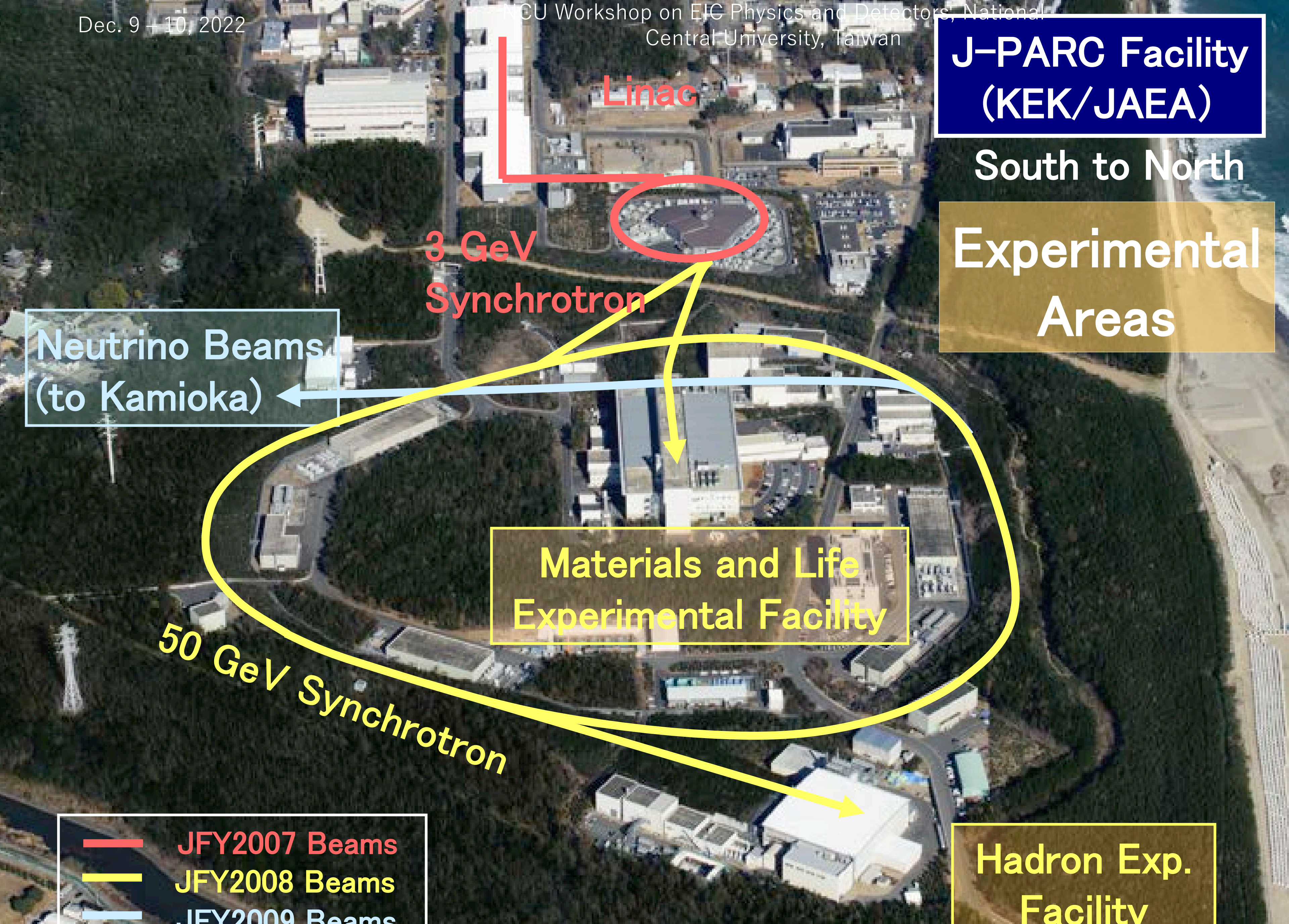
HADRONIC PHYSICS AT J-PARC

Dec. 9, 2022

Shin'ya Sawada
澤田　真也
KEK (High Energy Accelerator Research Organization)

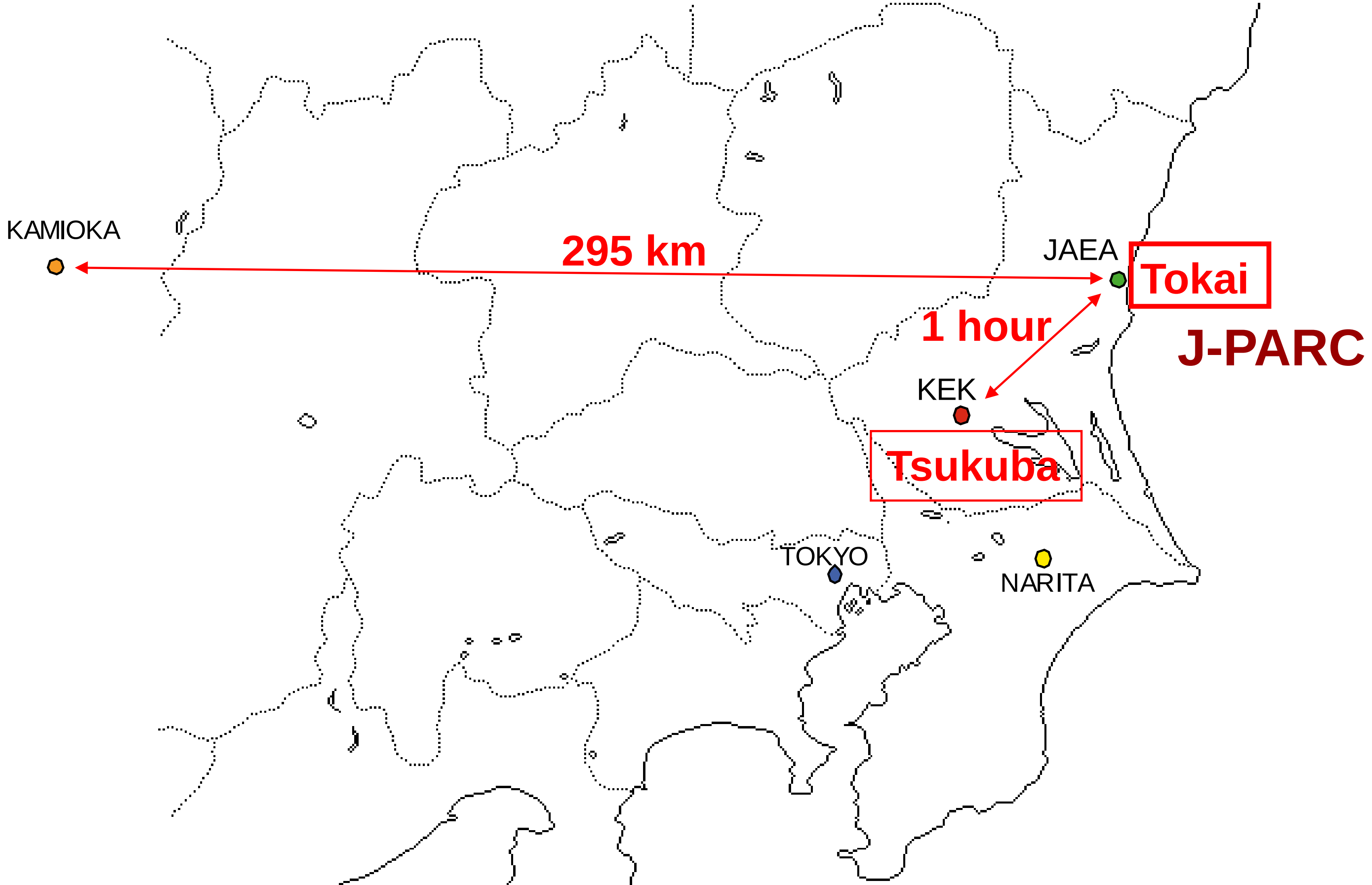
Contents

- J-PARC
- Hadronic physics and Hadron Experimental Facility (Hadron Hall)
  - Major physics goals
  - Beam lines
  - Recent results
- Extension of the Hadron Experimental Facility
- Summary

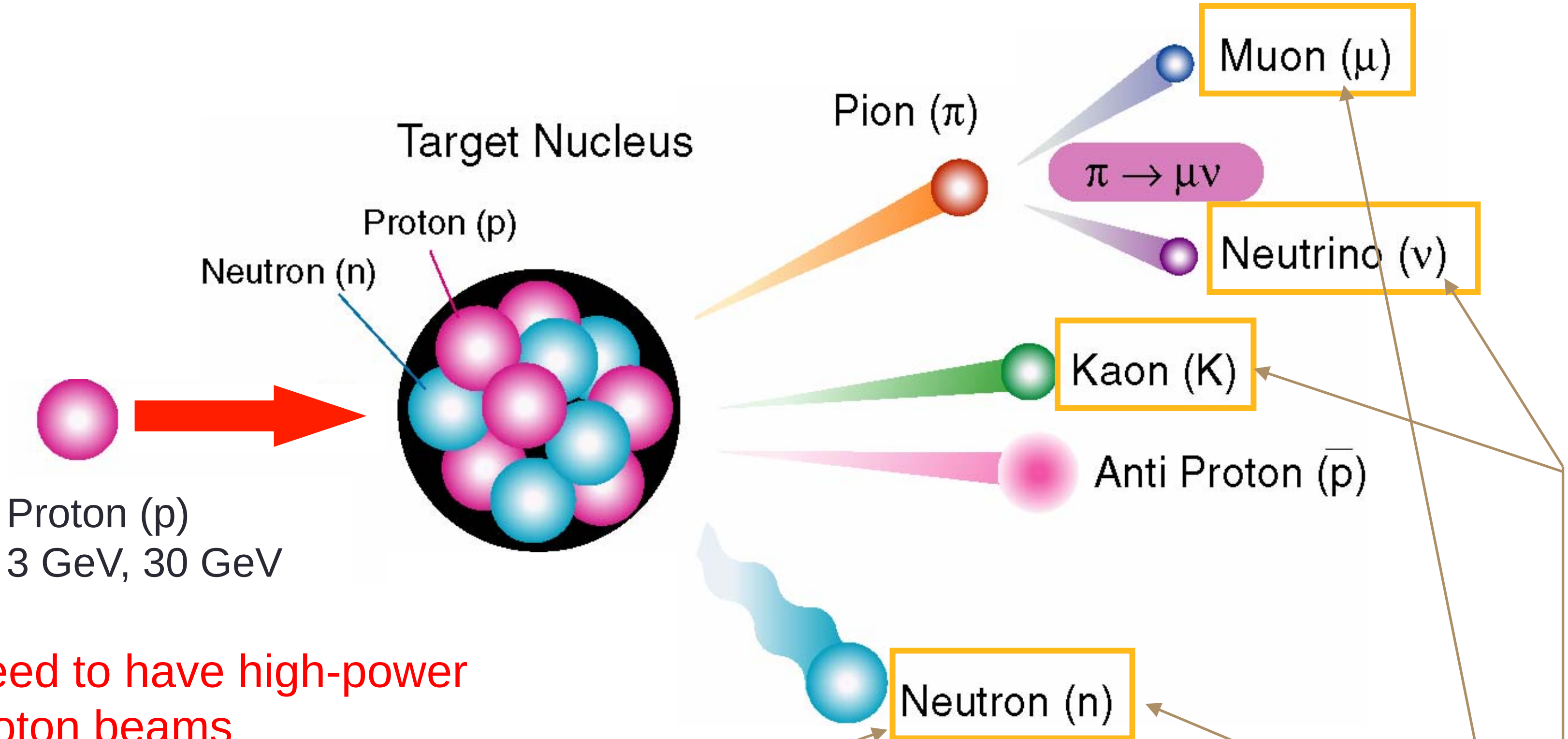


Bird's eye photo in January of 2016

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 RCS

Nuclear & Particle Physics at MR

R&D toward Transmutation at Linac

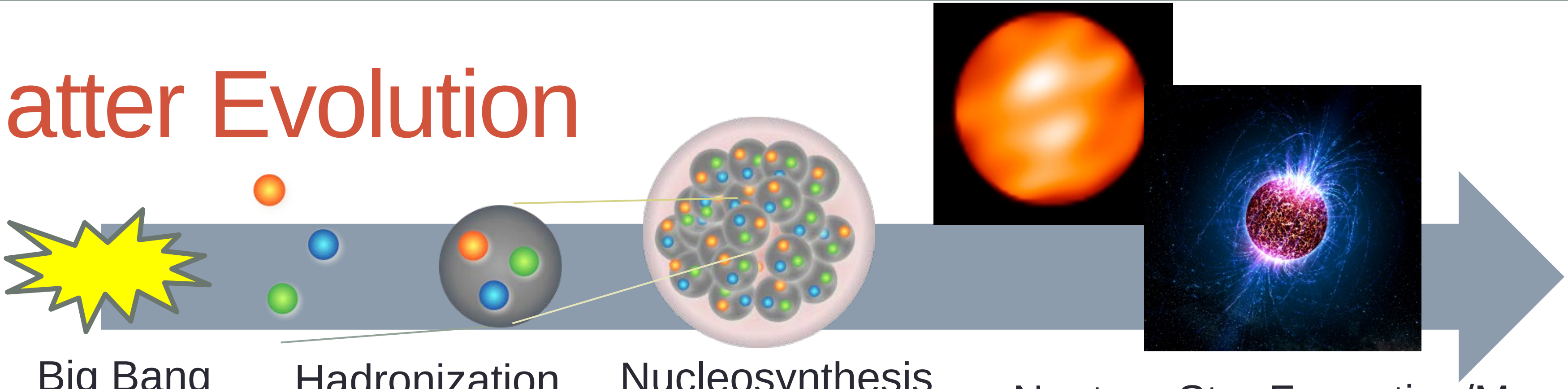
EIC Physics and J-PARC Physics

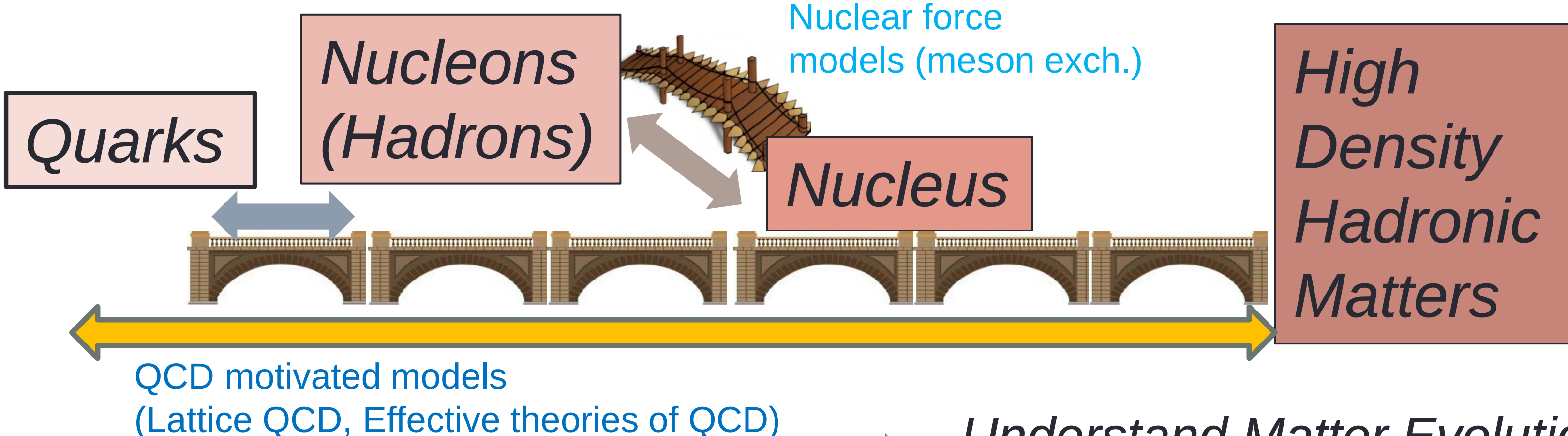
- EIC Physics
  - High energy
  - Parton degrees of freedom
  - QCD

- J-PARC Hadronic Physics
  - Medium or low energy
  - Nucleon/Meson degrees of freedom + parton degrees of freedom
  - QCD and/or QCD-motivated models

- But still, their physics should be bridged.

Matter Evolution





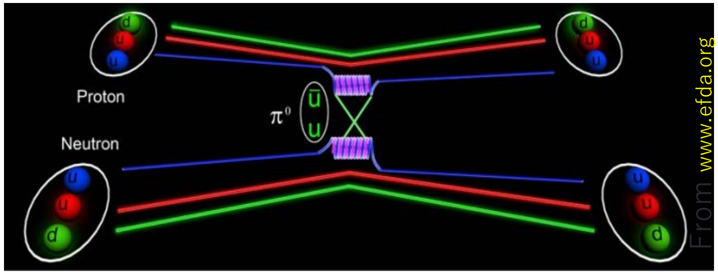
Properties of various forms of matter → *Understand Matter Evolution in Universe*

Three Research Topics at J-PARC

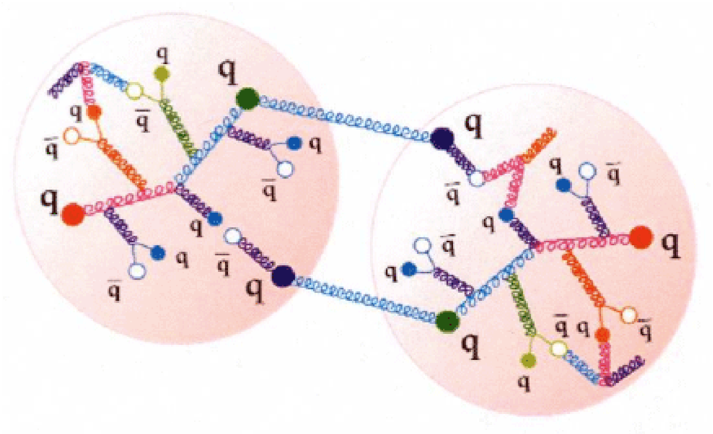
- Structure of hadrons
- Hadron interaction and properties of high density hadronic matter
- Properties of hadrons in matter

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.

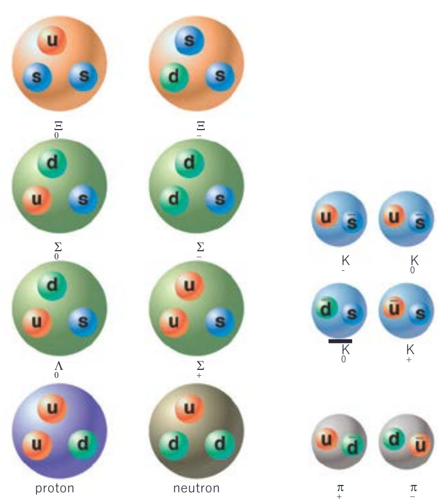


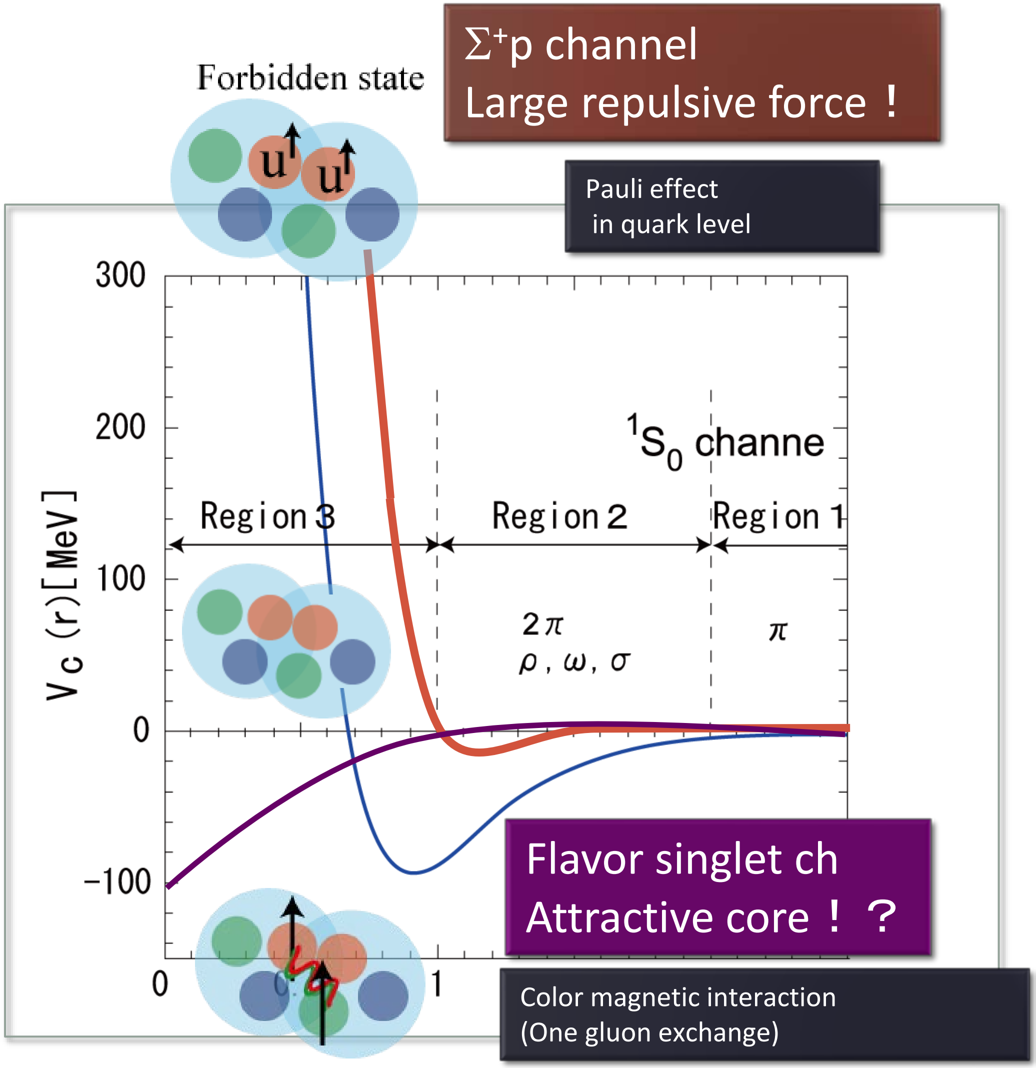
  - But at the short range, substructures of the nucleon should affect the interaction.



Nuclear/Hadron Physics at J-PARC

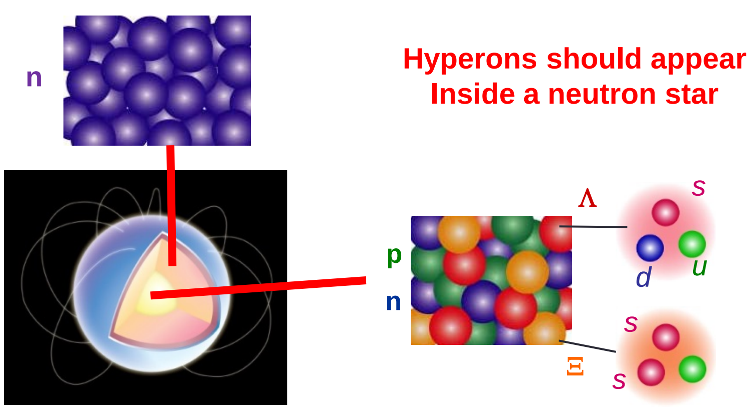
- Especially, the origin of the repulsive core and the spin-orbit force has not been understood.
- We explore the hadron interaction not only with up and down quarks but also with strange quarks.



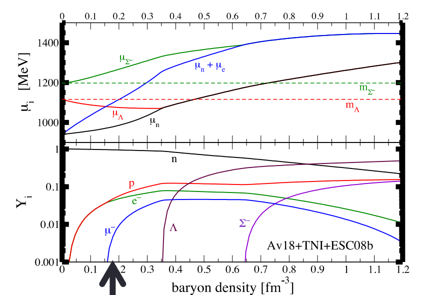


Importance of understanding hadron interaction

- 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.

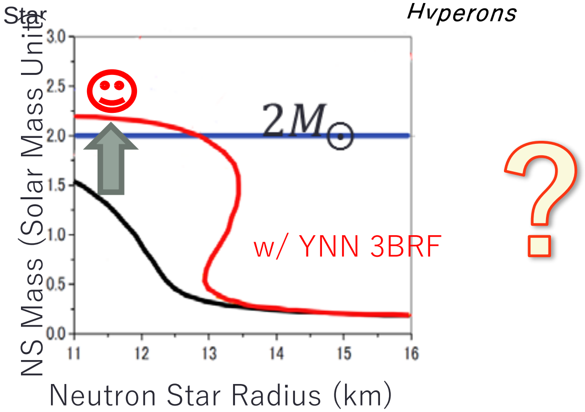


Theoretical prediction from known YN, YY 2-body interactions (Y=hyperon)



ρ0 (normal nuclear density)

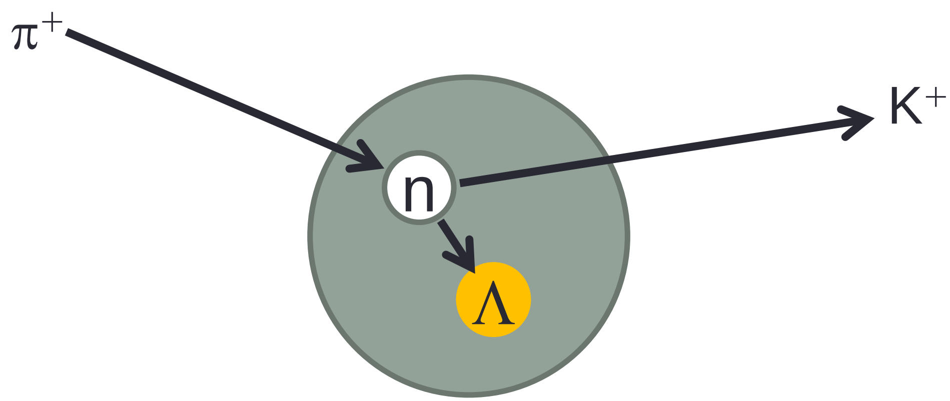
I. Bombaci, arXiv:1601.05339v1



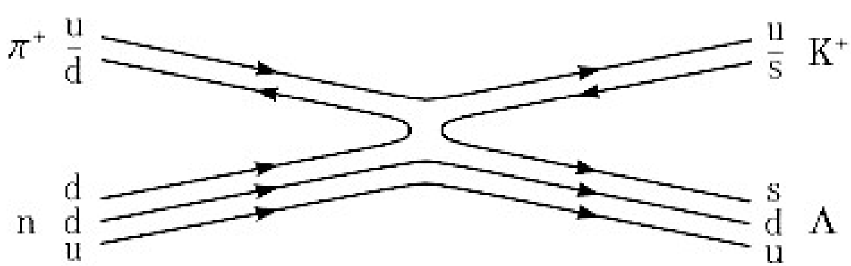
Neutron star merger detected by gravitational waves also attracts interests on the EoS.

How to produce hyperons and hypernuclei?

- (pi, K) reactions

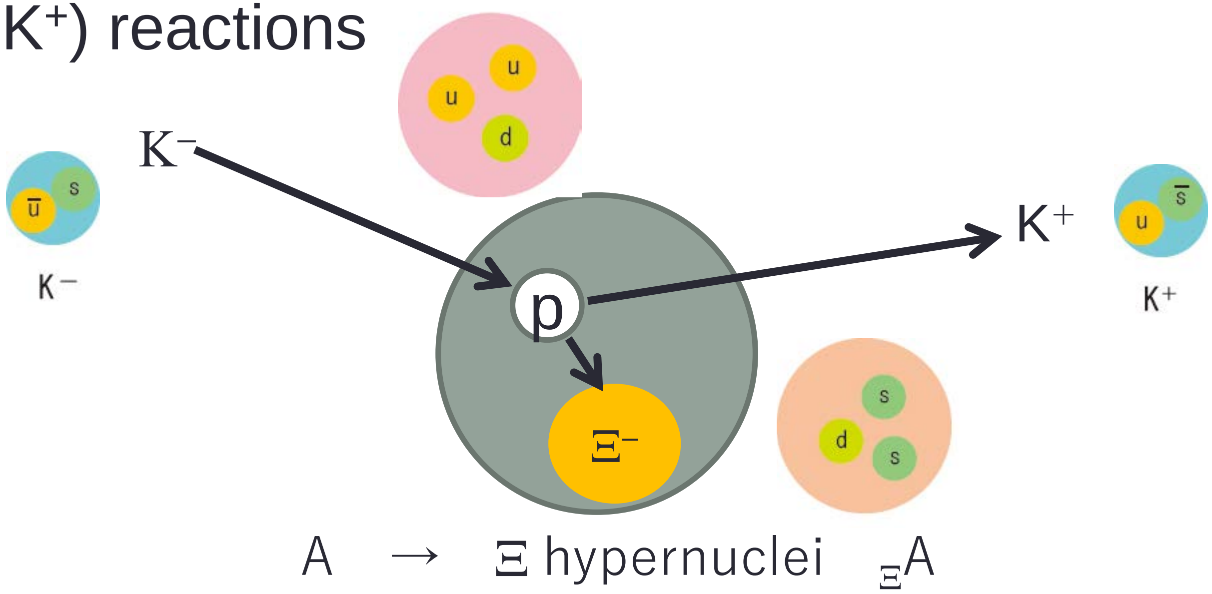


A $\rightarrow$ Λ hypernuclei ${}_{\Lambda}A$



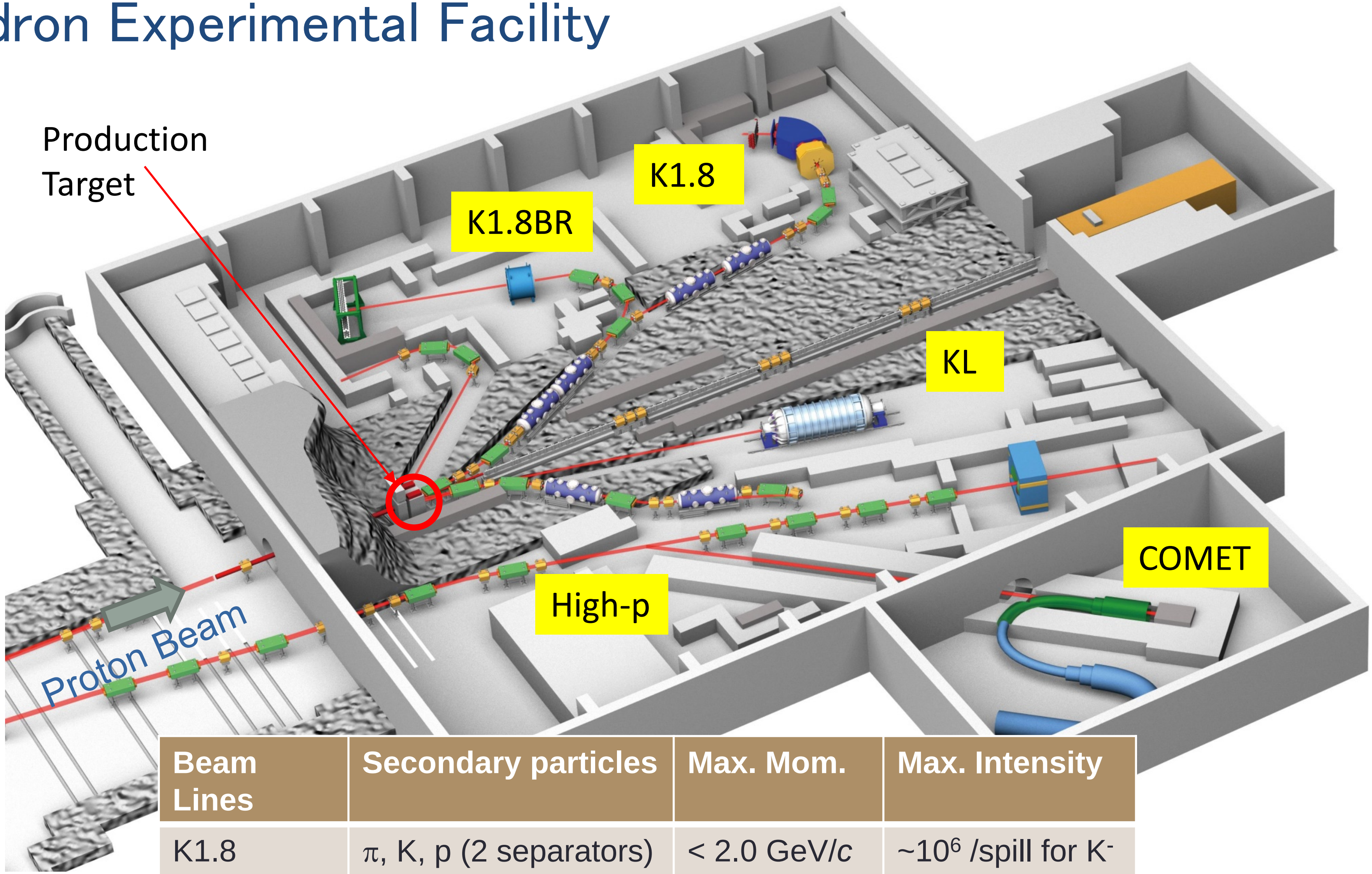
How to produce hyperons and hypernuclei?

- (K^-, K^+) reactions



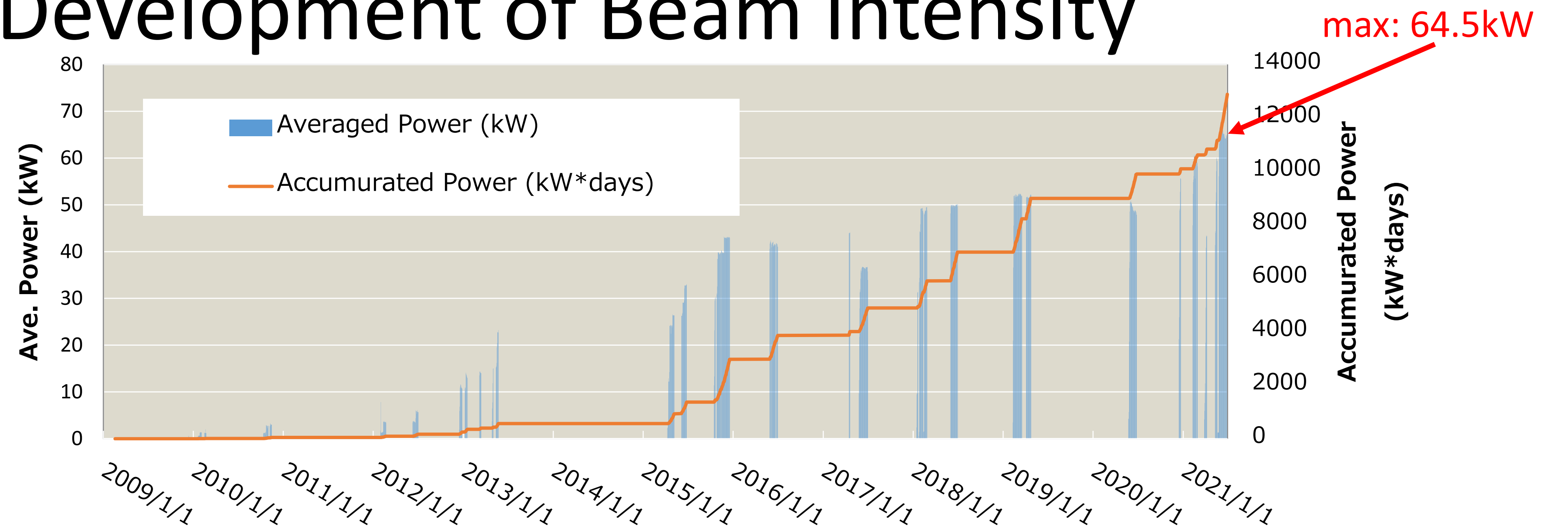
High intensity pi and K beams are important to produce more hyperons and hypernuclei.

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

Development of Beam Intensity



Accumulated beam time and intensity for HD

※ 8-GeV operation was not included.

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

K beam intensity

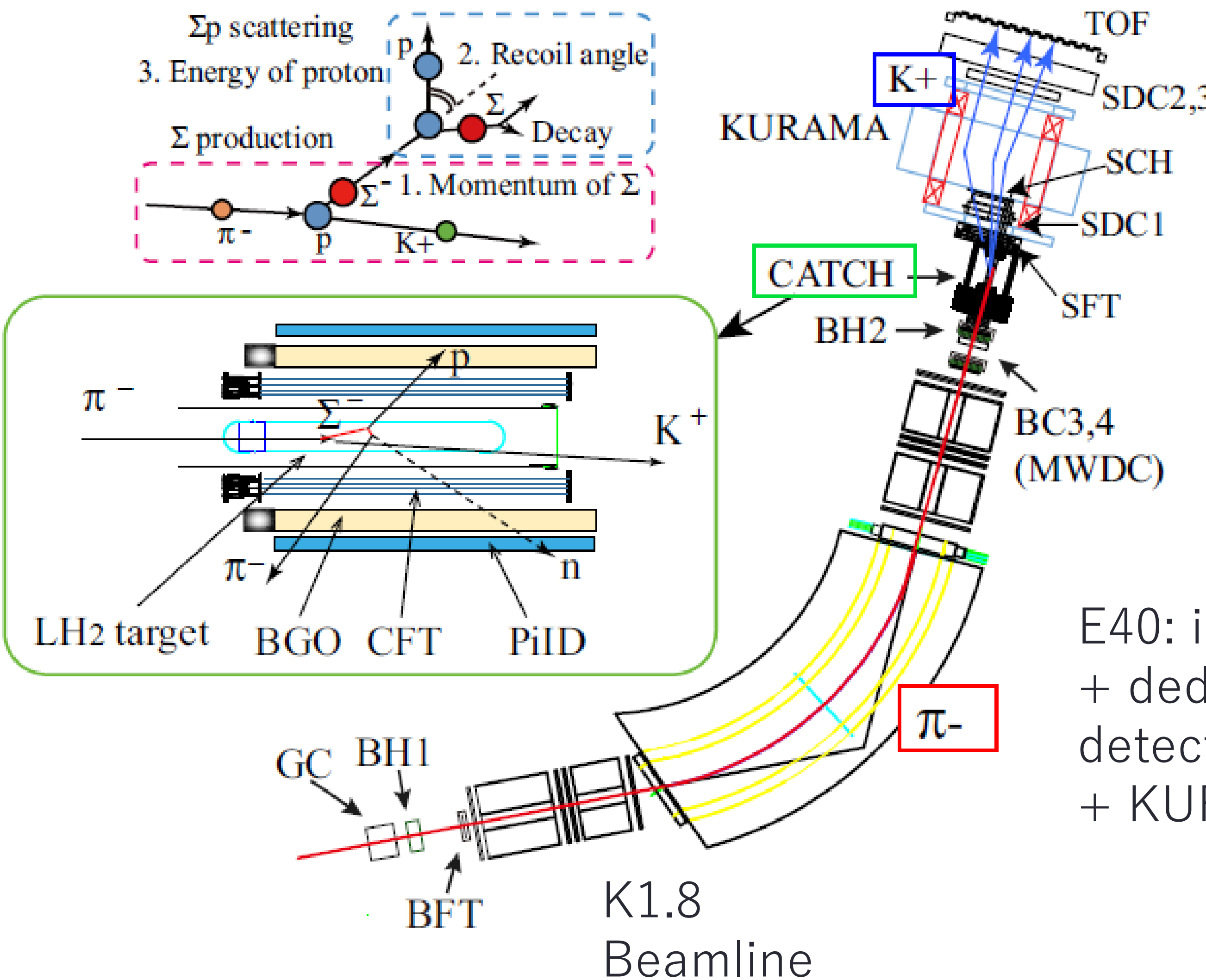
KEK-PS: K purity was for example ~25%.

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 (with 51kW primary proton beam):

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%
	7.0×10^5 K^-	5.4×10^{13}	1.8GeV/c, purity=44%

Hyperon Scattering



E40: intense pi beams
+ dedicated CATCH detectors
+ KURAMA spectrometer

PHYSICAL REVIEW C **104**, 045204 (2021)

Hyperon Scattering

Measurement of the differential cross sections of the $\Sigma^- p$ elastic scattering in momentum range 470 to 850 MeV/c

K. Miwa,[1] J. K. Ahn,[2] Y. Akazawa,[3] T. Aramaki,[1] S. Ashikaga,[4] S. Callier,[5] N. Chiga,[1] S. W. Choi,[2] H. Ekawa,[6] P. Evtoukhovitch,[7] N. Fujioka,[1] M. Fujita,[8] T. Gogami,[4] T. Harada,[4] S. Hasegawa,[8] S. H. Hayakawa,[1] R. Honda,[3] S. Hoshino,[9] K. Hosomi,[8] M. Ichikawa,[4,14] Y. Ichikawa,[8] M. Ieiri,[3] M. Ikeda,[1] K. Imai,[8] Y. Ishikawa,[1] S. Ishimoto,[3] W. S. Jung,[2] S. Kajikawa,[1] H. Kanauchi,[1] H. Kanda,[10] T. Kitaoka,[1] B. M. Kang,[2] H. Kawai,[11] S. H. Kim,[2] K. Kobayashi,[9] T. Koike,[1] K. Matsuda,[1] Y. Matsumoto,[1] S. Nagao,[1] R. Nagatomi,[9] Y. Nakada,[9] M. Nakagawa,[6] I. Nakamura,[3] T. Nanamura,[4,8] M. Naruki,[4] S. Ozawa,[1] L. Raux,[5] T. G. Rogers,[1] A. Sakaguchi,[9] T. Sakao,[1] H. Sako,[8] S. Sato,[8] T. Shiozaki,[1] K. Shirotori,[10] K. N. Suzuki,[4] S. Suzuki,[3] M. Tabata,[11] C. d. L. Taille,[5] H. Takahashi,[3] T. Takahashi,[3] T. N. Takahashi,[15] H. Tamura,[1,8] M. Tanaka,[3] K. Tanida,[8] Z. Tsamalaidze,[7,12] M. Ukai,[3,1] H. Umetsu,[1] S. Wada,[1] T. O. Yamamoto,[8] J. Yoshida,[1] and K. Yoshimura[13]
(J-PARC E40 Collaboration)

Quark Cluster Model

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

Nimegen

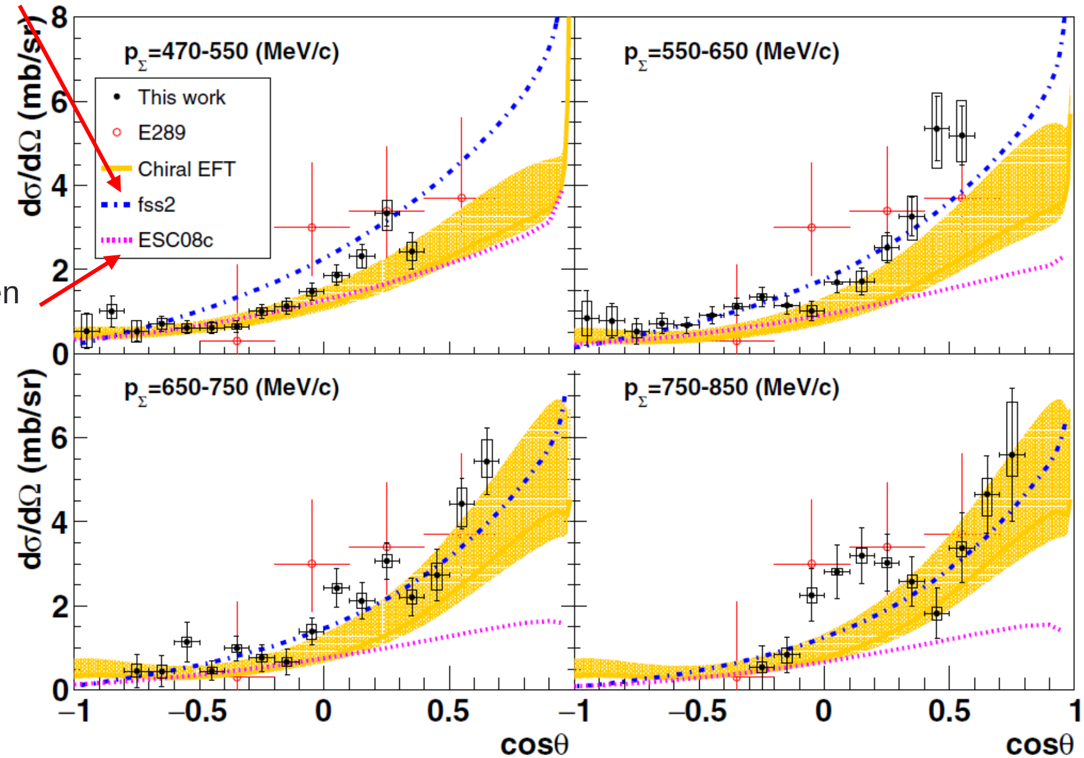
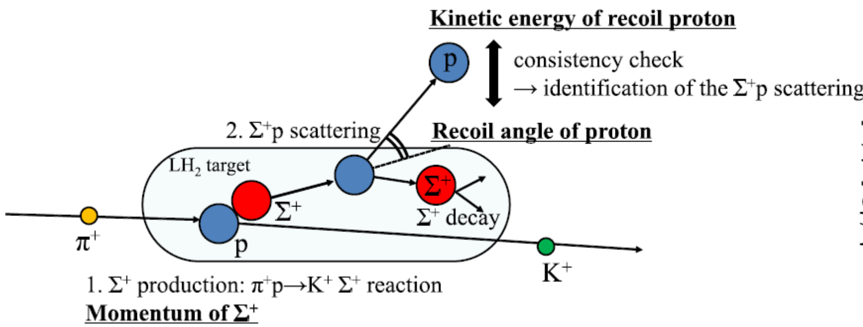
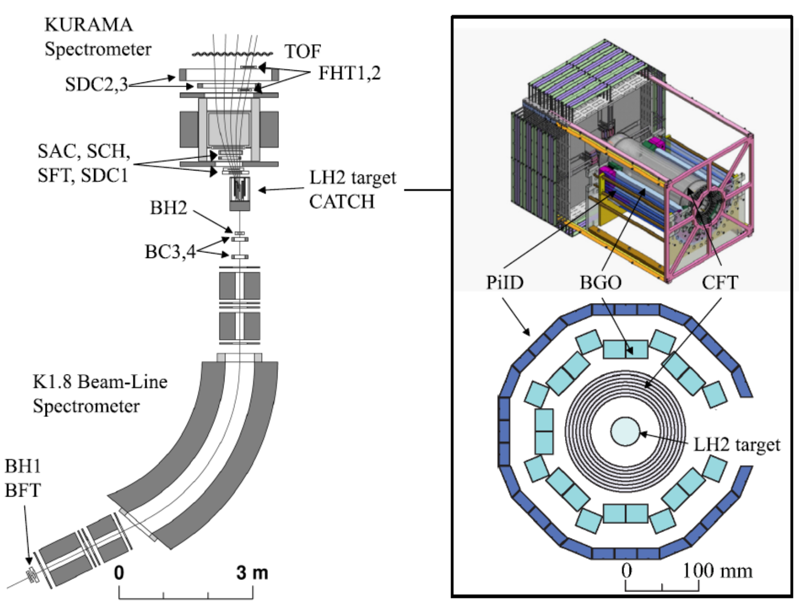


FIG. 17. Differential cross sections obtained in the present experiment (black points). The error bars and boxes show statistical and systematic uncertainties, respectively. The red points are averaged differential cross sections of $400 < p$ (MeV/c) < 700 taken in KEK-PS E289 (the same points are plotted in all of the four-momentum regions). The dotted (magenta), dot-dashed (blue), and solid (yellow) lines represent the calculated cross sections by the Nijmegen ESC08c model based on the boson-exchange picture, the fss2 model including QCM, and the extended χEFT model, respectively.

Σ^+ scattering





PTEP
Prog. Theor. Exp. Phys. 2022 093D01(35 pages)
DOI: 10.1093/ptep/ptac101

Measurement of differential cross sections for $\Sigma^+ p$ elastic scattering in the momentum range 0.44–0.80 GeV/c

T. Nanamura[1,2], K. Miwa[3,4], J. K. Ahn[5], Y. Akazawa[4], T. Aramaki[3], S. Ashikaga[1], S. Callier[6], N. Chiga[3], S. W. Choi[5], H. Ekawa[7], P. Evtoukhovitch[8], N. Fujioka[3]

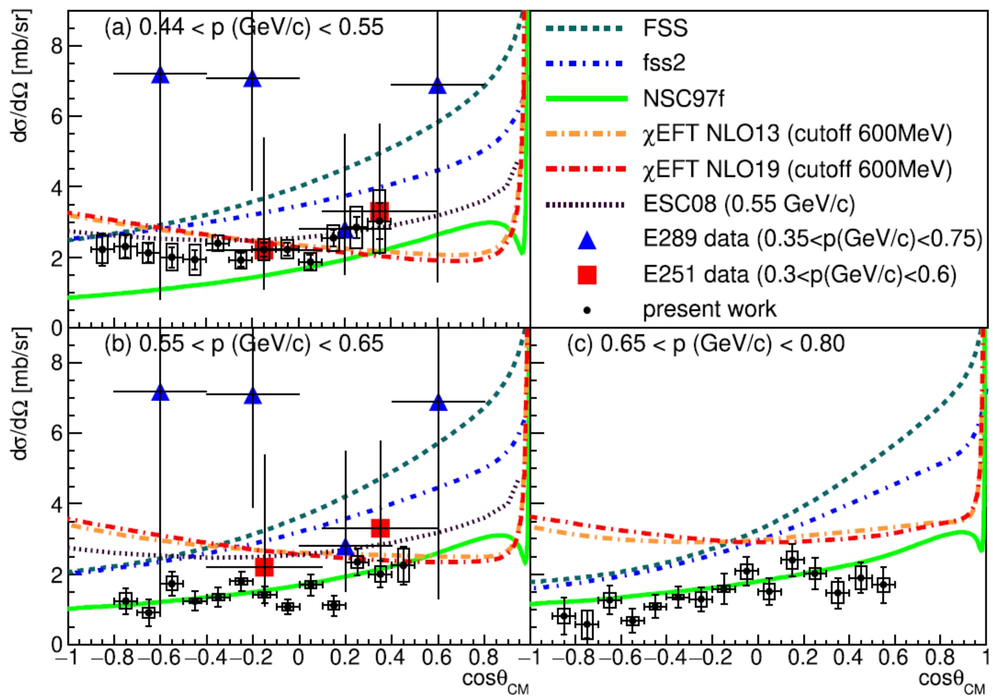
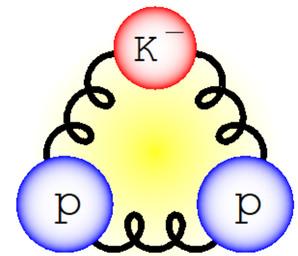
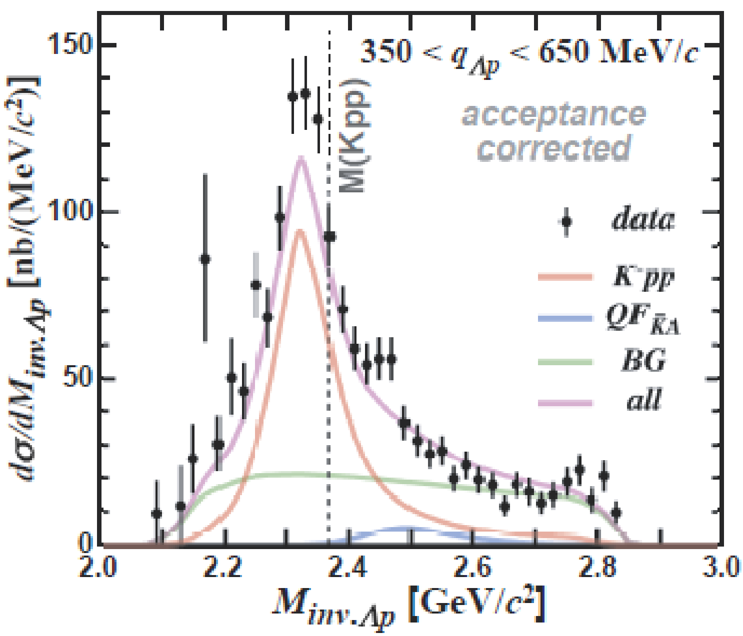


Fig. 24. Derived differential cross sections of the $\Sigma^+ p$ scattering for the three momentum regions. The error bars and boxes show the statistical and systematic uncertainties, respectively. The red boxes and blue triangles represent the data of past measurements, KEK E251 [33] and KEK E289 [32], respectively. The blue dotted and dot-dashed lines show the calculations from FSS and fss2 [6], respectively. The green solid lines and black dashed lines show the calculations from the Nijmegen NSC97f [8] and ESC08 [15] models, respectively. The orange and red dot-dashed lines show the calculations from the χEFT NLO models [19,20].

K^-pp 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


Contents lists available at ScienceDirect
Physics Letters B
www.elsevier.com/locate/physletb

"K^-pp", a $\overline{K}$-meson nuclear bound state, observed in ^{3}He(K^-, Λp)n reactions

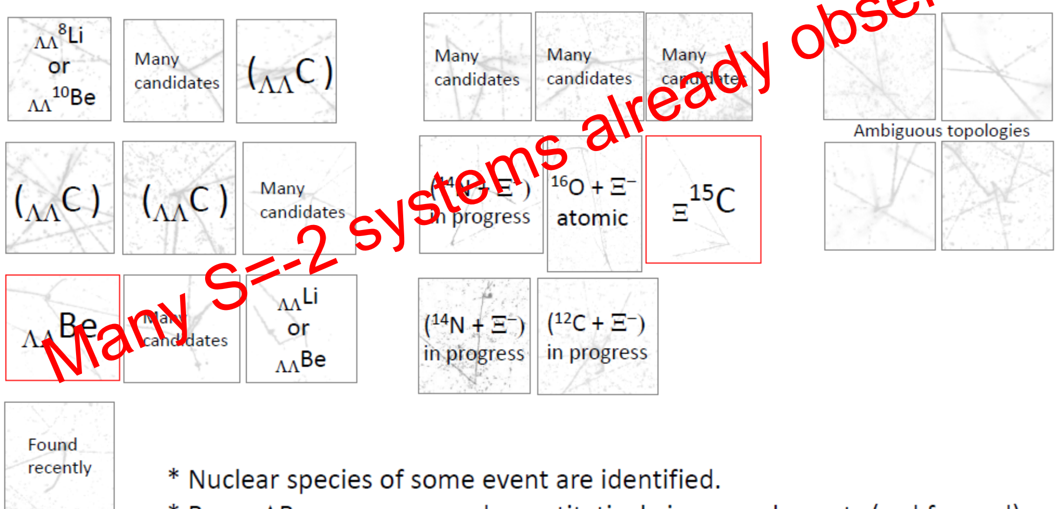
J-PARC E15 collaboration, S. Ajimura[a], H. Asano[b], G. Beer[c], C. Berucci[d], H. Bhang[e], M. Bragadireanu[f], P. Buehler[d], L. Busso[g,h], M. Cargnelli[d], S. Choi[e], C. Curceanu[i], S. Enomoto[j], H. Fujioka[k], Y. Fujiwara[l], T. Fukuda[m], C. Guaraldo[i], T. Hashimoto[n], R.S. Hayano[l], T. 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]

E07: S=-2 Spectroscopy with emulsion

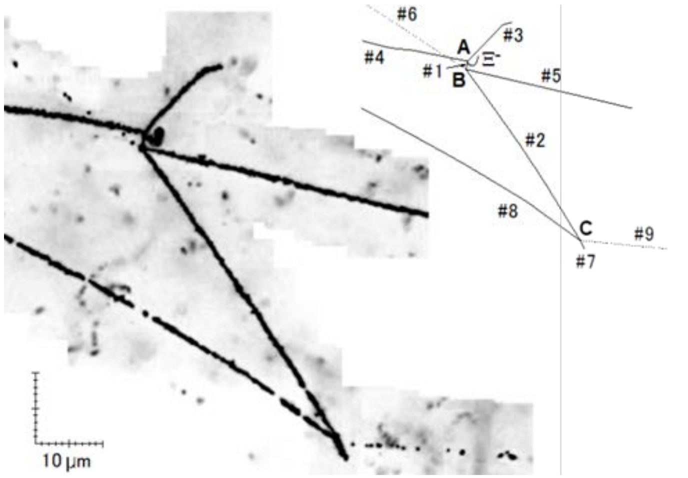
20190113T18
So far, 53% of emulsion sheets has been scanned at least once.

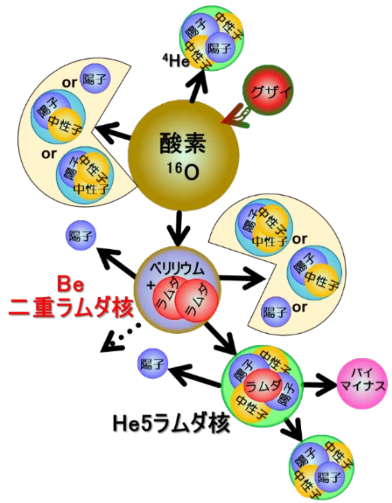
	KEK-PS E373	E07 (current)
Ξ^- stop with nuclear fragment	430	1145 (1145/430 = 2.7)
Double strangeness system	9	22

10 double Lambda events / 8 twin events / 4 double or twin



* Nuclear species of some event are identified.
* B_{Ξ^-} or $\Delta B_{\Lambda\Lambda}$ are measured quantitatively in several events (red framed).





"Mino" event

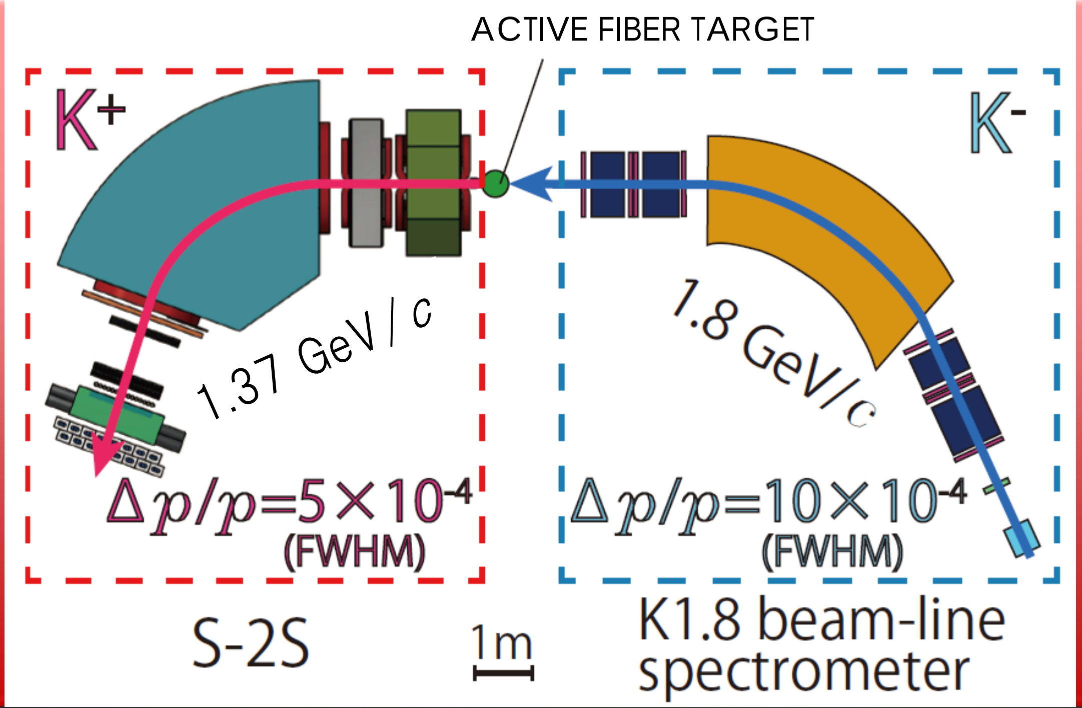
PTEP Prog. Theor. Exp. Phys. 2019, 021D02 (11 pages) DOI: 10.1093/ptep/pty149

Letter

Observation of a Be double-Lambda hypernucleus in the J-PARC E07 experiment

H. Ekawa[1,2,*], K. Agari[3], J. K. Ahn[4], T. Akaishi[5], Y. Akazawa[3], S. Ashikaga[1,2],

Multi-Strangeness world revealed with S-2S



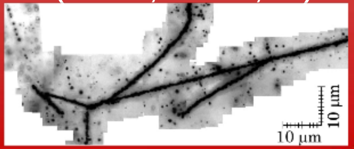
J-PARC K1.8

(K-,K+) spectroscopy

- ΔE<2 MeV
- ΔΩ=55msr

Establish the Ξ bound states

- Hints in Emulsion
- (KISO, IBUKI,…)

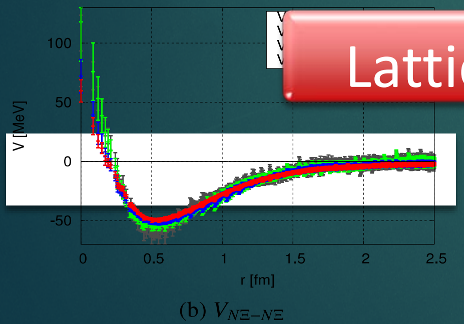


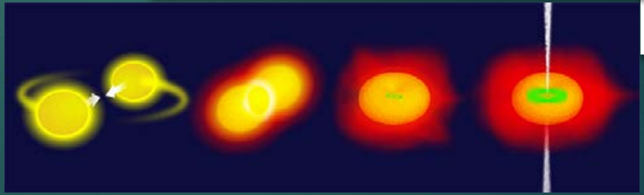
B-B Interactions

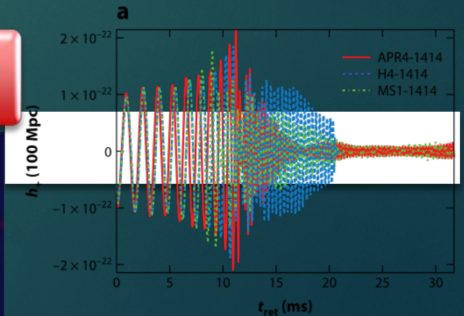
EOS@ High-density

Lattice QCD

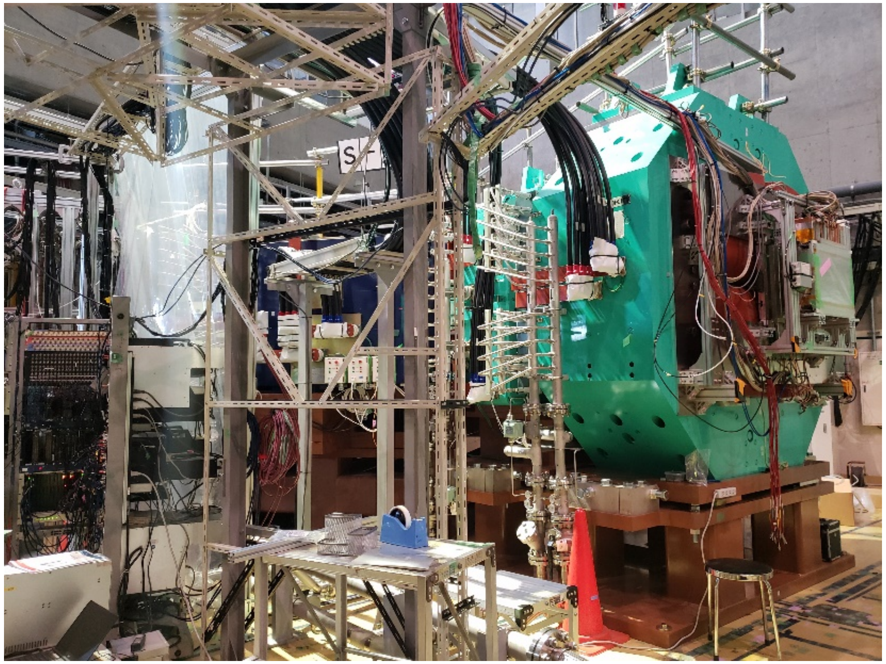
Binary NS Merger







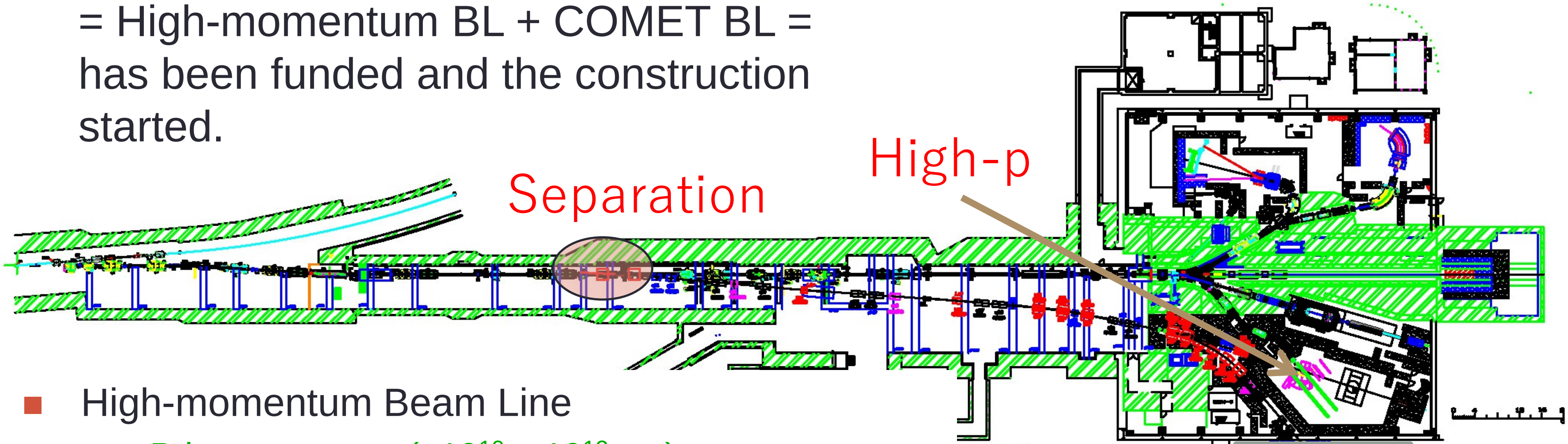
S-2S Preparation



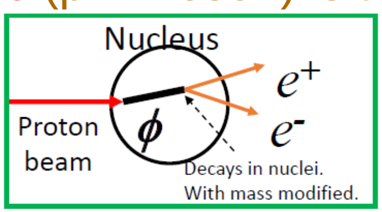
Students/Postdocs are working hard…

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.



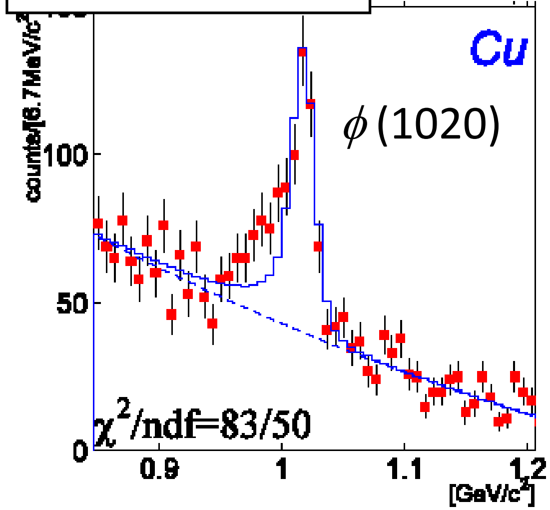
  - Unseparated secondary particles (pi, …)
    - High-resolution secondary beam by adding several quadrupole and sextupole magnets.

- 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.

J-PARC E16

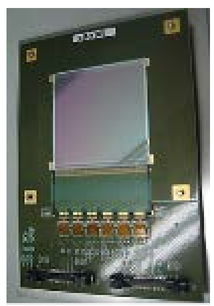
- Invariant mass spectra of e^+e^- pairs in pA collisions
  - Vector meson mass modification due to nuclear matter effects
  - High statistics/Good resolution
- Similar as KEK-PS E325, but with x100 stat.

KEK E325 results

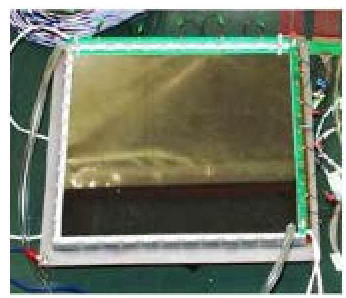


High stat.
Better res.

Spectrometer magnet

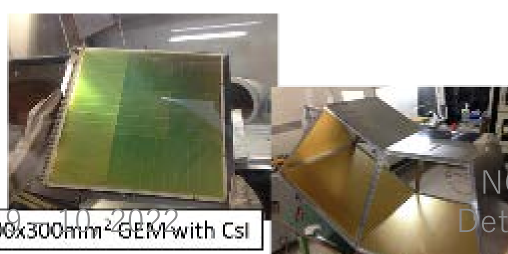


SSD



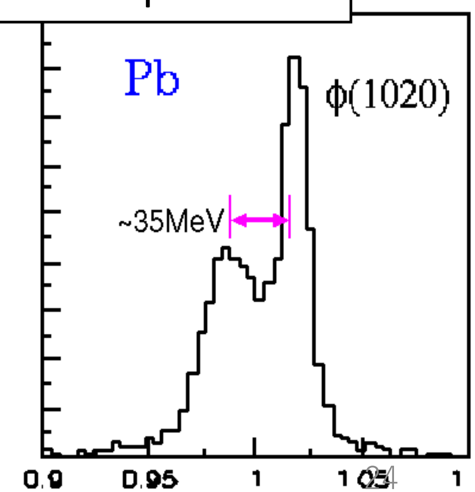
GEM Tracker

Electron ID (HBD and Lead Glass)



300x300mm² GEM with CsI

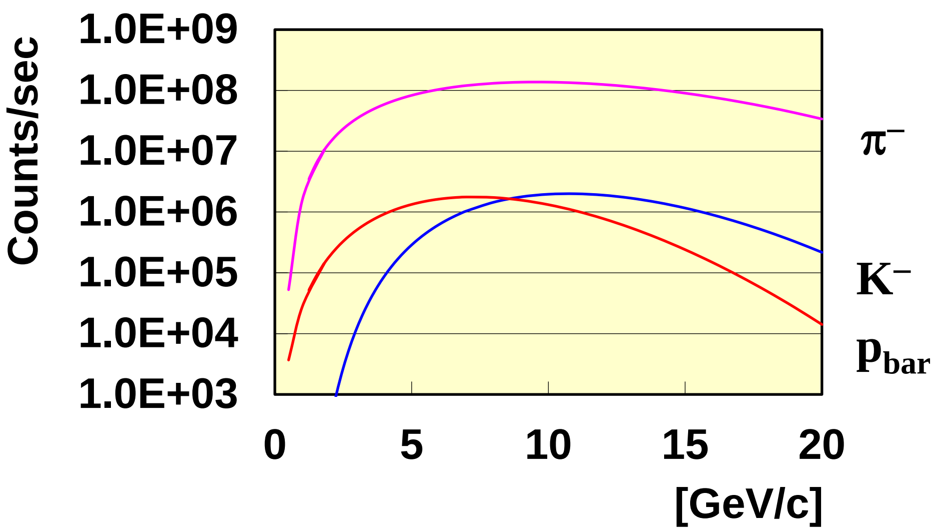
J-PARC expectation



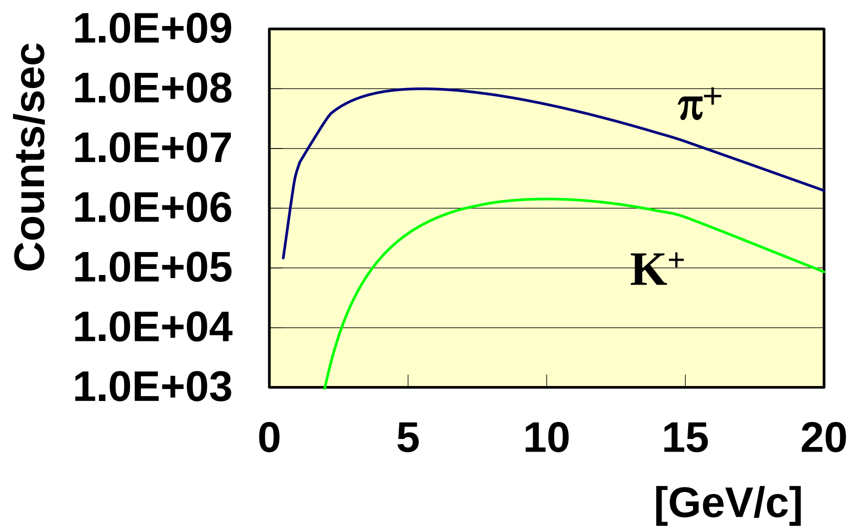
Unseparated Secondary Beam in the future

Noumi

Prod. Angle = 0 deg. (Neg.)



Prod. Angle = 3.1 deg (Pos.)



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

GPD with pion beams at J-PARC

PHYSICAL REVIEW D 93, 114034 (2016)

Accessing proton generalized parton distributions and pion distribution amplitudes with the exclusive pion-induced Drell-Yan process at J-PARC

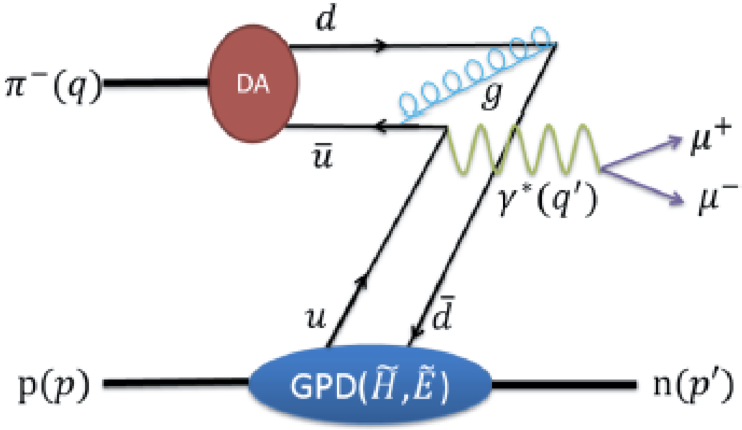
Takahiro Sawada[*] and Wen-Chen Chang[†]
Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

Shunzo Kumano[‡]
KEK Theory Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), 1-1, Oho, Tsukuba, Ibaraki 305-0801, Japan and J-PARC Branch, KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, 203-1, Shirakata, Tokai, Ibaraki 319-1106, Japan

Jen-Chieh Peng[§]
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801, USA

Shinya Sawada[¶]
High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

Kazuhiro Tanaka[**]
Department of Physics, Juntendo University, Inzai, Chiba 270-1695, Japan and J-PARC Branch, KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, 203-1, Shirakata, Tokai, Ibaraki 319-1106, Japan
(Received 15 May 2016; published 29 June 2016)



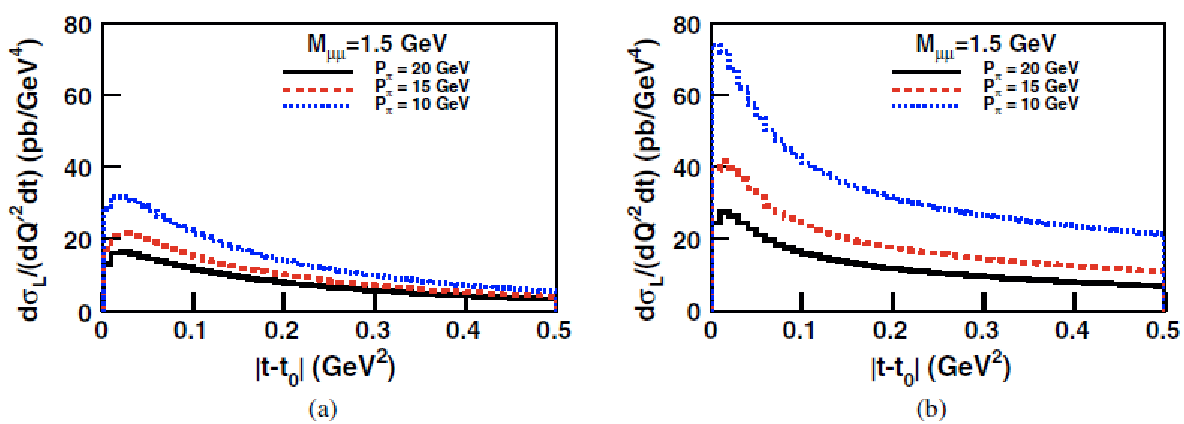
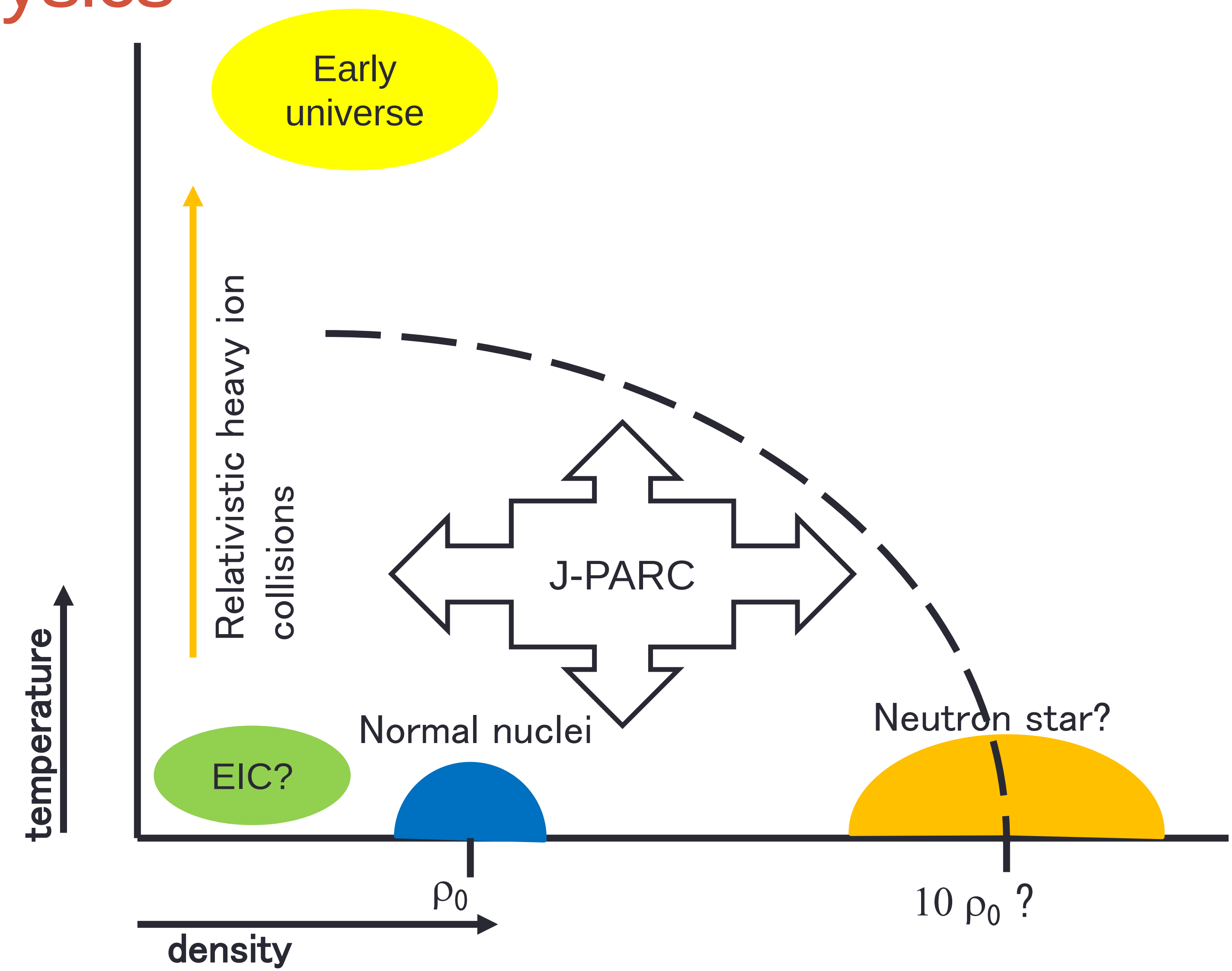


FIG. 10. Differential cross sections of exclusive Drell-Yan events, Eq. (20), as a function of $|t - t_0|$ at $M_{\mu^+\mu^-} = 1.5$ GeV for $P_\pi = 10$, 15, and 20 GeV with the input GPDs: (a) BMP2001 and (b) GK2013.

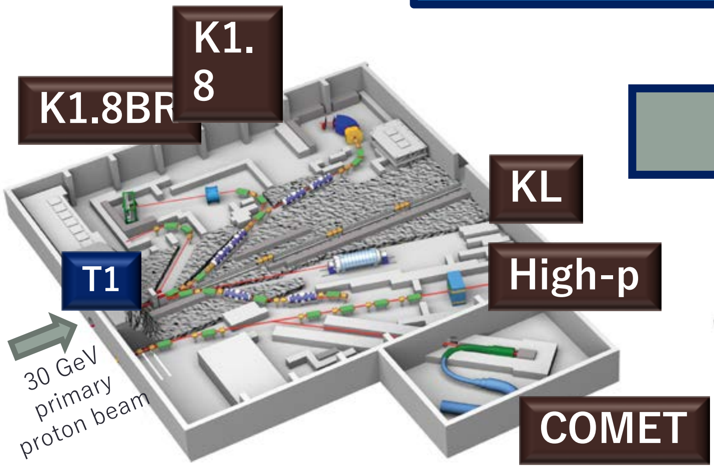
J-PARC connects subfields of hadronic physics



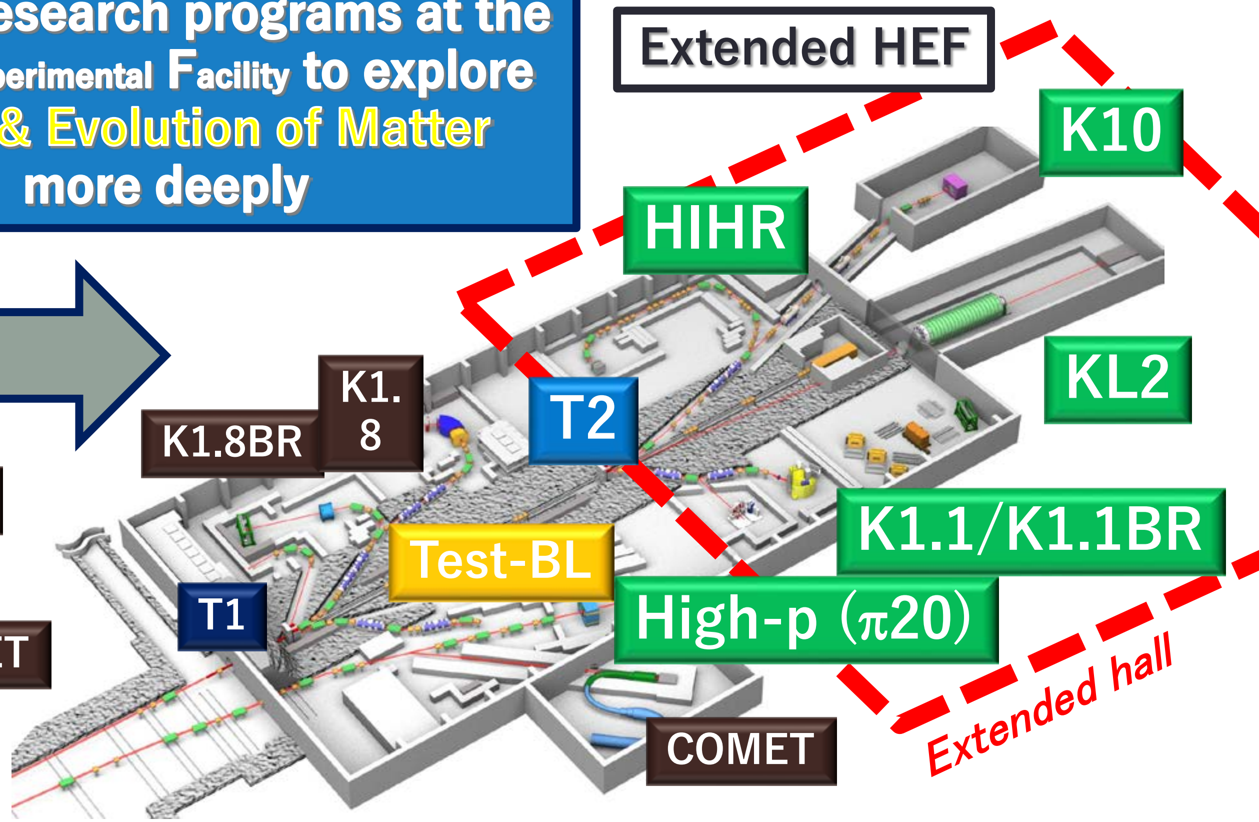
Hadron Experimental Facility eXtension (HEF-ex)

Present HEF (2009～)

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)

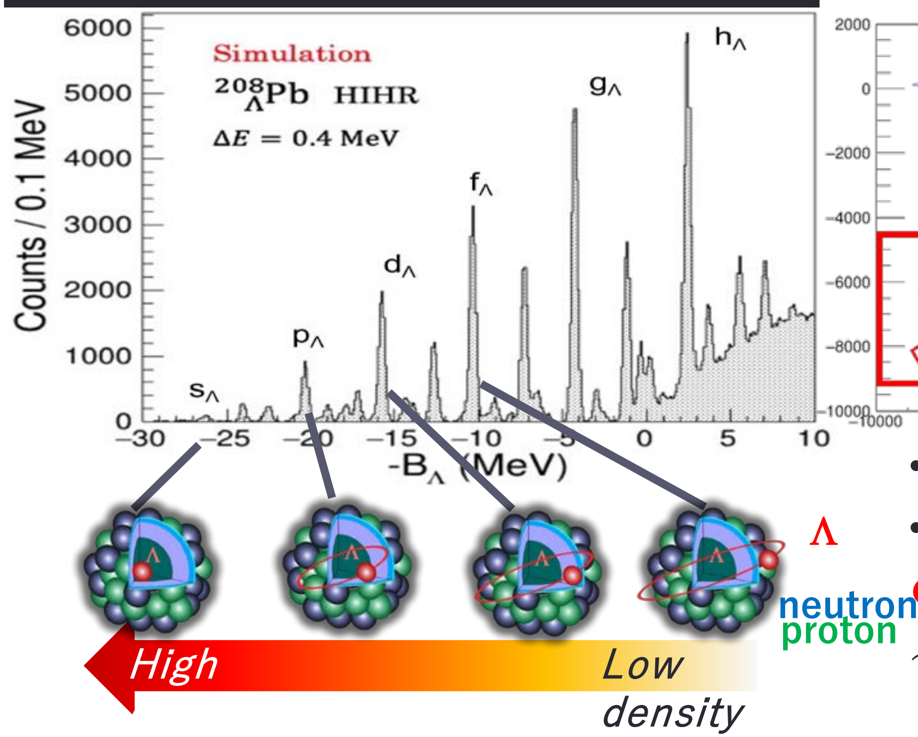

Cultural property servey, Forest land development, …
J-PARC
Hadron Exp. Facility
Jan, 2016

Strangeness Nuclear Physics: Hyperon in Dense Environment

Why can heavy neutron stars exist?

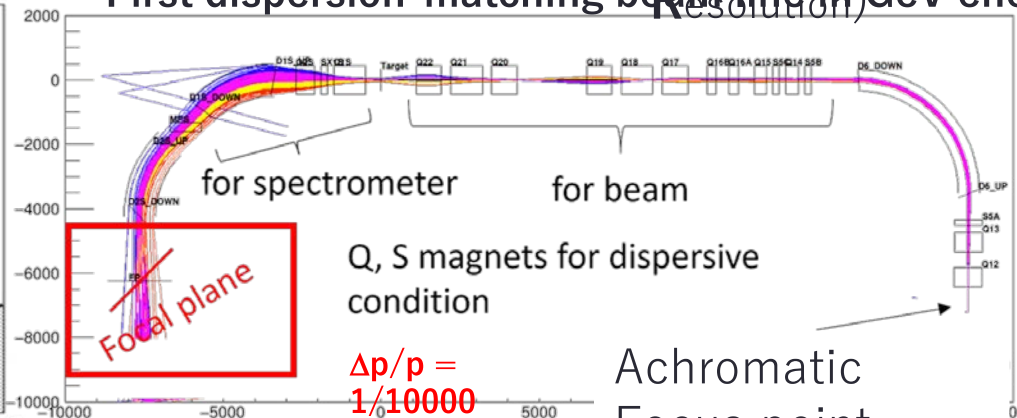
➢ **Hyperons (Λ, Ξ, …) emerge in dense neutron star matter?**

Ultra-high-resolution Λ-hyp. spectroscopy



HIHR beam line (High-Intensity High-Resolution)

First dispersion-matching beam line in GeV energy



- No need for beam tracking
- Intense π beam of > 10^8 /pulse
- **Break through the resolution limit:**

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

KEK Project Implementation Plan (KEK-PIP) 2022

KEK Project Implementation Plan 2022

June 24, 2022

High Energy Accelerator Research Organization (KEK)

1. Purpose

High Energy Accelerator Research Organization (KEK) published KEK Roadmap 2021 in May 2021. It described in detail the status of research fields related to KEK and the strategy for the research program to be pursued at KEK in the future, focusing on the fourth medium-range goals/plans period, JFY2022–JFY2027. The Project Implementation Plan (PIP) 2022 was developed as a concrete implementation plan for the realization of the KEK Roadmap 2021, particularly from the viewpoint of funding resources.

KEK Project Implementation Plan (KEK-PIP) 2022

2.1 J-PARC

In the resource allocation for J-PARC, priority is given to securing the operation of the Main Ring for six months per year or longer in total for fast extraction (FX) and slow extraction (SX), followed by maintenance and improvement of the accelerator and three research facilities: Material and Life Science Experimental Facility (MLF), Neutrino Experimental Facility, and Hadron Experimental Facility. In JFY2022, the construction of a new facility for the muon g-2/EDM experiment is to begin. It will be partially supported by KEK's discretionary budget. In the materials and life sciences at MLF, launching a new research project in the short term in response to social situations might be necessary, and a budgetary measure might be considered separately. COMET will be supported within the operation budget until the first phase is completed, and then second-phase construction will be considered, reflecting the progress in the first phase and considering international competition.

KEK Project Implementation Plan (KEK-PIP) 2022

8. Projects to Be Prioritized for New Budget Requests

One of the objectives of formulating KEK-PIP2022 is to establish a program for new research projects to be implemented at KEK over the next 6 years. At the beginning of this process, the research institutes and laboratories of KEK submitted 13 proposals as research projects that required a new budget. KEK then requested that the Science Advisory Committee of KEK recommend fewer projects out of nine projects that KEK had selected prior to the Committee discussion. Considering the advice of the Committee, KEK finally decided to proceed with five research projects in the following two categories as KEK's priority plan. The criteria for choosing a priority plan are as follows. (i) The proposed project must have scientific importance and international competitiveness. (ii) The program must be appropriate to achieve the goal, (iii) The program can be recommended as a role that KEK should play in the global scientific community centered on accelerator-based science. (iv) The financial feasibility of the proposed project does not need to be considered a prioritization criterion by the Committee.

Category I: A Project to Be Implemented by KEK without Specifying the Rank

- **R&D for New Light Source Facility**

KEK Project Implementation Plan (KEK-PIP) 2022

Category II: Projects to make new budget requests according to priority

Of the new research programs proposed in the process of formulating KEK-PIP2022, the following four are given high priority, and appropriate efforts will be made to receive new budgetary measures in this order.

II-1. Extension of the J-PARC Hadron Experimental Facility

In the J-PARC hadron experimental facility, various elementary particle and nuclear experiments are being conducted using kaons and muons obtained from high-intensity protons. The proposed program aims to greatly extend the diversity of research by expanding the hadron experimental facility to increase the energy range, intensity, and momentum resolution of the secondary beams. This project has high scientific significance and international competitiveness in a wide range of sciences, from nuclear and particle physics to cosmology, with unique beamlines and apparatuses. Timely realization of the project will benefit both the international research community and KEK by extending its capability and efficiency in the high-intensity frontier. Because considerable in-kind and personnel contributions in the construction phase are expected from universities and institutes, synchronized cooperation with them will be required to minimize the shutdown period.

Summary

- J-PARC is a multipurpose proton accelerator facility, from materials science to nuclear/particle physics.
- Hadron Experimental Facility utilizes secondary beams such as pions and kaons. The intensity and purity of these beams are important.
- The beam power has been improved gradually to 64.5 kW. The Hadron Experimental Facility is now in the era of K-induced experiments.
- A major goal is to investigate hadron interactions and structures.
- The extension of the Hadron Experimental Facility is expected, and KEK/J-PARC is making efforts for its realization.