# Hadron spectroscopy at J-PARC with HypTPC

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@Fundamental Problems in
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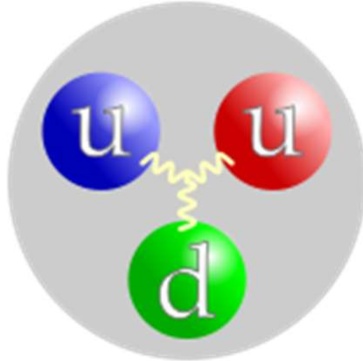
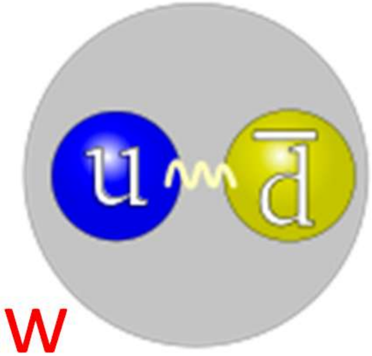
# Introduction – What are exotic hadrons?



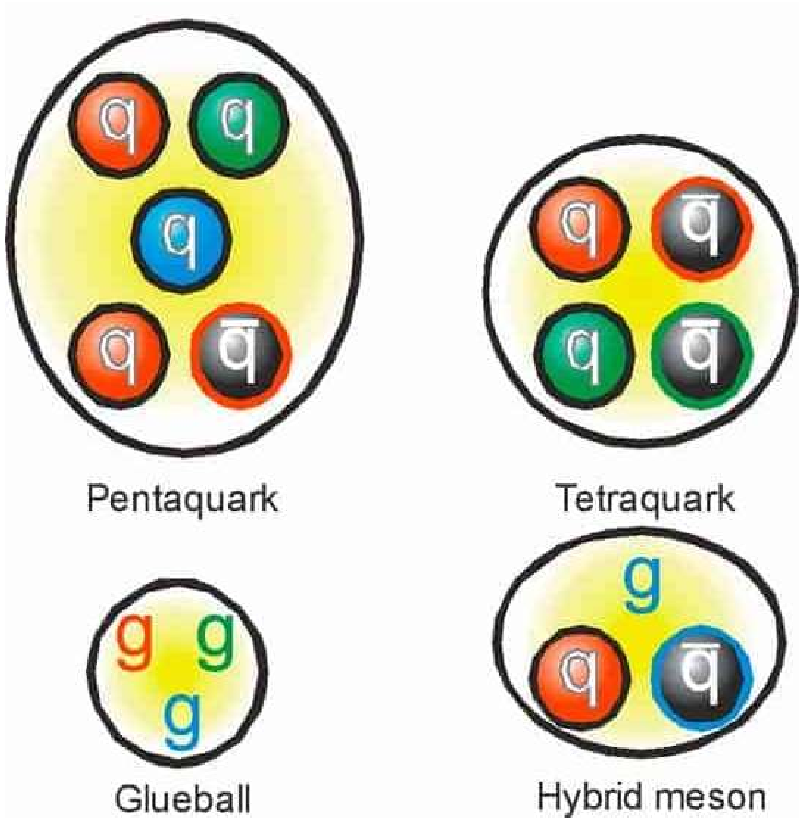

- Standard classification of hadrons based on quark model
  - 3 quarks (baryon: proton, neutron, …)
  - Pair of a quark and an anti-quark (meson: pion, …)

→ Works very well for ground states and low excited states

- Exotic hadrons:
  - Not well described by the quark model

# Possible types of exotic hadrons

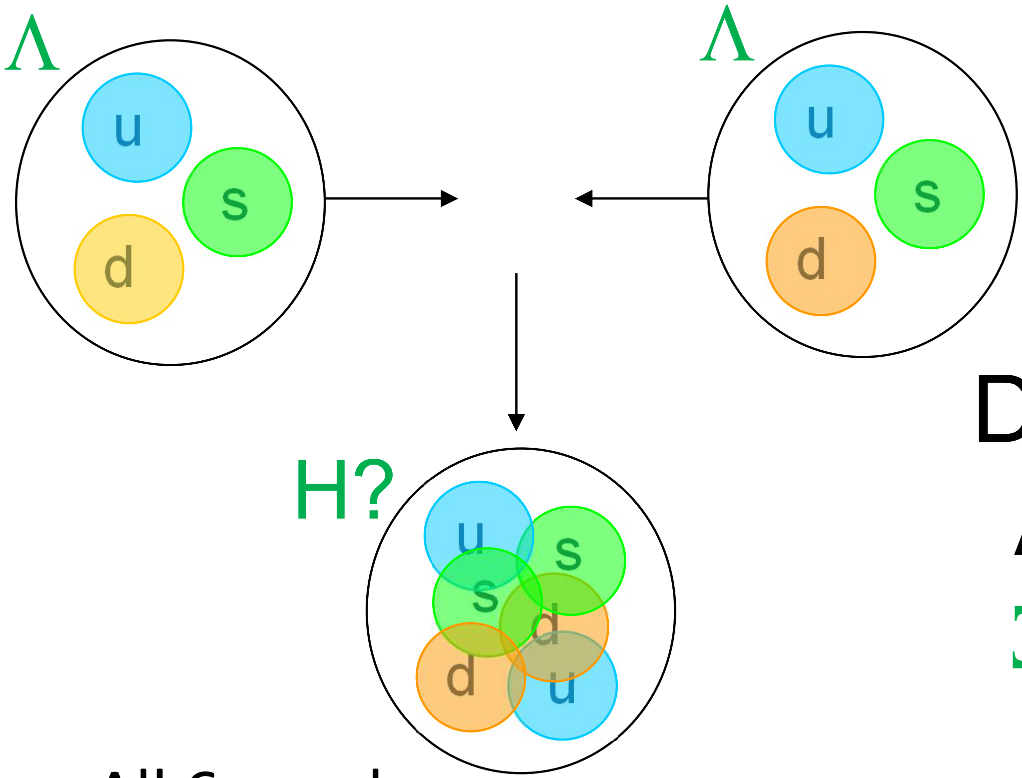
- Multiquark
  - Tetraquark: $qq\bar{q}\bar{q}$
  - Pentaquark: $qqqq\bar{q}$
  - Hexaquark: $qqqqqq$
- Molecular state
  - Loosely bound 2 (or more) hadrons
- Gluonic excitation
  - Glueball, hybrid ($q\bar{q}g, qqqg, \ldots$)
- They can mix together (with other types/ordinal hadrons)



# H dibaryon

An $uuddss$ hexaquark in S-wave (spin=isospin=0)

Highly symmetric → expected to be stable (like an $\alpha$)




All 6 quarks in s-state

Does it really exist?

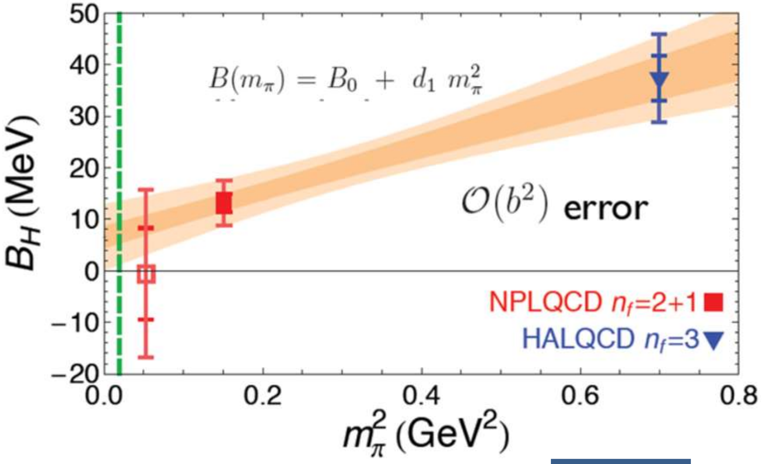
As a bound state of $\Xi$(uss) and N(udd)?

Resonance?

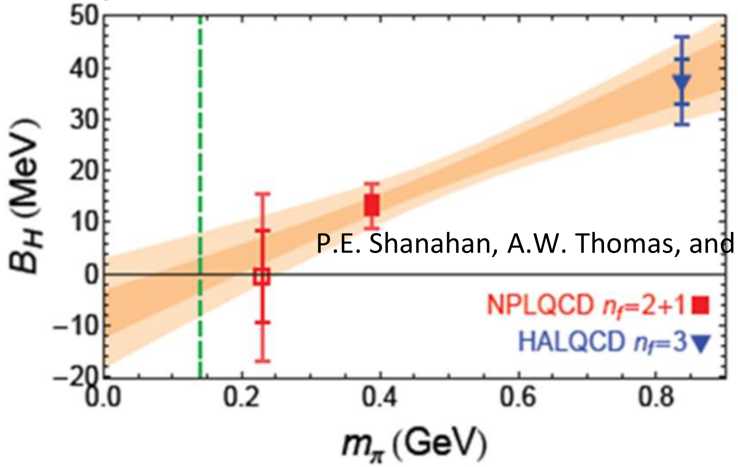
⇒ Still an open & important question

# Lattice QCD calculation for H dinaryon

Physical π mass




Physical π mass

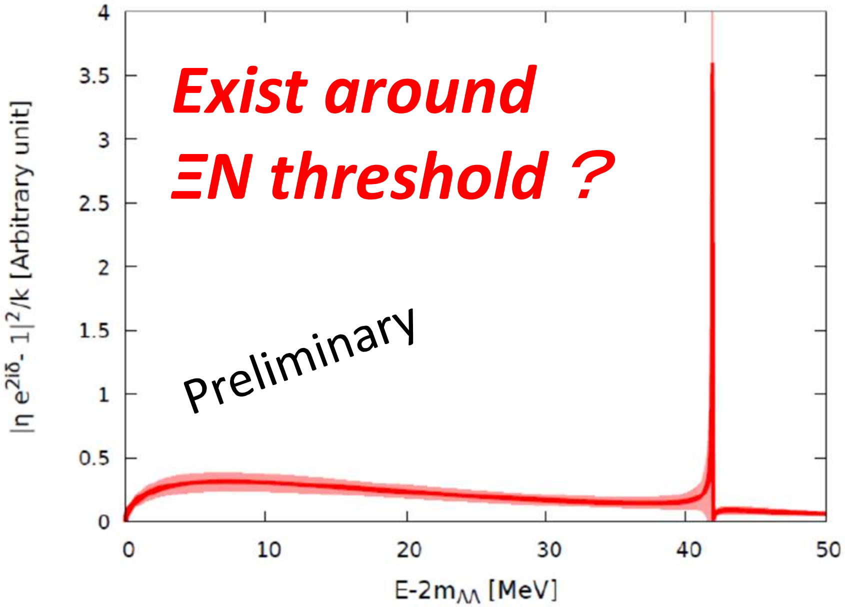


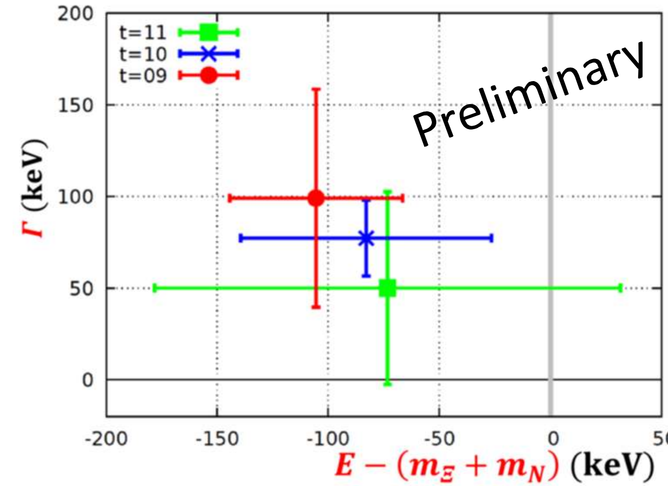

P.E. Shanahan, A.W. Thomas, and R.D. Young, PRL 107 (2011).

**Calculation at almost physics point**

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

| | Mass [MeV] |
|---|---|
| π | 146 |
| K | 525 |
| $m_\pi/m_K$ | 0.28 |
| N | 956±12 |
| Λ | 1121±4 |
| Σ | 1201±3 |
| Ξ | 1328±3 |



# Lattice QCD vs ALICE data

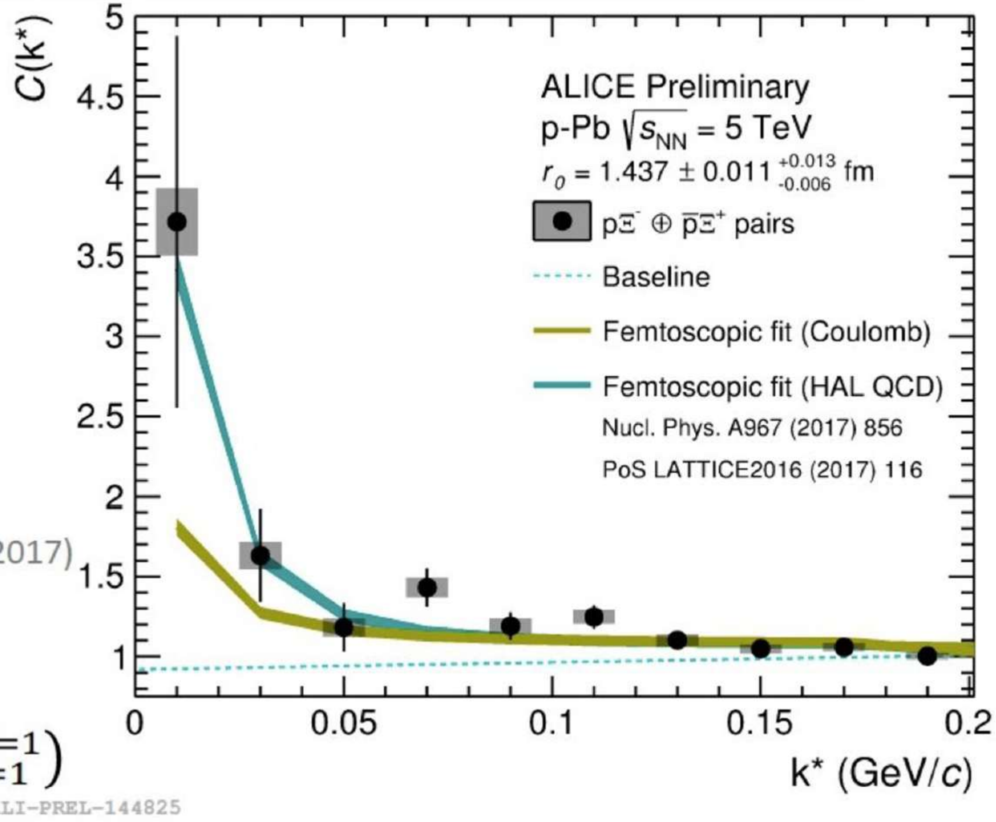
ALICE

## p-$\Xi^-$ Correlation Function in p-Pb 5.02 TeV

- **First observation of strong attractive interaction in p-$\Xi^-$**
  - 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)

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

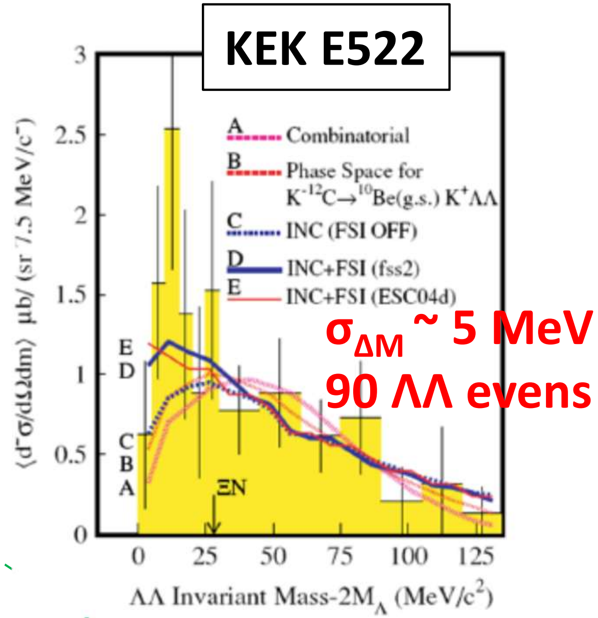


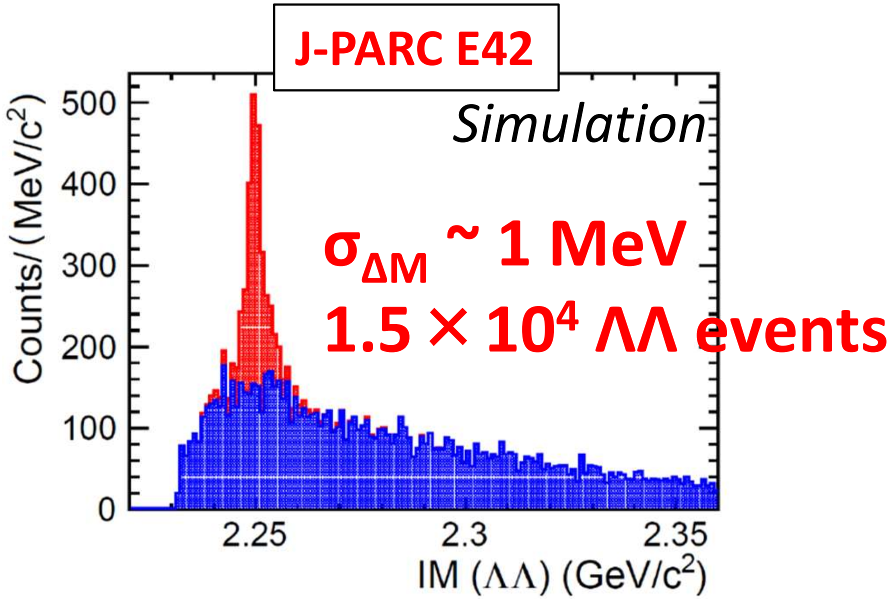

Valentina Mantovani Sarti (TUM Physics Department – E62) 10

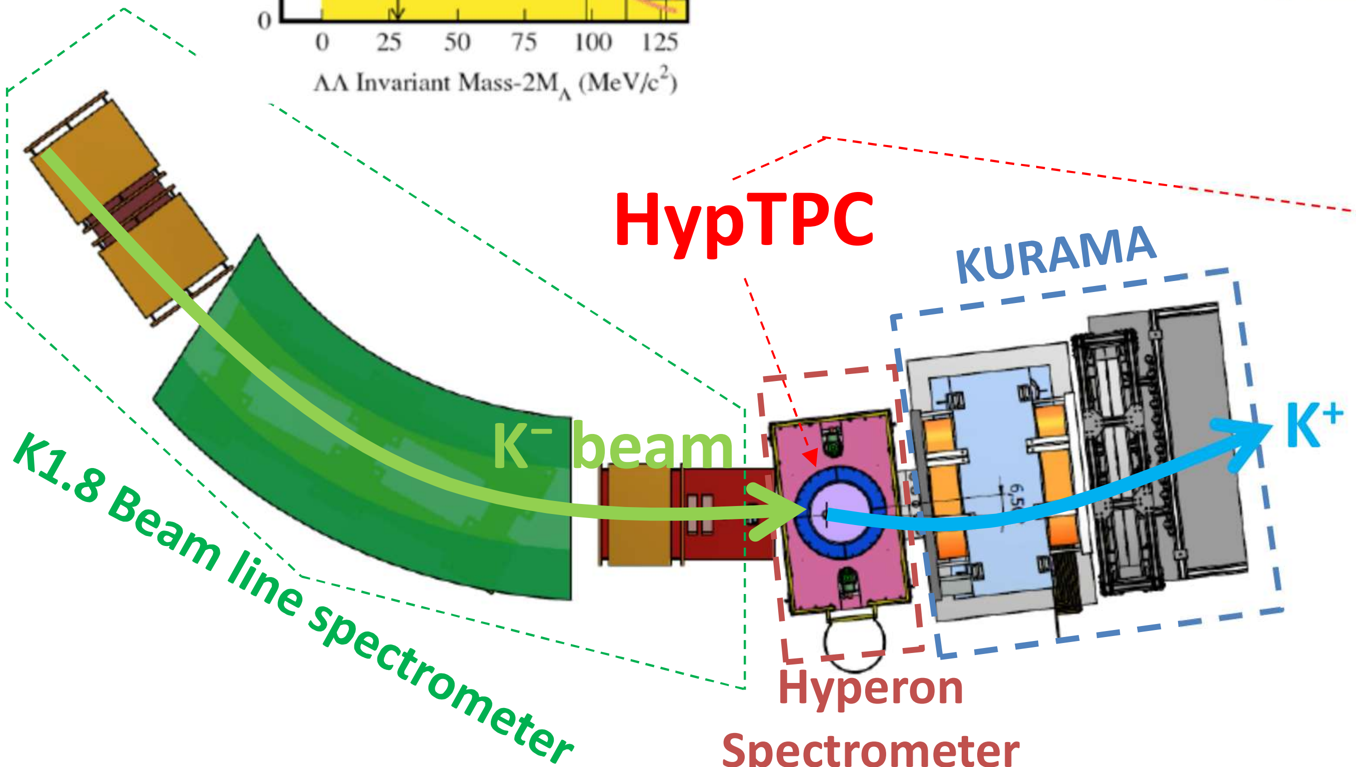
Talk by Valentina Mantovani Sarti (TUM) at MESON2018 (June 8, 2018)

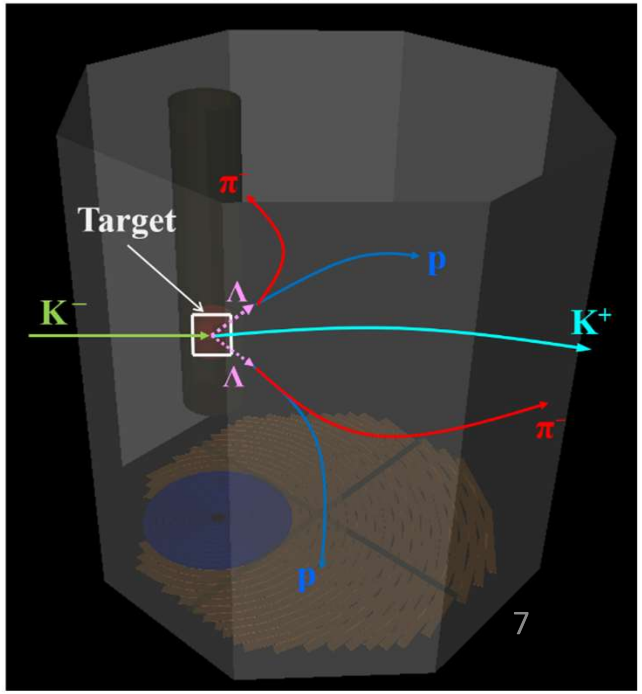
# J-PARC E42 experiment

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



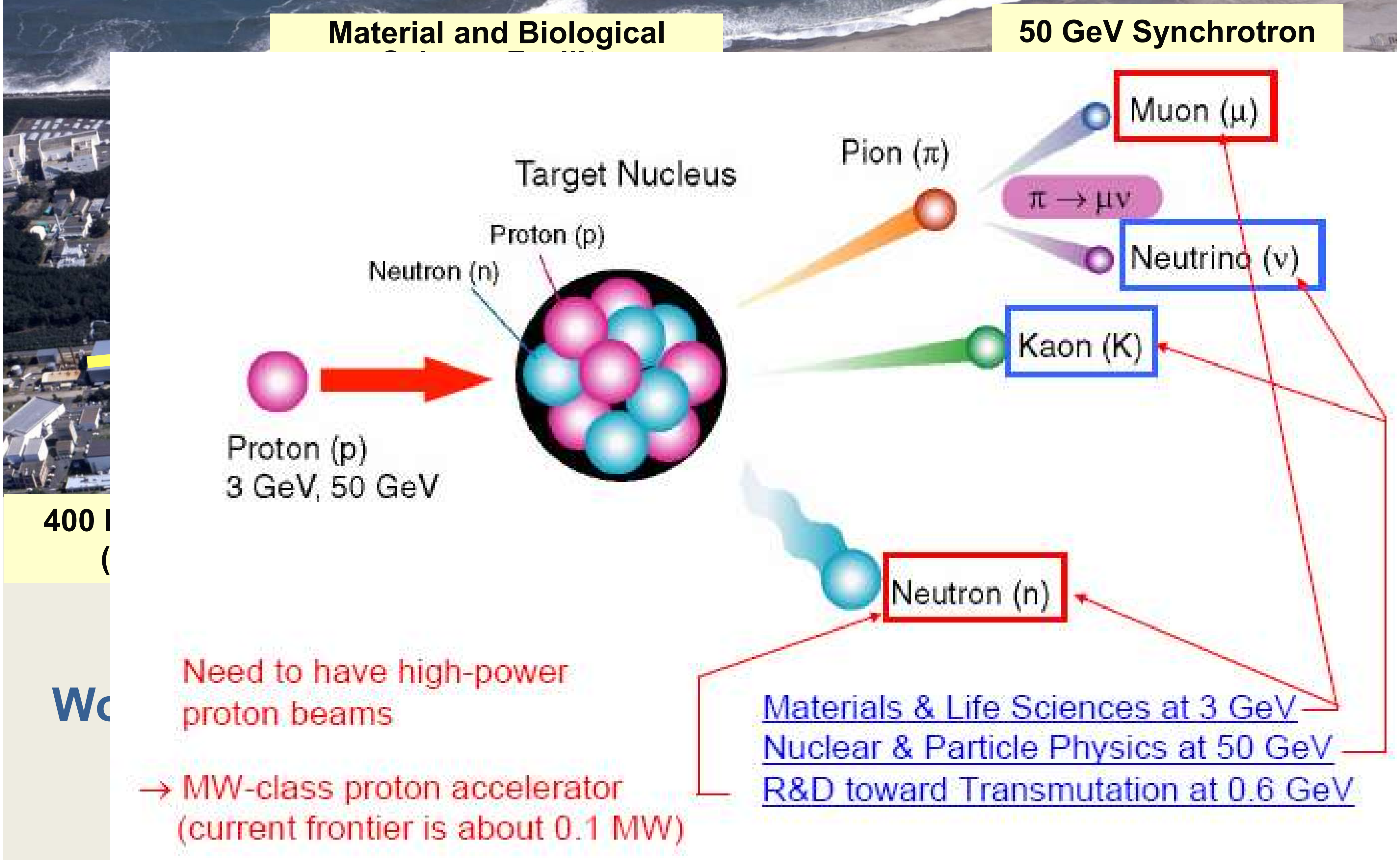



# J-PARC

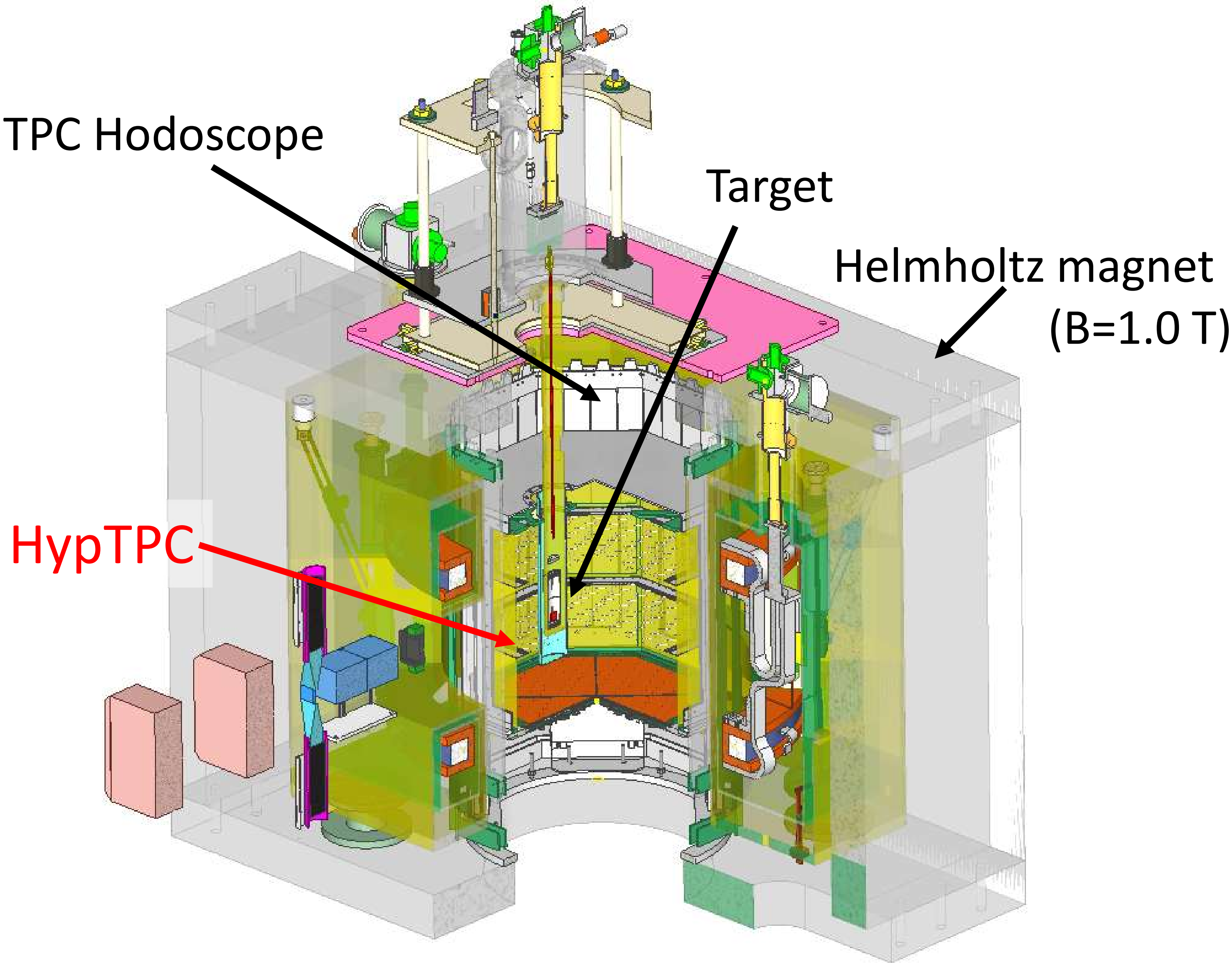
Tokai, Japan

## (Japan Proton Accelerator Research Complex)



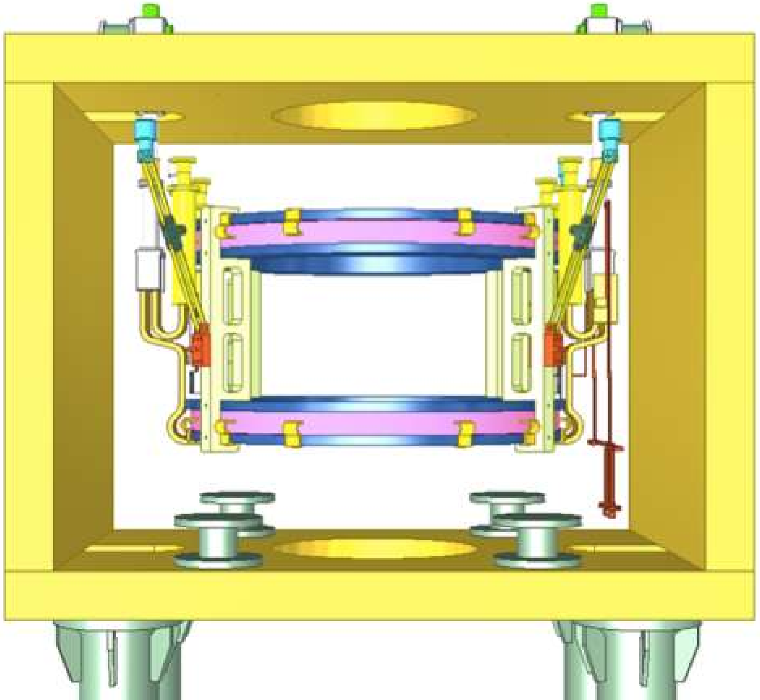
# Hadron Hall

# Hyperon Spectrometer

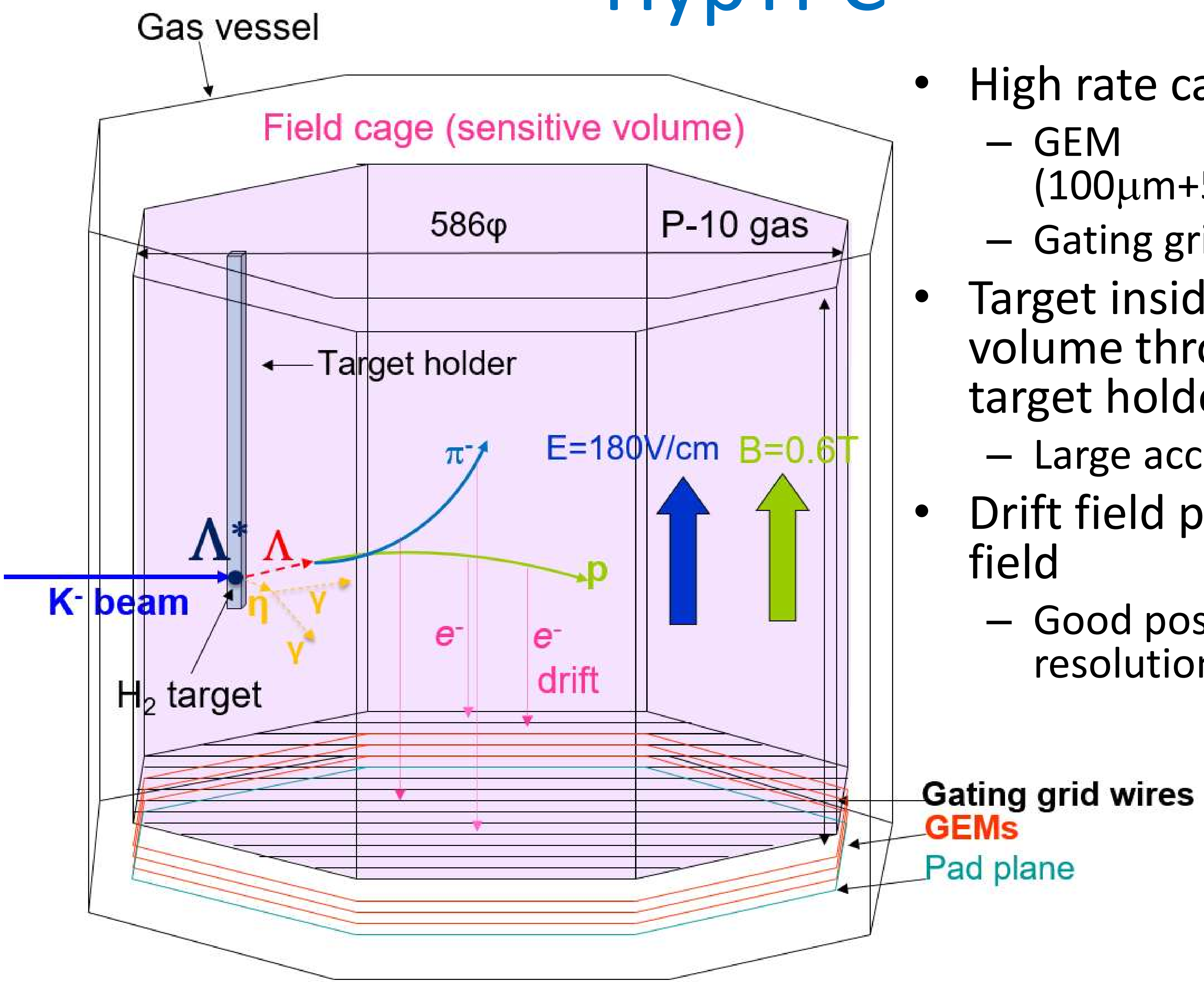


# The Superconducting magnet

- 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

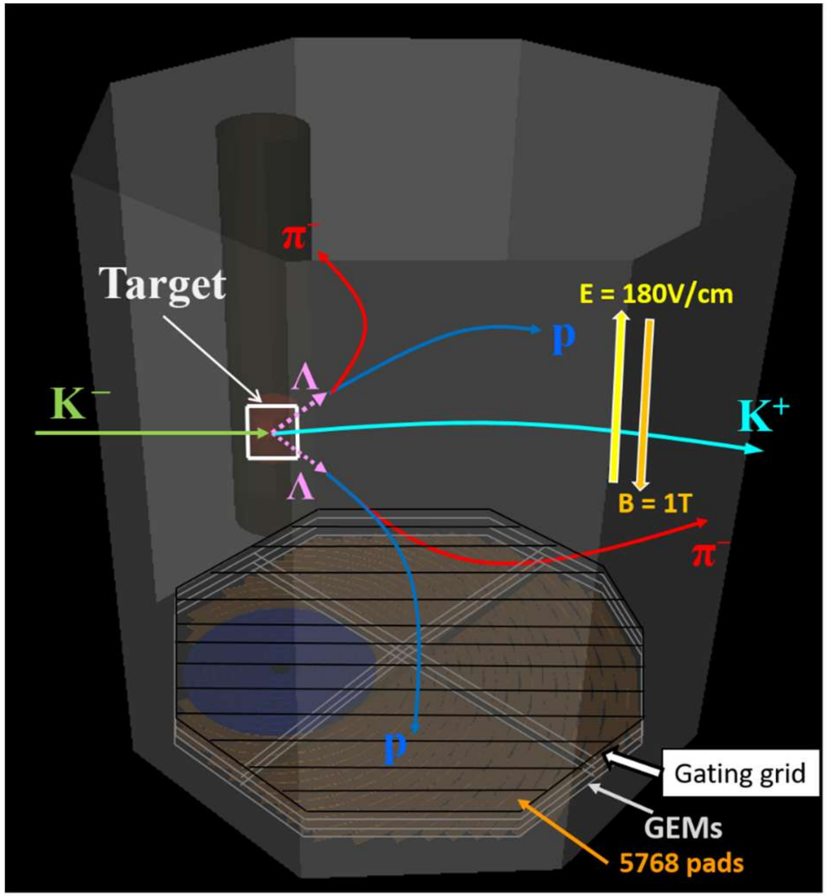


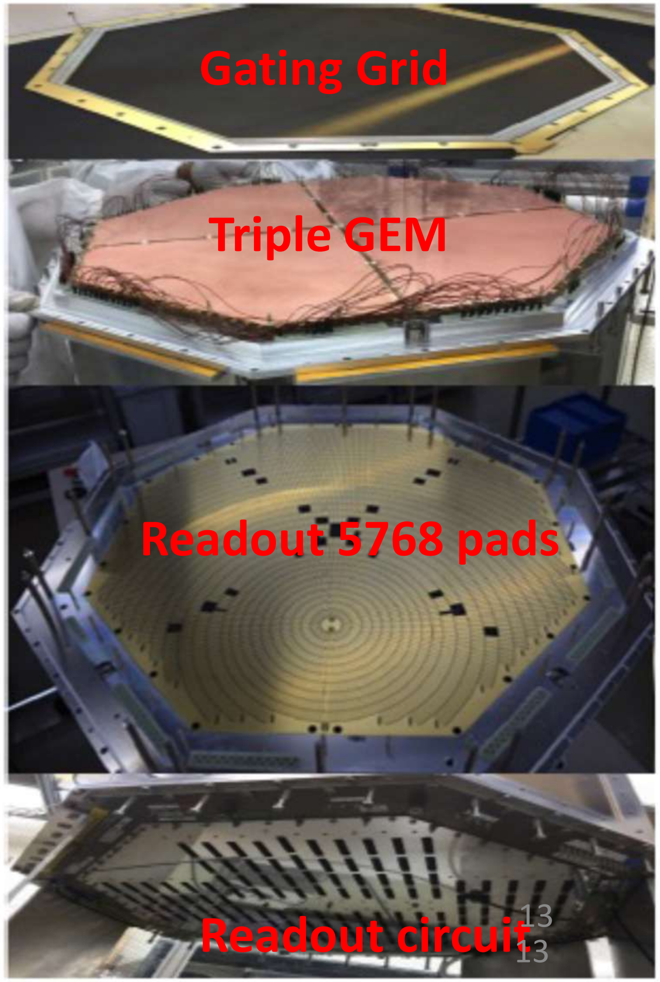

- High rate capability
  - GEM (100μm+50μm+50μm)
  - Gating grid
- Target inside the drift volume through the target holder
  - Large acceptance
- Drift field parallel to B-field
  - Good position resolution

# More on HypTPC

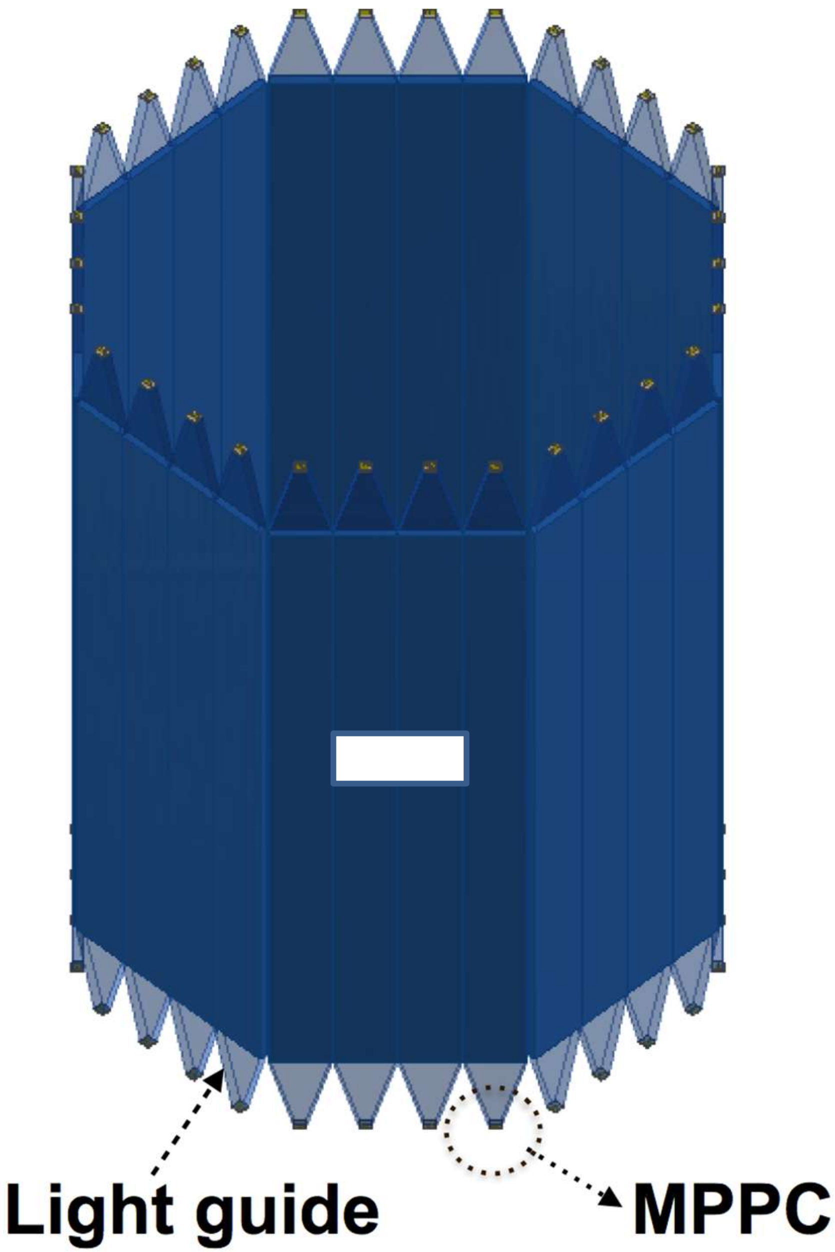
- ○ Octagonal prism field cage
- ○ 5768 readout pads
  - Inner(10 rows): 2.1-2.7 × 9 $mm^2$
  - Outer(22 rows): 2.3-2.4 × 12.5 $mm^2$
- ○ Gating grid: ϕ50 μm, 1mm space

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



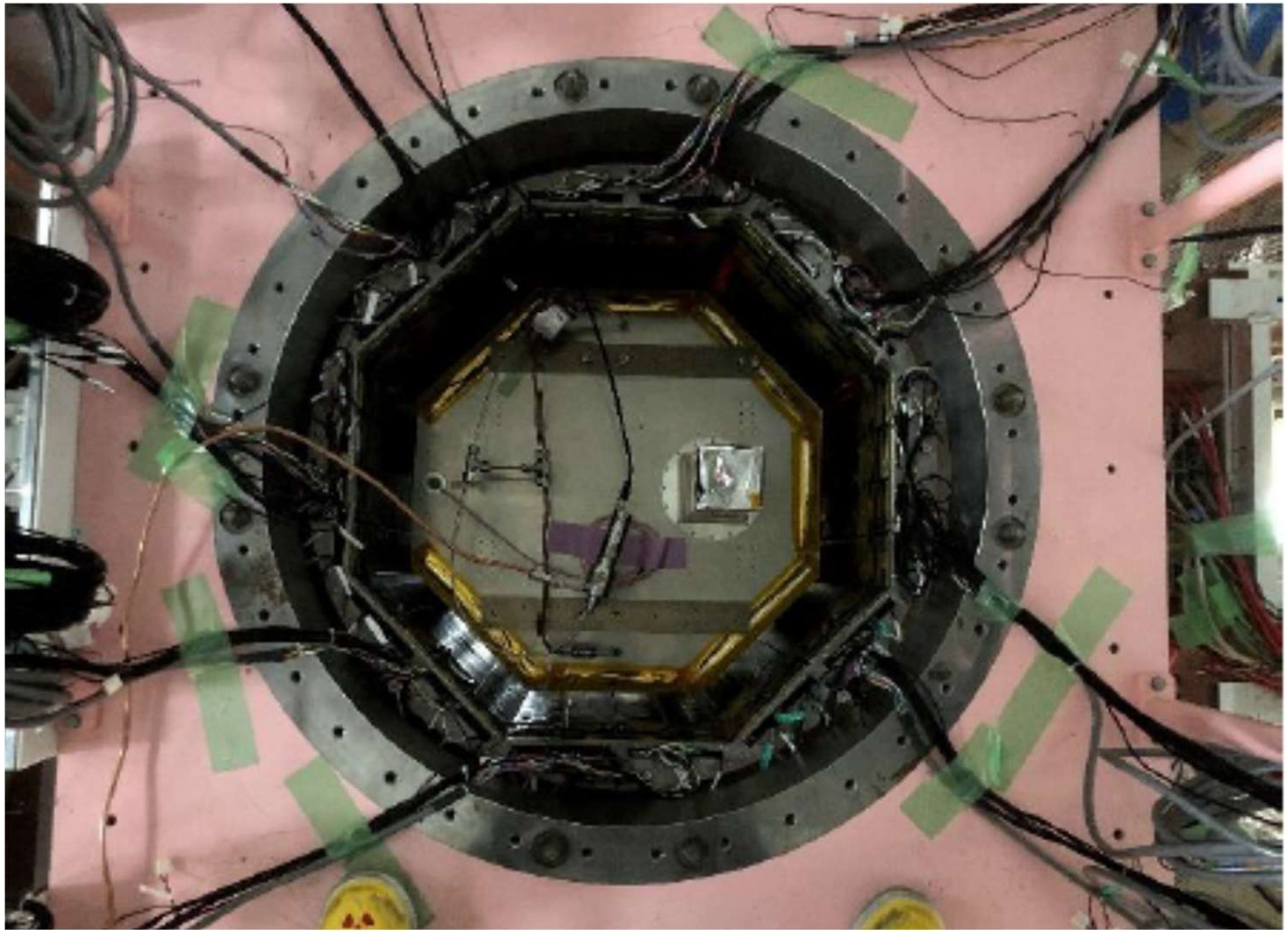



# TPC Hodoscope



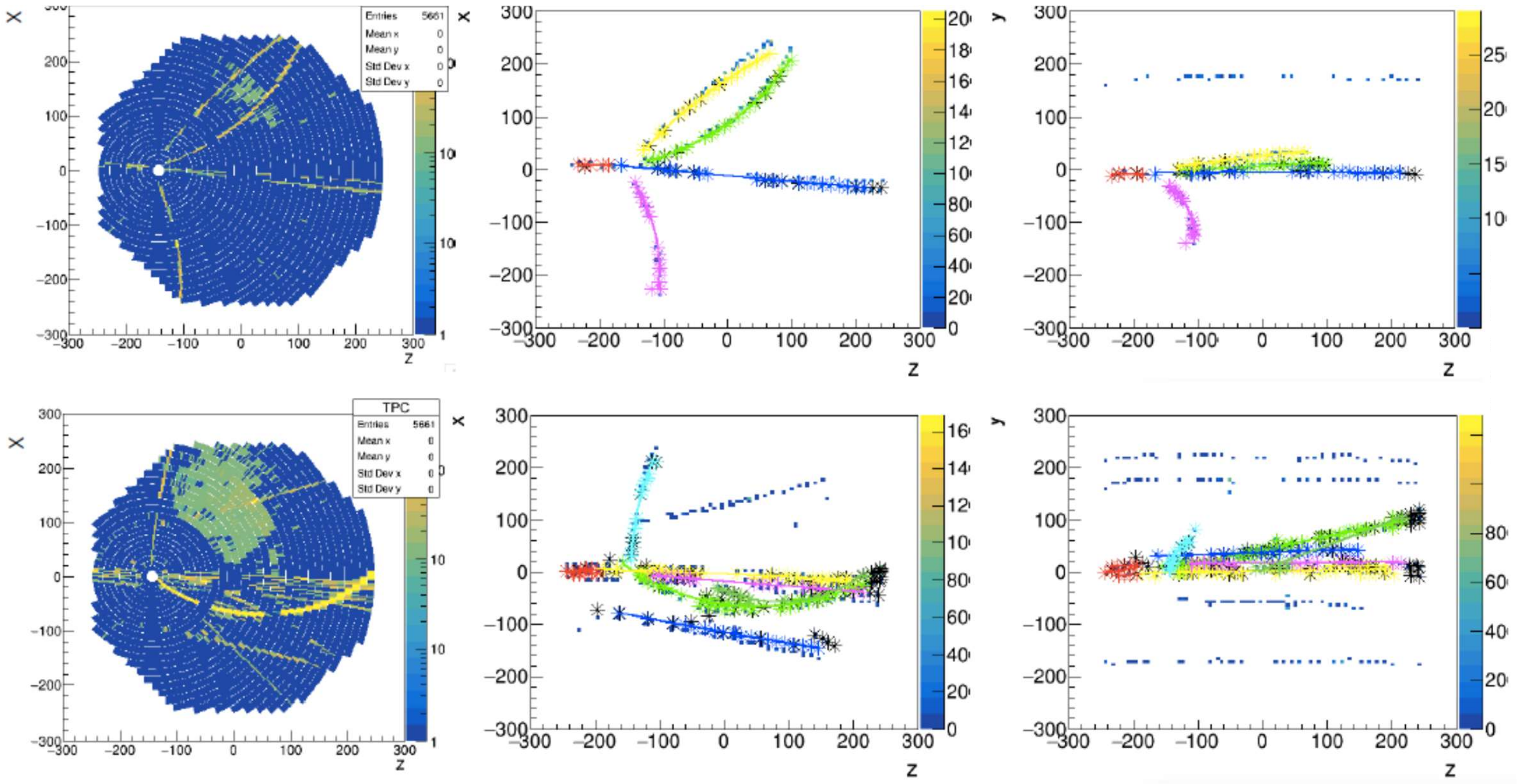

- Used for trigger/TOF
- 32 segments of plastic scintillator array surrounding HypTPC.
- Plastic scintillator of 80cm x 7cm x 1cm
- MPPCs on both ends
  - PMTs not used due to the strong magnetic field.

# Run in 2021



- Data taking is finished
- Analysis ongoing

# Event display

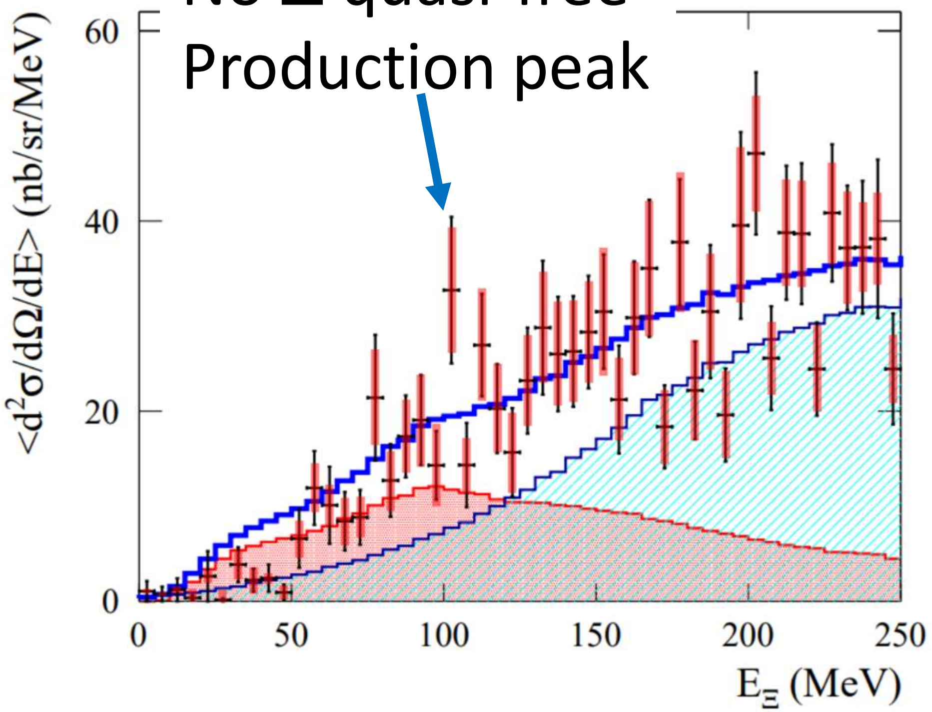


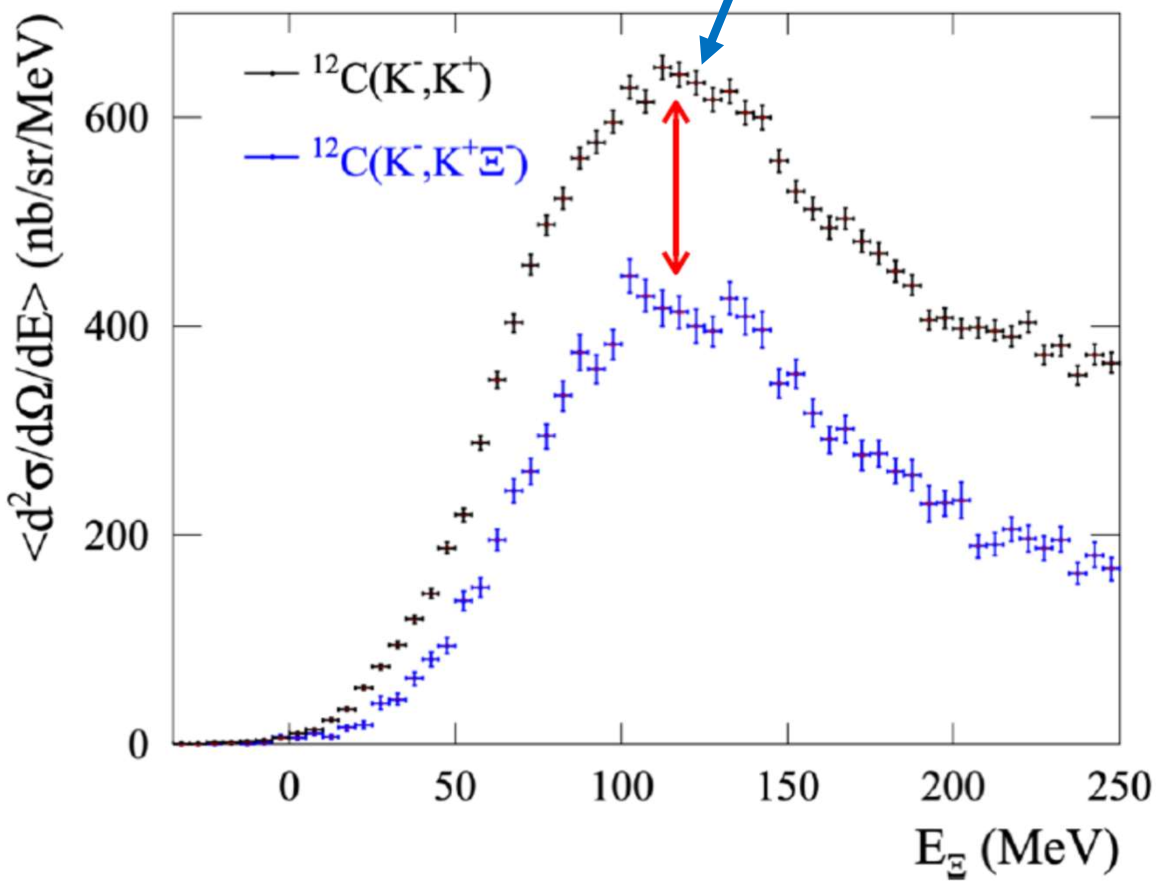

HypTPC worked very well.

# Result 1 – $\Xi^{-}p$ cross sections

- $\Xi^{-}$ production is tagged by the $(K^{-},K^{+})$ reaction
- Find final states: $\Xi^{-}p$, $\Lambda\Lambda$, or nothing
  → Estimate conversion cross sections
  $\Xi^{-}p \rightarrow \Lambda\Lambda, \Xi^{0}n$

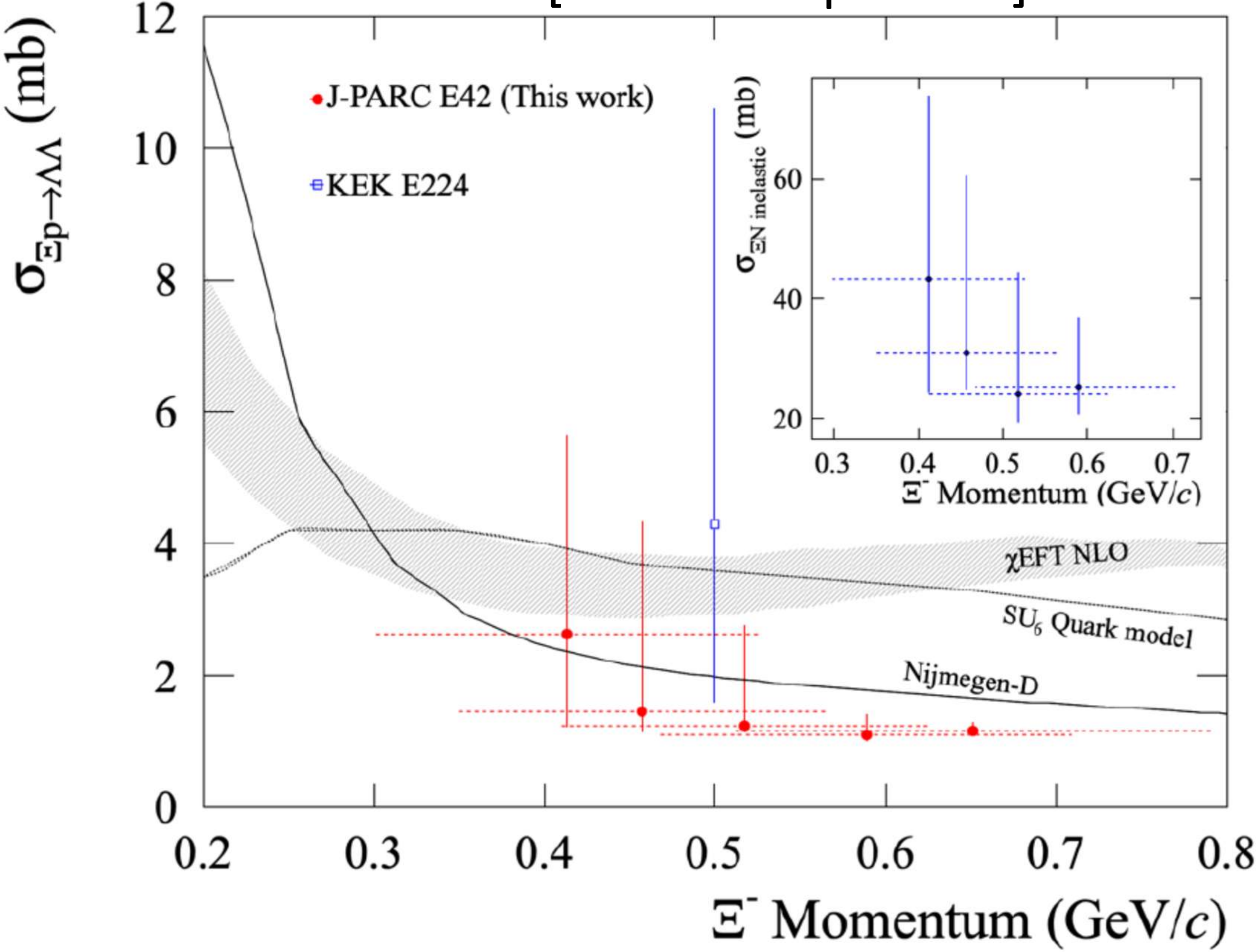
No $\Xi$ quasi-free
Production peak



# $\Xi N \rightarrow \Lambda\Lambda$ conversion

[PTEP**2025**.ptaf064]



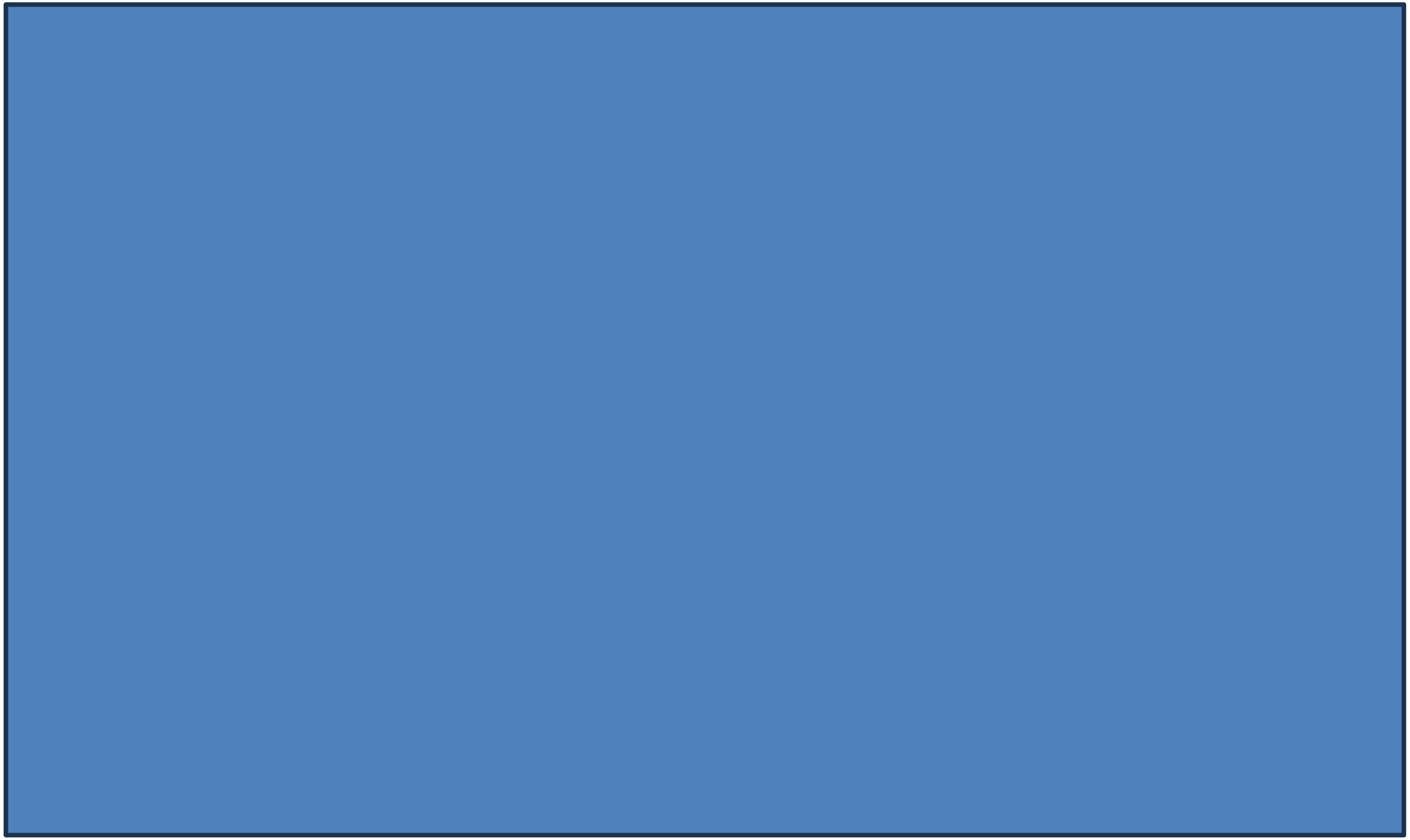

- $\Xi^{-}p \rightarrow \Lambda\Lambda$ is estimated to be ~1 mb

→ Surprisingly Small

→ Impact on hypernuclei

- $\Xi^{-}p \rightarrow \Xi^{0}n$ is ~30 mb

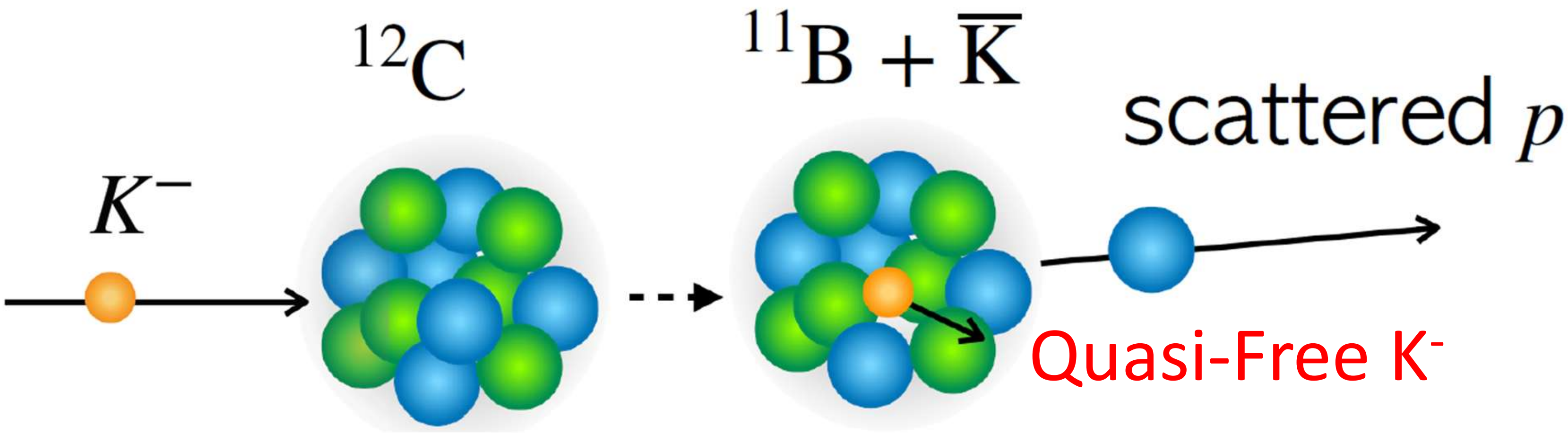
# Result 2 – $\Lambda\Lambda$ invariant mass



- Some enhancement in the low mass region
  → A hint of H dibaryon??

# Byproduct – Kaon absorption in nuclei

[PRL132.132501(2026)]




- Find probability to find $K^-$ in HypTPC

→ Optical potential using Eikonal approximation

$$V_0 = -72^{+3}_{-5}\,(\text{stat.})^{+0}_{-8}\,(\text{syst.})\ \text{MeV}$$

$$W_0 = -100^{+7}_{-1}(\text{stat.})^{+0}_{-16}(\text{syst.})\ \text{MeV}$$

gives rather shallow $V_0$ and strong absorption

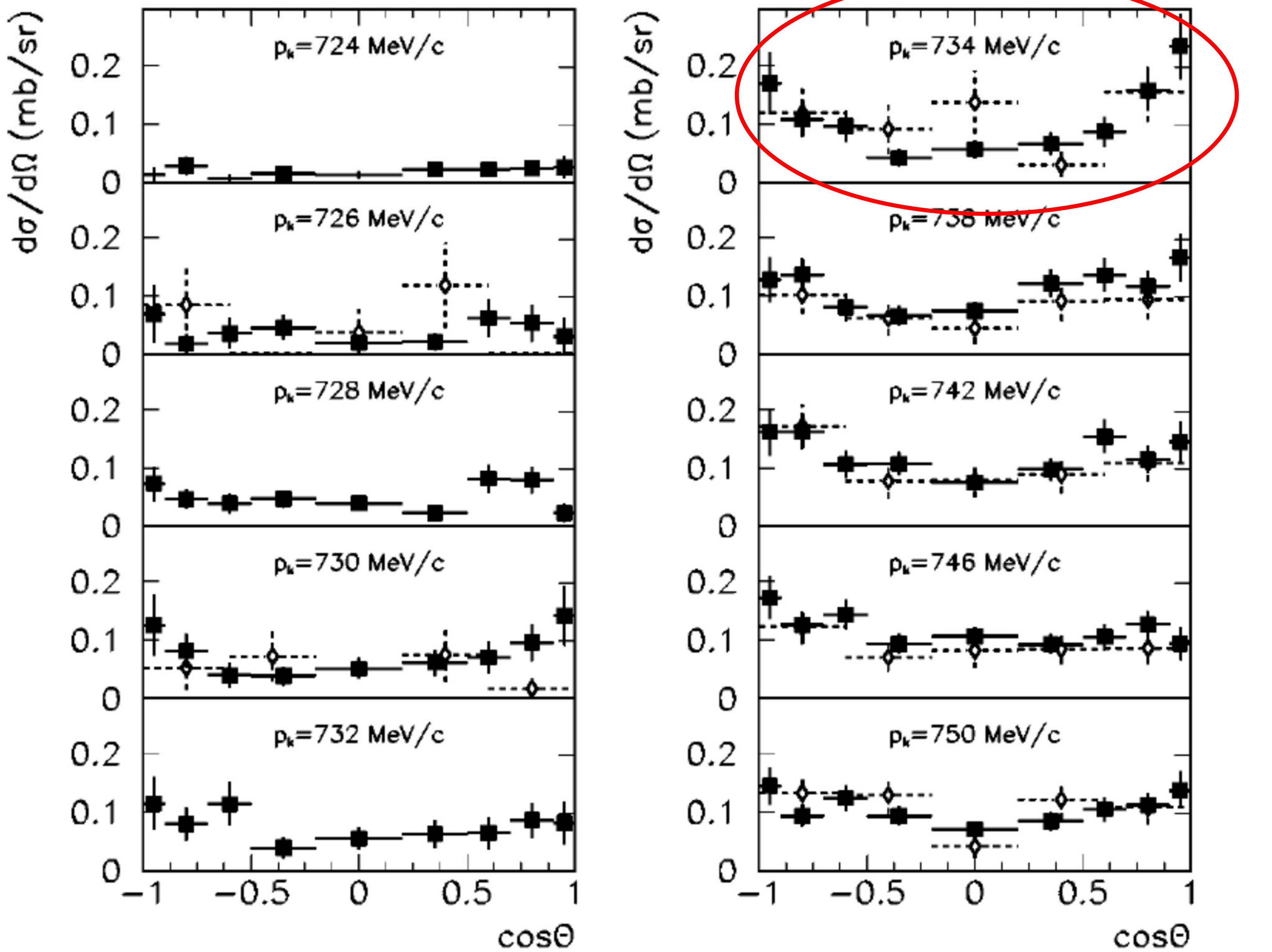
# *J-PARC E72 experiment*

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

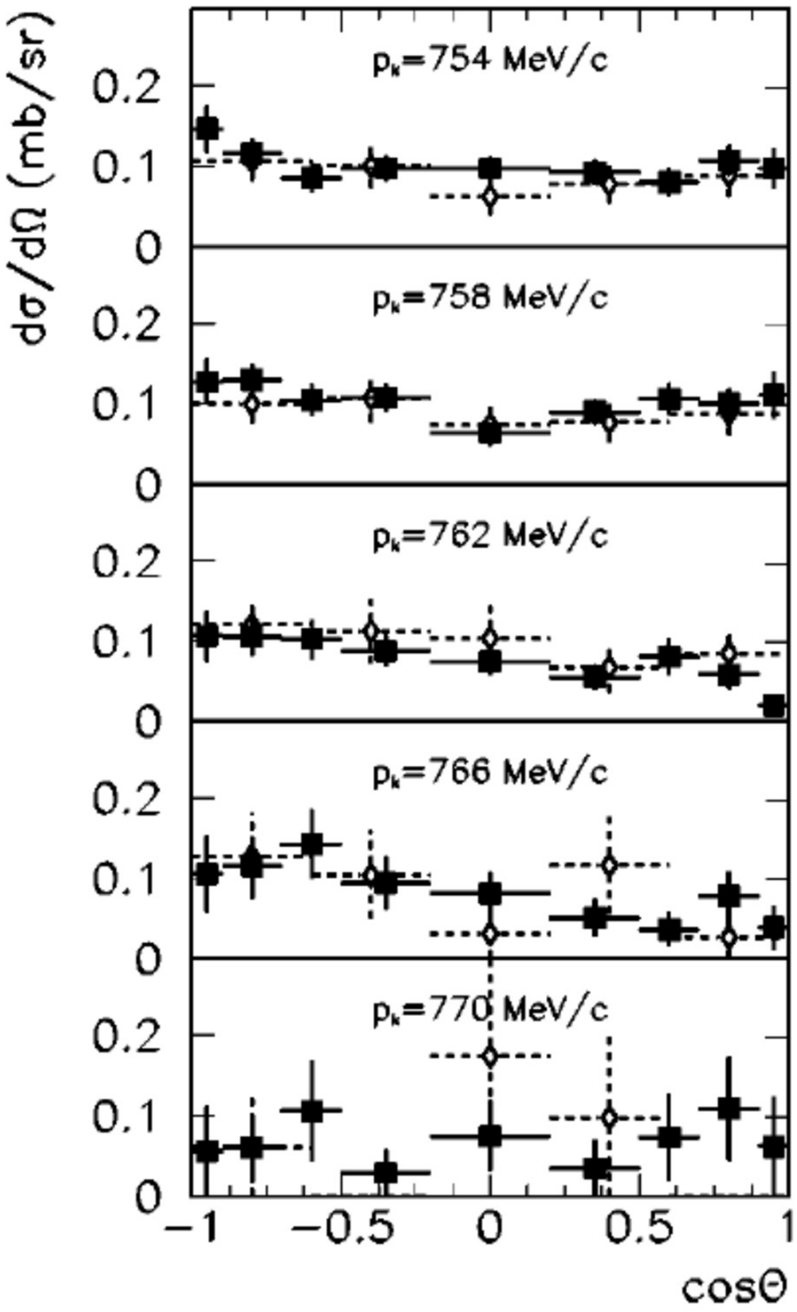
# A new $\Lambda$ resonance around 1670 MeV?

- 2 independent theory groups claim there is a new narrow $\Lambda^*$ 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, $\Gamma$=10+22-4 MeV
  - Liu & Xie [PRC85.038201, PRC86.055202]
    $J^P=3/2^-$ ($D_{03}$), M=1668.5$\pm$0.5 MeV, $\Gamma$=1.5$\pm$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 $\Lambda^*$ 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.

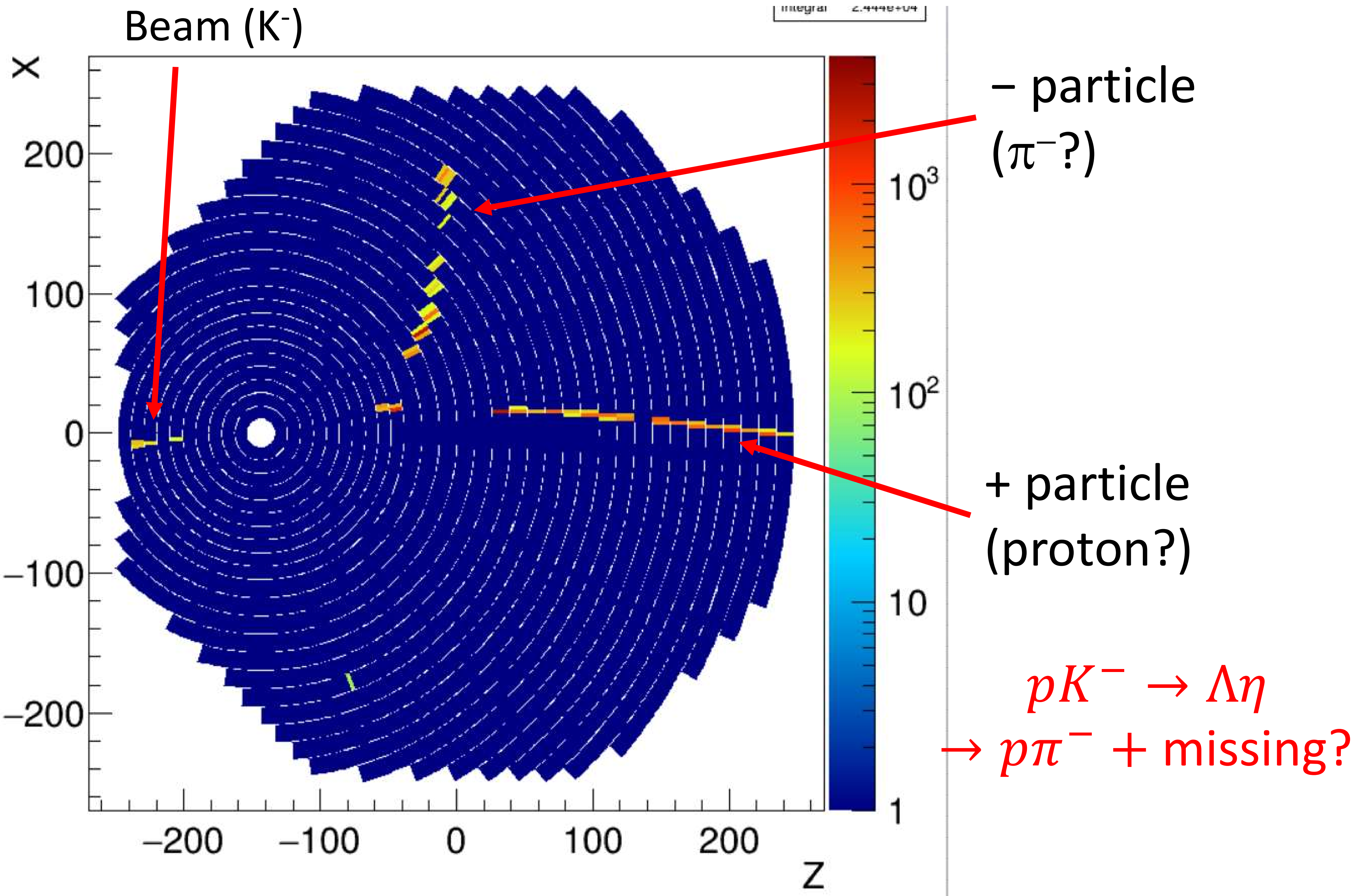
- It is near the $\Lambda\eta$ threshold, but threshold cusp is unlikely.
  - Visible cusp appears only in S wave
- A molecular state in P or D? Then, where is the S state?
  - Cf. X(3872) & $\Lambda(1405)$ are in S wave.

→ **It may be a new type of exotic state!**
  - Mixture of a molecular state and a 3-quark state???
  - $udss\bar{s}$ pentaquark???

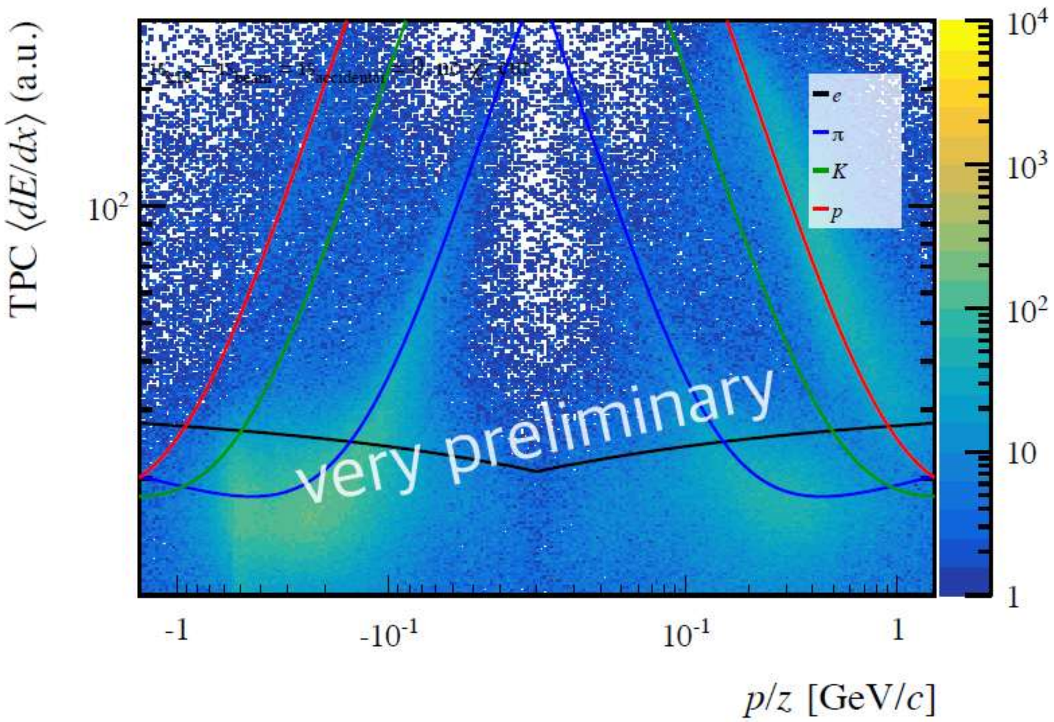
# J-PARC E72

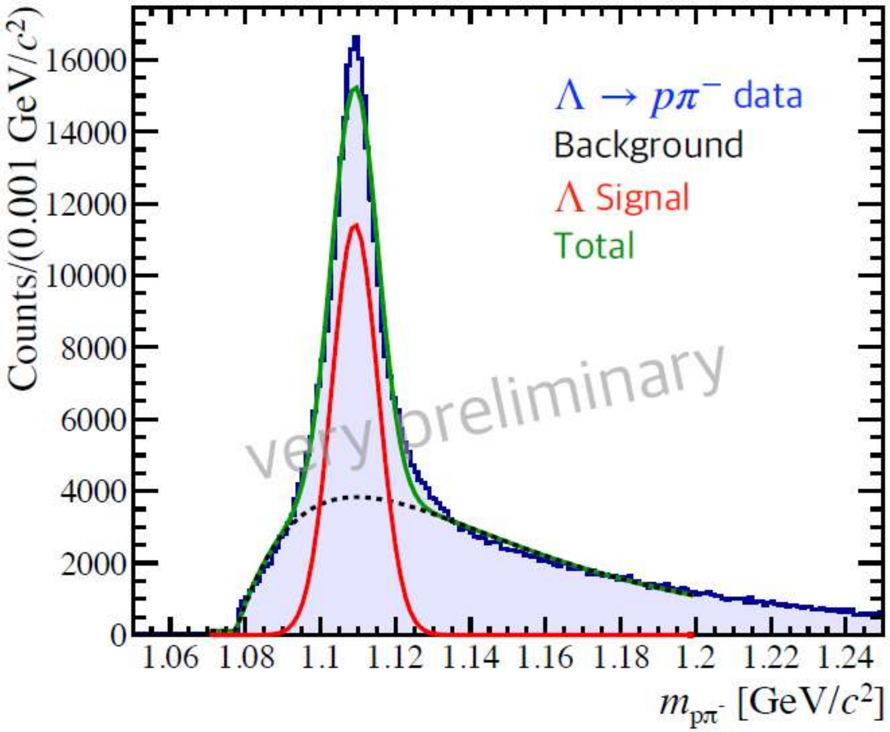
- Repeat the Kp → $\Lambda\eta$ experiment again with a large acceptance detector, i.e., HypTPC
  - Confirm angular distribution & the new resonance
  - Determine parity by $\Lambda$ polarization measurement
- Principle
  - K beam momentum: 720-770 MeV/c
  - Momentum resolution: 1 MeV/c or better
    → Can identify narrow resonance of $\Gamma$=1.5 MeV
  - Detect $\Lambda$ → p$\pi^-$, identify $\eta$ by missing mass
- We are taking data right now!
  - Next beamtime expected in this November.

# Event display



# Analysis progress



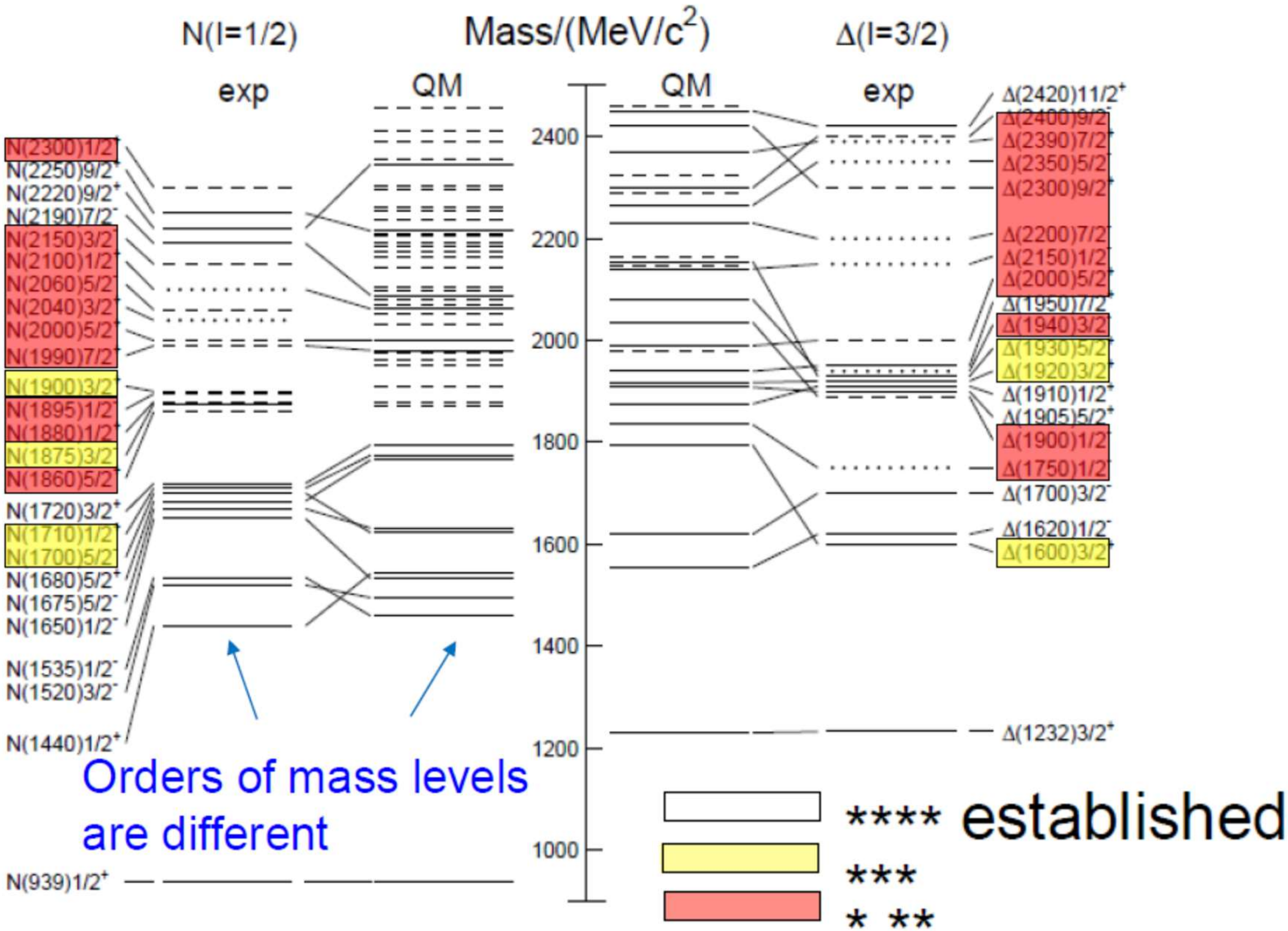

- Particle ID is in a good shape
- Λ peak is clearly seen, the resolution is still to be improved.

# *J-PARC E45 experiment*

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

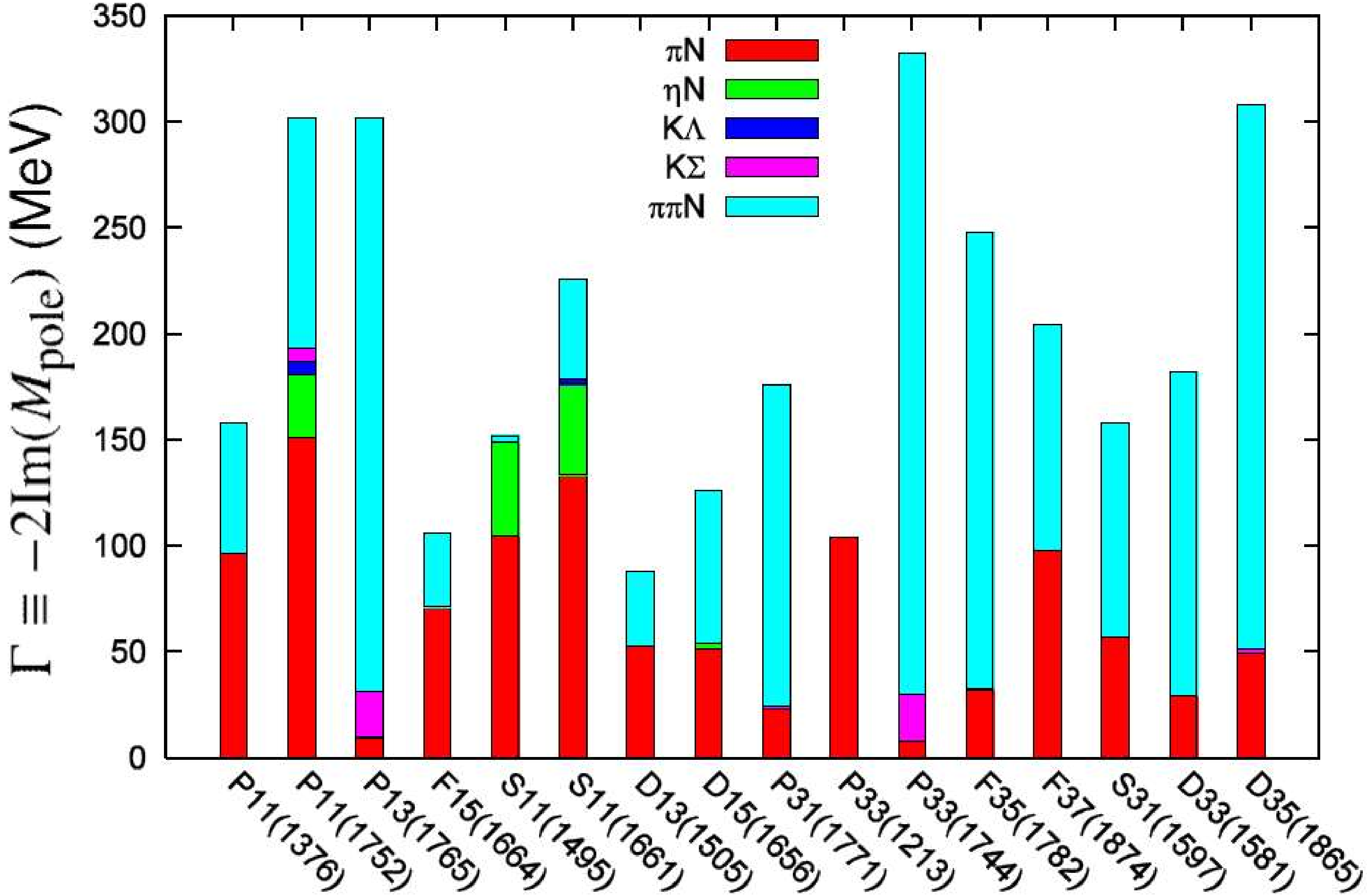
# Missing resonances

- A lot of states are predicted by QM, but not observed
- Measured by using mainly πN → πN, γN → πN 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 $(\pi,2\pi)$ 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)*

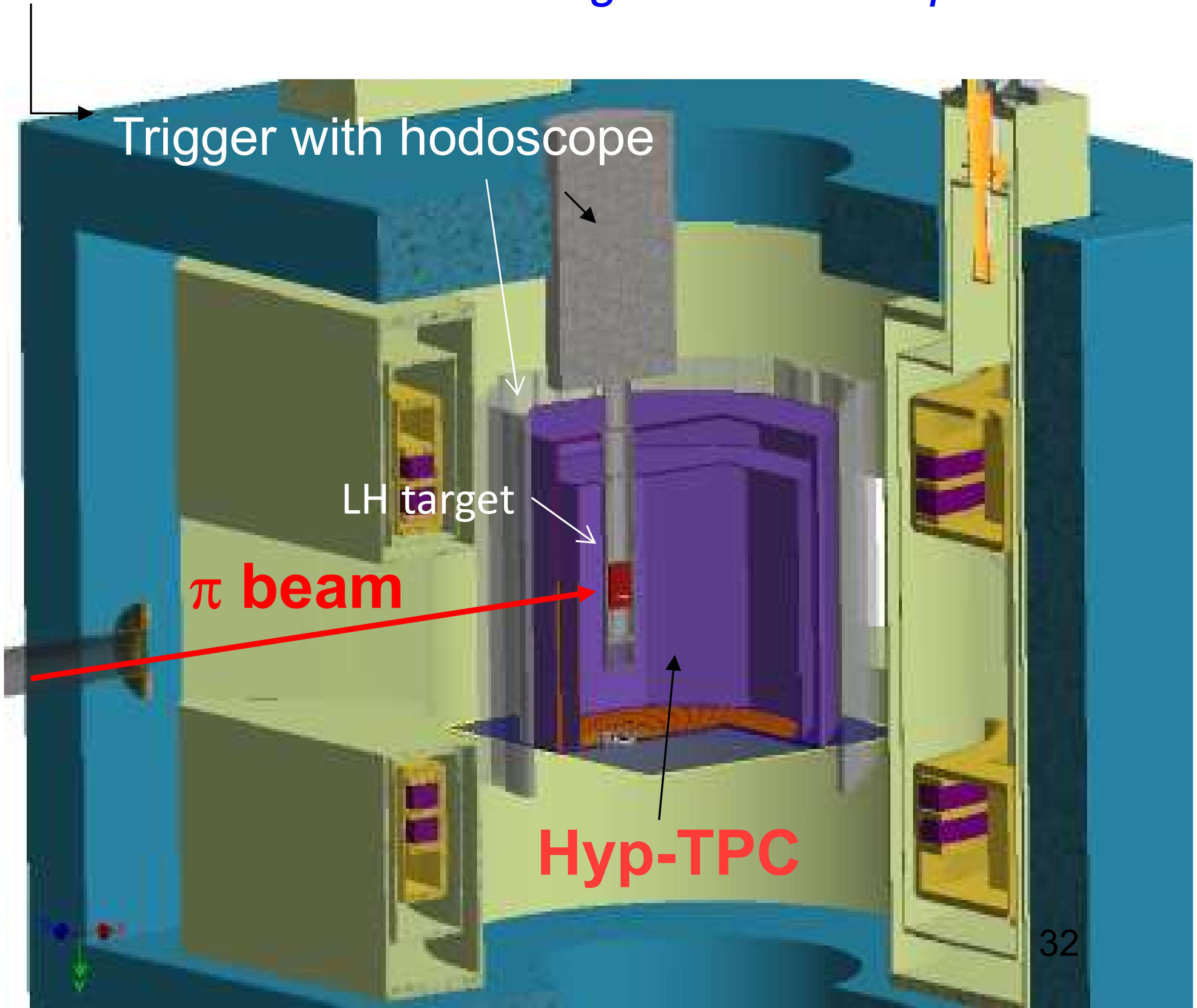
$\pi^- p \rightarrow K^0 \Lambda$,

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

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

x100 more statistics than ever

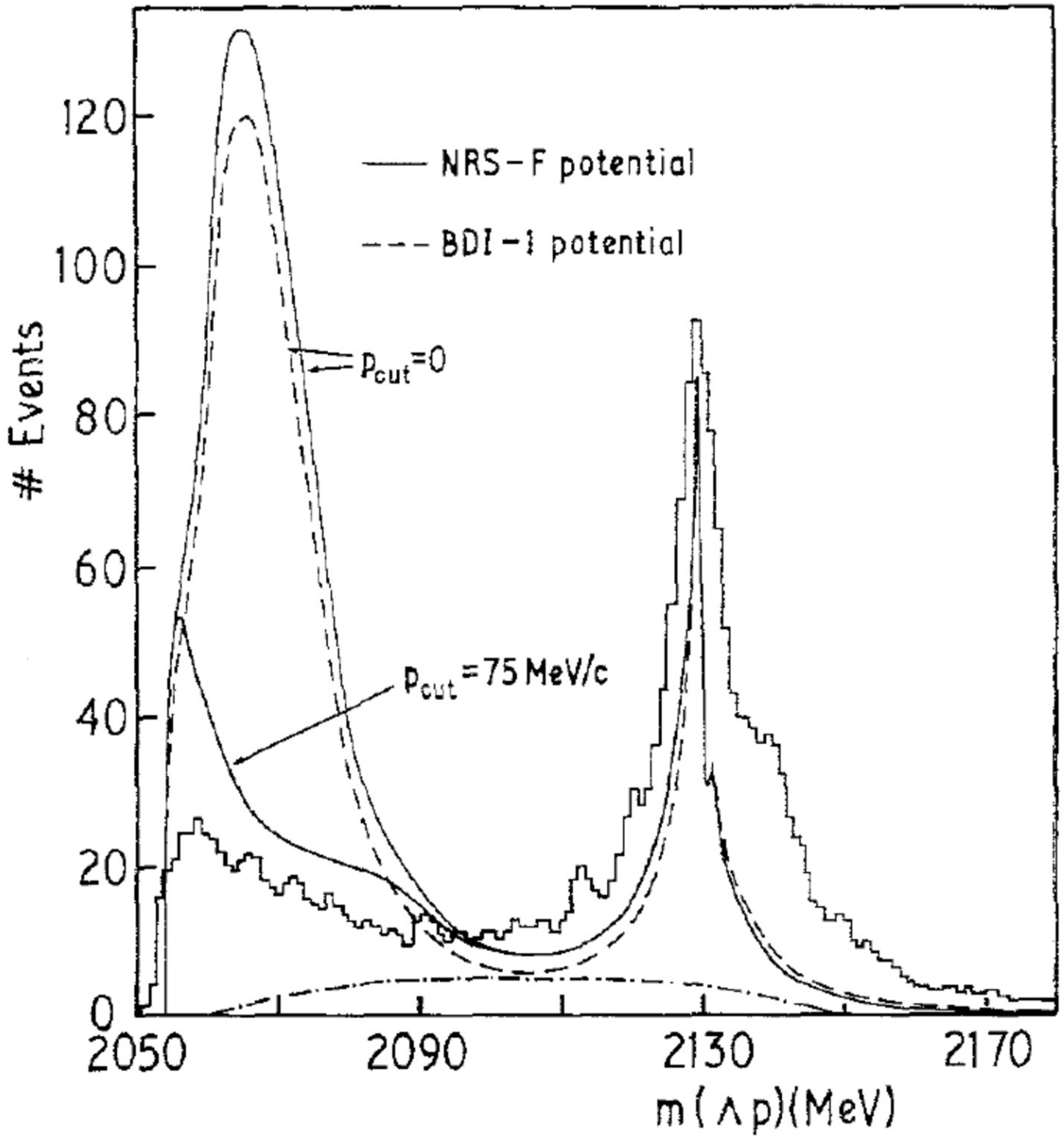
First run expected in Nov.-Dec. 2026



# *J-PARC E90 experiment*

# *~$\Sigma$N scattering length using threshold cusp~*

# ΣN cusp




- Seen in $K^-$(stopped)+d $\rightarrow \Lambda p \pi^-$ and many others
- Spectrum shape gives ΣN scattering
  - However, resolution is not enough in the past measurements

# What should we do?

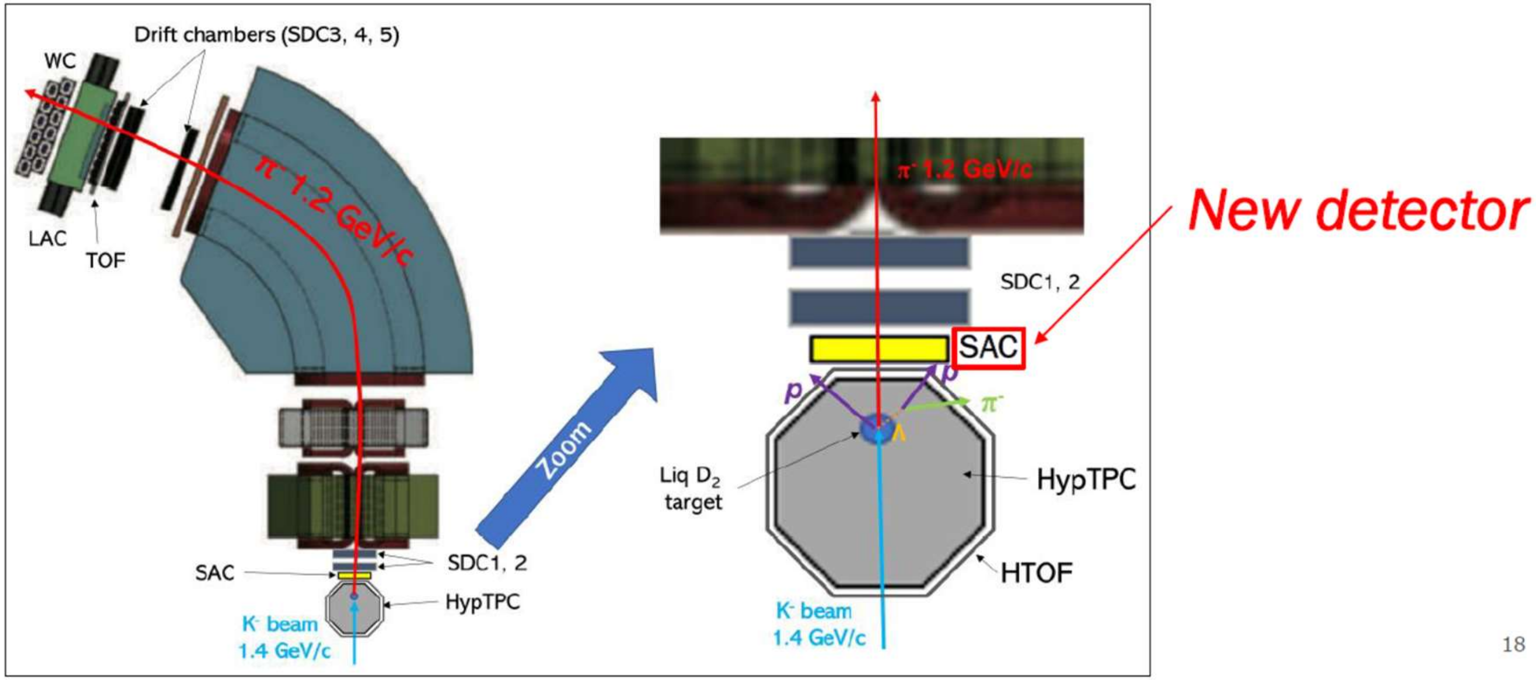
- Try even higher resolution
  - 0.4 MeV ($\sigma$) would be enough
- Tagging of the final state is necessary
  - Must be $\Lambda$N to derive $\Sigma$N (I=1/2) scattering length
  - $\Sigma$N (I=3/2) contaminate if not tagged
- J-PARC E90
  - 0.4 MeV resolution with d($K^-$,p) reaction at $p_K \sim 1.4$ GeV/c thanks to the high resolution of S-2S spectrometer.
  - Tagging of decay particles by the Hyperon Spectrometer → $4\pi$ acceptance

# E90 setup

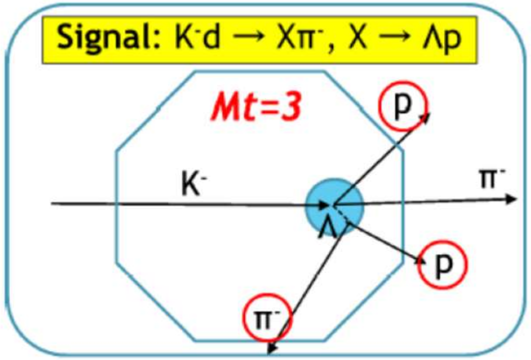
## SET UP

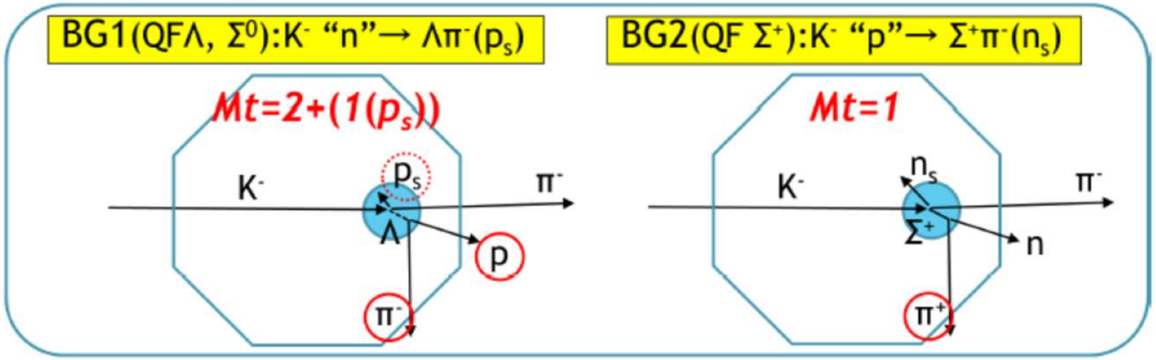
- Reaction: $K^- d \to \Lambda p \pi^-$ at 1.4 GeV/c
- S-2S(developed for E70): $\pi^-$ measurements → measurement of missing mass spectrum
  - Good mass resolution: $\Delta M \sim 0.4$ MeV ($\sigma$), ($\Delta p/p$(K18)=$3.3\times10^{-4}$(FWHM), $\Delta p/p$(S-2S)=$6.0\times10^{-4}$(FWHM))
- HypTPC(developed for E42): Final state ($\Lambda p$) restriction and background suppression

Momentum transfer
～200 MeV/c

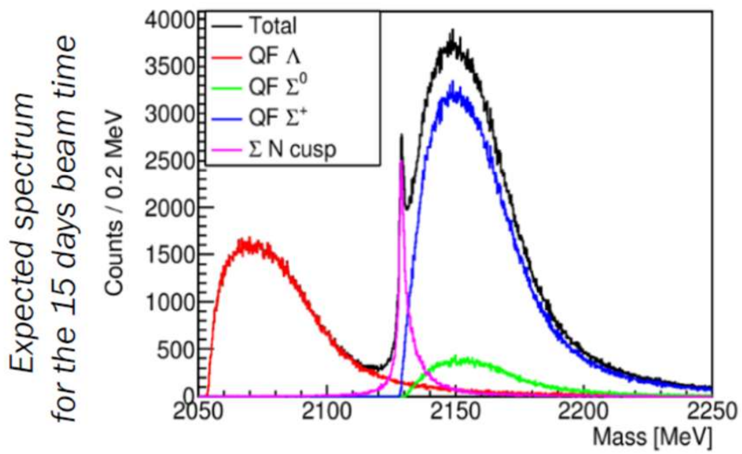


# QF BACKGROUND SUPPRESSION BY HYPTPC



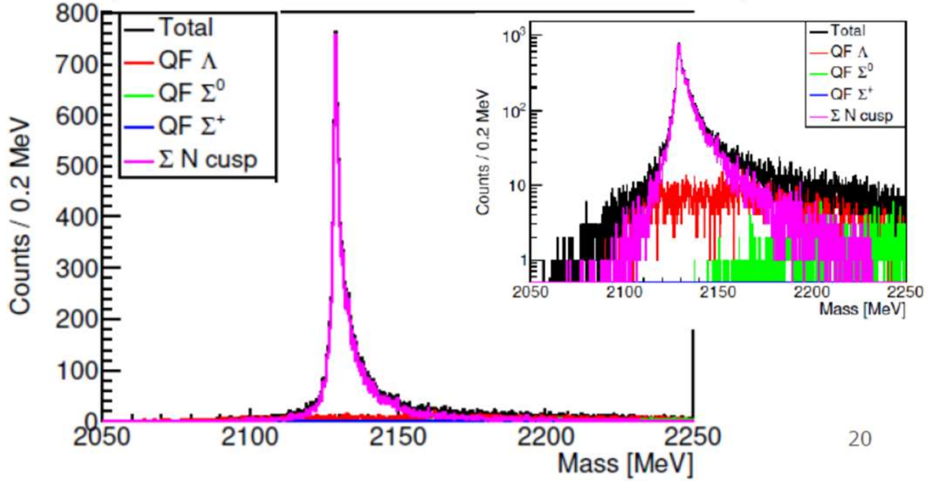




Simulated inclusive spectrum d($K^-$, $\pi^-$)

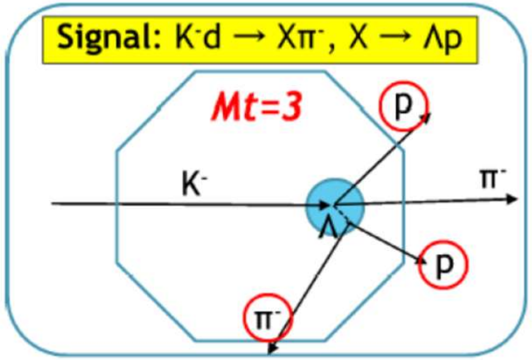


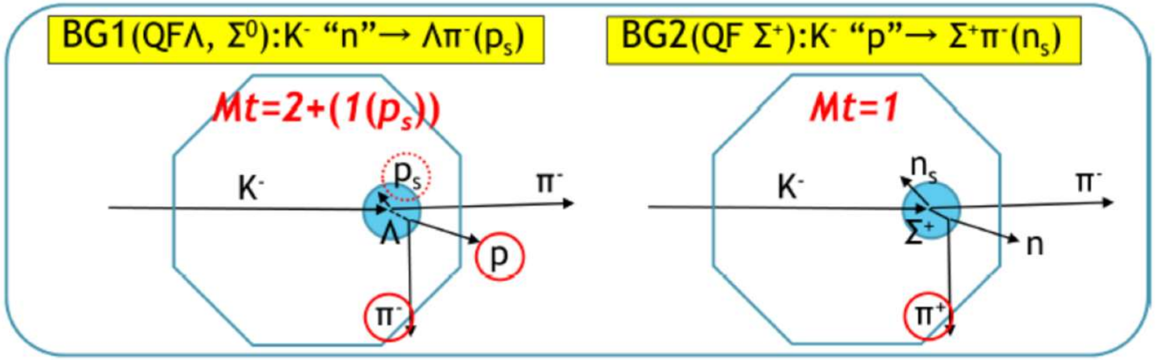


**Multiplicity = 3 without ($K^-$, $\pi^-$)**



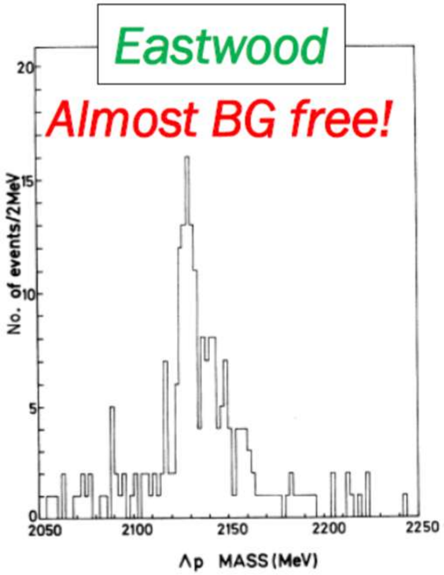
# QF BACKGROUND SUPPRESSION BY HYPTPC

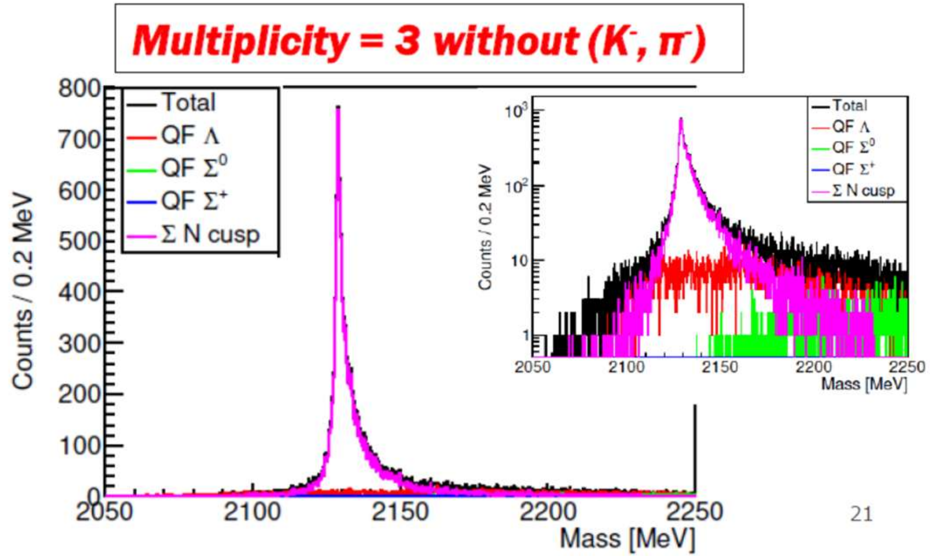



$K^-d \rightarrow \Lambda p \pi^-$
@1.45 and 1.65 GeV/c
(Bubble chamber)

$\cos\theta_{CM} > 0.9$
$p_{proton} > 150$ MeV/c

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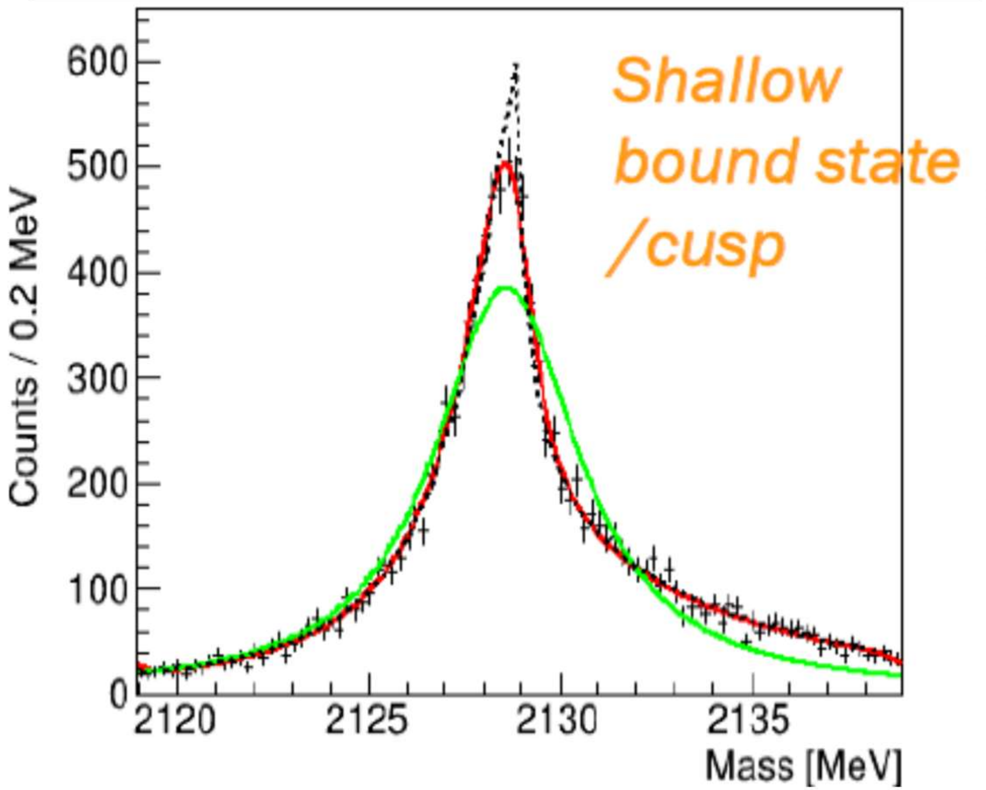
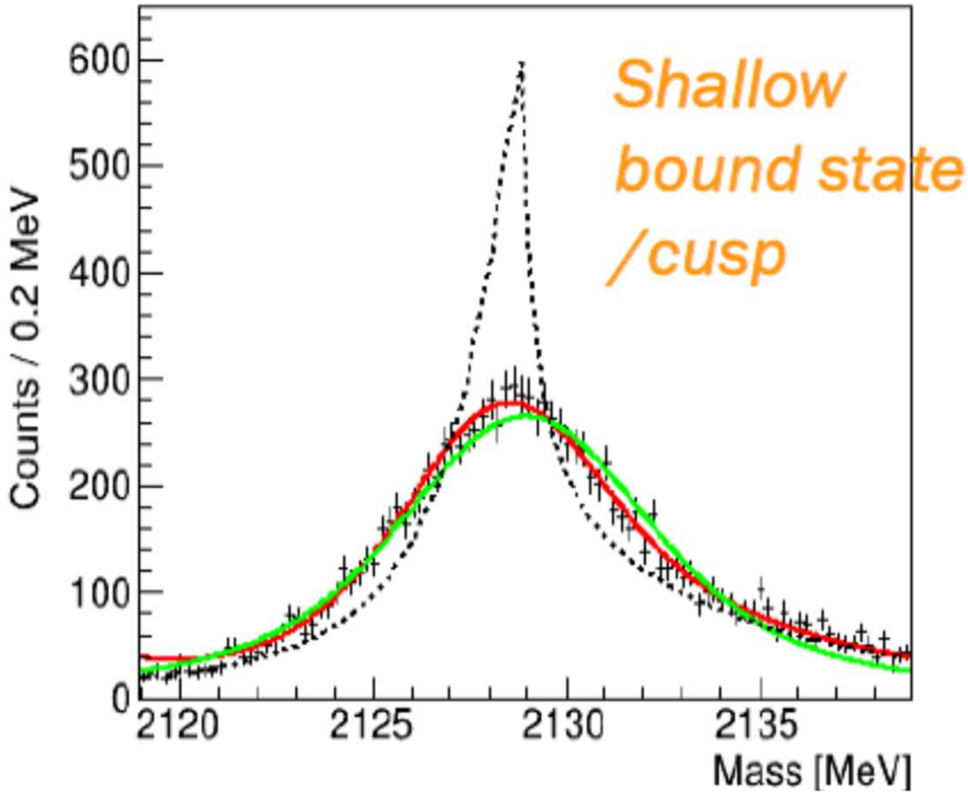
# Importance of resolution

σ＝0.4 MeV




σ＝2 MeV

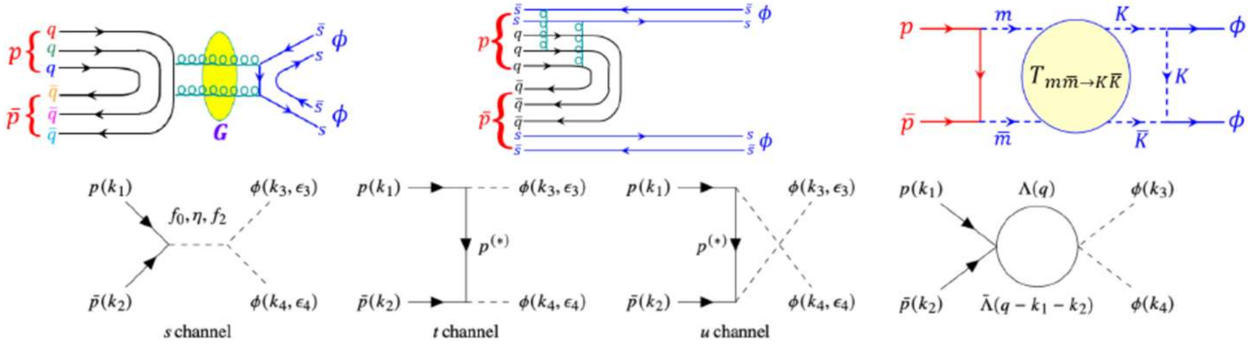



Identification possible with σ＝0.4 MeV, but not with 2 MeV

# *Further experiments*

# E104: $\bar{p}p \to \phi\phi$ production

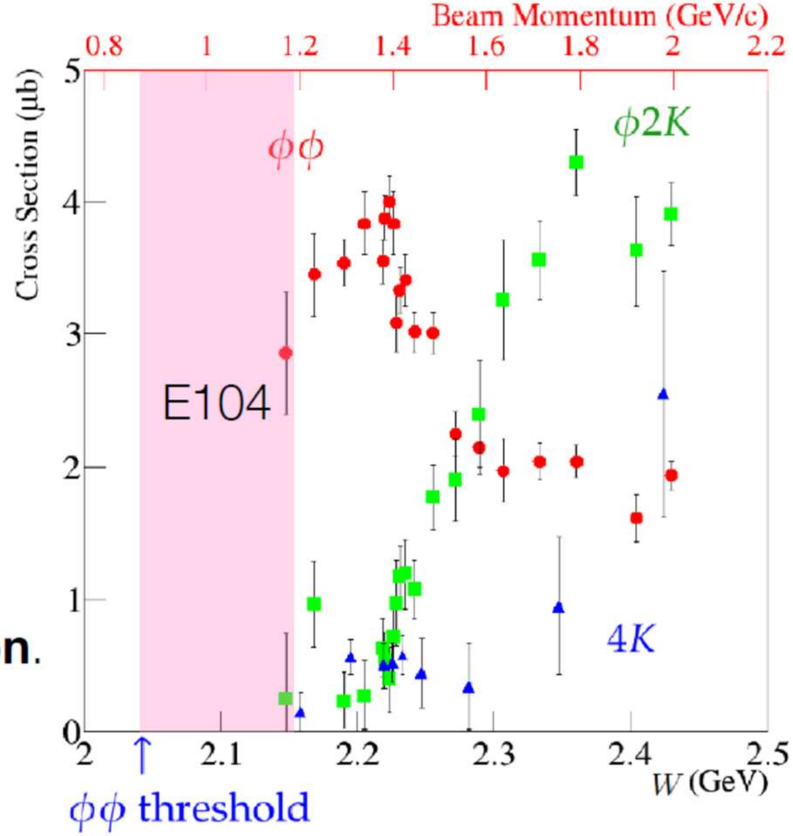
$\bar{p}p \to \phi\phi \to K^+K^-K^+K^-$




**$\phi\phi$ production is OZI suppressed.**

- Past data suggested **unexpectedly large cross section**.
- Large enhancement may indicate **substantial OZI violation**.
- **Spin observables** from $4K$ final state help disentangle underlying **production mechanisms**.

**Large OZI rule violation :** $\mu$b (experiment) $\leftrightarrow$ 10 nb (theory)




- E104 will run in Nov.-Dec. beam time.
- Other possibilities – $\Theta^+$ search with d($K^+$,p), etc.

# Summary

- Exotic hadrons – hadrons beyond the quark model
- We developed a powerful multi-purpose time-projection-chamber, HypTPC.
  - Internal target – $4\pi$ acceptance
  - High-rate capability, good momentum resolution
- E42: Search for H-dibaryon -- results are available
  - $\Xi$N-$\Lambda\Lambda$ conversion is very weak
  - A hint of H dibaryon in $\Lambda\Lambda$ invariant mass
- E72: Search for new $\Lambda$* resonance – Now running
- E45, E90, E104 & more