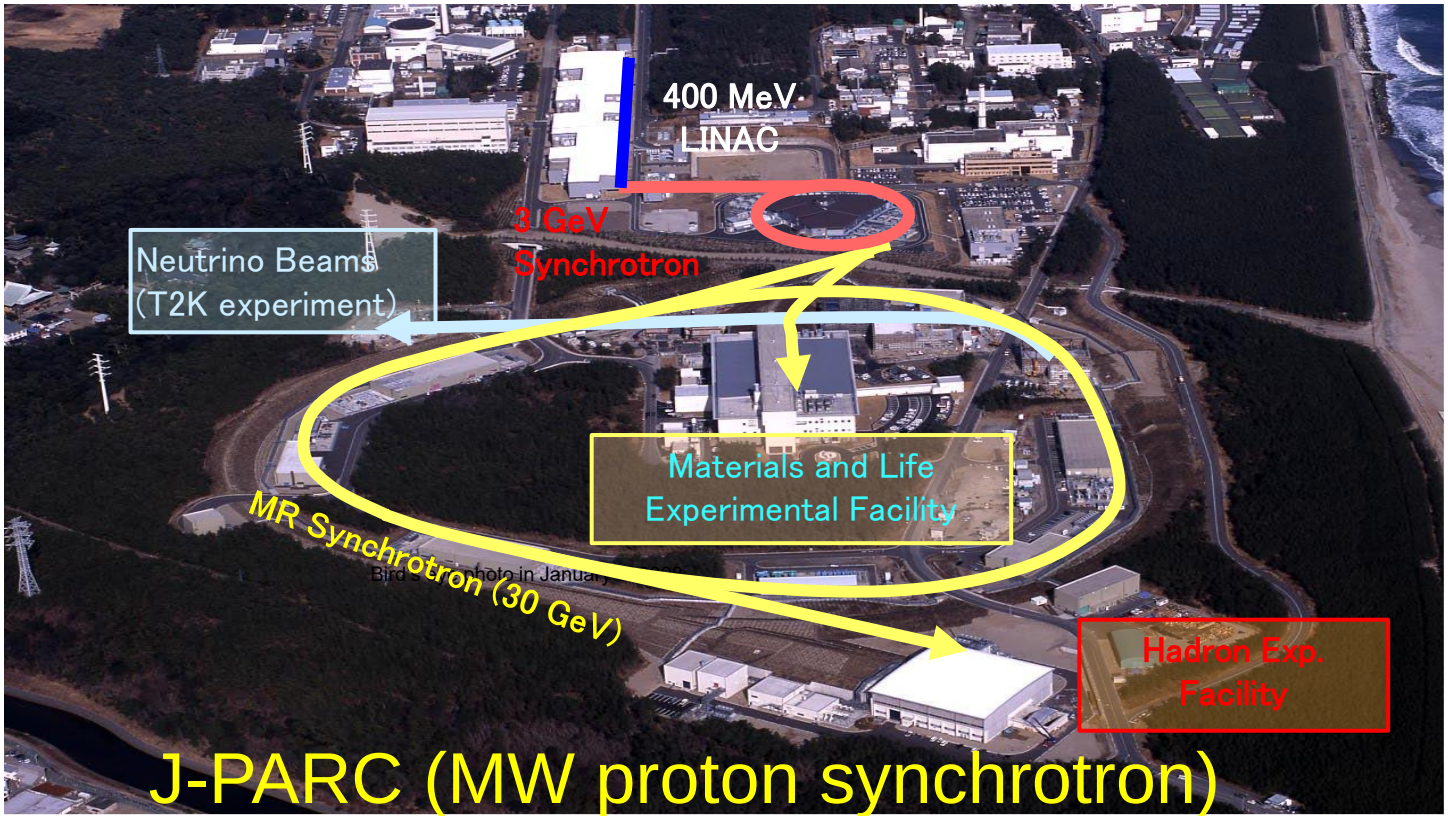
Studies of baryon resonances with meson beams at J-PARC -J-PARC E45 and E72-

Hiroyuki Sako (ASRC/J-PARC, JAEA)
for the J-PARC E45 and E75 Collaborations
APCTP Workshop on Nuclear Physics 2022
Jeju
11-16 July 2022

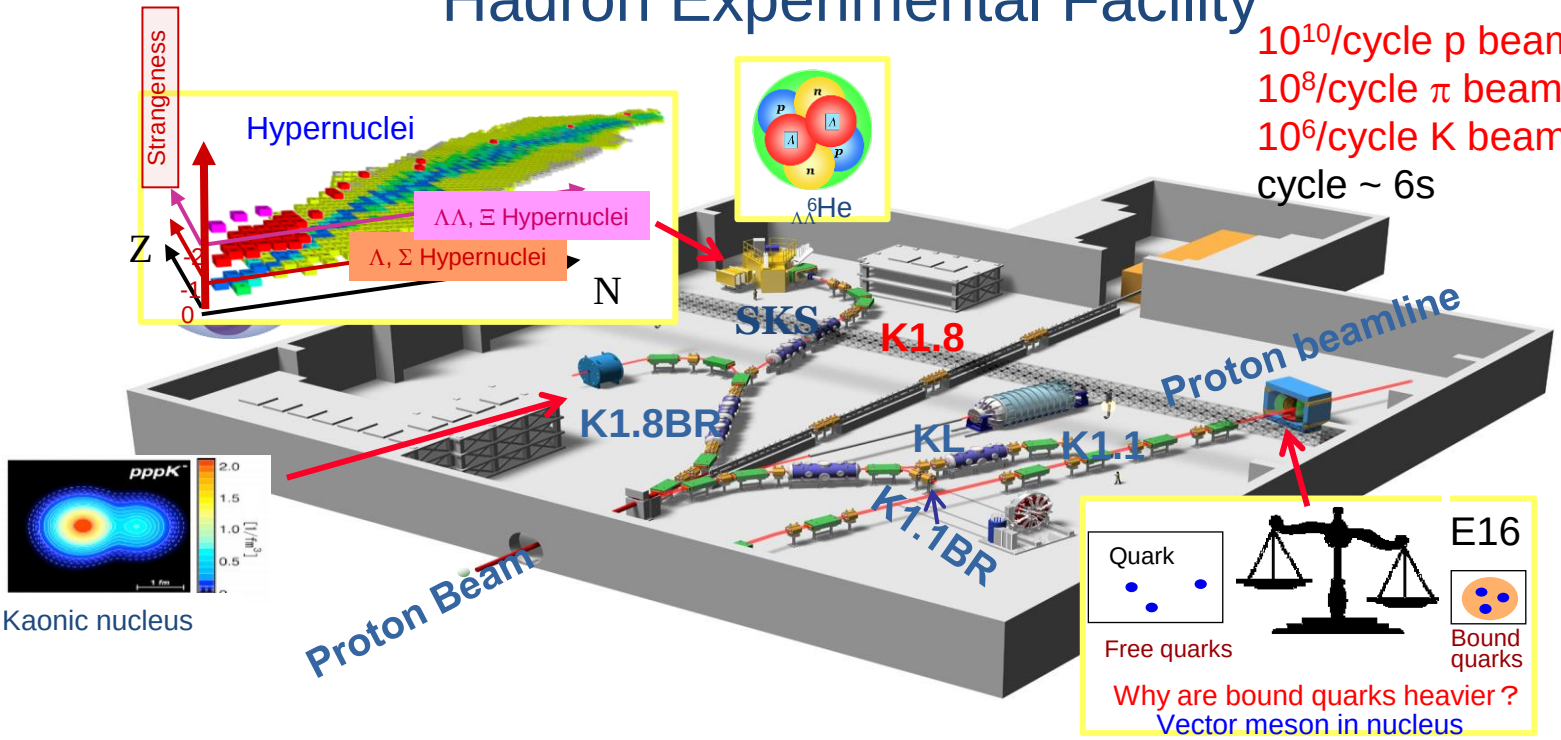
1. J-PARC E45 (N^*, Δ^* spectroscopy)
2. J-PARC E72 ($\Lambda(1665)$)
3. Preparation status of the experiments
4. Summary

J-PARC Accelerator Complex



Hadron Experimental Facility

10^{10}/cycle p beams
10^{8}/cycle π beams
10^{6}/cycle K beams
cycle ~ 6s

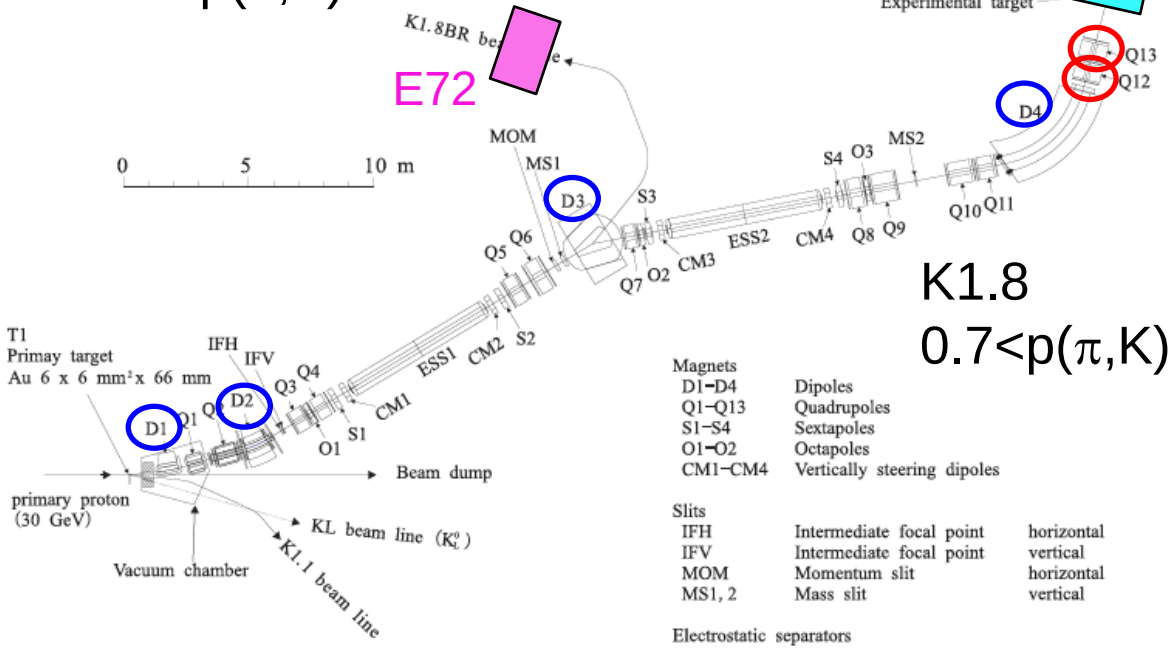


K1.8/K1.8BR beamlines

K1.8BR
p(π,K)<1.15 GeV/c

E72

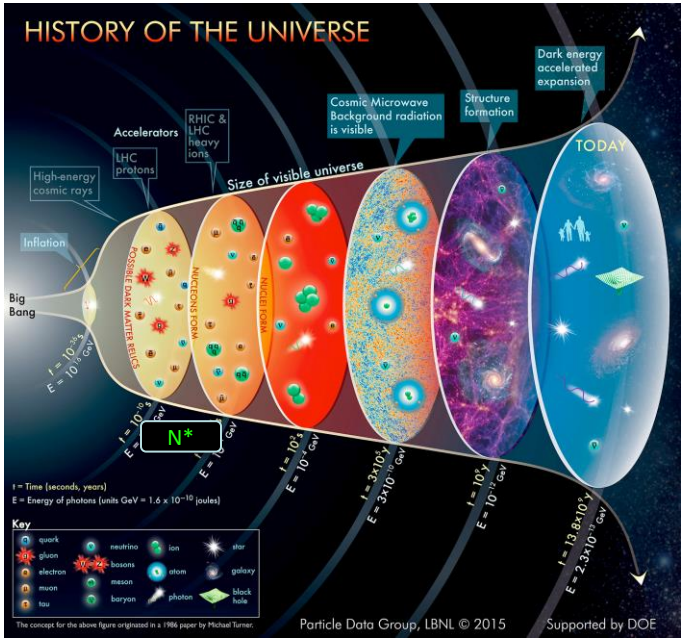
E45



K1.8
0.7<p(π,K)<2.0 GeV/c

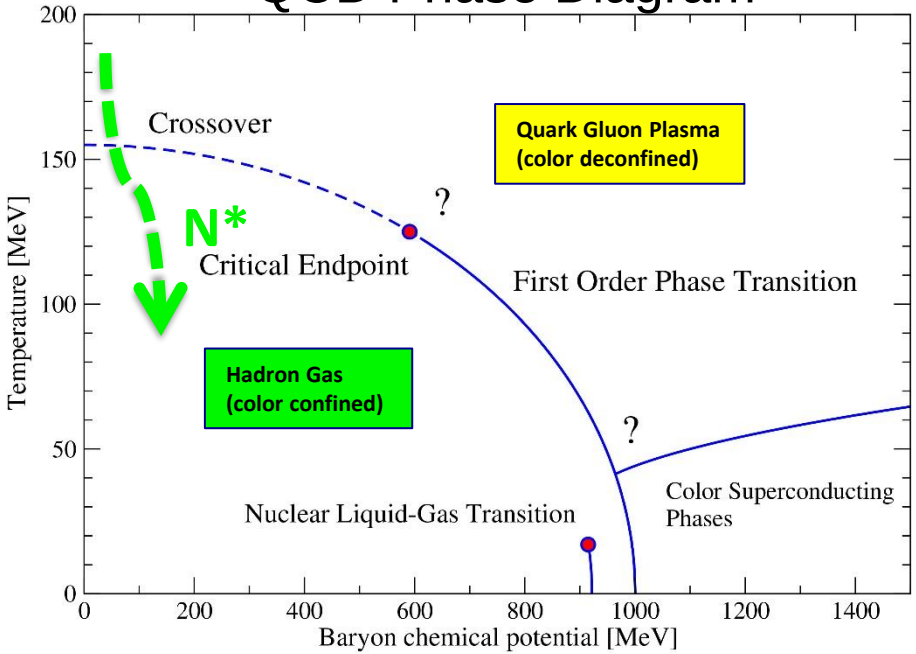
Magnets		
D1−D4	Dipoles	
Q1−Q13	Quadrupoles	
S1−S4	Sextapoles	
O1−O2	Octapoles	
CM1−CM4	Vertically steering dipoles	
Slits		
IFH	Intermediate focal point	horizontal
IFV	Intermediate focal point	vertical
MOM	Momentum slit	horizontal
MS1, 2	Mass slit	vertical
Electrostatic separators		
ESS1, 2		

N* in the History of the Universe



Particle Data Group 2014

QCD Phase Diagram



EPJ A Highlight - Confirming the validity of the Silver-Blaze property for QCD at finite chemical potential

Dramatic events occur in the microsecond old Universe.

- The transition from the QGP to the hadronic phase is dominated by excited baryons.

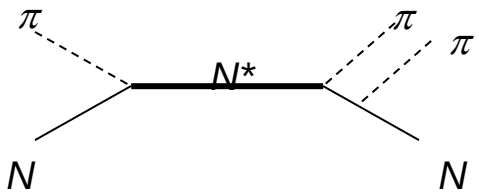
A quantitative comparison betw. LQCD and Hadron gas model requires more excited states than found to date => **missing baryons.** *(A. Majumder and B. Muller, PRL 105, 250222 (2010))*

J-PARC E45

Studies of baryon resonances in (π,2π) reactions

Goals

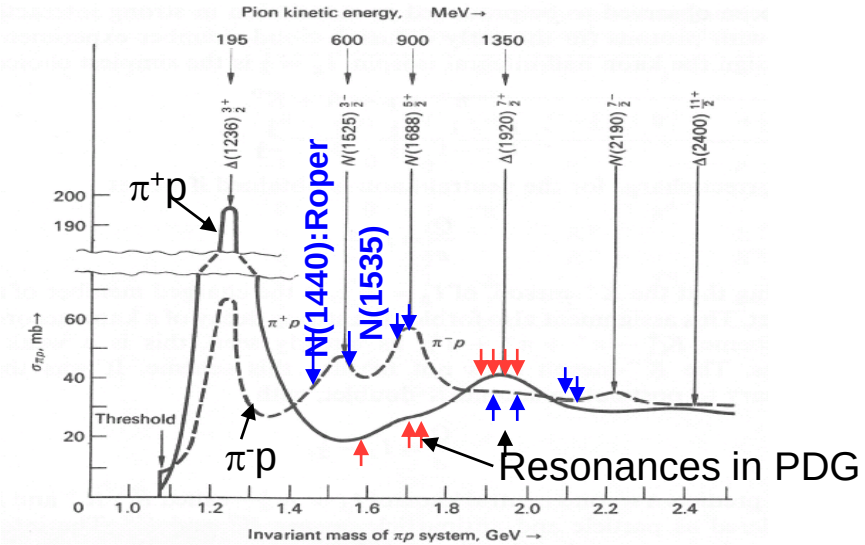
- Establish N^* and Δ^* resonances up to 2 GeV/c^2
- Search for new baryon states
  - *e.g.* hybrid baryons (*qqqg*)
- Deeper understanding of non-perturbative QCD



J-PARC E45 Collaboration

H. Sako, K. Imai, S. Hasegawa, S. Sato, K. Tanida, Y. Ichikawa , T. Hashimoto	(Japan Atomic Energy Agency)
P. Cole	(Lamar Univ.)
K. Joo, S. Diehl, A. Kim. U. Shrestha, R. Capobianco, V. Klimenko,	
J. Richards, N. Trotta, T. Hayward, P. Simmerling, R. Santos	(Univ Connecticut)
C. Djalali	(Ohio Univ.)
J.K. Ahn, S.H. Kim, W.S. Jung, S.B. Yang, B.M. Kang, S.W. Choi, H.I. Lee, S.J. Lee	(Korea Univ)
S. Nakamura, M. Niiyama	(Kyoto Univ.)
H. Fujioka	(Tokyo Inst. Tech.)
T. Takahashi, K. Ozawa, H. Sugimura	(KEK)
K. Nakazawa, H. Ekawa	(RIKEN)
S. H. Hwang	(KRISS)
S. H. Hayakawa, J. Yoshida	(Tohoku Univ.)
T. Ishikawa	(ELPH, Tohoku Univ.)
B. Briscoe, 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, Osaka Univ.)
Y. Azimov	(Petersburg Nuclear Physics Institute)
V. Shklyar	(Univ. Giessen)
A. Svarc	(Ruder Boskovic Institute)
S. Ceci	(RBI-Zagreb)
M. Hadzimehmedovic, H. Osmanovic	(Univ. Tulza)

Baryon spectroscopy :
Physics of broad and overlapping resonances



D.H.Perkins, Introduction to High Energy Physics

- ✓ **Width: a few hundred MeV.**
- ✓ **Resonances are highly overlapped in energy except Δ(1232).**

→Partial Wave Analysis to extract hidden resonances

Measure cross sections as a function of

- **Incident pion energy**
- **Scattering angle**

In broad range (with fine bins) to extract resonance poles

PDG data for N* and Δ* resonances

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

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

Many resonances have not been established experimentally.

**** Established
***
* **

Most of the *Ns so far were measured from**

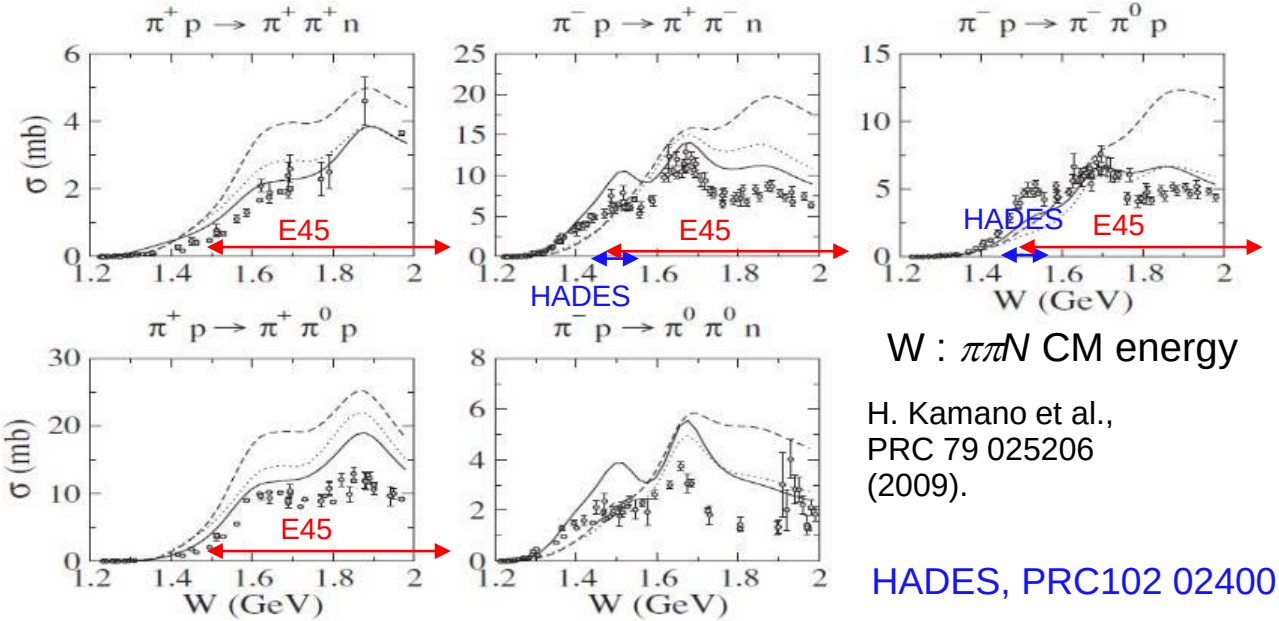
$$\pi N \to \pi N\,, \quad \gamma N \to \pi N \qquad \gamma N \to \pi\pi N$$

***πN→ππN* data necessary to resolve remaining resonances**

PDG 2020

World's $\pi N \to \pi\pi N$ data

Only 240K events measured in 1970's



W : $\pi\pi N$ CM energy

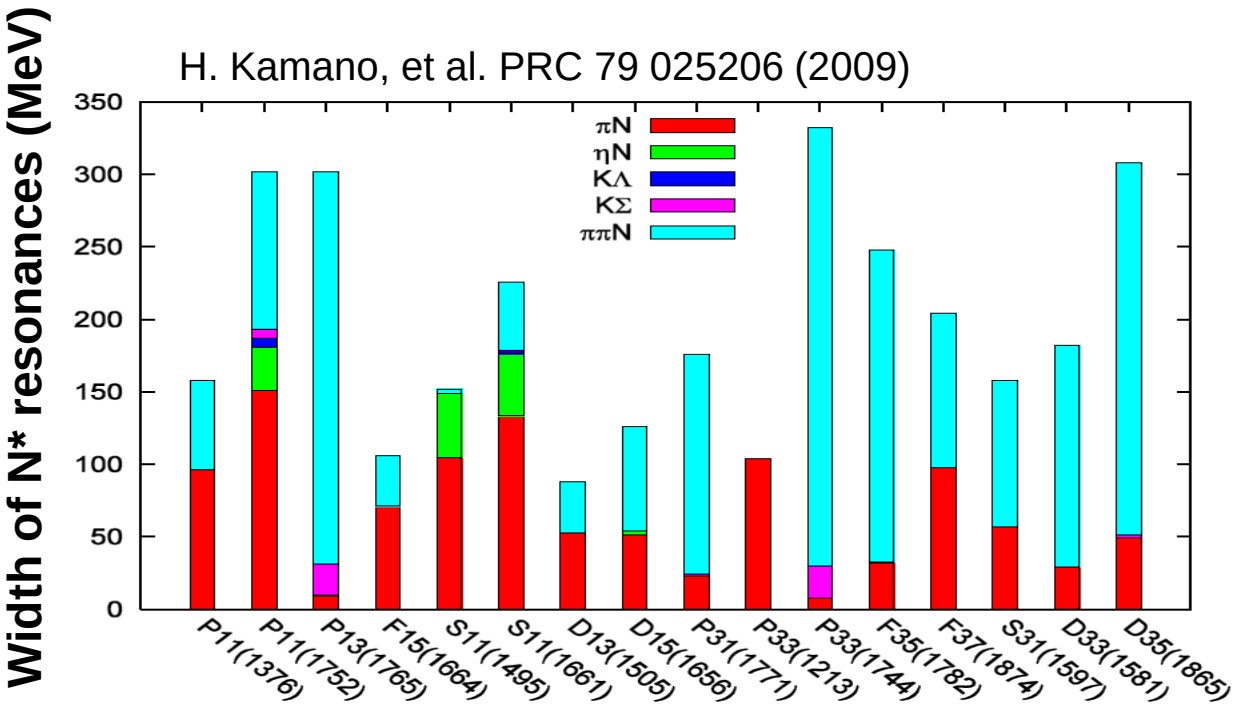
H. Kamano et al., PRC 79 025206 (2009).

HADES, PRC102 024001 (2020)

E45 is a unique experiment to measure these reactions with high-intensity pion beams. We expect at least 100 times statistics for E45 over the world's data.

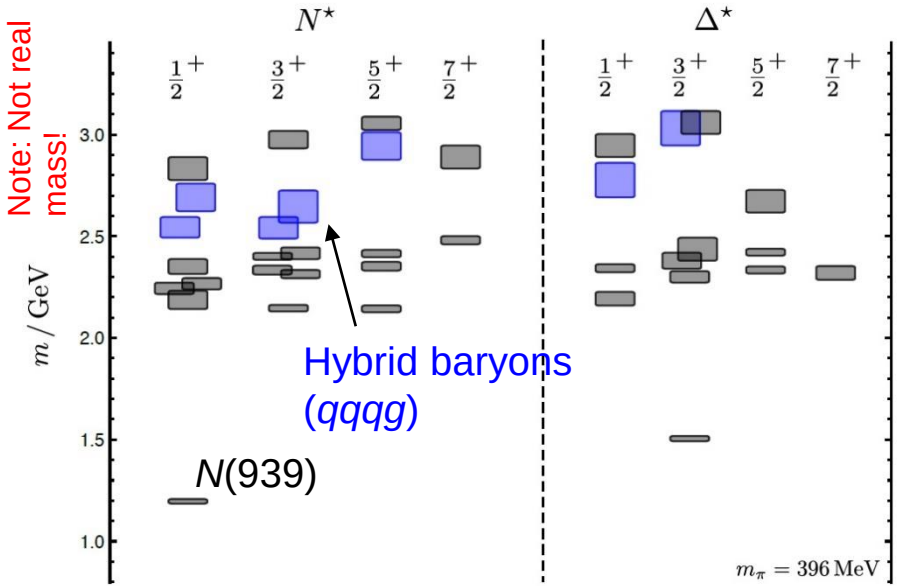
Importance of $\pi\pi N$ Decay

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



Lattice QCD calculations

J. Dudek et al., PRD85 (2012) 054016



Hyperon Spectrometer for E45

Measurement of (π,2π) in large acceptance TPC (HypTPC)

π^{+-} beam on liquid-H_2 target

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

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

2 charged particles + *1 neutral particle*

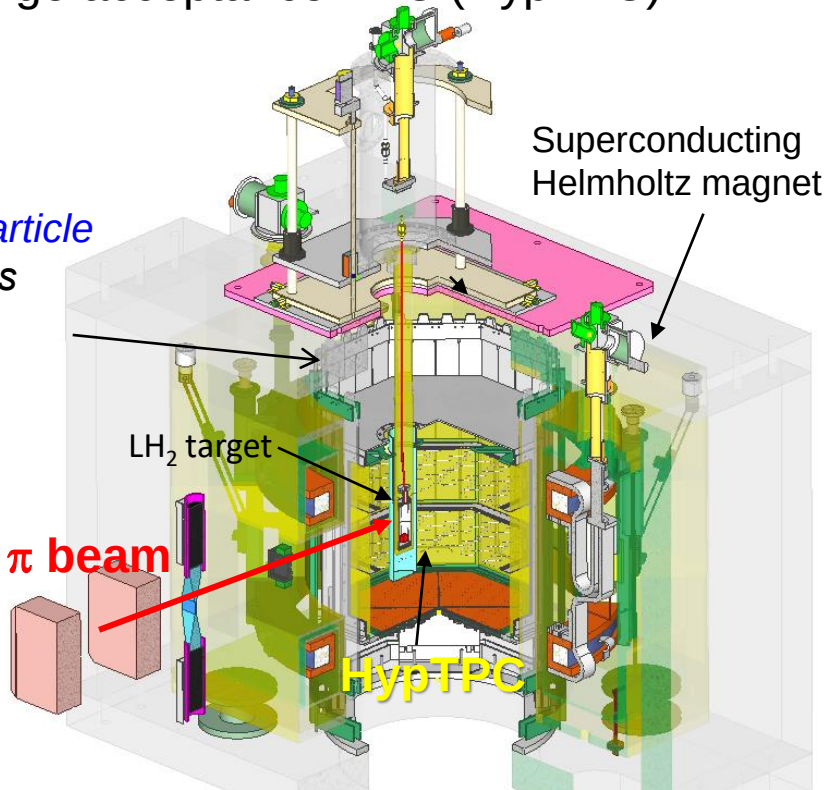
→*missing mass*

Trigger with HTOF

$\pi N \rightarrow KY$ *(2-body reaction)*

$\pi^- p \rightarrow K^0 \Lambda$,

$\pi^+ p \rightarrow K^+ \Sigma^+$ (I=3/2, Δ*)



Beam time request and expected statistics

π beam rate : 10^6 / spill (2s)

- Liquid H_2 target : 5 cm thick
- TPC acceptance : 40%
- (π,2π) cross section : ~2 mb ($\pi^+p \rightarrow \pi^+\pi^+n$)

⇒ 160 events / spill

- πp CM energy (W) : 1.50 – 2.15 GeV (p= 0.73 – 2.0 GeV/c)
- No. of bins : π^- beam : 24 (energy) x 20 (angle)
  π^+ beam : 23 (energy) x 20 (angle)
- No. of events / bin : 32 K

⇒ 30M events in 15 days

Enhances world's $\pi\pi N$ data statistics (0.24M) by a factor of 130

E45 expected data summary

HADES

- only π^- beam
- $\sqrt{s}$~1.5 GeV run done
- Plan for $\sqrt{s}$~1.7 GeV
- No continuous energy scan

E45(proposal)

		π^- beam			π^+ beam		
$\sqrt{s}$(GeV)	p(GeV/c)	N($\pi^+\pi^-$n) (/spill)	N($\pi^0\pi^-$p) (/spill)	Hours(π^-)	N($\pi^+\pi^+$n) /spill)	N($\pi^0\pi^+$p) (/spill)	Hours(π^+)
2.15	1.98	655.1	380.4	4.4	1162.2	281.5	5.9
2.13	1.92	655.1	380.4	4.4	1162.2	281.5	5.9
2.10	1.87	655.1	380.4	4.4	1162.2	281.5	5.9
2.08	1.81	655.1	380.4	4.4	929.8	281.5	5.9
2.05	1.75	655.1	380.4	4.4	929.8	281.5	5.9
2.03	1.70	655.1	380.4	4.4	929.8	281.5	5.9
2.00	1.65	655.1	380.4	4.4	929.8	281.5	5.9
1.97	1.58	655.1	380.4	4.4	929.8	281.5	5.9
1.94	1.52	655.1	380.4	4.4	929.8	281.5	5.9
1.91	1.46	655.9	409.1	4.1	925.5	267.1	6.2
1.87	1.38	654.2	383.7	4.3	961.9	240.1	6.9
1.83	1.30	608.6	358.4	4.7	901.9	183.4	9.1
1.79	1.22	609.4	380.4	4.4	806.4	125.1	13.3
1.76	1.15	679.6	443.8	3.8	696.5	125.9	13.2
1.73	1.10	770.9	497.9	3.3	704.9	110.7	15.1
1.70	1.05	858.8	521.5	3.2	753.1	131.0	12.7
1.68	1.02	902.7	530.8	3.1	800.4	151.3	11.0
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	584.9	394.7	4.2
1.54	0.77	540.1	407.4	4.1	383.7	60.9	27.4
1.52	0.74	515.6	408.3	4.1	280.6	47.3	0.0
Total(h)				96.7			218.6

HADES Proposed

HADES Completed

J-PARC E72

Search for a narrow Λ resonance using the $p(K^-,\Lambda)\eta$ reaction

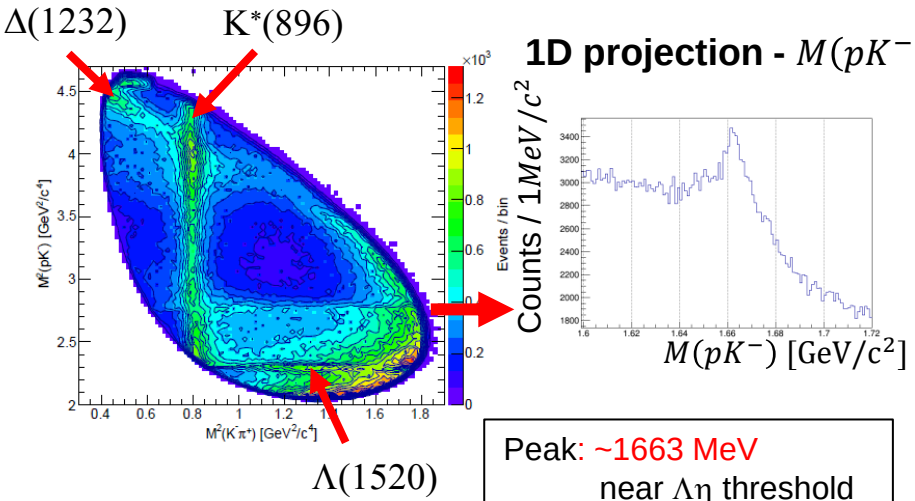
E72 Collaboration

- *Japan Atomic Energy Agency:* S. Hasegawa, T. Hashimoto, Y. Ichikawa, K. Imai, H. Sako, S. Sato, K. Tanida
- *Ohio University:* Chaden Djalali, Utsav Shrestha
- *Lamar University:* Phil Cole
- *RCNP, Osaka University:* H. Noumi, K. Shirotori, S.B. Yang
- *University of Connecticut:* Kyungseon Joo, Nikolay Markov, Andrey Kim, Stefan Diehl, David Riser, Brandon Clary, Thomas O'Connell, Frank Cao, Kevin Wei
- *Florida International University:* L. Guo
- *RIKEN:* M. Iwasaki, S. Okada, F. Sakuma, H. Asano, Y. Ma
- *ELPH, Tohoku University:* H. Ohnishi, A. Tokiyasu
- *Tohoku University: S. H. Hayakawa*
- *Korea University:* J.K. Ahn, S.W. Choi, W.S. Jung, B.M. Kang, S.H. Kim, K.Y. Roh, H.M. Yang
- *INFN Frascati:* Alberto Clozza, Catalina Curceanu, Kristian Piscicchia, Alessandro Scordo
- *Kyoto University:* M. Niiyama
- *Korea Research Institute of Standards and Science:* S.H. Hwang

E72: Search for a new narrow $\Lambda^*(1665)$

Hints for $\Lambda^*(1665)$ from previous experiments

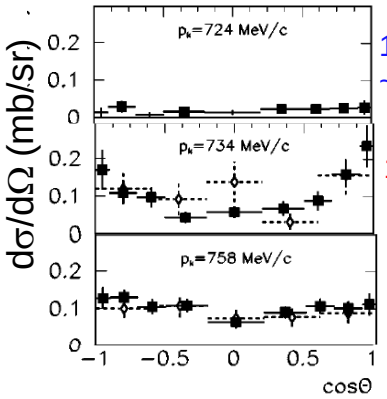
Belle: $\Lambda_c^+ \to pK^-\pi^+$ [PRL117.011801]



1D projection - $M(pK^-)$

Peak: ~1663 MeV
near $\Lambda\eta$ threshold
(1663.5 MeV)
Width: ~10 MeV

Crystal Ball at BNL
$K^-p \to \Lambda\eta$
[PRC64.055205])

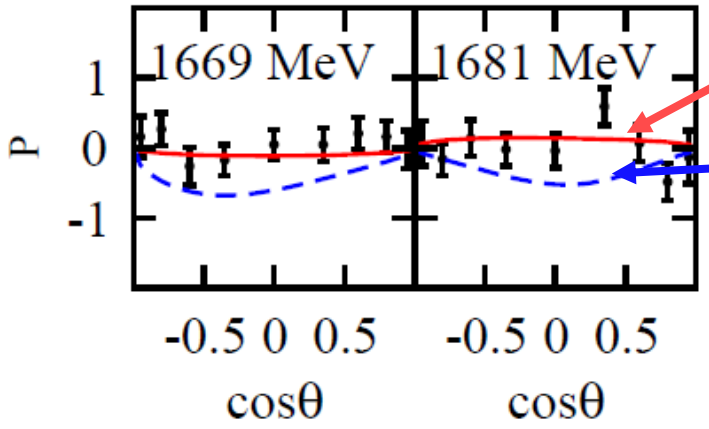


1664MeV
~$\eta\Lambda$ threshold

1669MeV→Resonance?

1679MeV

Λ Polarization in CB data



No new resonance

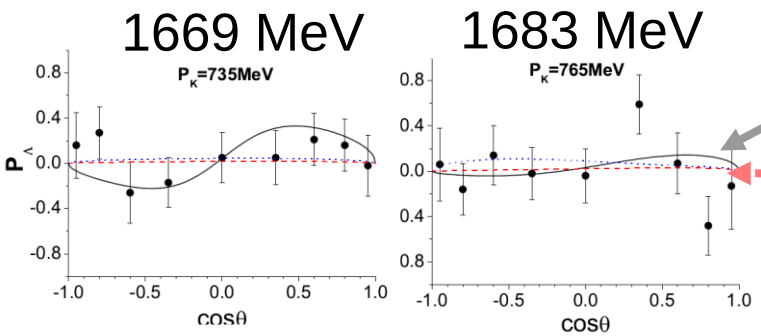
$3/2^+$ (P_{03})

1671^{+2}_{-8} MeV

$\Gamma=10^{+22}_{-4}$ MeV

Kamano et al.

[PRC92.025205]



$3/2^-$ (D_{03})

1668.5 ± 0.5 MeV

$\Gamma=1.5\pm0.5$ MeV

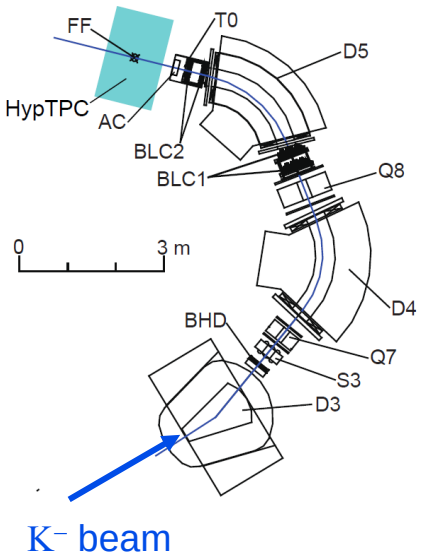
No new resonance

Liu and Xie

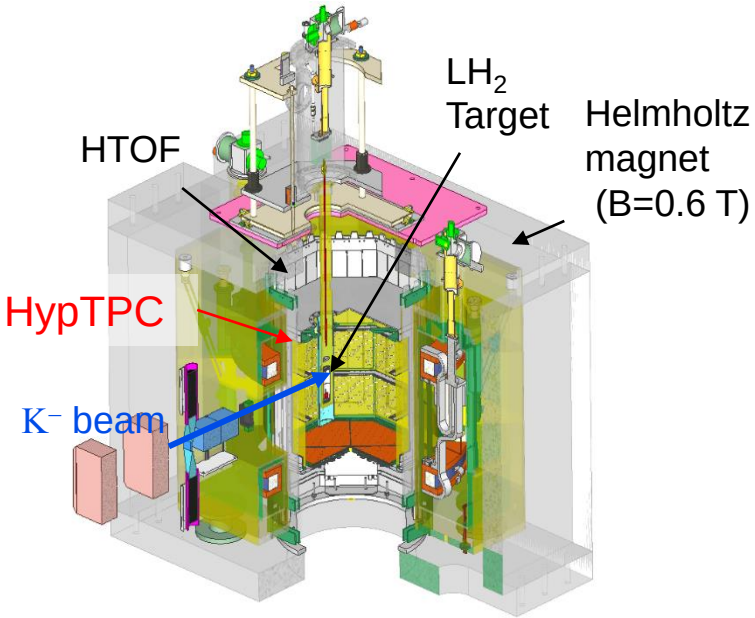
[PRC86.055202]

To distinguish between P and D waves,
100 times more statistics than CB is required

E72 setup



Hyperon Spectrometer



300k events in 2 weeks
(100 times of CB data)

$K^- p \rightarrow \Lambda\eta$

Reconstruct $\Lambda \rightarrow p\pi^-$ in TPC

Identify η w/ missing mass

Trigger in hodoscope

- 2 charged particles
- proton with large ΔE

Beam momentum: 735 MeV/c (±2%) at K1.8BR

HypTPC

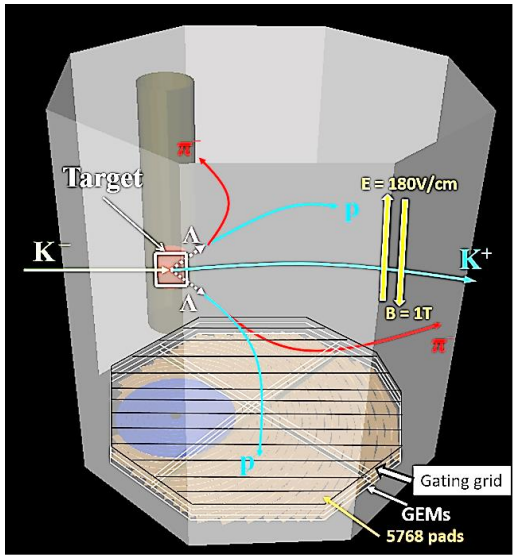
- ○ Octagonal prism field cage
- ○ Inner target system → Large Acceptance
- ○ Suppression of ion back flow
  - Triple GEM stack

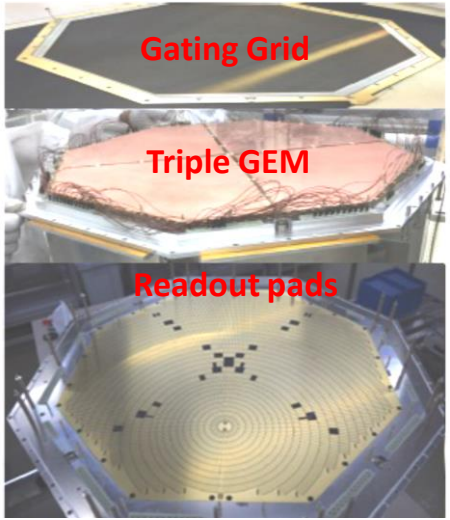
  (100 + 50 + 50 μm thick GEMs)
  - Gating grid wires

Maximum beam rate : 10^6Hz

- ○ ~6000 readout pads

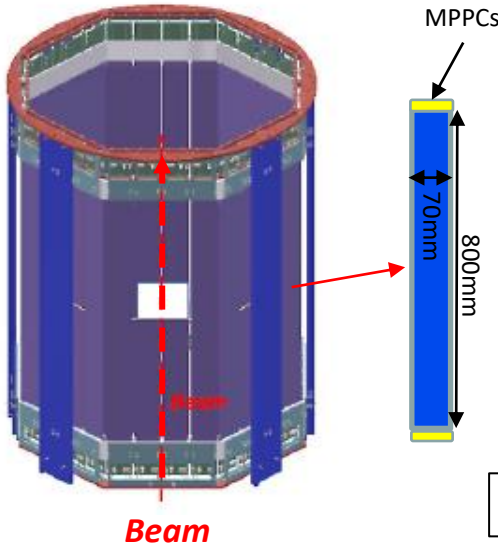
  ~2.4×11 mm^2
- ○ Gas: Ar-CH_4(9:1) (v_{drift} ~ 5.3 cm /μs)
- ○ Gain ~ 10^4
- ○ Position resolution < 300 μm
- ○ Δp/p = 1-3% for π and p





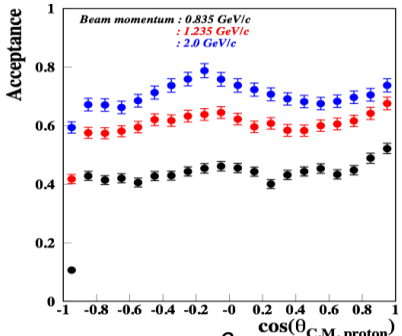
TPC Hodoscope (HTOF)

Hodoscope



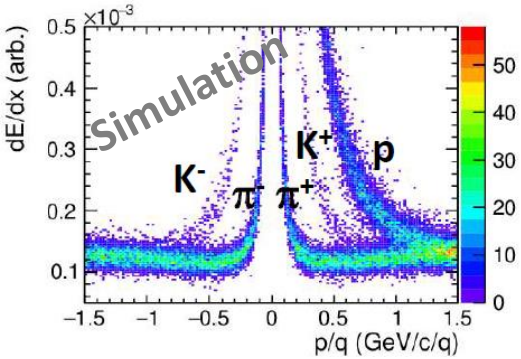
- Surrounding HypTPC for trigger and PID
- 32 segments (70*800*10 mm^3)
- MPPC used as a light sensor
- Timing resolution of ~150 ps
- PID: using dE/dx (TPC), TOF, and p/q.

Acceptance

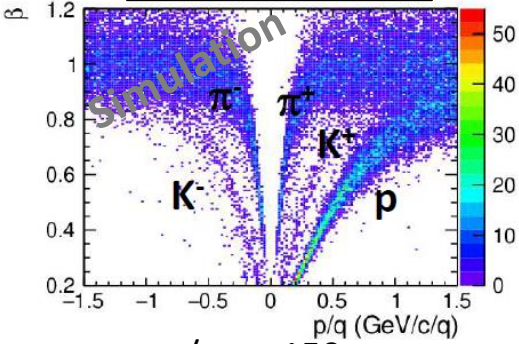


$\pi^+ p \rightarrow \pi^+ \pi^0 p$ reaction

PID: dE/dx(TPC) vs p/q



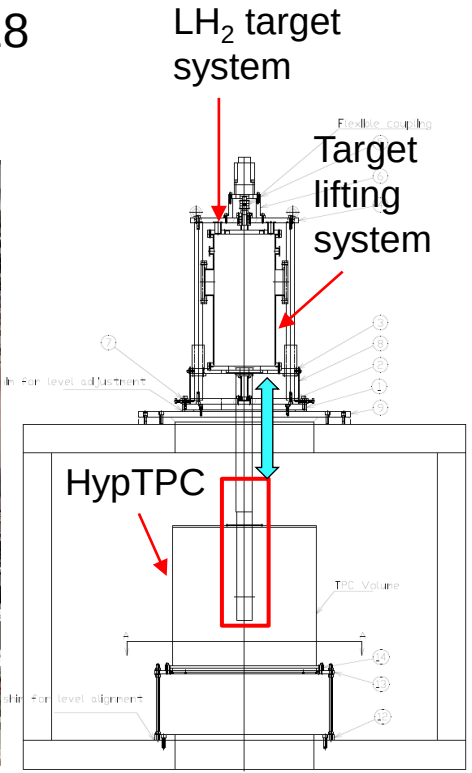
PID: TOF(β) vs p/q

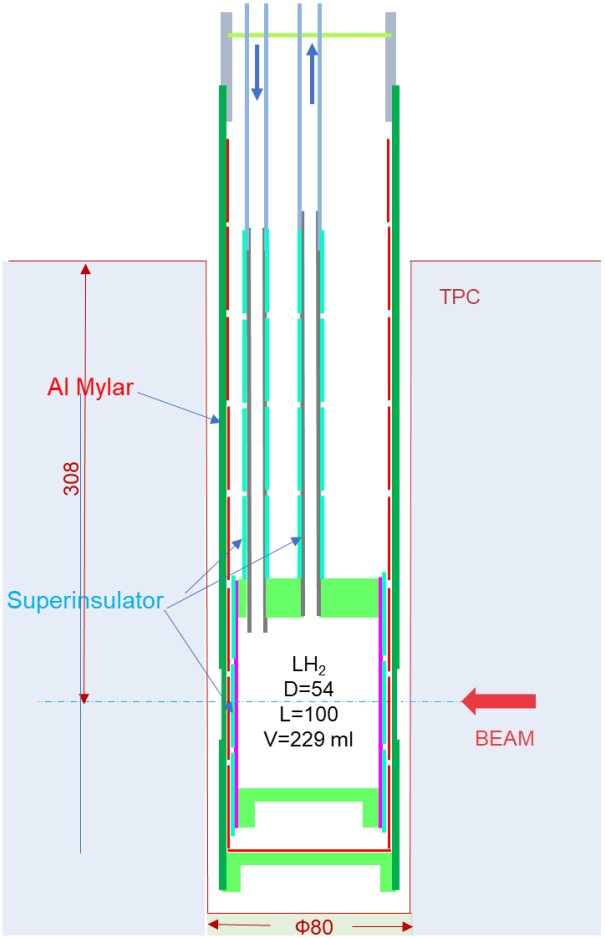


w/ σ_T = 150 ps

Liquid H_2 target

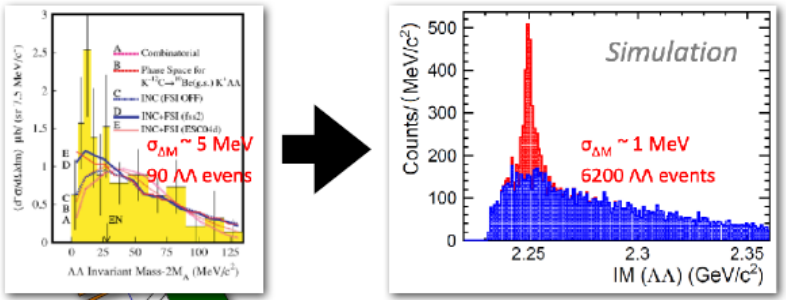
- Target system completed in 2018





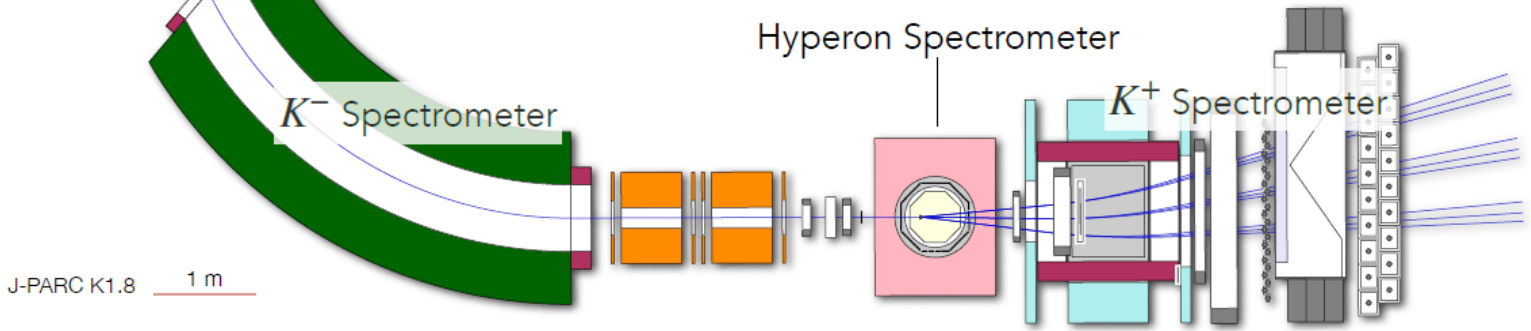
J-PARC E42 experiment

H dibaryon search experiment via $^{12}C(K^-, K^+)$ reaction at $p_{K^-} = 1.8$ GeV/c



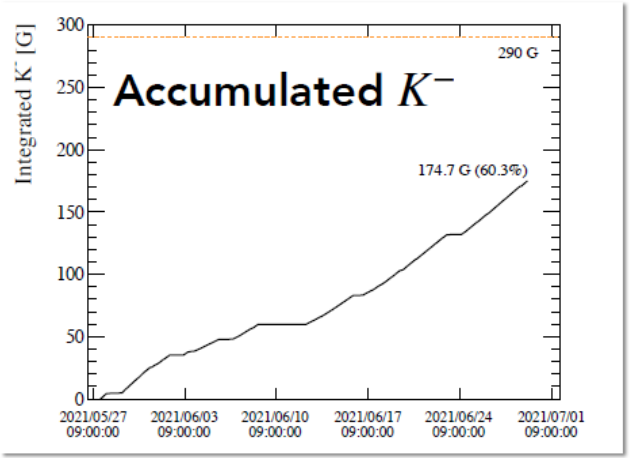
Upgraded previous study to higher resolution and statistics

Sensitivity to a wide mass range of $\Lambda p\pi^-$, $\Lambda\Lambda$, $\Xi^- p$

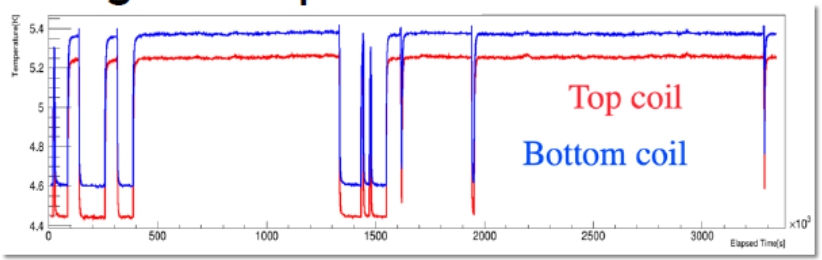


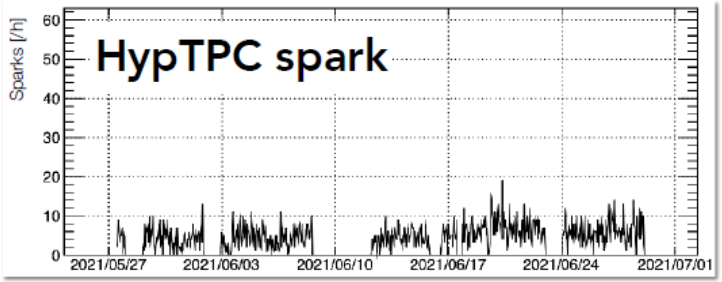
J-PARC E42 Run

- **22.7 days** of physics data in May and June 2021
- Total beam count : **1.75×10¹¹** K^-
- Long-term stable operation of superconducting magnet and HypTPC up to **350 kHz** beam.

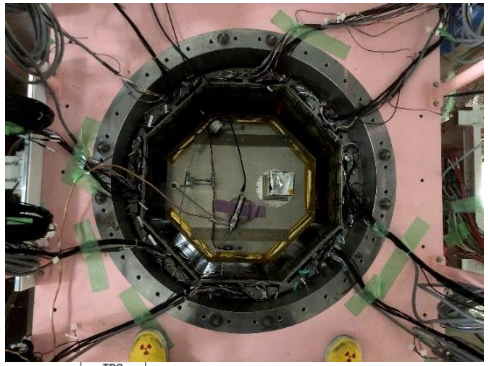


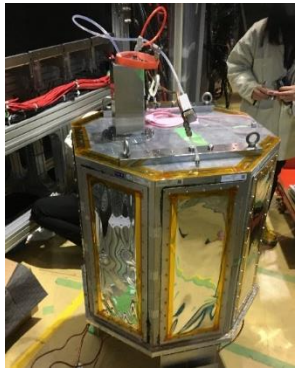
Magnet temperature

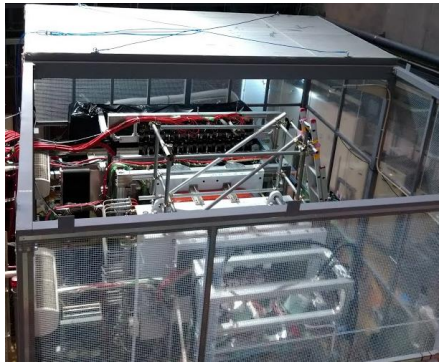


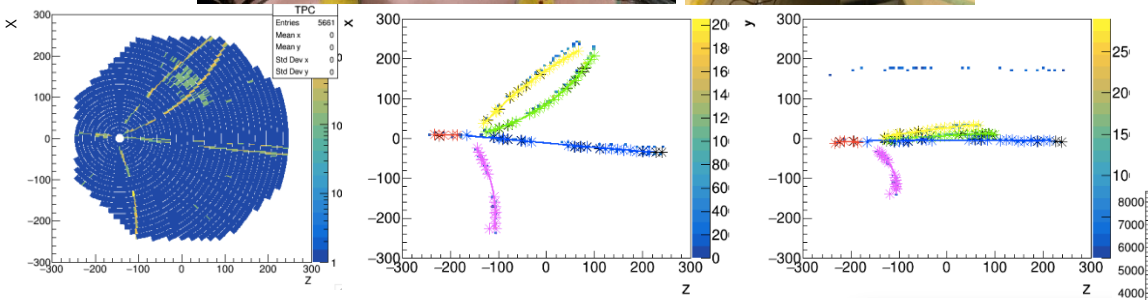


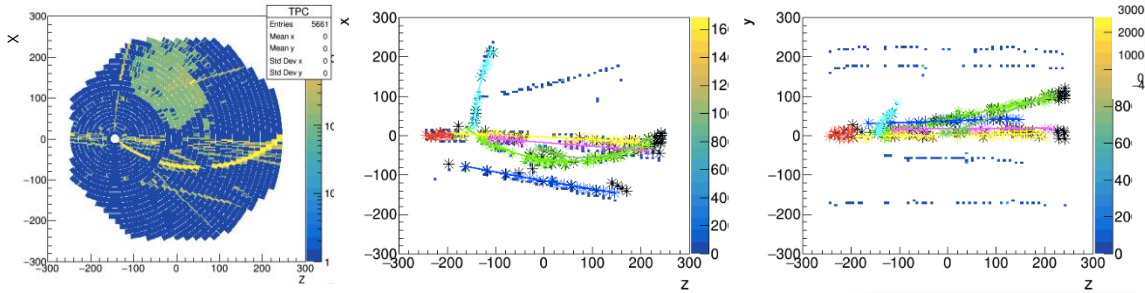
HypTPC tracking at E42 (H-dibaryon search)

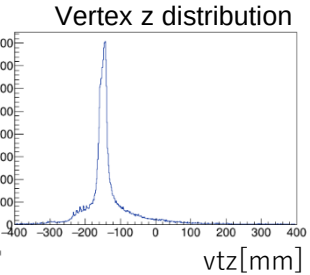












Summary

E45 : Study of baryon resonances in (π,2π) reactions

- Establish N* and Δ* resonances up to 2 GeV/c^2 with 130 times more statistics than previous data
- Search for hybrid baryons
- Expected beam time: ~2025

Require PWA in collaboration with theory groups

E72 : Search for a new Λ^* (1665) resonance

- Measurement of p(K^-,Λ)η
  - 100 times more statistics than Crystal Ball
  - Differential cross section and Λ polarization

  → Parity determination
  - Expected beam time : ~2024

Hyperon spectrometer

- Large acceptance spectrometer for E45 and E72 based on Helmholtz magnet and HypTPC
- Its performance demonstrated at E42 (H-dibaryon search) experiment