A New pK^- Peak Structure at $\Lambda\eta$ Threshold and J-PARC E72

CENUM Workshop

September 2nd, 2022

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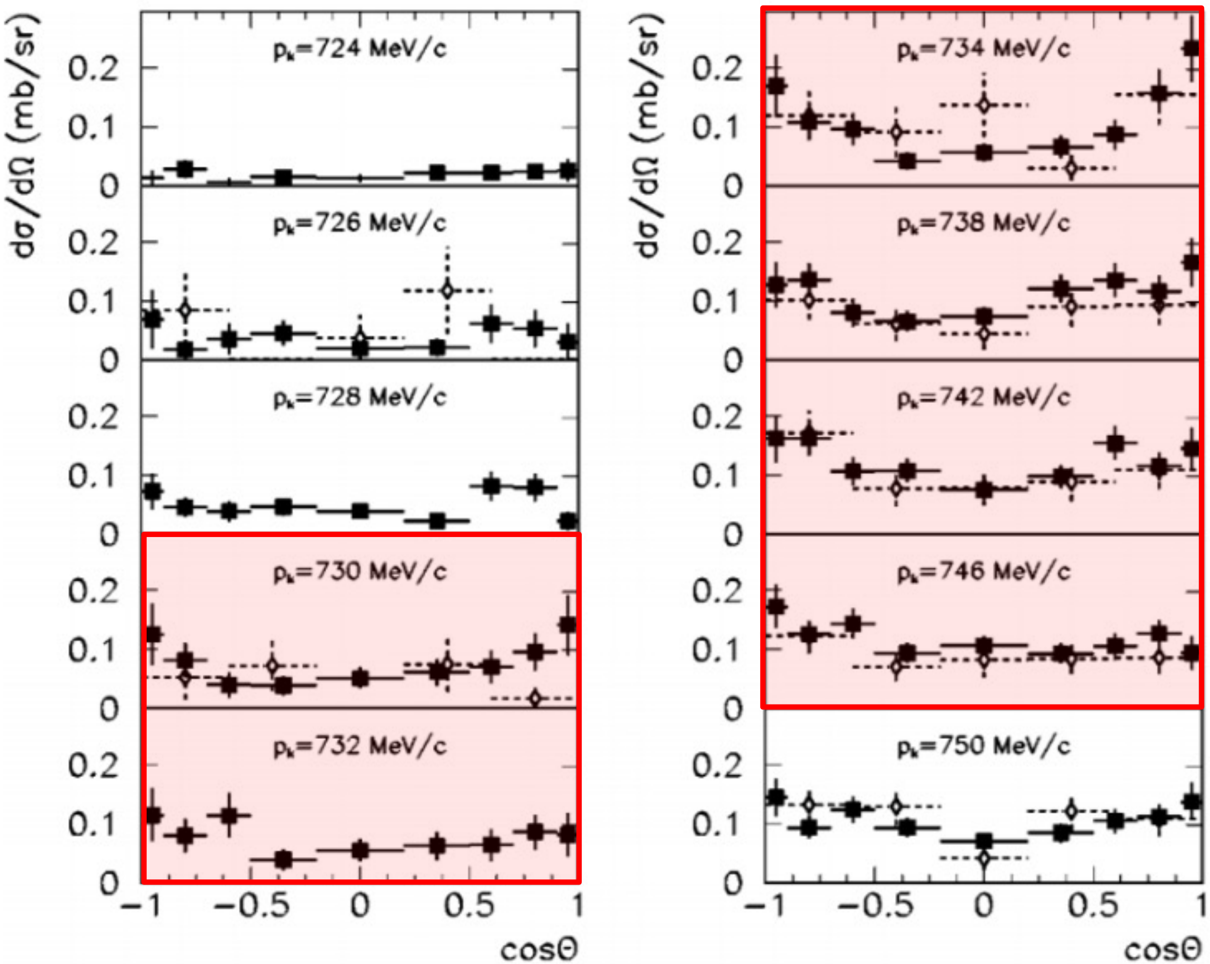
Contents

- Differential cross sections of $K^{-}p \to \eta\Lambda$, Crystal Ball group



Crystal Ball,
PRC 64, 055205

Quadratic shapes from $\sqrt{s} = 1669$ to $1677\ \mathrm{MeV}/c^{2}$
→A narrow resonance (~$1.670\ \mathrm{GeV}/c^{2}$) with $\mathbf{J = 3/2}$

- Partial wave analyzes of the $Kp \rightarrow \eta\Lambda$ data sample

→ Kamano et al. $\mathrm{J^p = 3/2^+ \ (P_{03})}$, $\mathrm{M = 1671\ MeV}/c^2$, $\Gamma = 10\ \mathrm{MeV}/c^2$

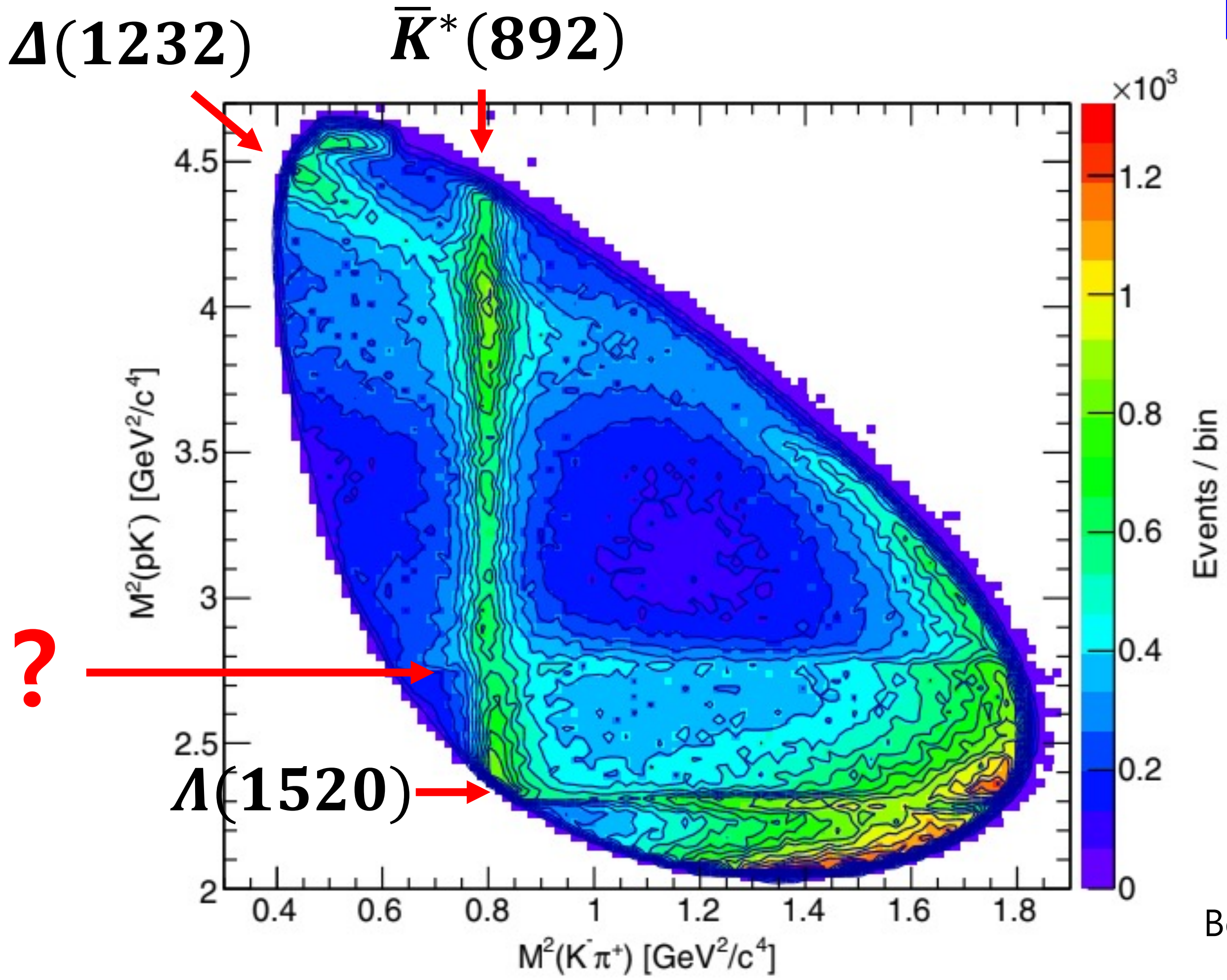
PRC 92, 025205

→ Liu & Xie. $\mathrm{J^p = 3/2^- \ (D_{03})}$, $\mathrm{M = 1668.5\ MeV}/c^2$, $\Gamma = 1.5\ \mathrm{MeV}/c^2$

PRC 85, 038201

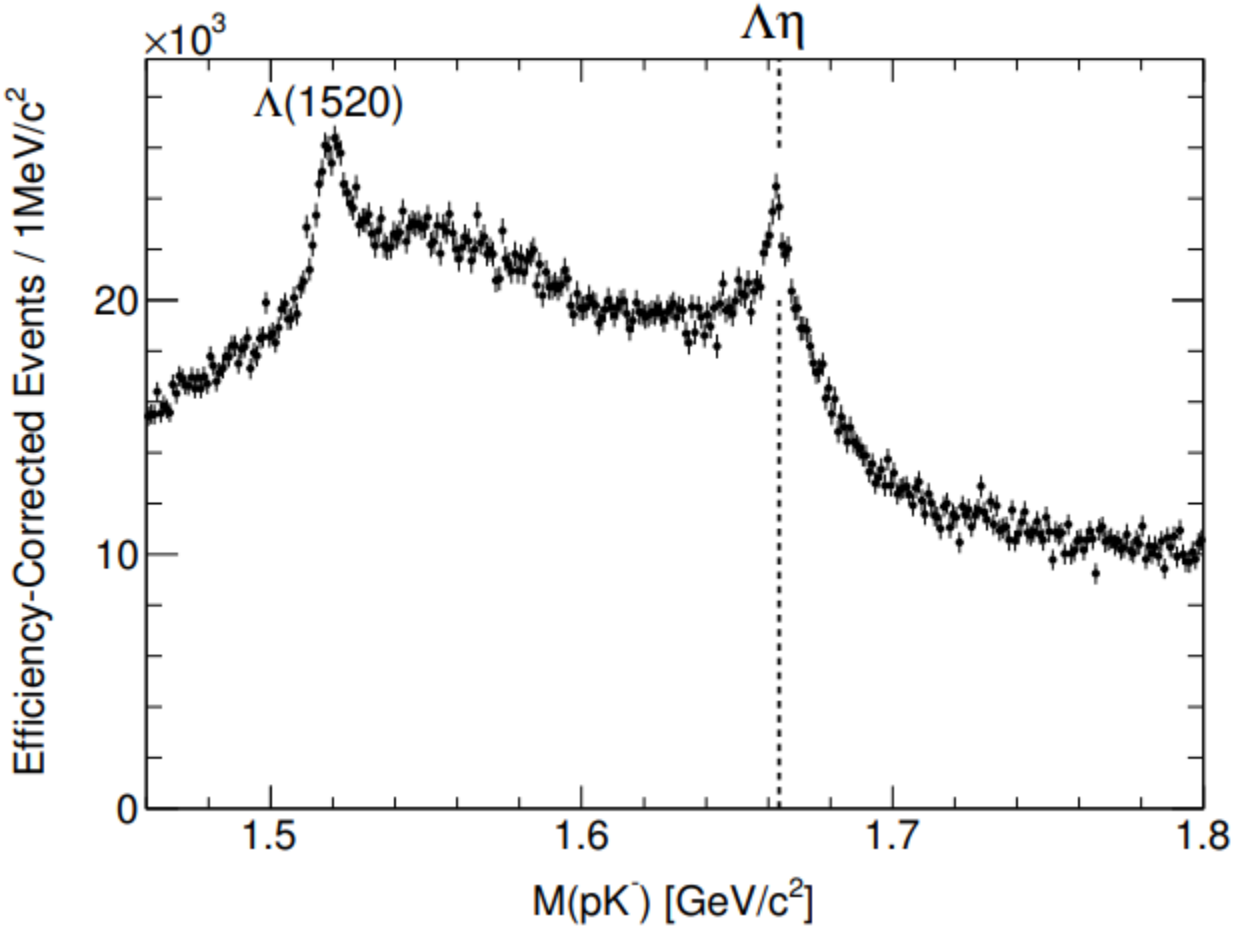
→ Both results indicate that there is a narrow Λ* with 3/2 spin near $\eta\Lambda$ mass threshold.

- Dalitz plot of $\Lambda_c^+ \to pK^-\pi^+$,



Belle, PRL 117, 011801

- $M(pK^-)$ Distribution of $\Lambda_c^+ \to pK^-\pi^+$ decays



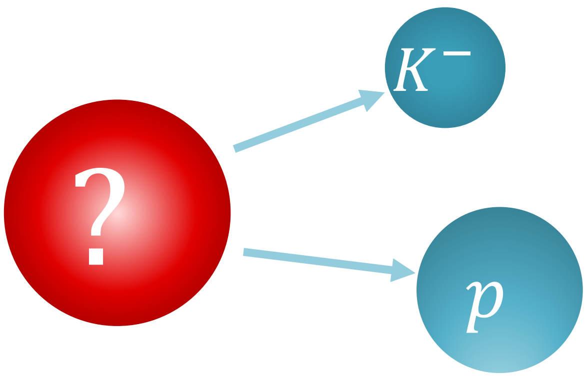
- Λ^* and Σ^* have wider widths near the ~1665 MeV/c^2 region on the PDG.

Baryon	**Mass** (MeV/c^2)	**Width** (MeV/c^2)
$\Lambda(1670)$	1660-1680	25-50
$\Sigma(1660)$	1630-1690	40-200
$\Sigma(1670)$	1665-1685	40-80
$\Lambda(1690)$	1685-1695	50-70

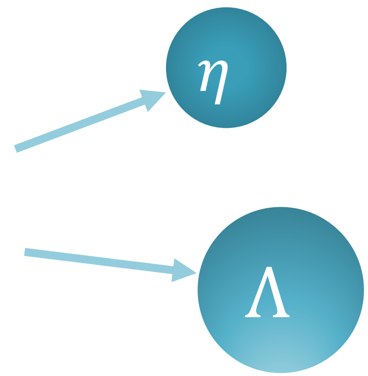
→ The narrow peak is distinguished from known baryons due to its narrow width.

What is it?

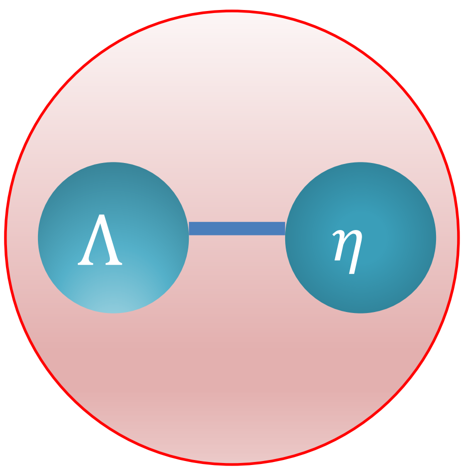
Mass: ~1665 GeV/c^2
Width: ~10 MeV
Spin: 3/2



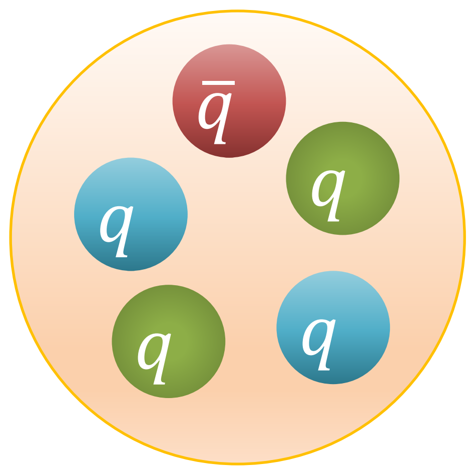
or



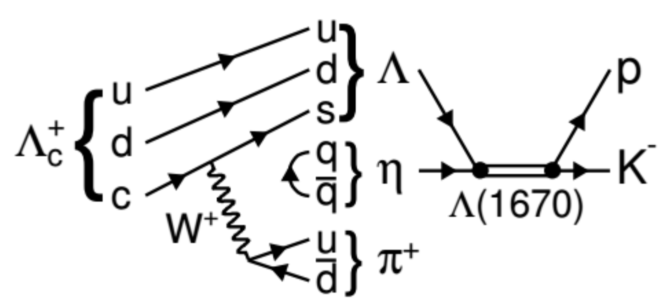
molecular state?



Pentaquark?

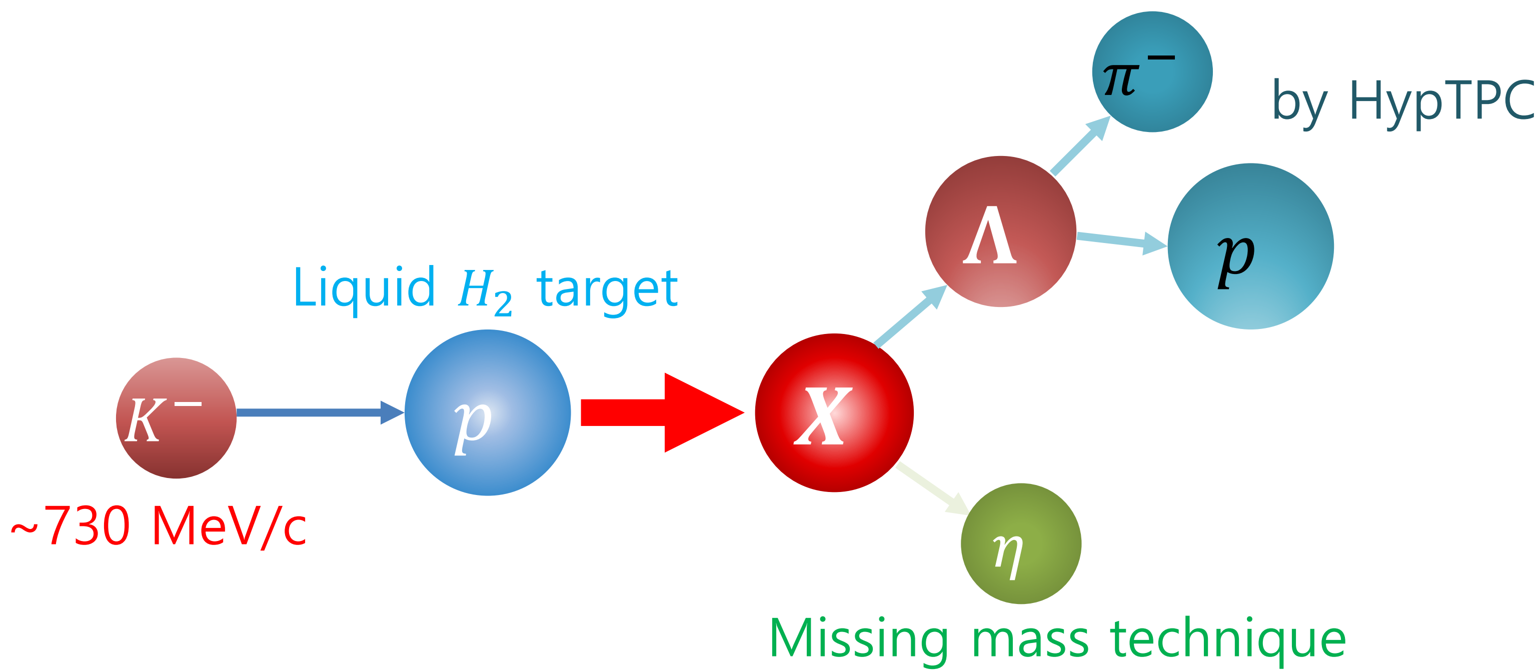


A threshold cusp or ...??

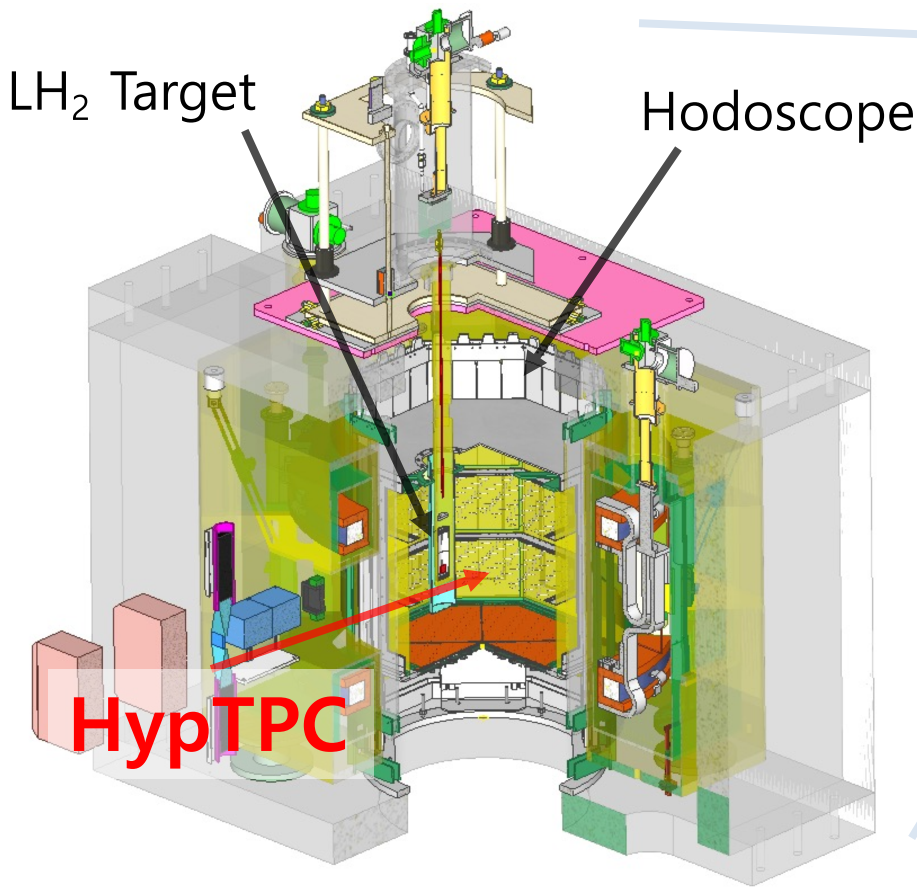


The new Λ^* search at J-PARC (J-PARC E72).

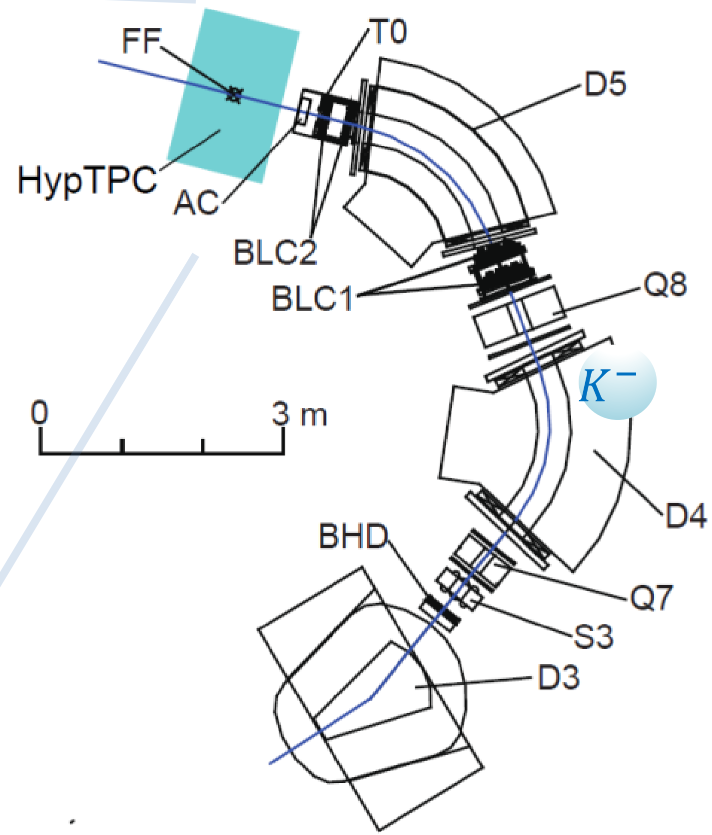
- We aim to observe the Λ^* at the first time and measure its properties including the spin and the parity.
- $K^- p \to \eta\Lambda$ reaction with 730 MeV/c K^- beam and hypTPC having a large acceptance.



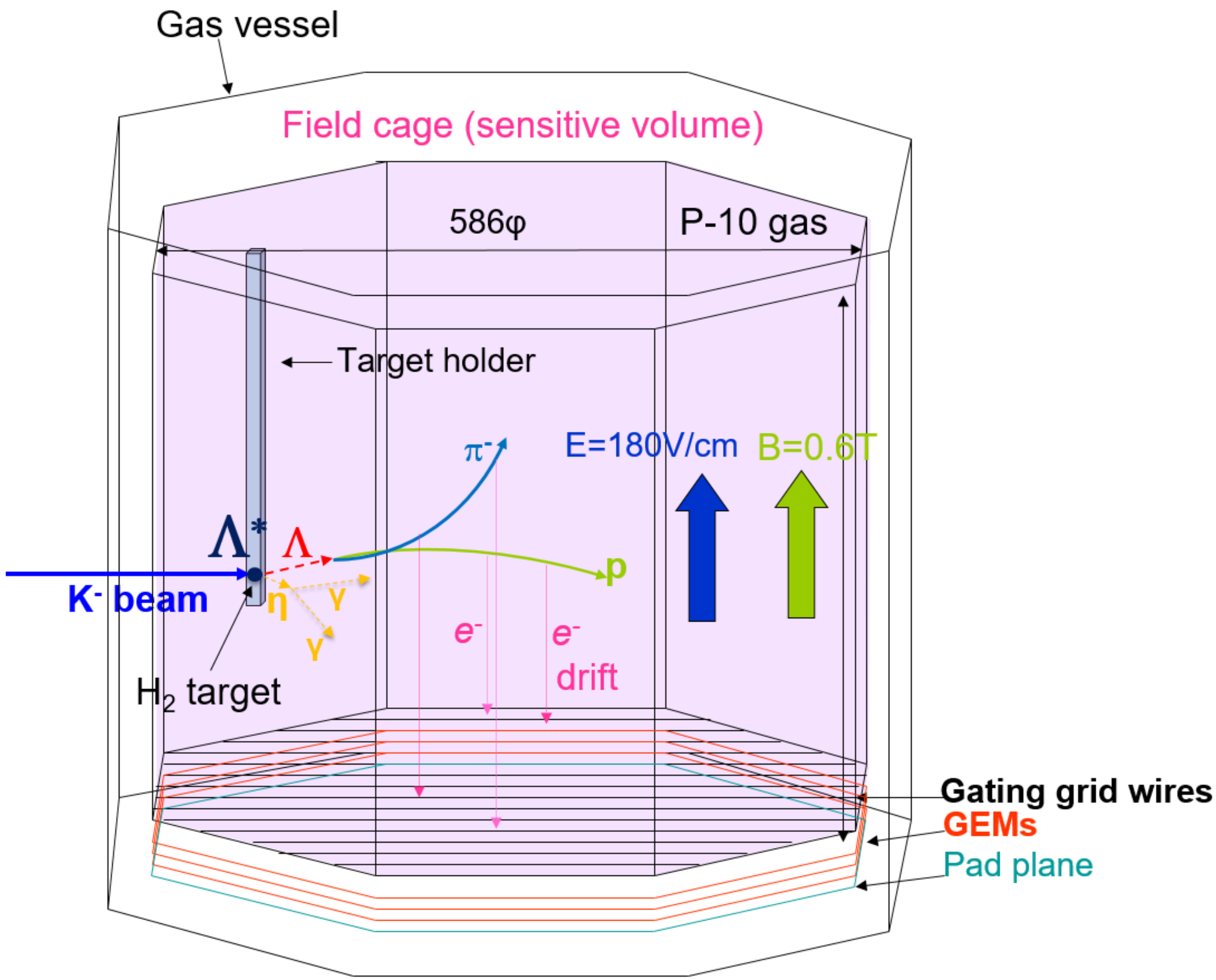
- J-PARC K1.8BR beamline: 700~800 MeV/c K^- beam with ~30 k/spill
- Hyperon spectrometer: Large acceptance with HypTPC



Helmholtz magnet (B=1.0 T)



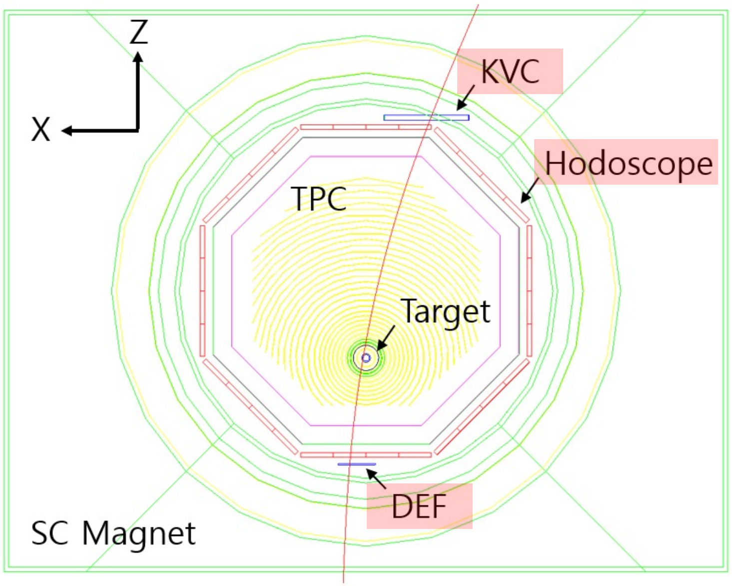
- A new TPC for hadron experiments at J-PARC
- High resolution and large acceptance
- Good performance in previous experiment (J-PARC E42)



Trigger

- Trigger type
- Trigger A: Two or more hits of THD.
- Trigger B: At least one hit of THD with large energy deposit (> 4 MeV).
- Both A & B: 'K^- beam trigger by beamline spectrometer' and KVF veto.

- Expected trigger rate (50 kW beam)
- All kaon reactions at Target: 140 /spill
- At other materials: 200 /spill
- K^- beam decay: 240 /spill
- Total: ~600 /spill



Expected Spectrometer Performance

*with worse analysis level

- Resolution

- Momentum of π^-: 2.2% @full range
- Momentum of p: 3.8% @full range
- Invariant mass of Λ: 1.6 MeV/c^2
- Missing mass of η: 1.3 MeV/c^2

- Acceptance

- (Trigger A||B)&'Λ reconstruction': 83%

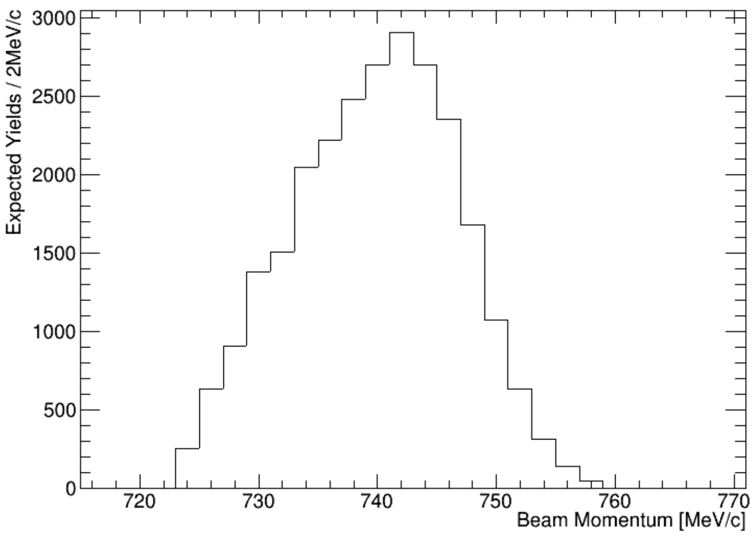
Expected Yield

*Using realistic parameters (50 kW beam and Φ54 mm target).

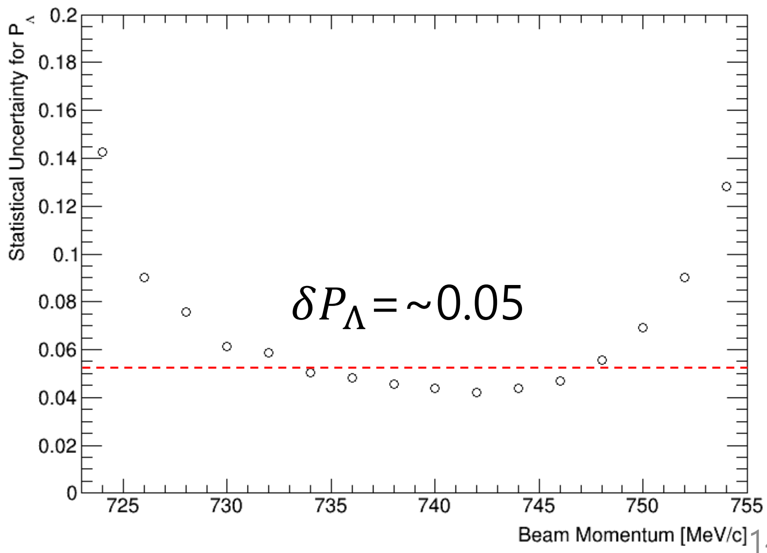
- Parameters

- Branching fraction of $\Lambda \to p\pi^-$: 0.64 - K^- beam hit target: 15 k/spill
- Protons in target: $2.1\times10^{23}\times0.9\ /\mathrm{cm}^2$
- Cross-section: Crystal-ball experiment data
- Acceptance: ~83% - Overall eff.: 0.8

Expected yield per 1 day



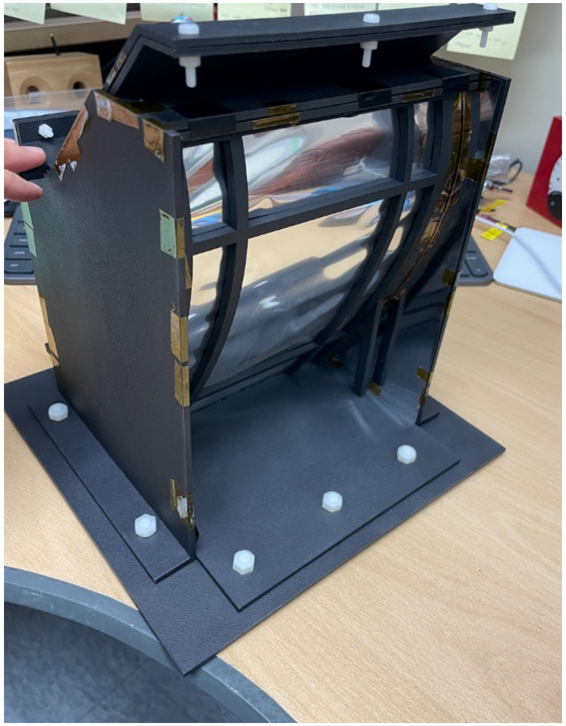
Expected stat. uncertainty of P_Λ for 21 days (per each reaction angle bin)



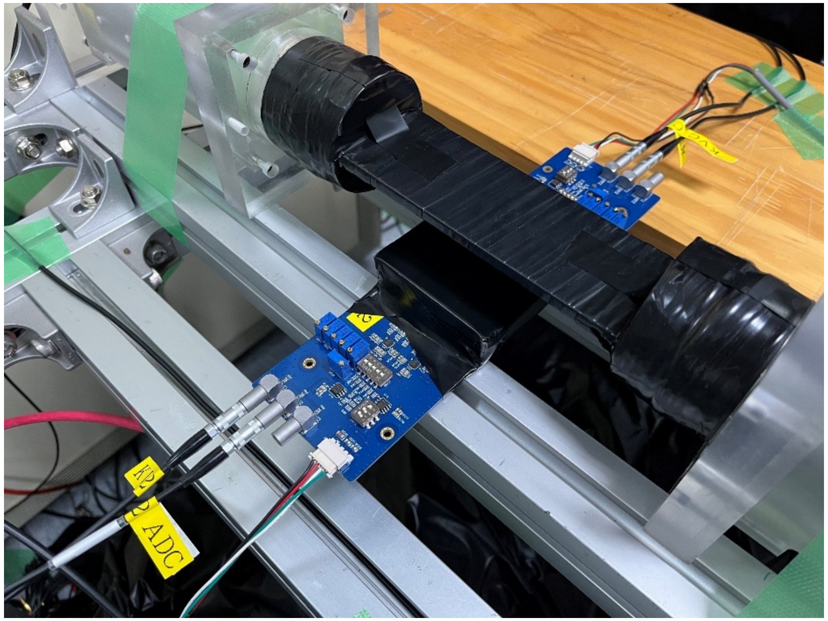
- The 'Stage-2' approved.
- A new LH2 target with a larger diameter.

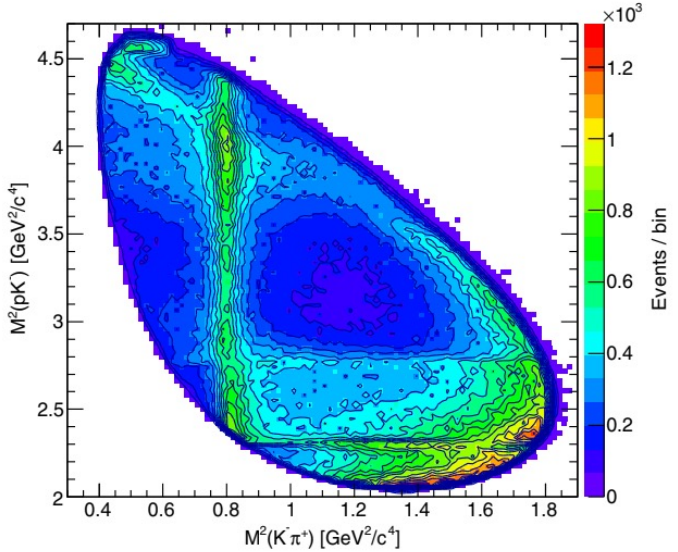
  Φ54 mm → Φ80 mm
- New trigger counters with MPPC.
- All spectrometers will be ready in 2022.

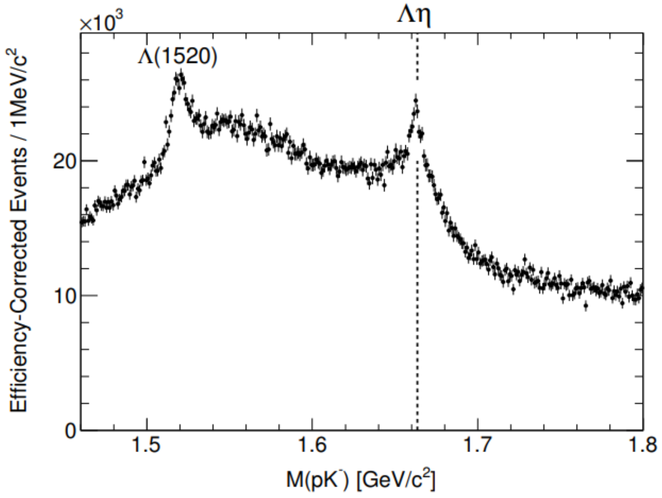
Prototype of BAC



Prototype of KVC



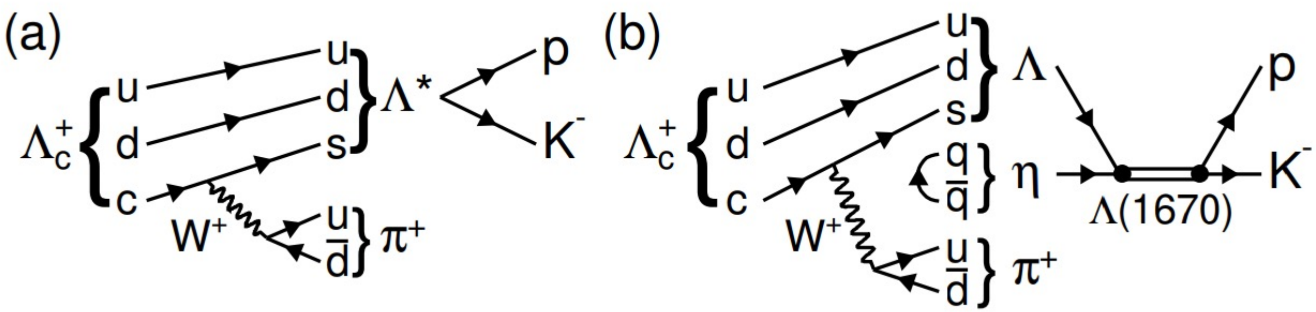




Two approaches to explain the peaking structure.

(a) Breit-Wigner function: a new resonance

(b) Flatté function: a visible cusp enhanced by $\Lambda(1670)$ pole



- Breit-Wigner function: a resonance peak of unstable particles.

$$N(W) = \frac{K}{(W - W_r)^2 + \Gamma^2/4}$$

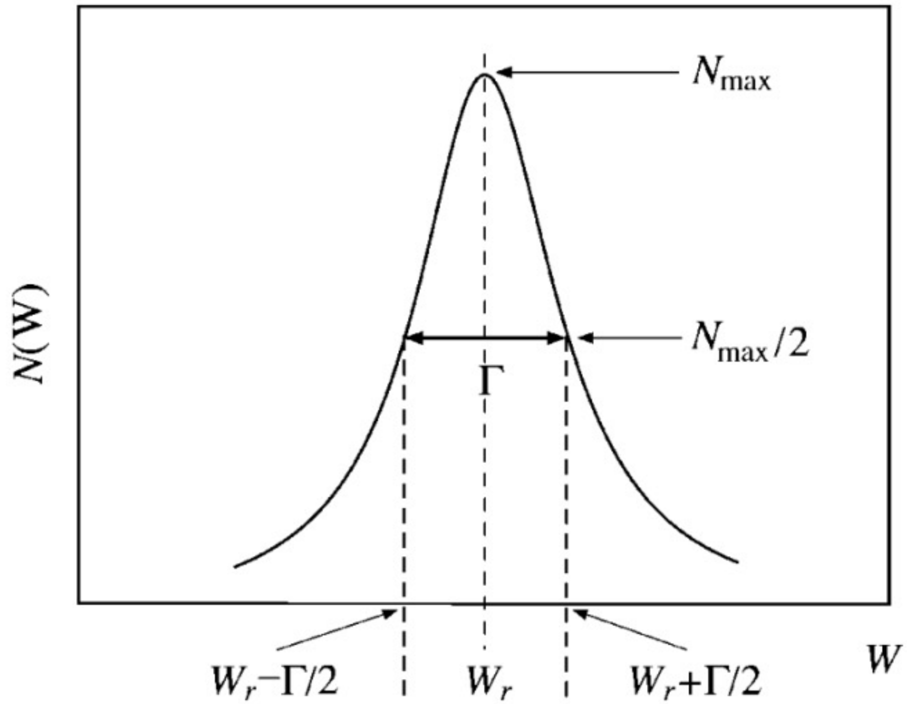


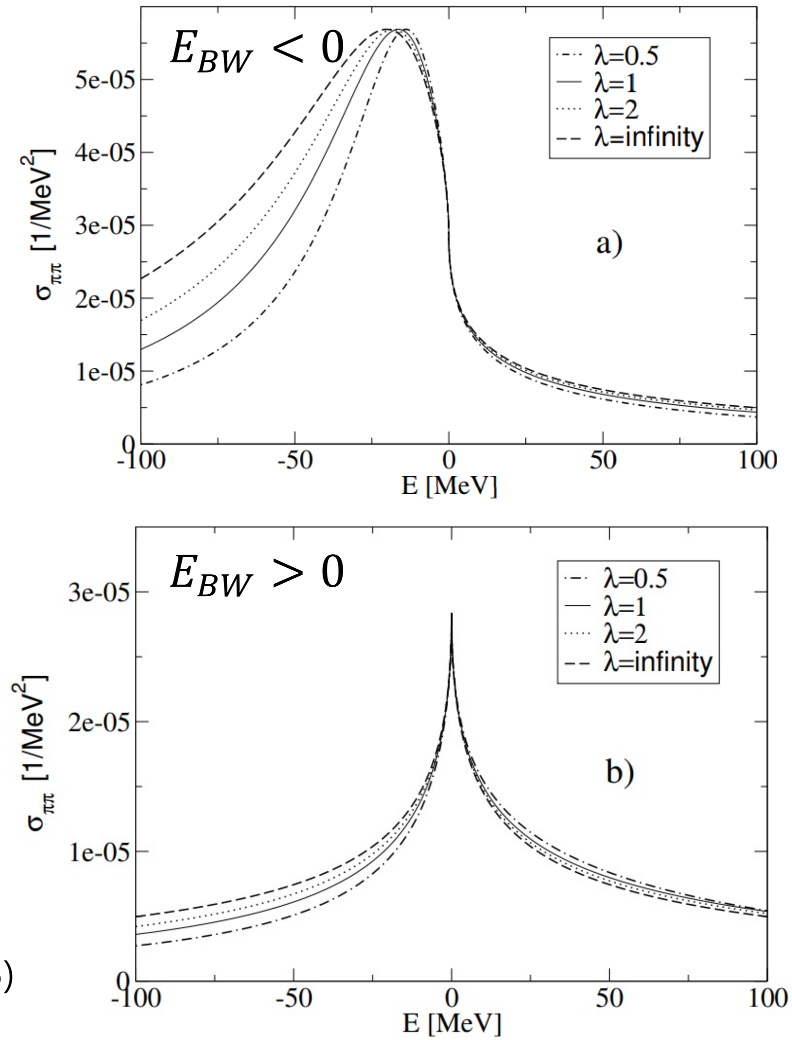
Figure 3.10 Plot of the Breit–Wigner formula (3.26).

B.R. Martin, Nuclear and Particle Physics An Introduction, Wiley (2009)

- Flatté Function: a peaking structure at a threshold
  ex) a threshold cusp

$$f_{\rm el} = -\frac{1}{2q}\frac{\Gamma_P}{E - E_{\rm BW} + i\frac{\Gamma_P}{2} + i\bar{g}_K\frac{k}{2}}$$

$k = \sqrt{m_K(\sqrt{s} - 2m_k)}$
*k is imaginary when $m < 2m_K$

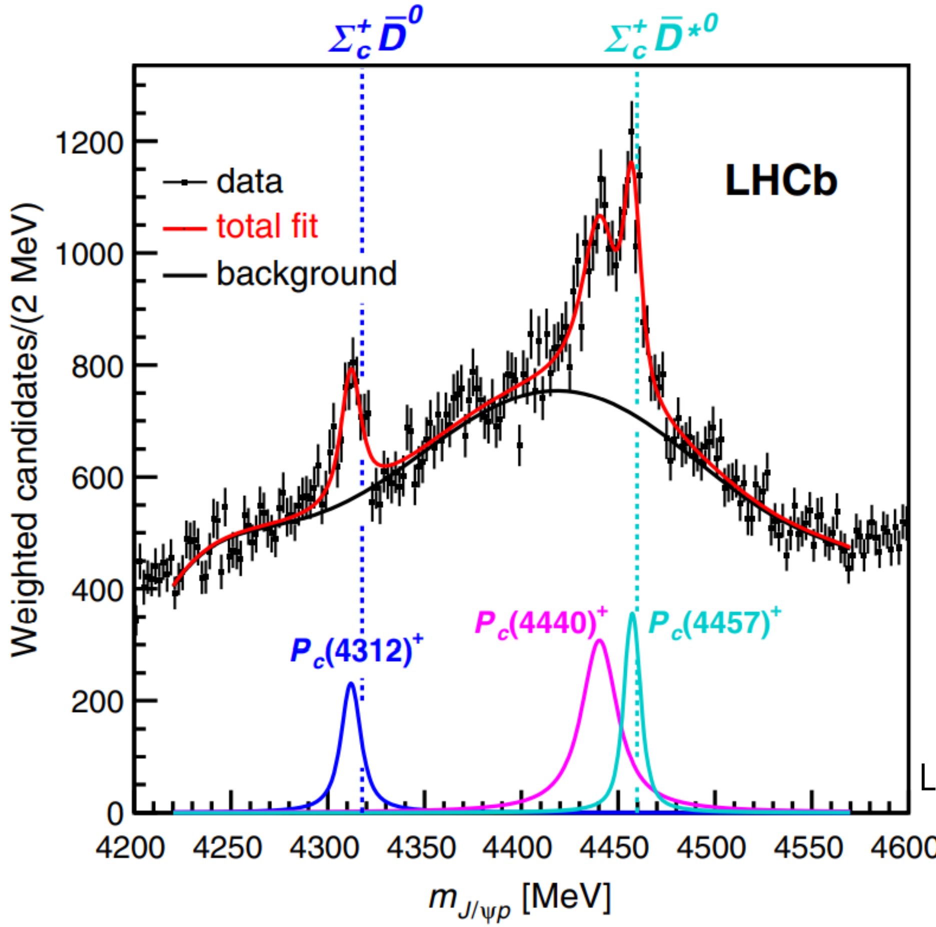


V. Baru et al., Eur. Phys. J. A 23, 523 (2005)

- Narrow pentaquarks states near meson-baryon thresholds
  - New analysis with 246 k $\Lambda_b^0 \to J/\psi K^- p$ decays
- Three narrow peak structures observed near meson-baryon thresholds

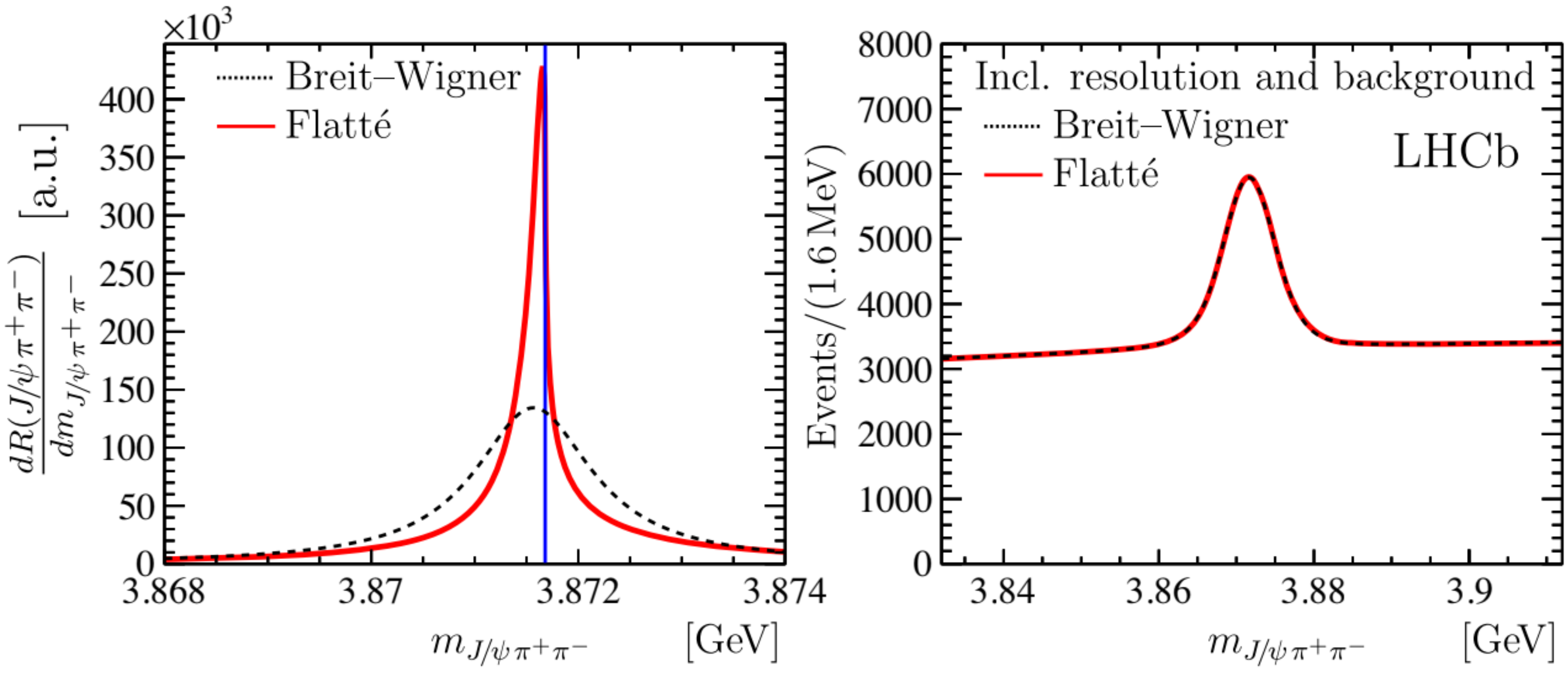
→ molecular states of baryon-meson

→ triangle-diagram process (?)



LHCb, PRL 122, 222001 (2019)

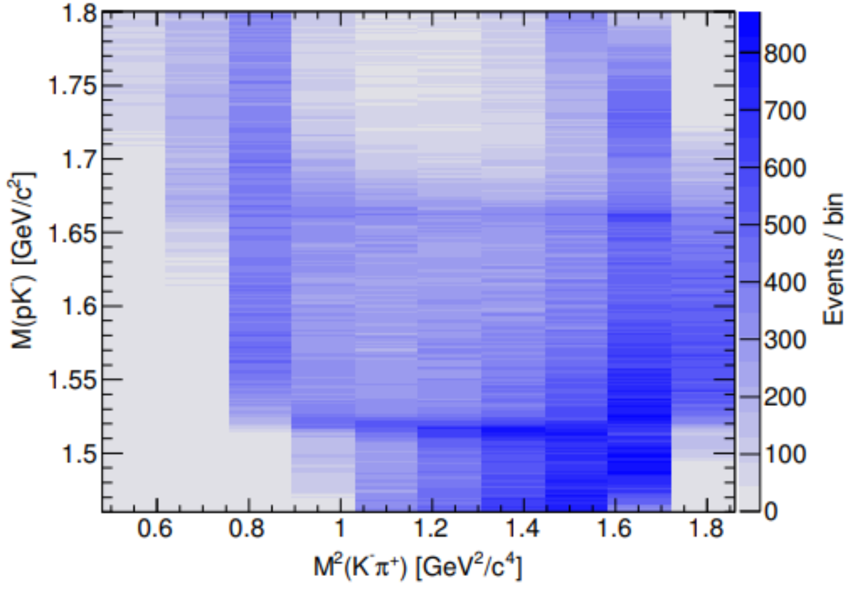
- Breit-Wigner and Flatté functions for $x(3872)$ at $M(J/\psi\,\pi^+\pi^-)$



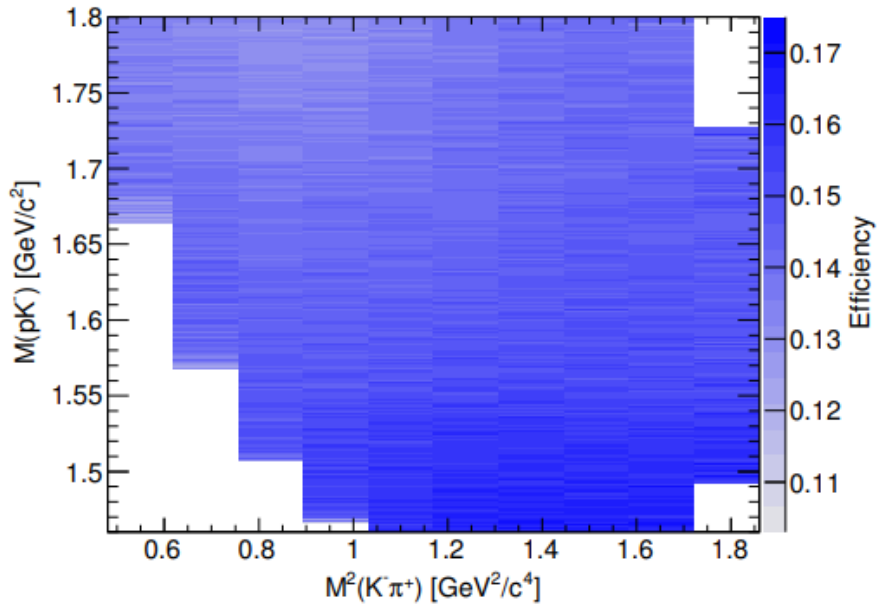
LHCb, PRD 102, 092005 (2020)

- Efficiency correction on scatter plot due to non-uniform density.

Real Data in Signal Region



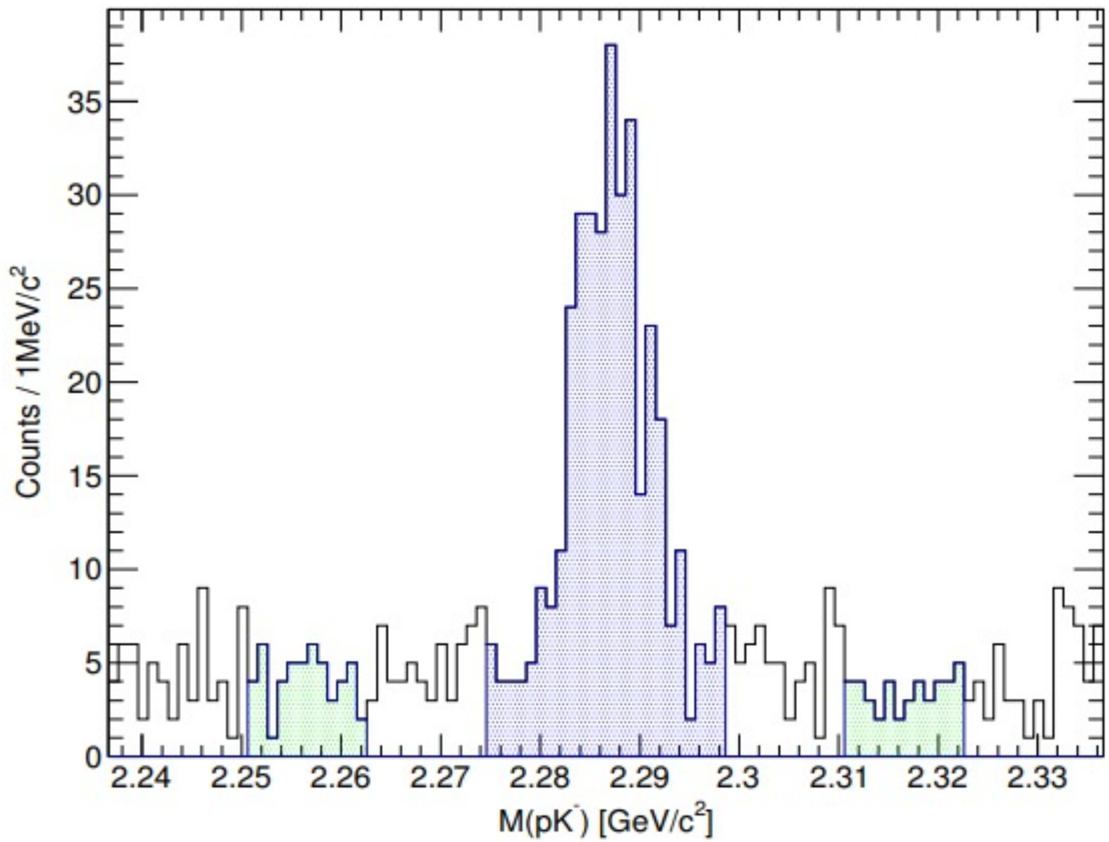
Efficiency Table



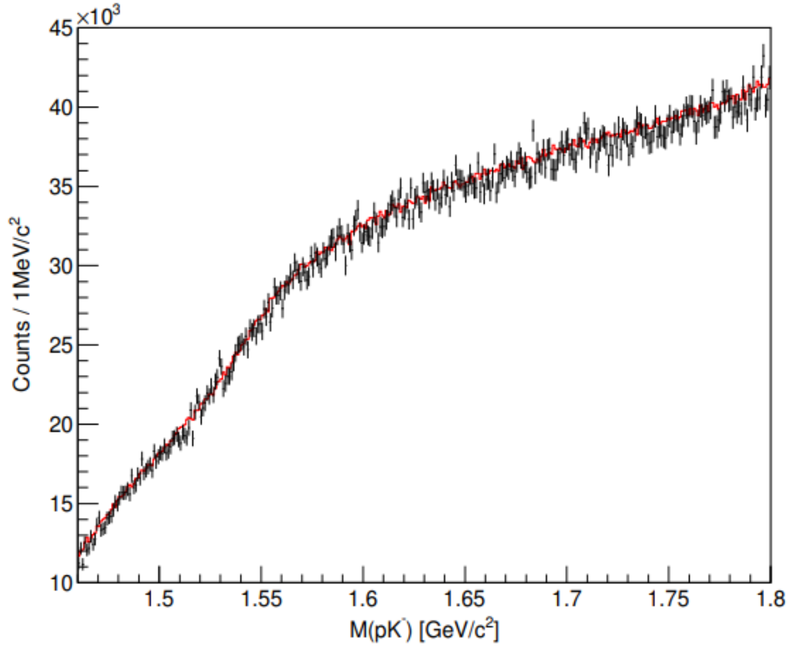
→ Bin-by-bin correction

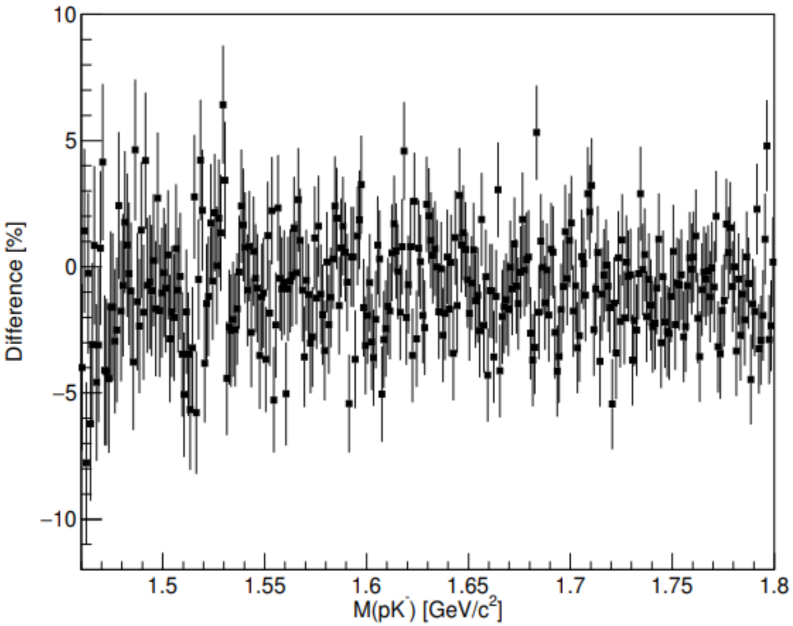
- Non-Λ_c^+ Background Subtraction:

We subtract the events in the sidebands from the signal region.



▪ Generic MC test for the efficiency correction and background subtraction.

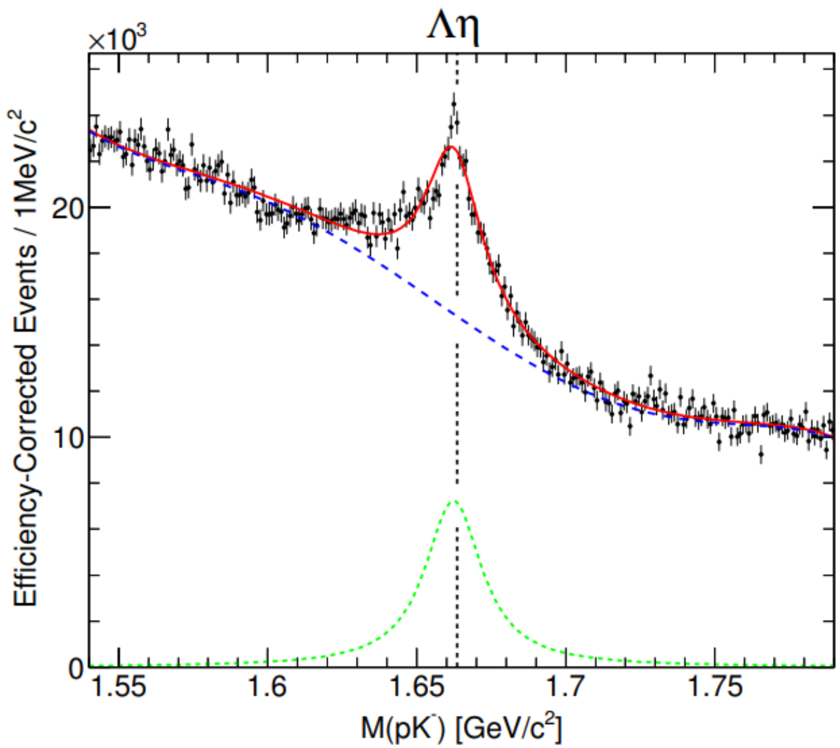




→ Successfully reproduced.

- BW fit results

: non-relativistic BW function (signal) + 5th polynomial functions (background)



Mass $(\mathbf{MeV}/c^2)$	**Width** $(\mathbf{MeV})$	χ^2/ndf
1662.4±0.3	23.5±1.6	1.35 (328/242)

- Non-relativistic Flatté function,

$$\frac{dN}{dm} \propto |f(m)|^2 = \left| \frac{1}{m - m_f + \frac{i}{2}\left(\Gamma' + \bar{g}_{\Lambda\eta} k\right)} \right|^2$$

where m_f: Flatté mass

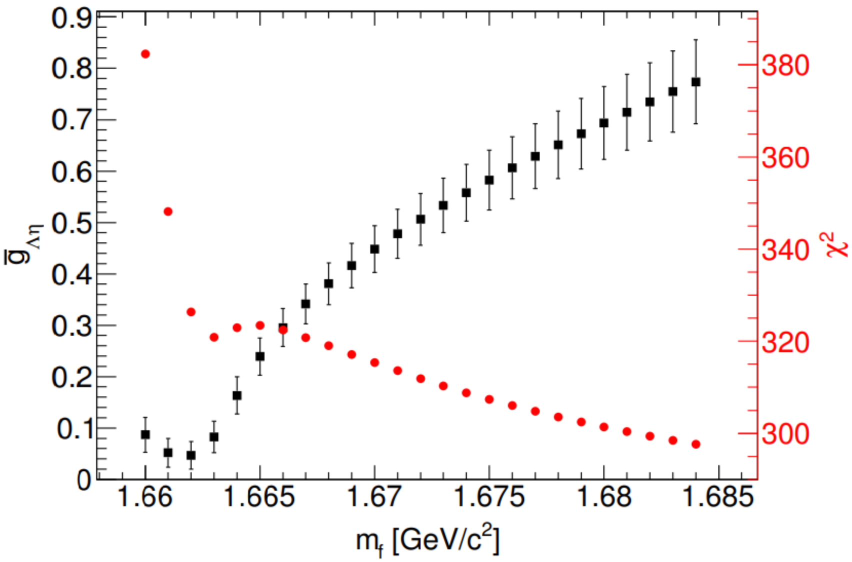
Γ': a sum of partial widths other than $\Lambda\eta$ decay

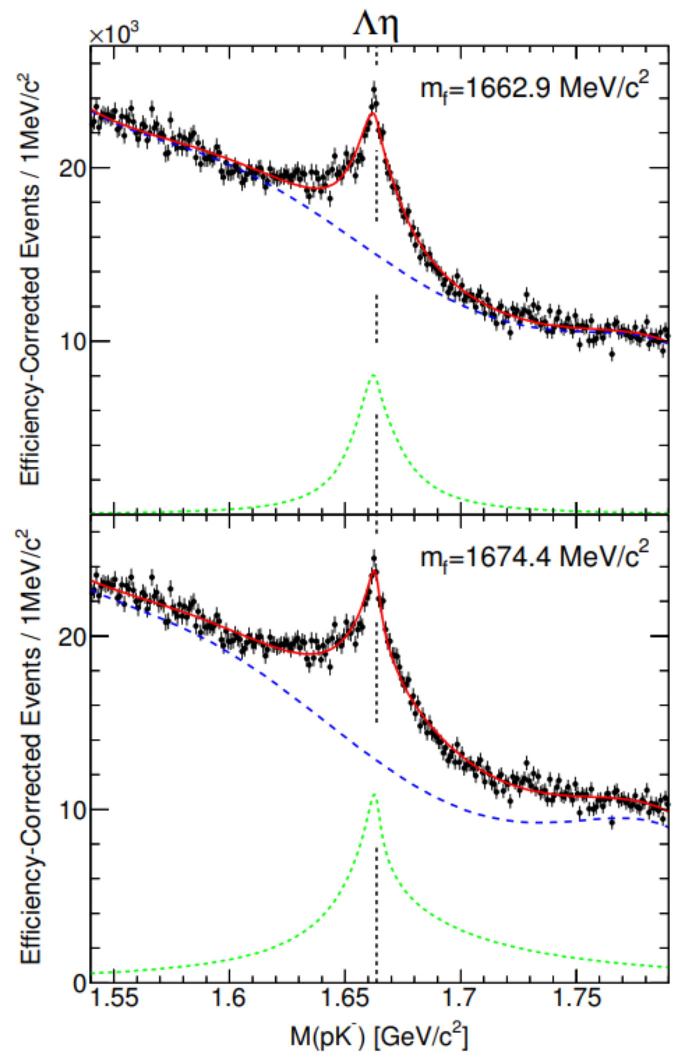
$\bar{g}_{\Lambda\eta}$: coupling constant of $\Lambda\eta$ channel

k: $\sqrt{2\mu_{\Lambda\eta}(m - m_\Lambda - m_\eta)}$, *$k$ is imaginary when $m < m_\Lambda + m_\eta$

- Flatté fit results

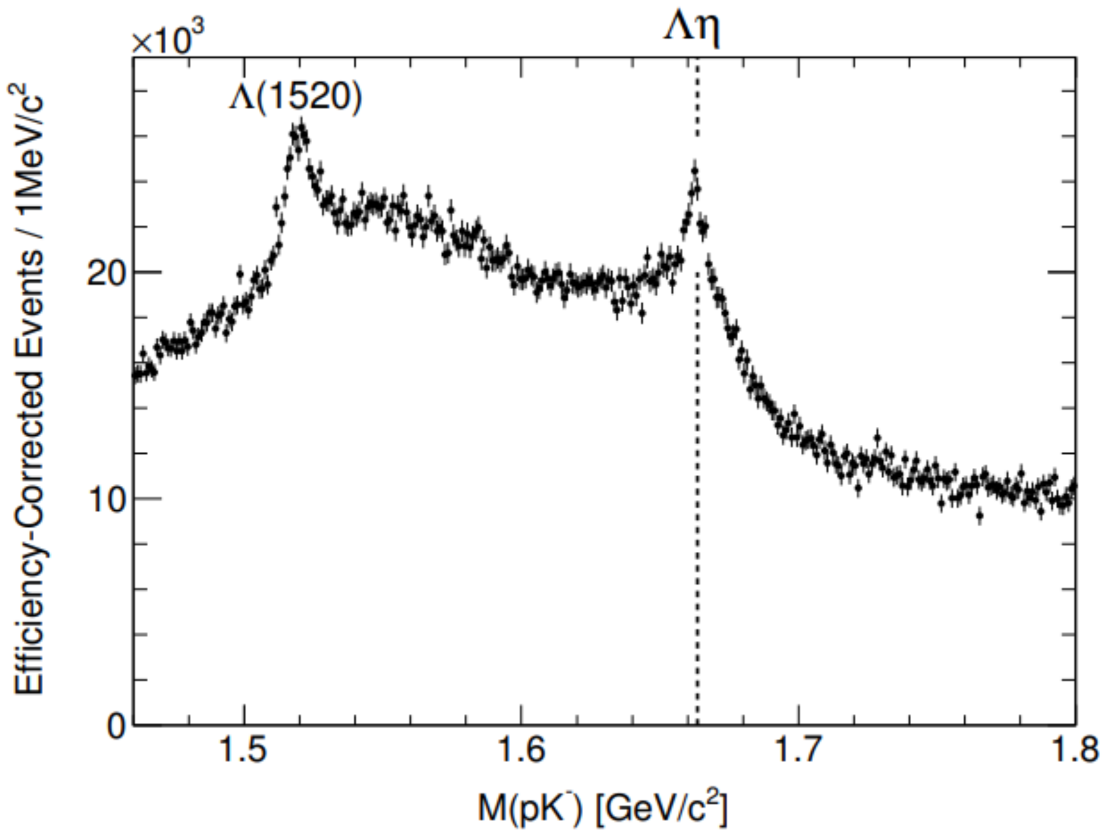
: The scaling behavior of parameters → m_f fixed.





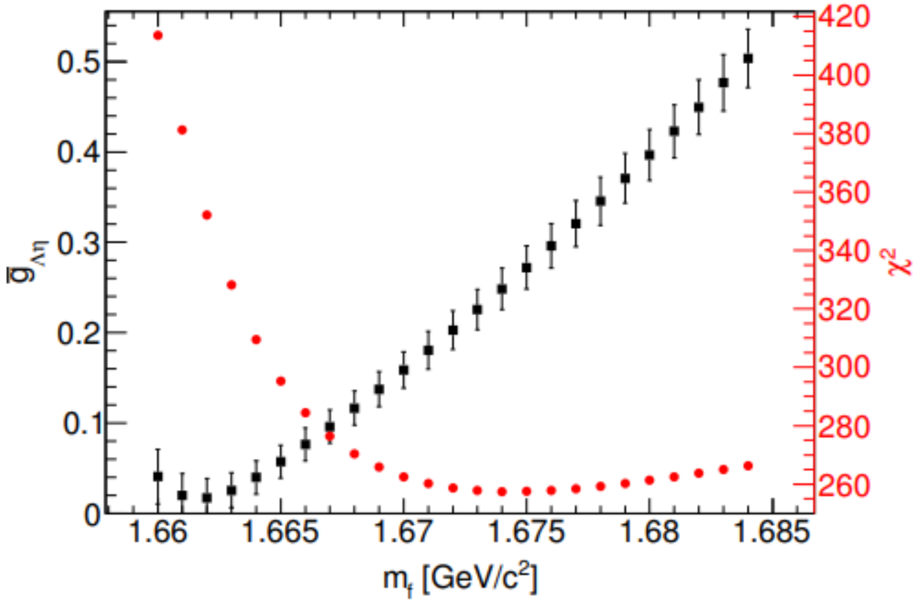
- Interference with other amplitudes:

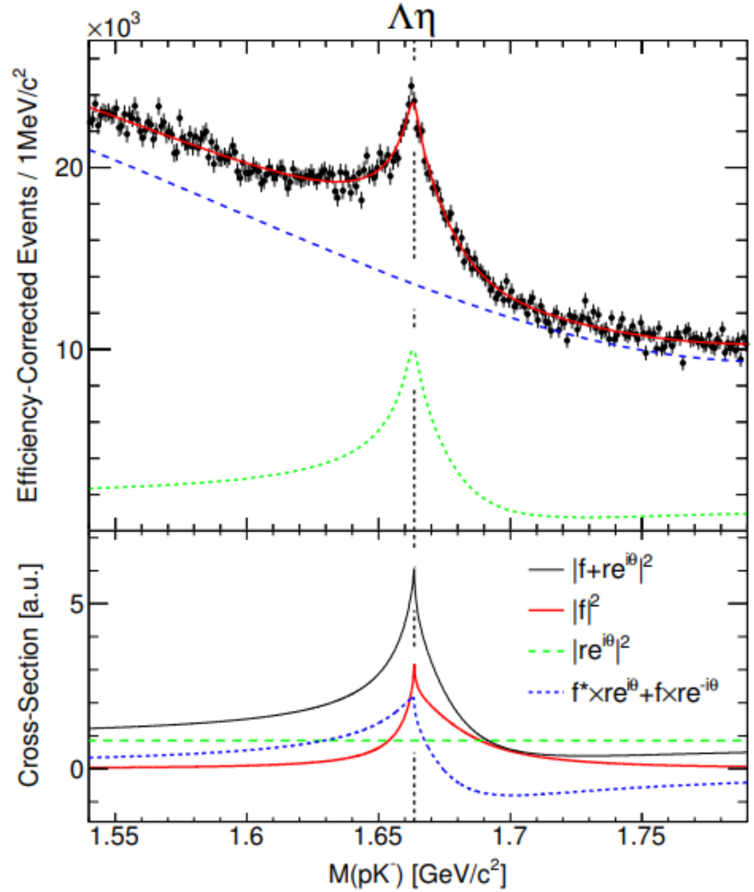
a constant can be coherently added, $\frac{dN}{dm} \propto \left| f(m) + re^{i\theta} \right|^2$, to represent interference with other amplitudes.



- Flatté fit results with the interference term,

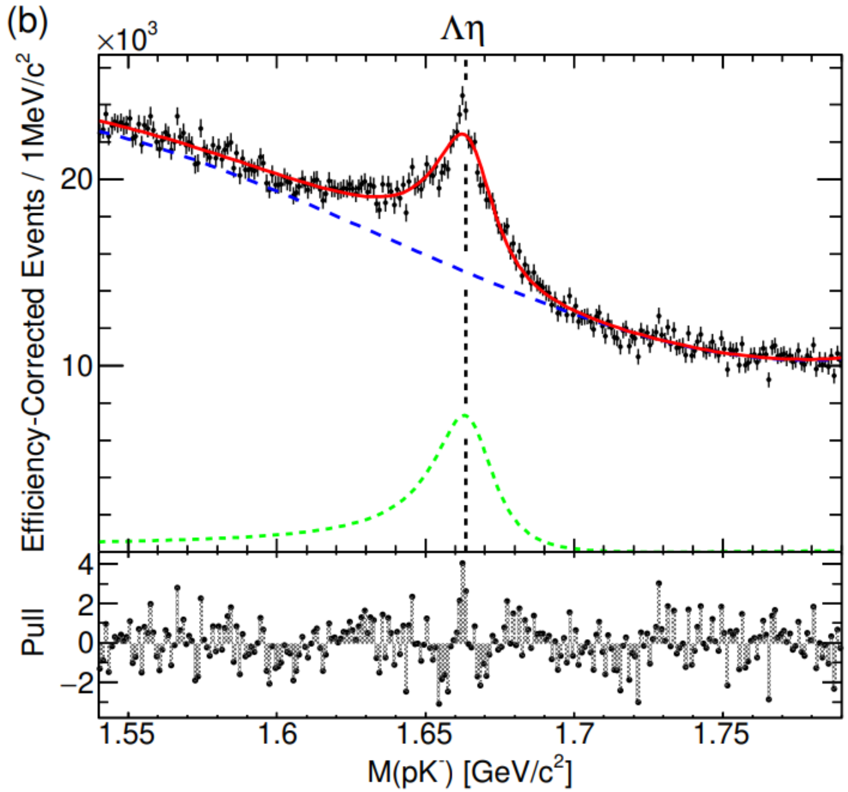
*$m_f = 1674.4\ \mathrm{MeV}/c^2$ and $\theta = \pi$ fixed.





m_f (MeV/c^2)	Γ' (MeV)	$\bar{g}_{\Lambda\eta}$	χ^2/ndf
1674.4 (fixed)	27.2±1.9	0.258±0.023	1.06 (257/243)

- BW fit results with the interference term

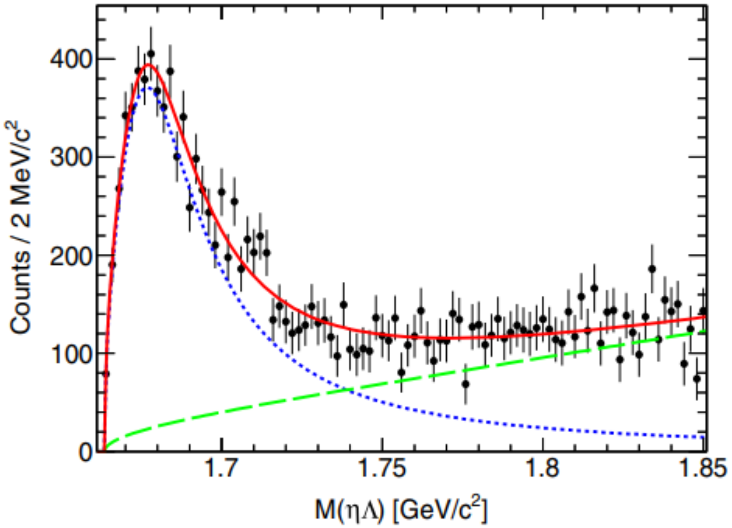


Mass (MeV/c^2)	Width (MeV)	χ^2/ndf
1665.4±0.5	23.8±1.2	1.27 (308/242)

- The peak structure is significantly favored to a threshold cusp by 7σ than a hadron resonance.
- Significant interference with other amplitudes is seen.

- In Flatté fit results, the mass and width of $\Lambda(1670)$ are consistent with the recent measurement

Channel	Mass (MeV/c^2)	Width (MeV)
$\Lambda_c^+ \to \eta\Lambda\pi^+$	1674.3±0.8±4.9	36.1±2.4±4.8
$\Lambda_c^+ \to pK^-\pi^+$	1674.4 (fixed)	$50.3 \pm 2.9^{+4.2}_{-4.0}$



Belle, PRD 103, 052005 (2021)

Summary

- Evidence of a new exotic hadron is seen in Belle and Crystal Ball results.

$\Lambda*$: $\mathrm{M} = \sim 1665\,\mathrm{MeV}/c^2$, $\mathrm{J} = 3/2$, and $\Gamma = \sim 10\,\mathrm{MeV}$

- J-PARC E72: Search for the Λ* through $p(K^{-}, \Lambda)\eta$ reaction.
- A new target and trigger counters are being developed.
- All detectors will be ready in 2022.

- Line-shape analysis for the new pK^{-} peak structure near $\Lambda\eta$ threshold.
- Two assumptions: a new hadron resonance and a threshold cusp.
- The peak structure is significantly favored to a threshold cusp by 7σ than a hadron resonance.
- It is the first case to identify a threshold cusp by a spectrum shape.

*Backup Slides

HypTPC

■ Time projection chamber

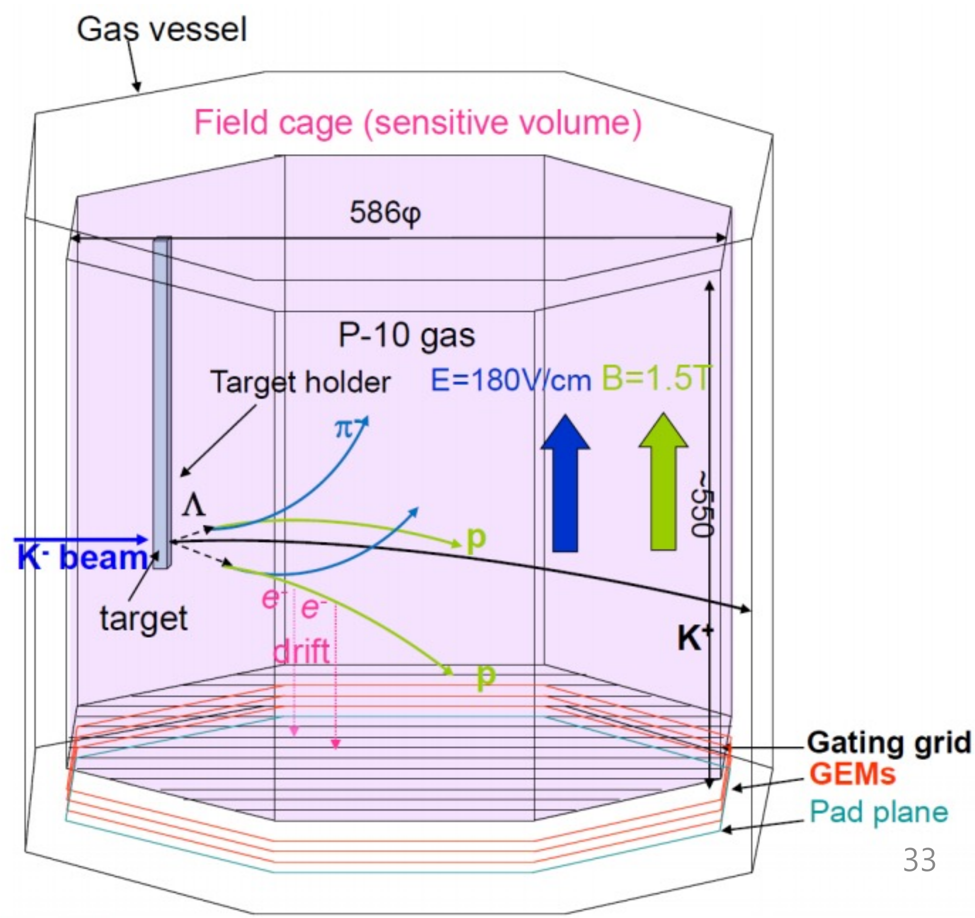
→ Developed for hadron experiments, H-dibaryon search (E42) and baryon spectroscopy (E45) at J-PARC

→ The JAEA hadron group is one of main collaborators of these experiments.

→ Construction already completed.

→ Large acceptance ~4π

→ Position resolution < 300 μm



How to Determine Spin and Parity

■ Angular distribution

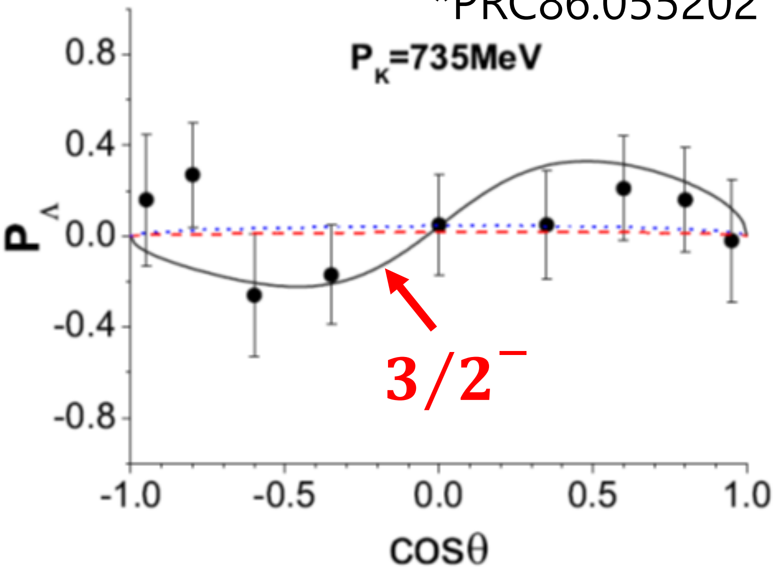
→ When $J = 3/2$ or high, $\cos^2\theta$ term is appeared. Other cases, constant or $\cos\theta$ distribution.

→ However, we cannot distinguish $3/2^+$ and $3/2^-$.

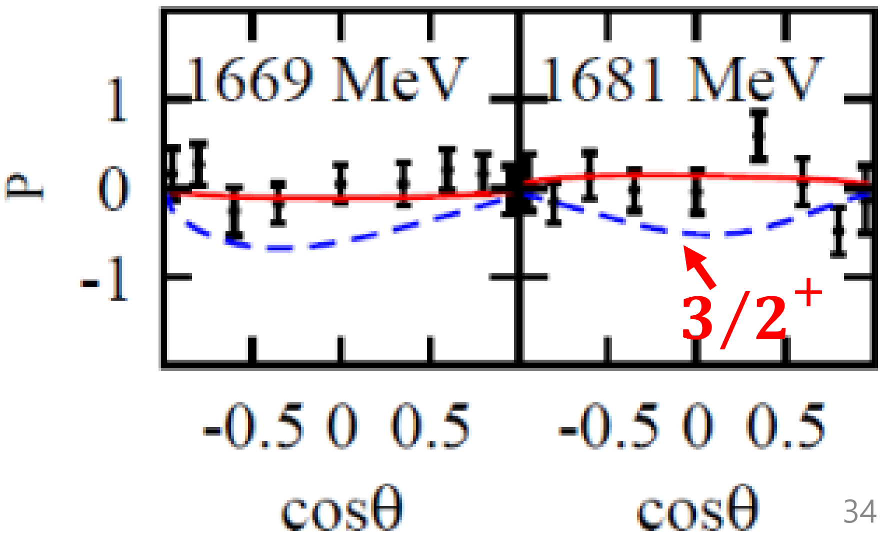
■ We can determine the parity from Λ polarization distribution.

→ P wave ($3/2^+$) and D wave ($3/2^-$) can be distinguished by the Λ polarization distribution.

*PRC86.055202



*PRC92.025205

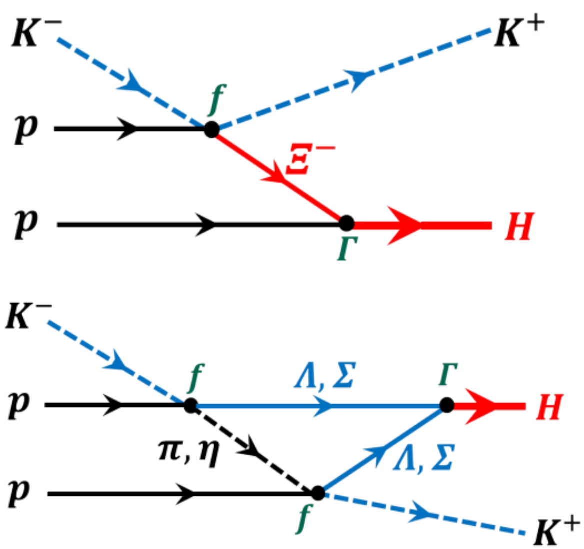


H-dibaryon Search (E42) and Baryon Spectroscopy (E45)

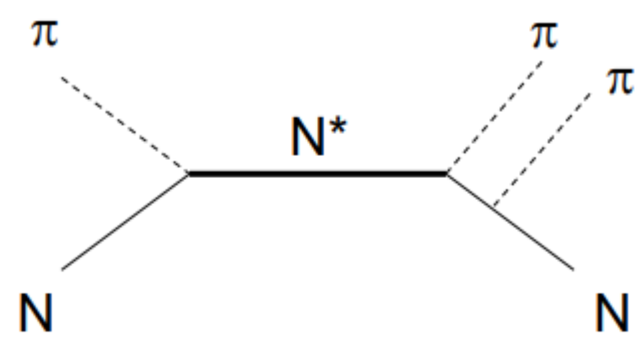
■ These two experiments are being prepared by the JAEA hadron group as a series of experiments using the HypTPC. Both experiments will extend our knowledge of hadron structure and provide a key information for non-perturbative QCD calculation.

■ The E42 is a search for H-dibaryon consisting of $uuddss$ quarks. It will provide a crucial information to determine whether the H-dibaryon exists or not.

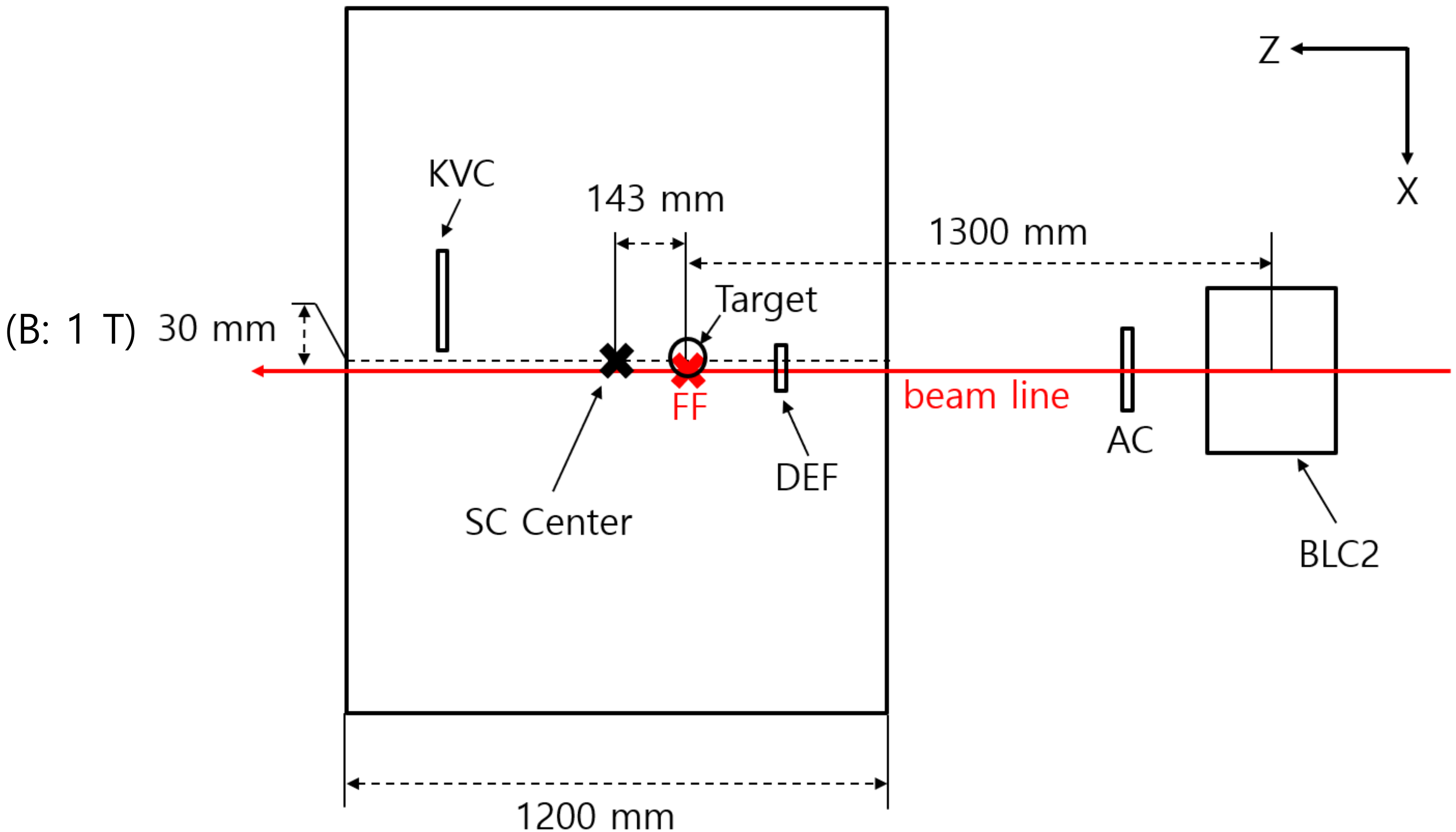
■ The E45 is a baryon spectroscopy with $(\pi, 2\pi)$ reaction (J-PARC E45). Precise experimental data of high mass baryons will be taken and we also expect to observe new nucleon resonances.



H-dibaryon production process, 1.8 GeV/c K beam



N^* production process, 1.8 GeV/c π beam



→ Target locates at FF.

Trigger

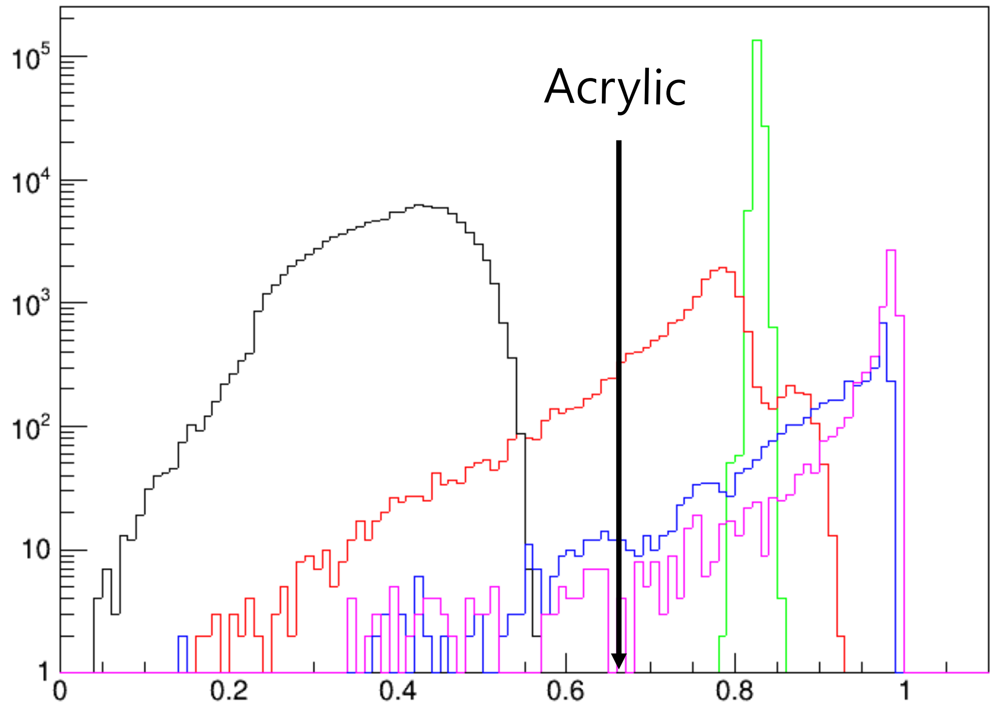
-2 types of trigger (A||B) will be used.

-Type A: nhToF>1 && DEF && $\overline{\mathrm{KVC}}$

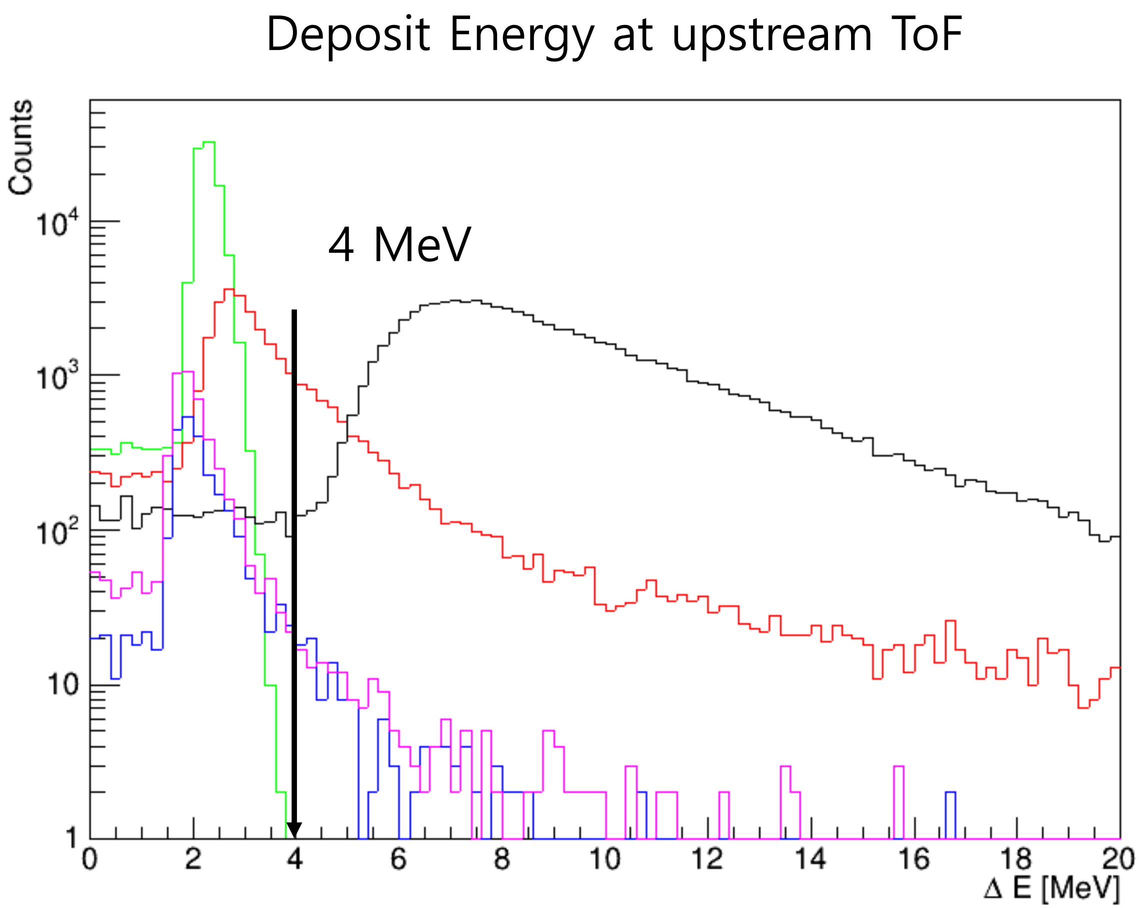
-Type B: nhToF>0 (at 0-6 and 30-31 segments) and Edep > 4 MeV && DEF && $\overline{\mathrm{KVC}}$

p from Lambda
pi- from Lambda
beam
pi- from beam decay
mu- from beam decay

velocity distribution at KVC

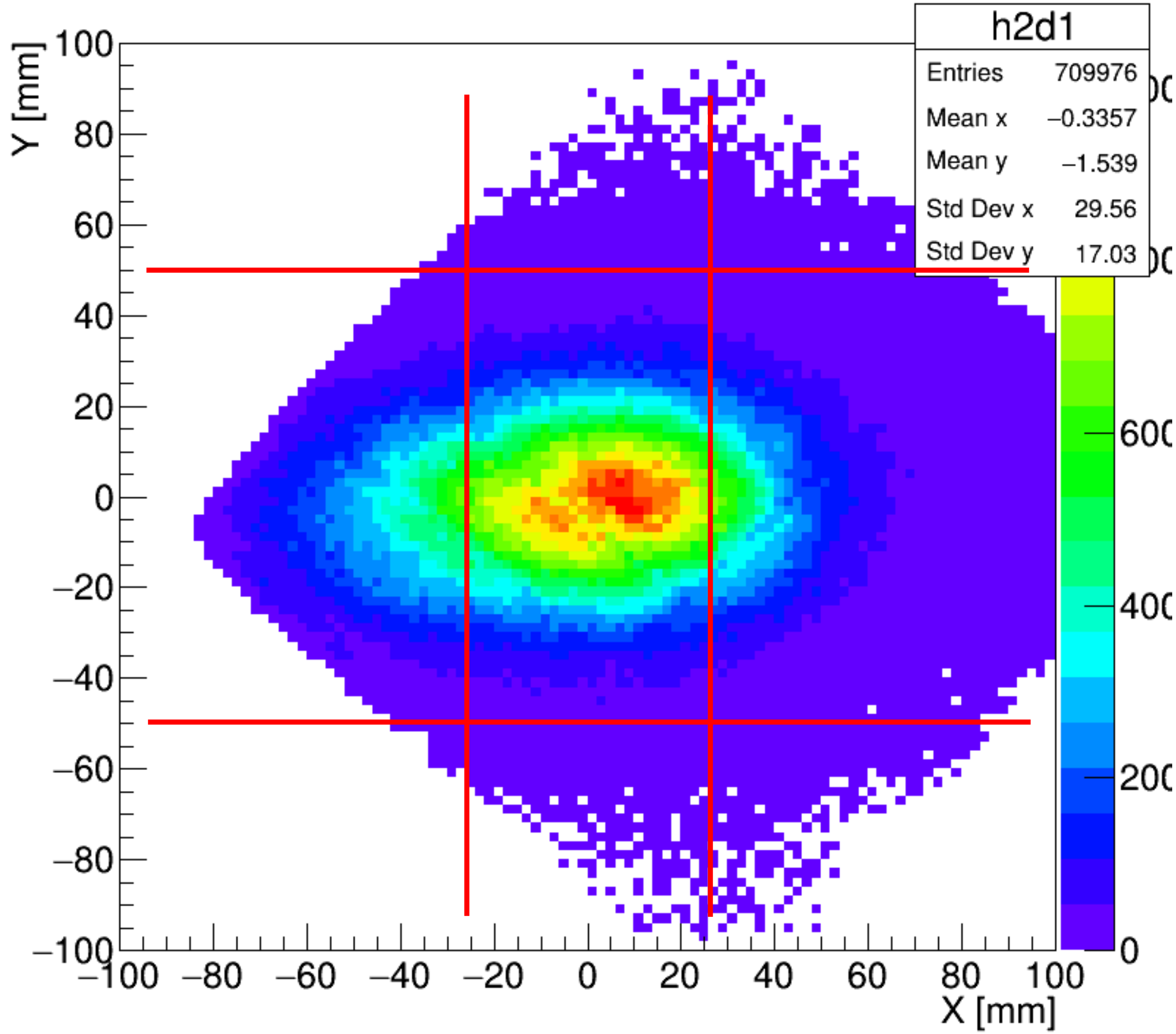


p from Lambda
pi- from Lambda
beam
pi- from beam decay
mu- from beam decay



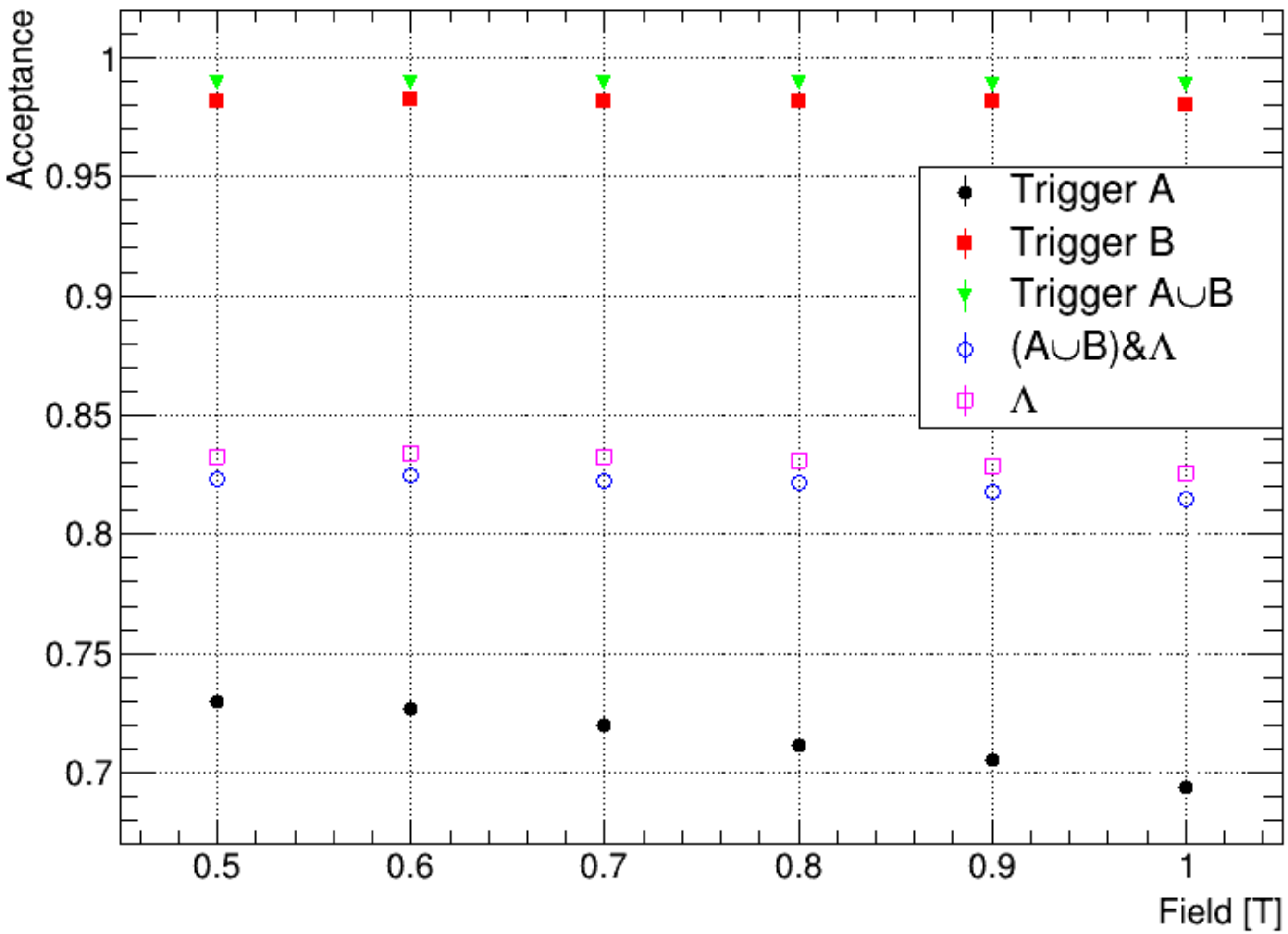
Beam Profile

-Real K beam data in K1.8BR FF z-position



Field Optimization

-Center of beam momentum: 730 MeV/c



Beam Momentum Calibration

■ The same way as the Crystal-ball analysis, $\sigma \approx P_{\eta}^{CM}$.

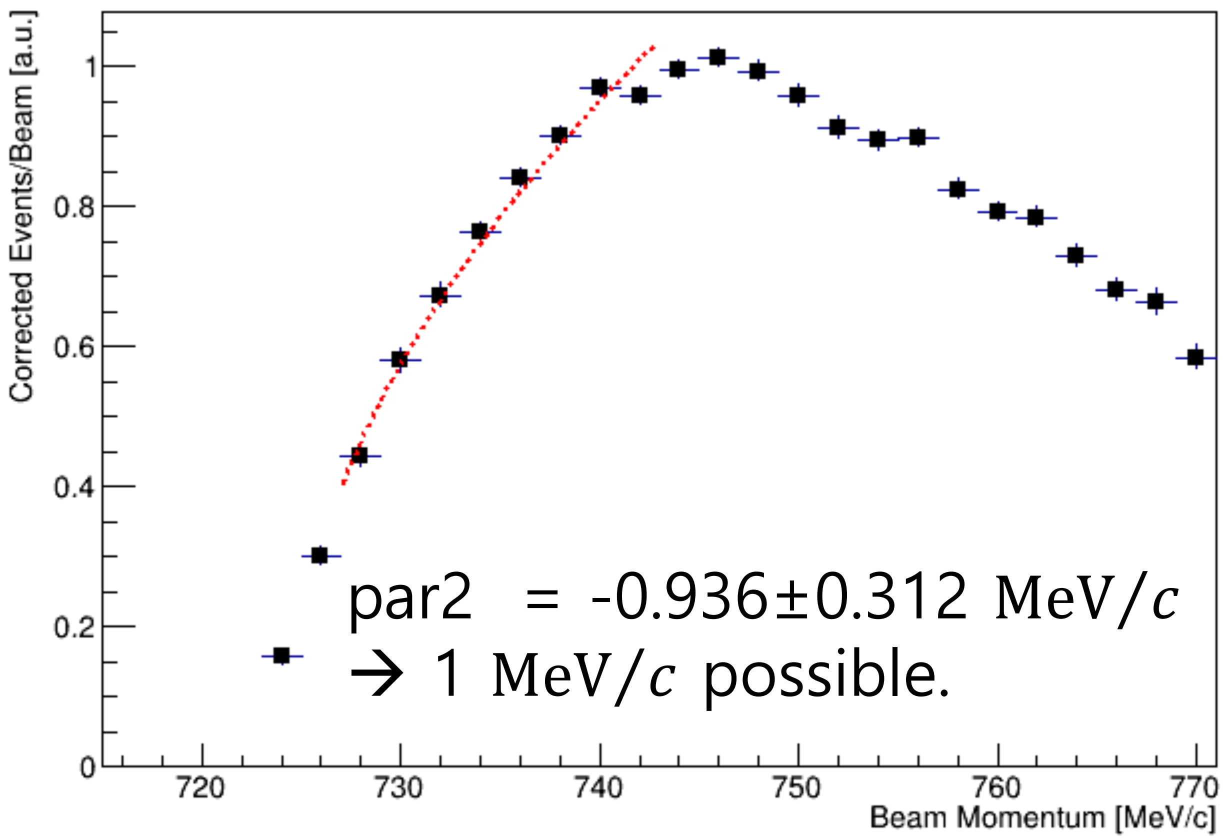
■ Calibration runs, beam energy scanning, can determine the absolute momentum.

- beam momentum: 685, 705, 725, 745, and 765 MeV/c (covers 670~780 MeV/c range).
- half day for each momenta.

■ ±1 MeV/c level calibration is possible.

■ Events/Beam distribution after an acceptance correction

- Fitting function: $par_1 \times p^*$, $p^* = f(p_{beam} + par_2)$ is η momentum in C.M.



par2 = -0.936±0.312 MeV/c

→ 1 MeV/c possible.

- Systematic uncertainties

TABLE I. Systematic uncertainties in Γ', $\bar{g}_{\Lambda\eta}$, and Γ_{tot} from Flatté fit for the pK^- peak structure.

Source	Γ' (MeV)	$\bar{g}_{\Lambda\eta}$ ($\times 10^{-3}$)	Γ_{tot} (MeV)
Bin size	± 0.0	± 3	± 0.3
Detector resolution	$+0.3, -0.4$	$+7, -6$	± 0.2
Absolute mass scale	± 0.8	$+5, -6$	± 1.3
Fit range	$+1.1$	-36	$+0.8, -2.4$
Efficiency correction	± 0.6	± 8	± 0.2
PDF model	$+3.5, -1.9$	$+9, -29$	$+3.4, -2.1$
θ	± 3.3	± 59	± 2.0
Total	$+5.0, -3.9$	$+61, -75$	$+4.2, -4.0$