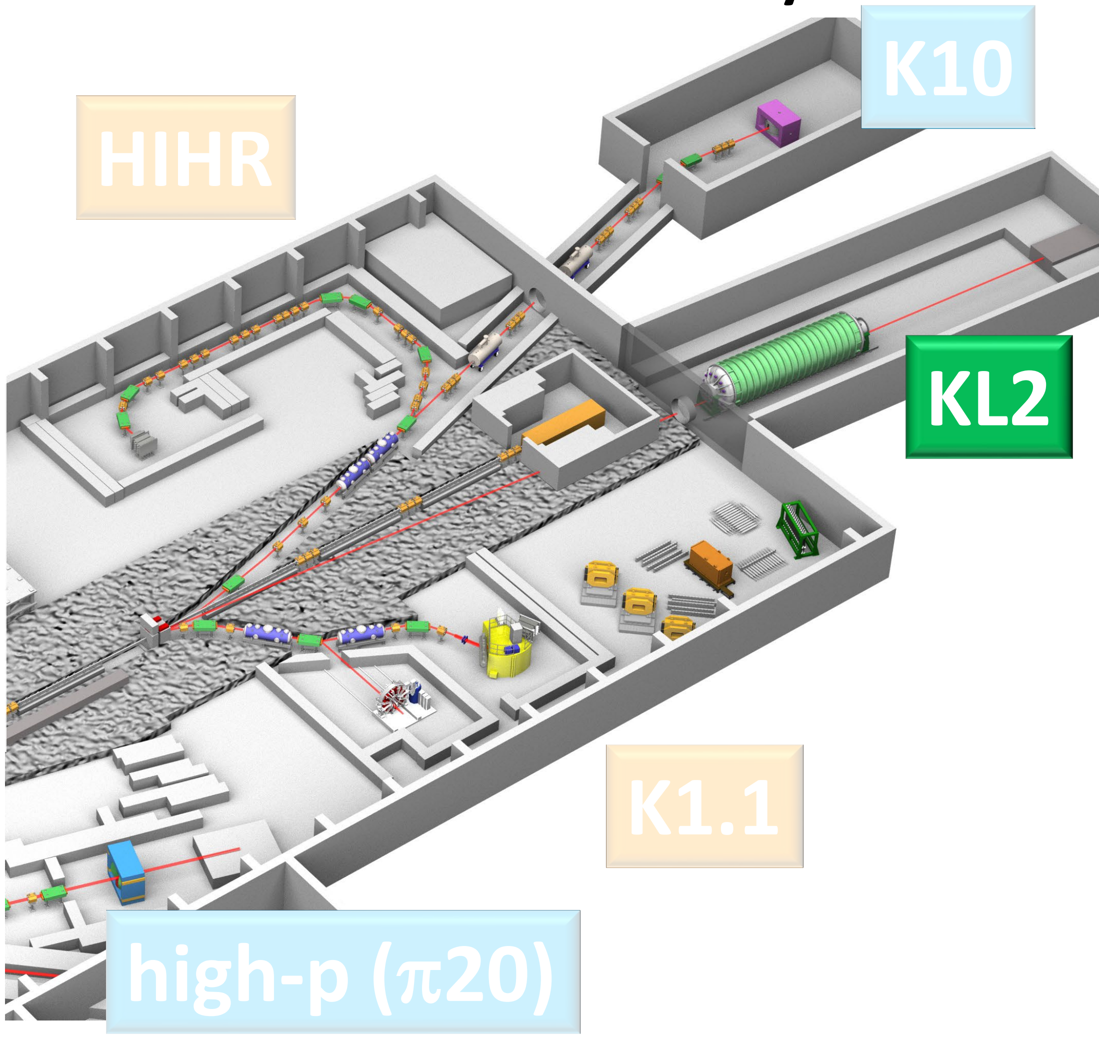
KL2 **Highest-sensitive $K_L^0 \to \pi^0 \nu \bar{\nu}$ measurement**

- intense neutral K beam



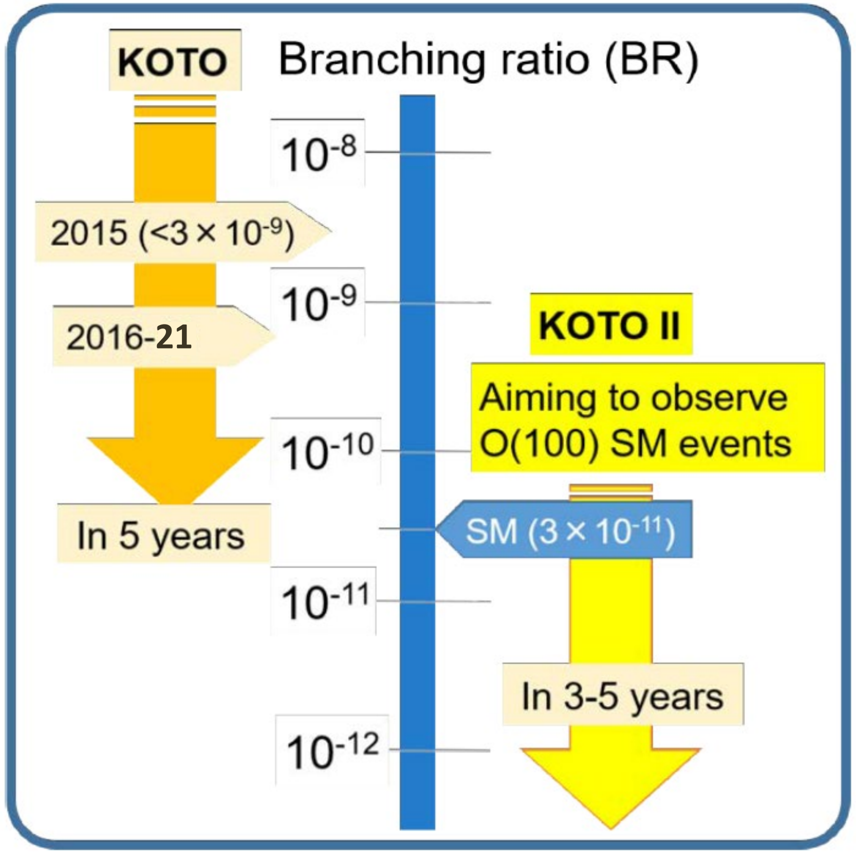
Flavor Physics: New Physics Search at KOTO Step-2

Is there new physics beyond the Standard Model?

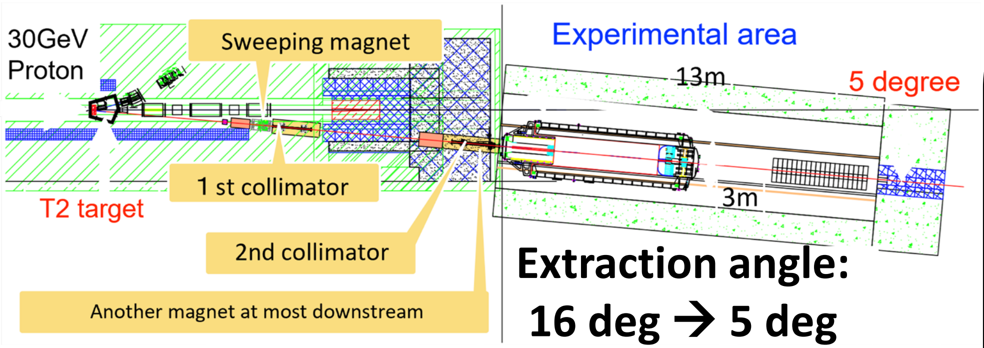
Rare kaon decay: $K_L^0 \rightarrow \pi^0 \nu \bar{\nu}$

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%)

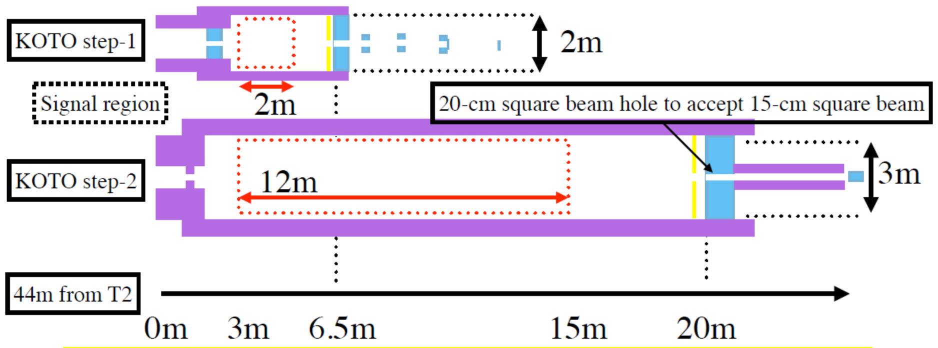


Sensitive to ~*O*(100) TeV physics



Extraction angle: 16 deg → 5 deg

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%

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 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

2022/06/24

KEK Science Advisory Committee

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

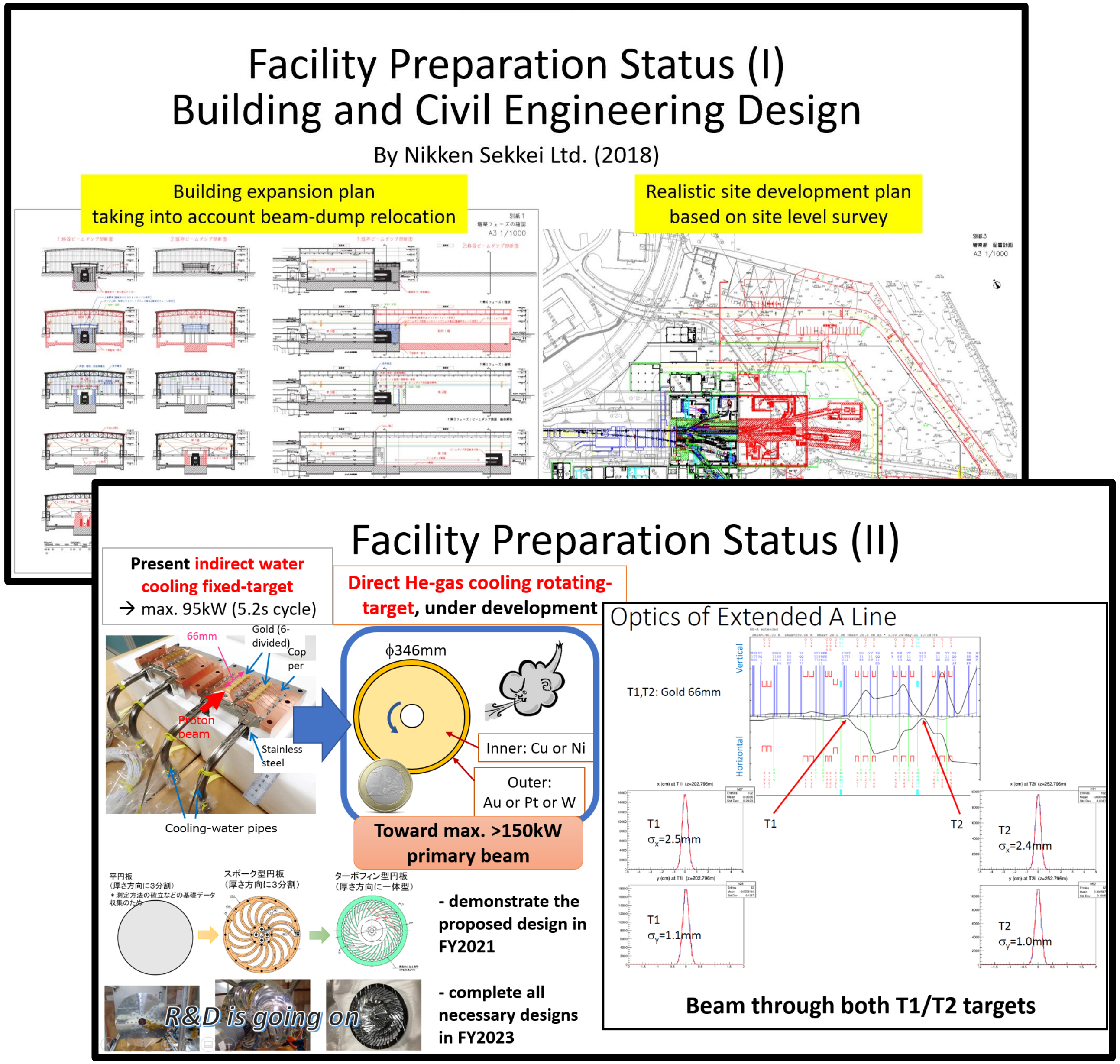
About KEK

What is KEK

Mission

Organization

Corporatedevelopment



Status of the Extension Project

top queue (carryover): **H-line and g-2/EDM**

PIP2016 (2016-21)		
1st	J-PARC upgrade for Hyper-K	DONE
2nd	HL-LHC/ATLAS	DONE
3rd	H-line and g-2/EDM	
4th	**HEF Extension**	

PIP2022 (2022-27)	
1st	**HEF Extension**
2nd	Contribution to HL-LHC
3rd	LiteBIRD
4th	Transmission Muon Microscope

- g-2/EDM remains in the "queue" of budget requests
  - ➢ HEF-ex is considered as the next to g-2/EDM.
- Construction cost has been increased.
  - ➢ (150+15) Oku-yen at PIP2022 → (200+20) Oku-yen after COVID-19/Ukraine-War
- Cost reduction/optimization, staging plans with smaller steps, and seeking budgetary support from outside KEK are being discussed for early realization of the project.
  - ➢ We need community's help!

"International workshop" and "town meeting" on the Extension Project for J-PARC Hadron Experimental Facility 2025 (HEF-ex WS/town-meeting 2025)

- A workshop with the 2nd Town Meeting is planned as a pre-WS of HYP2025
  - aiming to promote broader international discussions
- September 26-27 (2 days)
  - 1.5 days for WS, 0.5 days for TM
- Venue: RIKEN (Wako)

September 9 2025

Sun	Mon	Tue	Wed	Thu	Fri	Sat
	1	2	3	4	5	6
7	8	9	10	11	12	13
14	15	16	17	18	19	20
21	22	23	24	25	26	27
28	29 HYP	30 HYP				

WS&TM (26–27)

October 10 2025

Sun	Mon	Tue	Wed	Thu	Fri	Sat
			1 HYP	2 HYP	3 HYP	4
5	6	7	8	9	10	11
12	13	14	15	16	17	18
19	20	21	22	23	24	25
26	27	28	29	30	31	

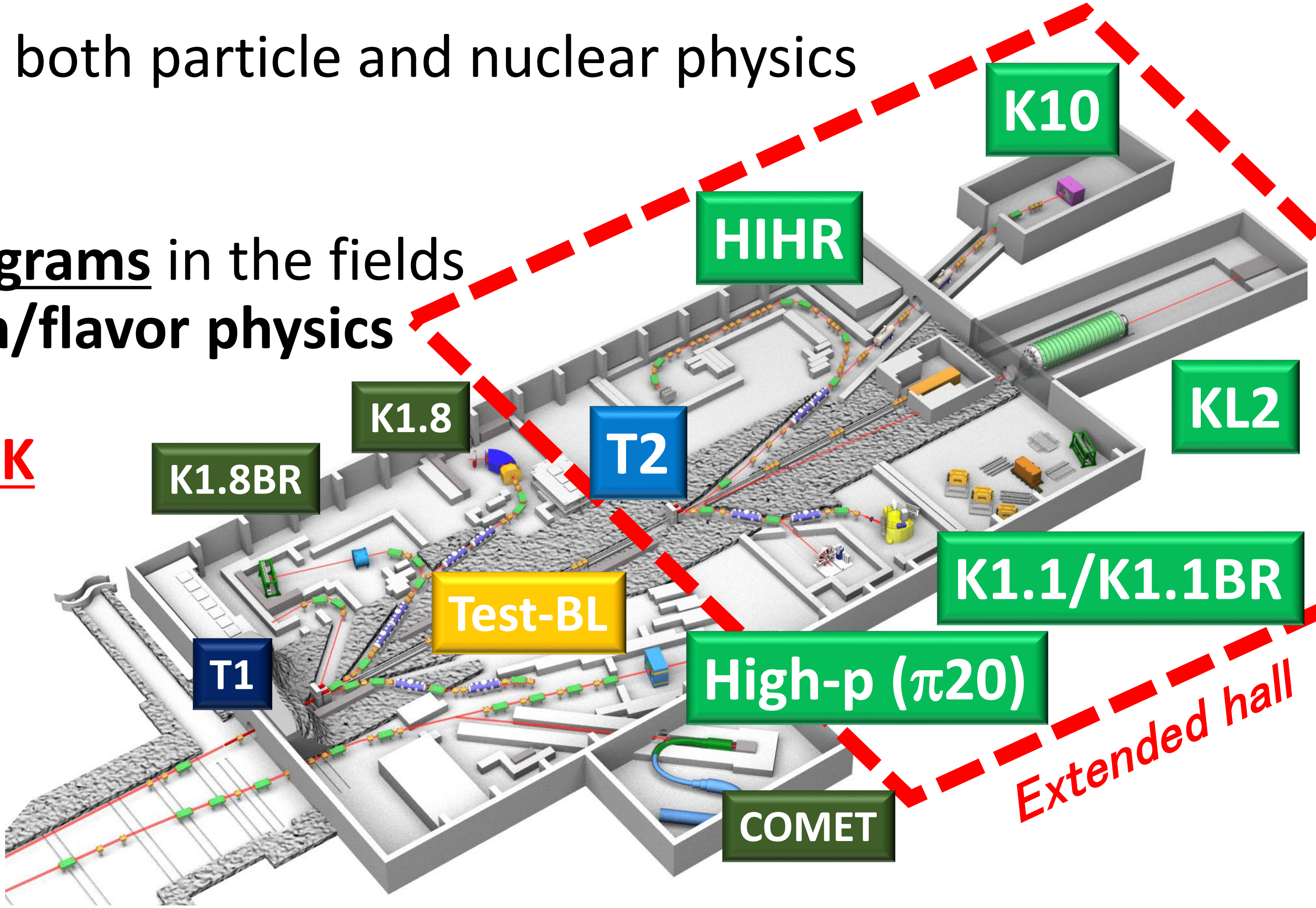
Summary of the Extension Project of the J-PARC Hadron Experimental Facility

- **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

Let's work together to make progress on the project!



Thank you for your attention!

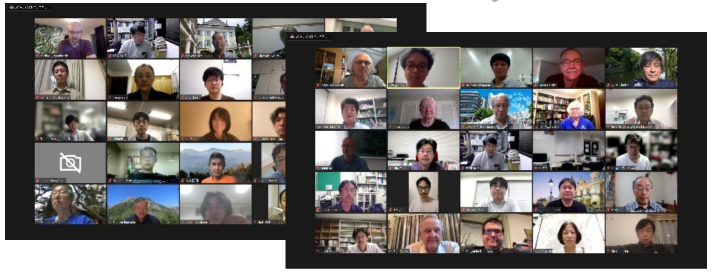
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html

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



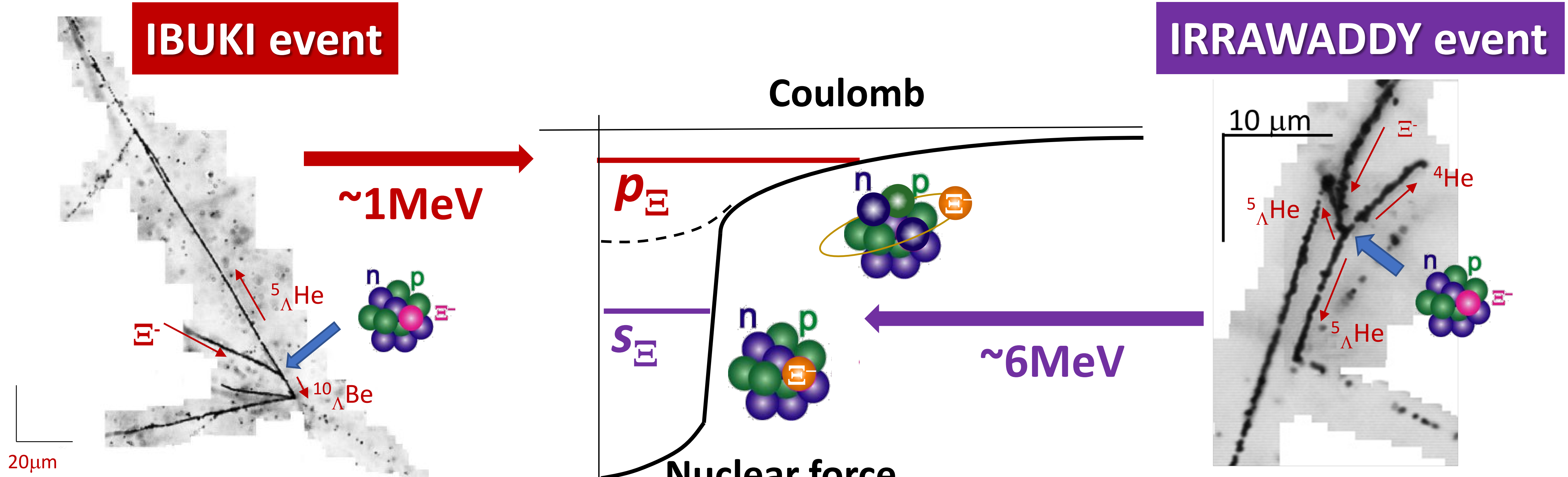
2nd J-PARC HEF-ex WS, Feb.16-18 2022, online

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

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

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

- <u>Attractive Ξ-nuclear potential</u> was confirmed from observation of Ξ-hypernuclei in emulsion at J-PARC (E07)



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

B_{Ξ^-} = 1.27 ± 0.21 MeV

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

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

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

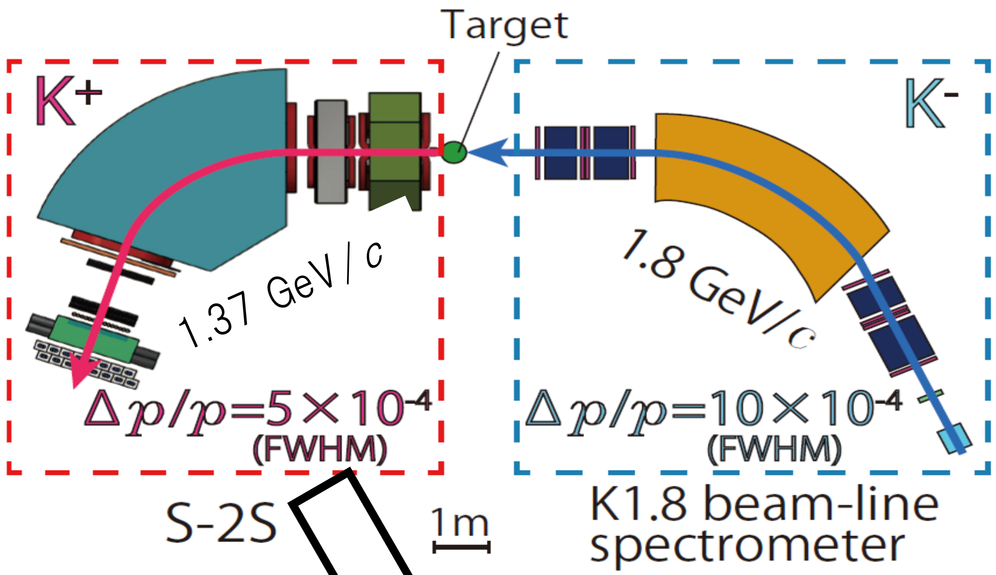
$^{15}_{\Xi}$C -> $^{5}_{\Lambda}$He + $^{5}_{\Lambda}$He + ^{4}He + n

B_{Ξ^-} = 6.27 ± 0.27 MeV

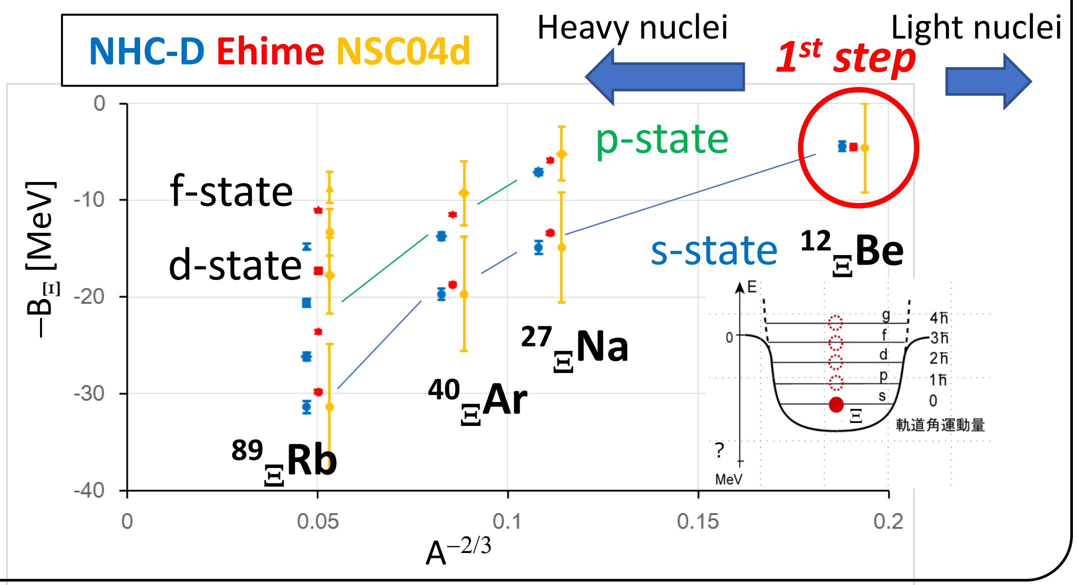
M. Yoshimoto et al., PTEP 2021, 073D02

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

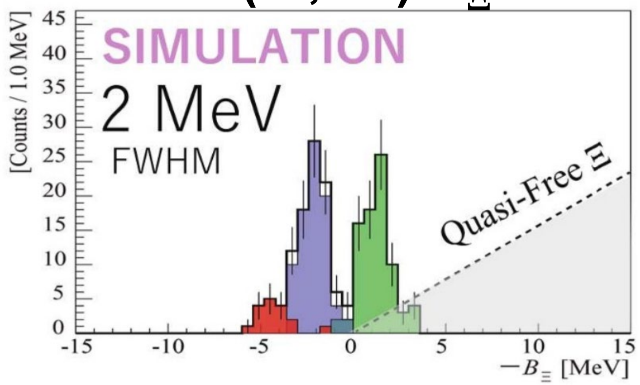


Calculated Ξ binding energy (and width)

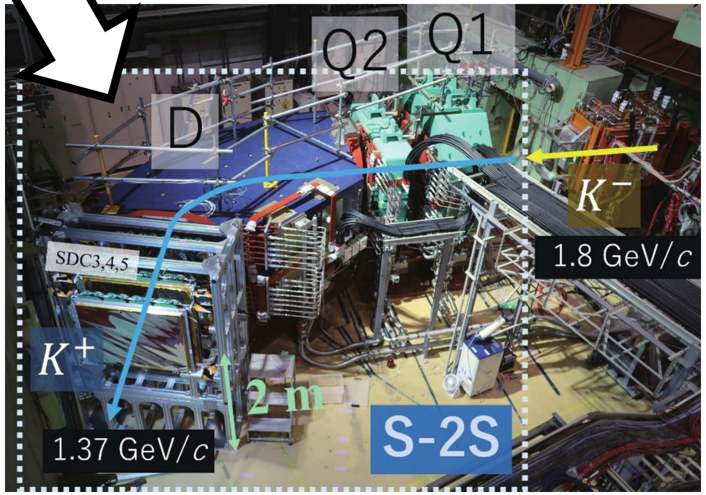


1st step is ongoing

^{12}C (K⁻, K⁺) $^{12}_{\Xi}$Be



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

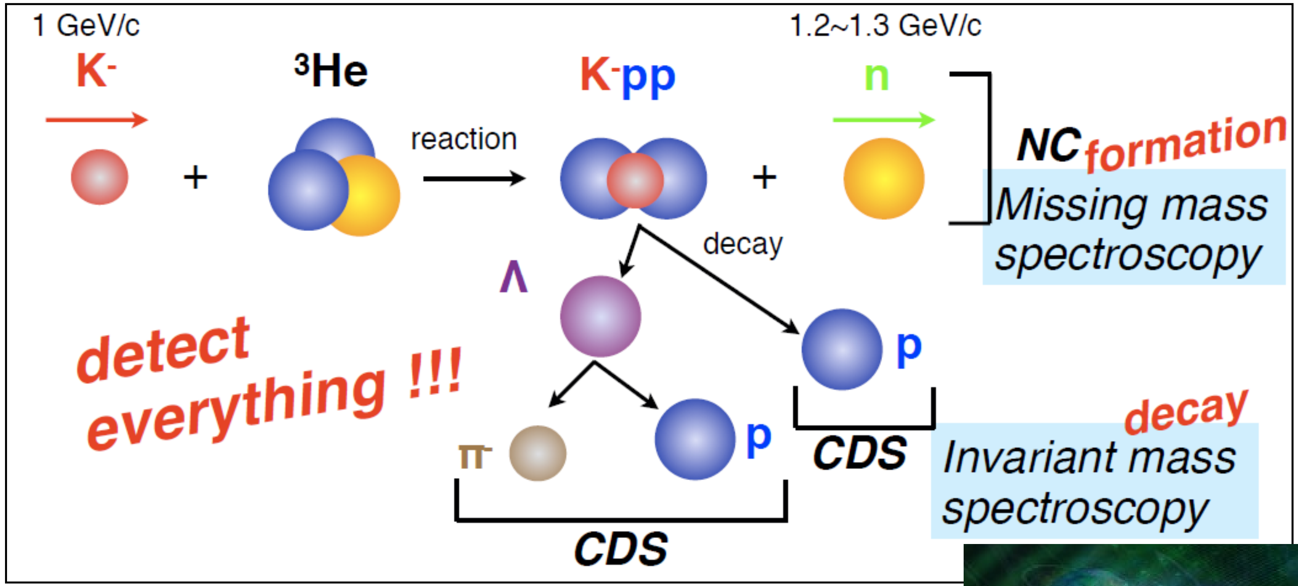


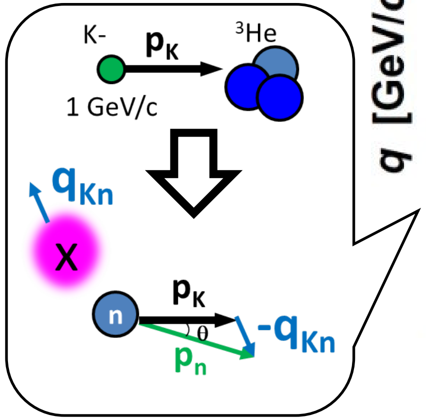
Results coming soon

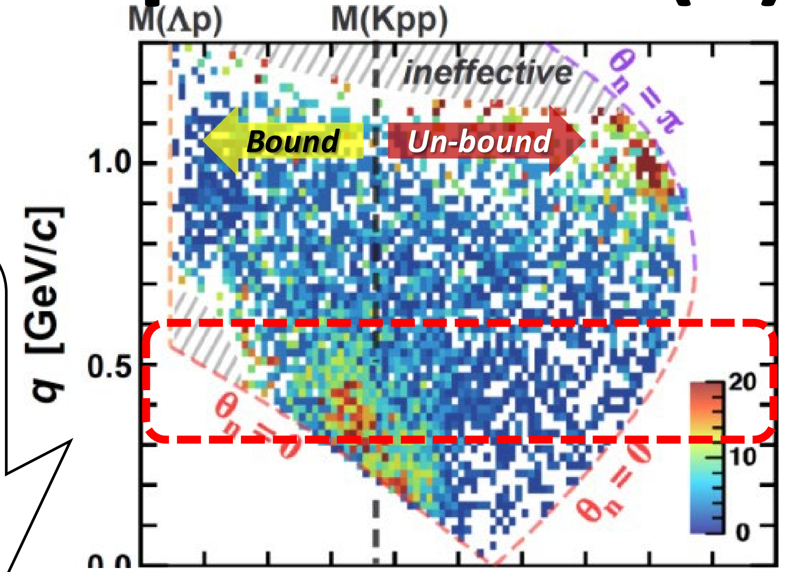
Highlights of the intense K⁻ beam experiments (2)

Kaonic nuclei

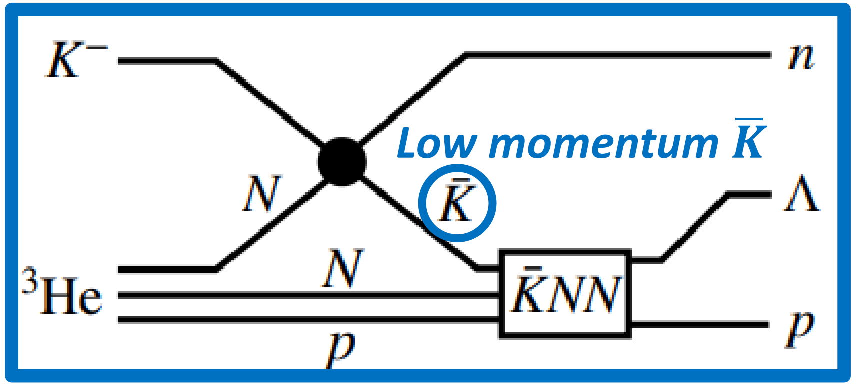
- "K⁻pp" bound state was observed in ^{3}He(K⁻,n)Λp at J-PARC (E15)

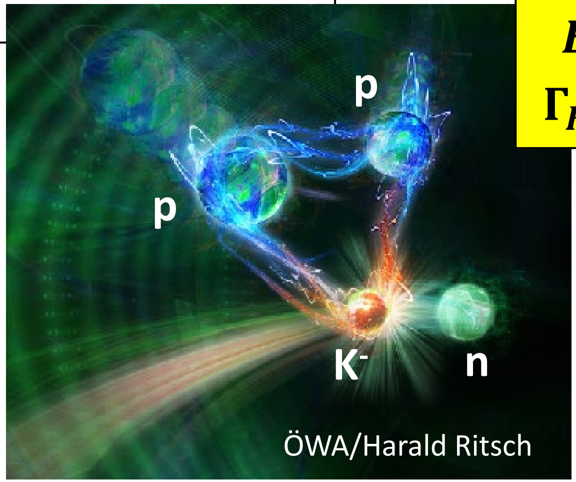




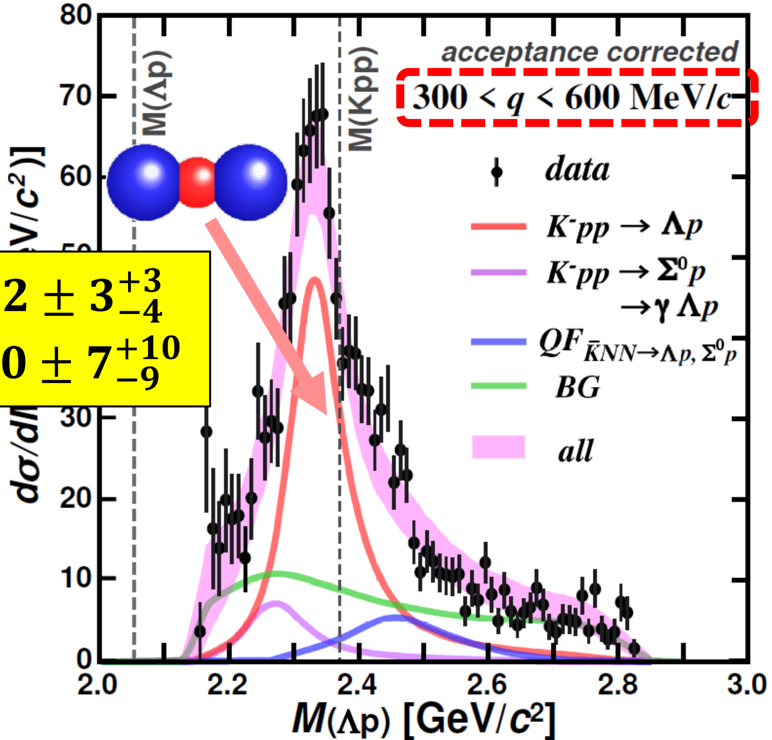


PLB789(2019)620., PRC102(2020)044002.



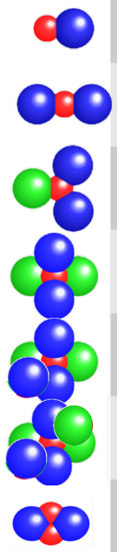


$$B_{Kpp} = 42 \pm 3^{+3}_{-4}$$
$$\Gamma_{Kpp} = 100 \pm 7^{+10}_{-9}$$

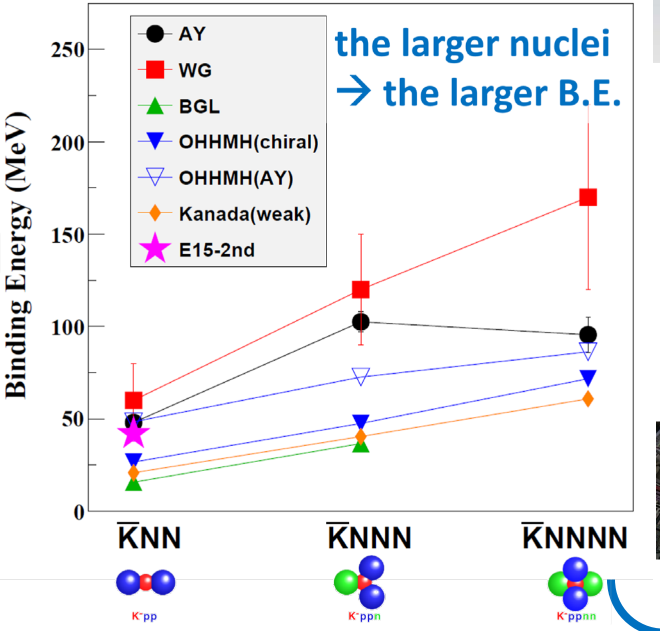


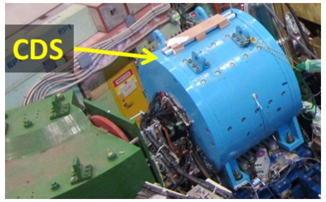
Highlights of the intense K⁻ beam experiments (2) Kaonic nuclei

- 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

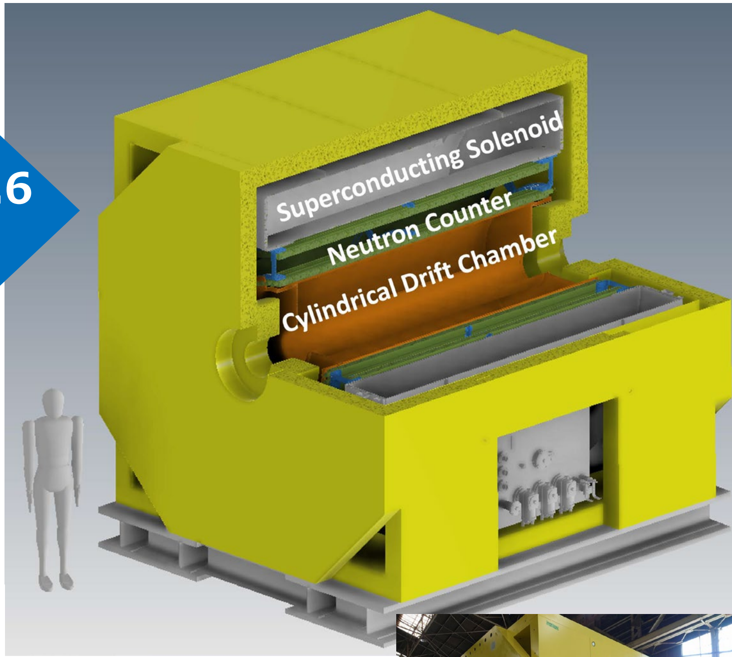


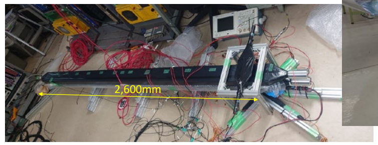
	Reaction	Decays
$\bar{K}N$	d(K⁻,n)	$\pi^{\pm 0}\Sigma^{\mp 0}$
$\bar{K}NN$	³He(K⁻,N)	Λp/Λn
$\bar{K}NNN$	⁴He(K⁻,N)	Λd/Λpn ← first step
$\bar{K}NNNN$	⁶Li(K⁻,d)	Λt/Λdn
$\bar{K}NNNNN$	⁶Li(K⁻,N)	Λα/Λdd/Λdpn
$\bar{K}NNNNNN$	⁷Li(K⁻,N)	Λαn/Λddn
$\bar{K}\bar{K}NN$	$\bar{p}$ + ³He	ΛΛ

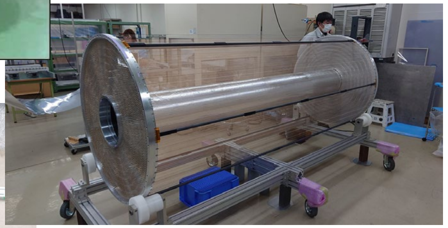




✓Solid angle: x1.6
✓Neutron eff.: x7







Will start in FY2026

Strangeness Nuclear Physics

	HIHR	JLab	Mainz
Reaction	(π^+, K^+)	(e,e'K+)	Decay π
Achievable Precision (keV)	◎ <100	◎ <100	◎ <100
Applicable hypernuclei	◎ All Z	○ Light – Medium Heavy (Larger Z, higher BG)	× Only Ground states of light hypernuclei
Availability of Neutron rich HY	◎ DCX $^{A}_{\Lambda}$(Z-2)	○ $^{A}_{\Lambda}$(Z-1)	○ Fragmentation only 2body-decay
Flexibility of beamtime	◎ Permanently Installed Beamline & Spectrometer	× Large-scale Installation (several months)	○ Kaon Spectrometer Installation (a few weeks)
Absolute Energy Calibration	△ $^{12}_{\Lambda}$C $p(\pi^-, K^+)\Sigma^-$ Decay π	◎ $p(e, e'K^+)\Lambda, \Sigma^0$	○ Elastic e scattering

Systematic measurement can be performed @ HIHR

(π+,K+): n→Λ
(e,e'K+): p→Λ
=> Inf. on CSB

- 2-/3-body interactions via femtoscopy
- Huge data-set in Run3 (2022-25) ~
- <u>Sensitive to S-wave (lower-mom. region)</u>

Comple-mentary

Spin observables in scattering

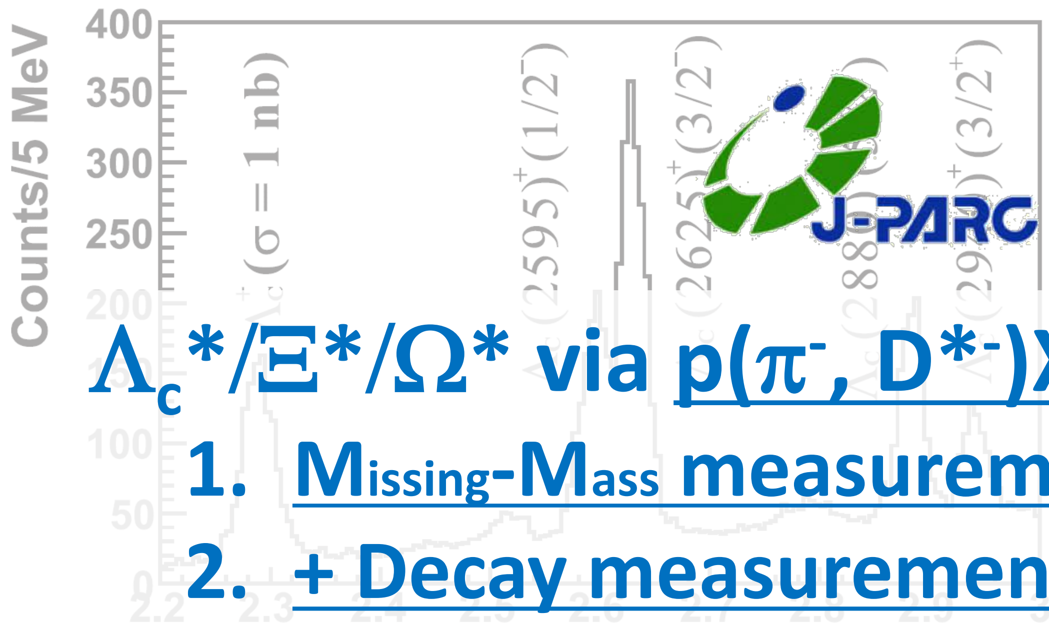
More detailed information @ K1.1

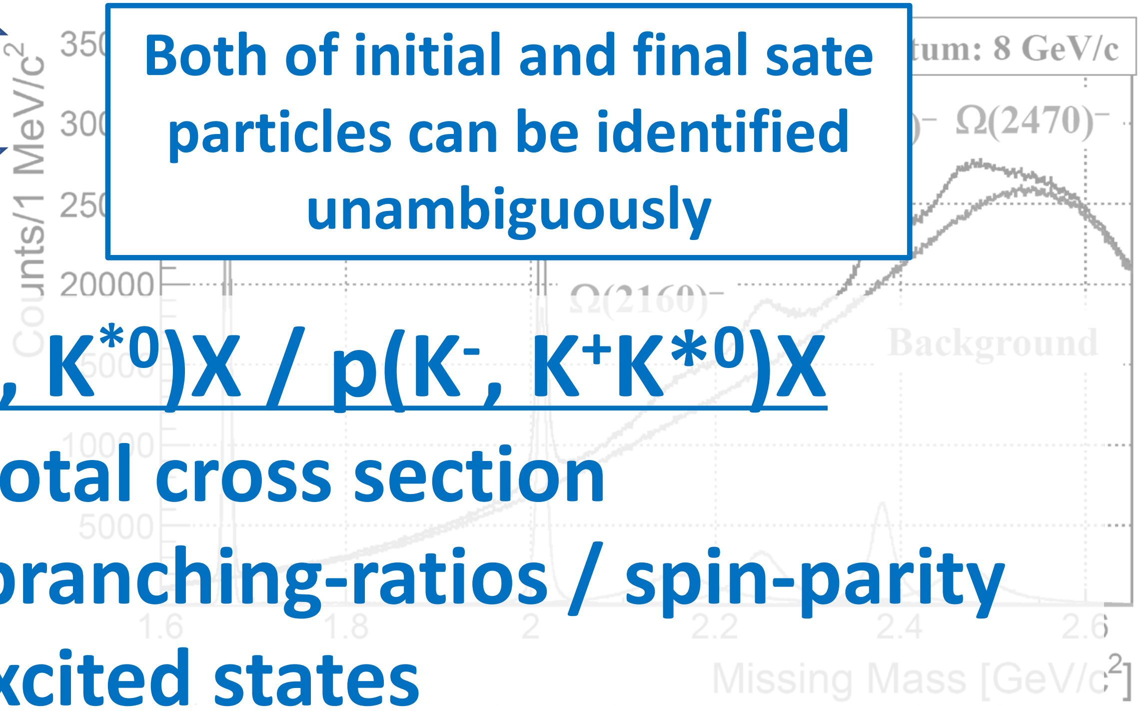
- **differential quantities (dσ/dΩ, etc.)**
- **spin observables**
- **<u>Sensitive to higher partial wave in addition to S-wave</u>**

Diquarks in Baryons

- High capabilities of hadron spectroscopy in *c*-sector, via inv. mass reconst.

Comple-mentary





Both of initial and final sate particles can be identified unambiguously

Λ_c*/Ξ*/Ω* via p(π⁻, D*⁻)X / p(K⁻, K*⁰)X / p(K⁻, K⁺K*⁰)X

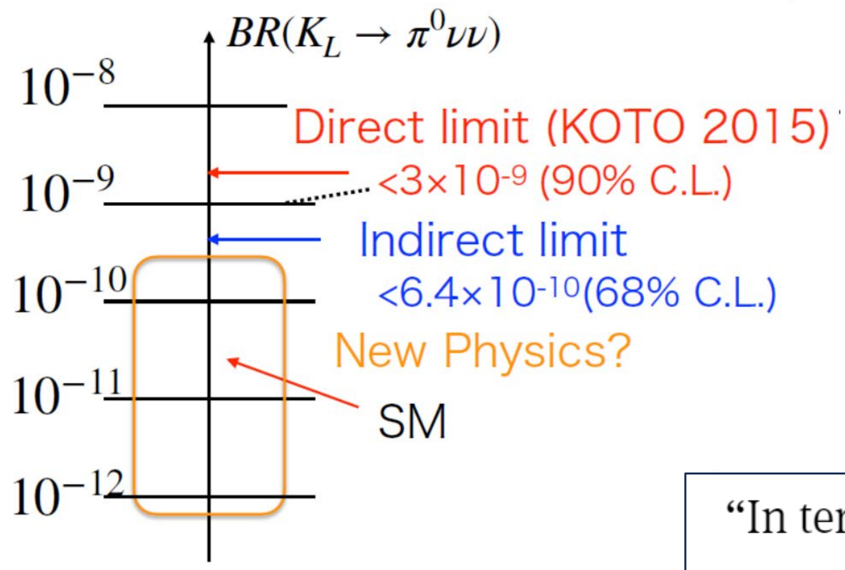
1. Missing-Mass measurement → total cross section
2. \+ Decay measurement → branching-ratios / spin-parity
3. Direct production of highly-excited states

K Rare Decays @ CERN

- NA62@CERN: $K^+ \to \pi^+\nu\bar{\nu}$ has been investigated
  - Run1: 2016-18, Run2: 2021-24 $\mathrm{BR}(K^+ \to \pi^+\nu\bar{\nu}) = (10.6^{+4.0}_{-3.4}|_{\mathrm{stat}} \pm 0.9_{\mathrm{syst}}) \times 10^{-11}$ at 68% CL.

JHEP06(2021)093

- HIKE@CERN: $K^{+/0} \to \pi^{+/0} l^+ l^-, K_L^0 \to \pi^0\nu\bar{\nu}$ searches are planned as the next of NA62, but...



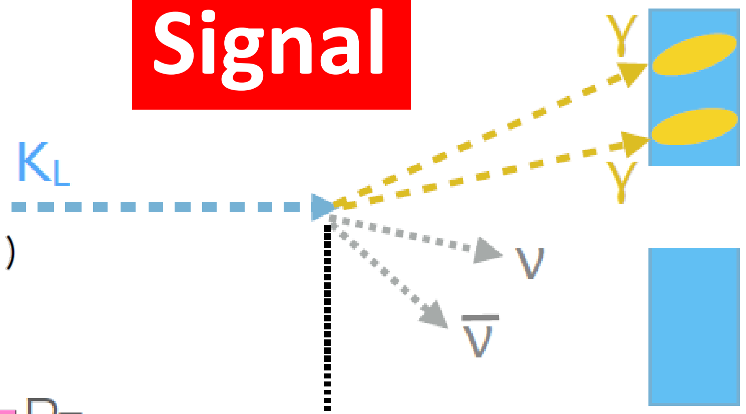
https://cerncourier.com/a/ship-to-chart-hidden-sector/

> "In terms of their science, SHiP and HIKE/SHADOWS were ranked equally by the relevant scientific committees," explains CERN director for research and computing Joachim Mnich. "But a decision had to be made, and SHiP was a strategic choice for CERN."

$K_L^0 \to \pi^0 \nu\bar{\nu}$ search @ KOTO/KOTO2

$K_L \to \pi^0 \nu\bar{\nu}$ BR=3×10^{-11}

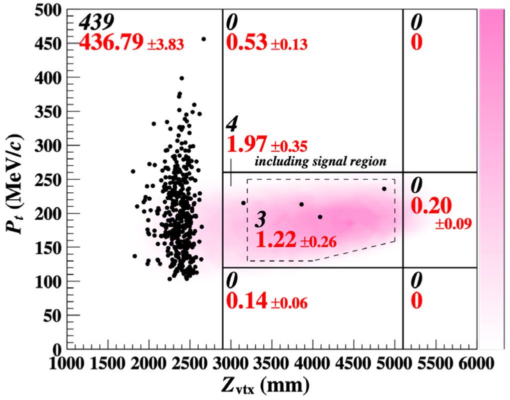
Signal

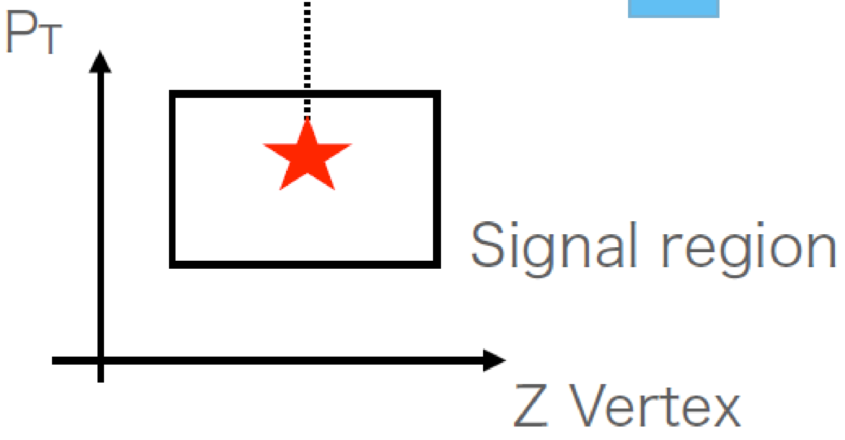


Assuming 2γ from π^0,
Calculate z vertex.

$M^2(\pi^0)=2E_1E_2(1-\cos\theta)$

Calculate π^0 transverse momentum

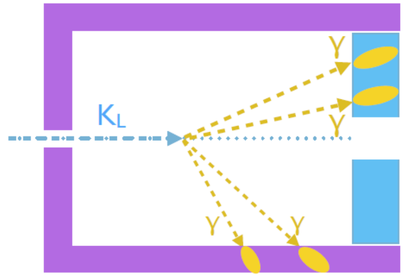




Backgrounds

$K_L \to \pi^0\pi^0$ BR=8.6×10^{-4}

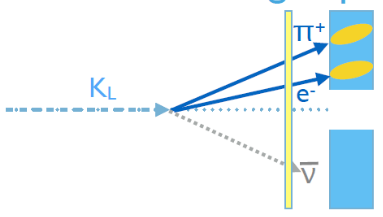
more photons



✱ Cover decay volume with veto detectors

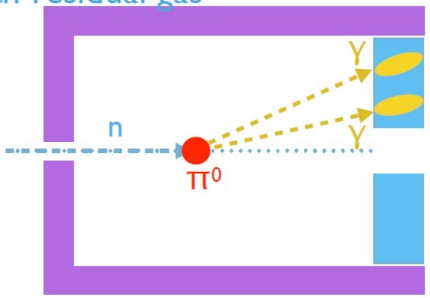
$K_L \to \pi^+ e^- \bar{\nu}$ BR=4.0×10^{-1}

charged particles



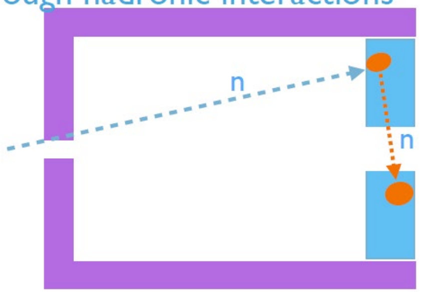
✱ Detect charged particles with plastic scintillators

π0 Production through the interaction with residual gas



✱ Keep the decay volume to be high vacuum

Neutron make 2 clusters through hadronic interactions



✱ Discriminate "neutron cluster" from "photon cluster"

Production rates by hadronic reaction

- $\pi^- p \rightarrow D^{*-} Y_c^{*+}$ reaction @ 20 GeV/c
  - **Production cross section: Overlap of wave function** → $R \sim \langle \varphi_f | \sqrt{2}\sigma_- \exp(i\vec{q}_{eff}\vec{r}) | \varphi_i \rangle$
    - charm and *q-q* (spectator)
  - Large production rate of highly excited states → $I_L \sim \boxed{(q_{eff}/\alpha)^L} \exp(-q_{eff}^2/\alpha^2)$
  - **Both one- and two-quark processes (σ_Λ:σ_Σ = 2:1)**

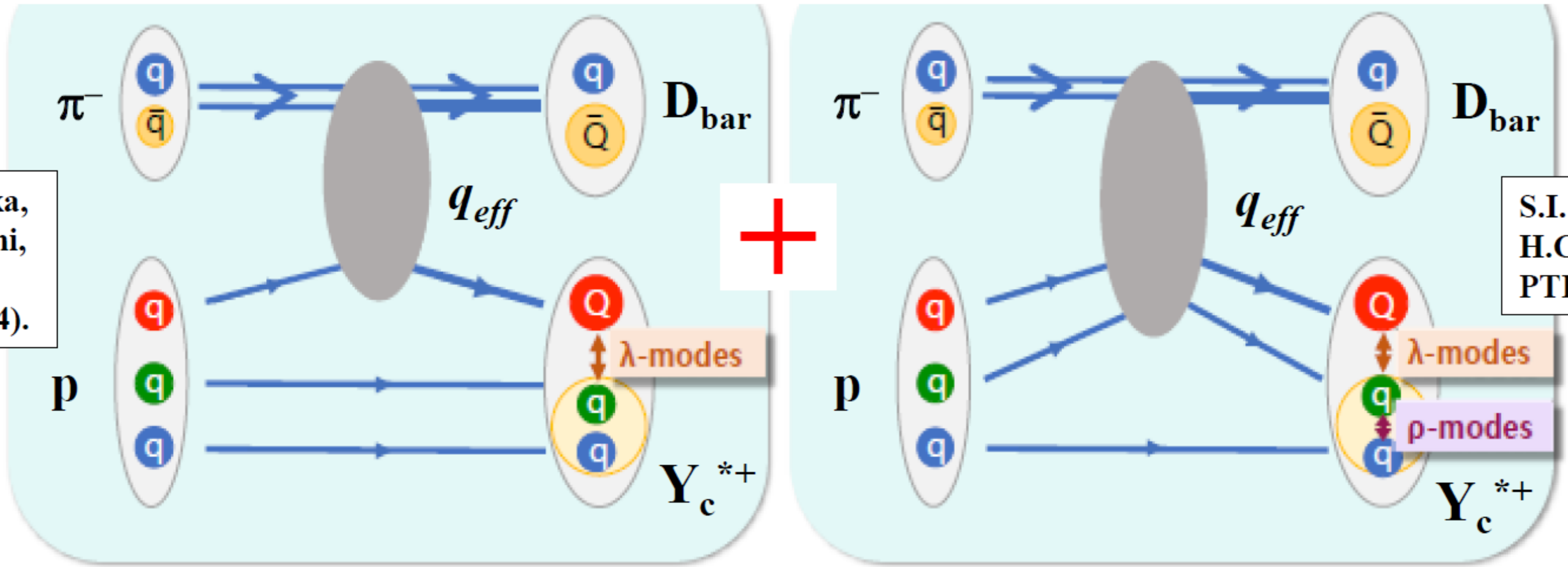
Mom. Trans.: q_{eff}~1.4 GeV/c
α~0.4 GeV ([Baryon size]$^{-1}$)

One-quark process

* λ-mode states w/ finite *L* are populated.

Two-quark process

* Comparable ρ-mode states are expected.



S.H. Kim, A. Hosaka, H.C. Kim, H. Noumi, K. Shirotori PTEP 103D01 (2014).

S.I. Shim, A. Hosaka, H.C. Kim, PTEP 2020, (2020) 5, 053D01

Timeline of the Project

		1st Year	2nd Year	3rd Year	4th Year	5th Year	6th Year	7th Year	
			construction parallel to beam operation in the first 4 years, beam-suspension in the next 2.5 years						
Hadron Hall	Start of budget request	***The Extension Project of H**adron **E**xperimental **F**acility (7 years)*							
	Current Programs with SX Power towards 100kW					**Hall Extension**			**Expanded Programs**

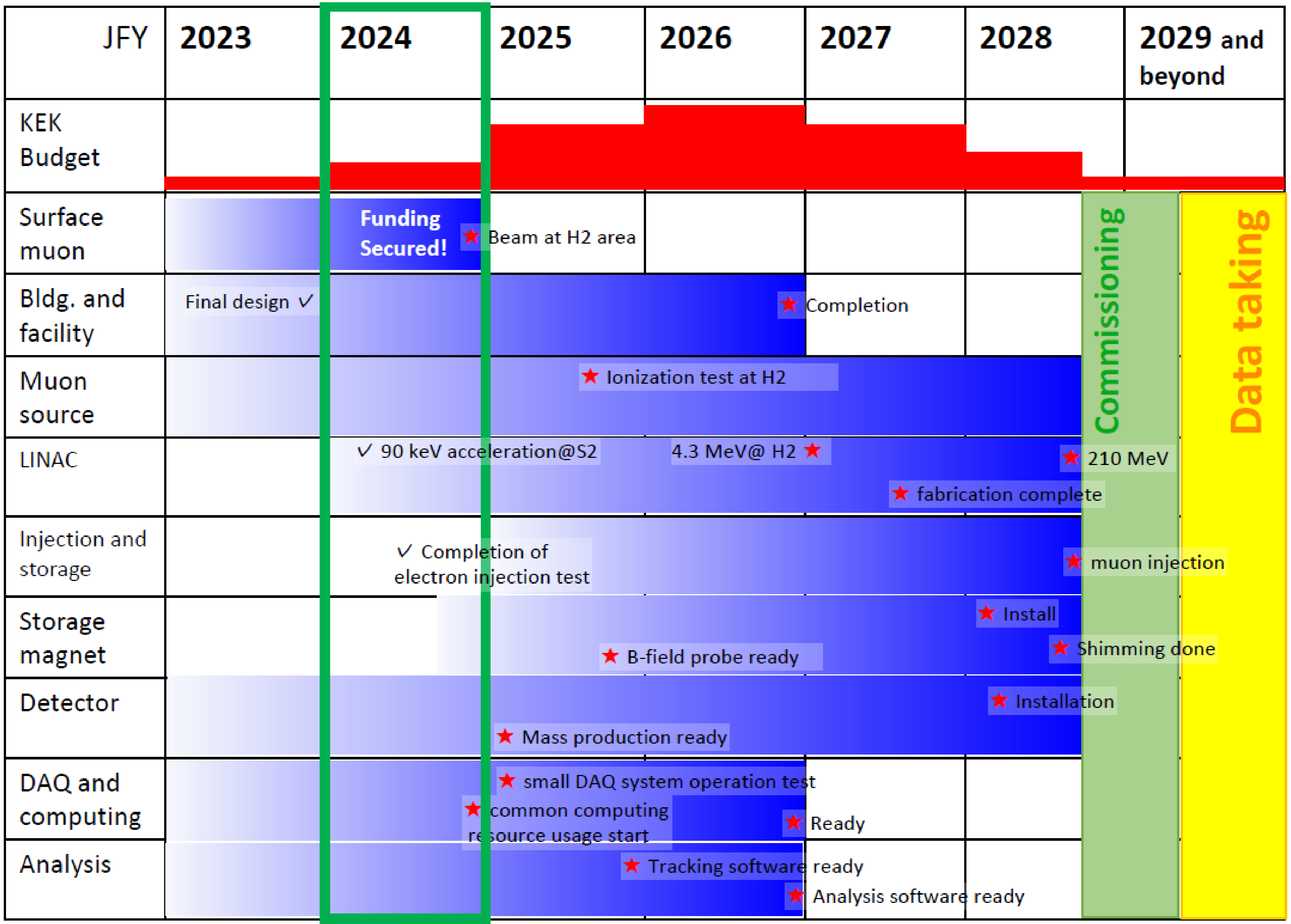
We will soon start the project

→ We are working on getting the timeline consistent with current programs

E34 : Muon g-2 / EDM

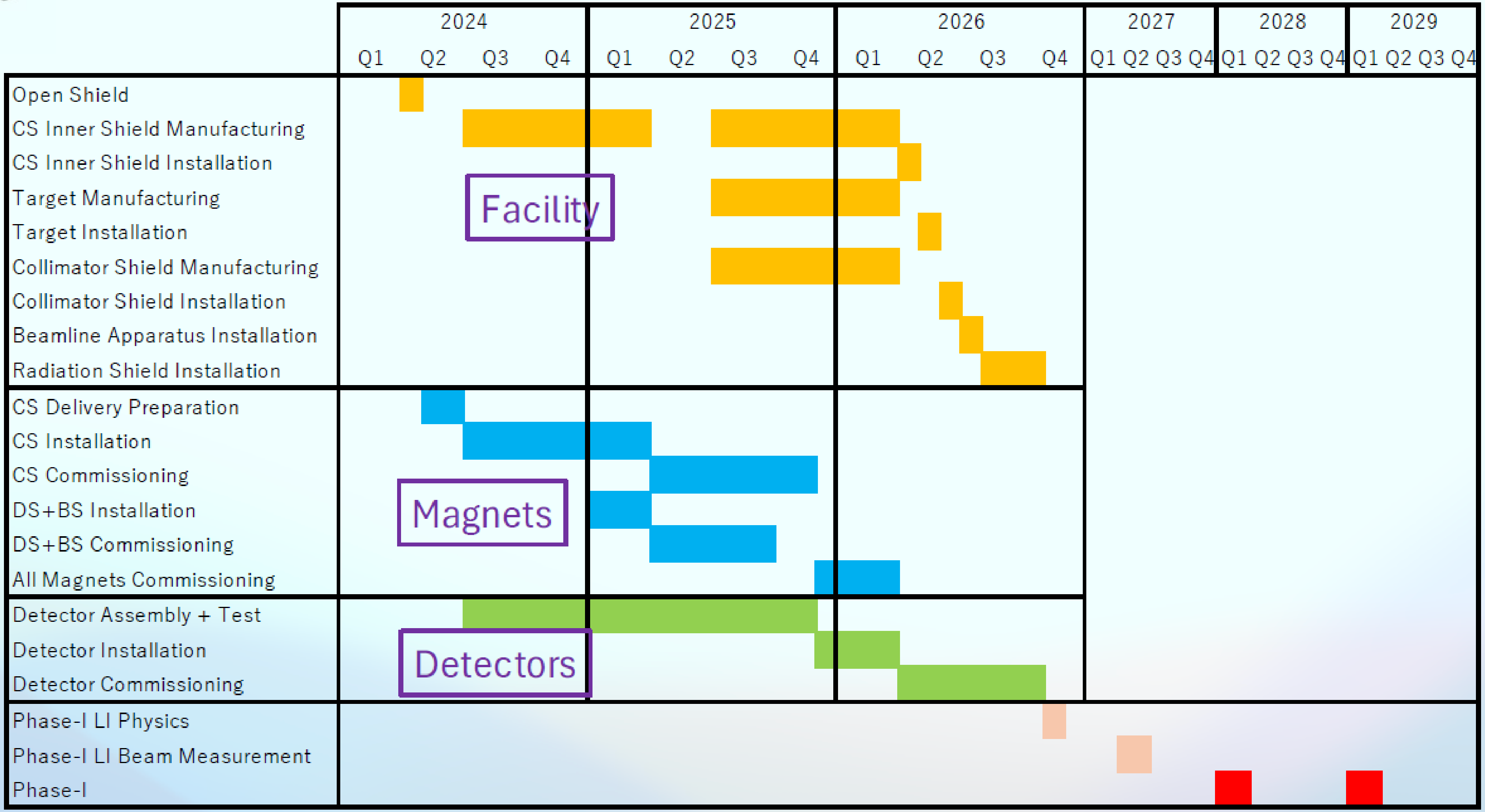
Schedule and Milestones

J-PARC PAC38, 2024 Jul



Schedule

J-PARC PAC38, 2024 Jul



Note: Mu2e's best possible plan — physic data in 2027(calendar year)

The Timeline+

subject to change

- Aggressive version of intended schedule by IPNS.
- PIP = Project Implementation Plan

PIP2016
1. Hyper-K /J-PARC upgrades
2. HL-LHC
3. muon g-2/EDM
4. HEF extension

PIP2022
1. HEF extension
2. HL-LHC++
3. LiteBIRD
4. Muon Microscope

J-PARC PAC38, 2024 Jul