



# Hadron Physcs at J-PARC

October 19, 2026

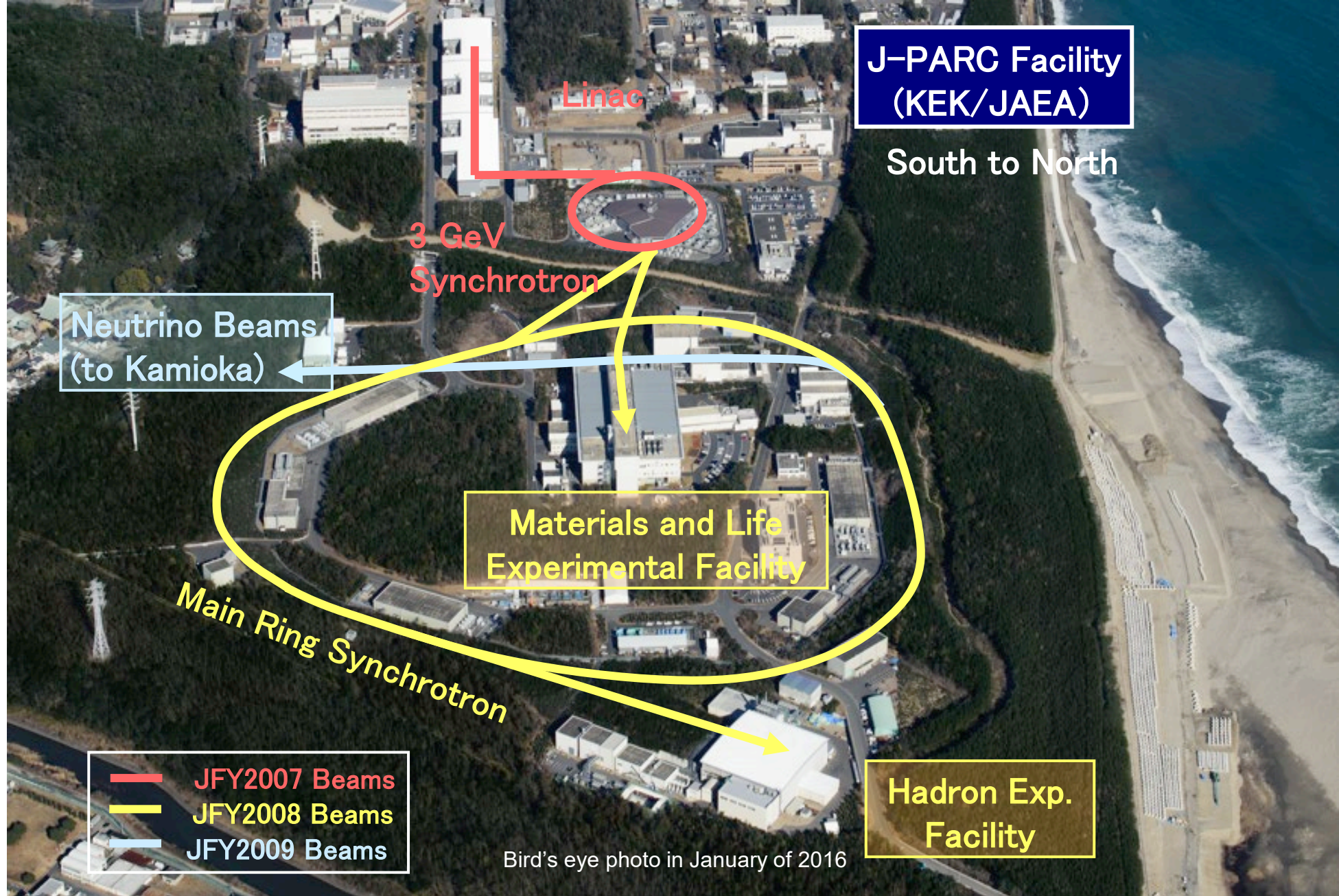
High Energy Accelerator Research Organization (KEK)

J-PARC Center

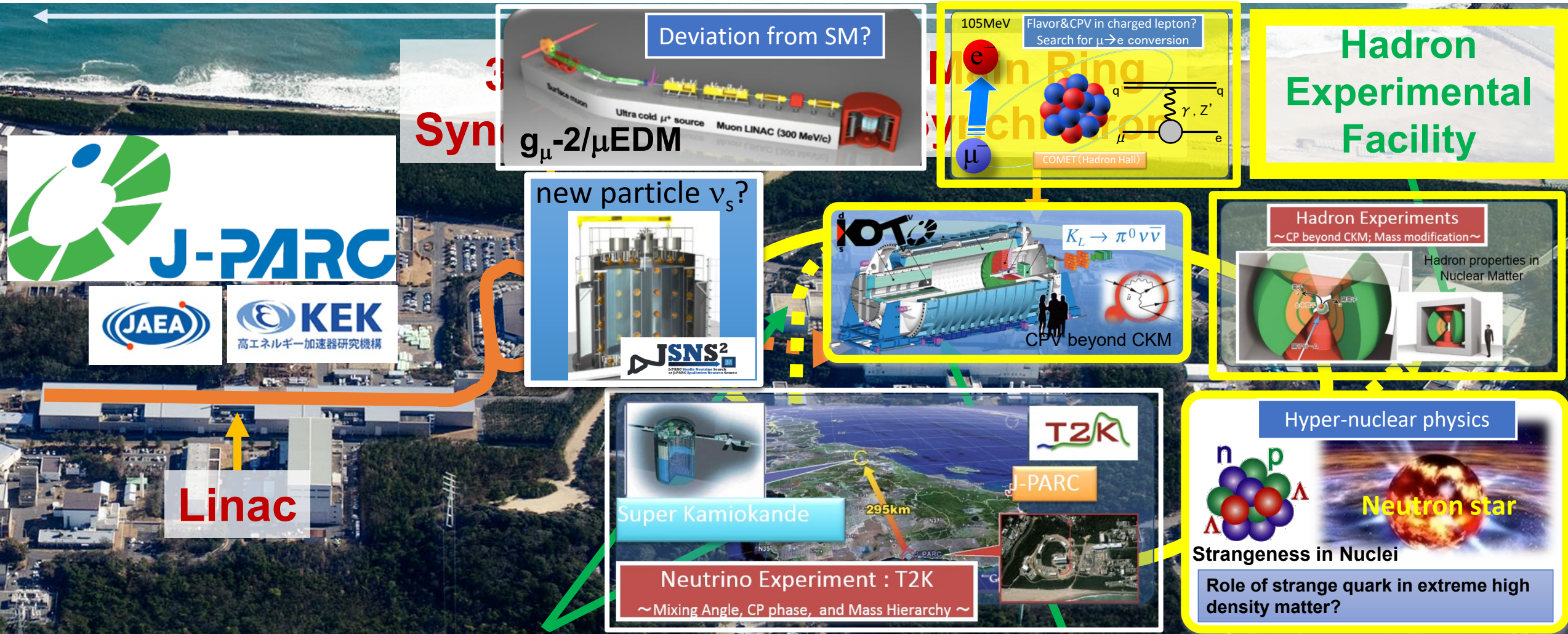
SAWADA, Shinya

# Contents

- J-PARC and Hadron Experimental Facility
- Research
- Future
- Summary



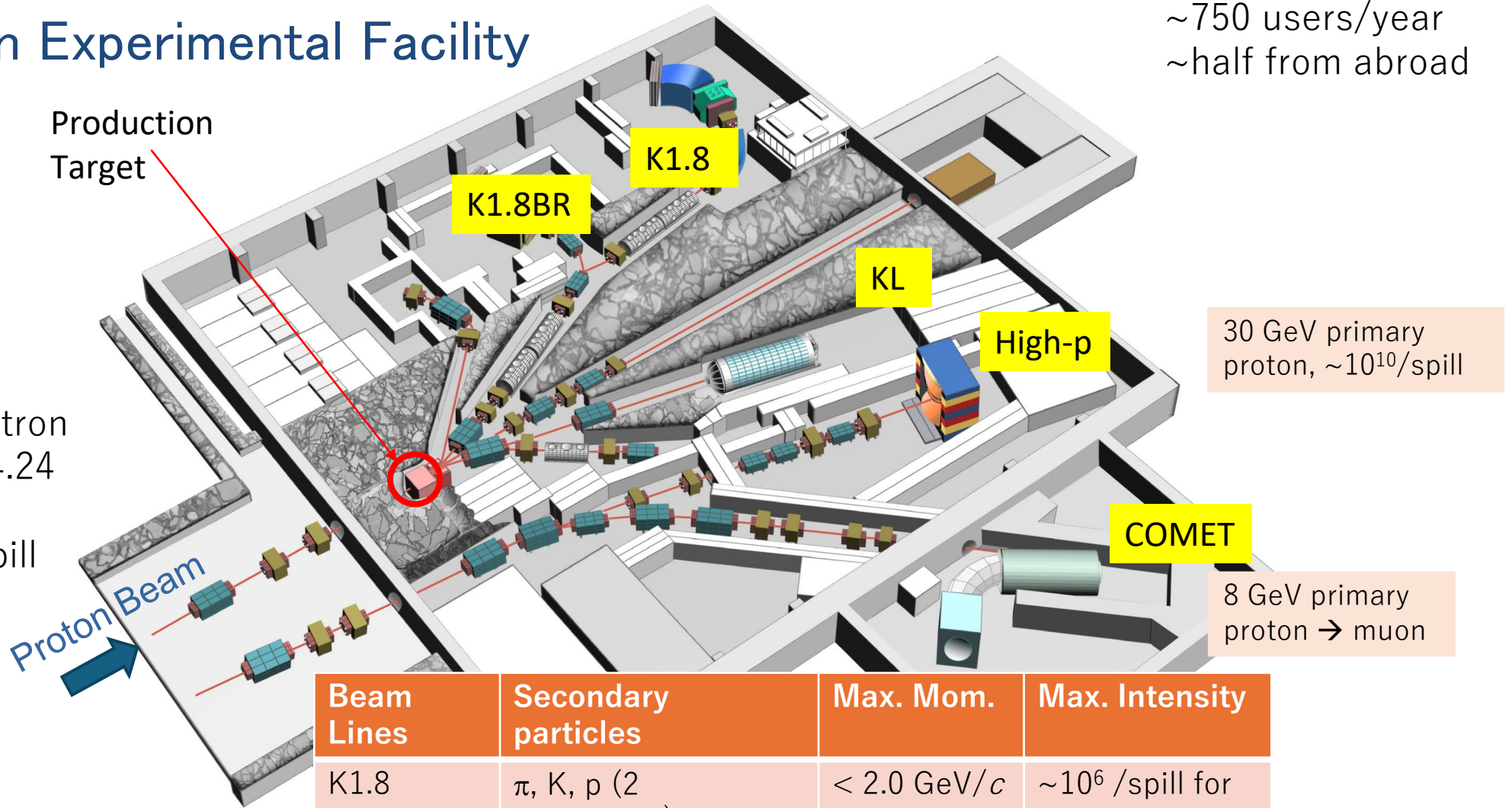
# Particle and Nuclear Physics @ J-PARC



# Hadron Experimental Facility

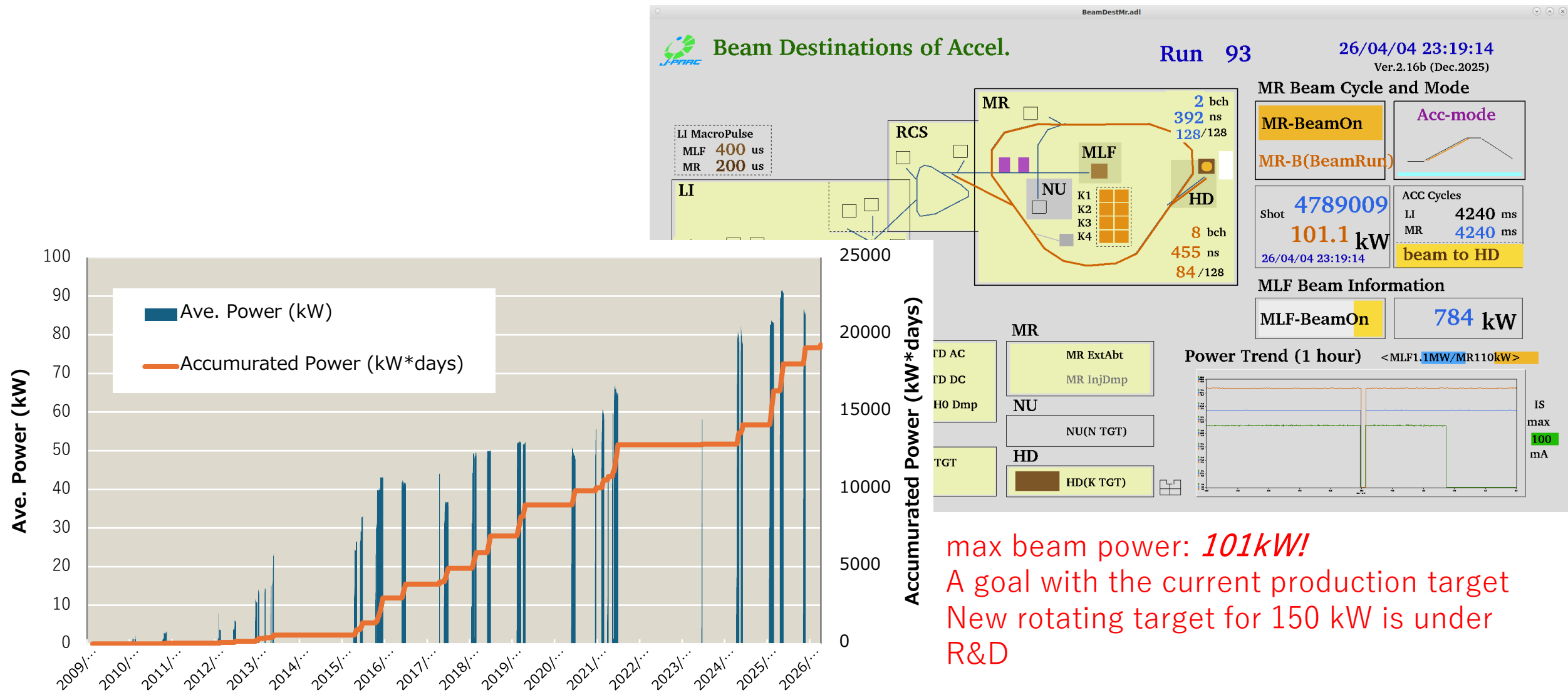
~750 users/year  
~half from abroad

- 30 GeV protons
- Slowly extracted from MR synchrotron
- 2 s beam out of 4.24 s cycle
- $>80$  T protons/spill

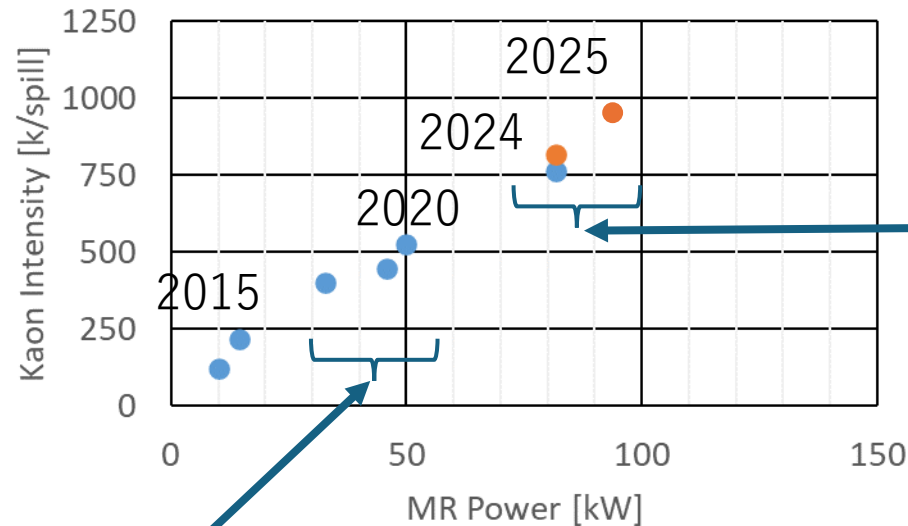


| Beam Lines | Secondary particles         | Max. Mom.                | Max. Intensity               |
|------------|-----------------------------|--------------------------|------------------------------|
| K1.8       | $\pi$ , K, p (2 separators) | $< 2.0 \text{ GeV}/c$    | $\sim 10^6$ /spill for $K^-$ |
| K1.8BR     | $\pi$ , K, p (1 separator)  | $< 1.1 \text{ GeV}/c$    | $\sim 10^5$ /spill for $K^-$ |
| KL         | Neutral Kaon                | $\sim 2.1 \text{ GeV}/c$ | $\sim 10^7$ /spill           |

# SX Beam Power History



# More Kaon Physics with Higher Intensity Kaon Beam



K intensity@K1.8: 986 K-/spill w/ 92kW  
proton beam, with 78% purity (2025)

S=-2 missing mass experiments  
with a magnetic spectrometer

**PTEP**

Prog. Theor. Exp. Phys. **2020**, 123D01 (34 pages)  
DOI: 10.1093/ptep/ptaa139

An event excess observed in the deeply bound  
region of the  $^{12}\text{C}(K^-, p)$  missing-mass spectrum

**PTEP**

Prog. Theor. Exp. Phys. **2024** 091D01 (13 pages)  
DOI: 10.1093/ptep/ptae133

Missing-Mass Measurement of the  $^{12}\text{C}(K^-, K^+)$   
Reaction at 1.8 GeV/c with the Superconducting  
Kaon Spectrometer

S=-2 emulsion  
experiments

- Artificial intelligence pioneers the double-strangeness factory, [Nature Commun. 16 \(2025\) 1, 11084](#)
- X atomic X-ray spectroscopy using a counter-emulsion hybrid method, [PTEP2022,123D01 \(2022\)](#)
- High-resolution measurement of hypernuclear events in a nuclear emulsion with hard X-ray microscopy, [Eur.Phys.J.A 58 190 \(2022\)](#)
- First observation of a nuclear s-state of a X hypernucleus,  $^{15}_{\chi}\text{C}$ , [PTEP2021, 073D02 \(2021\)](#)
- Observation of Coulomb-Assisted Nuclear Bound State of  $X^{-}-^{14}\text{N}$  System, [Phys. Rev. Lett. 126, 062501 \(2021\)](#)
- Observation of Double-strangeness Nuclei using Nuclear-emulsion Technology, [Bull. Soc. Photogr. Imag. Japan, 30, 22 \(2020\)](#)
- Observation of a Be double-Lambda hypernucleus in the J-PARC E07 experiment, [PTEP2019, 021D02 \(2019\)](#)

# 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

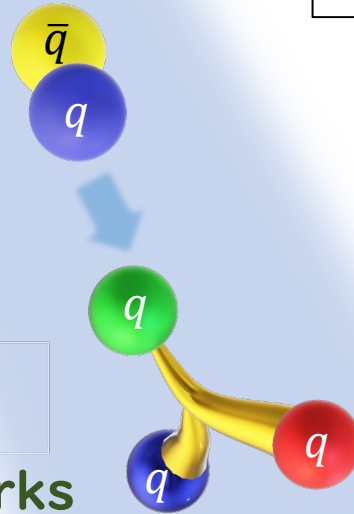
Kaon rare decays  
 $\mu \rightarrow e$  conversion

### 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

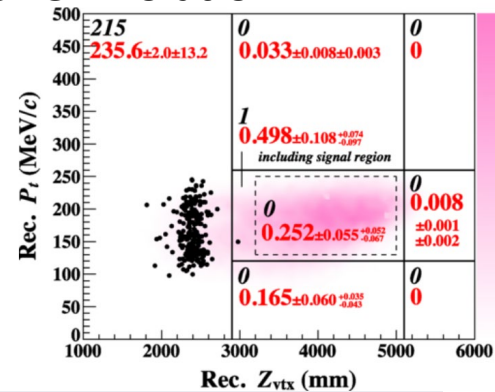


# Achievements in Research at the Hadron Experimental Facility

## Flavor Physics

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

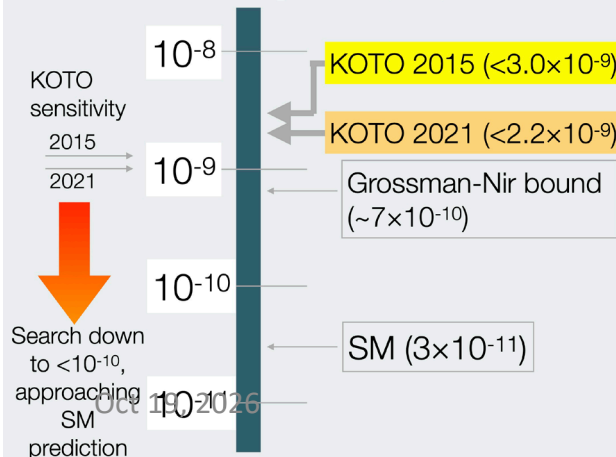
→ Approaching the SM sensitivity for CP violation



KOTO 2021

Single Event Sensitivity =  $9 \times 10^{-10}$

Branching ratio (BR)

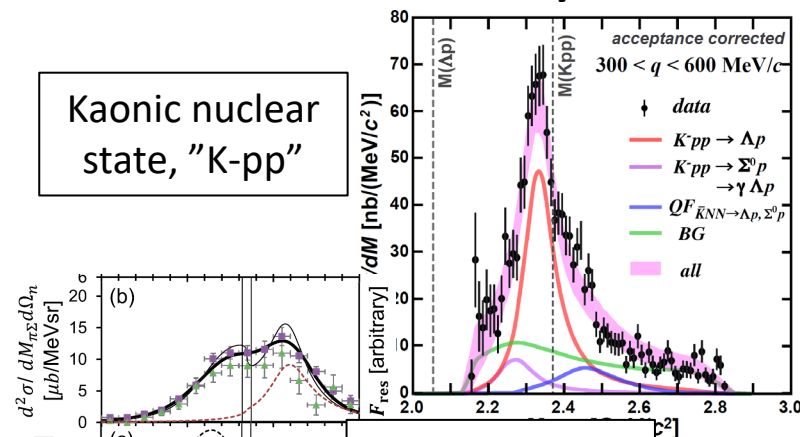


## Hadron Physics

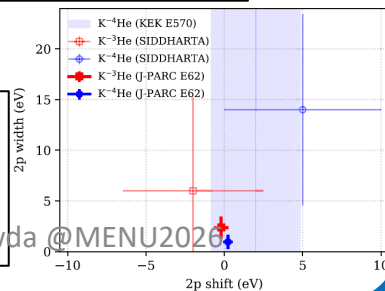
Observation of an exotic hadron bound system including  $K^-$  meson

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

Kaonic nuclear state, "K-pp"



Ultra-precise measurement of kaonic atoms

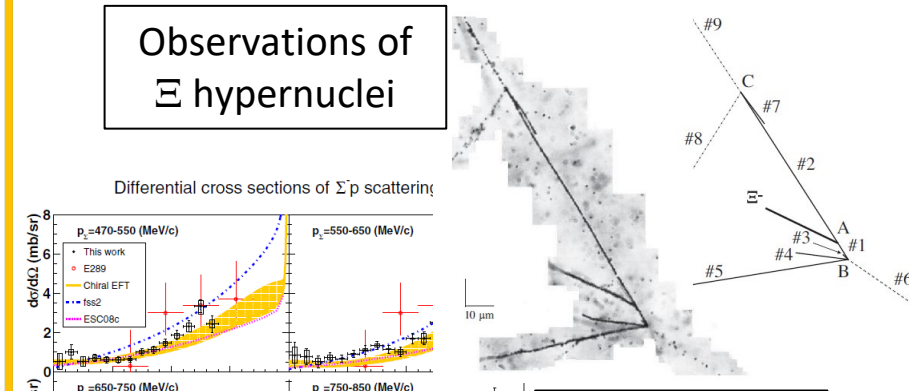


## Strangeness Nuclear Physics

A lot of progress in hypernuclear research

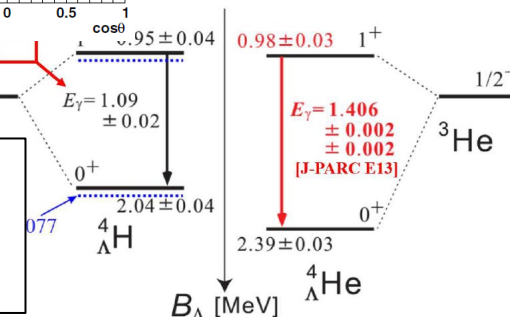
→ Clarified attractive  $S=-2$   $\Xi N$  interaction and deepened  $S=-1$   $\Lambda N, \Sigma N$  interactions

Observations of  $\Xi$  hypernuclei



First precise  $\Sigma N$  scattering

Charge-symmetry breaking in the  $\Lambda N$  interaction

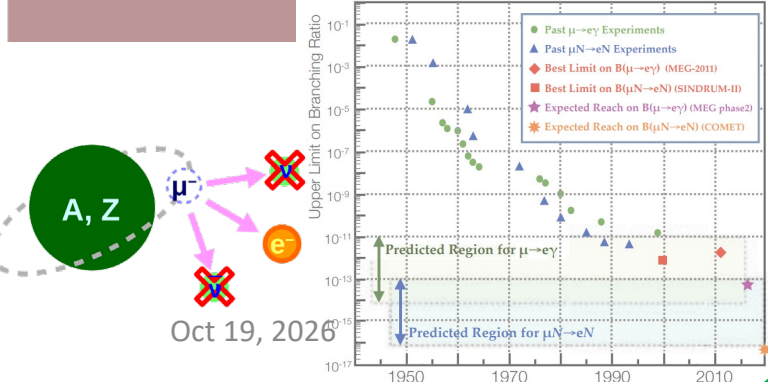
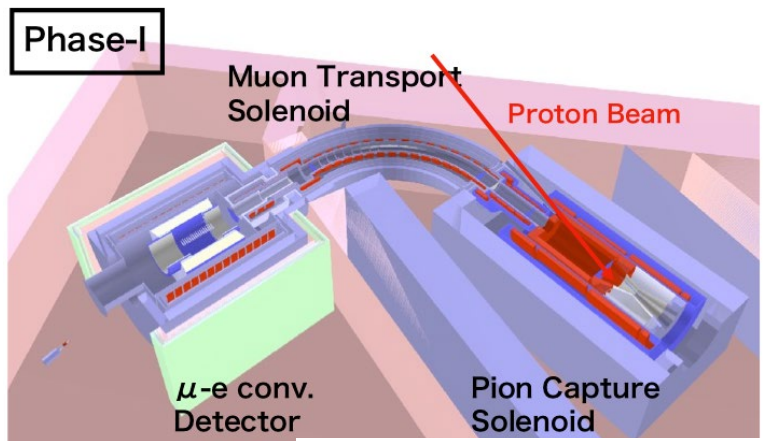


# Ongoing Research Programs at the Hadron Experimental Facility

## Flavor Physics

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

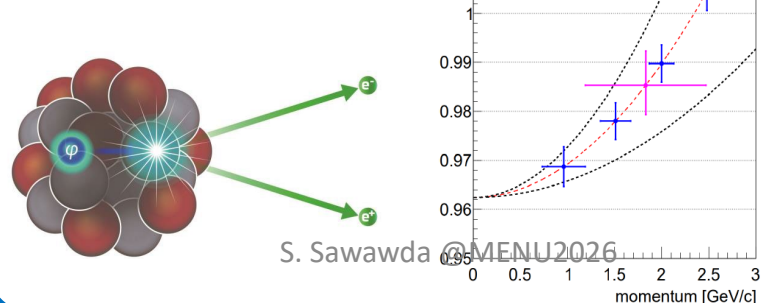
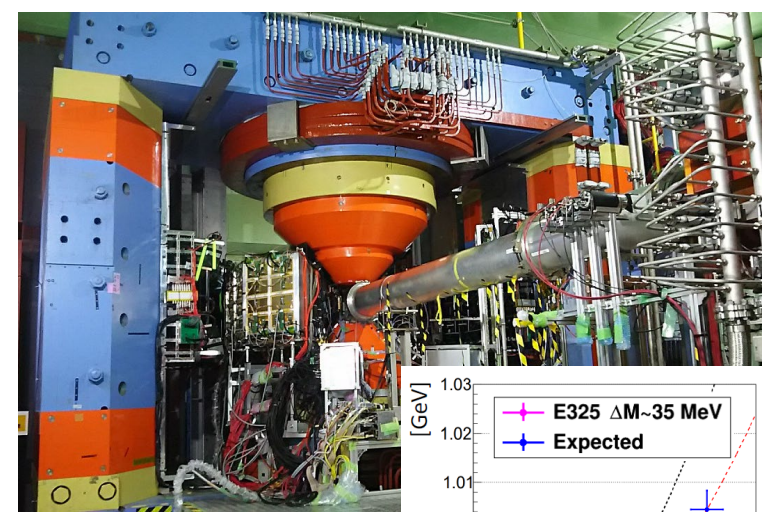
→ Search for charged lepton flavor violation



## Hadron Physics

Measurement of spectral modification of  $\phi$  meson in nuclei (2020~)

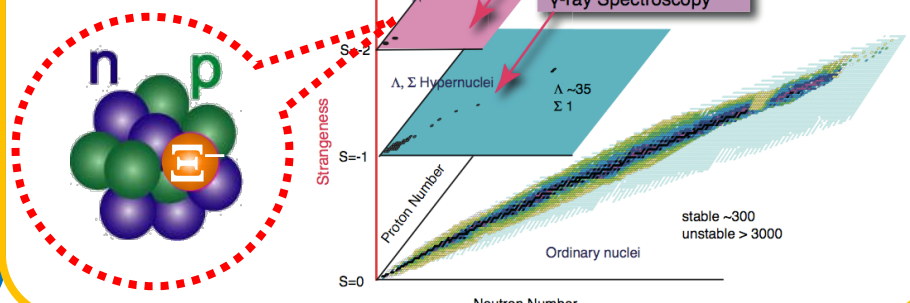
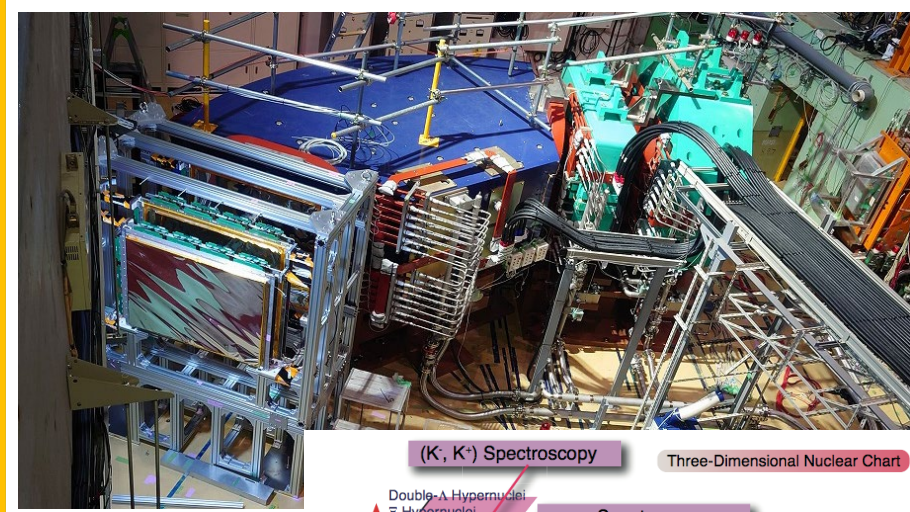
→ Investigate mass-generation mechanism of hadrons

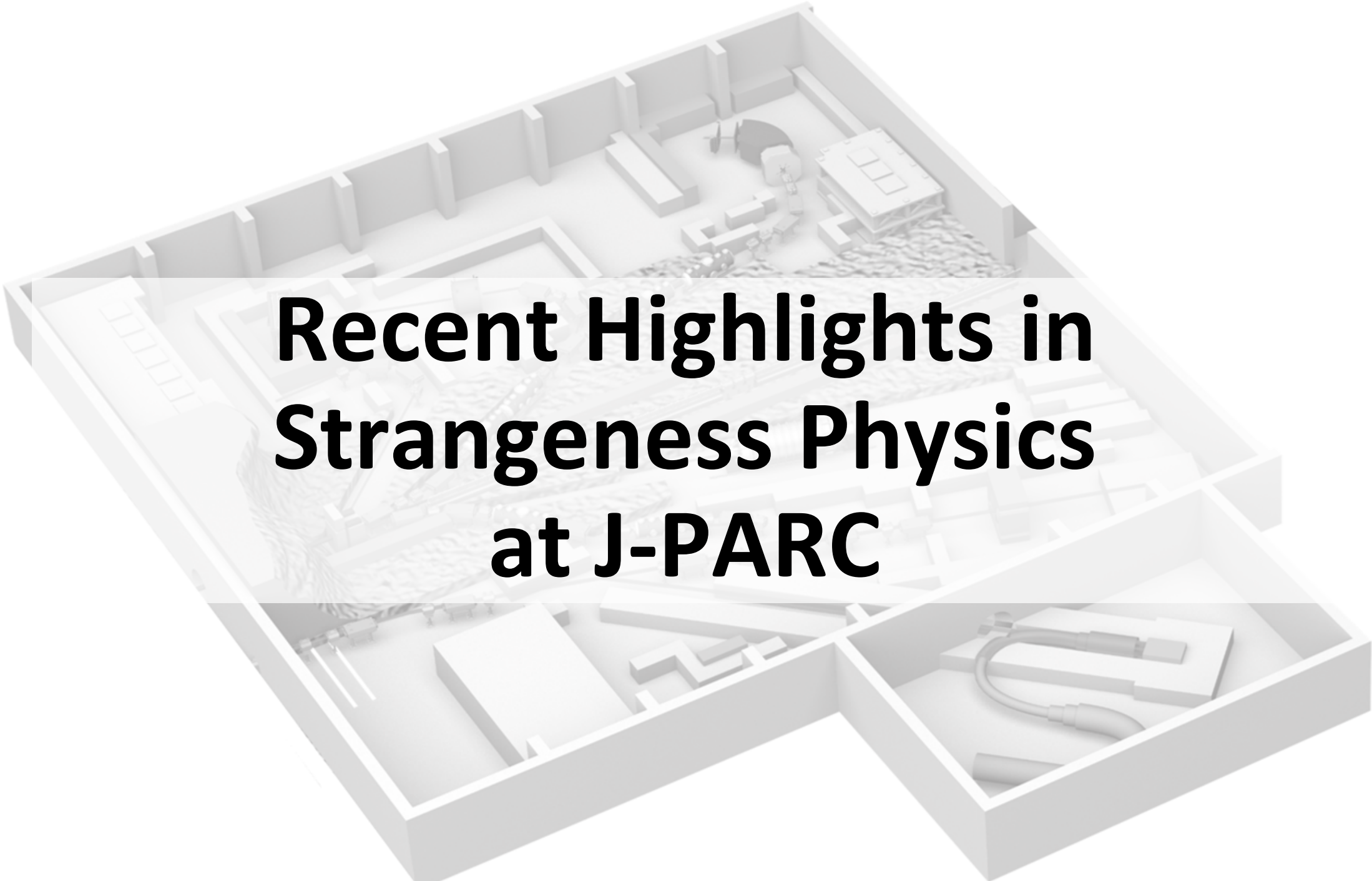


## Strangeness Nuclear Physics

High-resolution spectroscopic study of  $S=-2$   $\Xi$ -hypernuclei

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



A 3D perspective rendering of a particle detector layout, likely for the J-PARC experiment. The layout is contained within a rectangular frame with internal dividers. It features various components including a central circular structure, several rectangular blocks, and a complex network of cables and connectors. The entire scene is rendered in a light gray, wireframe-like style.

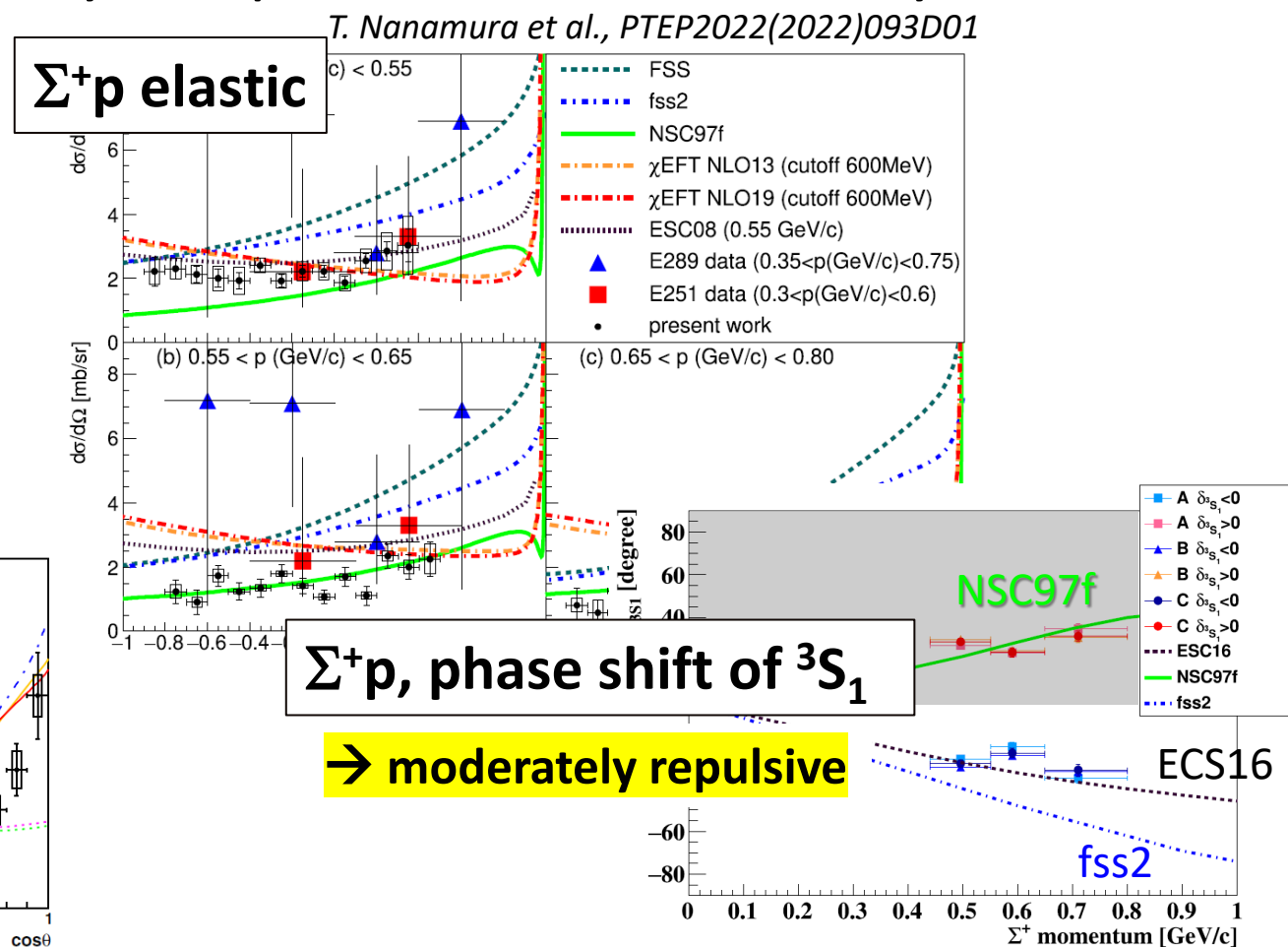
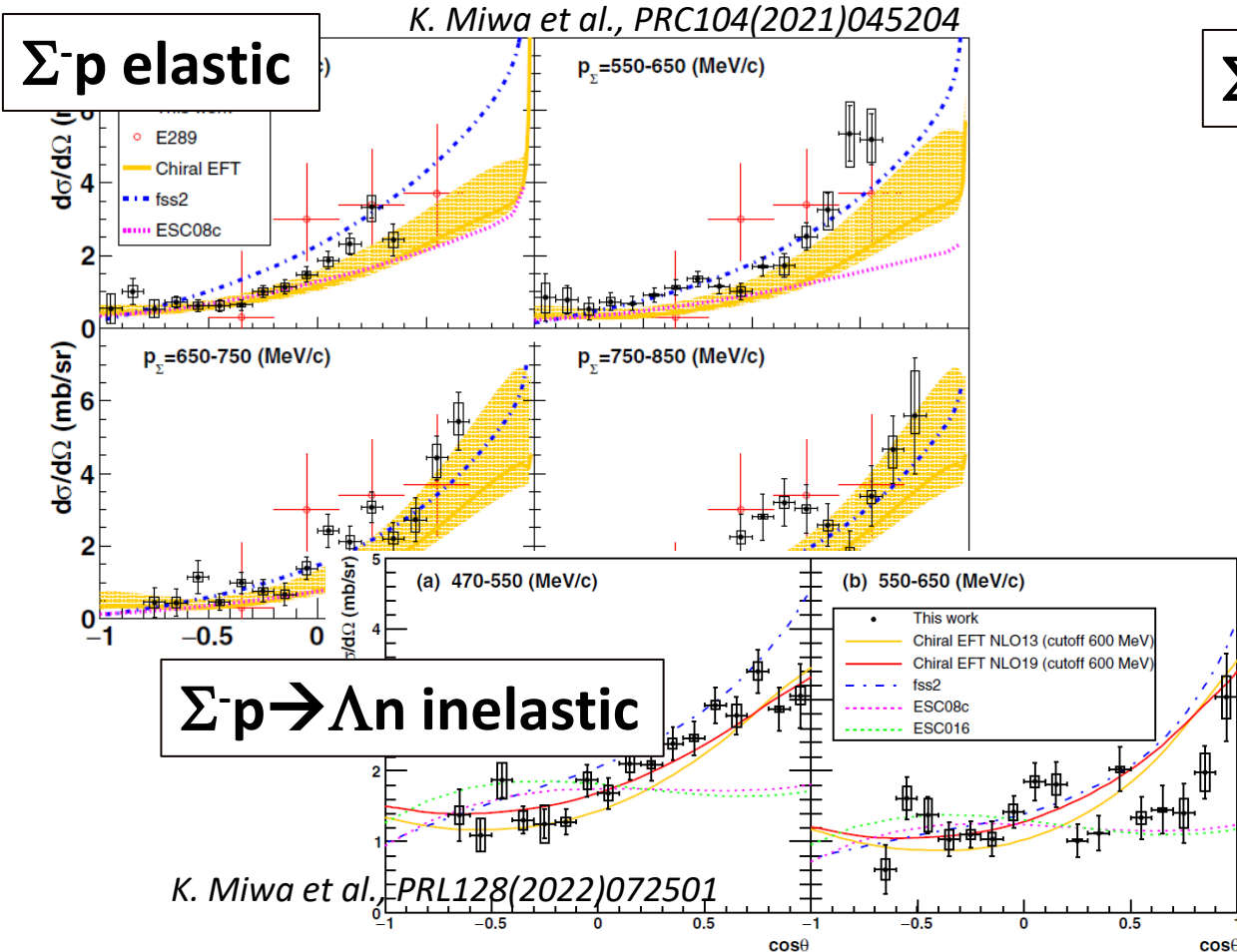
# **Recent Highlights in Strangeness Physics at J-PARC**

# YN Scattering

## – From NN to BB Interaction –

● Precision data of  $\Sigma p$  scatterings obtained around 400-800 MeV/c (E40)

✓ Precise data allow detailed study of  $\Sigma p$  interaction vs. theory



# Hypertriton ( ${}^3_{\Lambda}\text{H}$ )

## – A Important Benchmark in Hypernuclear Physics –

- Hypertriton binding energy measured by two experiments:

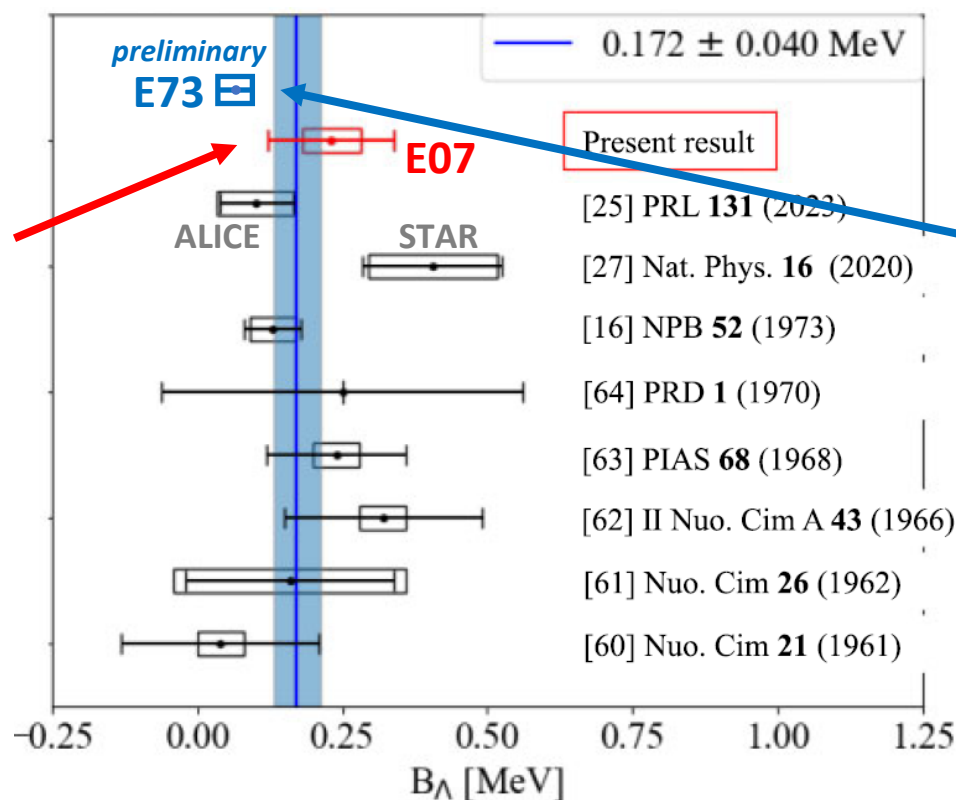
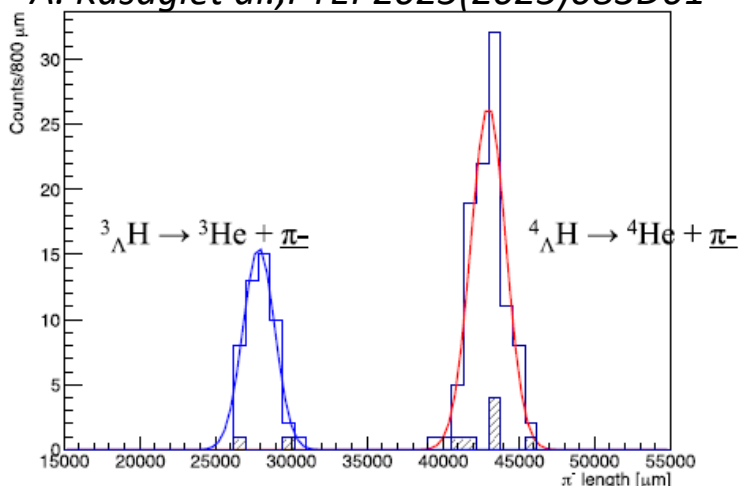
- E07: Emulsion exposed to  $\text{K}^-$  beam, analyzed with machine learning
- E73: Evaluated from  ${}^{3,4}\text{He}(K^-, \pi^0){}^{3,4}_{\Lambda}\text{H}$  cross sections (preliminary)

### E07: Emulsion

determined from  $\pi$  momentum  
obtained from  $\pi$  range

$$B_{\Lambda} = 0.23 \pm 0.11 \pm 0.05 \text{ MeV}$$

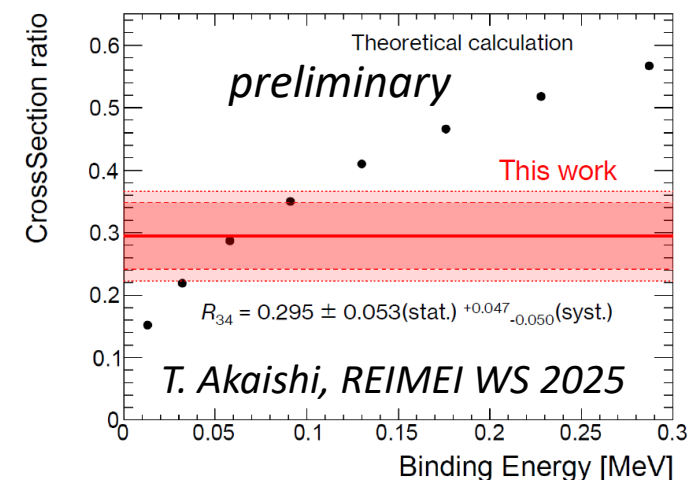
A. Kasagiet al., PTEP2025(2025)083D01



### E73: ${}^{3,4}\text{He}(K^-, \pi^0){}^{3,4}_{\Lambda}\text{H}$

evaluated from  $\sigma_{\Lambda^3\text{H}}/\sigma_{\Lambda^4\text{H}}$  by  
comparison with theoretical calculation

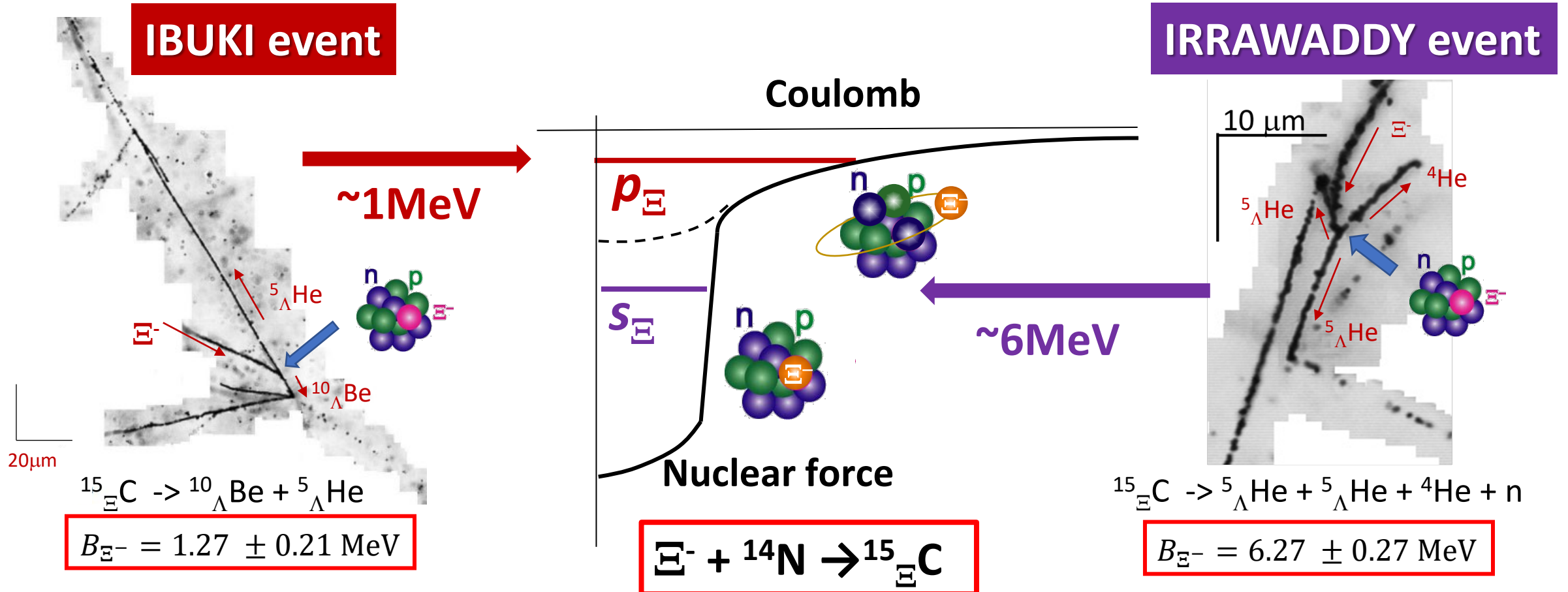
$$B_{\Lambda} = 0.061^{+0.028}_{-0.022} {}^{+0.024}_{-0.021} \text{ MeV} \quad \text{preliminary}$$



# $\Xi$ -hypernuclei in Emulsion

## – First Step to the $\Xi$ N Interaction –

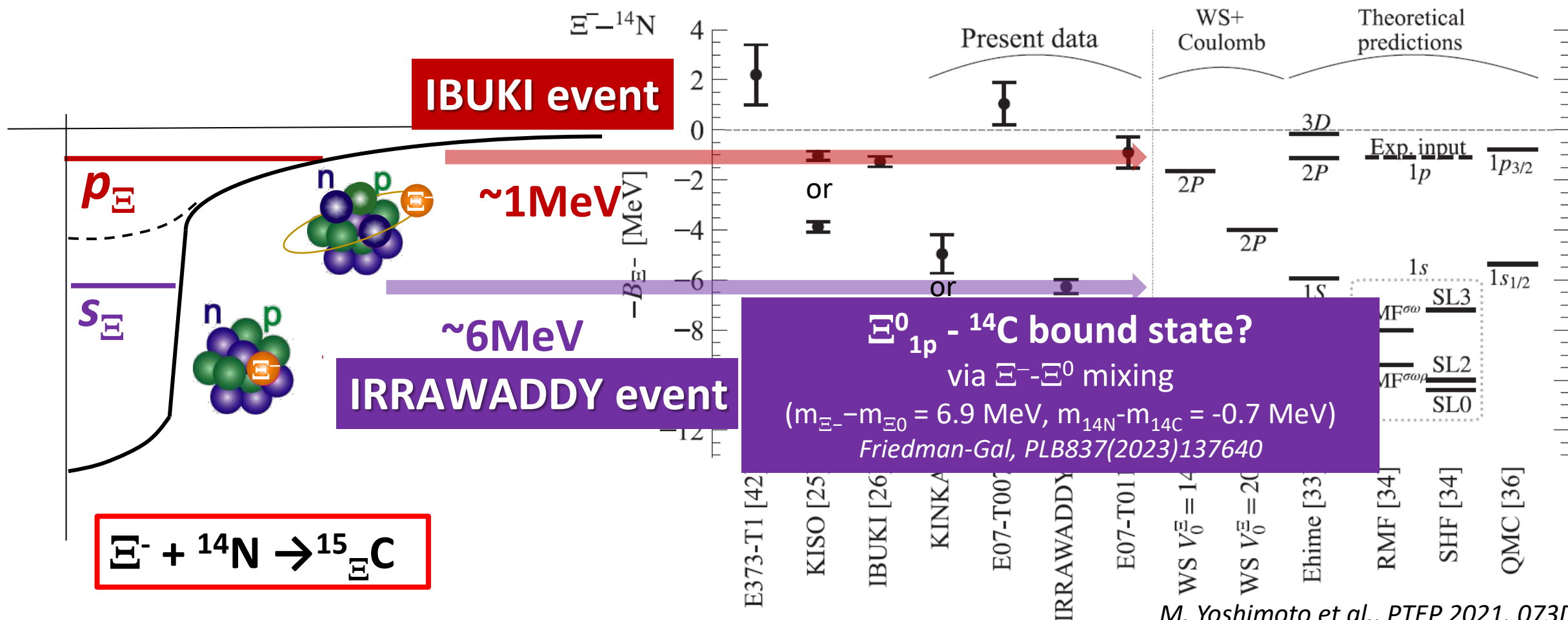
- Attractive  $\Xi$ -nuclear potential was confirmed from observation of  $\Xi$ -hypernuclei in emulsion (E07)



# $\Xi$ -hypernuclei in Emulsion

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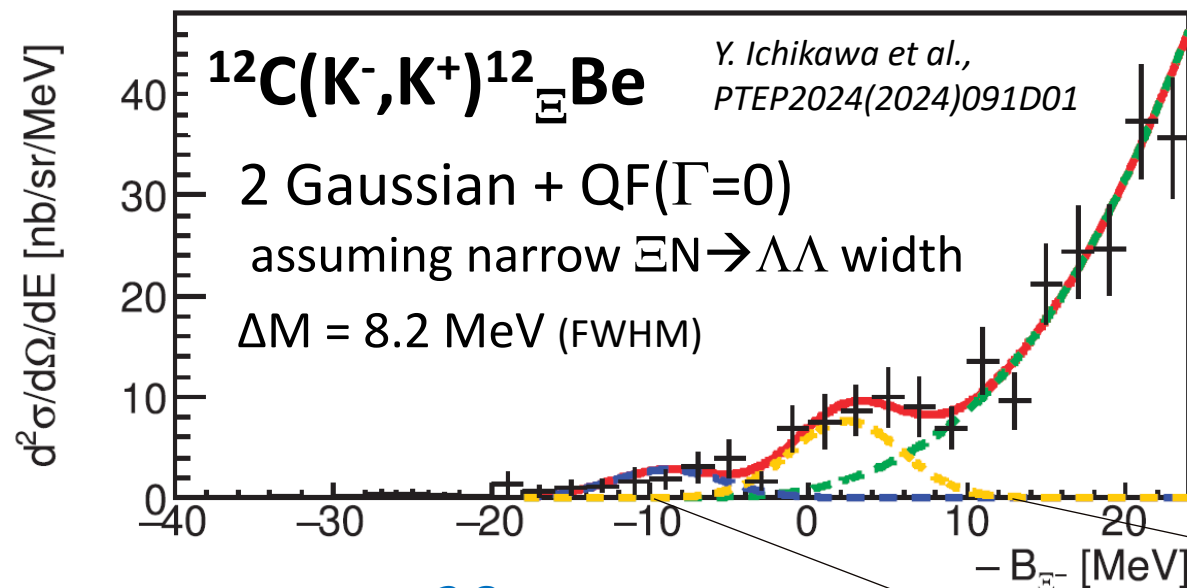
- Attractive  $\Xi$ -nuclear potential was confirmed from observation of  $\Xi$ -hypernuclei in emulsion (E07)



# $\Xi$ -hypernuclear Spectroscopy

– Toward a Precise Determination of the  $\Xi N$  Interaction –

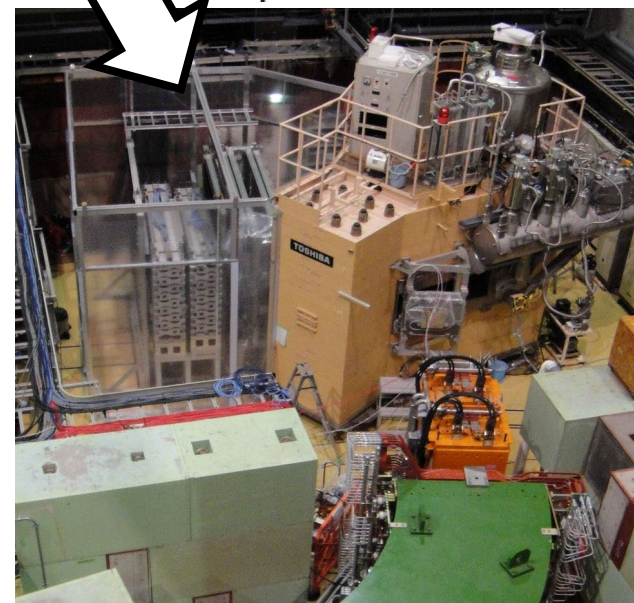
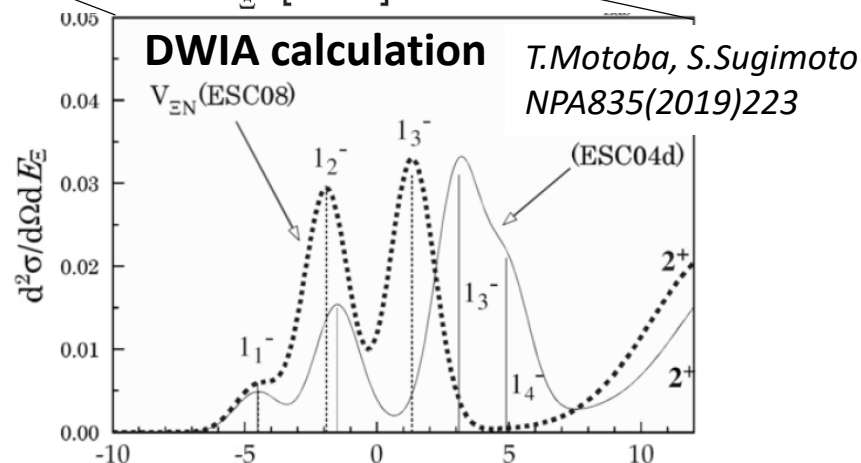
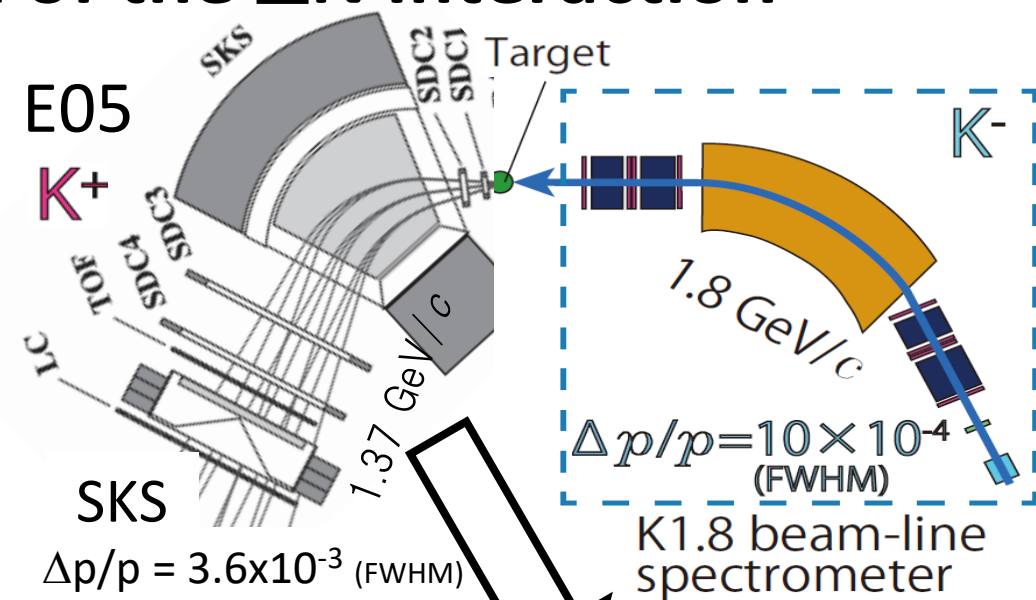
- $\Xi$ -hypernuclear peaks were first observed in E05



$$B_{\Xi^-}^{1st} = 8.9 \pm 1.4^{+3.8}_{-3.1} \text{ MeV}$$

$$B_{\Xi^-}^{2nd} = -2.4 \pm 1.3^{+2.8}_{-1.2} \text{ MeV}$$

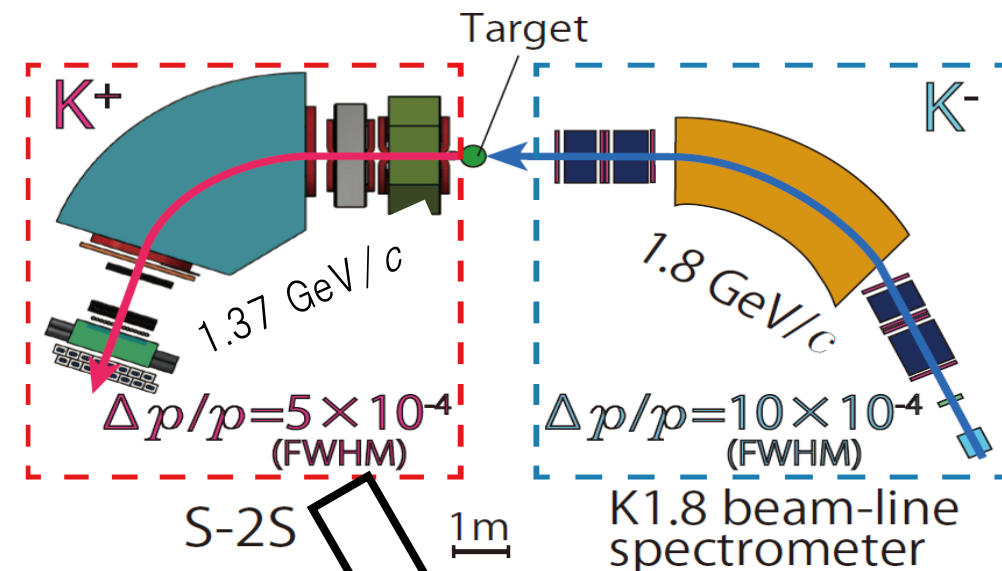
Need more precise measurements  
to investigate the detailed structure  
→ E70 with  $\Delta M = 2$  MeV (FWHM) using S-2S



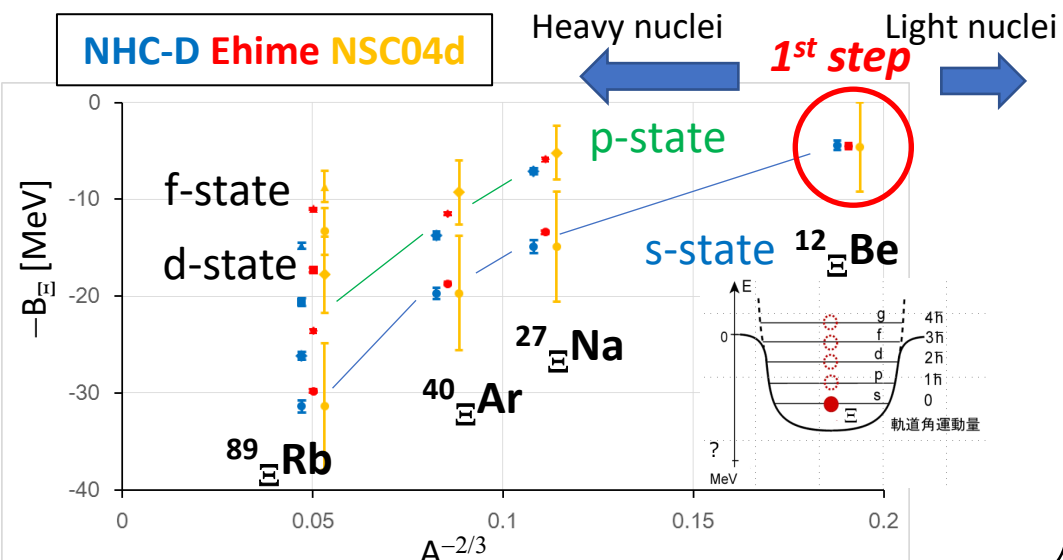
# $\Xi$ -hypernuclear Spectroscopy

## – Toward a Precise Determination of the $\Xi$ N Interaction –

- Systematic measurements will be strongly promoted at J-PARC, starting from E70
- The precise  $\Xi$ -hypernuclear spectroscopy
  - $\Xi$  potential – both  $\text{Re}(V_{\Xi})$  and  $\text{Im}(V_{\Xi})$
  - isospin dependence ( $\propto 1/A$ )
  - $\Xi$ N- $\Lambda\Lambda$  conversion

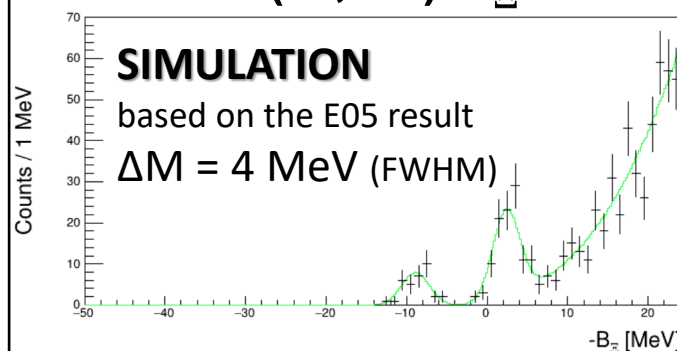


Calculated  $\Xi$  binding energy (and width)

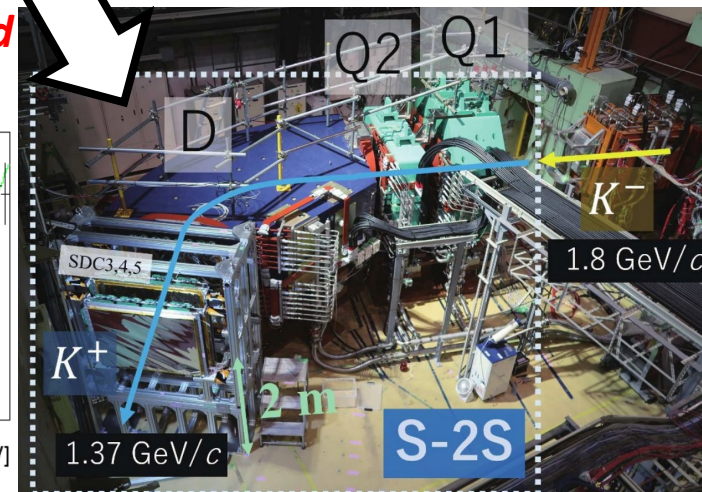


**1<sup>st</sup> step data-taking is completed**

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



T. Gogami et al.,  
The 38th J-PARC PAC (2024)

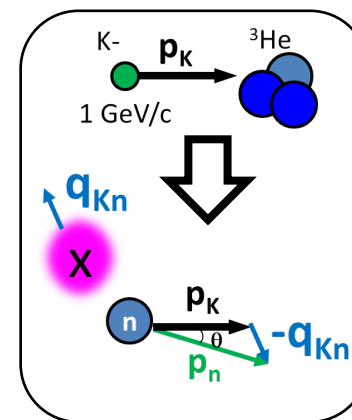
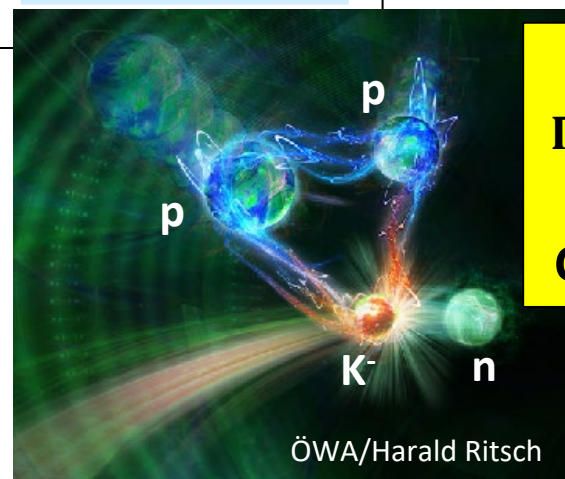
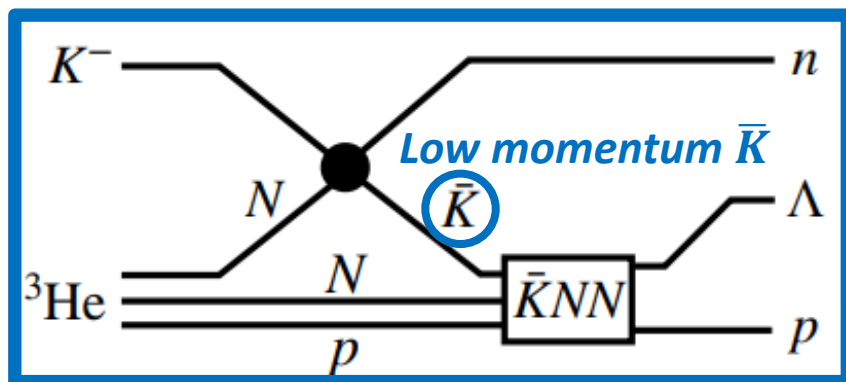
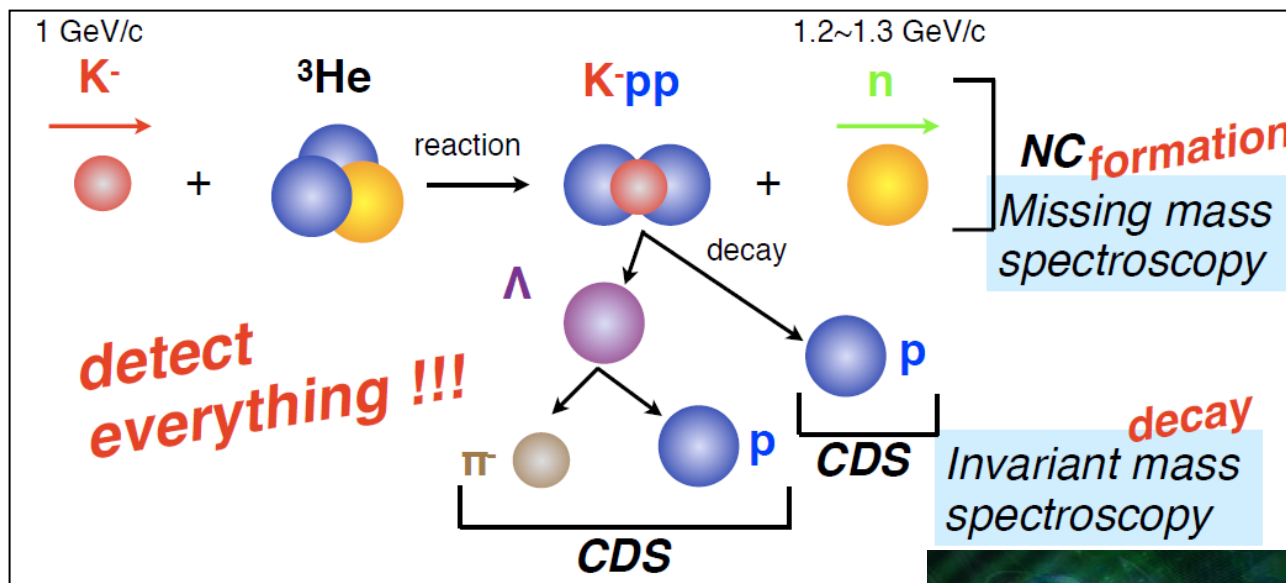


**Results coming soon**

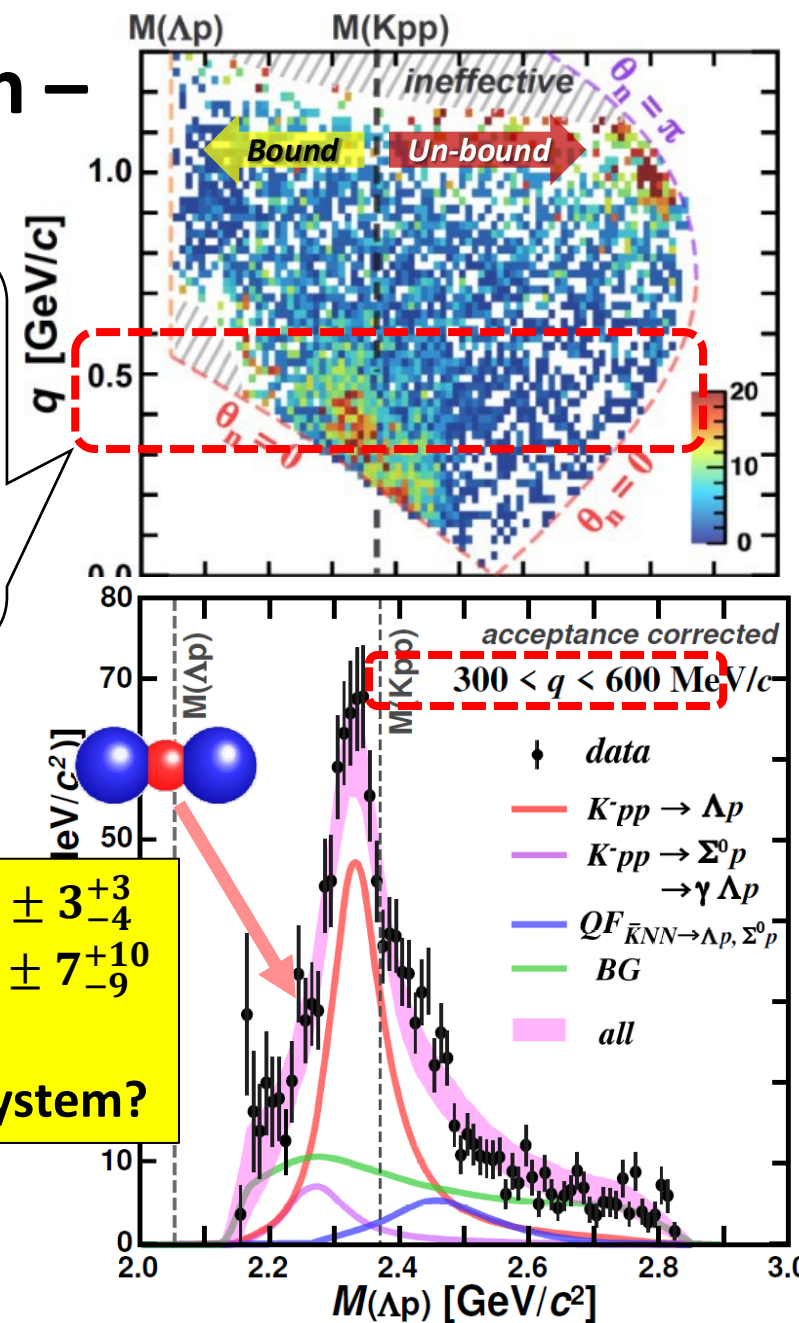
# Kaonic Nuclei

## – A New Form of Nuclei Composed of a Real Kaon –

- “K<sup>-</sup>pp” bound state was observed via  ${}^3\text{He}(\text{K}^-, \Lambda p)n$  in E15



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



$$B_{Kpp} = 42 \pm 3^{+3}_{-4}$$

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

→ **Compact system?**

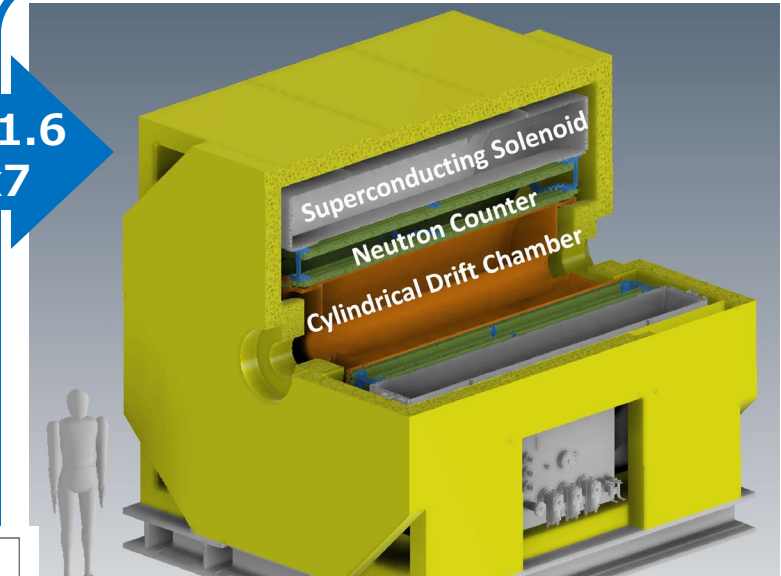
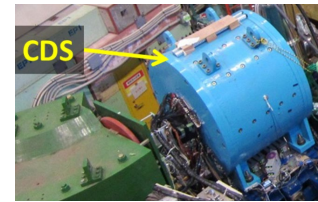
# Kaonic Nuclei

## – Toward a Further Understanding of Kaonic Nuclei –

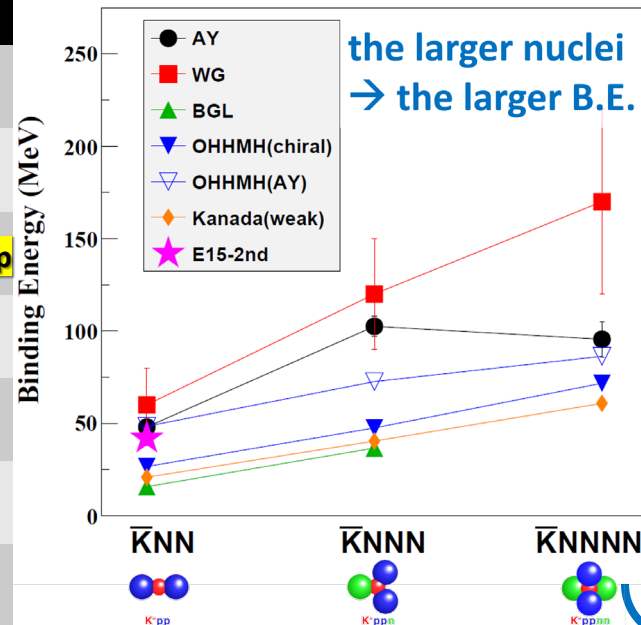
● Systematic measurements will be carried out at J-PARC, starting from E80

- Mass number dependence
  - Binding energy, Branching ratio,  $q$  dependence, ..
- Spin/parity determination
- Internal structure extracted with theoretical investigations

✓ Solid angle: x1.6  
✓ Neutron eff.: x7



|                    | Reaction                  | Decays                                      |
|--------------------|---------------------------|---------------------------------------------|
| $\bar{K}N$         | $d(K^-, n)$               | $\pi^{\pm 0} \Sigma^{\mp 0}$                |
| $\bar{K}NN$        | ${}^3\text{He}(K^-, N)$   | $\Lambda p / \Lambda n$                     |
| $\bar{K}NNN$       | ${}^4\text{He}(K^-, N)$   | $\Lambda d / \Lambda pn$ ← first step       |
| $\bar{K}NNNN$      | ${}^6\text{Li}(K^-, d)$   | $\Lambda t / \Lambda dn$                    |
| $\bar{K}NNNNN$     | ${}^6\text{Li}(K^-, N)$   | $\Lambda \alpha / \Lambda dd / \Lambda dpn$ |
| $\bar{K}NNNNNN$    | ${}^7\text{Li}(K^-, N)$   | $\Lambda \alpha n / \Lambda ddn$            |
| $\bar{K}\bar{K}NN$ | $\bar{p} + {}^3\text{He}$ | $\Lambda\Lambda$                            |



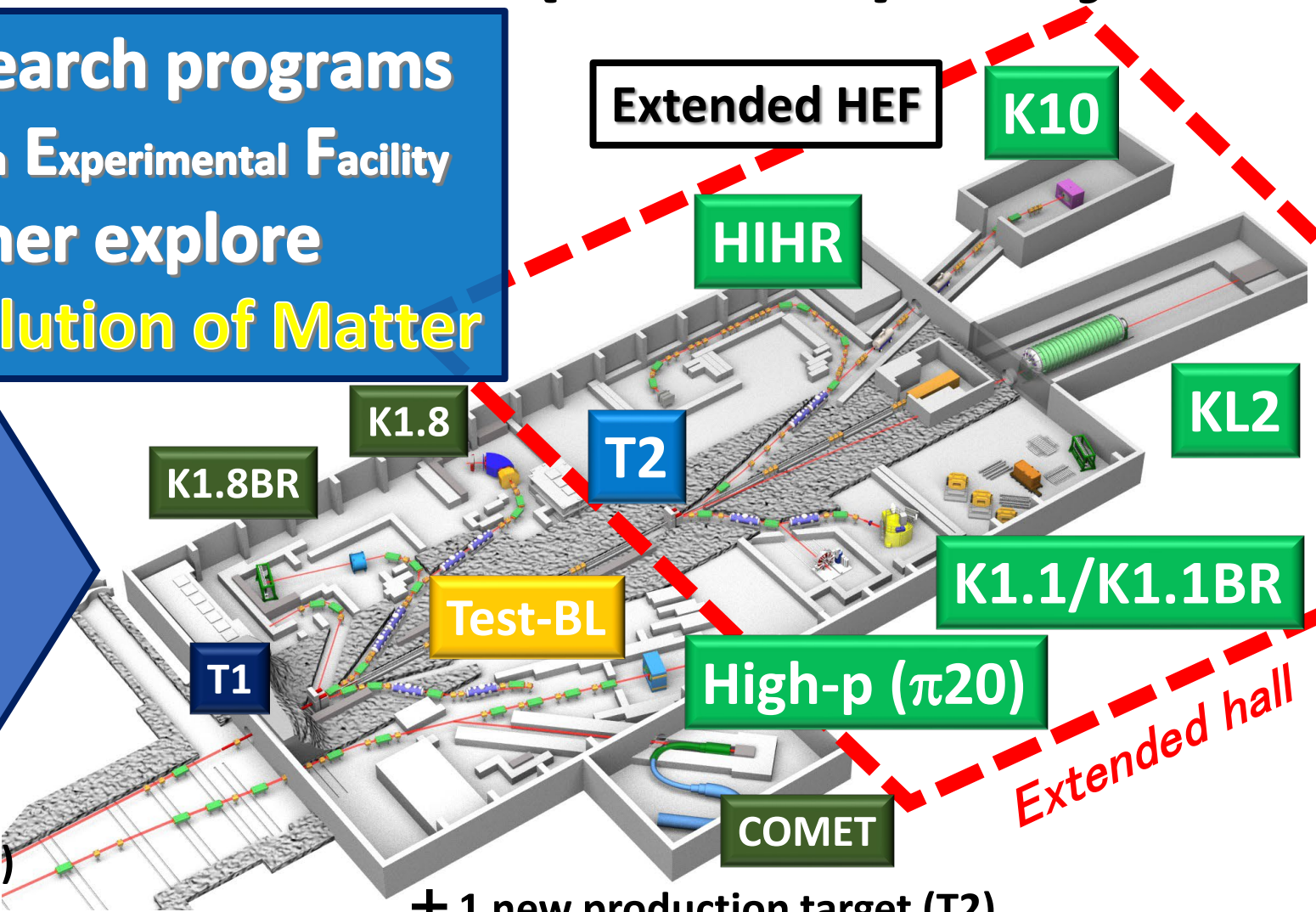
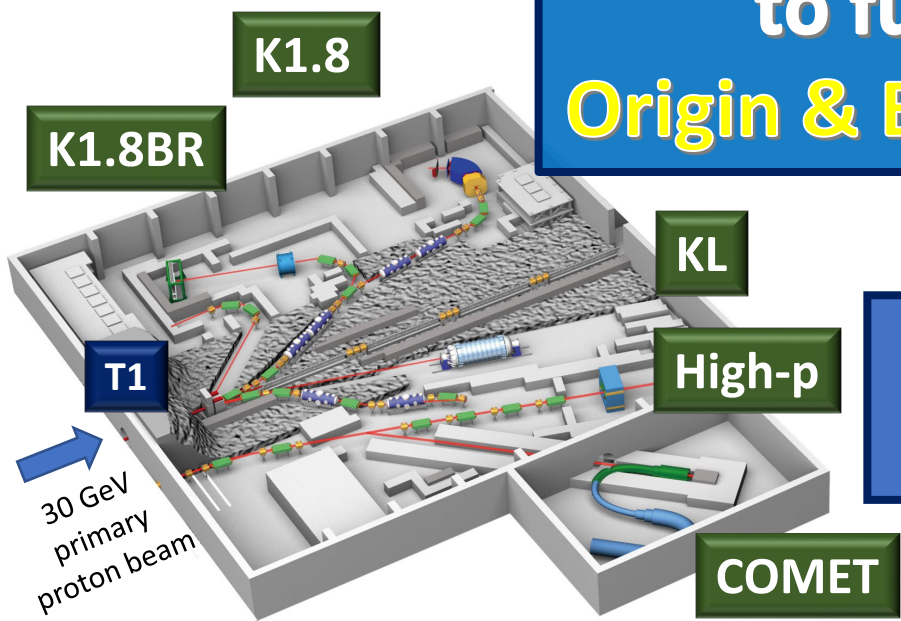
Will start in 2027

# 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)

## Determine density dependent $\Lambda N$ interaction

HIHR

### Ultra-high-resolution $\Lambda$ hypernuclei spectroscopy

- intense dispersion matched  $\pi$  beam

K1.1

### Systematic $\Lambda N$ scattering measurement

- intense polarized  $\Lambda$  beam

## Investigate diquarks in baryons

high-p  
( $\pi 20$ )

### High-resolution charm baryon spectroscopy

- intense high-momentum  $\pi$  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

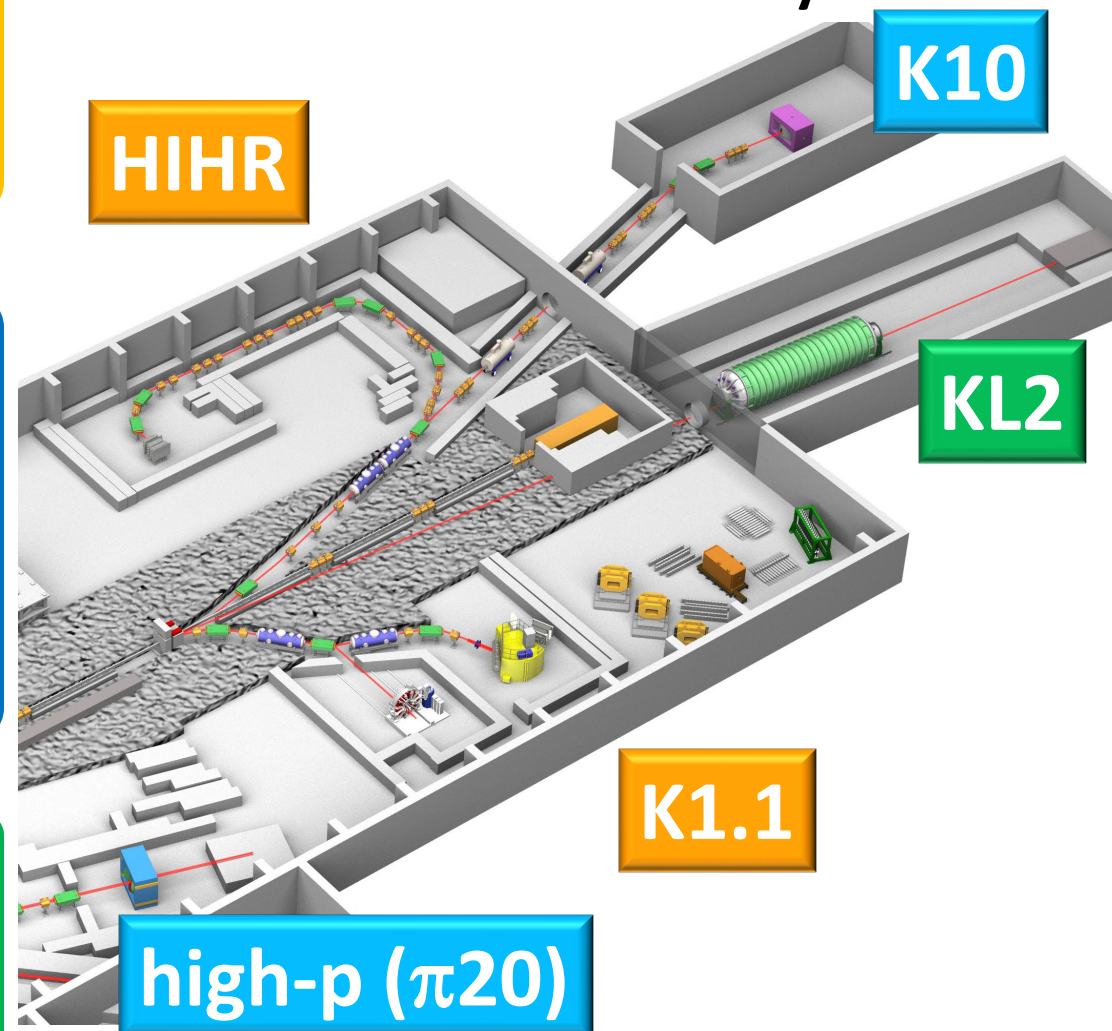
- intense neutral K beam

Oct 19, 2026

S. Sawawda @MENU2026

# Expanded Research Programs

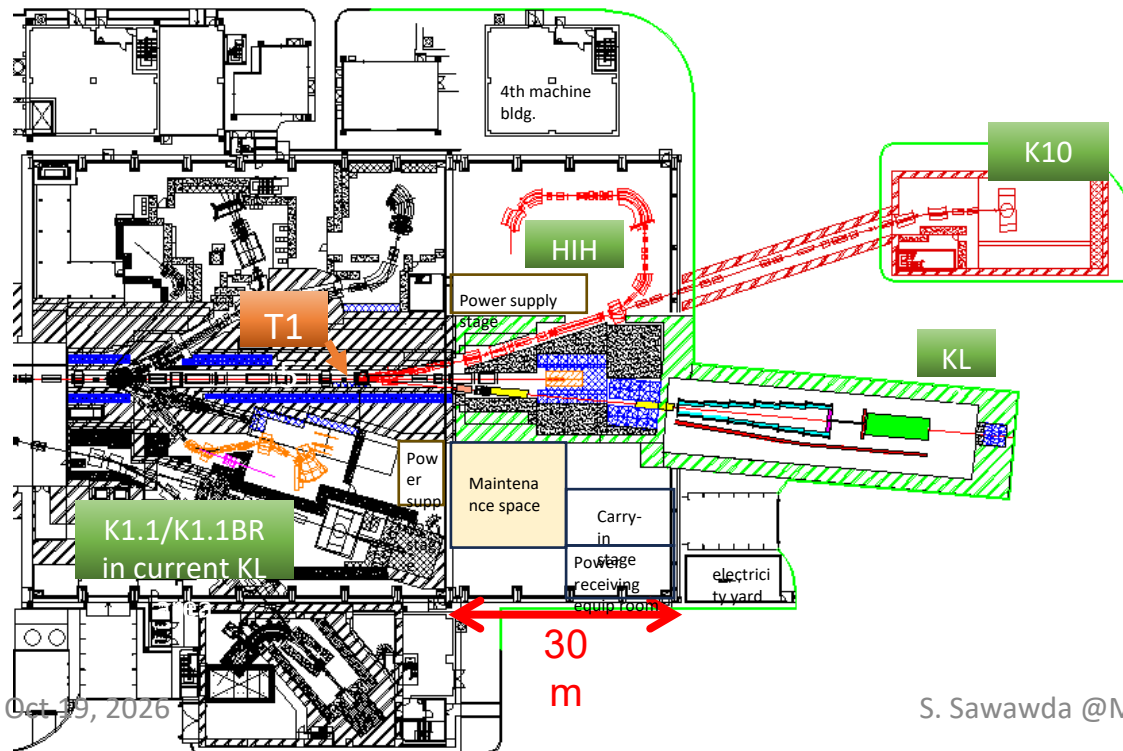
at the Extended Facility



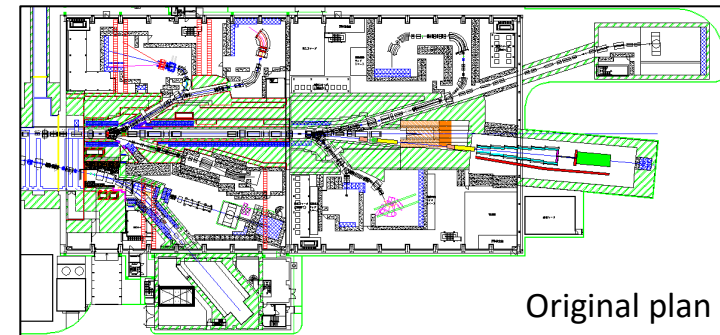
# Staging approach for extension

- In KEK-PIP2022 (Project Implementation Plan), HEF-ex project got 1<sup>st</sup> priority for the budget request.
- However, construction cost was significantly increased after COVID-19: 150 → 200 Oku-yen.
- Cost reduction/optimization and staging plans with smaller steps are under discussion for early realization of the project.

## Reduced plan (under discussion)



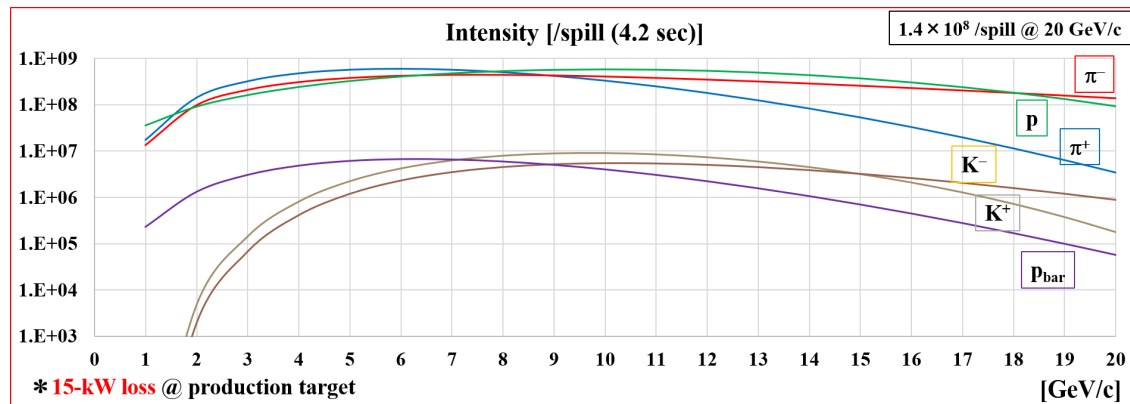
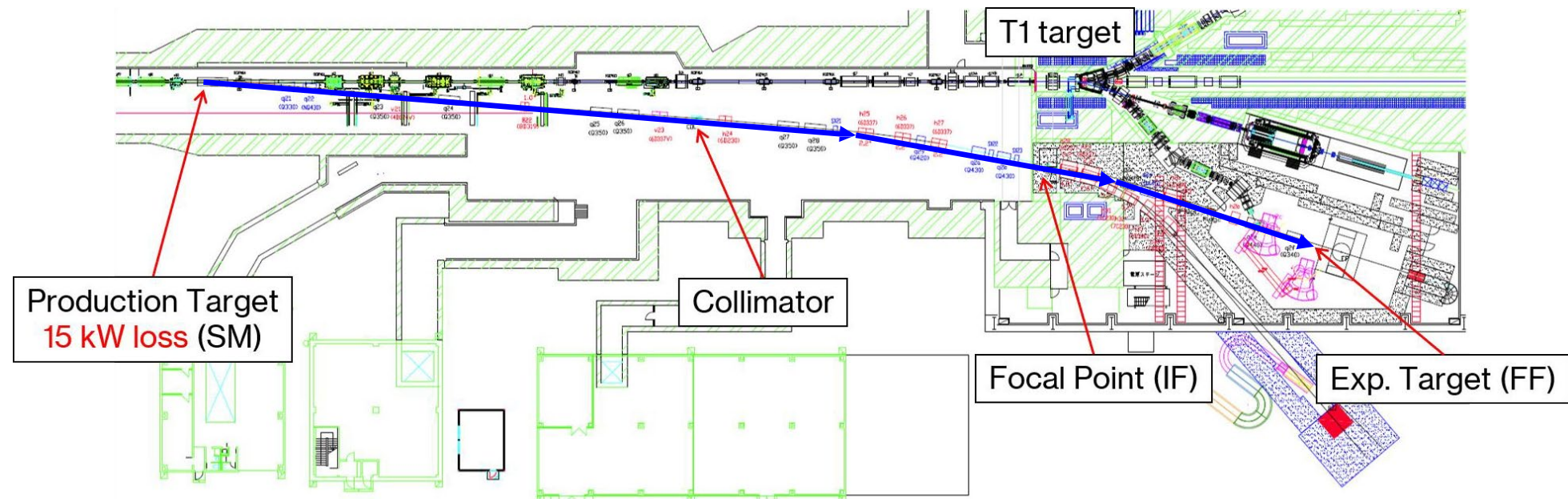
- 2nd target is installed in current hall. (referred to as “T1.5” to distinguish from T2 in the original plan)
- K1.1/K1.1BR are built in current KL area.



# Near Future Hadron Physics at Hadron Experimental Facility

- Strangeness nuclear physics: continuing  $S=-1$  and  $S=-2$  experiments at K1.8 and K1.8BR
  - K1.8:  $\gamma$  and missing mass spectroscopy of  $\Lambda$  hypernuclei  
missing mass spectroscopy of  $S=-2$  hypernuclei
  - K1.8BR: kaonic nuclei
- Hadron physics experiments: pi20 and K10
- Promotion of extensive use of the facility to enhance its value

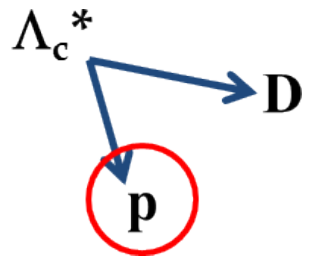
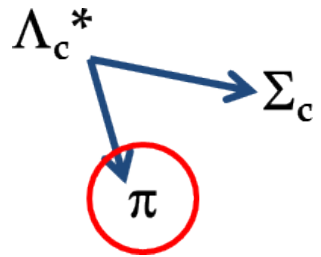
# 2ndary beams at High-Momentum Beamline: $\pi 20$



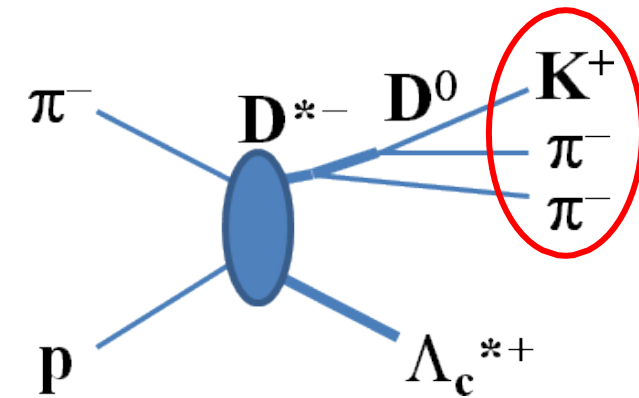
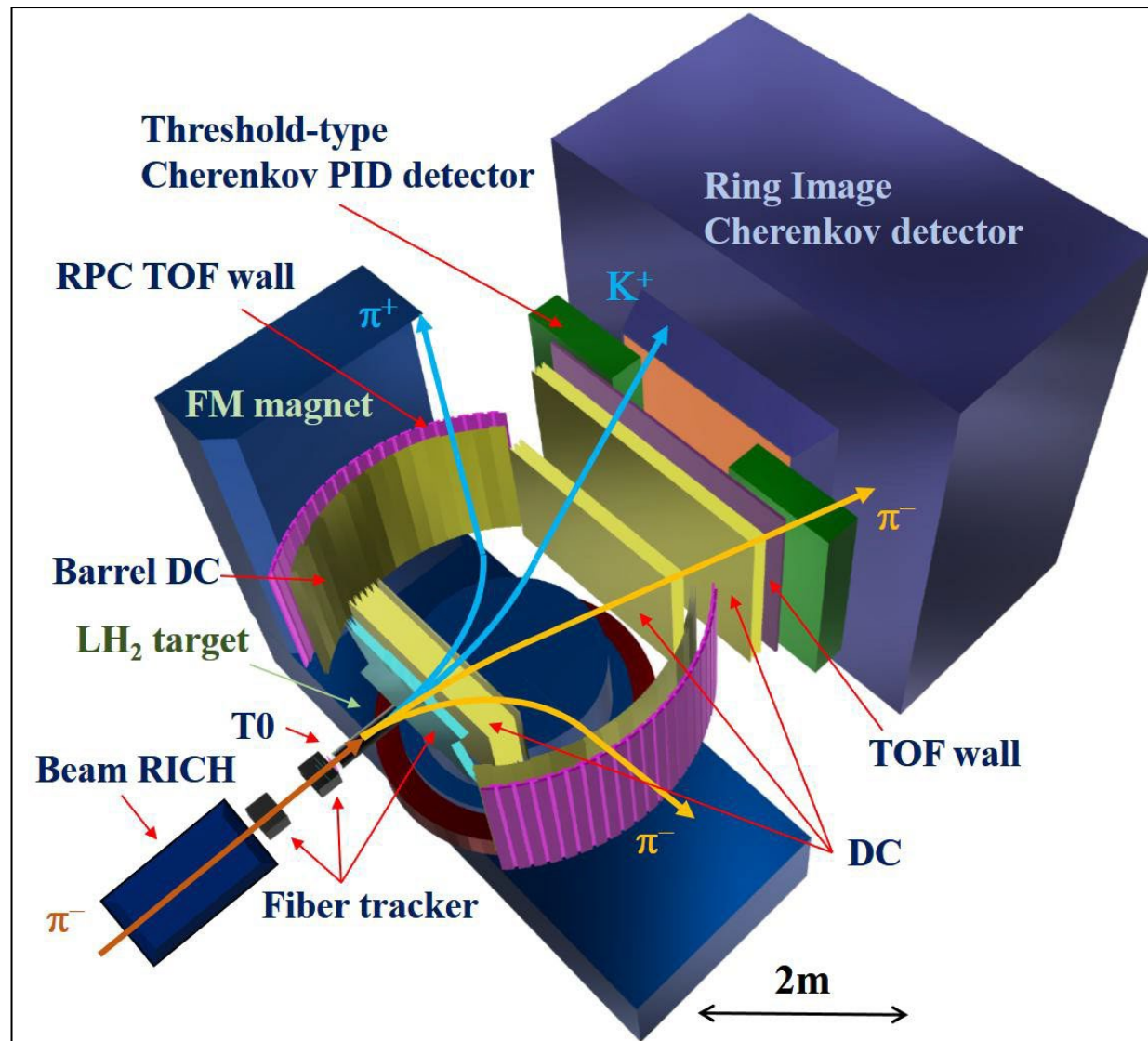
$\pi$ , K, pbar up to 20 GeV/c  
 design intensity  $>107/\text{spill}$  ( $\pi^\pm$ , p),  $>105/\text{spill}$  ( $K^-$ , pbar)  
 $\Delta p/p \sim 0.1\%$



# MARQ spectrometer at $\pi 20$



Decay  
measurement  
\*Branching ratios  
 $\pi^\pm$  &  $p$ :  $< 4.0 \text{ GeV}/c$

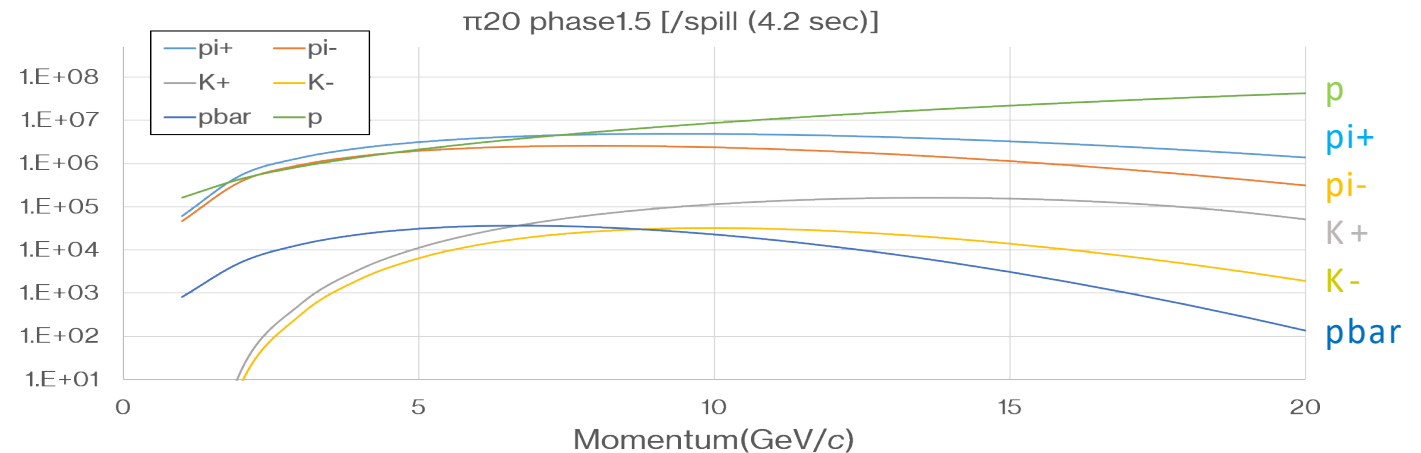


Missing mass  
measurement  
\*Production rate  
 $K^+$  &  $\pi^-$ :  $2-16 \text{ GeV}/c$   
Slow  $\pi_s^-$ :  $0.5-1.7 \text{ GeV}/c$

E50 collaboration extensively  
preparing the MARQ  
spectrometer

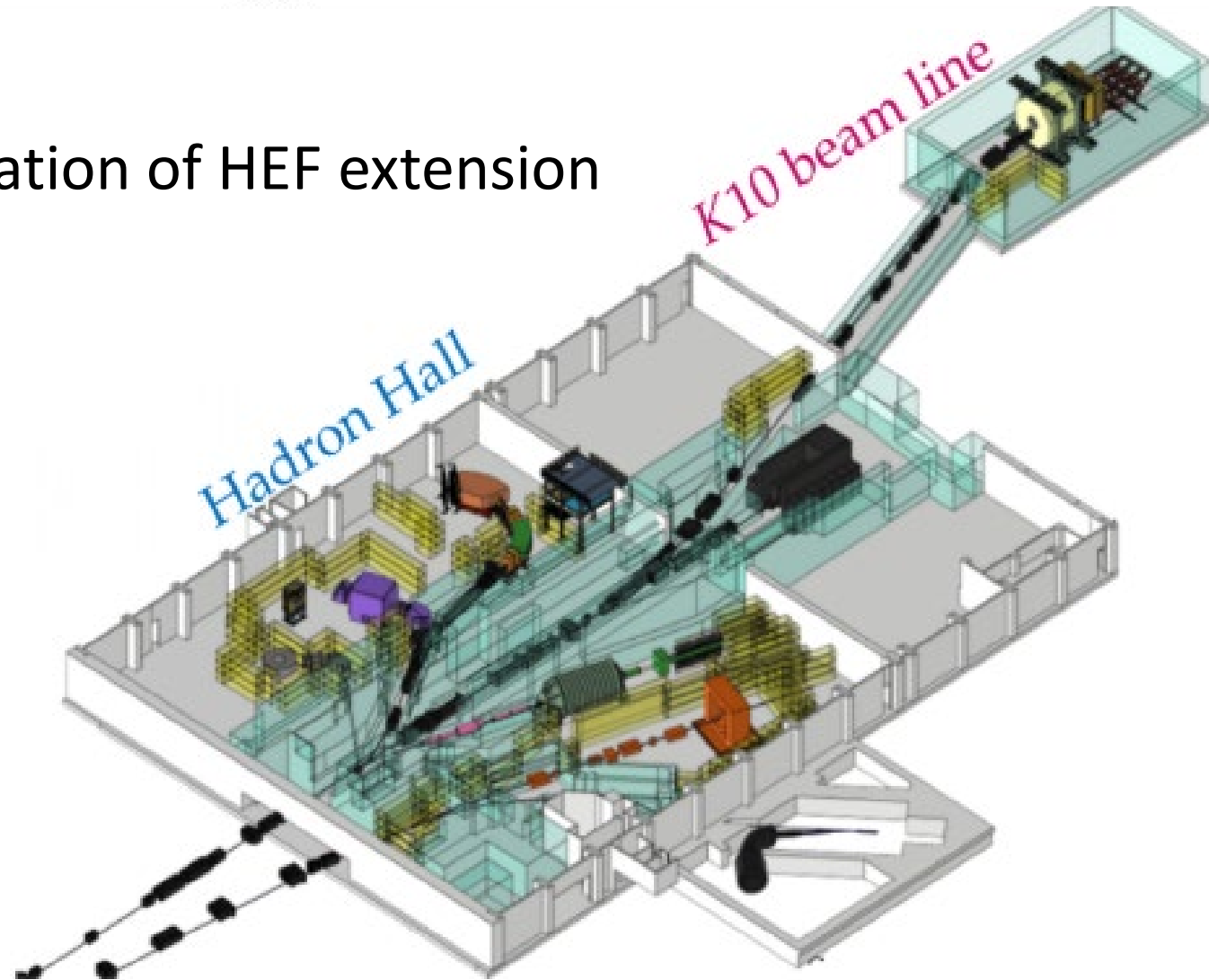
# Physics with Phase 1.5

- E50,  $\pi^-p$  reaction at 20 GeV/c
  - background study, same  $D^{*-}$  final state, about 2.4 mb
- Hyperon production,  $\pi^-p \rightarrow Y^{*0}K^{*0}$  at 5 GeV/c
- $K^-p$  reaction at 5-10 GeV/c
  - background study,  $K^+$  and  $K^{*0}$  production, about 3 mb (JAM)
  - $K^-p \rightarrow K^+\Xi^-$ , 7.2  $\mu\text{b}$  at 5 GeV/c, about  $4 \times 10^2$  events/week
  - $K^-p \rightarrow \Xi^-K^+K^{*0}$ , 1.0  $\mu\text{b}$  at 5 GeV/c, about  $0.5 \times 10^2$  events/week



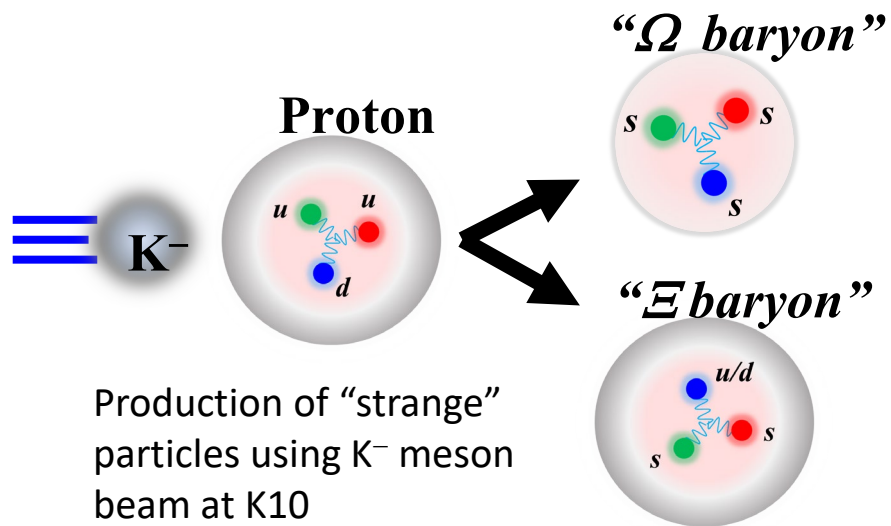
# K10

- Partial realization of HEF extension

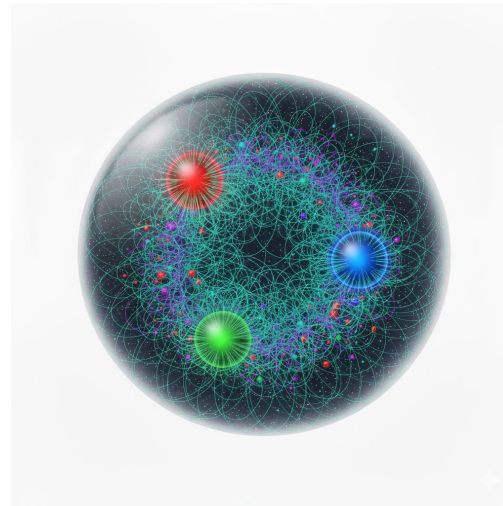


# K10

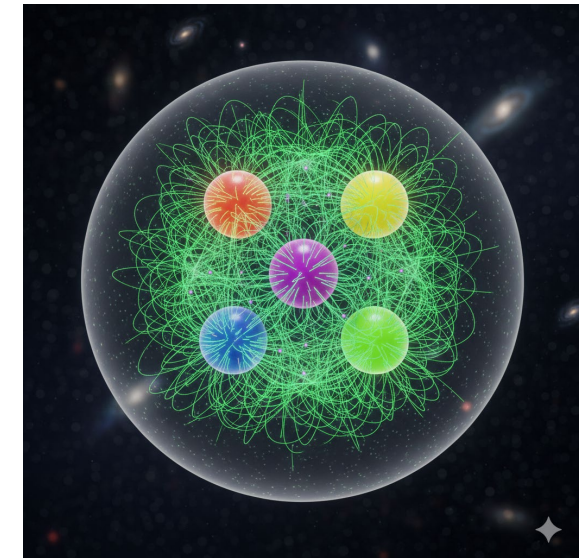
- Physics at K10 is a natural extension of the physics at  $\pi 20$ .



Omega and Xsi spectroscopy



GPD and related topics

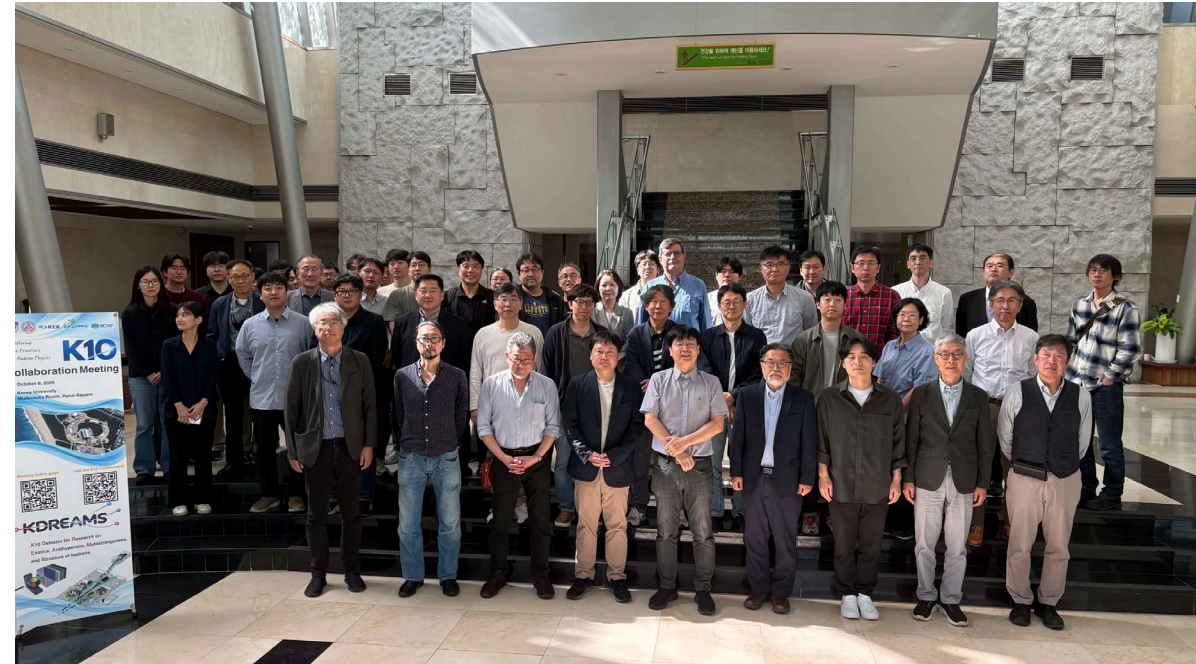


Extotic hadrons

## How hadrons are emerged?

# K10

- Collaboration was established and the 1<sup>st</sup> collaboration meeting was held at Korea University on October 9, 2026.
  - 81 collaborators
  - 5 countries
  - 31 institutions
- “Yellow Report” is being prepared.



# Near Future Hadron Physics at Hadron Experimental Facility

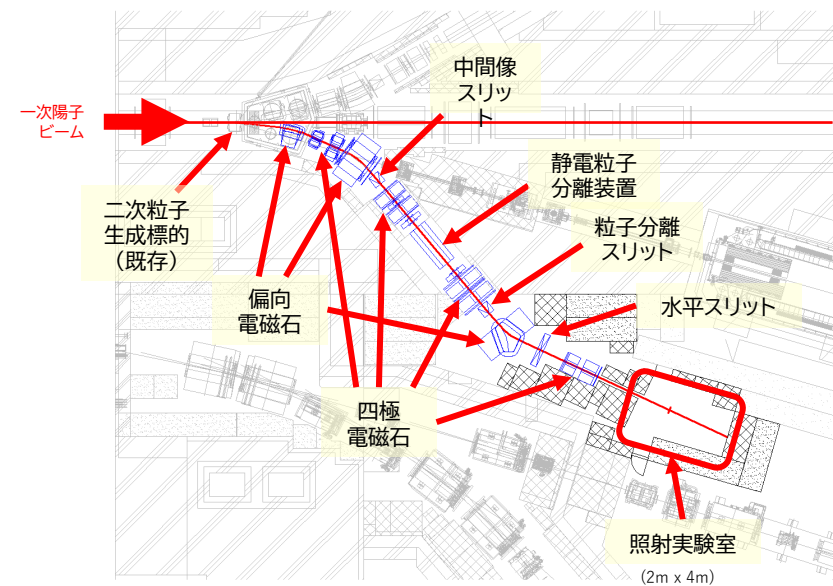
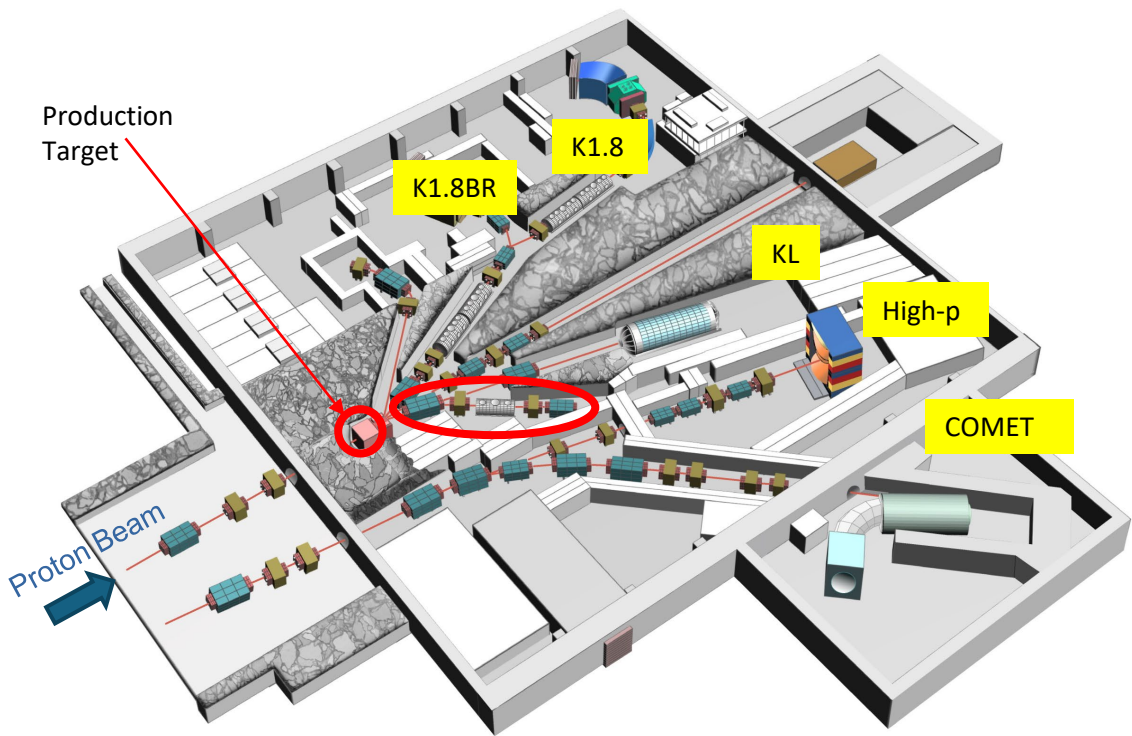
- Strangeness nuclear physics: continuing  $S=-1$  and  $S=-2$  experiments at K1.8 and K1.8BR
- Hadron physics experiments: pi20 and K10
- Promotion of extensive use of the facility to enhance its value
  - Use of HEF beams for other areas than hadron and particle physics is being considered to enhance the value of HEF
  - Beam line will be constructed for space industry to test mainly Single Event Effect to semiconductors.
  - Muon beam application is under consideration.

# New Beamline: SP (Space) Line

Funded by the Space Strategy Fund

Will be constructed in 5 years at the previous K1.1 beamline space

Mainly used for evaluation of Single Event Effect of electronics of spacecrafts.



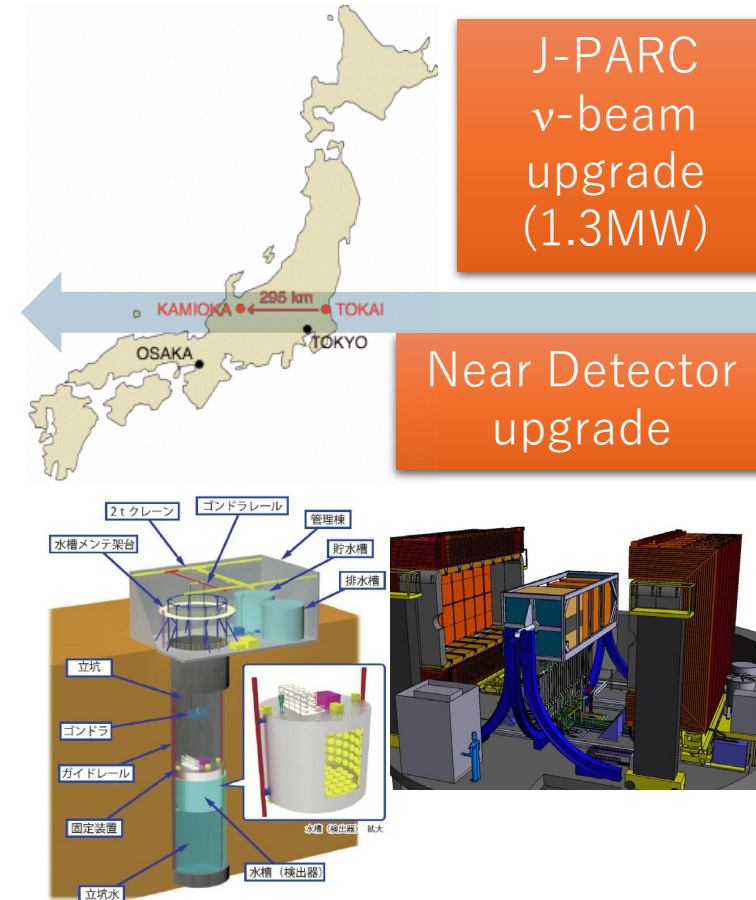
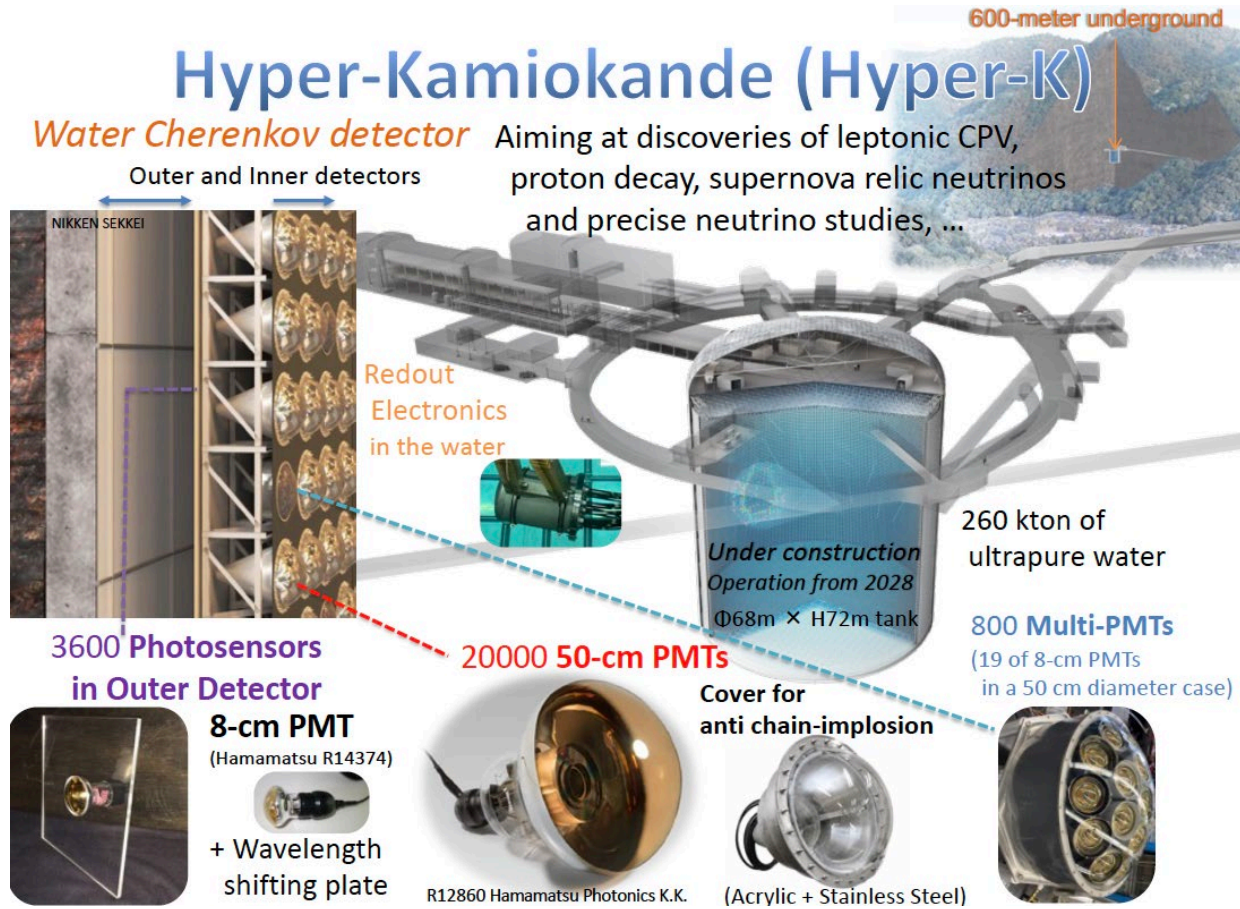
|                |                              | remarks                                          |
|----------------|------------------------------|--------------------------------------------------|
| particle       | proton                       | antiptotons, pions are available also            |
| kinetic energy | 10 MeV~510 MeV               |                                                  |
| intensity      | ~10 <sup>7</sup> /s          | Intensity/cm2 is variable based on the spot size |
| spot size      | a few mm ~ 10 cm in diameter | variable                                         |

# J-PARC Main Ring in coming several years

- Hyper-Kamiokande will start operation in JFY2028.
- For several years after start of Hyper-Kamiokande, priority of operation of J-PARC Main Ring (MR) might be given to the neutrino beam.
- While beam operation at the Hadron Experimental Facility (HEF) might be limited during these years, a lot of fruits are expected after these years, as HEF would be the leading facility at J-PARC MR.
  - Good physics program/experiments are awaited.

# Hyper-Kamiokande Overview

T. Nakadaira



New Huge Water Cherenkov Detector  
(Fiducial mass = 190kt)

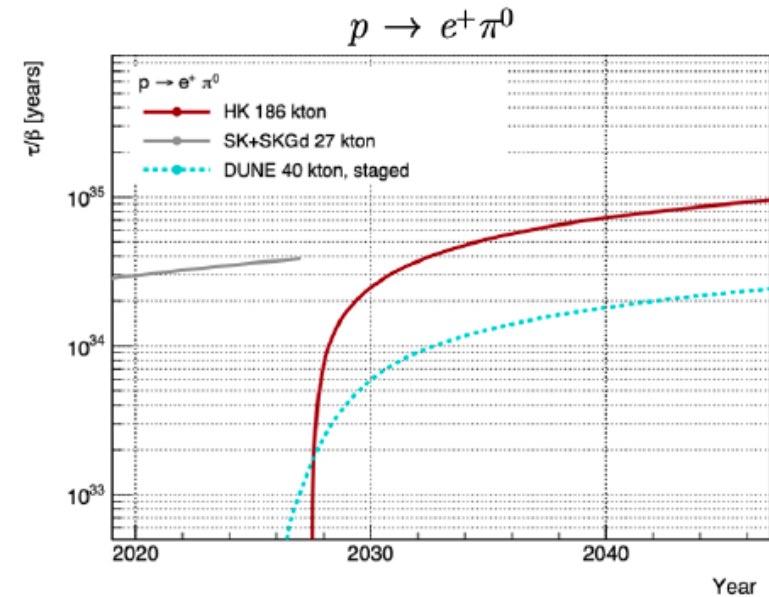
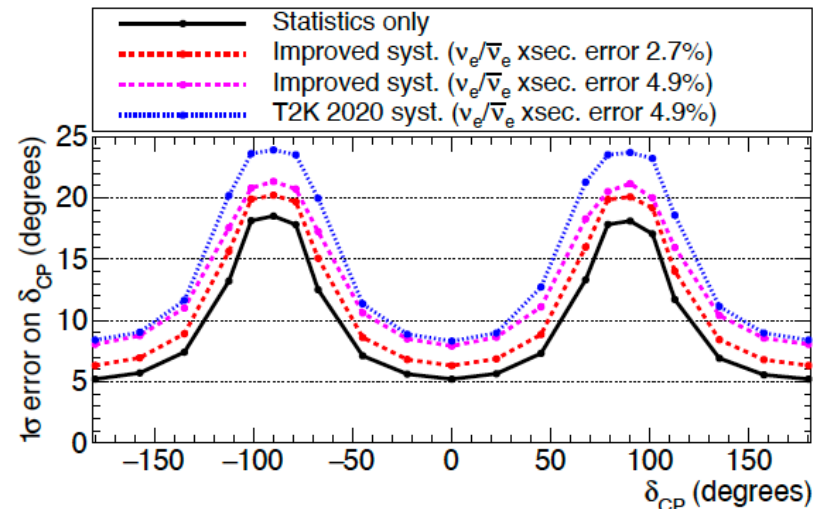
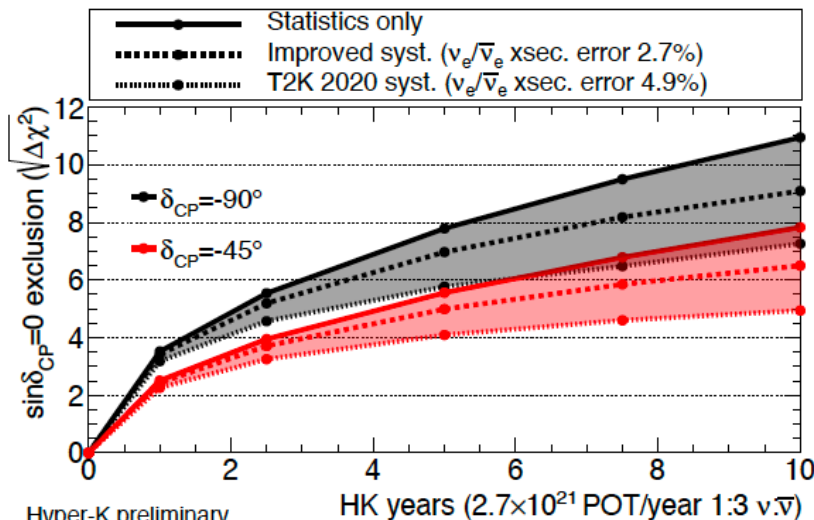


Under construction from 2020, Data taking in JFY2028~

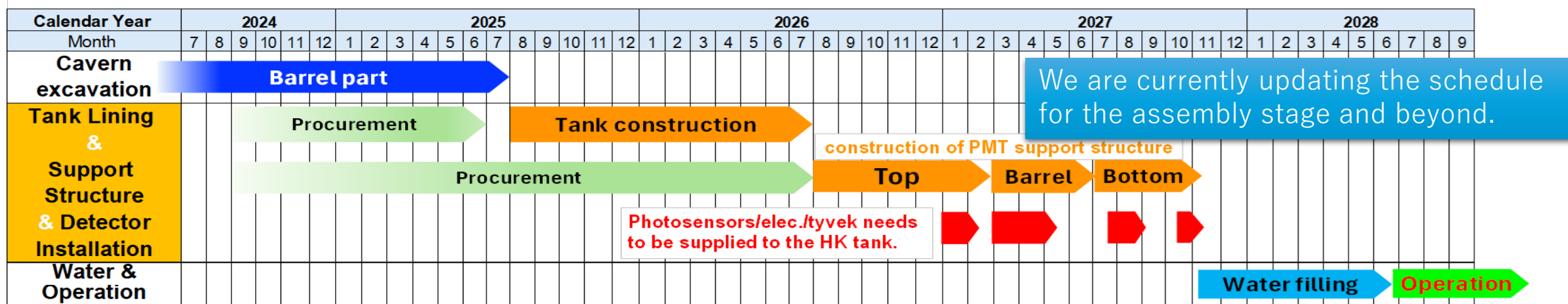
# Hyper-K will challenge the big questions of nature

- Search for CPV (matter – anti-matter asymmetry ) in Leptons
  - Measure the size of CP asymmetry ( $\delta\text{CP}$ ) with precision of  $\lesssim 20^\circ$ .
- Search for the evidence of GUT: Proton decay search with reach of  $10^{35}$  years.
- Advancing neutrino astronomy and astrophysics

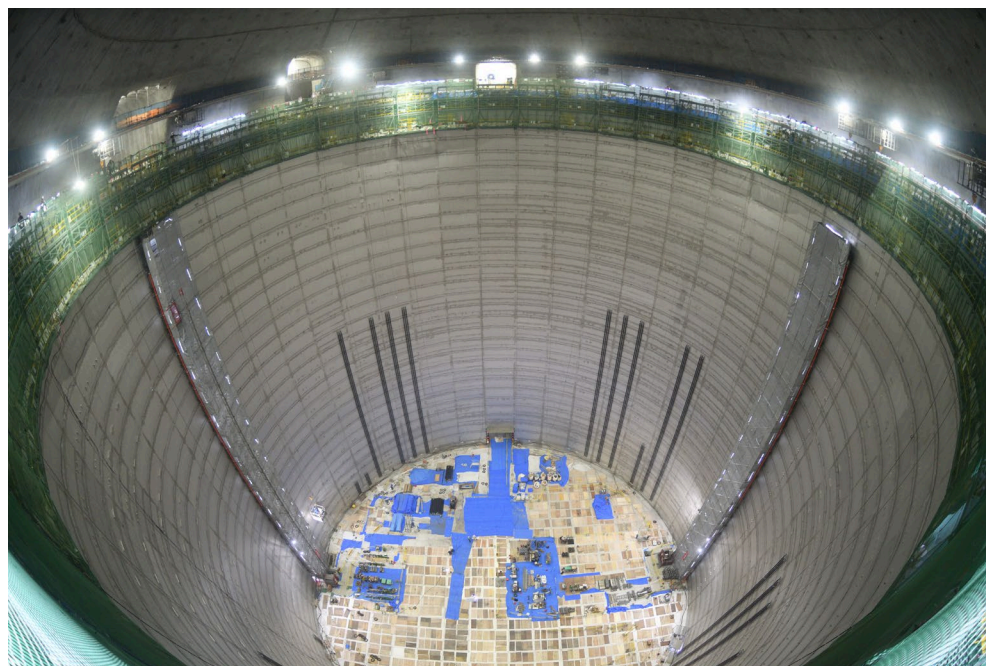
Stable high-power neutrino beam (Net.  $\sim 5$  months/year) for  $\sim 10$  years, and systematic error control is quite important to achieve goals.



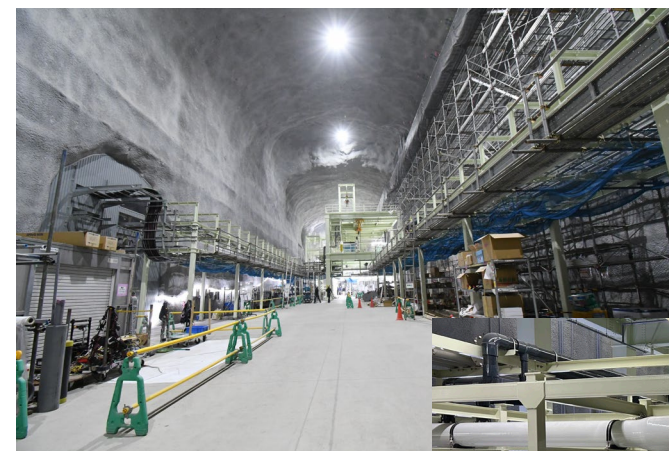
# HK Construction Status @ Kamioka



Cavern excavation  
(~2025, Jul.)

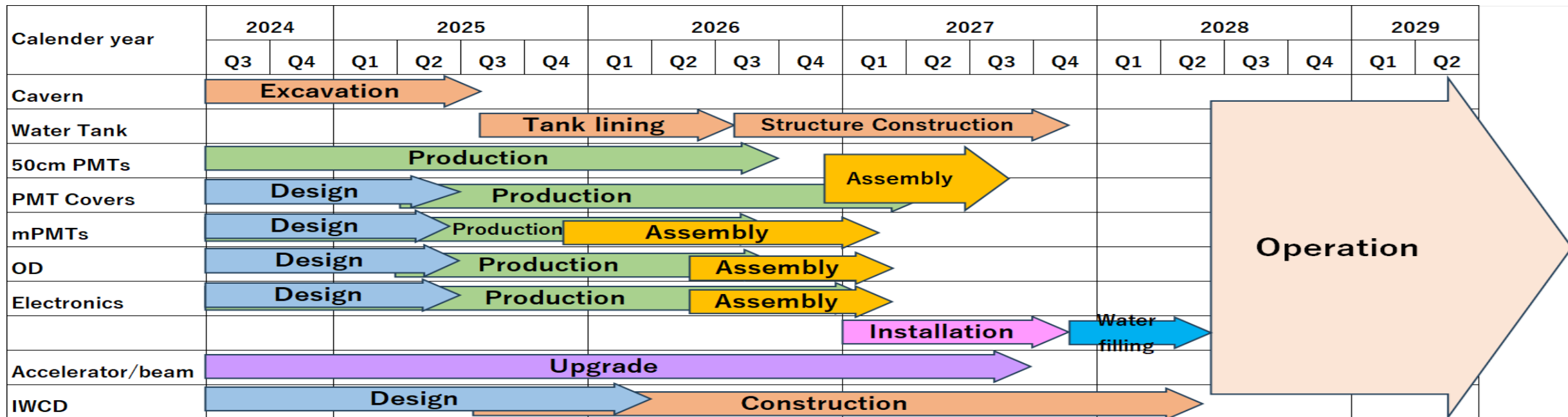


Water Tank: under construction  
(2026, Jul.)



Pure-water system: under construction  
(@ 2026, Apr./May.)

# HK Construction Status @ Kamioka



100 PMTs × 2 rooms using Super-K electronics

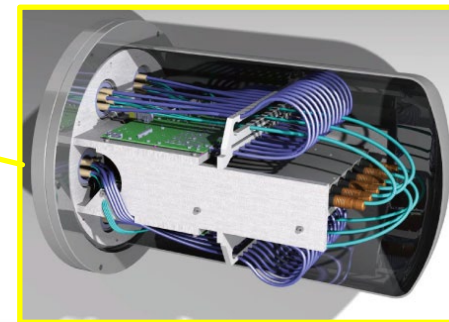


Mass-production & test of 20-inch PMT



**CERN-NP08**

Assembly of electronics for HK



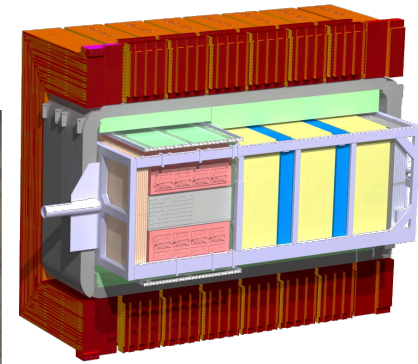
Assembling with covers



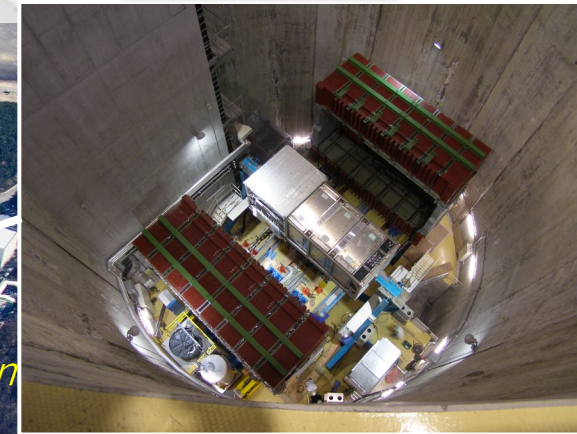
We are currently updating the schedule for the electronics and assembly stage and beyond.

# J-PARC Neutrino Beam for HK

ND280

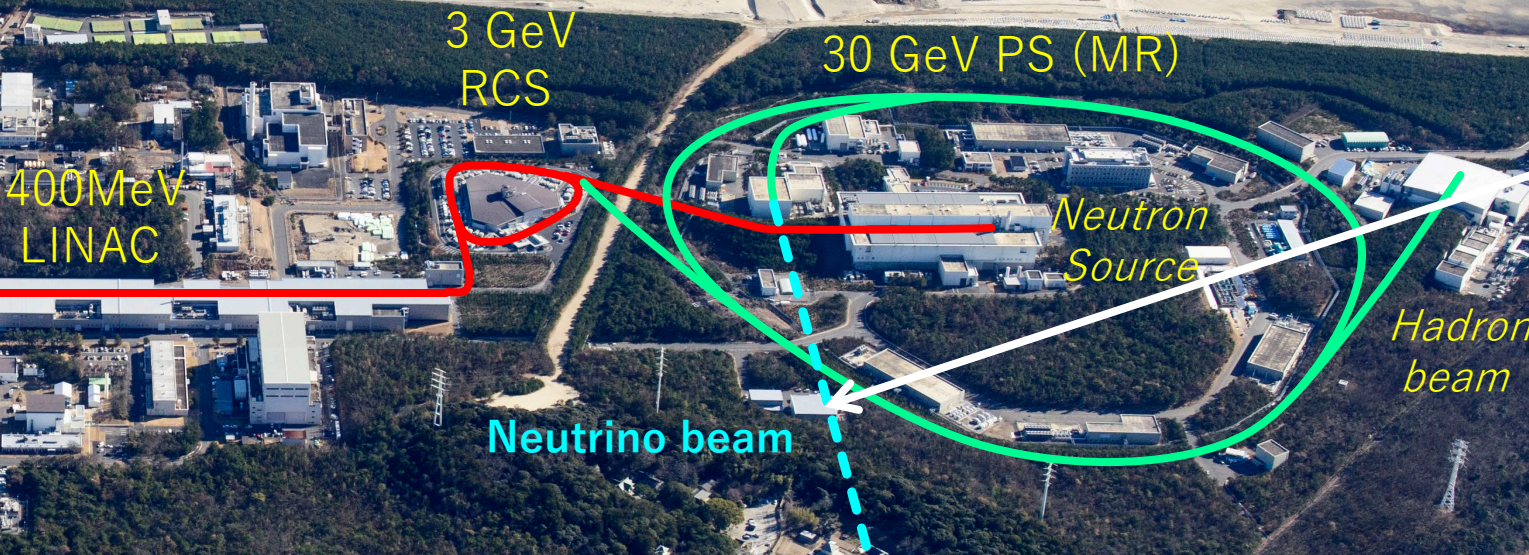


UA1 Magnet

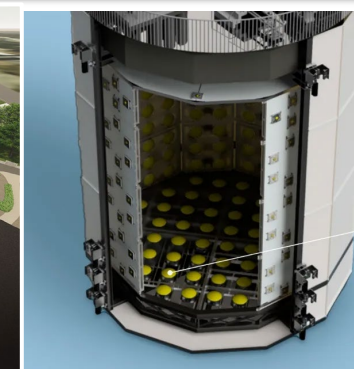
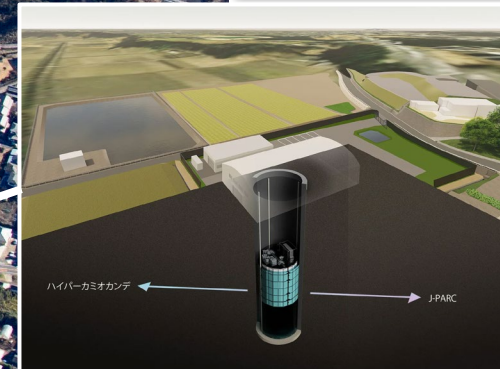
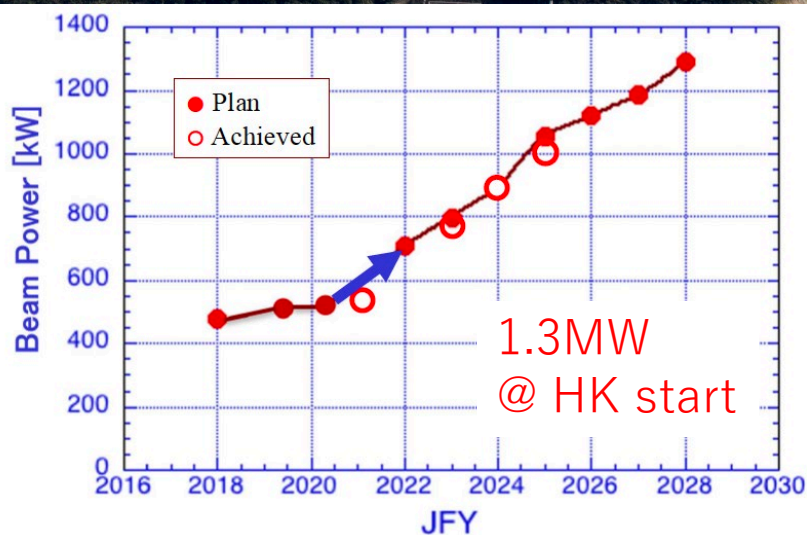


Precise meas. of  $\nu_\mu$ -N,  $\bar{\nu}_\mu$ -N interaction.  
 $\bar{\nu}_\mu$  contamination  $\nu_\mu$ -beam, and vice versa.

IWCD (Intermediate Water Cerenkov detector)



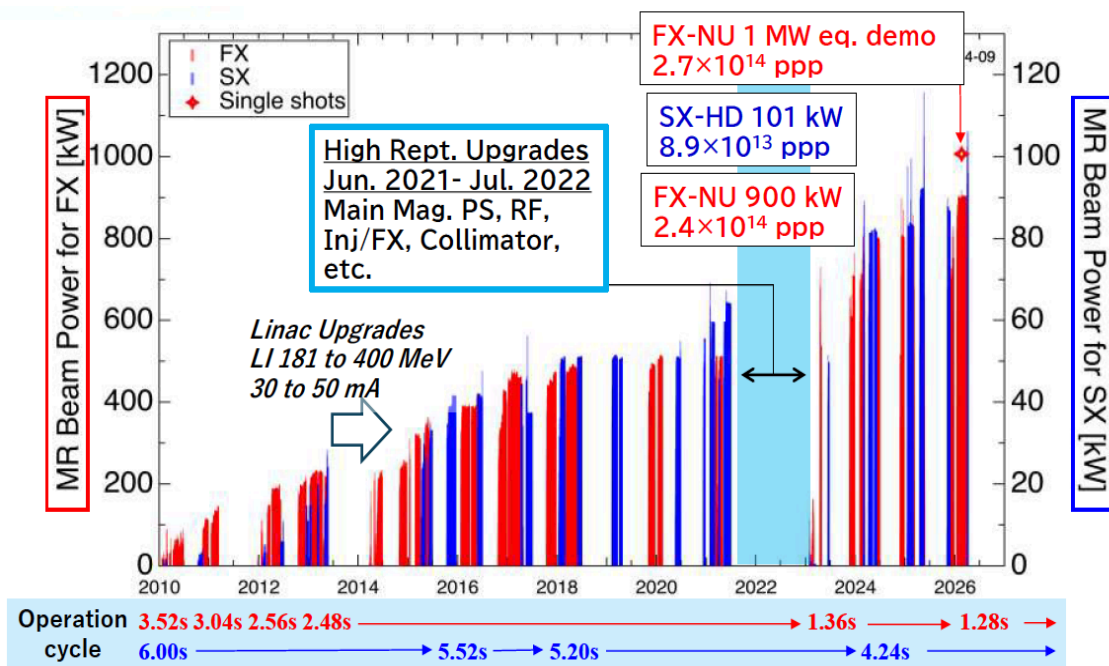
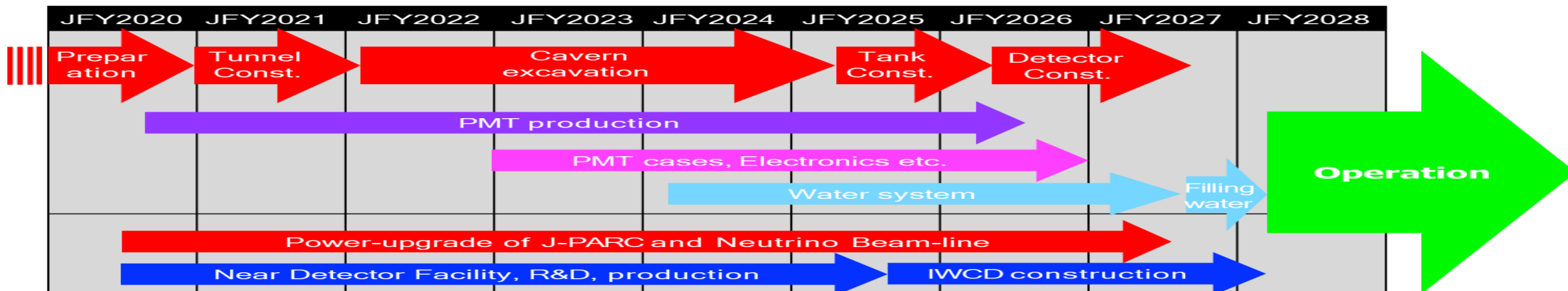
## MR & Nu-beam Upgrade



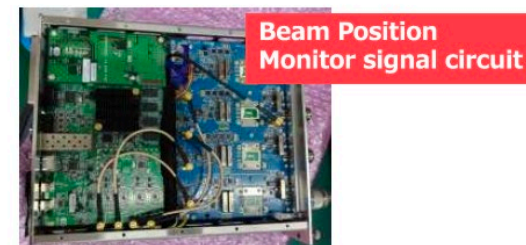
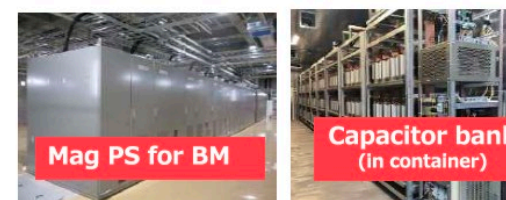
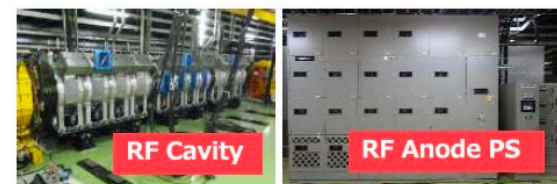
Precise meas. of  $\nu_e$ -N,  $\bar{\nu}_e$ -N int. with the same detection principle as Far-detector  
← **Key to achieve HK physics goal.**

T. Nakadaira

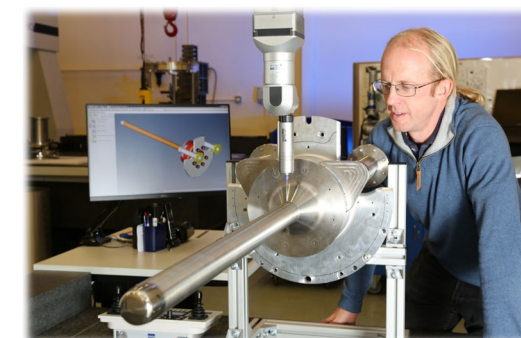
# HK: Construction Status @Tokai



~900kW stable neutrino beam  
& ~1MW demo. are achieved. (2026, Mar.)



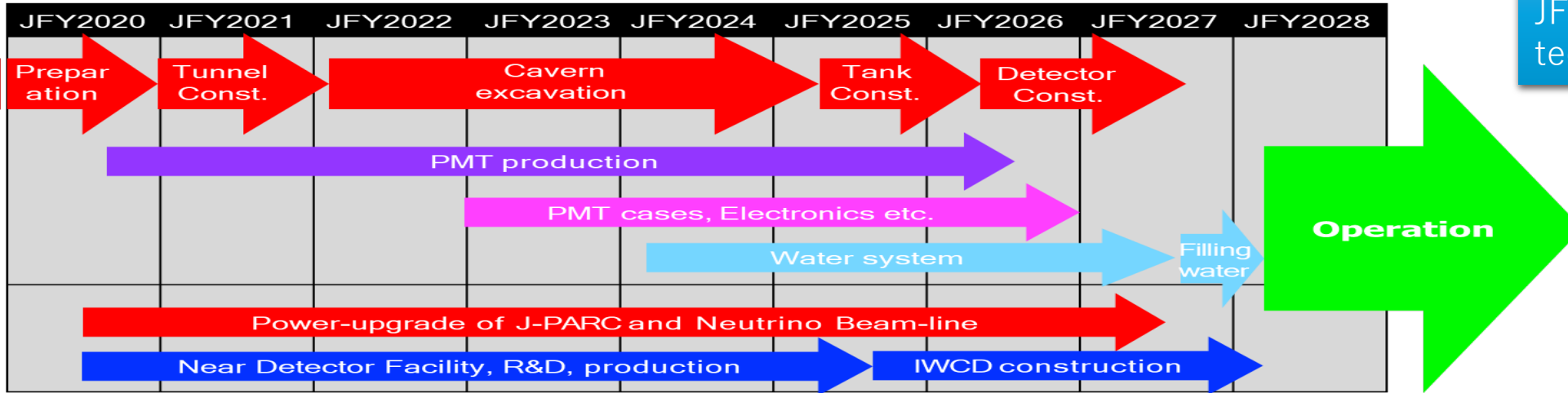
MR RF & Mag. PS  
upgrade (~JFY2027)



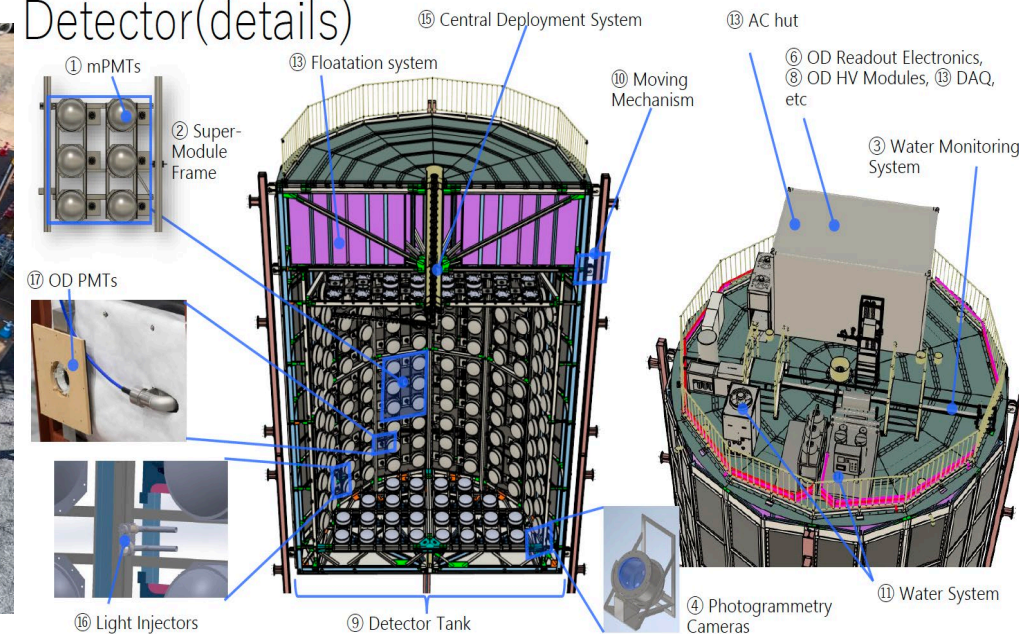
1.3MW target system, CW system,  
remote maintenance upgrade

# HK: Construction Status @Tokai

~2month T2K beam time in JFY2027 for T2K→HK ND280 tech./knowledge transfer



## Detector(details)



Civil construction of IWCD site (JFY2025~JFY2027)

mPMT production & Detailed design is in progress.

# Summary

- J-PARC Hadron Experimental Facility has achieved its intensity milestone of 100 kW.
- A lot of result especially for  $S=-1$  and  $S=-2$  systems.
- More fruits to come with existing beamlines.
- For hadron physics, high-momentum pion beams are being prepared. In addition, the collaboration is working extensively to realize the K10 beam.
- Multipurpose use of Hadron Experimental Facility is also considered.
- Hyper-Kamiokande will start in JFY2028.