A possible new Λ^* resonance with J=3/2 in Λ_c decay and $K^- p \to \Lambda\eta$

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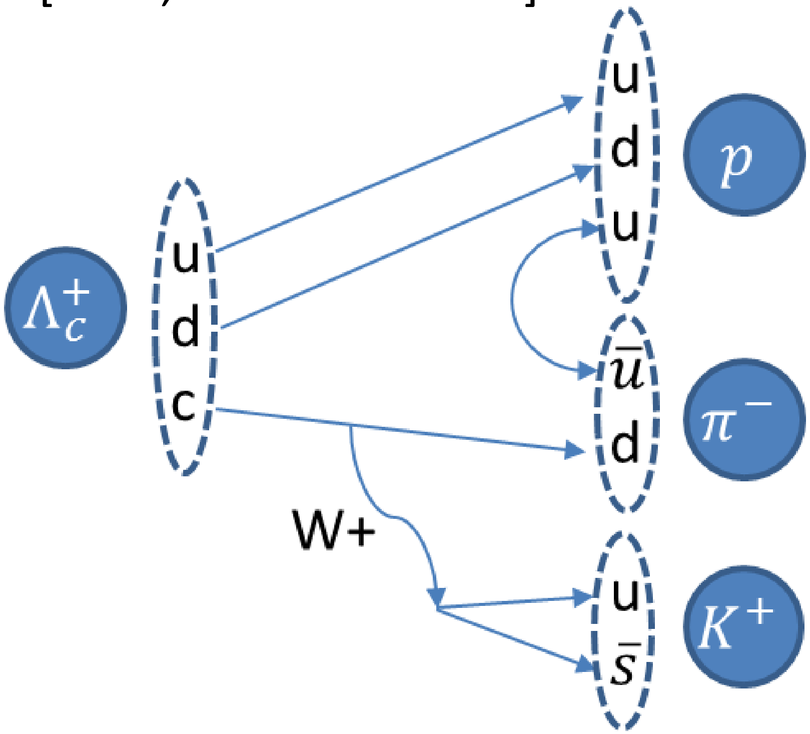
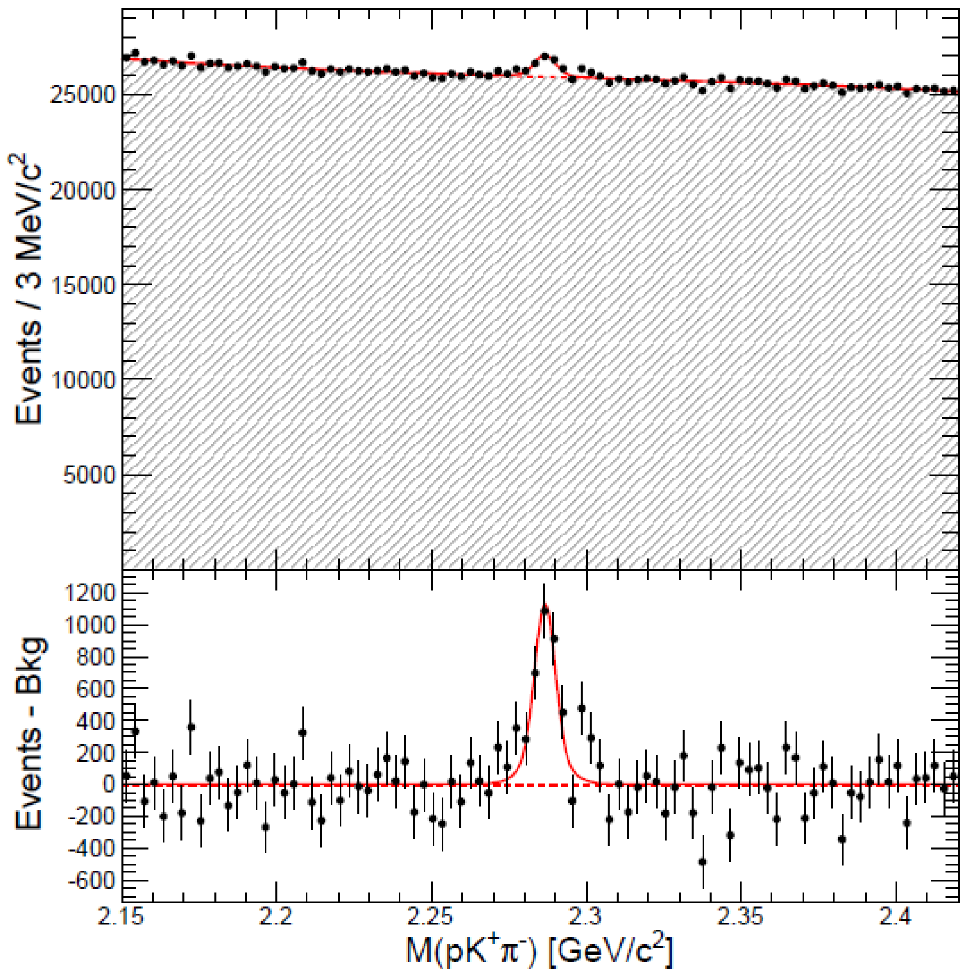
Doubly Cabibbo suppressed decay

[Belle, PRL117.011801]

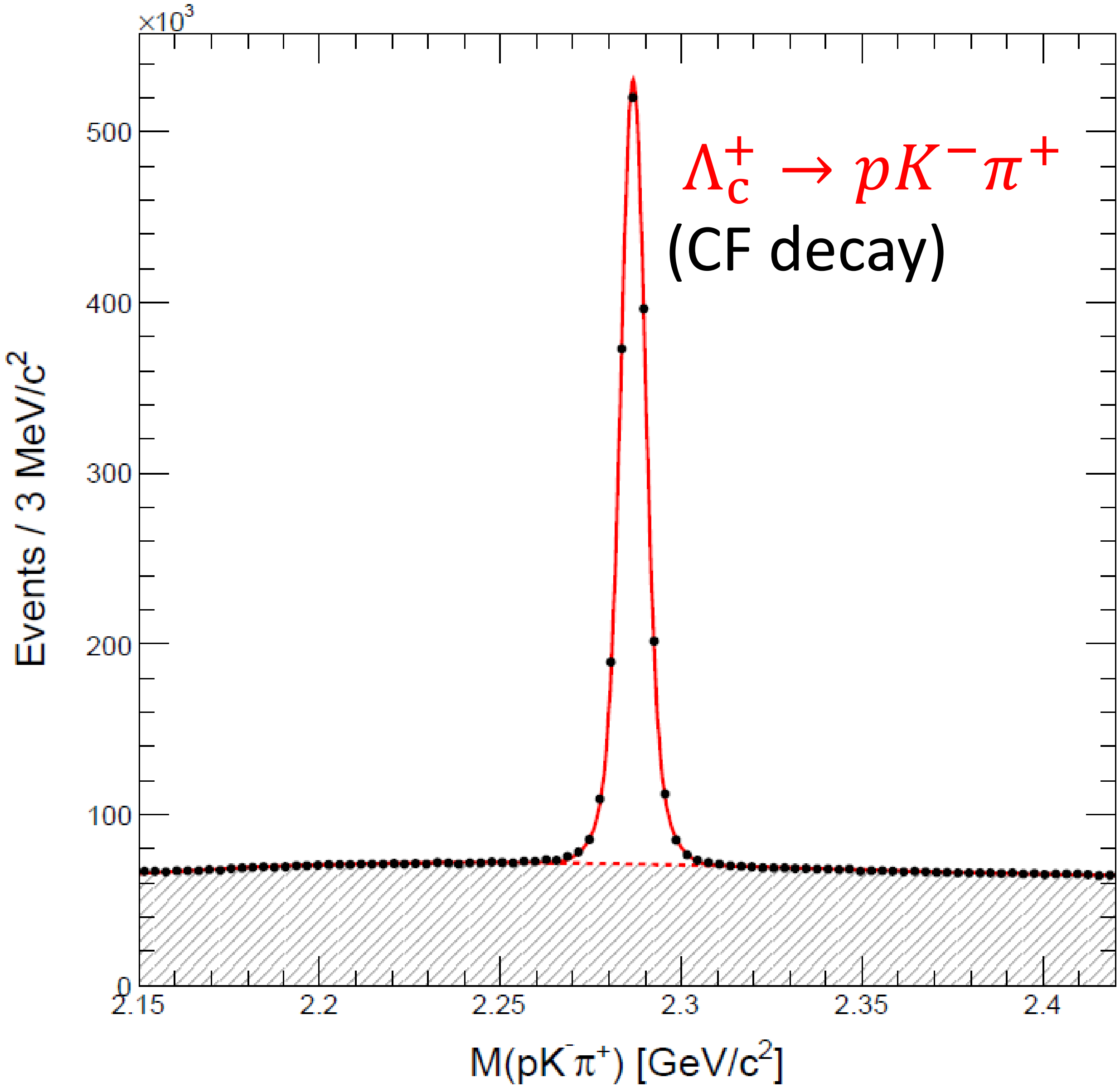




- Observed for the first time in baryons
- The rarest decay of Λ_c

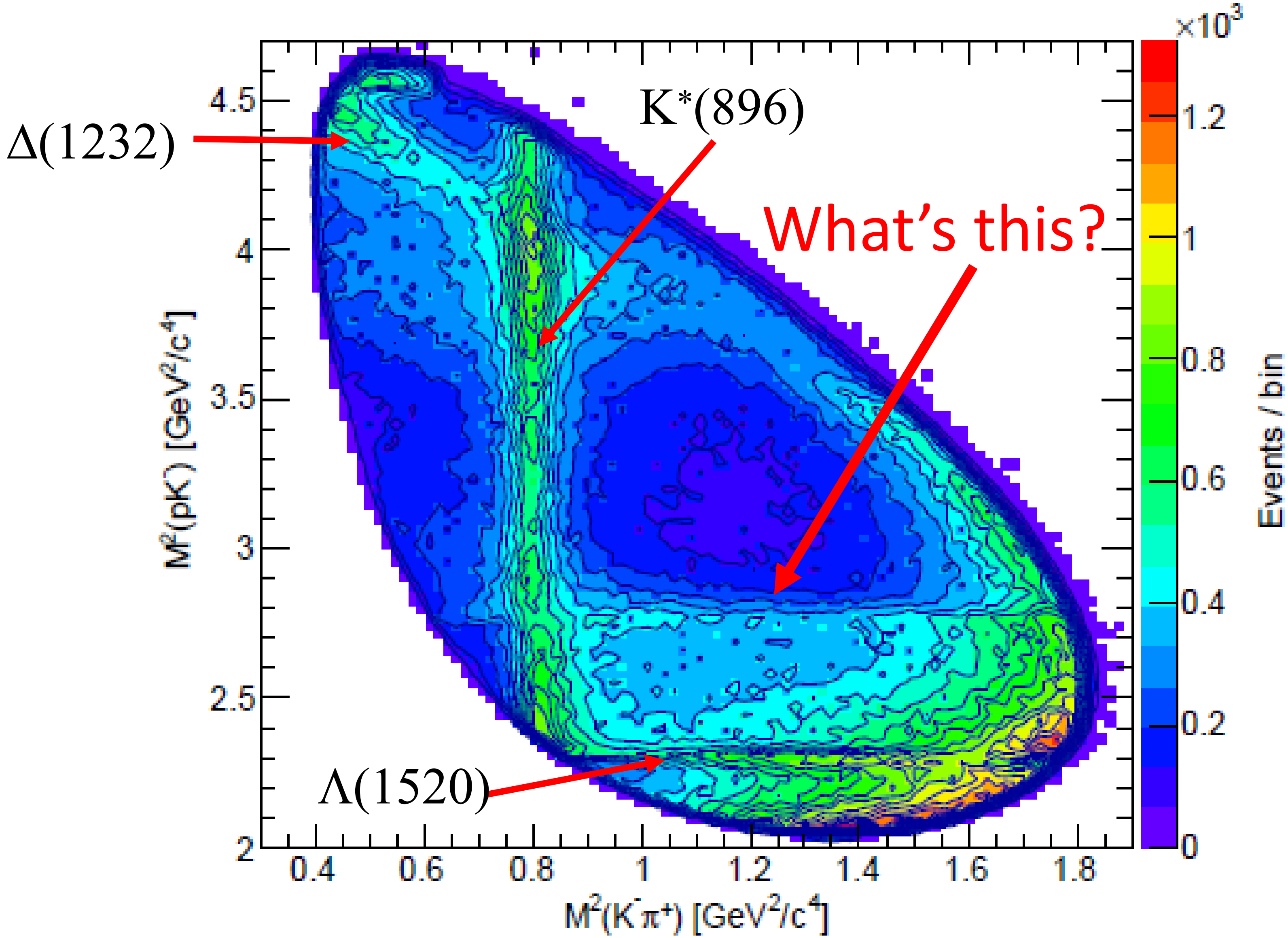
$$BR(\Lambda_c^+ \to pK^+\pi^-) = (1.61 \pm 0.23^{+0.07}_{-0.08}) \times 10^{-4}$$

Cabibbo favored channel



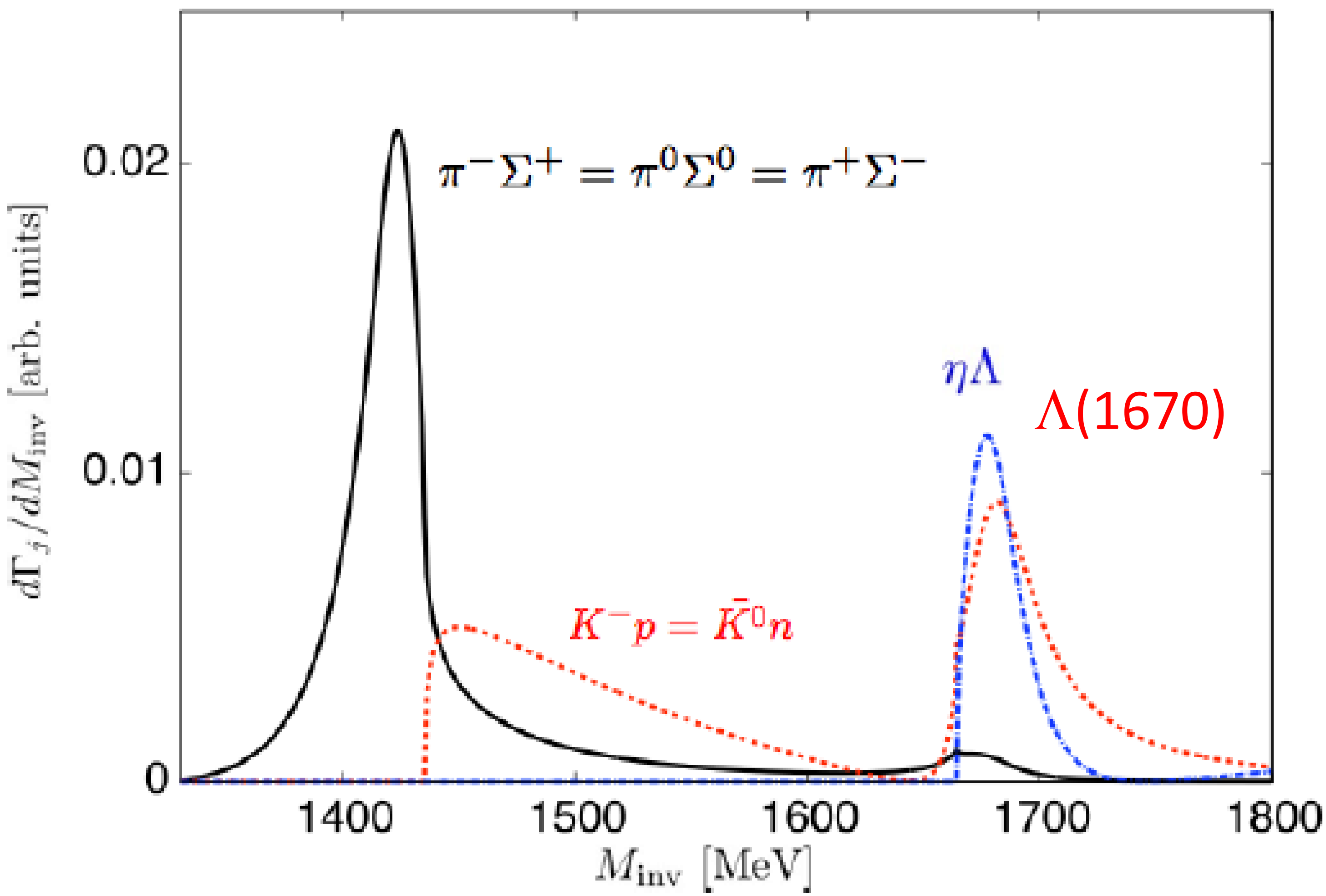
1.5 M events reconstructed with a good S/N ratio

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



Prediction from theory side

- Miyahara, Hyodo & Oset, PRC **92**, 055204 (2015)



Λ(1670) is predicted, but …

Then, what's that?

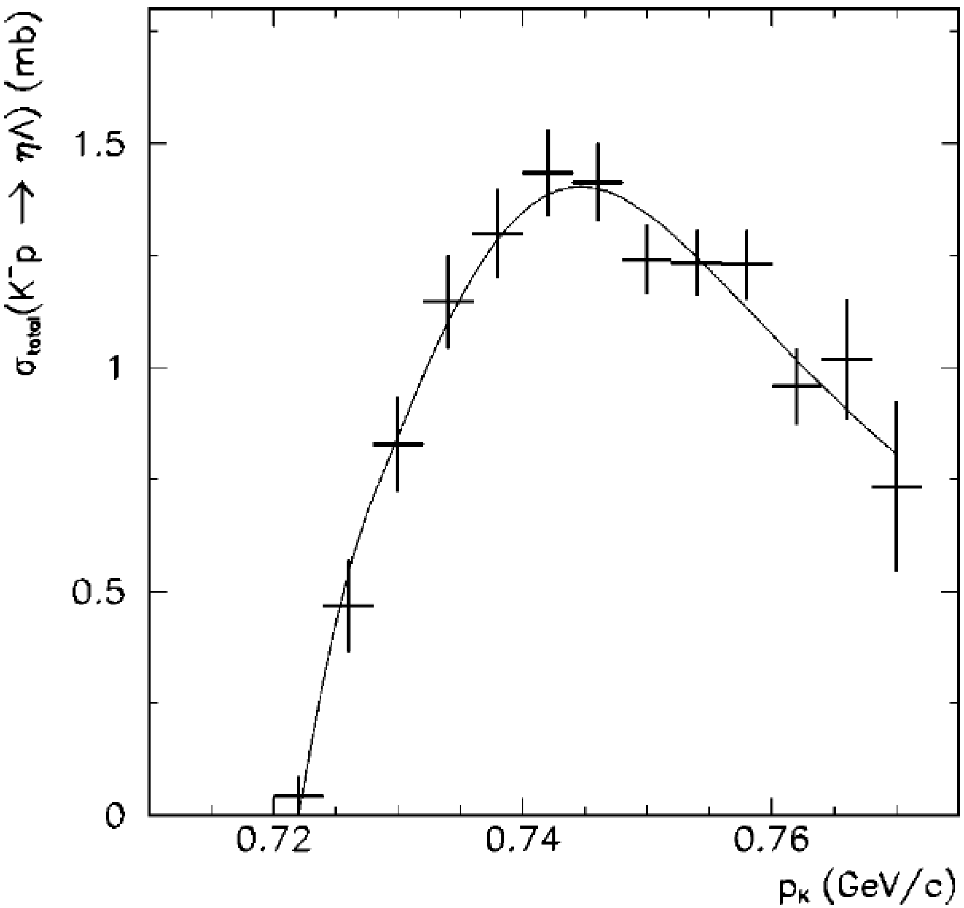
- The peak position is ~1663 MeV, near the $\Lambda\eta$ threshold (1663.5 MeV)
- Width is ~10 MeV, significantly narrower than Λ, Σ resonances in this region
  - Λ(1670): 25-50 MeV
  - Σ(1660): 40-200 MeV
  - Σ(1670): 40-80 MeV
  - Λ(1690): ~60 MeV
- BG shape is strange – maybe due to interference with BG amplitude?

A new idea

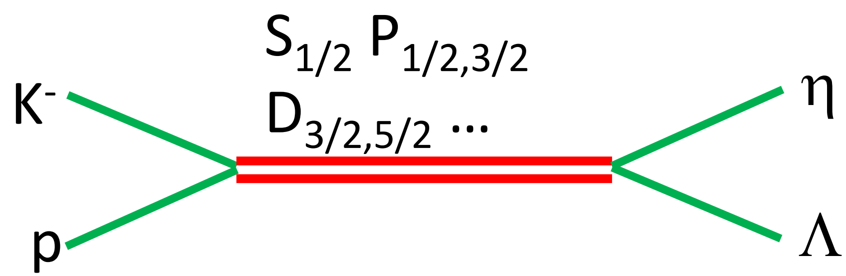
- 2 independent groups claim there is a new narrow Λ^* resonance at this energy with J=3/2
  - Kamano et al. [PRC90.065204, PRC92.025205]
    $J^P=3/2^+$ (P_{03}), M=1671+2-8 MeV, Γ=10+22-4 MeV
  - Liu & Xie [PRC85.038201, PRC86.055202]
    $J^P=3/2^-$ (D_{03}), M=1668.5 $\pm$ 0.5 MeV, Γ=1.5 $\pm$ 0.5 MeV
- The reason is the same
  - From $K^- p \rightarrow \Lambda\eta$ measurement near the threshold by Crystal Ball collaboration at BNL [PRC64.055205]
  - Especially the angular distribution → Model independent
  - Parity is not determined
- There is no state in quark models
  - It must be an exotic
  - $uds s\bar{s}$?

Crystall Ball data for $K^-p \rightarrow \Lambda\eta$

- Total cross section – this can be explained by usual $\Lambda(1670)1/2^-(S_{01})$ resonance



Differential cross section
(or angular distribution)



- s-channel
- $S_{1/2}$
  $W(\theta,\varphi) \propto |Y_{00}|^2 = \text{const} - \text{uniform}$
- $P_{1/2}$ – spin non-flip + flip
  $W(\theta,\varphi) \propto \frac{2}{3}|Y_{10}|^2 + \frac{1}{3}|Y_{11}|^2 = \text{const}$
- Interference?
  $W(\theta,\varphi) \propto \frac{2}{3}|Y_{10} + \delta Y_{00}|^2 + \frac{1}{3}|Y_{11}|^2$
  → The intereference term $\propto Y_{10}\ {Y_{00}}^* \propto \cos\theta$
- $\cos^2\theta$ term needs J=3/2 or higher amplitude

Example distribution

$3/2 \rightarrow 1/2 + 0$

- λ=1 (P-wave)

  $J_z=3/2 \rightarrow J_z'=1/2$: $m=\Delta J_z=1$

  $$W(\theta,\varphi) \propto |Y_{11}|^2 \propto \sin^2\theta$$

  $J_z=1/2 \rightarrow J_z'=1/2, -1/2$: $m=\Delta J_z=0,1$ (weight by C-G coefficient)

  $$W(\theta,\varphi) \propto \frac{2}{3}|Y_{10}|^2 + \frac{1}{3}|Y_{11}|^2 \propto 3\cos^2\theta + 1$$

- λ=2 (D-wave)

  $J_z=3/2 \rightarrow J_z'=\pm 1/2$: $m=\Delta J_z=1,2$

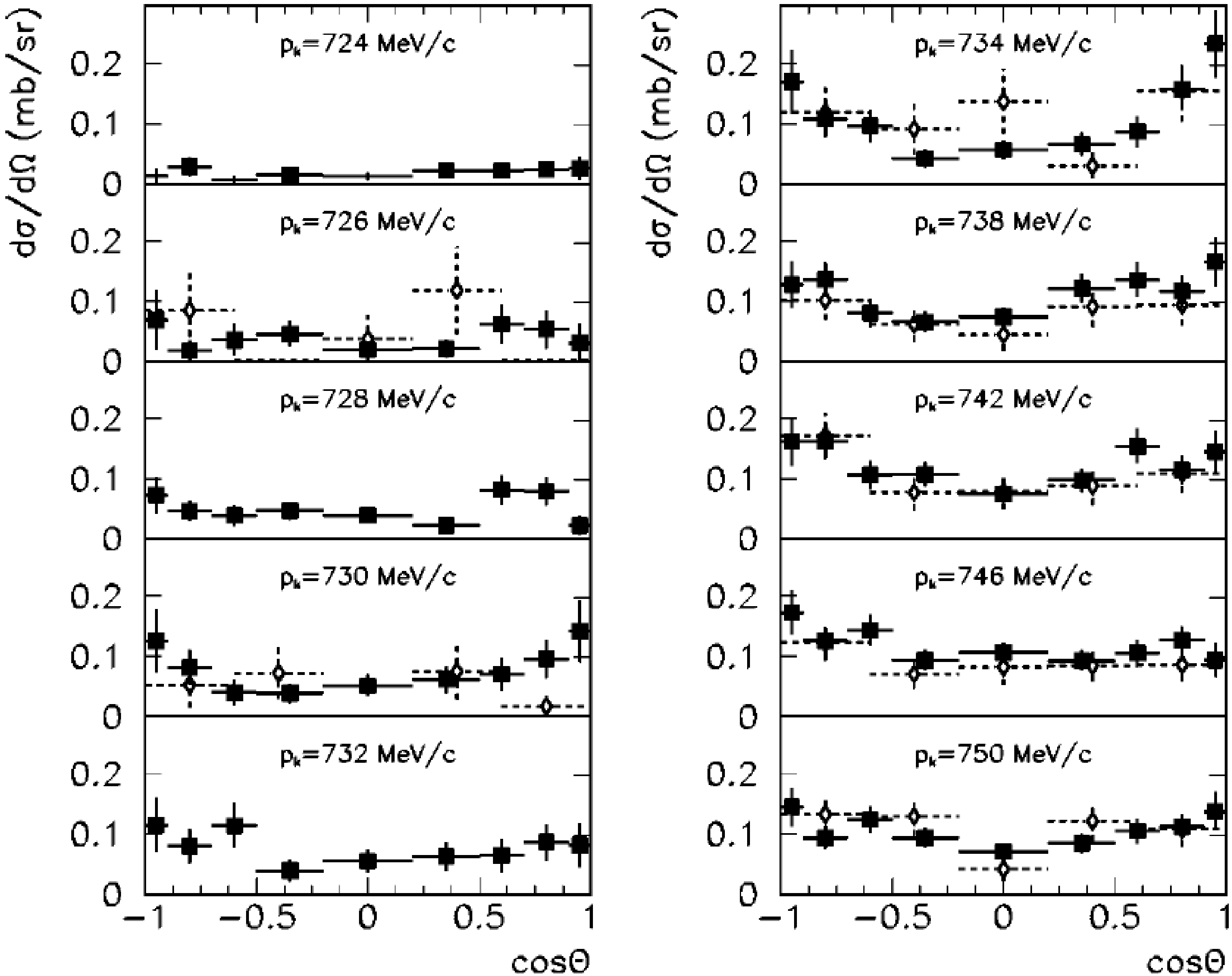
  $$W(\theta,\varphi) \propto \frac{1}{5}|Y_{21}|^2 + \frac{4}{5}|Y_{22}|^2 \propto \sin^2\theta$$

  $J_z=1/2 \rightarrow J_z'=\pm 1/2$: $m=\Delta J_z=0,1$

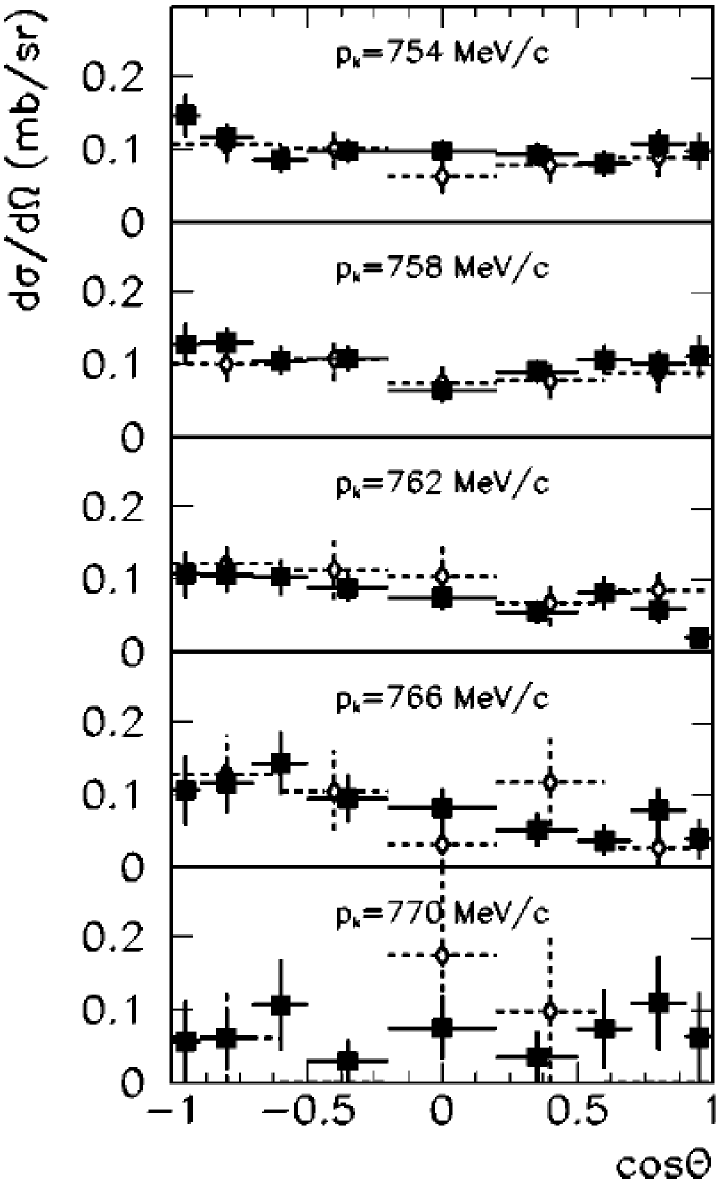
  $$W(\theta,\varphi) \propto \frac{2}{5}|Y_{20}|^2 + \frac{3}{5}|Y_{21}|^2 \propto 3\cos^2\theta + 1$$

Generally, λ cannot be distinguished

Differential cross sections (1)



Differential cross sections (2)



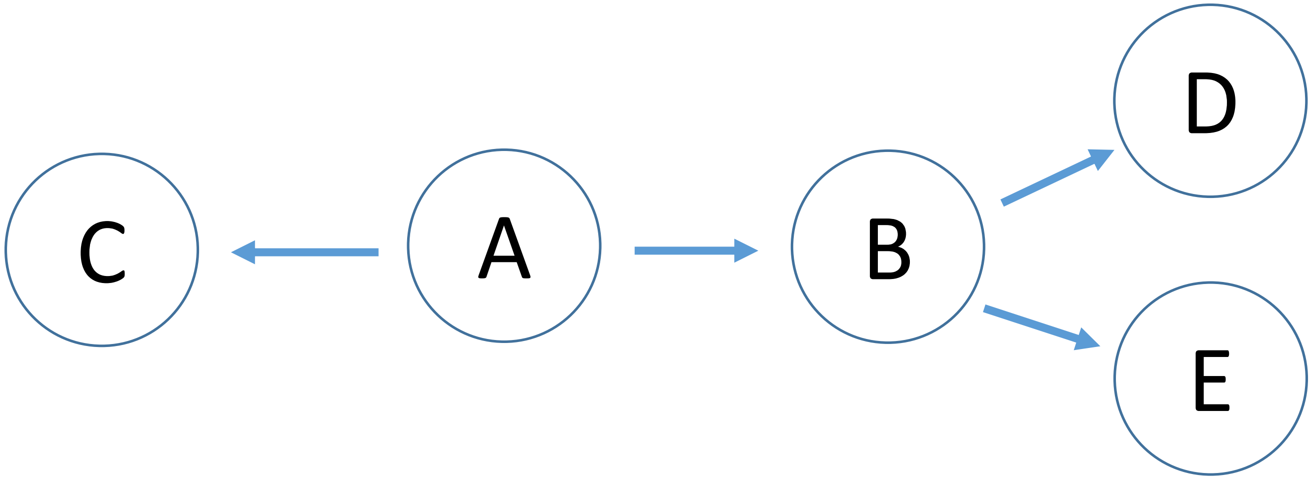
- Flat near the threshold
  - Expected for J=1/2 (S-wave)
- Concave-up around p_K=734 MeV/c (√s=1669 MeV)
- Flat again for p_K > 750 MeV/c (√s=1677 MeV)

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

Measurement@Belle

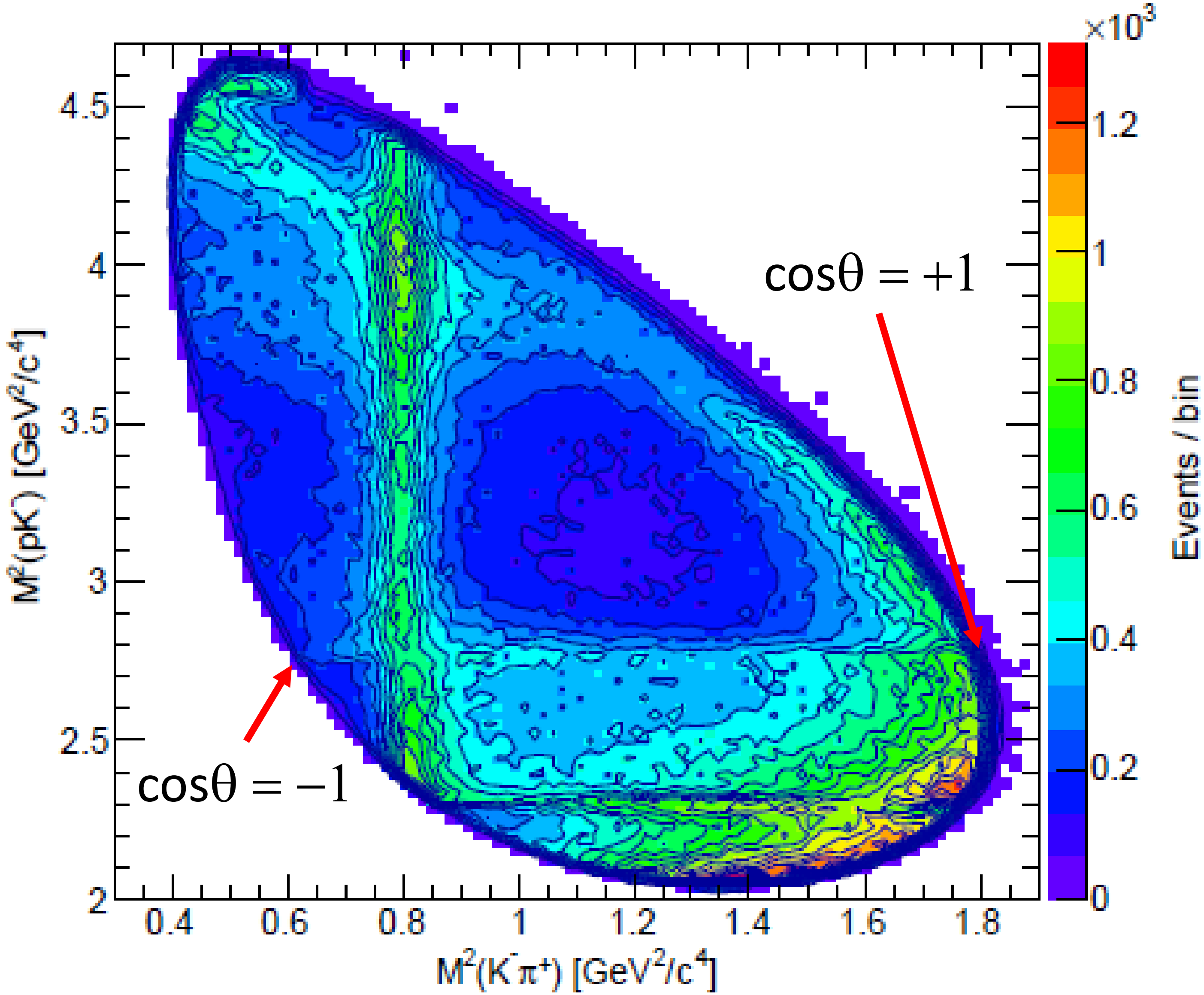
- The peak in the M(pK$^-$) spectrum in $\Lambda_c \rightarrow pK^-\pi^+$ decay is due to the new Λ^* resonance?
- If yes, key measurements are
  - J=3/2 – angular distribution (correlation) between π^+ and K$^-$
    $1+3\cos^2\theta$ for pure J=3/2 amplitude
    flat for pure J=1/2 amplitude
  - I=0, strongly couples to $\Lambda\eta$ channel
    → Important to see $\Lambda\eta$ channel
  - Width
- Parity is also important, but…
  - Needs measurement of polarization of Λ in the $\Lambda\eta$ channel.
  - In principle possible, but needs very high statistics
  - Practically difficult @Belle, maybe possible at Belle2

Angular correlation in Dalitz plot



- m_A, m_B=m_{DE}: fixed
- Then, m^2_{DC} (or m^2_{CE}) and $\cos\theta_{DC}$have linear relation. ($\cos\theta_{DC}$= $\pm$1 → edges of the resonance line)
- Intensity of resonance line reflects angular distribution.

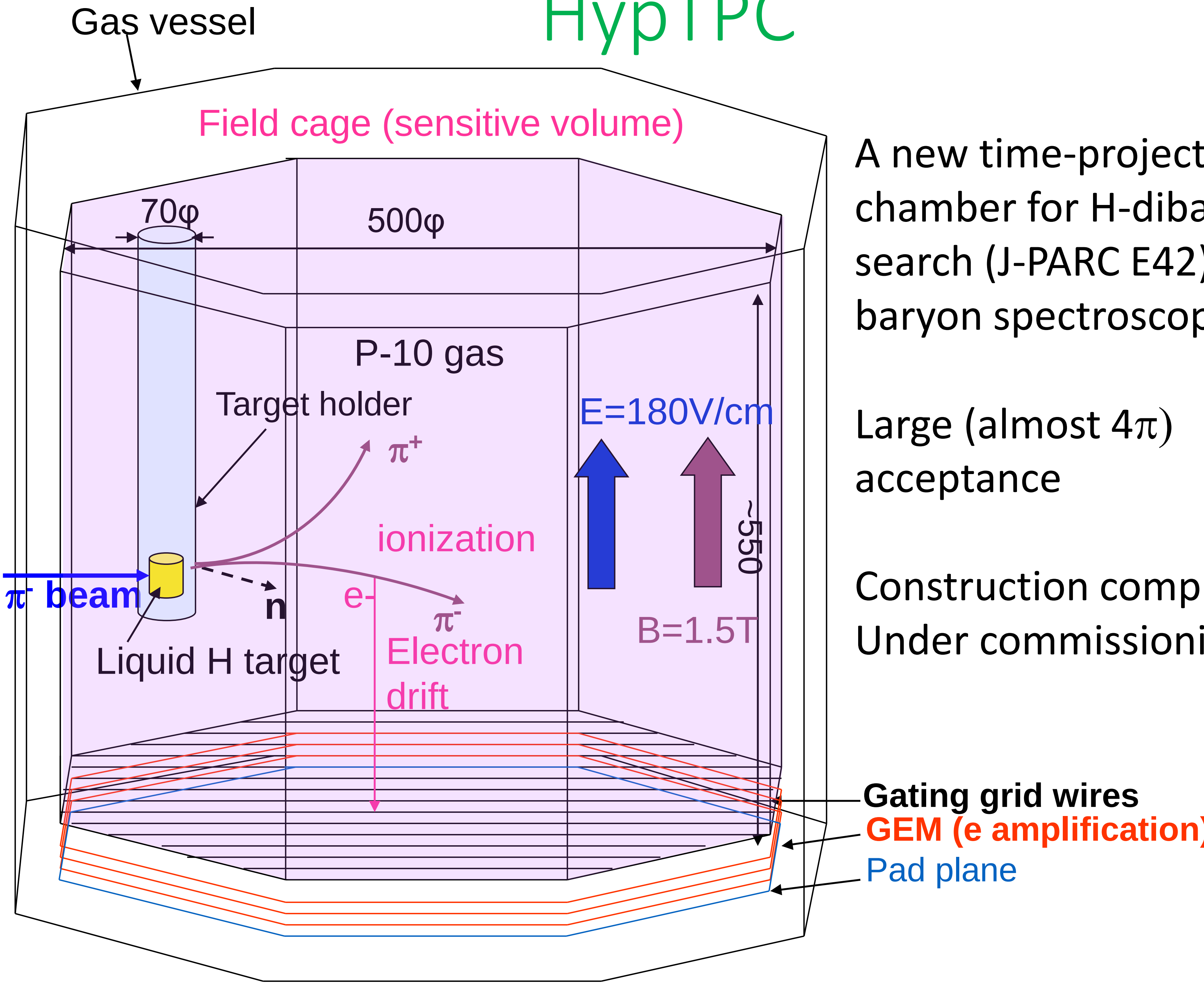
Dalitz plot: $\Lambda_c^+ \to pK^-\pi^+$ [PRL117.011801]



New experiment at J-PARC

- Repeat the Kp → $\Lambda\eta$ experiment again with HypTPC (or with J-PARC E31 setup)
- Principle
  - K beam momentum: 720-770 MeV/c
    2 settings: 735 MeV/c & 755 MeV/c ($\pm$3%)
    → K1.8BR or K1.1 beamline
  - Momentum resolution: 1 MeV/c or better
    → Can identify narrow resonance of Γ=1.5 MeV
  - Detect Λ → pπ^-, identify η by missing mass
    → Mass resolution of HypTPC does not affect Λ^* mass resolution, but helps to reduce backgrounds
  - Both Λ and η go to forward direction
    On the threshold, both have $\beta = 0.4$
    → We need rather small acceptance

HypTPC



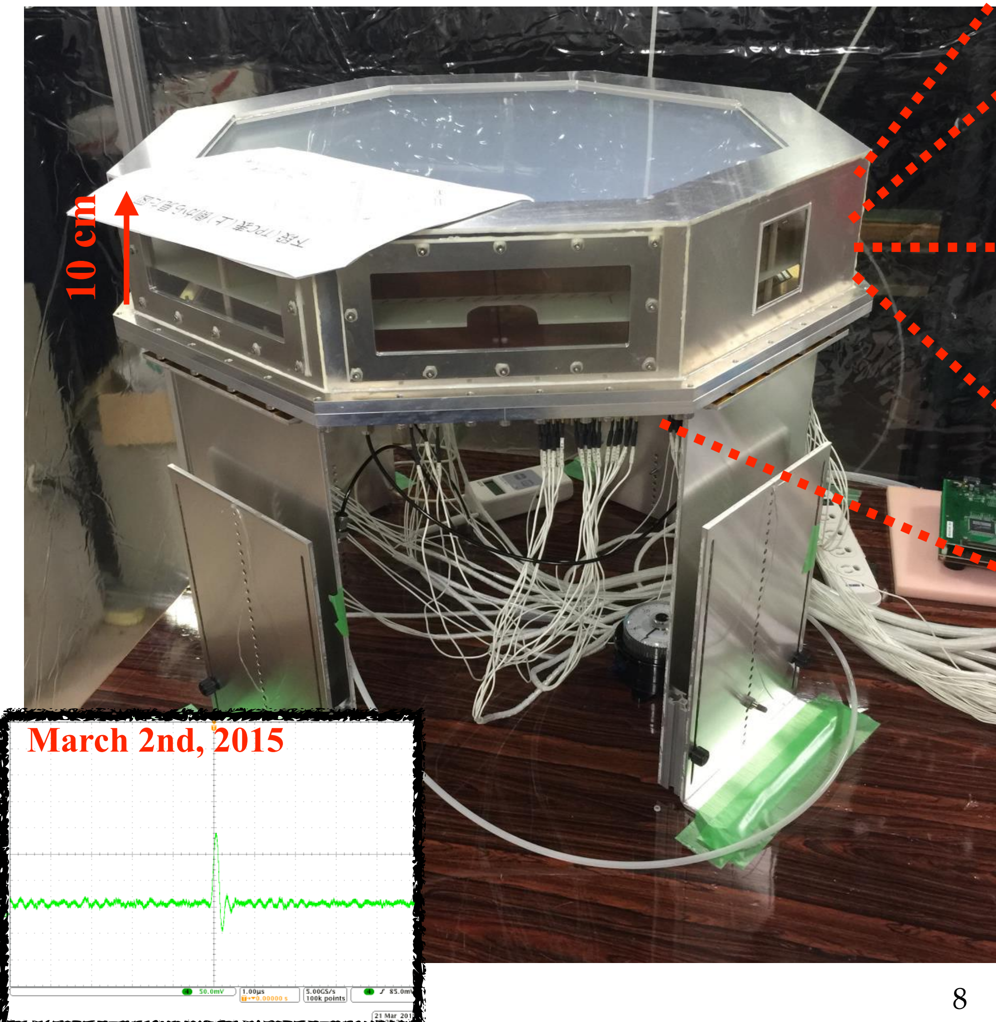
A new time-projection chamber for H-dibaryon search (J-PARC E42) & baryon spectroscopy (E45)

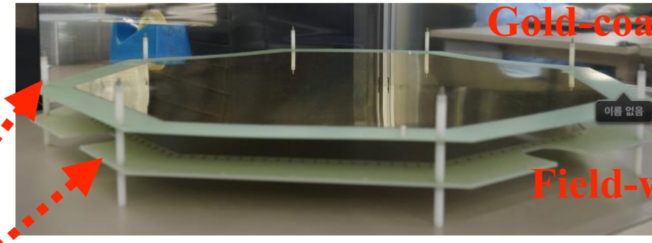
Large (almost 4π) acceptance

Construction complete.
Under commissioning

Construction of the HypTPC

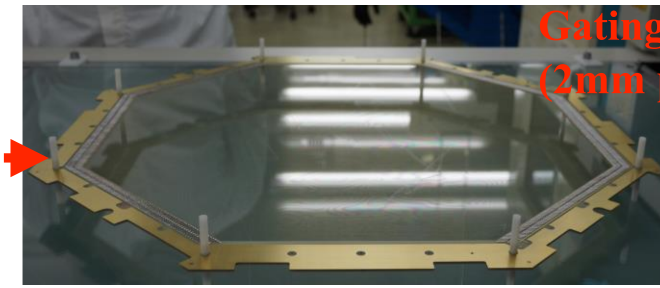
• HypTPC is ready with full size of read-out pad



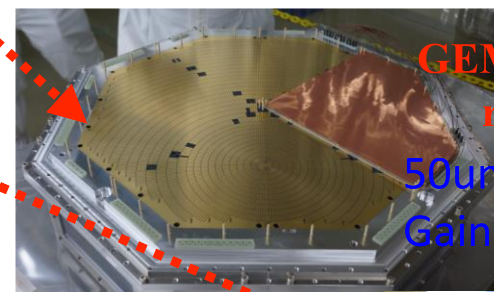


Gold-coated Cathode

Field-wire plane

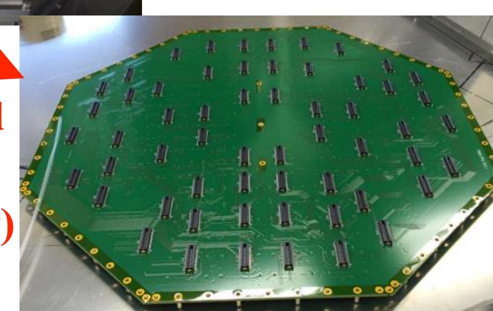


Gating grid
(2mm pitch)



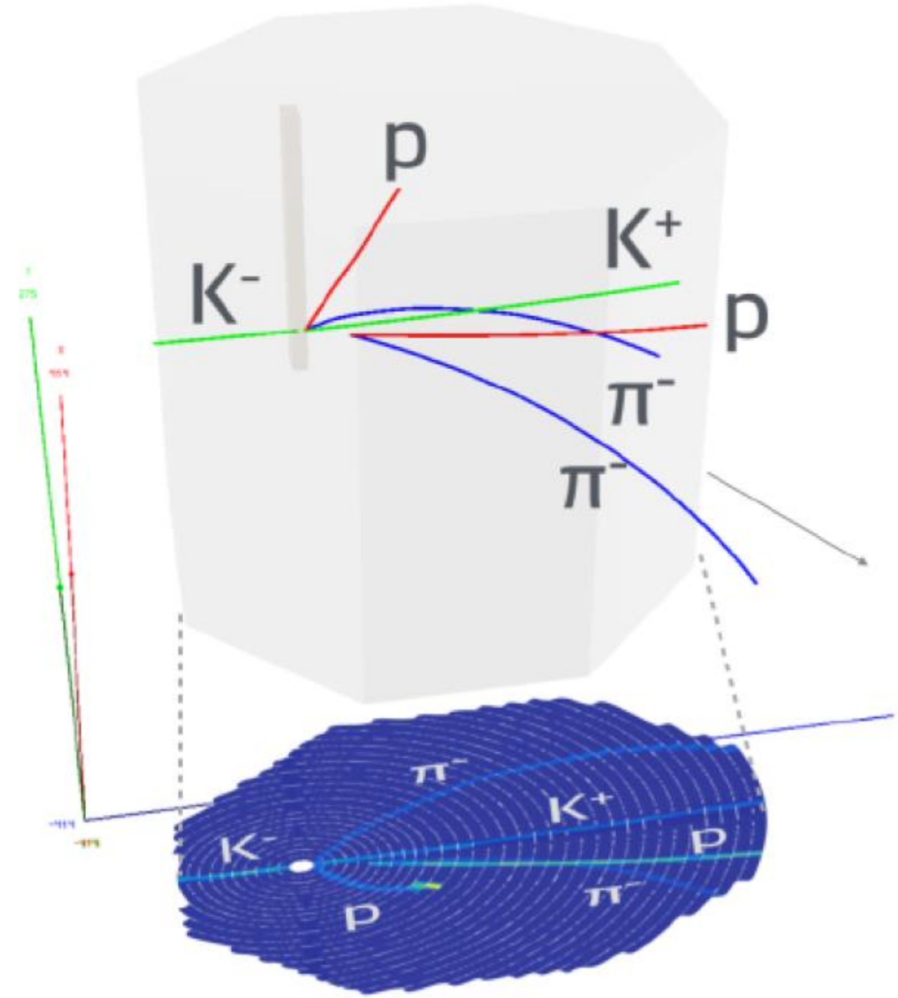
GEM (3 layers) &
read-out PAD

50um + 50um + 100um
Gain ~10^4

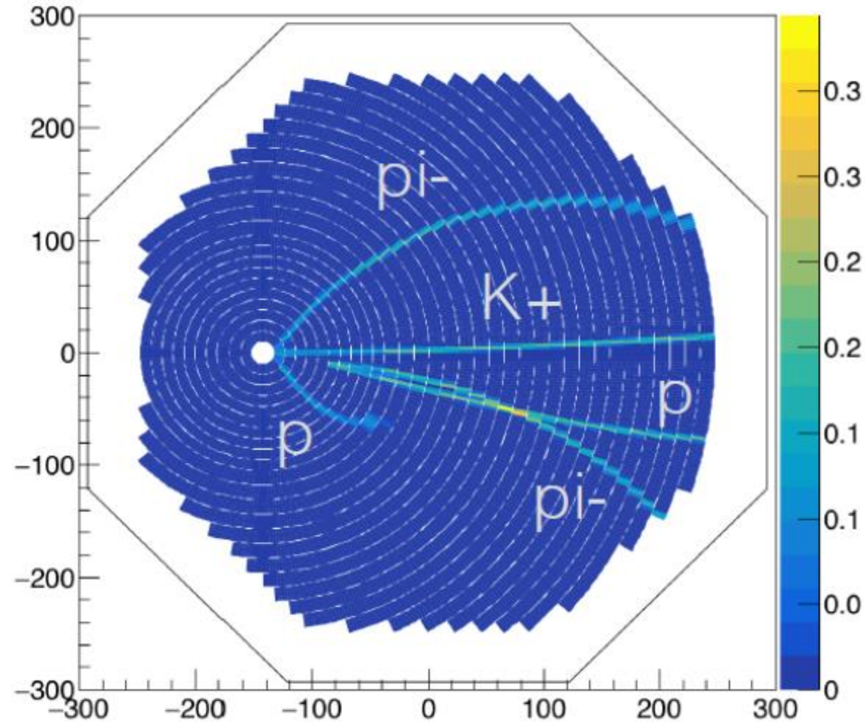


Conversion board
(read-out pad to
read-out circuit)

A Full Simulation on the HypTPC Performance



- $\Lambda\Lambda$ Production in the (K^-, K^+) Reaction.



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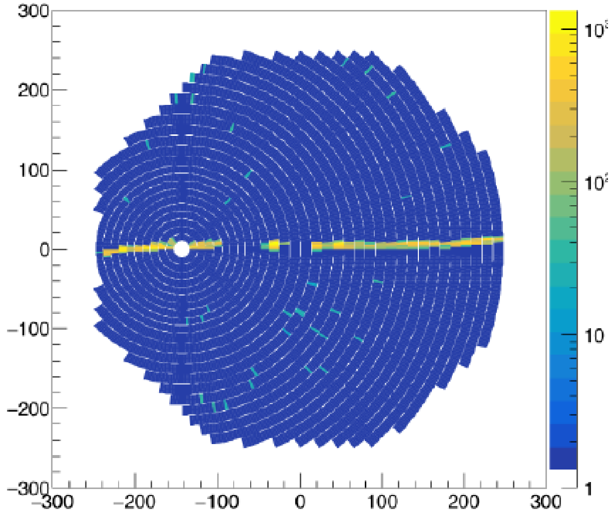
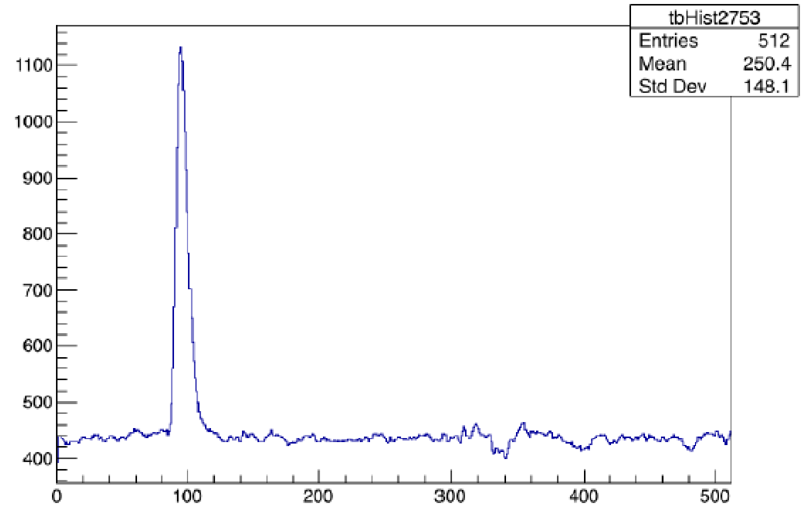
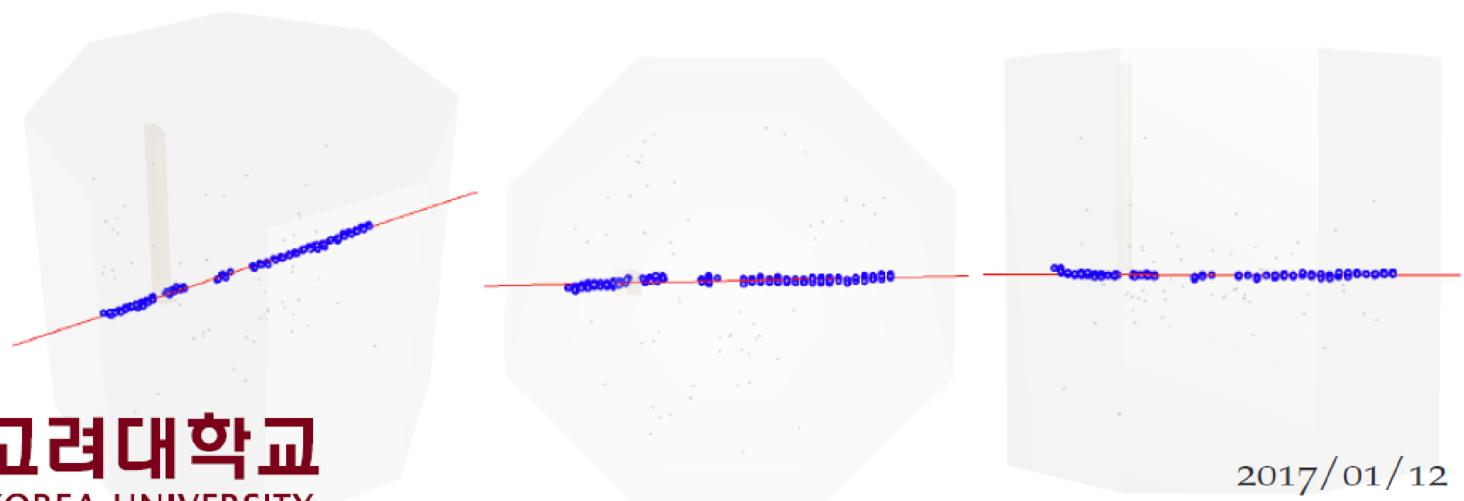
Preliminary ELPH Test Results





- A positron beam track is clearly reconstructed.



Yield estimation

- Beam intensity: 30 k/spill
- Target: Liq. H_2 5 cm (0.35 g/cm^2 or 2.1x10^{23}/cm^2)
- Reaction rate: 6.3/spill for 1 mb
- Acceptance & efficiency: 0.3?
  $\leftarrow$ need a simulation
- Event rate: 1200/h
  $\rightarrow$ 200k events in a week.
  Cf. Crystal Ball: 2700 events in total

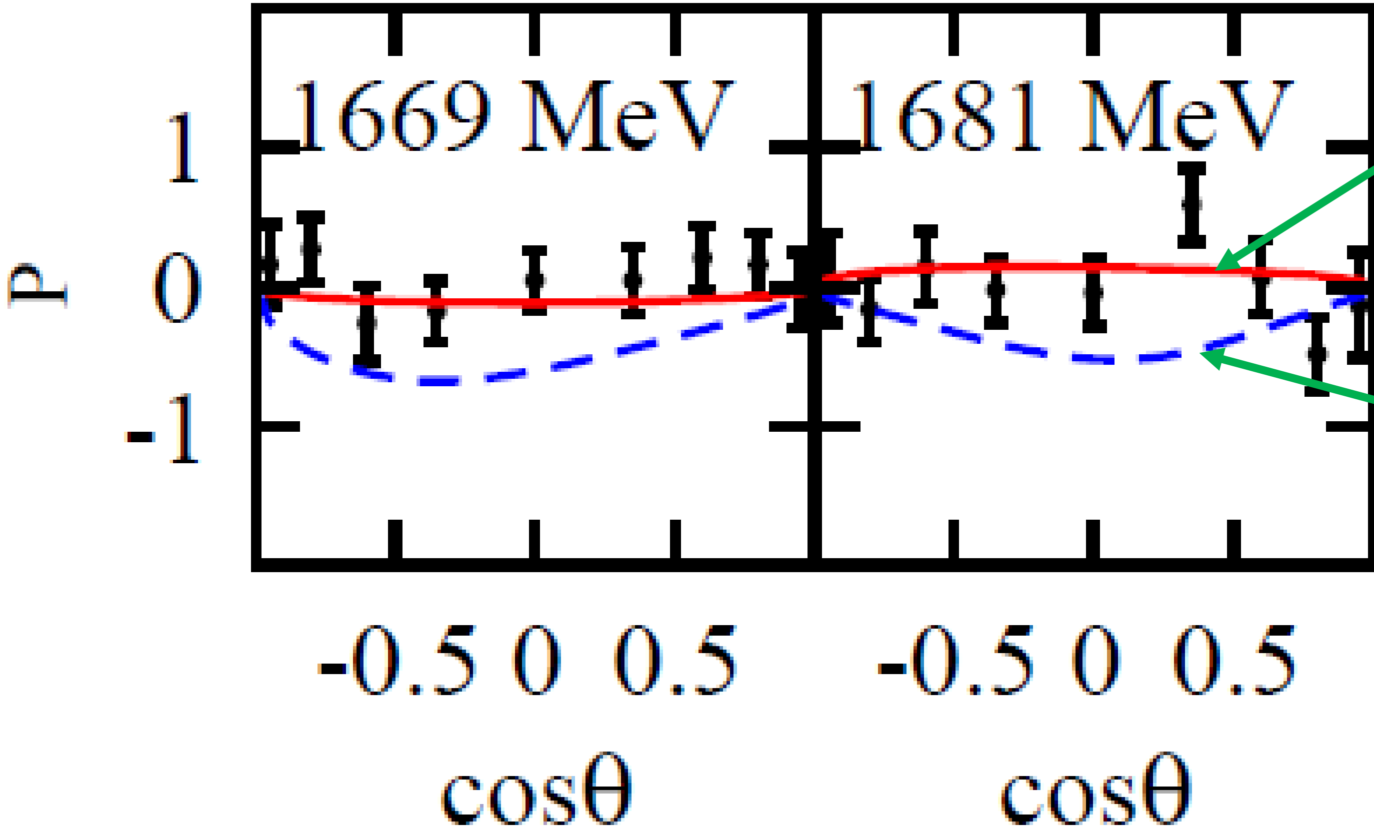
Trigger

- Interaction rate: 250/spill for total cross section of 40 mb → Strong trigger is not necessary
- Trigger: two (or more) charged particles with one of them being proton
  - Proton selection: large signal (~ 4 MIP) in hodoscope.
  - reduction of kaon decay background, too.
  - Proton hits forward segments only.
- Other reactions, such as Kp → $\pi\Lambda$, can be taken at the same time.

Identify parity

- Angular distribution is the same for $3/2^+$ (P wave) and $3/2^-$ (D wave)
  - Again, we need polarization of the final Λ
- Crystal-Ball data is very poor for polarization
  - Support for new resonance is not obtained

Polarization – Parity in CB data



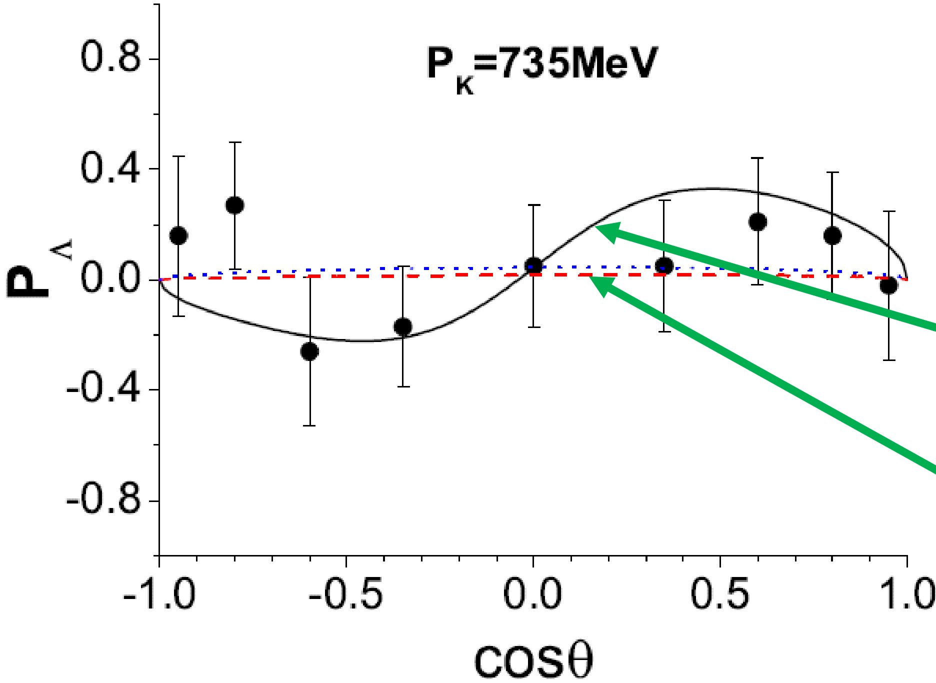
No new resonance

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

Model calc. by Kamano et al. [PRC92.025205]

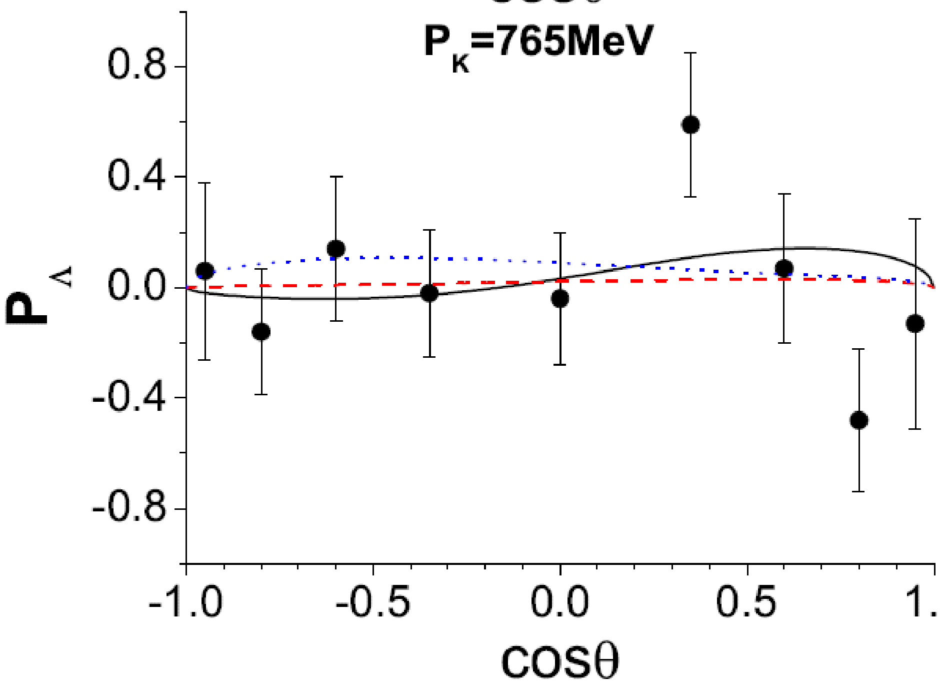
- Crystal ball data is average of 722-750 MeV/c & 750-770 MeV/c, not for each momentum.
  ⇔ Meanwhile, calculations are done on the points.

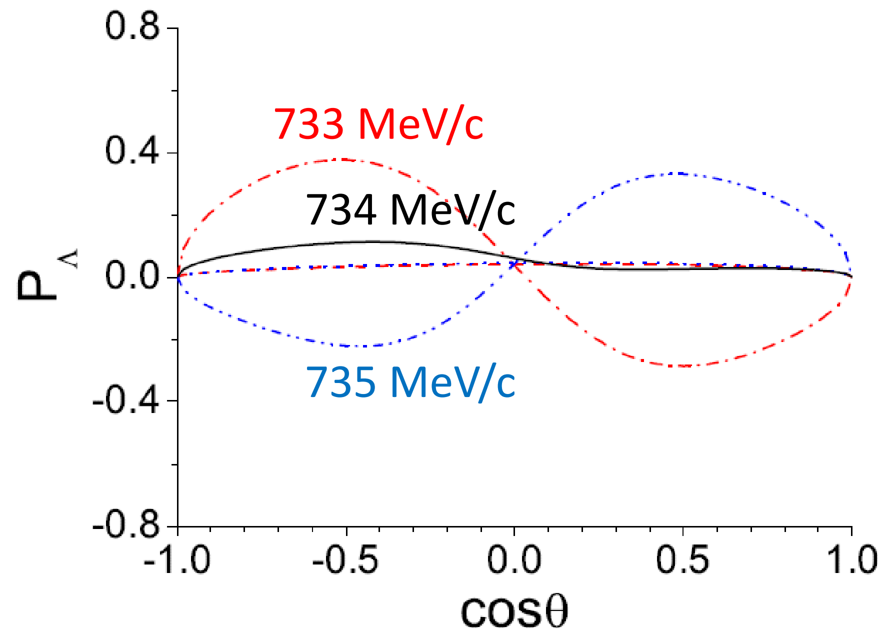
Calculation by Liu & Xie [PRC86.055202]



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

No new resonance





Identify parity

- Angular distribution is the same for $3/2^+$ (P wave) and $3/2^-$ (D wave)
  - Again, we need polarization of the final Λ
- Crystal-Ball data is very poor for polarization
  - Support for new resonance is not obtained
- How we can distinguish P&D?
  - P wave – no node, D wave – node
- We need δp~0.05 for each momentum/angle bin
  → Large statistics needed
  x16: δP 0.2 → 0.05
  x10: binning 2 → 20
  → Need ~2 weeks of beamtime. Looks feasible

Summary

- Hint of a new narrow Λ^* resonance is observed in $\Lambda_c \rightarrow pK^-\pi^+$ and $pK^- \rightarrow \Lambda\eta$ around 1670 MeV.
  - Are they the same?
  - Spin 3/2?
- No narrow spin 3/2 resonance in this region in QM $\rightarrow$ must be an exotic. $uds s\bar{s}$ pentaquark?
- Spin determination (& hence the confirmation of the resonance) would be possible using $\Lambda_c \rightarrow pK^-\pi^+$ data in Belle
- Parity determination needs a new experiment at J-PARC, using HypTPC, developed for H dibaryon search.