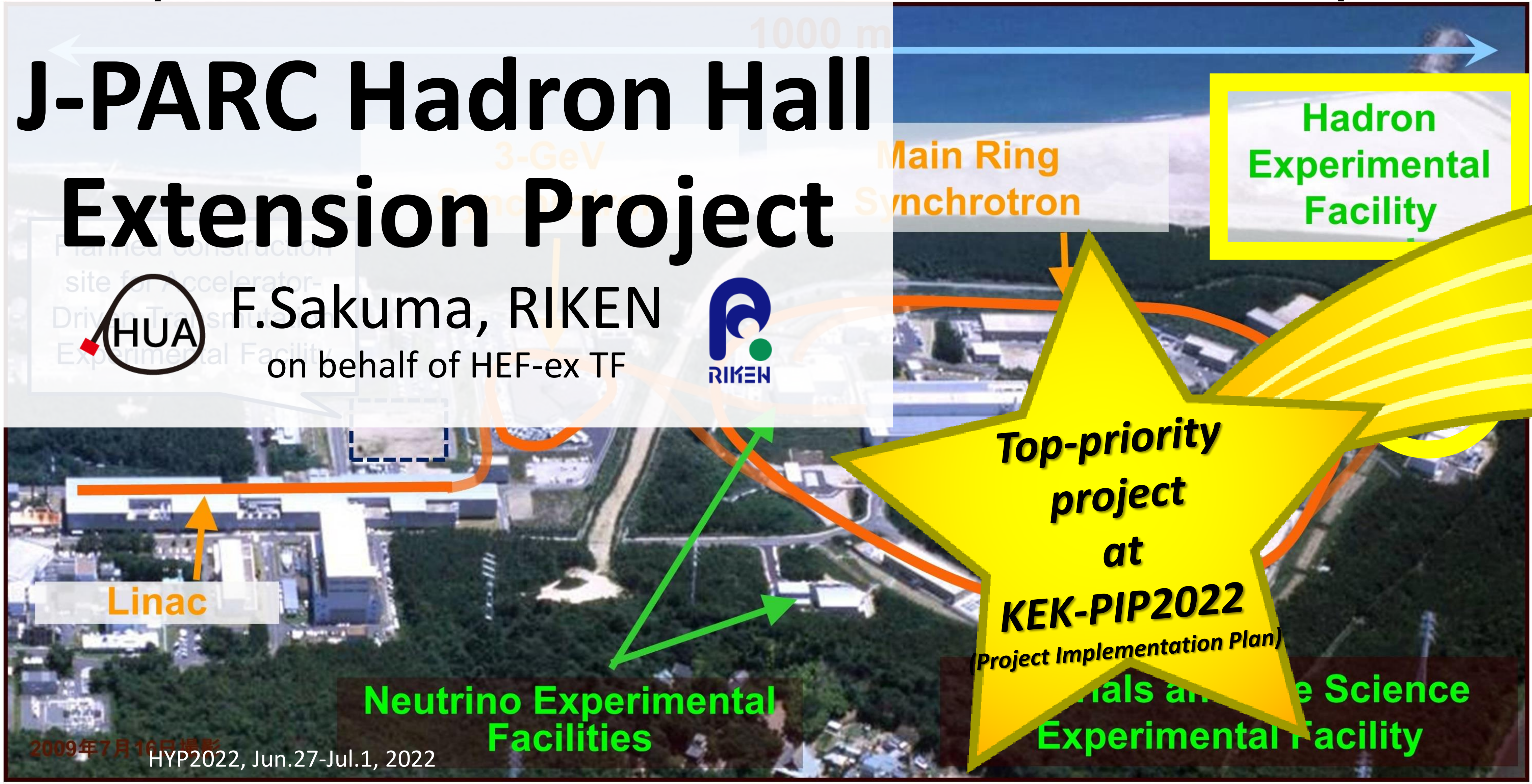
J-PARC

Japan Proton Accelerator Research Complex

# J-PARC Hadron Hall Extension Project


F.Sakuma, RIKEN

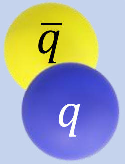
on behalf of HEF-ex TF

# Origin & Evolution of Matter

## Matter-Antimatter Symmetry

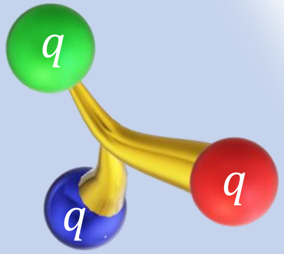
matter dominated universe




## 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

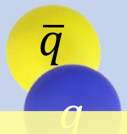
# Origin & Evolution of Matter

**Matter-Antimatter Symmetry**

**Origin of Matter Creation**

**Matter in Extreme Conditions**

dense matter in neutron stars




**Flavor Physics**

CP violation

weak interaction

Kaon rare decays

$\mu \rightarrow e$ conversion

**Hadron Physics**

quark interactions

Hadron spectroscopy

**Strangeness Nuclear Physics**

hadron interactions

hadronic many-body systems

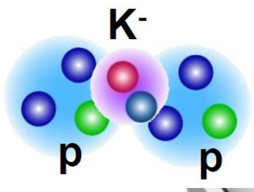
Hyperon-Nucleon scattering

Hypernuclear spectroscopy

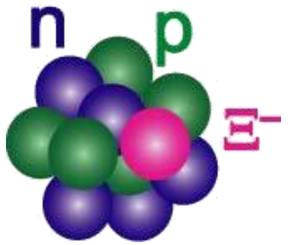

**J-PARC Hadron Experimental Facility is a unique facility where we can conduct comprehensive studies from "elementary particles" to "high-density hadronic matter"**

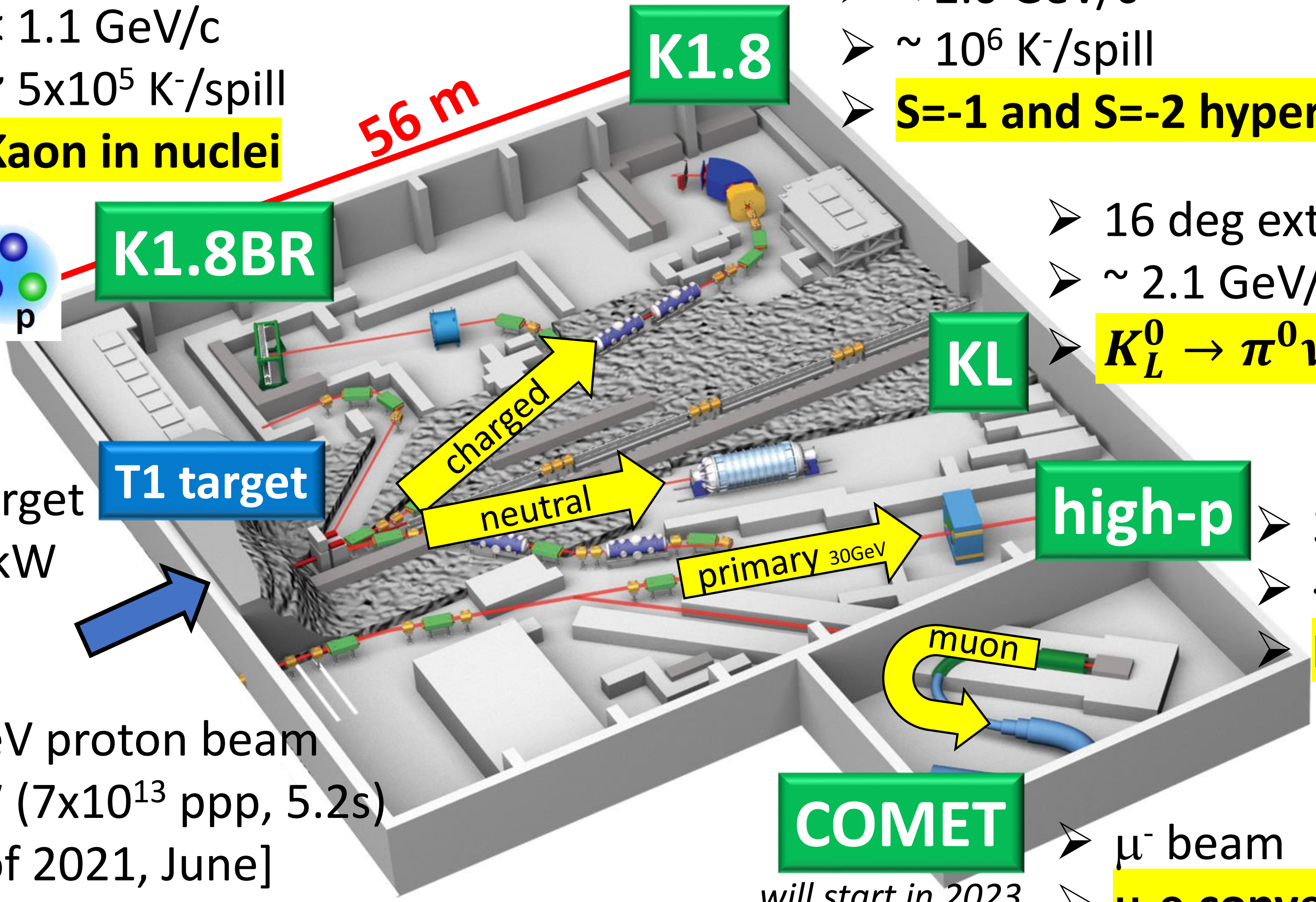
# Present Hadron Experimental Facility (HEF)

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

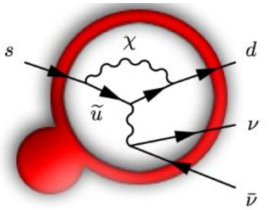



- < 2.0 GeV/c
- ~ 10$^6$ K$^-$/spill
- **S=-1 and S=-2 hypernuclei**



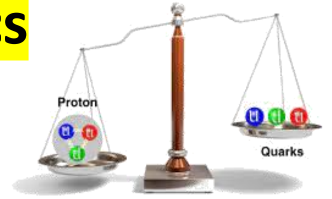




- 16 deg extraction
- ~ 2.1 GeV/c ~ 10$^7$ K$^0_L$/spill
- $K_L^0 \to \pi^0 \nu \bar{\nu}$



*launched in 2020*

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




- Au Target
- < 95 kW

- 30 GeV proton beam
- 65kW (7x10$^{13}$ ppp, 5.2s)
  [as of 2021, June]

*will start in 2023*

- μ$^-$ beam
- **μ-e conversion**

# Achievements in research at the Hadron Experimental Facility

## Flavor Physics

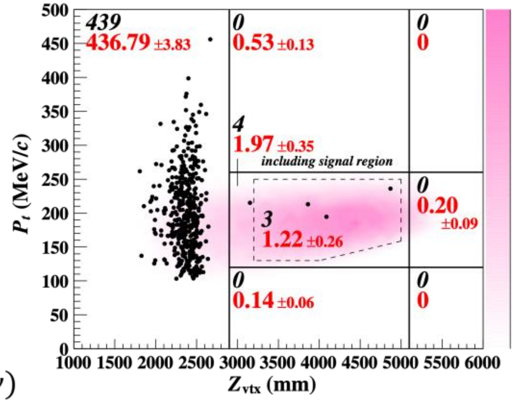
$K_L^0 \to \pi^0 \nu\bar{\nu}$ search @ KOTO

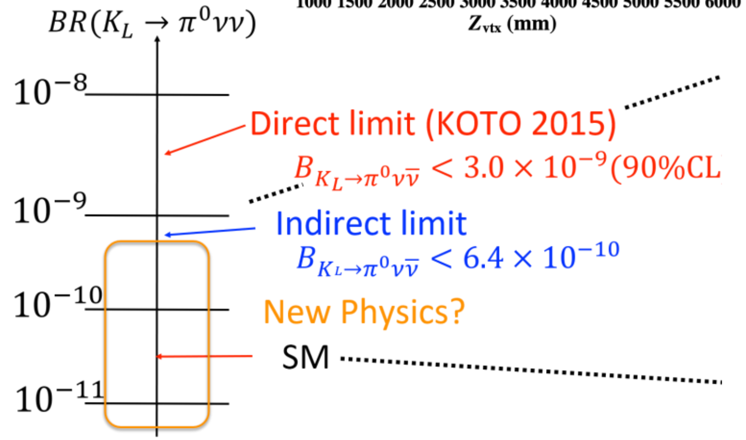
→ **Approaching the SM sensitivity for CP violation**

**KOTO 2016-18**

**KOTO 2015**

Single Event Sensitivity = $3 \times 10^{-9}$



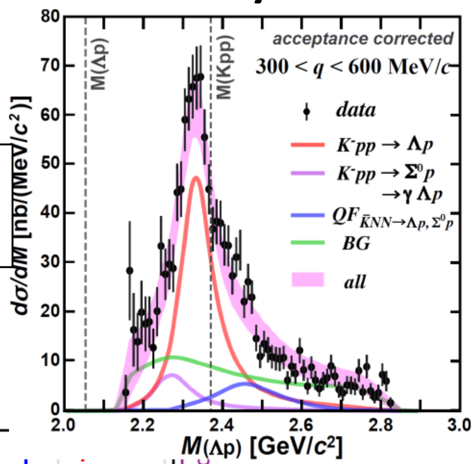



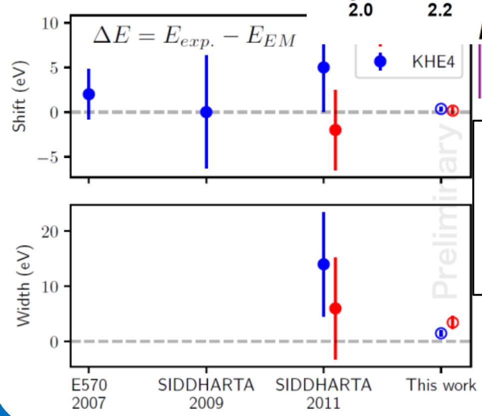

## Hadron Physics

Observation of an exotic hadron bound system including K⁻ meson

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

Kaonic nuclei, "K-pp"



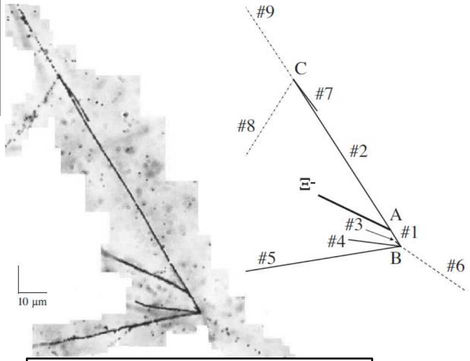

Ultra-precise measurement of kaonic atoms

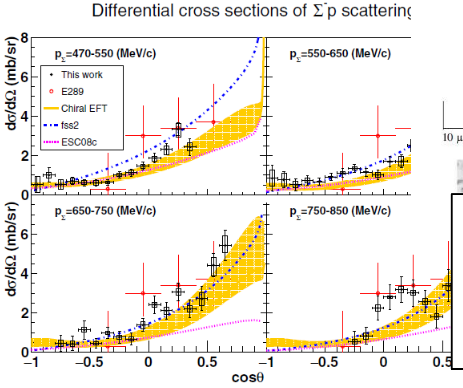
## Strangeness Nuclear Physics

A lot of progress in hypernuclear research

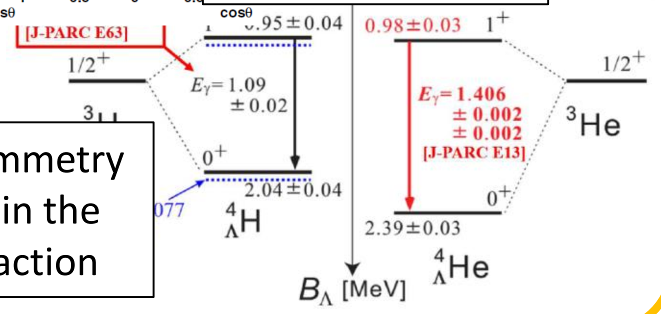
→ **Clarified attractive S=–2 ΞN interaction and deepened S=–1 ΛN, ΣN interactions**

Observation of Ξ hypernuclei




First precise hyperon-nucleon scattering




Charge-symmetry breaking in the ΛN interaction

# Achievements in research at the Hadron Experimental Facility

## Flavor Physics

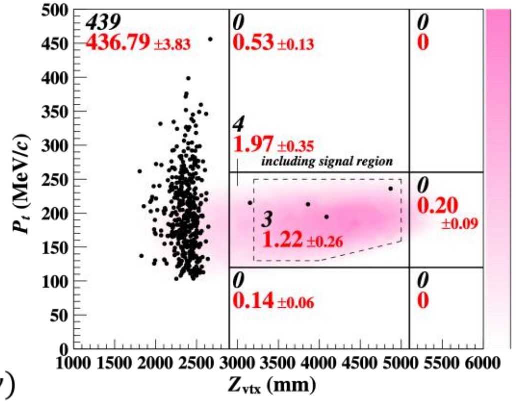
$K_L^0 \to \pi^0 \nu \bar{\nu}$ search @ KOTO

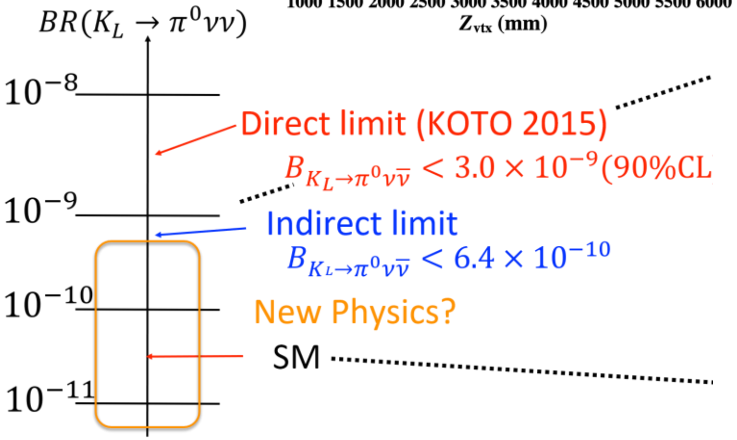
→ **Approaching the SM sensitivity for CP violation**

**KOTO 2015**

Single Event Sensitivity = $3 \times 10^{-9}$

**KOTO 2016-18**



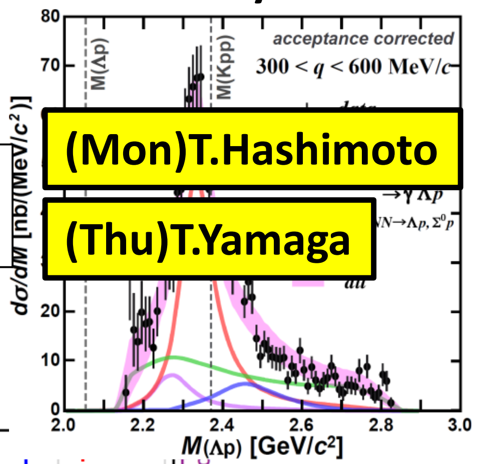




## Hadron Physics

Observation of an exotic hadron bound system including K⁻ meson

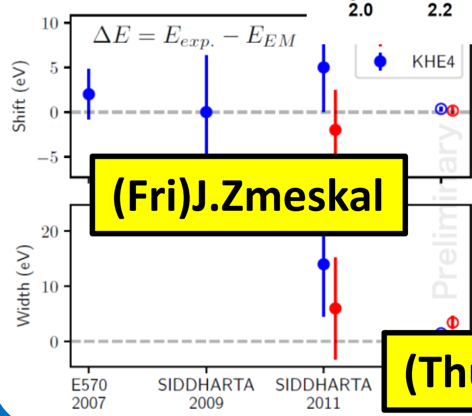
→ **Established a new direction to understand meson-baryon int.**

Kaonic nuclei, "K-pp"




**(Mon)T.Hashimoto**

**(Thu)T.Yamaga**




**(Fri)J.Zmeskal**

Ultra-precise measurement of kaonic atoms

**(Thu)S.Hayakawa**

## Strangeness Nuclear Physics

A lot of progress in hypernuclear research

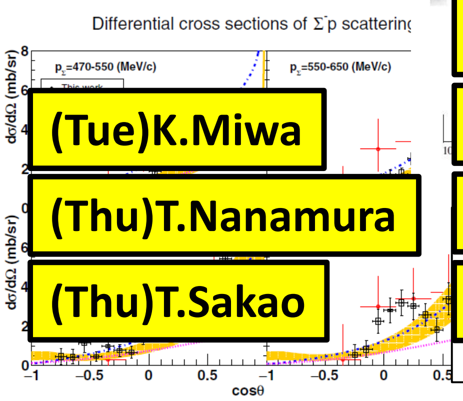
→ **Clarified attractive S=–2 ΞN interaction and deepened S=–1 ΛN, ΣN interactions**

Observation of Ξ hypernuclei

**(Mon)K.Nakazawa**

**(Mon)T.O.Yamamoto**

**(Tue)T.Saito**




**(Tue)K.Miwa**

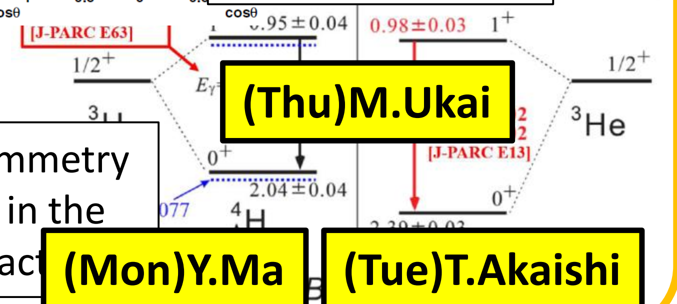
**(Thu)T.Nanamura**

**(Thu)T.Sakao**

**(Wed)M.Nakagawa**

**(Wed)Y.Ishikawa**

**(Thu)M.Fujita**




**(Thu)M.Ukai**

Charge-symmetry breaking in the ΛN interact

**(Mon)Y.Ma**

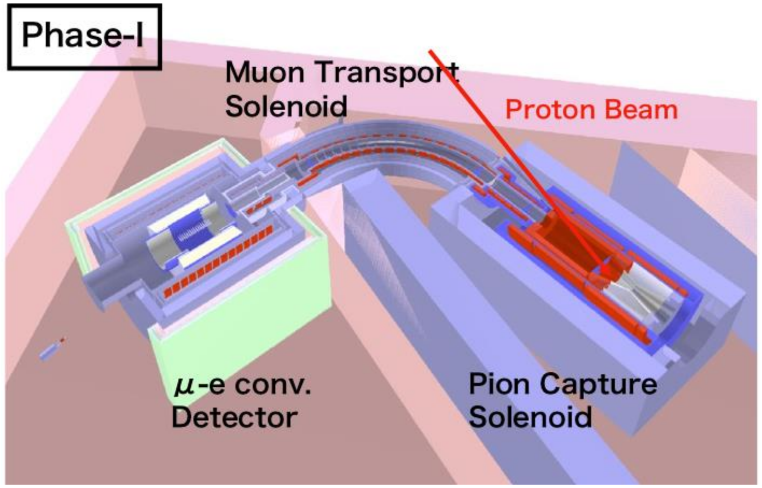
**(Tue)T.Akaishi**

# Future 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 cutting-edge spectrometer

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

# Future ... tal 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

**Further explore new physics**

...are decays
...onversion

Hadron Physics

quo...
had...

**Understand how quarks build hadrons**

...sm
...copy

Strangeness Nuclear Physics

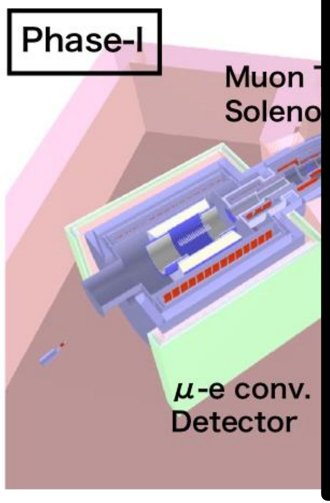
**Elucidate the nature of extremely dense matter**

Hypernuclear spectroscopy

Flavo...

Search for μ→e ...

→ **Search for c... vi...**




...ar Physics

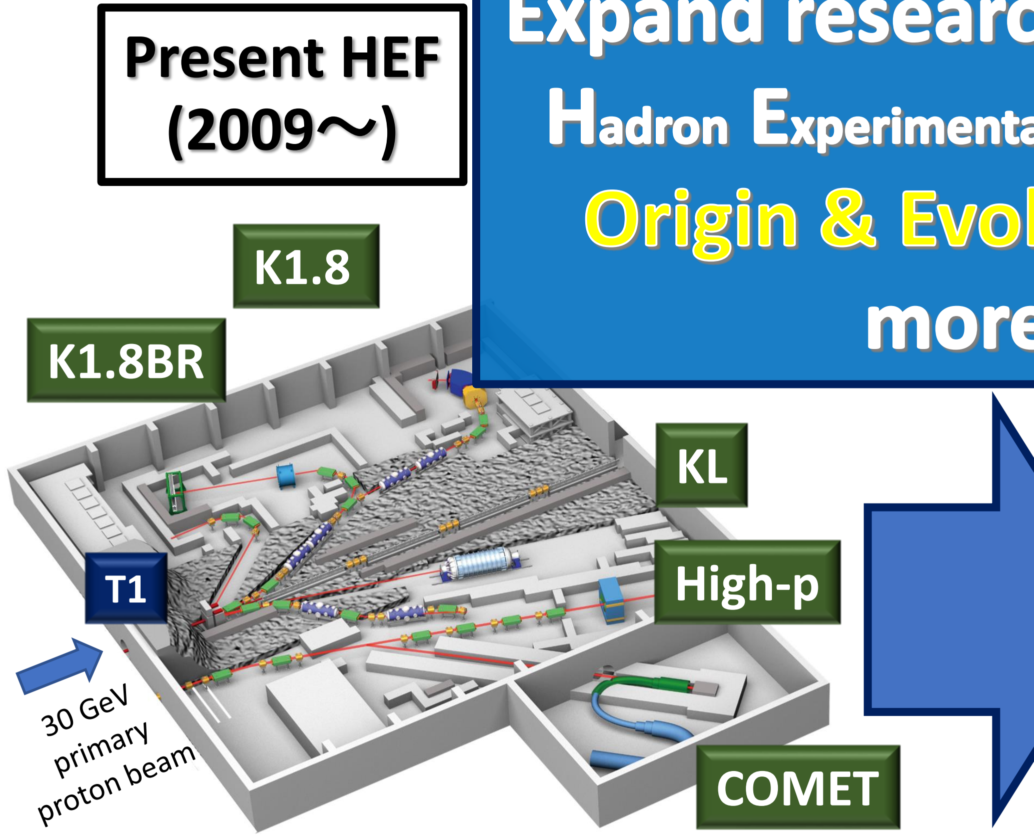
...opic study of
(2023~)

**systematic interactions**

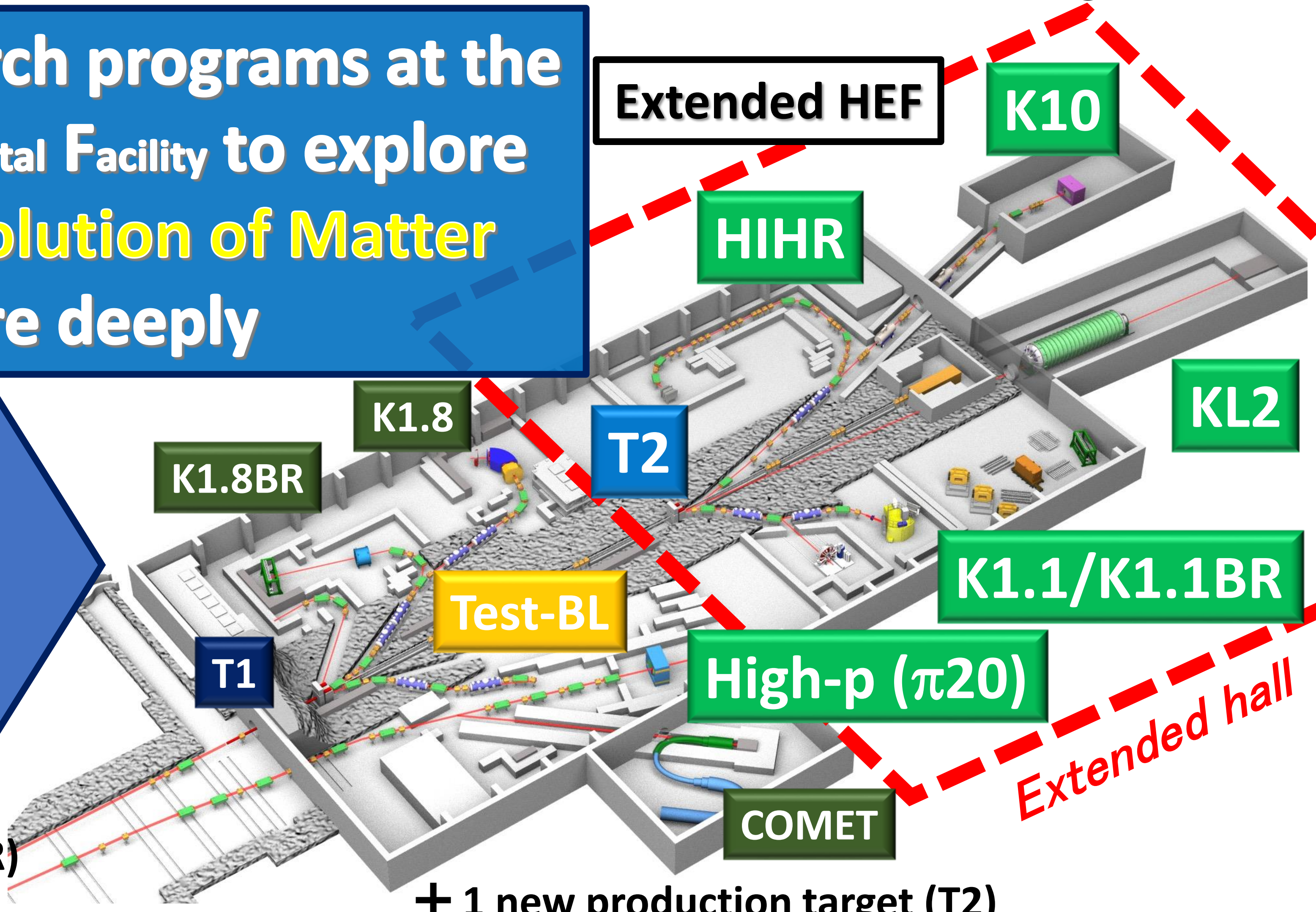
| *Futher research* | *Futher research* | *Futher research* |
|---|---|---|
| $K_L^0 \to \pi^0 \nu \bar{\nu}$ search with further sensitivity | Charmed and muti-strange baryon spectroscopies | Ultra-precise spectroscopy of S=−1 hypernuclei with cutting-edge spectrometer |
| **→ Explore beyond the SM sensitivity** | **→ Establish diquark in baryon** | **→ Extract density dependence of ΛN int.** |

# Hadron Experimental Facility extension (HEF-ex) Project

**Expand research programs at the Hadron Experimental Facility to explore Origin & Evolution of Matter more deeply**




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




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

# Expanded Research Programs

### at the Extended Facility

## Extract density dependent ΛN interaction

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

- intense dispersion matched π beam

**K1.1** **Systematic ΛN scattering measurement**

- intense polarized Λ beam

## Investigate diquarks in baryons

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

- intense high-momentum π beam

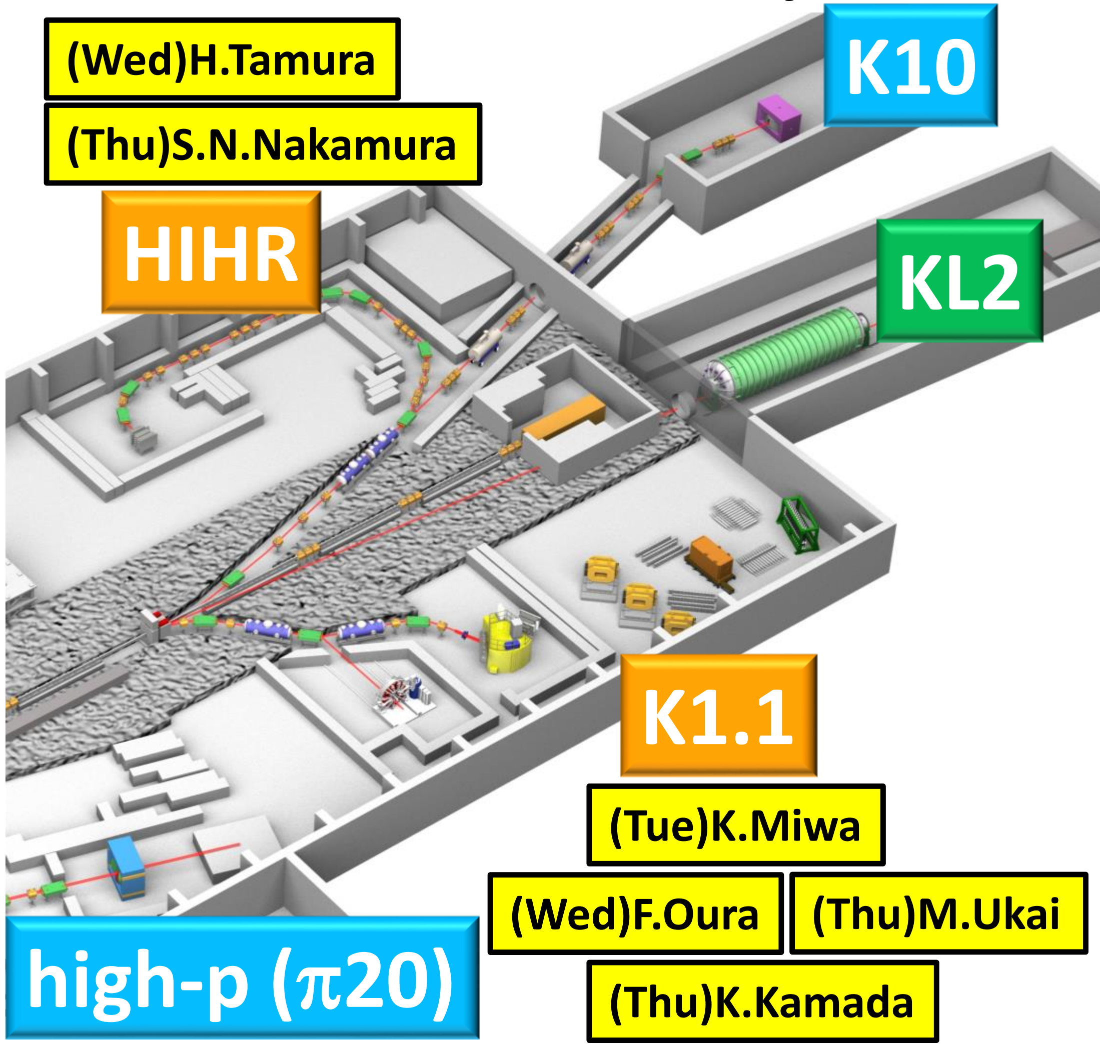
**K10** **High-resolution multi-strange baryon spectroscopy**

- intense high-momentum separated K beam

## Search for new physics beyond the SM

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

- intense neutral K beam

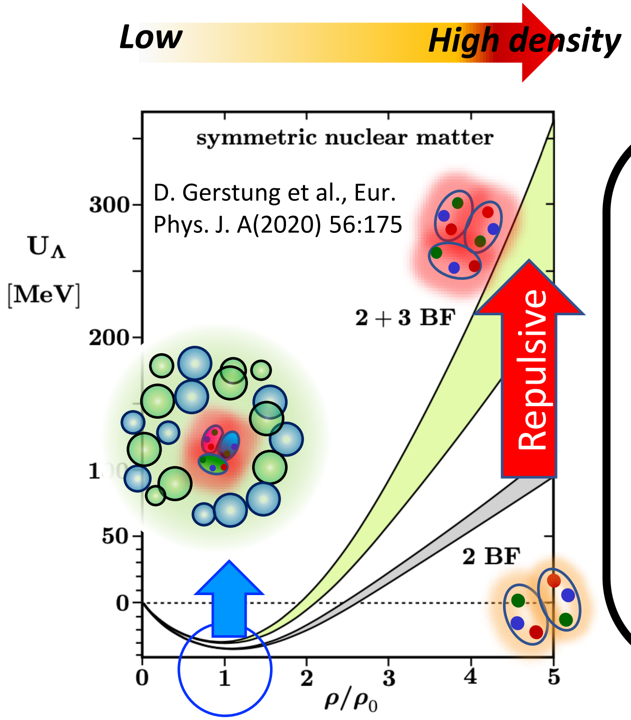


# Strangeness Nuclear Physics: Hyperon in Dense Environment

**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

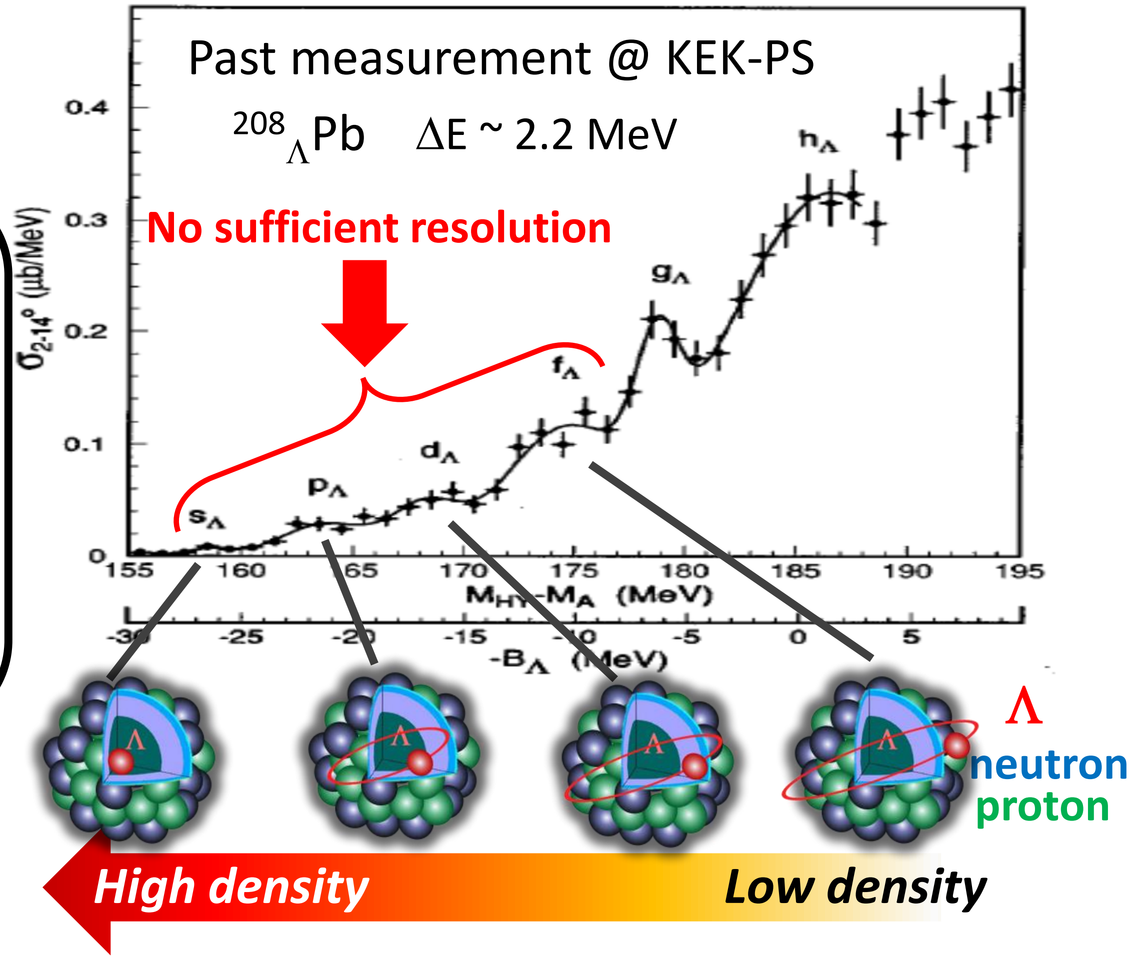
**heavy Λ-hypernuclei :**

Λ binding energies ($B_\Lambda$)

→ density dependent

ΛN interaction

→ We need precise measurements

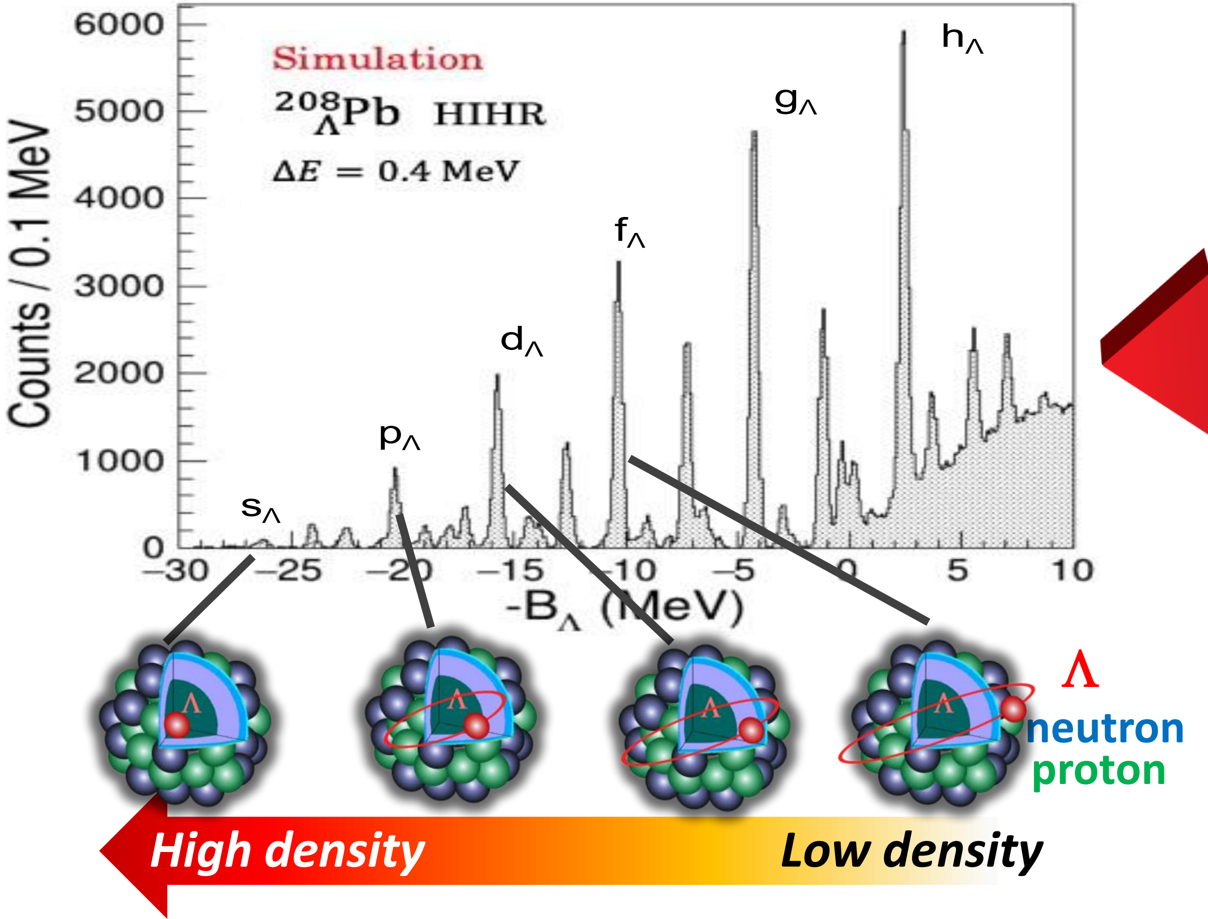


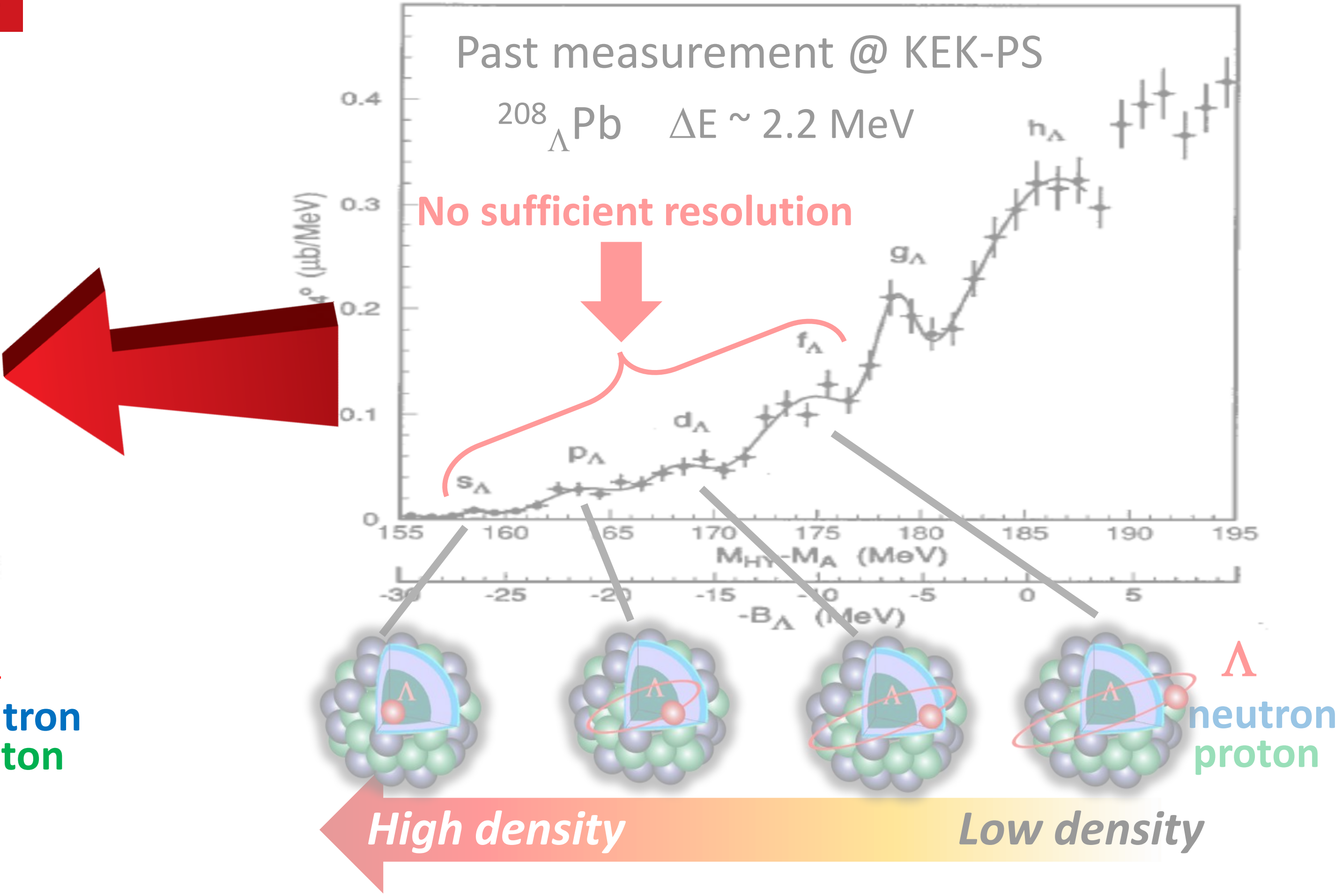
# Strangeness Nuclear Physics: Hyperon in Dense Environment

**Why can heavy neutron stars exist?**

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

**Need separation of each Λ orbital state**



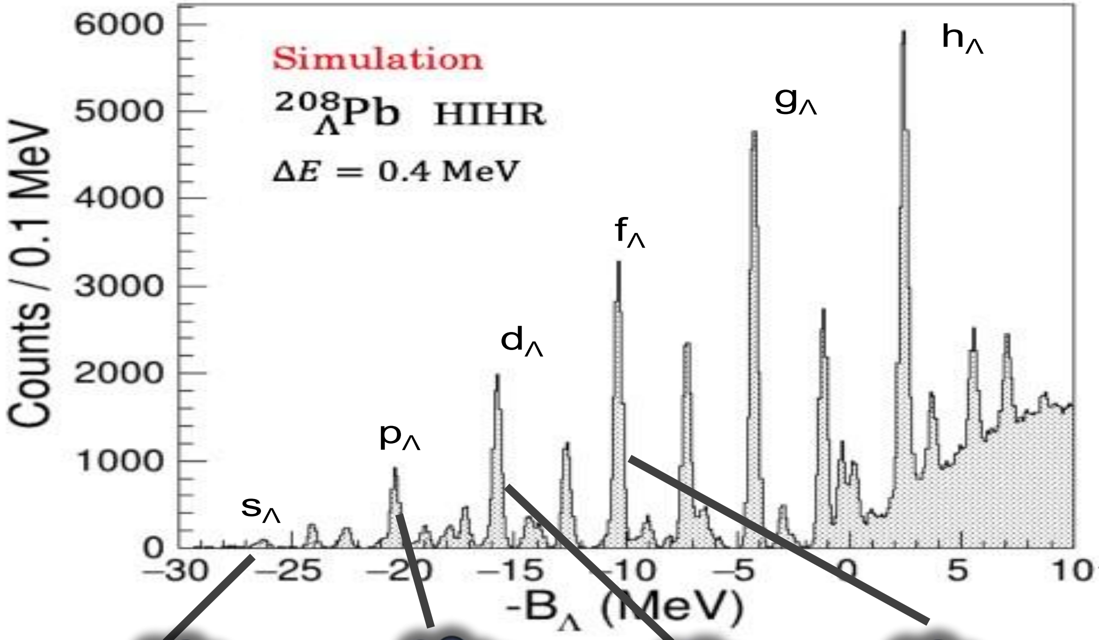



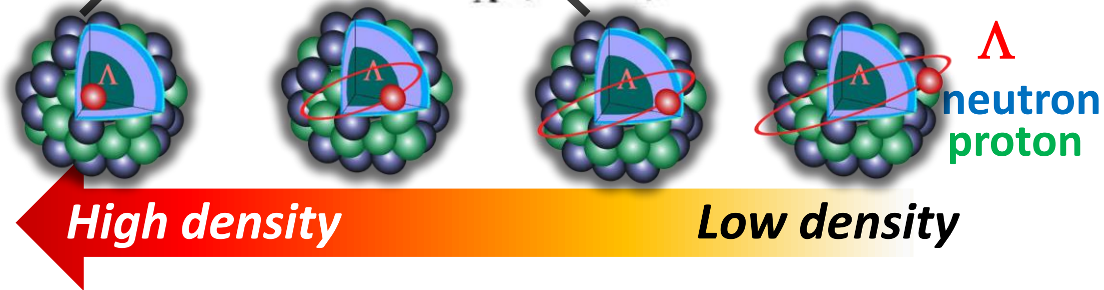
# Strangeness Nuclear Physics: Hyperon in Dense Environment

**Why can heavy neutron stars exist?**

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

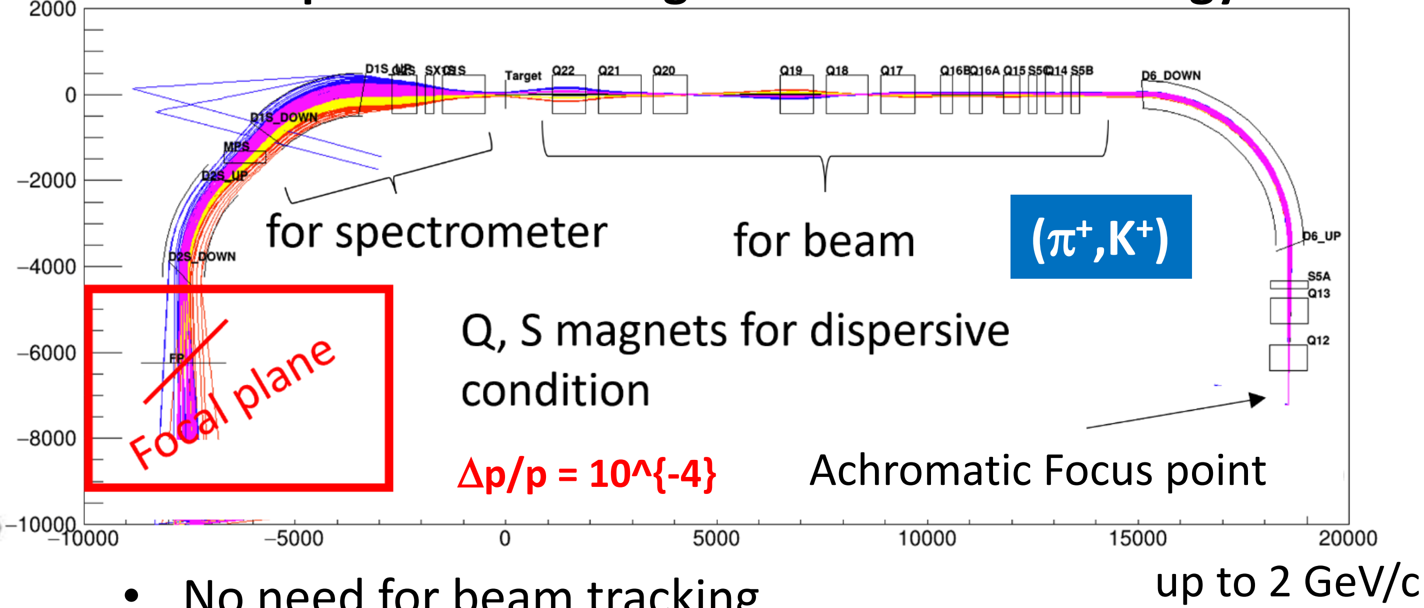
## Ultra-high-resolution Λ-hyp. spectroscopy




## 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:**

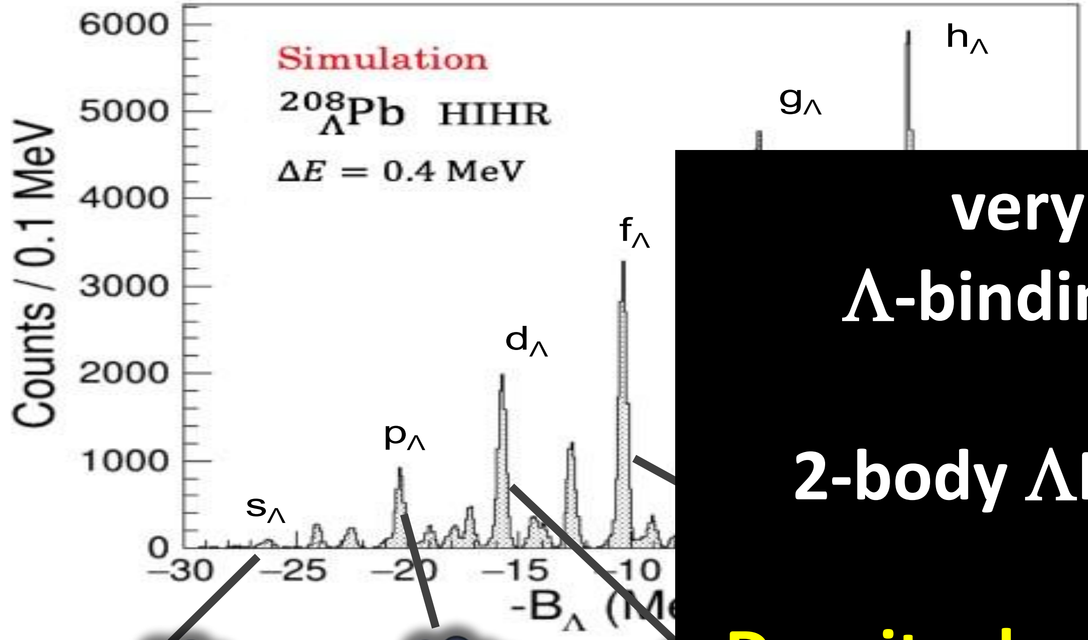
~2.2 MeV → better than ~0.4 MeV (FWHM)

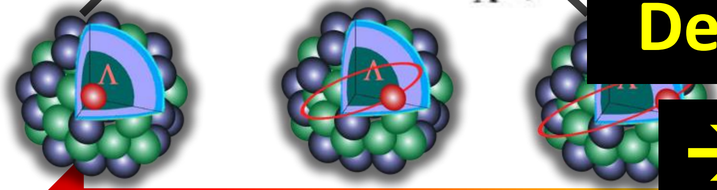
# Strangeness Nuclear Physics: Hyperon in Dense Environment

**Why can heavy neutron stars exist?**

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

**Ultra-high-resolution Λ-hyp. spectroscopy**



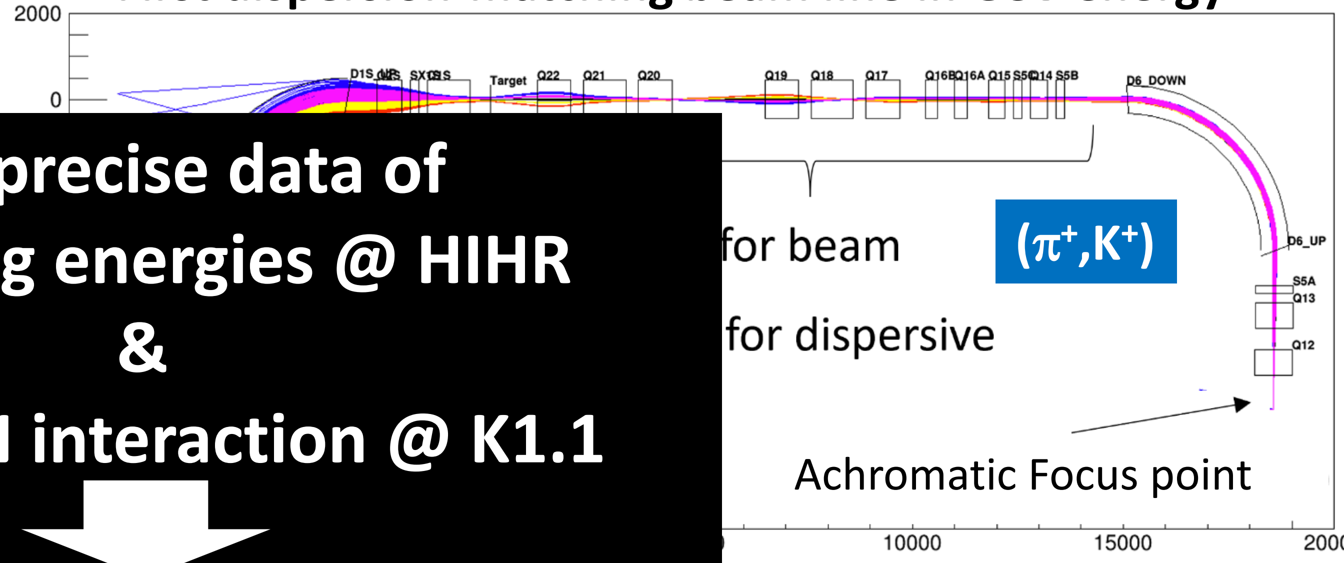



*High density*

*Low density*

**HIHR beam line** (High-Intensity High-Resolution)

**First dispersion-matching beam line in GeV energy**




up to 2 GeV/c

g

neutron

• Intense π beam of > 10^? /pulse

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

⇩

**Density dependent ΛN interaction**

**→ understanding neutron stars**

**e resolution limit:**

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

Behaver of non-perturbative QCD in low energy regime

# Hadron Physics: Diquarks in Baryons

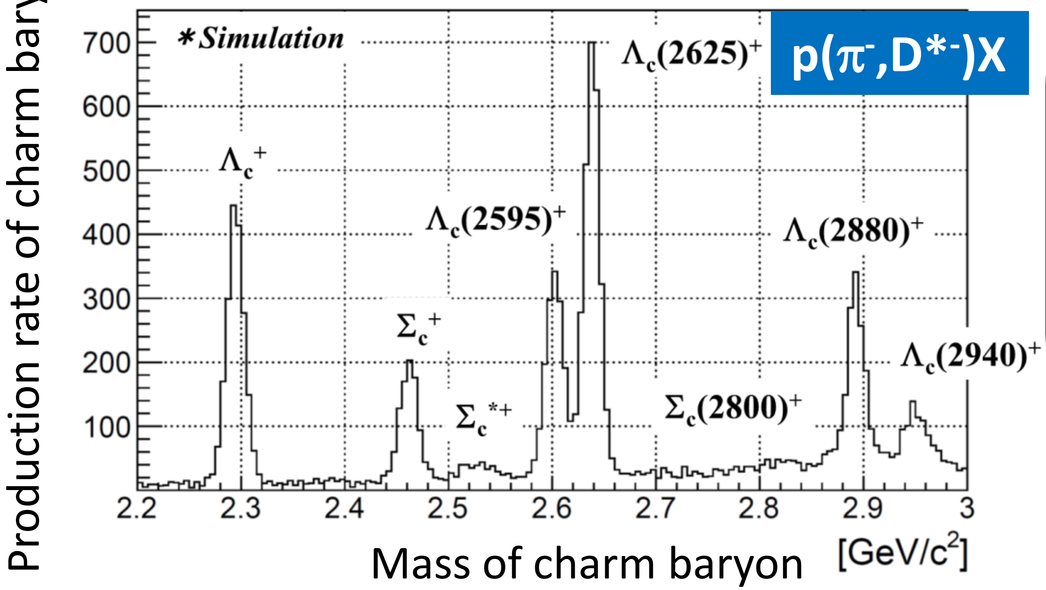
## How quarks build hadrons?

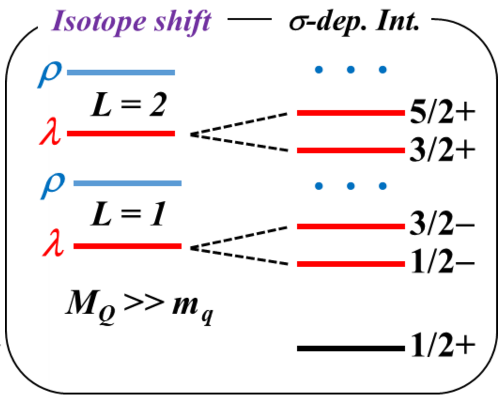
- Investigate **diquarks** in baryons **toward** understanding of **dense quark matter**

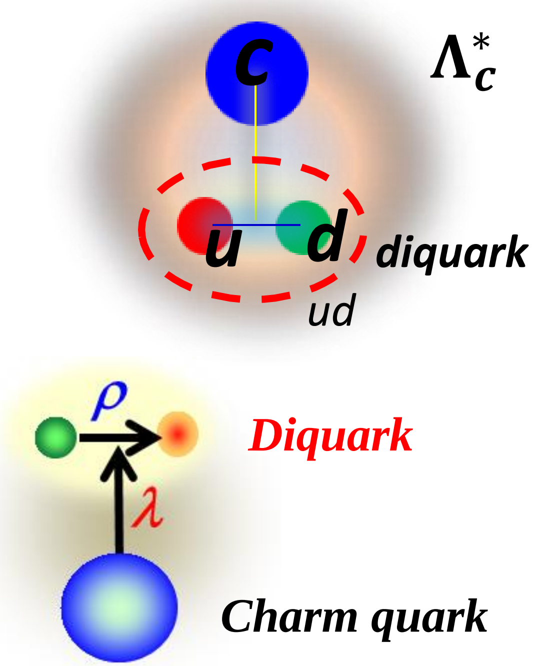
- **Charm Baryon Spectroscopy**
  with intense high-momentum π beam @ High-p (π20)

**Establish a diquark (*ud*)**

$\Lambda_c^*$: Disentangle "collective motion of *ud*" and "relative motion between *u* and *d*"




**"production rate" and "decay rate" will provide us information on diquark**

Behaver of non-perturbative QCD in low energy regime

# Hadron Physics: Diquarks in Baryons

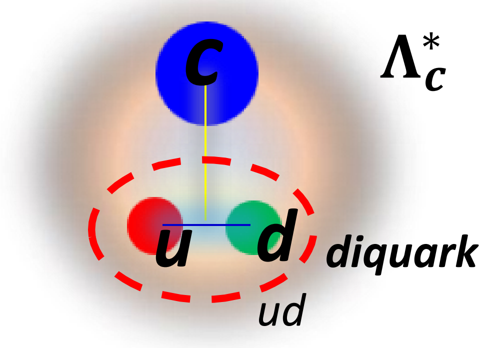
**How quarks build hadrons?**

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

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

**Establish a diquark (*ud*)**

$\Lambda_c^*$: Disentangle "collective motion of *ud*"
and "relative motion between *u* and *d*"



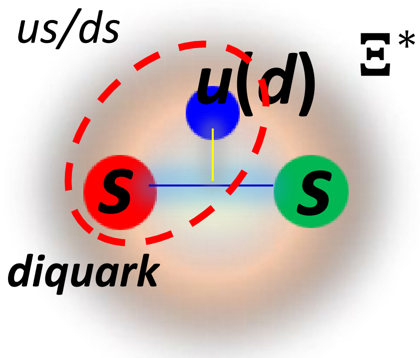

- **Multi-Strange Baryon Spectroscopy**
  with intense high-momentum K beam @ K10

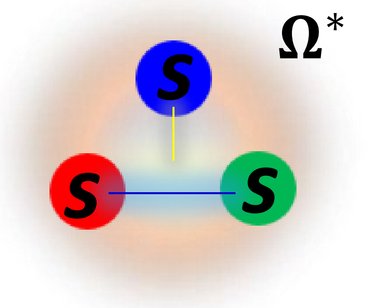
**Diquarks in different systems**

$\Xi^*$: *us/ds* diquark

$\Omega^*$: the simplest *sss* system

→ diquark is expected to be suppressed




**Systematic measurements of charm and multi-strange baryons will reveal the internal structure of baryons through the diquarks**

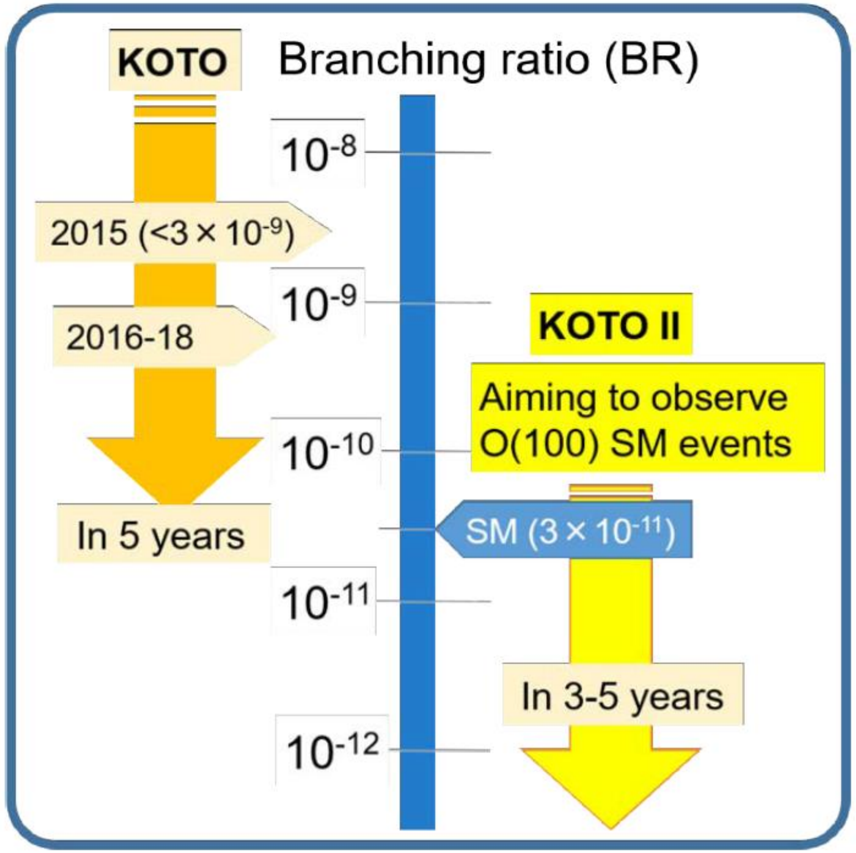
# Flavor Physics: New Physics Search at KOTO Step-2

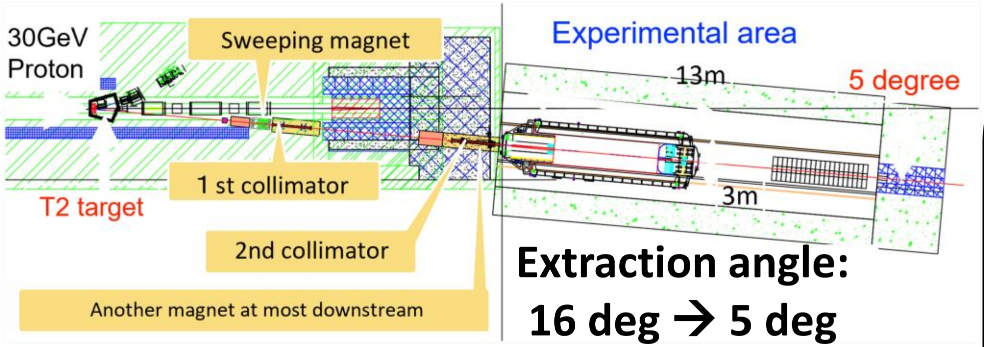
## Is there new physics beyond the Standard Model?

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

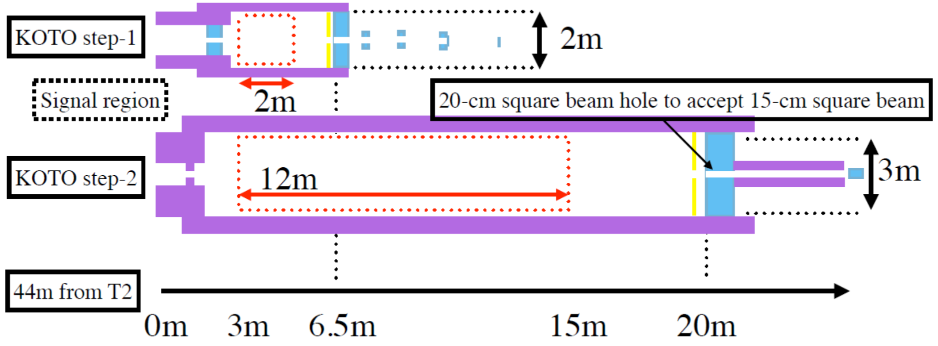
**One of the best probes for new physics search**

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




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



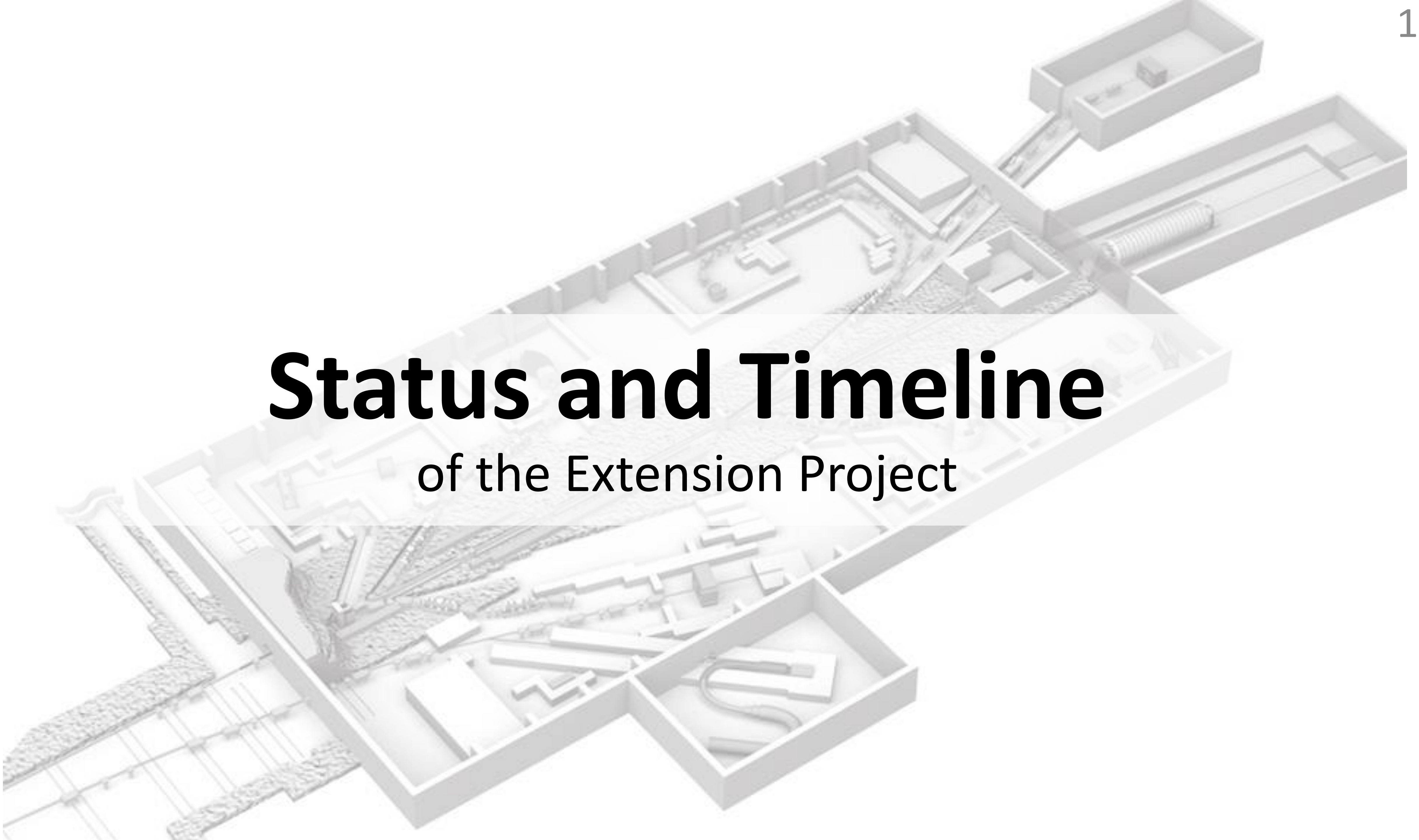

**Ultra-high sensitivity detector (~x70)**

## KOTO Step-2

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

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

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



# Status and Timeline

## of the Extension Project

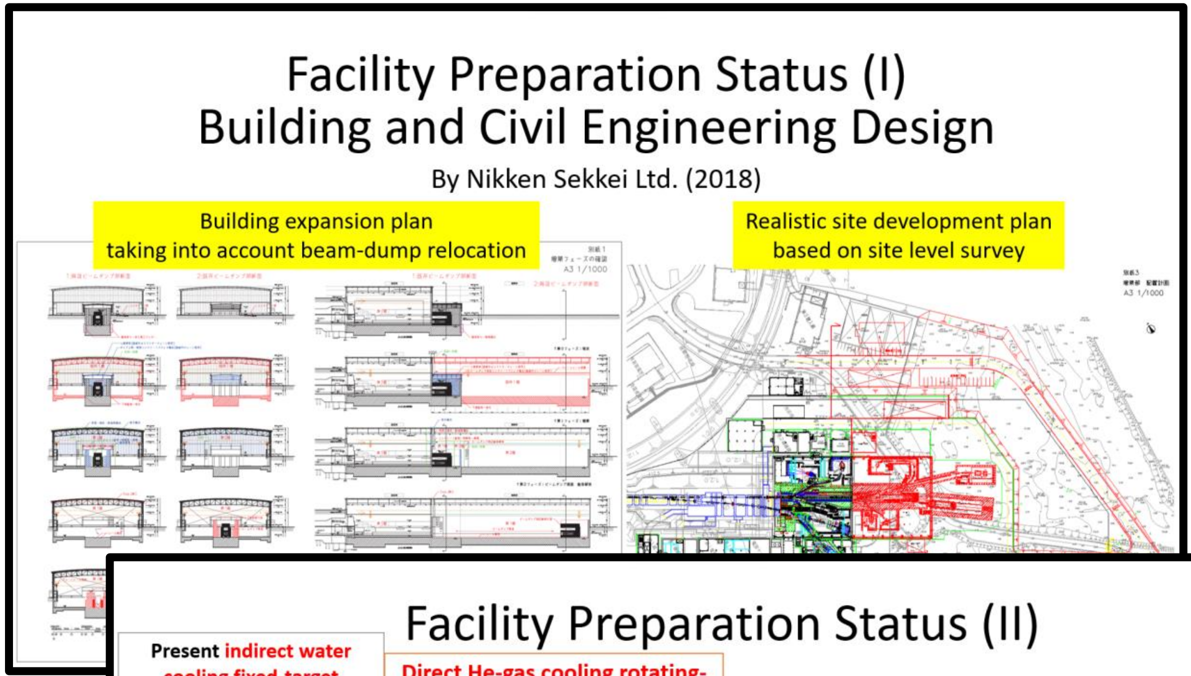
# Present Status of the Project

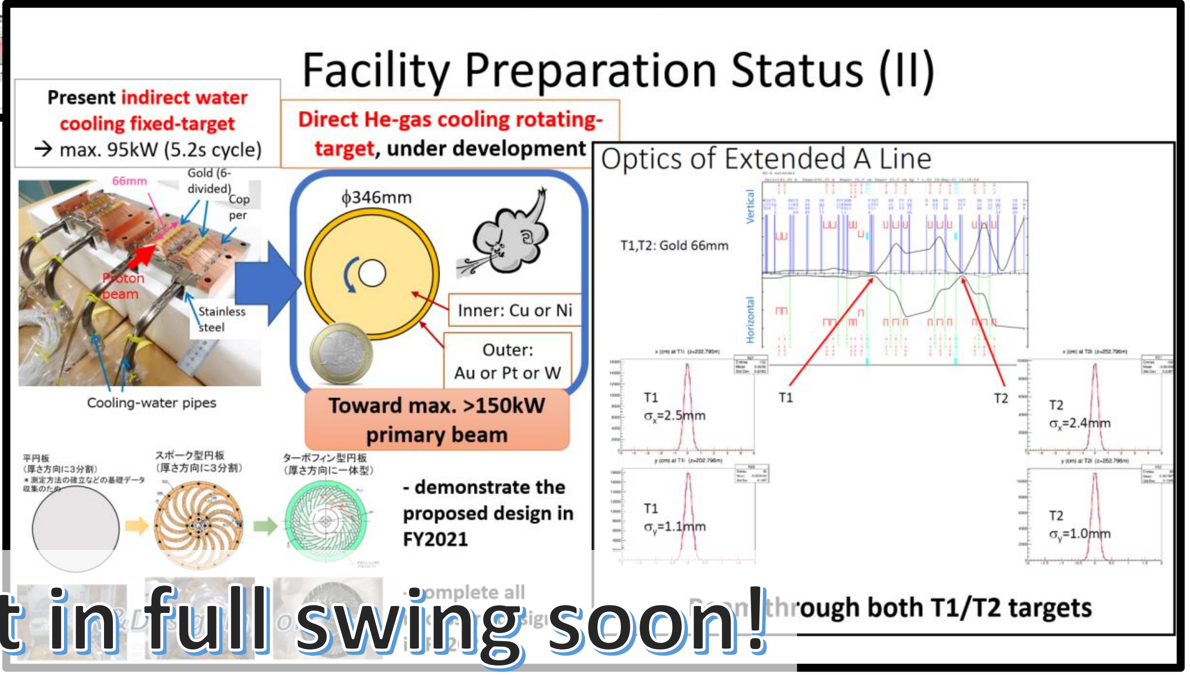
One of the candidate projects to be funded:

- ➢**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) [will be published soon]

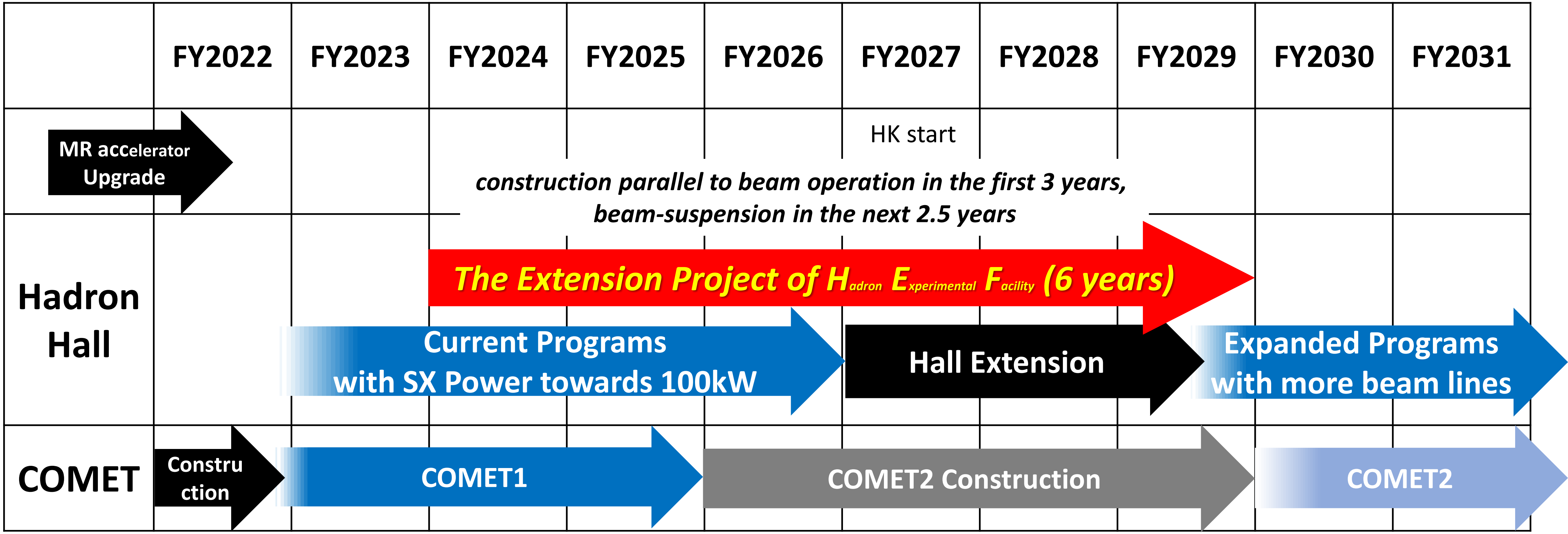

https://www.kek.jp/en/About/Roadmap/




**The project will start in full swing soon!**

# Timeline of the Project




**We will start the project in FY2024**

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

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

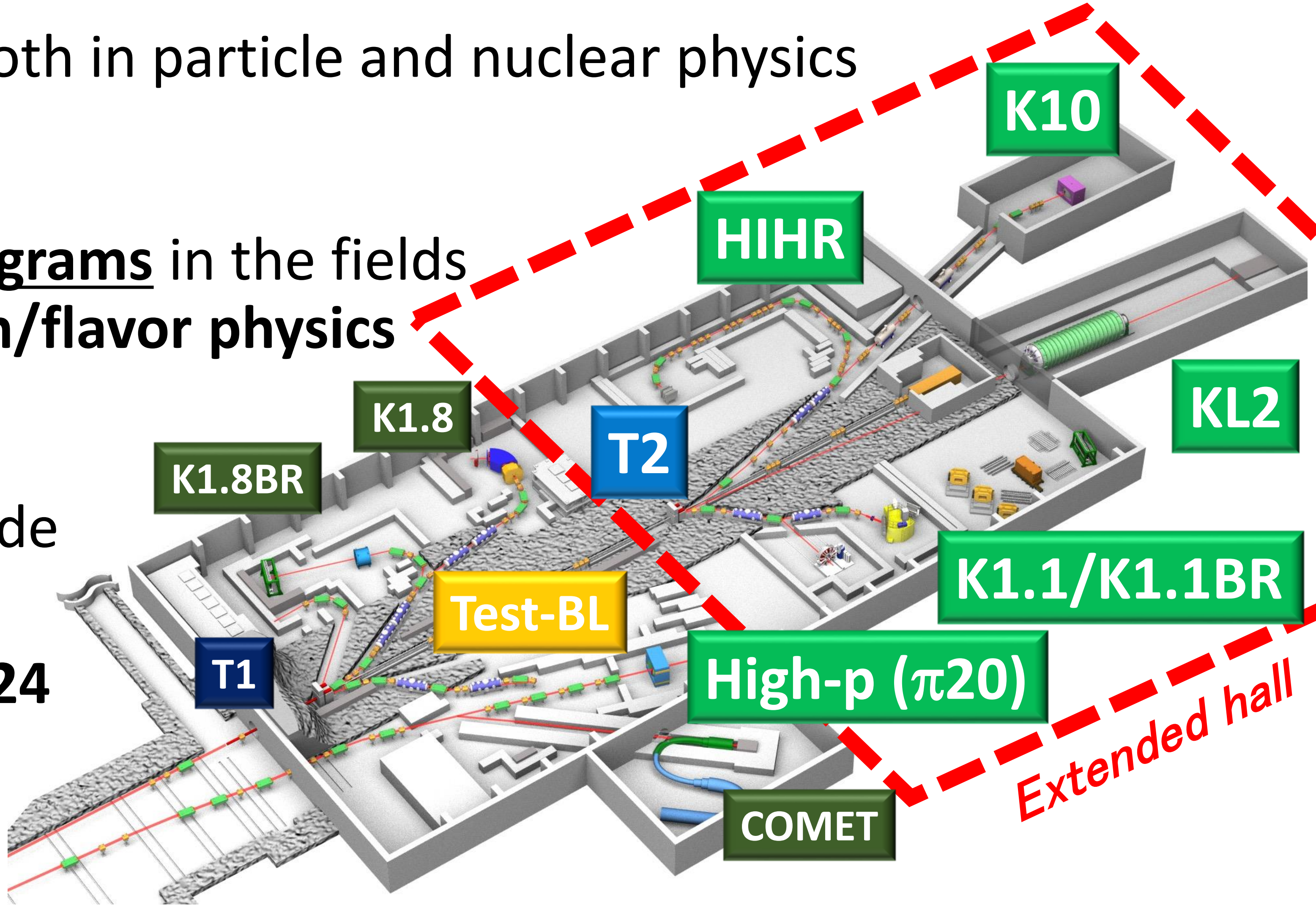
- **<u>Unique research programs</u>** both in particle and nuclear physics at high-intensity frontier

- **<u>World's leading research programs</u>** in the fields of **strangeness-nuclear/hadron/flavor physics**

- **<u>Top-priority project at KEK-PIP2022</u>** / Progress in facility-side preparation

→ The project will start in **FY2024**

**Stay tuned!**



# Thank you for your attention!

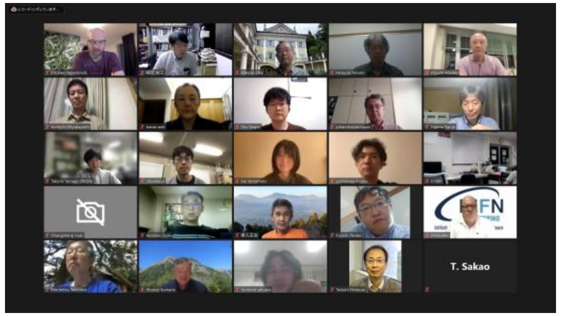
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html


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

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

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 (J-PARC HEF-ex WS), Feb.16-18 2022, online

We are looking forward to seeing you
at the 3rd J-PARC HEF-ex WS
planned in Feb.-Mar., 2023