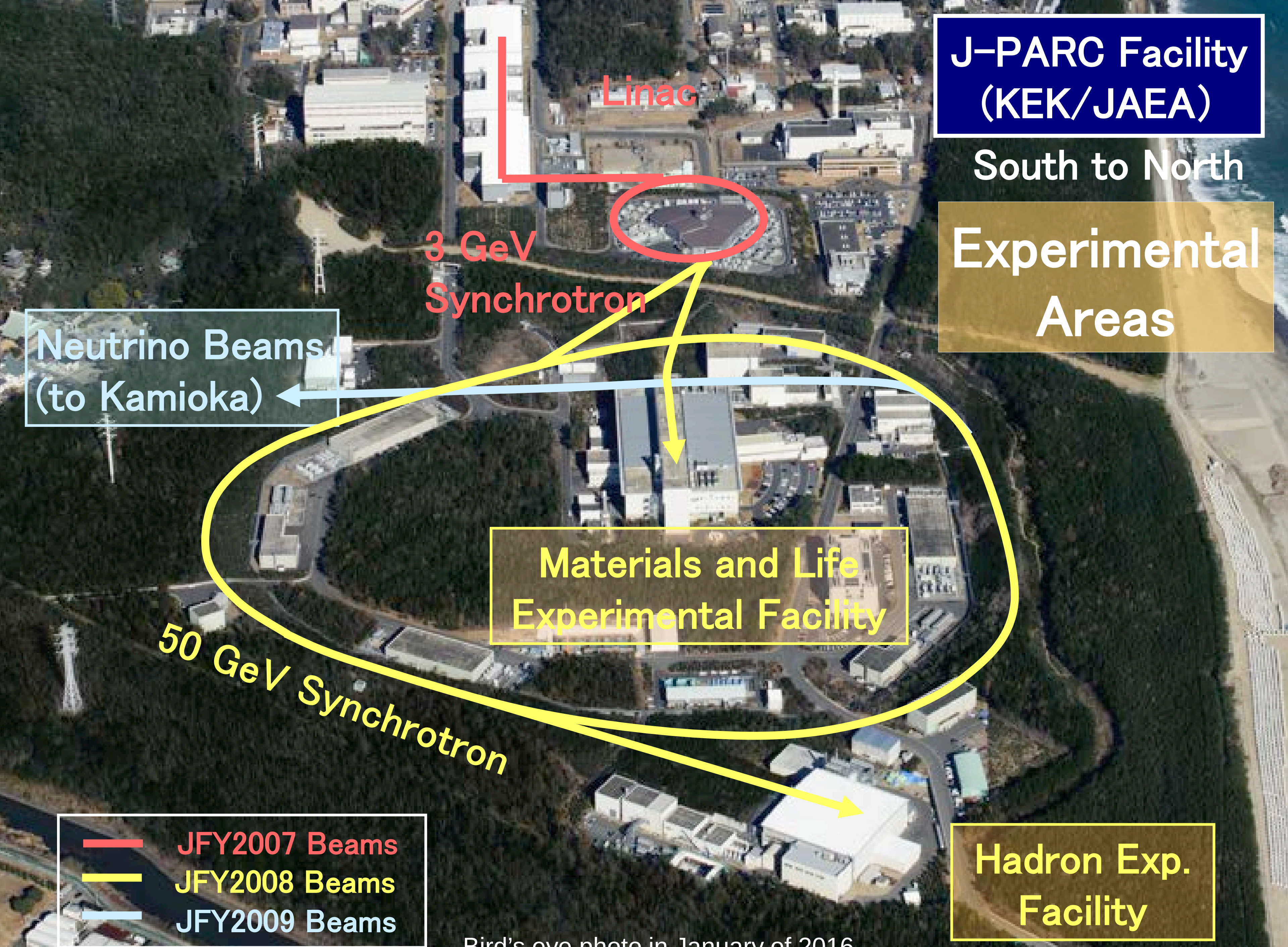
HADRON PHYSICS AT J-PARC

July 1, 2018
Shin'ya Sawada
澤田 真也
KEK (High Energy Accelerator Research Organization)

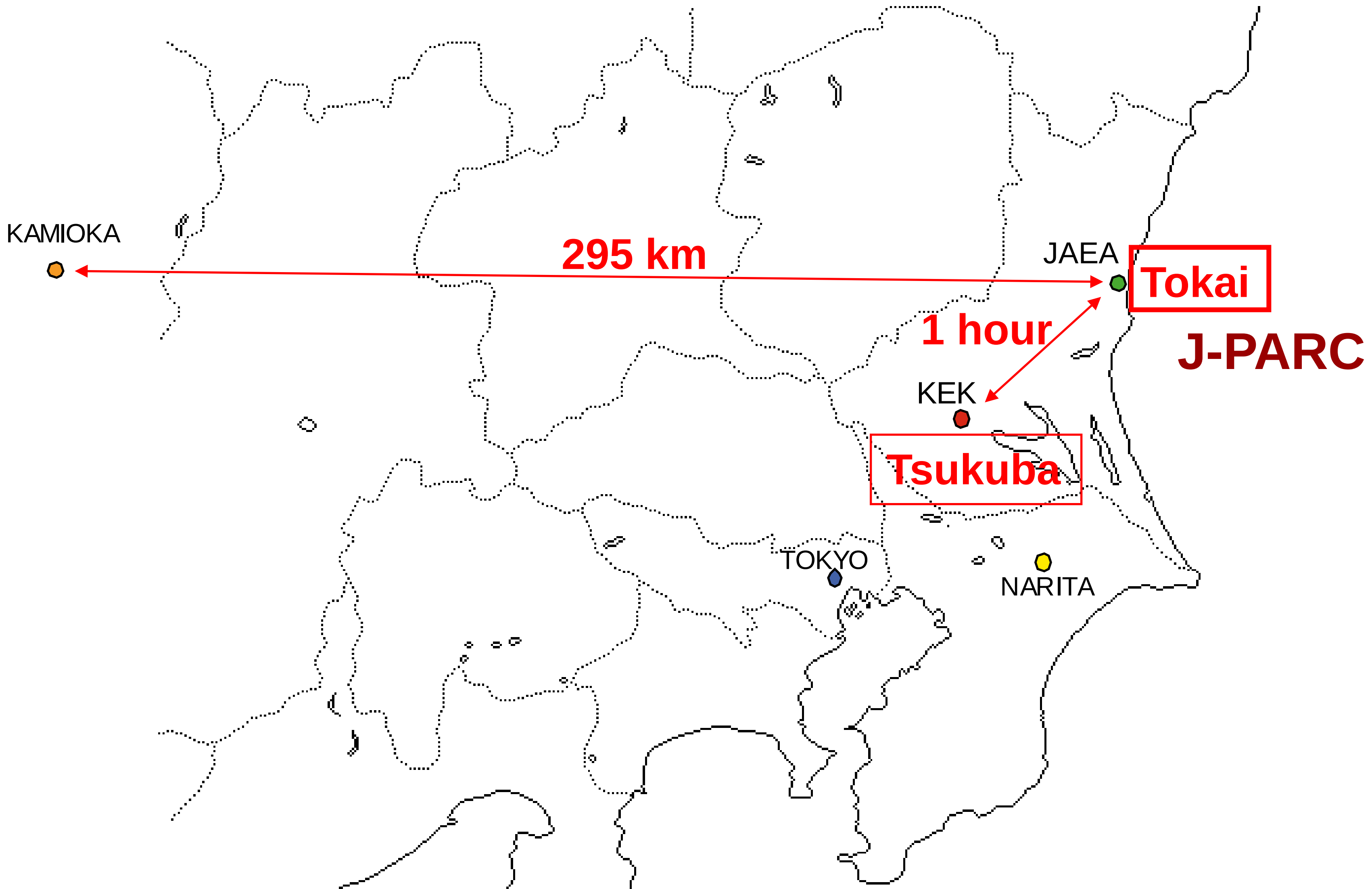
Contents

- J-PARC and Hadron Experimental Facility (Hadron Hall)
- Hadron physics overview and fruits so far obtained
- High-momentum beam line
- Extension
- Summary

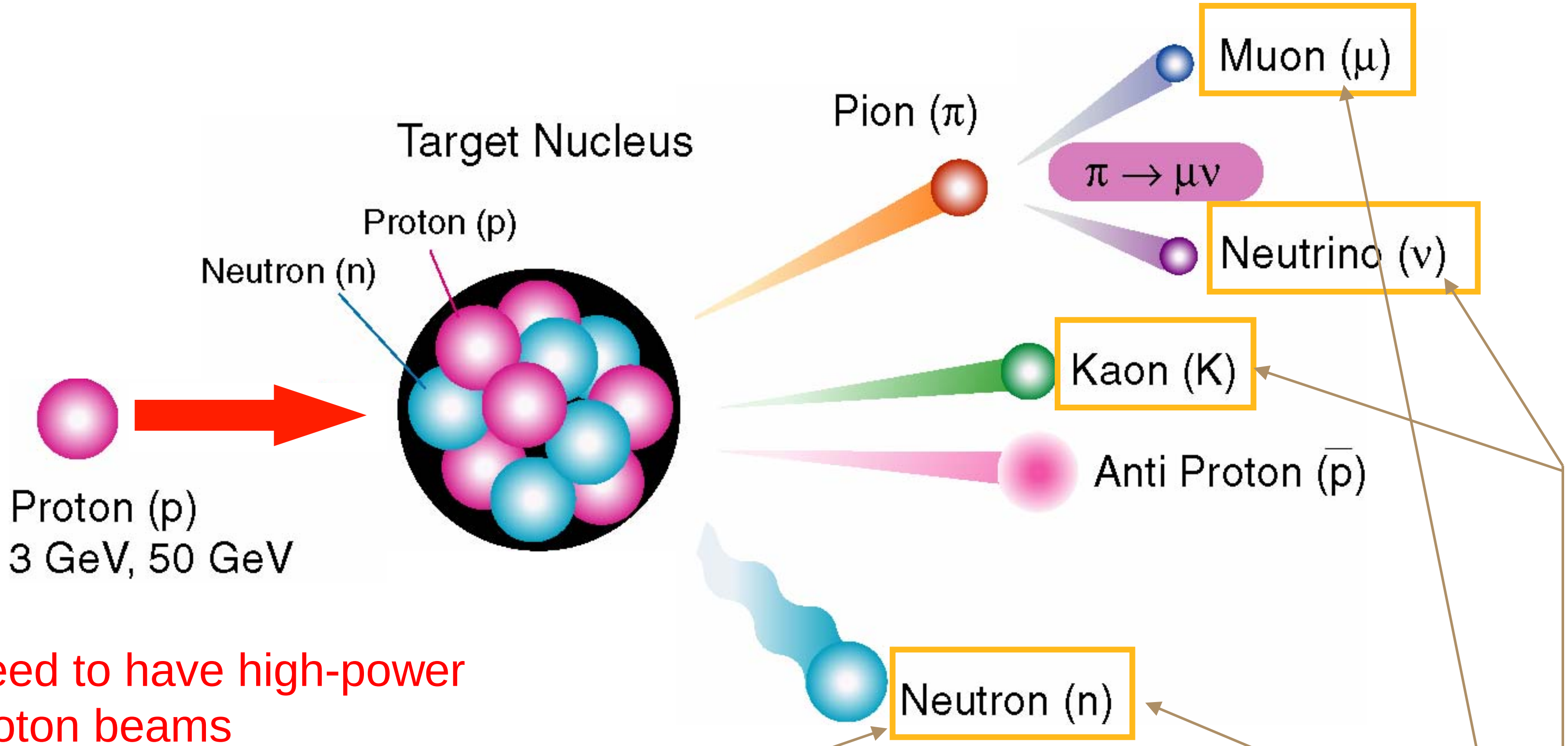


Bird's eye photo in January of 2016

Location of J-PARC



Goals at J-PARC

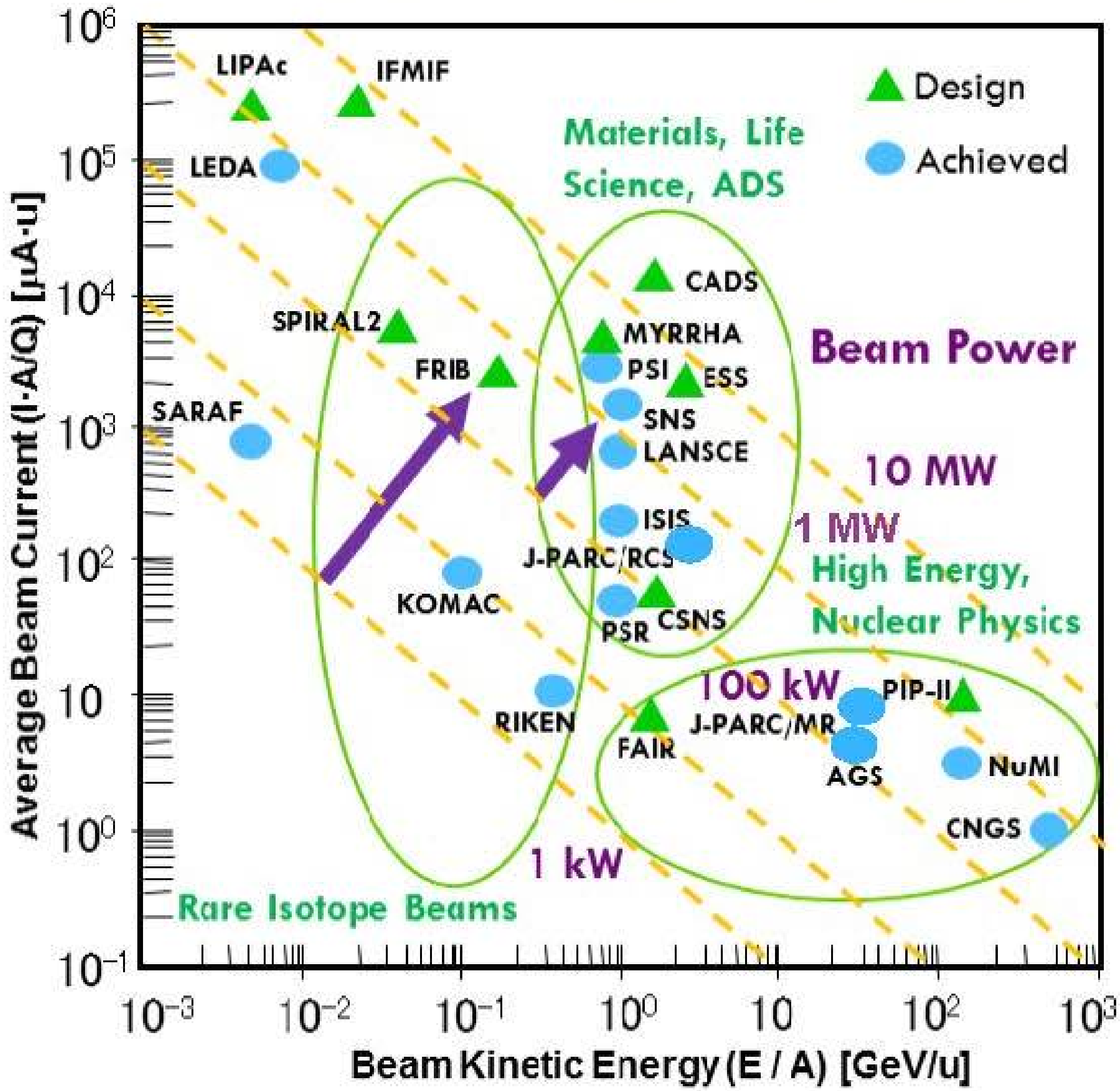


Need to have high-power proton beams

→ MW-class proton accelerator (current frontier is about 0.1 MW)

Materials & Life Sciences at 3 GeV
Nuclear & Particle Physics at 50 GeV
R&D toward Transmutation at 0.6 GeV

Hadron accelerators in the world



Jie Wei / Y. Yamazaki

Hadron Experimental Facility

Primary Beam Line: PTEP 2012, 02B008

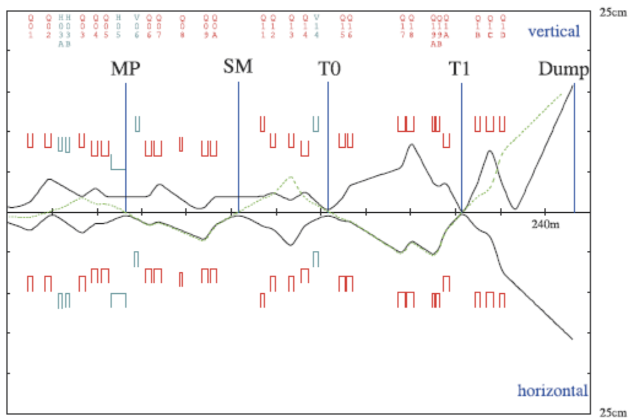
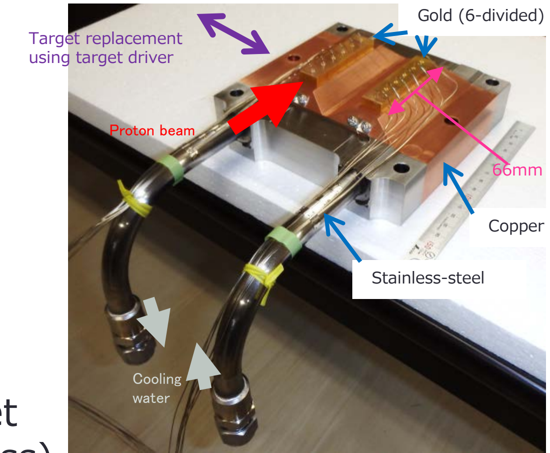
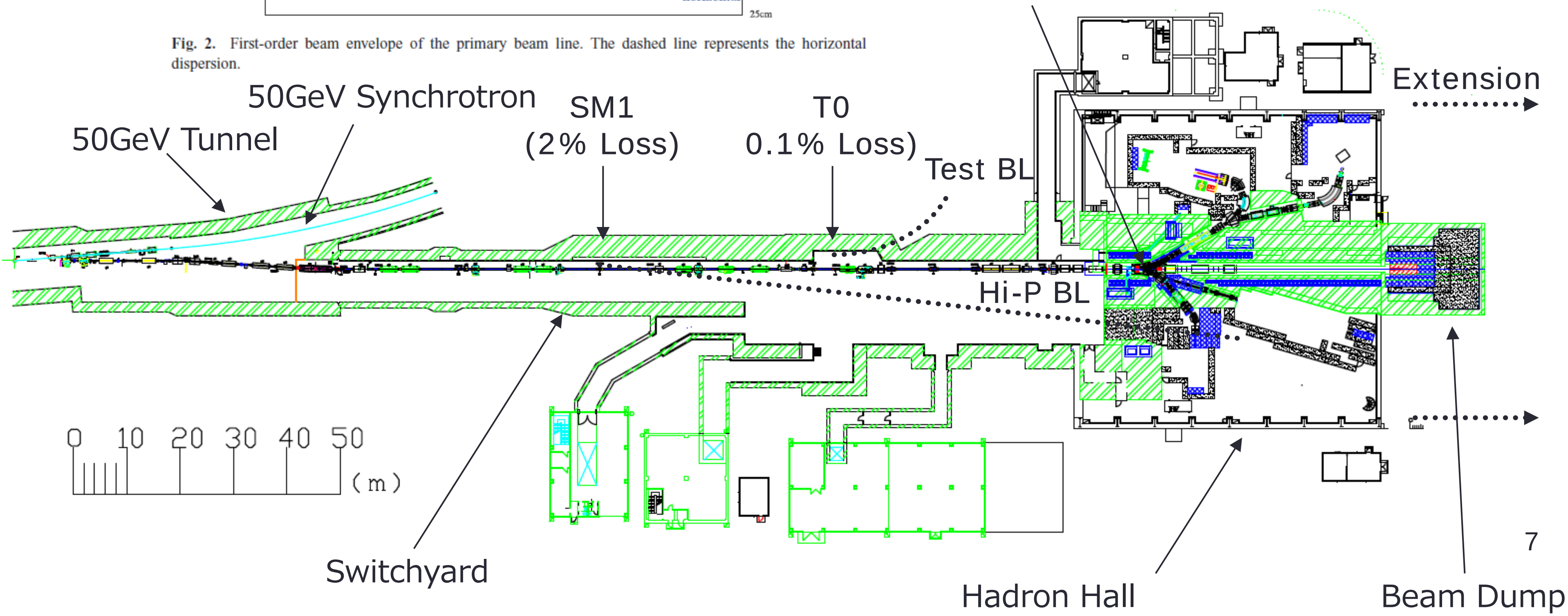
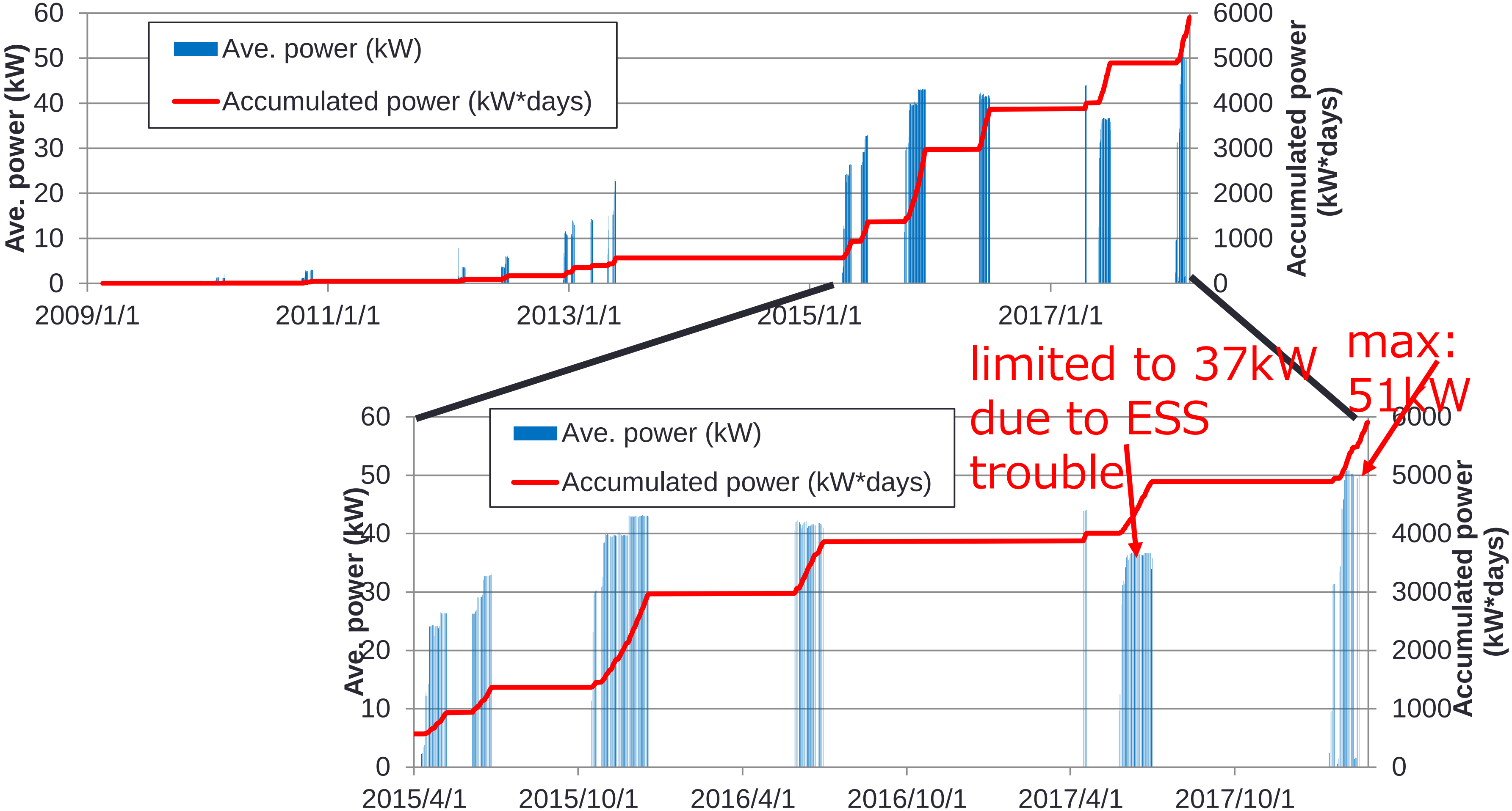


Fig. 2. First-order beam envelope of the primary beam line. The dashed line represents the horizontal dispersion.





Development of Beam Intensity

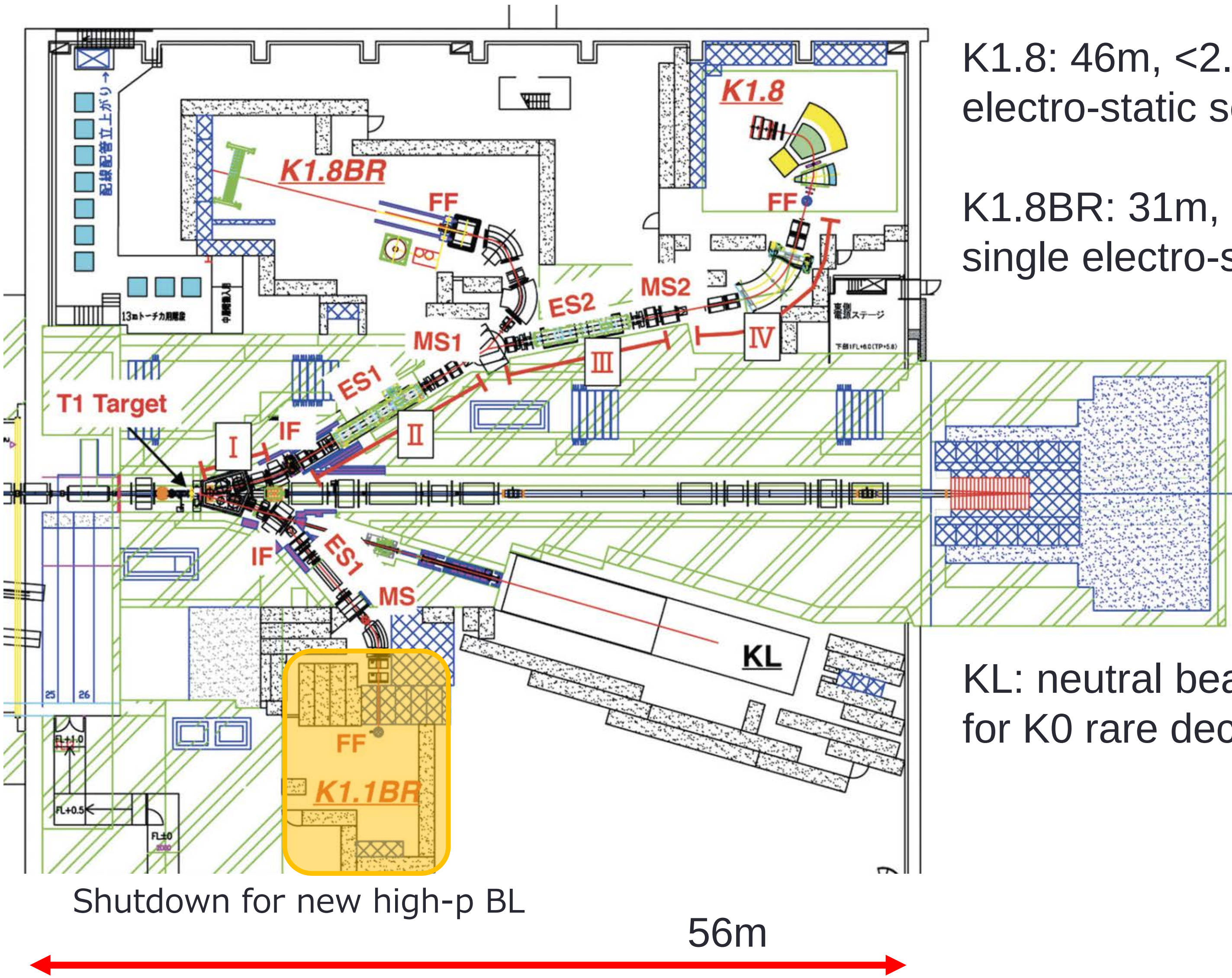


Accumulated beam time and intensity for HD

※spill: # of beam shots to HD

Before accident (Feb, 2009 – May, 2013): 1.26x10⁶ spills, 560 kW*days
JFY2015 run (Apr, 2015 – Dec, 2015): 1.05x10⁶ spills, 2338 kW*days
JFY2016 run (May, 2016 – Jun, 2016): 0.33x10⁶ spills, 875 kW*days
JFY2017 run (Apr, 2017 – Feb, 2018): 0.83x10⁶ spills, 2038 kW*days

Secondary Beam Lines



Shutdown for new high-p BL

56m

K1.8: 46m, <2.0 GeV/c, double electro-static separators

K1.8BR: 31m, <1.1 GeV/c, single electro-static separator

KL: neutral beam line dedicated for K0 rare decay experiment

K beam intensity

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

KEK-PS Beamline	K / spill (4s)	Protons / spill (4s)	Note
K2	$2x10^4$ K^-	$2x10^{12}$	1.67GeV/c, E522
	$1x10^4$ K^-	$3x10^{12}$	1.0GeV/c, E549
K5	$1.9x10^5$ K^+	$2.2x10^{12}$	0.66GeV/c, E470
	$6x10^3$ K^-	$1.5x10^{12}$	stopped, E549
K6	$1.3x10^4$ K^+	$0.87x10^{12}$	1.2GeV/c, E559

J-PARC K1.8 Beamline:

Beamline	K / spill (5.52s)	Protons / spill (5.52s)	Note
K1.8	$2x10^5$ K^-	$3.8x10^{13}$	1.8GeV/c, E07 purity=82.5%
	$5.8x10^5$ K^-	$3.5x10^{13}$	1.8GeV/c, purity=44%

Neutral Kaon Beam Line

Shiomi *et al.*, NIM A 664 (2012) 264 - 271

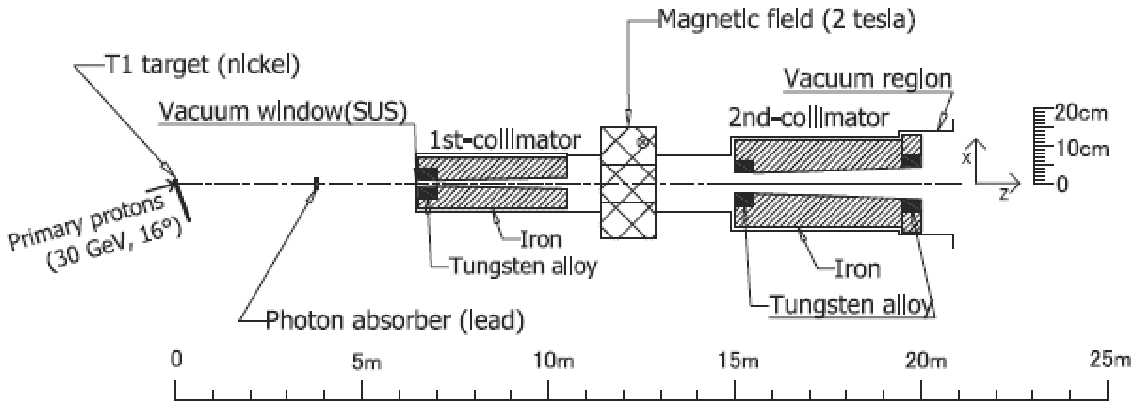


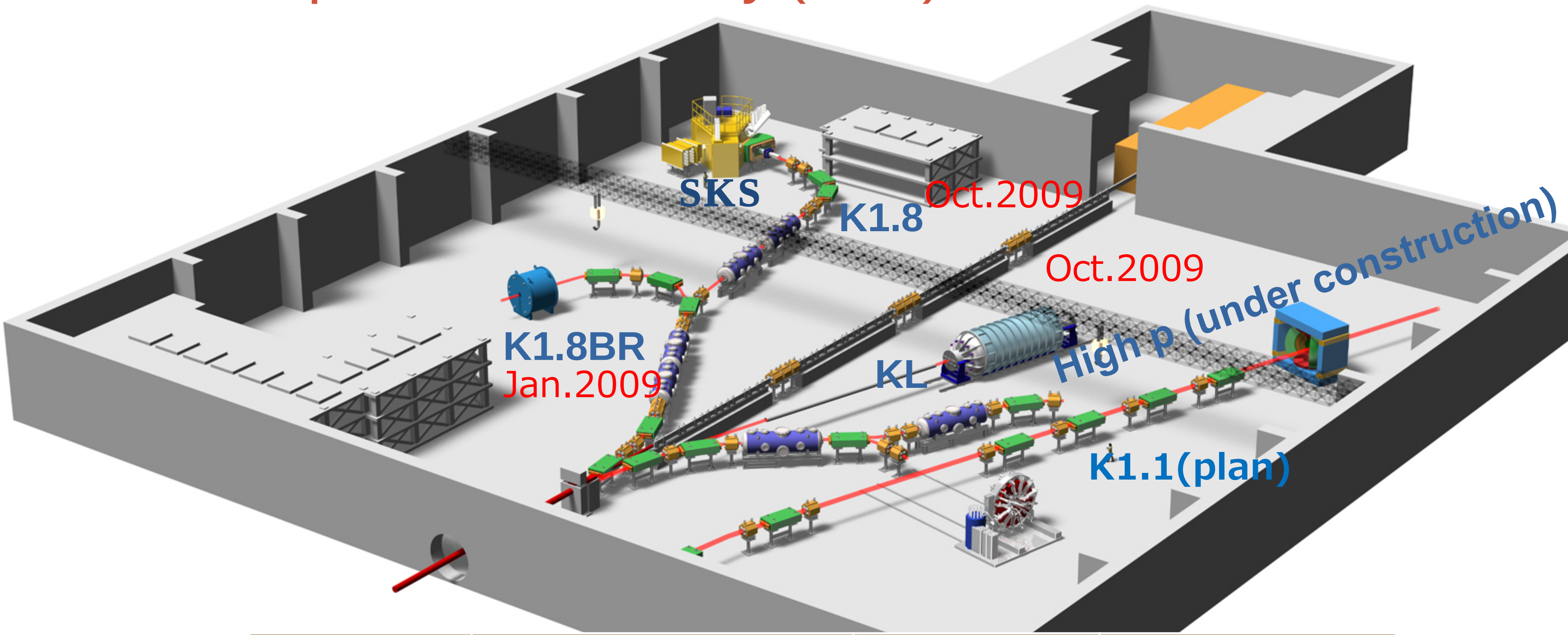
Fig. 1. Schematic layout of the neutral-kaon beam line. It consists of a pair of collimators and a sweeping magnet (2 T). A 7-cm-thick lead absorber is inserted in the beam line to reduce photons. Also shown is the coordinate system used in this paper: x in the horizontal, y in the vertical, and z in the beam directions. The origin of the coordinate is set at the center of the production target. The exit window of the beam line (not shown) is located at z=20.6 m.

Table 7

Resultant K_L^0 flux at the exit of the beam line. The K_L^0 yields for the Ni and the Pt targets and their ratio were summarized, together with the expectations by MC simulations. The first uncertainties are statistical and the second ones are systematic (discussed in Section 4.3).

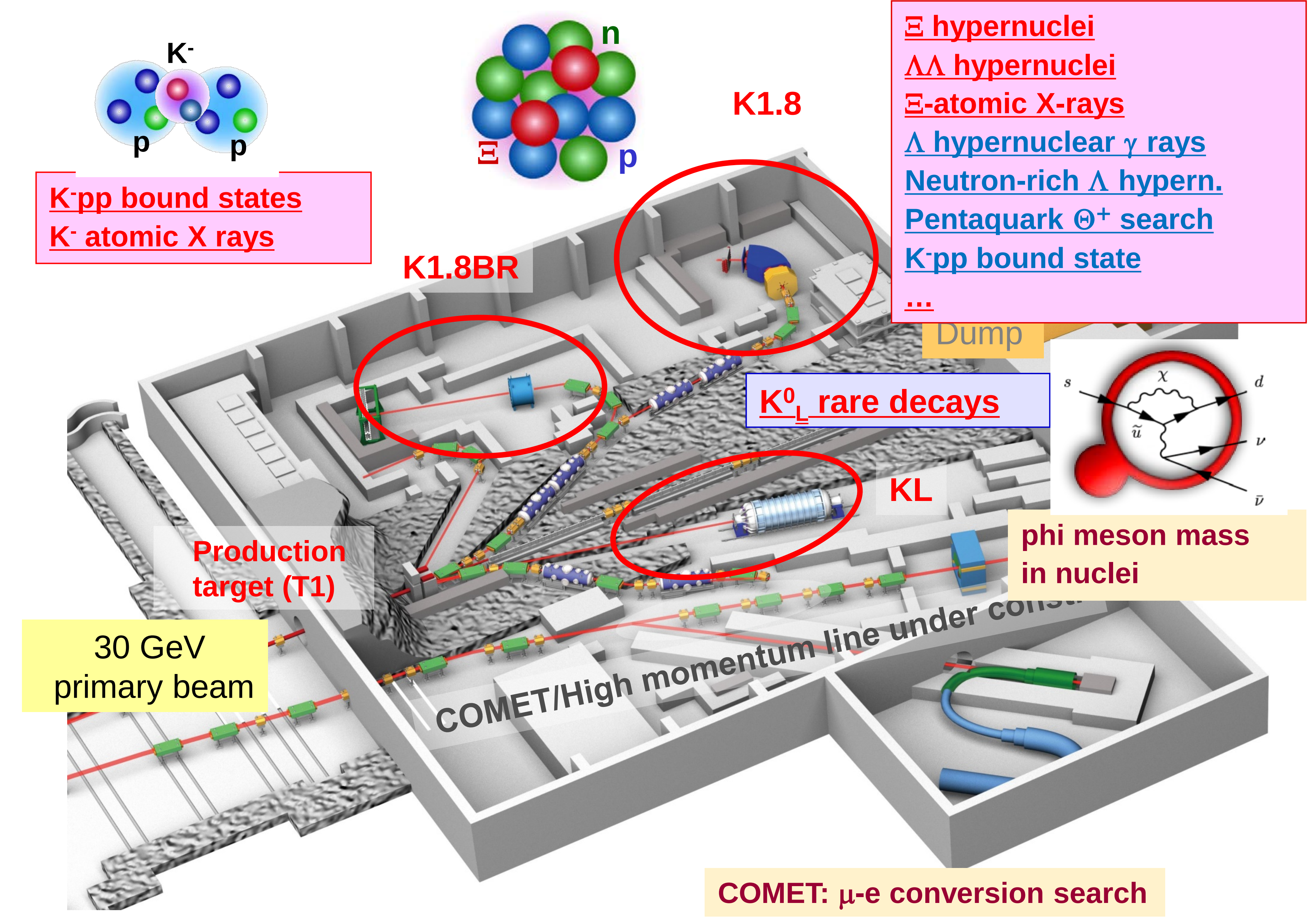
Target	Flux (normalized to 2×10^{14} POT)			
	Data	GEANT4	GEANT3	FLUKA
Ni (5.4-cm-long)	$(1.94 \pm 0.05^{+0.25}_{-0.24}) \times 10^7$	0.74×10^7	1.51×10^7	2.07×10^7
Pt (6.0-cm-long)	$(4.19 \pm 0.09^{+0.47}_{-0.44}) \times 10^7$	1.52×10^7	2.38×10^7	3.24×10^7
Pt/Ni ratio	$2.16^{+0.38}_{-0.36}$	2.05	1.58	1.56

Hadron Experimental Facility (HEF)



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

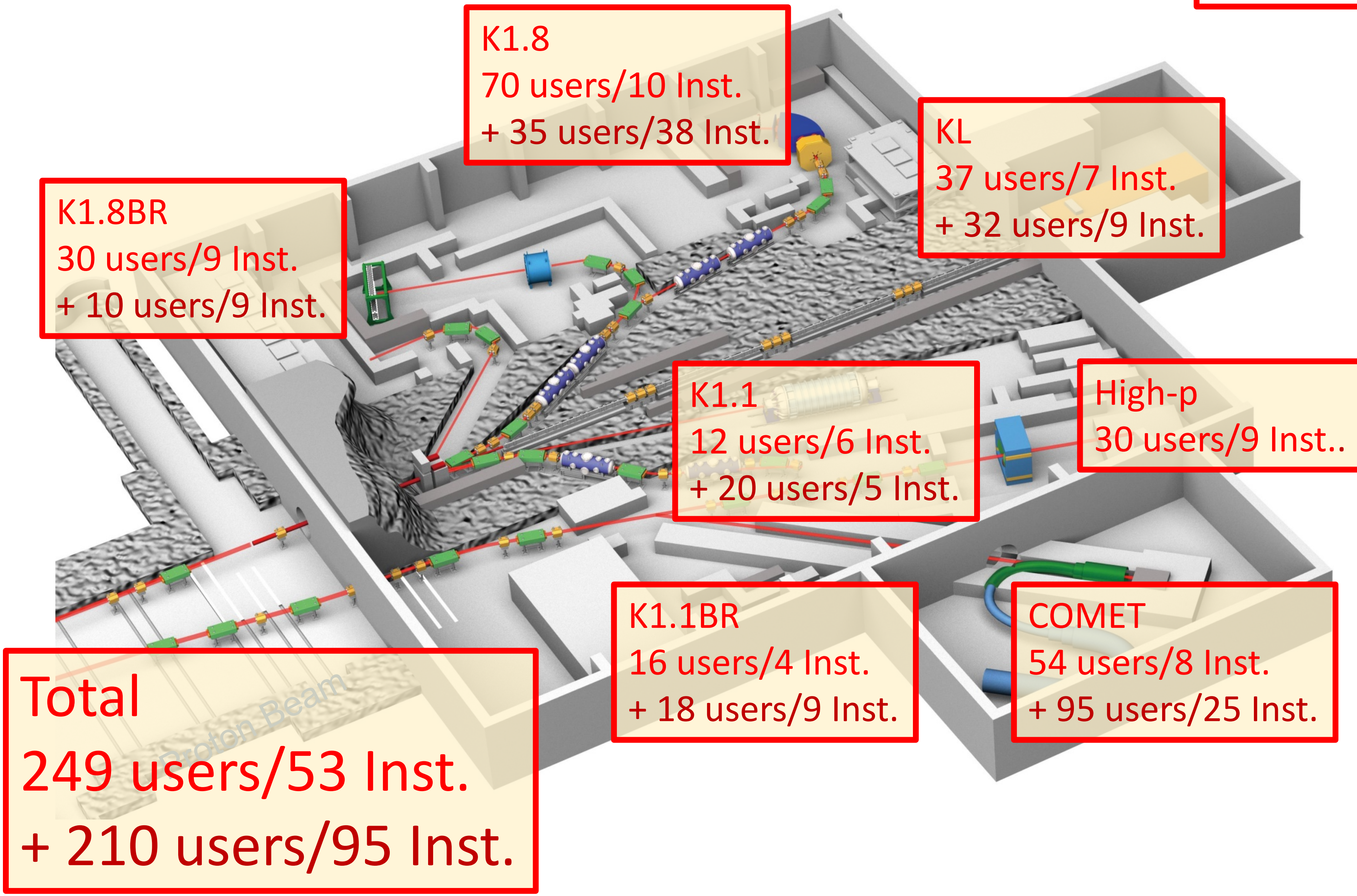
Intense Kaon Beam in the momentum range of ~ 1 GeV/c



K^-
p
p
n
Ξ
p
K^-pp bound states
K^- atomic X rays
K1.8
K1.8BR
Ξ hypernuclei
ΛΛ hypernuclei
Ξ-atomic X-rays
Λ hypernuclear γ rays
Neutron-rich Λ hypern.
Pentaquark Θ^+ search
K^-pp bound state
...
Dump
K^0_L rare decays
KL
phi meson mass in nuclei
Production target (T1)
30 GeV primary beam
COMET/High momentum line under const.
COMET: μ-e conversion search

Number of Users/Institutions (as of 2015)

domestic
abroad



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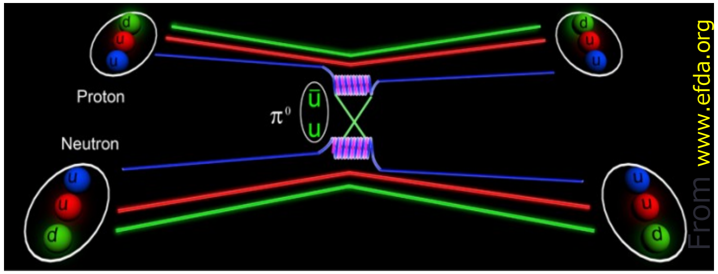
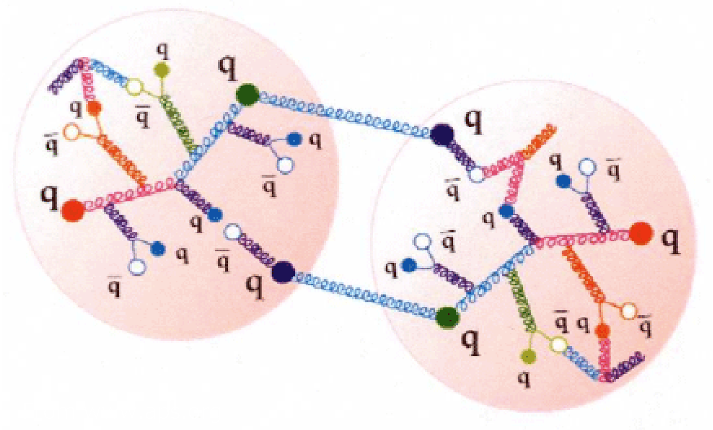
Nuclear/Hadron Physics at J-PARC

- Interaction and structure of hadrons!
  - Nucleon-nucleon interaction, especially at medium and long ranges, has been rather well studied, since Yukawa's prediction of the pi meson.

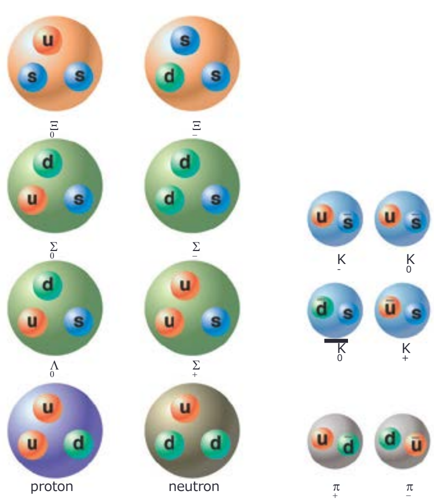


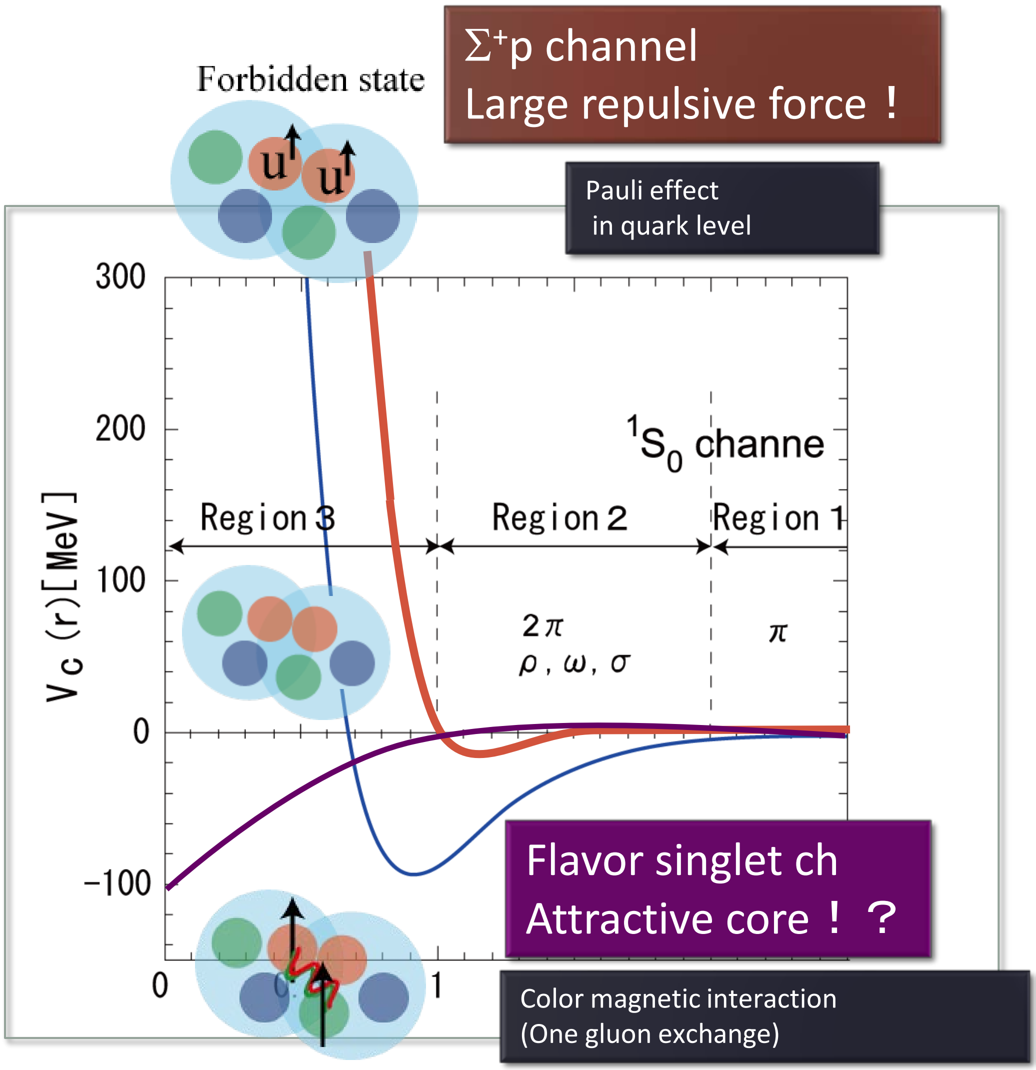
  - But at the short range, substructures of the nucleon should affect the interaction.



Nuclear/Hadron Physics at J-PARC

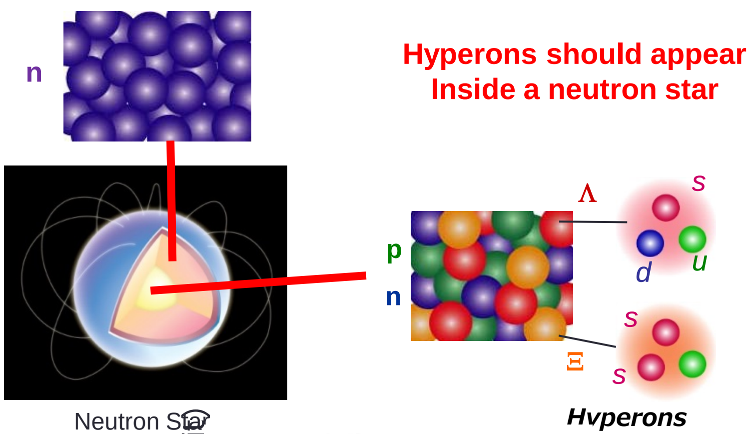
- Especially, the origin of the repulsive core and the spin-orbit force has not been understood.
- We explore the hadron interaction not only with up and down quarks but also with strange quarks.



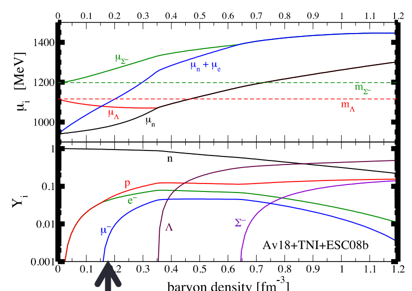


Importance of understanding hadron interaction

- Recent observation of 2-solar-mass neutron stars
  - 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.

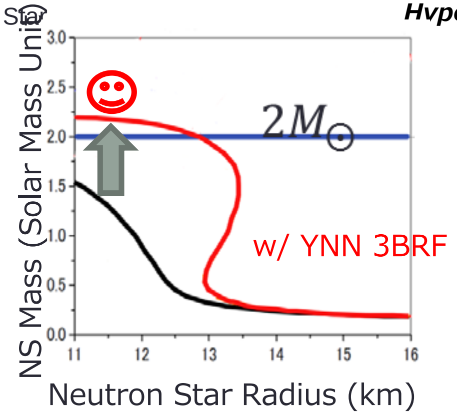


Theoretical prediction from known YN, YY 2-body interactions (Y=hyperon)



ρ0 (normal nuclear density)

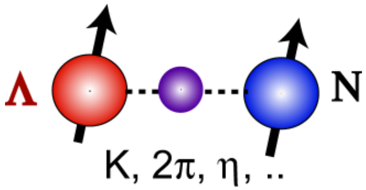
I. Bombaci, arXiv:1601.05339v1

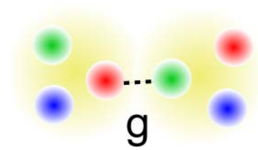


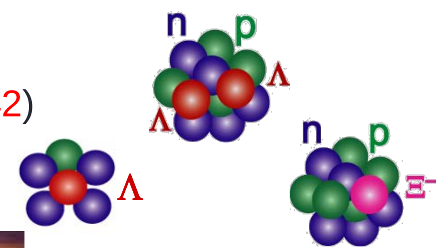
Neutron star merger detected by gravitational waves also attracts interests on the EoS.

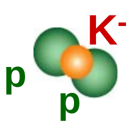
Nuclear/Hadron Physics at HEF

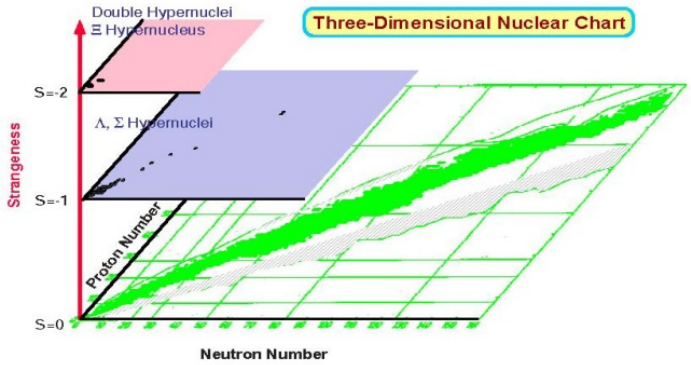
- Unified understanding of baryon-baryon forces
  - Meson exchange picture / quark pictures
  - Origins of short-range nuclear forces
  - Test lattice QCD calculations
    - Structure of various hypernuclei
      - γ-ray spectroscopy(E13), double-strangeness system(E03/E05/E07/E42)
    - YN scattering experiments (E40)
- YN, YY, K^{bar}N interactions in nuclear matter
  - High density matter in neutron stars
  - Baryon properties in nuclei
    - Structure of various hypernuclei (E10)
    - Kaonic nuclear bound states (E15/E17/E27/E31)
    - Hyperon properties in nuclei
- Hadrons in vacuum and medium
  - Exotic hadrons (E19)
  - In-medium property of hadrons → Chiral Symmetry Breaking (CSB)
    - meson-mass spectroscopy (E16)
  - Charmed baryon spectroscopy (E50)











Blue: performed or on-going
Red: plan

Major Fruits – Pion Era

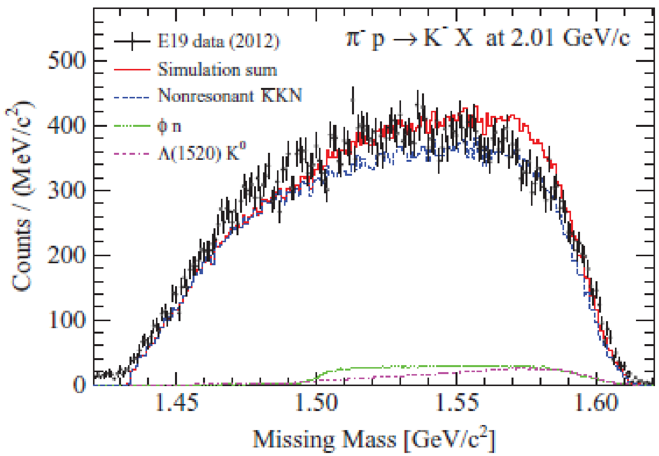
- Pion Era: At the beginning of the history, the proton intensity was lower so that only pions can be used as a beam for experiments in reality.
  - Search for the Θ^+ pentaquark via the $\pi^- p \rightarrow K^- X$ reaction at 1.92 GeV/c, K.Shirotori *et al*., Phys. Rev. Lett 109, 132002 (2012) (E19)
  - Search for $^{6}_{\Lambda}H$ hypernucleus by the $^{6}Li(\pi^-,K^+)$ reaction at p_p = 1.2 GeV/c", H.Sugimura *et al*., Phys. Lett. B729, 39 (2014) (E10)
  - Inclusive spectrum of the $d(\pi^+, K^+)$ reaction at 1.69 GeV/c, Y.Ichikawa *et al*., Prog. Theor. Exp. Phys. 2014, 101D03 (2014) (E27)
  - High-resolution search for the Θ^+ pentaquark via a pion-induced reaction at J-PARC", M.Moritsu *et al*., Phys. Rev. C90, 035205 (2014) (E19)
  - Observation of "K^-pp"-like structure in the $d(\pi^+,K^+)$ reaction at 1.69 GeV/c, Y.Ichikawa *et al.*, Prog. Theor. Exp. Phys. 2015, 021D01 (2015) (E27)

Results (1)

2010, Jan.2012

- E19:Search for Θ^+ by $\pi^- + p \rightarrow K^- X$
  - No peak was observed
  - U.L. of cross section : 0.28μb/sr
  - U.L. of Θ^+ width: 0.36 (1.9) MeV for ½ $^+$ (½$^-$)

PRL **109**, 132002(2012)
PRC **90**, 035205(2014)

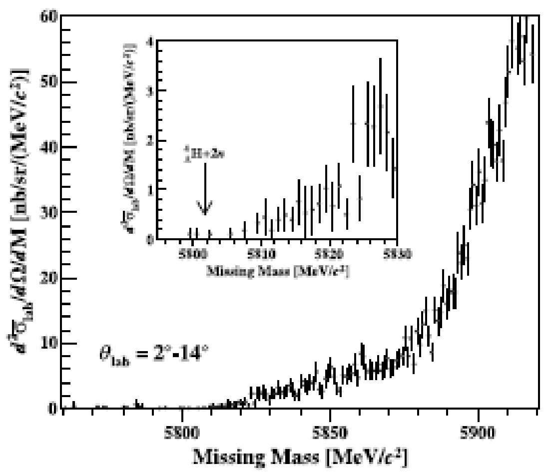


Dec.2012-Jan.2013

- E10:Neutron-rich $^6_\Lambda H$ via the $^6Li(\pi^-, K^+)$
  - No peak was observed
  - U.L. of cross section :1.2nb/sr

⇔ Observation of 3 candidates by FINUDA (PRL **108**,04251(2012))

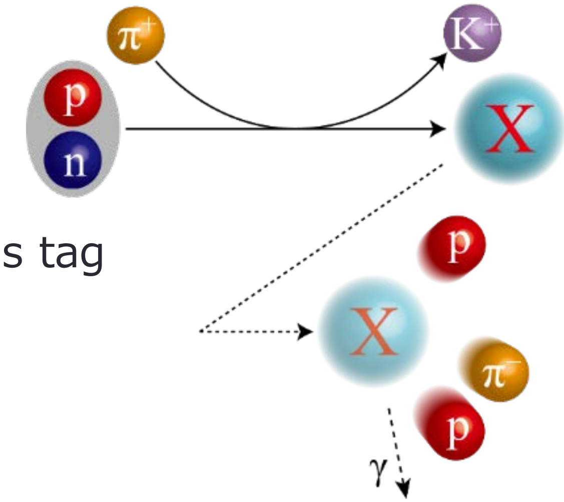
PLB **729**, 39 (2014)



Results (2)

- E27: Search for K^-pp bound states by the $d(\pi^+,K^+)$ at P_π=1.7GeV/c

Experimental Method



Jun. 2012

Missing mass spectrum is obtained with two protons tag

Observation of "K^-pp"-like structure

PTEP **2015**, 021D01 (2015)

Binding Energy	95	$^{+18}_{-17}$ (stat.) $^{+30}_{-21}$ (syst.) MeV
Width	162	$^{+87}_{-45}$ (stat.) $^{+66}_{-78}$ (syst.) MeV

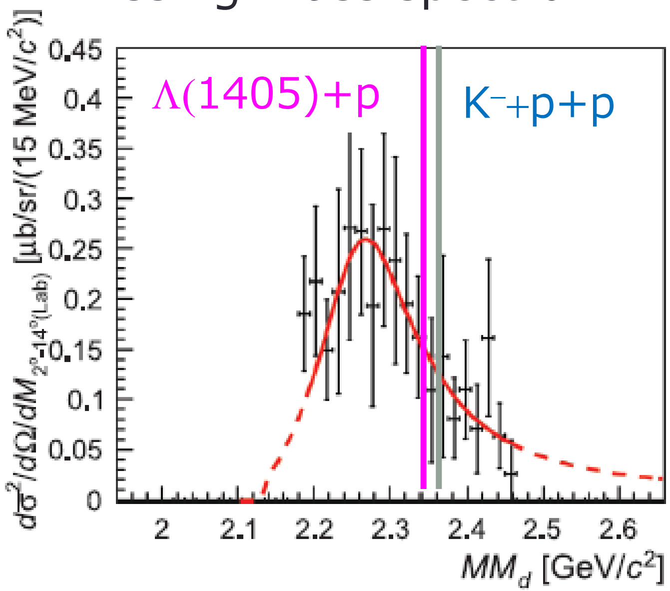
A positive signature of K^-pp bound state was obtained. Comparison with other experiments and theoretical studies are necessary and important to establish K^-pp bound state.

Analysis of inclusive spectrum was also published.

PTEP **2014**, 101D03(2014)

- ΣN-ΛN cusp
- Shift of Y* bump

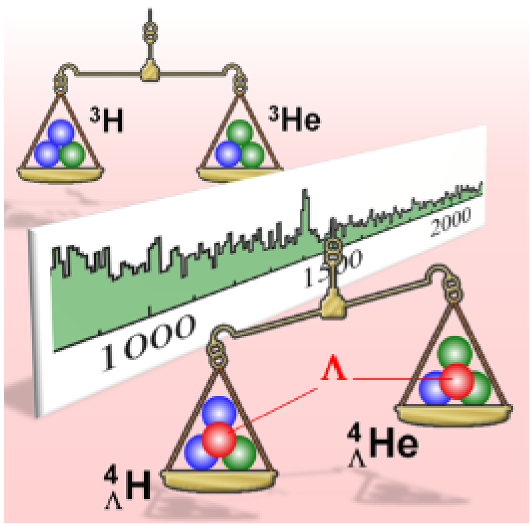
Missing mass spectrum



Major Fruits – Kaon Era

- Kaon Era: The proton intensity was improved to >20kW and the era for experiments with charged kaons as a beam started.
  - The first evidence of a deeply bound state of Ξ^{-}-^{14}N system, K. Nakazawa *et al.*, Prog. Theor. Exp. Phys. 2015, 033D02 (2015) (E07-pre)
  - Search for the deeply bound $K^{-}pp$ state from the semi-inclusive forward-neutron spectrum in the in-flight K^{-} reaction on helium-3, T.Hashimoto *et al*., Prog. Theor. Exp. Phys. 2015, 061D01 (2015) (E15)
  - Observation of Spin-Dependent Charge Symmetry Breaking in ΛN Interaction: Gamma-Ray Spectroscopy of $^{4}_{\Lambda}$He, T.O.Yamamoto *et al*., Phys. Rev. Lett. **115**, 222501 (2015) "Editor's Suggestion" (E13)
  - Structure near $K^{-}+p+p$ threshold in the in-flight ^{3}He(K^{-}, Λp)n reaction, J-PARC E15 Collaboration Y.Sada *et al.*, Prog. Theor. Exp. Phys. , 2016, 051D01 (2016) (E15)

PHYSICAL REVIEW LETTERS
moving physics forward



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)

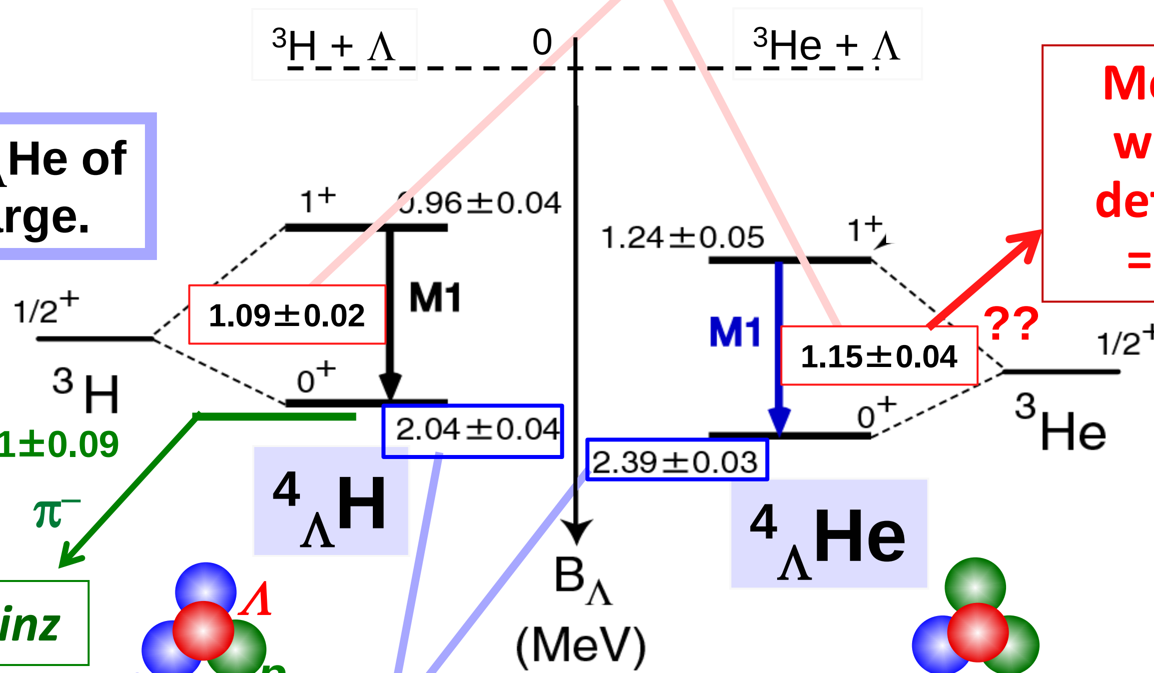
Press-released from Tohoku U., KEK, JAEA, J-PARC

Charge Symmetry Breaking puzzle in hypernuclei

^{3}H / ^{3}He binding energy difference due to strong int.
~60 keV

B_Λ diff. in $^4_\Lambda$H / $^4_\Lambda$He of 350 keV is too large.

Old NaI data
Bedjidian et al.
PLB 62 (1976) 467
PLB 83 (1979) 252



Measure with Ge detectors => E13

2.12±0.01±0.09
π⁻

Measured at Mainz

A. Esser et al.,
PRL 114 (2015) 12501

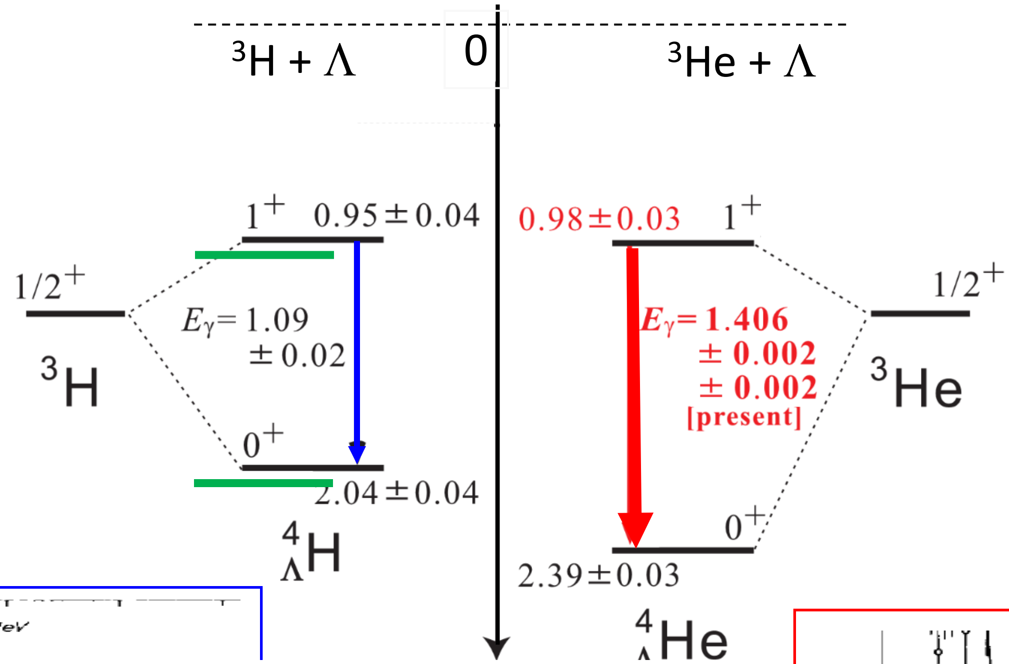
Old emulsion data — *no systematic errors given*

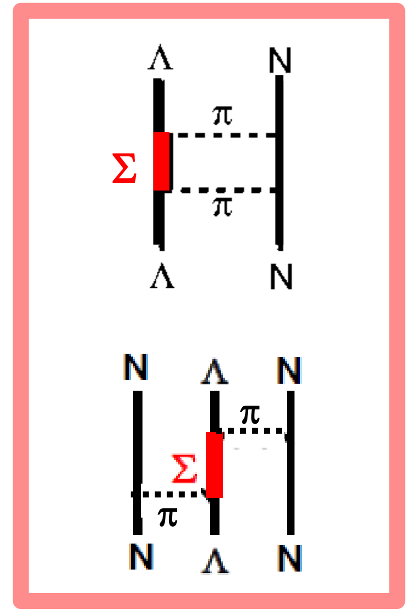
M. Juric et al. NPB 52 (1973) 1

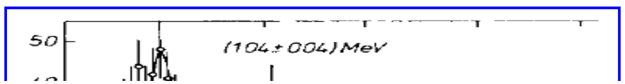
4-body exact calc's with Λ–Σ mixing using Nijmegen BB interaction models failed
=> Long standing puzzle

Experimental confirmation of CSB is necessary

Results







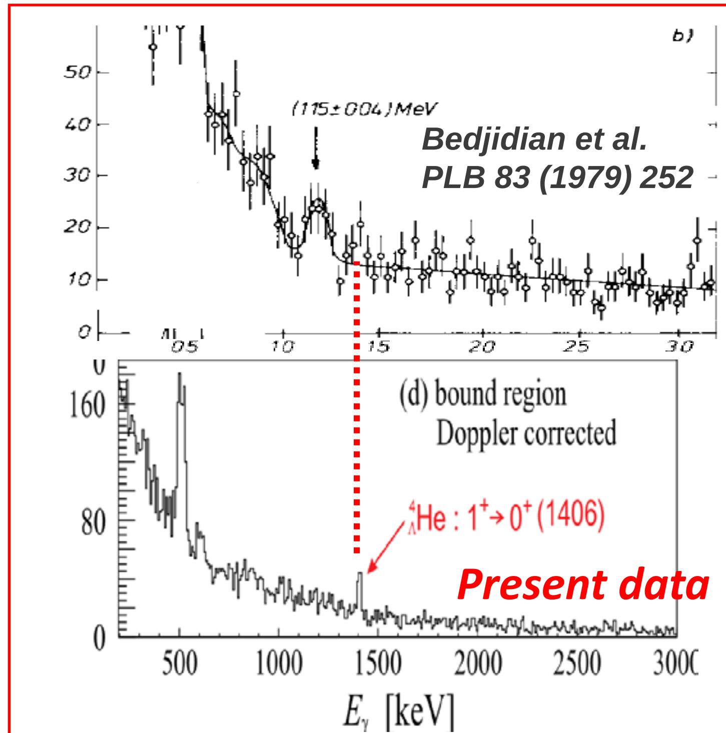
=> Existence of a large CSB effect confirmed only by γ-ray data

Combining with emulsion data,	**$\Delta B_\Lambda(1^+)$: 0.03±0.05 MeV** **$\Delta B_\Lambda(0^+)$: 0.35±0.05 MeV**

=> Large spin dependence in CSB found

=> CSB is sensitive to Σ mixing.
ΛN–ΣN coupling force in the existing BB int models should be modified.

Energy of γ-rays (MeV)



Results (3)

- E15: Search for K^-pp bound states by the $^3He(K^-,n)X \to \Lambda p$

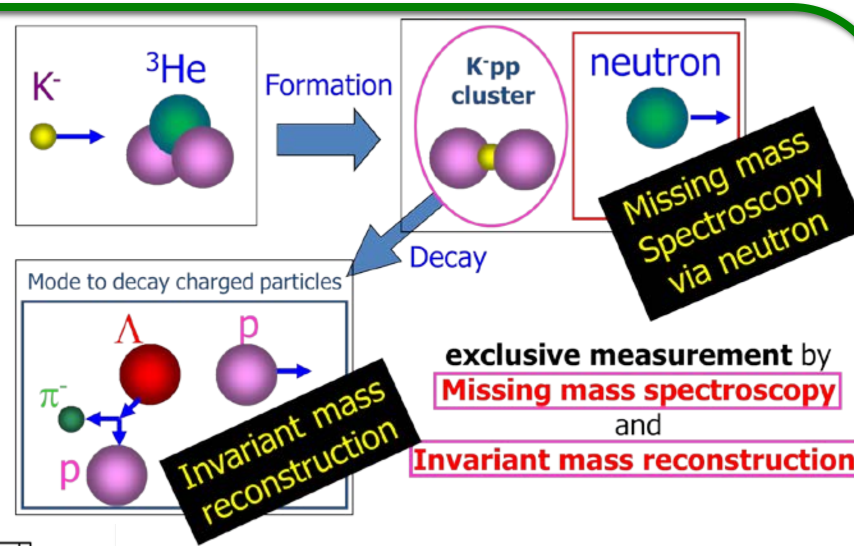
1st- stage RUN with limited statistics

PTEP (2015) 061D01

PTEP (2016) 051D01

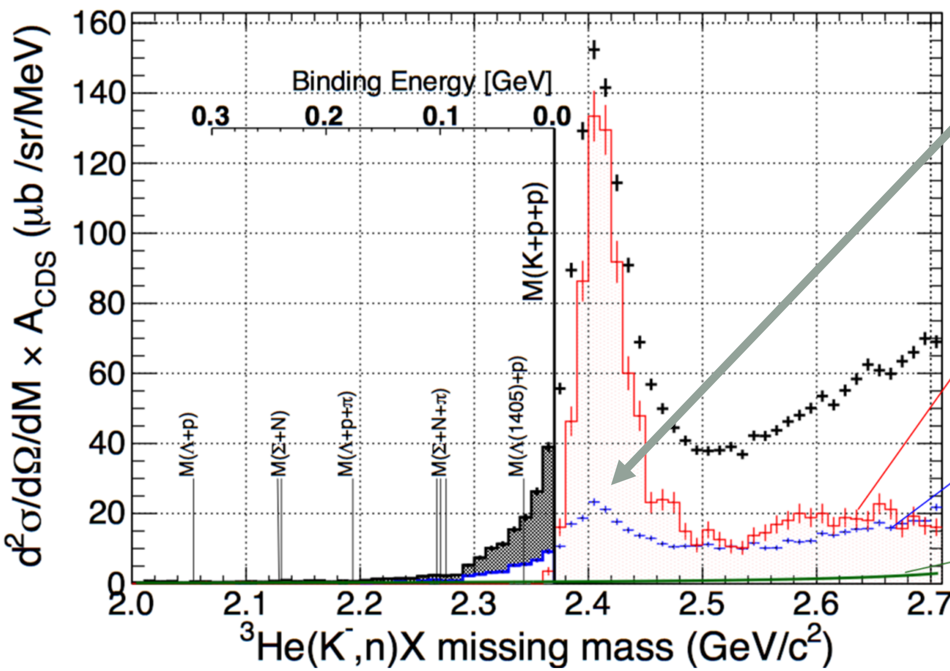
2nd- stage RUN

arXiv:1805.12275v1



exclusive measurement by **Missing mass spectroscopy** and **Invariant mass reconstruction**

PTEP (2015) 061D01



Significant enhancements were observed in a bound-region

"semi"-inclusive

~10MeV/c^2 resolution

K^0_s-tagged x 8

Contribution of $\Sigma \to n\pi$

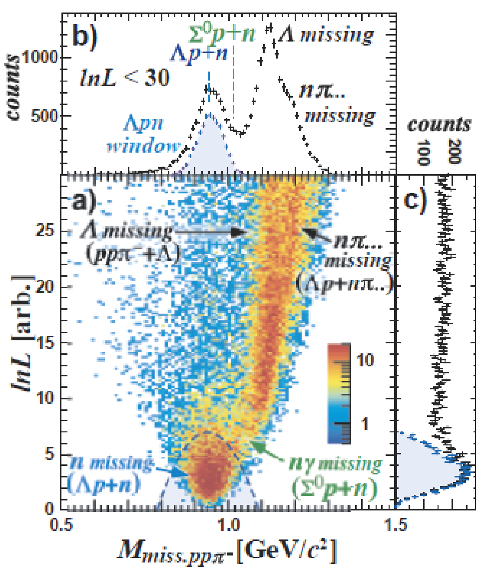
(No other contribution in a bound-region due to kinematical limitations)

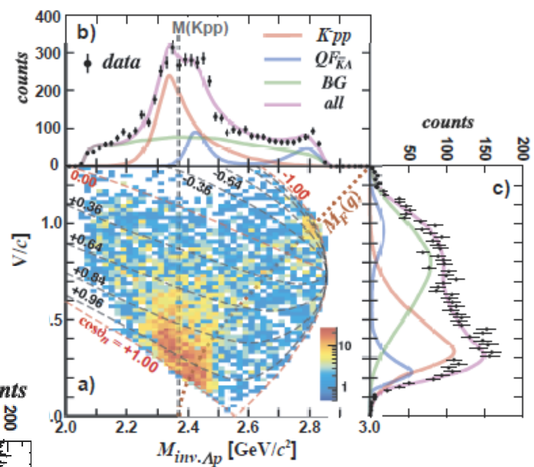
Accidental

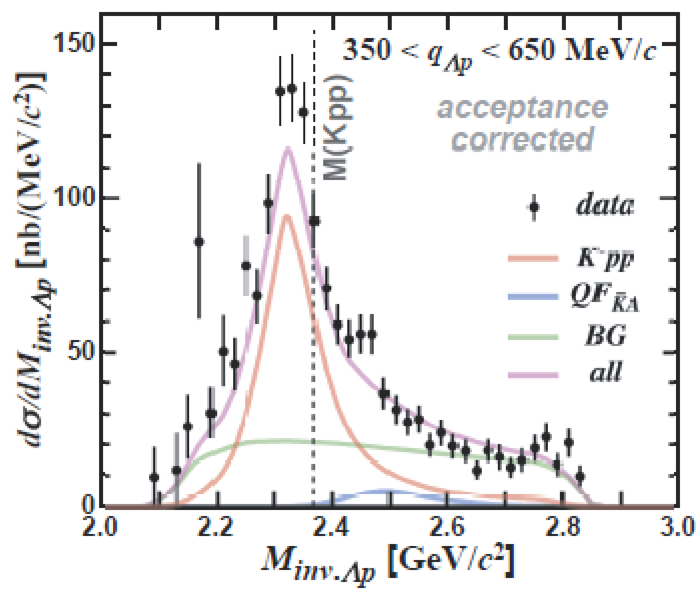
$K^{-}pp$ states

- The E15 collaboration has submitted a result from the 2nd run which is available on the arXiv.
- This should be a door to investigation of high density matter.

arXiv:1805.12275v1





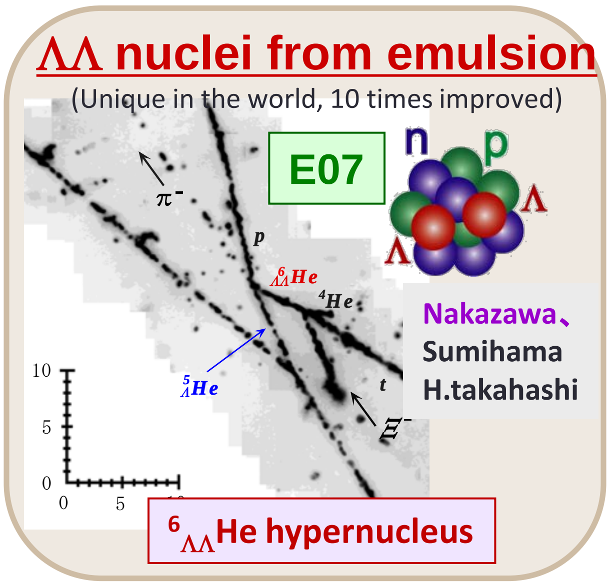


$B_{K\text{-}pp}$ = 47+-3(stat.)+3-6(sys.) MeV

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

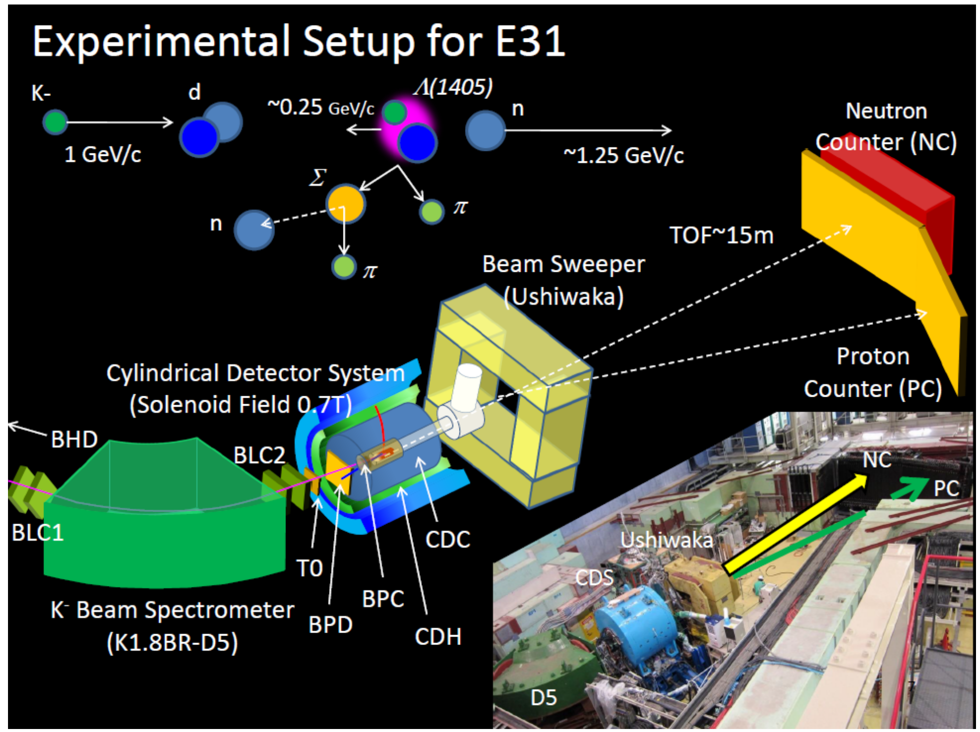
Experiments just completed

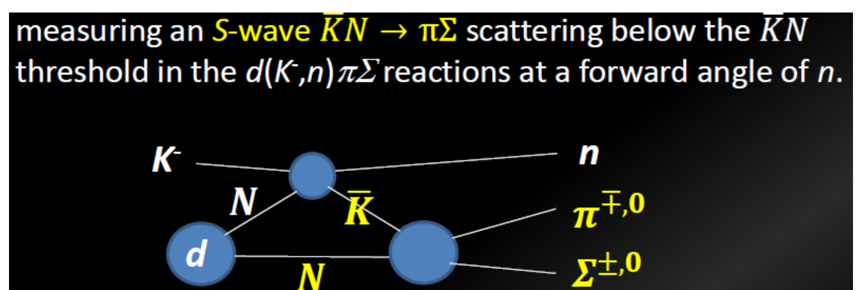
ΞN→ΛΛ int.



Just completed irradiation of 100 emulsion stacks

Lambda(1405) **E31**

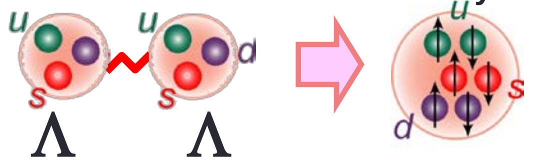




Near Future

ΛΛ int.

H dibaryon？



Σ^+p scattering（unique） Miwa, Tamura

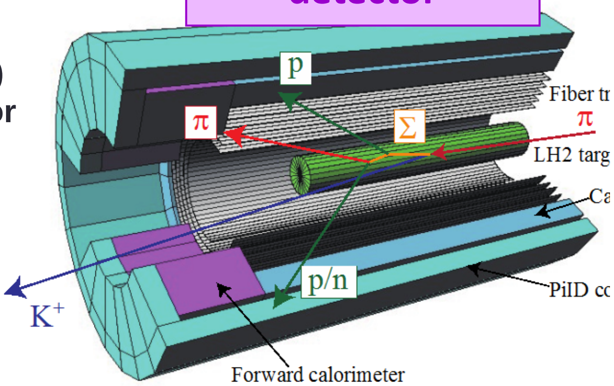
-> Σ^-n (= Σ^+p) int.

=> Σ^- exists in n-star or not

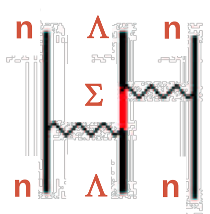
E40

Sattered proton detector

Ultra-fast (x100)
Tracking detector
Using MPPC



Λ–Σ coherent coupling

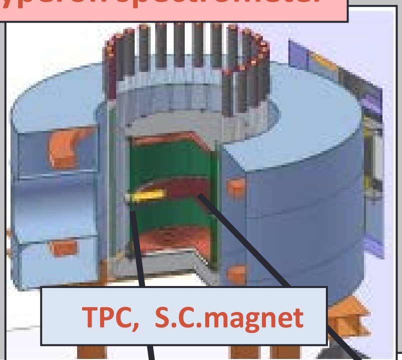


ΛΛ correlation

(Unique in the world)

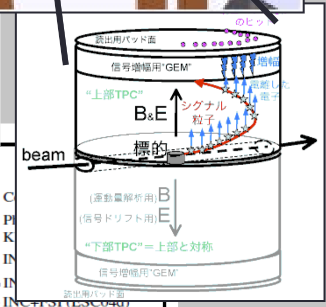
Hyperon spectrometer

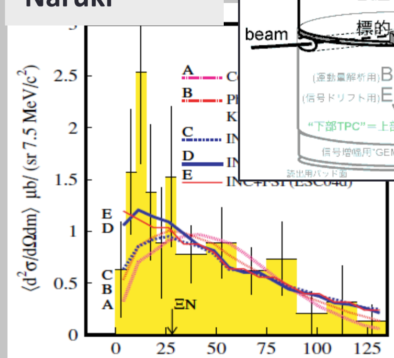
E42



TPC, S.C.magnet

Sato, Imai, Takahashi, Naruki





Peak in ΛΛ invariant mass

Particle Physics at Hadron Experimental Facility

- KOTO

PTEP

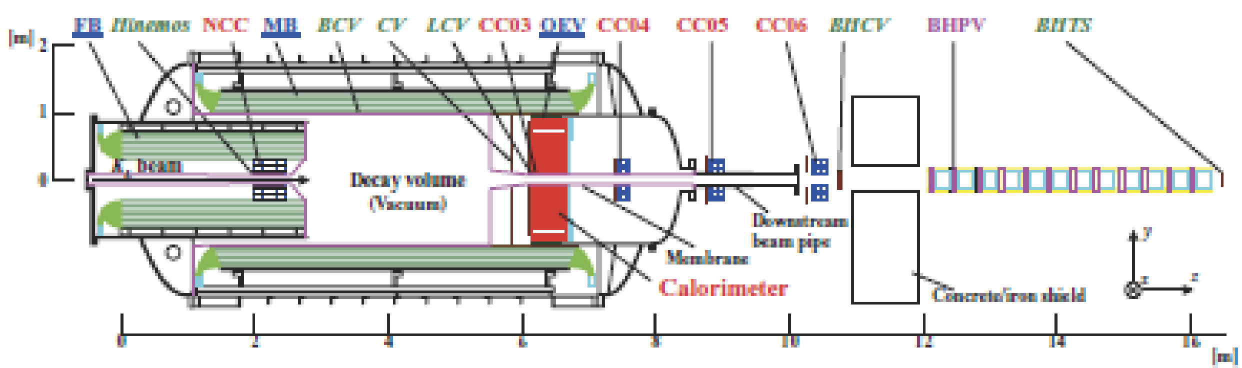
Prog. Theor. Exp. Phys. 2017, 021C01 (11 pages)
DOI: 10.1093/ptep/ptx001

Letter

A new search for the $K_L \to \pi^0 \nu\bar{\nu}$ and $K_L \to \pi^0 X^0$ decays

J-PARC KOTO Collaboration

We searched for the *CP*-violating rare decay of the neutral kaon, $K_L \to \pi^0 \nu\bar{\nu}$, in data from the first 100 hours of physics running in 2013 of the J-PARC KOTO experiment. One candidate event was observed while 0.34 ± 0.16 background events were expected. We set an upper limit of 5.1×10^{-8} for the branching fraction at the 90% confidence level (C.L.). An upper limit of 3.7×10^{-8} at the 90% C.L. for the $K_L \to \pi^0 X^0$ decay was also set for the first time, where X^0 is an invisible particle with a mass of 135 MeV/c^2.

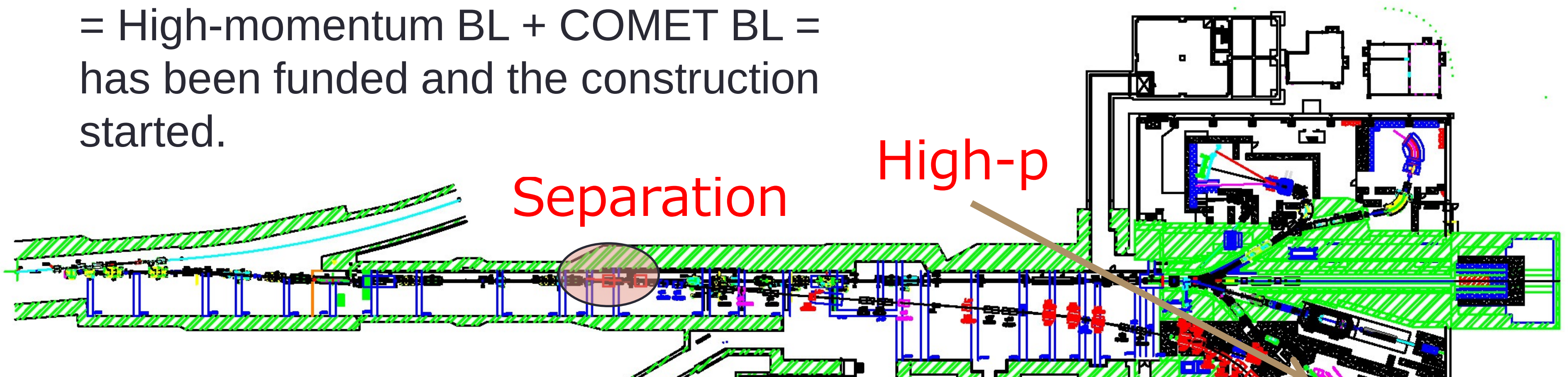


Contents

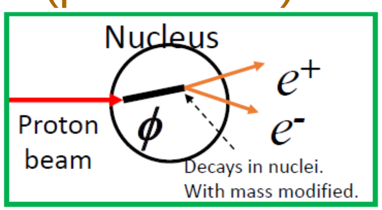
- J-PARC and Hadron Experimental Facility (Hadron Hall)
- Hadron physics overview and fruits so far obtained
- High-momentum beam line
- Extension
- Summary

New Primary Proton Beam Line

- New primary Proton Beam Line
  = High-momentum BL + COMET BL =
  has been funded and the construction started.



- High-momentum Beam Line
  - Primary protons (~10^{10} – 10^{12}pps)
    - E16 (phi meson) is the first experiment.

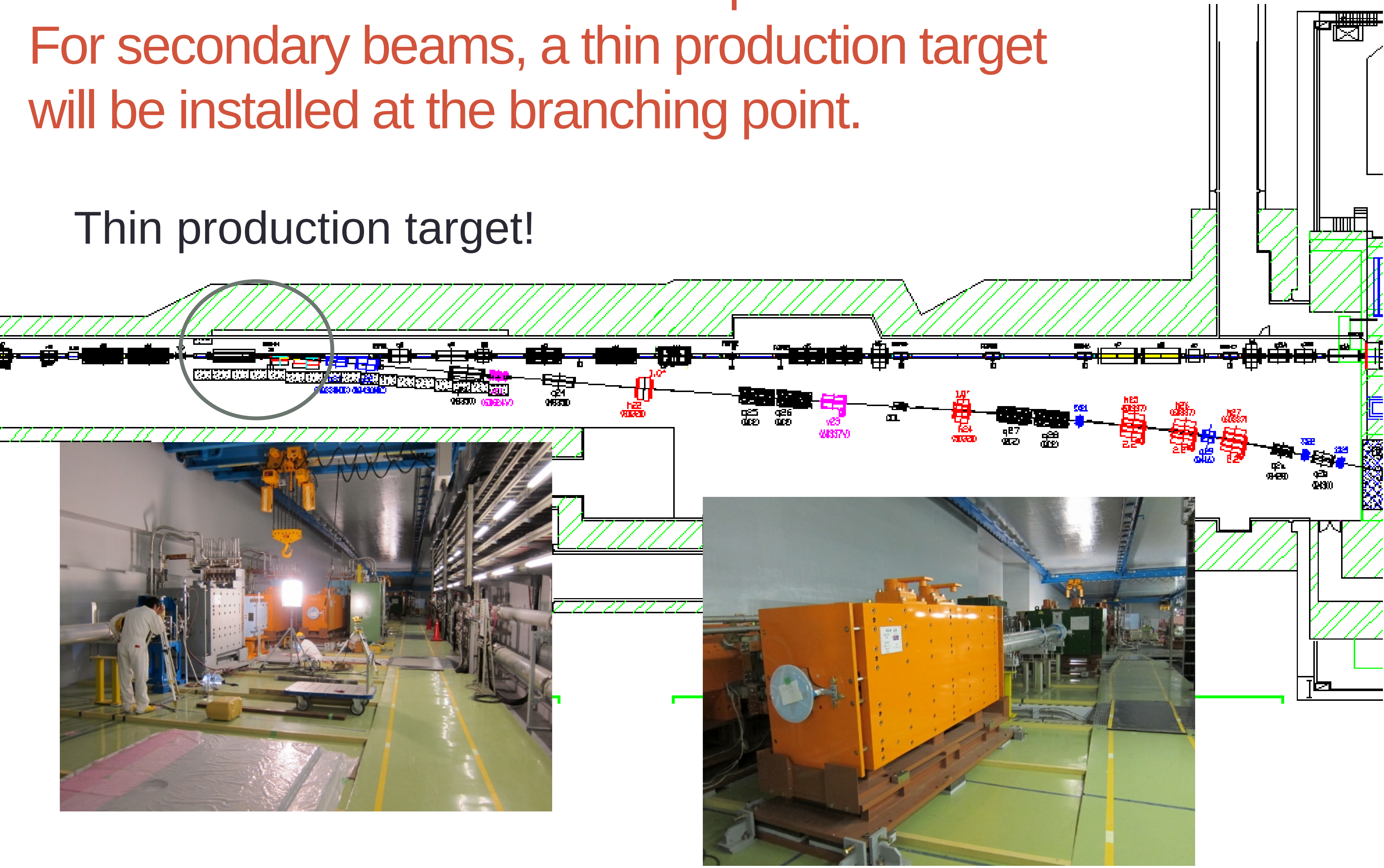


  - Unseparated secondary particles (pi, …)
    - High-resolution secondary beam by adding several quadrupole and sextupole magnets.

- COMET
  - Search for μ to e conversion
  - 8 GeV, 50 kW protons
  - Branch from the high-momentum BL
  - Annex building is being built at the south side.

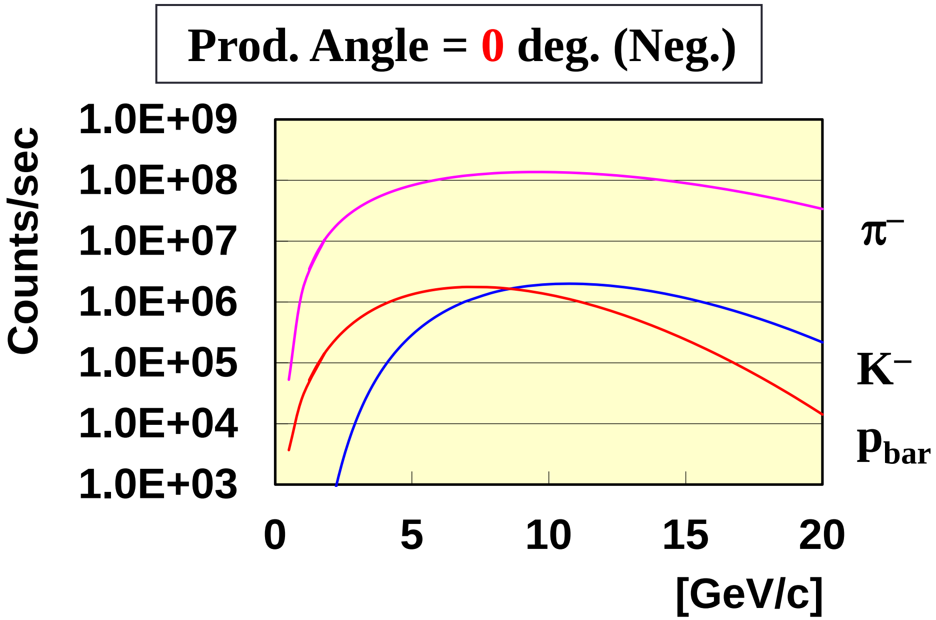
Beam line elements have been placed.
For secondary beams, a thin production target will be installed at the branching point.

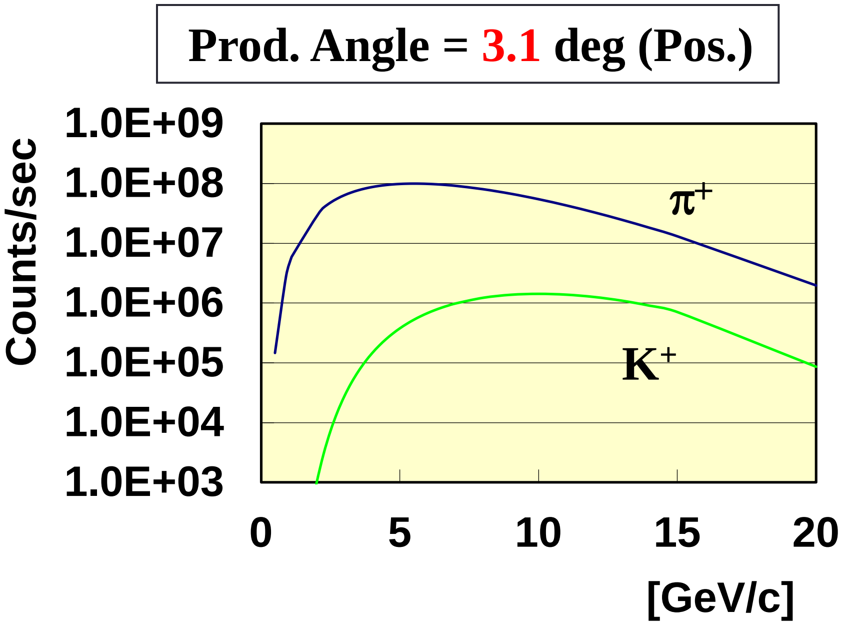
Thin production target!



Unseparated Secondary Beam

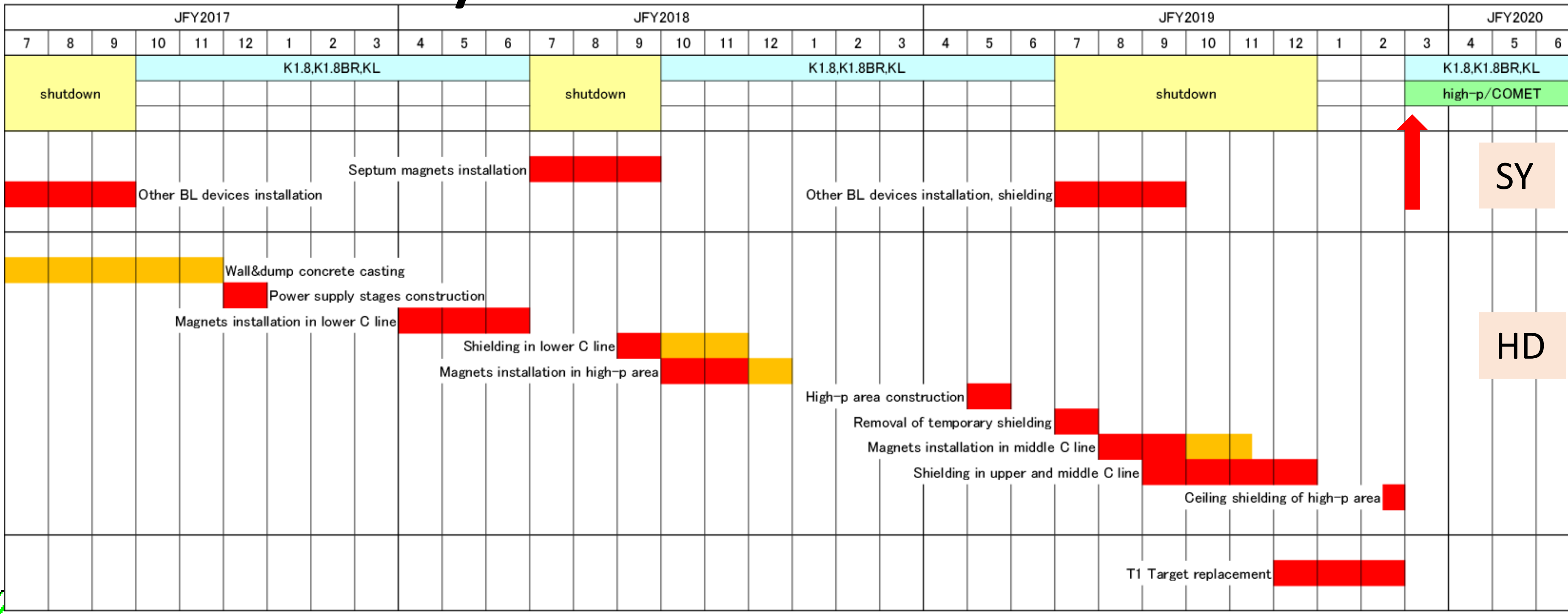
Noumi

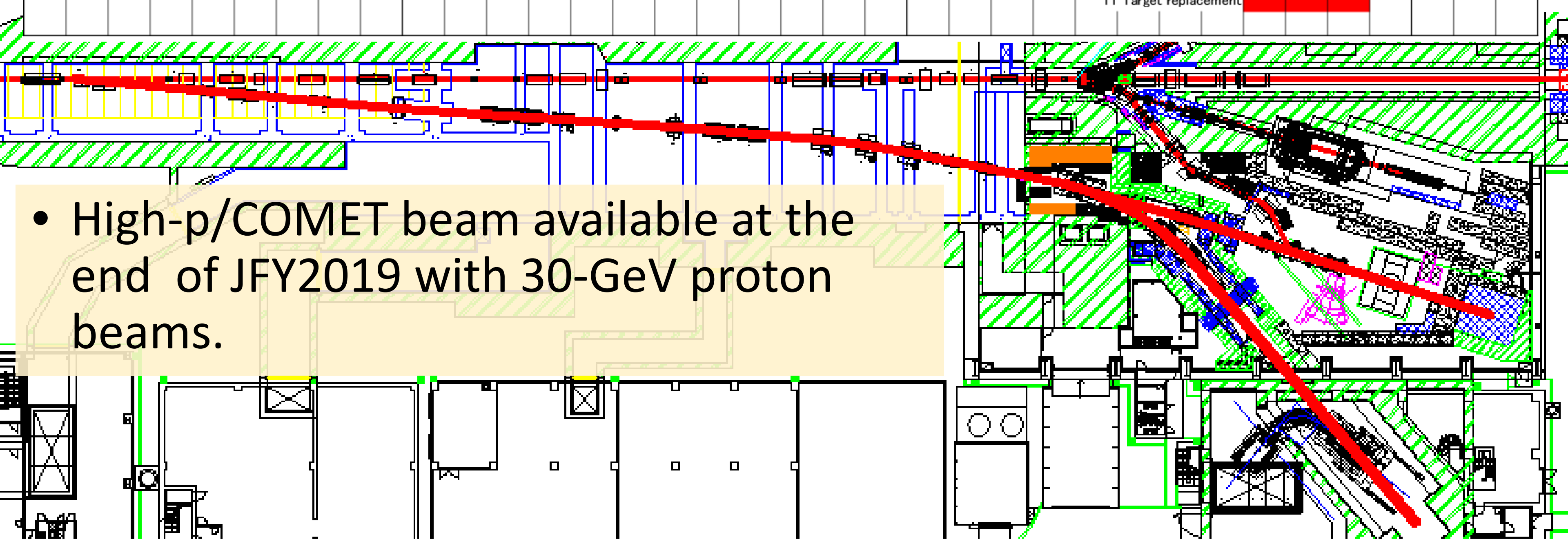




* Sanford-Wang:15 kW Loss on Pt, Acceptance :1.5 msr%, 133.2 m

A Possibility





- High-p/COMET beam available at the end of JFY2019 with 30-GeV proton beams.

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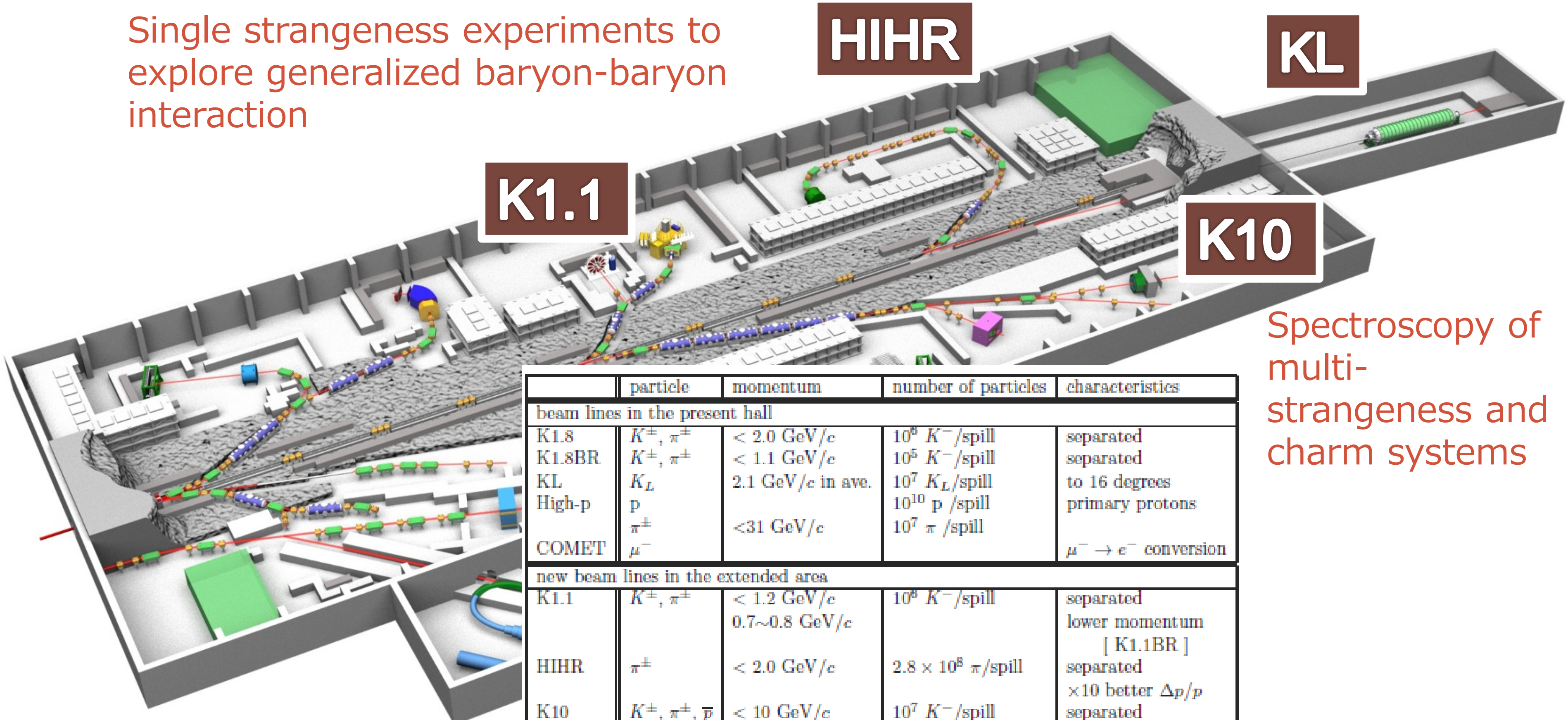
Hadron Hall Extension

From discovery to measurement of K0 rare decay

- Extend the Hadron Hall for ~105m.
- Construct 2 production targets with beam lines.

Single strangeness experiments to explore generalized baryon-baryon interaction



Spectroscopy of multi-strangeness and charm systems

	particle	momentum	number of particles	characteristics
beam lines in the present hall				
K1.8	$K^{\pm}$, $\pi^{\pm}$	$<$ 2.0 GeV/c	10^{6} K^{-}/spill	separated
K1.8BR	$K^{\pm}$, $\pi^{\pm}$	$<$ 1.1 GeV/c	10^{5} K^{-}/spill	separated
KL	K_L	2.1 GeV/c in ave.	10^{7} K_L/spill	to 16 degrees
High-p	p		10^{10} p /spill	primary protons
	$\pi^{\pm}$	<31 GeV/c	10^{7} π /spill	
COMET	μ^{-}			$\mu^{-} \to e^{-}$ conversion
new beam lines in the extended area				
K1.1	$K^{\pm}$, $\pi^{\pm}$	$<$ 1.2 GeV/c	10^{6} K^{-}/spill	separated
		0.7~0.8 GeV/c		lower momentum [K1.1BR]
HIHR	$\pi^{\pm}$	$<$ 2.0 GeV/c	2.8×10^{8} π/spill	separated
				$\times$10 better $\Delta p/p$
K10	$K^{\pm}$, $\pi^{\pm}$, $\overline{p}$	$<$ 10 GeV/c	10^{7} K^{-}/spill	separated
new KL	K_L	5.2 GeV/c in ave.	10^{8} K_L/spill	to 5 degrees
				n/K_L optimized

Hadron Hall Extension

- Hadron Hall extension has been proposed to the Science Council of Japan for their recommendation as a next big project, and selected as one of the 28 important big projects in their “Master Plan 2016”.
- The Institute of Particle and Nuclear Studies, KEK has made the discussion for future projects (ILC, neutrino, and Hadron extension) at the research program committee, and they have concluded that the Hadron extension should be promoted, as well as other projects.
- At the discussion of the KEK Project Implementation Plan, the Hadron Hall Extension was assigned a priority to realize.

- The Hadron Extension Committee under the Hadron Hall Users’ Association (HUA) published a document of the outline of the proposal, “Extension of the J-PARC Hadron Experimental Facility – summary report –”, as arXiv:1706.07916v1 [nucl-ex].
- International workshop to discuss closely the experiments and the facility was held at Tokai on March 26 – 28, 2018. https://kds.kek.jp/indico/event/26022/

Summary

- The beam operation at the Hadron Facility restarted from April, 2015 after an accident in May, 2013.
- The beam power at the restart was 24kW, and then improved gradually to 51kW. The Hadron Experimental Facility is now in the era of K-induced experiments.
- The high-momentum beam line is under construction, and will be available in a few years, for hadron physics experiments.
- The extension of the Hadron Hall has been proposed, and got a good message from initial reviews.