Hadronic Physics Program at J-PARC

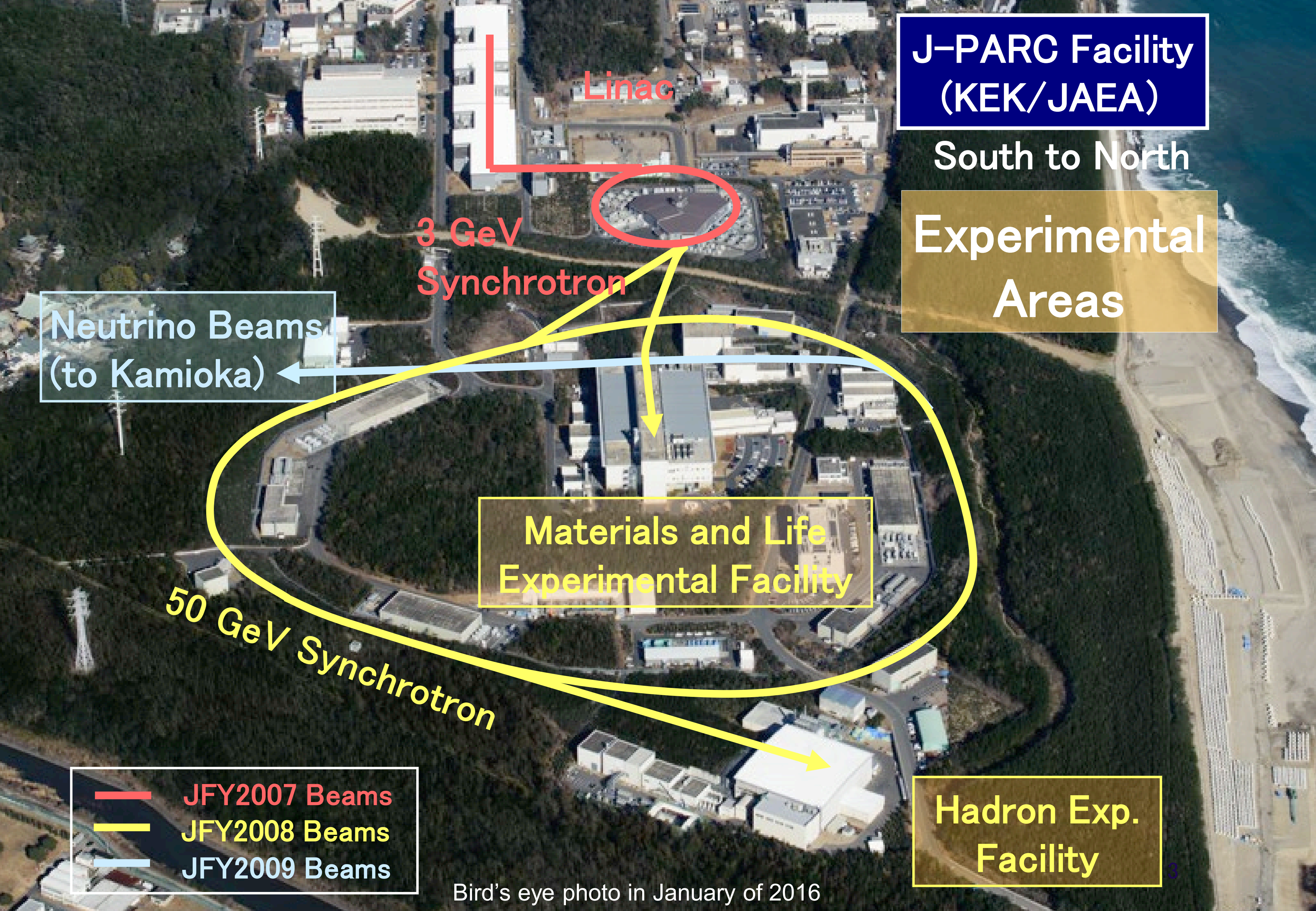
APCTP Focus Program in Nuclear Physics 2021 Part II

Science Opportunities with EIC

July 20, 2021

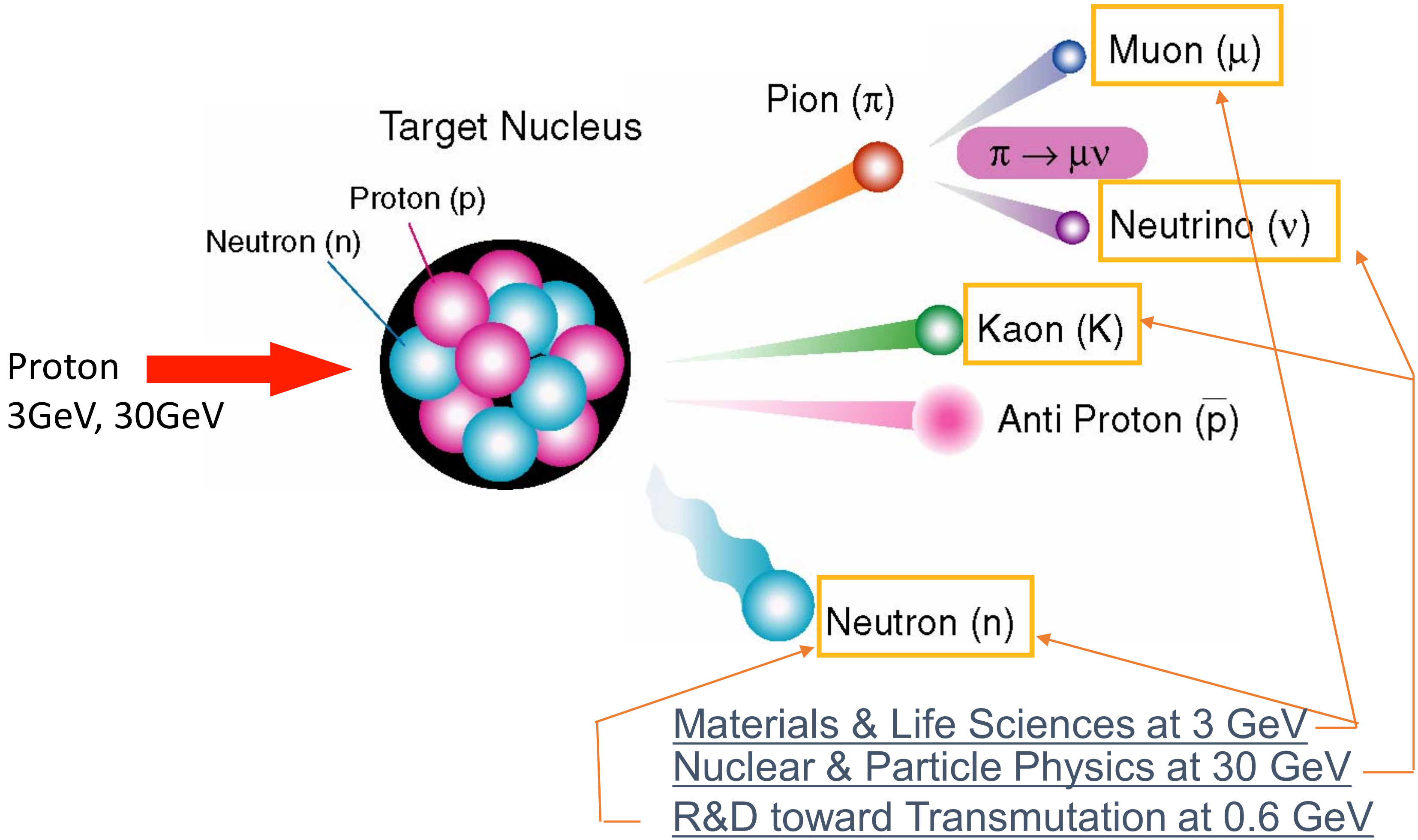
Shinya Sawada (KEK/J-PARC)

Contents

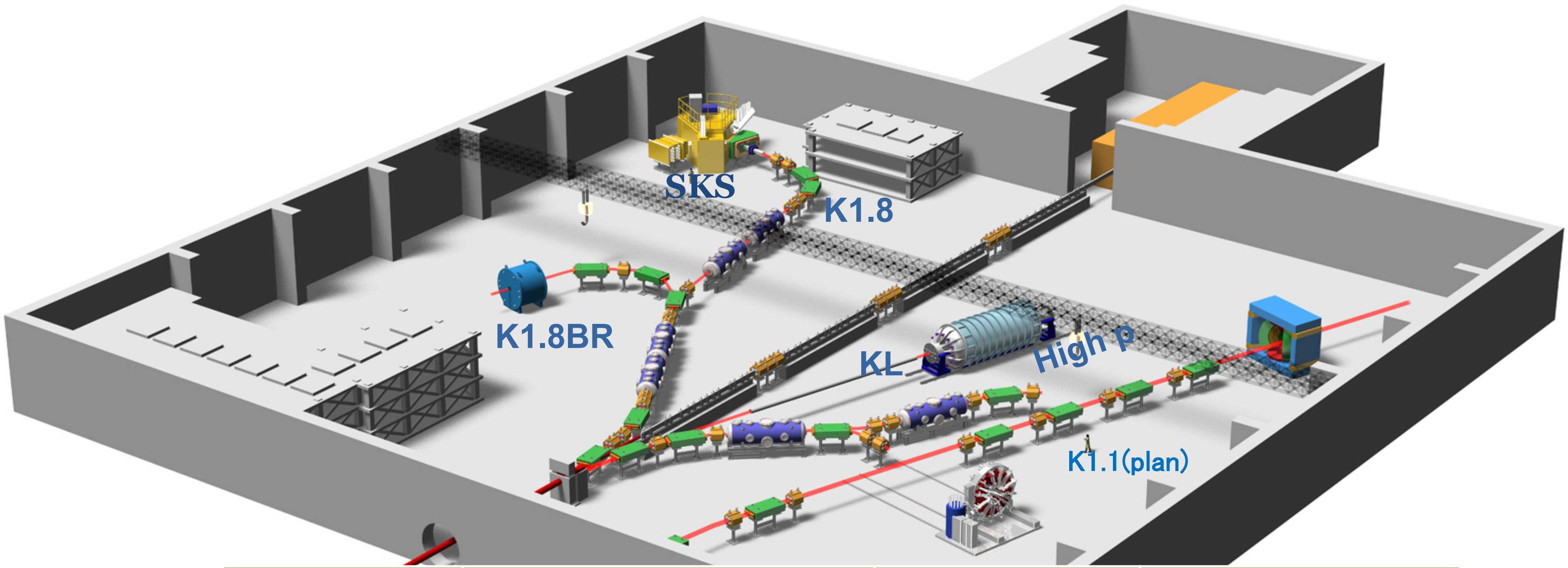


Bird's eye photo in January of 2016

Goals at J-PARC

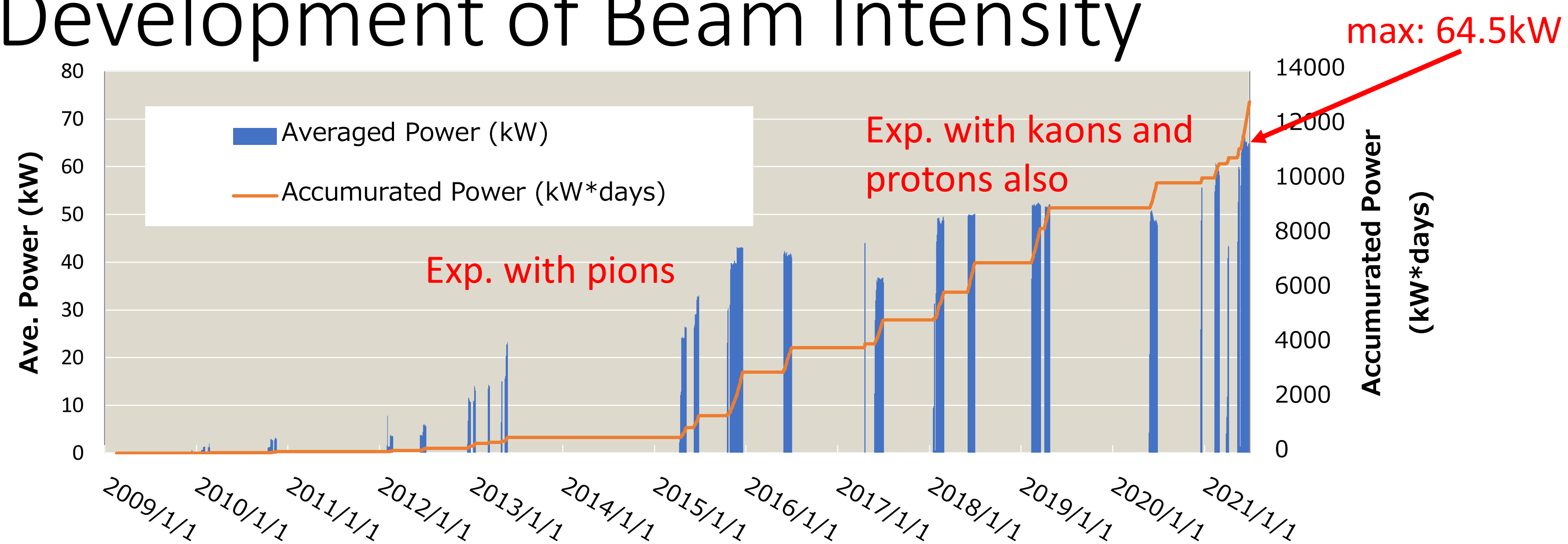


Hadron Experimental Facility



Beam Lines	Secondary particles	Max. Mom.	Max. Intensity
K1.8	π, K, p (2 separators)	< 2.0 GeV/c	~10^6 /spill for K^-
K1.8BR	π, K, p (1 separator)	< 1.1 GeV/c	~10^5 /spill for K^-
KL	Neutral Kaon	~ 2.1 GeV/c	~10^7 /spill
High-p	Proton	30 GeV	~10^{10} /spill

Development of Beam Intensity



__Accumulated beam time and intensity for HD (as of 19th Jun, 2021)__

Before accident (Feb, 2009 – May, 2013)	1.28×10^6 spills	568 kW*days
JFY2015 run (Apr, 2015 – Dec, 2015)	1.07×10^6 spills	2365 kW*days
JFY2016 run (May, 2016 – Jun, 2016)	0.34×10^6 spills	893 kW*days
JFY2017 run (Apr, 2017 – Feb, 2018)	0.81×10^6 spills	2039 kW*days
JFY2018 run (Jun, 2018 – Mar, 2019)	0.76×10^6 spills	2321 kW*days
JFY2019 run (Apr, 2019)	0.25×10^6 spills	765 kW*days
JFY2020 run (May, 2020 – Apr, 2021)	0.65×10^6 spills	1844 kW*days
JFY2021 run (May, 2021 – Jun, 2021)	0.54×10^6 spills	2045 kW*days

※spill: # of beam shots to HD

※ 8-GeV operation was not included.

K beam intensity

KEK-PS: K purity was for example ~25%.

KEK-PS Beamline	K / spill (4s)	Protons / spill (4s)	Note
K2	2×10^4 K^-	2×10^{12}	1.67GeV/c, E522
	1×10^4 K^-	3×10^{12}	1.0GeV/c, E549
K5	1.9×10^5 K^+	2.2×10^{12}	0.66GeV/c, E470
	6×10^3 K^-	1.5×10^{12}	stopped, E549
K6	1.3×10^4 K^+	0.87×10^{12}	1.2GeV/c, E559

J-PARC K1.8 Beamline

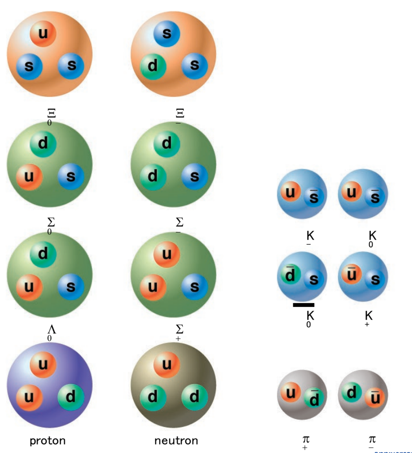
Beamline	K / spill (5.2s)	Protons / spill (5.2s)	Note
K1.8	3.3×10^5 K^-	5.4×10^{13}	1.8GeV/c, E07 purity=82.5%
	7.3×10^5 K^-	7×10^{13}	1.8GeV/c, purity=48%

Hadronic physics opportunities at the Hadron Experimental Facility

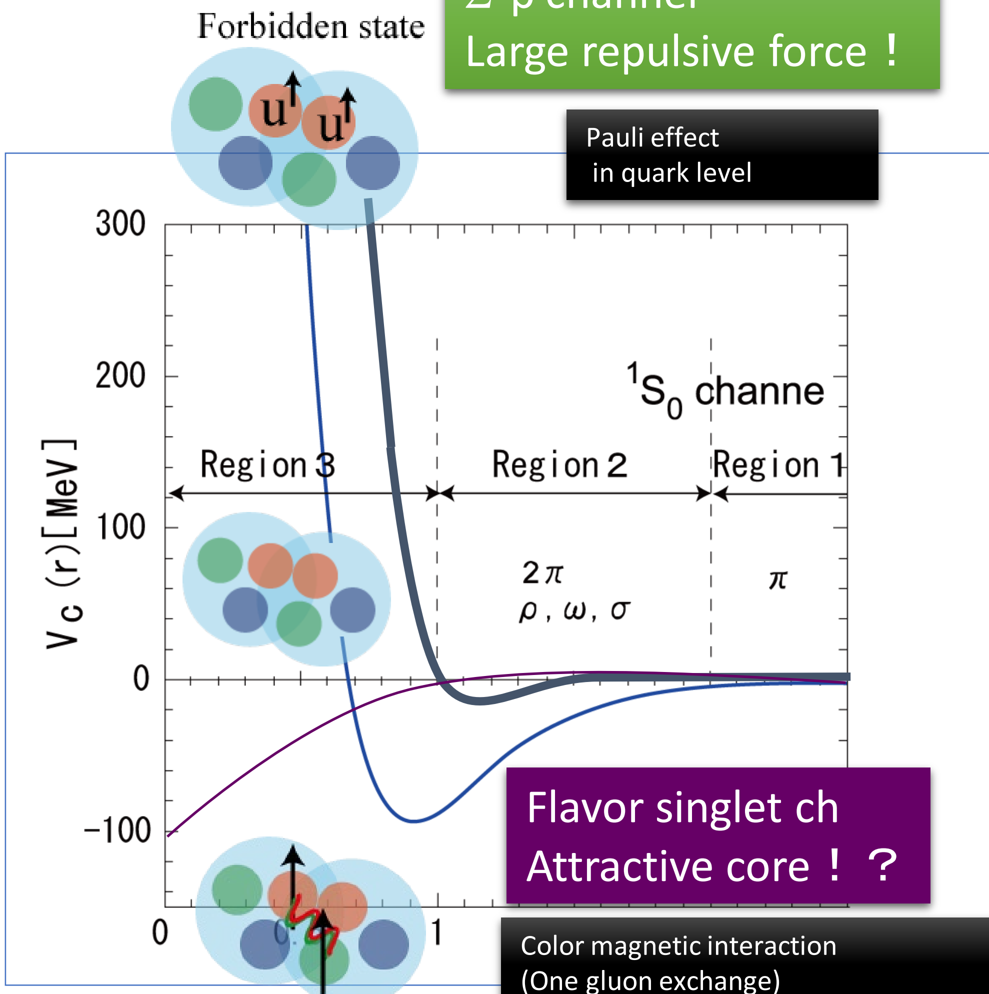
- Experiments with pions/kaons
  - Hadron interactions structures are eagerly investigated.
  - Strangeness degree of freedom is one of the keys.
  - Understanding of the hadron interaction in a microscopic way leads also to understanding of very dense nuclear matter such as neutron star.
- Experiments with primary protons
  - Mass modification of a vector meson inside nuclei
- Kaon rare decay experiment

Hadron interactions with strangeness

- Nucleon-nucleon interaction, especially at medium and long ranges, has been rather well studied, since Yukawa's prediction of the pi meson.
- Especially, the origin of the repulsive core and the spin-orbit force has not been understood.
- We explore the hadron interaction not only with up and down quarks but also with strange quarks.



Σ^+p channel
Large repulsive force！



Pauli effect
in quark level

Flavor singlet ch
Attractive core！？

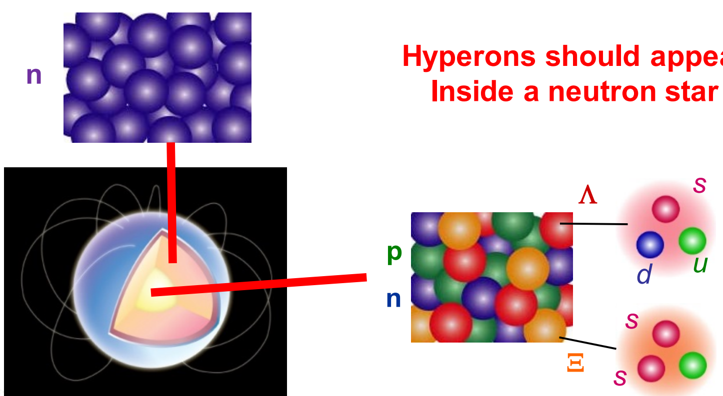
Color magnetic interaction
(One gluon exchange)

Importance of understanding hadron interaction

- We need to understand the bound system by the strong interaction in completely different scales from hadrons to a giant nucleus, a neutron star, in a microscopic way.
- Recent observation of 2-solar-mass neutron stars suggests
  - Our understanding of hadron interaction and the equation of state (EoS) based on it cannot well describe the neutron star EoS.
  - Baryon interaction in nuclear matter is important.
- Gravitational waves from neutron star merger provide an information on a kind of the stiffness of the EoS.

Strangeness is a key!

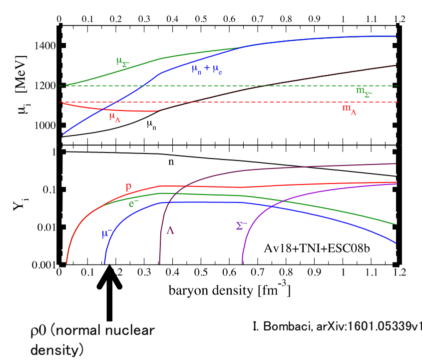
Neutron Matter



Neutron Star

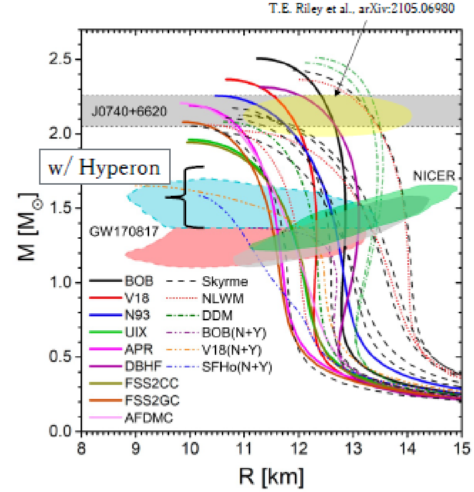
Hyperons

Theoretical prediction from known YN, YY 2-body interactions (Y=hyperon)



I. Bombaci, arXiv:1601.05339v1

T.E. Riley et al., arXiv:2105.06980



G.F. Burgio et al., arXiv:2105.03747

Toward microscopic understanding of the strong interaction and nuclear matter

Data

Nuclear data: binding energy of hyperons through spectroscopy

NN scattering data (rich)

YN scattering data (sparce)

Theoretical tools

Baryon-Baryon interaction by Lattice QCD

Chiral Effective Field Theory

Baryon-Baryon interaction by meson exchange models

Understanding of the repulsive core?

Realistic strong interaction which can reproduces hypernuclei and neutron stars

Hyper-nuclear spectroscopy (S=-1)

PHYSICAL REVIEW LETTERS

moving physics forward

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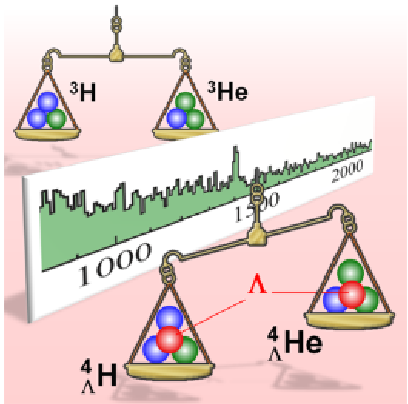


EDITORS' SUGGESTION

Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of $^4_\Lambda\mathrm{He}$

The energy spacing of the spin-doublet states in the $^4_\Lambda$He hypernucleus indicate a large spin dependent charge symmetry breaking in the ΛN interaction.

T. O. Yamamoto *et al.* (J-PARC E13 Collaboration)

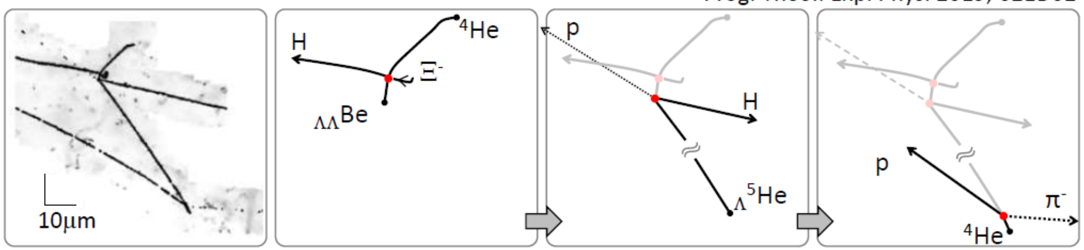
Phys. Rev. Lett. **115**, 222501 (2015)

Hyper-nuclear spectroscopy (S=-2)

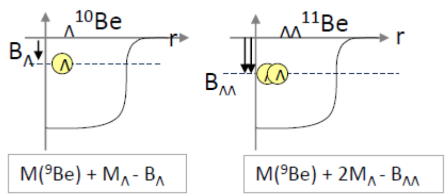
- Double strangeness nuclei are produced through (K^-, K^+) reactions.
- Nuclear emulsions were used with relatively lower intensity K^- beam. “Counter” experiments to come.

MINO event

H. Ekawa et al.,
Prog. Theor. Exp. Phys. 2019, 021D02

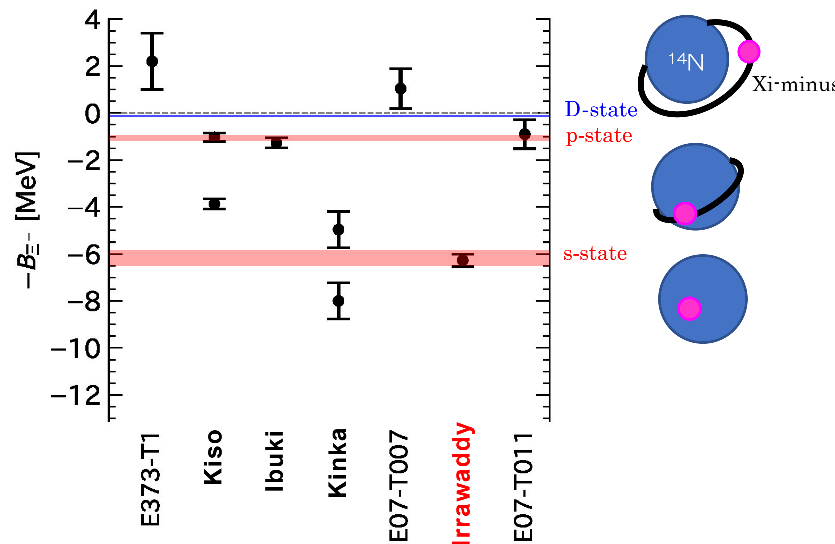


$$^{16}O + \Xi^- \to (^{10}_{\Lambda\Lambda}Be,\ ^{11}_{\Lambda\Lambda}Be,\ ^{12}_{\Lambda\Lambda}Be) + {}^4He + (t,\ d,\ p),$$
$$\hookrightarrow {}^5_\Lambda He + (p, d, t) + p + xn,$$
$$\hookrightarrow {}^4He + p + \pi^-.$$



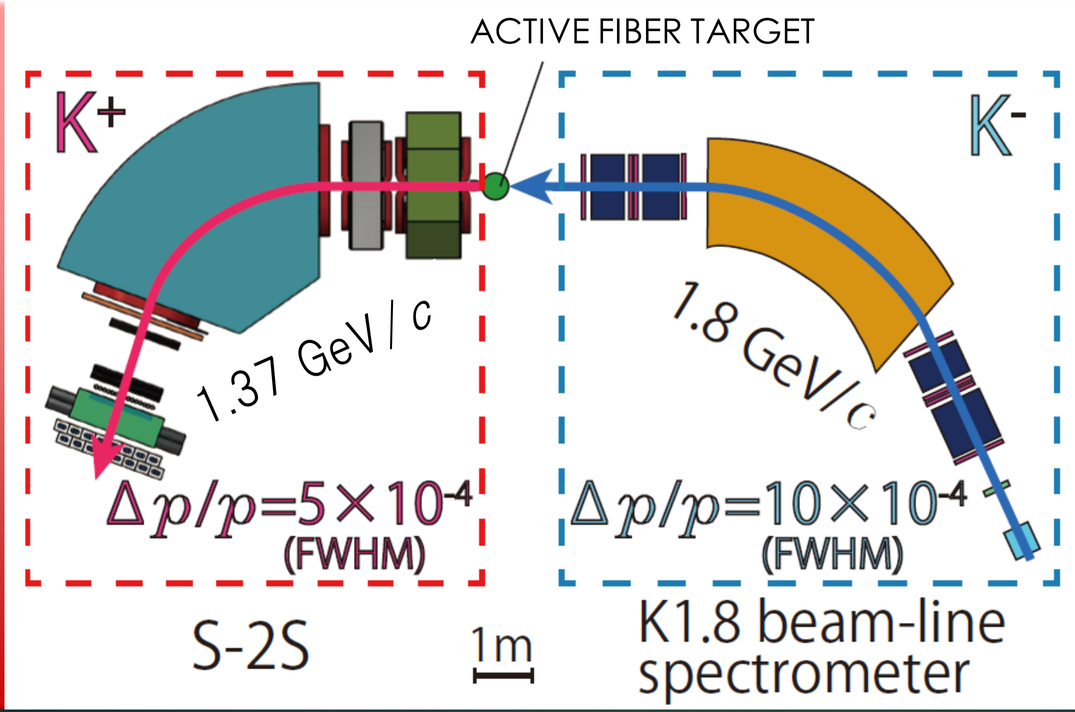
	Possible interpretations	$B_{\Lambda\Lambda}$ [MeV]	Kinematic fitting χ^2 (DOF=3)
Most probable	Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{10}$Be + ^{4}He + t	15.05 +- 0.11	11.5
➡	Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{11}$Be + ^{4}He + d	19.07 +- 0.11	7.3
	Ξ^- + ^{16}O -> $_{\Lambda\Lambda}{}^{12}$Be* + ^{4}He + p	13.68 +- 0.11 + E_{ex}	11.3

Where, B_{Ξ^-} = 0.23 MeV (3D state)



Summary of Ξ^--^{14}N

Multi-Strangeness world revealed with S-2S



J-PARC K1.8

(K^-,K^+) spectroscopy

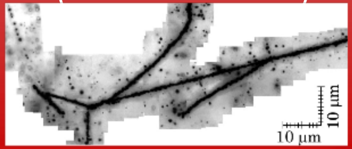
ΔE<2 MeV

ΔΩ=55msr

Establish the Ξ bound states

Hints in Emulsion

(KISO, IBUKI,…)

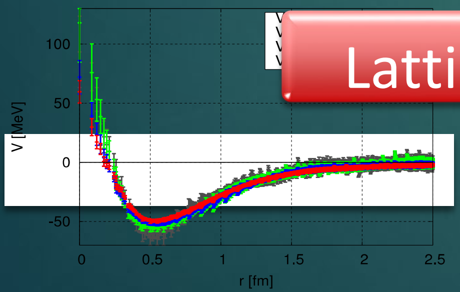


B-B Interactions

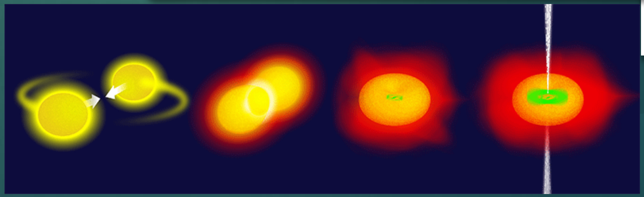
EOS@ High-density

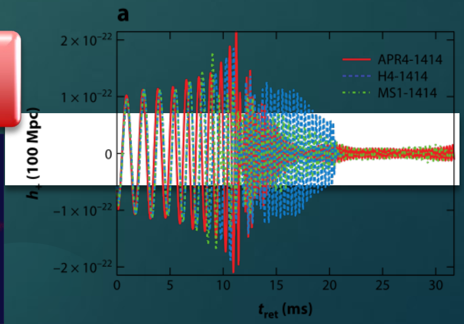
Lattice QCD

Binary NS Merger



(b) $V_{N\Xi-N\Xi}$



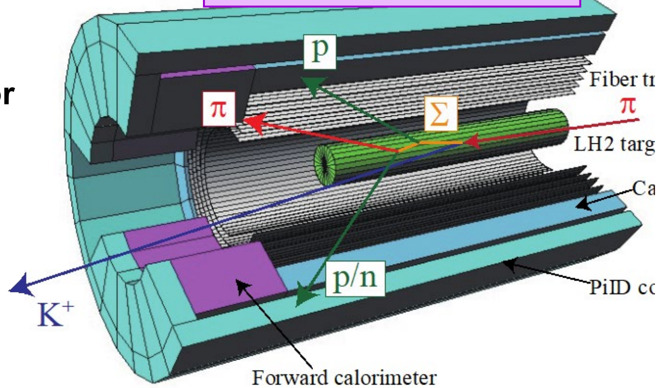


YN interaction

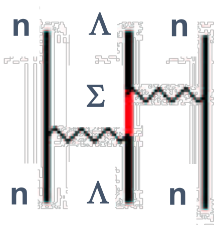
E40

Sattered proton detector

Ultra-fast (x100) Tracking detector Using MPPC

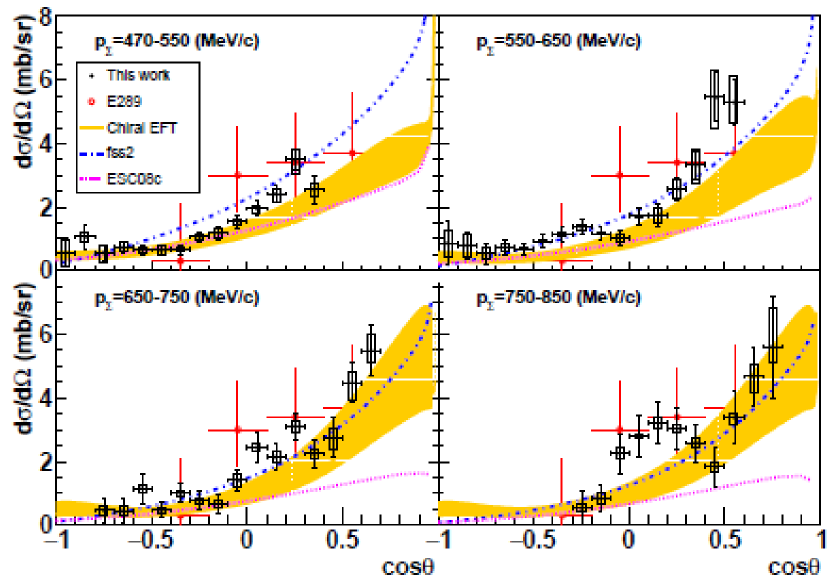


Λ–Σ coherent coupling



arXiv:2104.13608

Differential cross sections of $\Sigma^- p$ scattering

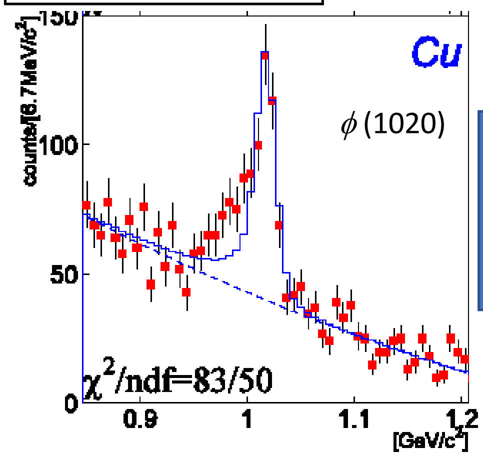


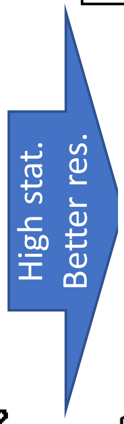
See Miwa-san's talk on Friday, July 23.

Mass modification of vector mesons

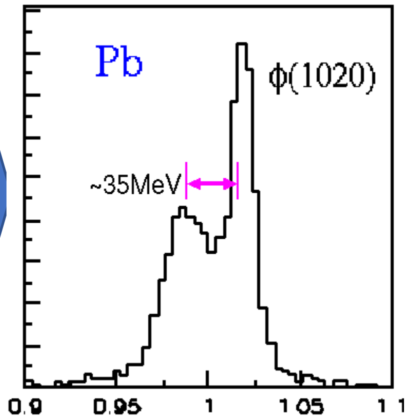
- Invariant mass spectra of e^+e^- pairs in pA collisions
  - Vector meson mass modification due to nuclear matter effects
  - High statistics/Good resolution
- Similar as KEK-PS E325, but with x100 stat.
- The beam line construction was completed and the engineering run was conducted until June, 2021. The physics run will start in 2022.

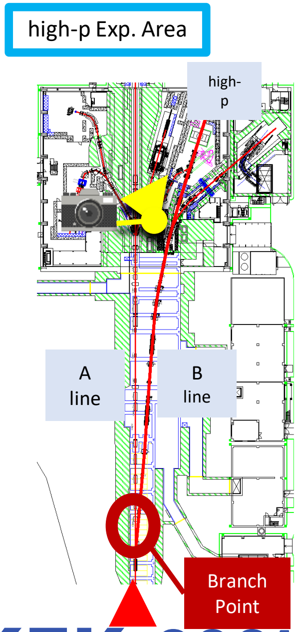
KEK E325 results

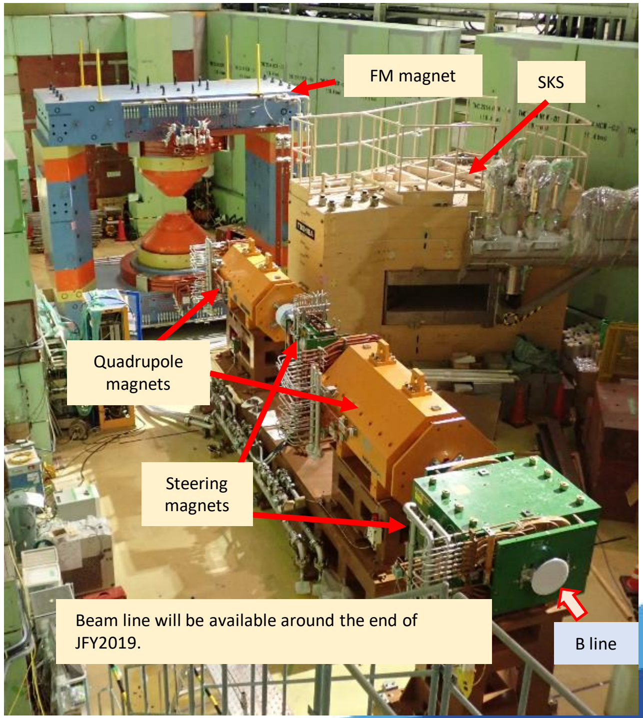




J-PARC expectation

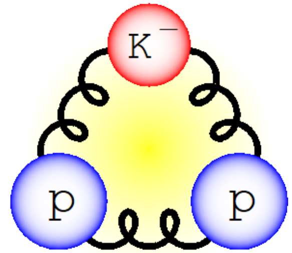


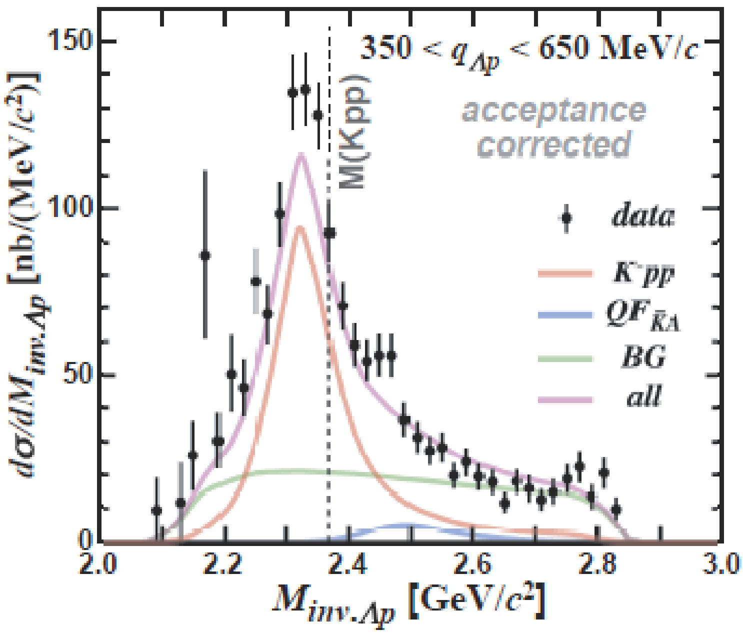




K^-pp bound states

- The E15 collaboration has announced findings of a bound state of $K^- + p + p$.
- This should be a door to investigation of high density matter.





$B_{K\text{-}pp}$ = 47+-3(stat.)+3-6(sys.) MeV

$\Gamma_{K\text{-}pp}$ = 115+-7(stat.)+10-9sys.) MeV

Physics Letters B 789, 620-625 (2019)

Contents lists available at ScienceDirect

Physics Letters B

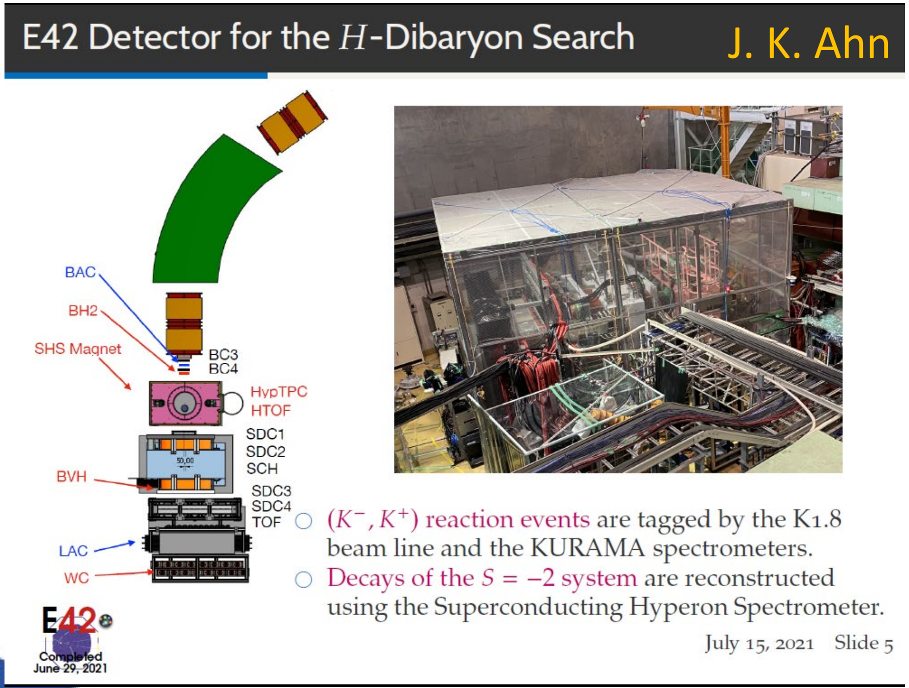
www.elsevier.com/locate/physletb

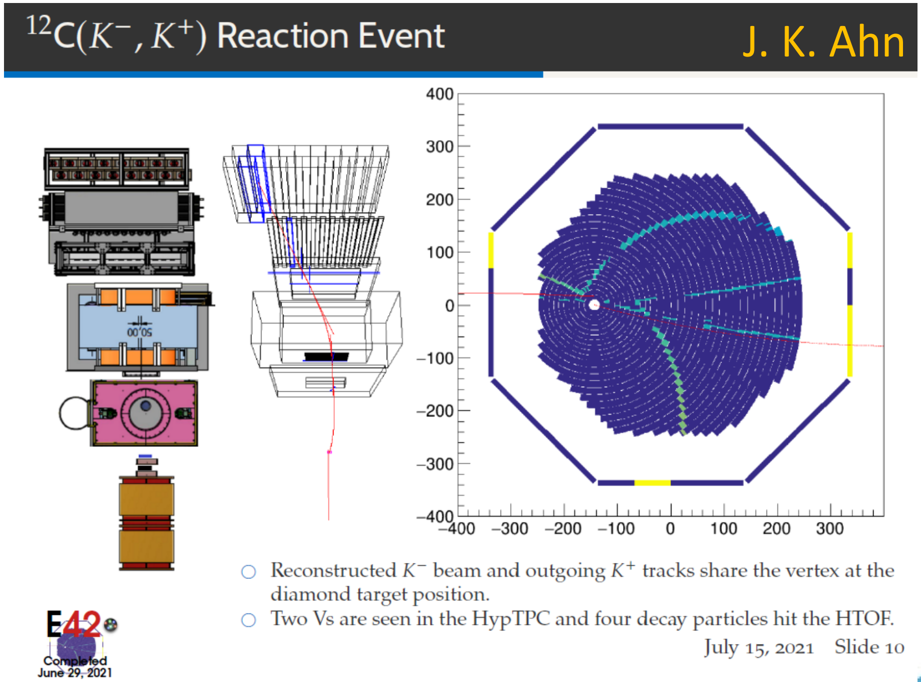
"K^-pp", a $\bar{K}$-meson nuclear bound state, observed in $^3\mathrm{He}(K^-, \Lambda p)n$ reactions

J-PARC E15 collaboration, S. Ajimura [a], H. Asano [b], G. Beer [c], C. Berucci [d], H. Bhang [e], M. Bragadireanu [f], P. Buehler [d], L. Busso [g,h], M. Cargnelli [d], S. Choi [e], C. Curceanu [i], S. Enomoto [j], H. Fujioka [k], Y. Fujiwara [l], T. Fukuda [m], C. Guaraldo [i], T. Hashimoto [n], R.S. Hayano [l], T. Hiraiwa [a], M. Iio [j], M. Iliescu [i], K. Inoue [a], Y. Ishiguro [o], T. Ishikawa [l], S. Ishimoto [j], K. Itahashi [b], M. Iwasaki [b,k,*], K. Kanno [l], K. Kato [o], Y. Kato [b], S. Kawasaki [a], P. Kienle [p,1], H. Kou [k], Y. Ma [b], J. Marton [d], Y. Matsuda [l], Y. Mizoi [m], O. Morra [g], T. Nagae [o], H. Noumi [a], H. Ohnishi [q,b], S. Okada [b], H. Outa [b], K. Piscicchia [i], Y. Sada [a], A. Sakaguchi [a], F. Sakuma [b,*], M. Sato [j], A. Scordo [i], M. Sekimoto [j], H. Shi [i], K. Shirotori [a], D. Sirghi [i,f], F. Sirghi [i,f], K. Suzuki [d], S. Suzuki [j], T. Suzuki [l], K. Tanida [n], H. Tatsuno [r], M. Tokuda [k], D. Tomono [a], A. Toyoda [j], K. Tsukada [q], O. Vazquez Doce [i,p], E. Widmann [d], T. Yamaga [b,a,*], T. Yamazaki [l,b], Q. Zhang [b], J. Zmeskal [d]

H-Dibaryon Search

- E42 experiment headed by Prof. Jung Keun Ahn (Korea).
- The H-dibaryon is the lightest S=-2 system which can be decomposed into a symmetric six-quark object made from uuddss and two baryon states involving $\Lambda\Lambda$, ΞN, and $\Sigma\Sigma$ components.
- The experiment measured the event topology with the (K^-, K^+) reactions.
- The beam time was successfully carried out from May through June, this year.





Kaon rare decay experiment

PHYSICAL REVIEW LETTERS **126,** 121801 (2021)

Editors' Suggestion

Study of the $K_L \to \pi^0 \nu \bar{\nu}$ Decay at the J-PARC KOTO Experiment

J. K. Ahn,[1] B. Beckford,[2] M. Campbell,[2] S. H. Chen,[3] J. Comfort,[4] K. Dona,[2] M. S. Farrington,[5] K. Hanai,[6] N. Hara,[6] H. Haraguchi,[6] Y. B. Hsiung,[3] M. Hutcheson,[2] T. Inagaki,[7] M. Isoe,[6] I. Kamiji,[8] T. Kato,[6] E. J. Kim,[9] J. L. Kim,[9] H. M. Kim,[9] T. K. Komatsubara,[7,10] K. Kotera,[6] S. K. Lee,[6] J. W. Lee,[6,*] G. Y. Lim,[7,10] Q. S. Lin,[5] C. Lin,[3] Y. Luo,[5] T. Mari,[6] T. Masuda,[11] T. Matsumura,[12] D. Mcfarland,[4] N. McNeal,[2] K. Miyazaki,[6] R. Murayama,[6,†] K. Nakagiri,[8,‡] H. Nanjo,[8,§] H. Nishimiya,[6] Y. Noichi,[6] T. Nomura,[7,10] T. Nunes,[6] M. Ohsugi,[6] H. Okuno,[7] J. C. Redeker,[5] J. Sanchez,[2] M. Sasaki,[13] N. Sasao,[11] T. Sato,[7] K. Sato,[6,‖] Y. Sato,[6] N. Shimizu,[6] T. Shimogawa,[14,¶] T. Shinkawa,[12] S. Shinohara,[8,§] K. Shiomi,[7,10] R. Shiraishi,[6] S. Su,[2] Y. Sugiyama,[6,¶] S. Suzuki,[14] Y. Tajima,[13] M. Taylor,[2] M. Tecchio,[2] M. Togawa,[6,¶] T. Toyoda,[6] Y.-C. Tung,[5,**] Q. H. Vuong,[6] Y. W. Wah,[5] H. Watanabe,[7,10] T. Yamanaka,[6] H. Y. Yoshida,[13] and L. Zaidenberg[2]

(KOTO Collaboration)

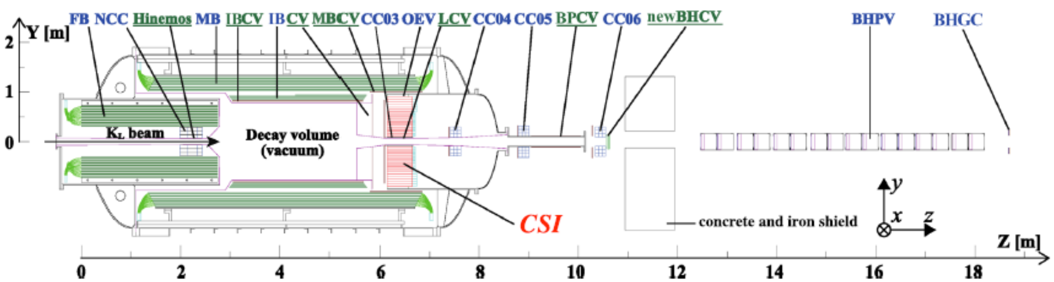
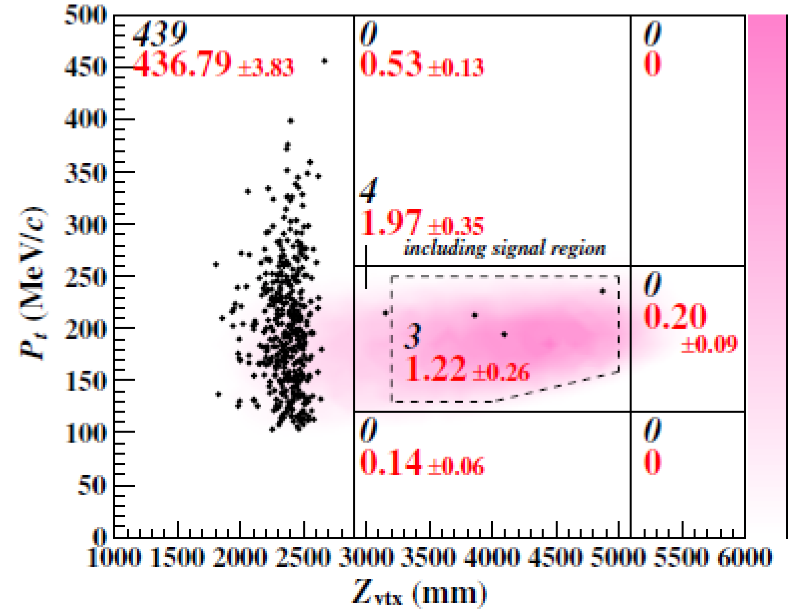


FIG. 1. Cross sectional view of the KOTO detector. The beam enters from the left. Detector components with their abbreviated names written in blue (in green and underlined) are photon (charged-particle) veto counters; see text for information about the abbreviations.

Results from 2016-2018 data.



The number of the events in the signal region is consistent with the expected background.

The number of the events in the signal region is consistent with the expected background.

KOTO is collecting more data with improved detectors against the background.

Future of the Hadron Experimental Facility

Origin & Evolution of Matter

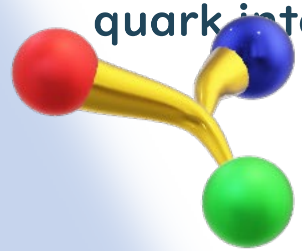
avor symmetry breaking
adron interaction
formation of a nucleus

Hypernuclei spectroscopy
YN scattering

Matter in Extreme Conditions

hyperon puzzle in neutron stars

chiral symmetry breaking
quark interaction



Hadron spectroscopy
Meson in nuclei

Matter Evolution

fundamental structure of matter

CP symmetry violation
weak interaction

Birth of Matter

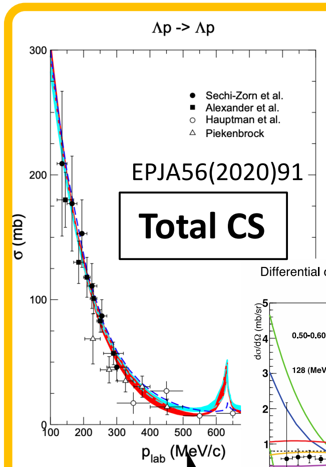
matter dominated universe

Kaon decays

Elucidation of Neutron Star Matter from Nuclear Physics

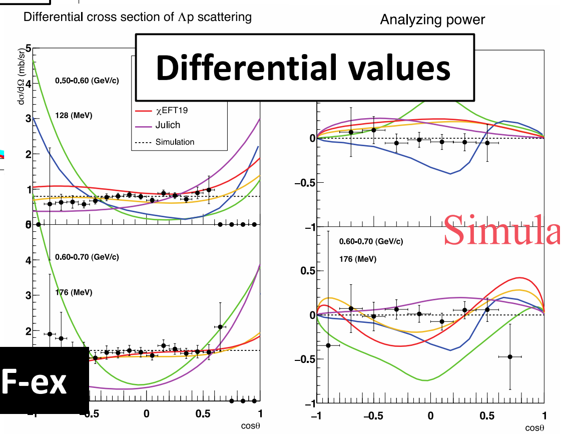
A tiny fraction of 3 Baryon Force effect is essential

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



Total CS

More accurate YN scattering data



Differential values

K1.1@HEF-ex

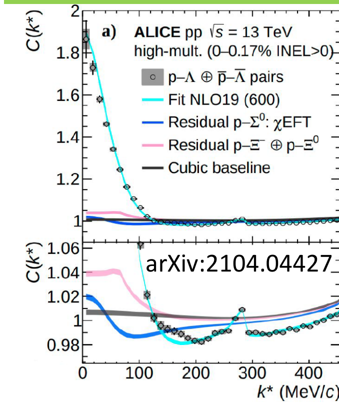
Ξ-hyp @ S-2S
ΛN @ High-p

input

input

input

Femtoscopy at HIC



Realistic BB interaction model

SU(3) Chiral EFT, Nijmegen models

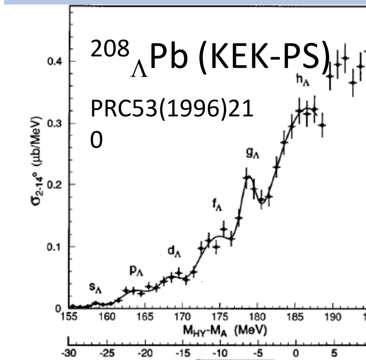
Potential from LQCD

Theoretical calculation of Λ single-particle energies

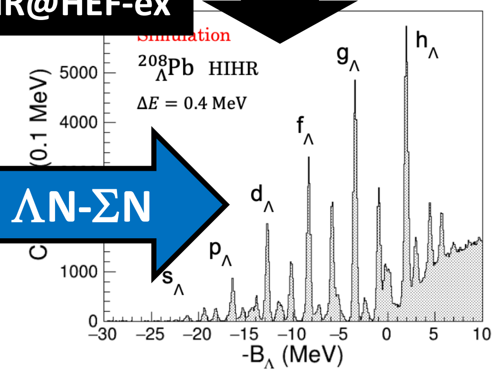
ΛNN, ΛN-ΣN

EOS, Neutron star matter

Much higher-resolution Λ spectroscopy

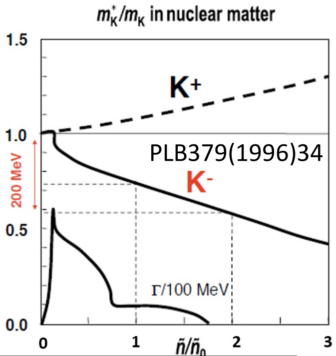


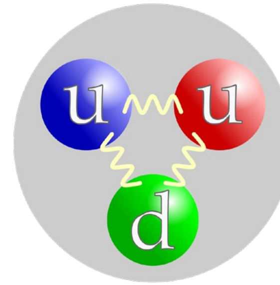
HIHR@HEF-ex



and γ-ray spectroscopy

Hadron Physics @ J-PARC





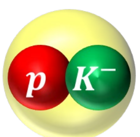
@ present HEF

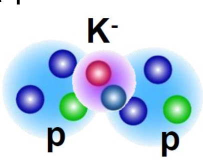
Explore low-E (non-pert.) QCD
- ➢ **Confinement of Hadron**
- ➢ **Chiral Symmetry Breaking**

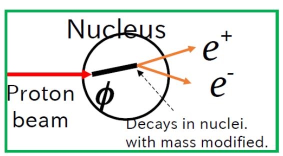
π20/K10@HEF-ex

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)



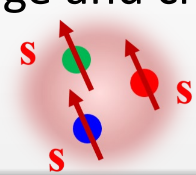


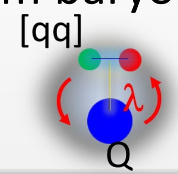


Expand physics to baryon

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

Toward New Physics: Flavor Physics

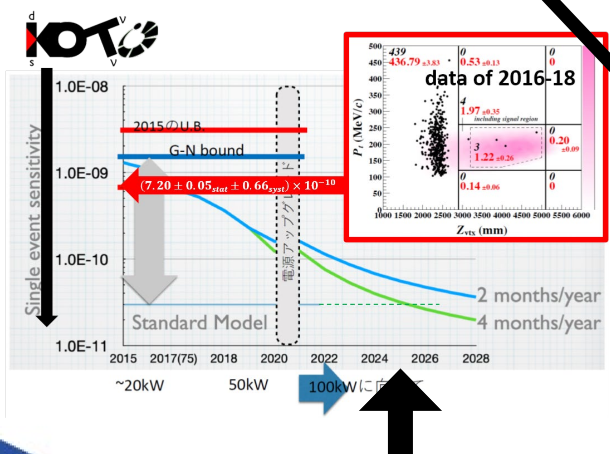
- So far, no clear evidence of new physics beyond the SM from direct searches
- **Flavor physics in intensity frontier** plays an important role more and more

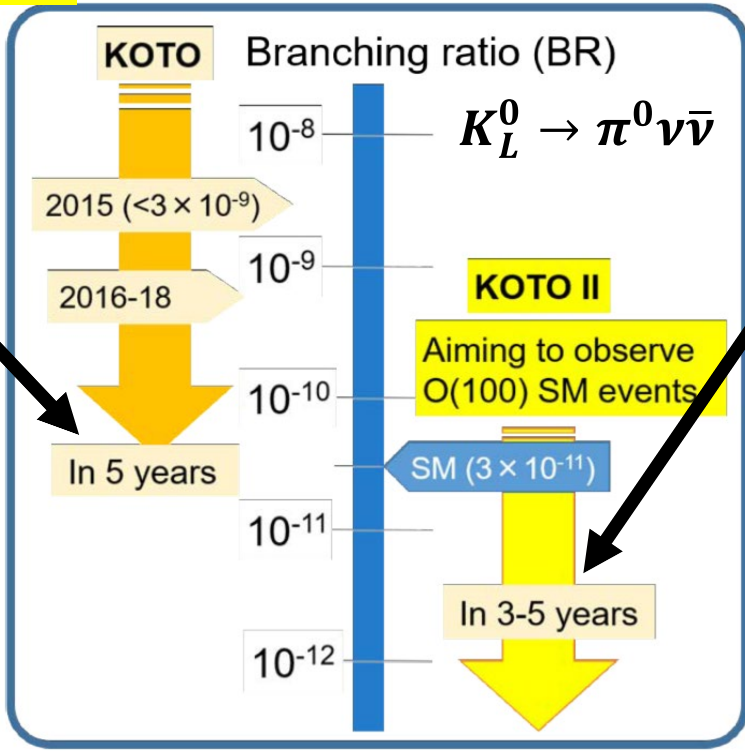
@ present HEF

Key Issue

KOTO:

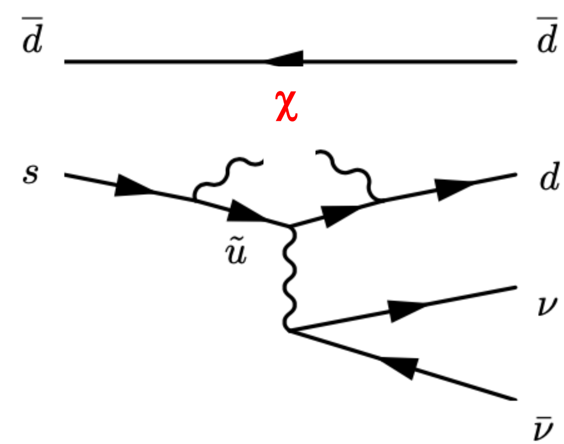
- Will reach the sensitivity of $O(10^{-11})$ around FY2025



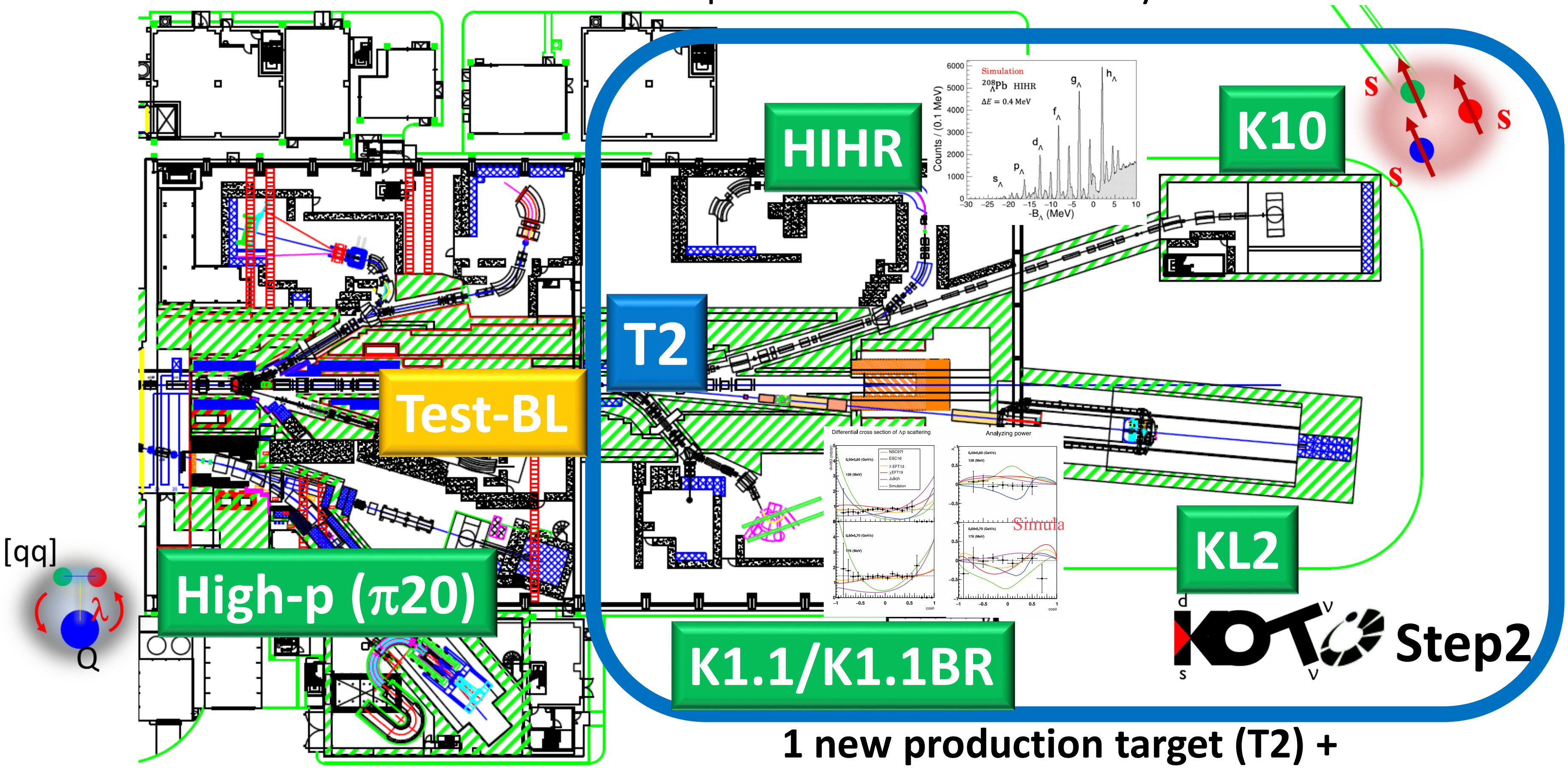


KOTO Step2: KL2@HEF-ex

- Will explore the region beyond the SM

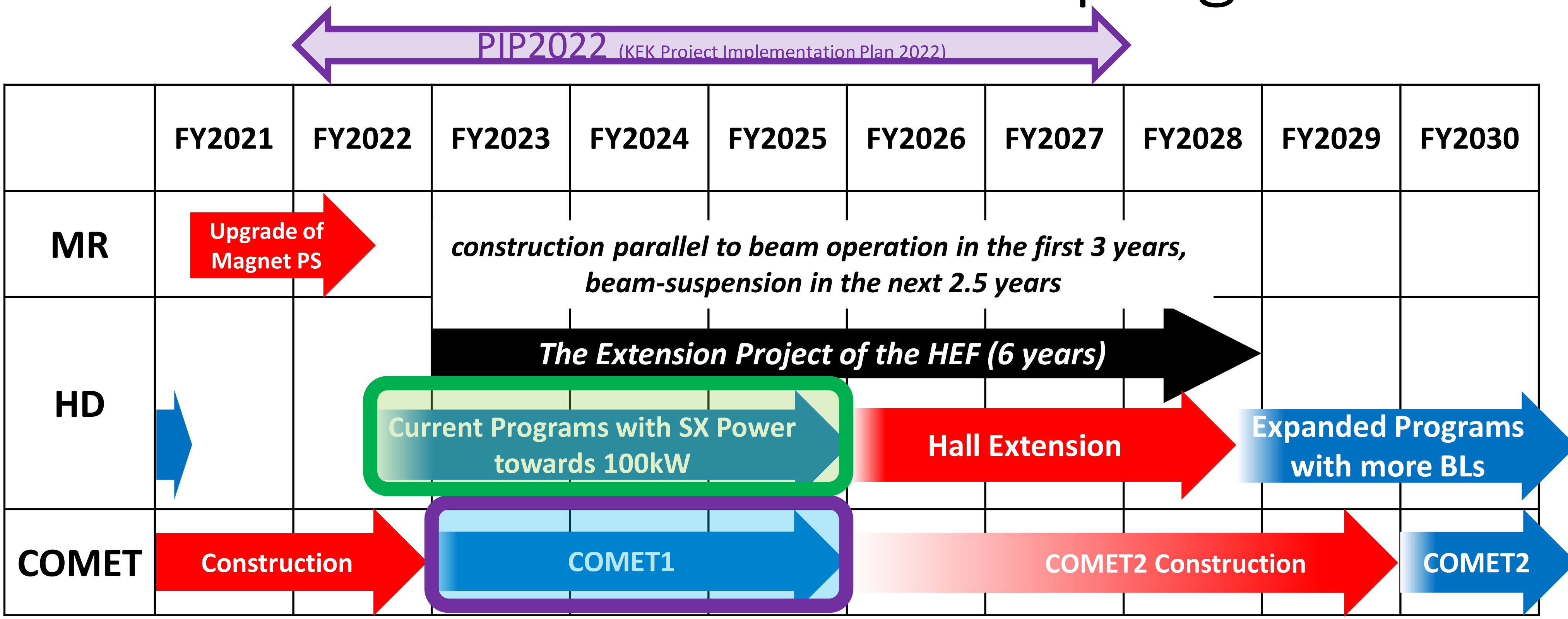


“Extended” Hadron Experimental Facility is Essential



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

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)**

Progress in the approval process of the HEF extension

- “Master Plan 2020” by the Science Council of Japan: Selected as one of the 31 important large scale projects.
- “Roadmap 2020” by MEXT: Selected as one of the 15 important large scale projects.
- “KEK Roadmap 2021” and “KEK Project Implementation Plan (KEK-PIP) 2022”:
  KEK-PIP 2022 defines the priority of the funding request from KEK to MEXT during the JFY2022-2027 period. We are working hard to get a good position, including workshops and reviews.

	2021												2022		
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3
SX shcedule		beam		beam			long shutdown								
events	31th PAC	SAC(3/19-20)					32th PAC						33th PAC		SAC
				speaker決定			1st WS(7/5-9で3日)							2nd WS	
								1st review(8月頭)			2nd review(11月-12月頭)				
									[中間報告]				[最終報告@PAC]		
HIHR/K1.1		第1回：5/23(domestic)、第2回：6/17-19(international)													
K10		第1回：5/13-14(domestic)、第2回：6/7-9(international)													
KL		適時勉強会													

Summary

- J-PARC provides opportunities of hadronic physics with hadron beams, such as pions, kaons, and protons.
- Toward understanding of the strong interaction, “strangeness” is a key. Research on hyper-nuclear spectroscopy and hyperon-nucleon scatterings is being conducted.
- Also, a rare kaon decay experiment is intensively taking data.
- In order to go forward, the extension project has been planned, and extensively discussed for approval.