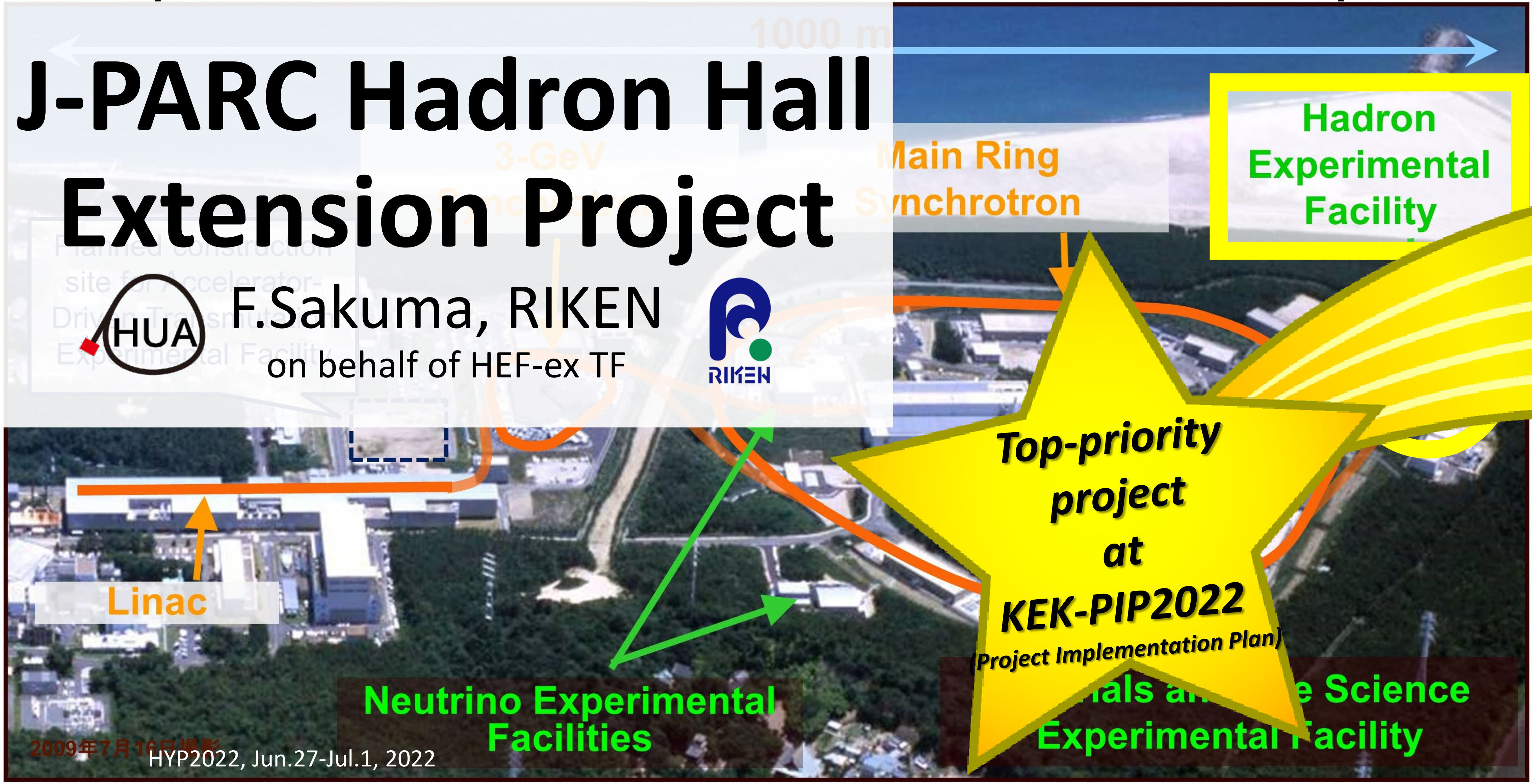
J-PARC

Japan Proton Accelerator Research Complex

J-PARC Hadron Hall Extension Project

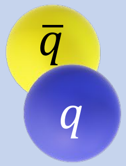
F.Sakuma, RIKEN
on behalf of HEF-ex TF



Origin & Evolution of Matter

Matter-Antimatter Symmetry

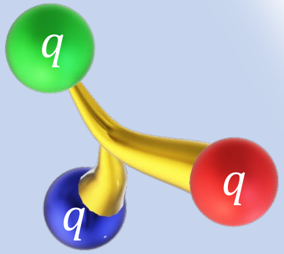
matter dominated universe



Flavor Physics

CP violation
weak interaction
→ new physics

Kaon rare decays
μ→e conversion



Origin of Matter Creation

formation of hadrons from quarks

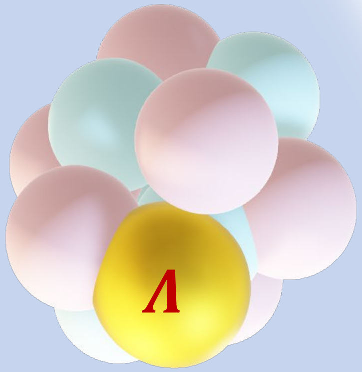
Hadron Physics

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

matter dom...

Flavor Physics

CP violation

weak interaction

Kaon rare decays

μ→e conversion

Hadron Physics

quark interactions

Origin of Matter Creation

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Hadron spectroscopy

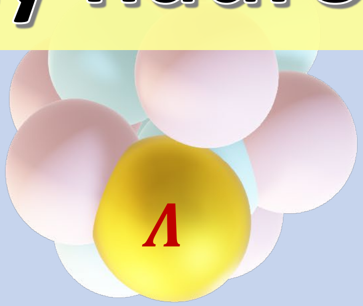
Meson in nuclei

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

Strangeness Nuclear Physics

Matter in Extreme Conditions

dense matter in neutron stars



hadron interactions

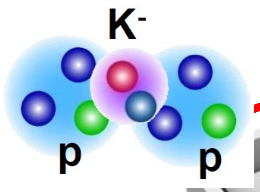
hadronic many-body systems

Hyperon-Nucleon scattering

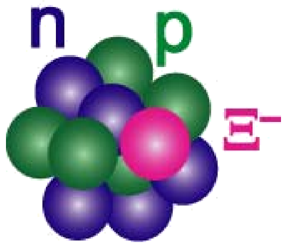
Hypernuclear spectroscopy

Present Hadron Experimental Facility (HEF)

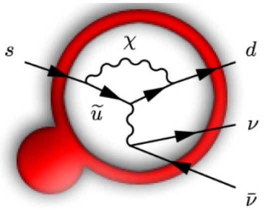
- < 1.1 GeV/c
- ~ 5×10^5 K^-/spill
- **Kaon in nuclei**

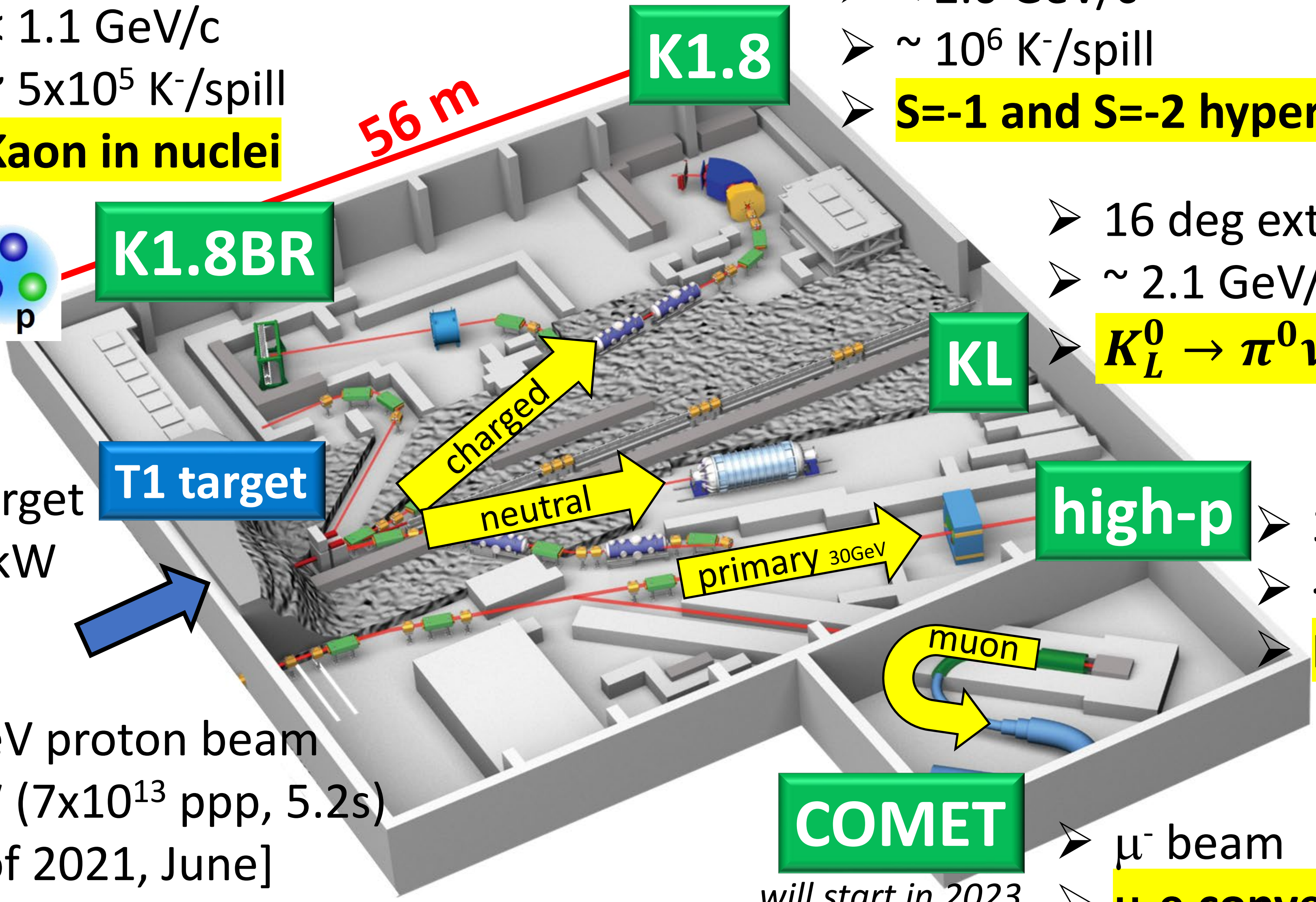


- < 2.0 GeV/c
- ~ 10^6 K^-/spill
- **S=-1 and S=-2 hypernuclei**



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

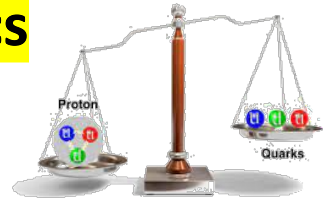




- Au Target
- < 95 kW

launched in 2020

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



- 30 GeV proton beam
- 65kW (7×10^{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

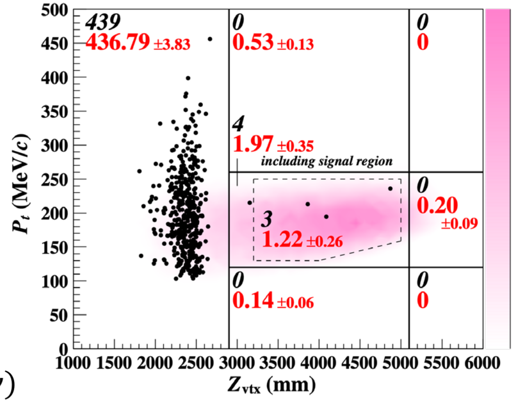
$K_L^0 \to \pi^0 \nu\bar{\nu}$ search @ KOTO

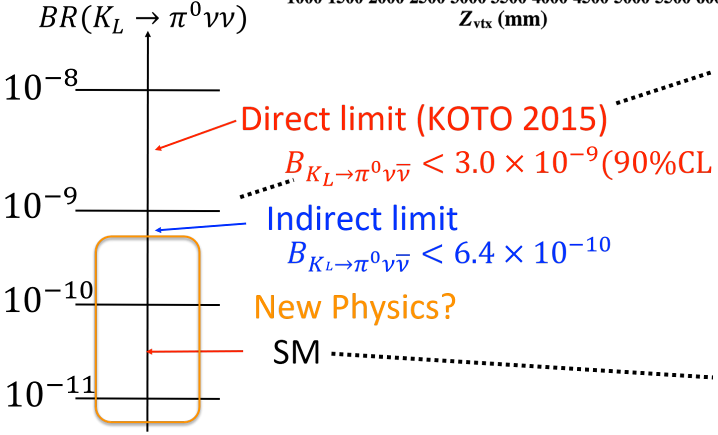
→ **Approaching the SM sensitivity for CP violation**

KOTO 2015

Single Event Sensitivity = 3×10^{-9}

KOTO 2016-18



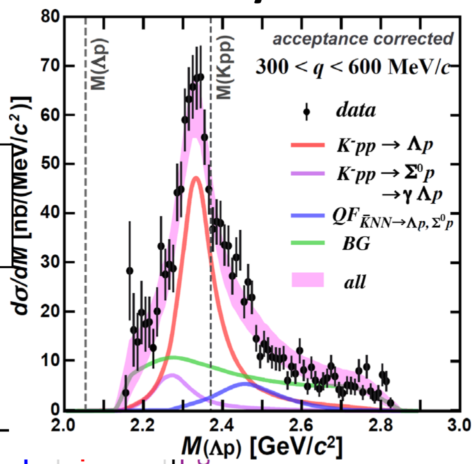


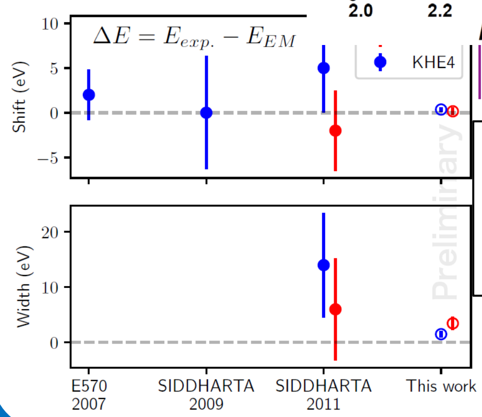
Hadron Physics

Observation of an exotic hadron bound system including K⁻ meson

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

Kaonic nuclei, "K-pp"





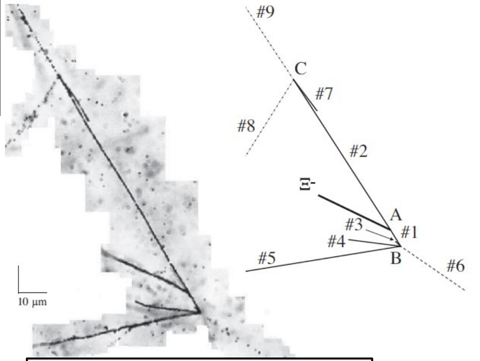
Ultra-precise measurement of kaonic atoms

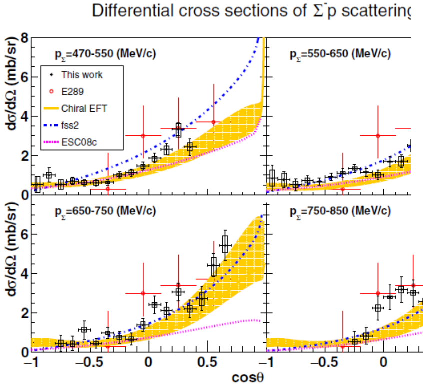
Strangeness Nuclear Physics

A lot of progress in hypernuclear research

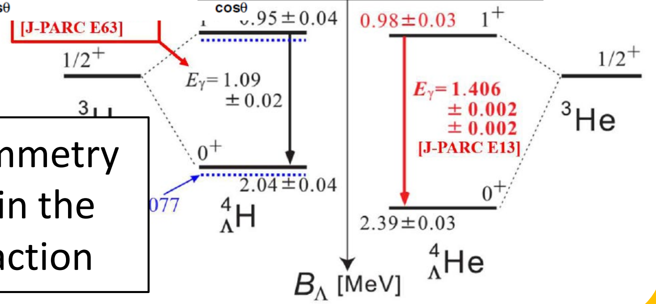
→ **Clarified attractive S=–2 ΞN interaction and deepened S=–1 ΛN, ΣN interactions**

Observation of Ξ hypernuclei





First precise hyperon-nucleon scattering



Charge-symmetry breaking in the ΛN interaction

Achievements in research at the Hadron Experimental Facility

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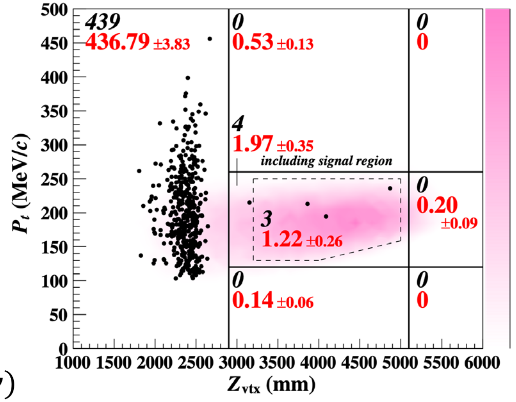

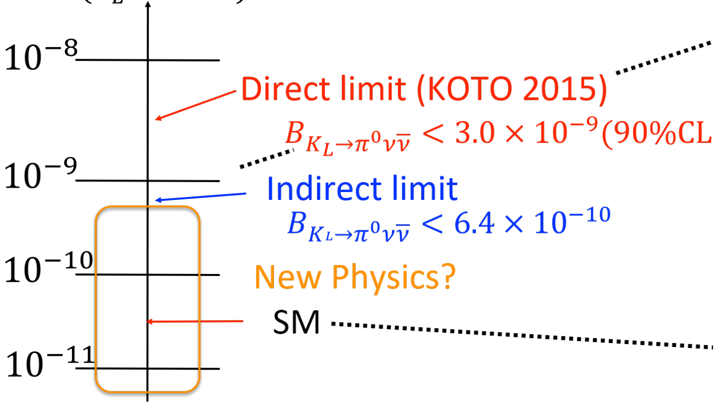

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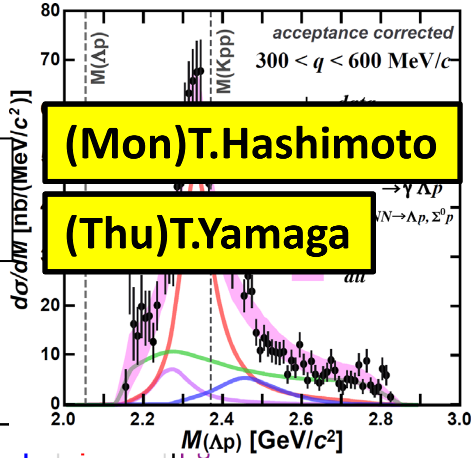
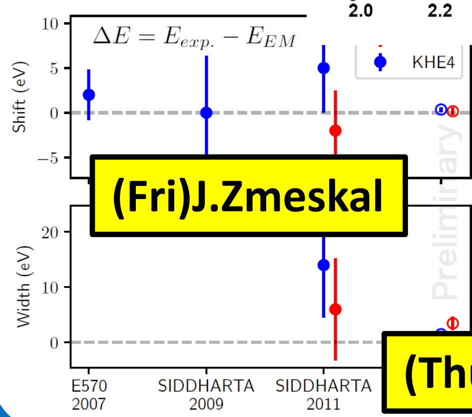
Kaonic nuclei, ”K-pp”



(Mon)T.Hashimoto

(Thu)T.Yamaga



(Fri)J.Zmeskal

Ultra-precise measurement of kaonic atoms

(Thu)S.Hayakawa

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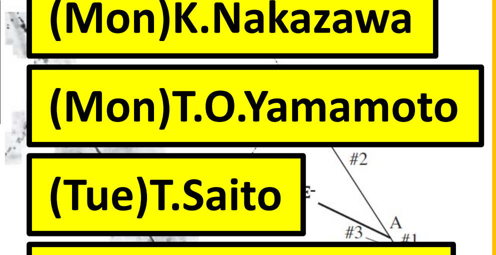


(Mon)K.Nakazawa

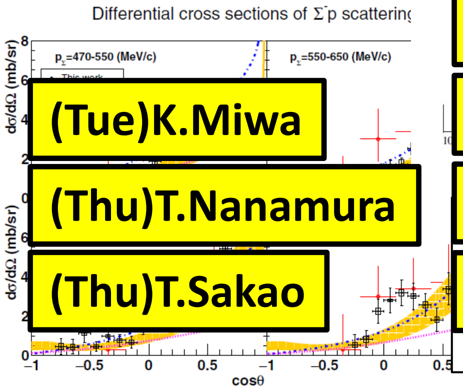
(Mon)T.O.Yamamoto

(Tue)T.Saito

(Wed)M.Nakagawa

(Wed)Y.Ishikawa

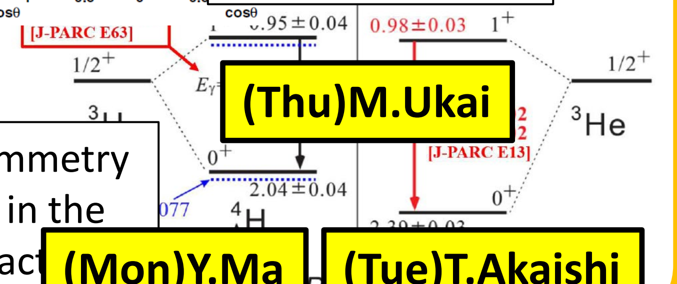
(Thu)M.Fujita



(Tue)K.Miwa

(Thu)T.Nanamura

(Thu)T.Sakao



(Thu)M.Ukai

Charge-symmetry breaking in the ΛN interact

(Mon)Y.Ma

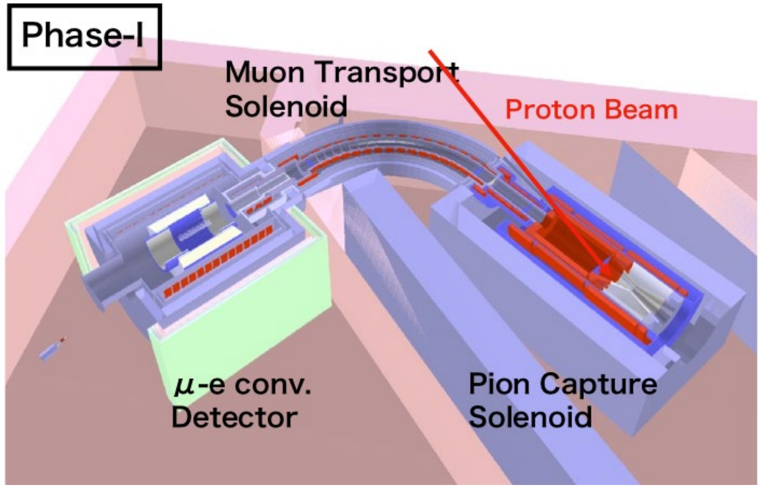
(Tue)T.Akaishi

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

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

→ Explore beyond the SM sensitivity

Hadron Physics

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

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

Futher research

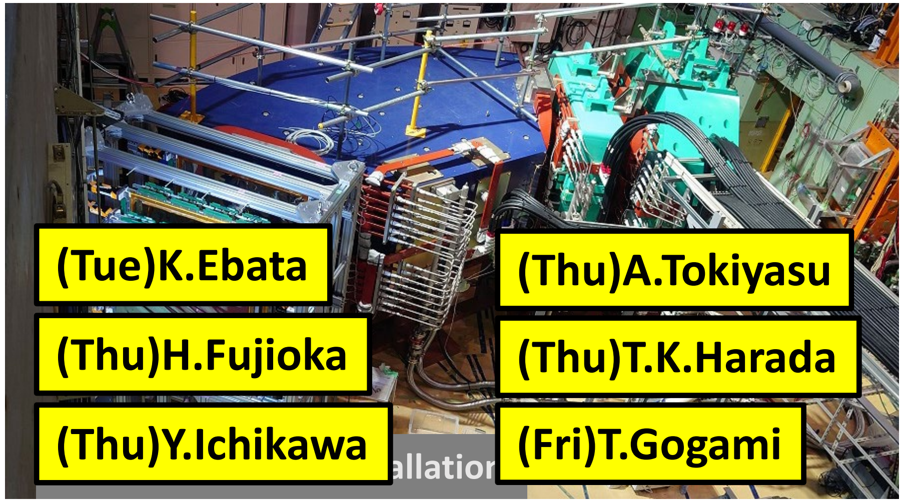
Charmed and muti-strange baryon spectroscopies

→ 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

Flavo...

Search for μ→e ...

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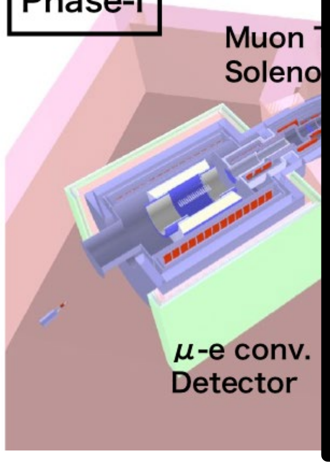
→ Search for c...

vi...

Phase-I



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

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had...

Understand how quarks build hadrons

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Strangeness Nuclear Physics

Elucidate the nature of extremely dense matter

H...
Hypernuclear spectroscopy

...ar Physics

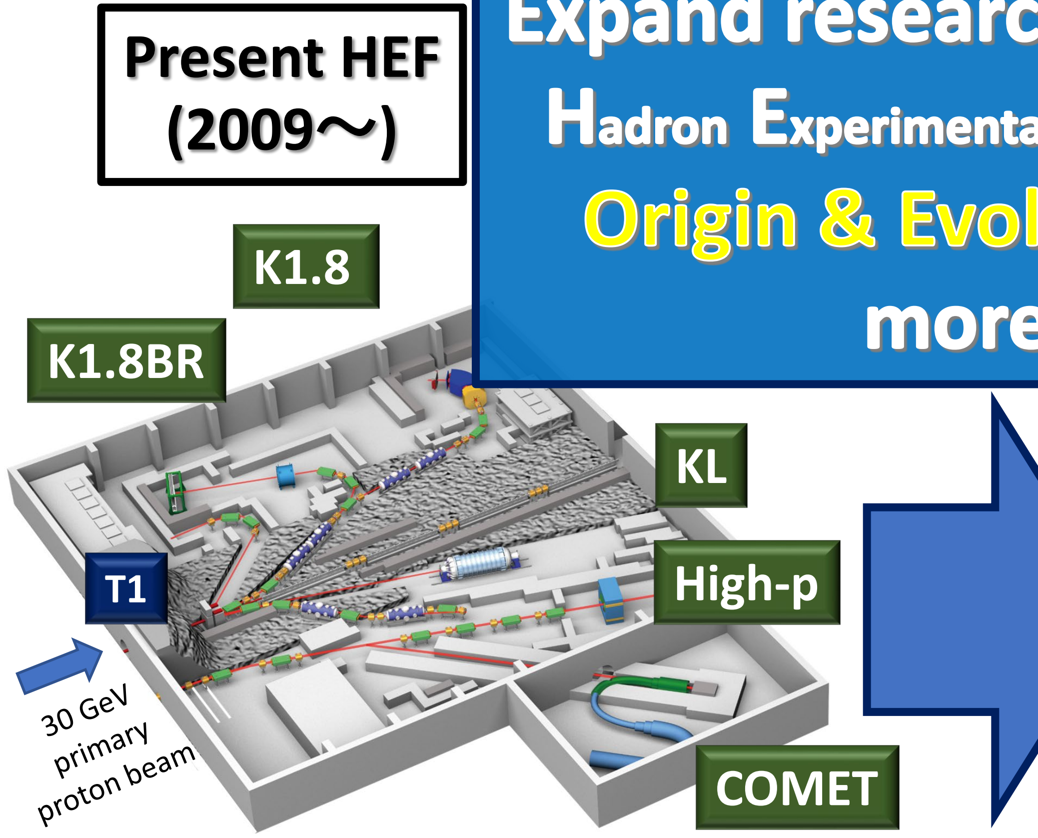
...opic study of
(2023~)

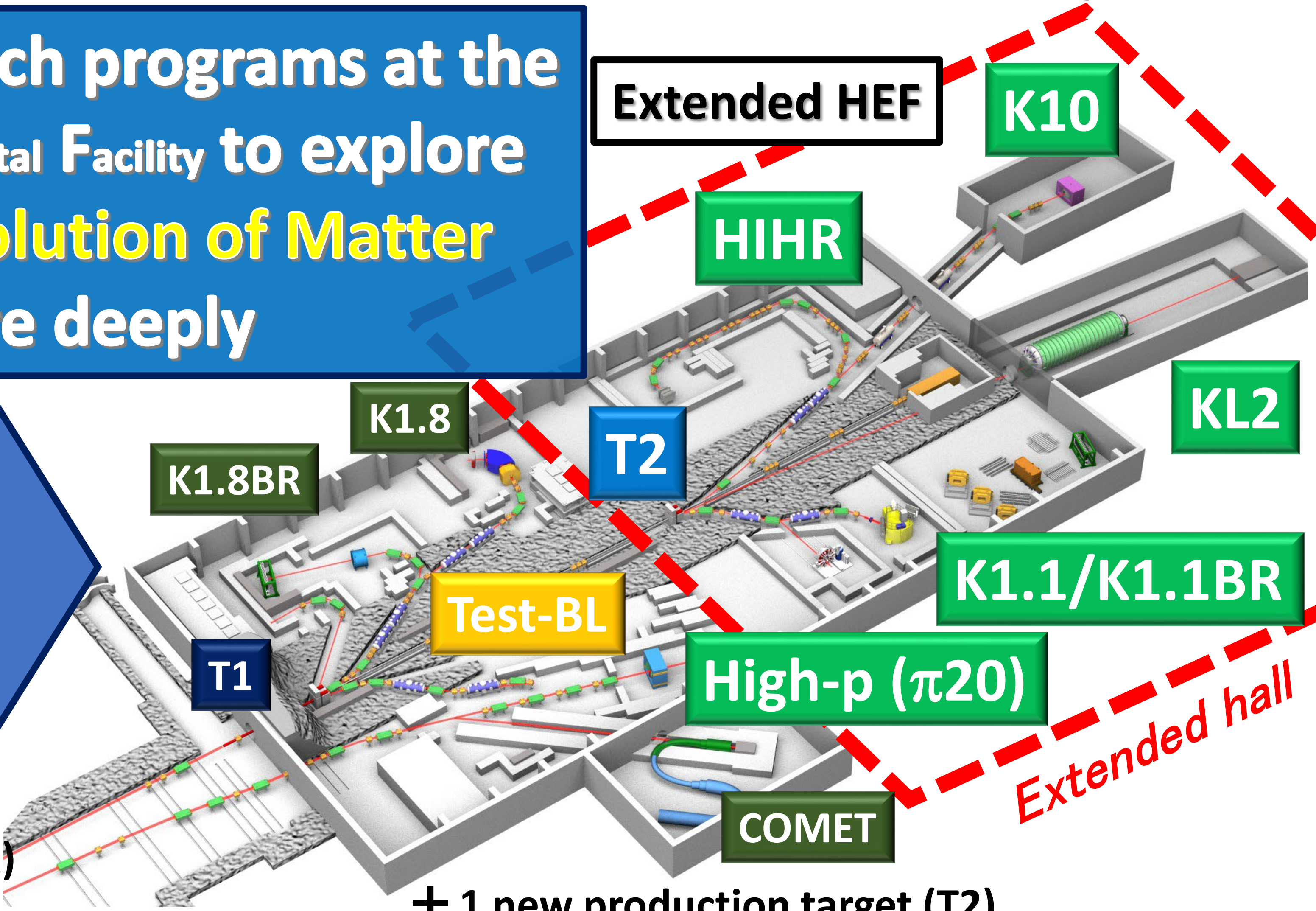
systematic
interactions

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

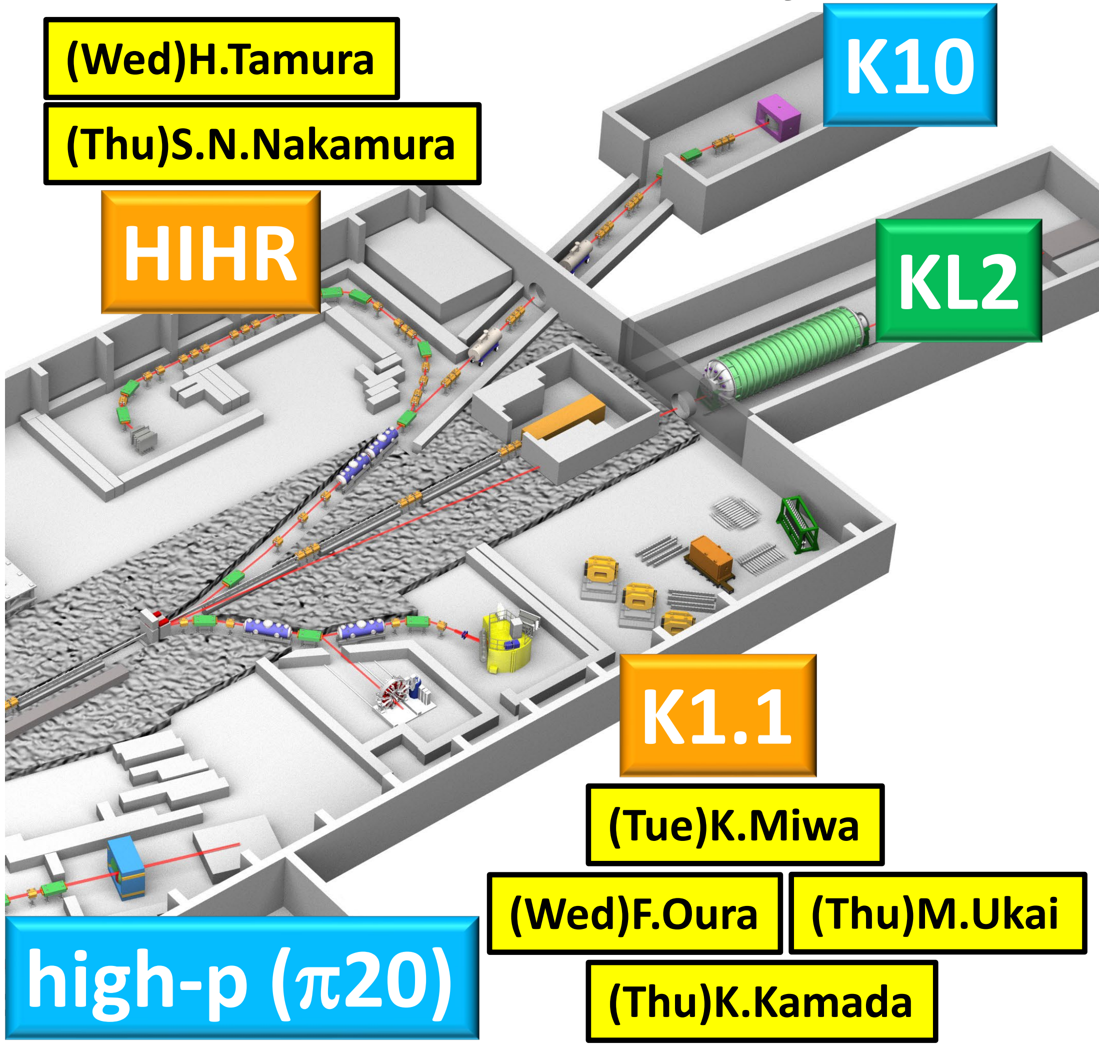
K10 **High-resolution multi-strange baryon spectroscopy**

- 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

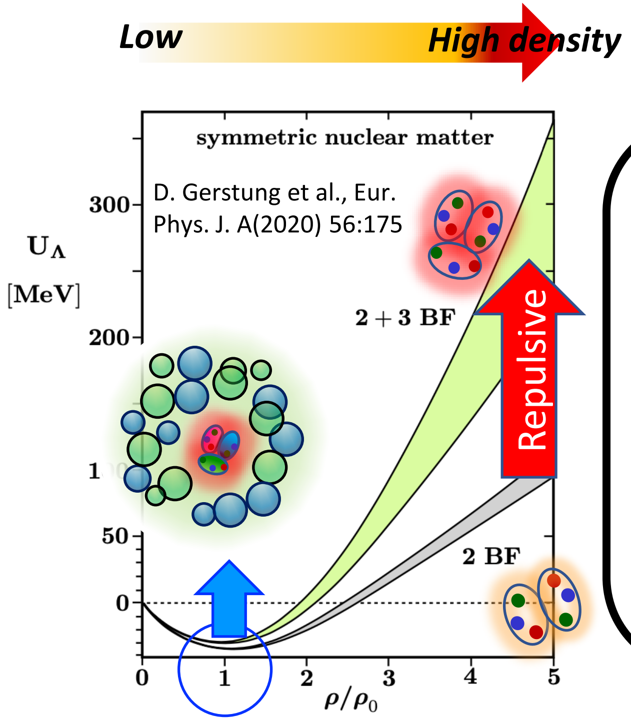


Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

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

ΛNN 3 Baryon Force is a key

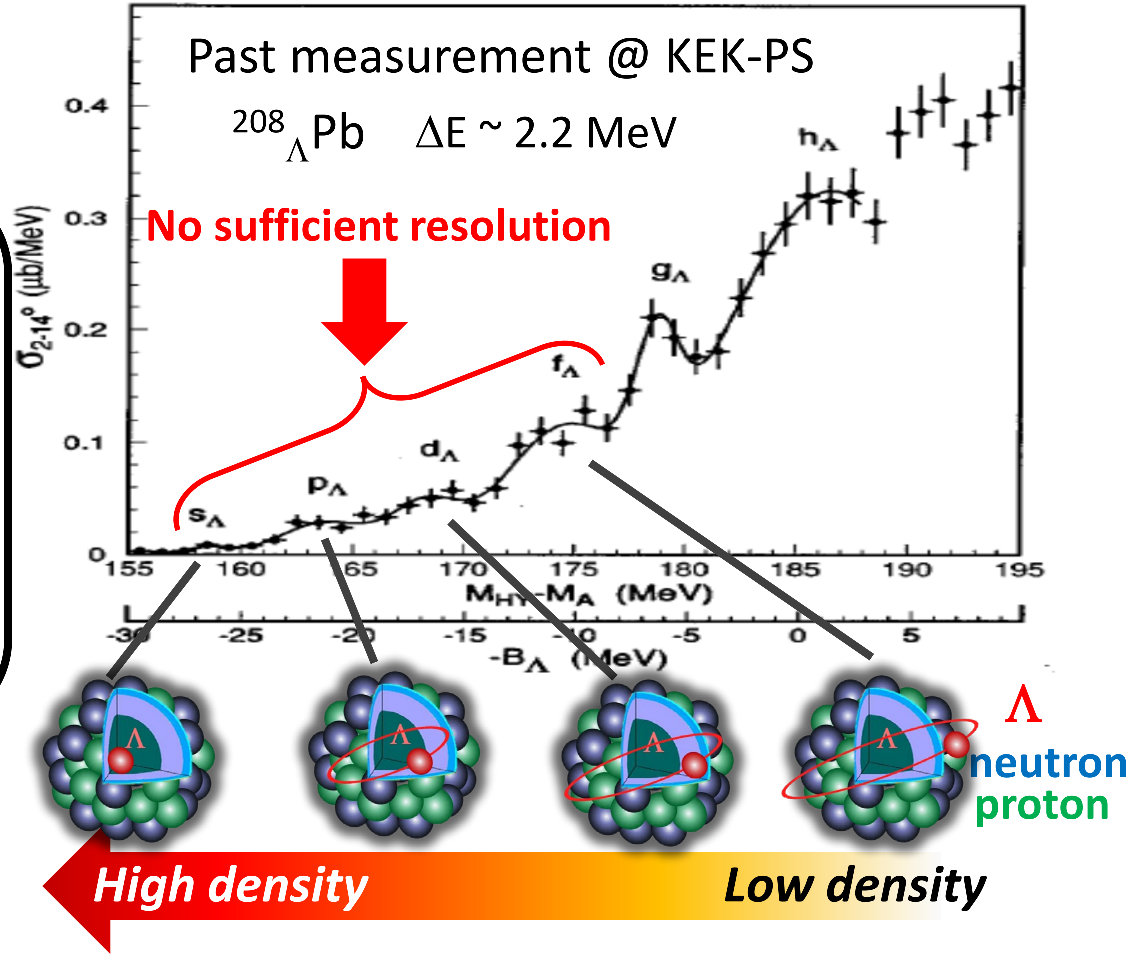


heavy Λ-hypernuclei :

Λ binding energies (B_Λ)

→ density dependent ΛN interaction

→ We need precise measurements



We need to determine

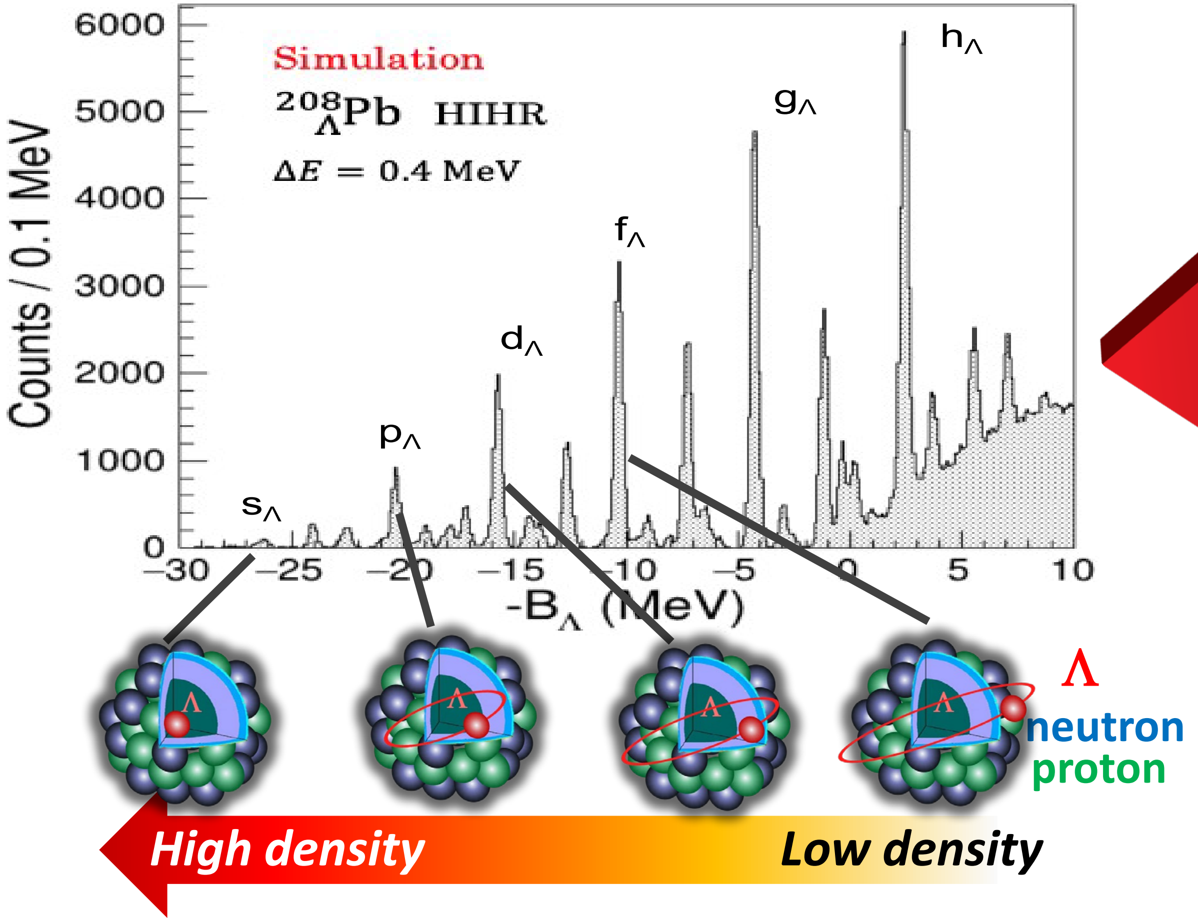
a tiny fraction of 3 Baryon Force effects

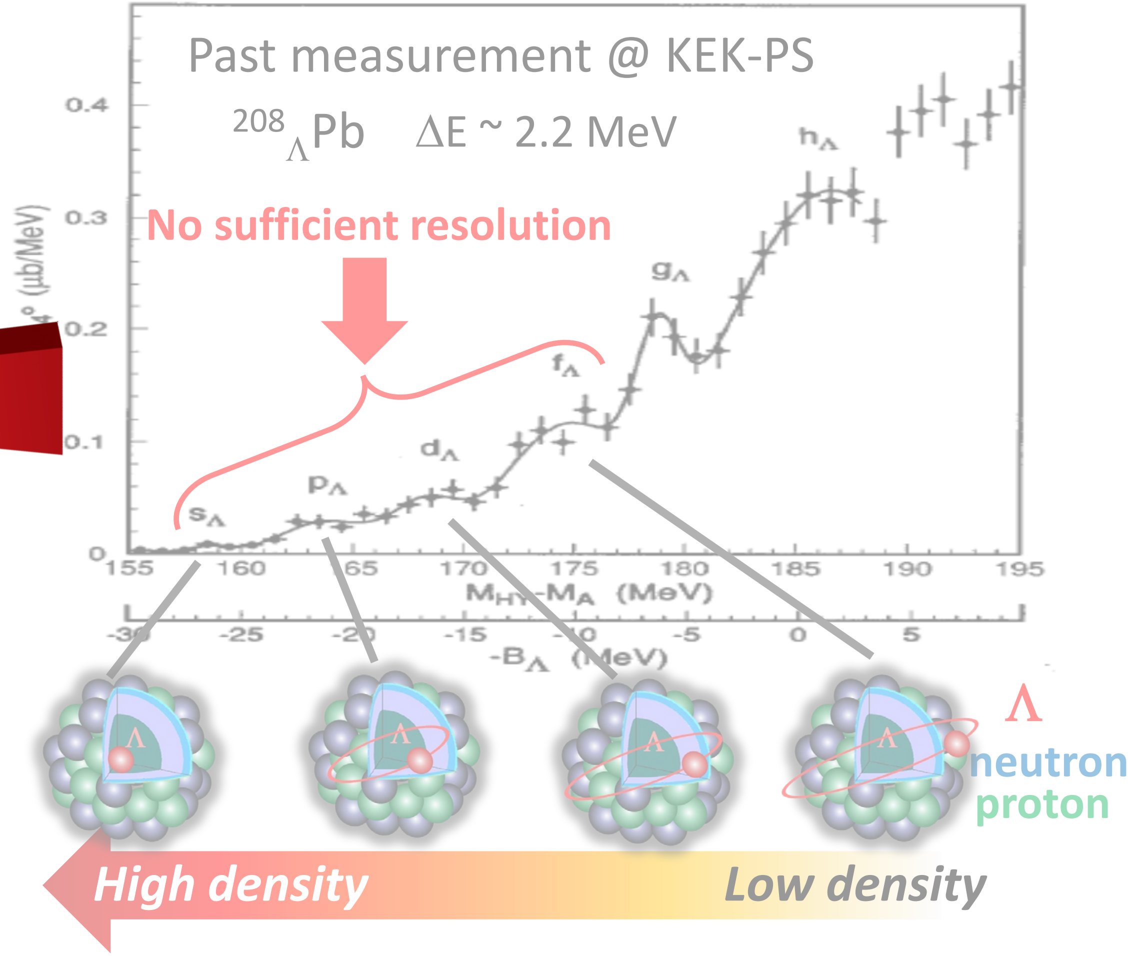
Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

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

Need separation of each Λ orbital state





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Why can heavy neutron stars exist?

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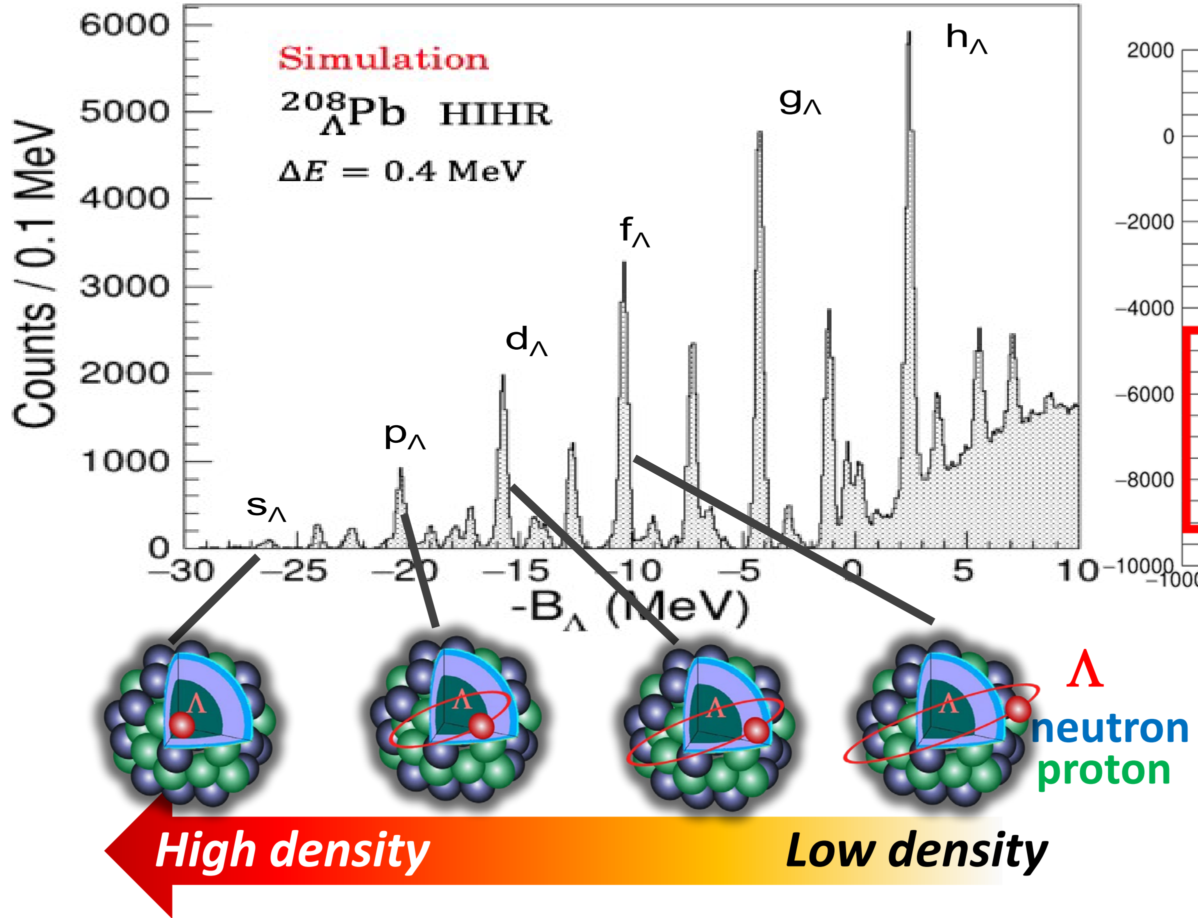
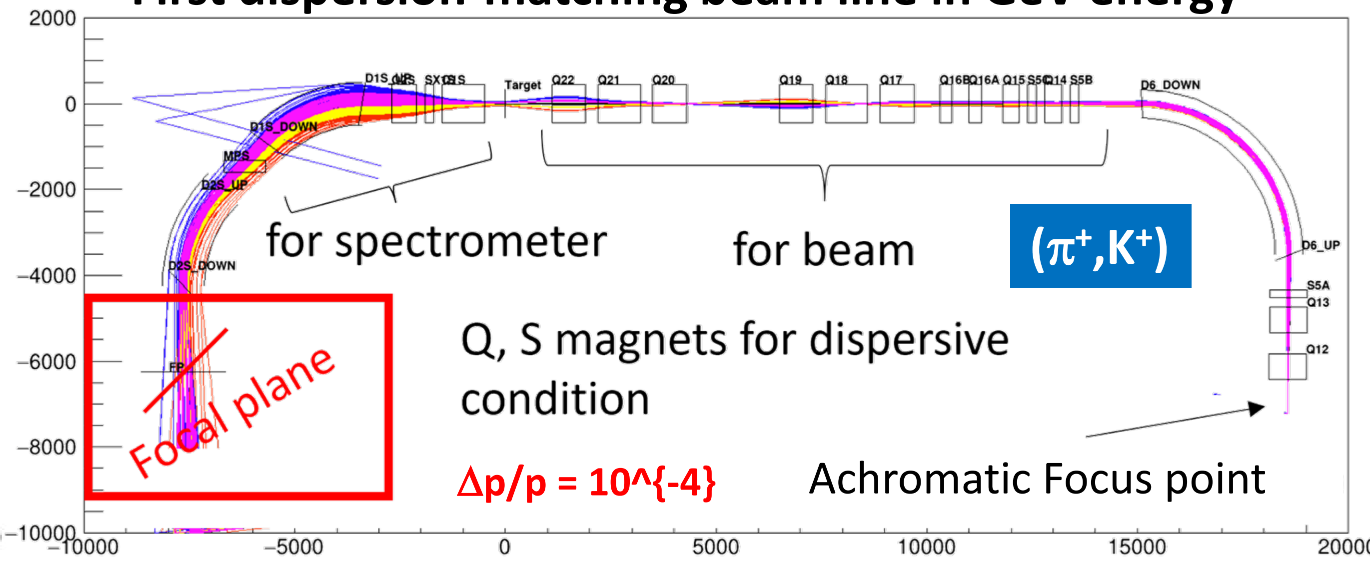
Ultra-high-resolution Λ-hyp. spectroscopy



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

Why can heavy neutron stars exist?

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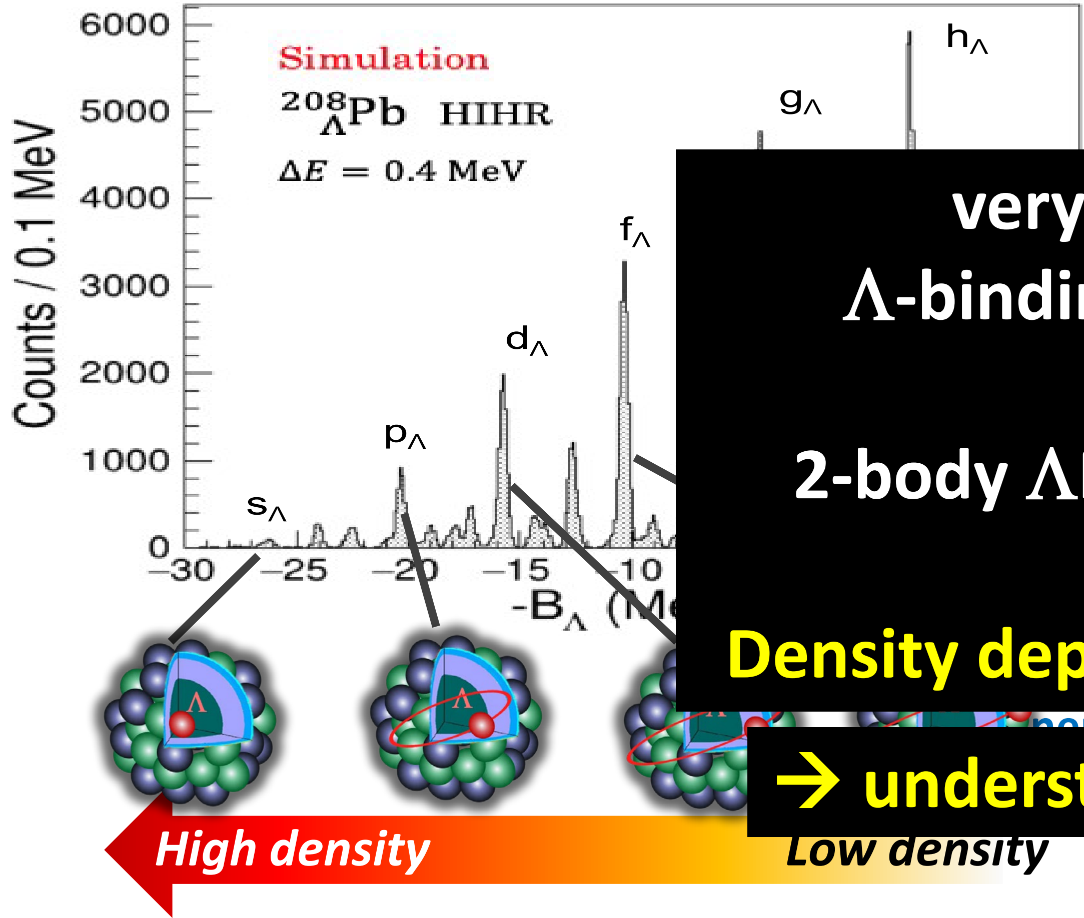
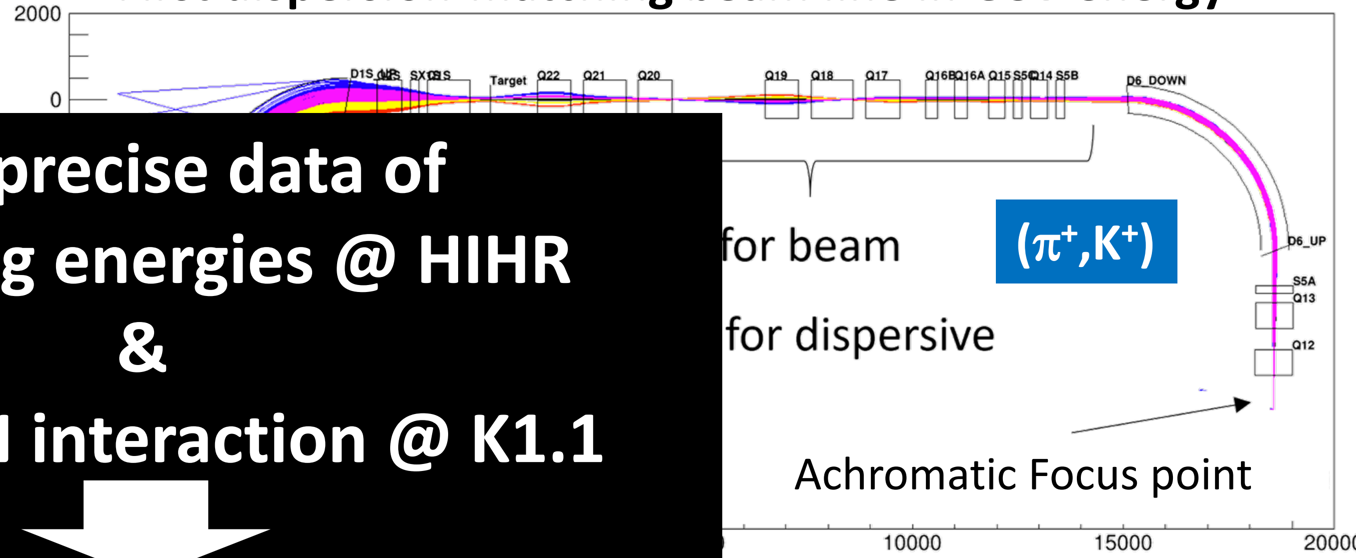
Ultra-high-resolution Λ-hyp. spectroscopy



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

First dispersion-matching beam line in GeV energy



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

Density dependent ΛN interaction

→ understanding neutron stars

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

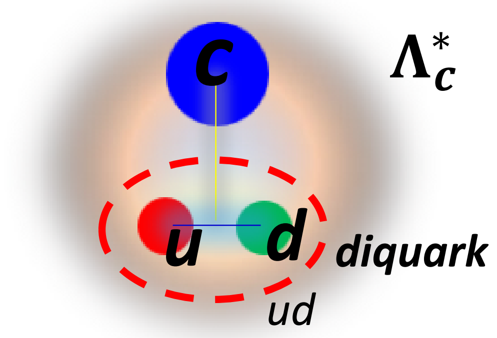
How quarks build hadrons?

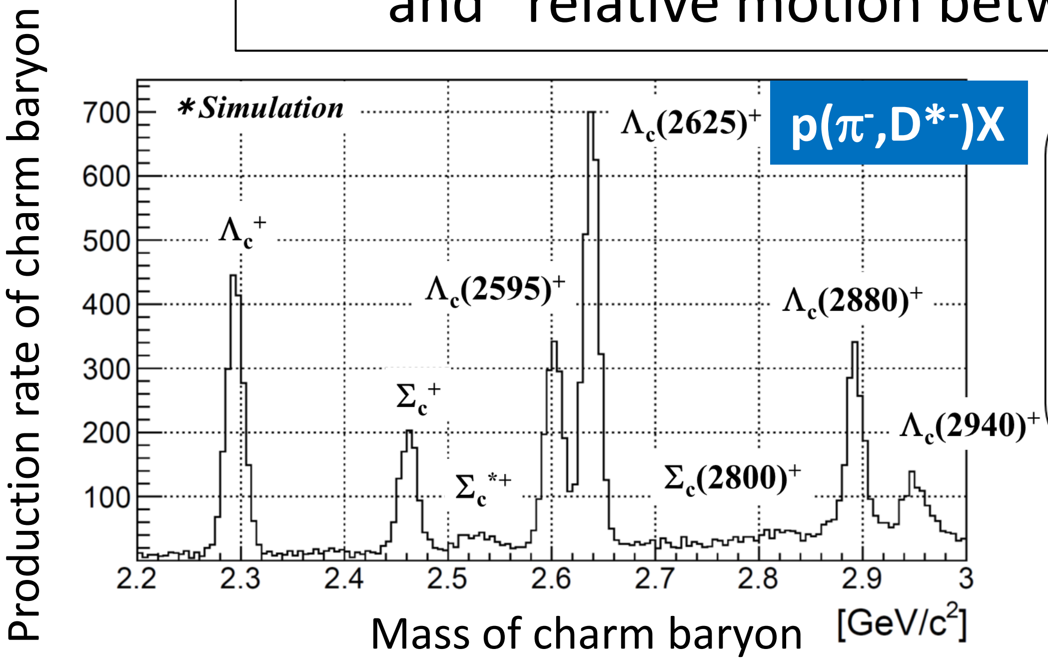
- Investigate **diquarks** in baryons **toward** understanding of **dense quark matter**

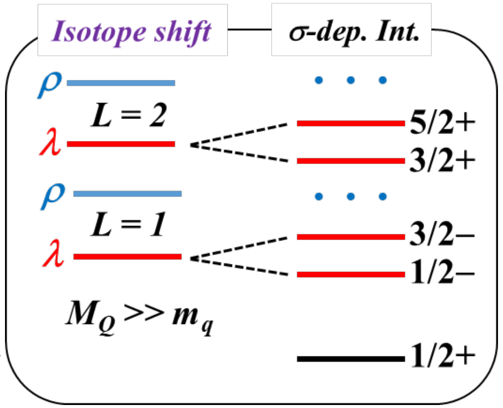
- **Charm Baryon Spectroscopy**
  with intense high-momentum π beam @ High-p (π20)

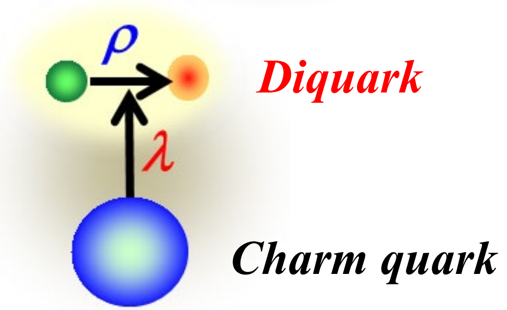
Establish a diquark (*ud*)

Λ_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

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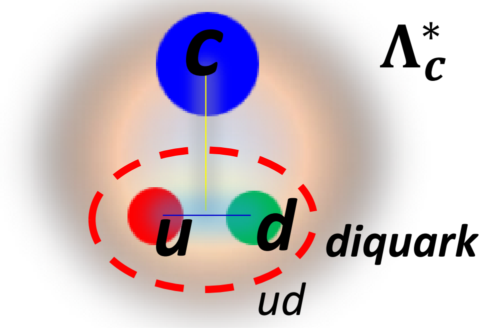


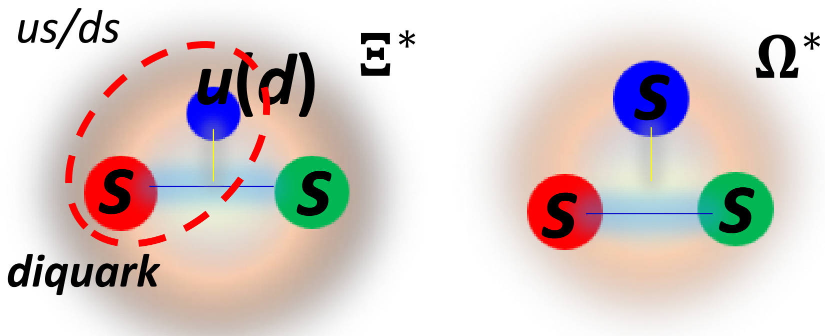
- **Multi-Strange Baryon Spectroscopy**
  with intense high-momentum K beam @ K10

Diquarks in different systems

Ξ^*: *us*/*ds* diquark

Ω^*: the simplest *sss* system

→ diquark is expected to be suppressed



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

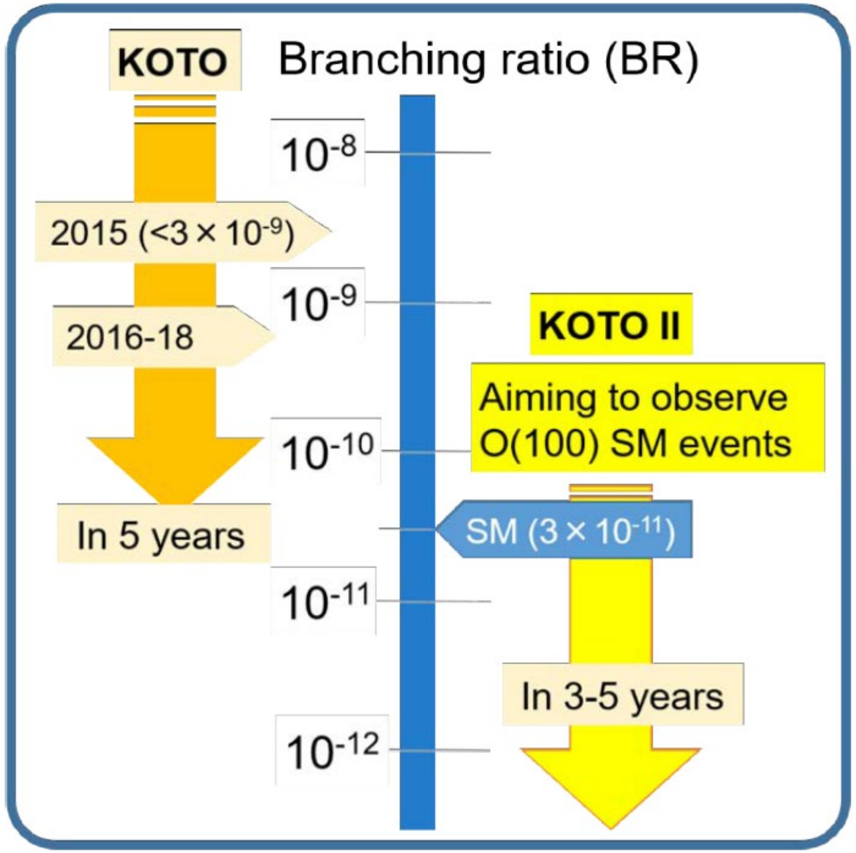
Flavor Physics: New Physics Search at KOTO Step-2

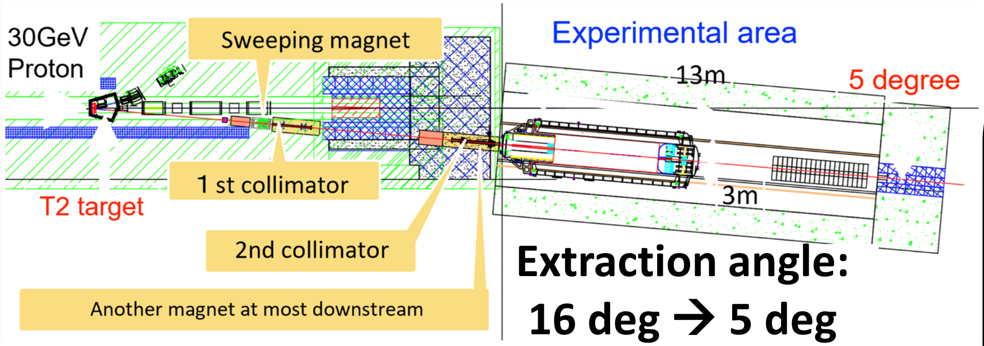
Is there new physics beyond the Standard Model?

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

One of the best probes for new physics search

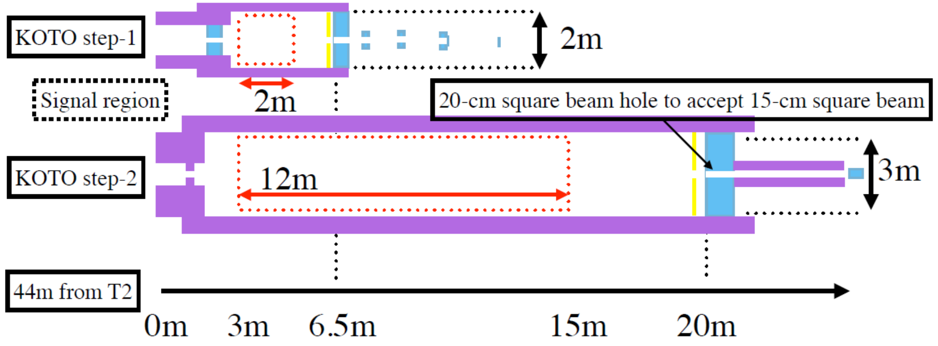
- Directly break CP symmetry
- Suppressed in the SM → Branching ratio ～ 3×10^{-11}
- Small theoretical uncertainties (～2%)





Extraction angle: 16 deg → 5 deg

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



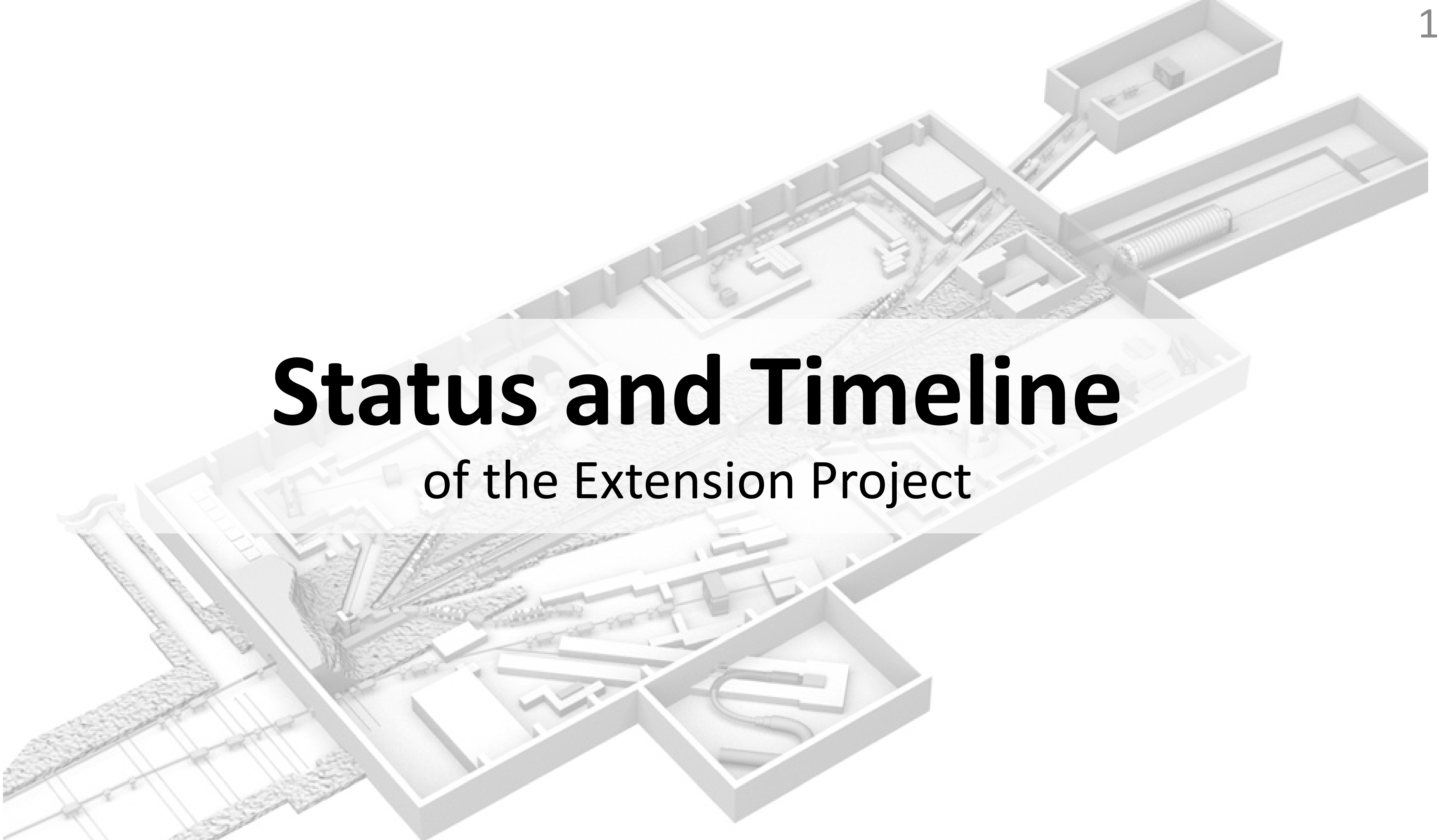
Ultra-high sensitivity detector (~x70)

KOTO Step-2

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

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

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



Status and Timeline

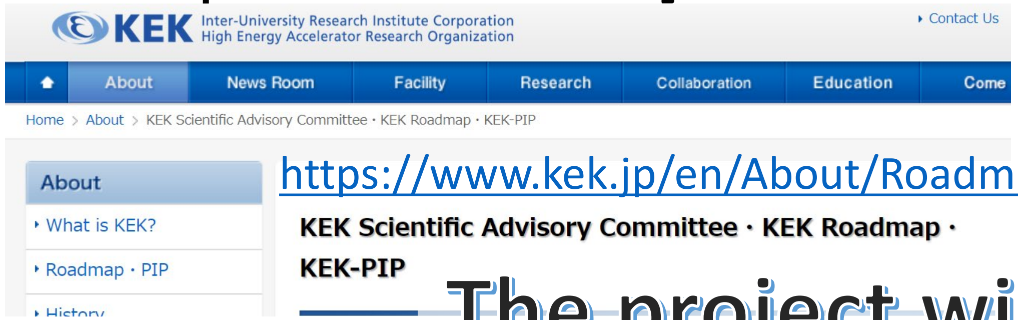
of the Extension Project

Present Status of the Project

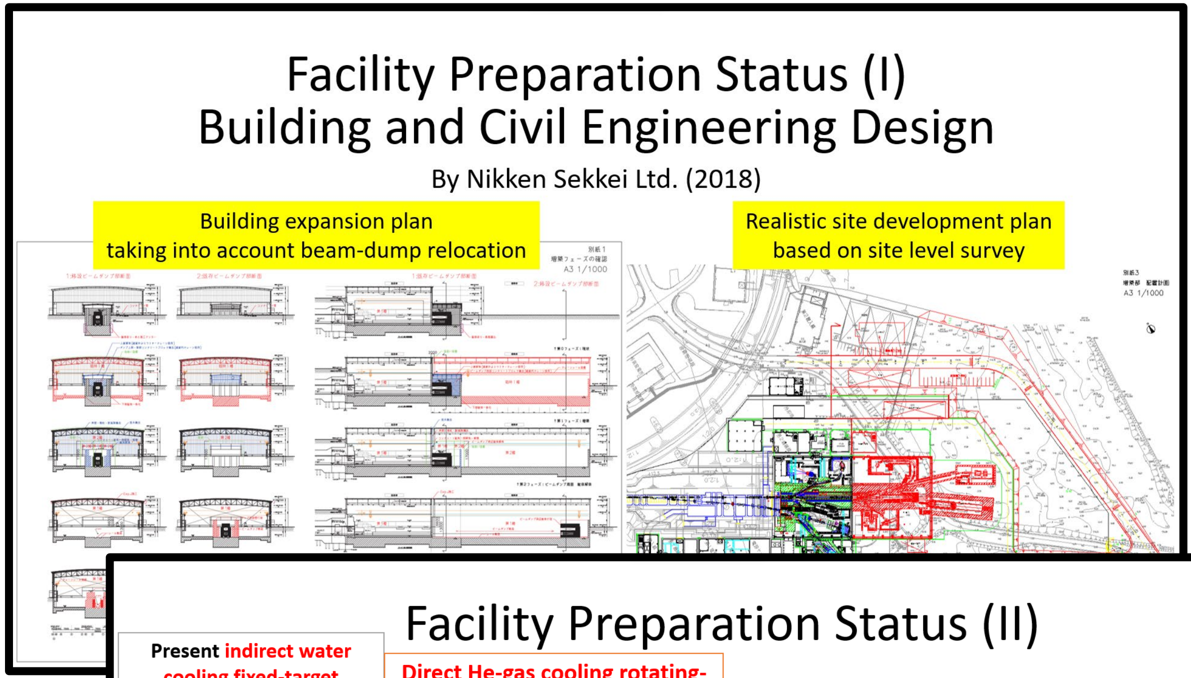
One of the candidate projects to be funded:

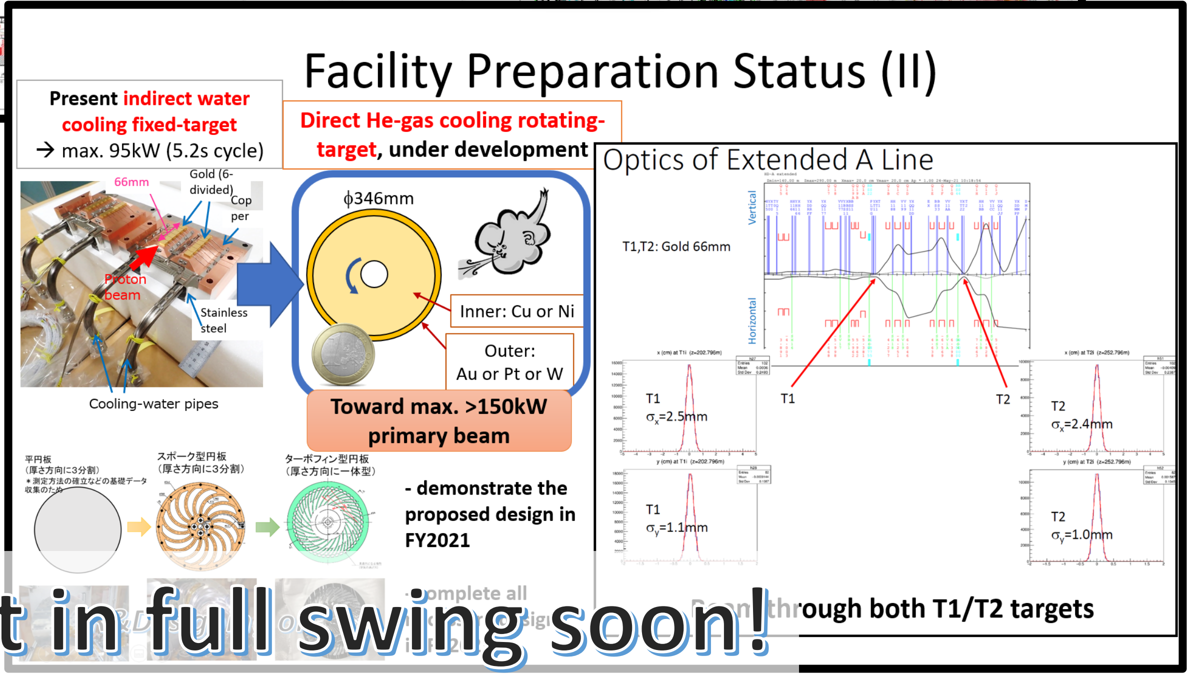
- ➢**MEXT Roadmap 2020** (2012, 2014)
- ➢**Science Council of Japan Master Plan 2020** (2011, 2014, 2017)

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]



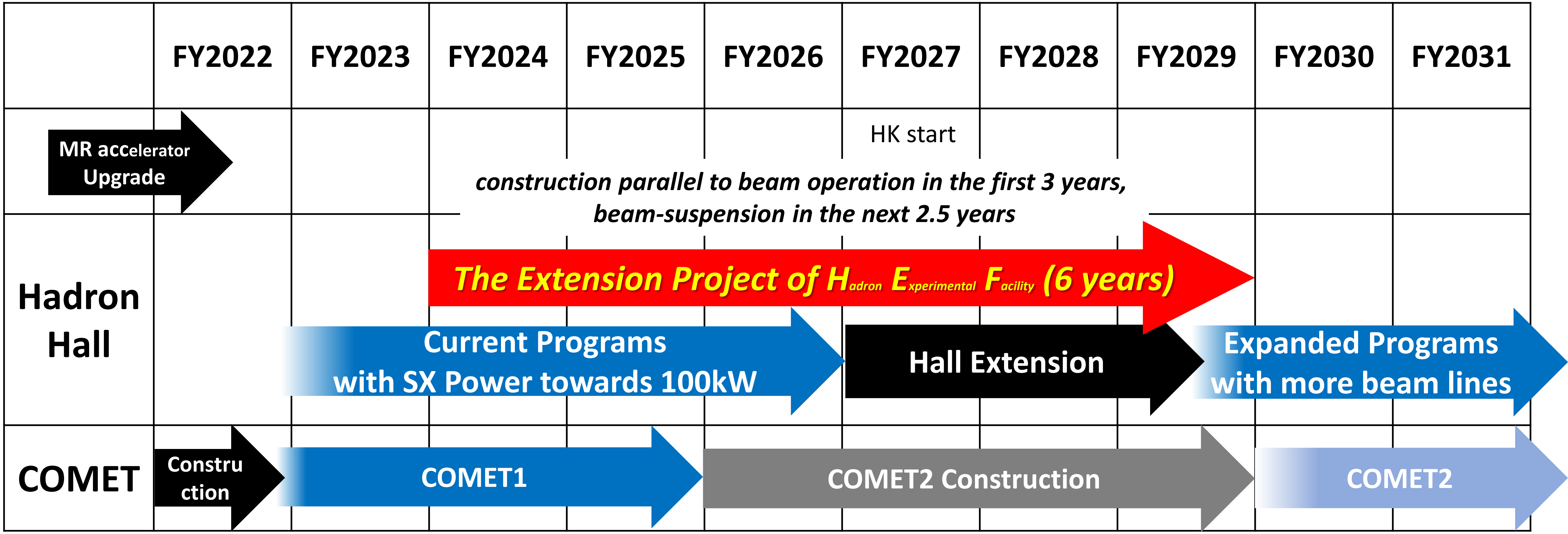
https://www.kek.jp/en/About/Roadmap/





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

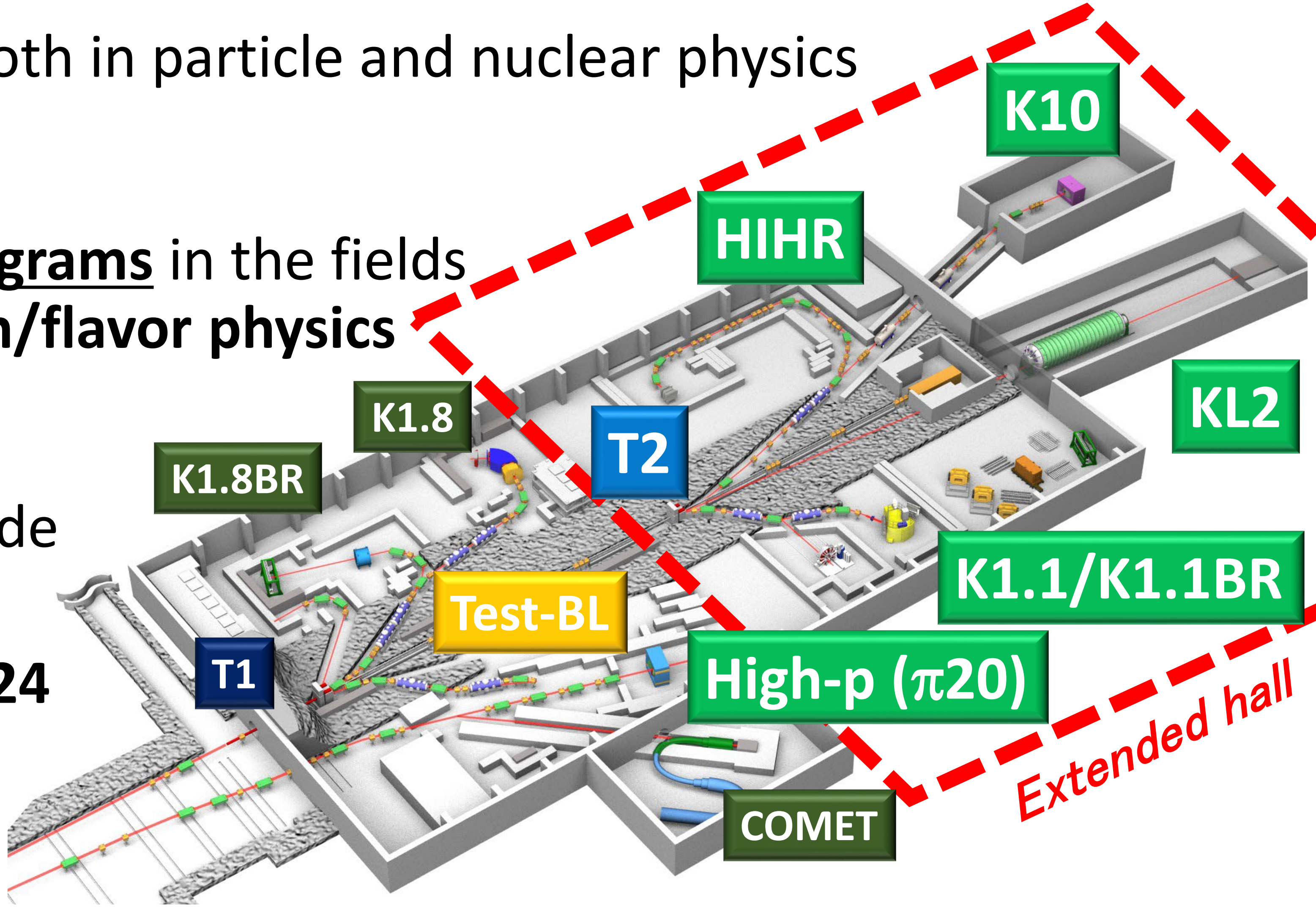
- **Unique research programs** both in particle and nuclear physics at high-intensity frontier

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

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

→ The project will start in **FY2024**

Stay tuned!



HUA Thank you for your attention!

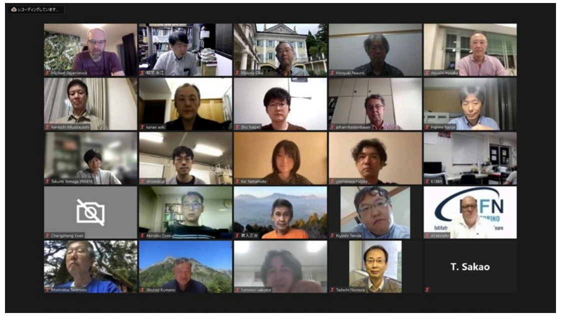
https://www.rcnp.osaka-u.ac.jp/~jparchua/en/hefextension.html

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