Baryon spectroscopy with Hyp-TPC at J-PARC

Kiyoshi Tanida
(Advanced Science Research Center,
Japan Atomic Energy Agency)

The 13th International Workshop on the Physics of Excited Nucleons
(NSTAR2022)
18 Oct. 2022

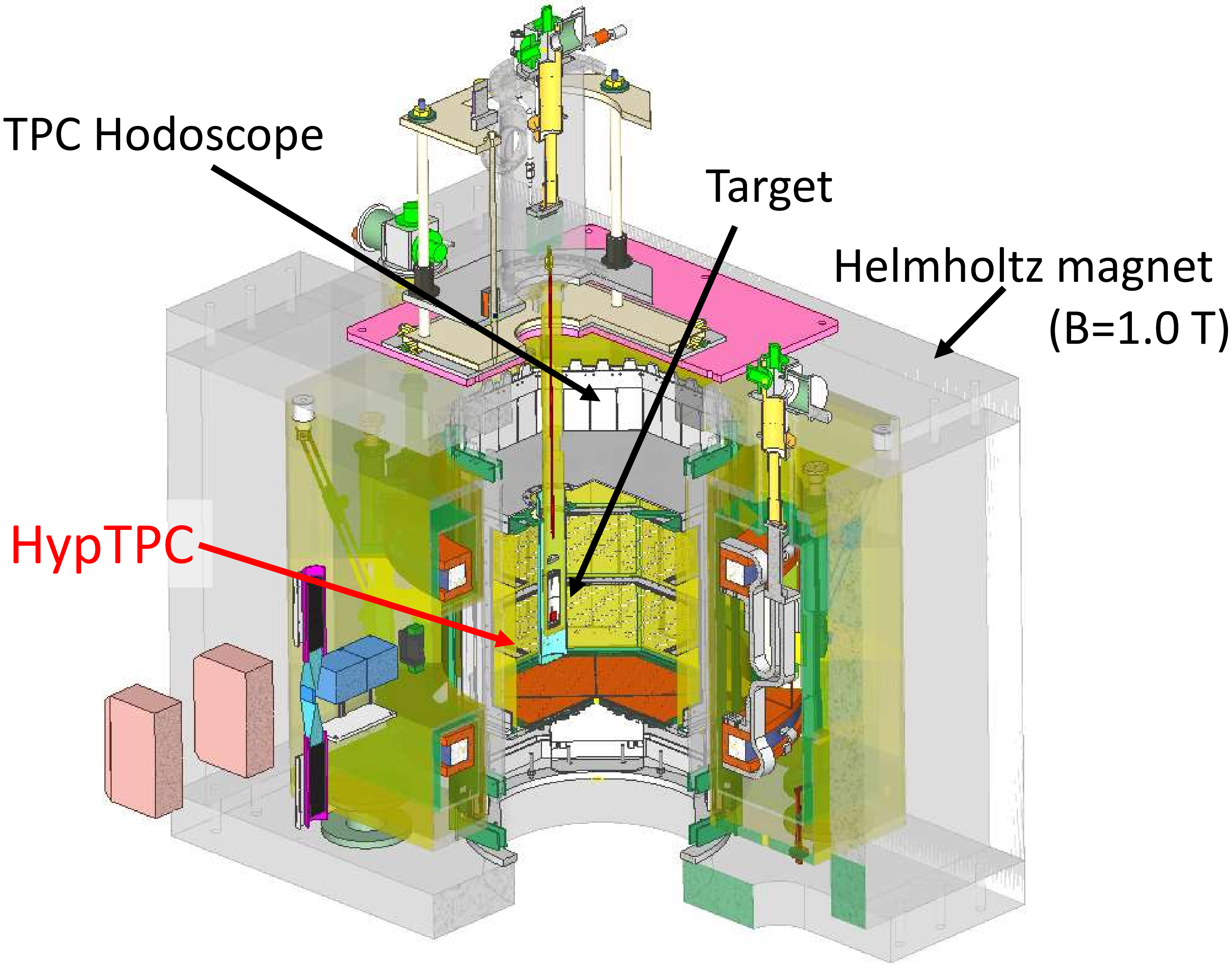
Introduction

- J-PARC : multi-purpose facility with high-intensity proton beam & various 2ndary beams (π, K, n, μ…)
- Hyp-TPC: multi-purpose detector for hadron spectroscopy – compact but large acceptance

Contents

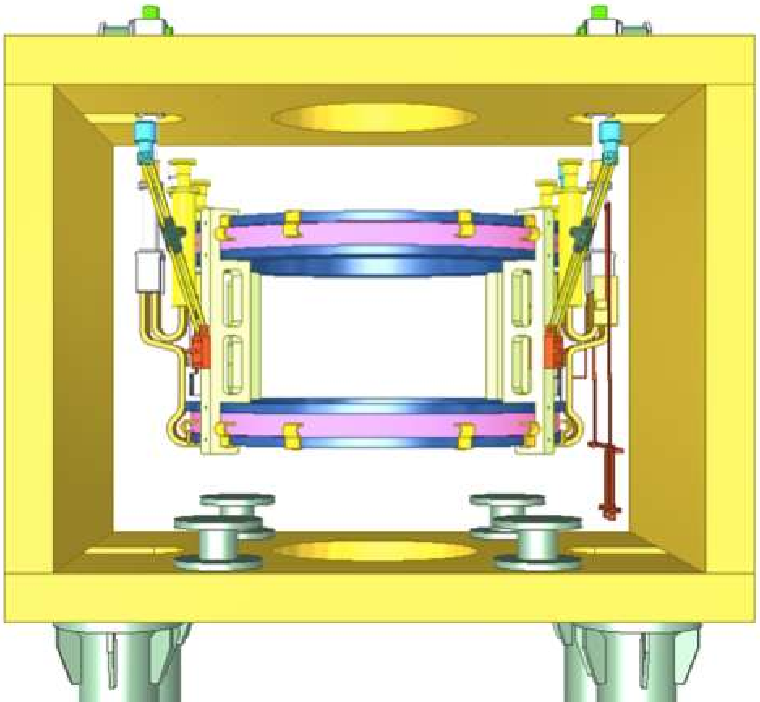
Part I.
Hyperon Spectrometer
& HypTPC

Overview of Hyperon Spectrometer

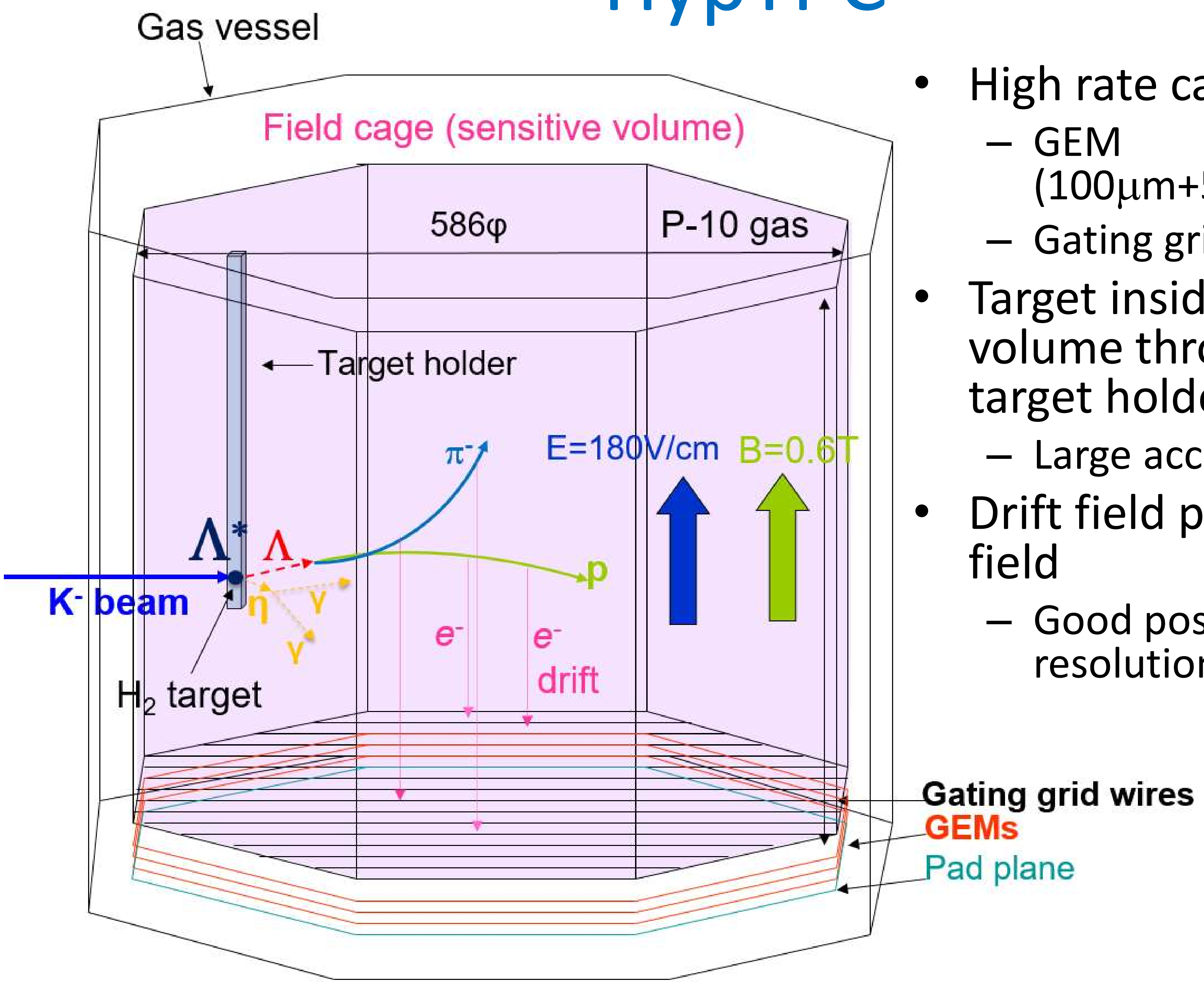


The Superconducting magnet

- Helmholz type, design maximum field : 1.5 T
- Conduction cooling with 2 GM cryocoolers
- Coil diameter : 1.0m
- Field uniformity : Br/By<1% in the TPC volume to achieve the good momentum resolution



HypTPC

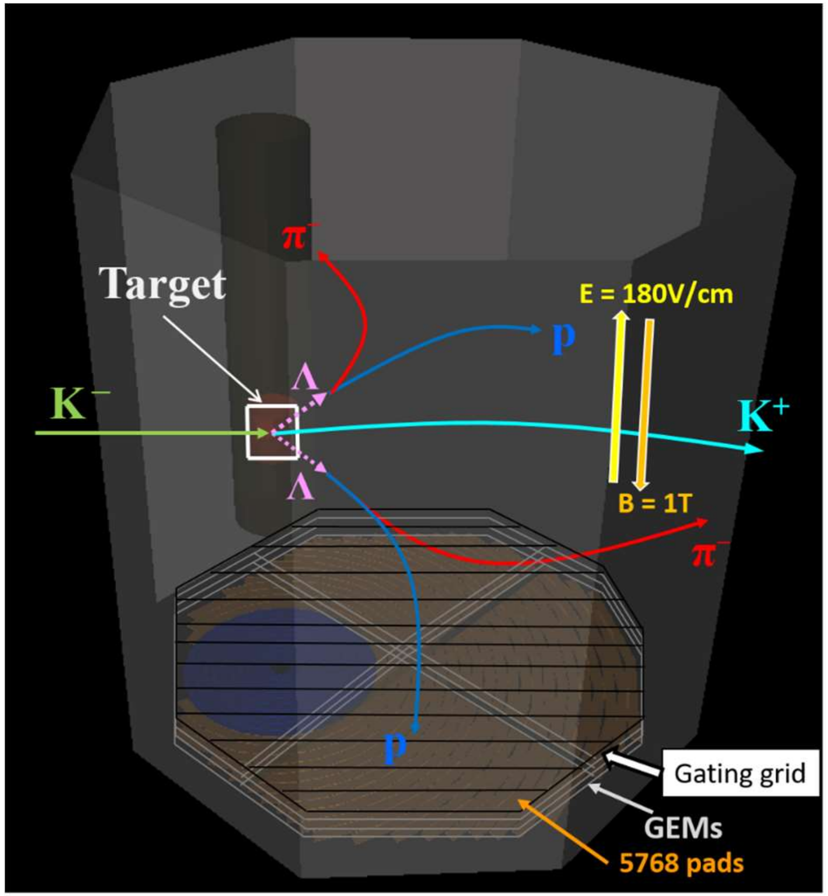


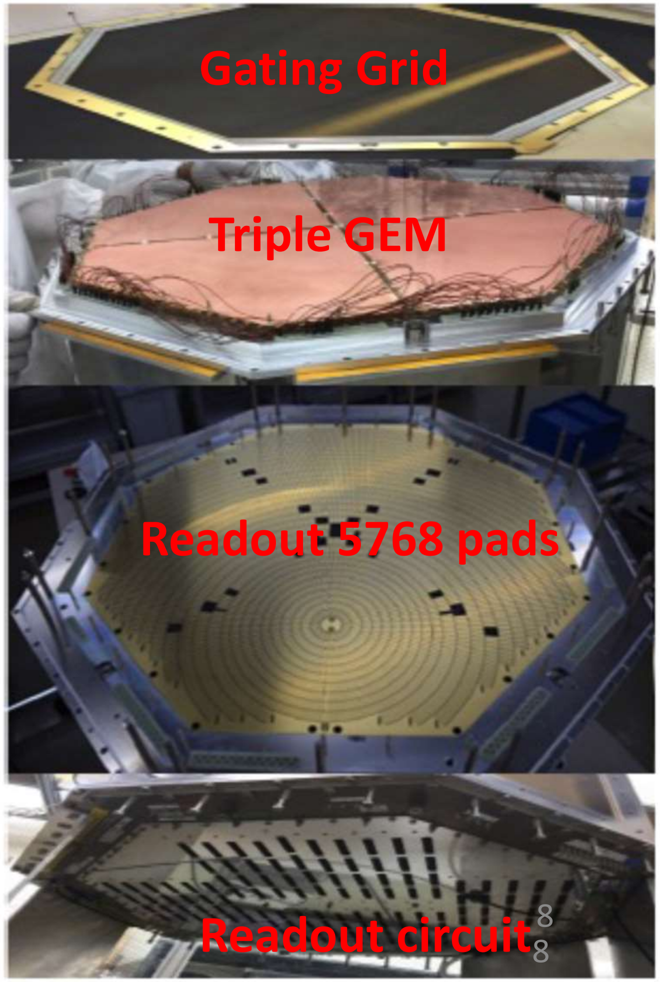
- High rate capability
  - GEM (100μm+50μm+50μm)
  - Gating grid
- Target inside the drift volume through the target holder
  - Large acceptance
- Drift field parallel to B-field
  - Good position resolution

More on HypTPC

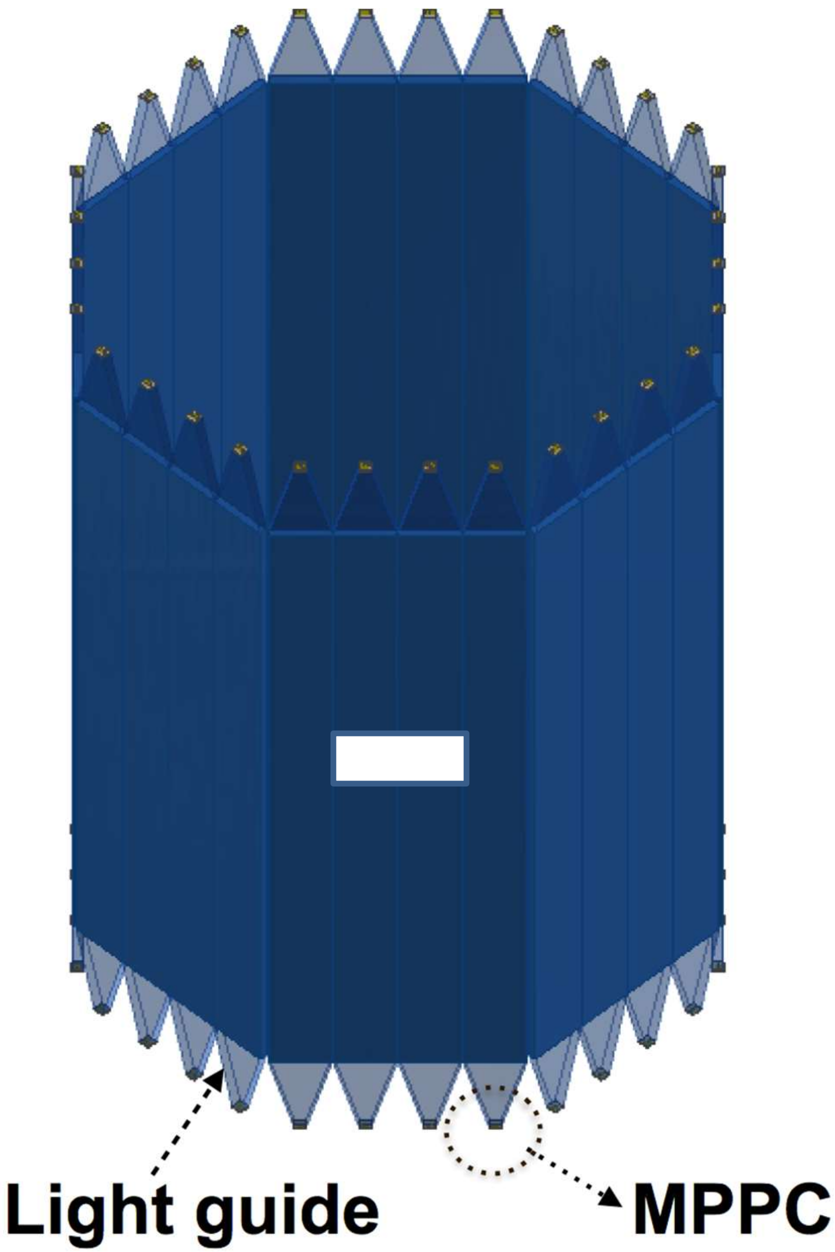
- Octagonal prism field cage
- 5768 readout pads
  - Inner(10 rows): 2.1-2.7 × 9 mm^2
  - Outer(22 rows): 2.3-2.4 × 12.5 mm^2
- Gating grid: ϕ50 μm, 1mm space

- Gas: P-10 (v_{max} ~ 5.3 cm /s)
- Gain ~ 10^4
- Position resolution < 300 μm
- Δp/p = 1-3% for π and p





TPC Hodoscope



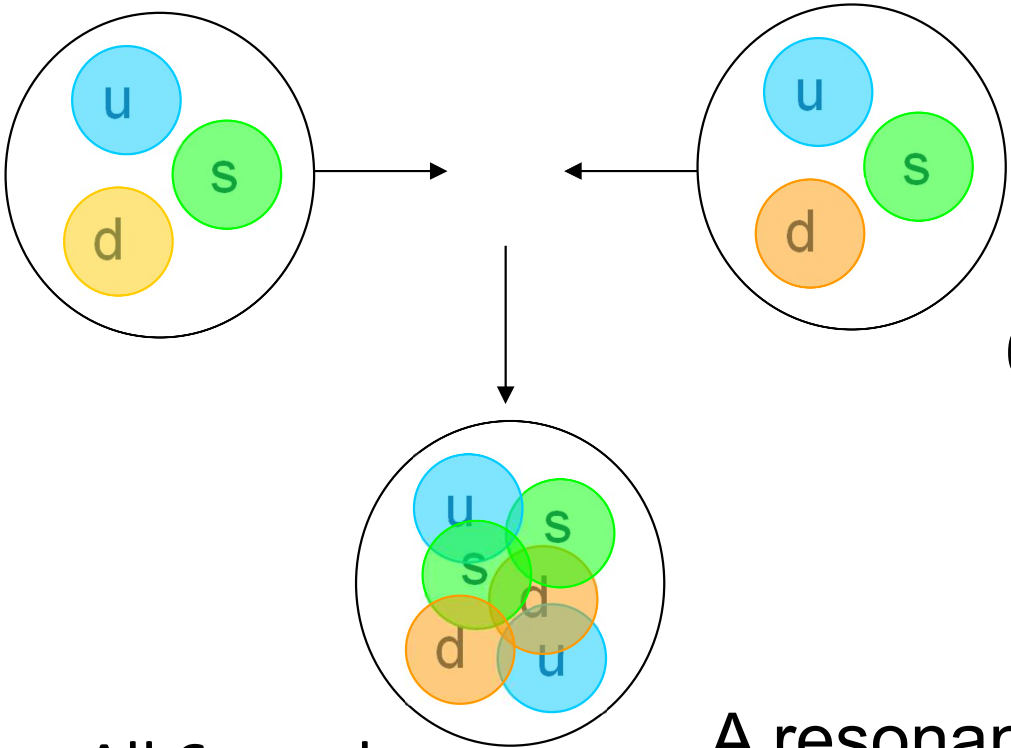
- Used for trigger/TOF
- 32 segments of plastic scintillator array surrounding HypTPC.
- Plastic scintillator of 80cm x 7cm x 1cm
- MPPCs on both ends
  – PMTs not used due to the strong magnetic field.

Part II.
Experiments using HypTPC

J-PARC E42 experiment ~Search for H dibaryon~

H dibaryon

Flavor-singlet (00) state (strangeness -2, isospin 0, or $^1S_0$ state in $\Lambda\Lambda - \Xi N - \Sigma\Sigma$ system)



All 6 quarks in s-state

Color-magnetic force is not repulsive, but attractive

6 quark state may exist

→ H dibaryon

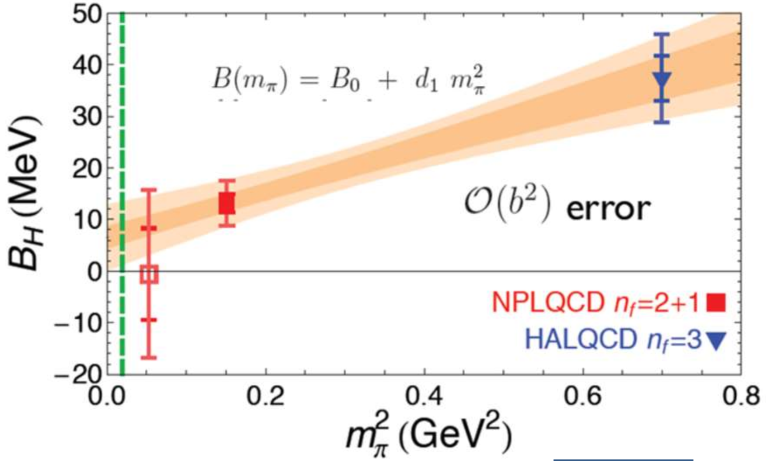
but not found so far

A resonant state just above $\Lambda\Lambda$ threshold?

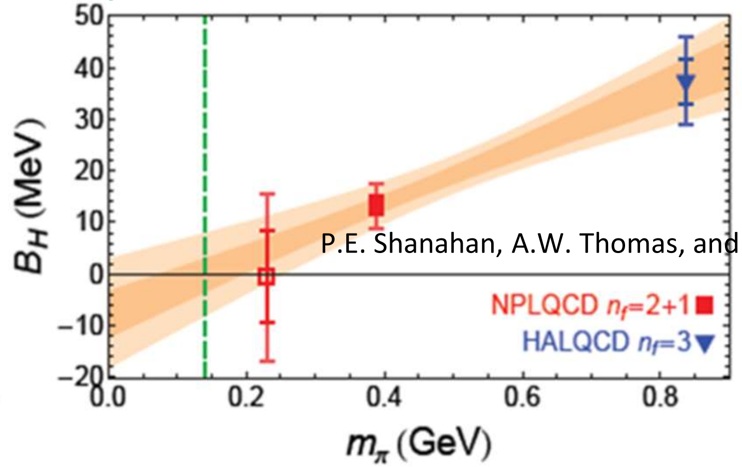
⇒ Still an open and important question

Lattice QCD calculation for H dinaryon

Physical π mass



Physical π mass

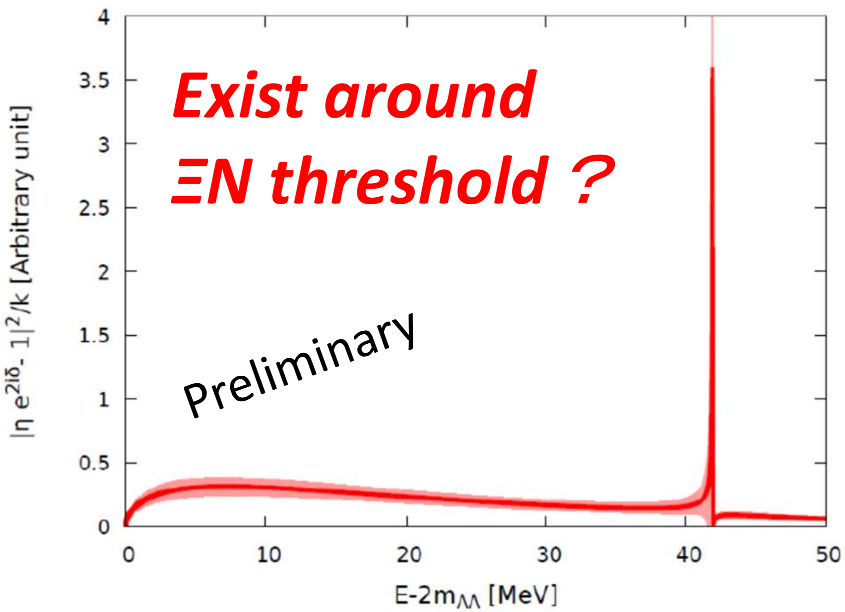


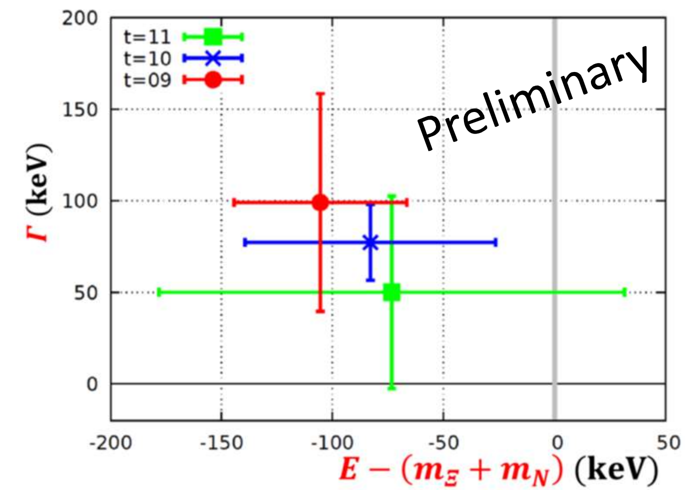
P.E. Shanahan, A.W. Thomas, and R.D. Young, PRL 107 (2011).

Calculation at almost physics point

K. Sasaki for the HAL Collab., Reimei 2016, Inha (2016).

	Mass [MeV]
π	146
K	525
m_π/m_K	0.28
N	956±12
Λ	1121±4
Σ	1201±3
Ξ	1328±3





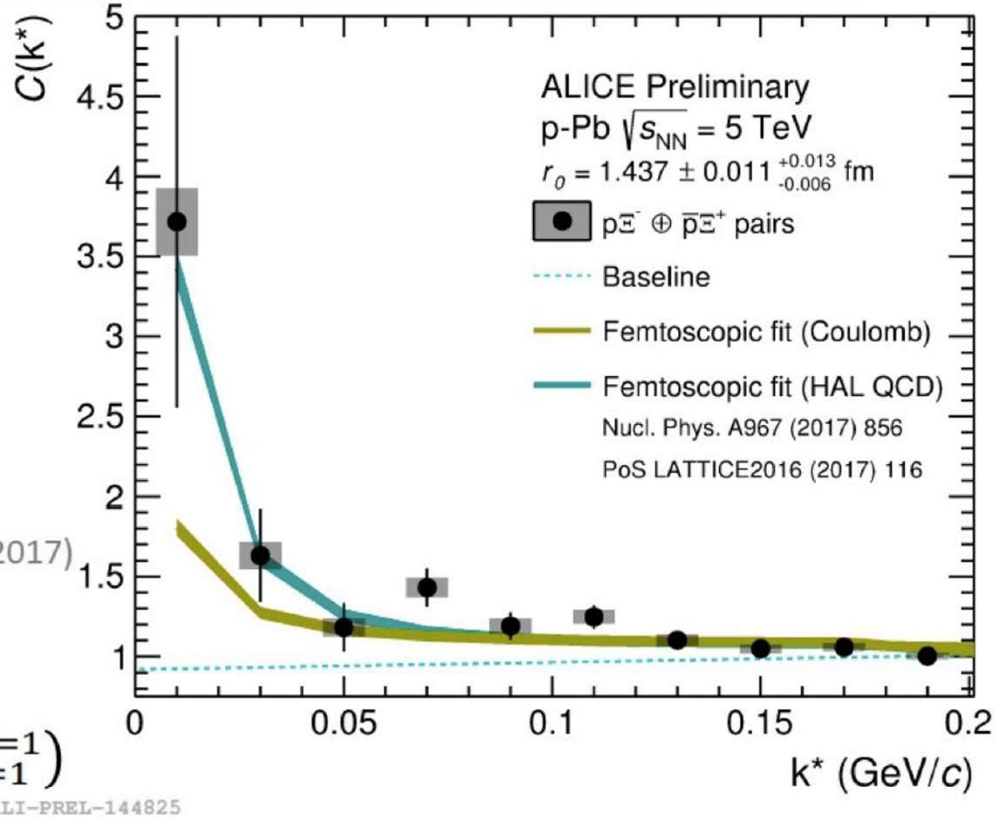
Lattice QCD vs ALICE data

ALICE

p-Ξ^- Correlation Function in p-Pb 5.02 TeV

- **First observation of strong attractive interaction in p-Ξ^-**
  - p-Value with and without strong potential (Coulomb only): 0.055 vs. 0.004
- modeled with preliminary QCD strong potential by the HAL QCD collaboration (Hatsuda et al., NPA967 (2017) 856, PoS Lattice2016 (2017) 116)

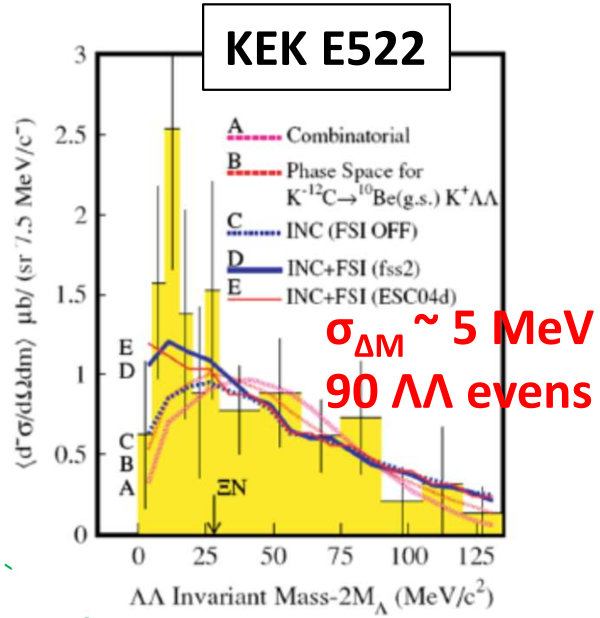
$$C(k^*) = \frac{1}{8}\left(C_{I=0}^{S=0} + C_{I=1}^{S=0}\right) + \frac{3}{8}\left(C_{I=0}^{S=1} + C_{I=1}^{S=1}\right)$$

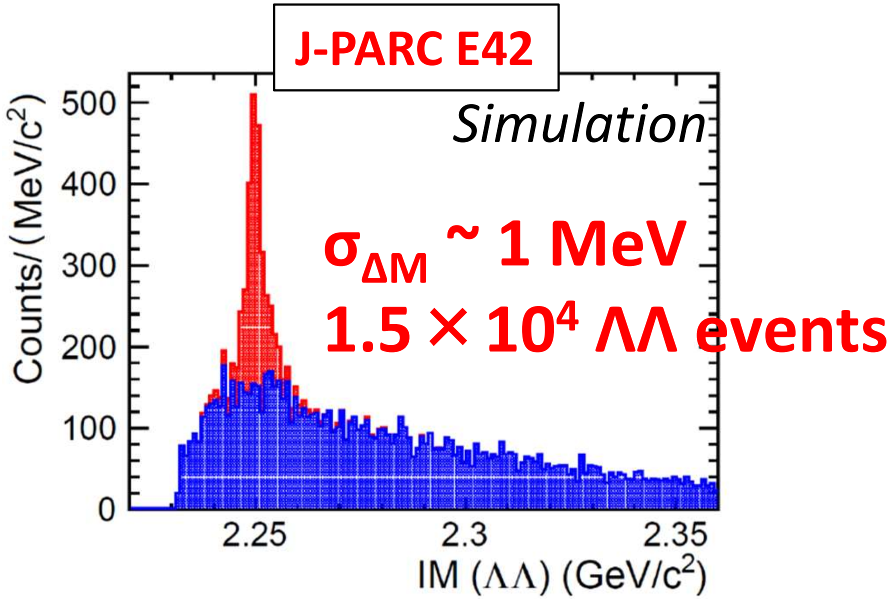


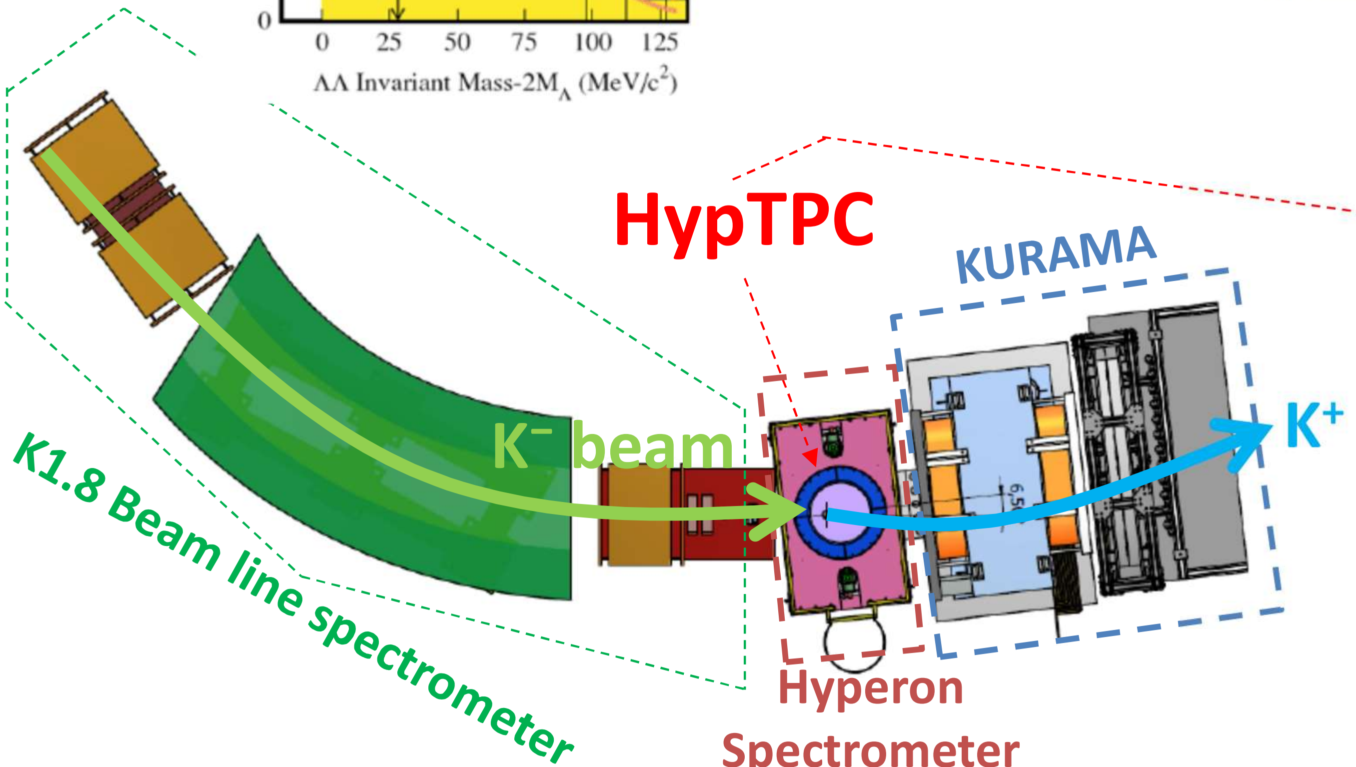
Talk by Valentina Mantovani Sarti (TUM) at MESON2018 (June 8, 2018)

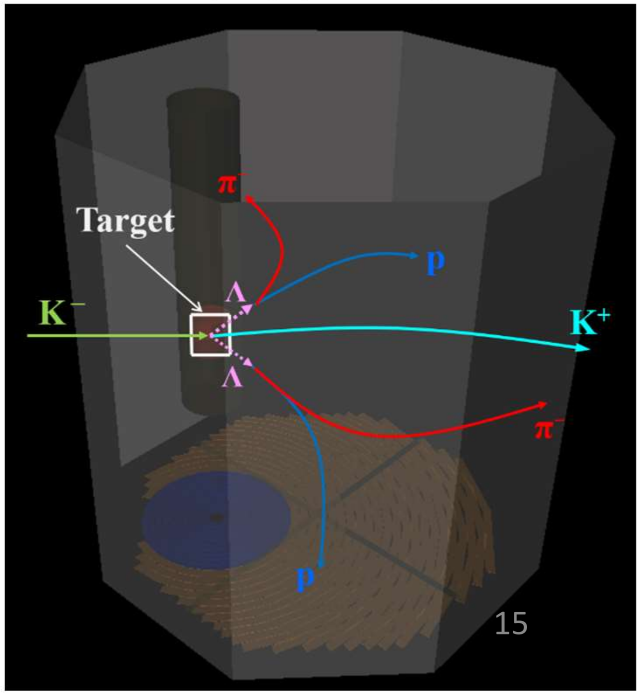
J-PARC E42 experiment

H-dibaryon search by using (K^-, K^+) reaction with diamond target.

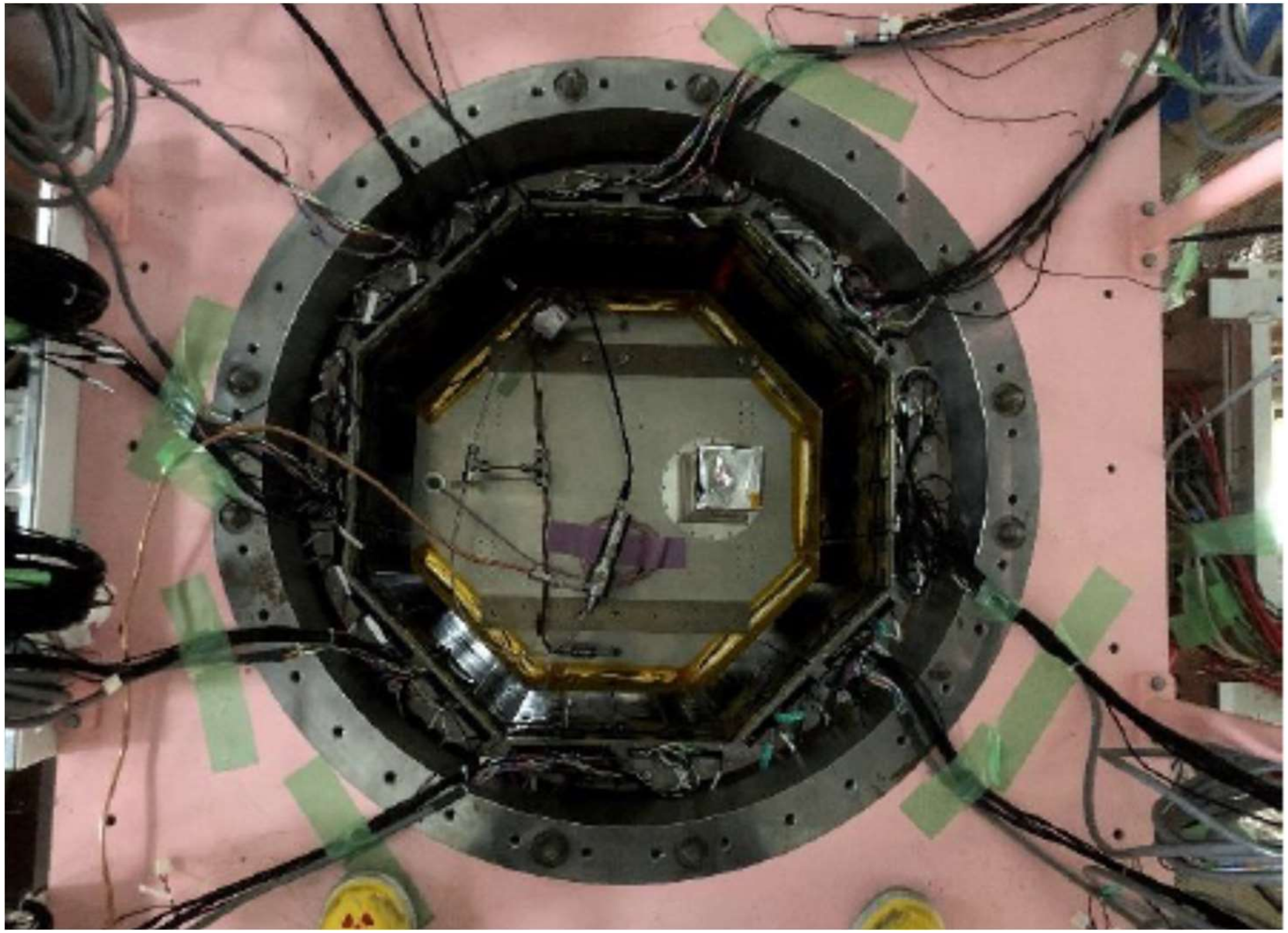






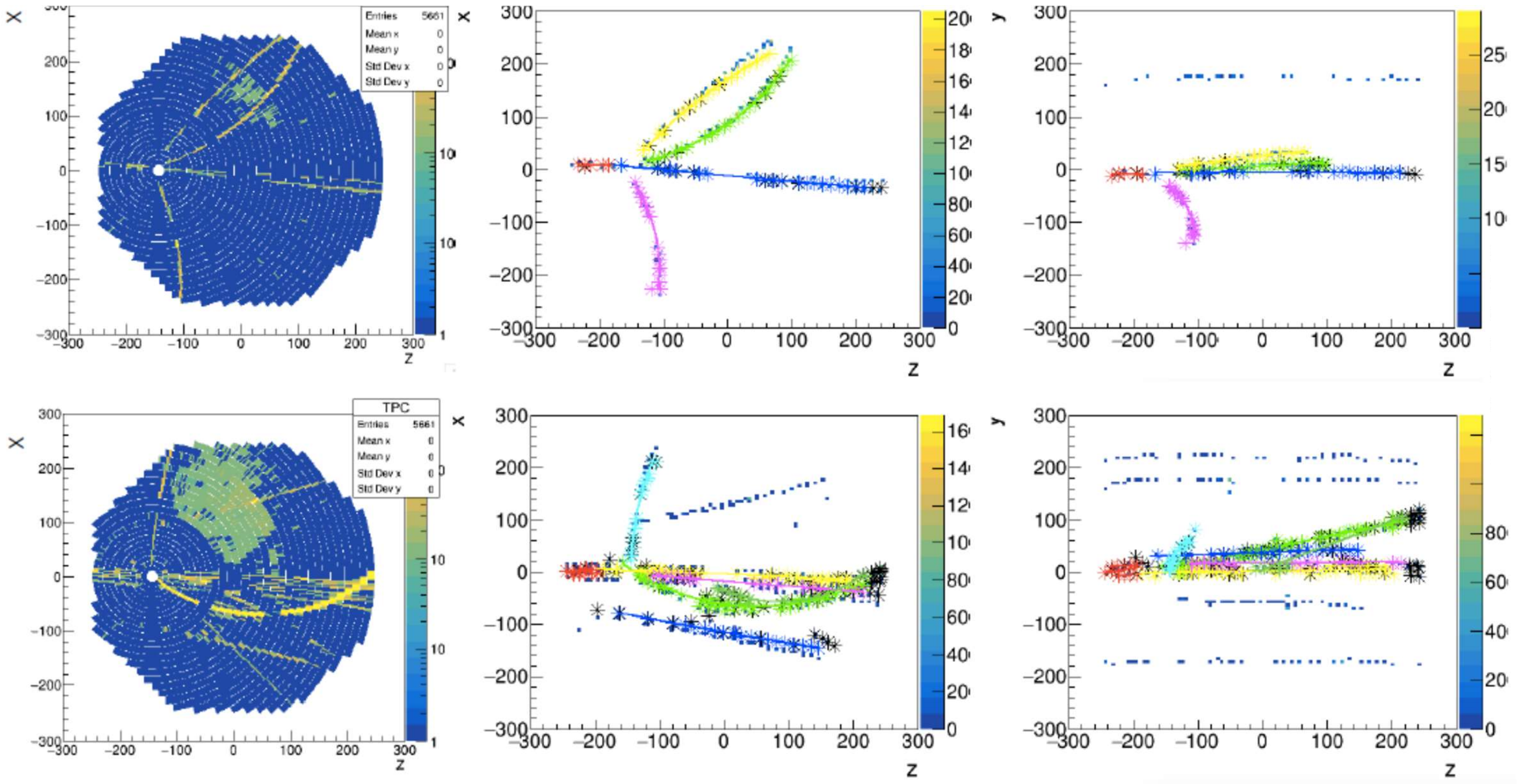


Run in 2021



- Data taking is finished
- Analysis ongoing

Event display

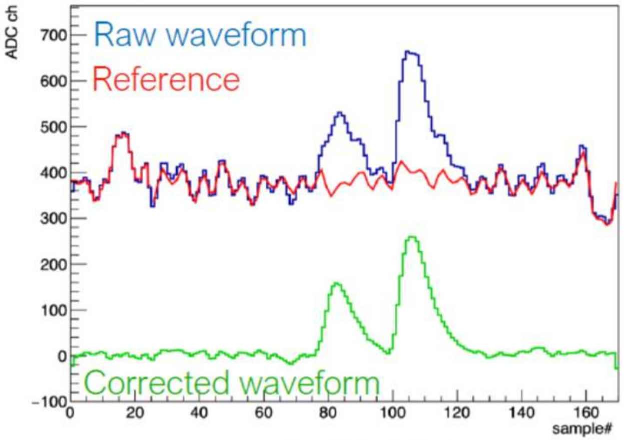


HypTPC worked very well.

Analysis status of HypTPC

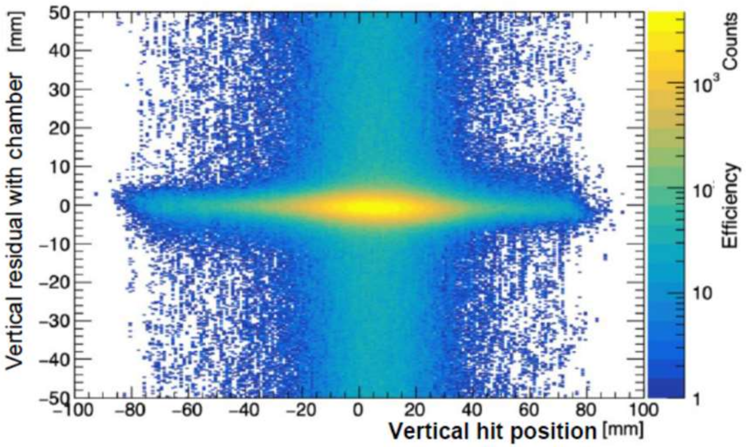
We are proceeding with careful analysis step by step, starting with basic calibration to evaluate efficiency and resolution.

Baseline correction of waveform



Even small dE MIPs, which were difficult to see due to noise in the online analysis, can be analyzed.

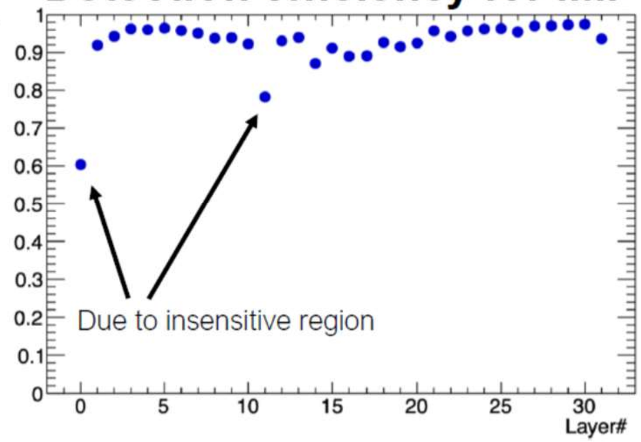
Drift velocity correction



Calibration using a drift chamber is also in progress.

We obtained the layer efficiency of ~94% in average.

Detection efficiency for MIP

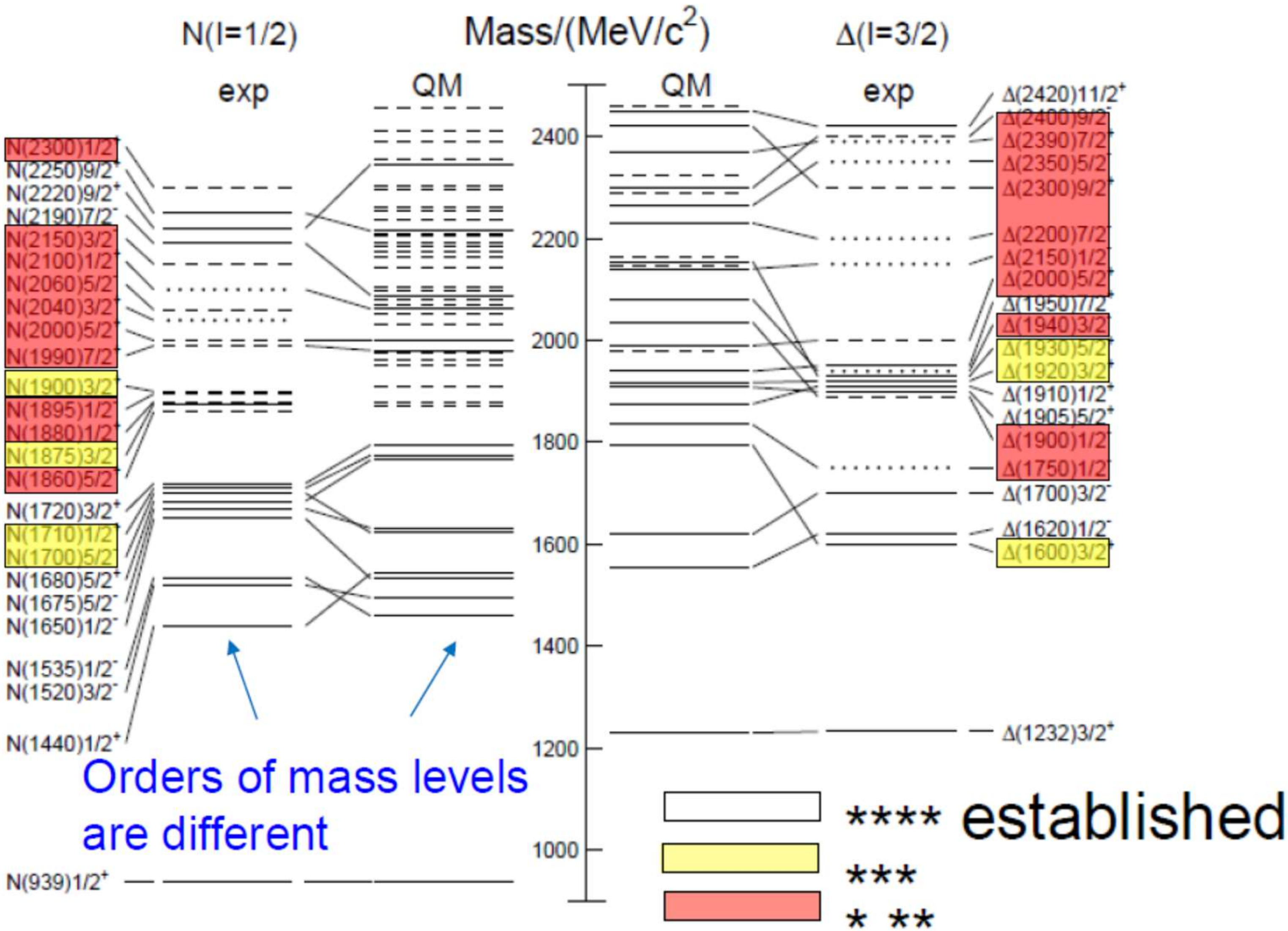


J-PARC E45 experiment

~Baryon spectroscopy by using $p(\pi, 2\pi)$ reaction~

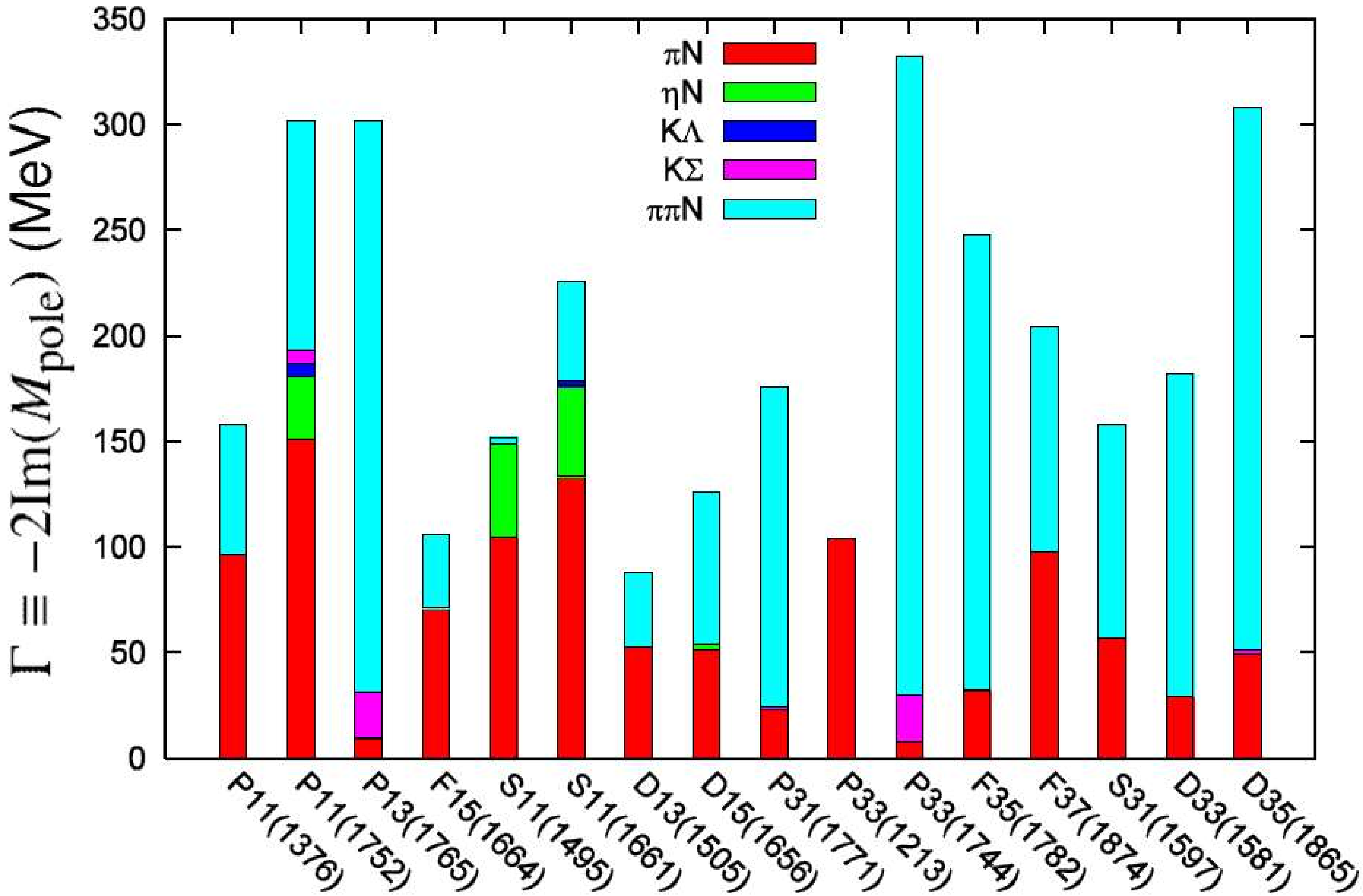
Missing resonances

- A lot of states are predicted by QM, but not observed
- Measured by using mainly $\pi N \rightarrow \pi N$, $\gamma N \rightarrow \pi N$ reactions



Importance of ππN (Width of *N** resonances)

Over half of the decay branchig fraction goes into 2π channel.



Kamano, Nakamura, Lee, Sato, 2012

E45 setup

Measure (π,2π) in large acceptance TPC in dipole magnetic field

$\pi^- p \rightarrow \pi^+ \pi^- n,\ \pi^0 \pi^- p$ 2 charged particles + 1 neutral particle

$\pi^+ p \rightarrow \pi^0 \pi^+ p,\ \pi^+ \pi^+ n$ $\rightarrow$*missing mass technique*

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

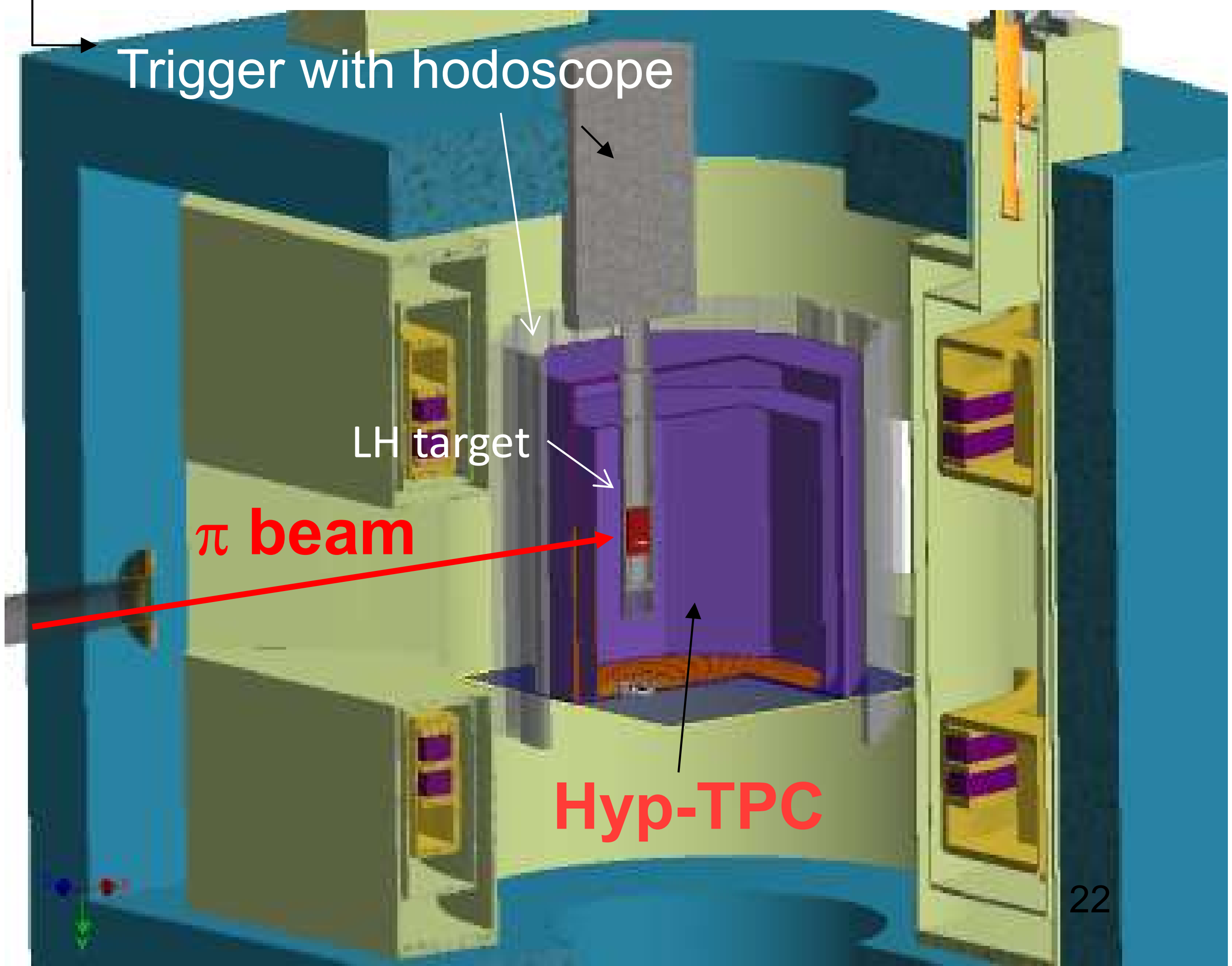
$\pi^- p \rightarrow K^0 \Lambda$,

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

π^{+-} beam on liquid-H target
(p= 0.73 – 2.0 GeV/c
W=1.5-2.15 GeV)

x100 more statistics than ever

Run expected in 2025-2026



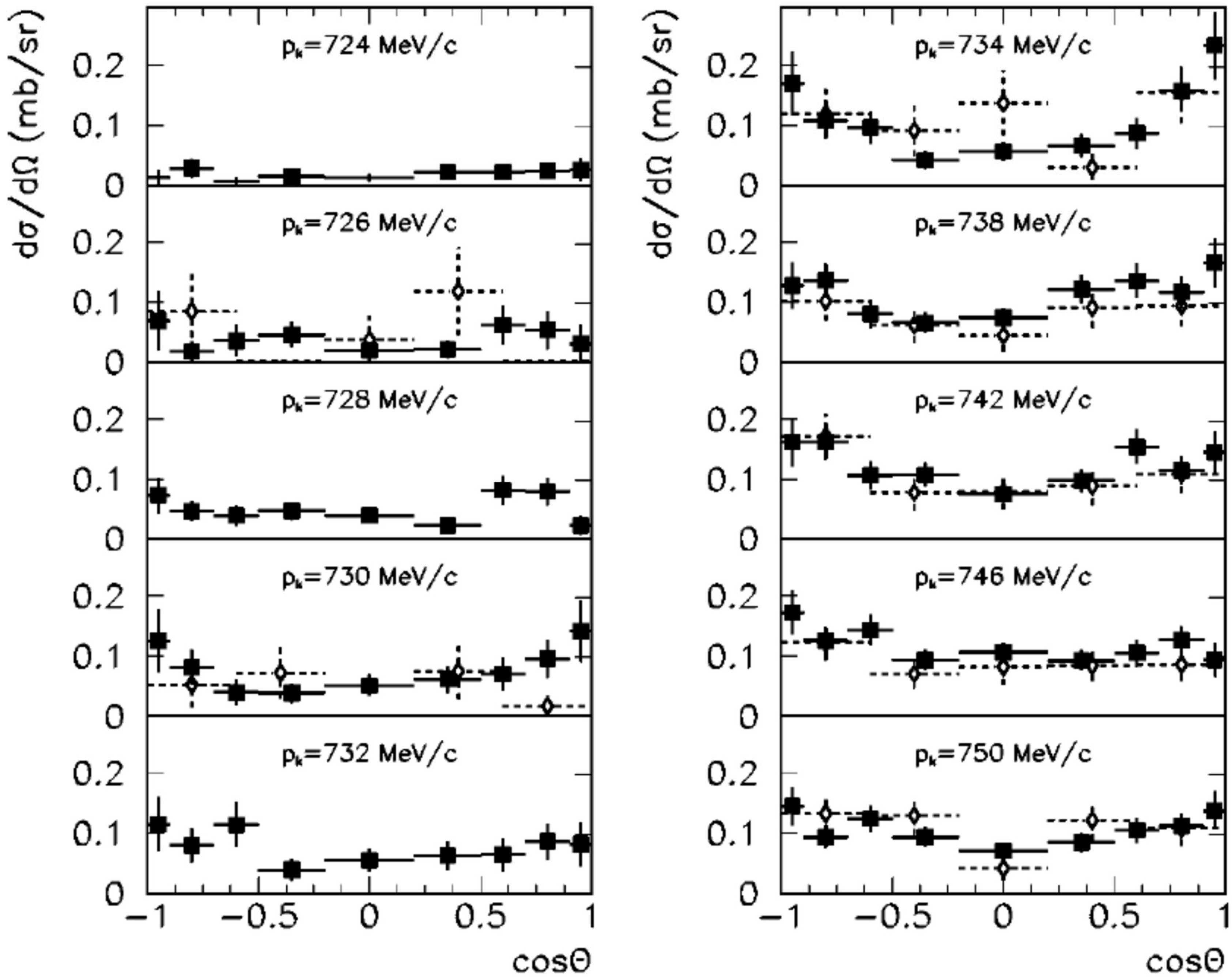
J-PARC E72 experiment

~Search for new Λ^* by using $K^- p \rightarrow \Lambda \eta$ reaction~

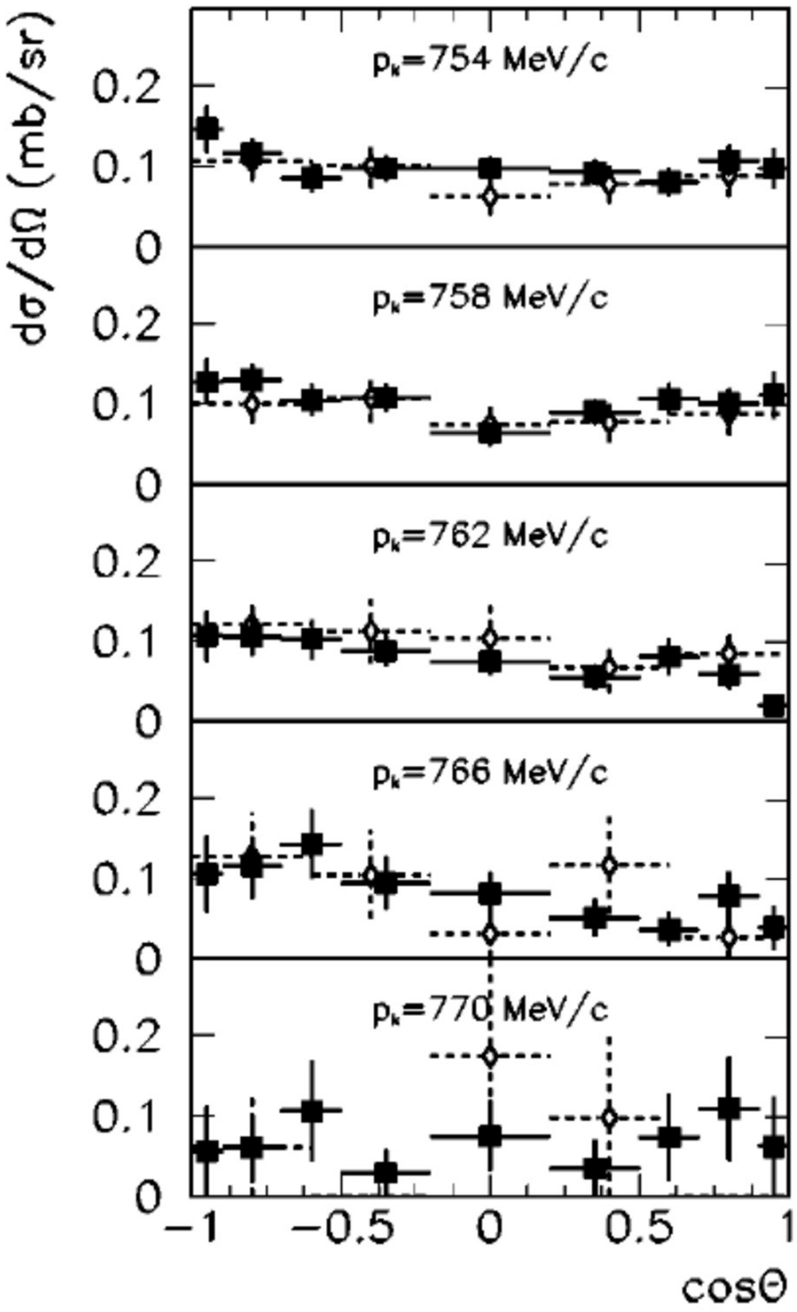
A new Λ resonance around 1670 MeV?

- 2 independent theory groups claim there is a new narrow Λ^* resonance around 1670 MeV with J=3/2
  - Kamano et al. [PRC90.065204, PRC92.025205]
    $J^P=3/2^+$ (P_{03}), M=1671+2-8 MeV, Γ=10+22-4 MeV
  - Liu & Xie [PRC85.038201, PRC86.055202]
    $J^P=3/2^-$ (D_{03}), M=1668.5±0.5 MeV, Γ=1.5±0.5 MeV
- The reason is the same
  - From $K^-p \rightarrow \Lambda\eta$ measurement near the threshold by Crystal Ball collaboration at BNL [PRC64.055205]
  - Model independent

Differential cross sections (1)



Differential cross sections (2)



- Flat near the threshold
  - Expected for J=1/2 (S-wave)
- Concave-up around p_K=734 MeV/c (√s=1669 MeV)
- Flat again for p_K > 750 MeV/c (√s=1677 MeV)

- Concave shape requires J=3/2 amplitude → reason for a narrow resonance; model independent

What can it be?

- The experimental data suggest the existence of a new Λ^* resonance with spin 3/2 (P_{03} or D_{03}), $\Lambda(1665)$:

  Q: What is the nature of $\Lambda(1665)$, if it really exists?

  A: We have few ideas at the moment, aside from that it must be exotic, and thus very interesting.

- It is near the $\Lambda\eta$ threshold, but threshold cusp is unlikely.
  - Visible cusp appears only in S wave
- A molecular state in P or D? Then, where is the S state?
  - Cf. X(3872) & $\Lambda(1405)$ are in S wave.

→ **It may be a new type of exotic state!**

  - Mixture of a molecular state and a 3-quark state???
  - $udss\bar{s}$ pentaquark???

J-PARC E72

- Repeat the Kp → $\Lambda\eta$ experiment again with a large acceptance detector, i.e., TPC (HypTPC)
  - Confirm angular distribution & the new resonance
  - Determine parity by Λ polarization measurement
- Principle
  - K beam momentum: 720-770 MeV/c
  - Momentum resolution: 1 MeV/c or better
    → Can identify narrow resonance of Γ=1.5 MeV
  - Detect Λ → $p\pi^-$, identify η by missing mass
- Run expected in 2024

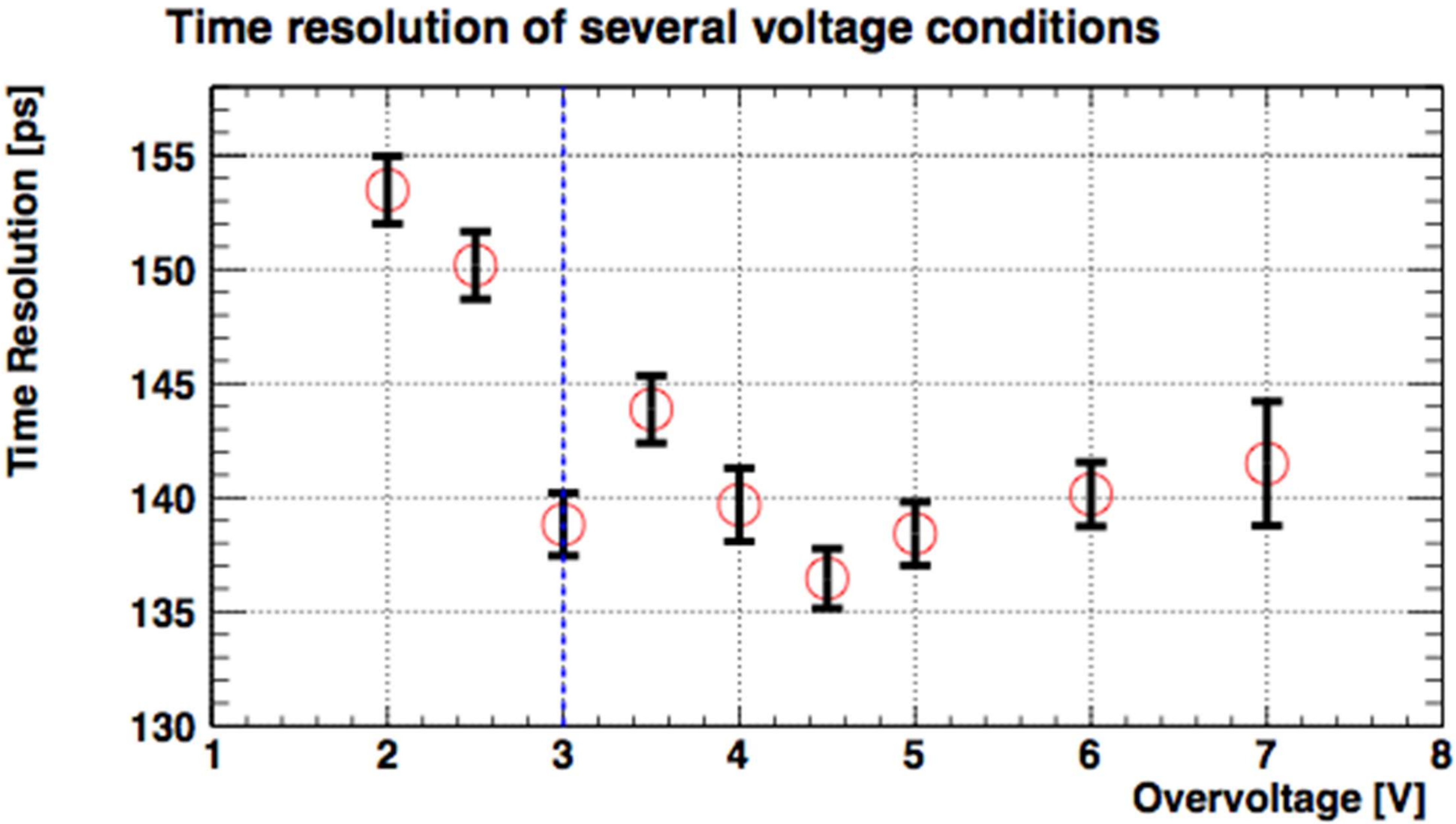
Summary

- We developed a powerful multi-purpose time-projection-chamber, HypTPC.
  - Internal target – 4π acceptance
  - High-rate capability, good momentum resolution
- Three experiments for baryons at J-PARC
  - E42: Search for H-dibaryon by using (K^-, K^+) reaction
    → Finished data taking. HypTPC worked well.
  - E45: Baryon spectroscopy by using $p(\pi, 2\pi)$ reaction
  - E72: Search for new Λ^* resonance via $p(K^-, \Lambda)\eta$
  - More are coming.

Backup

TOF resolution

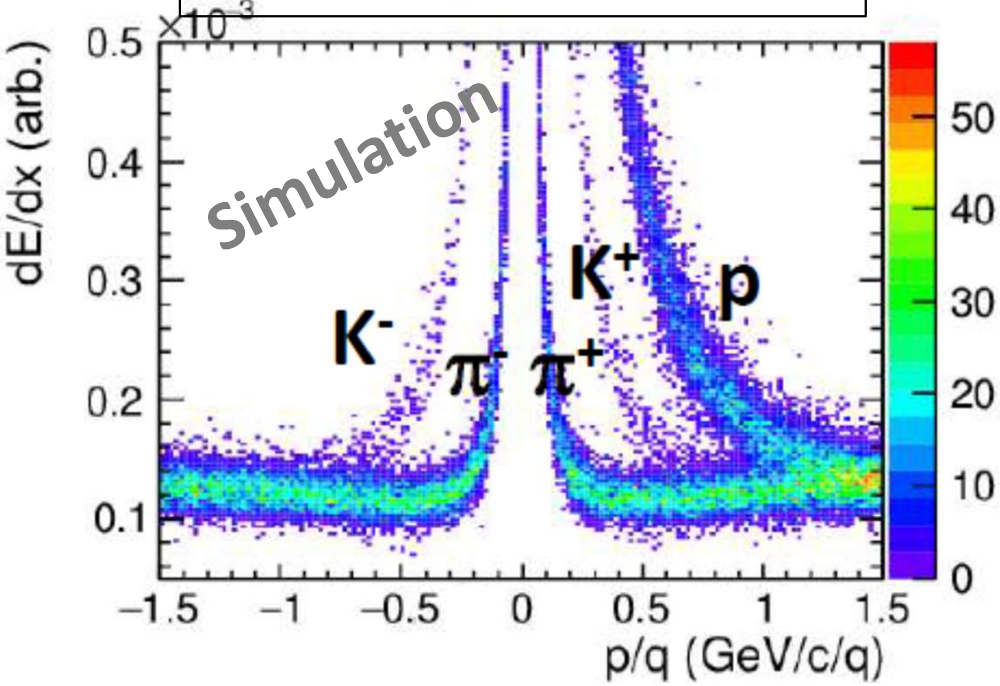
- Achieved ~140 ps resolution with a real size bar.



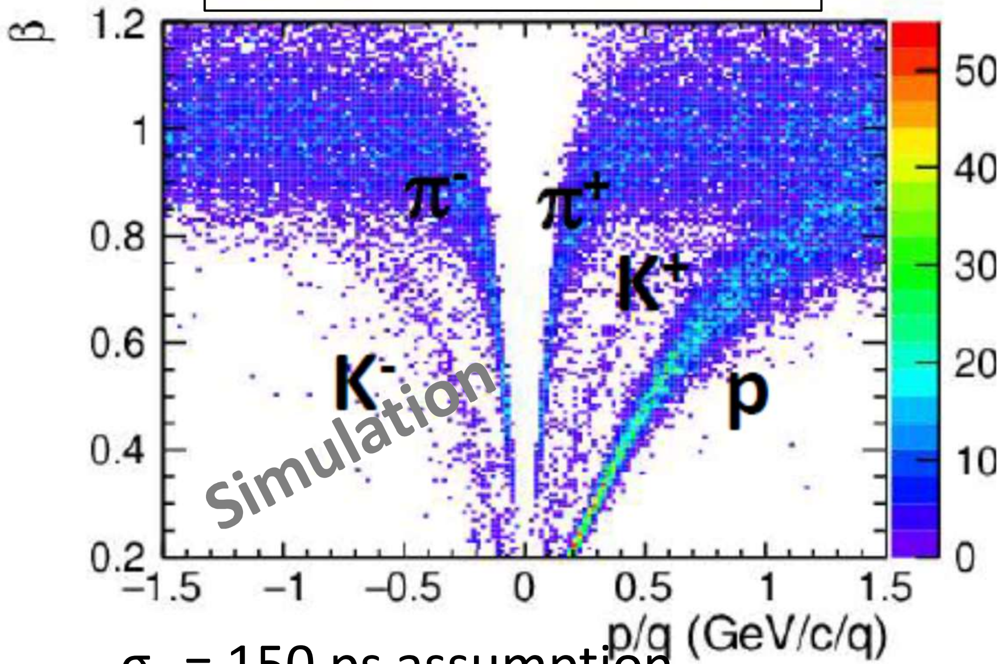
PID capability

- By dE/dx in TPC & TOF with the Hodoscope
  - π-p separation up to 0.9 GeV/c
  - K-π separation up to 0.5 GeV/c

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



PID: TOF(β) vs p/q



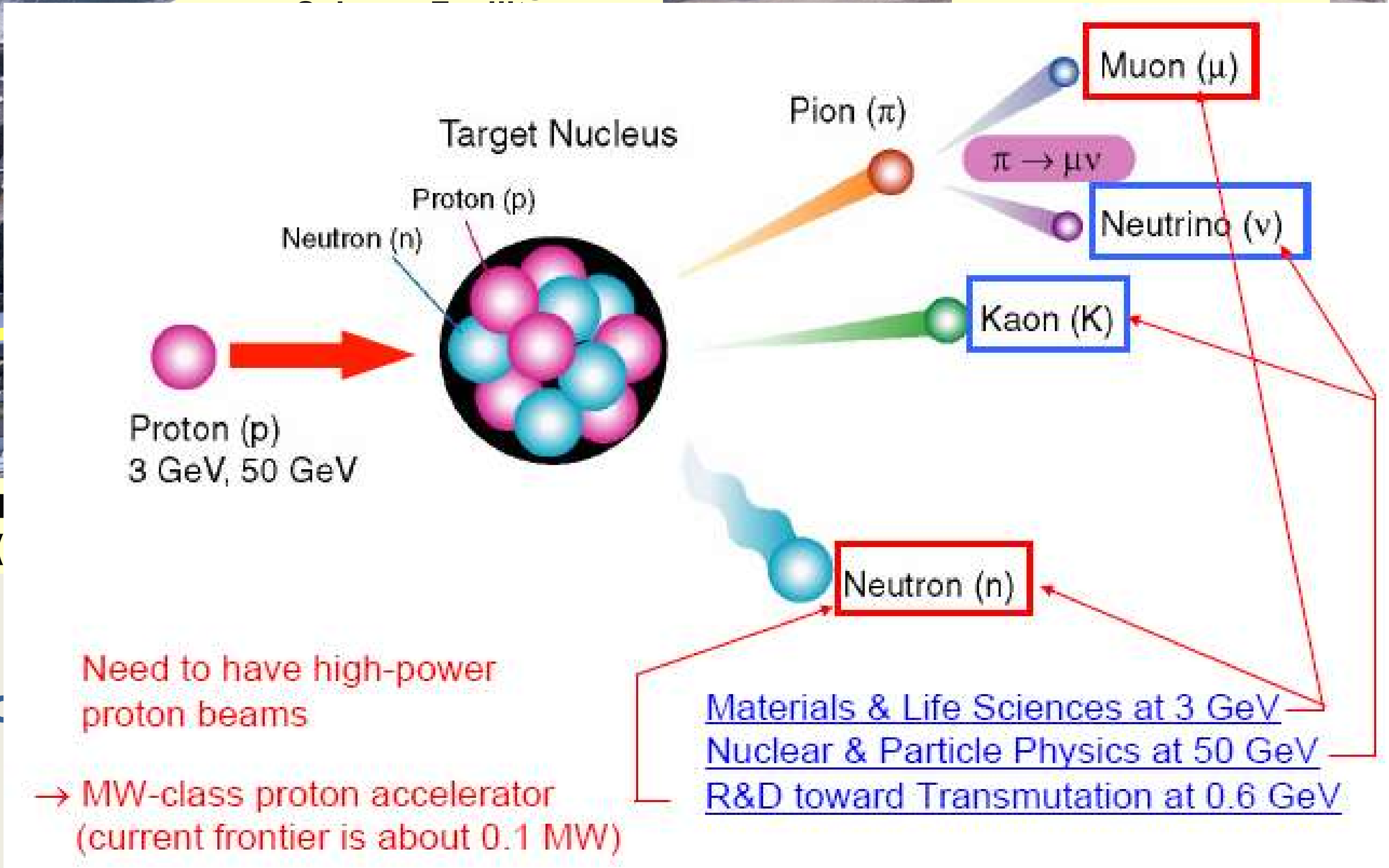
σ_T = 150 ps assumption

Part I.
Introduction of J-PARC

J-PARC

Tokai, Japan

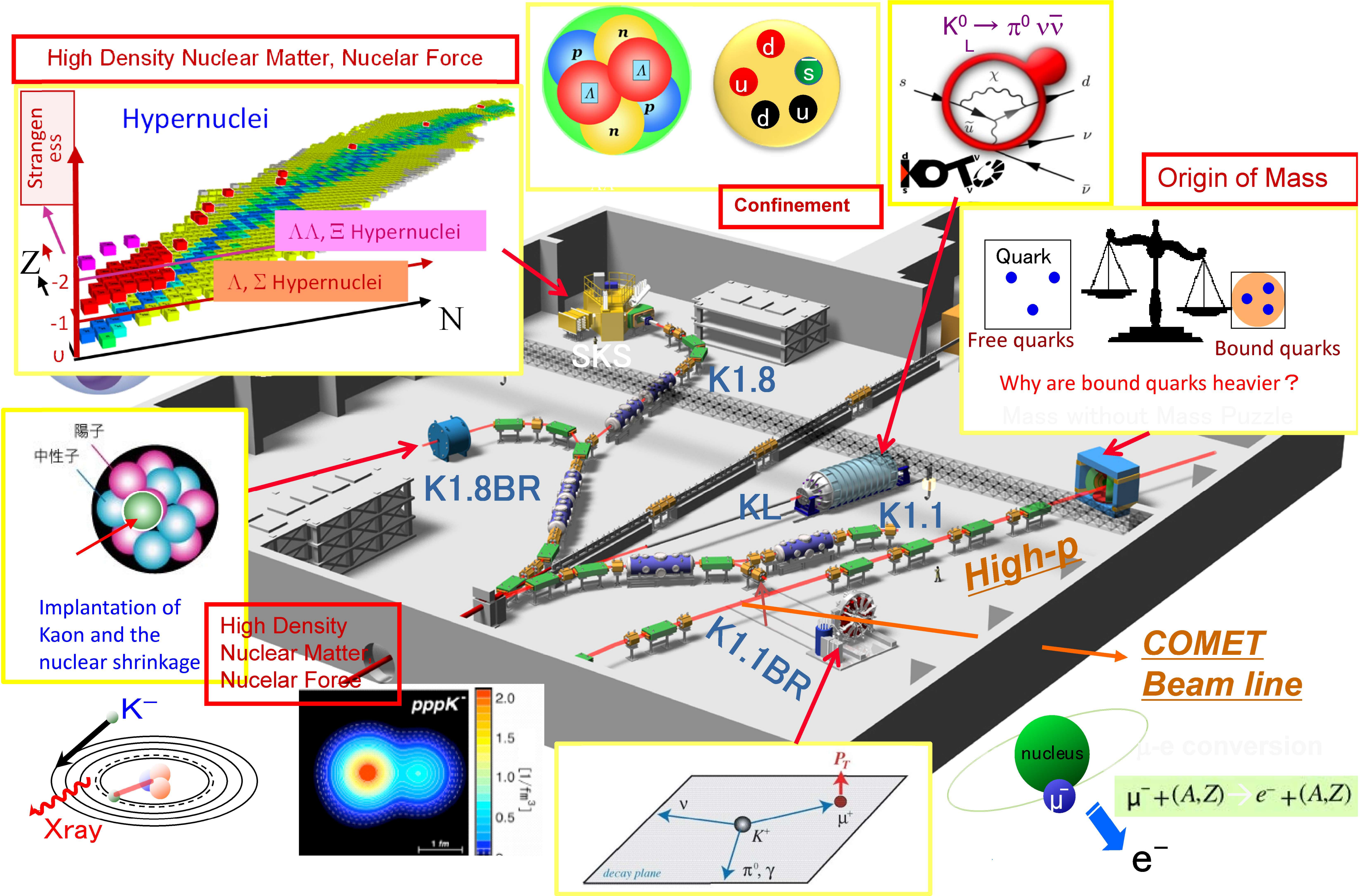
(Japan Proton Accelerator Research Complex)



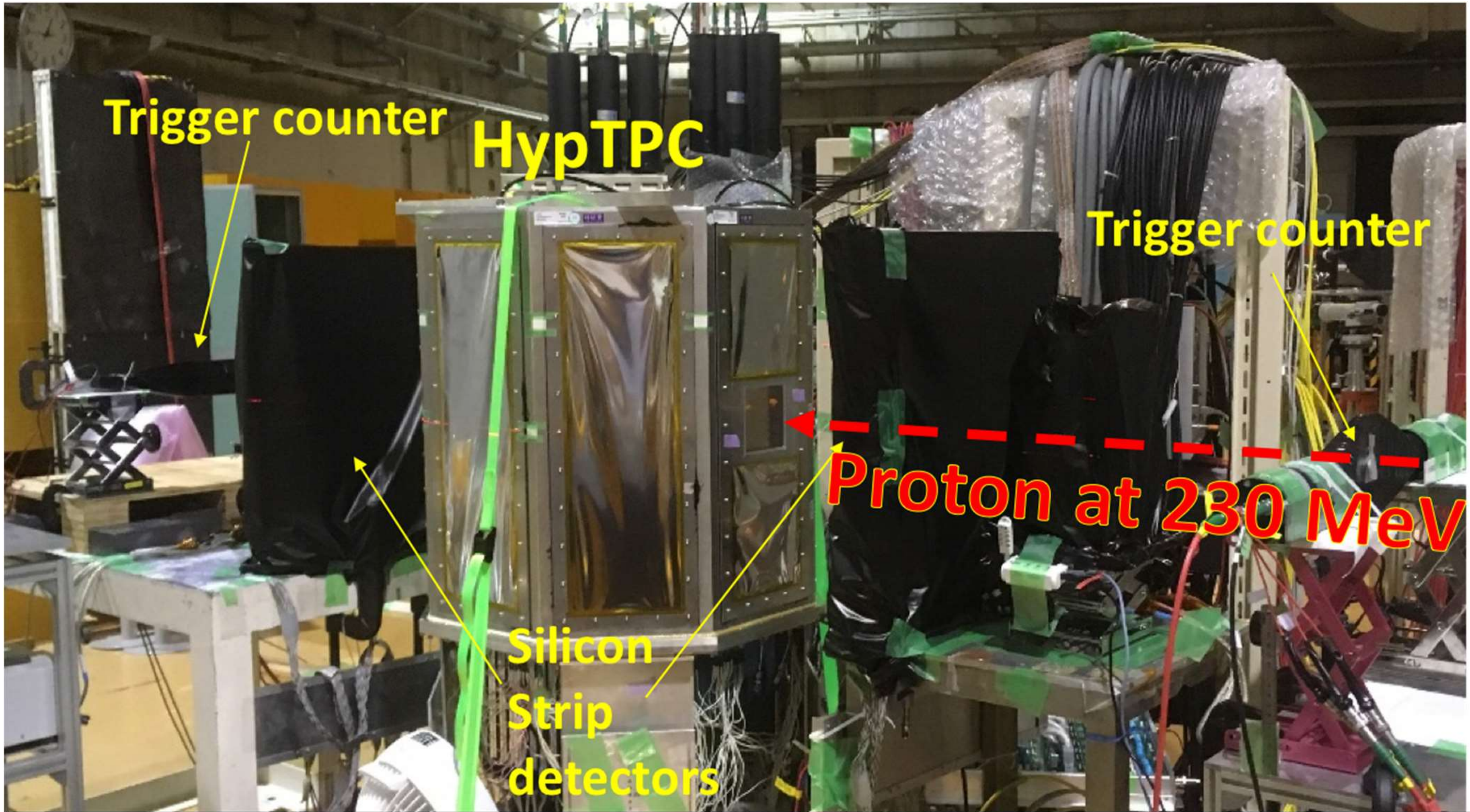
Wo

Nuclear & Hadron Physics in J-PARC

Experiments at a glance (not all)

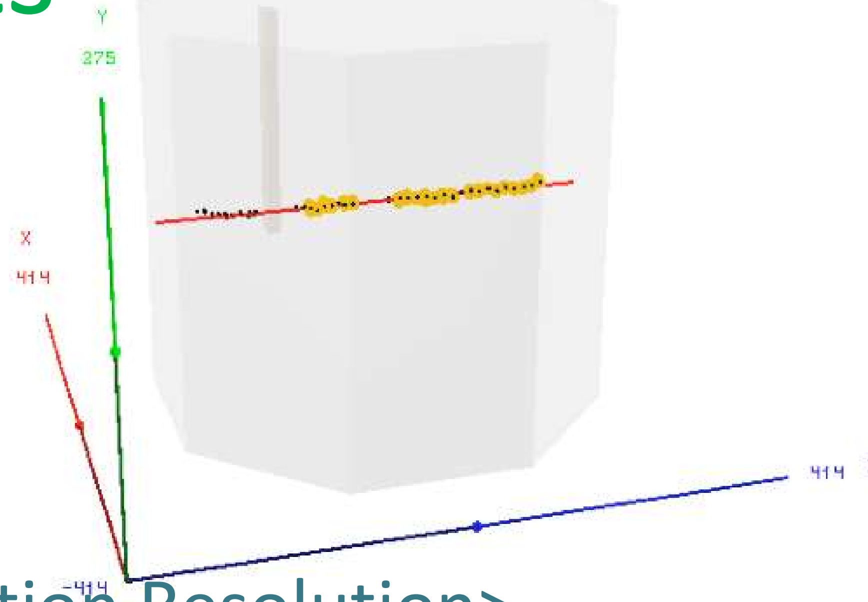


Test experiment at HIMAC



Test experiment at HIMAC (July 2018)

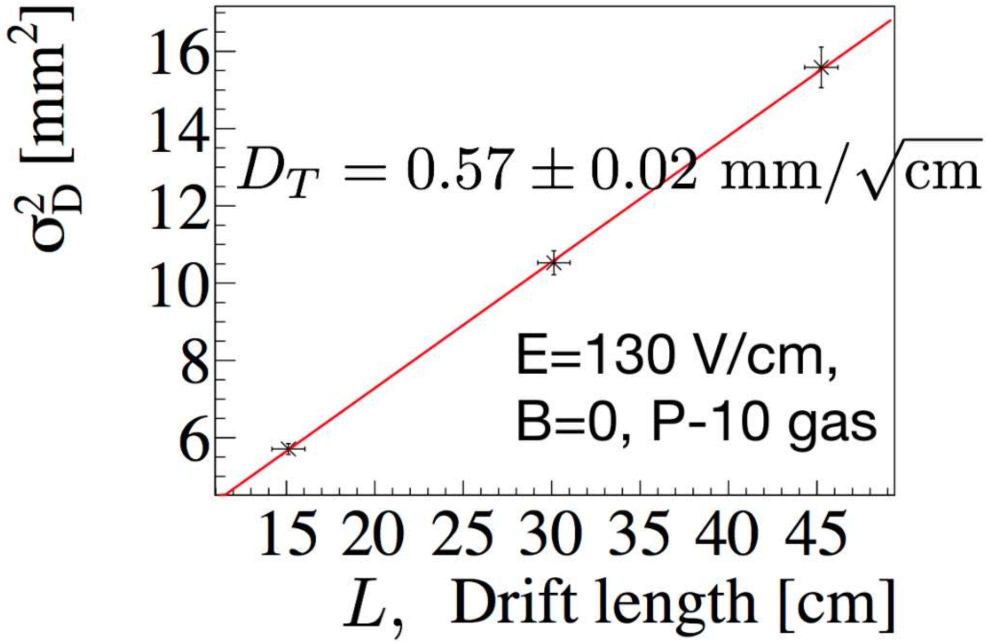
Test Results



Good resolution
obtained w/o magnetic field

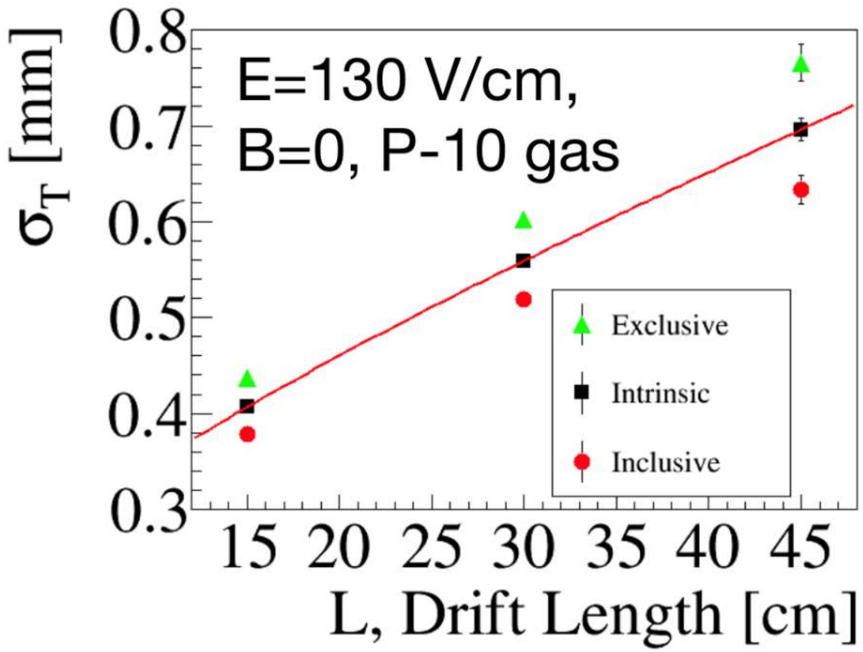
<Transverse Diffusion>

$$\sigma_T(L) = \sqrt{\sigma_0^2 + D_T^2 L}$$

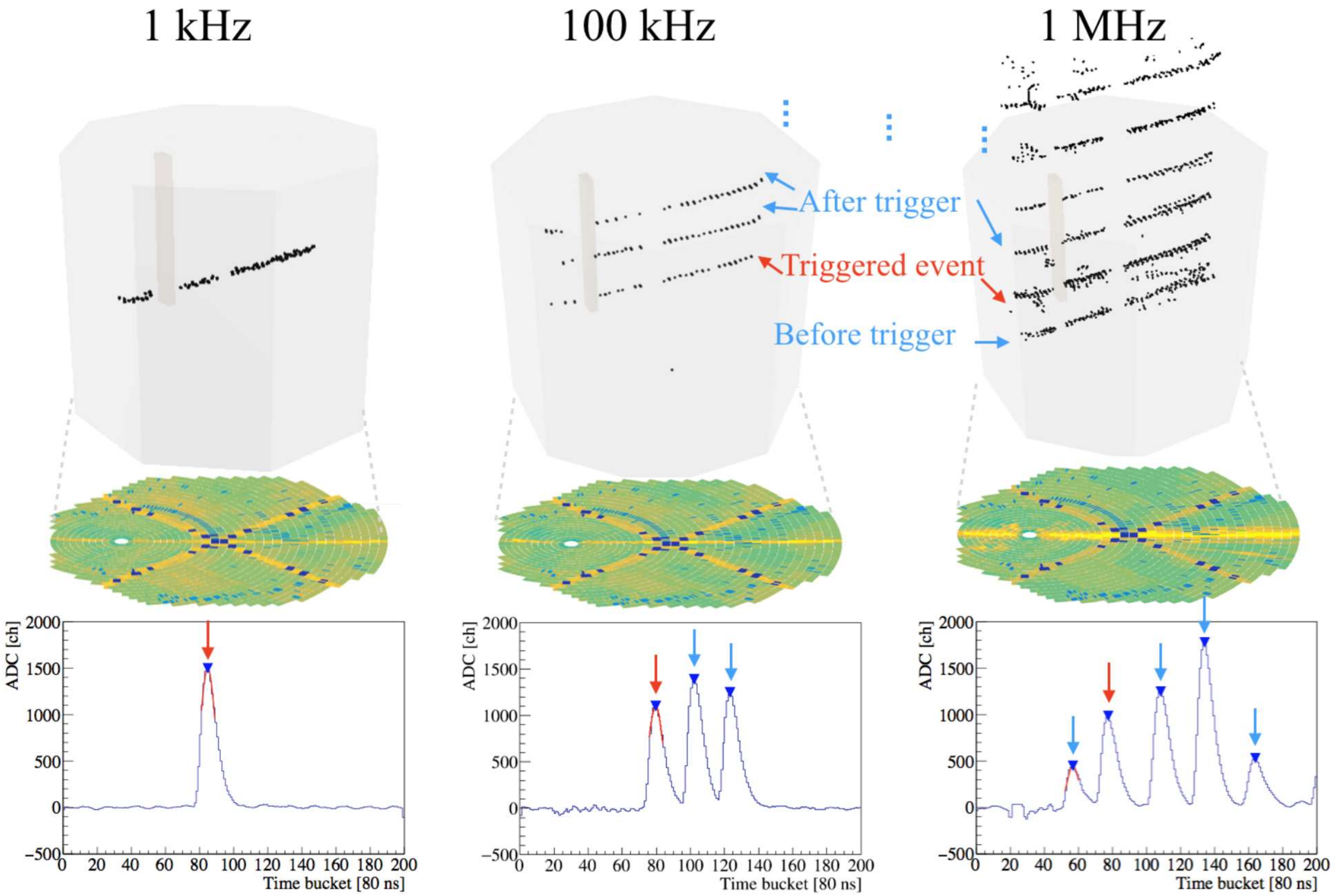


<Position Resolution>

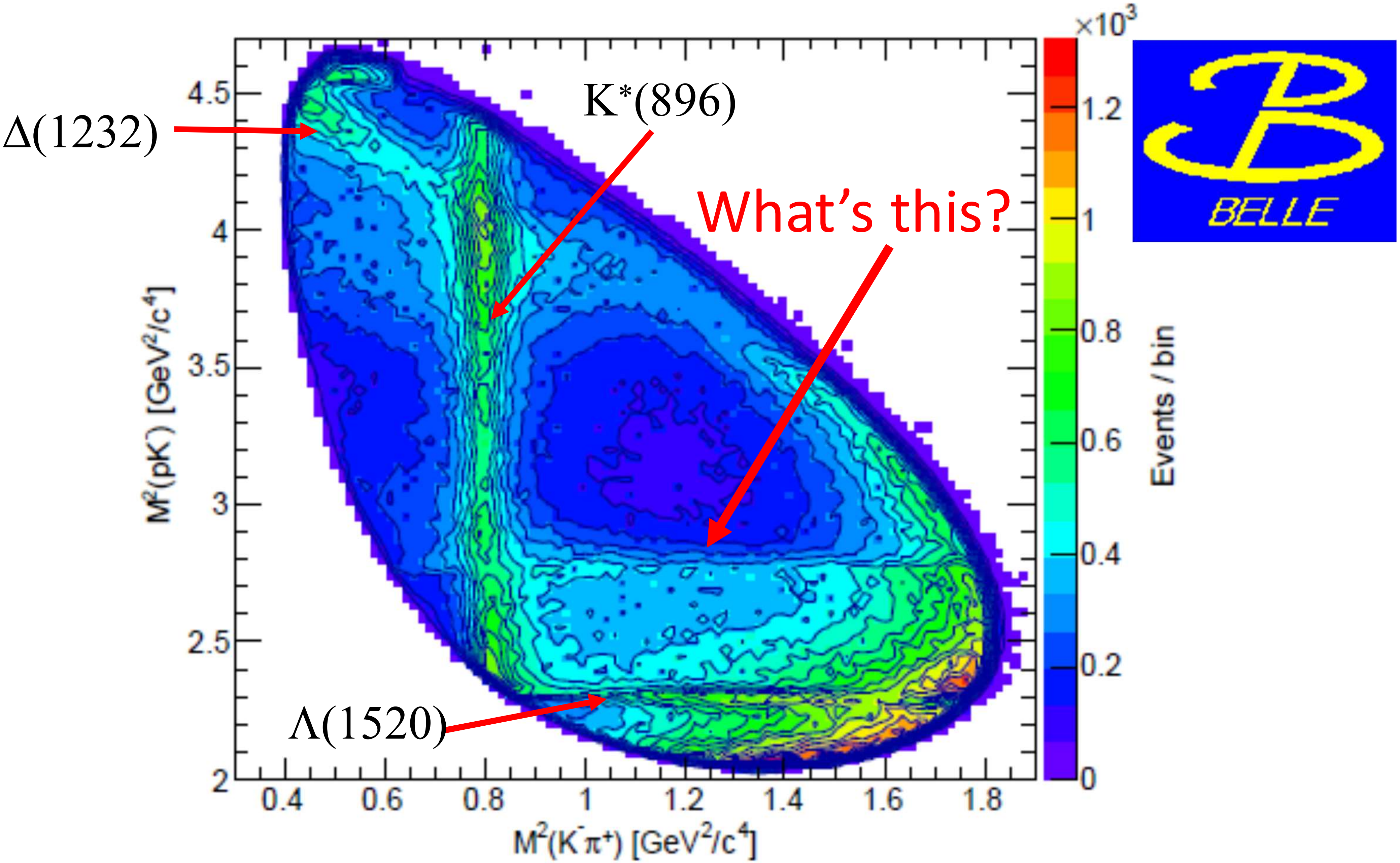
Expected to have 200-250 μm resolution under the B field of 1 T



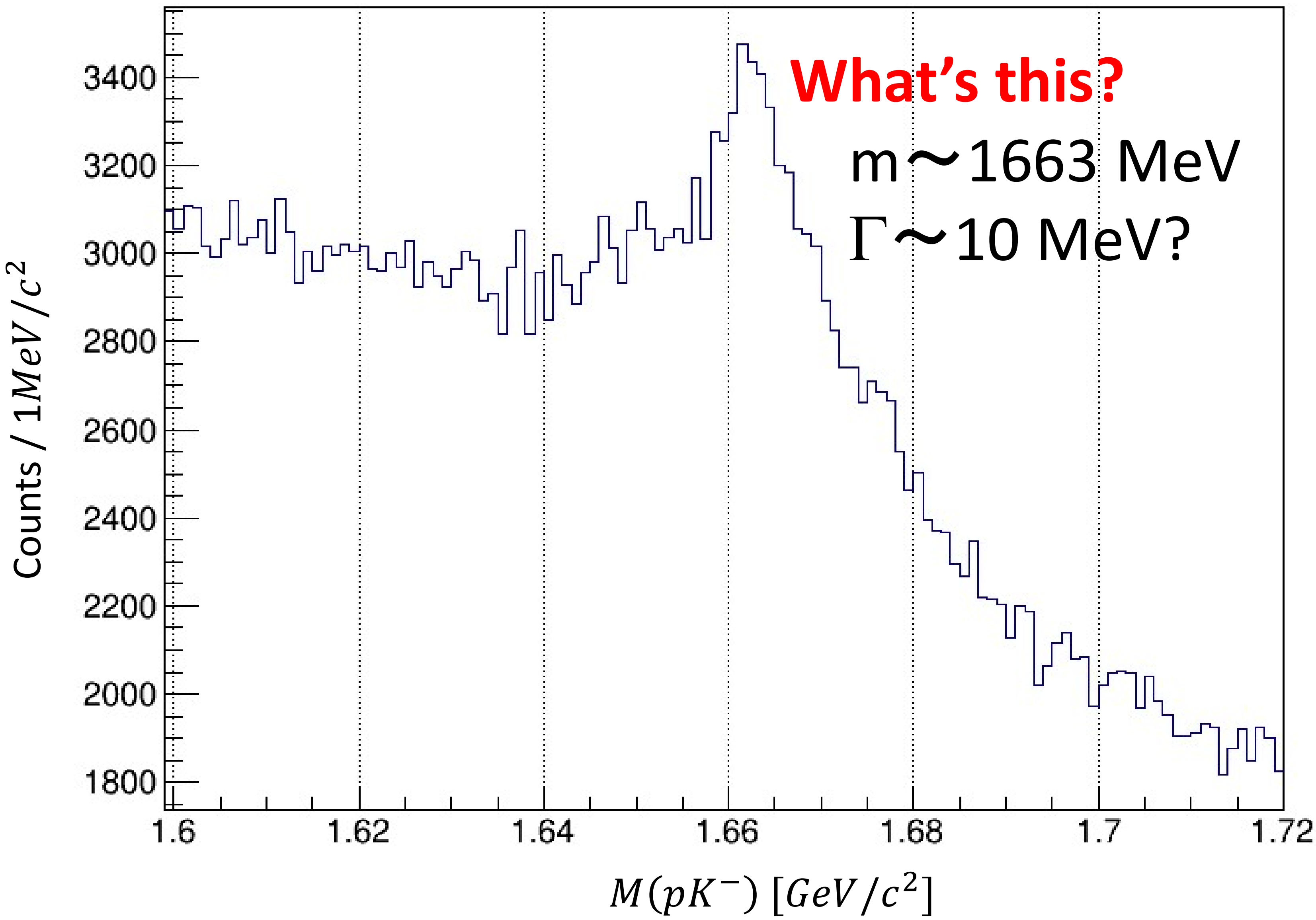
High rate capability



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



■ 1D projection -- $M(pK^-)$



What's this?

- The peak position is ~1663 MeV, near the $\Lambda\eta$ threshold (1663.5 MeV)
- Width is ~10 MeV, significantly narrower than Λ, Σ resonances in this region
  - Λ(1670): 25-50 MeV
  - Σ(1660): 40-200 MeV
  - Σ(1670): 40-80 MeV
  - Λ(1690): ~60 MeV
- No such narrow states are theoretically predicted in this region – exotic?