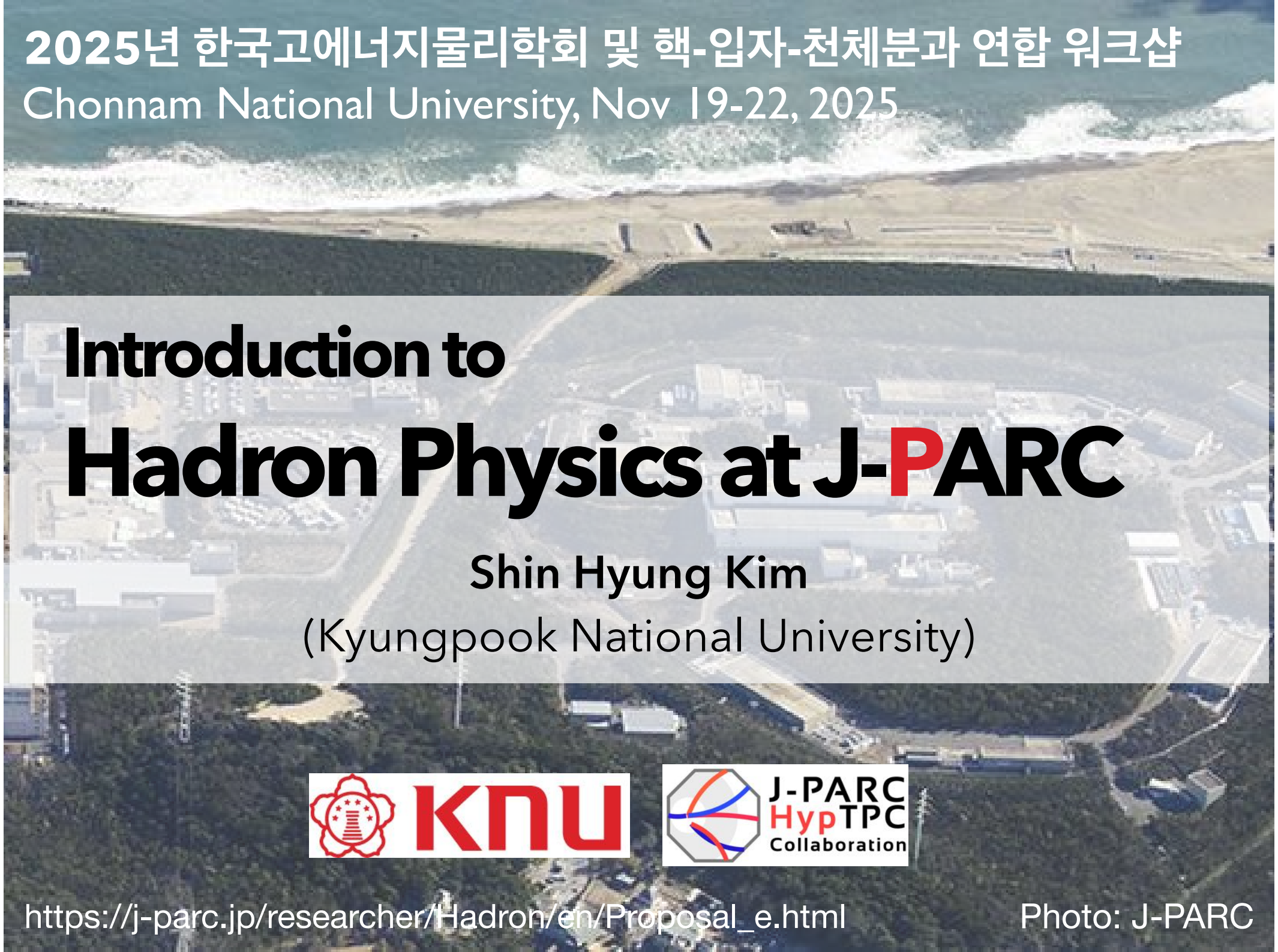

2025년 한국고에너지물리학회 및 핵-입자-천체분과 연합 워크샵

Chonnam National University, Nov 19-22, 2025

Introduction to
Hadron Physics at J-PARC

Shin Hyung Kim

(Kyungpook National University)

https://j-parc.jp/researcher/Hadron/en/Proposal_e.html

Photo: J-PARC

Hadron Physics

= Study of quantum many-body system governed by QCD

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Confinement

Hadron Physics

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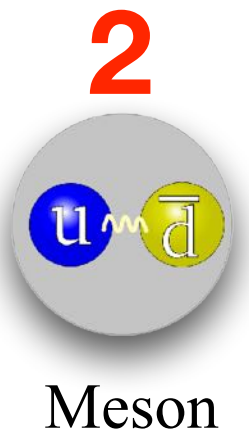
Confinement



Meson

Hadron Physics

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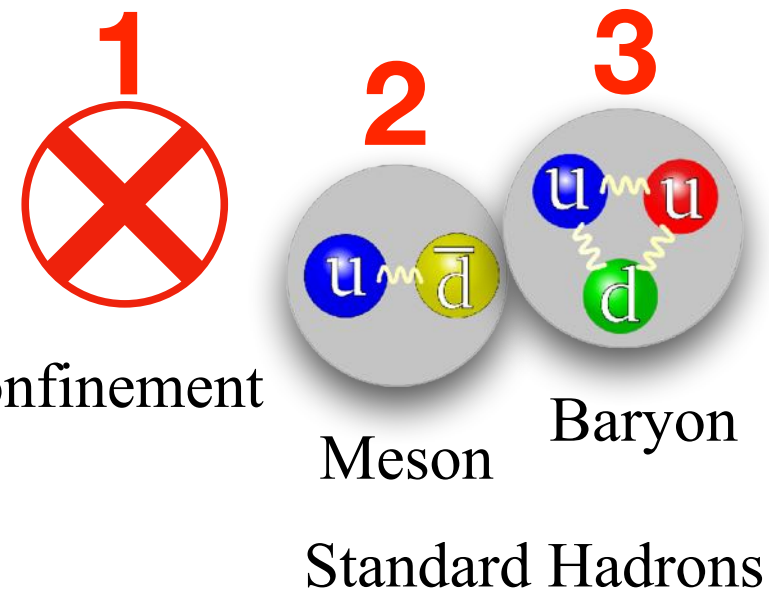

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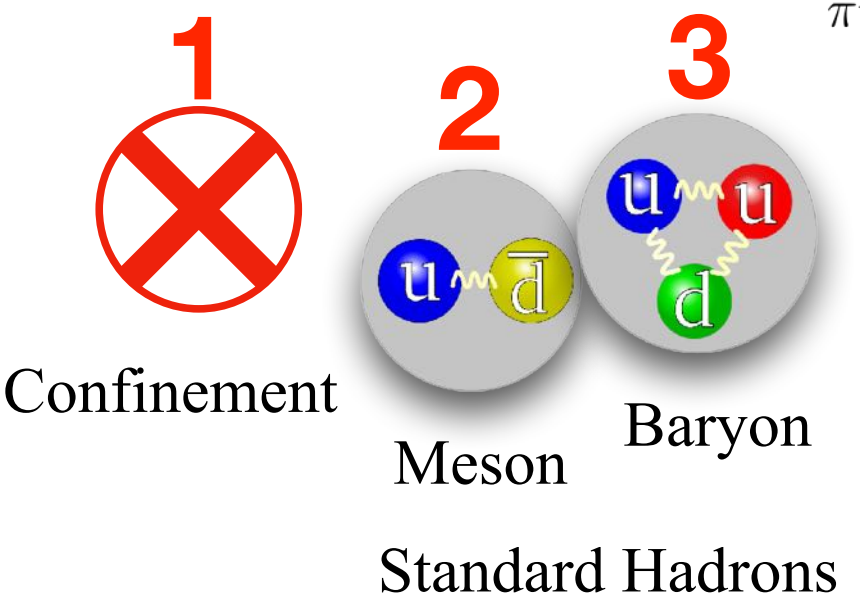

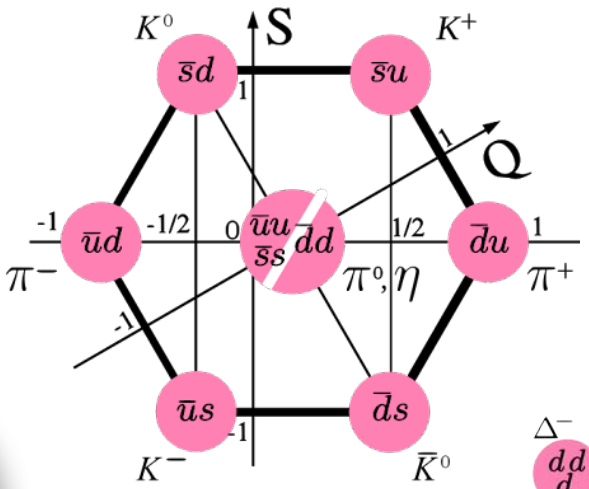

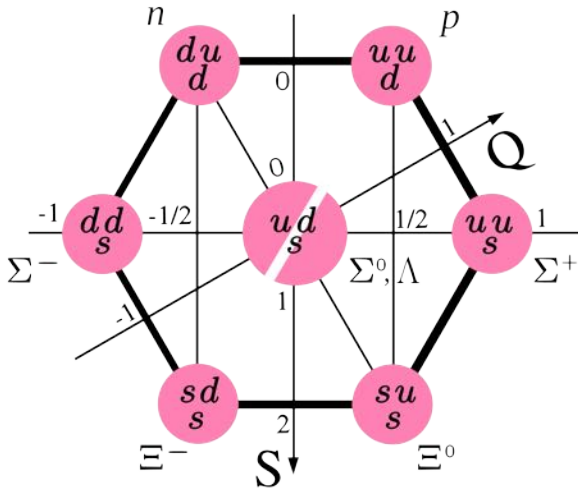

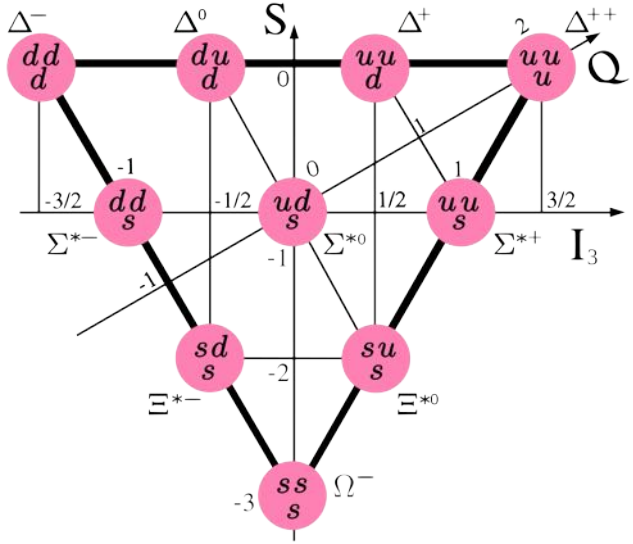

Hadron Physics

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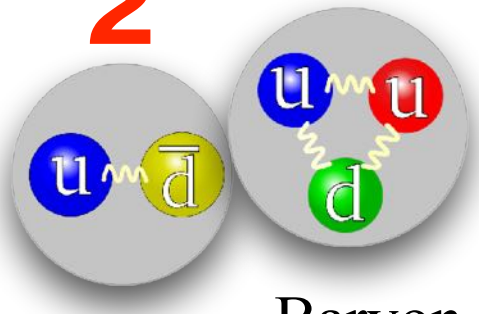
1

Confinement

2

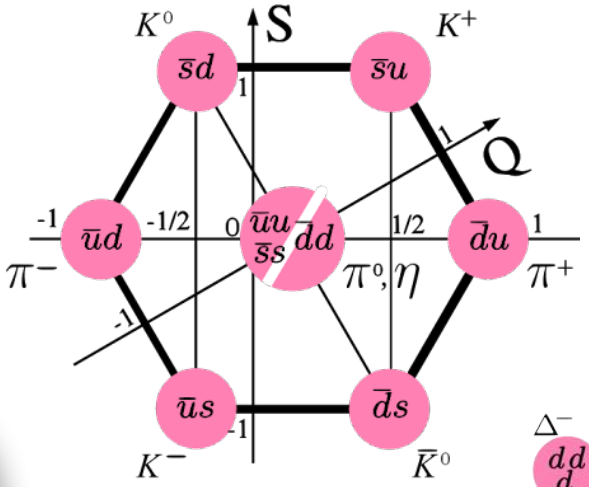
3

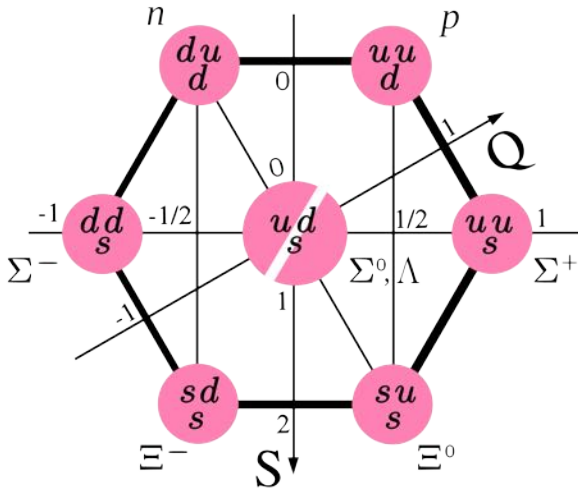


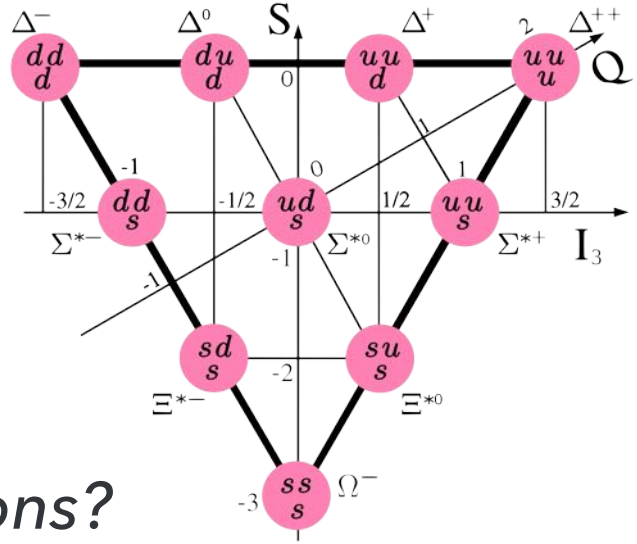
Meson

Baryon

Standard Hadrons







➔ *More hadrons?*

Hadron Physics

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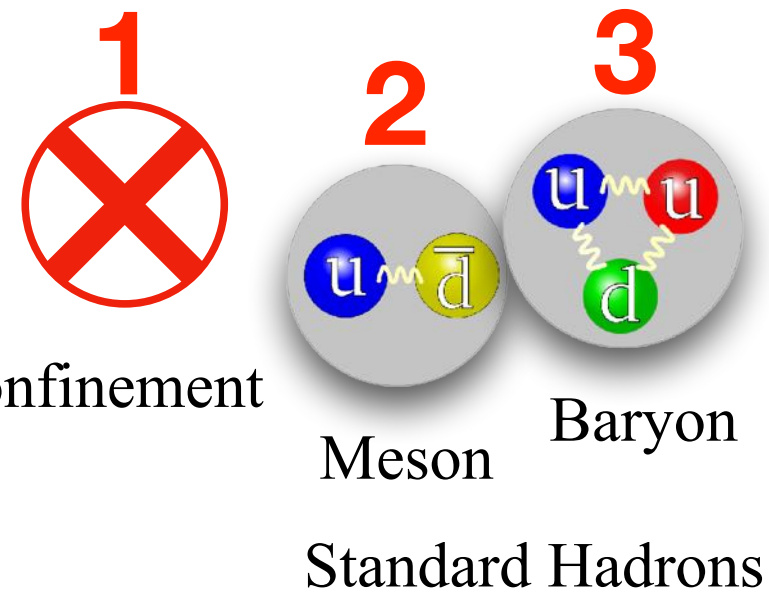

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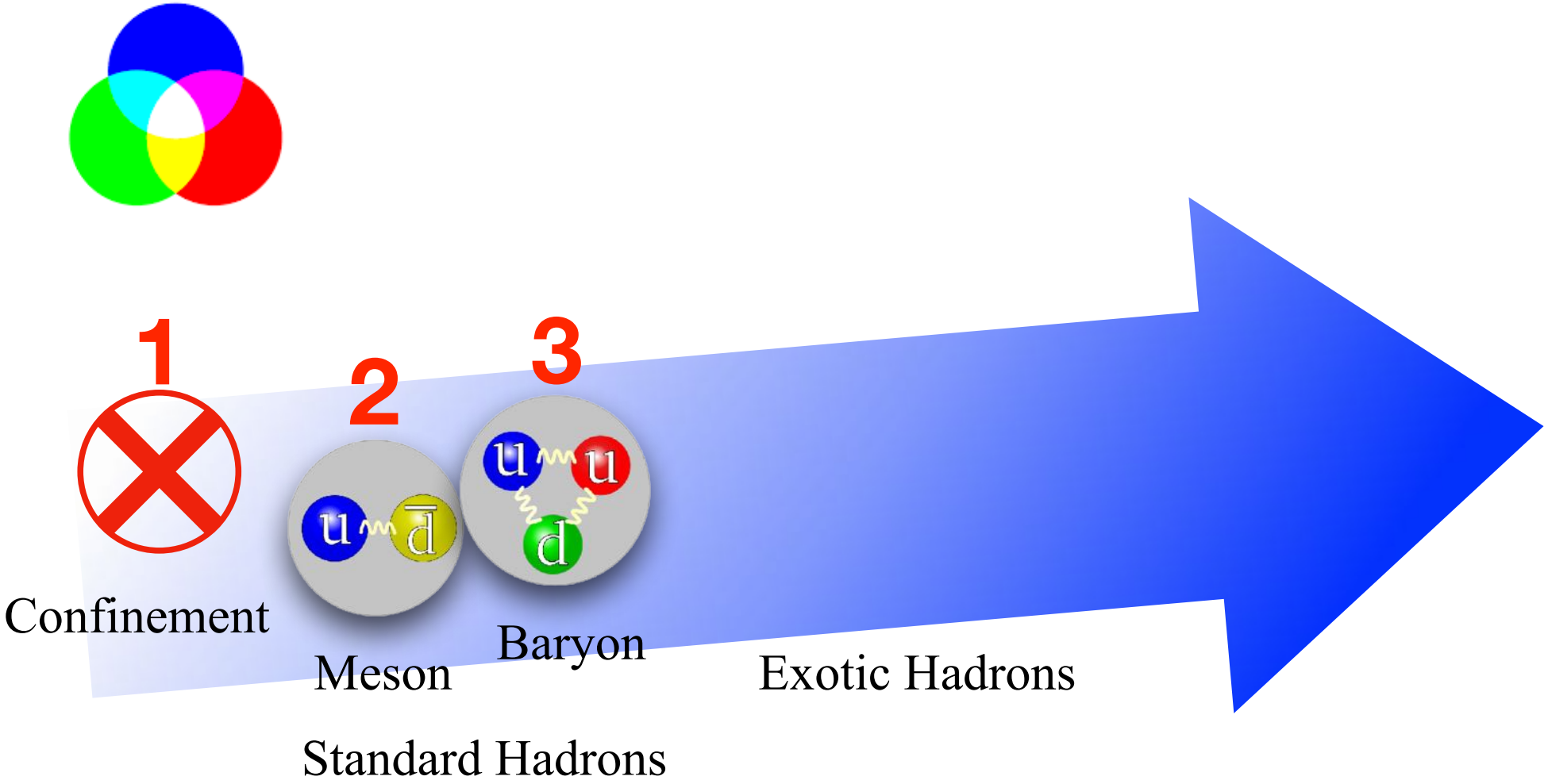

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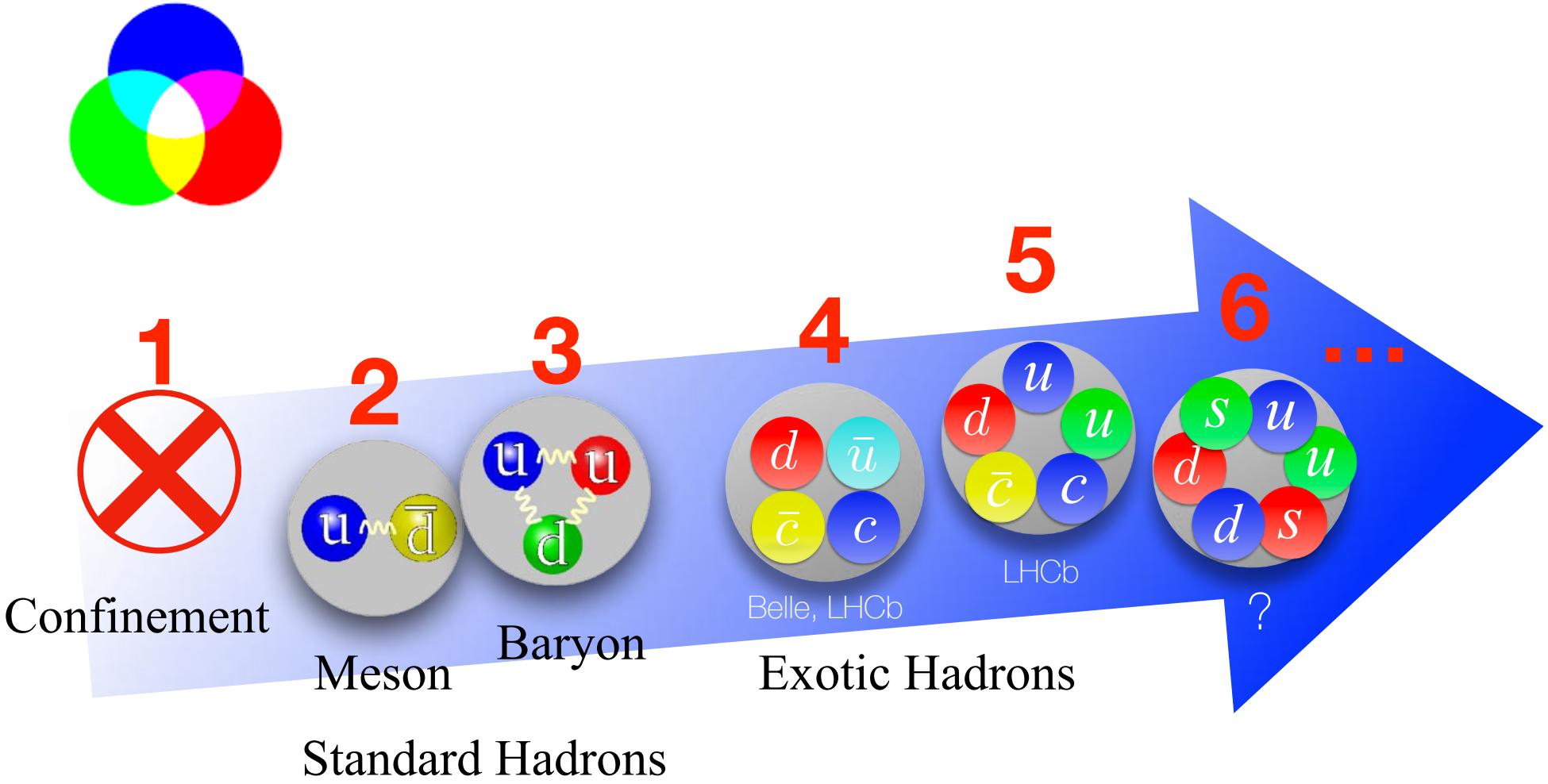

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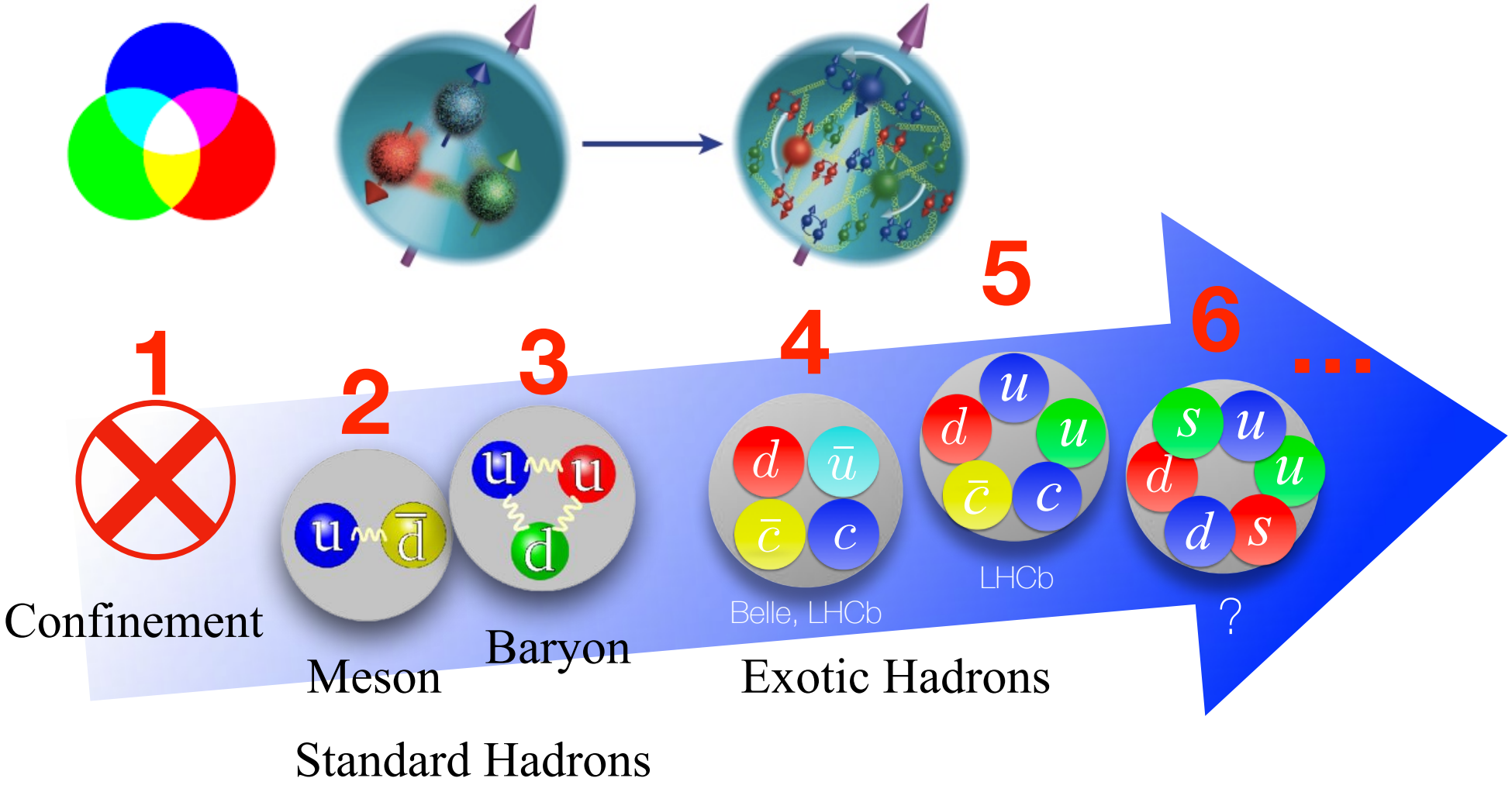

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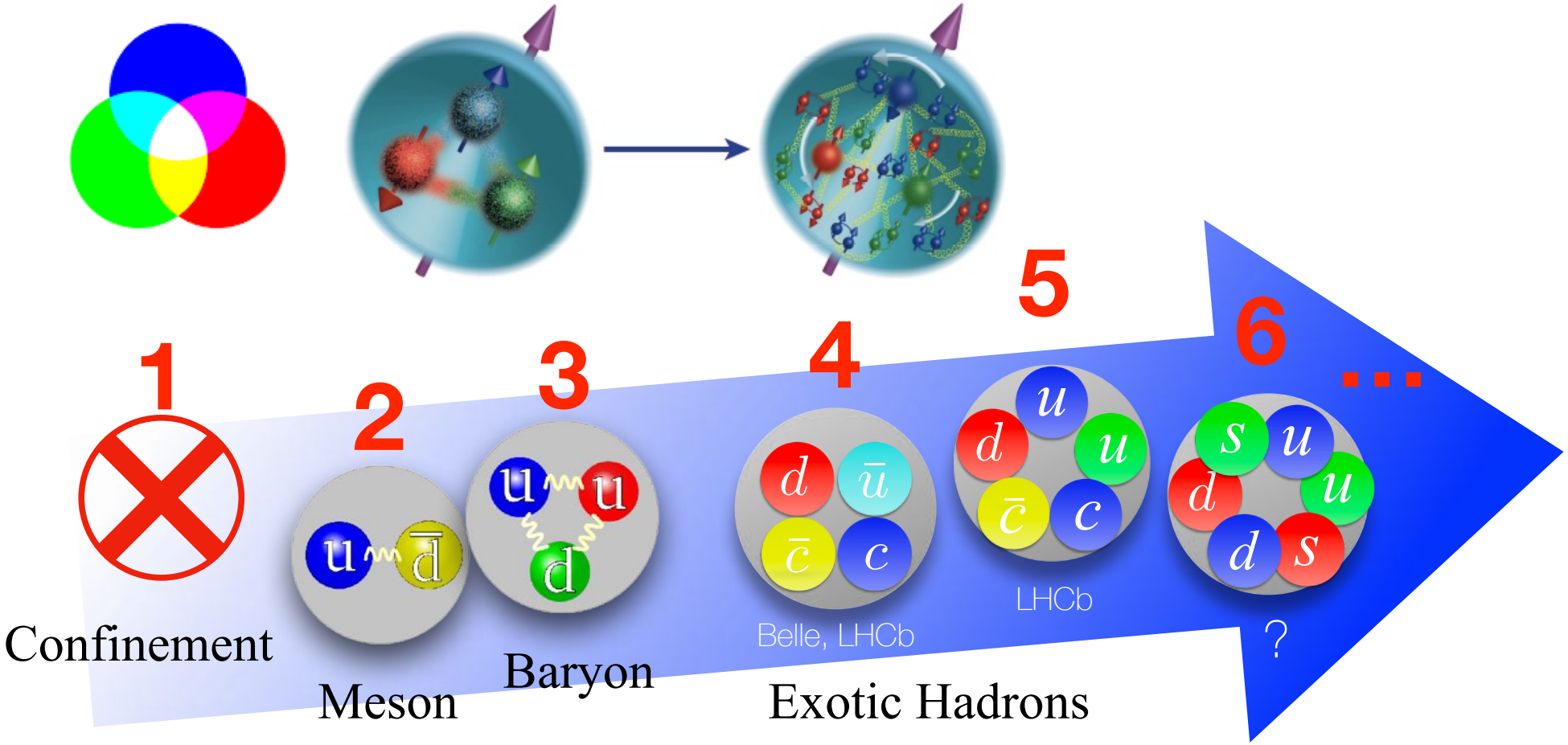

➔ *Origin of the hadron mass?*

➔ *Hadron structure?*

J-PARC

= Japan Proton Accelerator Research Complex

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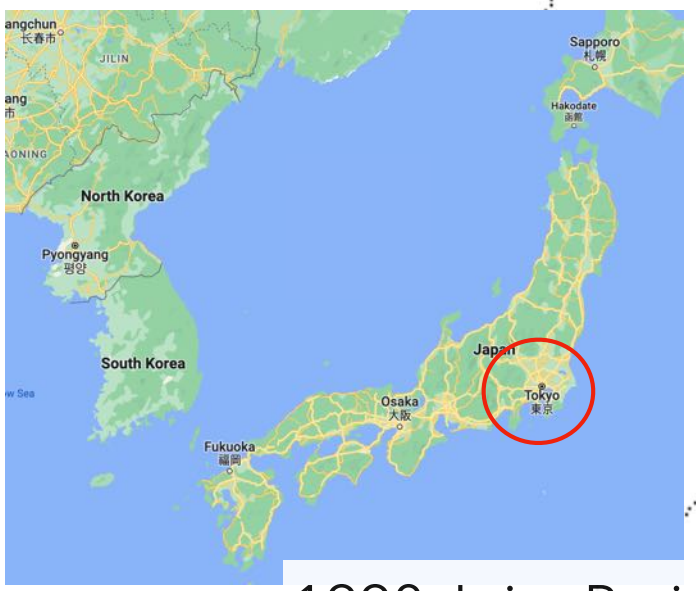


KAMIOKA

295 km

JAERI

Tokai

1 hour

KEK

Tsukuba

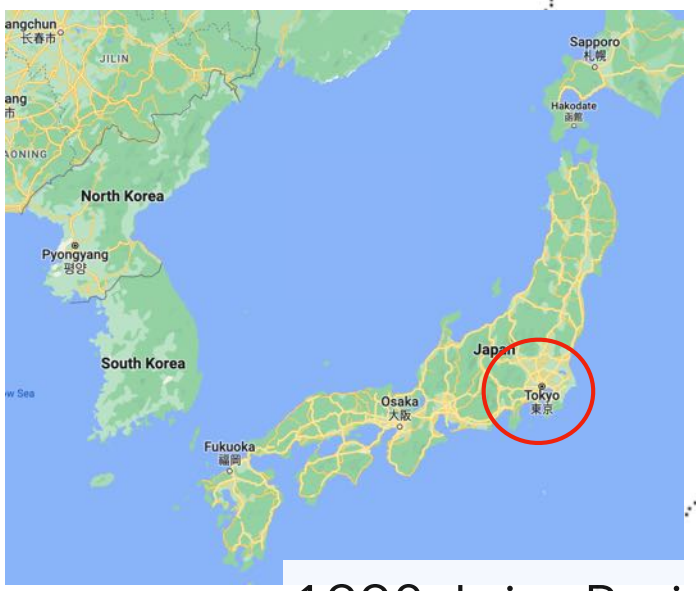
TOKYO

NARITA

1998 Joint Project
between KEK & JAEA
2001-2009 Construction

J-PARC

= Japan Proton Accelerator Research Complex



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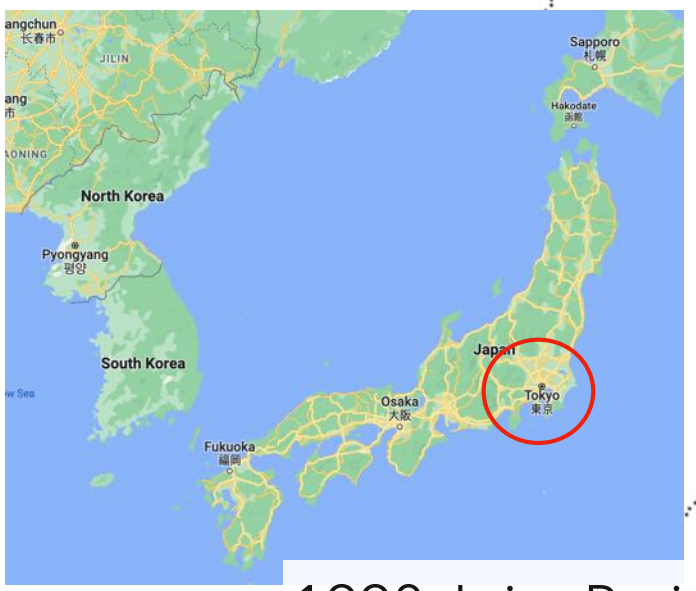

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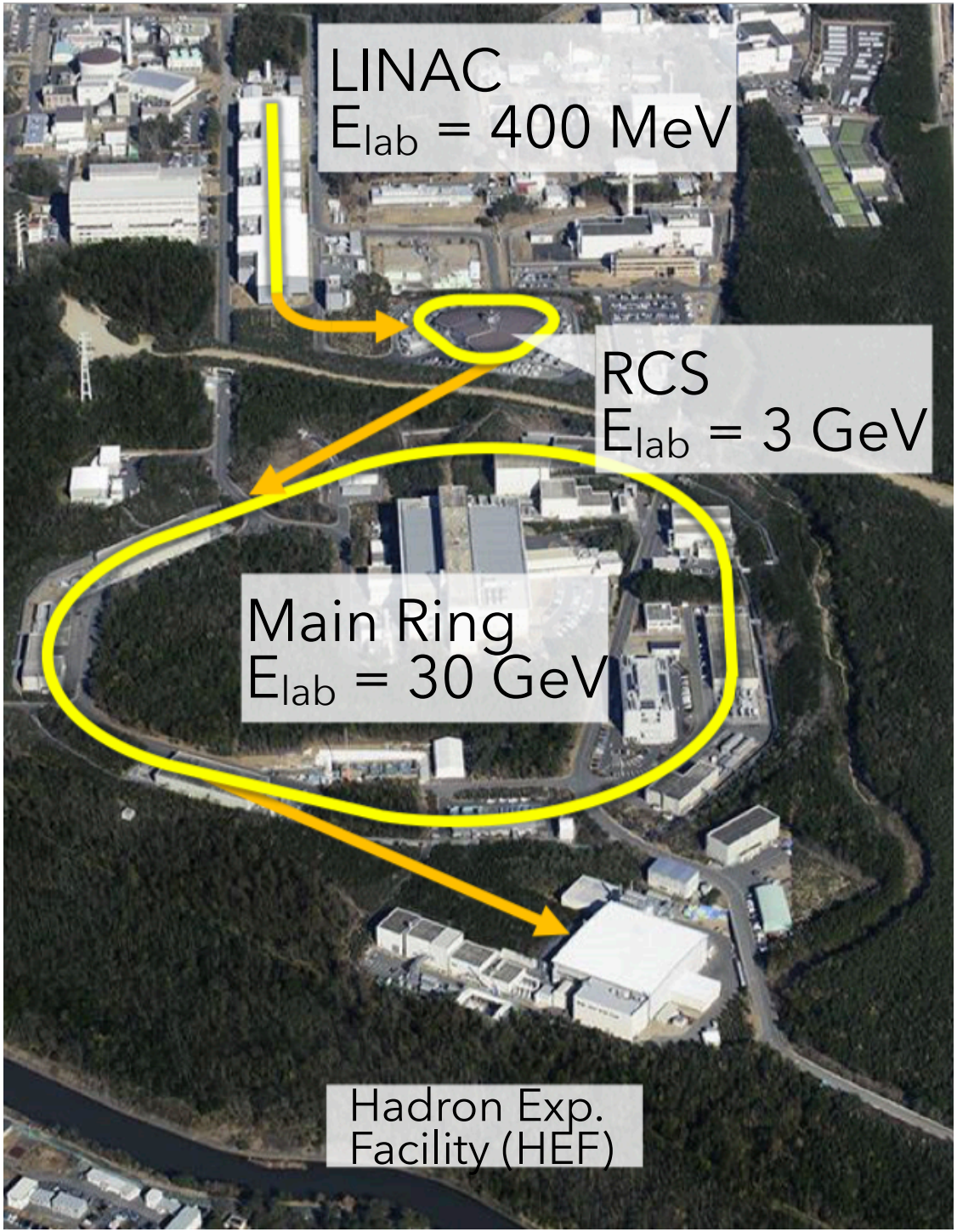
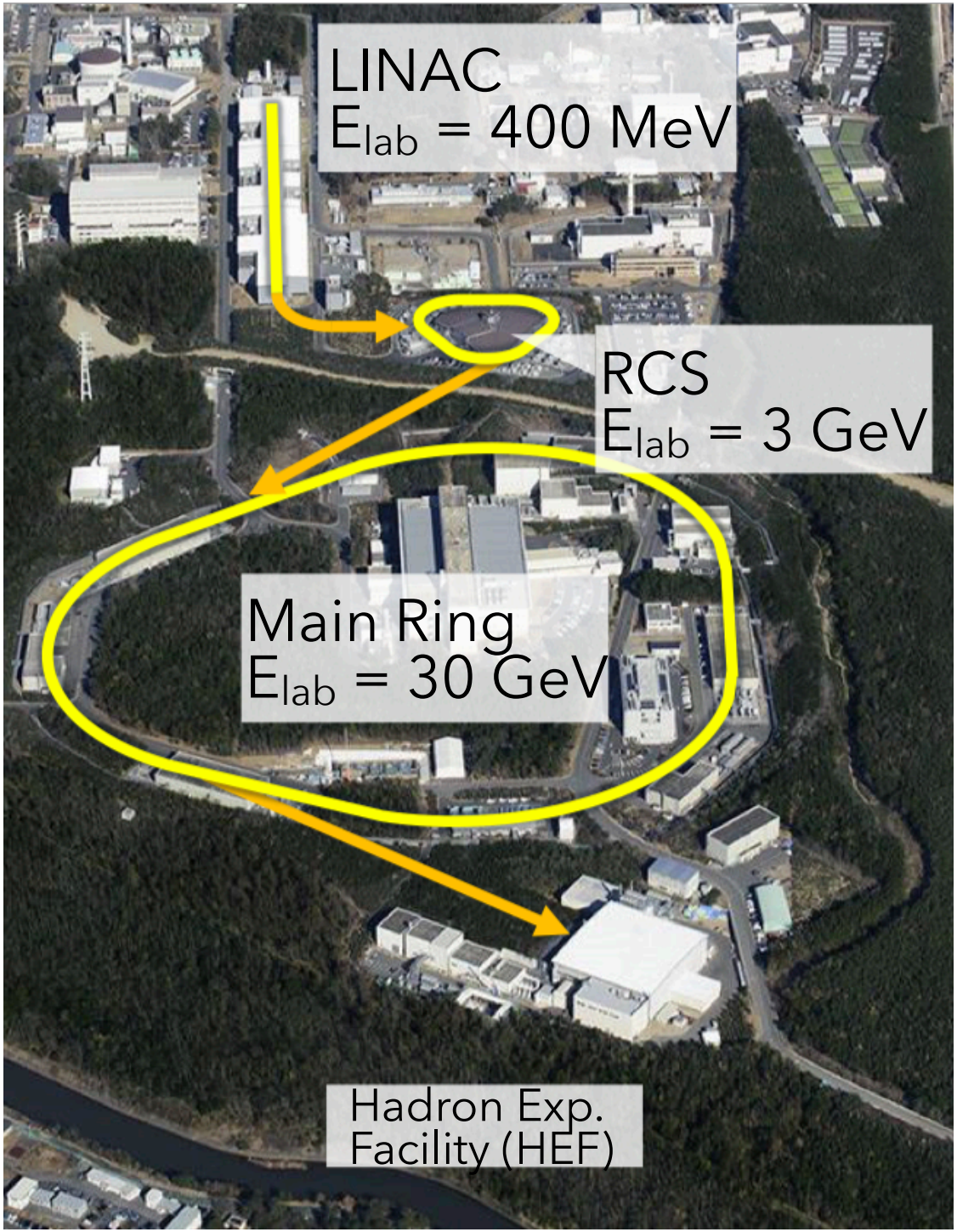
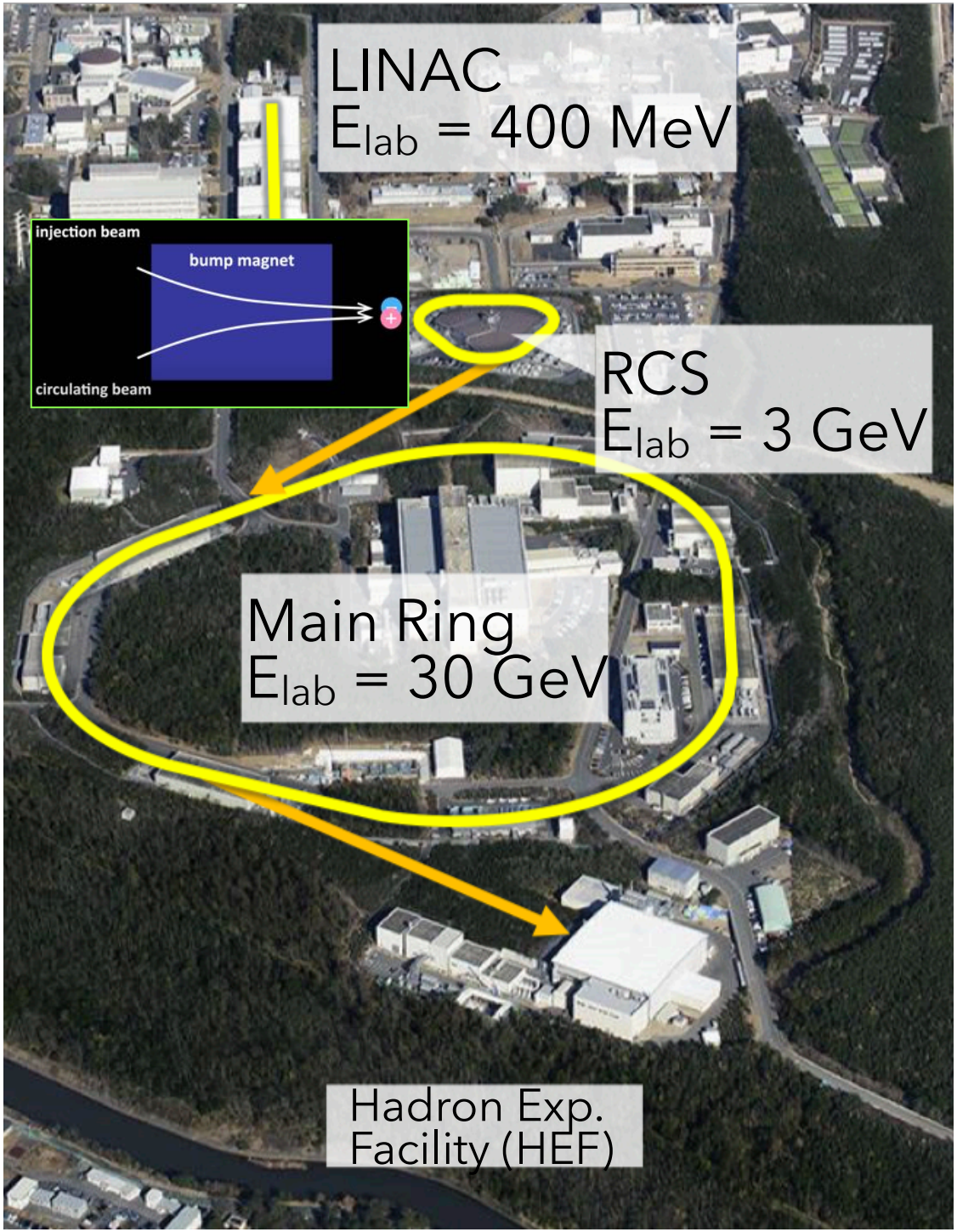

LINAC
E_{lab} = 400 MeV
RCS
E_{lab} = 3 GeV
Main Ring
E_{lab} = 30 GeV
Hadron Exp.
Facility (HEF)



- **Accelerators**
  - LINAC
  - RCS
  - Main Ring (MR)
    High intensity 1 MW



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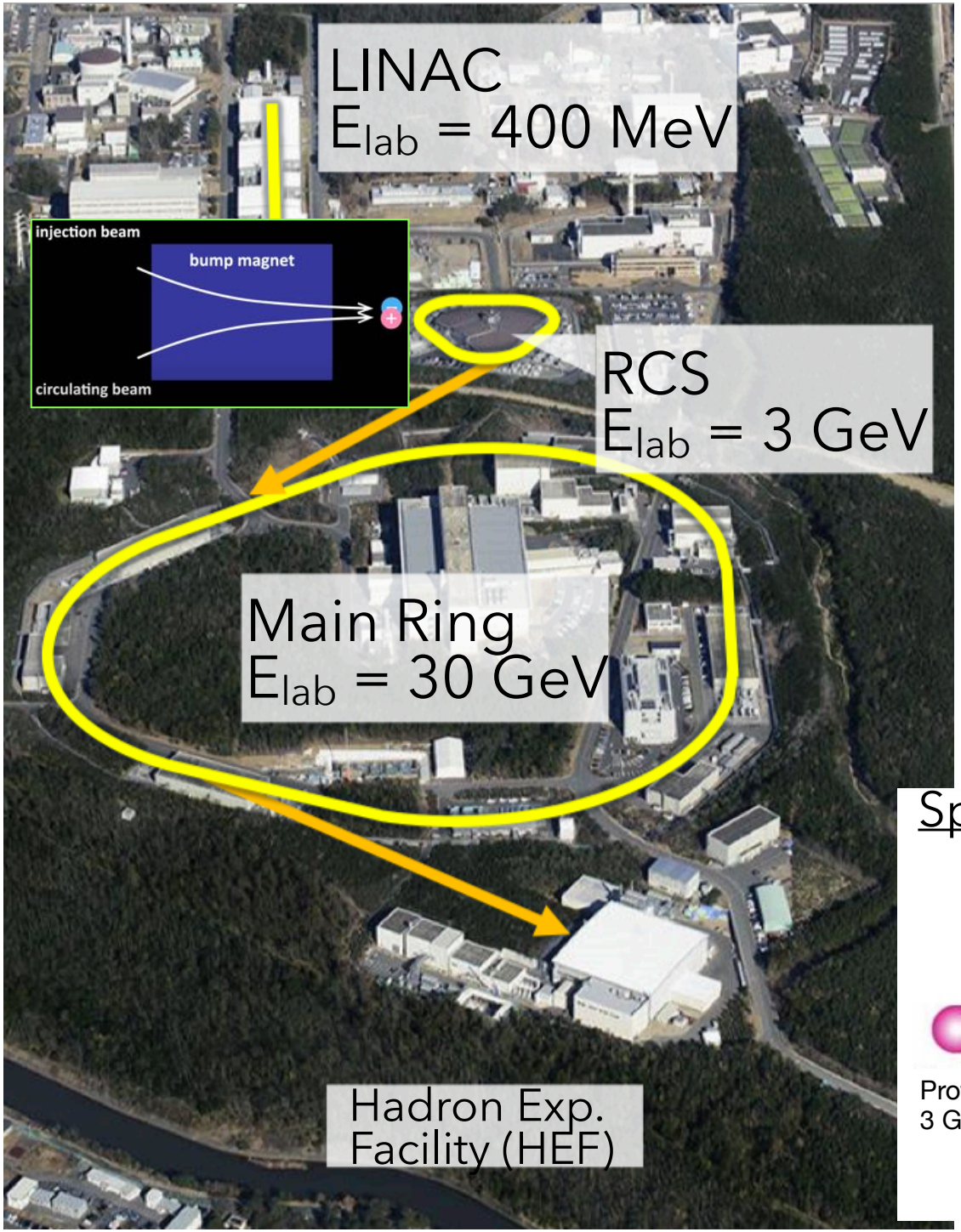

- **Accelerators**
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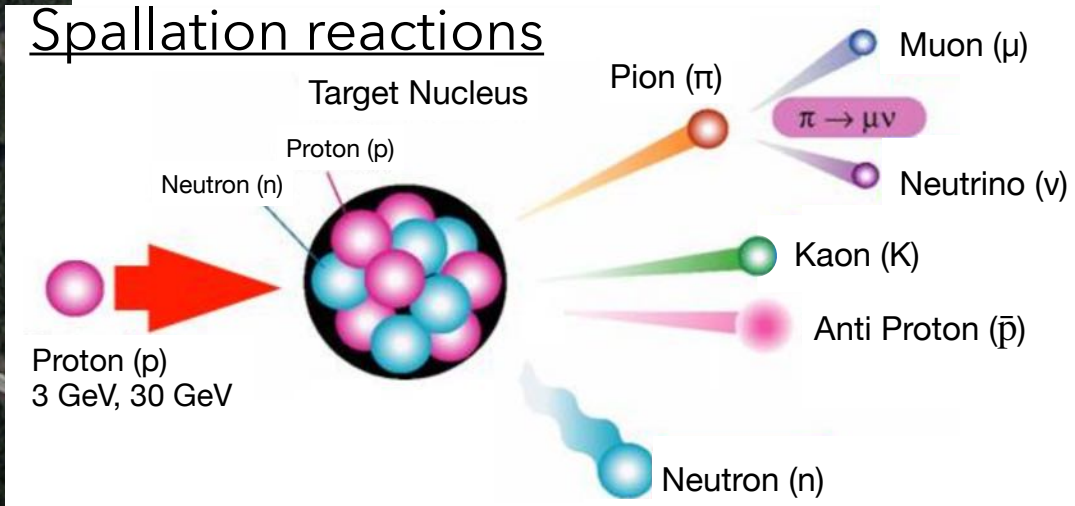
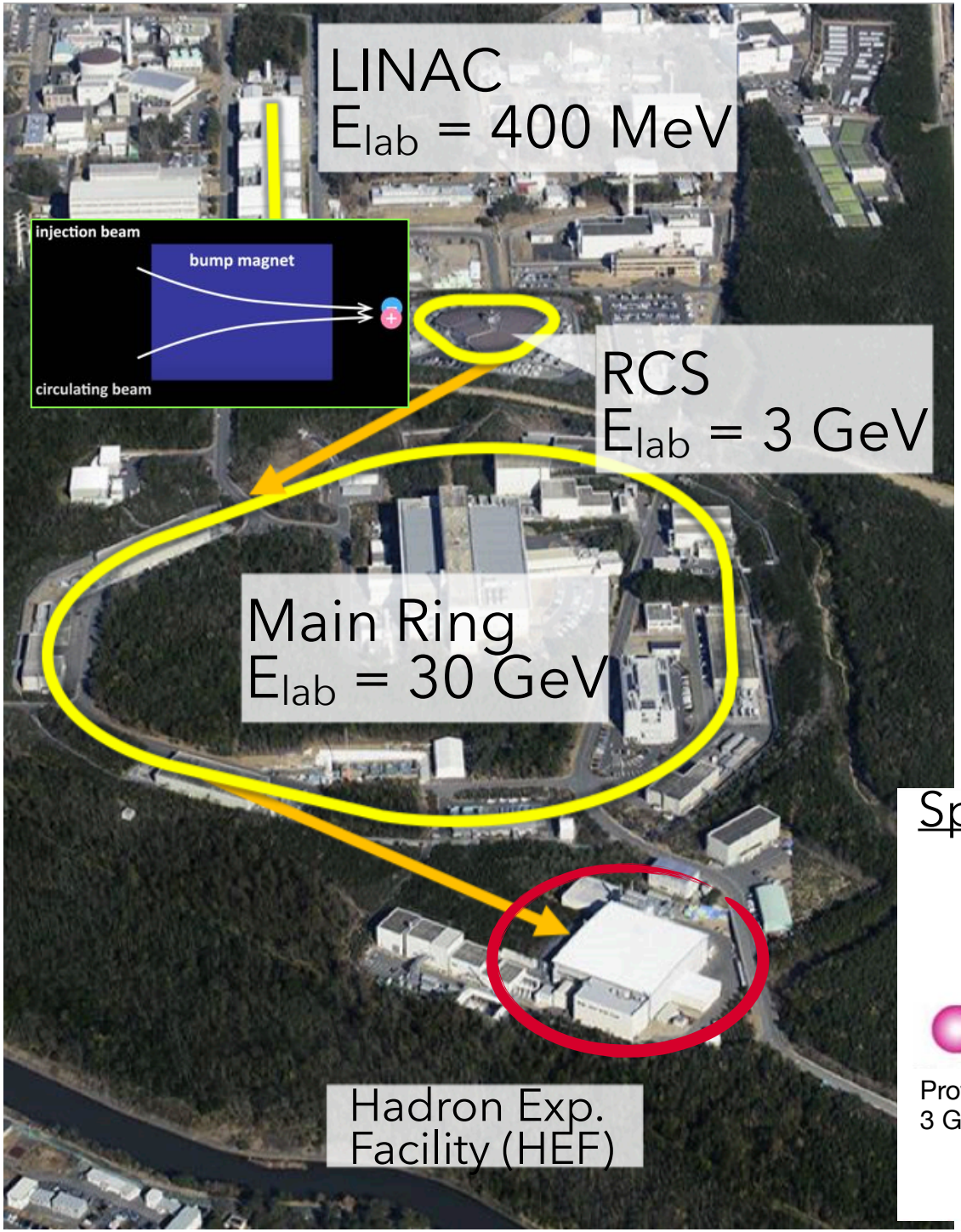
  - Material/Life science
  - Neutrino physics
  - Hadron/Nuclear physics





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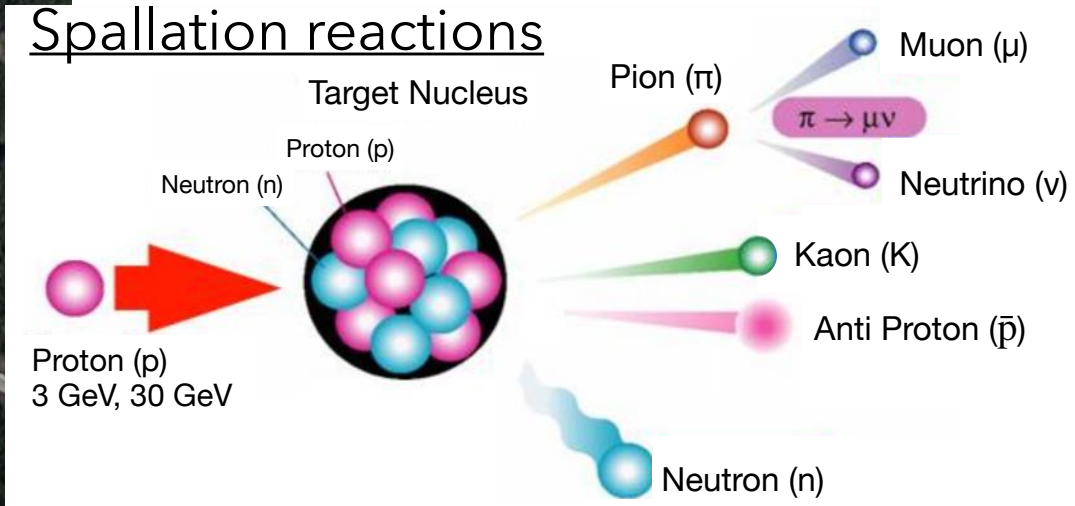
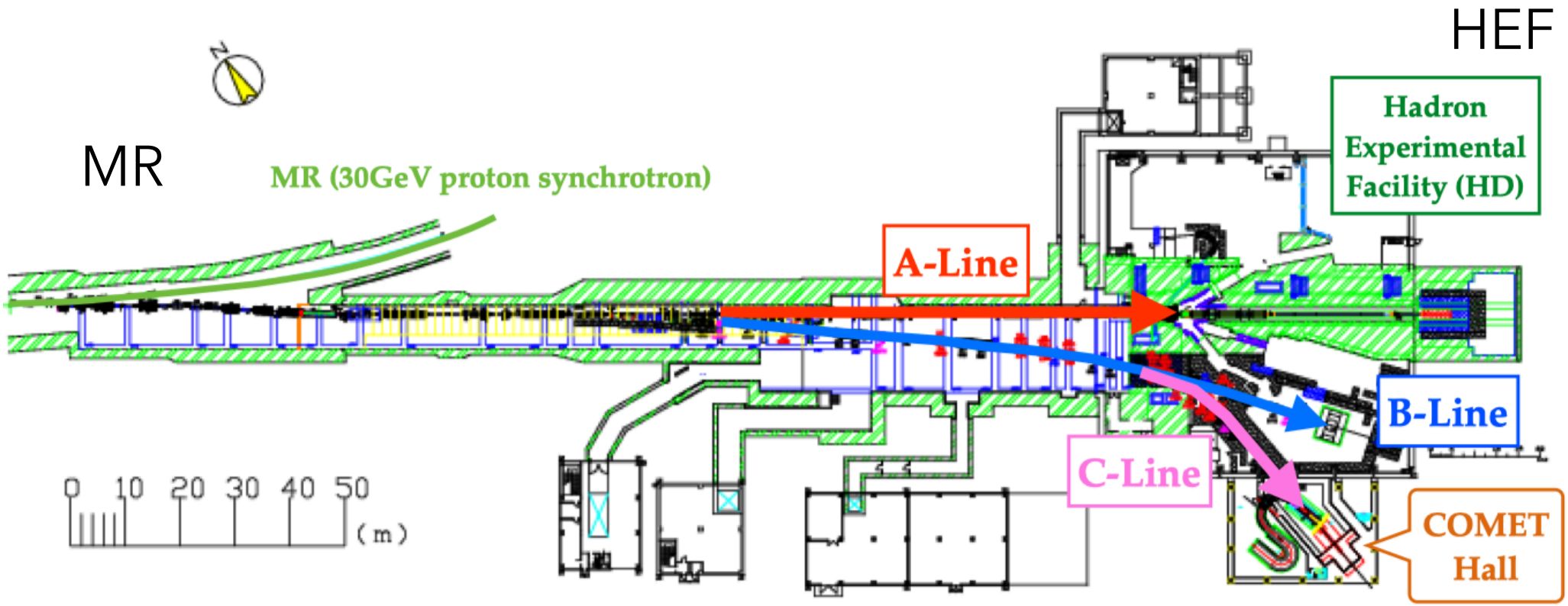


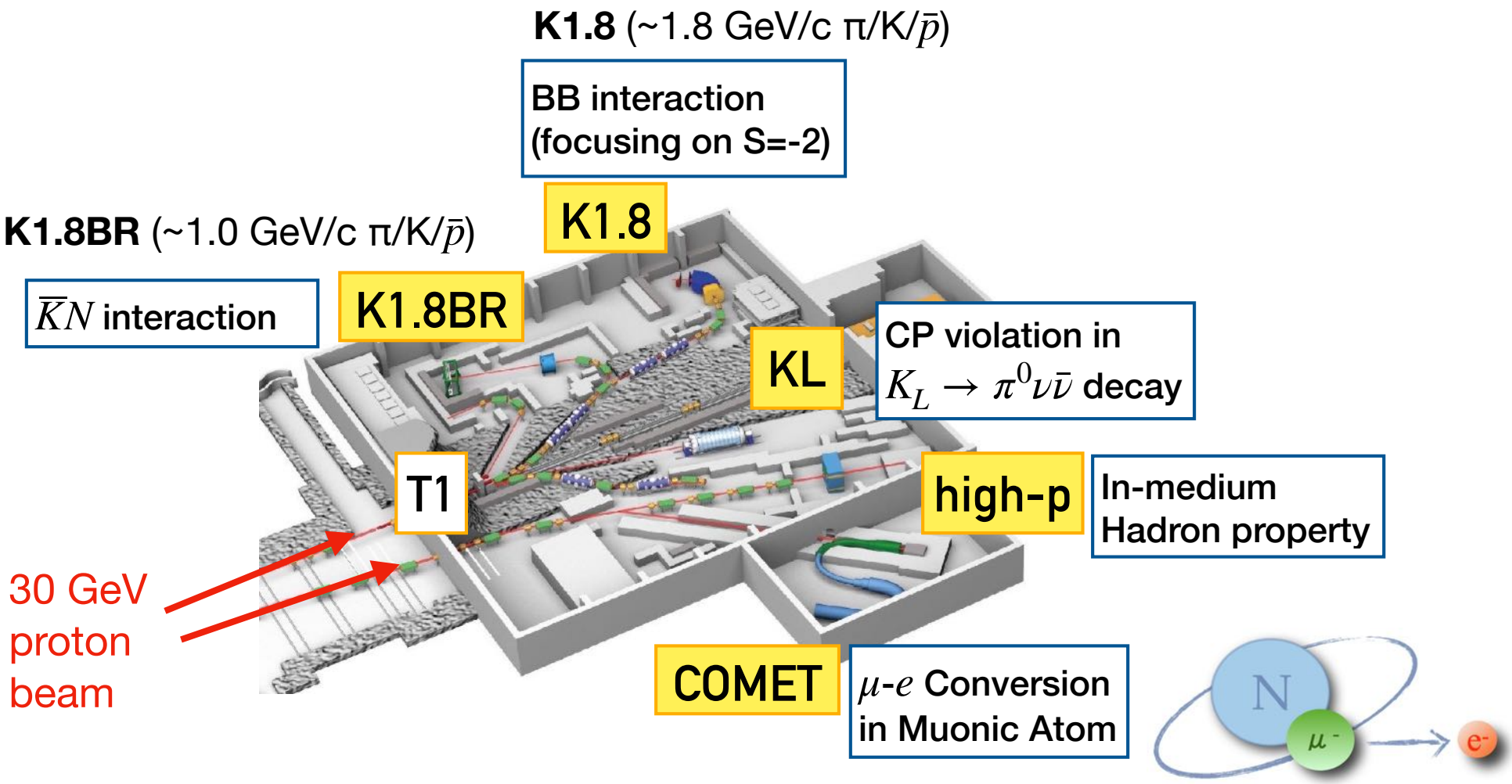
J-PARC Hadron Experimental Facility



- **Slow extraction**

- a duration of 2.1 s in every 4.24 s (1 spill)
- 90 kW stable operation
  - $>8\times10^{13}$ ppp World record! (Apr. 2025)

J-PARC Hadron Experimental Facility



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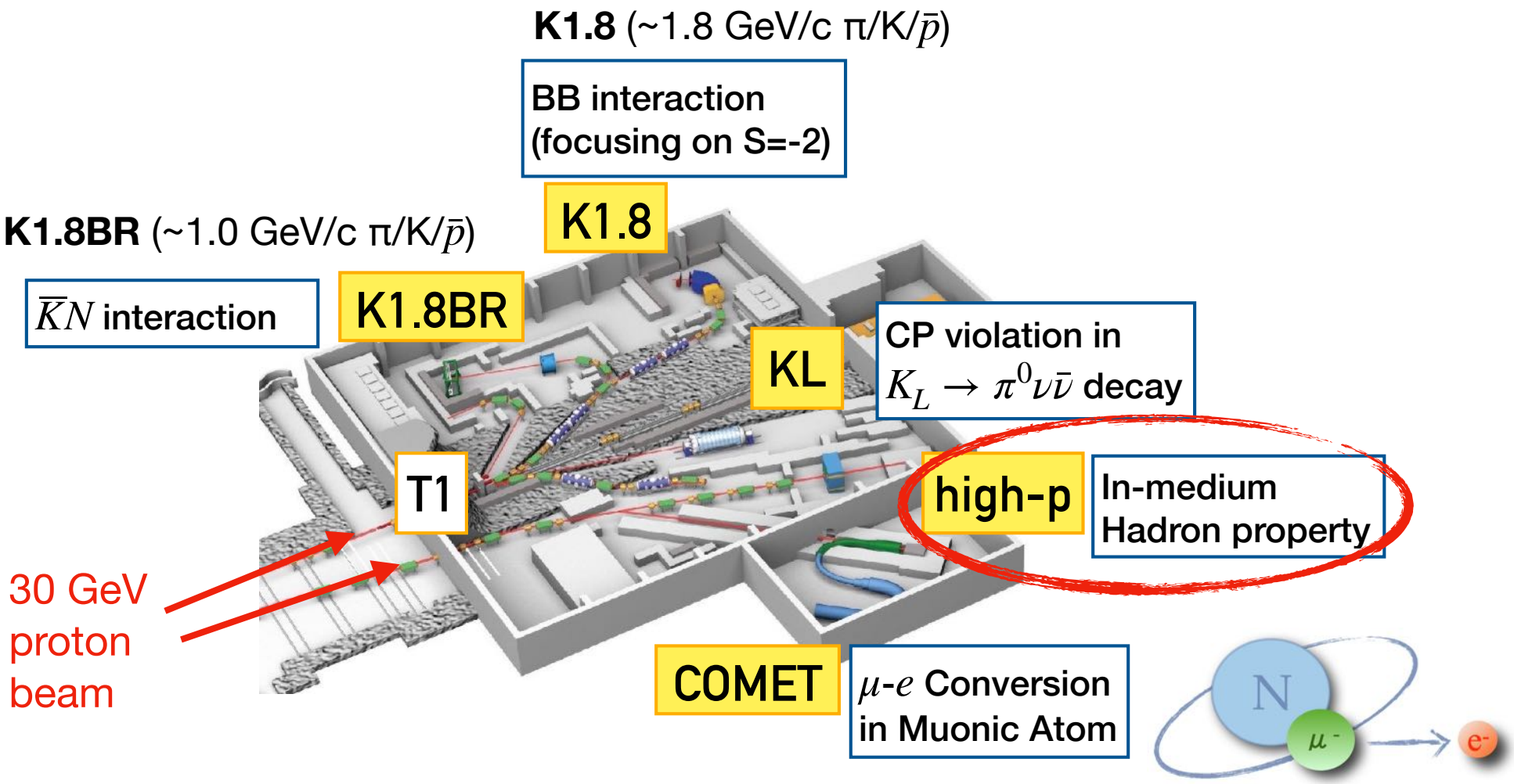
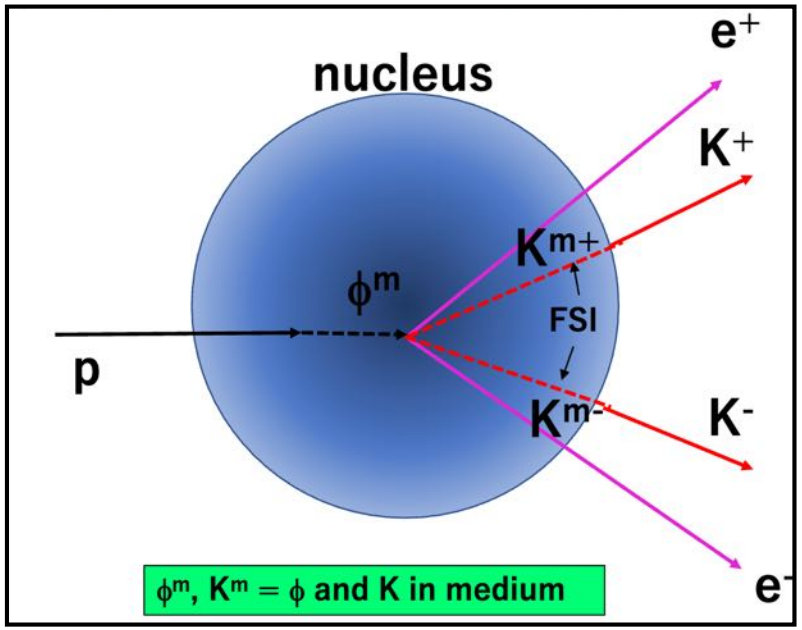


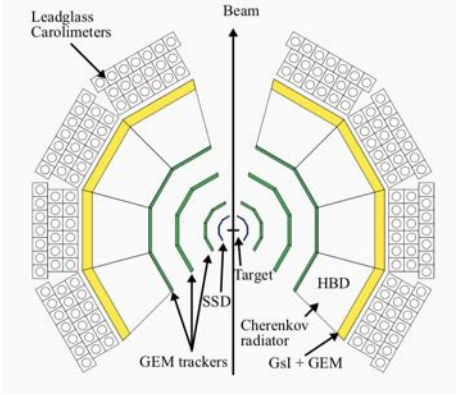
φ Mass Modification in Nuclei

J-PARC E16/E88: e^+e^- and K^+K^- measurements in pA collisions
Probe of quark condensate & partial chiral symmetry restoration

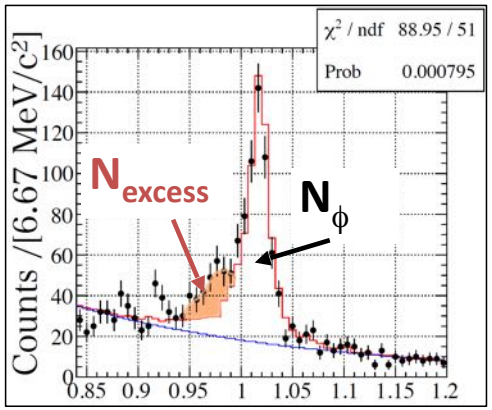


H. Sako

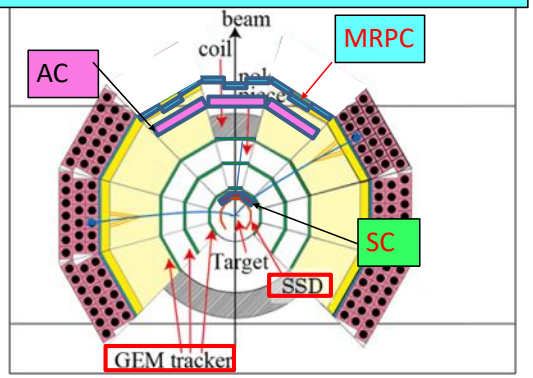
E16: dielectron including ϕ→e+e-



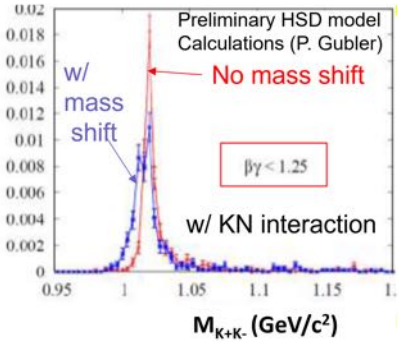
Expected spectrum (15k ϕ, p+Cu)



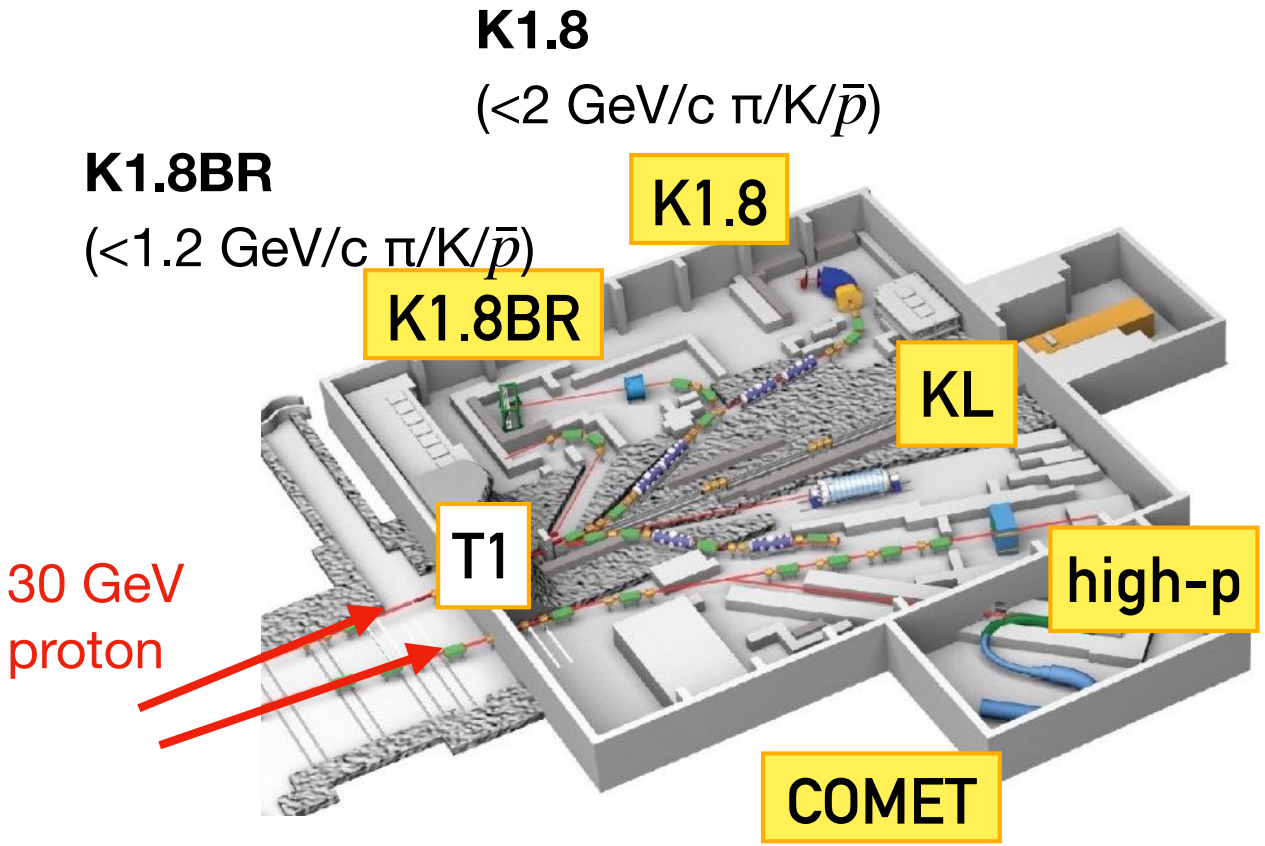
E88: ϕ→K+K- (proposed in 2022)



~1M ϕ→K+K-



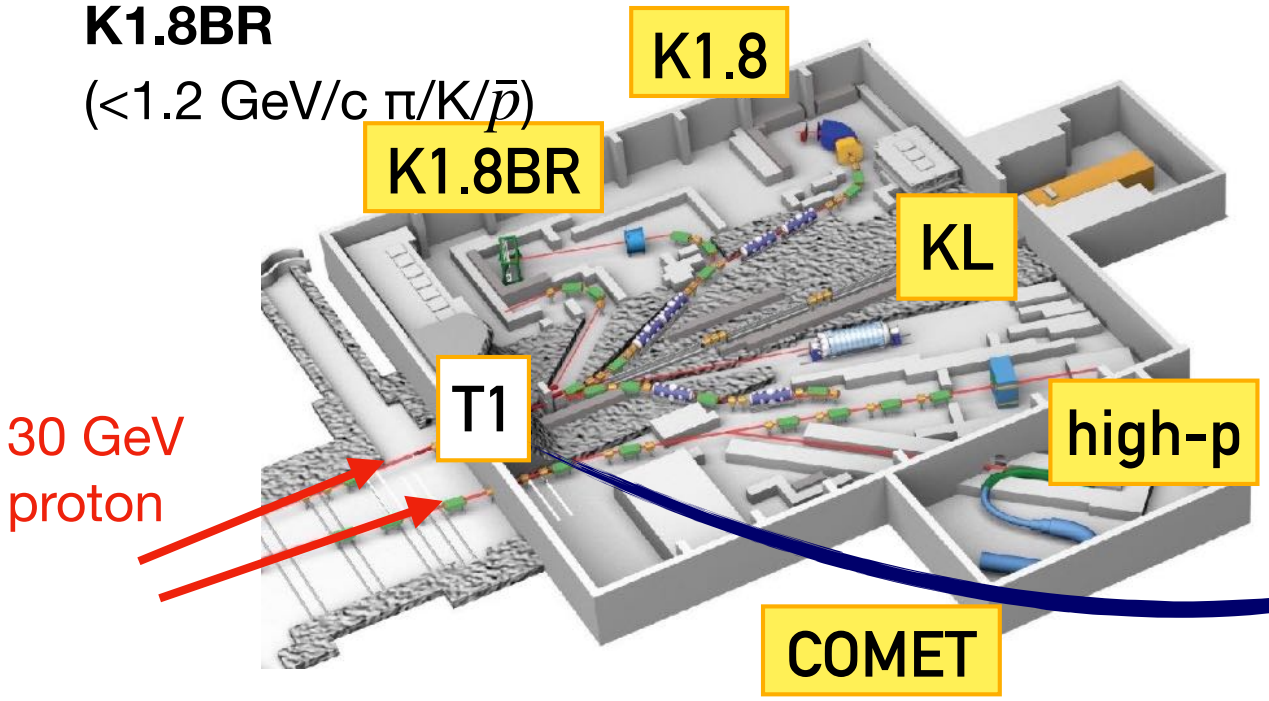
J-PARC Hadron Experimental Facility

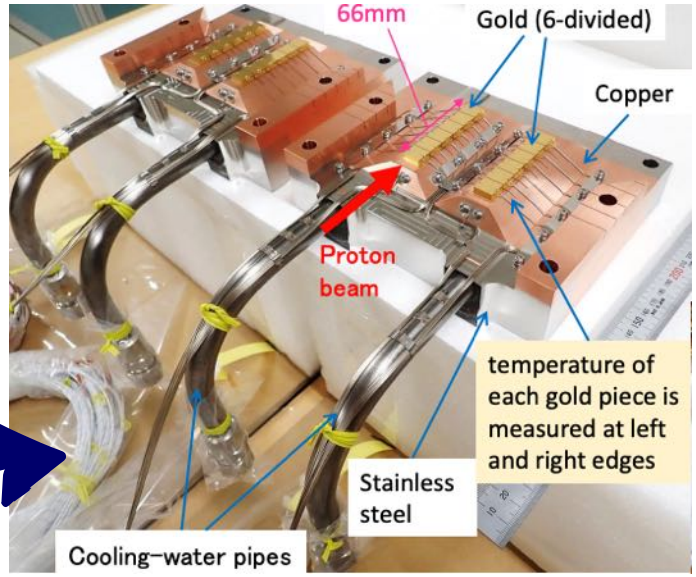


J-PARC Hadron Experimental Facility

K1.8
(<2 GeV/c π/K/$\bar{p}$)

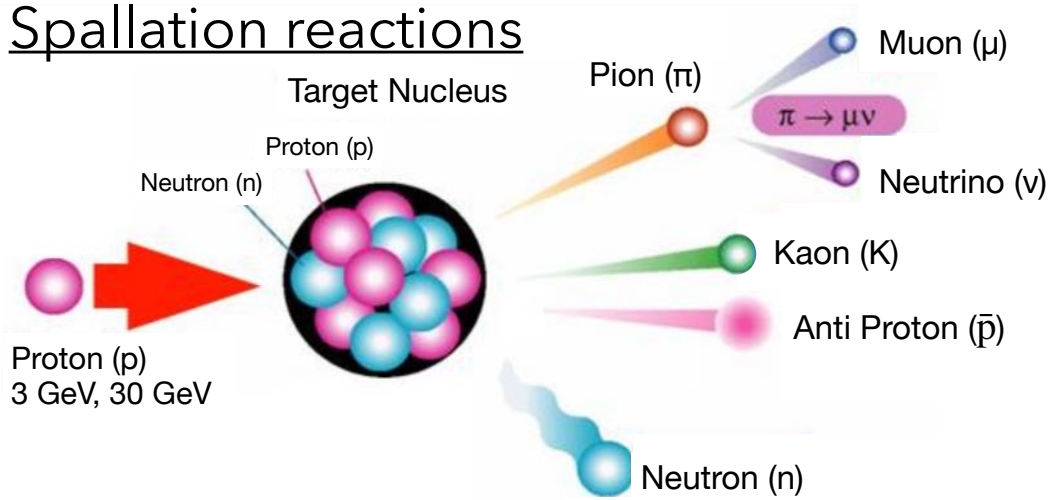
K1.8BR
(<1.2 GeV/c π/K/$\bar{p}$)





T1 Gold Target

J-PARC Hadron Experimental Facility



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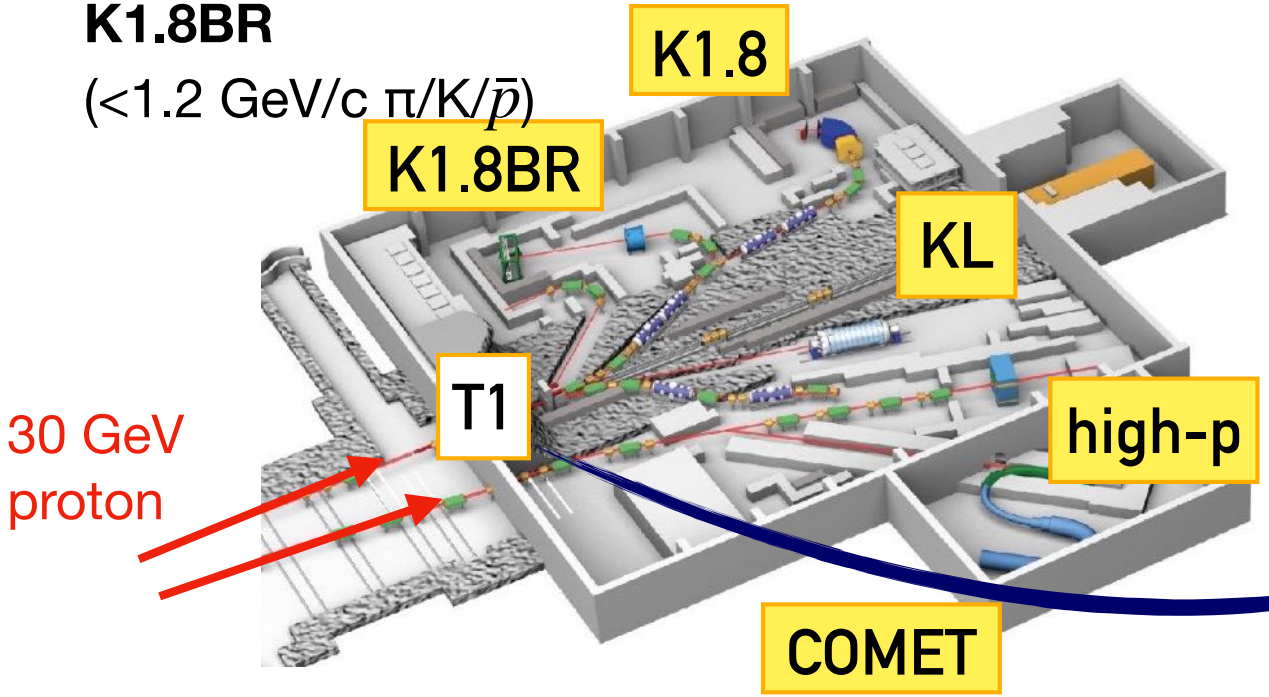

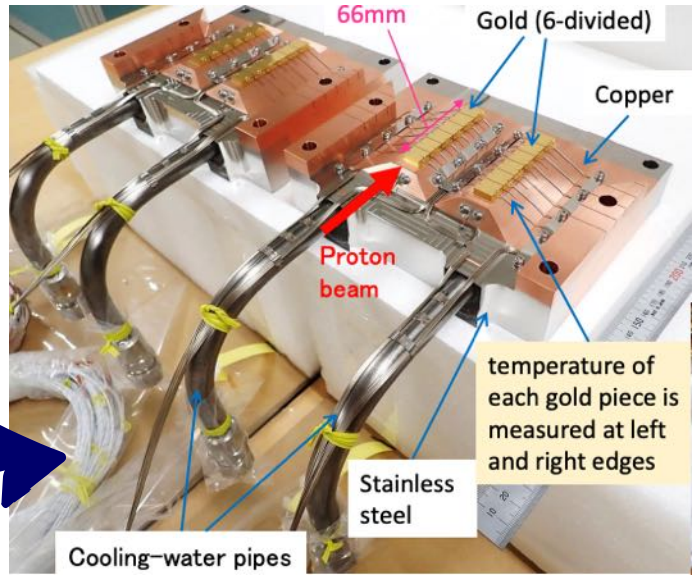

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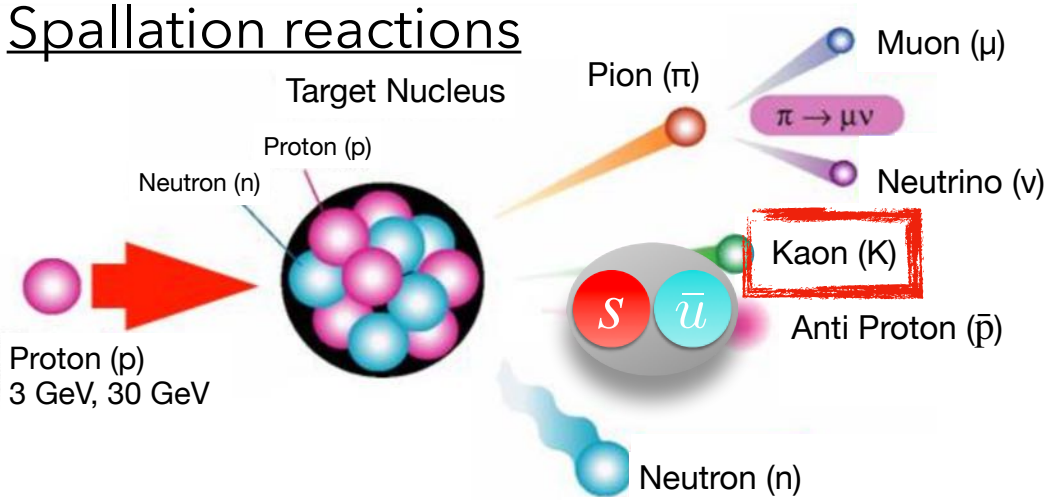

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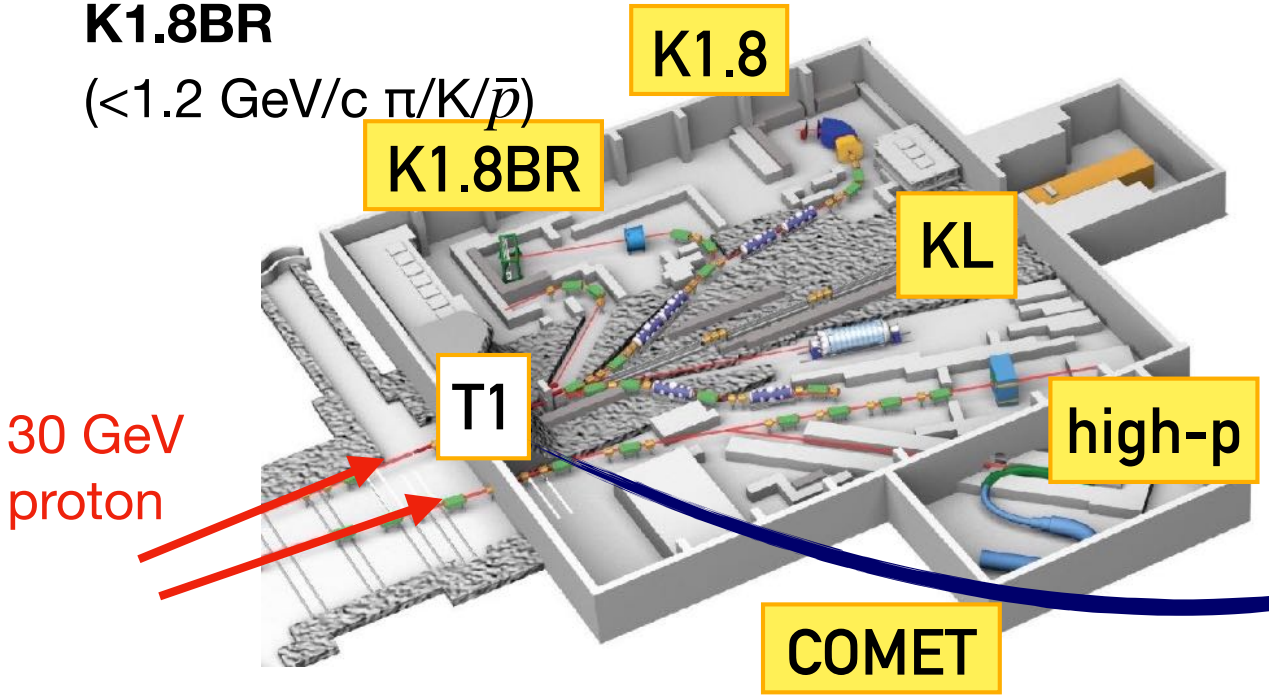

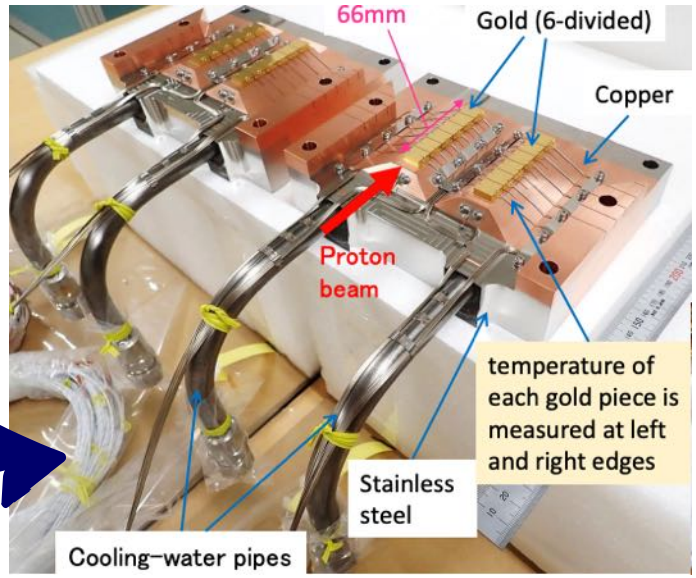

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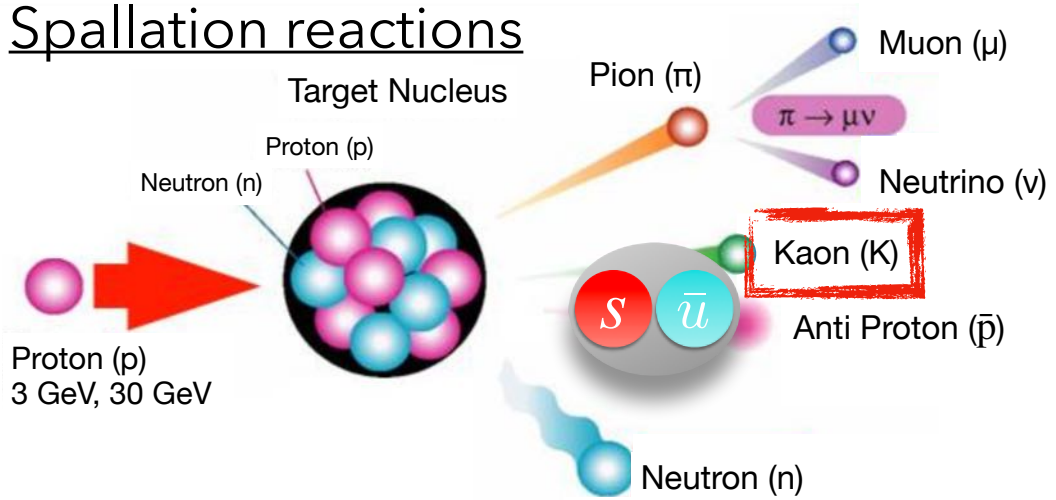
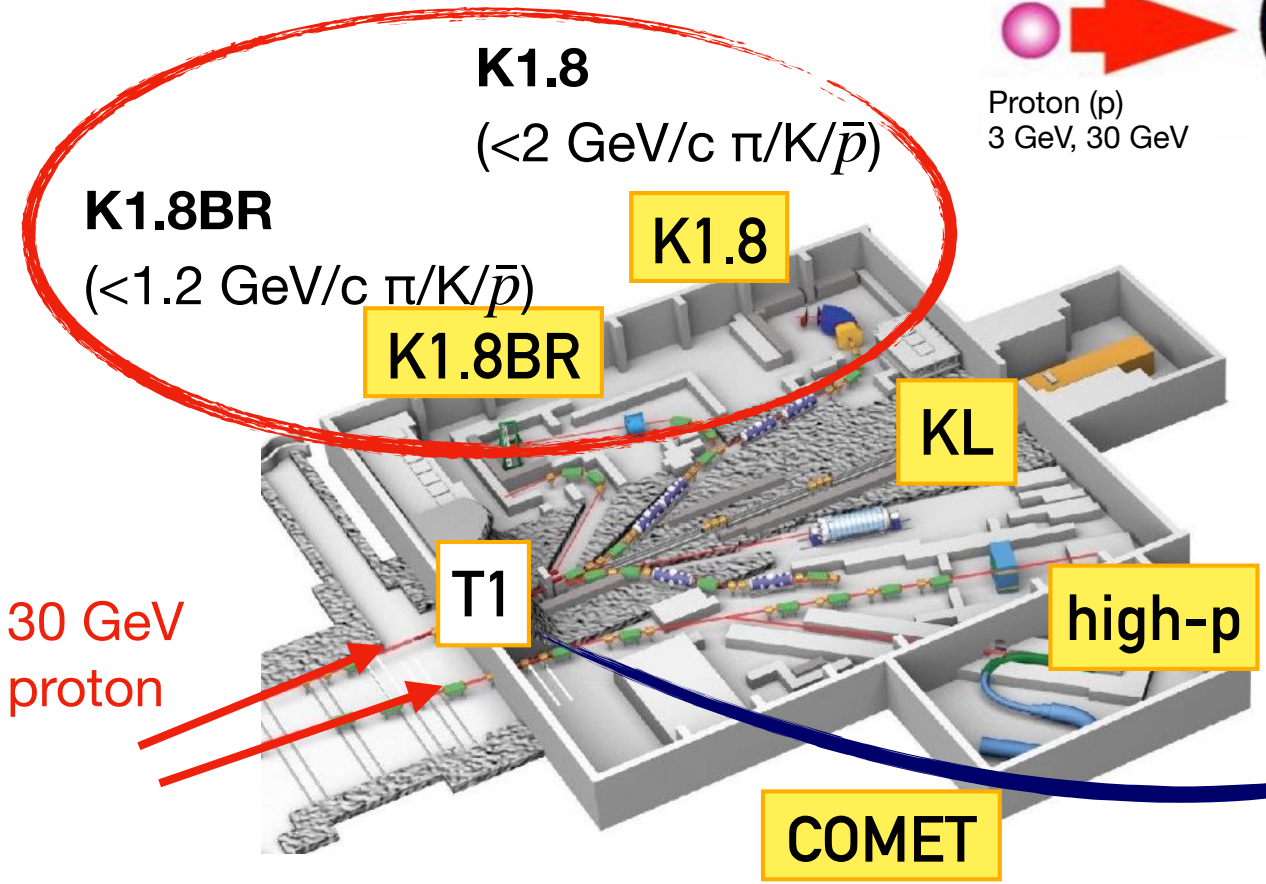
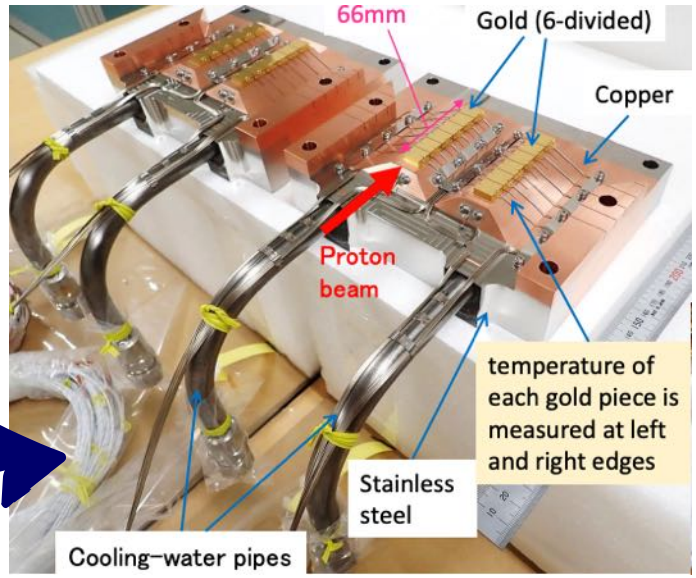






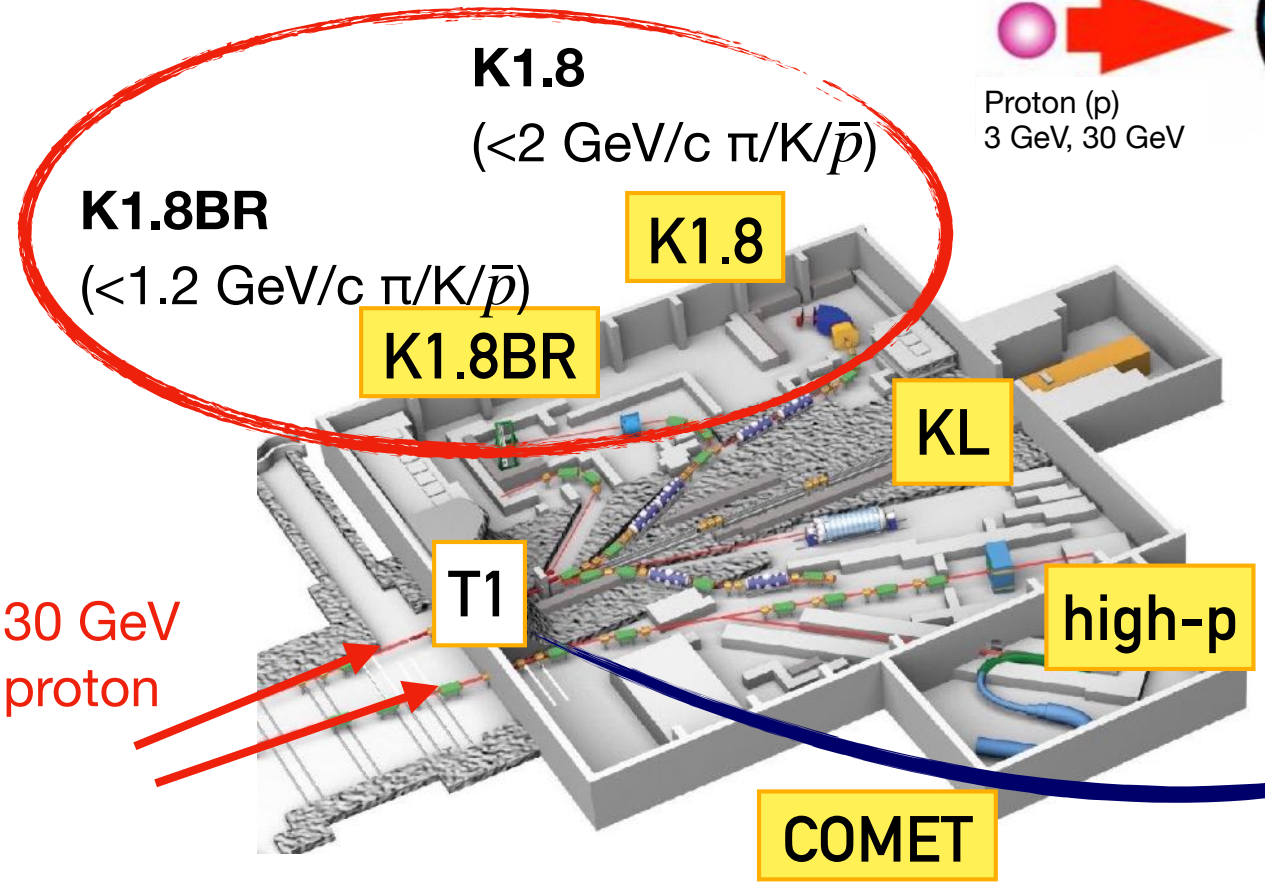
T1 Gold Target

J-PARC Hadron Experimental Facility

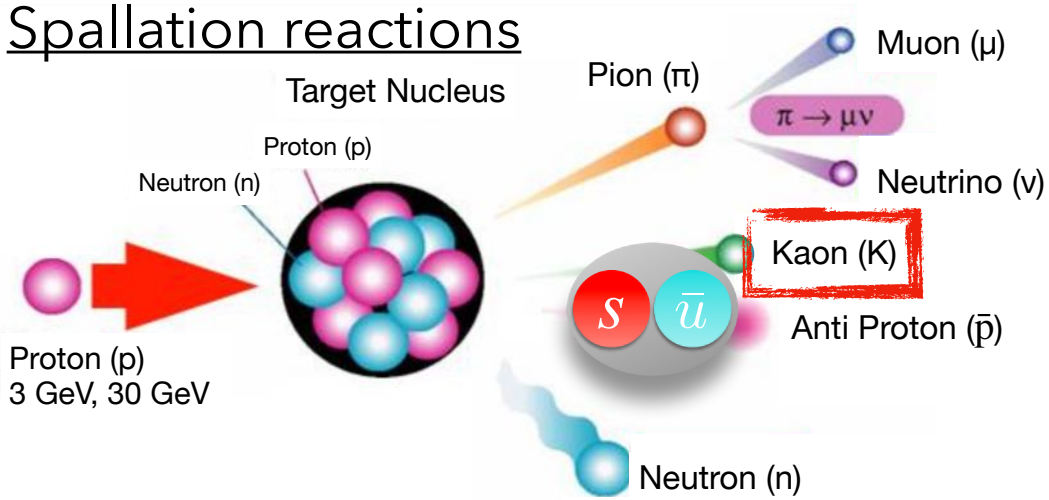
K^- or $\pi^{+/-}$ beams

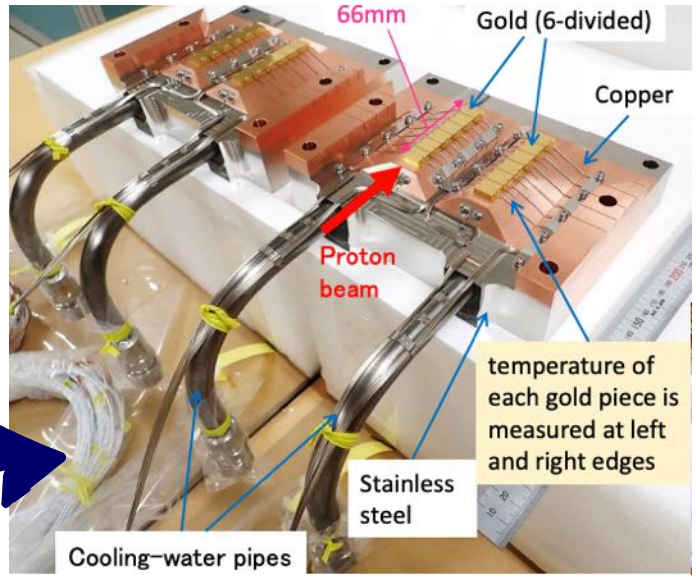
Ex) $K^-p \rightarrow K^+\Xi^-$, $\Xi^-p \rightarrow \Lambda\Lambda$,

$\pi^{+/-}p \rightarrow K^+\Sigma^{+/-}$, $K^-n \rightarrow \pi^-\Lambda$



Spallation reactions





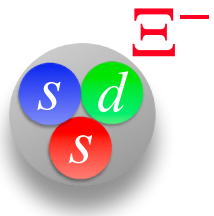
T1 Gold Target

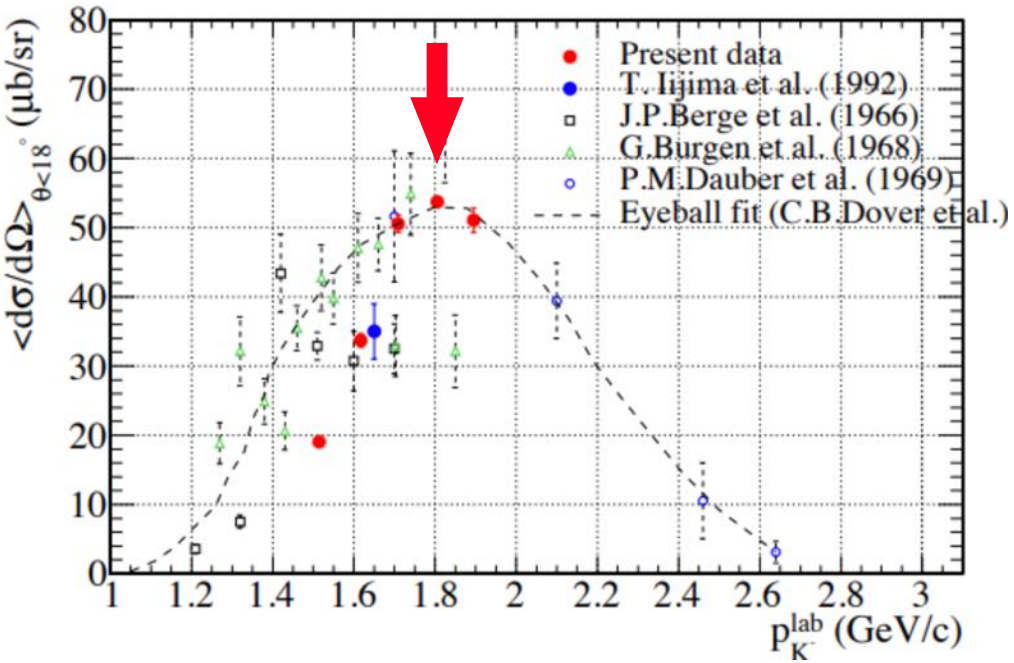
Choice of Beam Momentum

- K1.8 Beam Line

$K^- p \to K^+ \Xi^-$ reaction

Peak at ~1.8 GeV/c





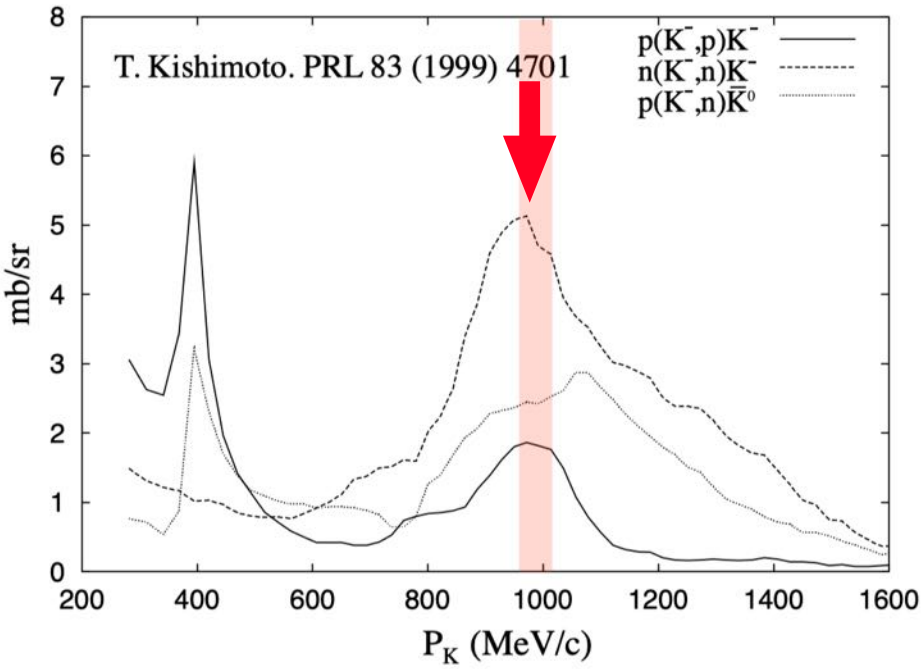
Study of double-strangeness system

Ex) H-dibaryon, Ξ^- hypernuclei

- K1.8BR Beam Line

(K^-, N) elementary cross sections at $\theta_N = 0^\circ$

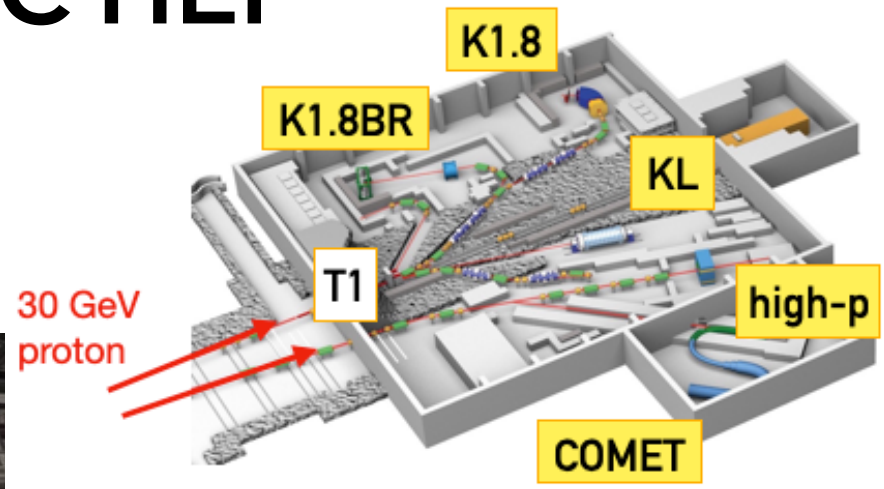
Peak at ~1.0 GeV/c

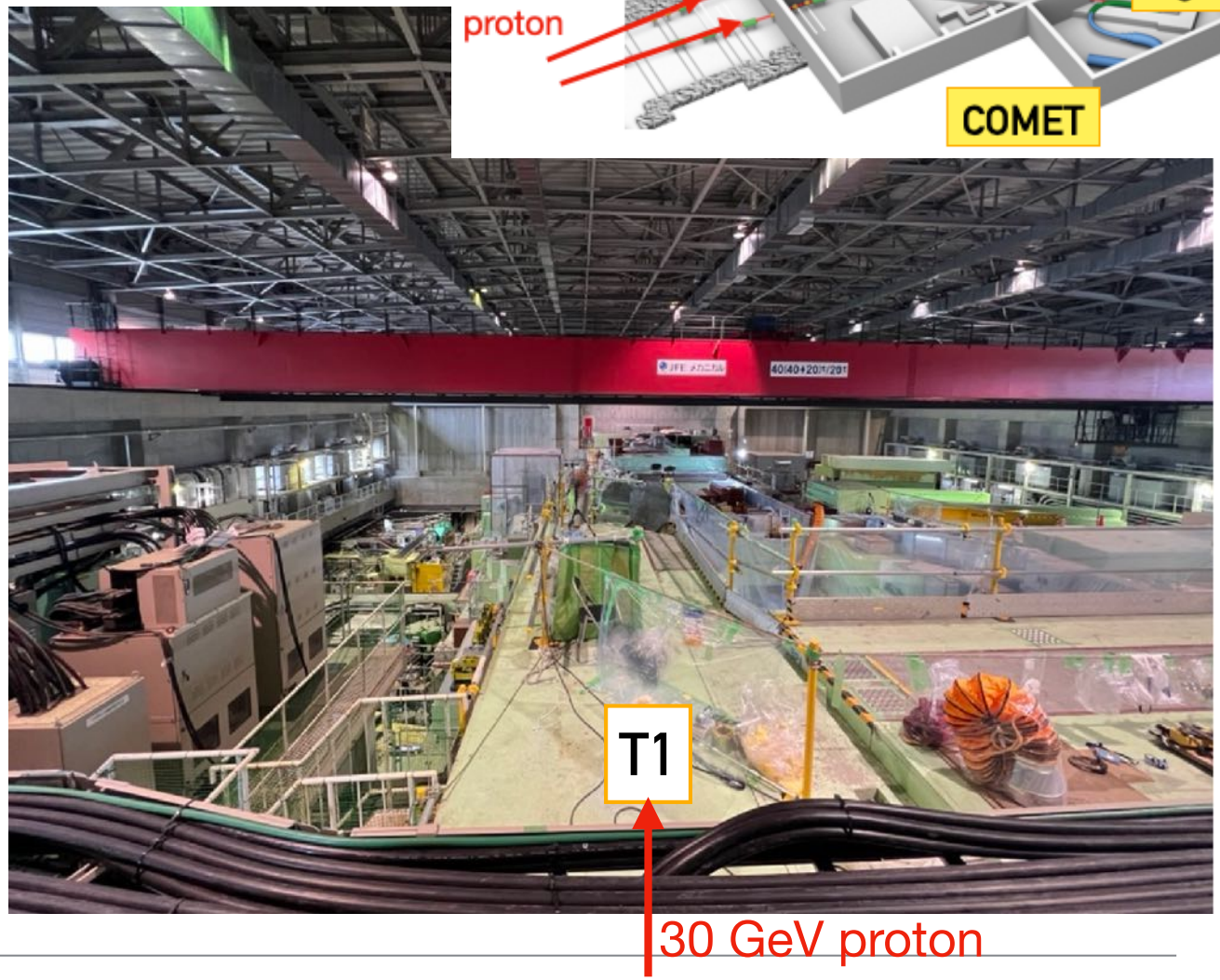


Study of Kaonic nuclei

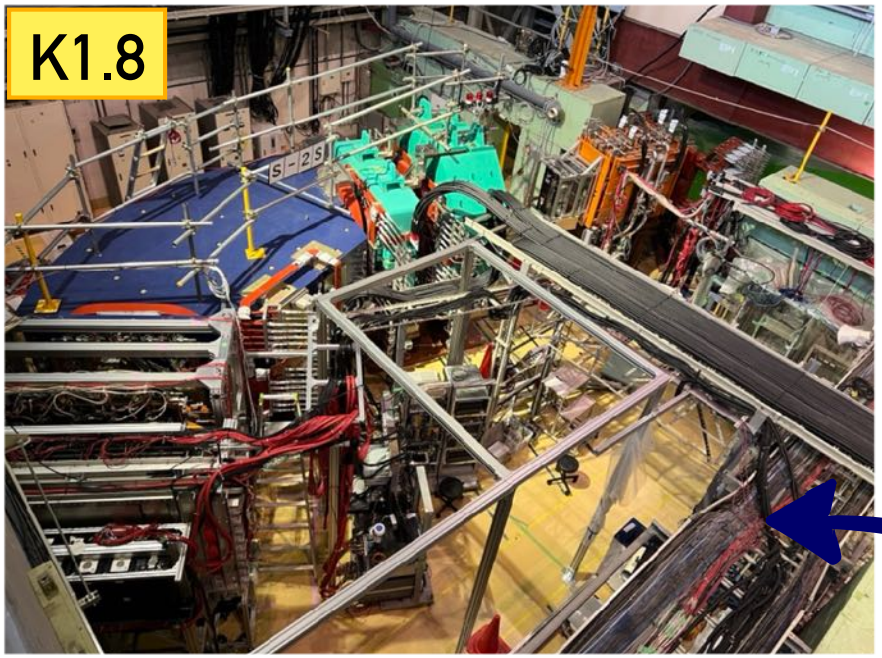
Ex) $^3\mathrm{He}(K^-, n)"K^- pp"$

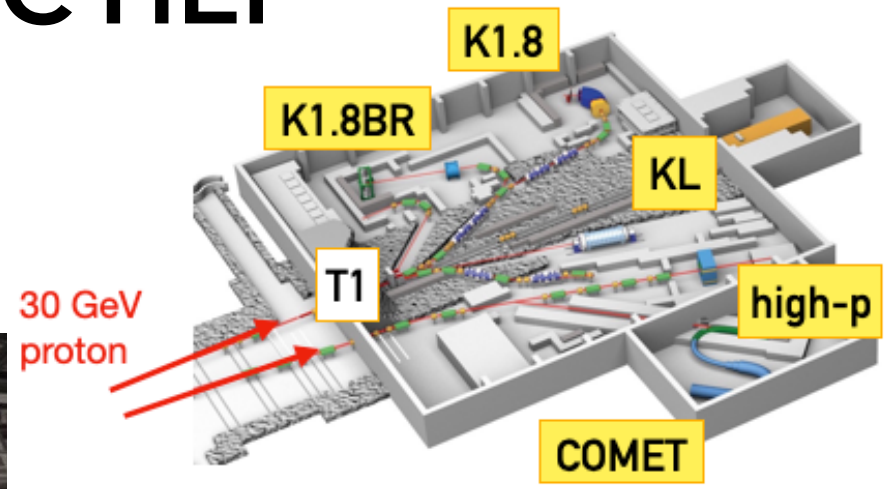
Current Status of J-PARC HEF

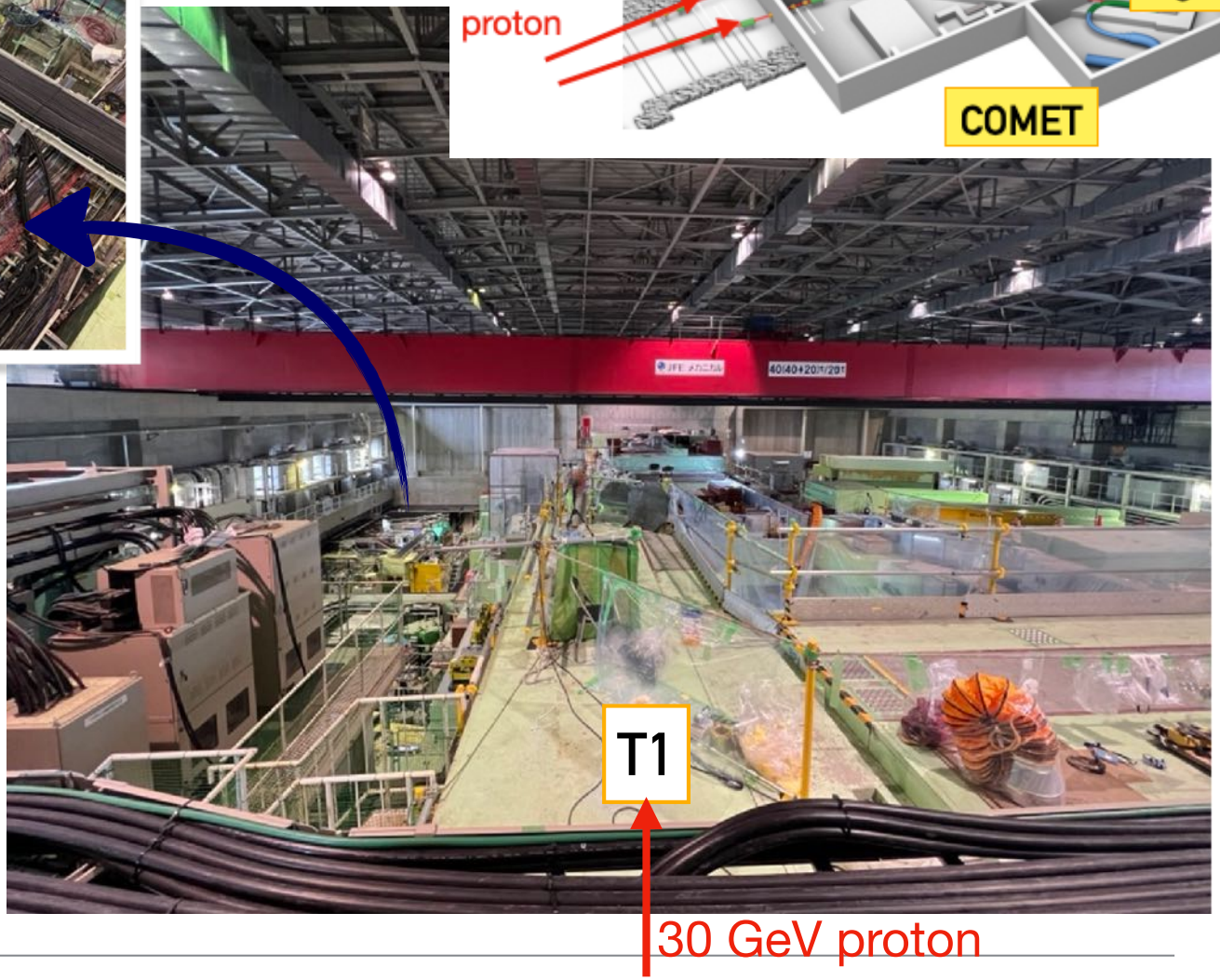




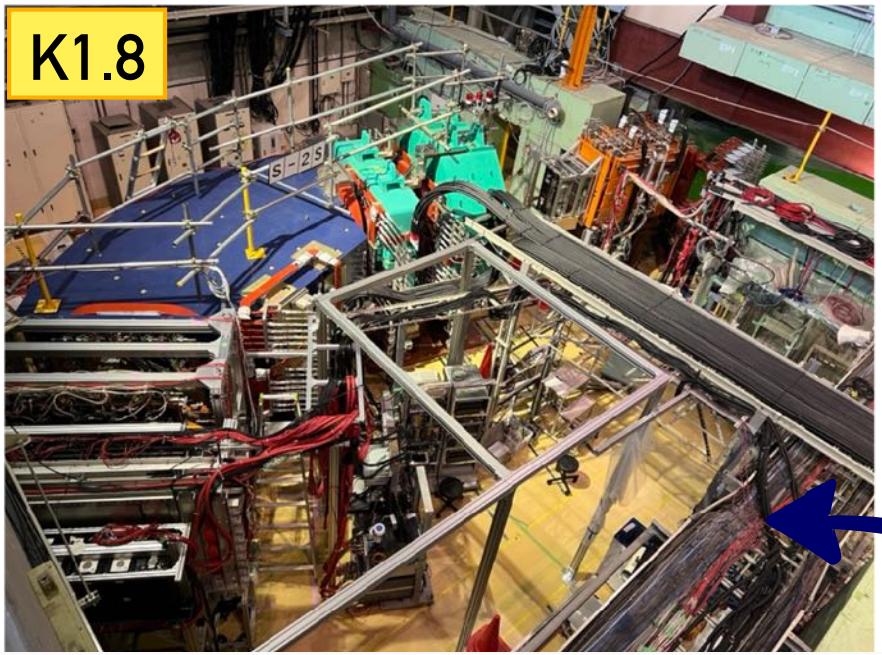
Current Status of J-PARC HEF

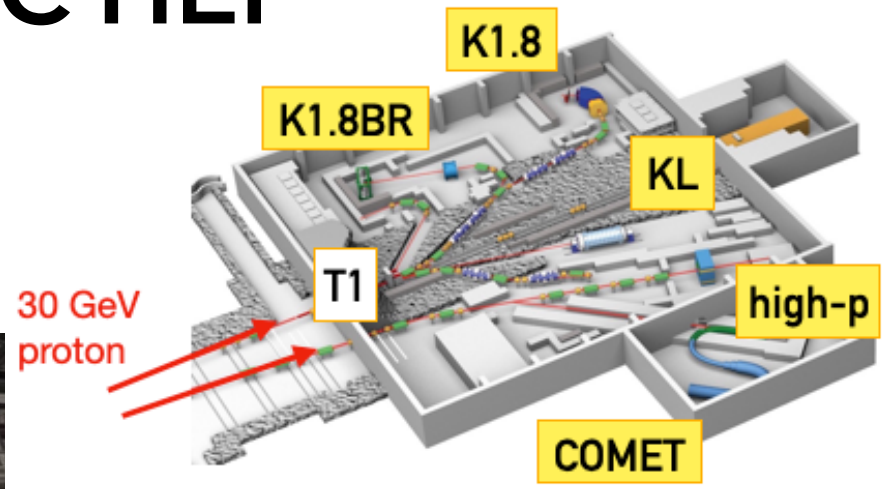


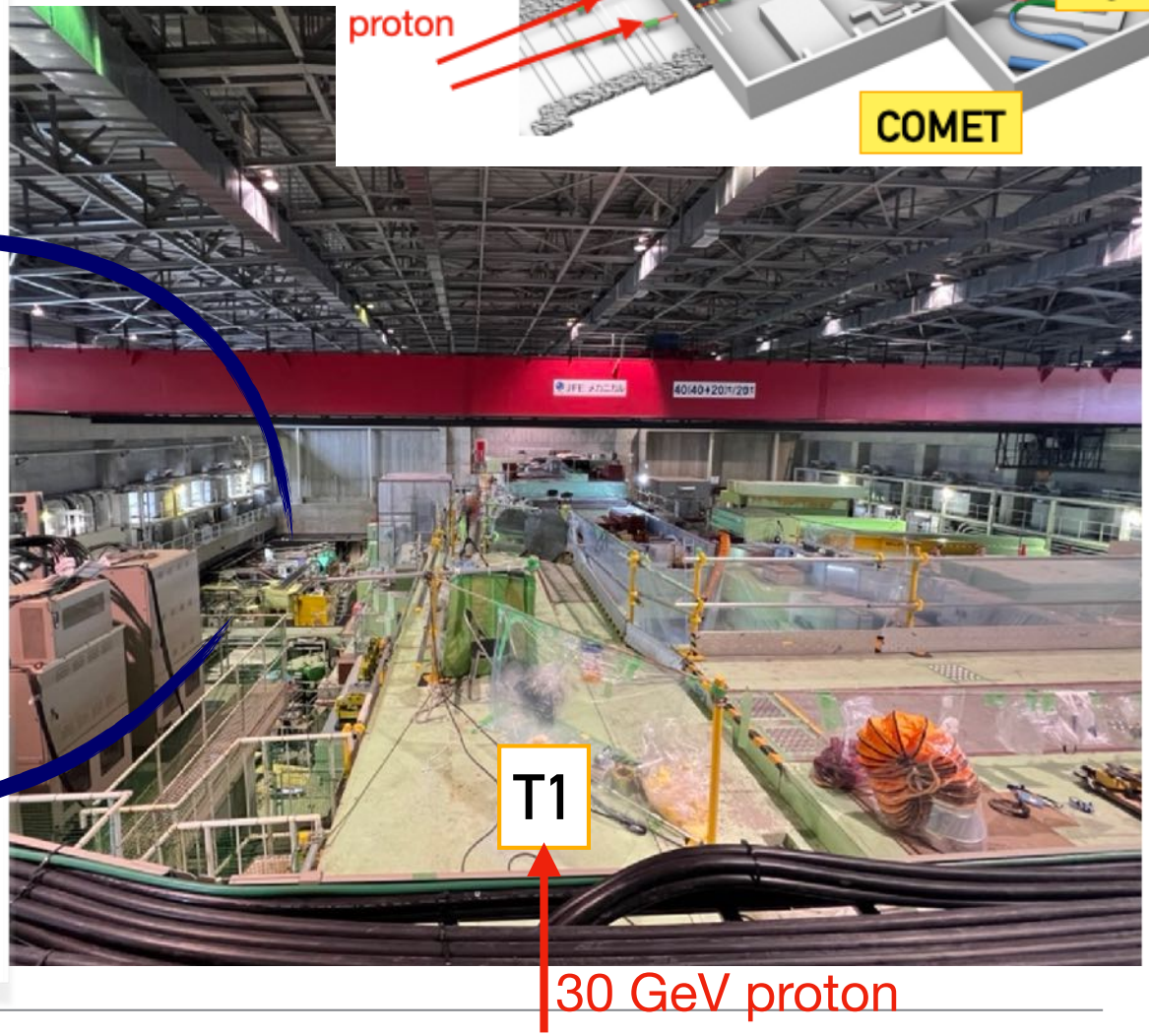




Current Status of J-PARC HEF

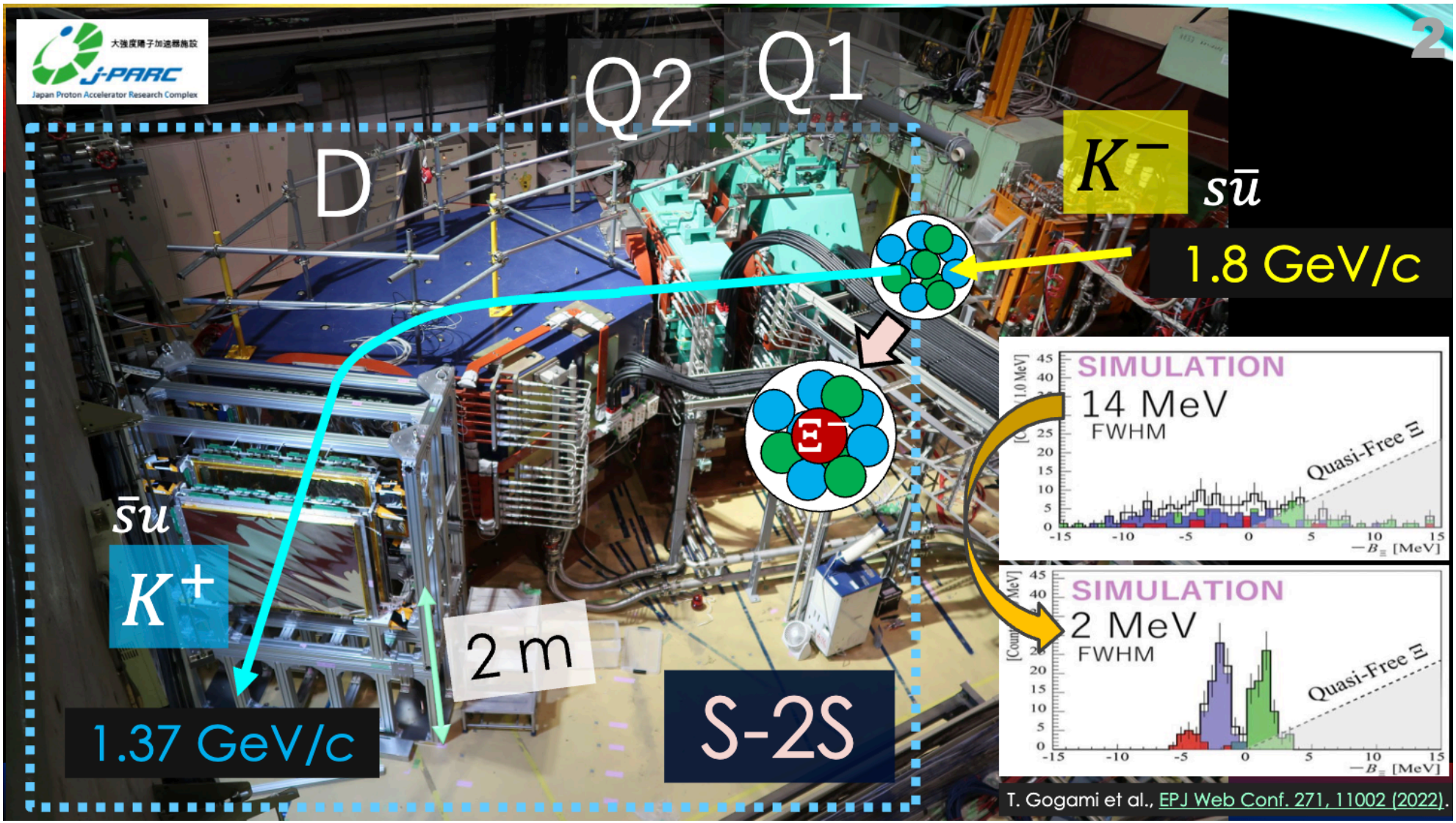




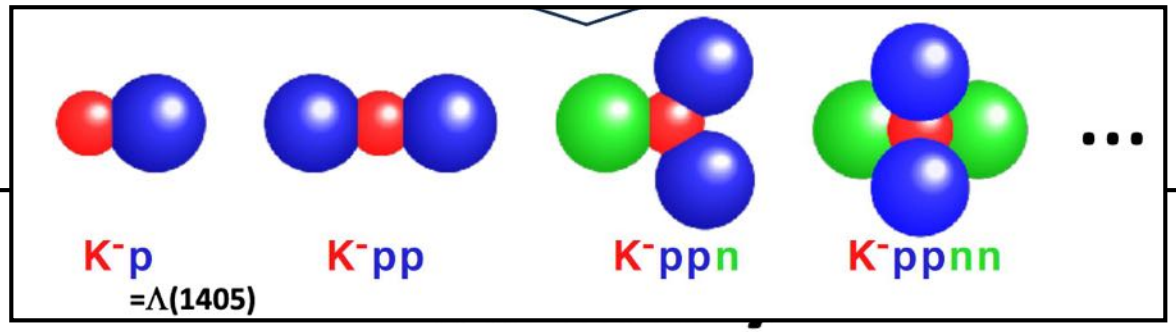


Ξ^- Hypernuclei Spectroscopy

T. Gogami



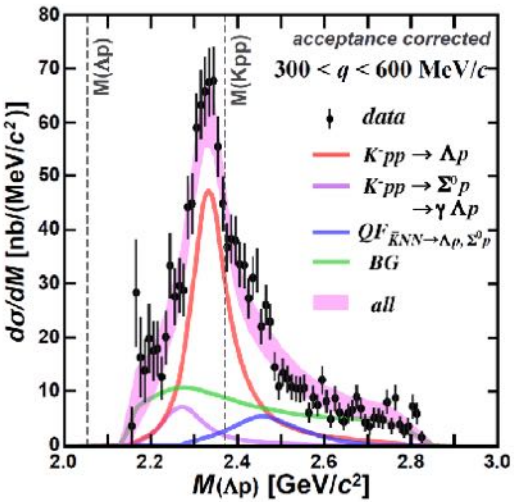
Kaonic Nuclei Search

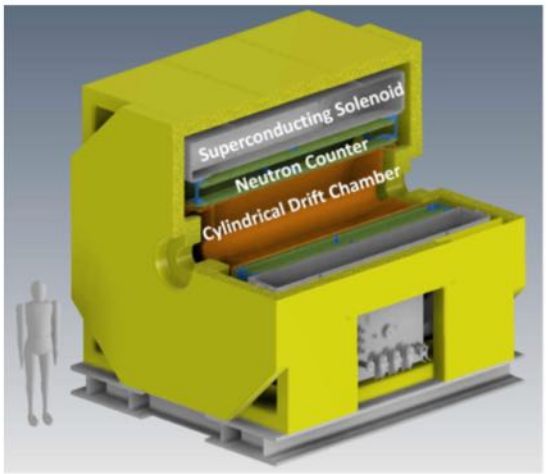


T. Hashimoto

31

- **Λ(1405)** from d(K-,n)
  - ✓πΣ: PLB837(2023)137637.
- **"K⁻pp"** from ^{3}He(K⁻, n)
  - ✓**Λp**: PLB789(2019)620., PRC102(2020)044002.
  - ✓**πYN**: PRC110(2024)014002.
- **"K⁻ppn"** from ^{4}He(K⁻,n)
  - ✓**Λd**: A hint has been observed.

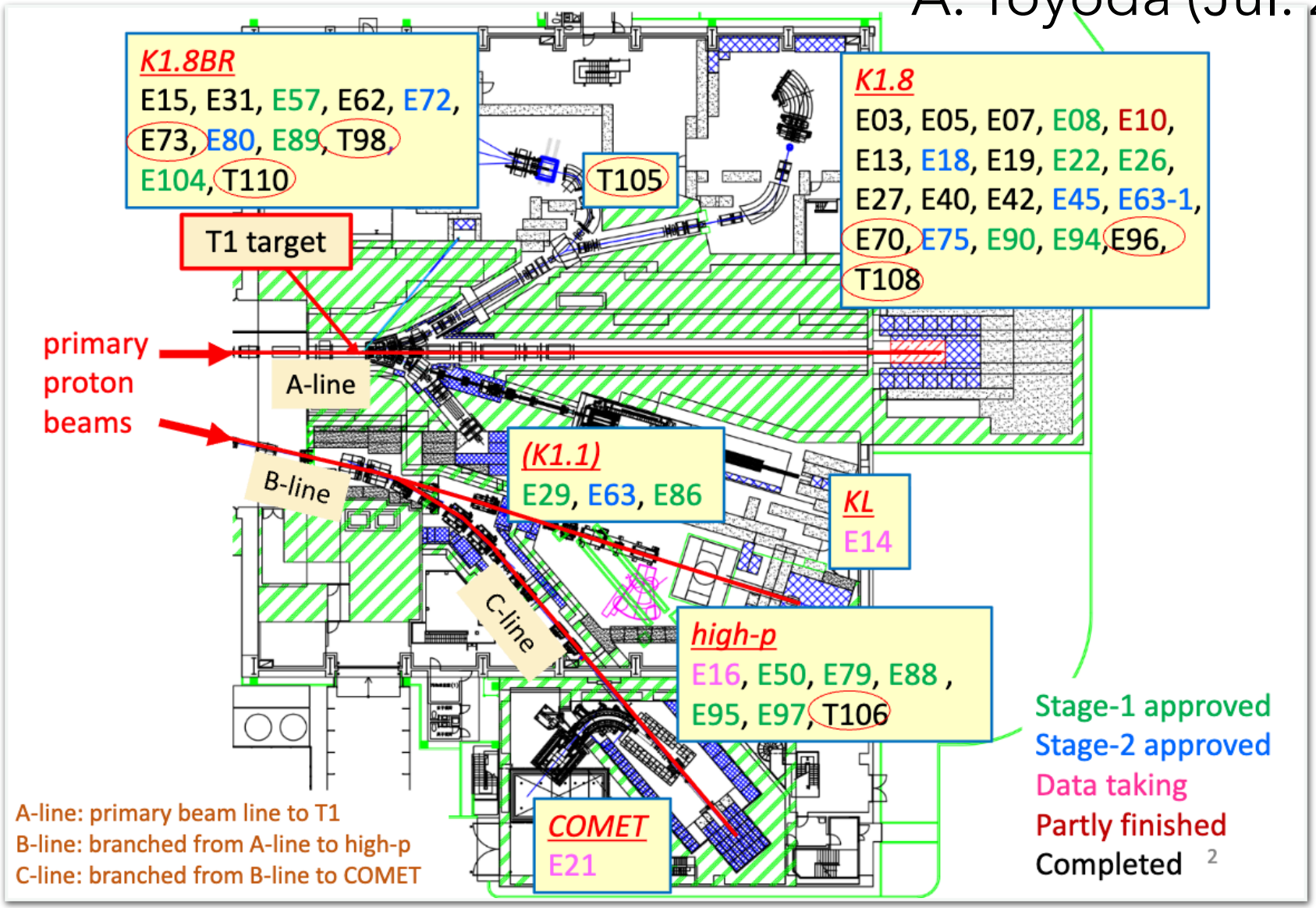




- New project has started from E80, "K⁻ppn", aiming at the systematic study of the kaonic nuclei
  - Constructing a large solenoid spectrometer
  - will start in early 2027

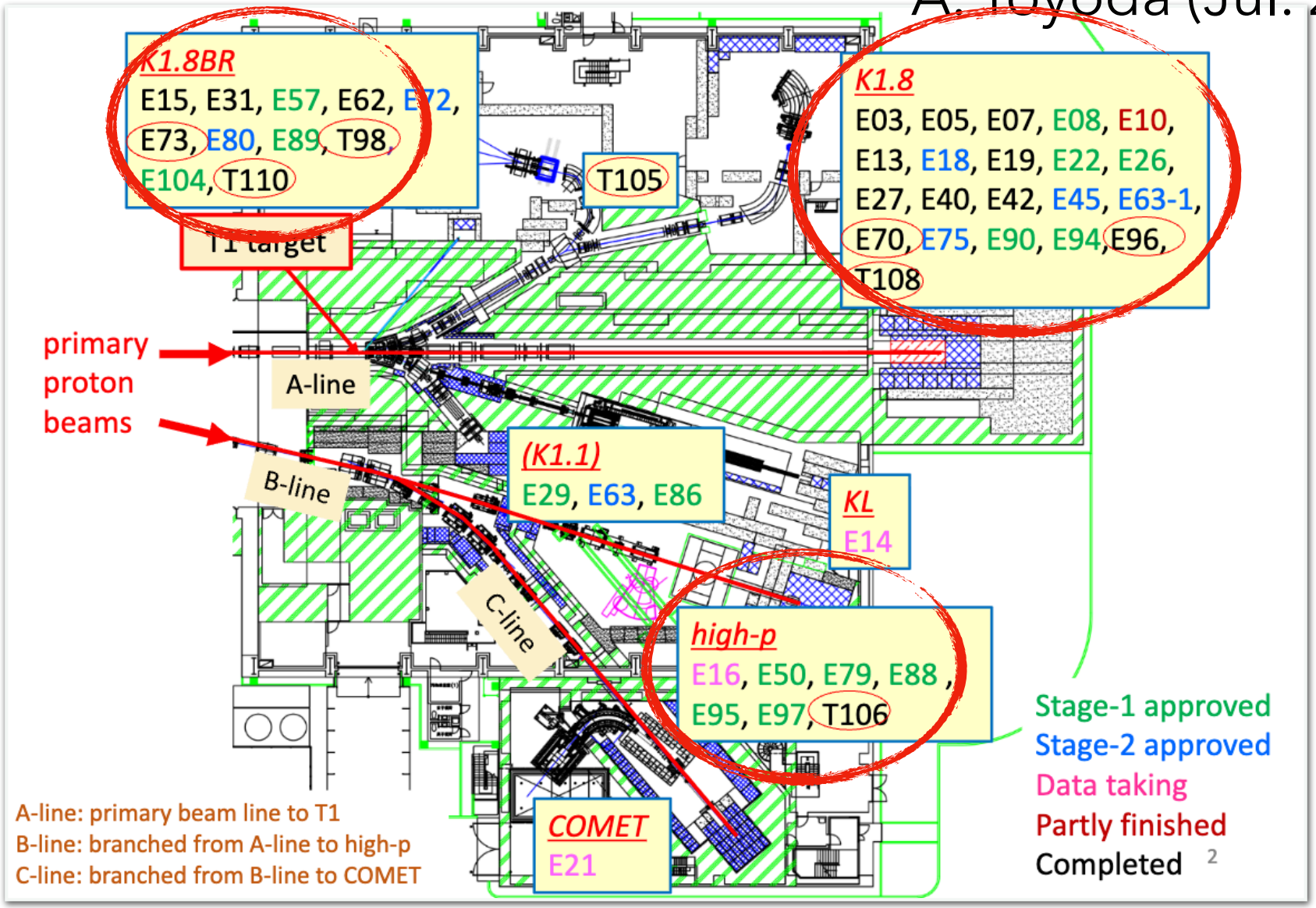
J-PARC Hadron Experimental Facility

A. Toyoda (Jul. 2025)



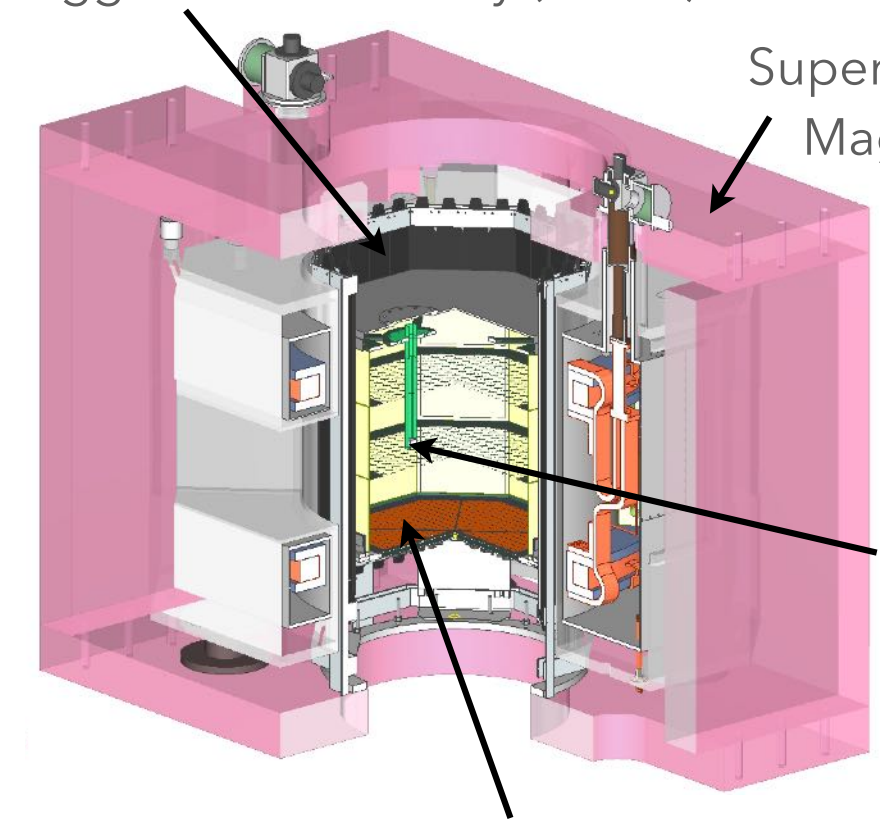
J-PARC Hadron Experimental Facility

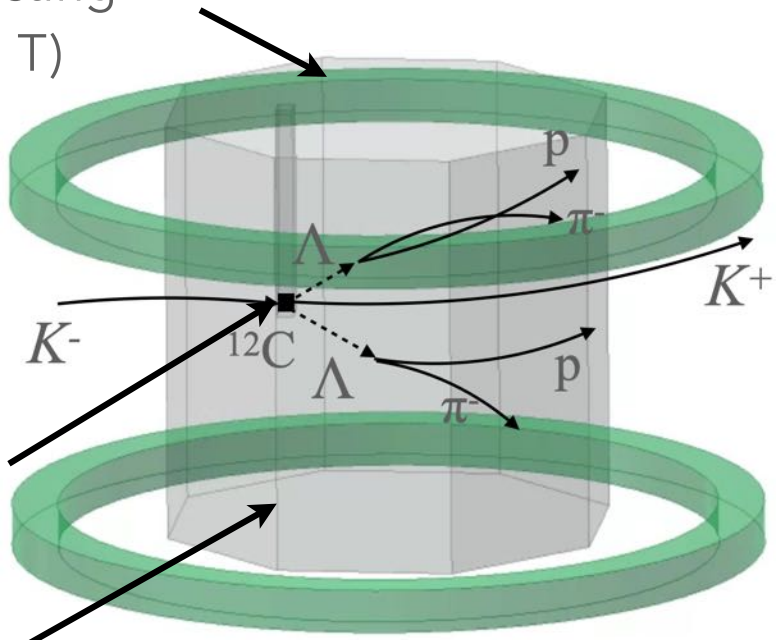
A. Toyoda (Jul. 2025)



Hyperon Spectrometer

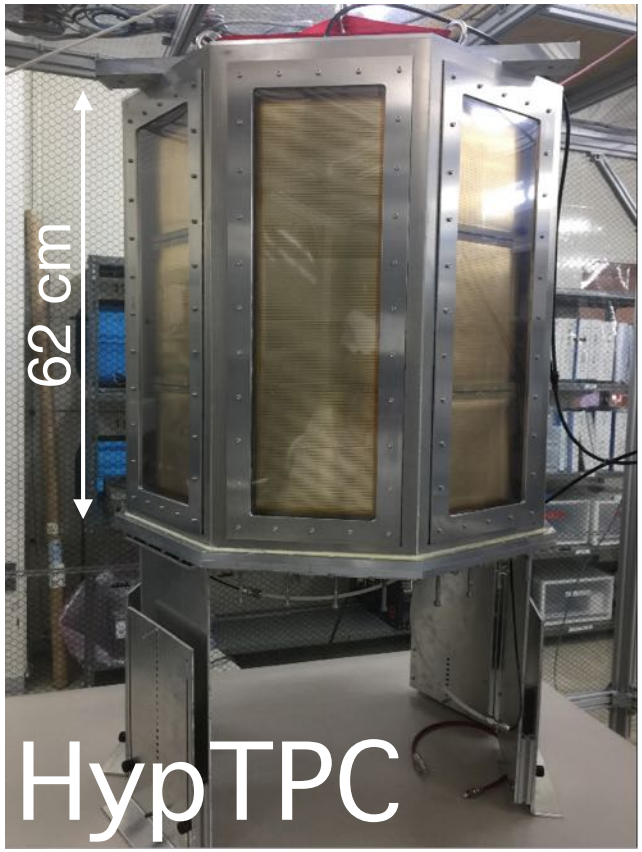
- Detect all charged particles' trajectories in 3D.





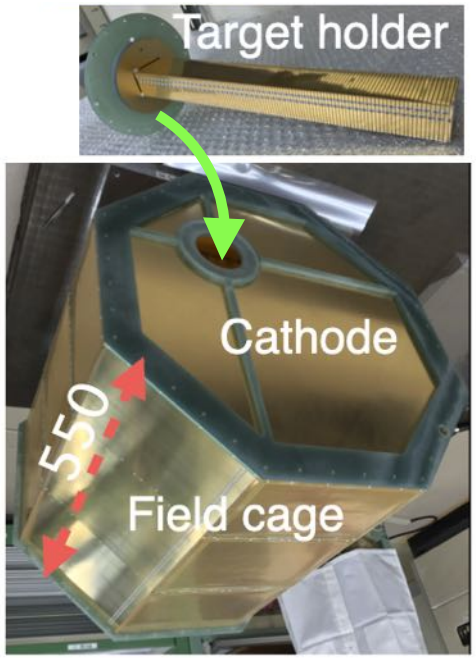
- Large acceptance (~4π)
- High rate capability (~10^6 cps)
- High resolution (σ ~1 MeV)

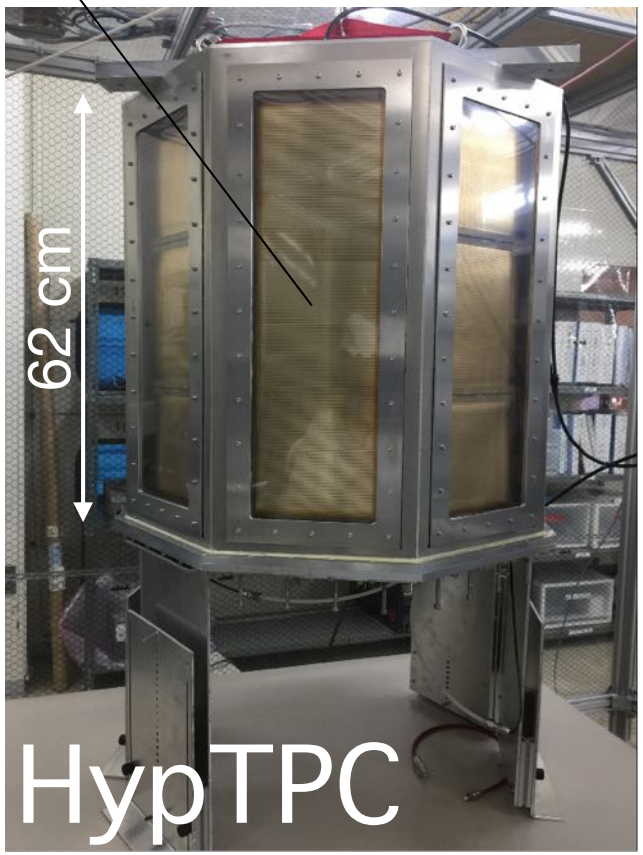
HypTPC



HypTPC

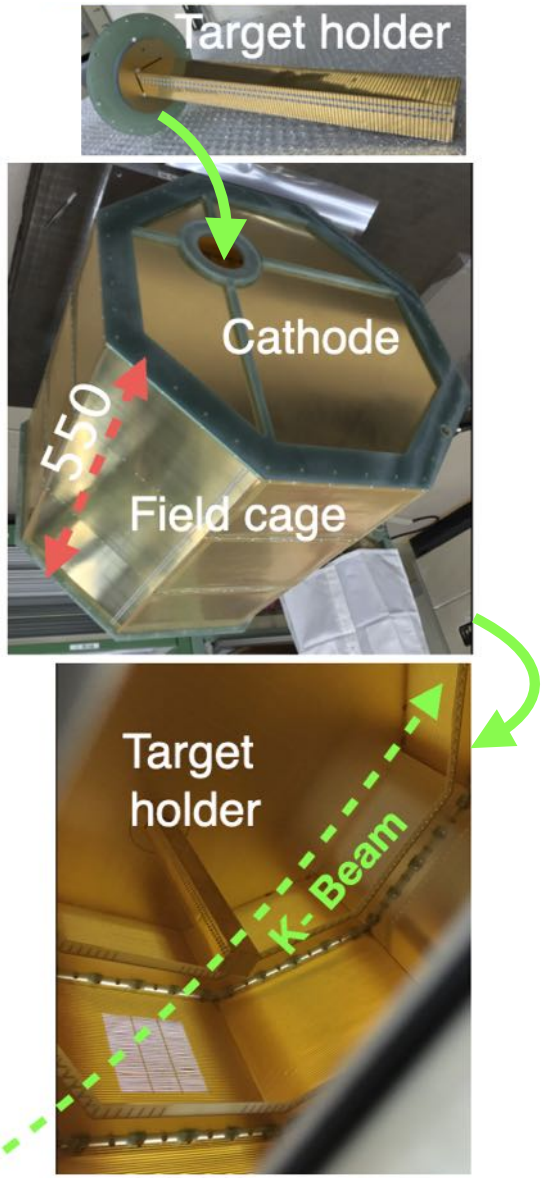
- 1. Drift region

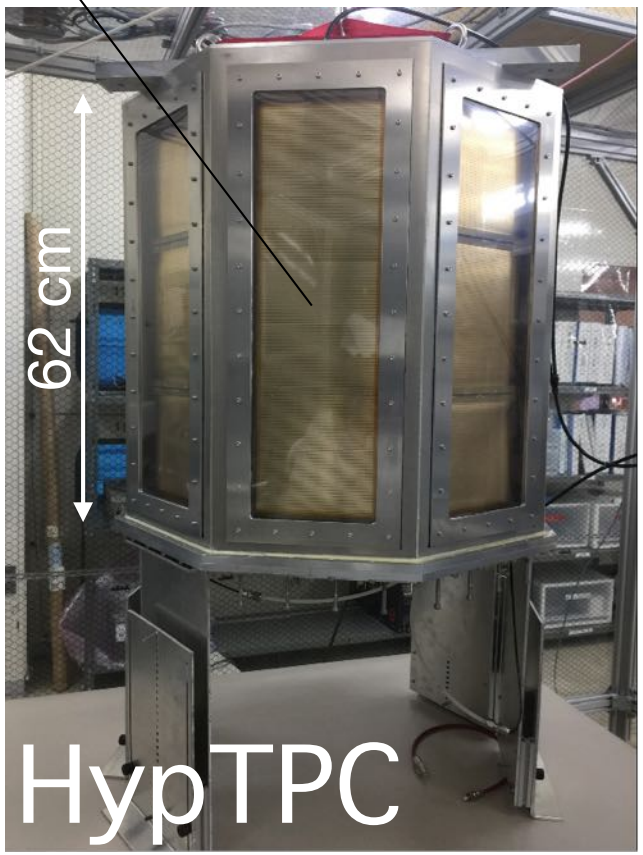




HypTPC

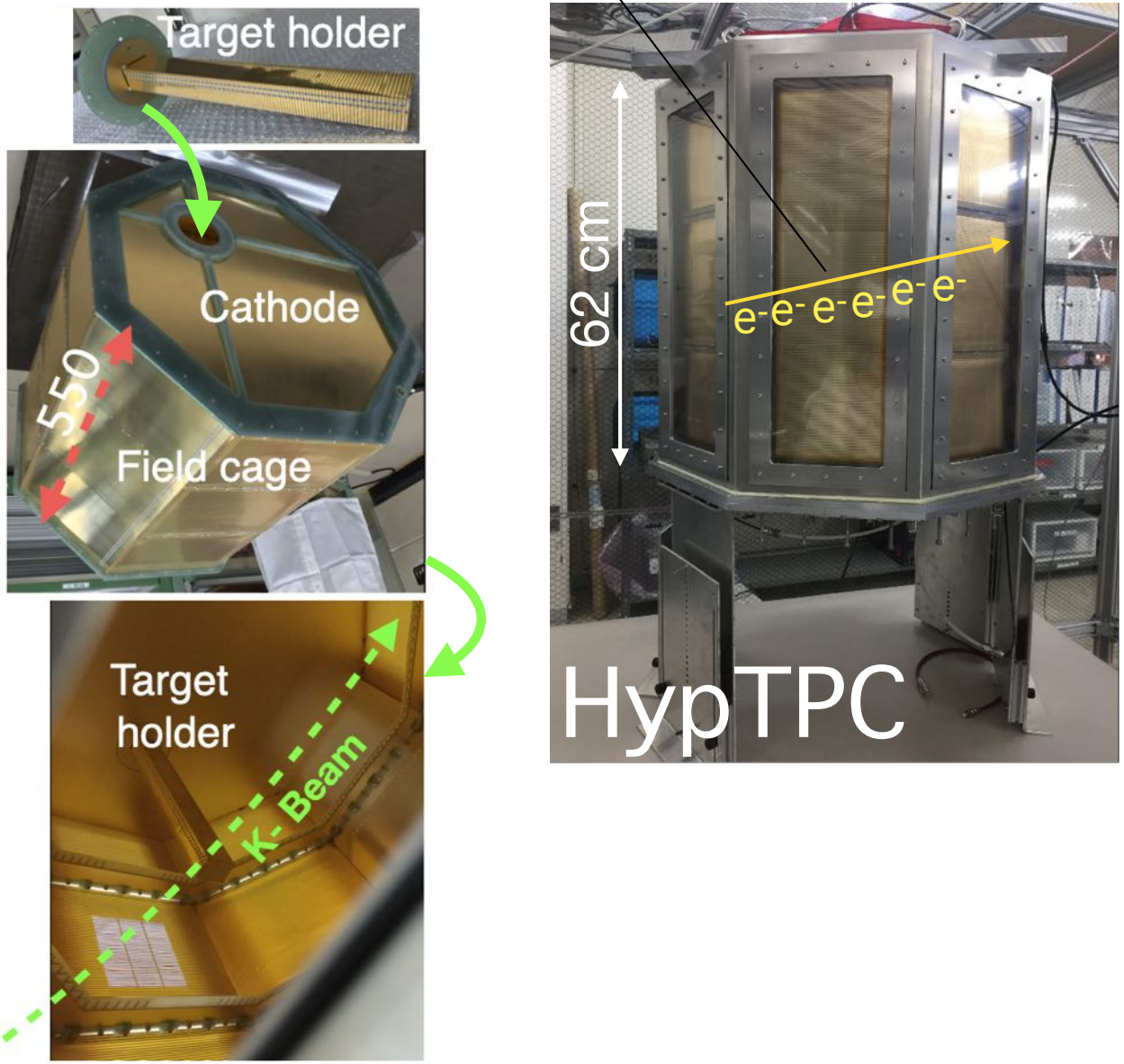
- 1. Drift region





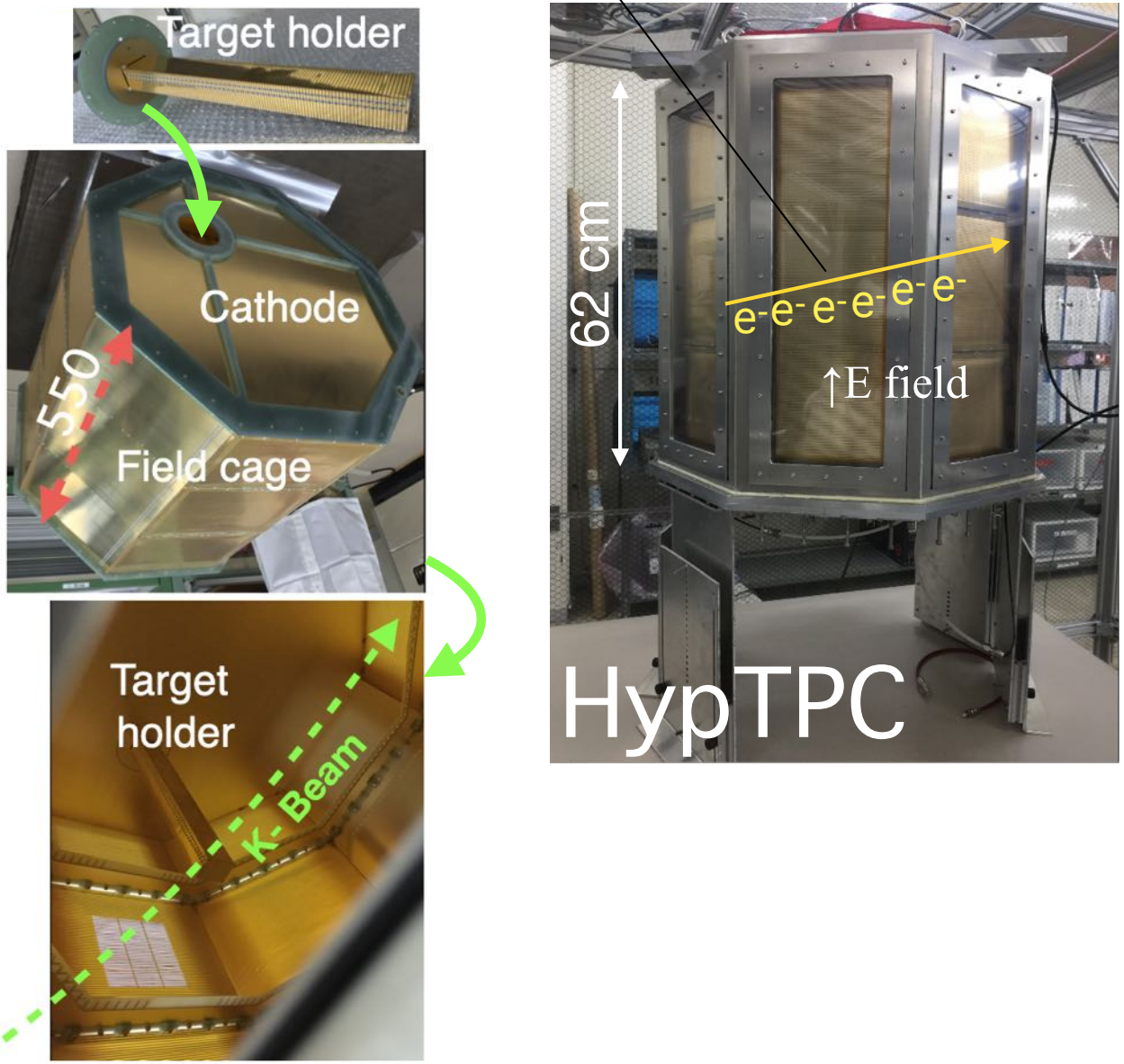
HypTPC

- 1. Drift region



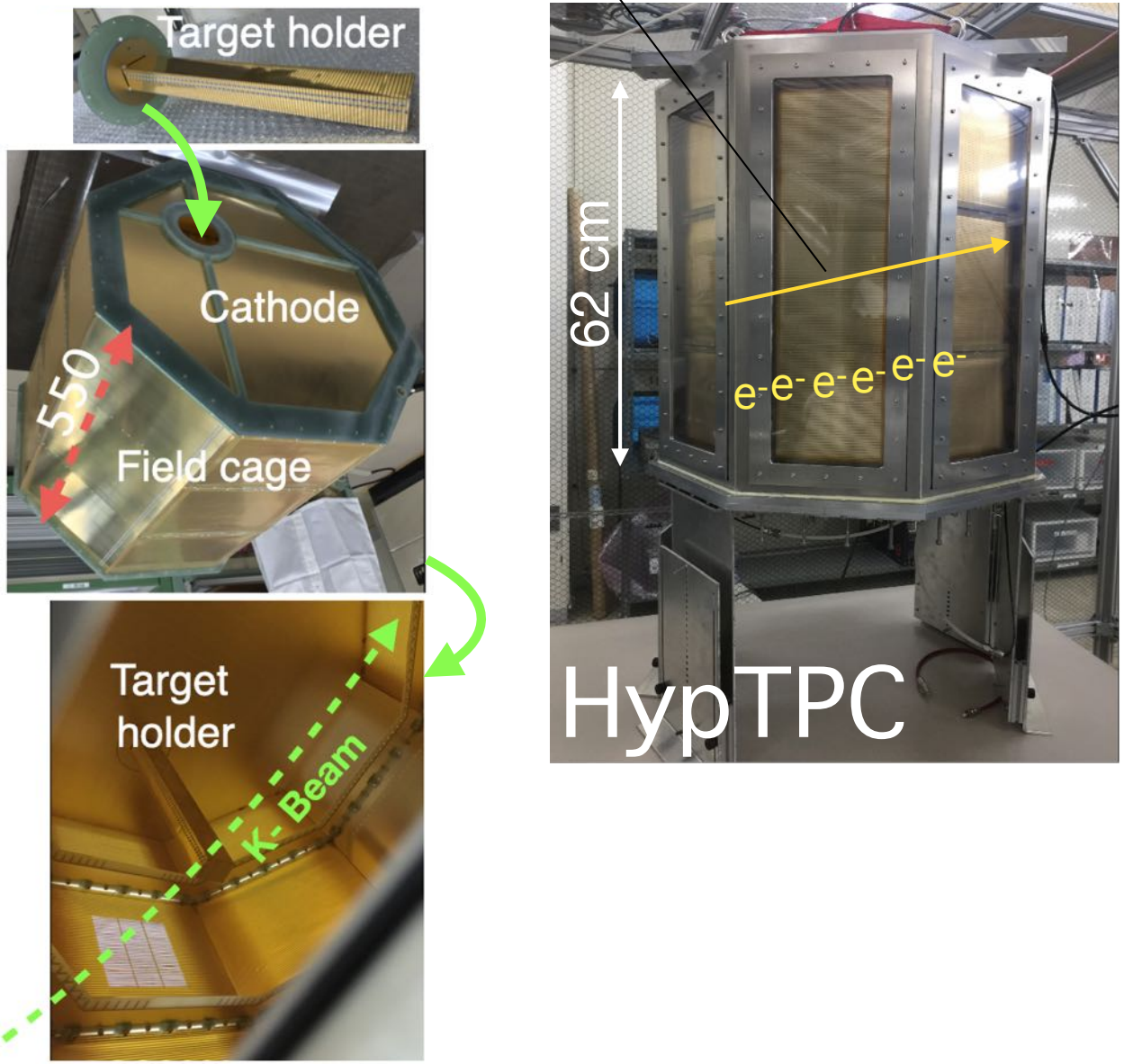
HypTPC

- 1. Drift region



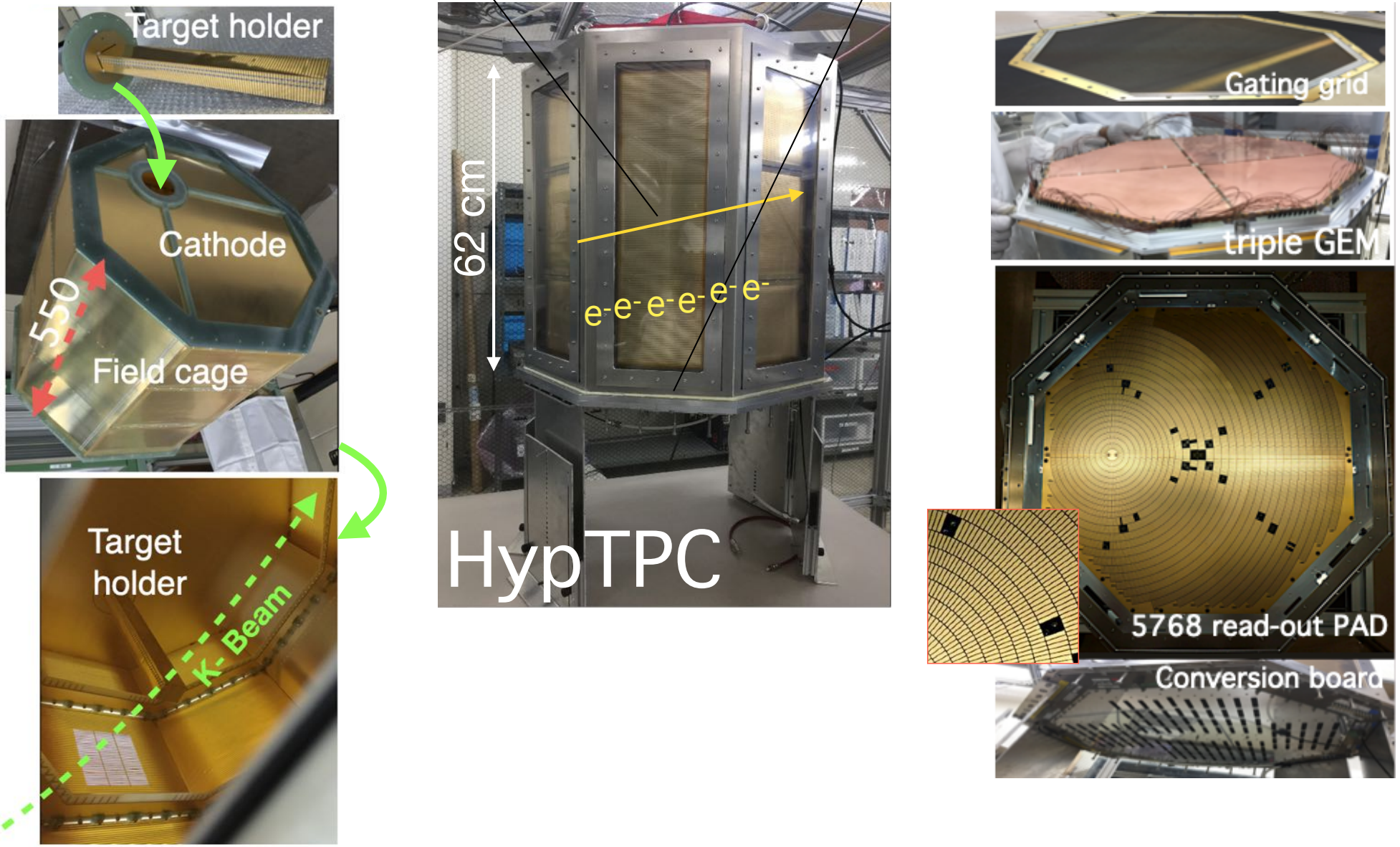
HypTPC

- 1. Drift region



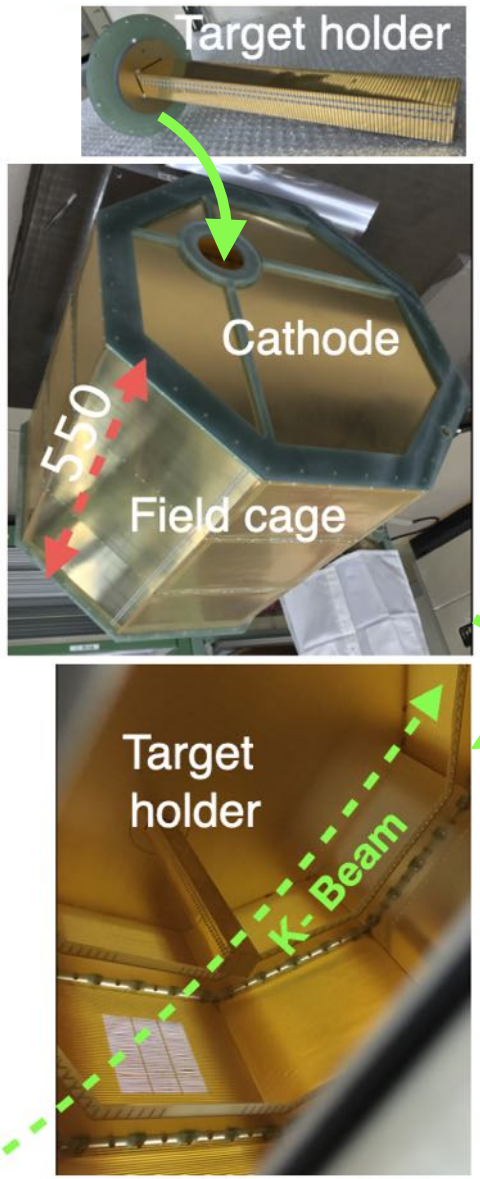
HypTPC

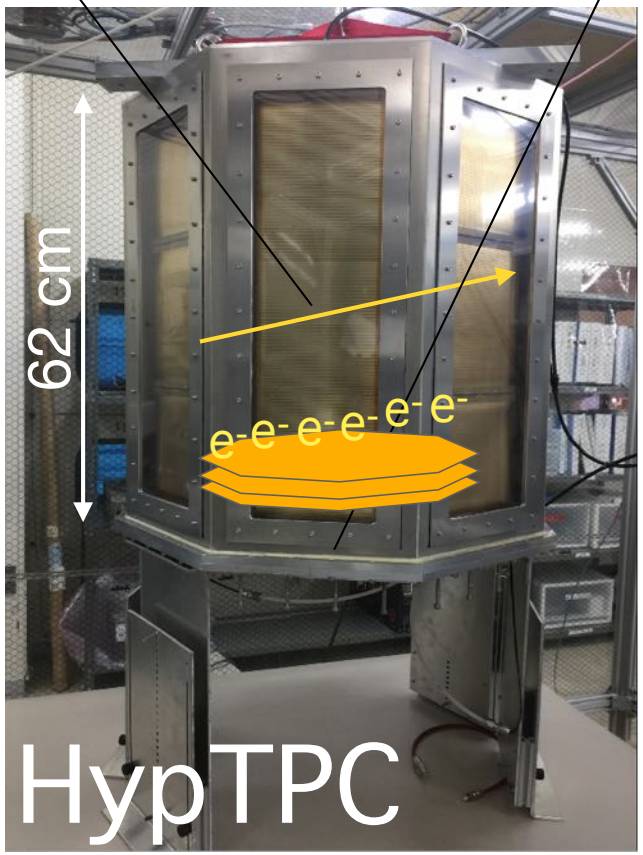
- 1. Drift region
- 2. Amplification Region

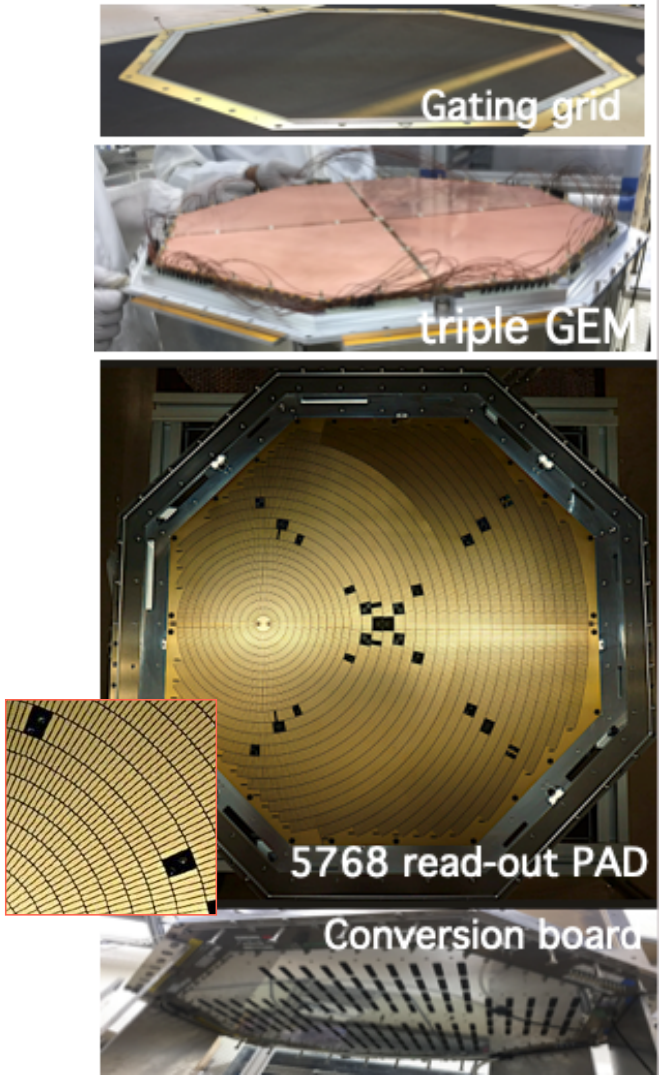


HypTPC

- 1. Drift region
- 2. Amplification Region

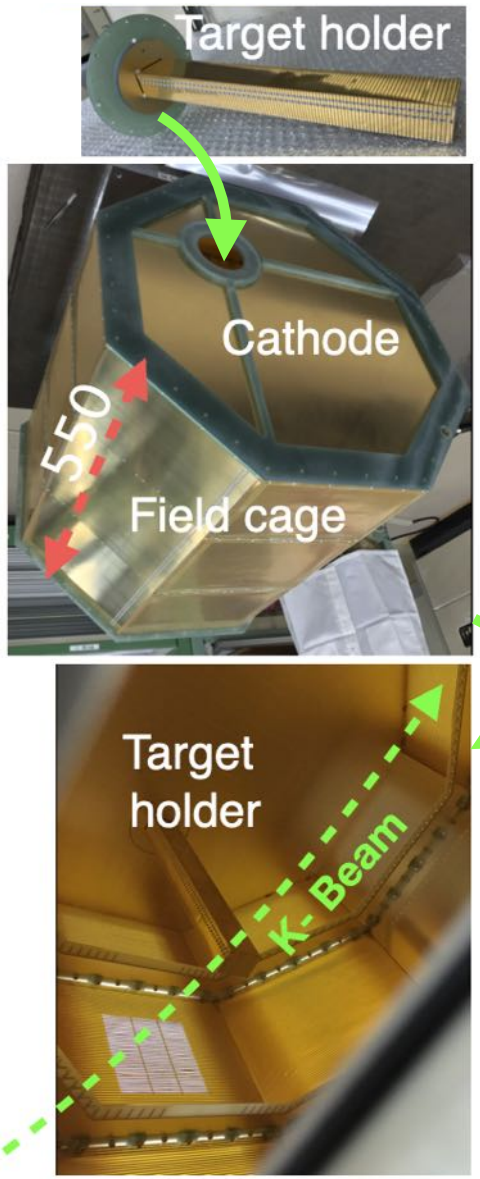


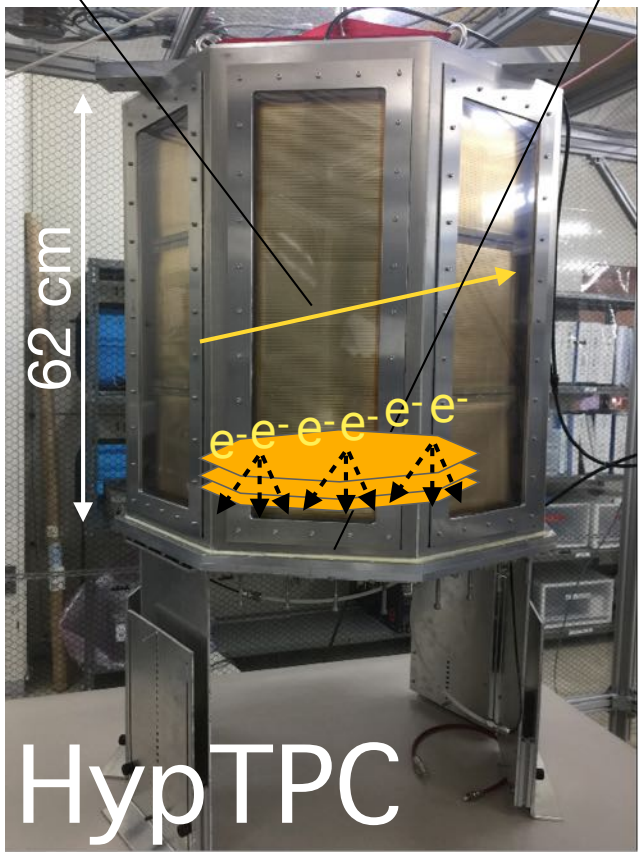


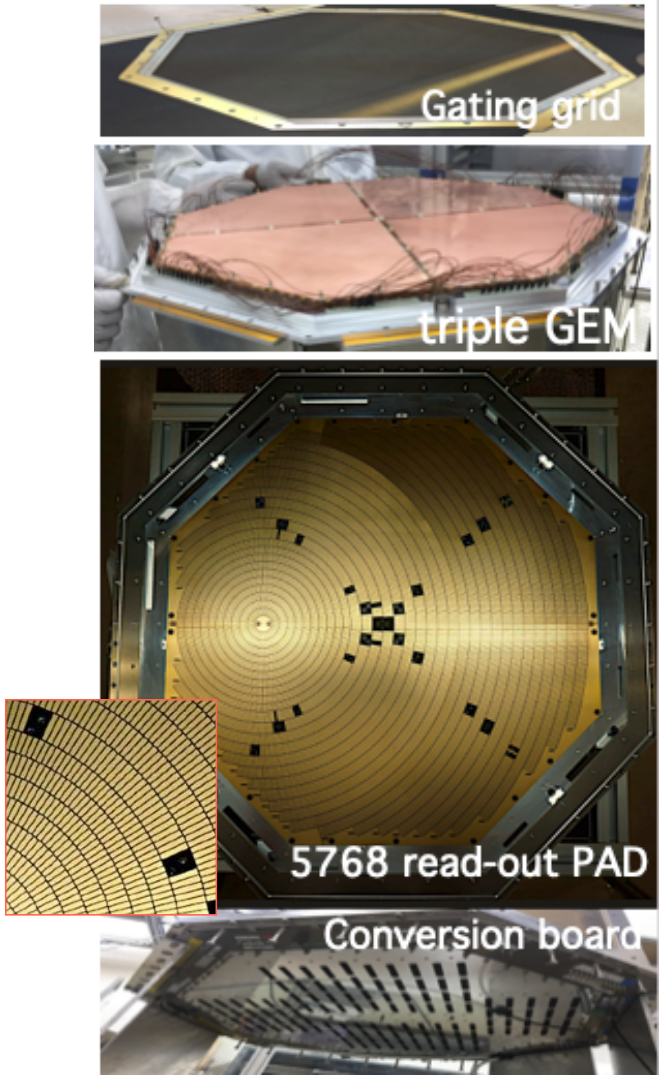


HypTPC

- 1. Drift region
- 2. Amplification Region

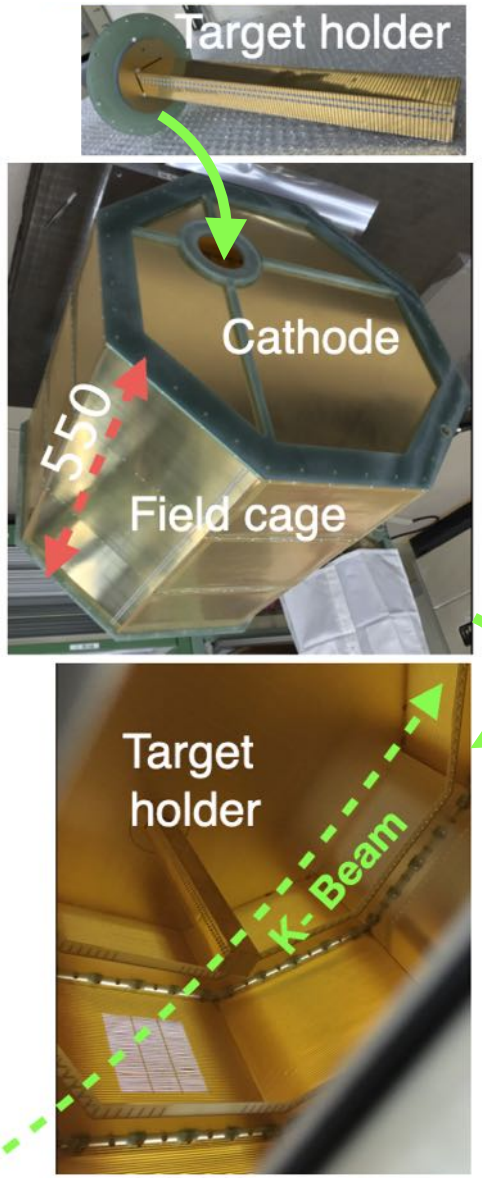


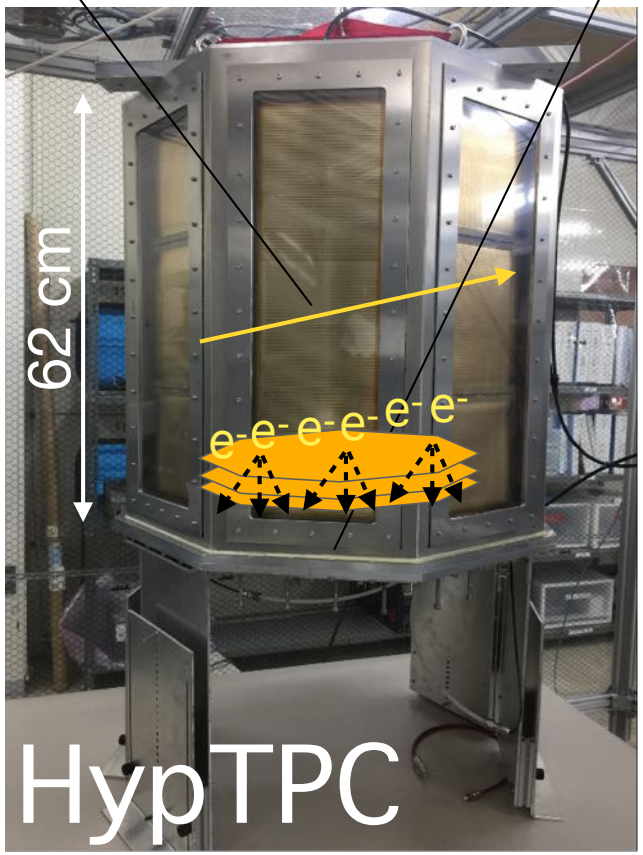


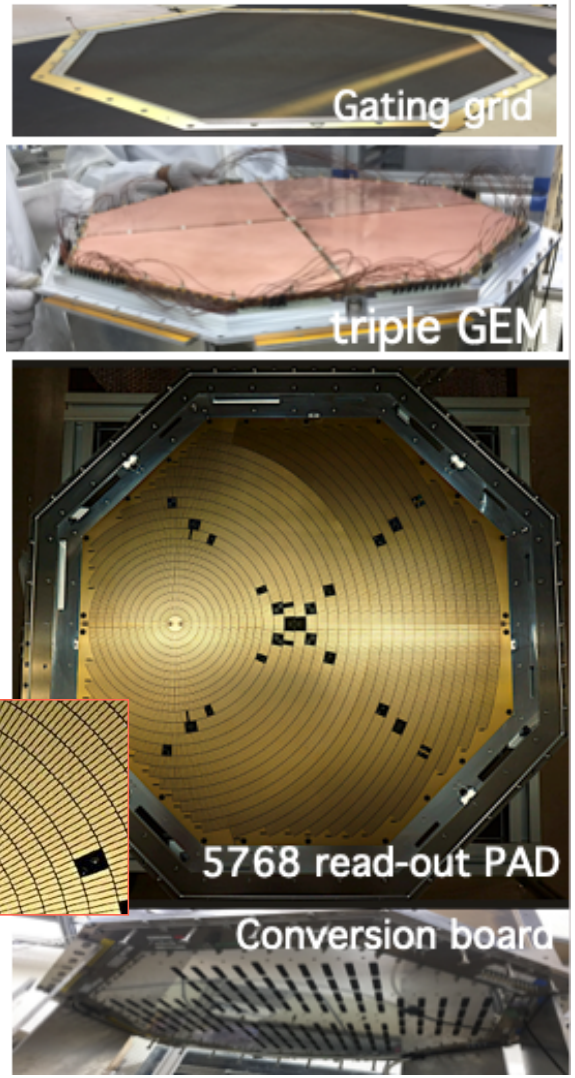


HypTPC

- 1. Drift region
- 2. Amplification Region



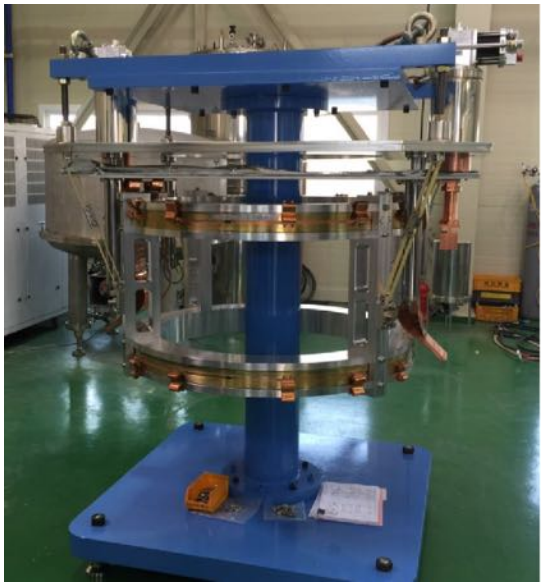


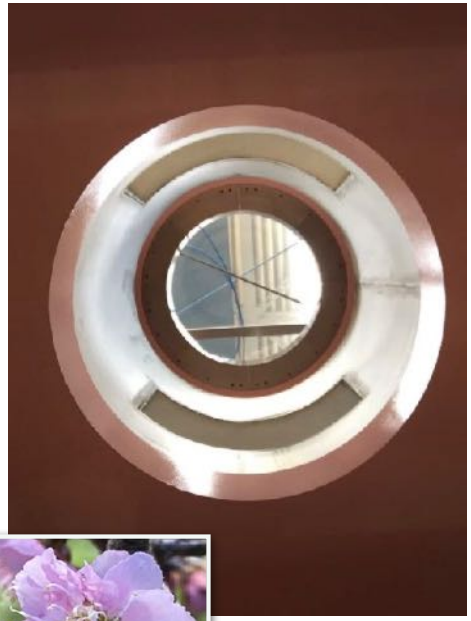


- 3. Read-out Electronics

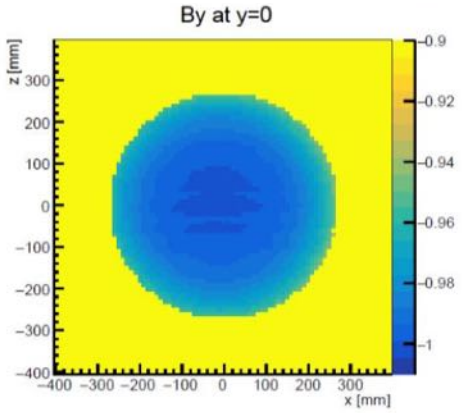
Superconducting Magnet

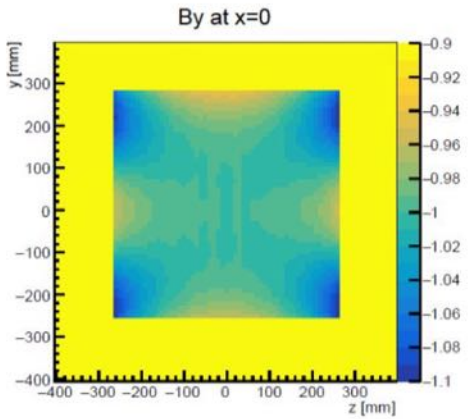
- Helmholtz-typed magnet (KR-tech, Daegu)
  ➔ large acceptance & high uniformity
- NbTi (T_c=9 K), conduction cooling
- Max. 1.5 T at 103 A (1.0 T for E42)





$$R = \left| \frac{P}{qB} \right|$$



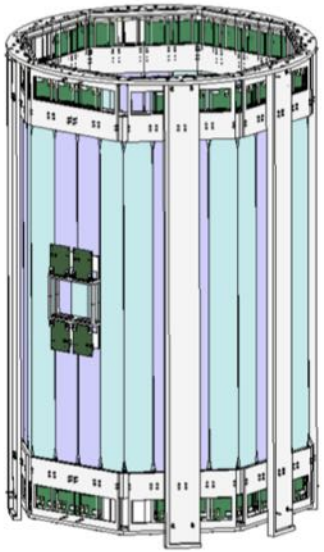


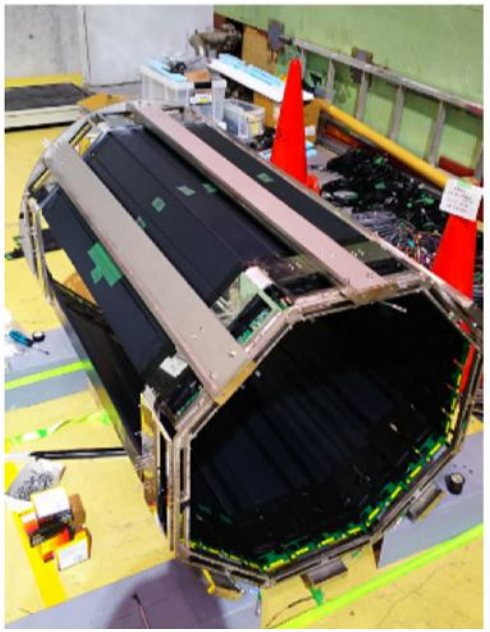
<2% uniformity

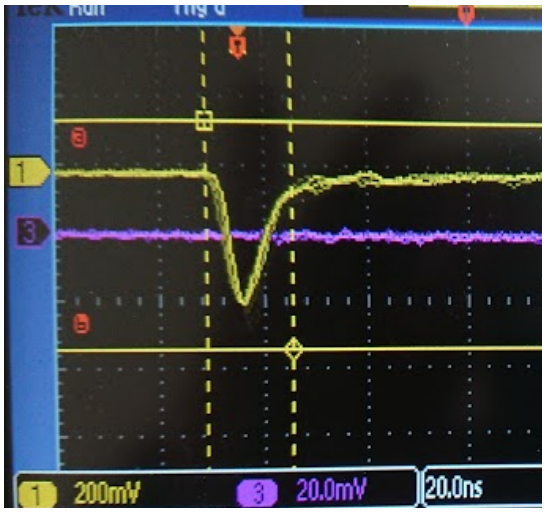
HTOF Array

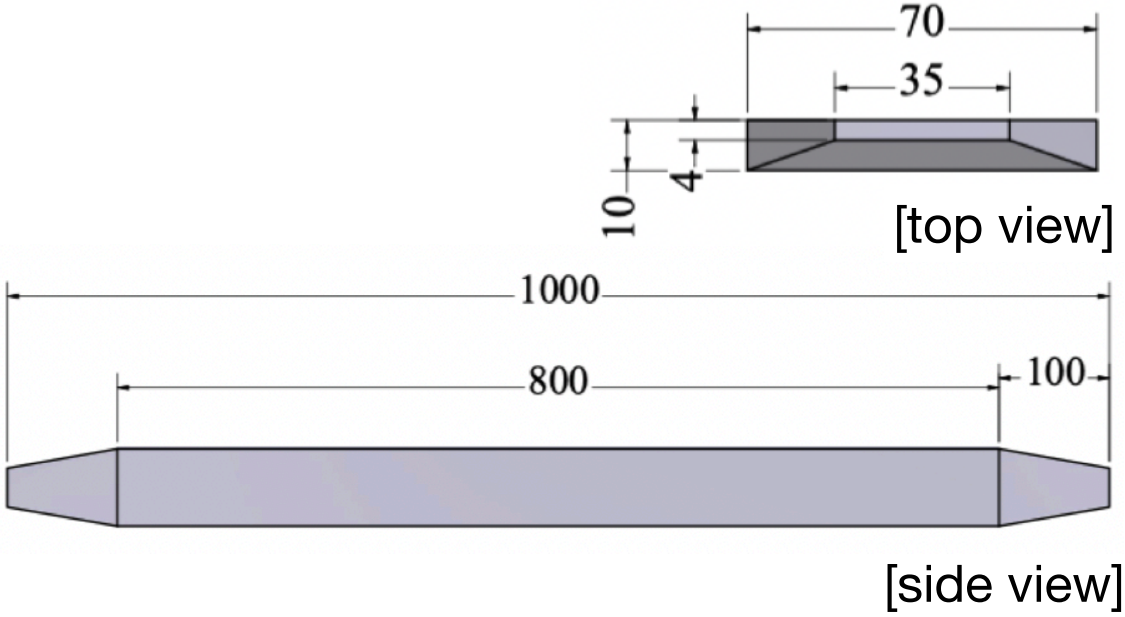
2021

- ultrafast scintillator (EJ-232)
- 34 segments with beam window
- 8 MPPCs (S13360-3060PE) at each end
- Resolution: ~130 ps



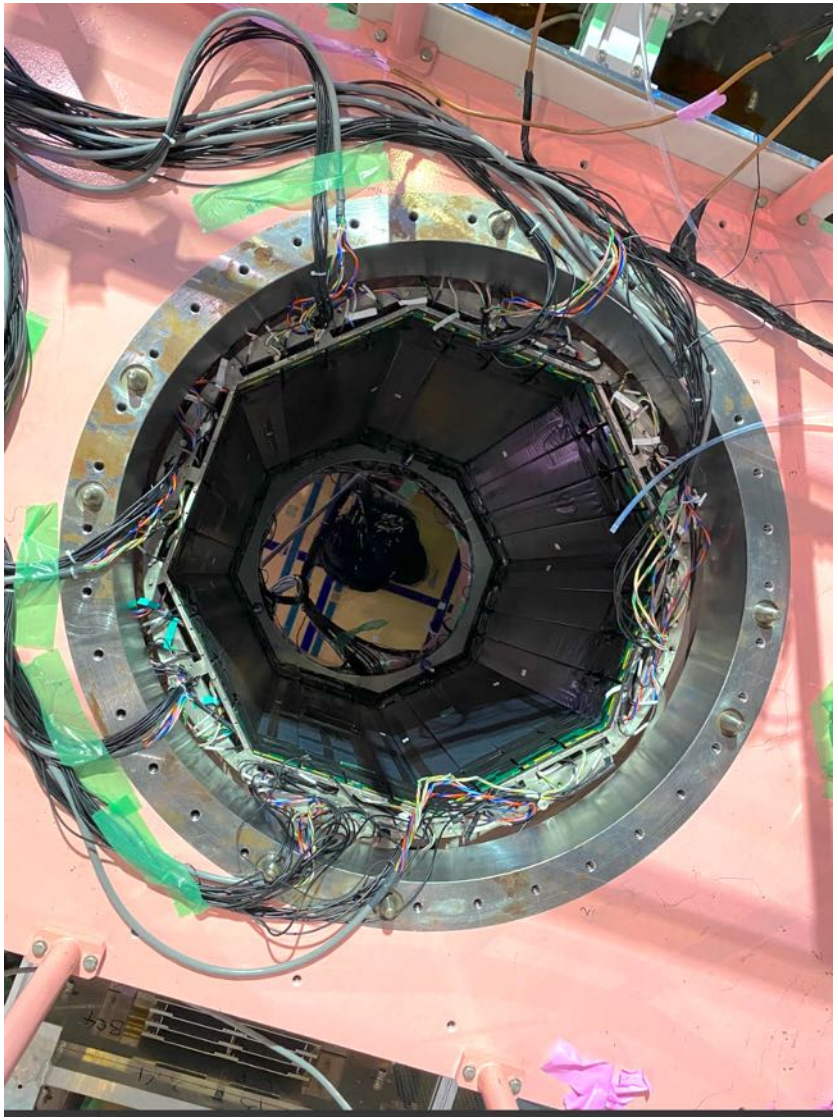


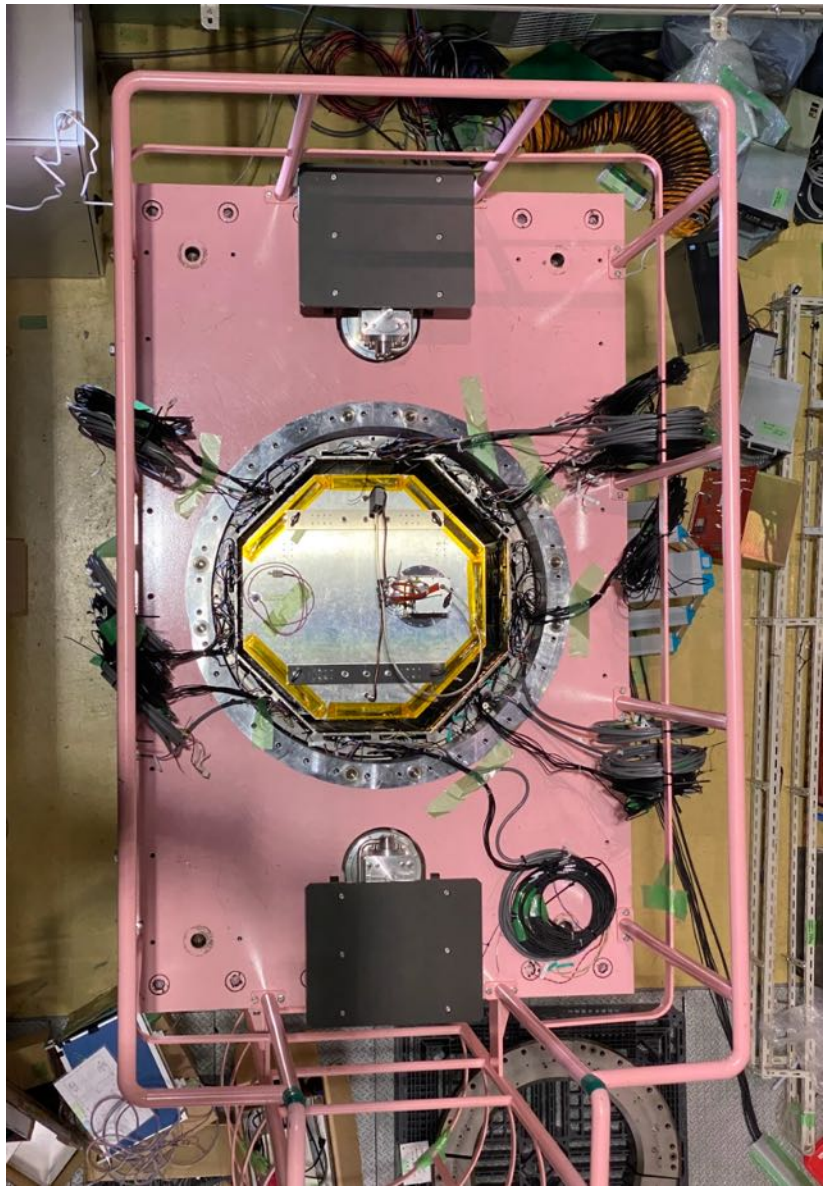




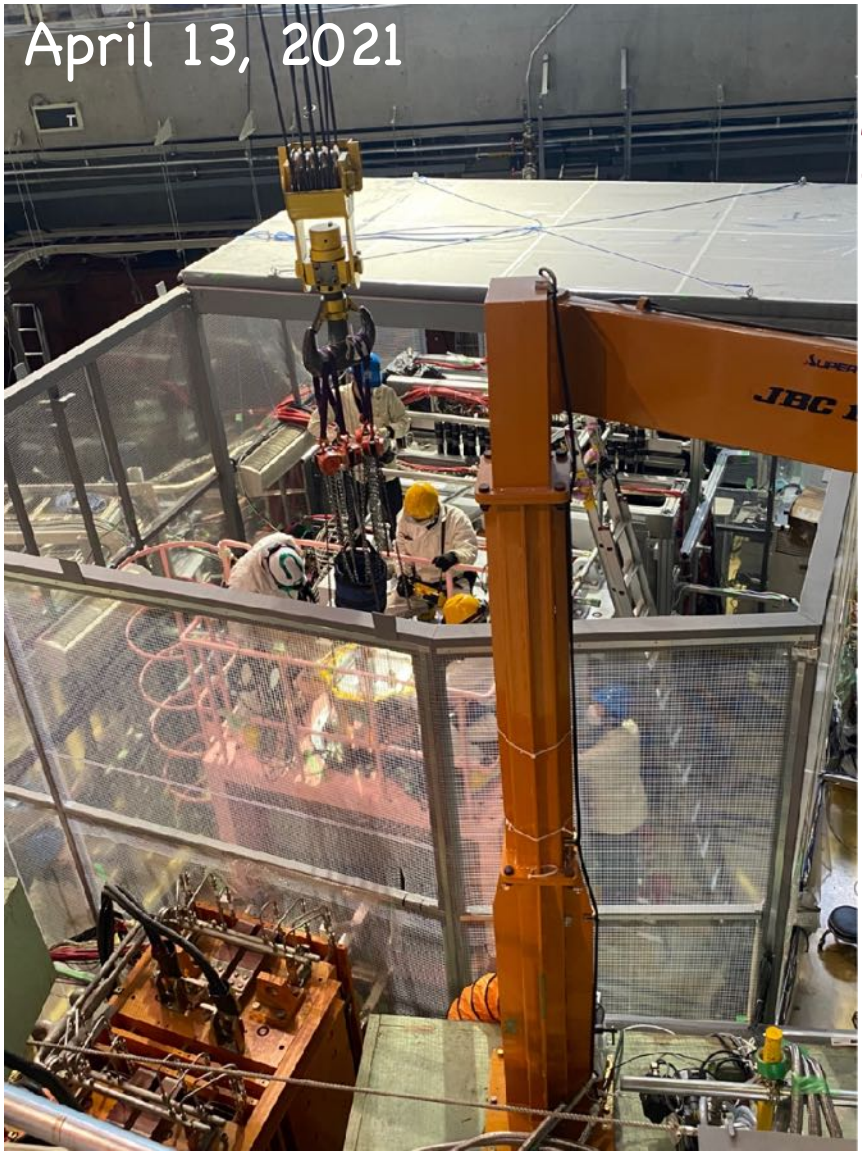
First Installation of HS

2021



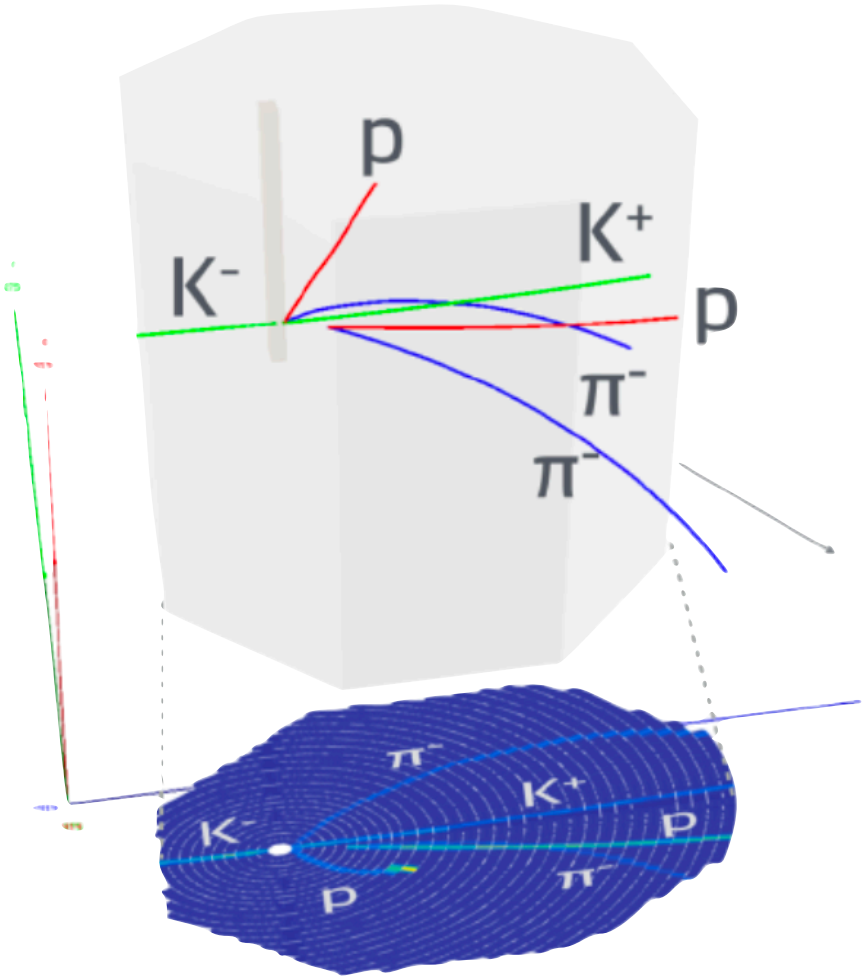


Hyperon Spectrometer at K1.8 Beam Line at J-PARC

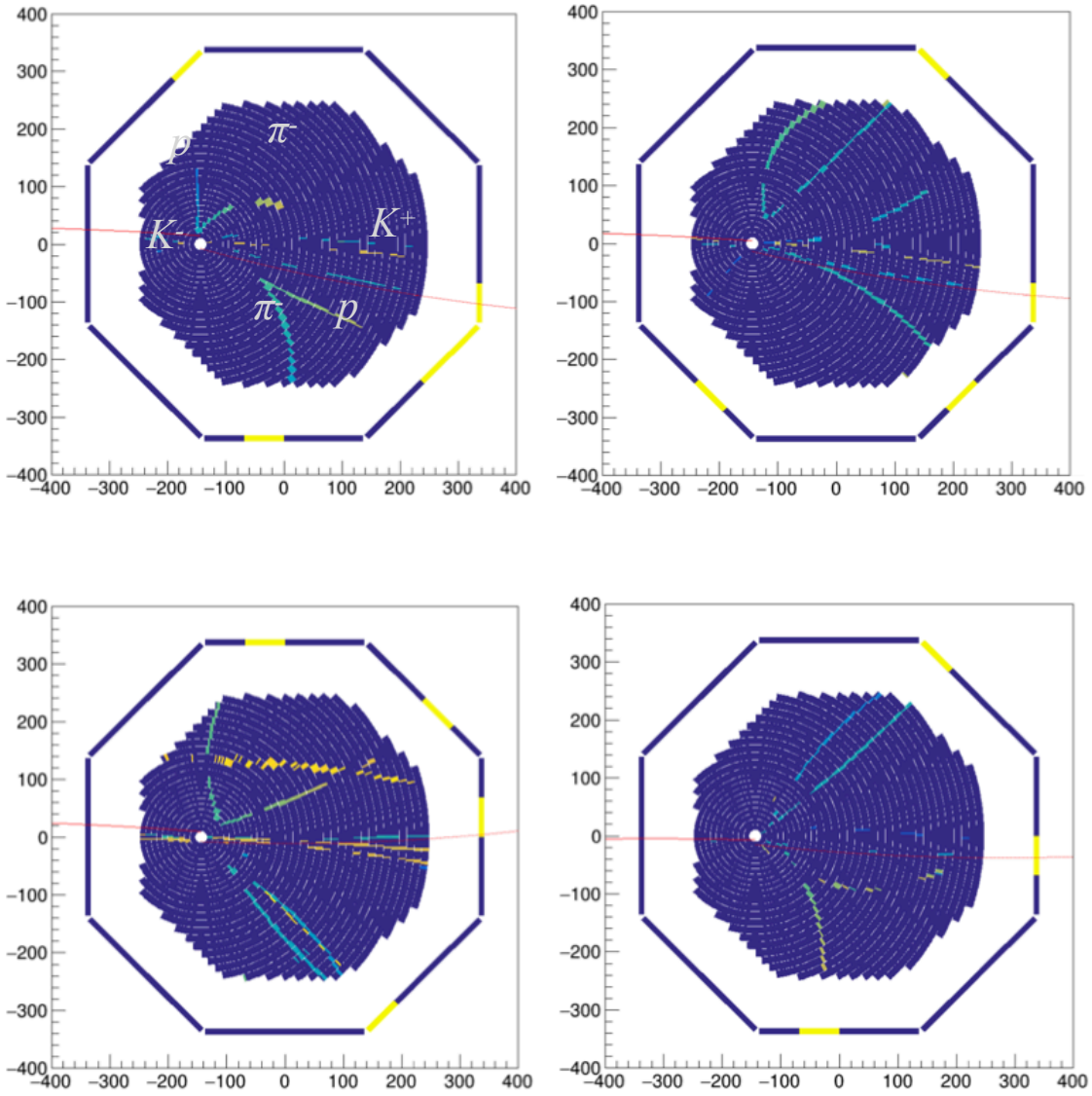


Hyperon Spectrometer

- *Simulation (J-PARC E42)*



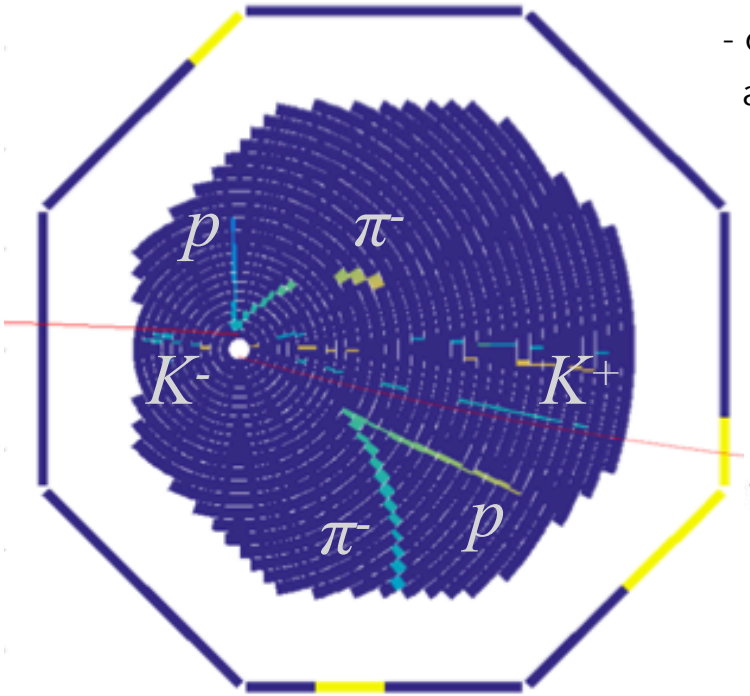
- *Event Display (J-PARC E42)*

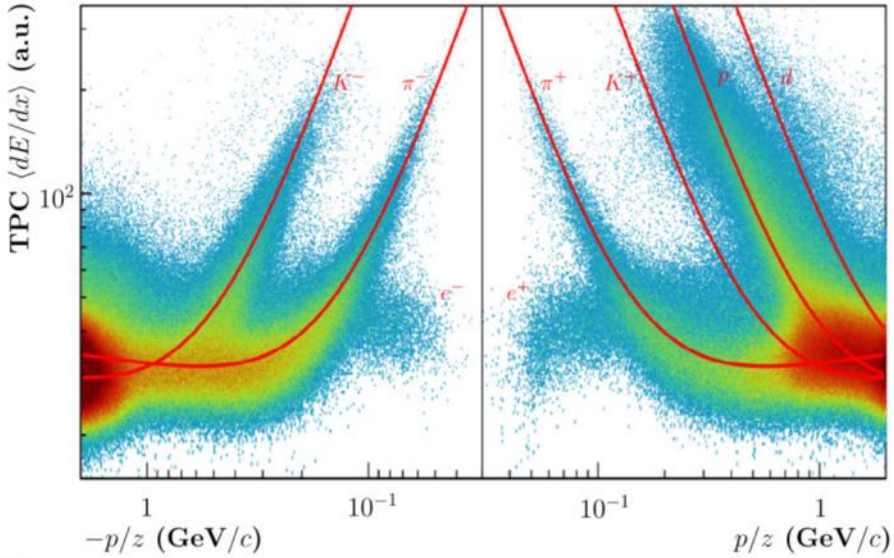


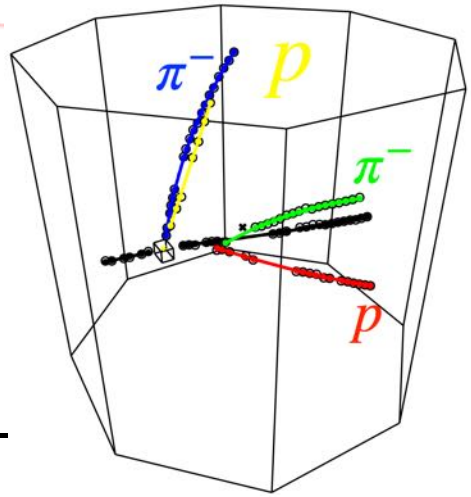
PID by Hyperon Spectrometer

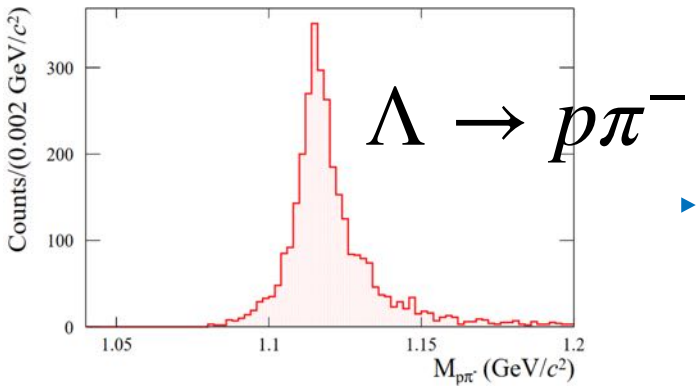
- HypTPC dE/dx

  - $\sigma_{<dE/dx>}/<dE/dx> \sim 20\%$ at $0.4 < p_T < 0.45$ GeV/c





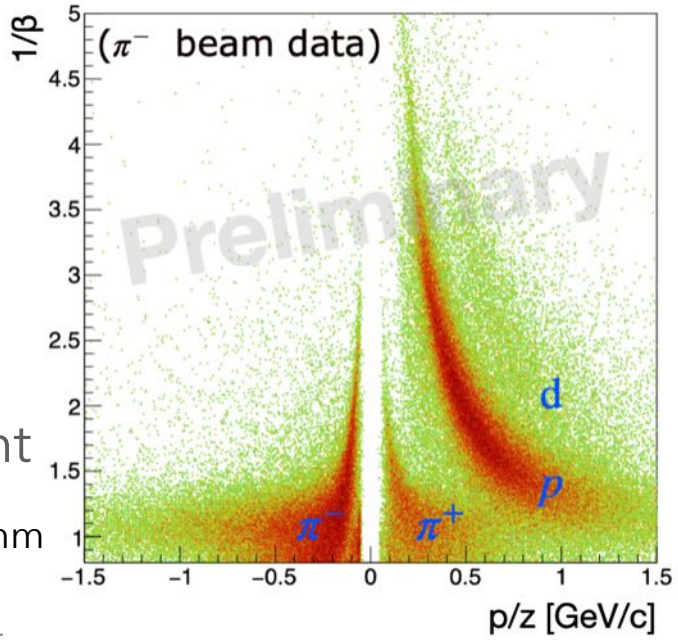




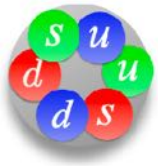
- HTOF Time-of-Flight

  flight length: 200~500 mm

  $\sigma_t \sim 120$ ps for π^-



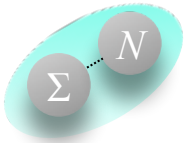
HypTPC Experiments at J-PARC



E42 *H*-dibaryon search in $^{12}C(K^-,K^+)$ reaction

E72 New Λ* search in $p(K^-,\Lambda)\eta$ reaction

E45 N* spectroscopy in $\pi^{\pm}p \to \pi\pi N$ reaction

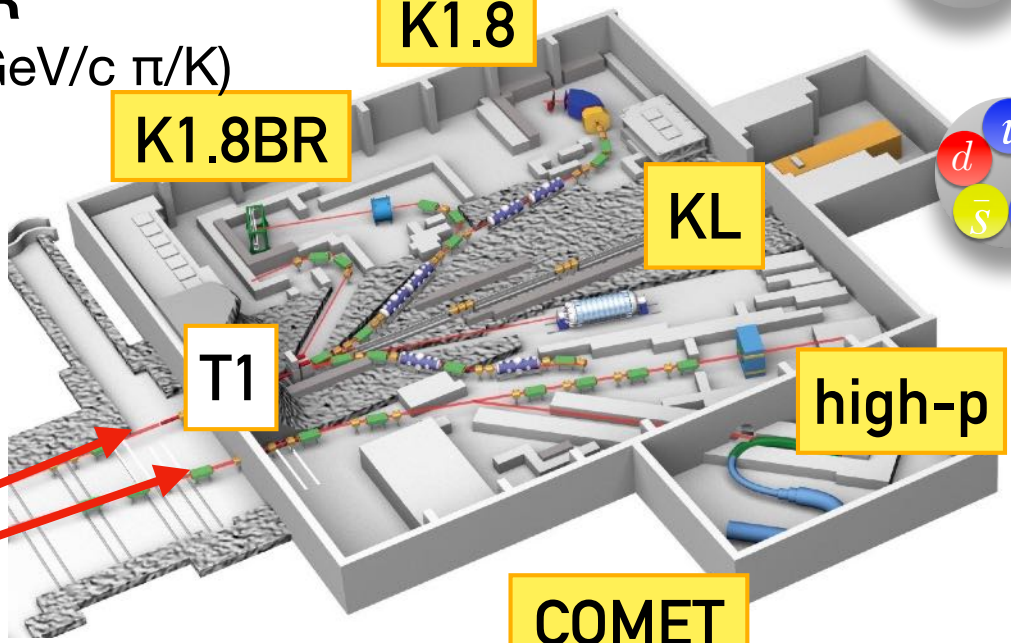


E90 ΣN cusp study in $d(K^-,\pi^-)\Lambda p$ reaction

E104 $\bar{p}p \to \phi\phi$ reaction

K1.8
(~1.8 GeV/c π/K)

K1.8BR
(~1.0 GeV/c π/K)

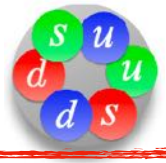


30 GeV proton

L0I/ P109 Θ+ search in $K^+d \to K^0pp$ reaction

J-PARC HypTPC Collaboration

HypTPC Experiments at J-PARC



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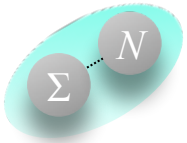

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K1.8BR
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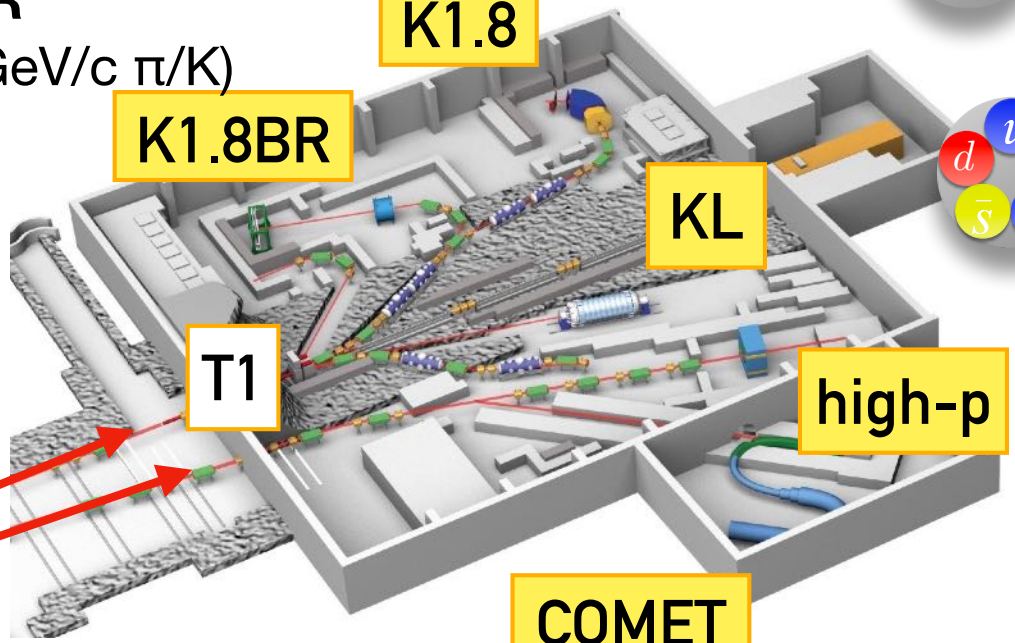

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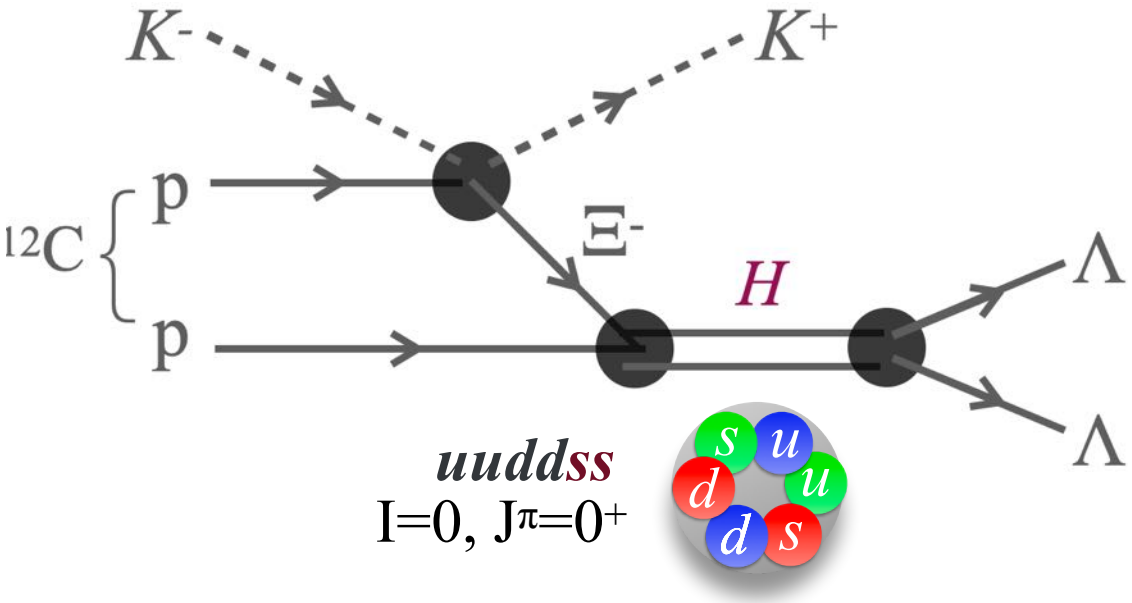

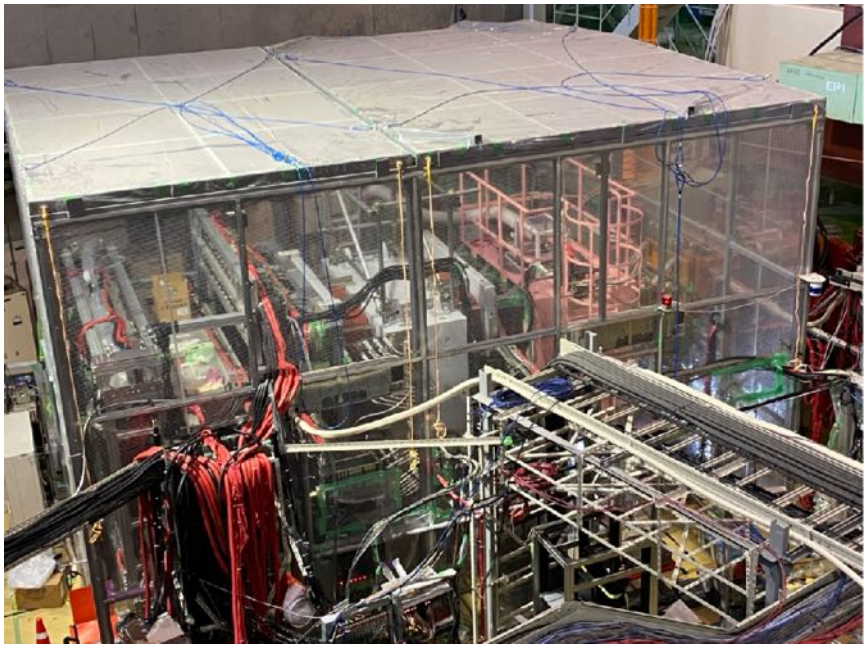

@K1.8 Beam Line in Hadron Experimental Facility , J-PARC

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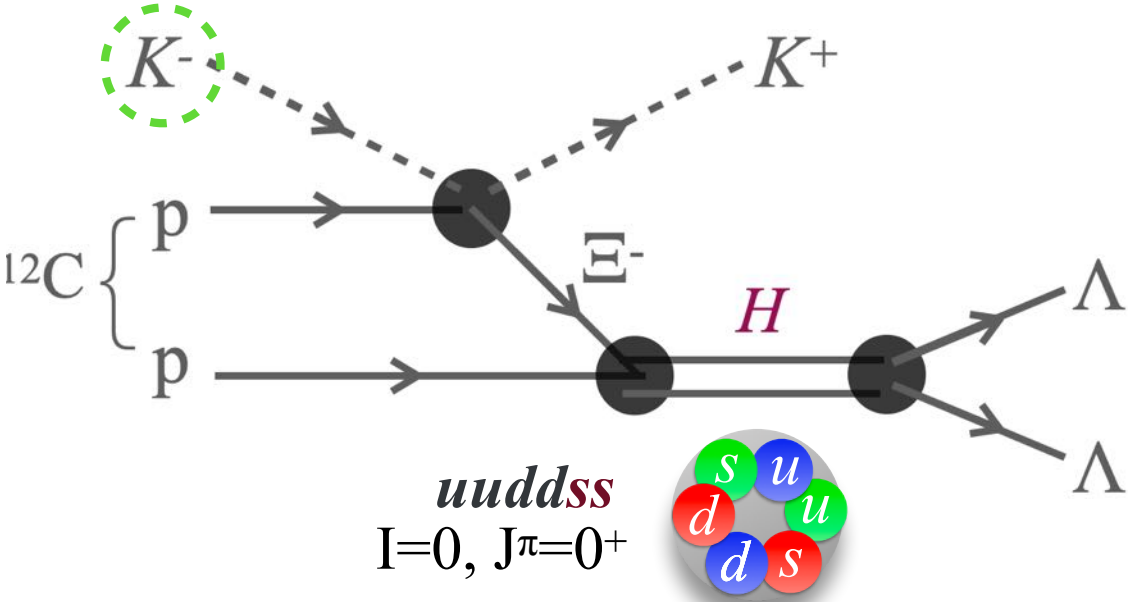
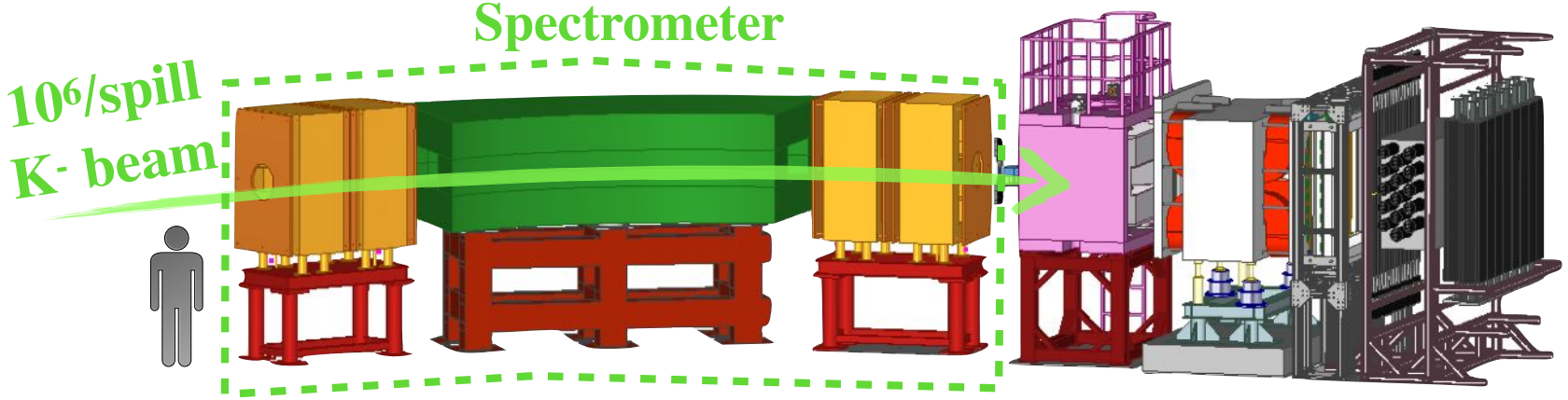


uuddss
I=0, Jπ=0+



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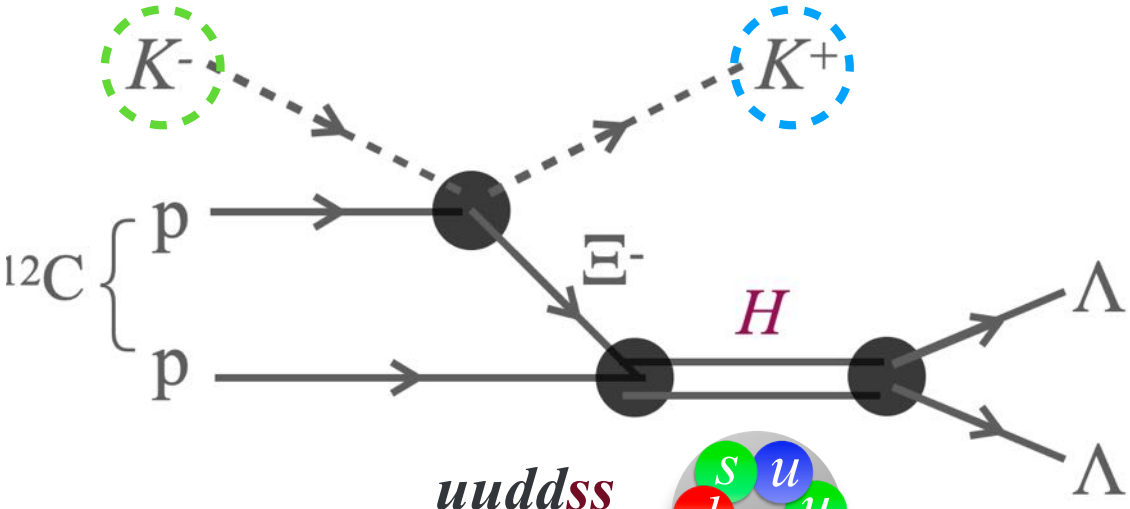

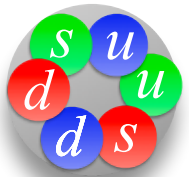

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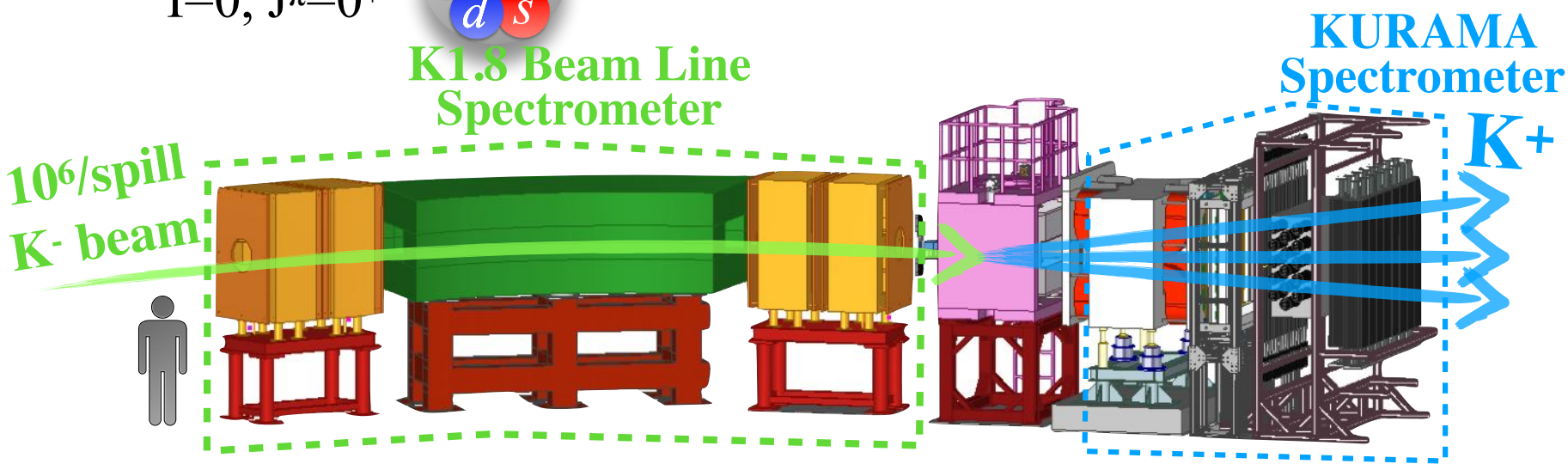

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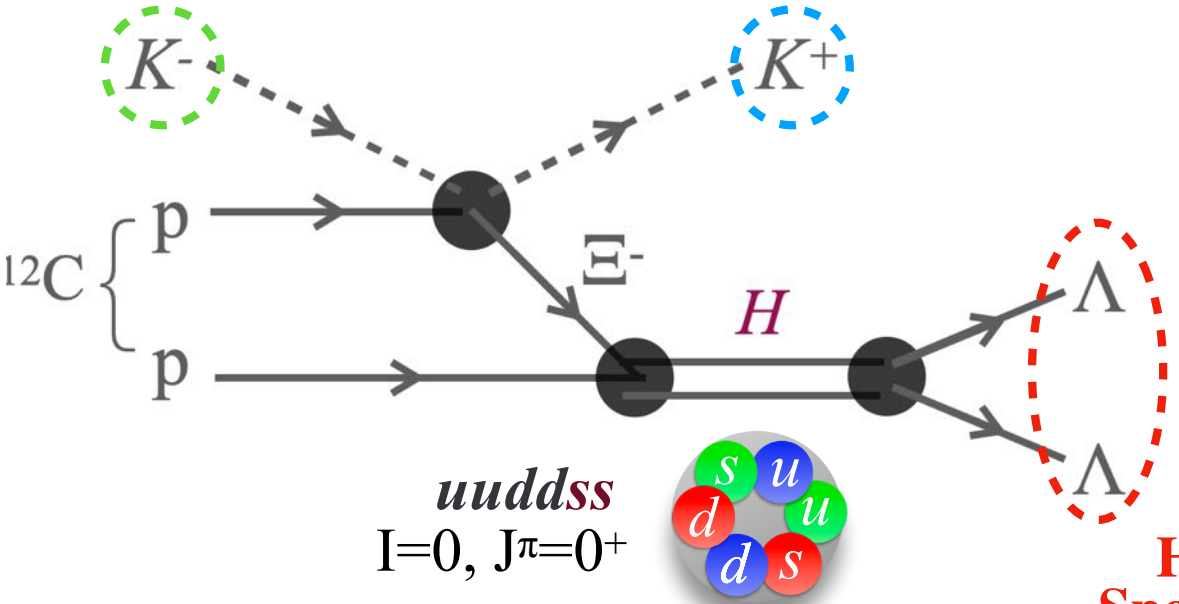
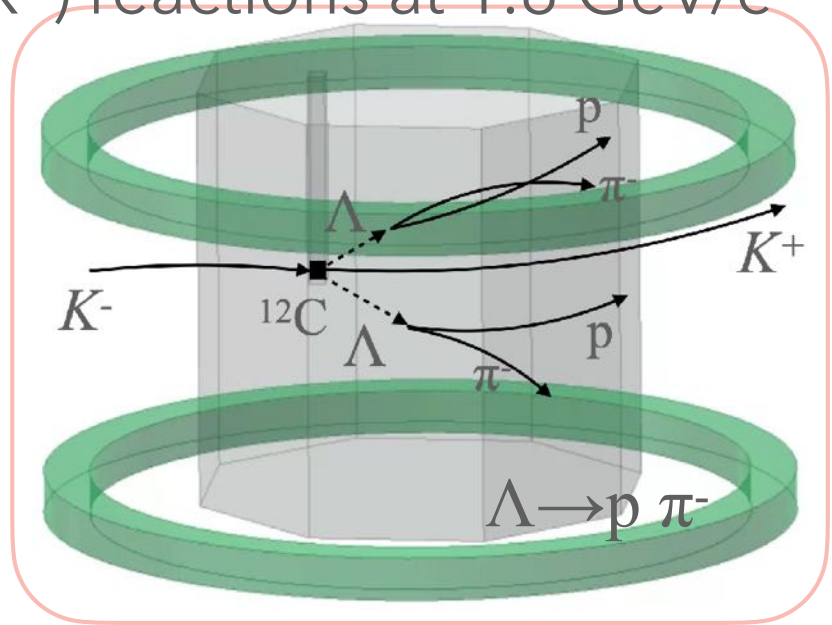
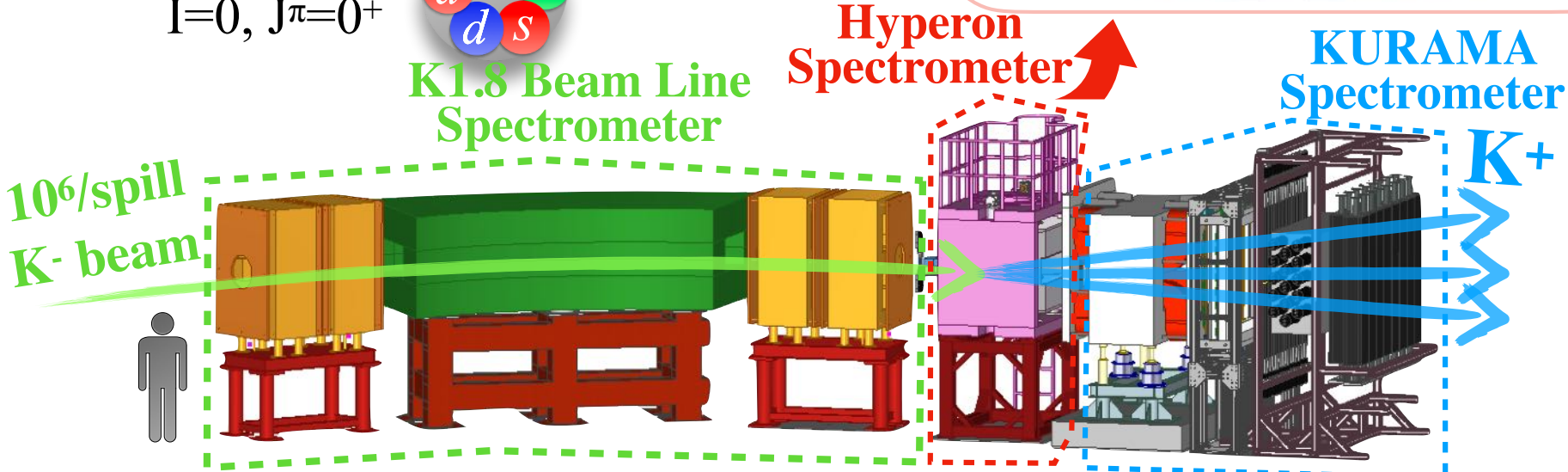


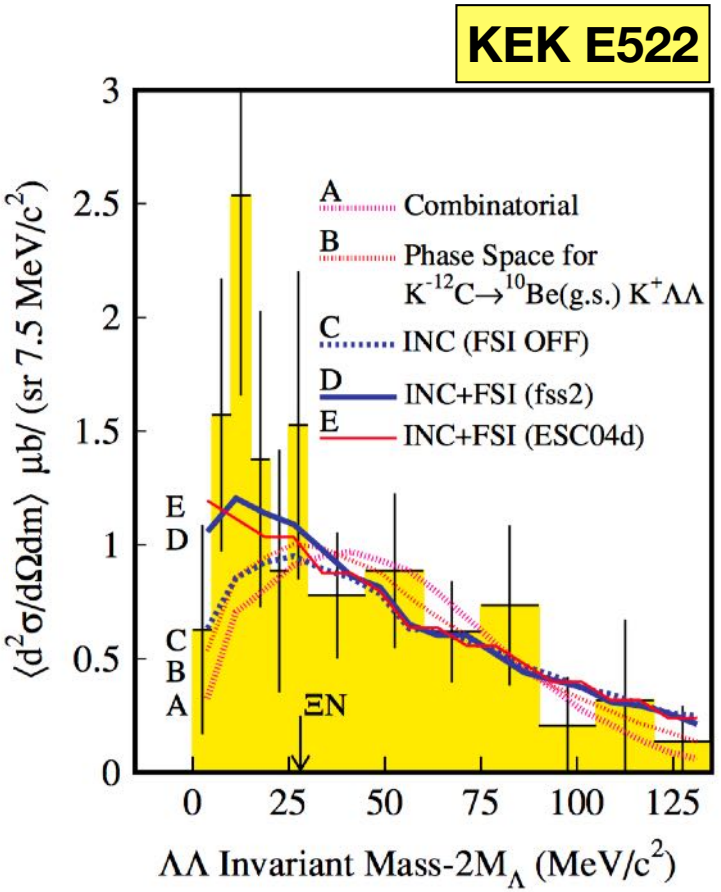




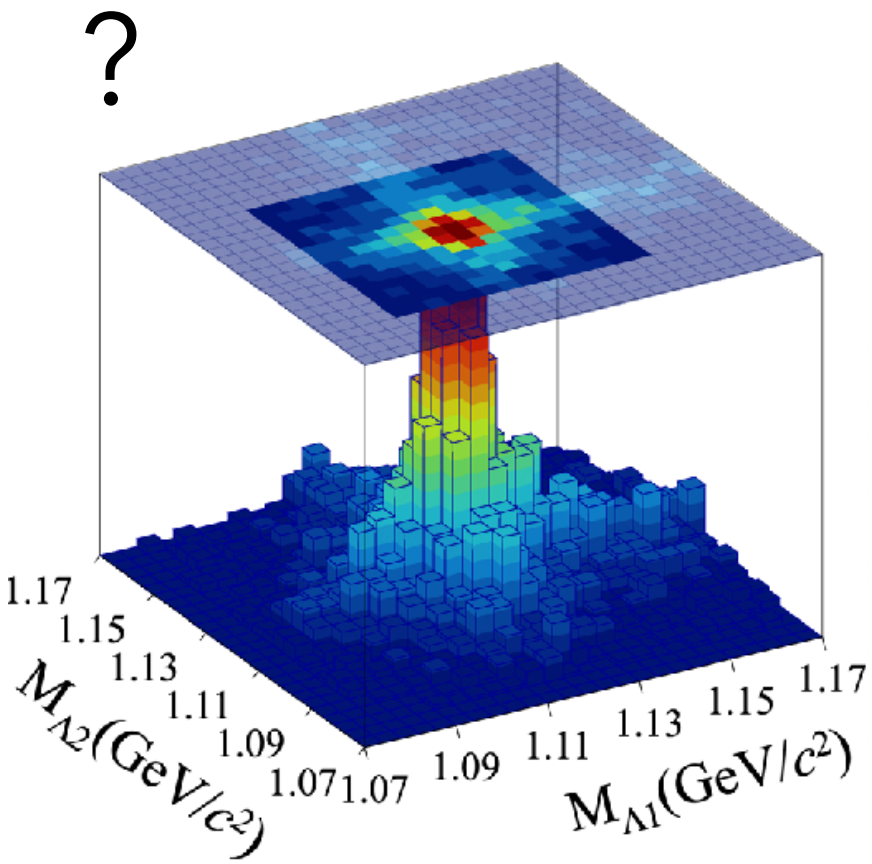
@K1.8 Beam Line in Hadron Experimental Facility , J-PARC

J-PARC E42: H-Dibaryon Search

Completed in 2021; analysis in the final stage

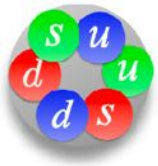


90 ΛΛ events



9k ΛΛ events

HypTPC Experiments at J-PARC



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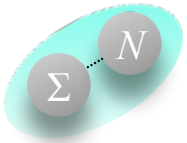

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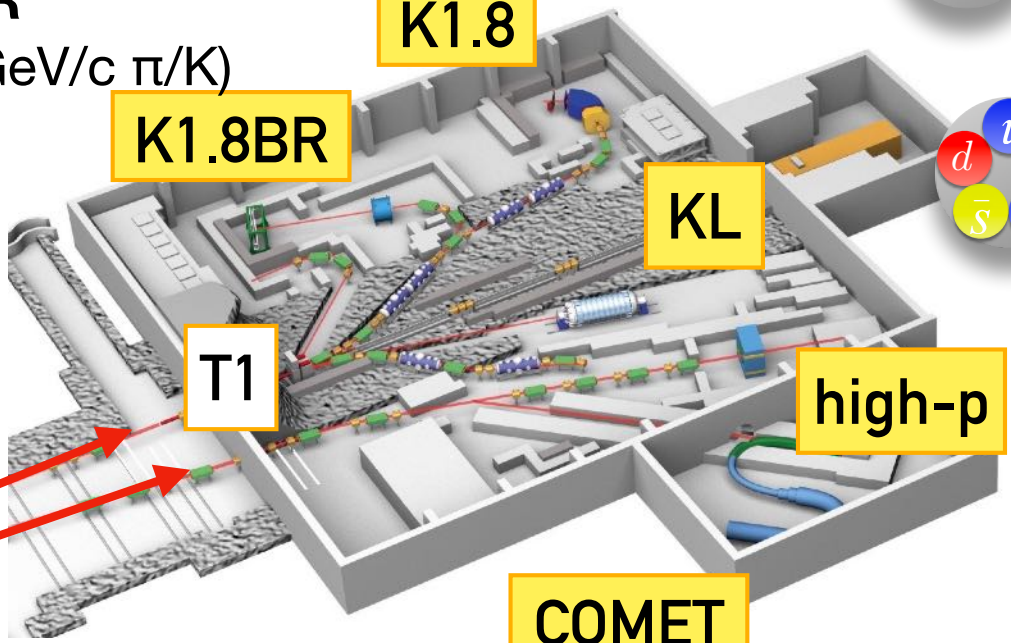

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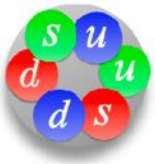
J-PARC HypTPC Collaboration

HypTPC Experiments at J-PARC



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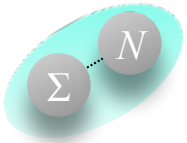

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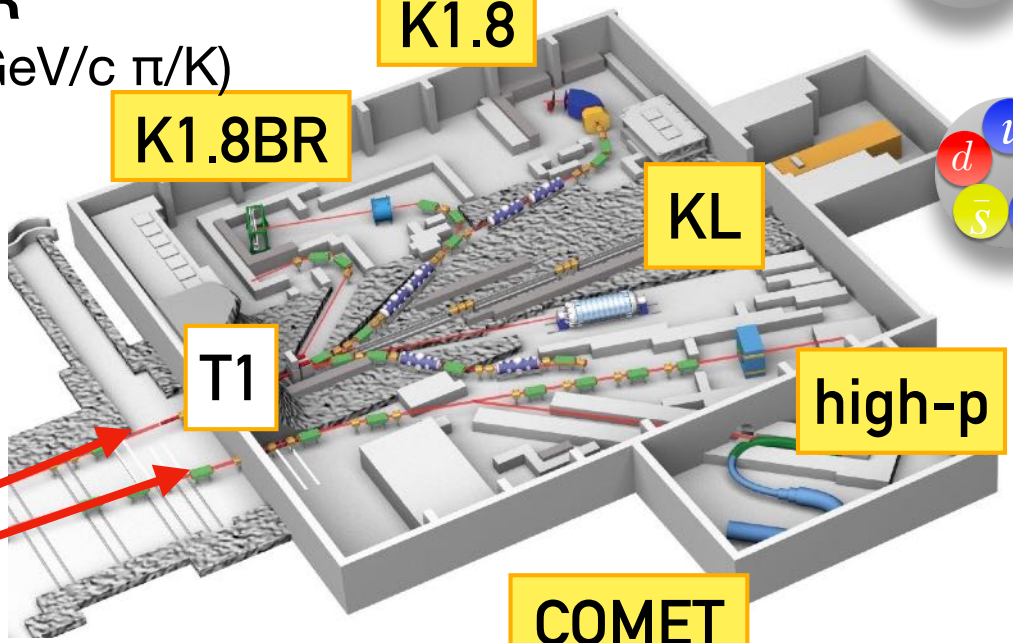


30 GeV proton

LOI/ P109 Θ⁺ search in $K^+d \to K^0pp$ reaction

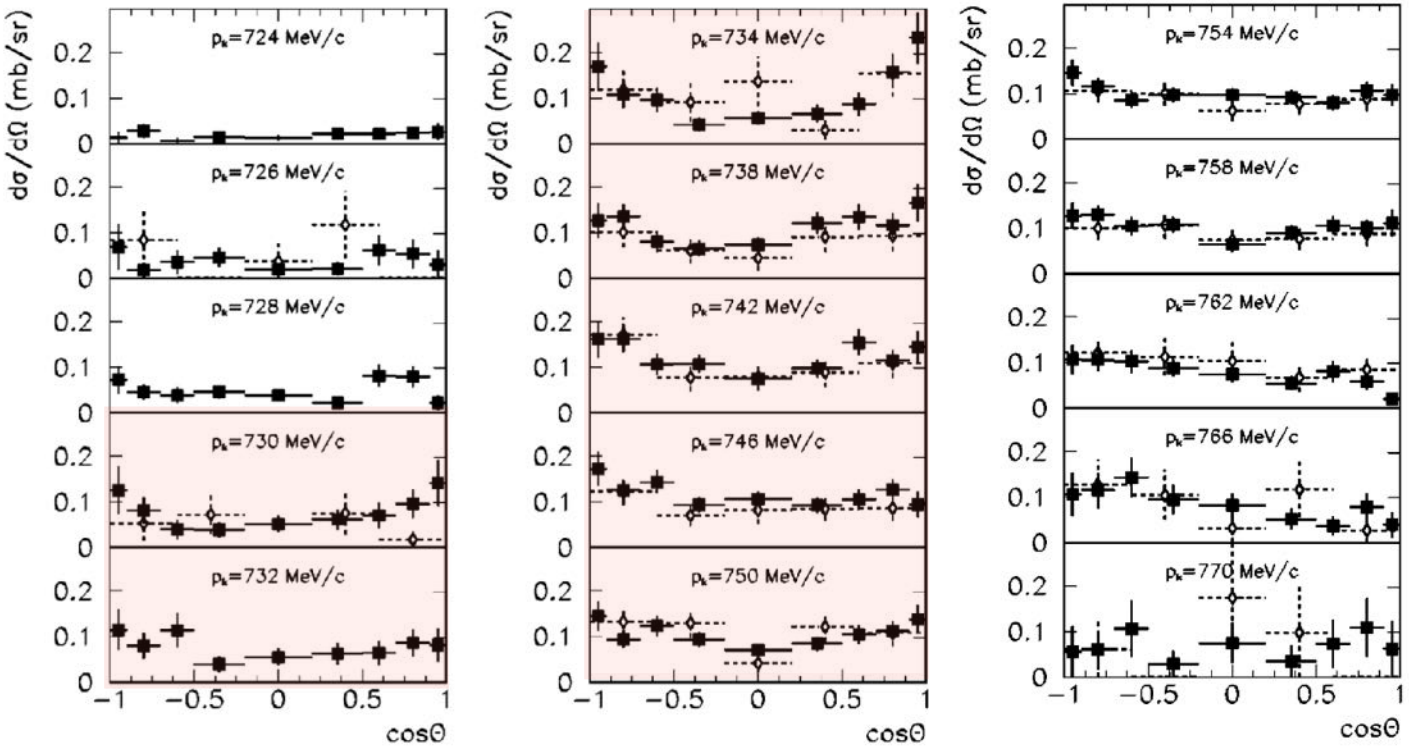
J-PARC HypTPC Collaboration

Narrow Λ* near Λη threshold?

- Differential Cross Section for $K^- p \to \Lambda\eta$

Crystal Ball, PRC 64, 055205 (2001)

Flat Quadratic Flat



- Concave-up only around p_K=734 MeV/c
- a narrow resonance, a J=3/2 (P or D waves) state

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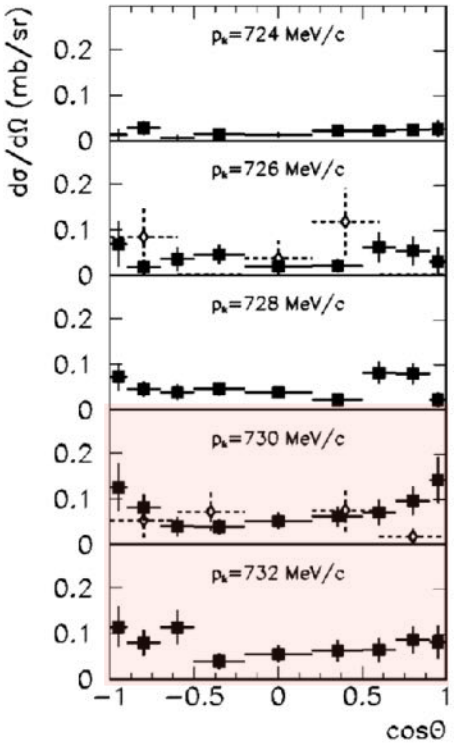
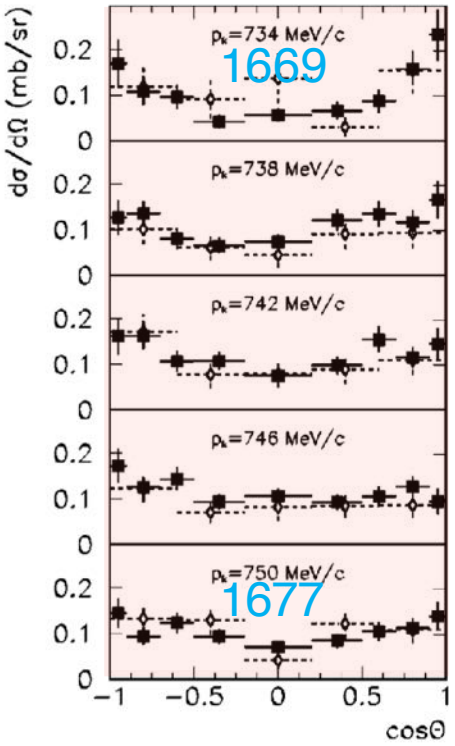


Quadratic



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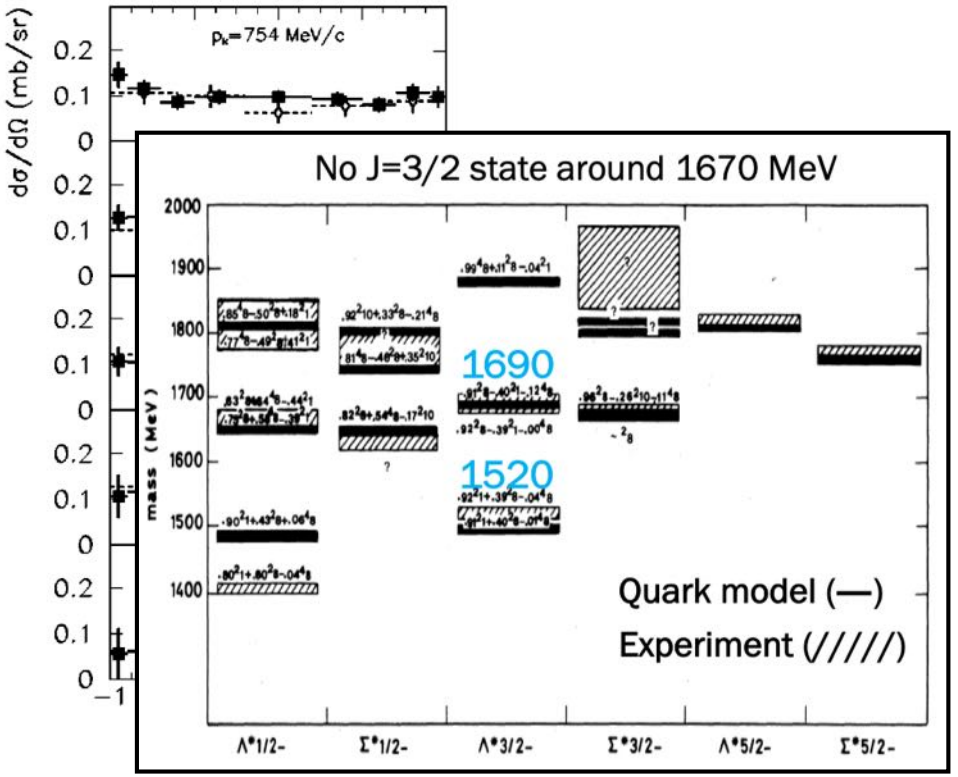


- Concave-up only around p_K=734 MeV/c
- a narrow resonance, a J=3/2 (P or D waves) state

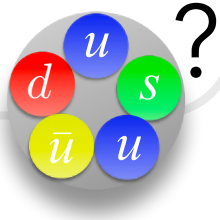
- should be exotic!
  - molecular state?
  - pentaquark?

E72: Narrow Λ* Search near Λη threshold

- $K^-p \rightarrow \Lambda\eta$ at 735 MeV/c at K1.8BR

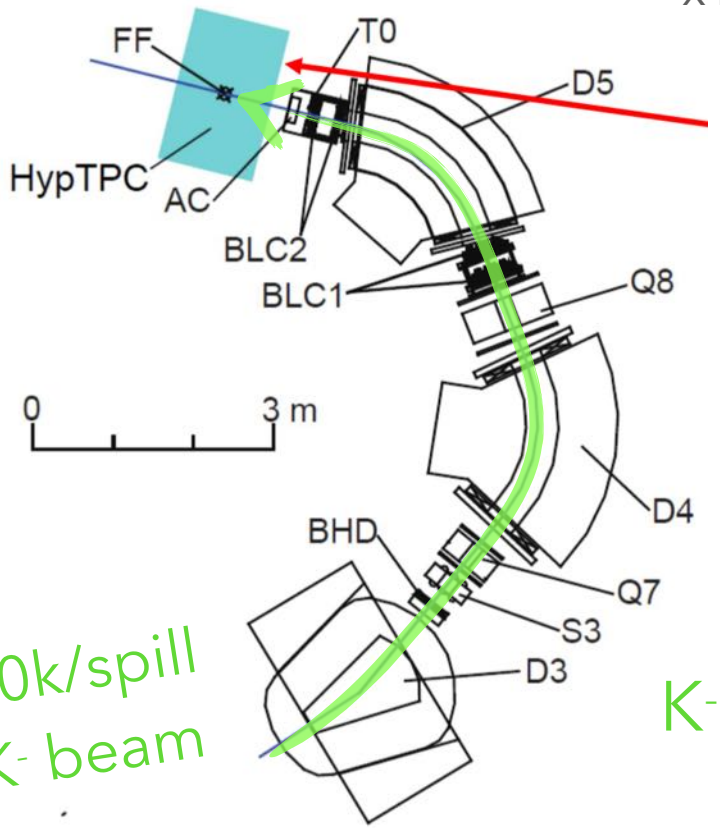
  $\Lambda \rightarrow p\pi^-$ (invariant mass), η(missing mass)
- Angular distribution → spin, Λ Polarization → parity

K1.8BR BL
HypTPC

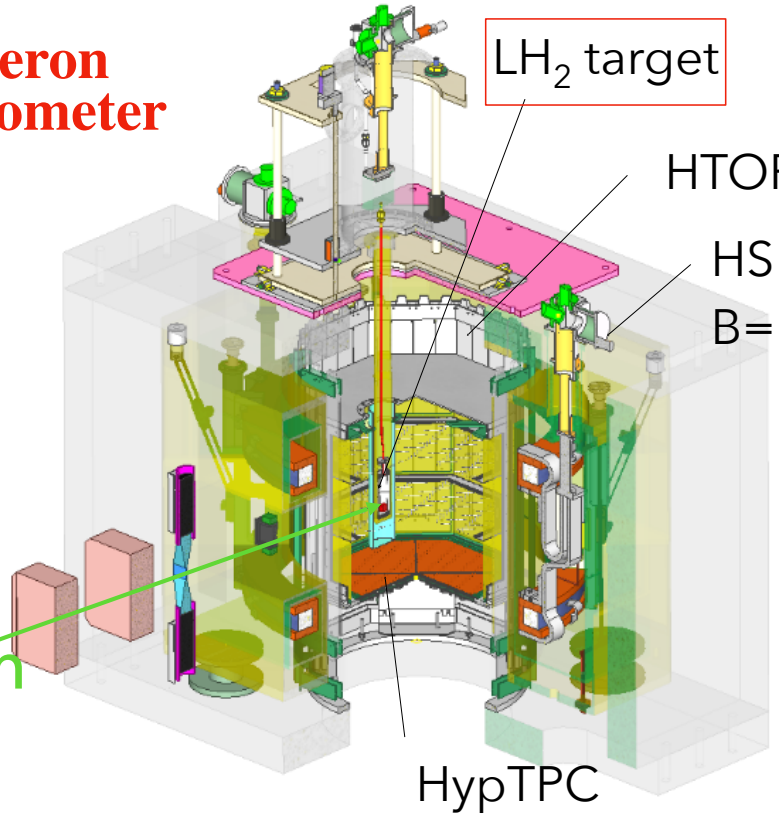


?

x100 higher statistics than Crystal Ball



Hyperon Spectrometer



@K1.8BR Beam Line, J-PARC

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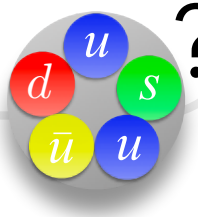

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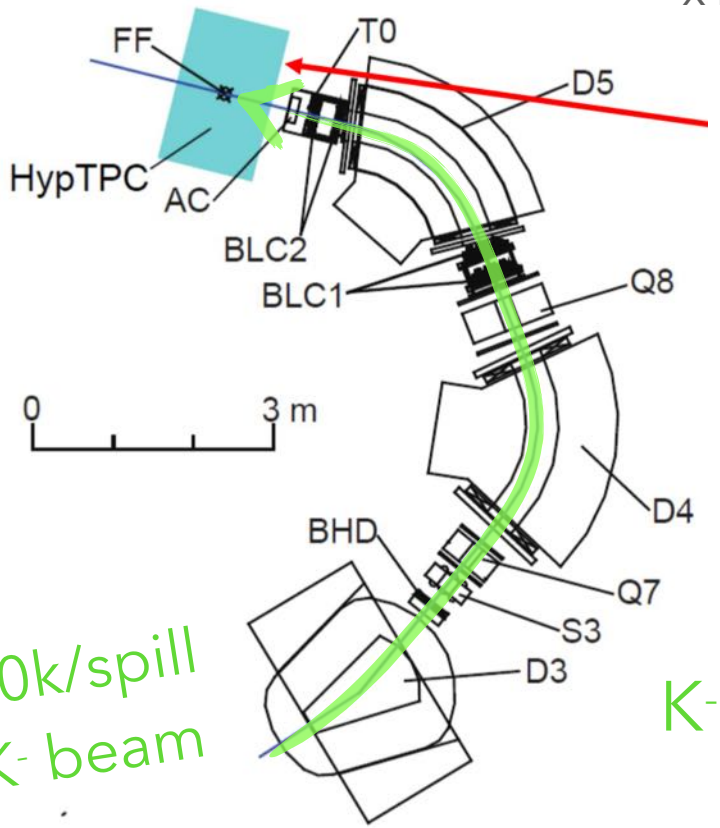

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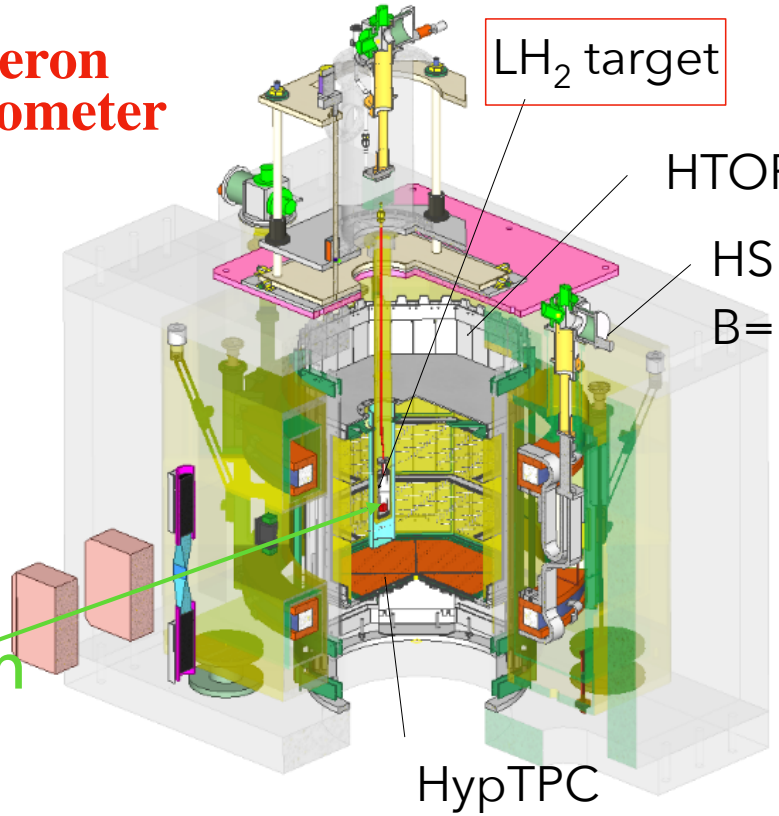
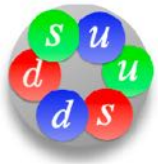


@K1.8BR Beam Line, J-PARC

Physics run just completed !

HypTPC Experiments at J-PARC



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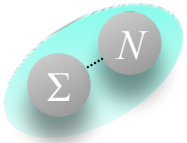

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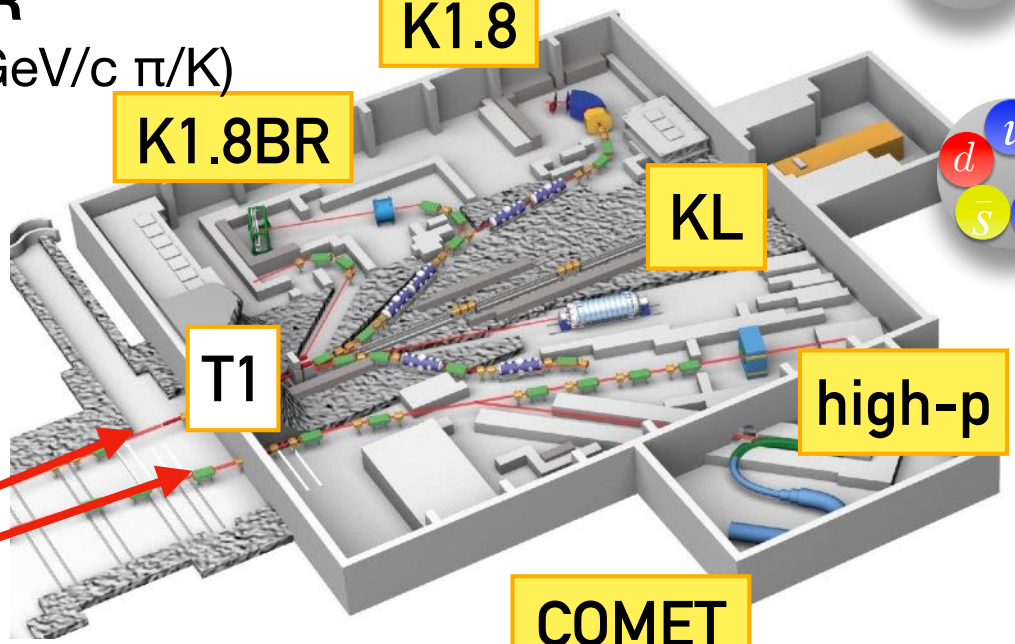

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J-PARC HypTPC Collaboration

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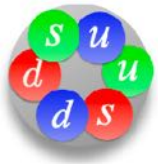

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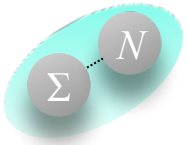

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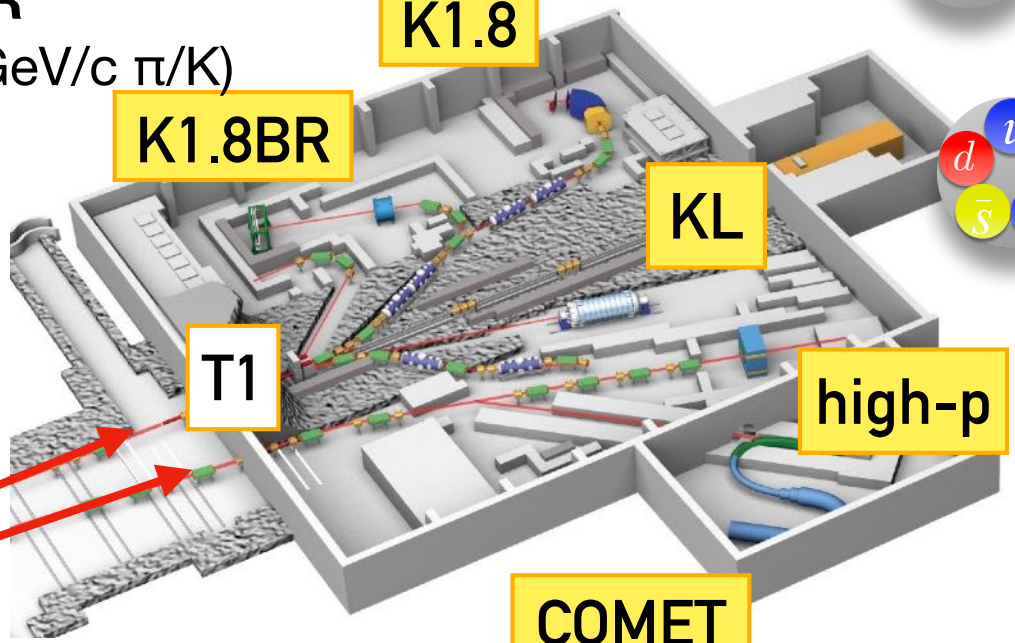


30 GeV proton

LOI/ P109 Θ+ search in $K^+d \to K^0pp$ reaction

J-PARC HypTPC Collaboration

N* and Δ* Baryon Spectroscopy

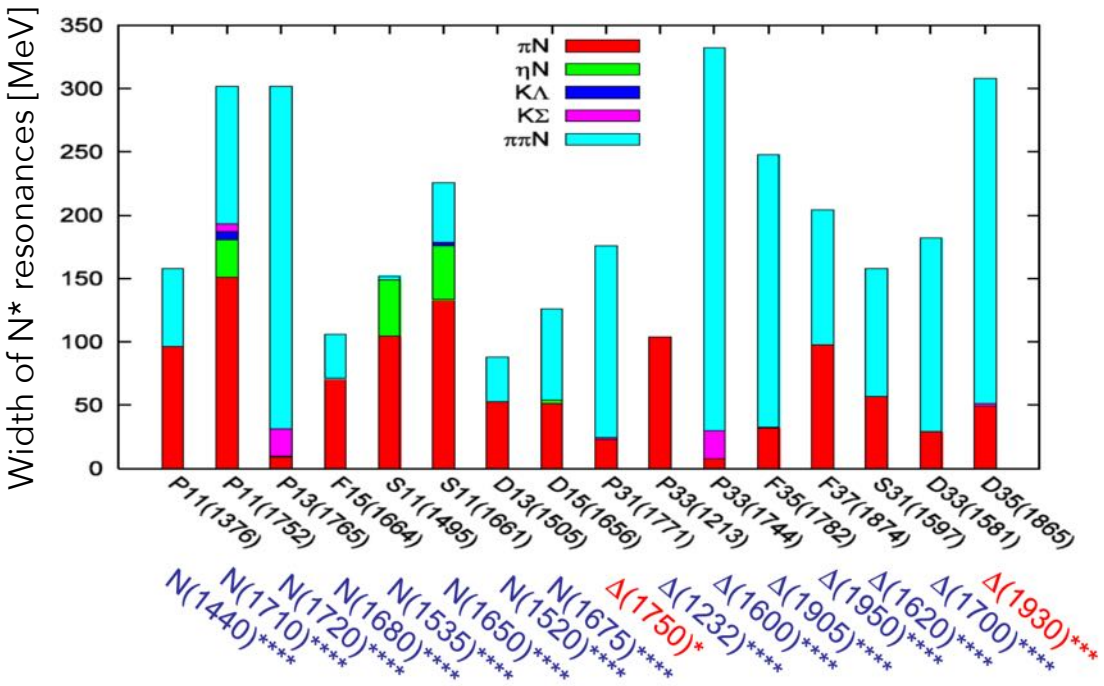
PDG 2022

N	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	****
$N(1720)$	$3/2^+$	****
$N(1860)$	$5/2^+$	**
$N(1875)$	$3/2^-$	***
$N(1880)$	$1/2^+$	***
$N(1895)$	$1/2^-$	****
$N(1900)$	$3/2^+$	****
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	***
$N(2100)$	$1/2^+$	***
$N(2120)$	$3/2^-$	***

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	****
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	***
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	***
$\Delta(1930)$	$5/2^-$	***
$\Delta(1940)$	$3/2^-$	**
$\Delta(1950)$	$7/2^+$	****
$\Delta(2000)$	$5/2^+$	**
$\Delta(2150)$	$1/2^-$	*

**** Established
***
* **

H. Kamano, et al. PRC 79 025206 (2009)

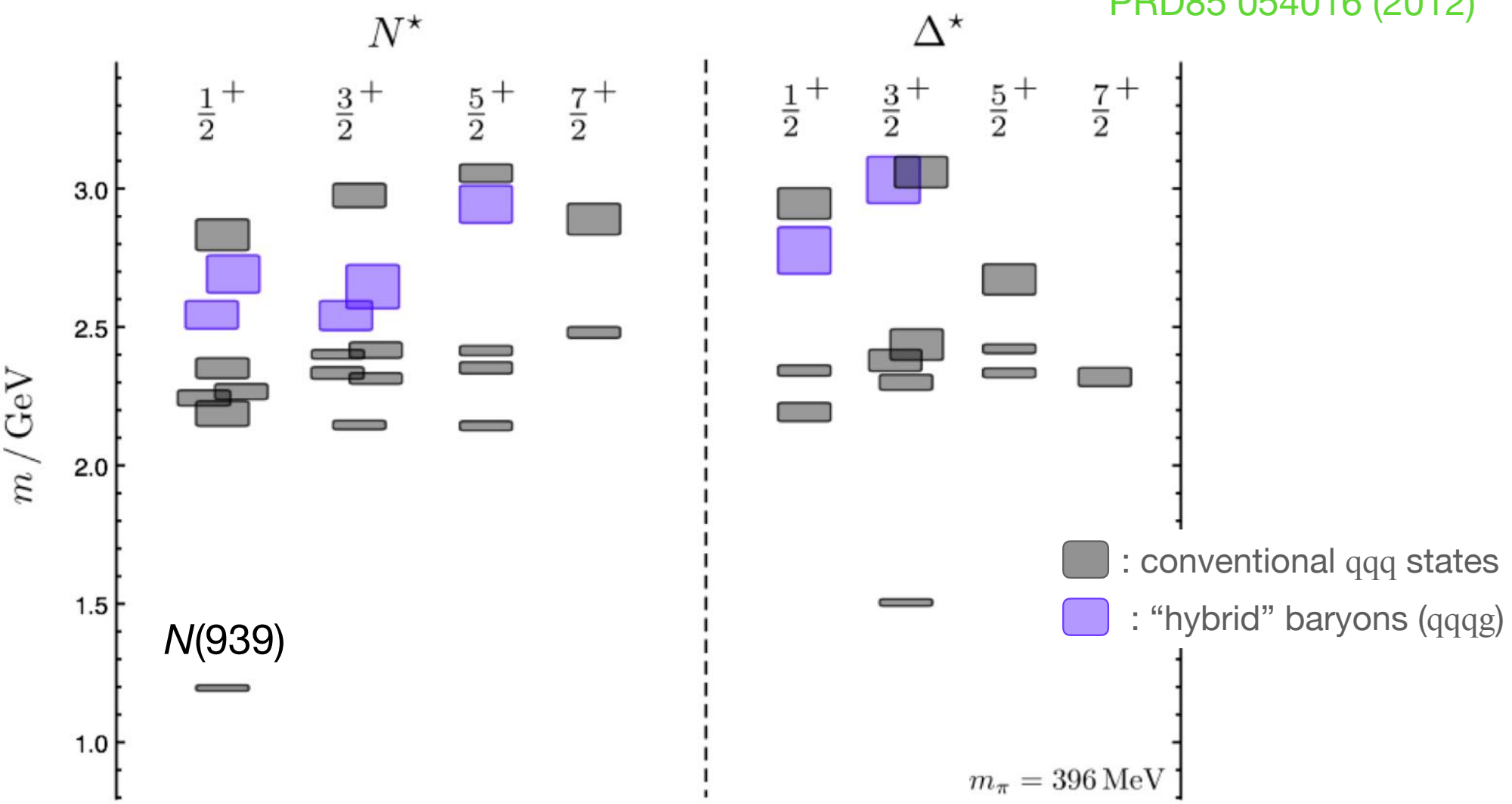


There are many N* and Δ* resonances which couple to ππN dominantly

- Most of the N* and Δ* so far were measured from $\pi N \to \pi N$, $\gamma N \to \pi N$, $\gamma N \to \pi\pi N$.
- $\pi N \to \pi\pi N$ data are necessary to resolve remaining resonances.

Lattice QCD Calculation

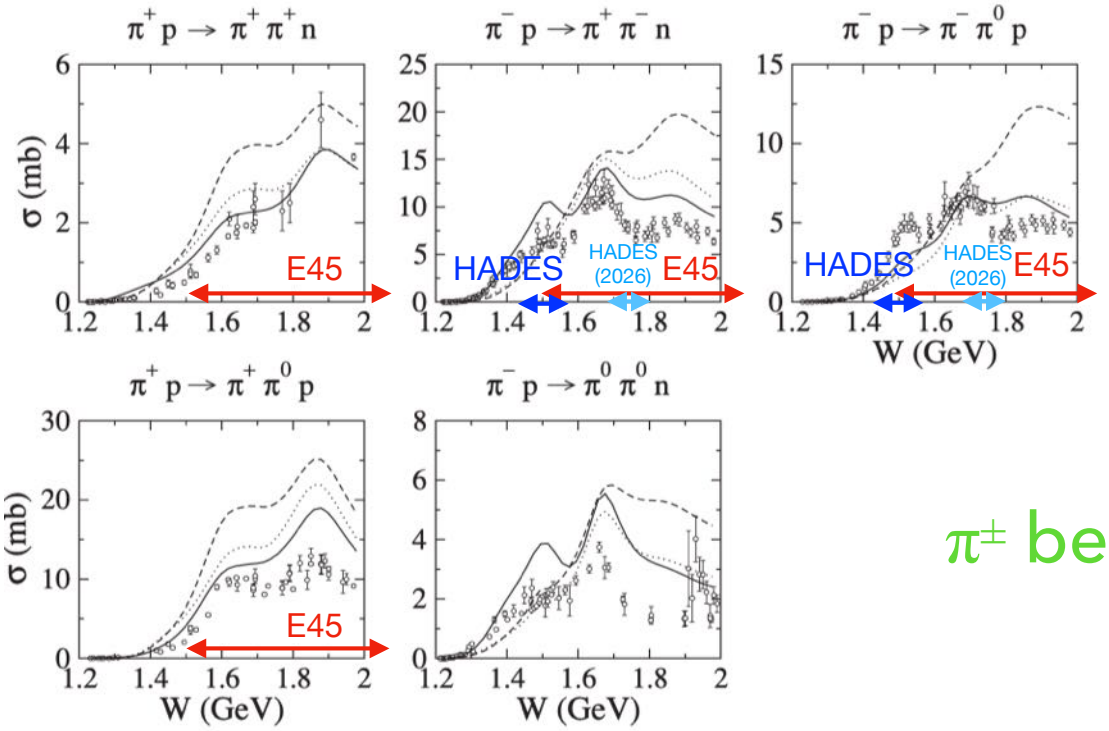
PRD85 054016 (2012)

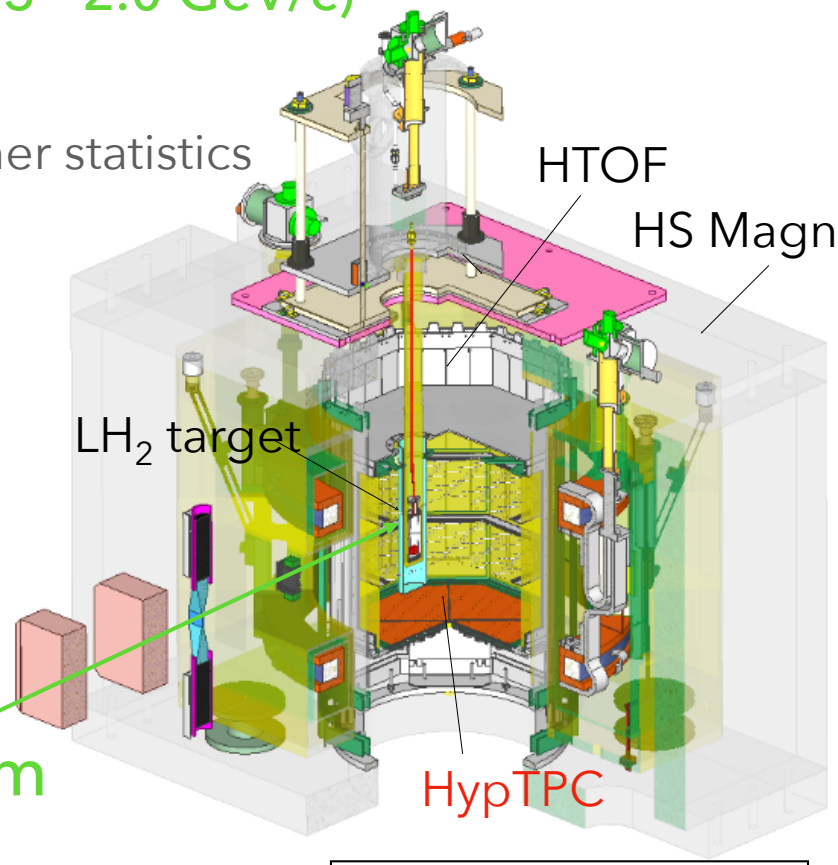


- Lattice QCD calculation predicts that **hybrid baryons** should exist.

E45: *N** and Δ* Spectroscopy

- *N**/Δ* spectroscopy with the $\pi p \to \pi\pi N$ and $\pi p \to KY$ reactions in the wide energy range of 1.5 - 2.15 GeV (p=0.73 - 2.0 GeV/c)
  - Updates on the world database ($\pi p \to \pi\pi N$)
    - 240k events measured in1970's → x100 higher statistics





K1.8 BL
HypTPC

$\pi^- p \to \pi^+\pi^- n$, $\pi^0\pi^- p$
$\pi^+ p \to \pi^0\pi^+ p$, $\pi^+\pi^+ n$
$\pi p \to K\Lambda$, $K\Sigma$

HADES, PRC 102, 024001 (2020)

H. Kamano et al., PRC 79, 025206 (2009)

J-PARC E45 Multiplicity Trigger

- Trigger: HTOF multiplicity-2 from $\pi^{\pm}p$ reactions at 1.5 - 2.15 GeV (p=0.73 - 2.0 GeV/c)
- $\pi p \rightarrow \pi\pi N$ reactions

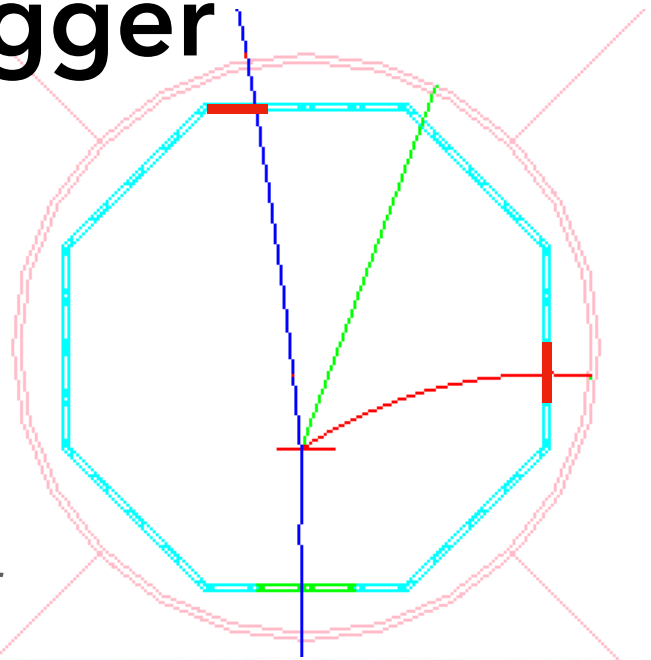
  $\pi^-p \rightarrow \pi^+\pi^-n$, $\pi^0\pi^-p$,
  $\pi^+p \rightarrow \pi^0\pi^+p$, $\pi^+\pi^+n$

- $\pi p \rightarrow \pi p$ reactions

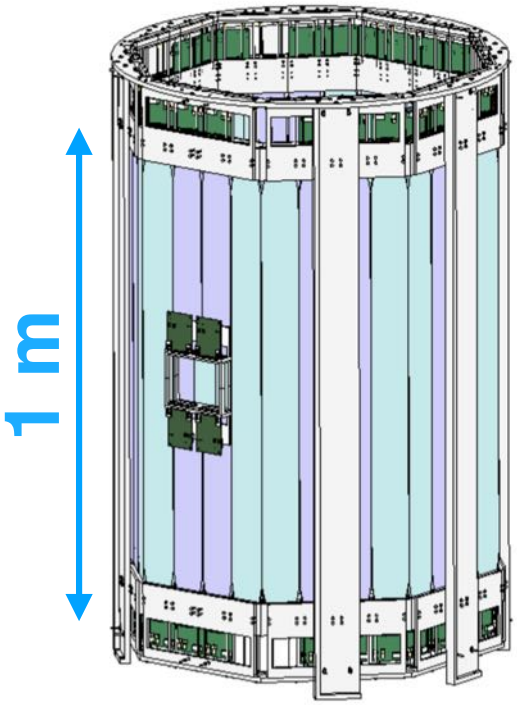
  $\pi^-p \rightarrow \pi^-p$,
  $\pi^+p \rightarrow \pi^+p$

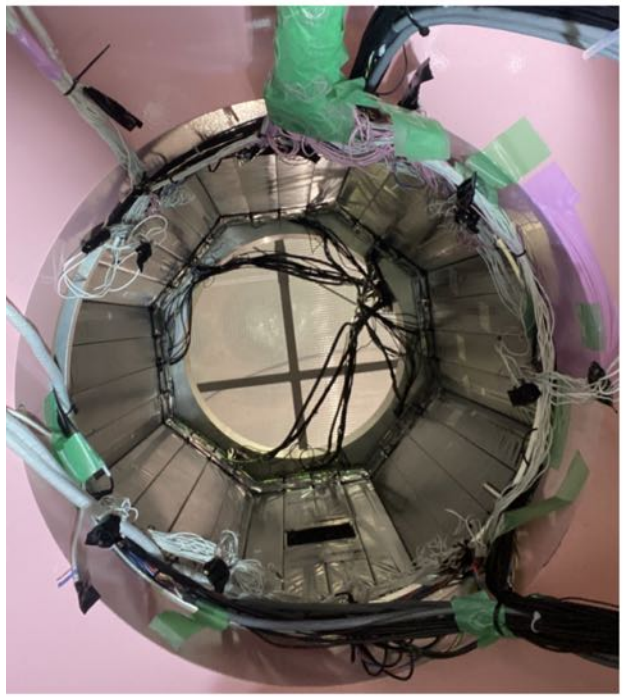
- $\pi p \rightarrow KY$ reactions

  $\pi^{\pm}p \rightarrow K\Lambda$, $K\Sigma$



- *HTOF detector*





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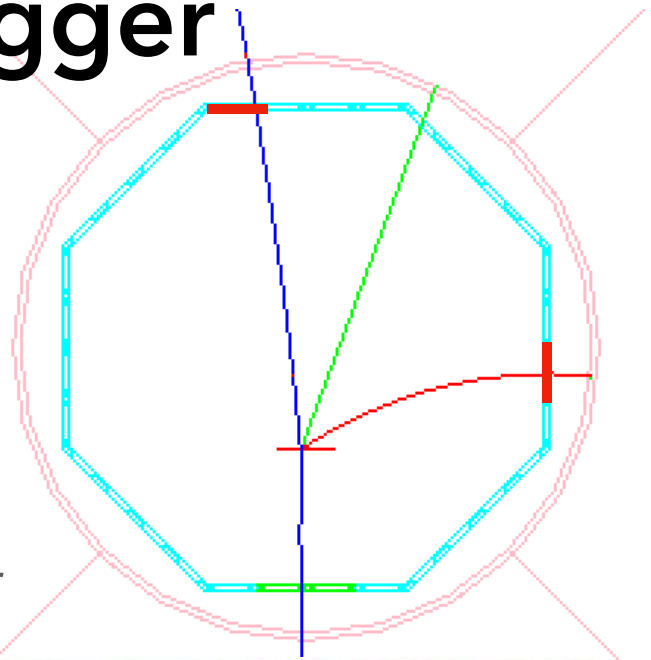
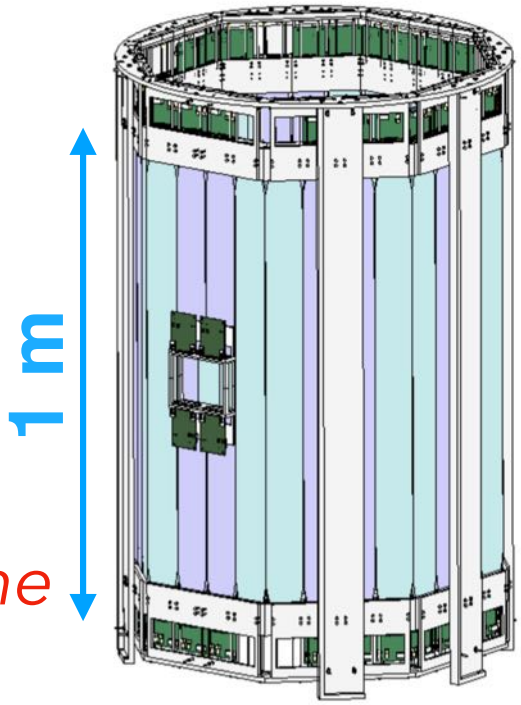
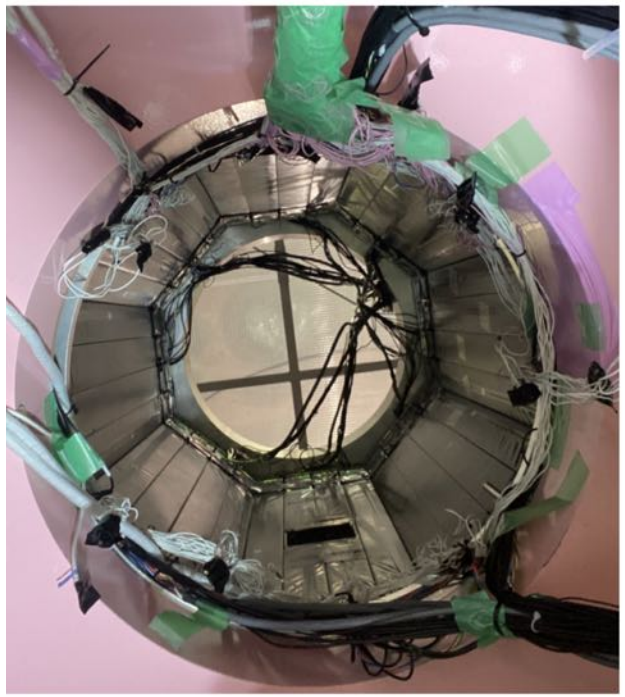


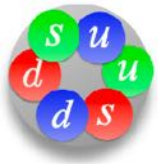
- *HTOF detector*





Waiting for the beam time after E72 !

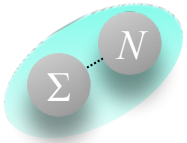
HypTPC Experiments at J-PARC



E42 *H*-dibaryon search in $^{12}C(K^-,K^+)$ reaction

E72 New Λ* search in $p(K^-,\Lambda)\eta$ reaction

E45 N* spectroscopy in $\pi^{\pm}p \to \pi\pi N$ reaction

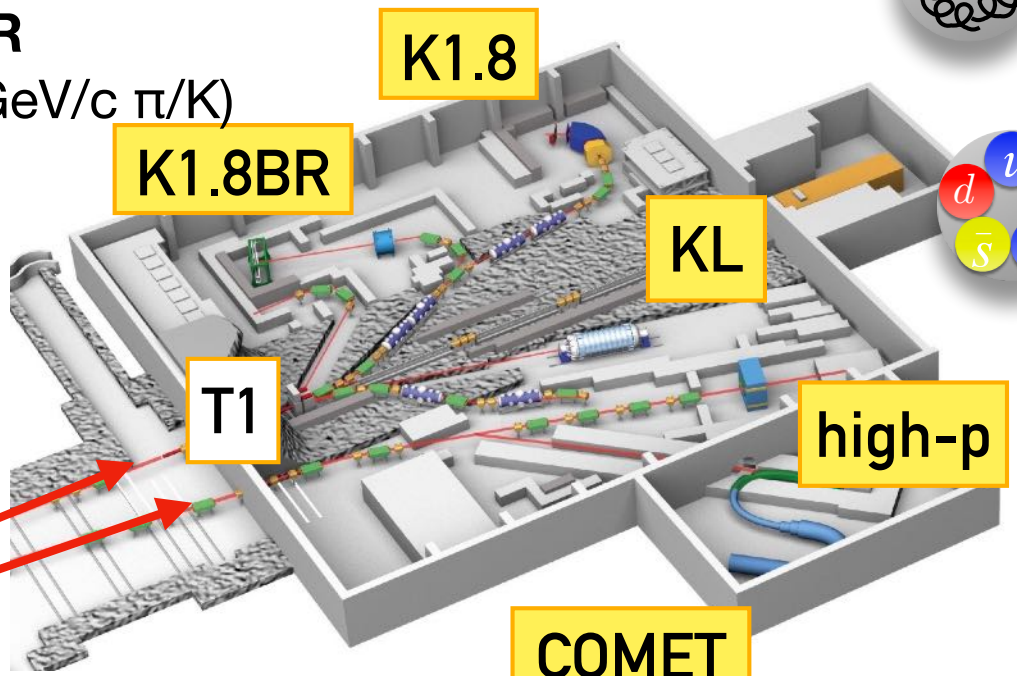


E90 ΣN cusp study in $d(K^-,\pi^-)\Lambda p$ reaction

E104 $\bar{p}p \to \phi\phi$ reaction

K1.8
(~1.8 GeV/c π/K)

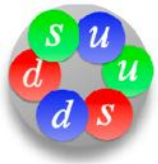
K1.8BR
(~1.0 GeV/c π/K)



LOI/ P109 Θ⁺ search in $K^+d \to K^0pp$ reaction

J-PARC HypTPC Collaboration

HypTPC Experiments at J-PARC



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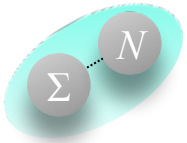

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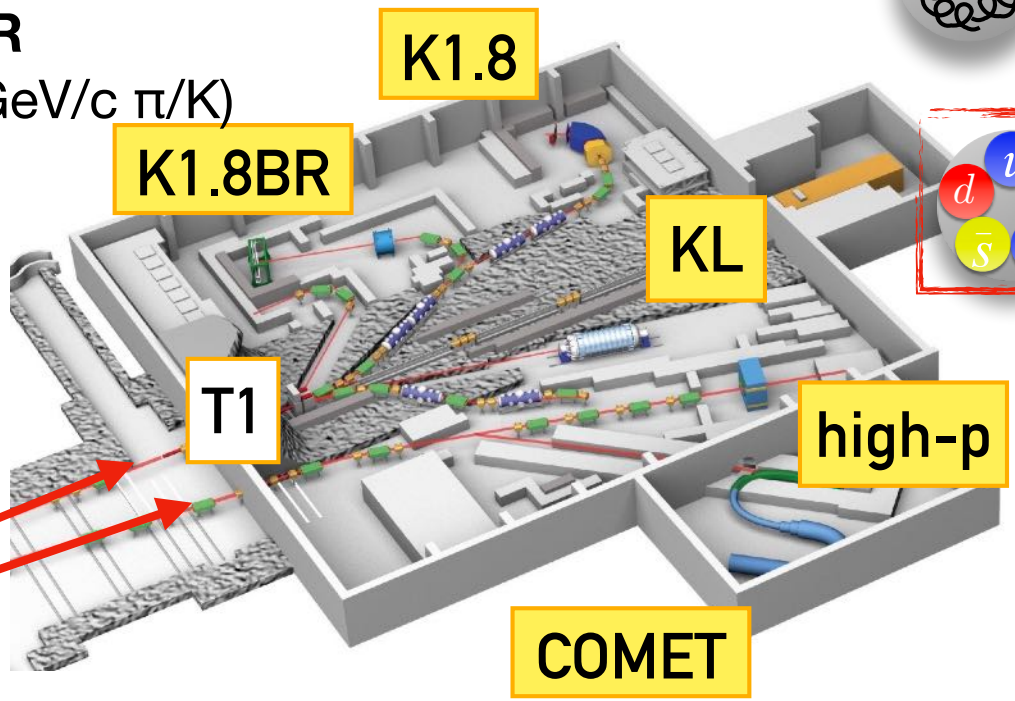
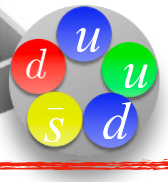




LOI/ P109 Θ⁺ search in $K^+d \to K^0pp$ reaction

J-PARC HypTPC Collaboration

Θ^+ Search History

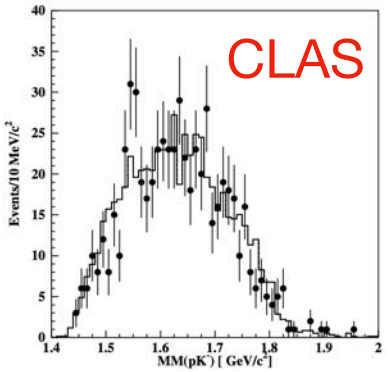
Photoproduction

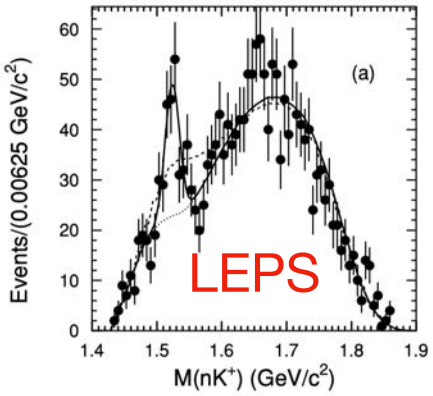
$\gamma d \rightarrow K^+ n K^- p$

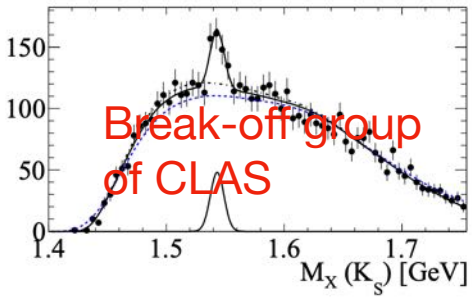
$\gamma p \rightarrow K^0_S K^+ n$

$\gamma p \rightarrow K^0_S K^0_L p$

$\gamma d \rightarrow K^0 p K^- p$



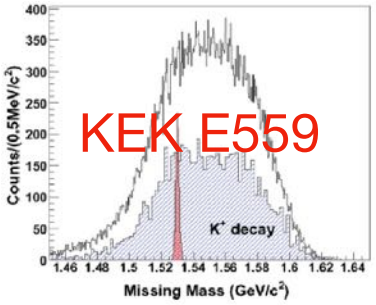


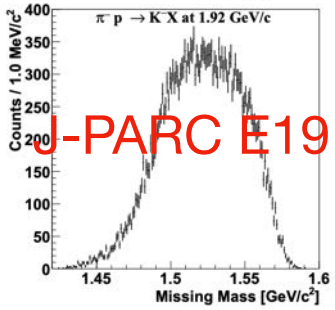


Hadronic production

$K^+ p \rightarrow \Theta^+ \pi^+$

$\pi^- p \rightarrow \Theta^+ K^-$





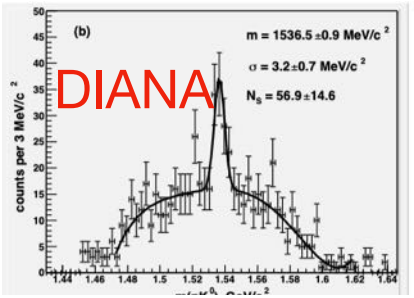
Direct formation on nuclei

$K^+ n(\text{in nuclei}) \rightarrow \Theta^+ \rightarrow K^0 p$

huge background

K^- angle acceptance

VS.



with a kinematic cut

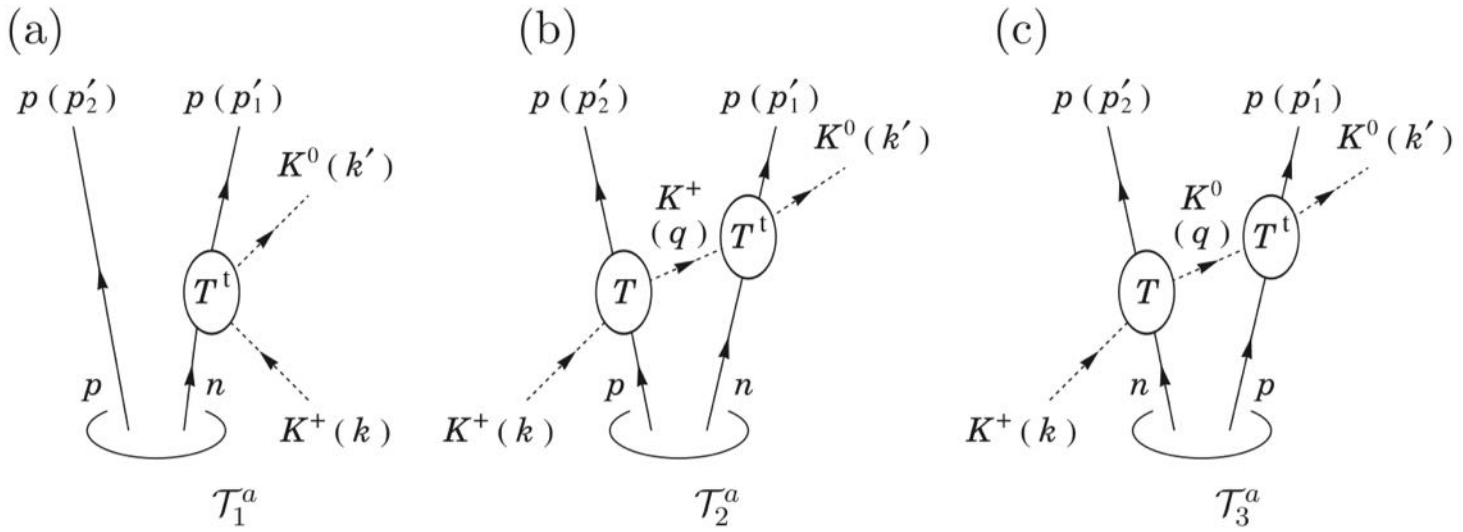
- A final attempt should be made for a definitive exclusion.

$K^+d \to K^0pp$ for the Θ^+ Production

Feasibility study of the $K^+d \to K^0pp$ reaction for the Θ^+ pentaquark

Prog. Theor. Exp. Phys., 2020, 063D03 (2020).

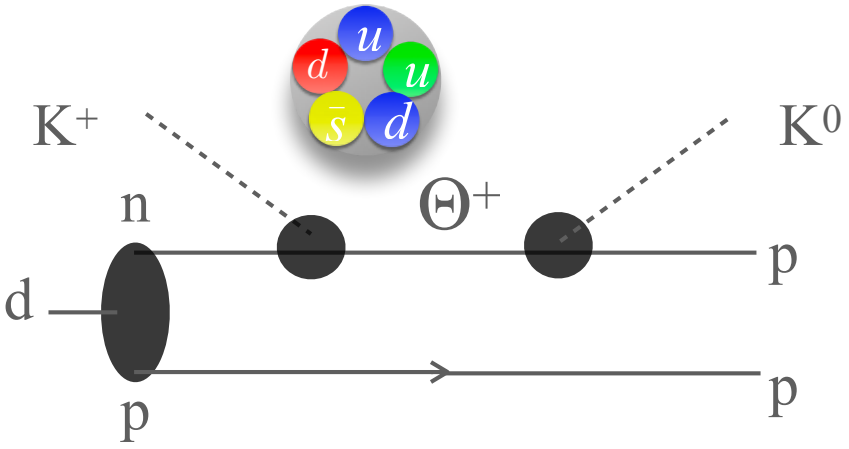
Takayasu Sekihara[1,2,3,*], Hyun-Chul Kim[1,4,5], and Atsushi Hosaka[1,2]

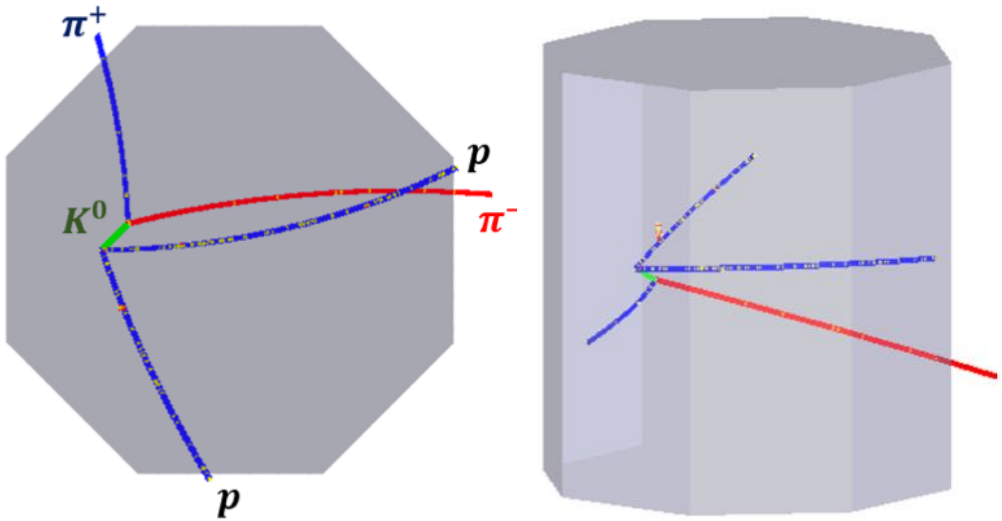


- They predicts that the $\Theta(1524)^+$ (Γ=0.5 MeV, $J^P=1/2^+$) production cross section is of the order of a few hundred μb to 1 mb at $p_{K+}\approx0.40$ GeV/c where impulse scattering process is dominant, and drops to ≤ 1 μb at $p_{K+}\approx0.85$ GeV/c at which two-step processes are dominant.

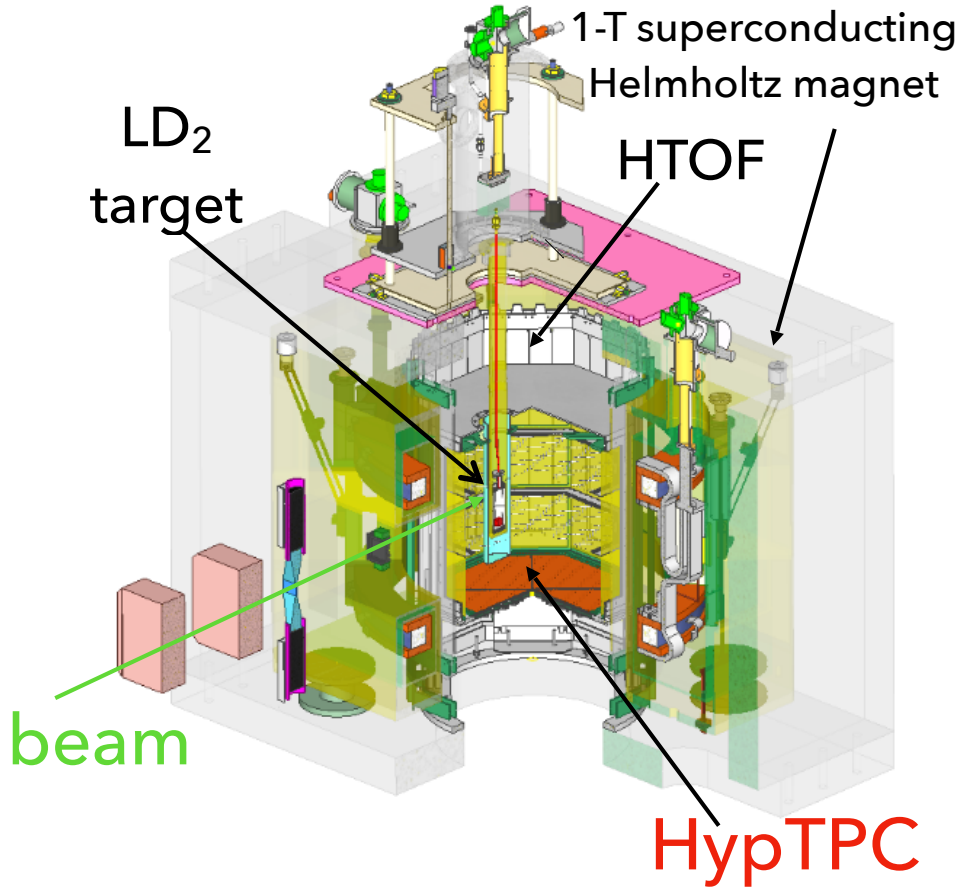
New Proposal at J-PARC

- $K^+d \rightarrow K^0pp$ ($K^0 \rightarrow \pi^-\pi^+$) at 0.5 GeV/c at K1.8BR or K1.1BR





K1.8BR/K1.1BR BL
HypTPC



- No significant background

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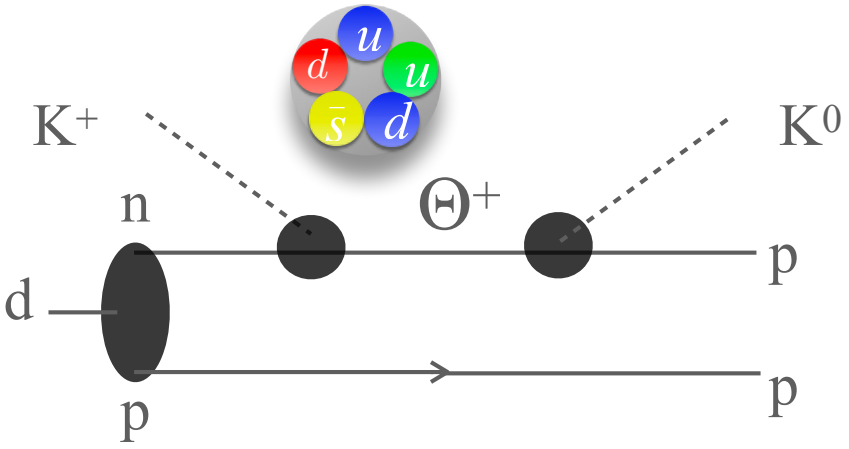
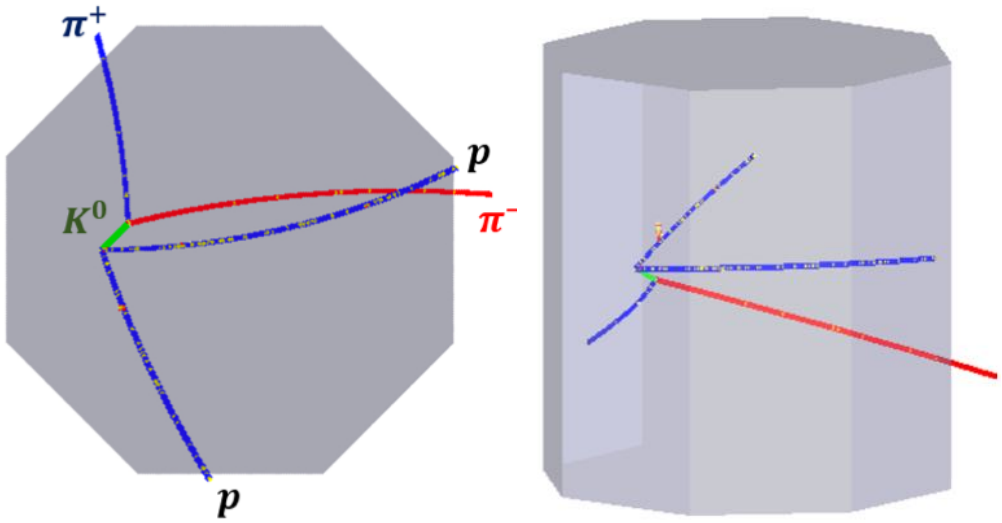
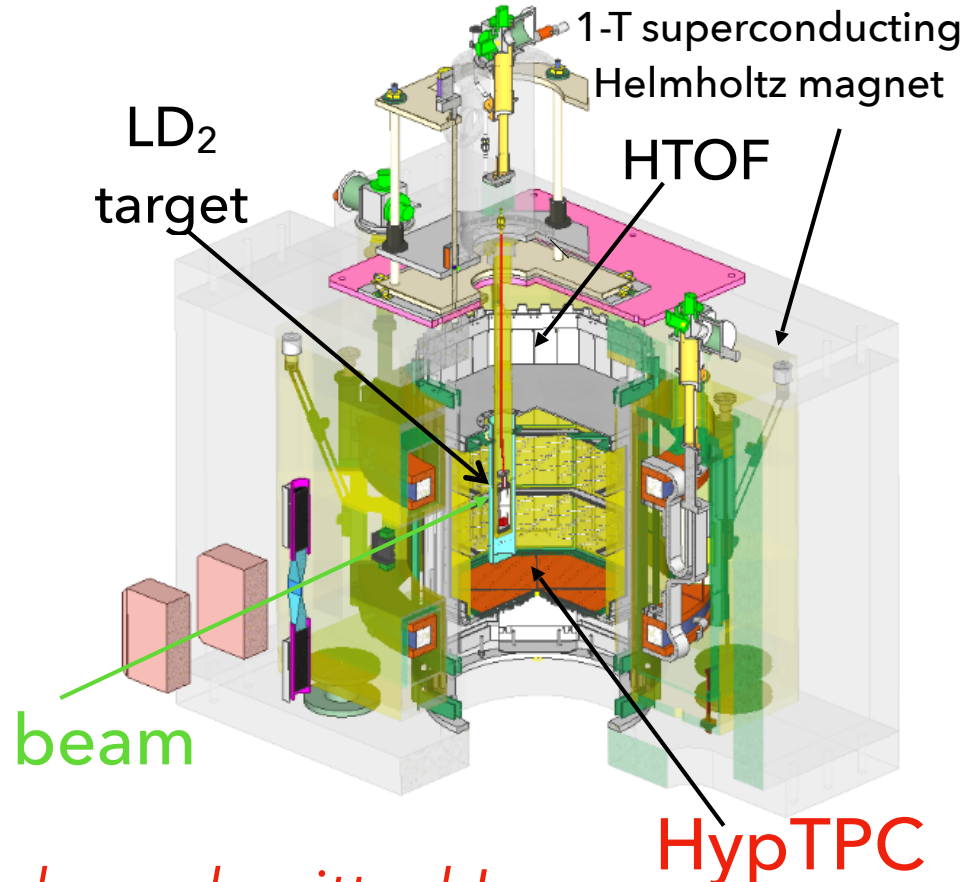




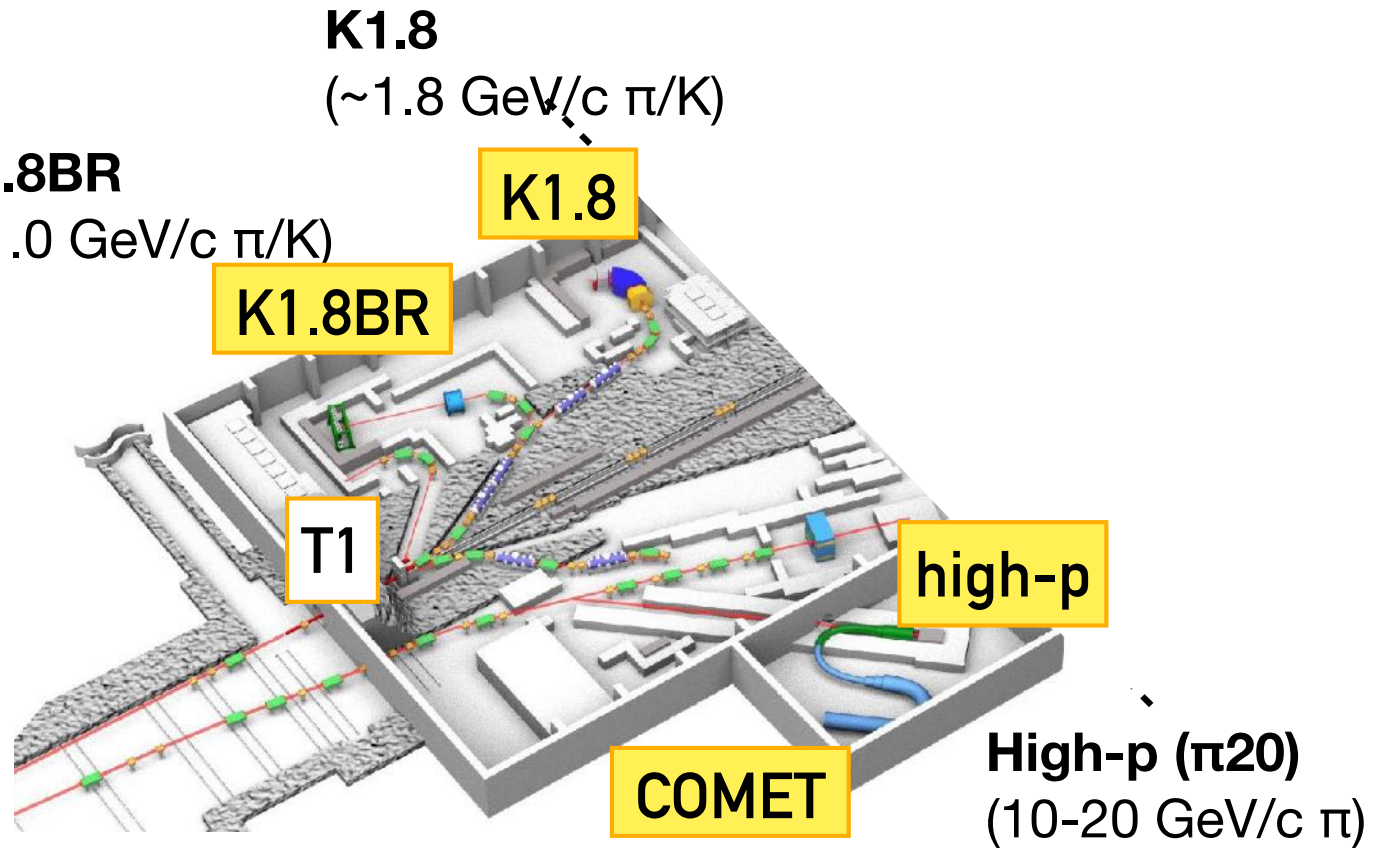
K1.8BR/K1.1BR BL
HypTPC



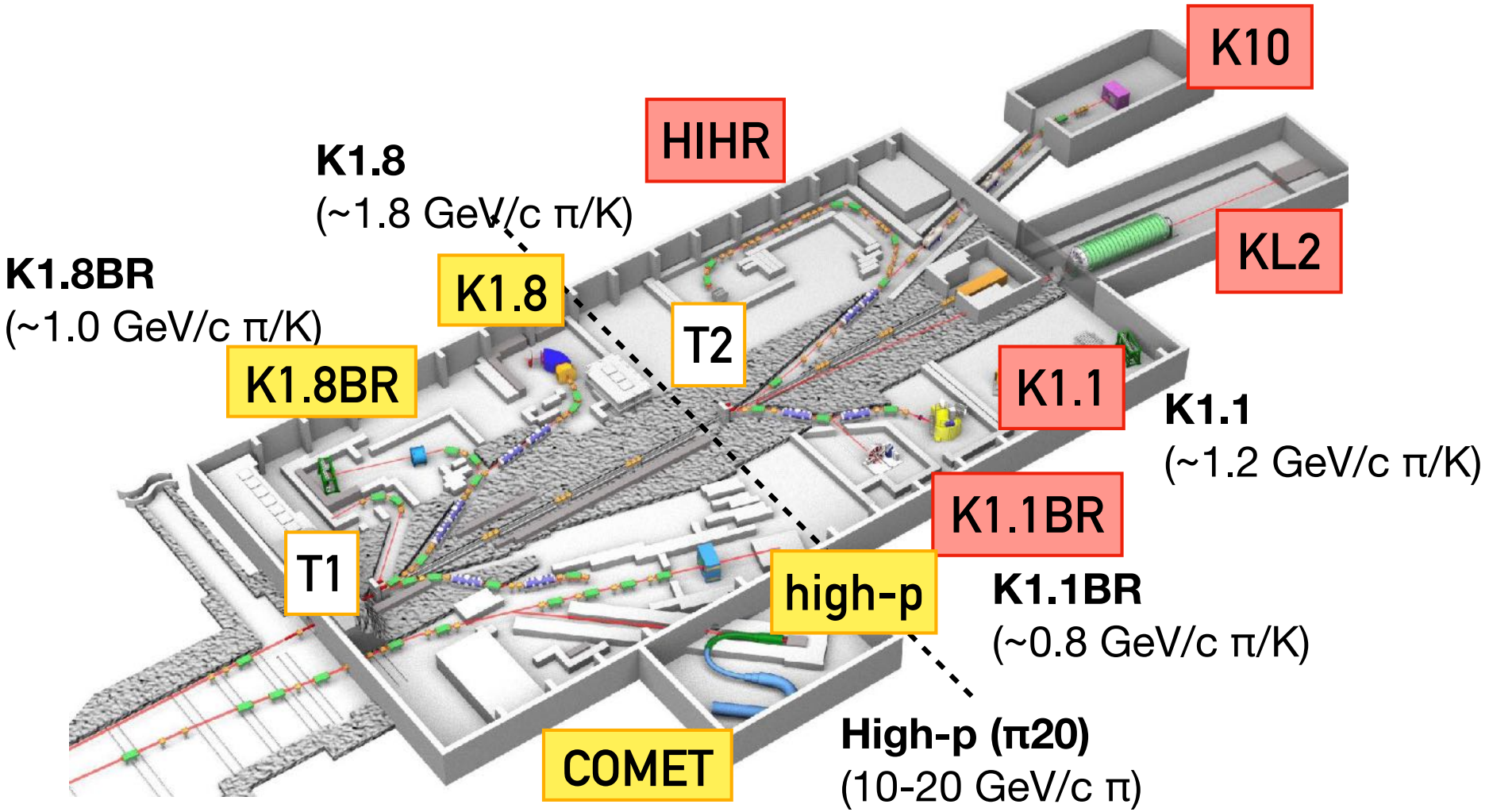
- No significant background

To be submitted !

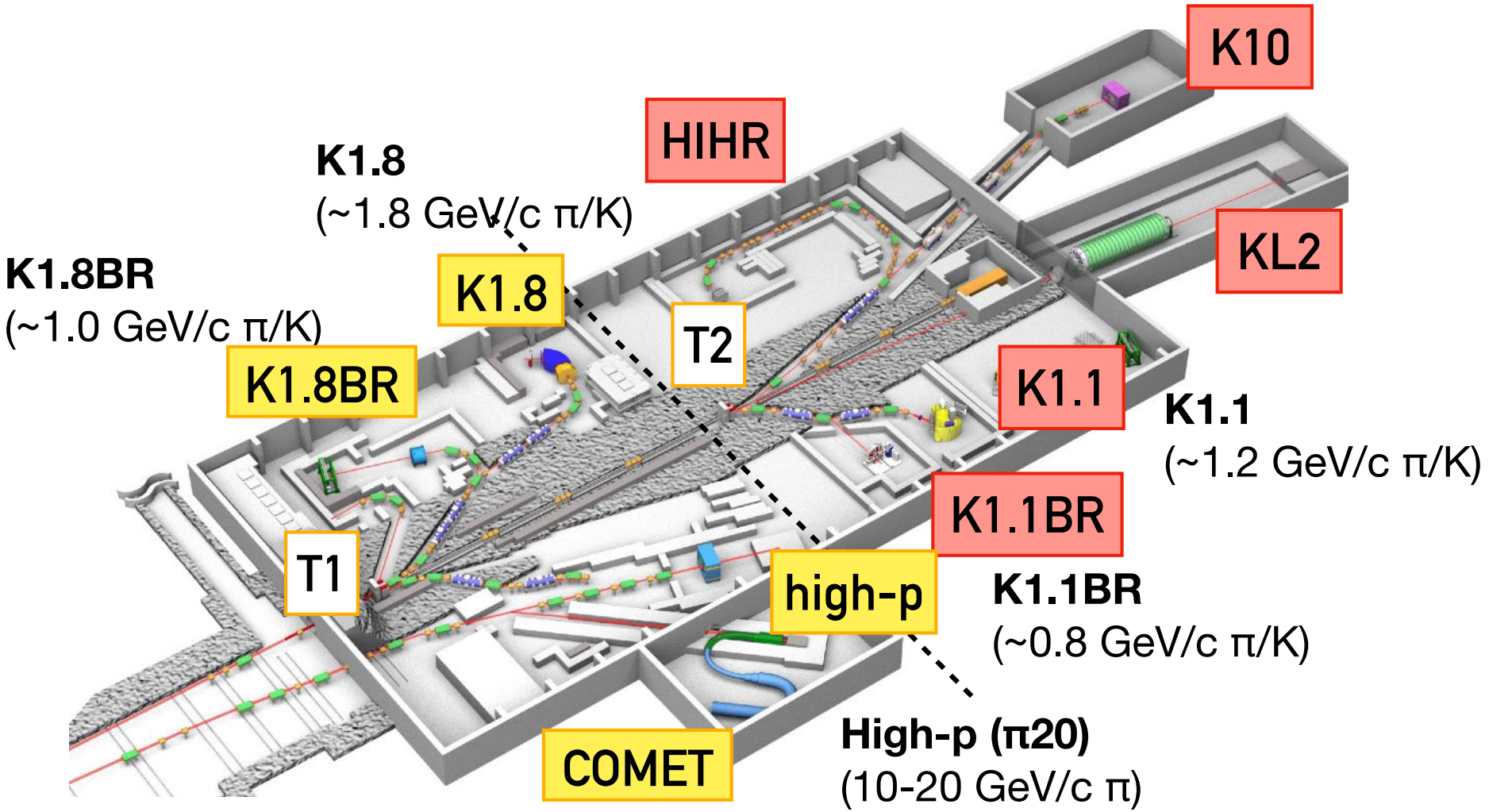
J-PARC HEF Extension Project



J-PARC HEF Extension Project



J-PARC HEF Extension Project



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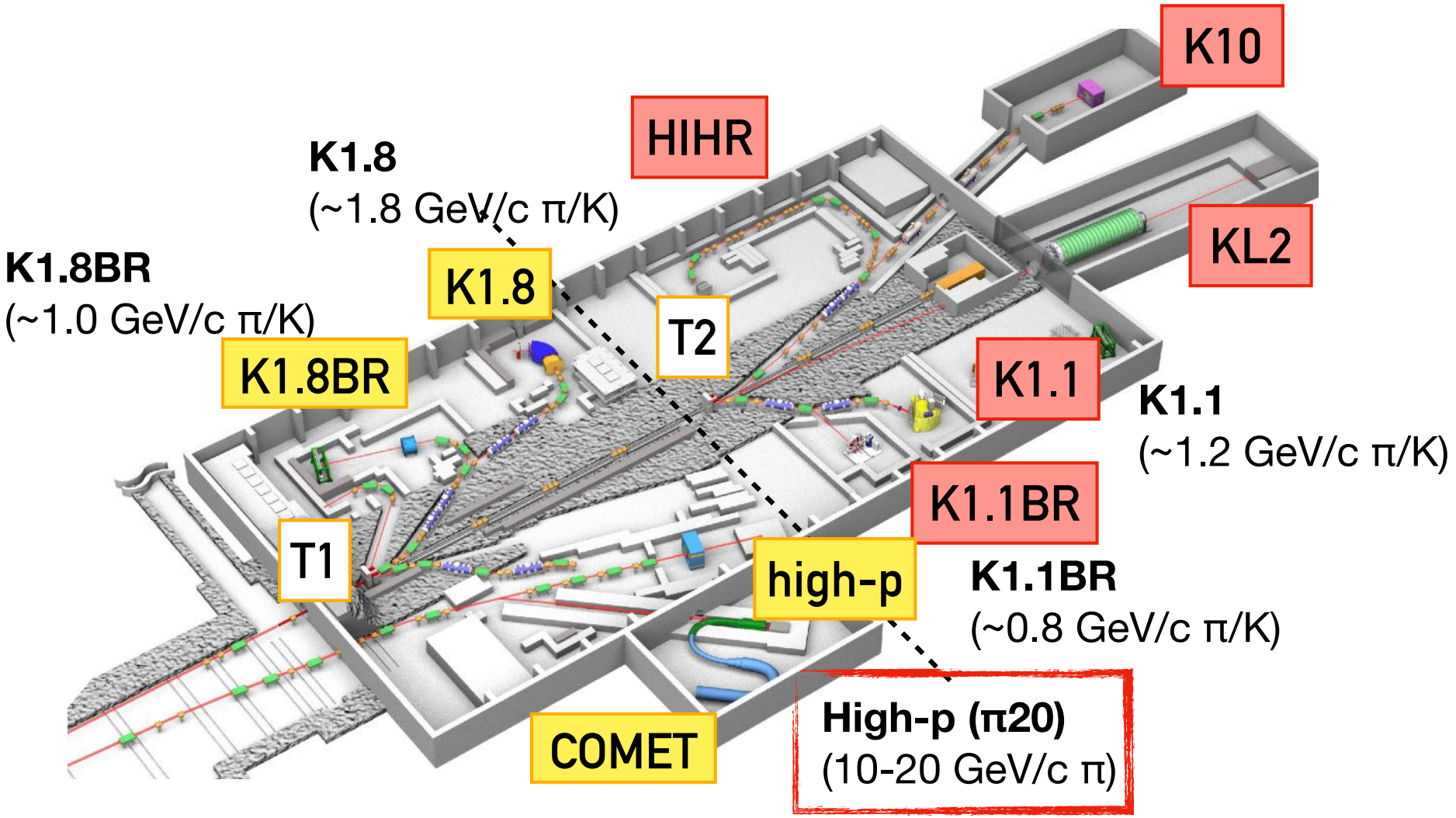

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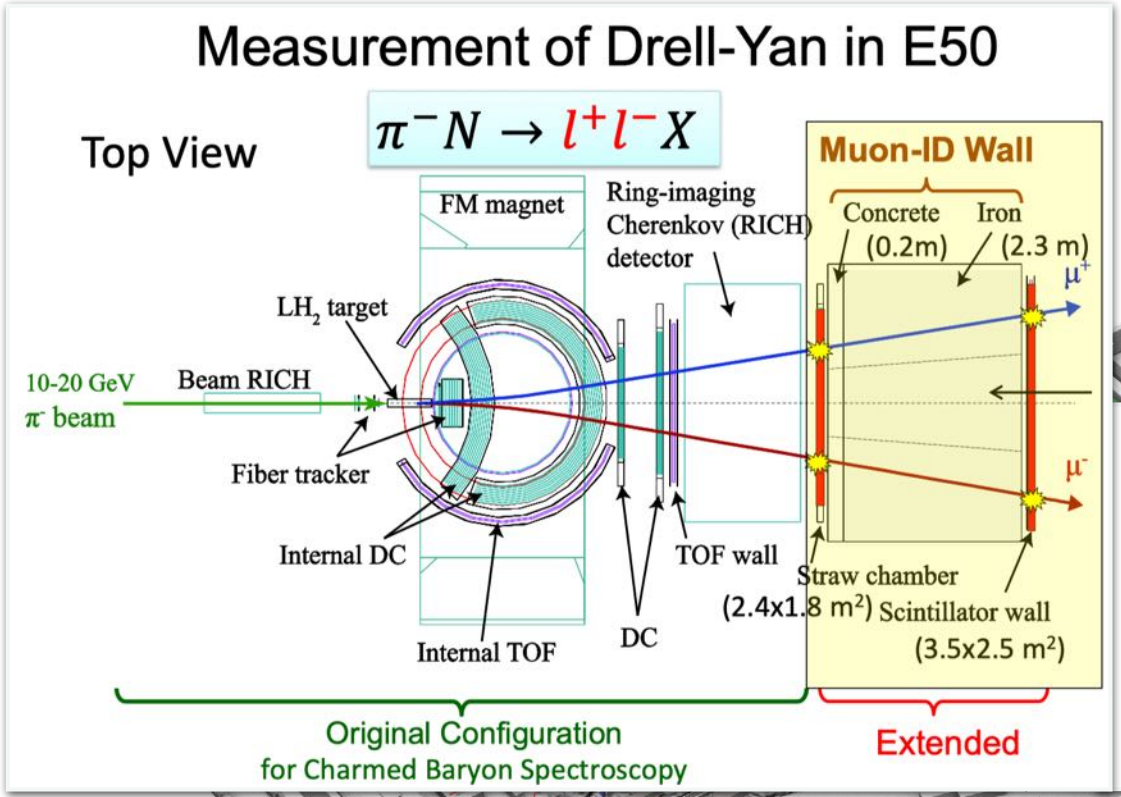
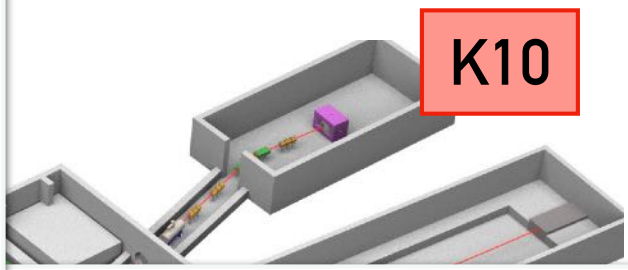
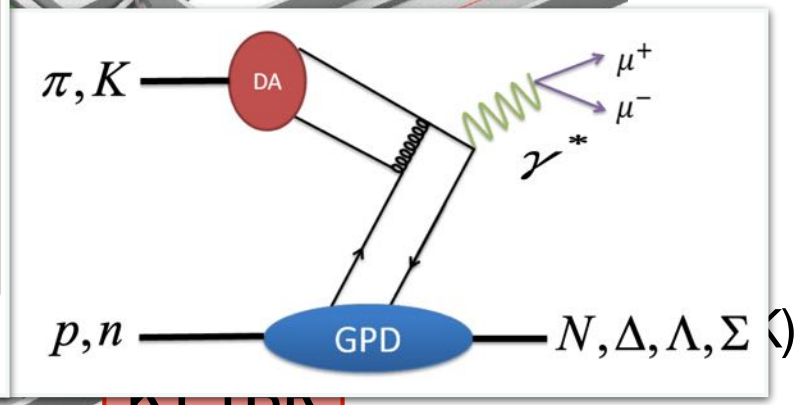
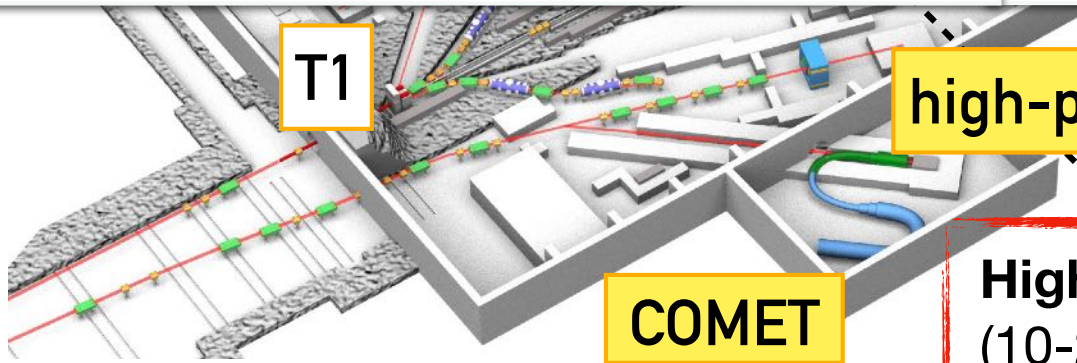


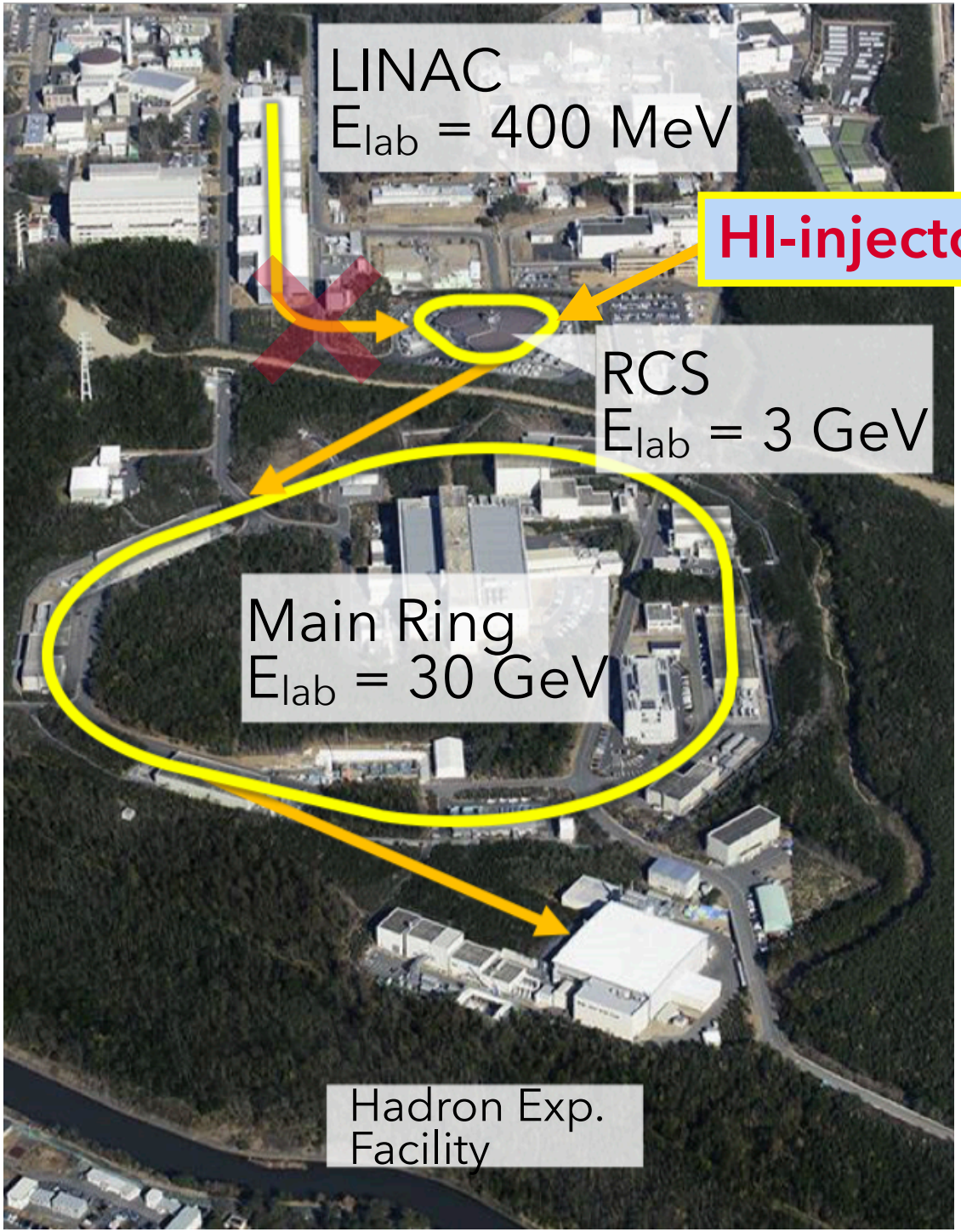






K1.1BR
(~0.8 GeV/c π/K)

High-p (π20)
(10-20 GeV/c π)



Accelerators

- ~~LINAC~~ → HI-injector
- RCS
- Main Ring (MR)

J-PARC-HI

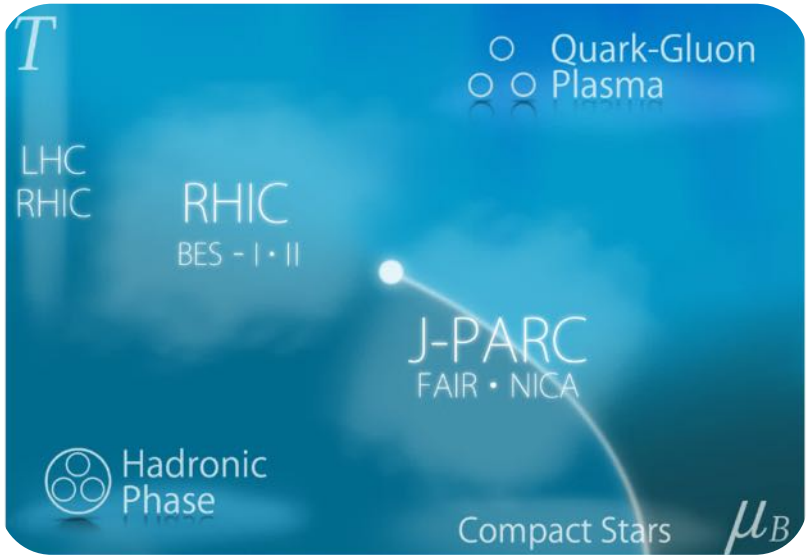
J-PARC Heavy Ion

- Heavy-ion beams with world highest luminosity
  - Max. Intensity: 10^{11} Hz
- $\sqrt{s_{NN}}$ **= 2 - 6 GeV**, or
  E_{lab} = 1 - 20 AGeV

Experimental facilities

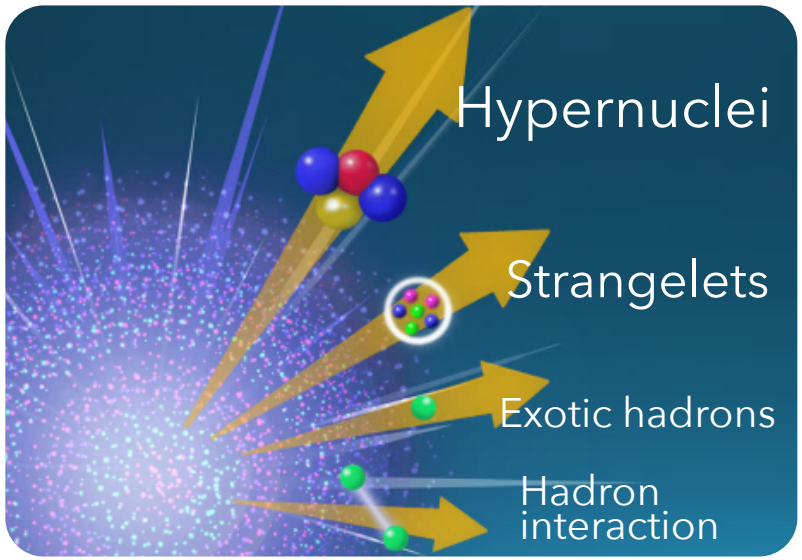
- Hadron hall

J-PARC-HI: Physics Goals



Exploring extremely dense medium
5-10 ρ_0

—QCD phase transitions & critical point
—Equation of state for neutron stars



Search for rare hadronic/
hypernuclear events

—Hadron interaction/structure
—Hypernuclear physics

Summary

➔ A wide range of hadron-physics experiments are being carried out at the J-PARC Hadron Experimental Facility.

➔ Korean groups are actively contributing through the HypTPC collaboration, and we will continue to expand physics opportunities and broaden our contributions.