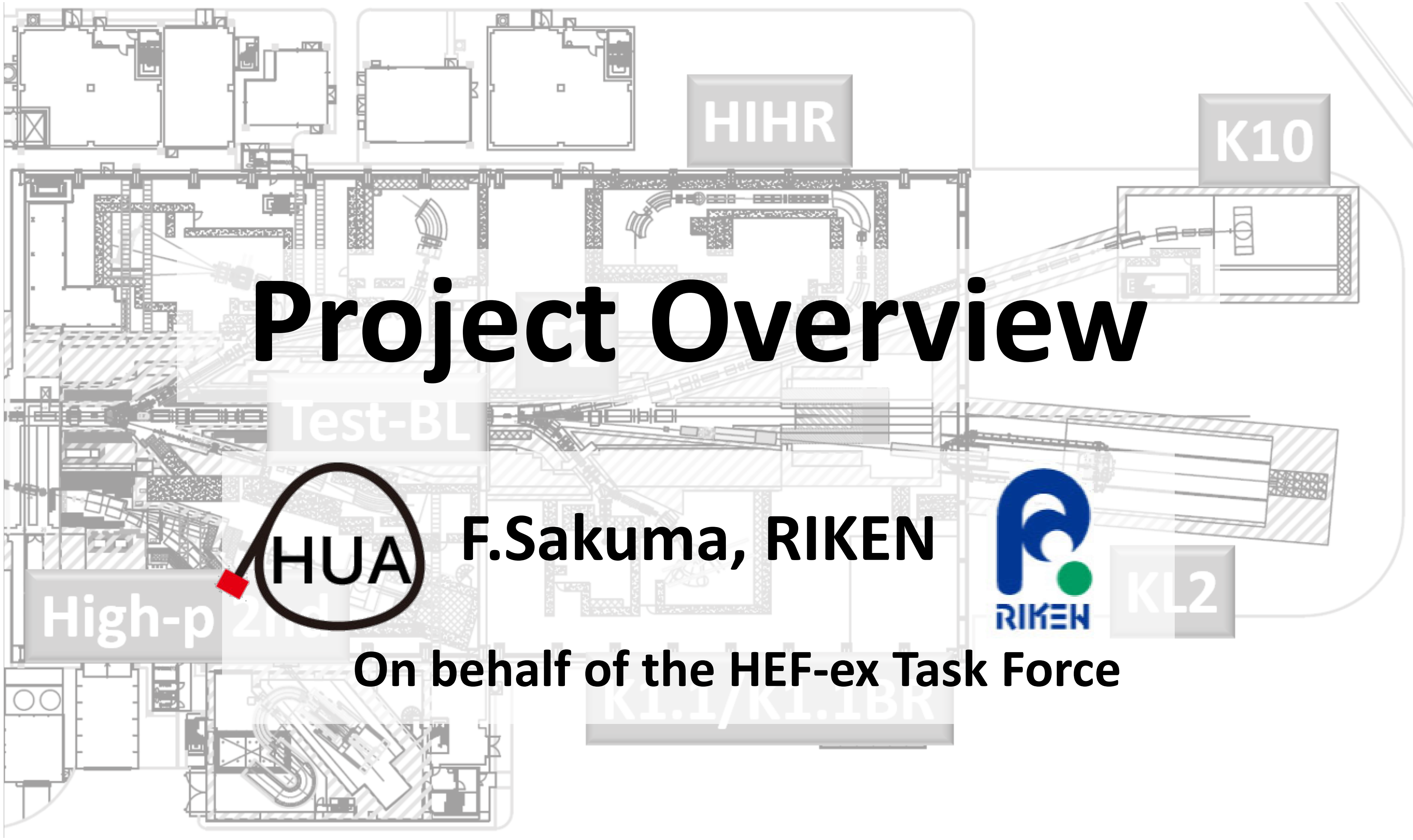


Project Overview

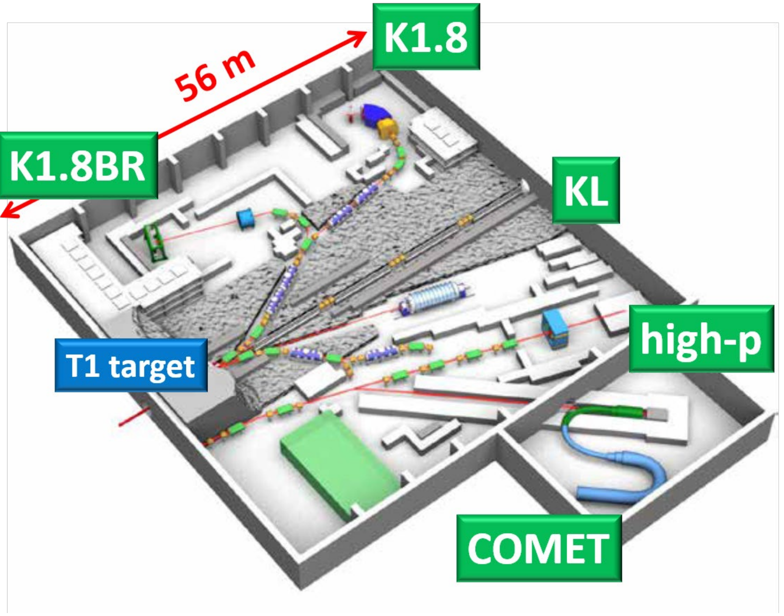
F.Sakuma, RIKEN

On behalf of the HEF-ex Task Force

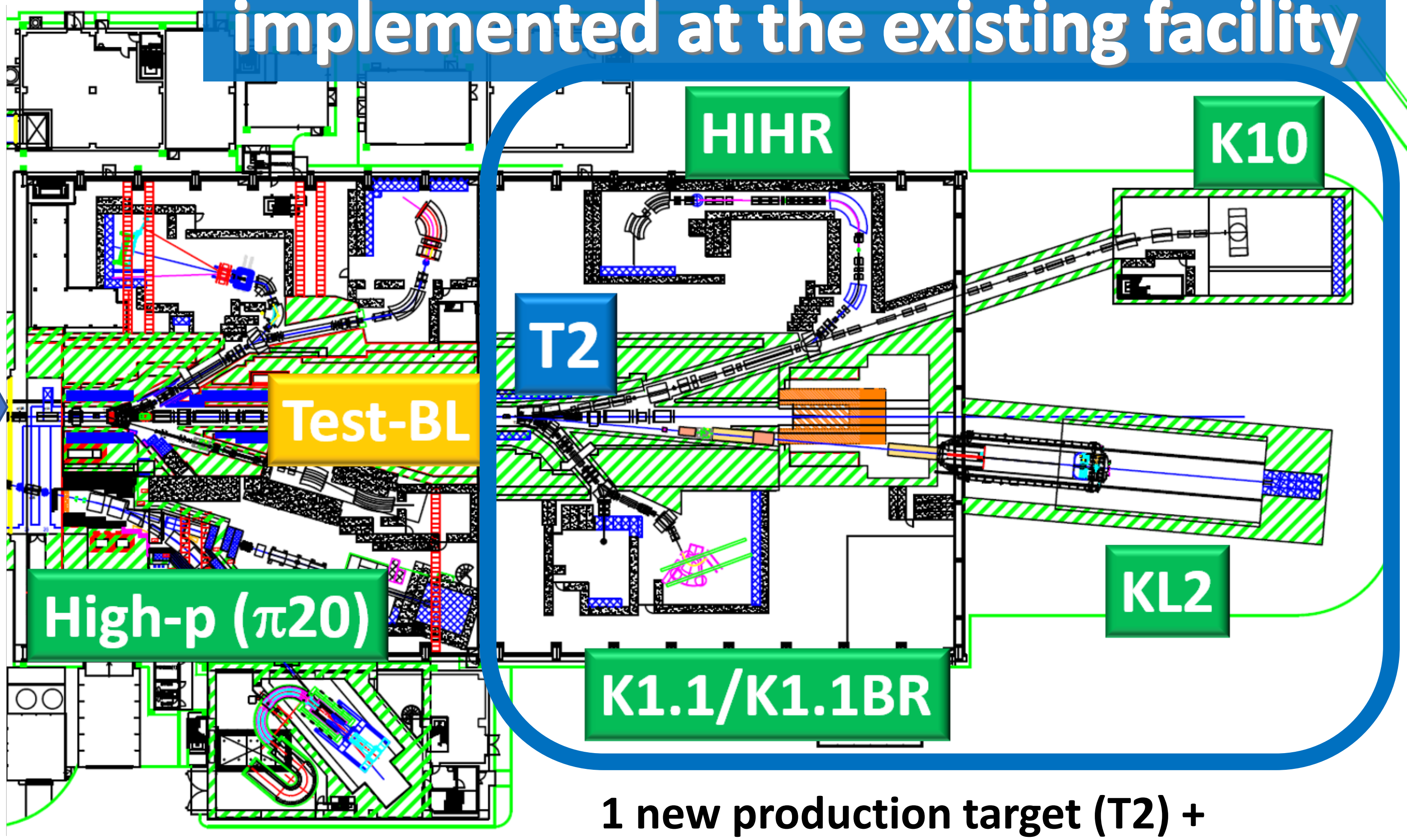
Hadron Experimental Facility extension (HEF-ex) Project

Open new physics that cannot be implemented at the existing facility

Present facility



1 production target (T1) +
2 charged beamlines (K1.8/1.8BR, High-p)
1 neutral beamline (KL)
1 muon beamline (COMET)



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

Contents

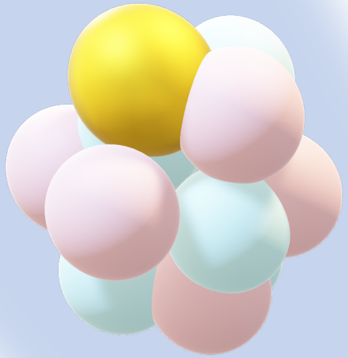
- **Introduction** of the Hadron Experimental Facility (HEF)
  - Goals of particle & nuclear physics
  - Recent achievements & present status
- **Key issues and strategy** for the physics programs at HEF in the future
  - Strangeness nuclear physics / Hadron physics / Flavor physics
- **Global situation**
- **Timeline** of the project
- **Summary**

Introduction

of the Hadron Experimental Facility

Origin & Evolution of Matter

Matter in Extreme Conditions

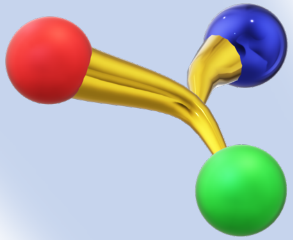


hyperon puzzle in neutron stars

flavor symmetry breaking
hadron interaction
formation of a nucleus

Hypernuclei spectroscopy
YN scattering

Matter Evolution

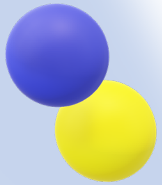


fundamental structure of matter

chiral symmetry breaking
quark interaction

Hadron spectroscopy
Meson in nuclei

Birth of Matter



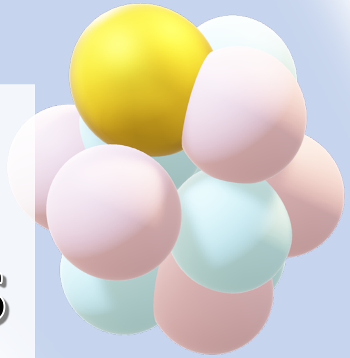
matter dominated universe

CP symmetry violation
weak interaction

Kaon decays

Origin & Evolution of Matter

Strangeness Nuclear Physics



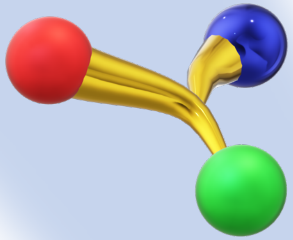
hyperon puzzle in neutron stars

flavor symmetry breaking
hadron interaction
formation of a nucleus

Hypernuclei spectroscopy
YN scattering

Hadron Physics

fundamental structure of matter

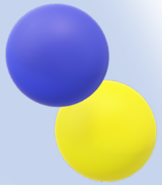


chiral symmetry breaking
quark interaction

Hadron spectroscopy
Meson in nuclei

Flavor Physics

matter dominated universe

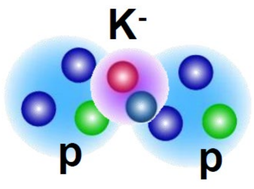


CP symmetry violation
weak interaction

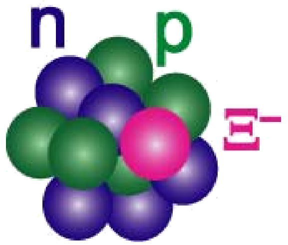
Kaon decays

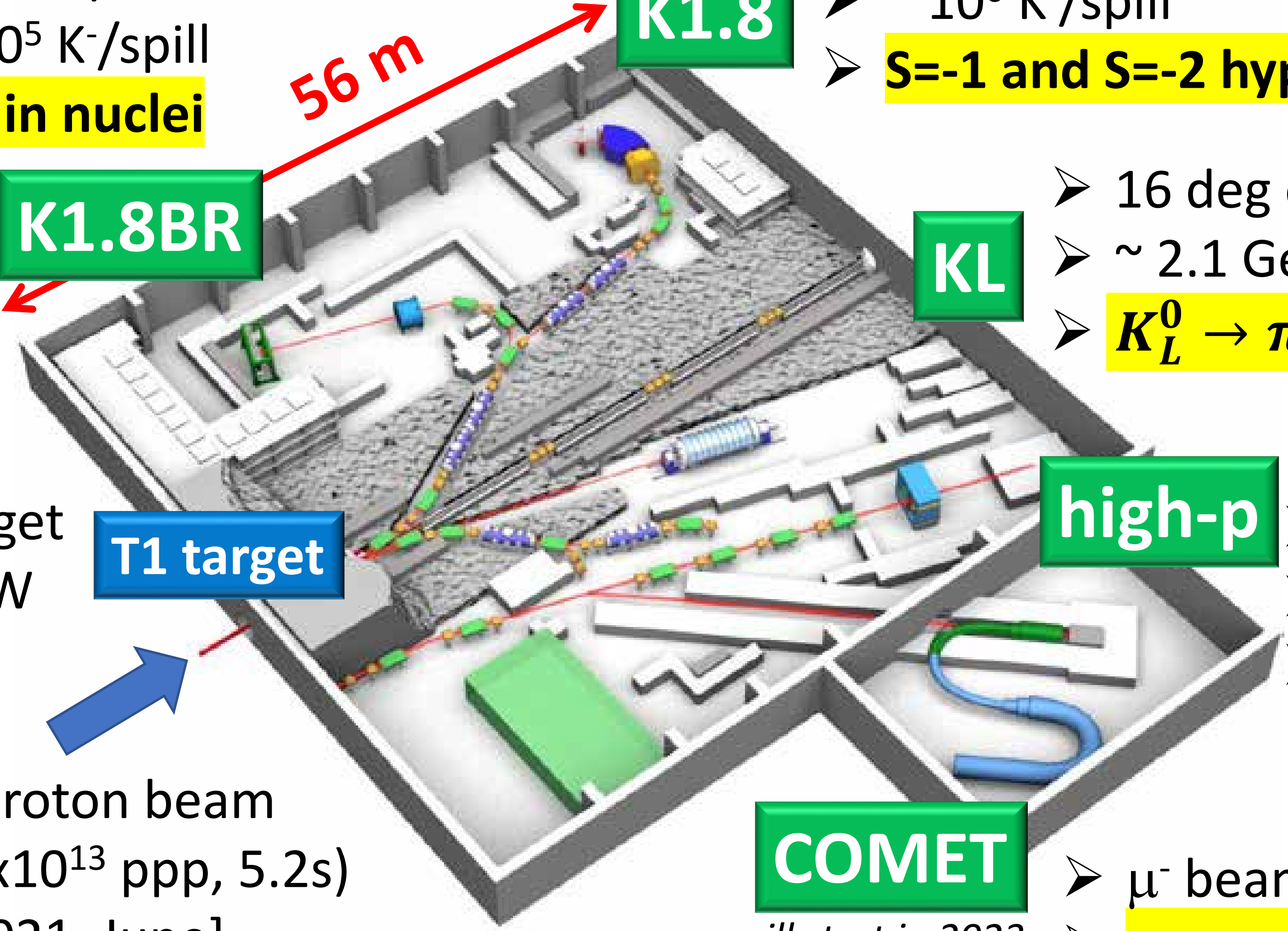
Present Hadron Experimental Facility (HEF)

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

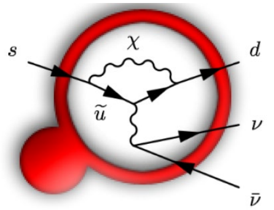


- < 2.0 GeV/c
- ~ 10^6 K$^-$/spill
- **S=-1 and S=-2 hypernuclei**



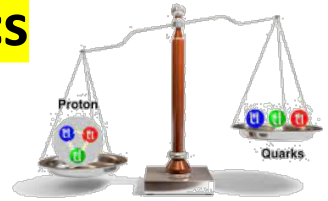


- 16 deg extraction
- ~ 2.1 GeV/c ~ 10^7 K^0_L/spill
- $K_L^0 \to \pi^0 \nu \bar{\nu}$



launched in 2020

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



- Au Target
- < 95 kW

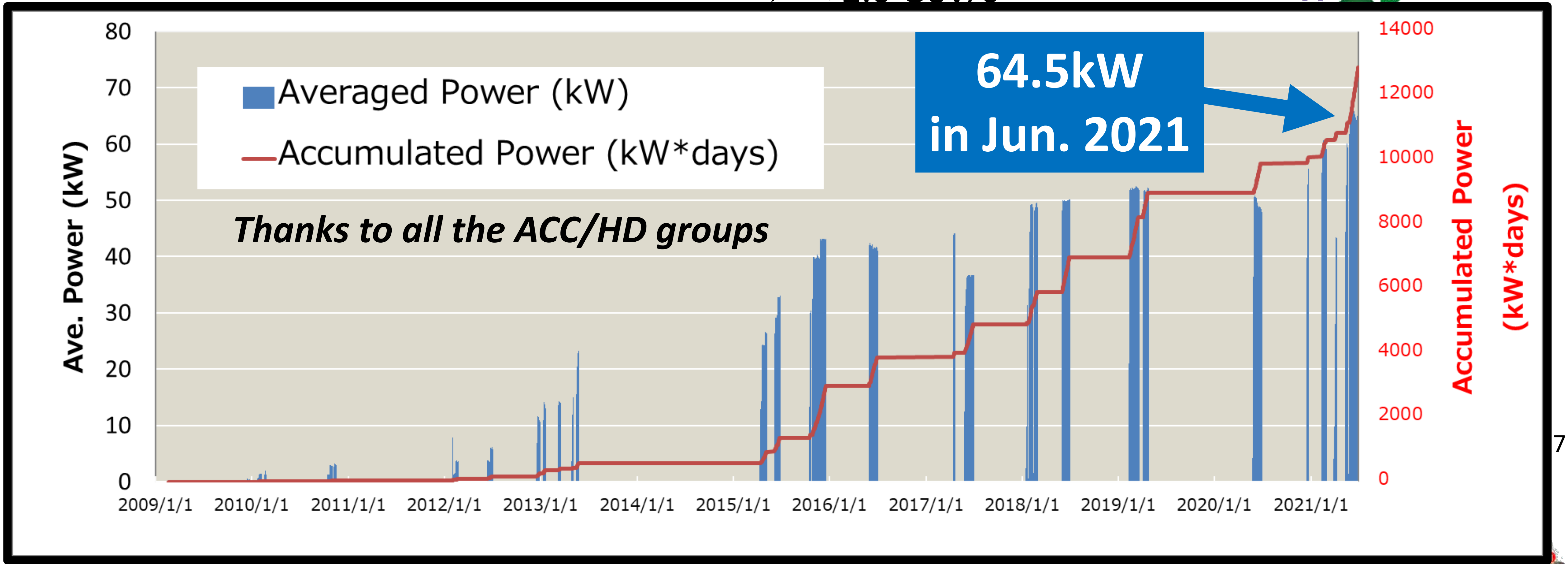
- 30 GeV proton beam
- 65kW (7x10^{13} ppp, 5.2s)
  [as of 2021, June]

will start in 2023

- μ$^-$ beam
- **μ-e conversion**

Present Hadron Experimental Facility (HEF)

- < 2.0 GeV/c



- 30 GeV proton beam
- 65kW (7×10^{13} ppp, 5.2s)
  [as of 2021, June]

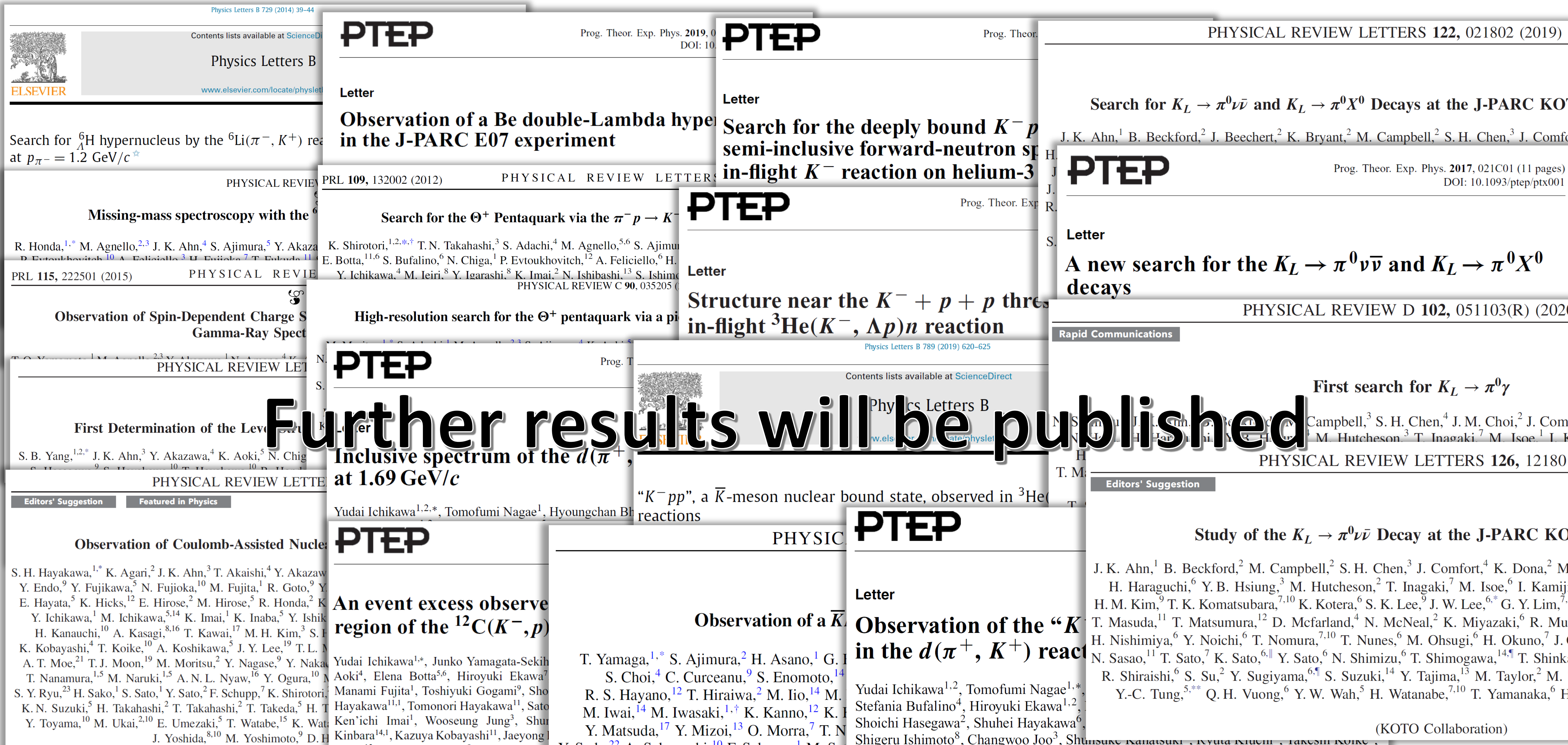
COMET

will be ready in 2023

- μ⁻ beam
- **μ-e conversion**

Outputs from the HEF

Since the first beam delivery in 2009, fruitful results have been obtained



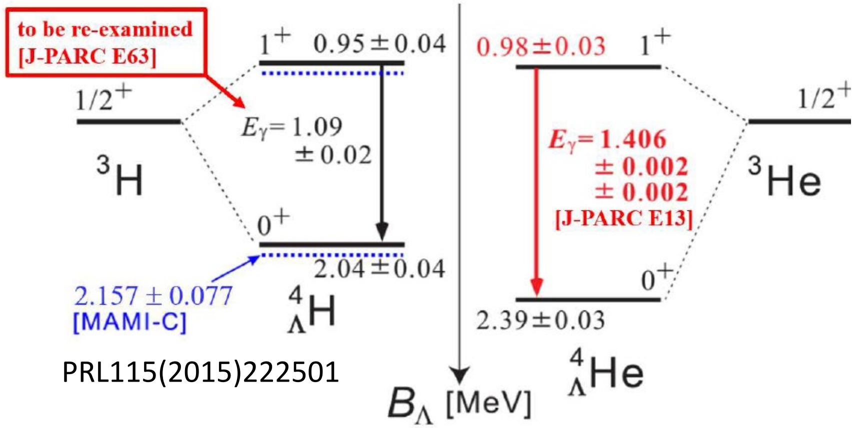
Further results will be published

Recent Achievements: Strangeness

- **S=-1 nuclei**: large charge symmetry breaking (E13)
- **S=-2 nuclei**: existence of Ξ bound state (E07)
- **Σp scattering**: strong repulsion in Σp (E40)

S=-1 | **E13, 2015**

Spin-dependent charge symmetry breaking in the ΛN int.

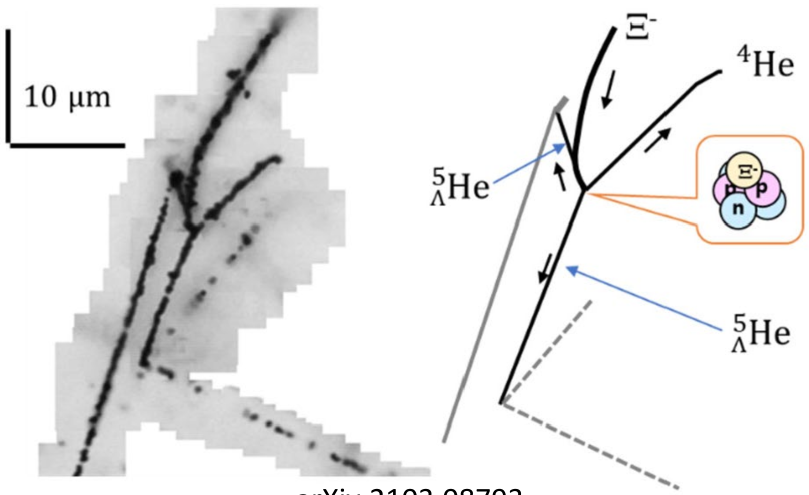


PRL115(2015)222501

New insight of

ΛN-ΣN interaction

S=-2 | **E07, 2021** | **$^{15}_{\Xi}$C, IRRAWADDY**



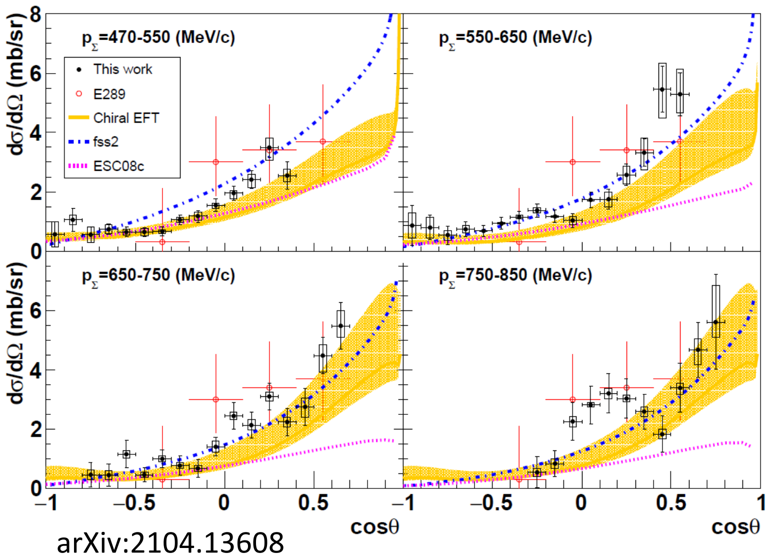
arXiv:2103.08793

New information on

ΞN interaction in nuclei

Scattering | **E40, 2021** | **Σ⁻p scattering**

Differential cross sections of Σ⁻p scattering



arXiv:2104.13608

Established

precise YN scattering method

Present Status: Strangeness

E42: H-dibaryon

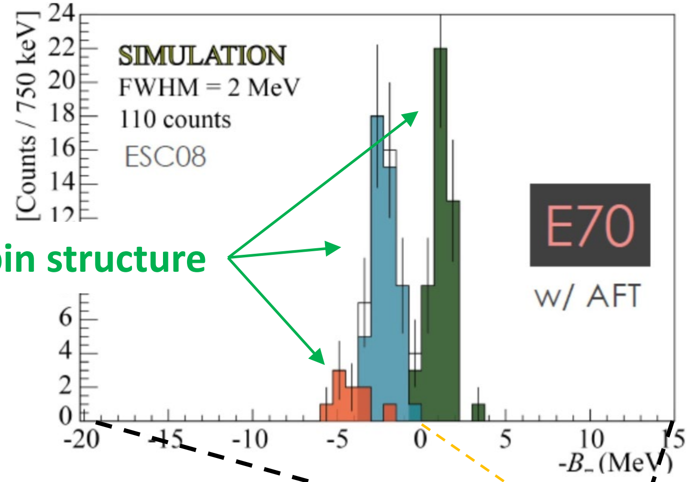
Hyp-TPC, Completed in June

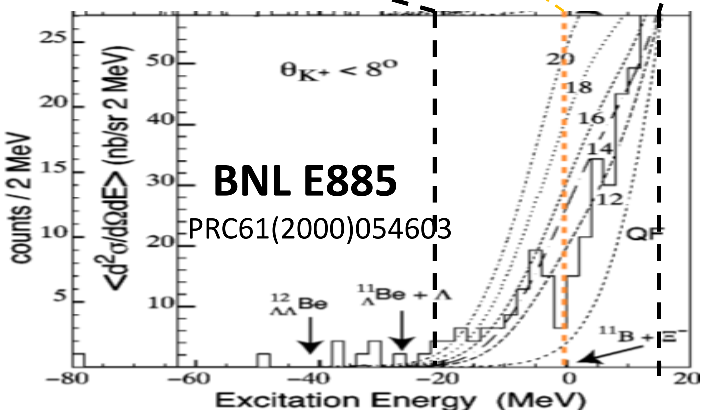
E70: Ξ-hypernuclei

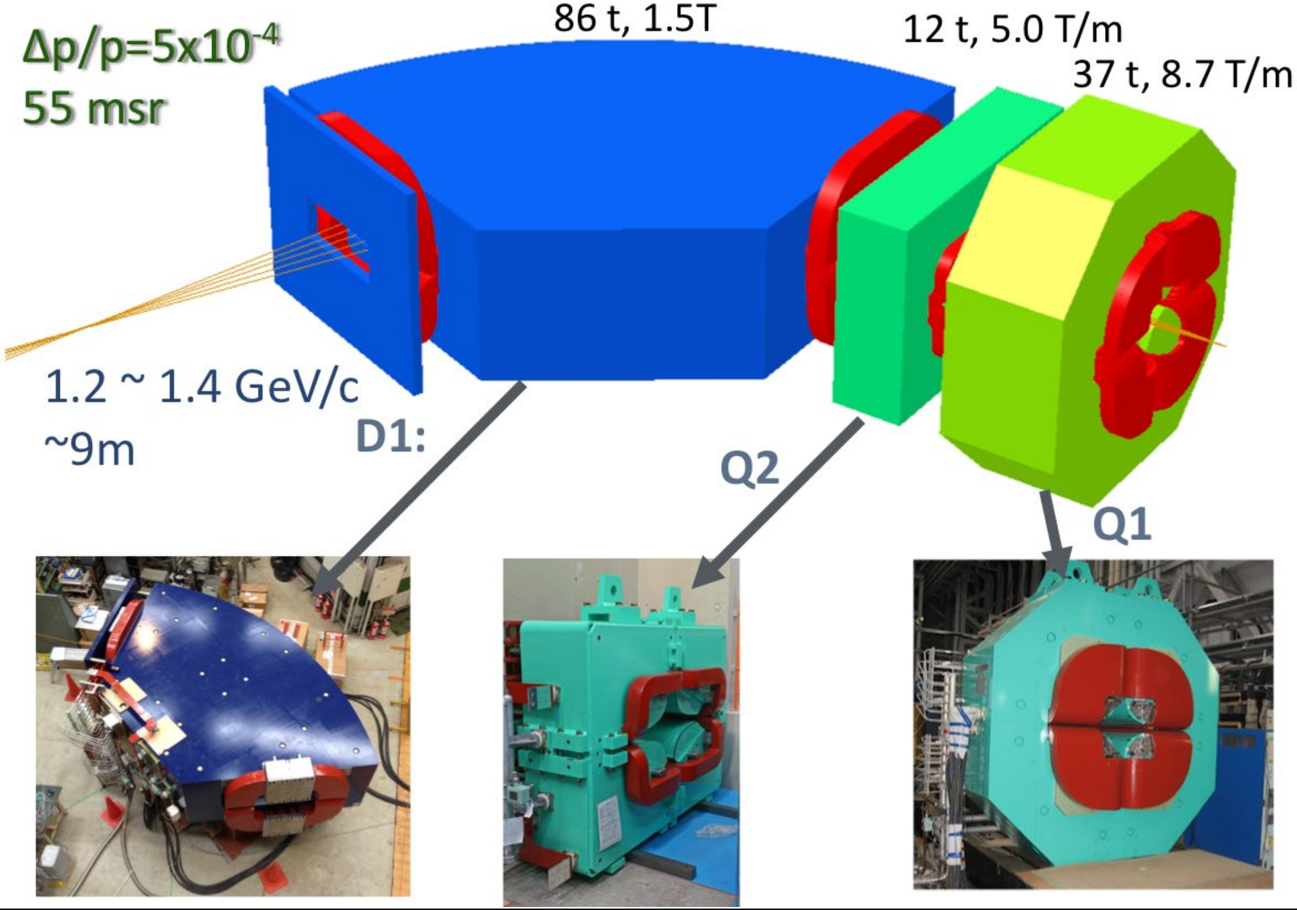
(K^-,K^+) spectroscopy with S-2S at K1.8

ΔM = 2-3 MeV (FWHM)

$\Delta\Omega$ = 55 msr





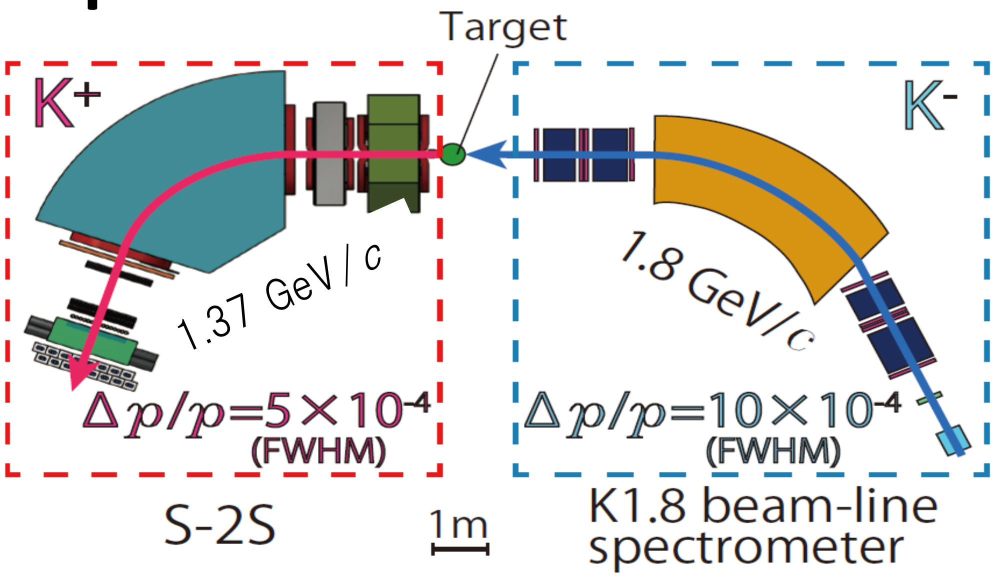


Further investigation of the ΞN interaction with more than ~5 times better resolution

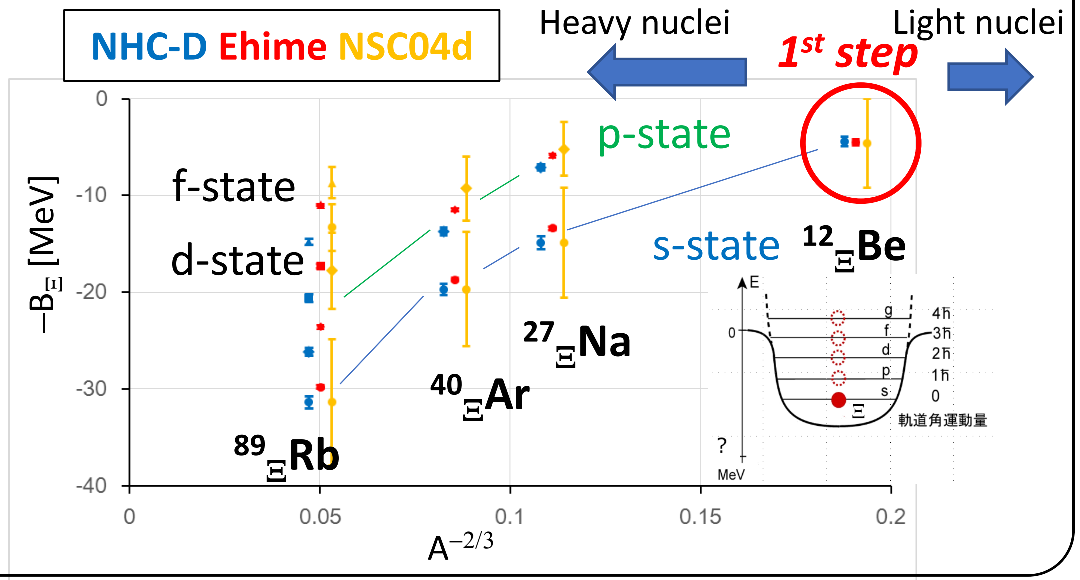
will start in FY2022

S=-2 Physics with S-2S Spectrometer

- **<u>The flagship experiment we have been waiting for at J-PARC</u>**
- The first Ξ-hypernuclei 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 from now on



Calculated Ξ binding energy (and width)



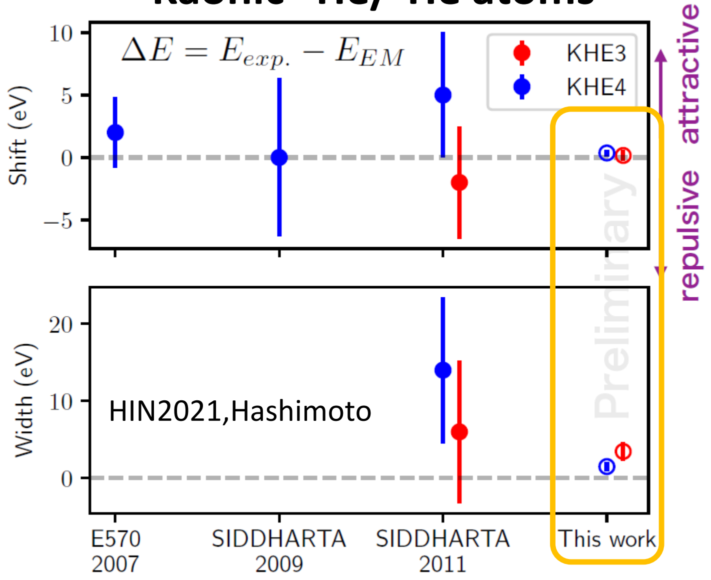
$^{12}_{\Xi}$Be	$^{7}_{\Xi}$H, $^{5}_{\Lambda\Lambda}$H	middle-heavy system
E70	**E75**	**New Exps.**
FY2022-23	FY2024-	FY2024-
1st step	***2nd step***	***3rd, 4th …***

Recent Achievements: Hadron

- **Kaonic atoms**: precise measurement of kaonic-^{3}He/^{4}He atoms (E62)
- **Λ(1405)**: line shape of $K^-N \rightarrow \pi\Sigma$ channel (E31)
- **Kaonic nuclei**: observation of “K^-pp” state (E15/E27)

K-atom **E62, 2021**

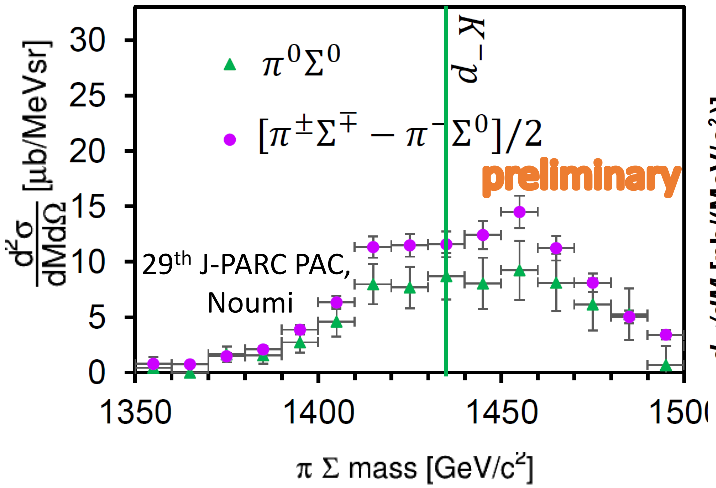
Kaonic-^{3}He/^{4}He atoms



Isospin dependence of the $K^{bar}N$ interaction

Λ(1405) **E31, 2021**

$\pi\Sigma$ line shape of $K^-N \rightarrow \pi\Sigma$

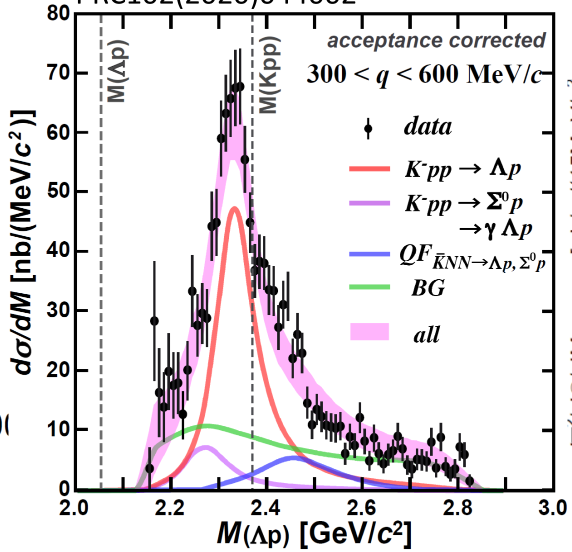


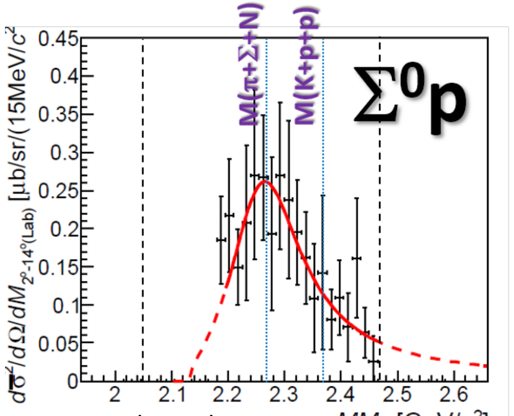
$K^{bar}N$ interaction below the threshold

K-nuclei **E15, 2020** **E27, 2015**

“K^-pp” bound state

PRC102(2020)044002





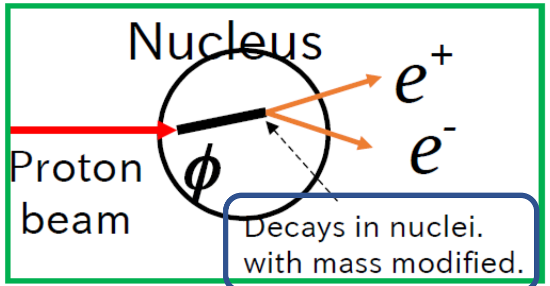
PTEP(2015)021D01

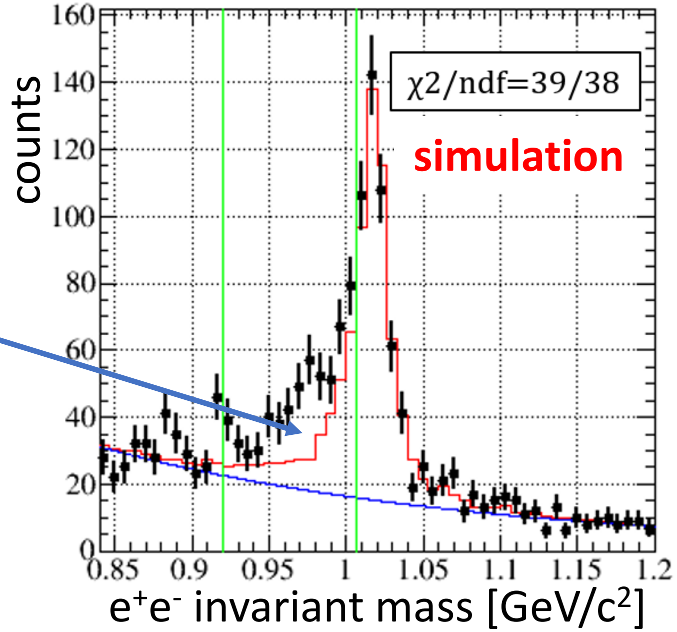
kaon properties in nuclear media

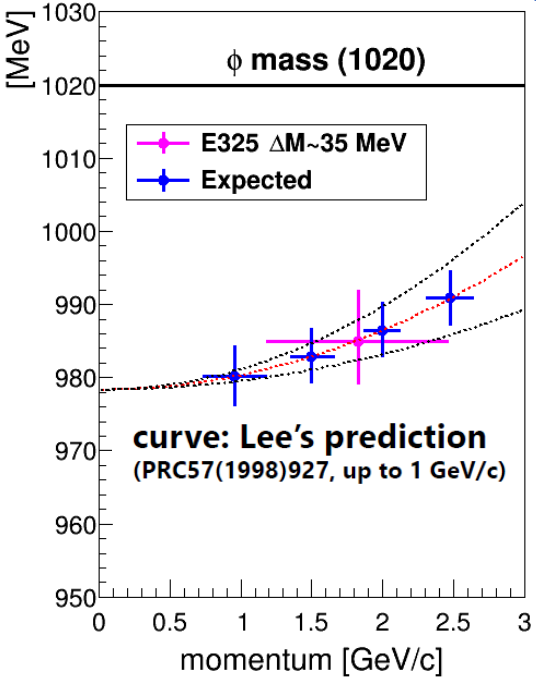
Present Status: Hadron

E16: ϕ-meson in nuclei

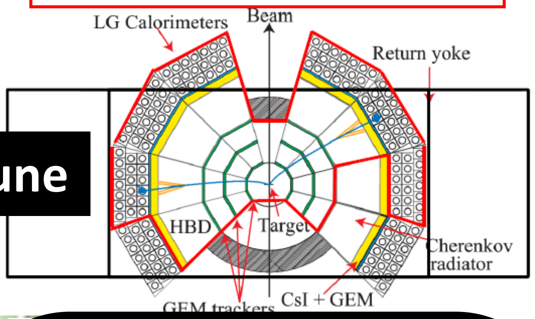
30 GeV primary proton

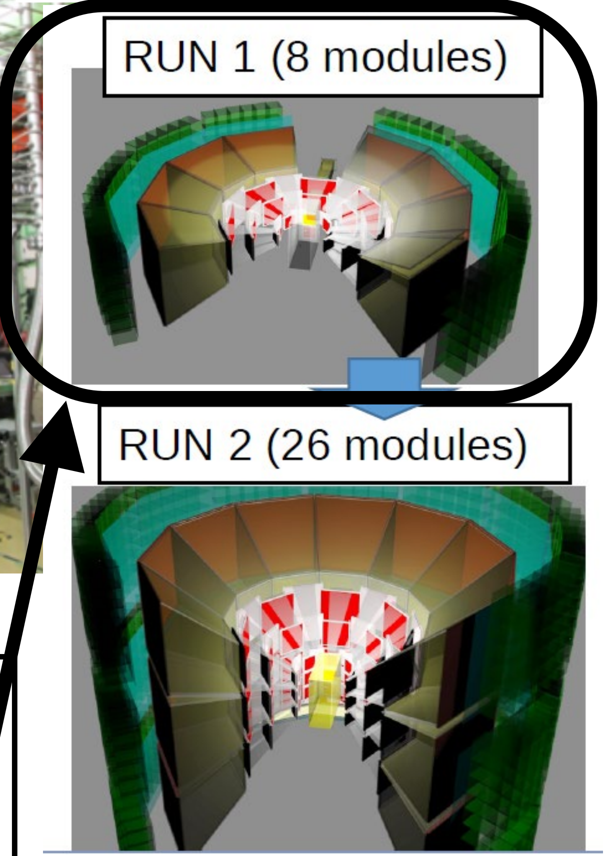






Run0: Completed in June





establish the spectral change of ϕ meson

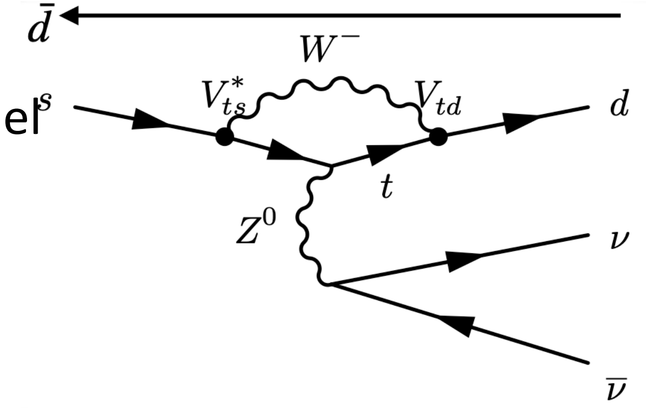
- **100 times as large statistics as the previous exp.**
- **$\langle \bar{s}s \rangle_\rho$, dispersion relation**

Run1 will start in FY2022

Recent Achievements: Flavor Physics

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

- Directly break CP symmetry
- Suppressed in the Standard Model
  - Branching ratio $\sim 3\times10^{-11}$
- Small theoretical uncertainties ($\sim$2%)

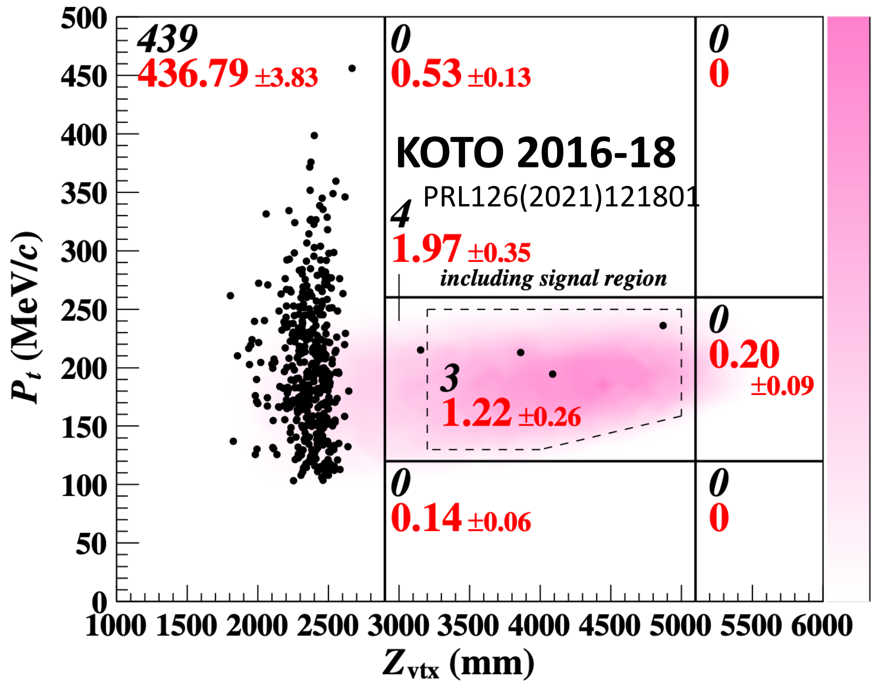


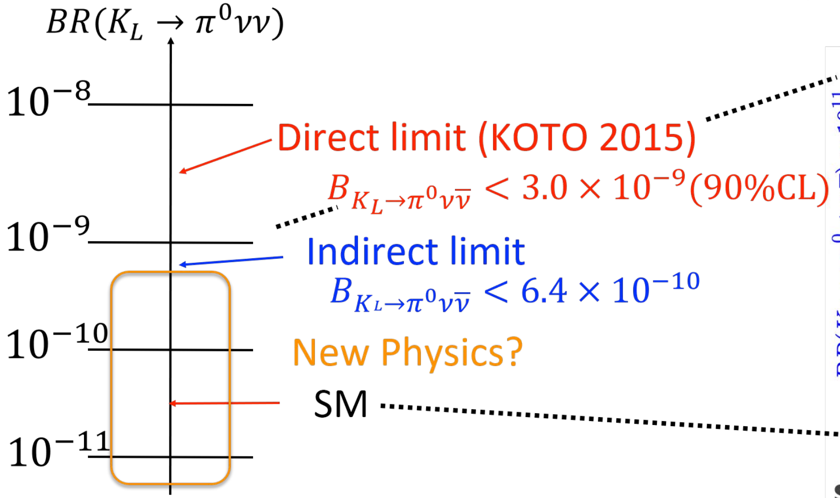
KOTO, 2021

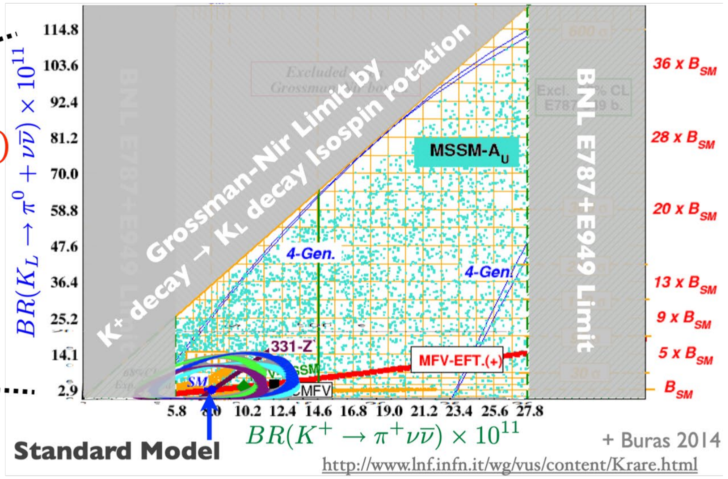
Single Event Sensitivity = $(7.20 \pm 0.05_{stat} \pm 0.66_{syst}) \times 10^{-10}$

Final PT vs Z plot

Black: observed, Red: expected BG, Contour: signal MC



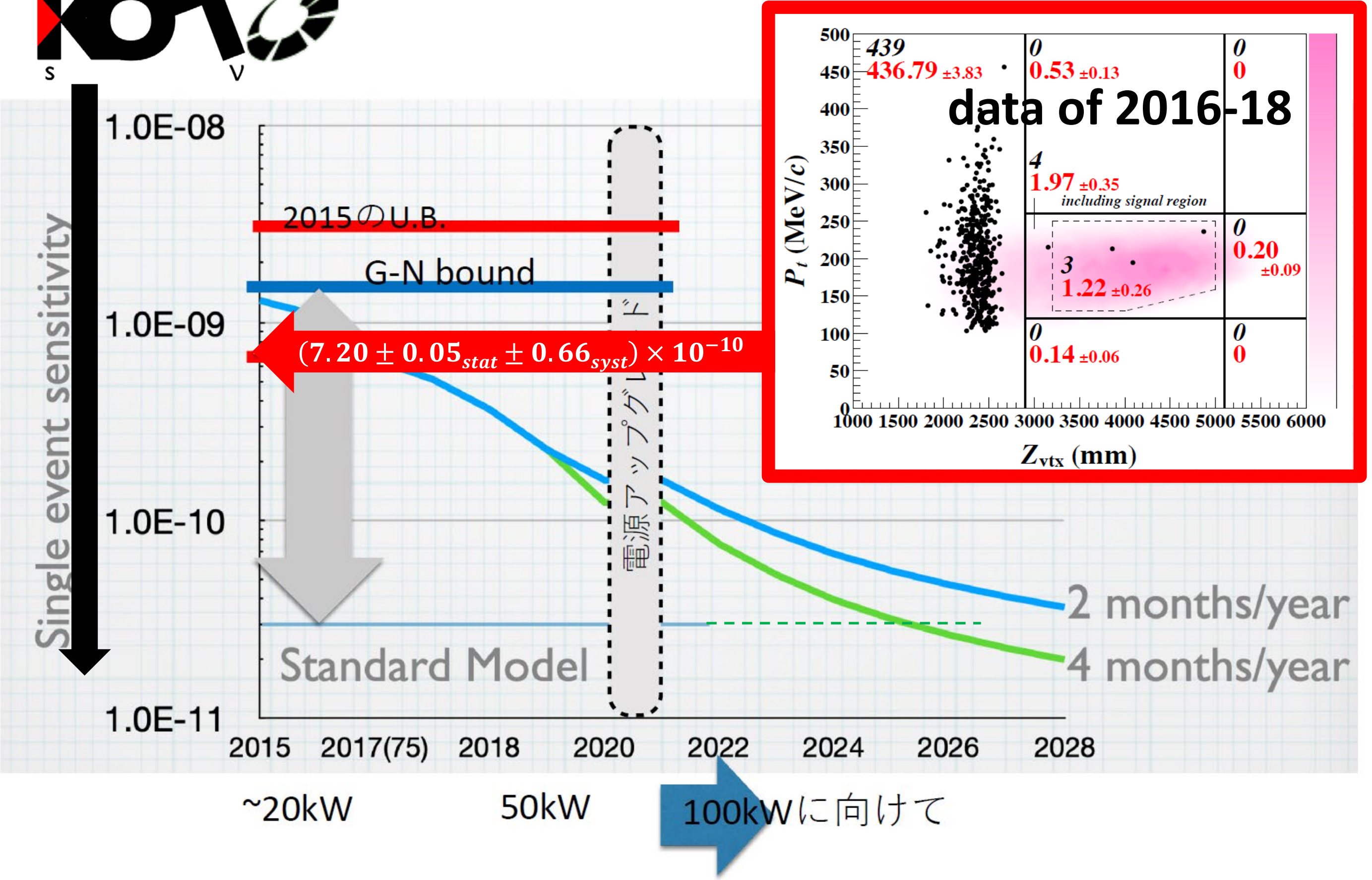




$N_{observed}$ (=3) is statistically consistent with N_{BG} (=1.22±0.26).

Present Status: Flavor Physics

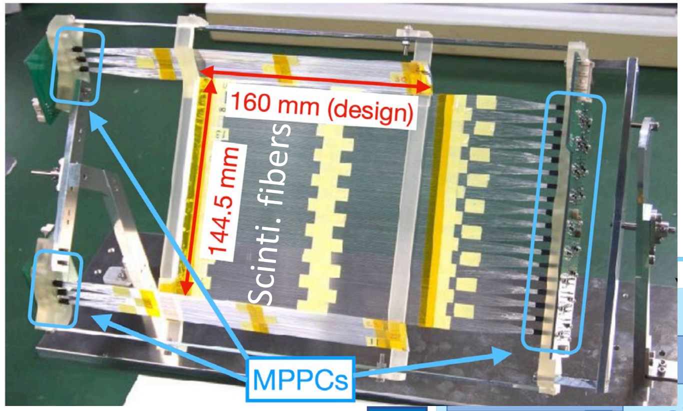
KOTO: $K_L^0 \to \pi^0 \nu \bar{\nu}$

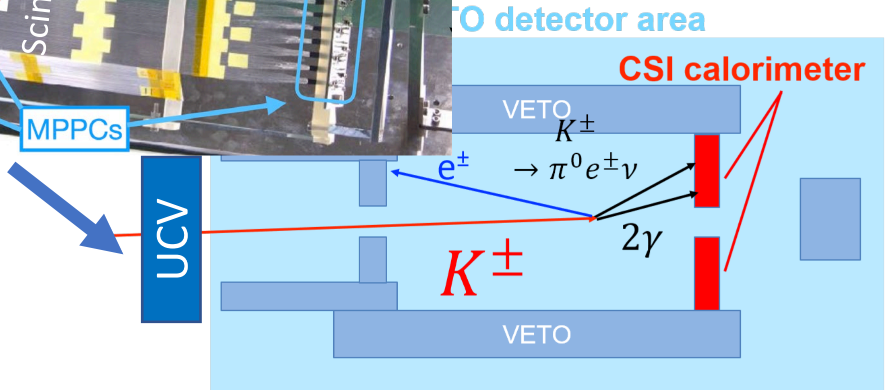


Background Table	Number of events
$K_L \to 3\pi^0$	0.01 ± 0.01
$K_L \to 2\gamma$ (beam halo)	0.26 ± 0.07[a]
Other K_L decays	0.005 ± 0.005
$K^{\pm}$	0.87 ± 0.25[a]
Hadron cluster	0.017 ± 0.002
CV η	0.03 ± 0.01
Upstream π^0	0.03 ± 0.03
	1.22 ± 0.26

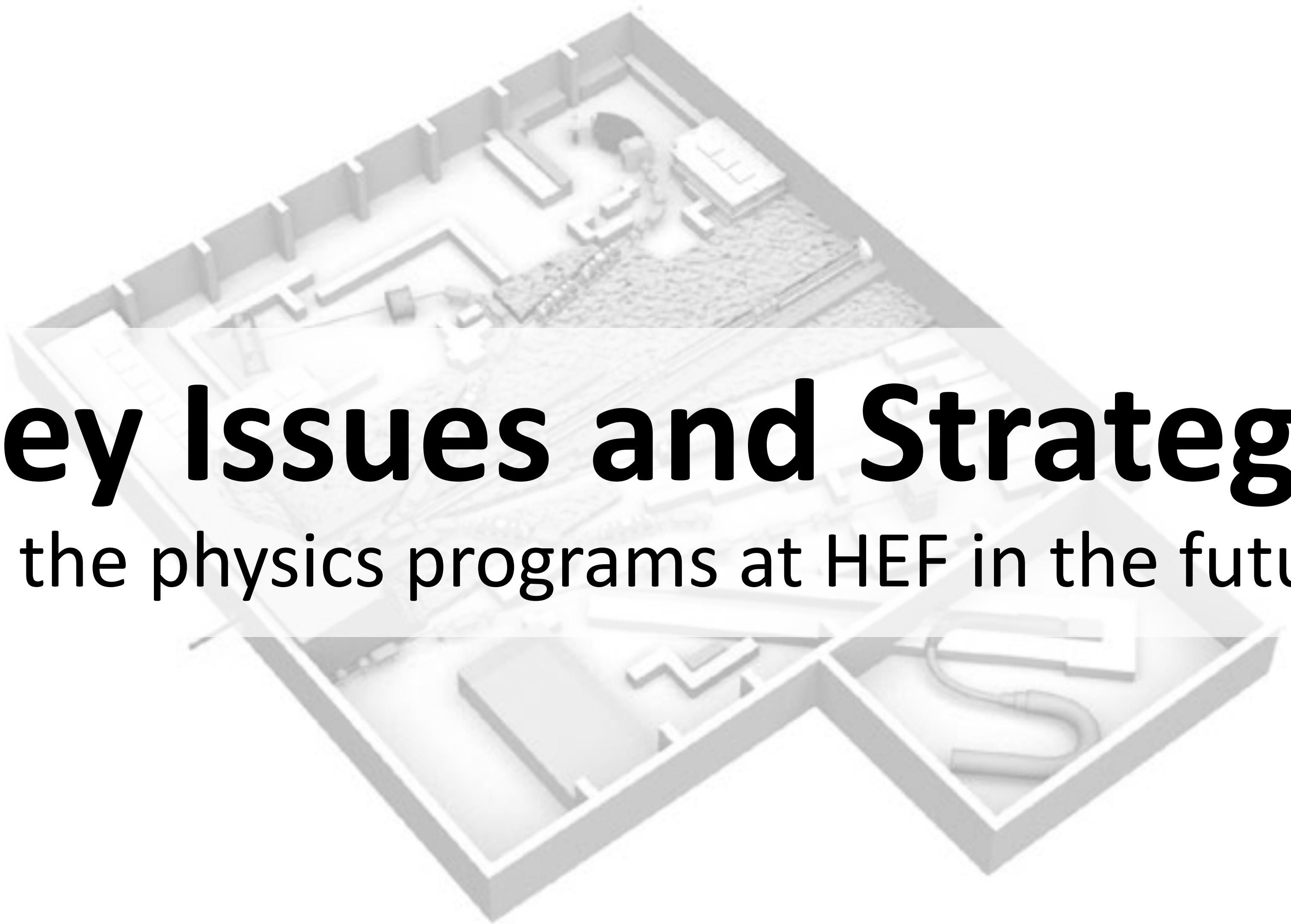
$K^{\pm} \to \pi^0 e^{\pm} \nu$ is the most serious contributor.

Upstream Charged Veto (UCV)





will continue data taking toward the SM sensitivity

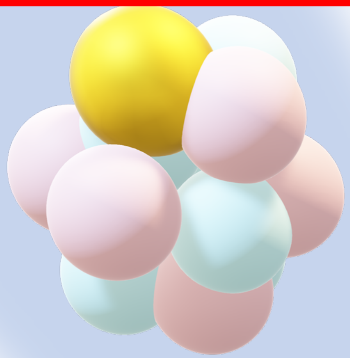


Key Issues and Strategy

for the physics programs at HEF in the future

Origin & Evolution of Matter

Matter in Extreme Conditions

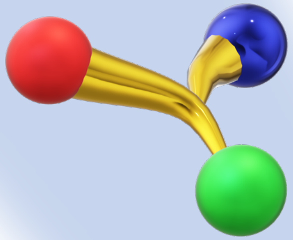


hyperon puzzle in neutron stars

flavor symmetry breaking
hadron interaction
formation of a nucleus

Hypernuclei spectroscopy
YN scattering

Matter Evolution

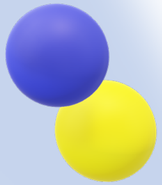


fundamental structure of matter

chiral symmetry breaking
quark interaction

Hadron spectroscopy
Meson in nuclei

Birth of Matter



matter dominated universe

CP symmetry violation
weak interaction

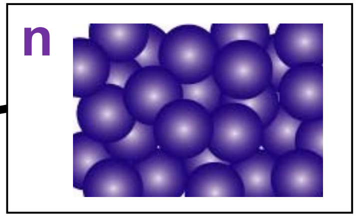
Kaon decays

Neutron Star Matter and YN/YNN Interactions

Key Issue

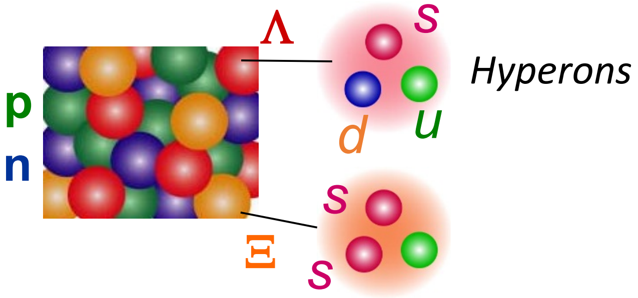
"Hyperon Puzzle"

Neutron Matter

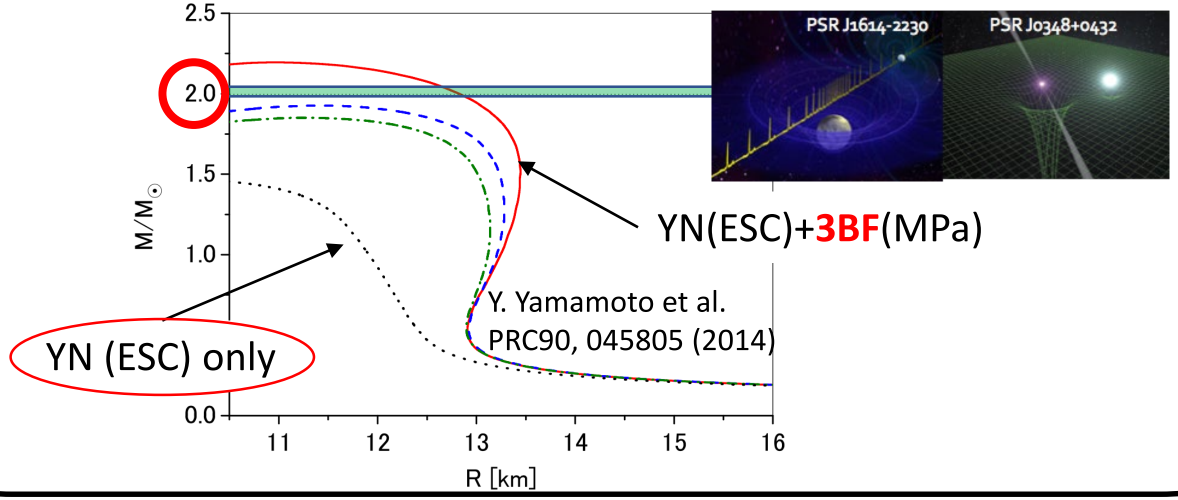


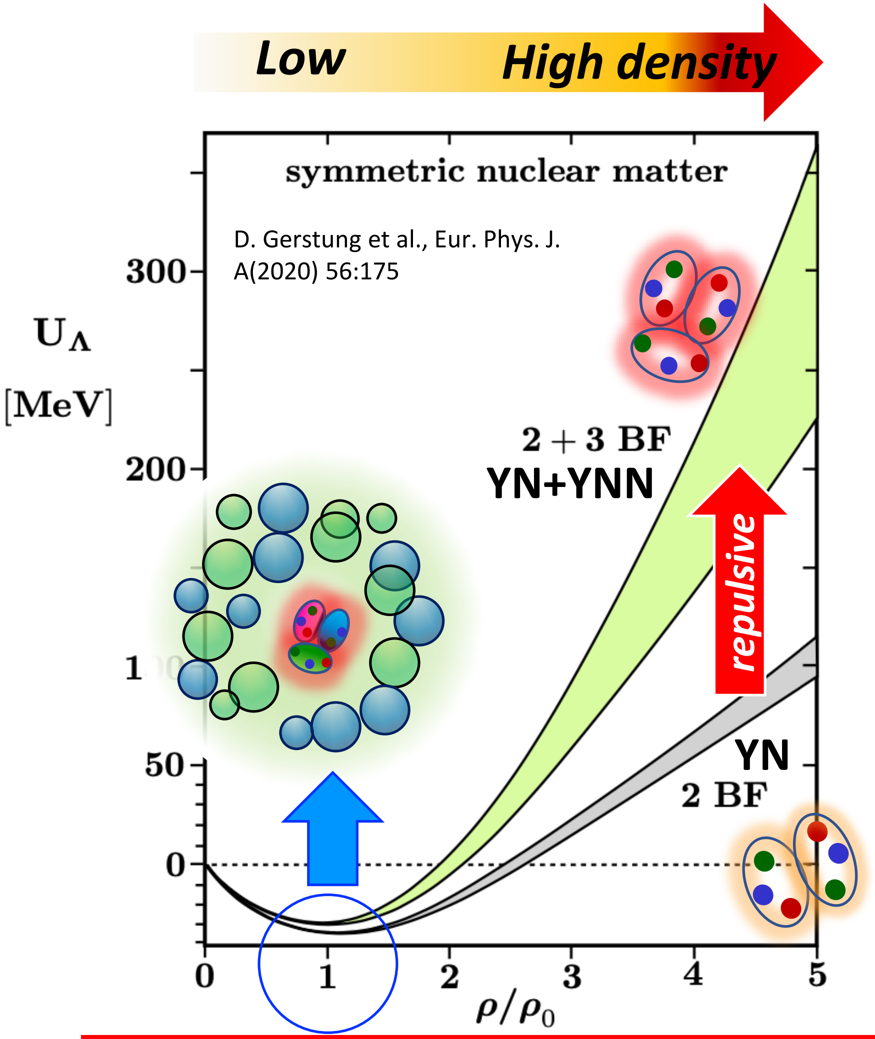
Strange Hadronic Matter ?

Hyperons should appear



Softening of EOS w/ hyperon appearance





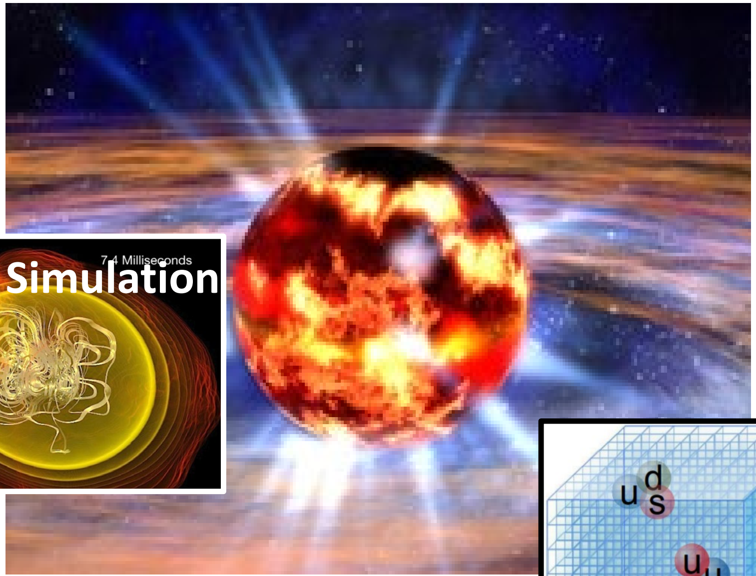
3 Baryon Force (3BF) is a key:

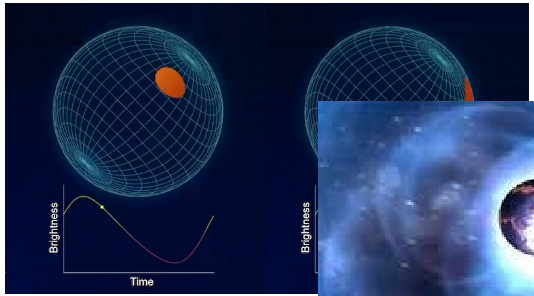
Significant repulsive contribution at high density

How to attack neutron star?

Macroscopic approach

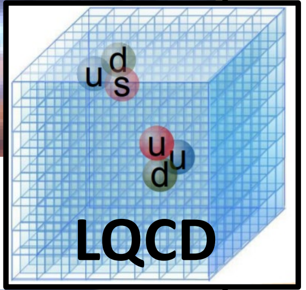
- **Astronomical observation**
- **Gravitational-wave observation**
  - Mass and radius
- **Theoretical models**
  - Structure, evolution, ..

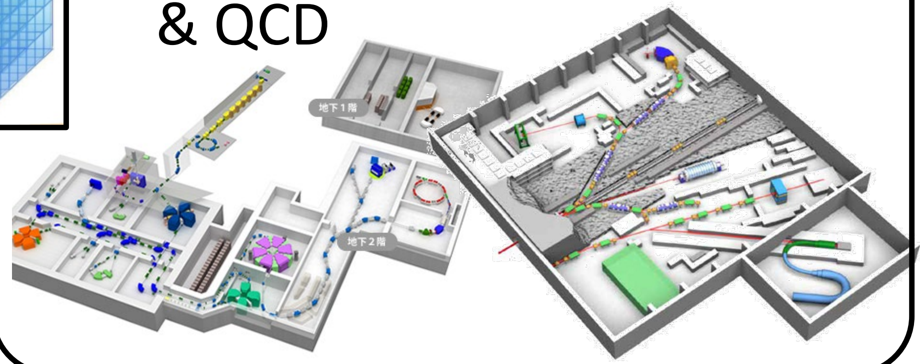




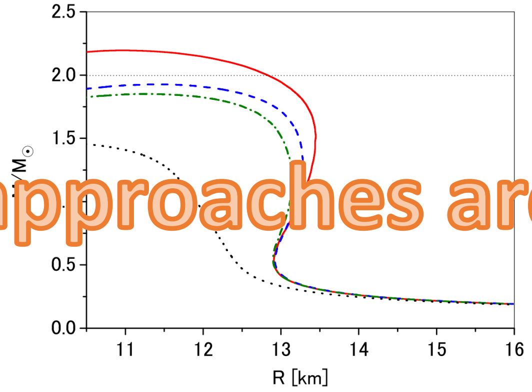
Microscopic approach

- **Experimental nuclear physics**
  - Density dependent BB/BBB interactions (including Y)
- **Theoretical models**
  - Realistic interaction models based on experimental data & QCD





Equation Of State



Give constraints in macroscale of 10^4 m

Both two approaches are essential

Provide answers in microscale of 10^{-15} m

We Have Provided **a lot of** Information on NS Matter

- **Λ potential → U_Λ = -30 MeV, attractive**
  - From Λ-hypernuclei
  - Start point of "hyperon puzzle"
- **Σ potential → U_Σ ~ +30 MeV, repulsive**
  - From Σ production in nuclei / Σp scattering
  - Exp. method of YN scattering established
- **Ξ potential → U_Ξ = ??, attractive**
  - From emulsion data
  - Just beginning to understand
- **New insight of the ΛN-ΣN conversion**
  - From charge symmetry breaking of Λ-hypernuclei
  - Theoretical models should be reconsidered
- **Theoretical improvement**
  - High-density matter EOS has been improved by nuclear theories
  - Effective Field Theories (EFT) will be improved based on experimental data from J-PARC
  - YN/YY/ΞN interactions have been calculated by LQCD

We need precise data more & more!

- **Kaon condensation??**
  - From observation of the deeply bound "K$^-$pp" state

Negative particles likely to appear in NS compared to neutral ones

Σ^- is repulsive

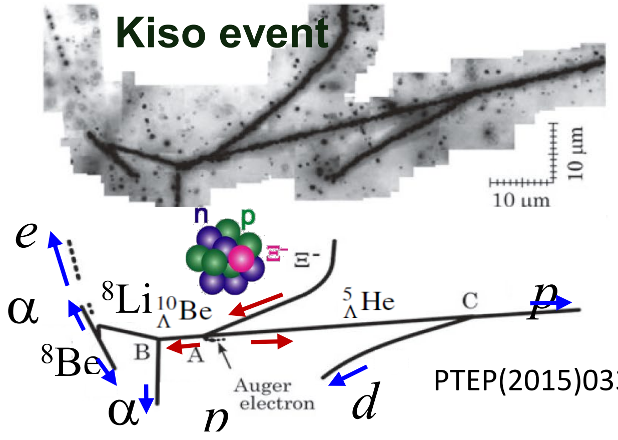
→

Ξ^- is the next key

S-2S@present HEF

(K$^-$ is also important)

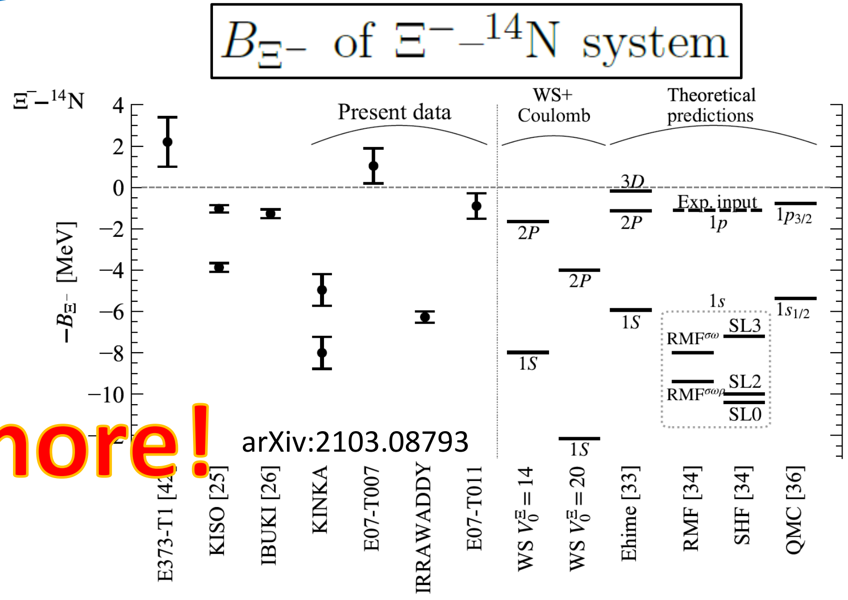
The first clear Ξ hypernucleus



PTEP(2015)033D02

Ξ^- + ^{14}N -> $_{\Xi}{}^{15}$C -> $_{\Lambda}{}^{10}$Be + $_{\Lambda}{}^{5}$He

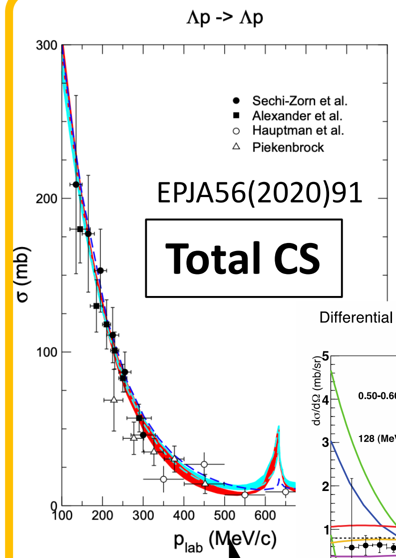
Attractive ΞN interaction was established

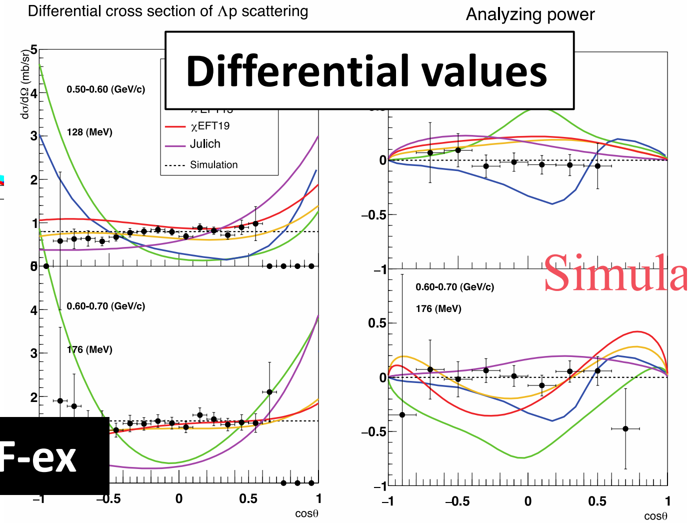


Elucidation of Neutron Star Matter from Nuclear Physics

A tiny fraction of 3 Baryon Force effect is essential

We need
- **Realistic YN interaction model**
- Precise Λ binding energy for wide-mass range for **density dependence of ΛN interaction** → **ΛNN interaction**

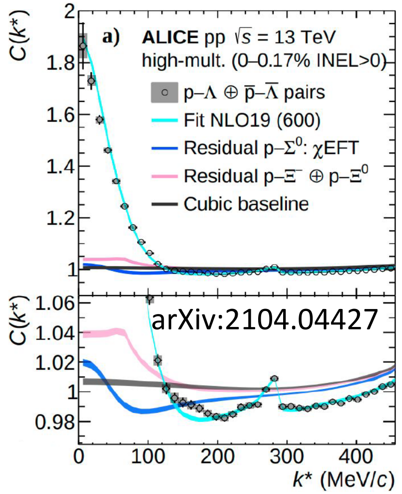




More accurate YN scattering data

K1.1@HEF-ex

Femtoscopy at HIC



Ξ-hyp @ S-2S
ΛN @ High-p

input input input

Realistic BB interaction model

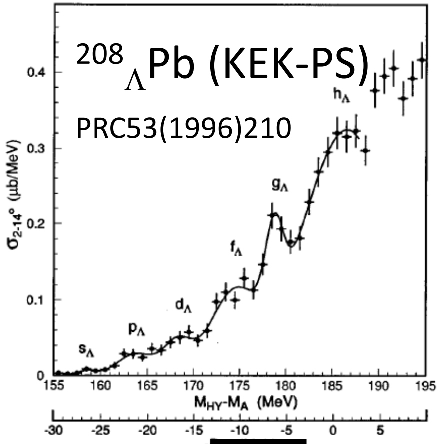
SU(3) Chiral EFT, Nijmegen models

Potential from LQCD

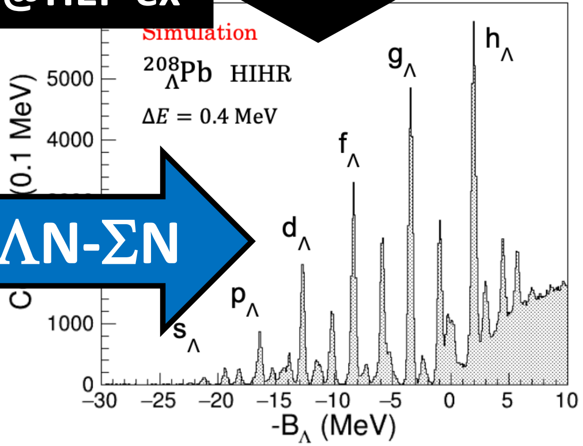
Theoretical calculation of Λ single-particle energies

EOS, Neutron star matter

Much higher-resolution Λ spectroscopy



HIHR@HEF-ex

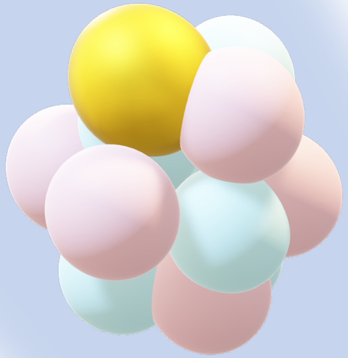


ΛNN, ΛN-ΣN

and γ-ray spectroscopy

Origin & Evolution of Matter

Matter in Extreme Conditions



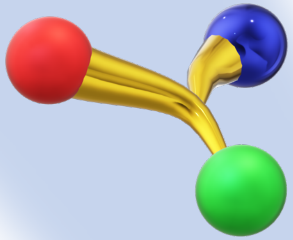
hyperon puzzle in neutron stars

flavor symmetry breaking
hadron interaction
formation of a nucleus

Hypernuclei spectroscopy
YN scattering

Matter Evolution

fundamental structure of matter

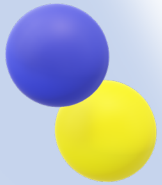


chiral symmetry breaking
quark interaction

Hadron spectroscopy
Meson in nuclei

Birth of Matter

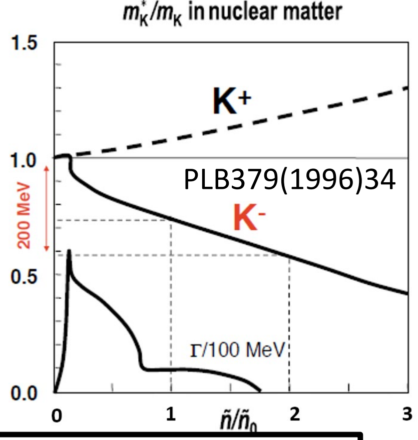
matter dominated universe



CP symmetry violation
weak interaction

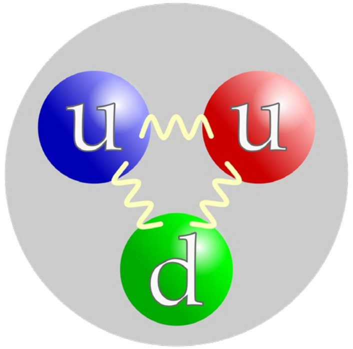
Kaon decays

Hadron Physics @ J-PARC



@ present HEF

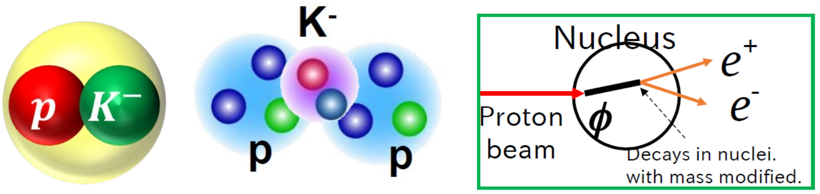
Explore low-E (non-pert.) QCD
- ➢ **Confinement of Hadron**
- ➢ **Chiral Symmetry Breaking**



π20/K10@HEF-ex

Meson properties in nuclei

- Investigation of meson properties has been proceeded at present HEF, using high-intensity kaon beam
  - $K^{bar}N - \pi\Sigma - \Lambda(1405)$
  - Kaonic atoms/nuclei
  - (ϕ meson in nuclei, now launched)

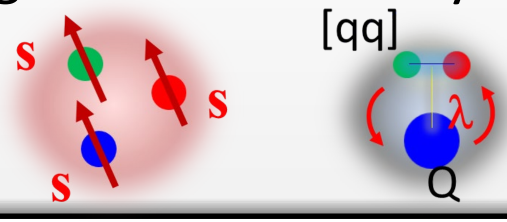


Expand physics to baryon

Key Issue Baryon structure

- Still no clear answer to "**How quarks build baryons?**"
- **Dynamics of non-trivial QCD vacuum in baryon structure** is a key
- comprehensive and systematic studies of **"detailed" baryon spectroscopy**

strange and charm baryons

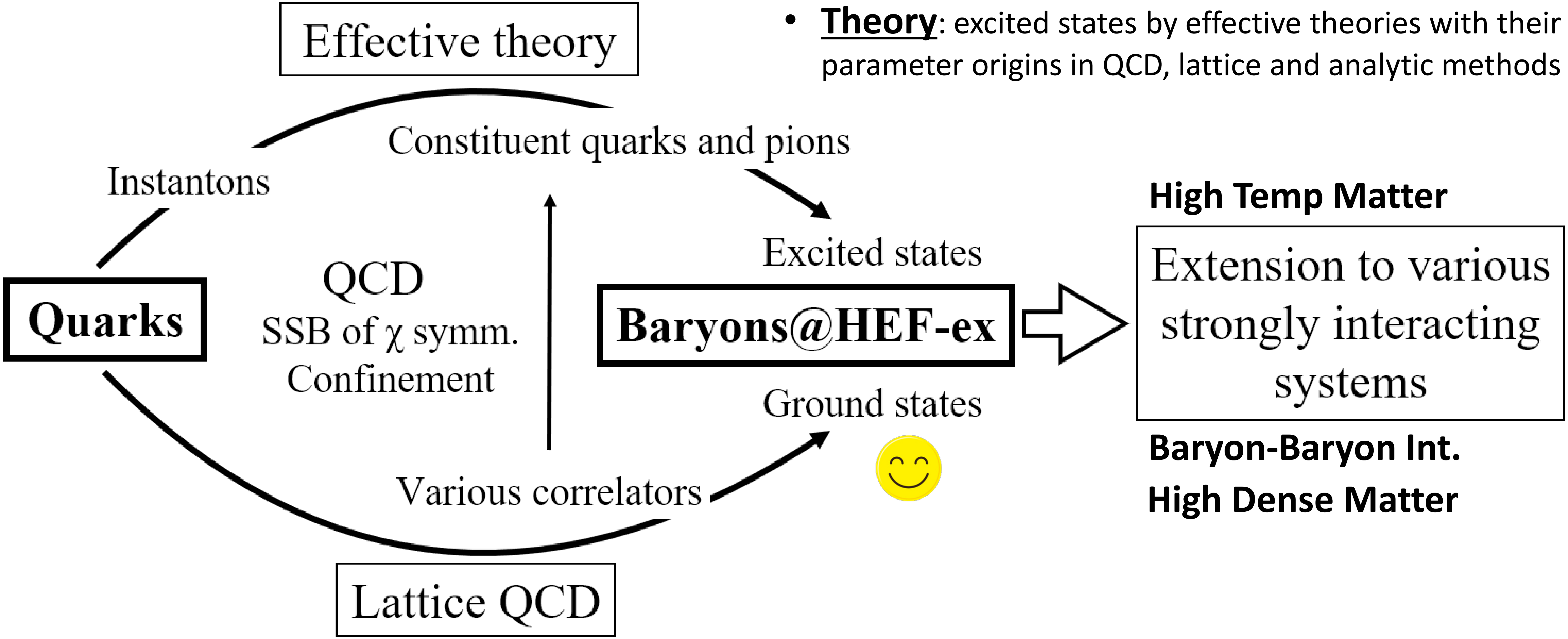


exotic hadron searches in *s*-sector

- Θ^+ penta-quark baryon
- *H*-dibaryon

Baryon Spectroscopy

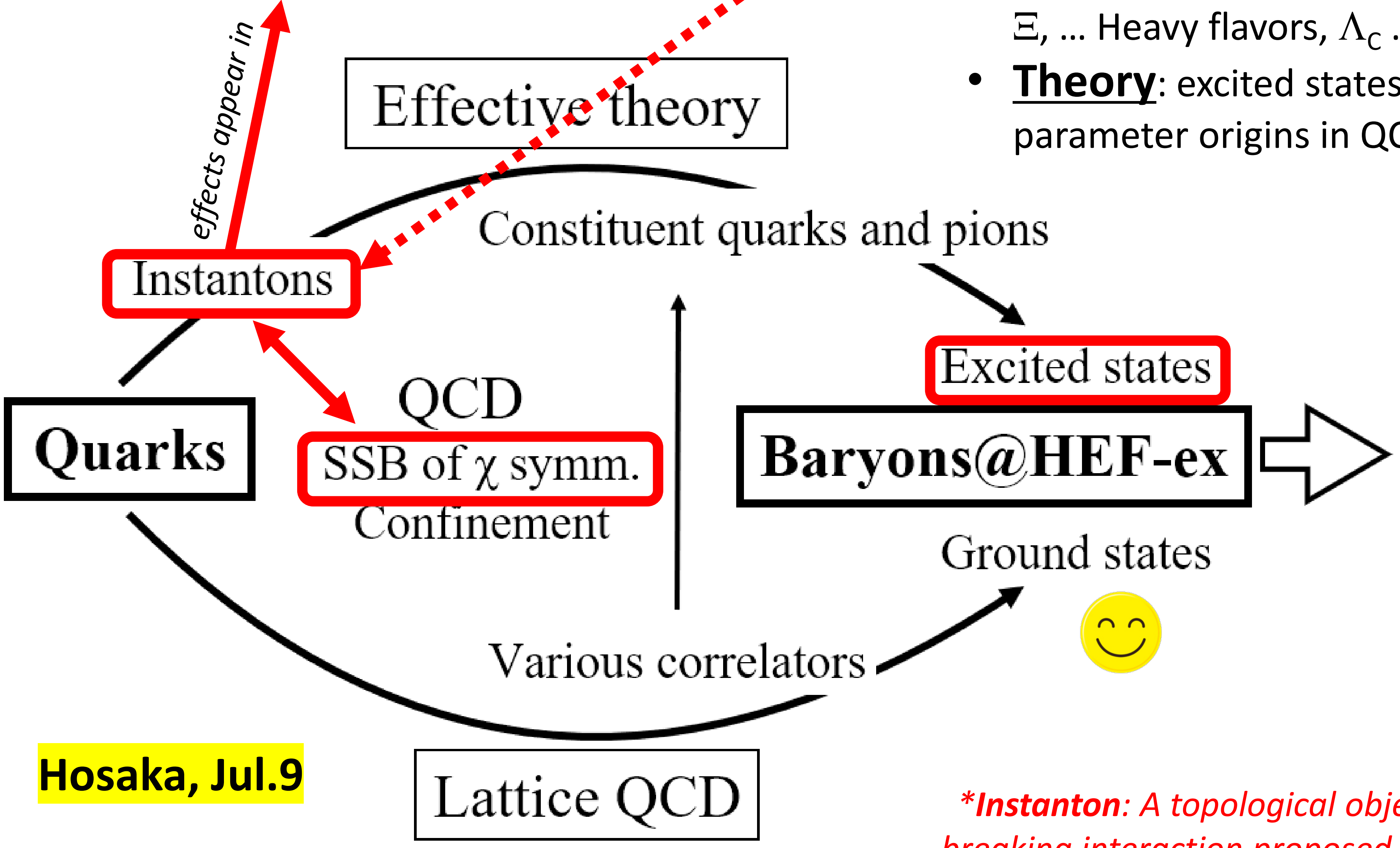
- **Experiment**: Spectroscopy with many strangeness, Ω, Ξ, … Heavy flavors, Λ_C …
- **Theory**: excited states by effective theories with their parameter origins in QCD, lattice and analytic methods



Dynamics of non-trivial QCD vacuum

- **Diquark correlation**
- **Spin-dependent force**
- **Quark motion**

- **Experiment**: Spectroscopy with many strangeness, Ω, Ξ, … Heavy flavors, Λ_C …
- **Theory**: excited states by effective theories with their parameter origins in QCD, lattice and analytic methods



High Temp Matter

Extension to various strongly interacting systems

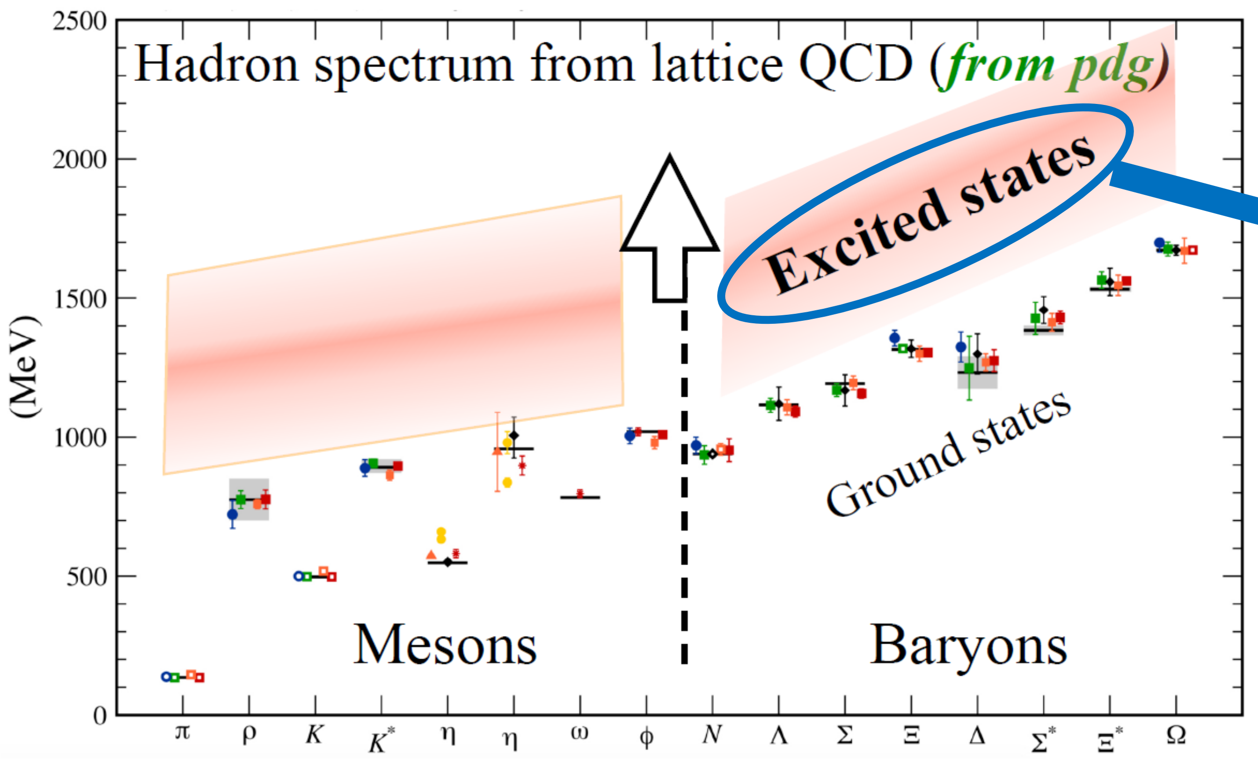
Baryon-Baryon Int.

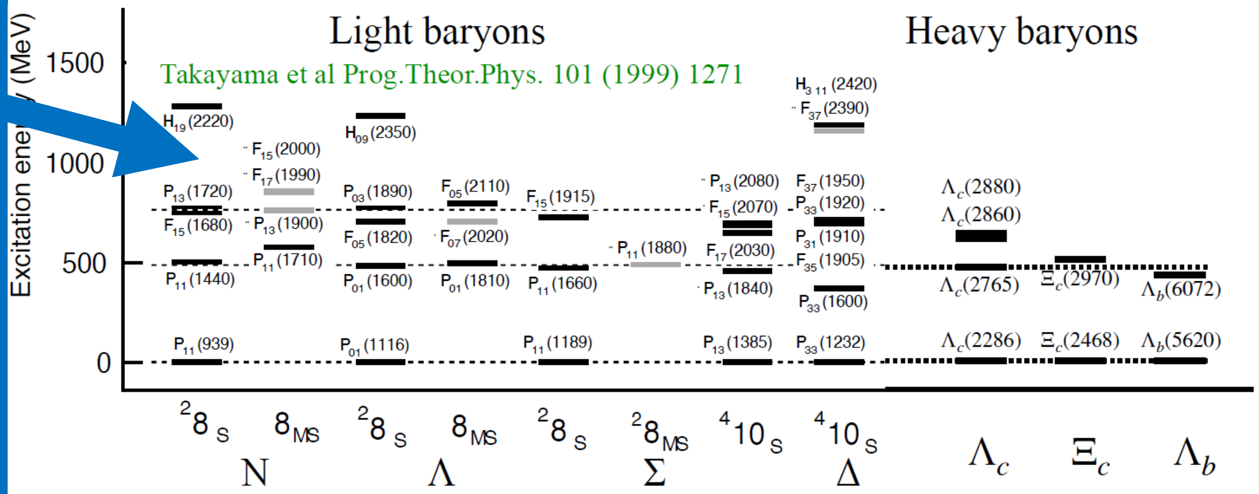
High Dense Matter

Hosaka, Jul.9

**Instanton*: A topological object of gluon that mediates the $U_A(1)$ breaking interaction proposed by Kobayashi, Maskawa, and ’t Hoot*

Importance of Baryon Spectroscopy





The spectrum shows systematic behavior

➢ Natural to expect a **simple** mechanism originated from low-energy QCD

In Lattice QCD:

- Ground states are well reproduced
- Many unsolved/unconfirmed issues in excited states
  (due to the complexity → a breakthrough is needed)

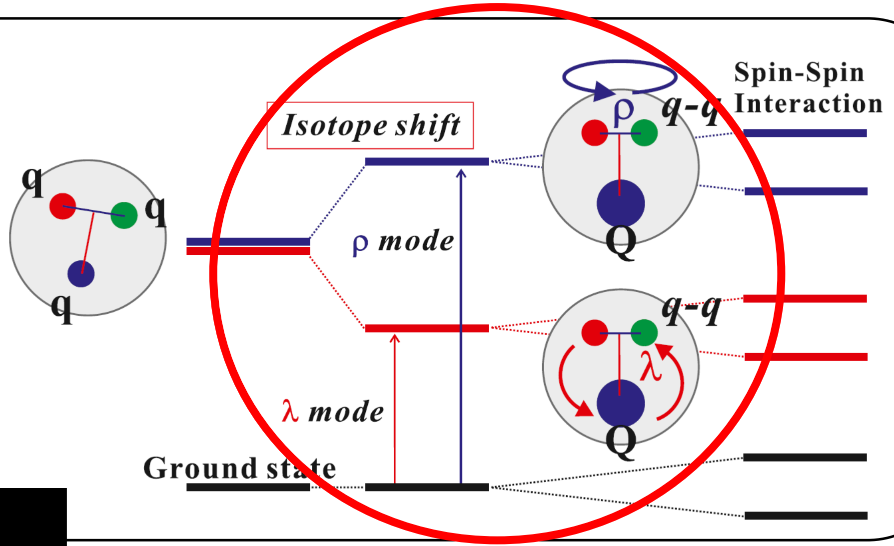
excited baryons clarify quark-gluon dynamics

Baryon Spectroscopy @ Extended HEF

1st step

- With high-momentum π (K) beam, by modifying the existing high-p beamline (mass-unseparated, π20)
  - Λ_c **spectroscopy → diquark correlation**
  - Basic investigation of ground state Ω → elementally cross section

p(π^-,D*$^-$)X

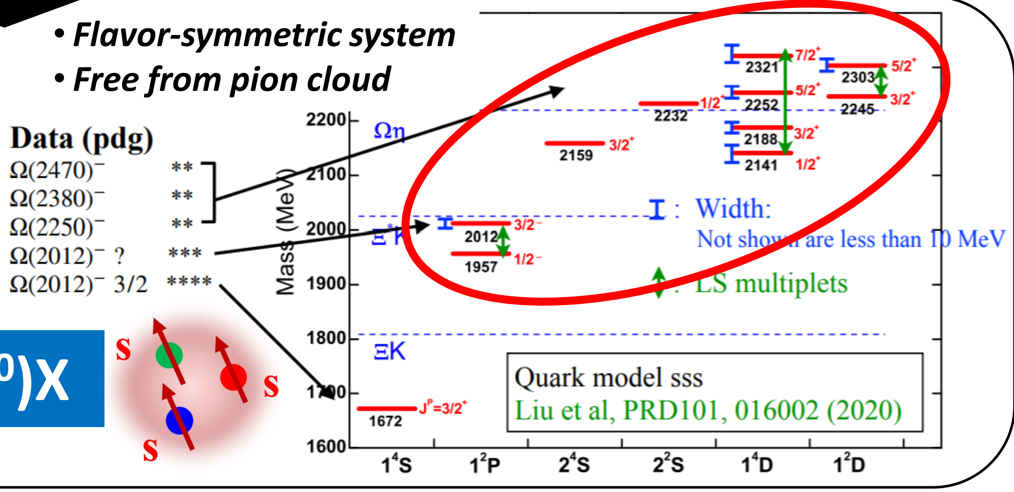


2nd step

- With high-momentum mass-separated K beam, by constructing a new beamline (K10)
  - Ω **spectroscopy → spin dependent force, quark motion**
  - ΩN bound state search

p(K$^-$, K$^+$K*^{0})X

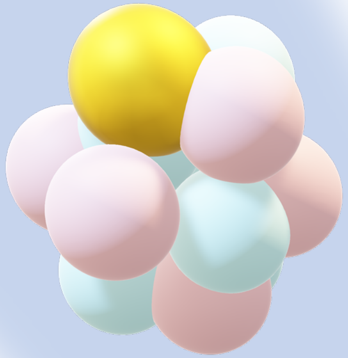
- *Flavor-symmetric system*
- *Free from pion cloud*



dynamics of non-trivial QCD vacuum in baryon structure

Origin & Evolution of Matter

Matter in Extreme Conditions

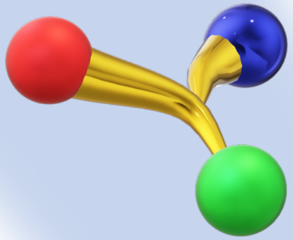


hyperon puzzle in neutron stars

flavor symmetry breaking
hadron interaction
formation of a nucleus

Hypernuclei spectroscopy
YN scattering

Matter Evolution



fundamental structure of matter

chiral symmetry breaking
quark interaction

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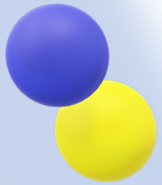
Meson in nuclei

Birth of Matter



matter dominated universe

CP symmetry violation
weak interaction

Kaon decays

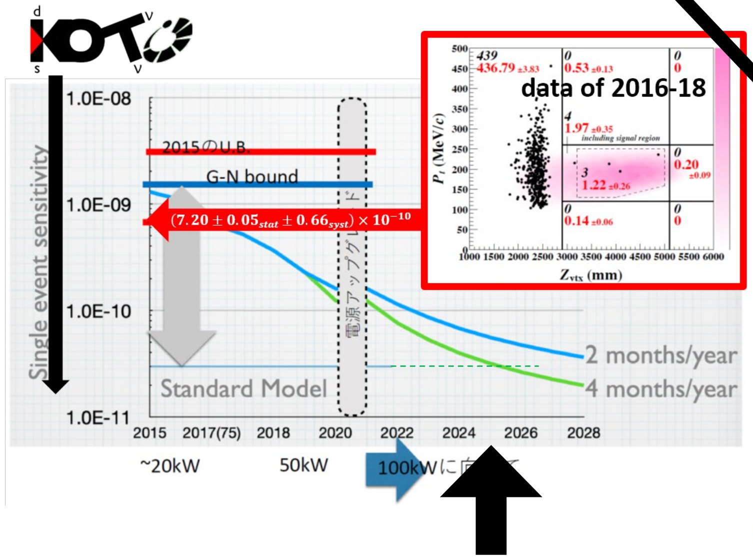
Toward New Physics: Flavor Physics

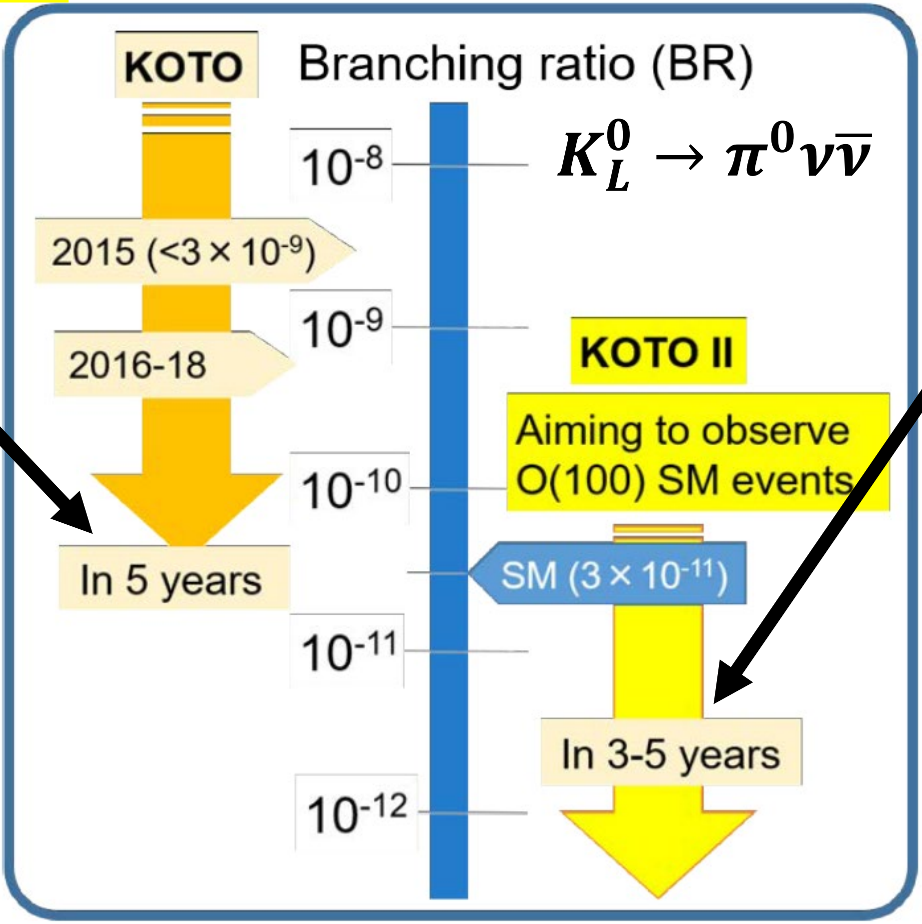
- So far, no clear evidence of new physics beyond the SM from direct searches
- **Flavor physics in intensity frontier** plays an important role more and more

Key Issue

@ present HEF **KOTO:**

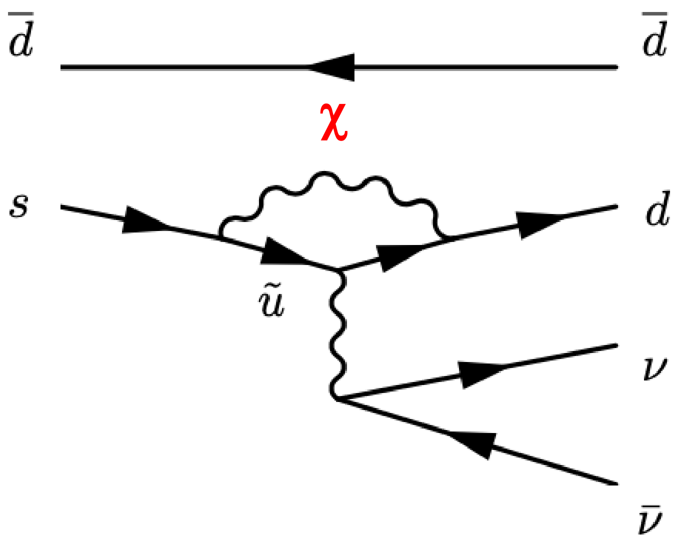
- Will reach the sensitivity of $O(10^{-11})$ around FY2025





KOTO Step2: **KL2@HEF-ex**

- Will explore the region beyond the SM



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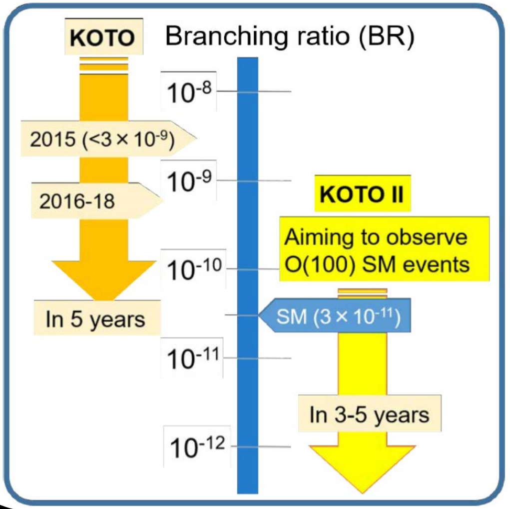
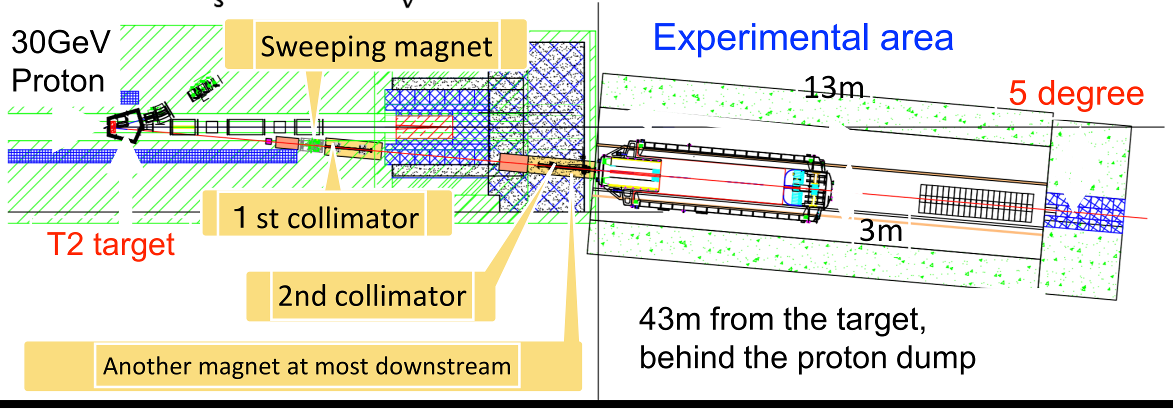
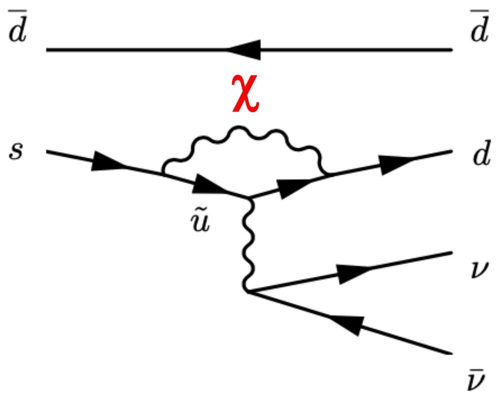
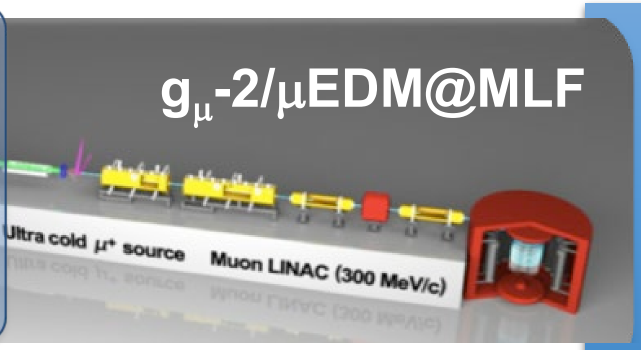
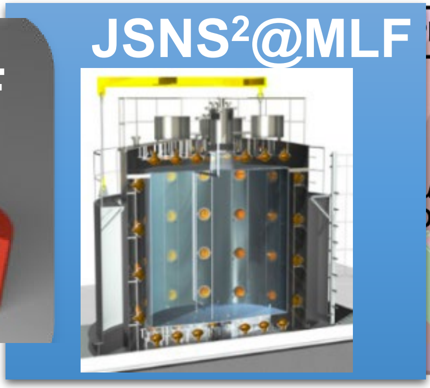


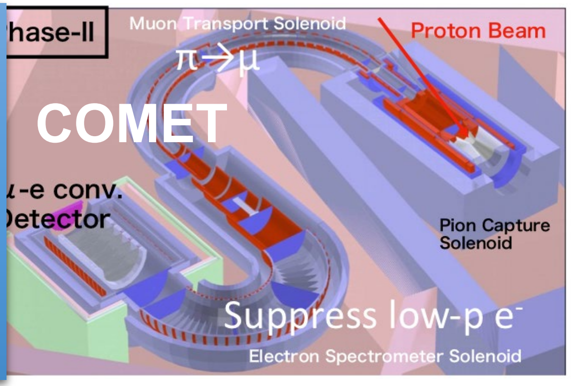
Step2 **KL2@HEF-ex**







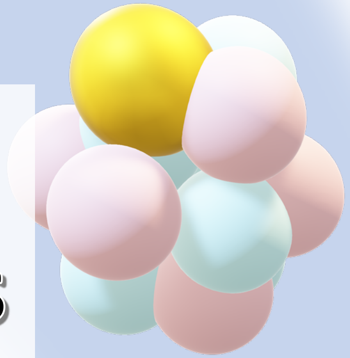




We attack the new physics via various approaches at J-PARC

Goals of the New Project

Strangeness Nuclear Physics

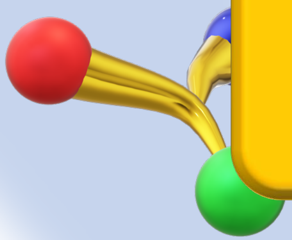


hyperon puzzle in neutron stars

Elucidate neutron star matter from nuclear physics, by solving the hyperon puzzle

Hadron Physics

fundamental structure of matter



Reveal baryon structure built by quarks, through spectroscopic study of *s*- and *c*-baryons

Flavor Physics

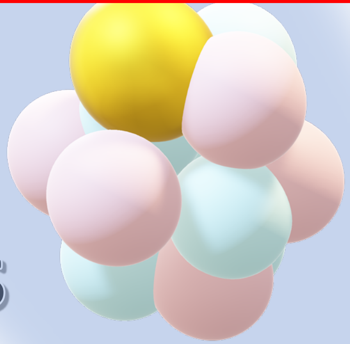
matter dominated univers

Discover new physics beyond the SM, by improving the sensitivities of rare kaon decay searches

Origin & Evolution of Matter

Strangeness Nuclear Physics

hyperon puzzle in neutron stars



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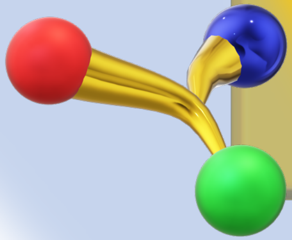
fundamental structure of matter



Flavor Physics

matter dominated universe

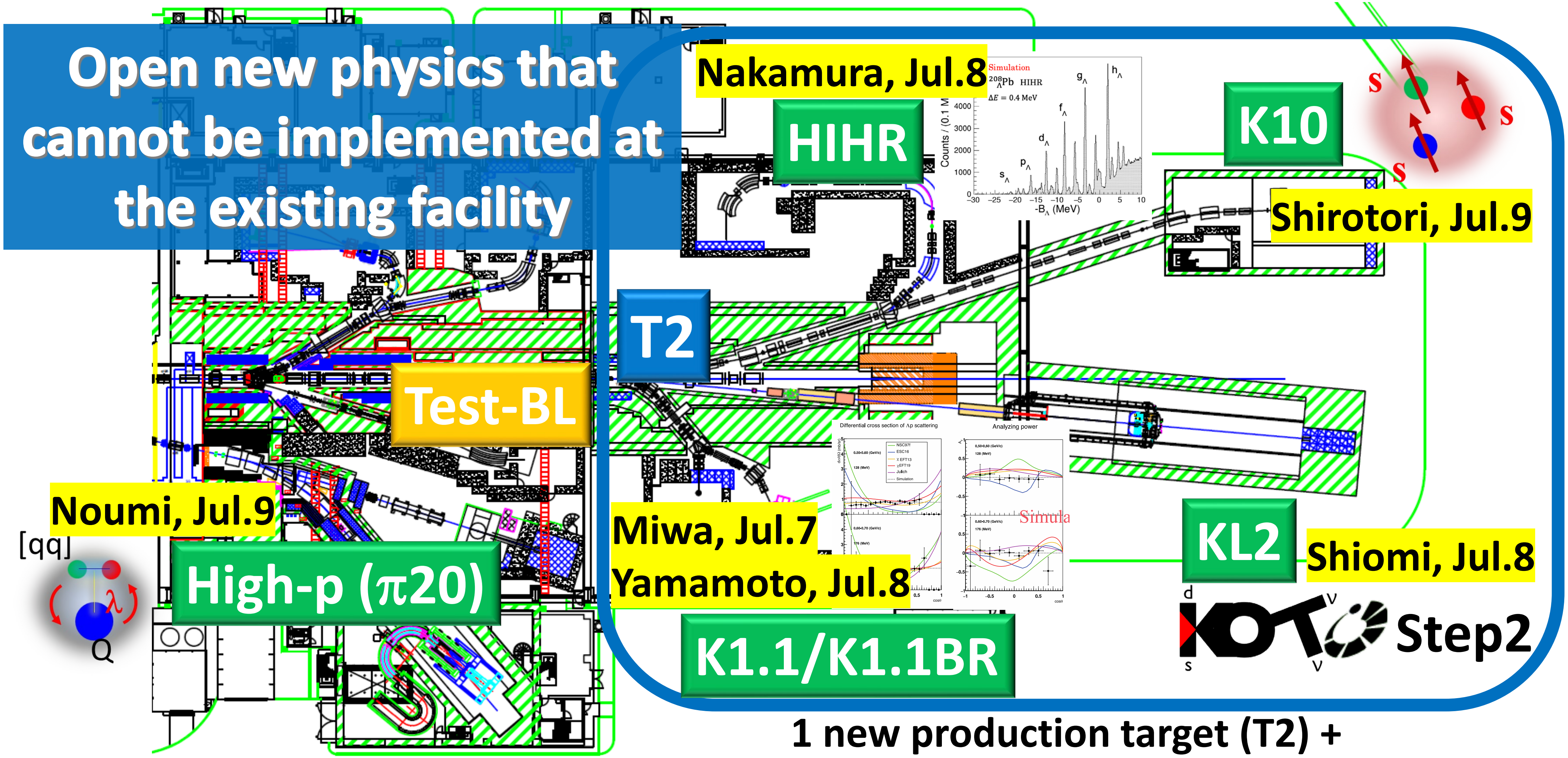
Elucidate neutron star matter from nuclear physics, by solving the hyperon puzzle

Reveal baryon structure built by quarks through spectroscopic study of *s*- and *c*-baryons

Discover new physics beyond the SM by improving the sensitivities of rare kaon decay searches

All programs are indispensable

"Extended" Hadron Experimental Facility is Essential



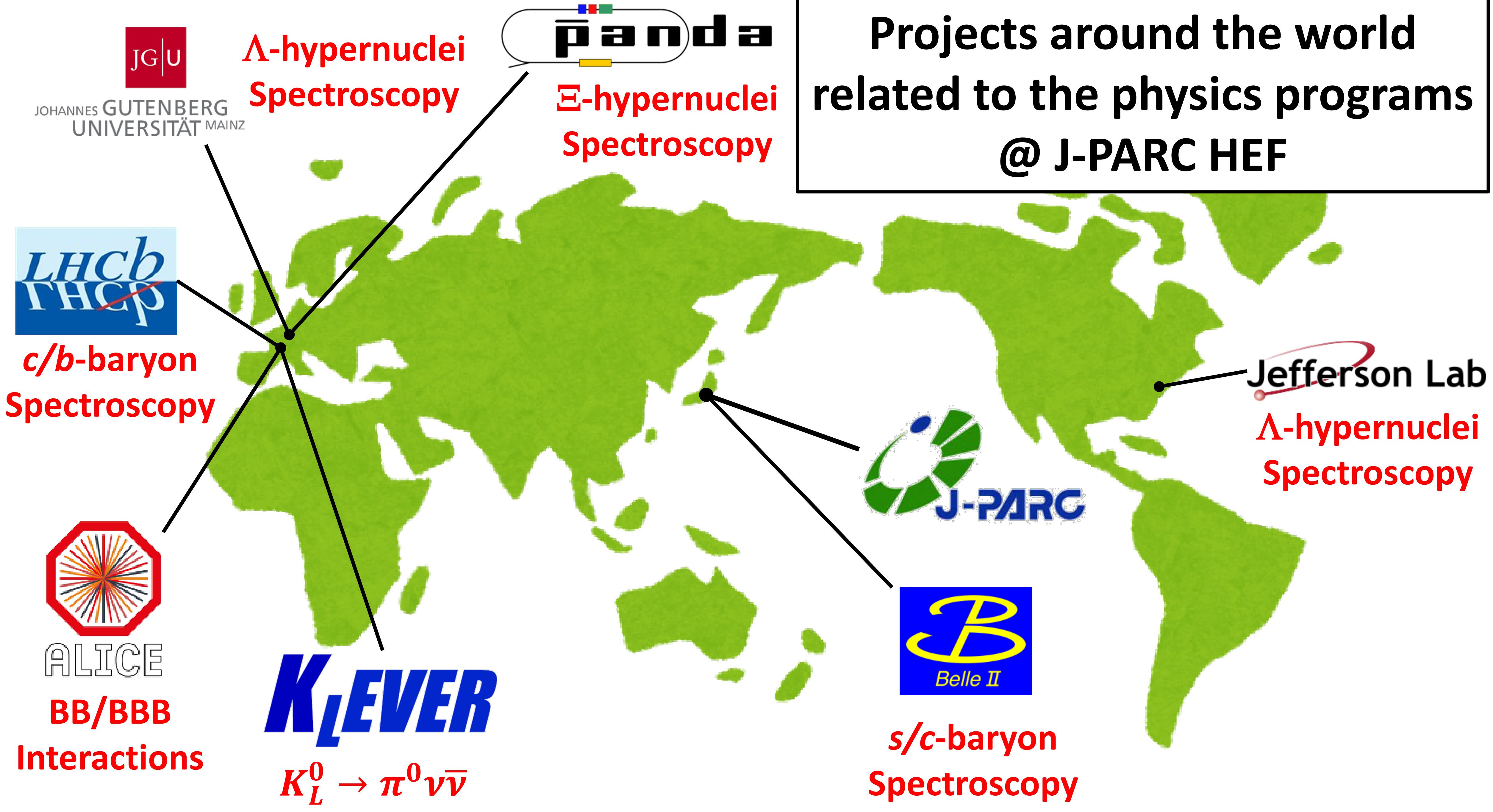
1 new production target (T2) +

4 new beamlines (HIHR, K1.1/K1.1BR, KL2, K10) +

2 modified beamlines (High-p (π20), Test-BL)

Global Situation

Projects around the world related to the physics programs @ J-PARC HEF



Strangeness Physics

Λ-hypernuclei Spectroscopy

BB/BBB Interactions

J-PARC · Jefferson Lab · JOHANNES GUTENBERG UNIVERSITÄT MAINZ

	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

ALICE

- 2-/3-body interactions via femtoscopy
- Huge data-set in Run3 (2022-24) ~
- Sensitive to S-wave (lower-mom. region)

Comple-mentary

More detailed information @ K1.1

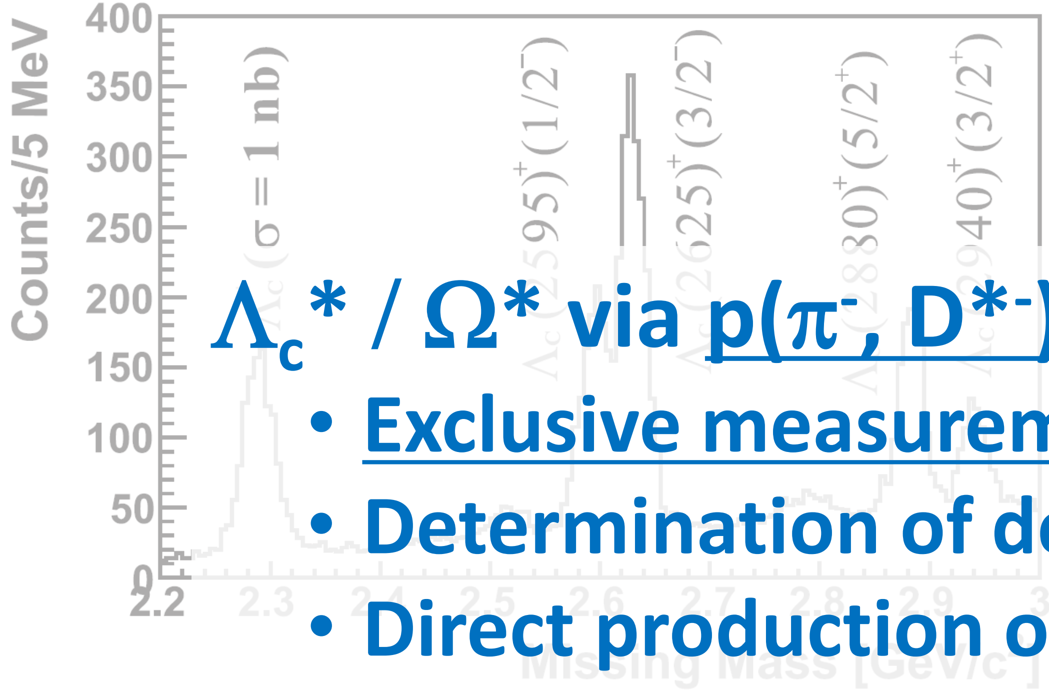
- **differential quantities (dσ/dΩ, etc.)**
- **spin observables**
- **Sensitive to higher partial wave in addition to S-wave**

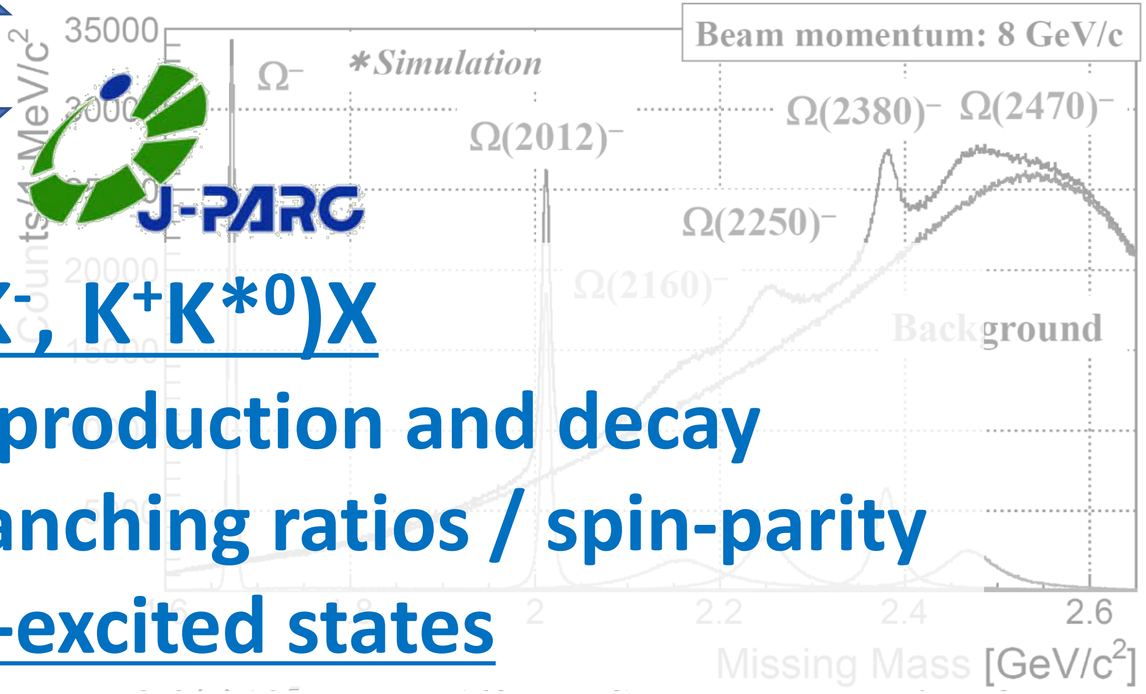
Hadron Physics

***s/c*-baryon Spectroscopy**

- High capabilities of hadron spectroscopy in *c*- and *b*-sectors, via <u>inv. mass reconst.</u>
  - ➢ Ω^* would be difficult to identify in high-π-multiplicity environment

Comple-mentary



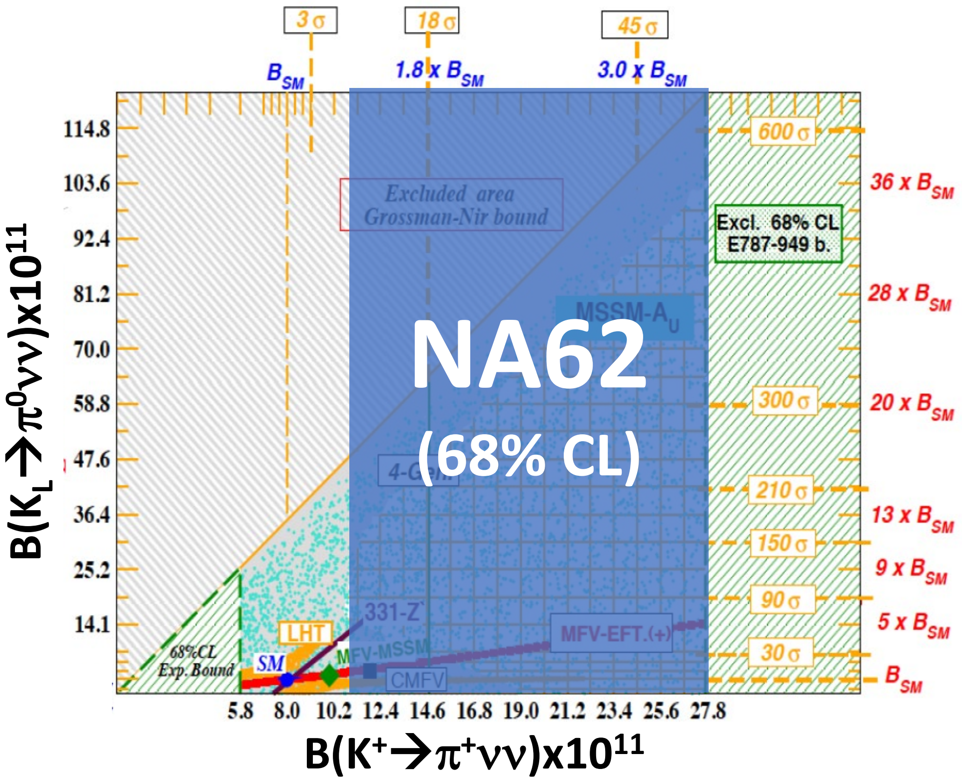


Λ_c^* / Ω^* via <u>$p(\pi^-, D^{*-})X$ / $p(K^-, K^+K^{*0})X$</u>

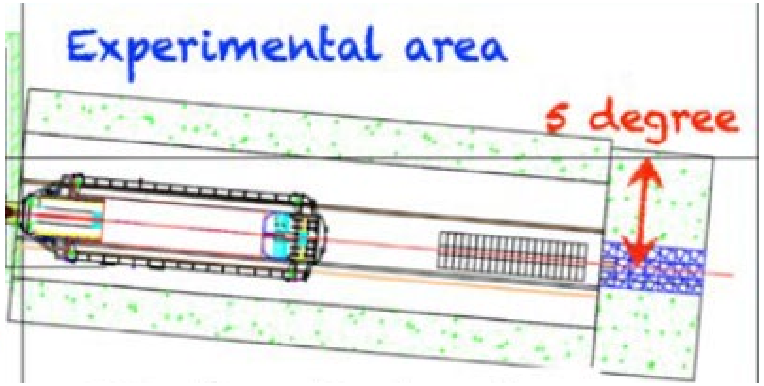
- **<u>Exclusive measurement</u> → production and decay**
- **Determination of decay-branching ratios / spin-parity**
- **Direct production of <u>highly-excited states</u>**

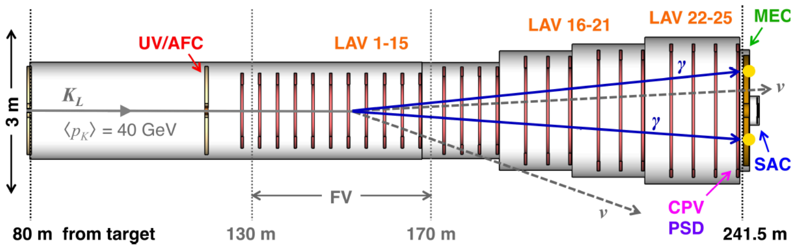
Flavor Physics $K_L^0 \to \pi^0 \nu \bar{\nu}$

- 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.
- KLEVER@CERN: $K_L^0 \to \pi^0 \nu \bar{\nu}$ search is planned as the next of NA62
  - aiming to start in LHC Run 4 (2027-)



Step2

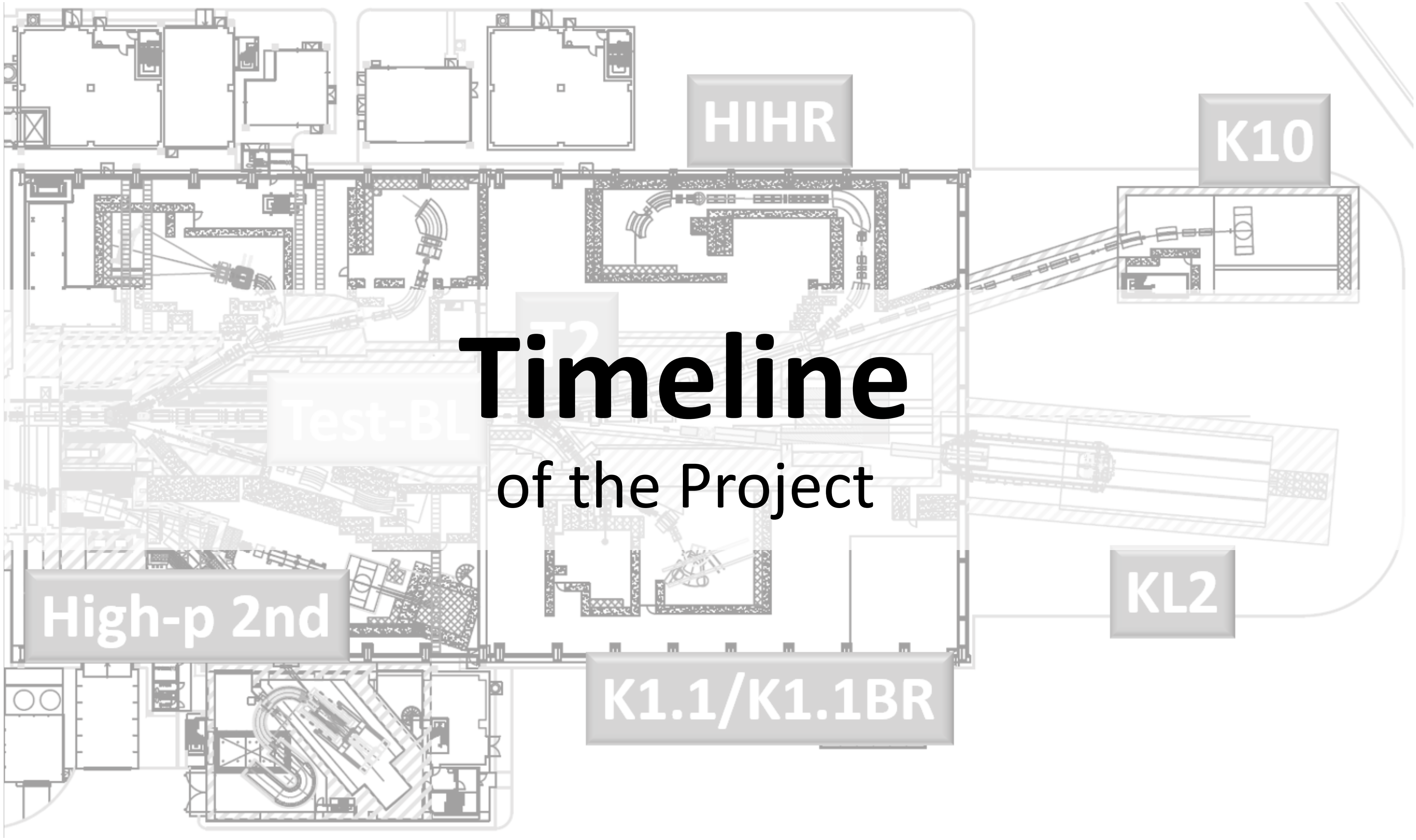




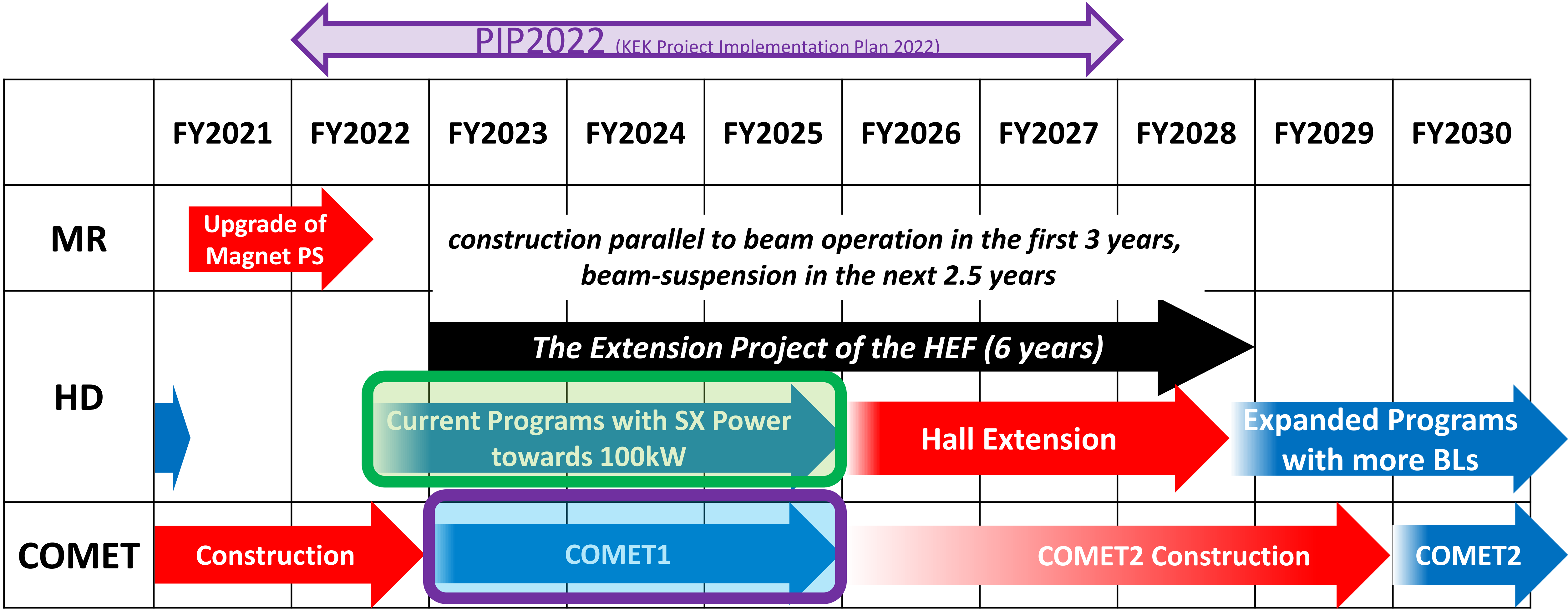
	KOTO Step2	KLEVER
K momentum	~5 GeV/c	~40 GeV/c
Expected # of events (SM)	~60	~60

Timeline

of the Project



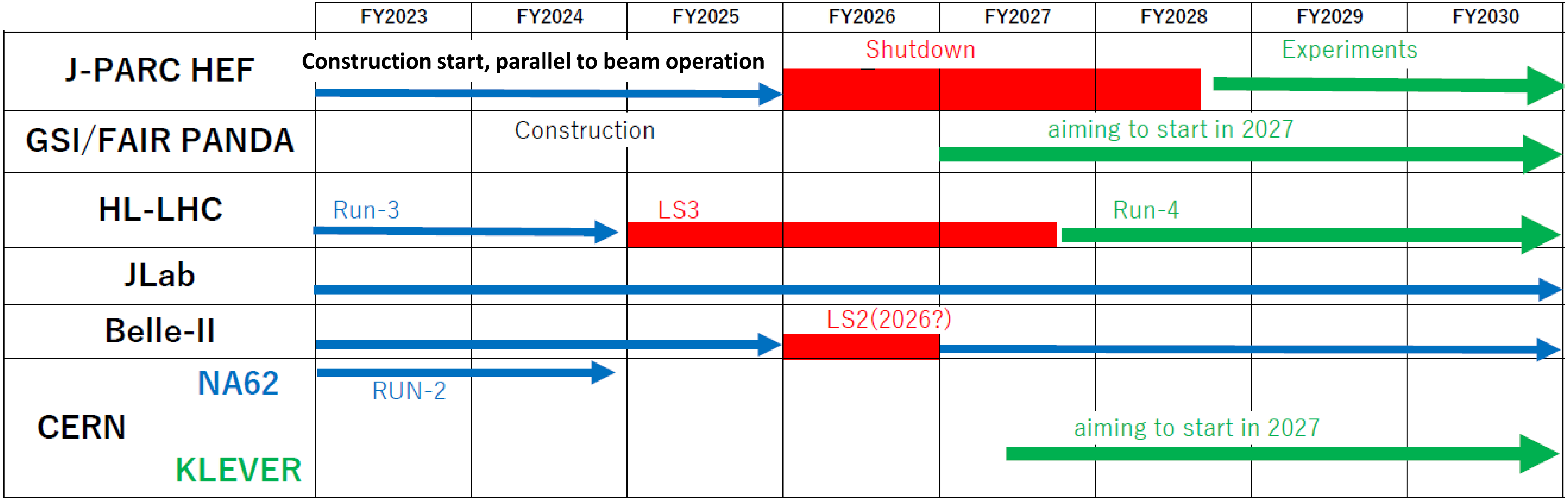
Timeline with the current programs



- **We would like to start the project from FY2023**
  - **4 years operation before beam suspension (except for COMET)**
  - **3 years operation for COMET (Beamline completion in FY2022)**

Urgency of the Project

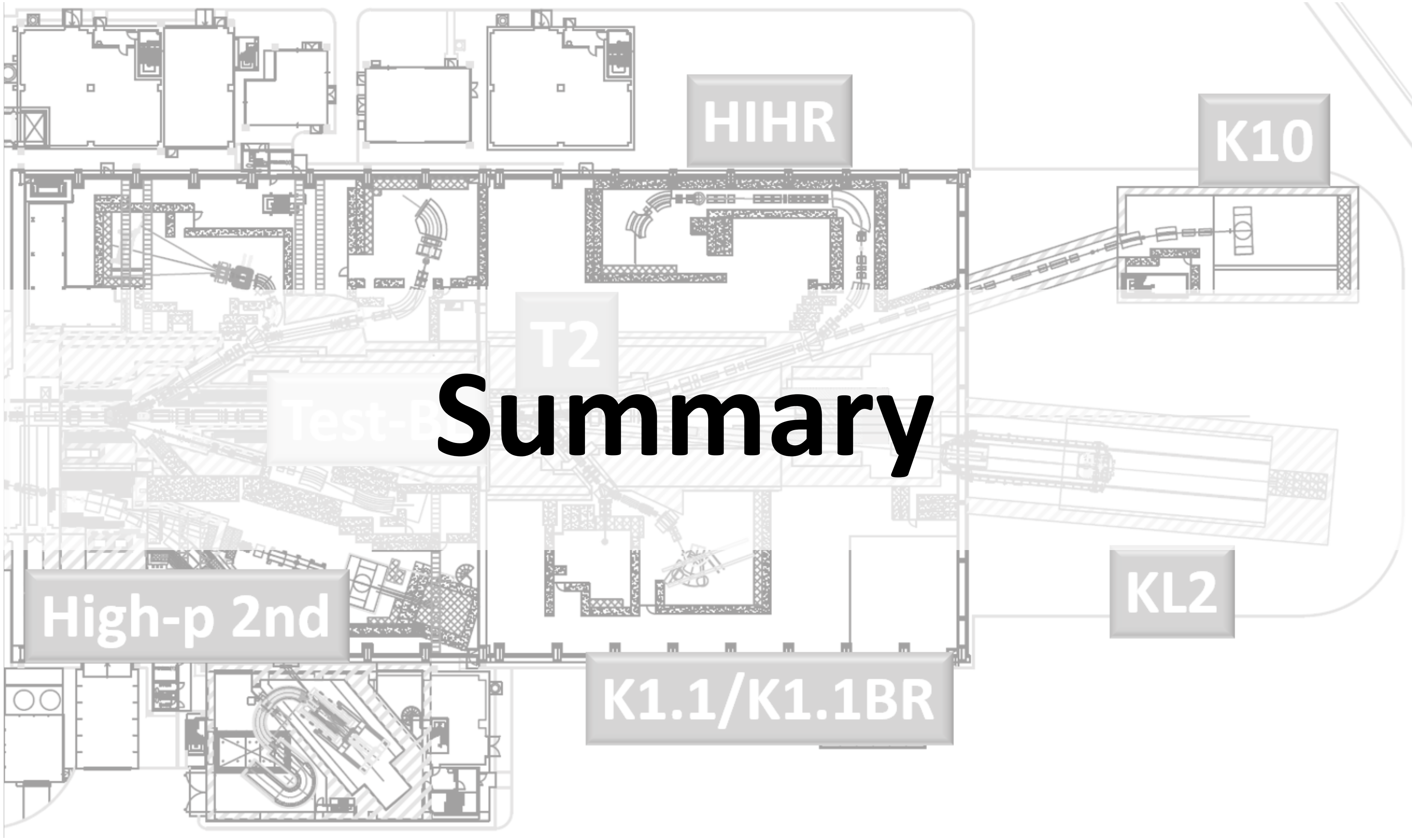
To promote particle and nuclear physics together with world's frontier facilities, contributions from the J-PARC HEF are essential



Around after 2027, PANDA, HL-LHC, and KLEVER will start their operations

→ To keep leading position in the field, early realization of the project is essential

Summary



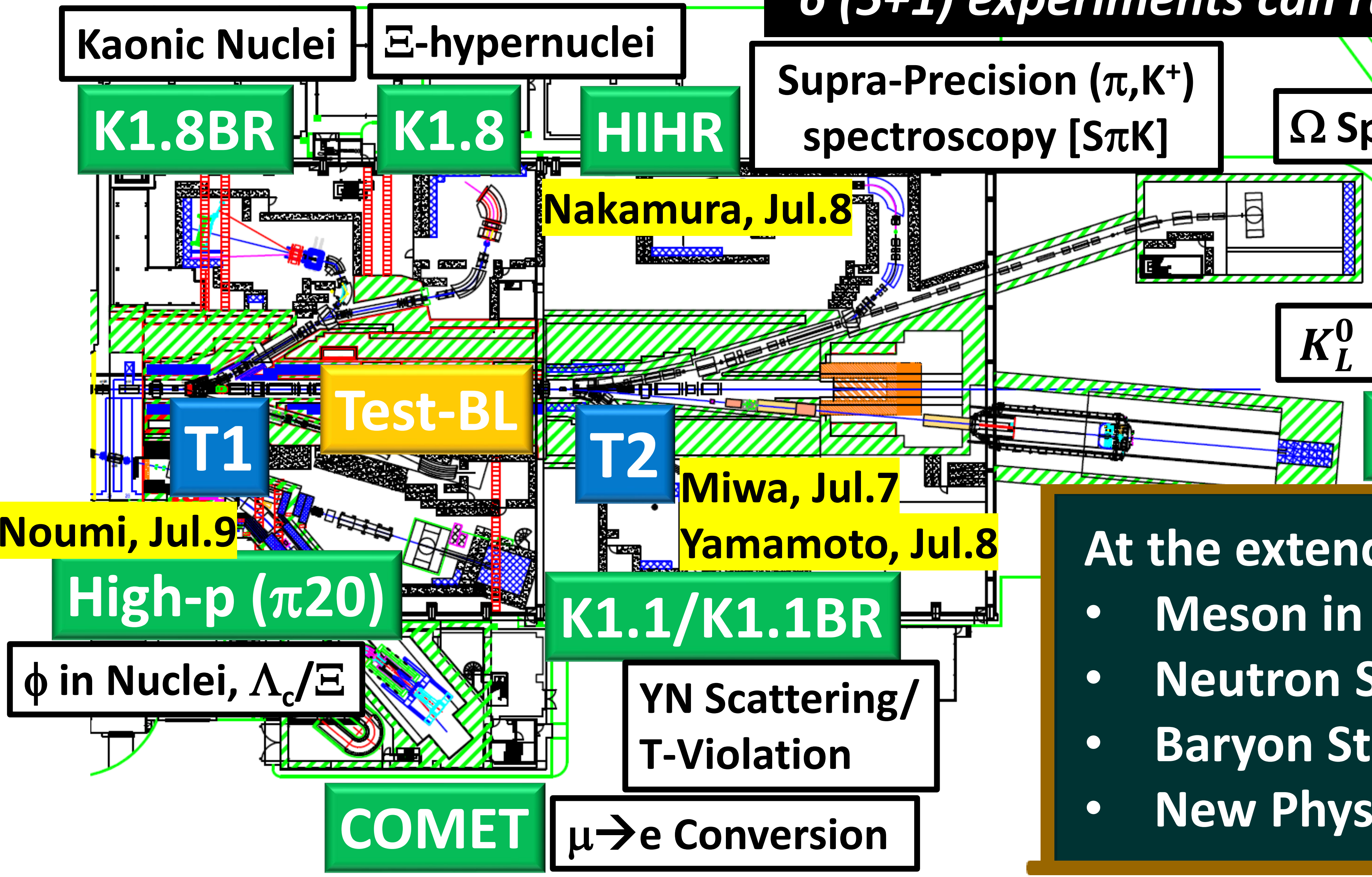
Summary

- **Open new physics that cannot be implemented at the existing facility**
  - Elucidate neutron star matter from nuclear physics, by solving the hyperon puzzle
  - Reveal baryon structure built by quarks, through spectroscopic study of strange and charm baryons
  - Discover new physics beyond the SM, by improving the sensitivities of rare kaon decay searches

- **Improve experiment-execution and beam-utilization efficiencies by realizing simultaneous execution of multiple experiments (3→6 experiments).**
  - Increase outputs
  - Contribute to human resource development, *i.e.*, increase the number of Ph.D recipients

Extend Physics Capability

6 (5+1) experiments can run at the same time



At the extended HEF, we attack:

- Meson in Nuclei
- Neutron Star Matter
- Baryon Structure
- New Physics beyond the SM

Thank you very much!