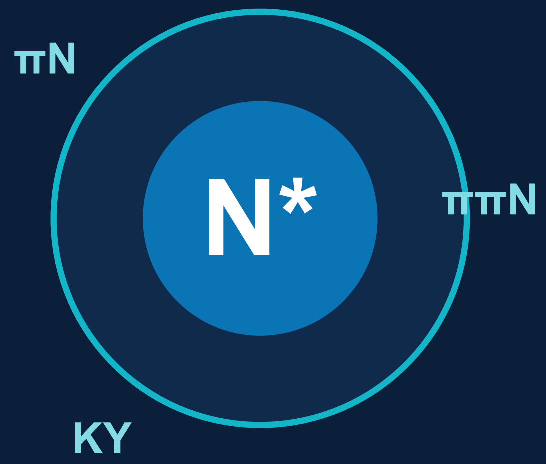
INTERNATIONAL WORKSHOP ON ORIGIN OF MASS AND MATTER IN THE UNIVERSE

APCTP • 24 July 2026

What Excited Nucleons Tell Us About QCD



Pion-beam reactions at J-PARC E45

Shin Hyung Kim • Kyungpook National University
for the J-PARC E45 Collaboration

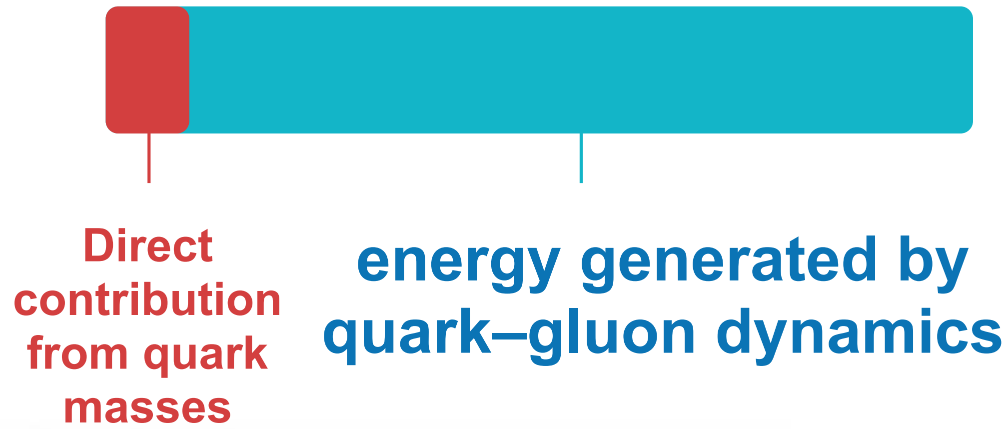
Most of the proton mass comes from QCD dynamics

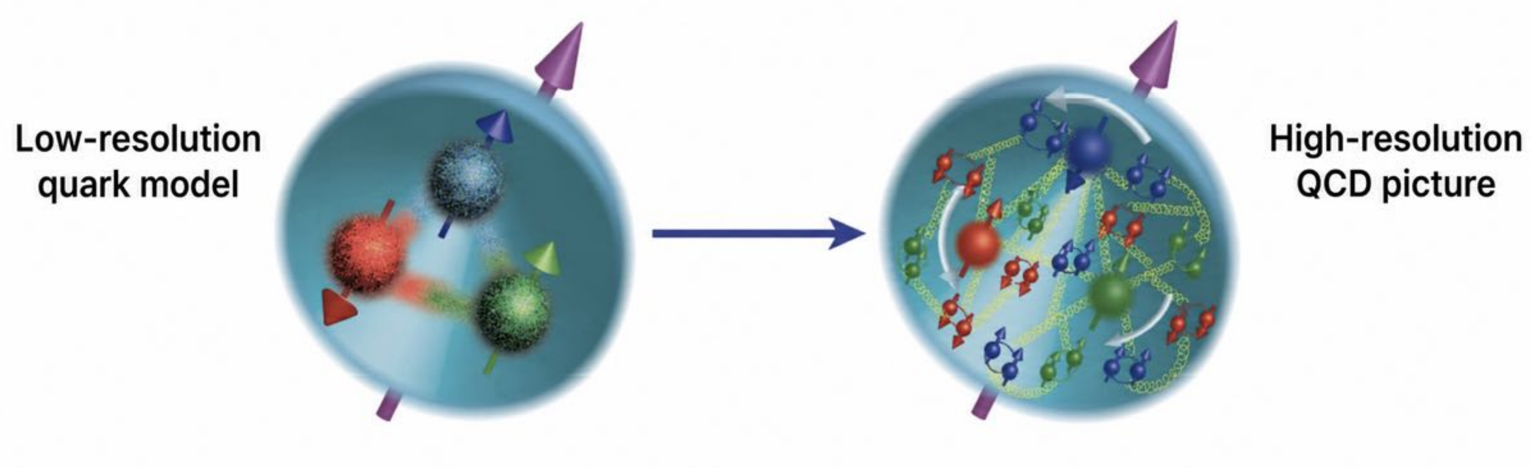
The up and down quark
masses account for only about

1%

**of the proton's total mass
of 938 MeV.**

A simple picture





**Most of the proton mass comes from the
strong interaction. → "QCD"**

Nucleon spectroscopy provides a window into QCD

QCD theory → **Interacting quarks and gluons** → **Nucleon excitation spectrum:** Masses, widths, decay modes, and coupling strengths

Excited states are very sensitive to how quarks and gluons interact.

Just as the hydrogen excitation spectrum revealed QM, the nucleon excitation spectrum reveals the dynamics of QCD.

By measuring the properties of excited nucleons and comparing them with theoretical calculations, we can test how well we understand non-perturbative QCD.

The excited-nucleon spectrum is still incomplete

PDG 2025

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
***
* **

Some predicted states have not yet been seen clearly.

- Broad, overlapping states cannot be found by peak counting alone.
- Most established N* states were identified mainly through

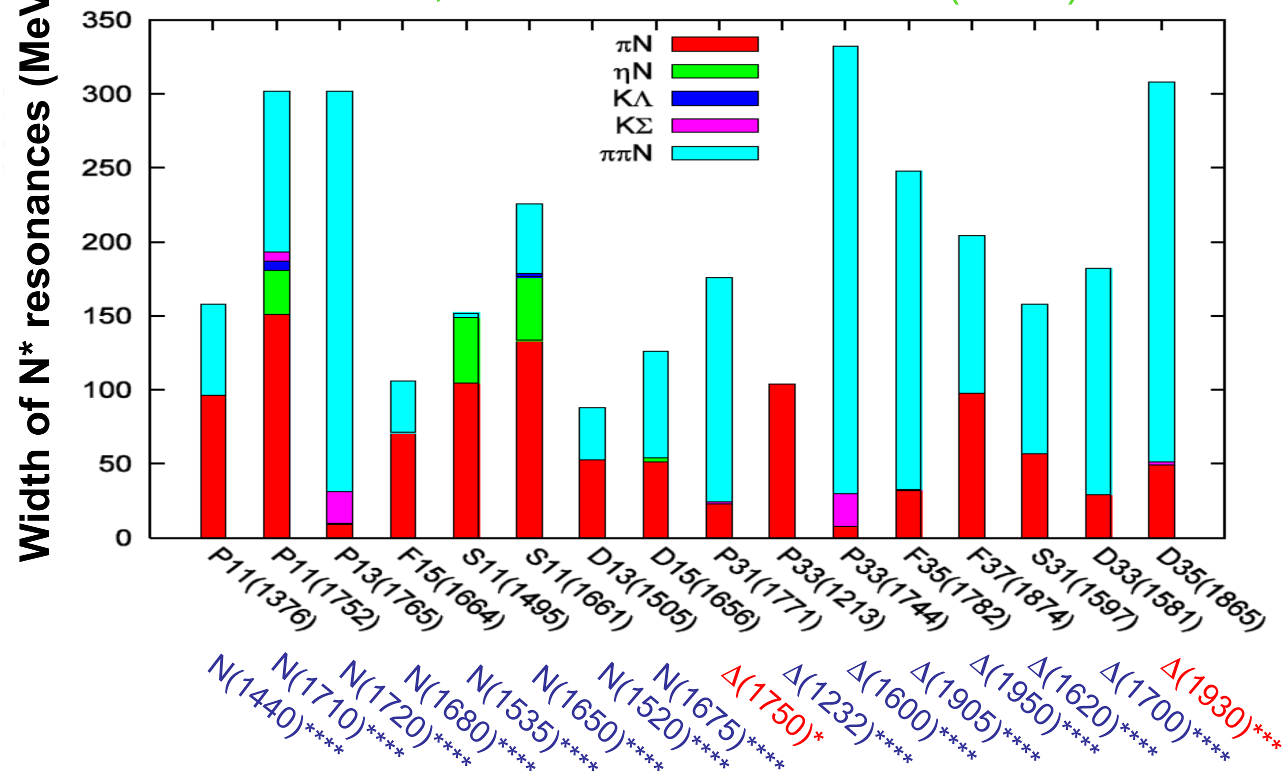
$$\pi N \to \pi N,\ \gamma N \to \pi N,\ \gamma N \to \pi\pi N$$

- $\pi N \to \pi\pi N$ data are necessary to resolve remaining resonances

Why $\pi\pi N$ decays are important

- Dynamical coupled-channel calculations predict that many N* and Δ* resonances have large ππN (πΔ, ρN, σN) decay fractions.

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



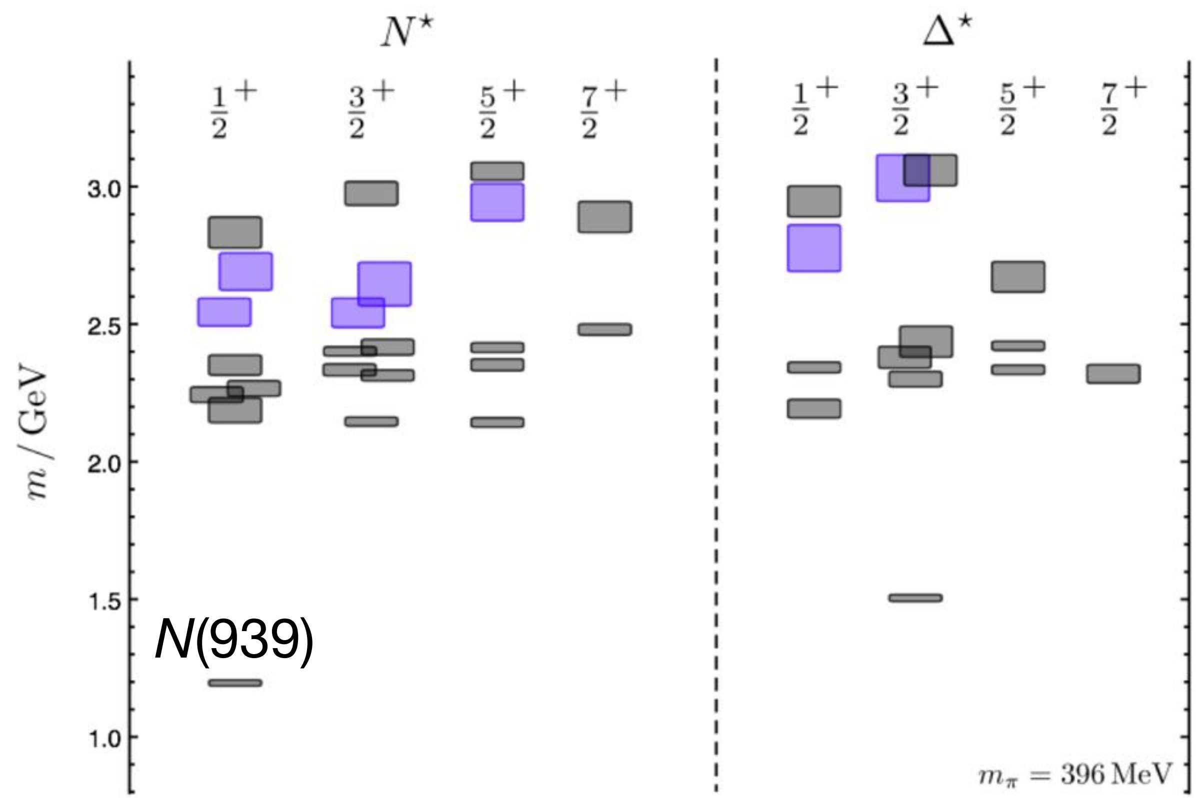
Intermediate states

πΔ **ρN** **σN**

- All three processes lead to the same final particles, but they have different invariant-mass and angular distributions.
- They also interfere with one another.

Two resonances with similar masses may have very different couplings to πΔ, ρN, σN. ➔ How a resonance decays helps us identify it.

Lattice QCD calculation



PRD85 054016 (2012)

: conventional qqq states

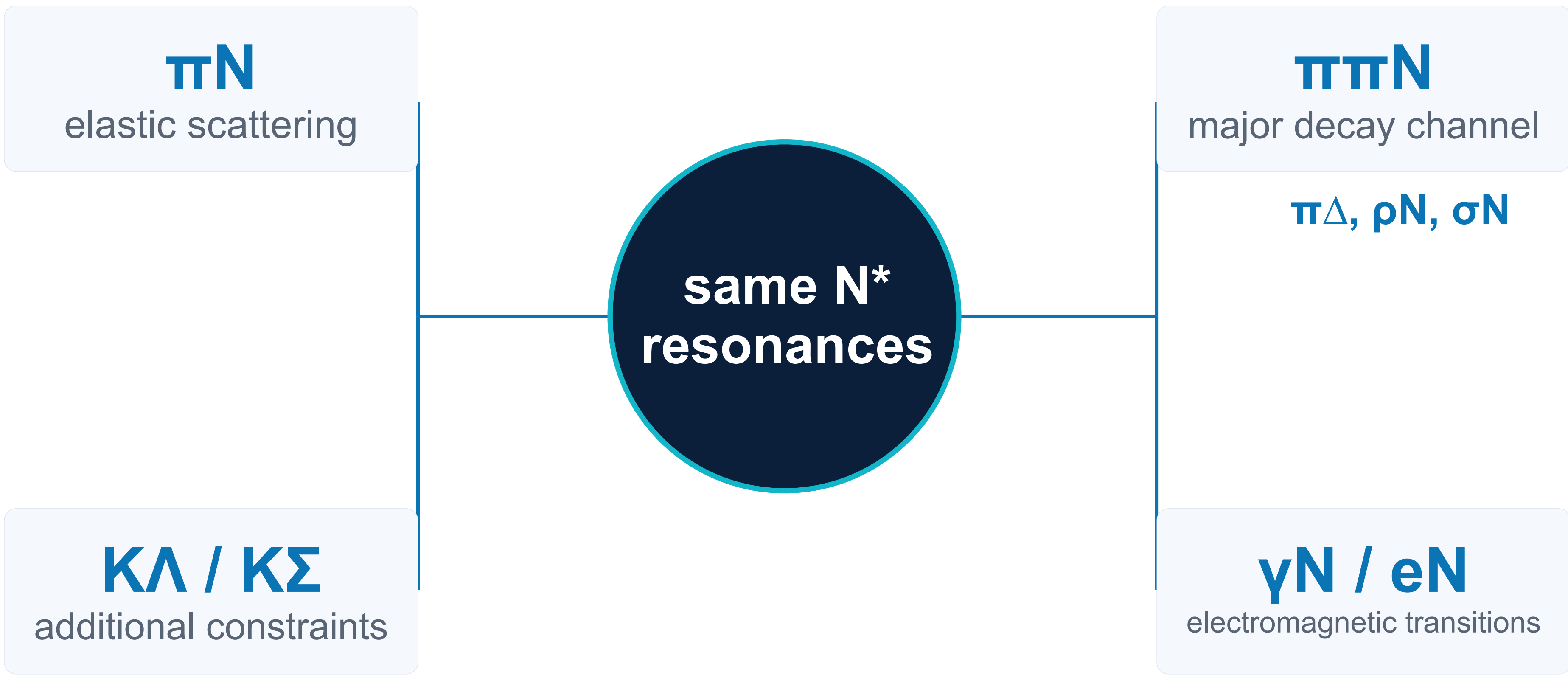
: "hybrid" baryons (qqqg)

- Lattice QCD calculation predicts that **hybrid baryons** should exist.
- Preliminary indications from photoproduction data at CLAS suggest an extra resonance, in addition to the known quark-model resonances in $\gamma p \rightarrow \pi^+\pi^- p$ reaction. ➔ Complementary hadronic data are necessary.

PLB805 135457 (2020)

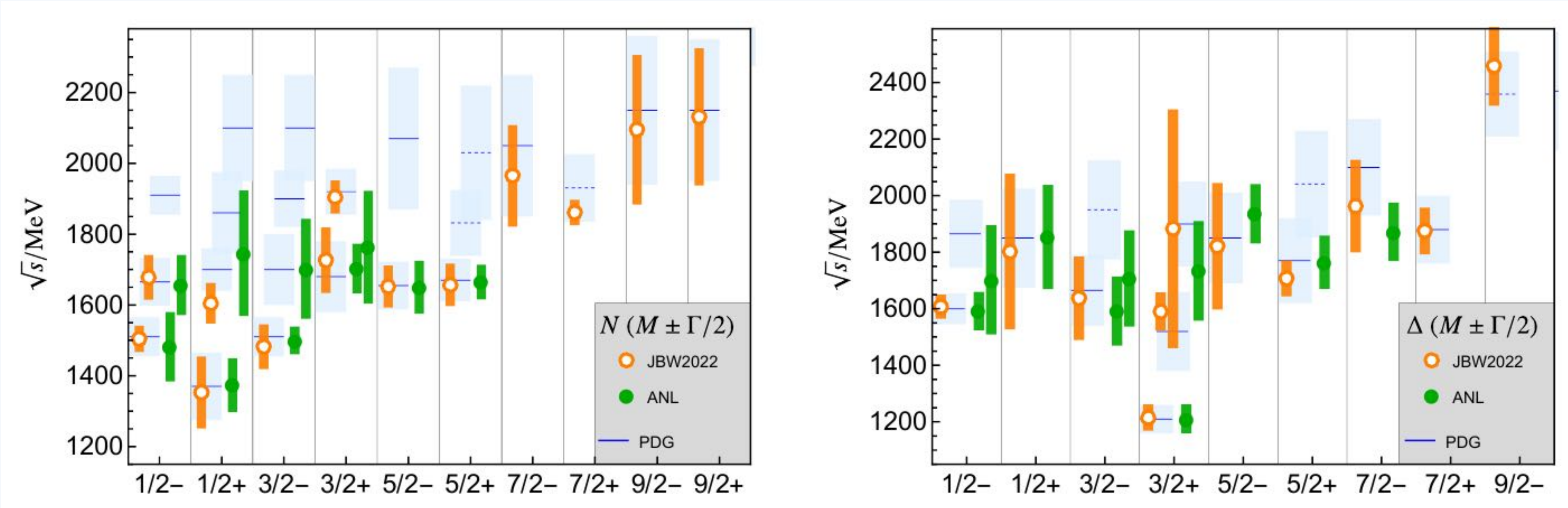
No single reaction is enough

The same N* resonance can appear in several different reactions.



- **The same pole must appear consistently in all connected reactions, although its strength can be very different in each channel.**
- **A coupled-channel analysis is essential to extract one consistent N* spectrum from all connected reactions.**

Different analyses still find different higher resonances



Döring et al., arXiv:2505.02745 (2025), Fig. 29.

*For ANL–Osaka, only resonances with M<2 GeV and Γ<400 MeV are shown.

- Different analyses agree on well-established low-mass resonances, such as Δ(1232) 3/2+, but give different results for higher-mass resonances.
- Results for broad, overlapping, and weakly coupled states depend strongly on the included reactions and data, and on how the amplitudes and backgrounds are modeled.

More precise data from multiple reaction channels are needed to better constrain the resonance spectrum.

Importance of pion-reaction data

Pion-beam reactions

- Directly probe strong-interaction scattering
- Fewer amplitudes to determine
- Very sensitive to inelastic decay channels

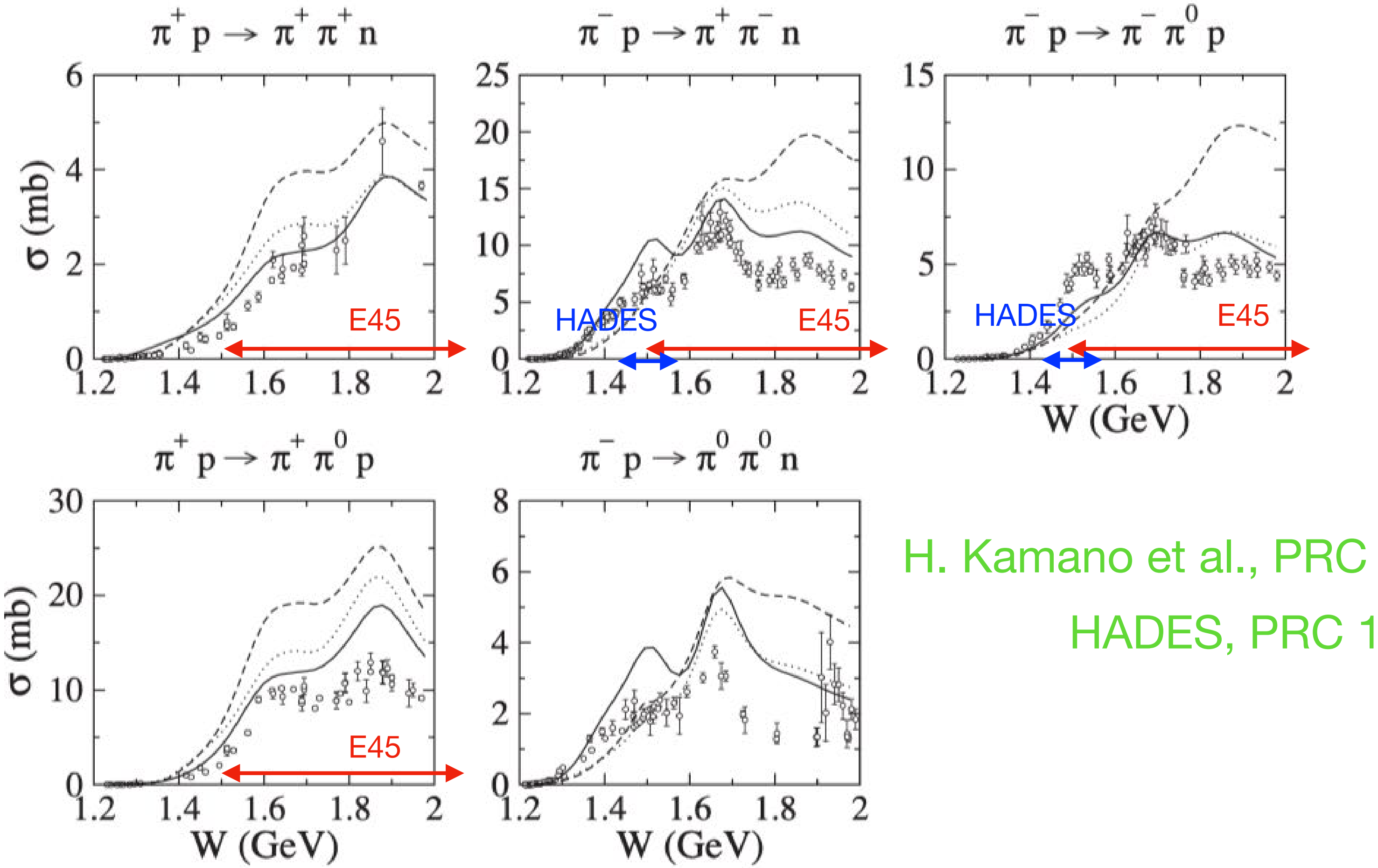
Photon and electron reactions

- Provide polarization information
- Measure electromagnetic transition strengths
- Still depend on final-state strong interactions

Pion beams directly probe hadronic interactions. Even photon- and electron-induced reactions need pion-beam data to describe final-state rescattering.

J-PARC E45: N* baryon spectroscopy

- *N** spectroscopy with the $\pi p \rightarrow \pi\pi N$ reactions in the wide energy range of 1.5 - 2.15 GeV (p=0.73 - 2.0 GeV/c) using high intensity beam at J-PARC.
- Updates on the world database ($\pi p \rightarrow \pi\pi N$)
  - 240k events measured in 1970's → ×100 higher statistics



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

HADES, PRC 102, 024001 (2020)

J-PARC E45 Experiment

J-PARC E45 Collaboration *co-spokespersons

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C. Djalali	(Ohio Univ.)
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S. Nakamura, M. Niiyama	(Kyoto Univ.)
H. Fujioka	(Tokyo Inst. Tech.)
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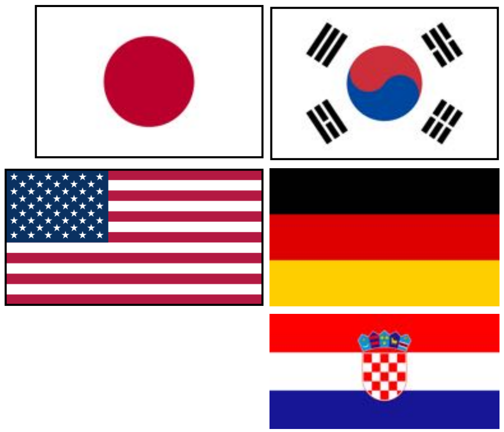
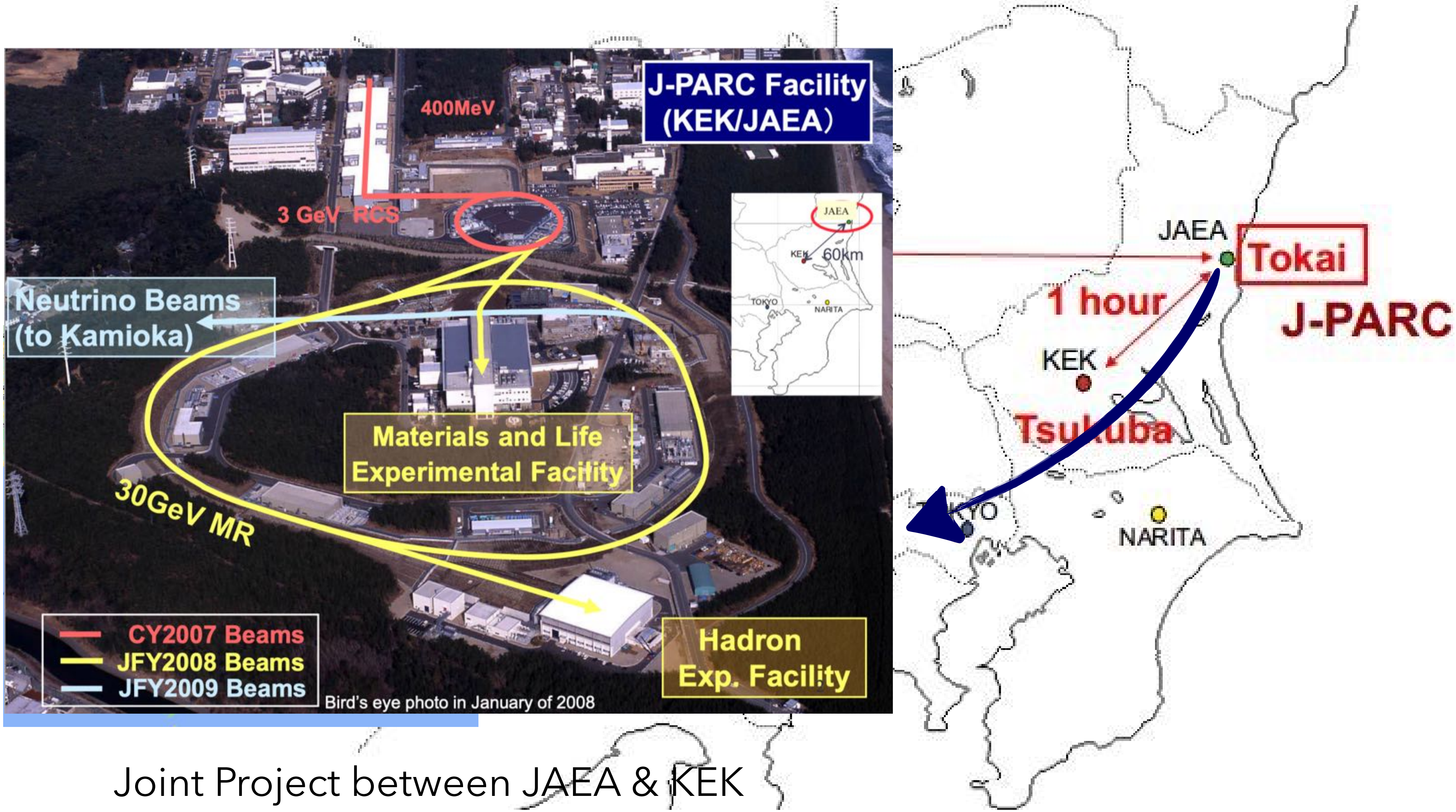
K. Nakazawa, H. Ekawa	(RIKEN)
S. H. Hwang	(KRISS)
Y. Ichikawa, S. Hayakawa, J. Yoshida	(Tohoku Univ.)
W. J. Briscoe, M. Doering, I. Strakovsky, R. Workman	(George Washington Univ.)
L. Guo	(Florida International Univ.)
T.S.-H. Lee	(Argonne National Lab.)
T. Sato, Y. Nakada	(Osaka Univ.)
K. Shirotori, S. Y. Ryu, H. Kamano	(RCNP)
V. Shklyar	(Univ. Giessen)
A. Svarc	(Ruder Boskovic Institute)
S. Ceci	(RBI-Zagreb)
M. Hadzimehmedovic, H. Osmanovic	(Univ. Tulza)



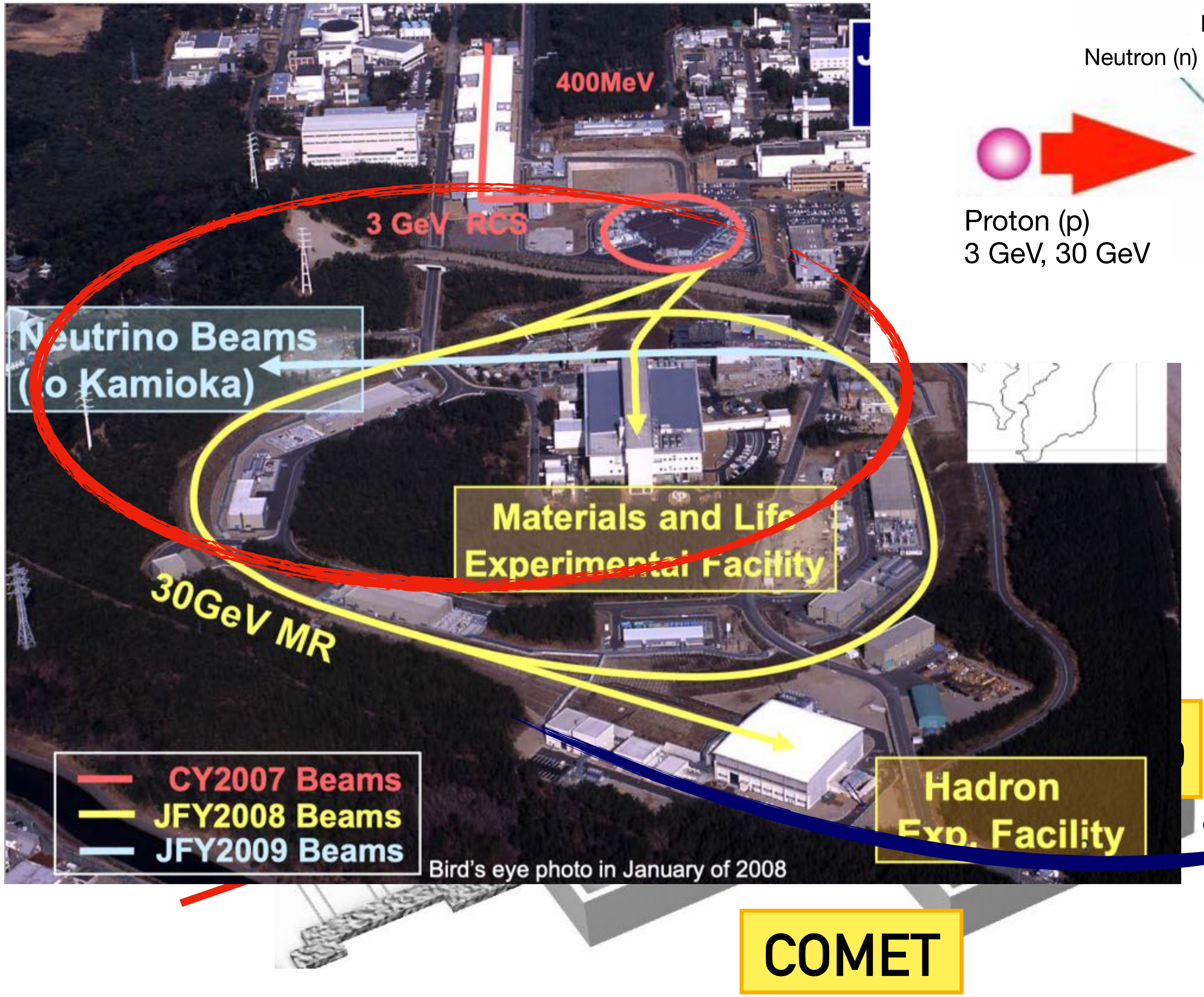
J-PARC (Japan Proton Accelerator Research Complex)

- the world's top class high-energy and high-intensity proton beam

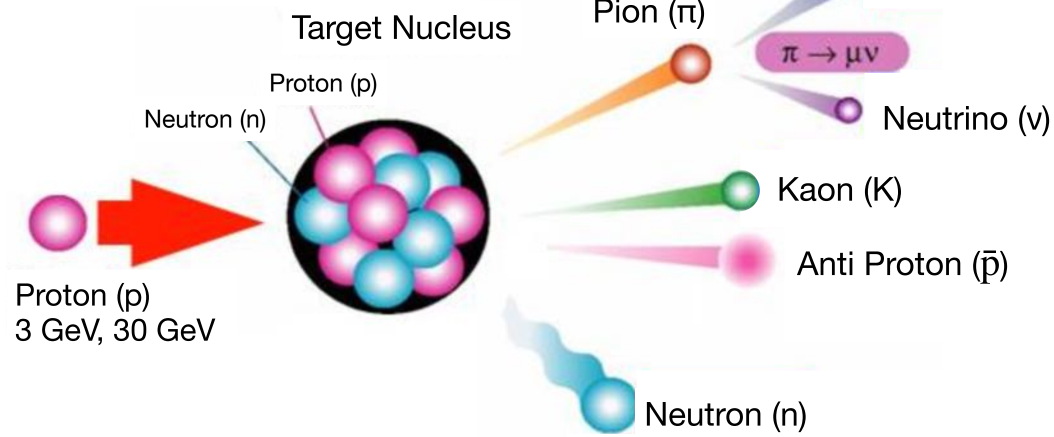


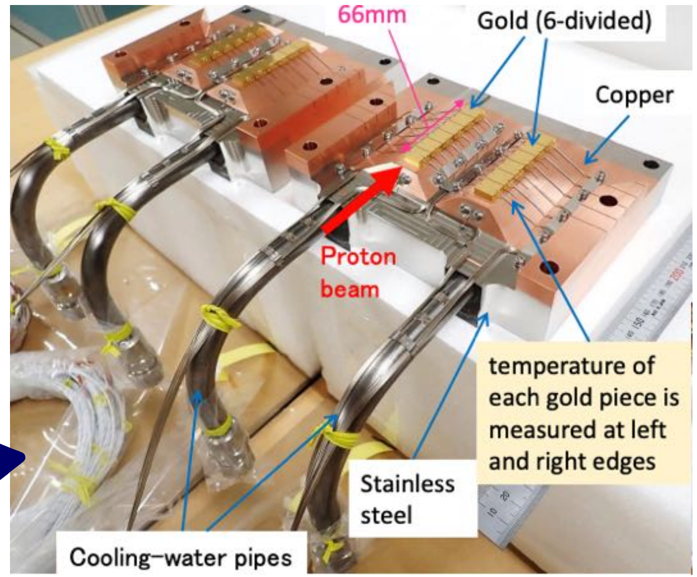
Joint Project between JAEA & KEK

J-PARC Hadron Experimental Facility



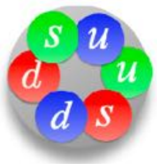
Spallation reactions





T1 Gold Target

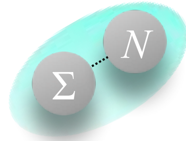
HypTPC experiments at J-PARC



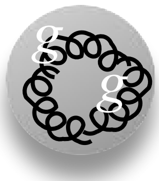
E42 *H*-dibaryon search in $^{12}C(K^-,K^+)$ reaction

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

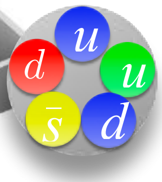
E72 New Λ* search in $p(K^-,\Lambda)\eta$ reaction



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



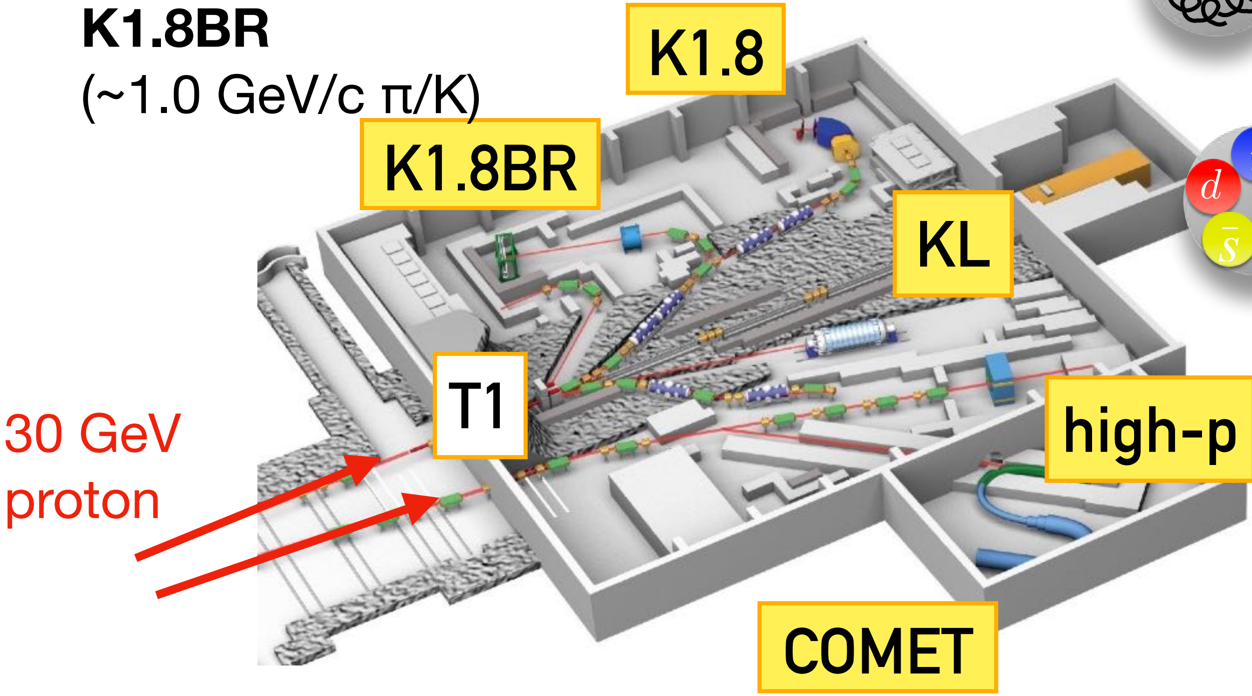
E104 $\bar{p}p \rightarrow \phi\phi$ reaction



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

K1.8
(~1.8 GeV/c π/K)

K1.8BR
(~1.0 GeV/c π/K)



J-PARC HypTPC Collaboration

J-PARC E45 experimental setup

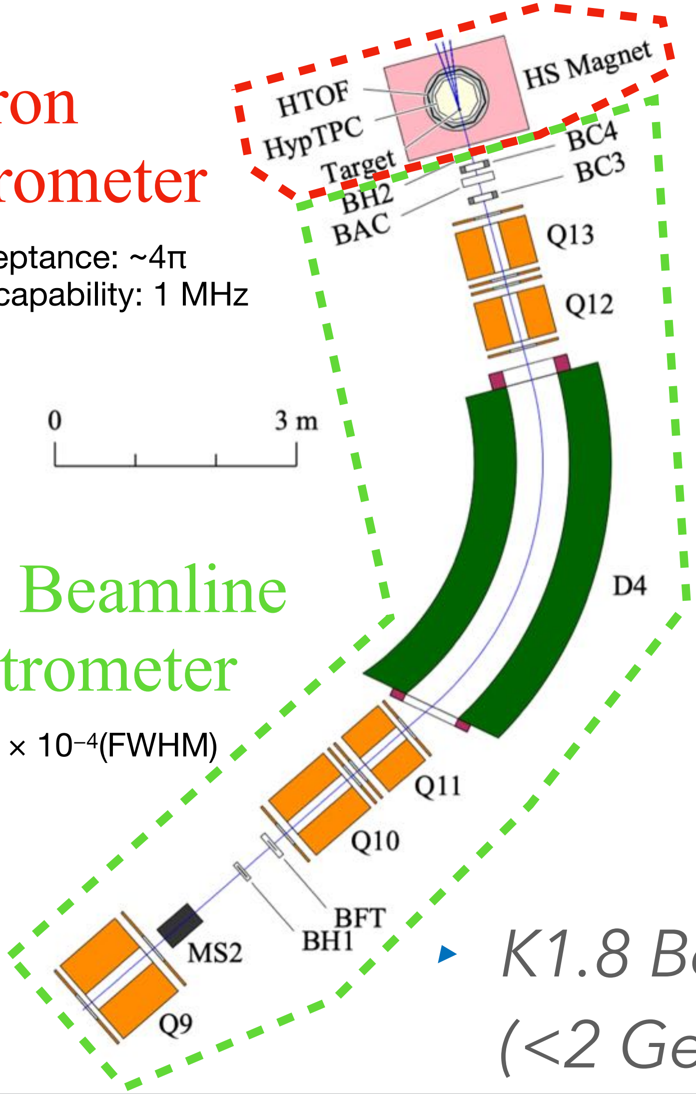
- *N** spectroscopy with the $\pi p \rightarrow \pi\pi N$ reactions in the wide energy range of 1.5 - 2.15 GeV (p=0.73 - 2.0 GeV/c) at J-PARC.

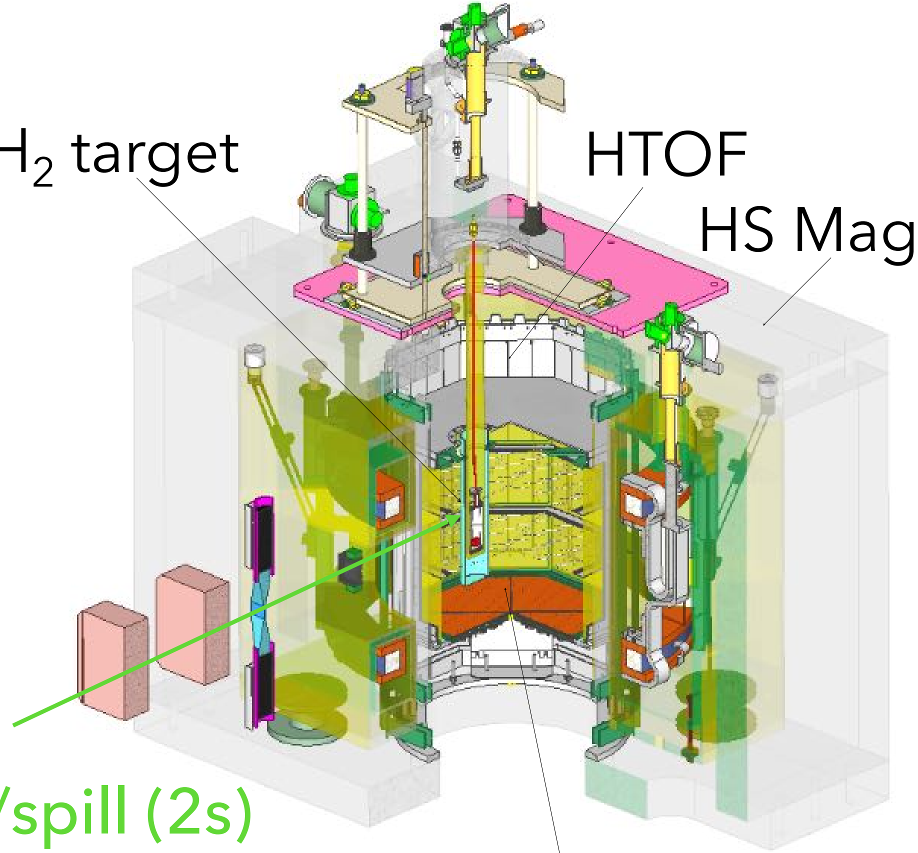
Hyperon Spectrometer

Large acceptance: ~4π
High-rate capability: 1 MHz

K1.8 Beamline Spectrometer

$\delta p/p = 3.3 \times 10^{-4}$(FWHM)

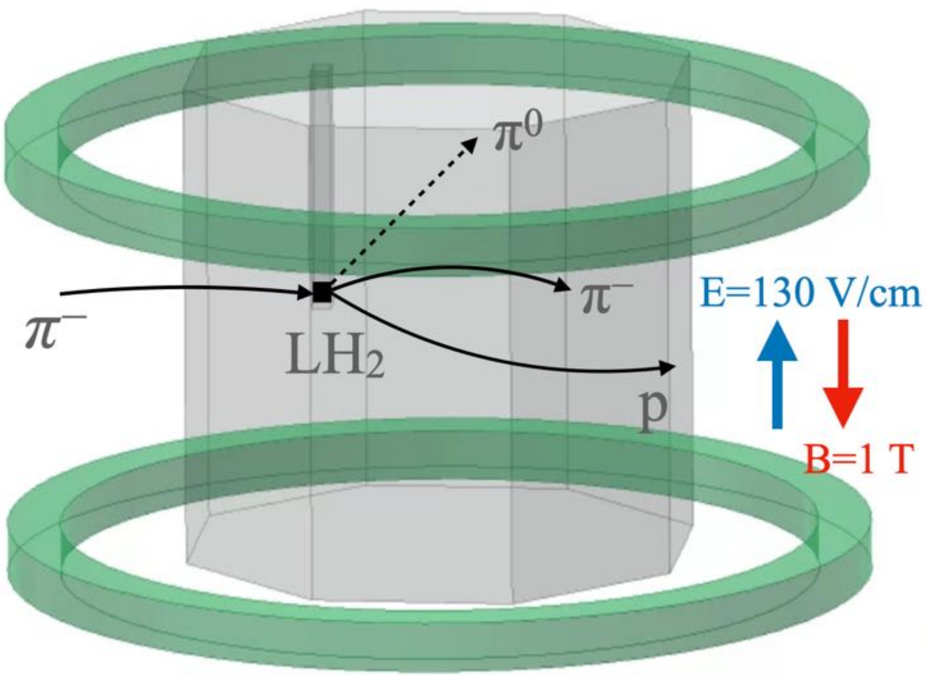


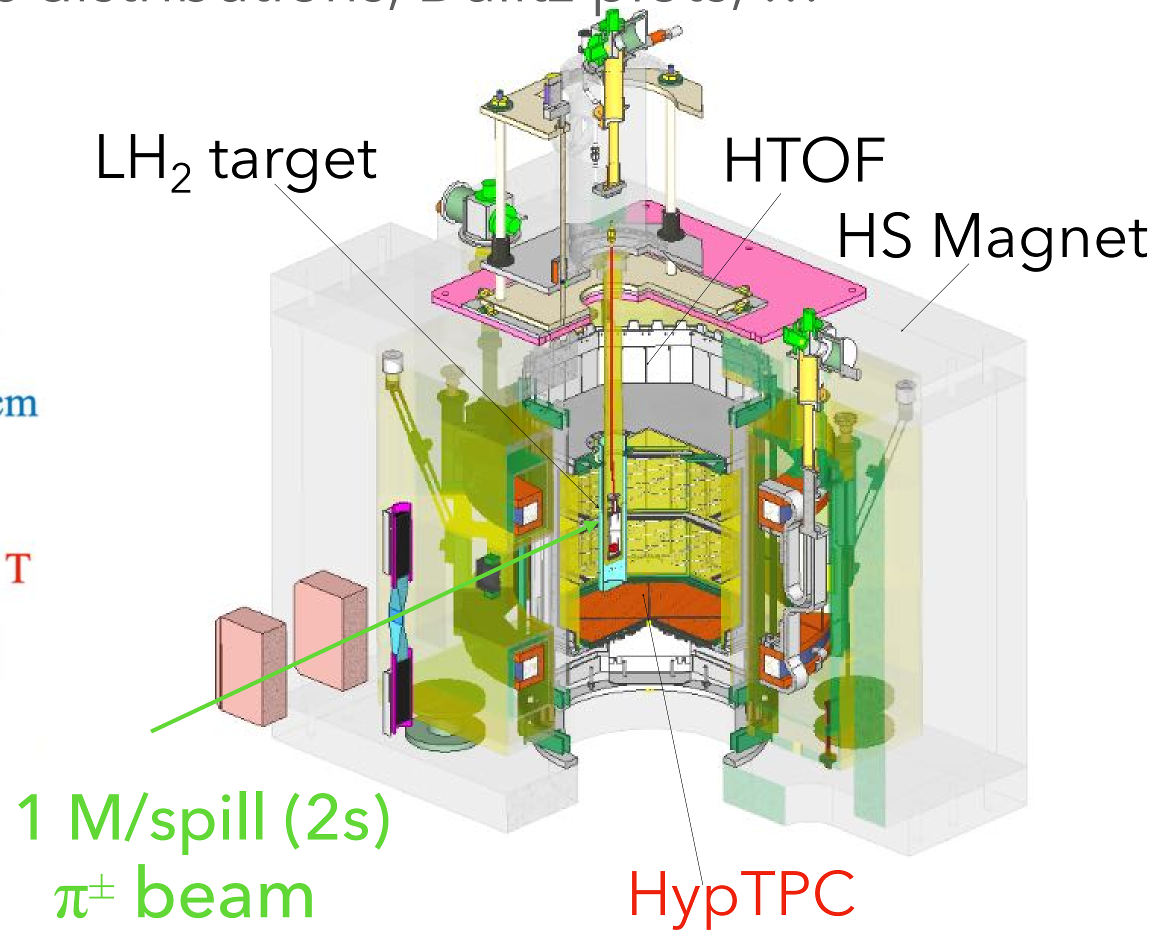


- *K1.8 Beamline (<2 GeV/c)*
- *Hyperon Spectrometer*

Hyperon Spectrometer

- Detect all charged particles' trajectories in 3D from the $\pi^{\pm}p$ reactions.
  ➔ angular distributions, mass distributions, Dalitz plots, …

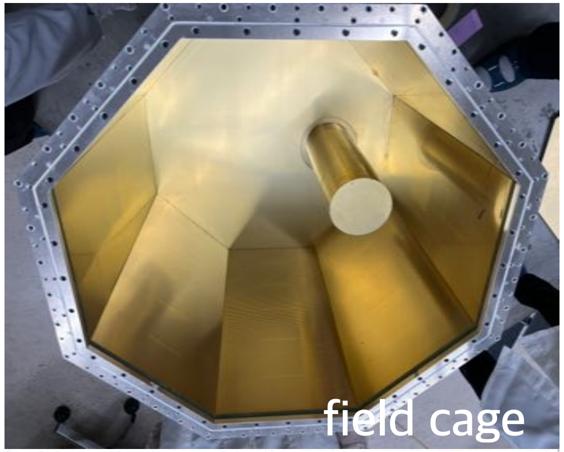


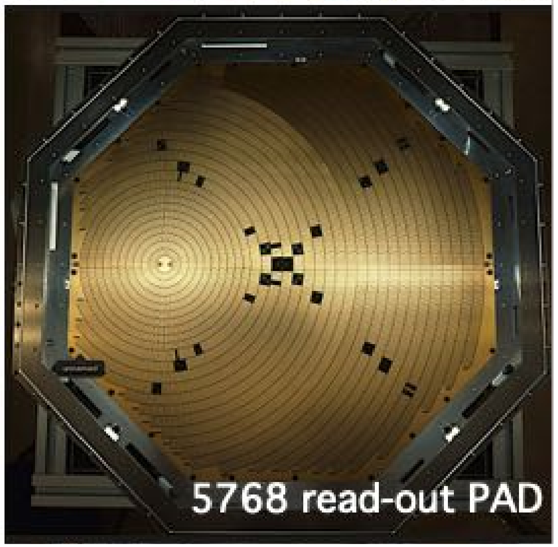


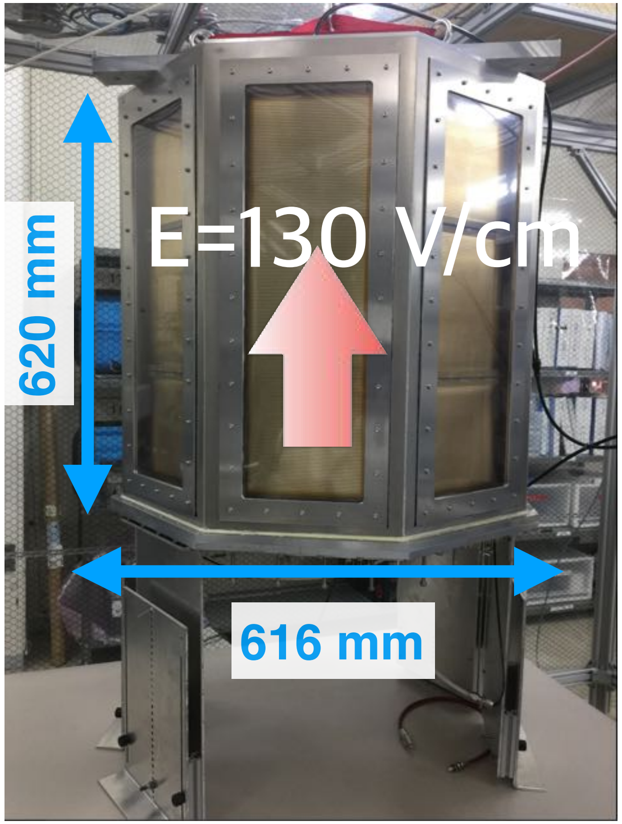
- Large acceptance (~4π)
- High rate capability (~10^6 cps)
- High resolution (σ ~1 MeV)

- *Hyperon Spectrometer*

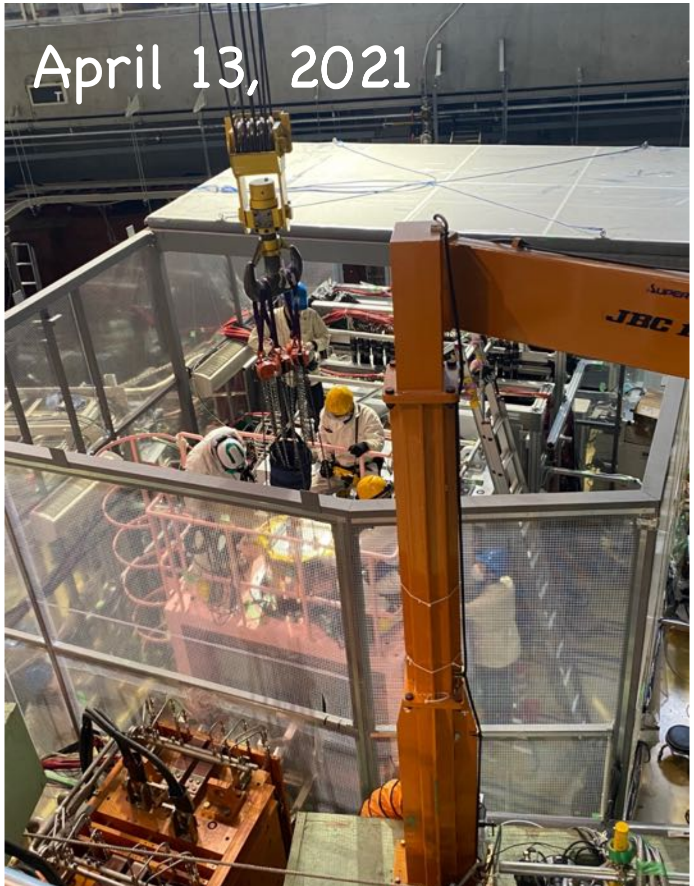
Hyperon Spectrometer

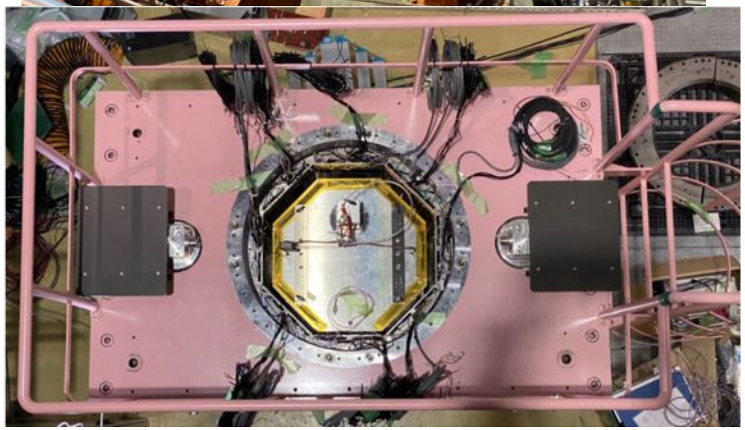






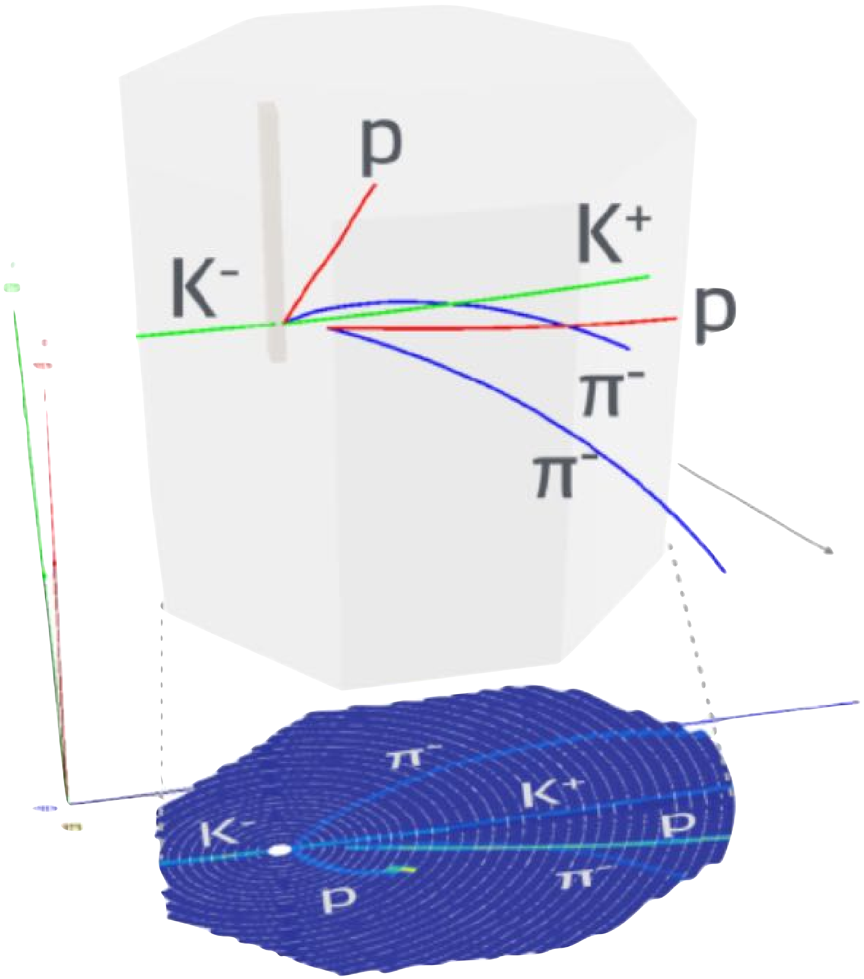
▸ *HypTPC*

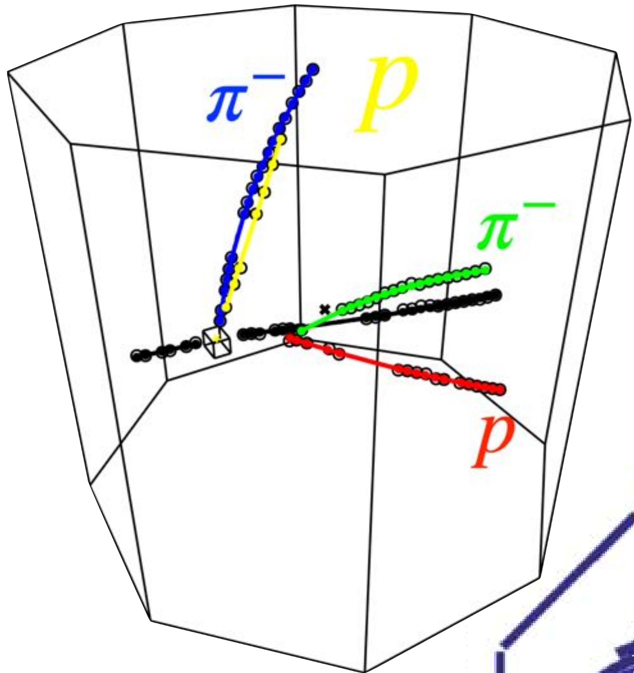


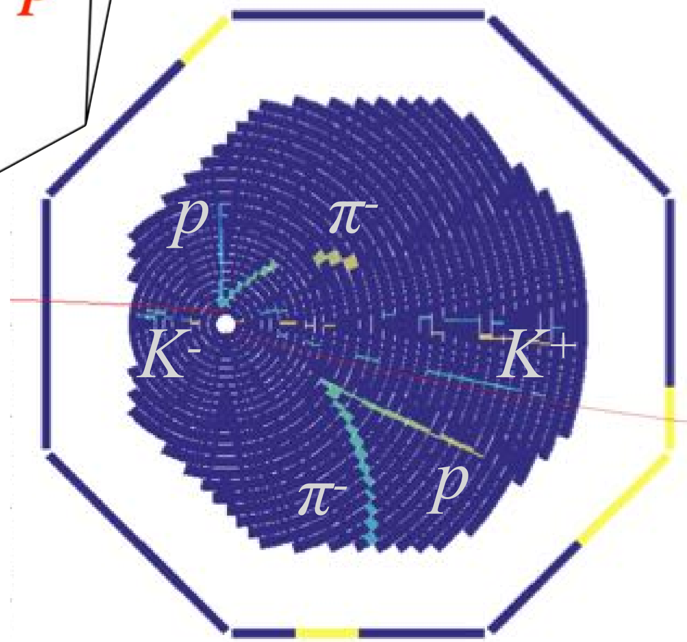


Hyperon Spectrometer

- *Simulation (J-PARC E42)*
- *Event Display (J-PARC E42)*

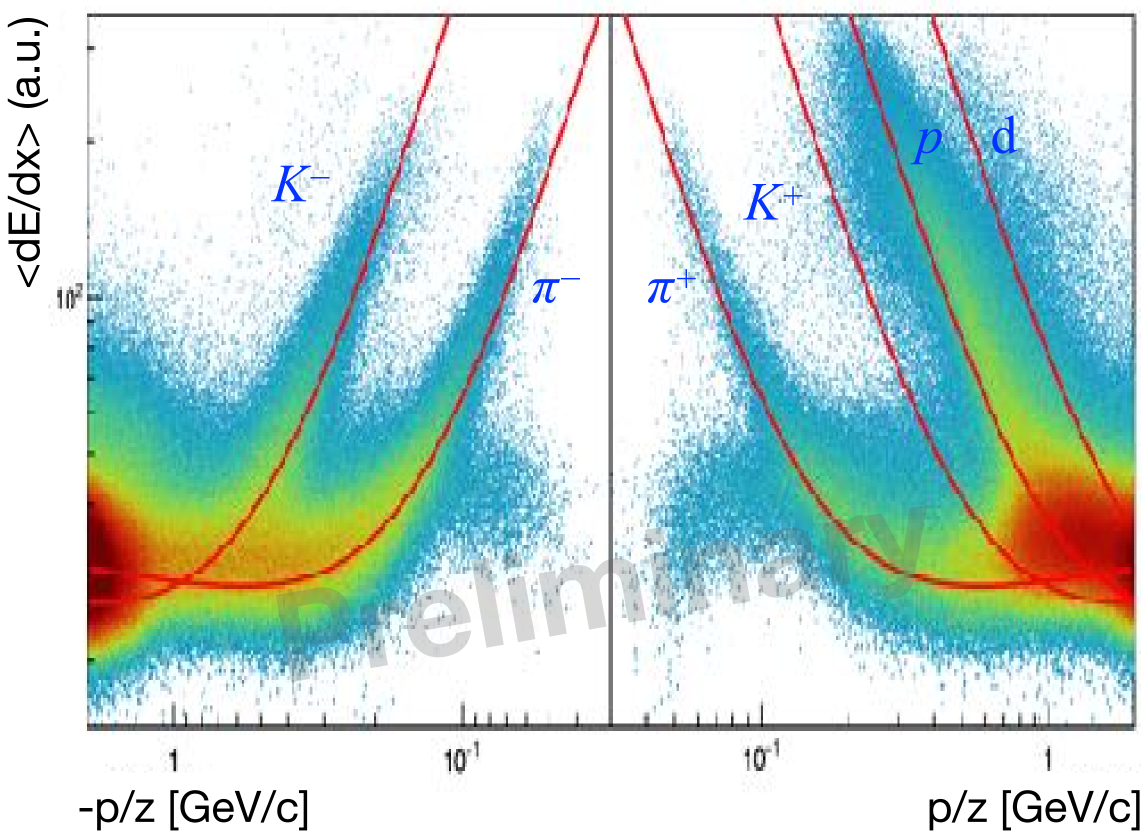




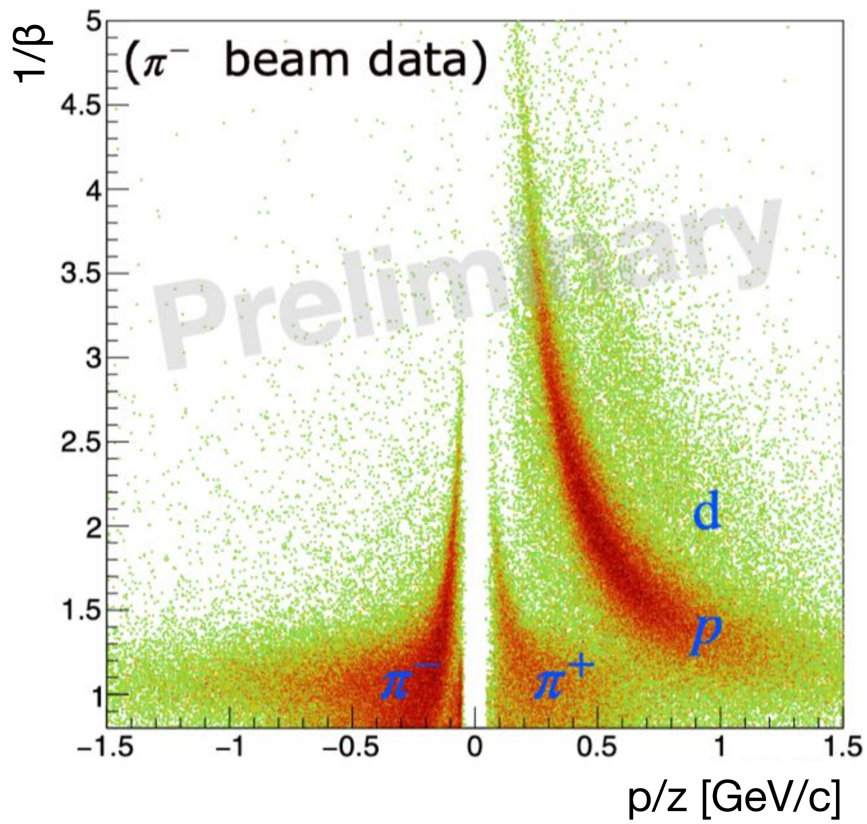


PID by Hyperon Spectrometer

- 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^-



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

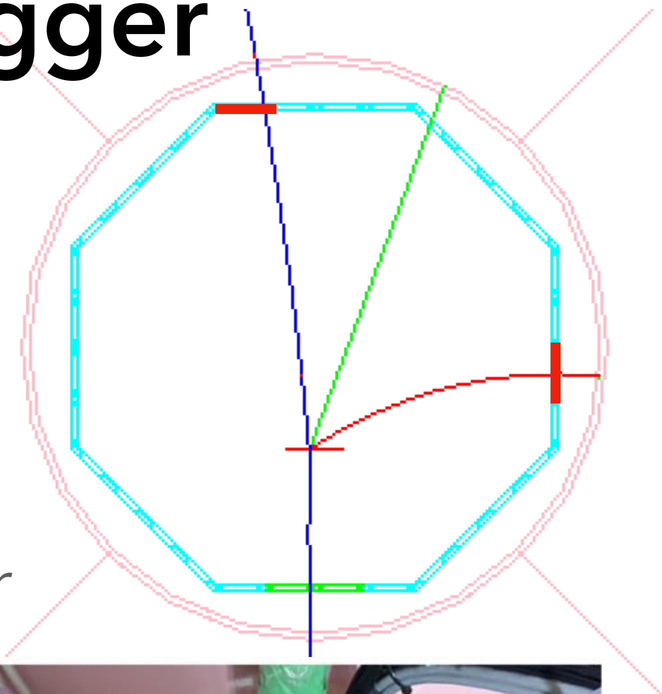
$\pi^{-}p \rightarrow \pi^{+}\pi^{-}n$, $\pi^{0}\pi^{-}p$,
$\pi^{+}p \rightarrow \pi^{0}\pi^{+}p$, $\pi^{+}\pi^{+}n$

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

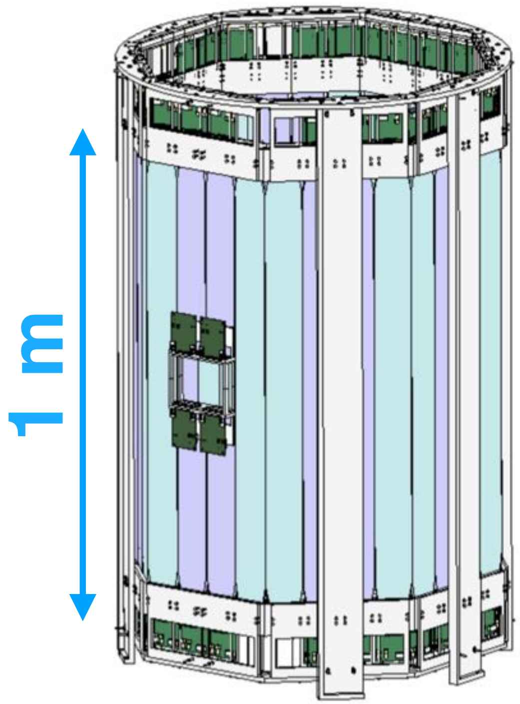
$\pi^{-}p \rightarrow \pi^{-}p$,
$\pi^{+}p \rightarrow \pi^{+}p$

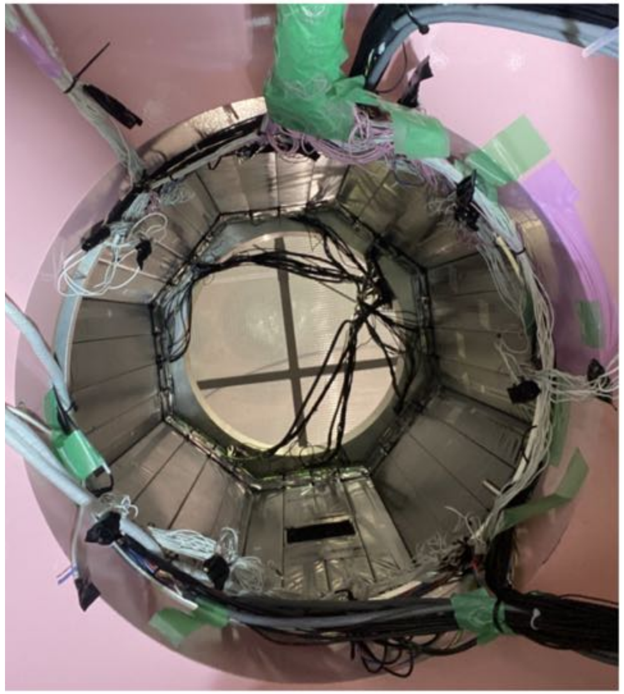
- $\pi p \rightarrow KY$ reactions

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



- *HTOF detector*





E45 data do not give a pole directly

E45 events

exclusive tracks and particle ID

→

Measured observables

cross sections, angles, and invariant masses

→

Coupled-channel amplitude fit

reaction amplitudes for all channels

→

Pole information

mass, width, and channel couplings

$\pi N \to \pi\pi N$

$\sigma(W)$, $d\sigma/d\Omega$

$M(\pi N)$, $M(\pi\pi)$

After analytic continuation, near the pole:

$$T_{ij}(W) \approx g_i g_j / (W - W_p) + \text{background}$$

A coupled-channel analysis connects E45 observables to resonance poles and QCD tests.

E45 Observables

Each observable constrains a different part of the full $\pi N \to \pi\pi N$ amplitude.

OBSERVABLE	WHY IT IS NEEDED
$\sigma(W)$	Energy dependence and overall reaction strength
$d\sigma/d\Omega$	Separate partial waves and their interference
$M(\pi N)$	Sensitive to the $\pi\Delta$ decay path
$M(\pi\pi)$	Test ρN and σN decay paths
Dalitz plot	Correlations and interference among decay paths
Decay angles	Spin-parity and relative phases

These observables are correlated because they come from the same events.
Together, they constrain the full amplitude much more strongly than one projected spectrum.

One Coupled-Channel Fit for All Reactions

The ANL–Osaka DCC model fits all connected reactions together

INPUT DATA

πN
ππN
KY

→

ANL–Osaka DCC fit

production
+ rescattering
+ channel transitions

→

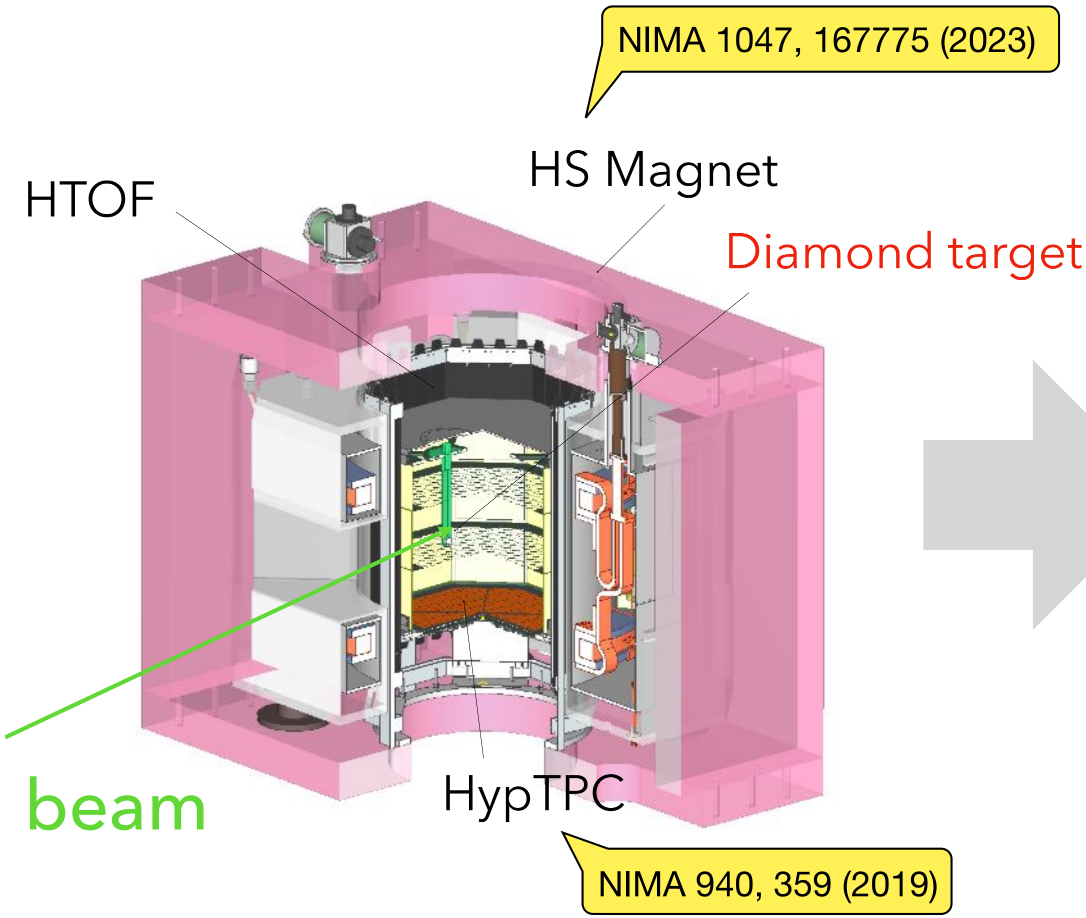
CONSISTENT AMPLITUDES

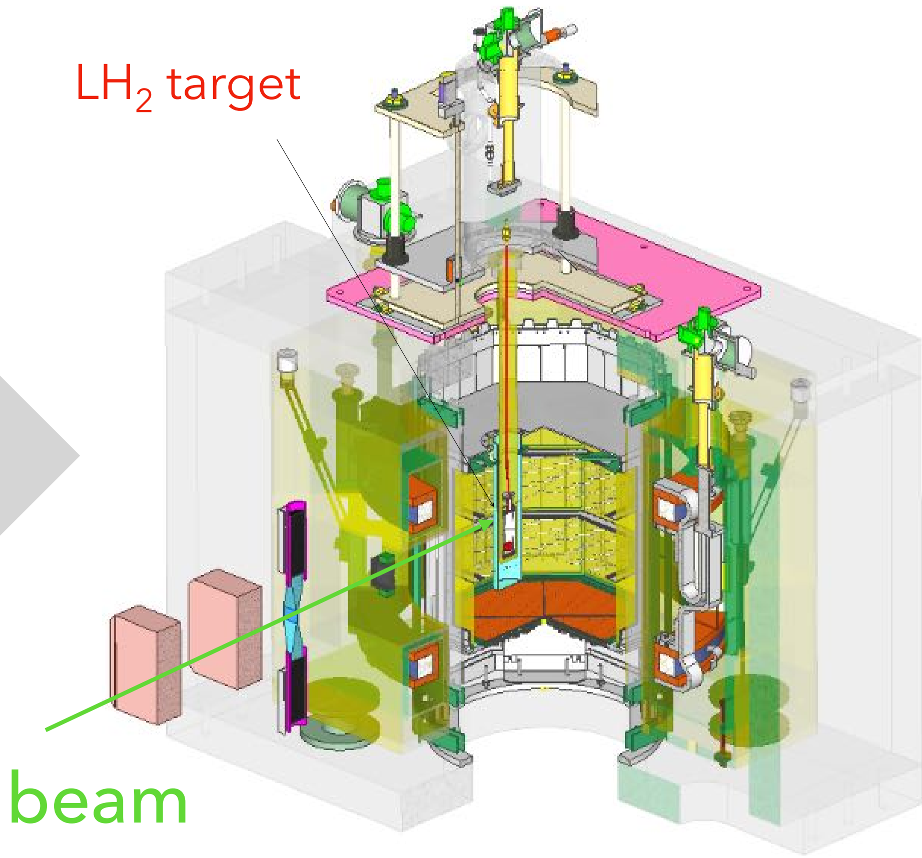
for all channels and observables

- **One common set of model parameters must describe all channels and observables simultaneously.**
- **The model parameters are refined by repeatedly comparing the calculated observables with the data.**
- **The extracted poles and couplings can then be compared with QCD-based calculations.**

Current Preparation Status

HypTPC Upgrade





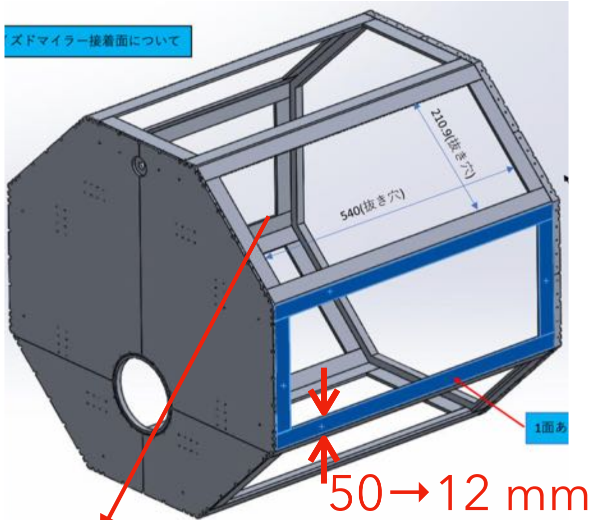
E42

May-Jun 2021

E45/E72/E104

HypTPC Upgrade

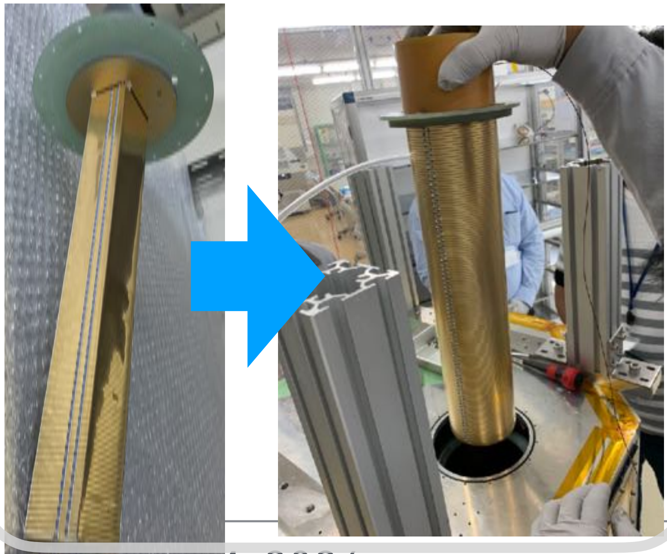
- Gas Vessel



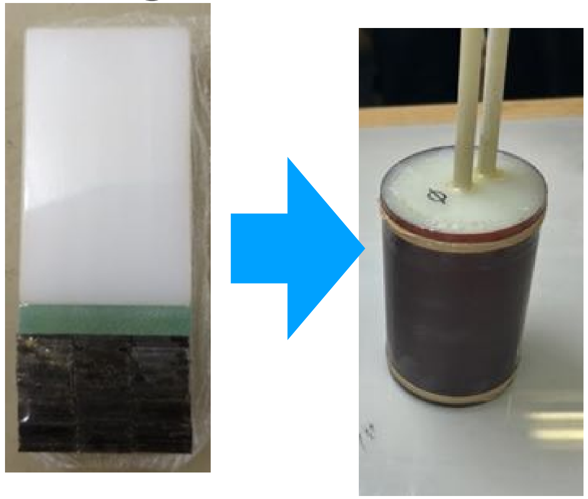
50→12 mm

Mylar → Al Mylar

- Target holder

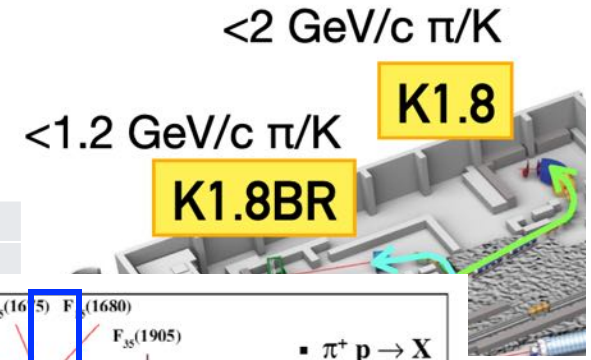


- Target



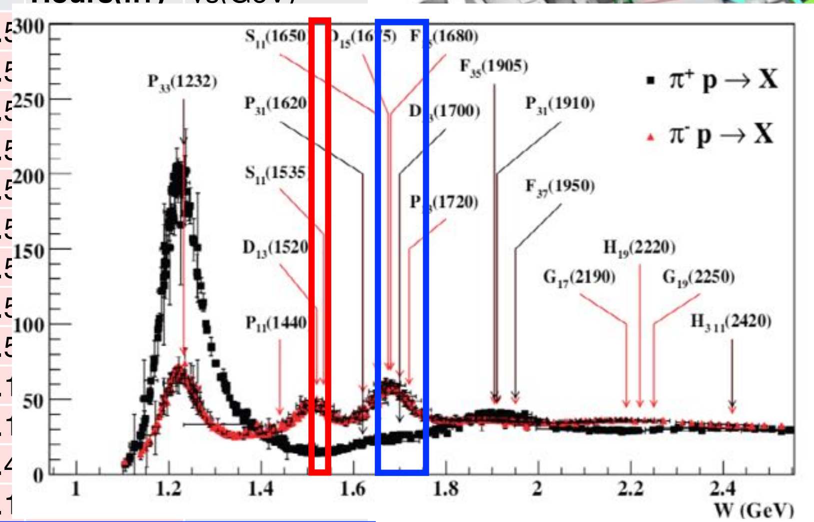
Target cooling/moving system

Low Momentum at K1.8BR



√s(GeV)	p(GeV/c)	π- beam N(π+π-n)	π- beam N(π0π-p)	π- beam Hours(π-)	π+ beam N(π+π+n)	π+ beam N(π0π+p)	π+ beam Hours(π+)	HADES (π-) √s(GeV)
2.15	1.98	655.1	380.4	4.4	1162.2	281.5		
2.13	1.92	655.1	380.4	4.4	1162.2	281.5		
2.10	1.87	655.1	380.4	4.4	1162.2	281.5		
2.08	1.81	655.1	380.4	4.4	929.8	281.5		
2.05	1.75	655.1	380.4	4.4	929.8	281.5		
2.03	1.70	655.1	380.4	4.4	929.8	281.5		
2.00	1.65	655.1	380.4	4.4	929.8	281.5		
1.97	1.58	655.1	380.4	4.4	929.8	281.5		
1.94	1.52	655.1	380.4	4.4	929.8	281.5		
1.91	1.46	655.9	409.1	4.1	925.5	267.1		
1.87	1.38	654.2	383.7	4.3	961.9	240.1		
1.83	1.30	608.6	358.4	4.7	901.9	183.4		
1.79	1.22	609.4	380.4	4.4	806.4	125.1		
1.76	1.15	679.6	443.8	3.8	696.5	125.9	13.2	HADES (2026?)
1.73	1.10	770.9	497.9	3.3	704.9	110.7	15.1	1.73
1.70	1.05	858.8	521.5	3.2	753.1	131.0	12.7	1.7
1.68	1.02	902.7	530.8	3.1	800.4	151.3	11.0	1.67
1.66	0.98	917.9	513.1	3.2	825.0	155.5	10.7	
1.64	0.94	885.0	567.2	2.9	829.2	149.6	11.1	
1.62	0.91	787.8	448.0	3.7	807.2	149.6	11.1	
1.60	0.87	690.6	412.5	4.0	724.4	127.6	13.1	
1.57	0.81	584.9	394.7	4.2	535.0	87.9	19.0	
1.54	0.77	540.1	407.4	4.1	383.7	60.9	27.4	1.55
1.52	0.74	515.6	408.3	4.1	280.6	47.3	35.2	1.52
Total (days)				4.0			11.2	HADES (2020)
BR beam time (days)				1.7			179.6	

at K1.8BR



3rd Resonance

- complementary measurement with HADES
- $\pi^- p \to K^0 \Lambda$

2nd Resonance

- HADES data cross-check
- π^+ complementary measurement

- The Phase-I beam time for the 3rd resonance region is allocated at the K1.8BR in November 2026

Summary

➔ The *N** spectrum is a long-standing problem, and the 3-body hadronic reaction data are required for the dynamical coupled-channels calculation.

➔ The J-PARC E45 will open a unique opportunity to study the *N** resonances in **$\pi p \rightarrow \pi\pi N$ and KY** reactions in **E_{CM}= 1.5 - 2.15 GeV.**

➔ The commissioning run was successfully completed at K1.8BR and the physics run for the **3rd resonance region** is currently waiting for the beam time in **November 2026**.

Stay tuned!