Hunting for near threshold (virtual) resonances in Belle and J-PARC

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Exotic hadrons near thresholds

- It is known that many exotic hadrons somehow appear near thresholds
  - E.g., X(3872) – D^0D^{*0}, Λ(1405) – KN, …
- These state can be understood as molecular states
  - Especially, when they are bound (Feschbach resonance)
- What happens if the interaction is NOT strong enough to make a bound state?
  → Virtual state
  - What is the signal for virtual state?

Near-threshold (re)scattering

- A simple calculation for a 2-body (re)scattering process (virtual intermediate state → final state):
$f_0 \sim \frac{1}{\frac{1}{kA} - i}$, $\sigma_0 = \frac{4\pi}{k^2}|f_0|^2$, A→complex (a+ib)
- Above the threshold:

$$\sigma_0 \propto \frac{1}{(1+kb)^2 + (ka)^2} \sim 1 - 2kb$$

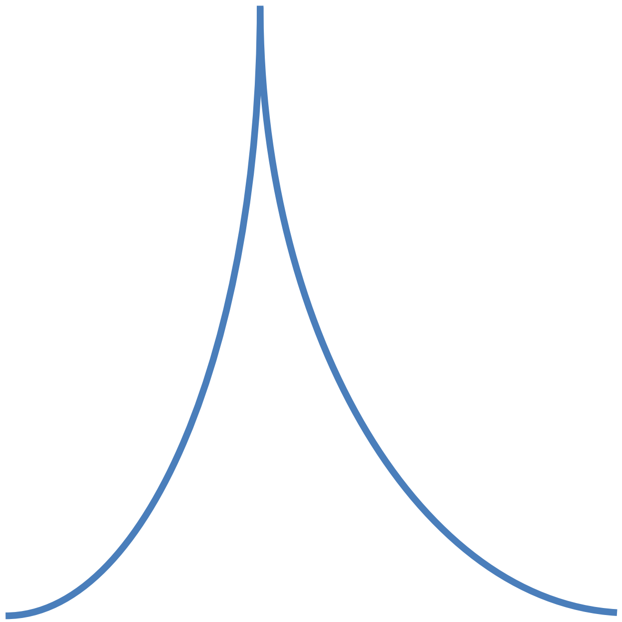
- Below the threshold:

$$\sigma_0 \propto \frac{1}{(1+|k|a)^2 + (|k|b)^2} \sim 1 - 2|k|a$$

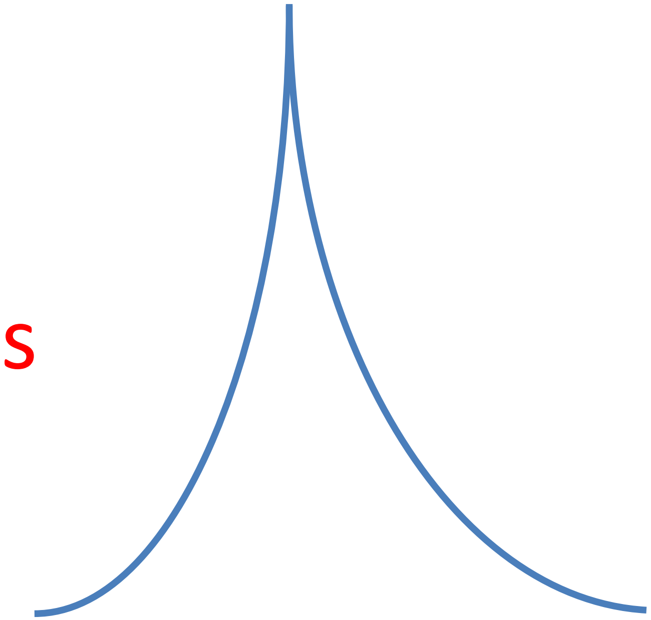
with $k = i\sqrt{2\mu|E|}$ is pure imaginary.

Threshold cusp

- Let's think a case: a > 0
  - Interaction is attractive, but not strong enough to make a bound state
- Pole: $k \sim -i/A$ is virtual
  - E < 0, but in different Riemann sheet
- Spectrum shape: maximum at the threshold (E=0)
  - Derivative diverges
  - Threshold cusp (in the narrow sense)



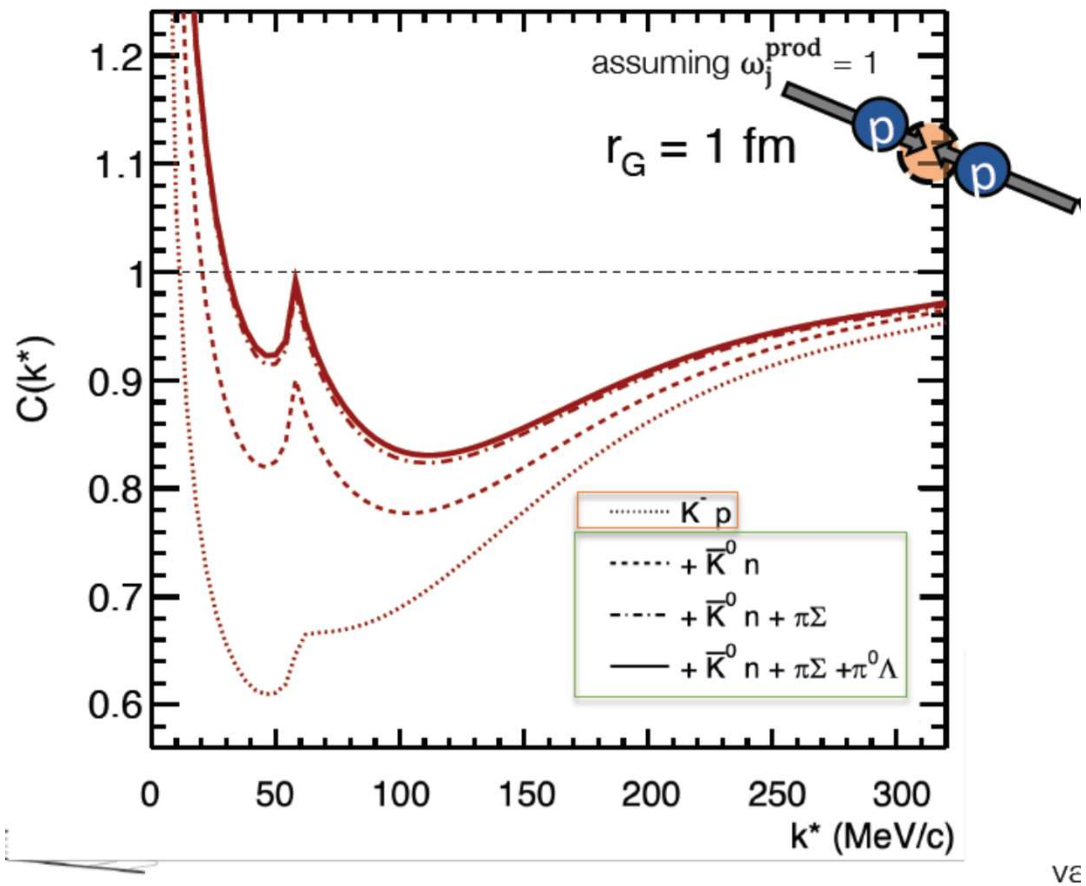
Threshold cusp

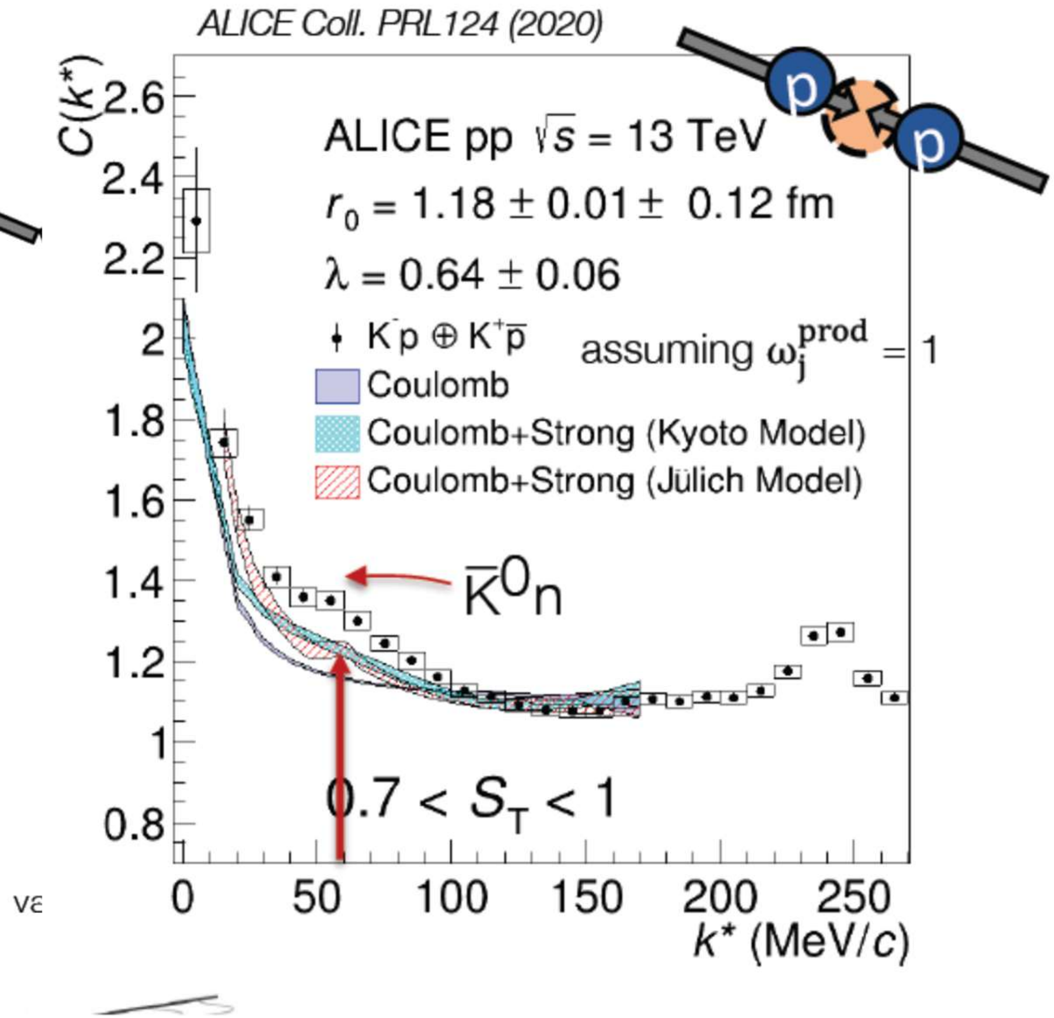


- In principle, can be distinguished from usual peak by the derivative at the peak, but practically there is experimental resolution.
  - Very few identified cases
- The statistics is highest at the threshold
- Low energy seen from the threshold
  → Behavior is roughly determined by the complex scattering length of the threshold channel
  → New method to measure scattering length

Theory vs actual

Borrowed slides of
Prof. Mantovani Sarti on Thusday





Topics of the day

I. Threshold cusps observed in Belle experiment
   - $\Lambda_c \to pK^-\pi^+$ (@$\Lambda\eta$ threshold)
   - $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$ (@$\bar{K}N$ threshold)

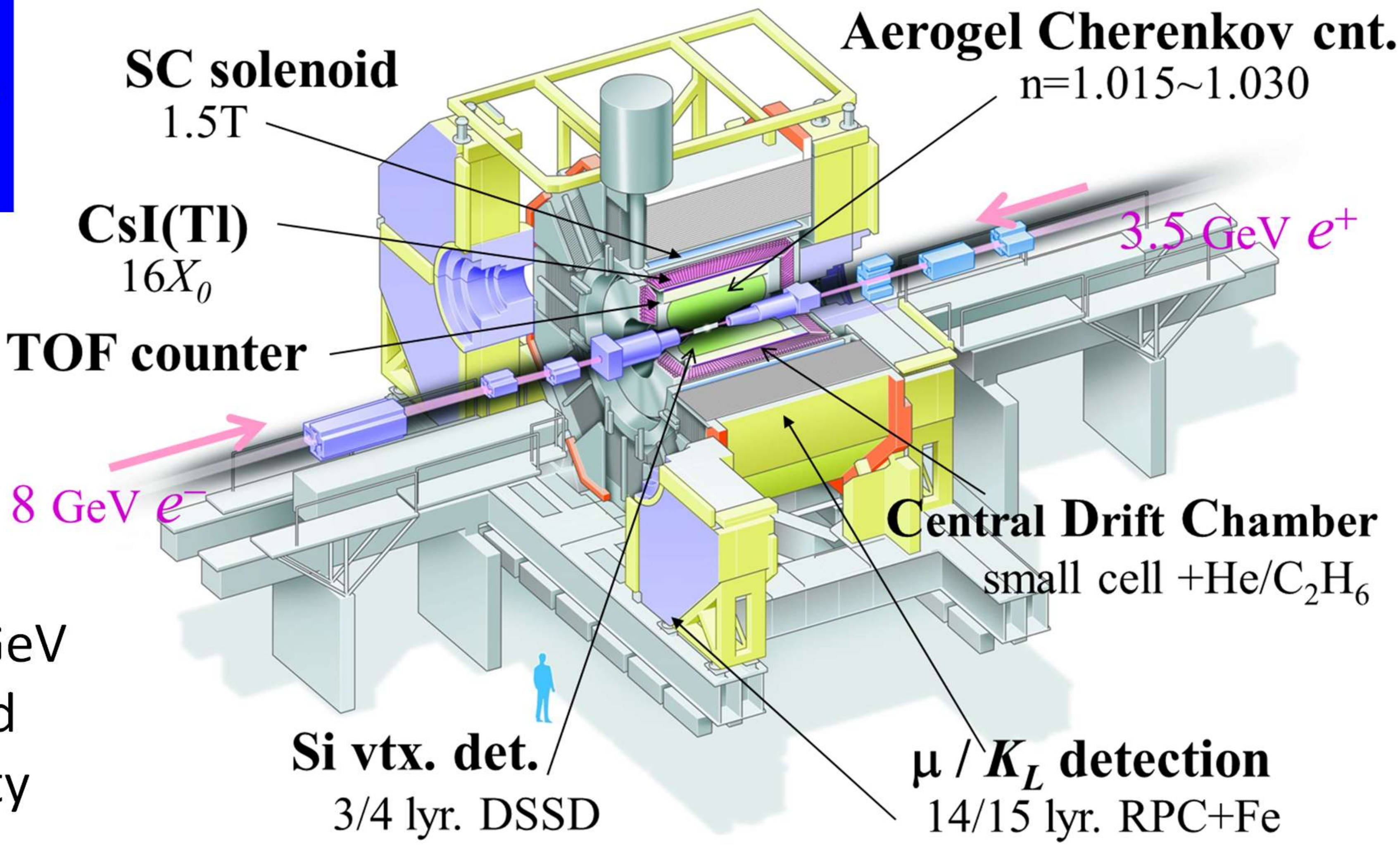
II. J-PARC E72: Search for new exotic narrow Λ^* near the $\Lambda\eta$ threshold

III. J-PARC E90(+α): ΣN scattering length via cusp spectroscopy (& beyond)

IV. Summary

I. Threshold cusps observed in Belle experiment

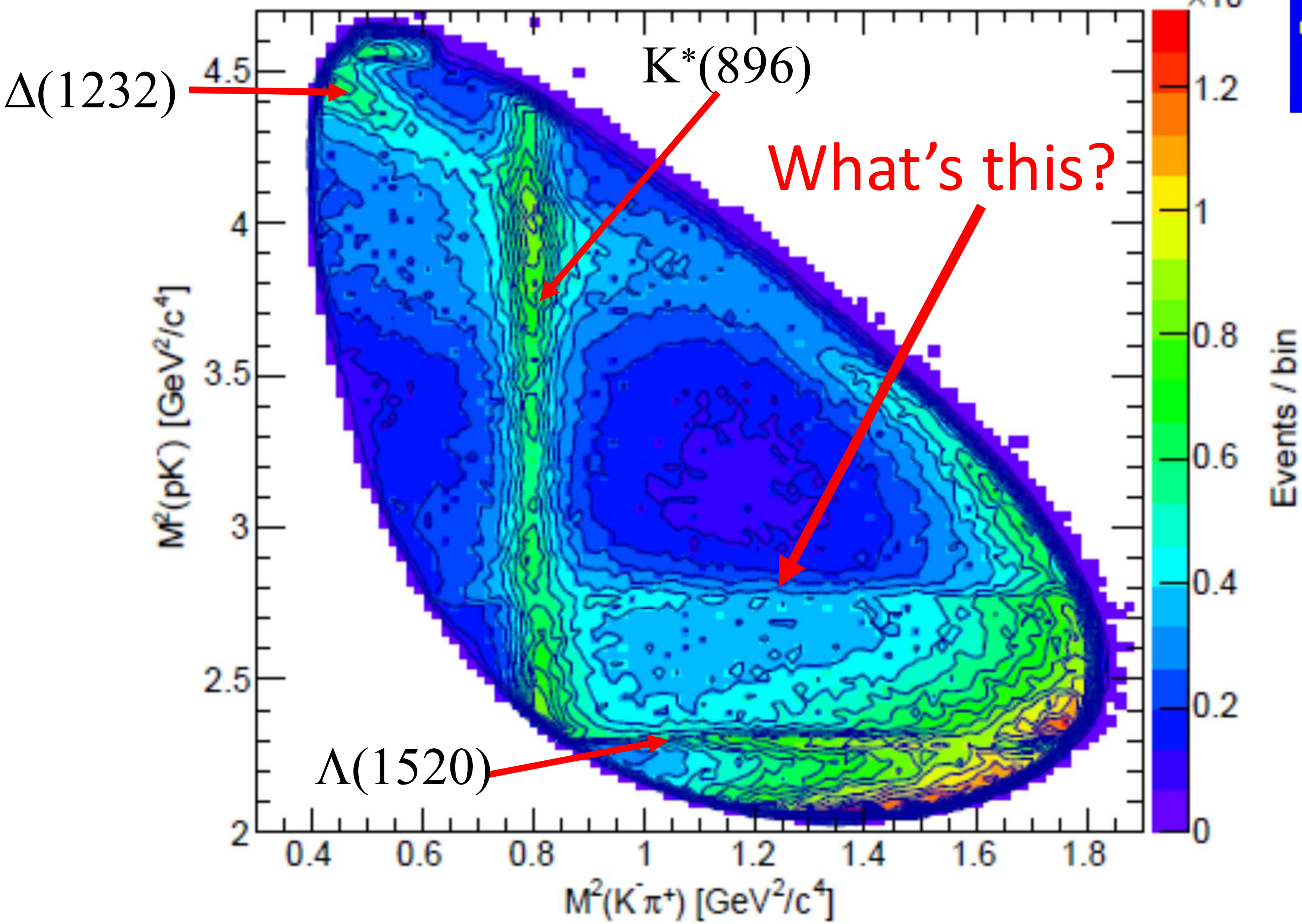
Belle experiment



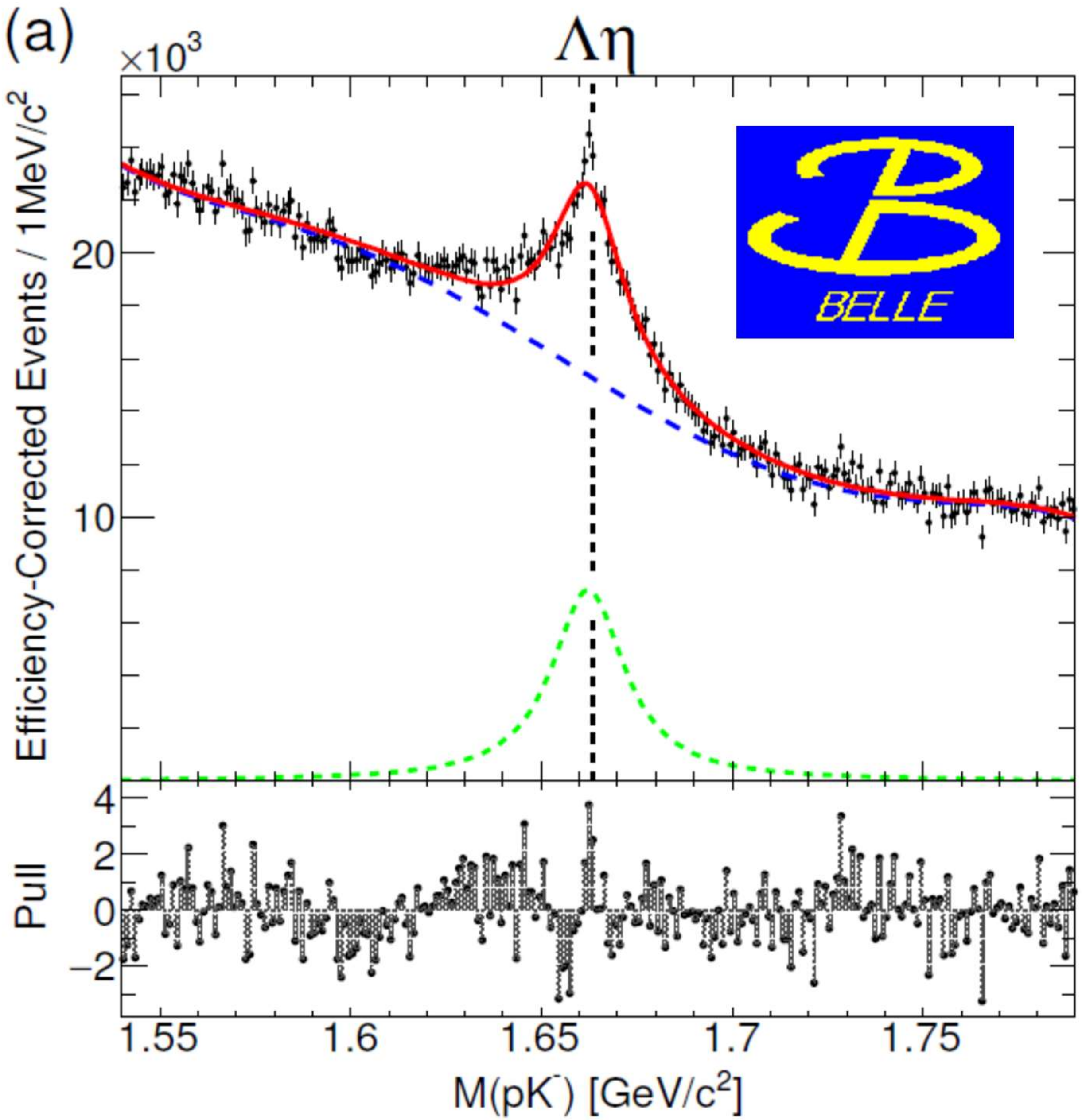
- √s~10.6 GeV
- Integrated Luminosity ~ 1 ab^{-1}
- Almost 4π, good momentum resolution (Δp/p〜0.1%), EM calorimeter, PID & Si Vertex detector
- Finished ~10 years ago, still producing ~20 papers/year

Peak structure in $\Lambda_c \to pK^-\pi^+$

[PRL117(2016)011801]



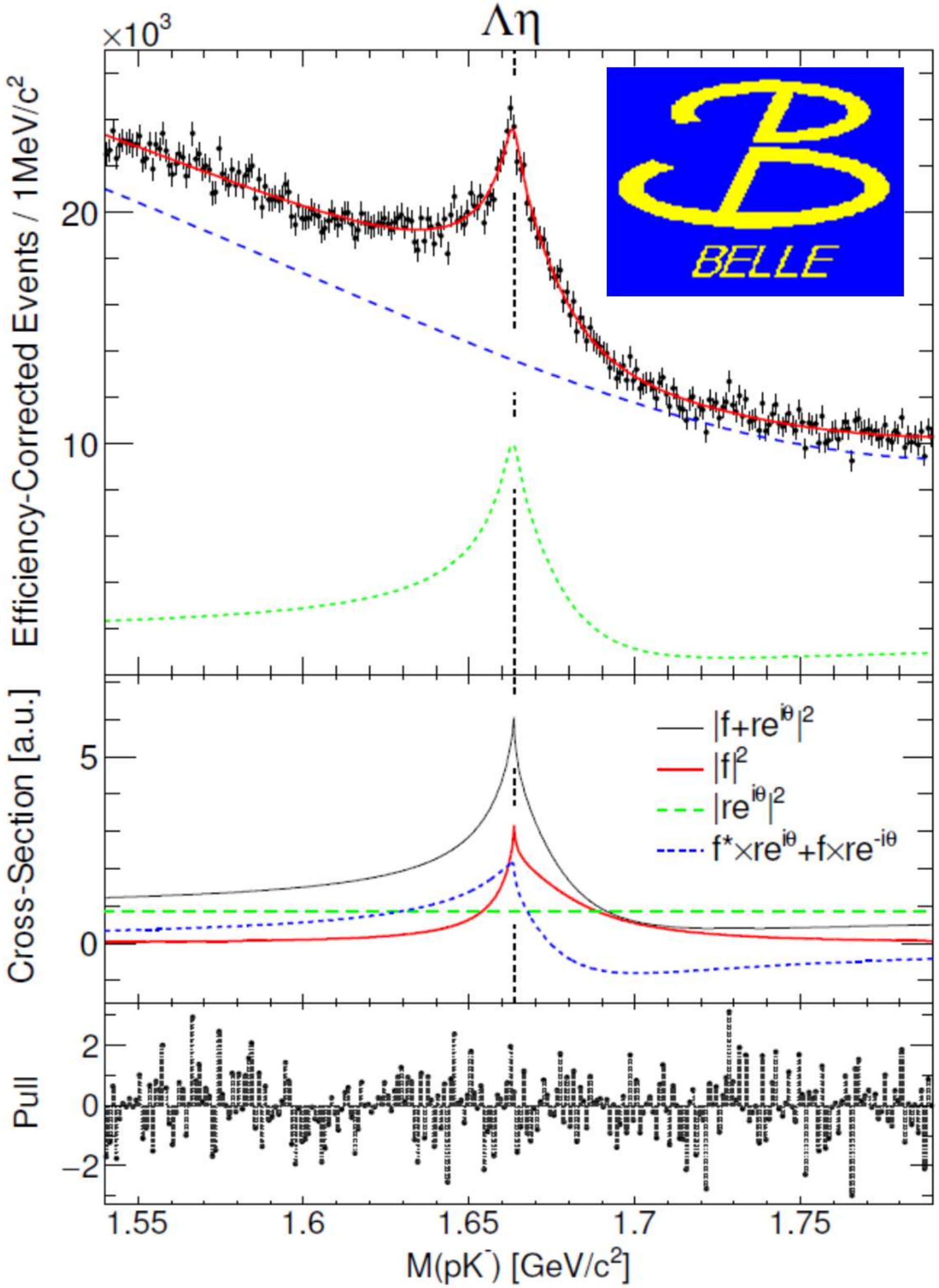
Fit to Breit-Wigner



- BW fit is not very good especially near the peak.
- Best χ^2/DOF: 308/243

[PRD108.L031104 (2023)]

Fit to Flatte



$$\frac{dN}{dm} \propto |f(m) + re^{i\theta}|^2$$

f(m): non-relativistic Flatte

$$\frac{1}{m - m_f + \frac{i}{2}(\Gamma' + \bar{g}_{\Lambda\eta}k)}$$

- Improved near the peak
- Best χ^2/DOF: 257/243
  - Better than BW by 7σ

Threshold cusp

- The fit explains the peak as a threshold cusp with nearby $\Lambda(1670)$
  → **First identification of a threshold cusp from the spectrum shape**
- Obtained $\Lambda(1670)$ parameters are consistent with those measured in $\Lambda_c \to \Lambda\eta\pi^+$ [PRD103 (2021) 052005]

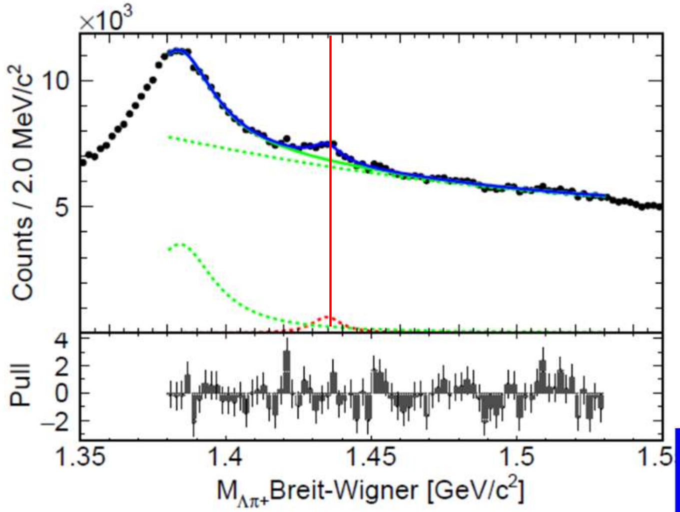
	Present result	$\Lambda\eta\pi^+$ mode
Mass (MeV/c^2)	1674.4	$1674.3 \pm 0.8 \pm 4.9$
Width (MeV)	$50.3 \pm 2.9^{+4.2}_{-4.0}$	$36.1 \pm 2.4 \pm 4.8$

- $\Lambda(1670)$ is usually considered as a 3-quark state, but may be a virtual molecular state

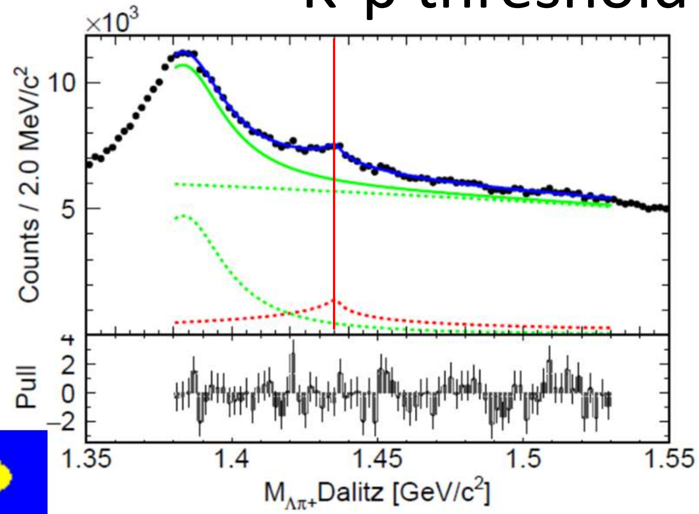
Peak at $\bar{K}N$ threshold in $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$

- Cusp candidates are observed in $\Lambda\pi^\pm$ invariant mass spectra, from Λ_c decay

K^{0}p threshold

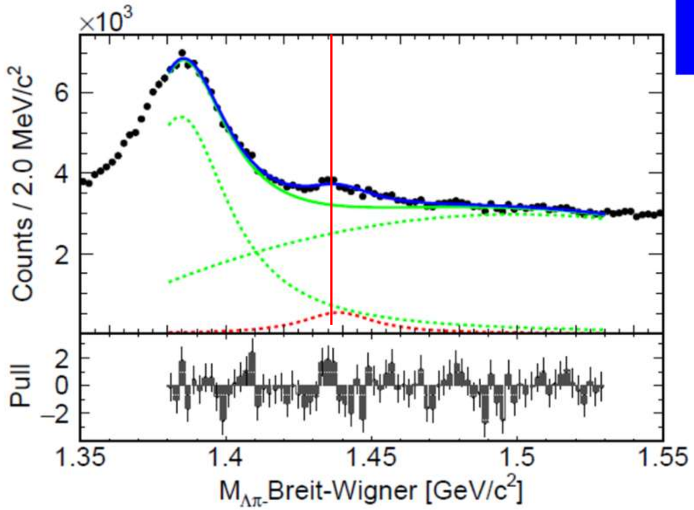


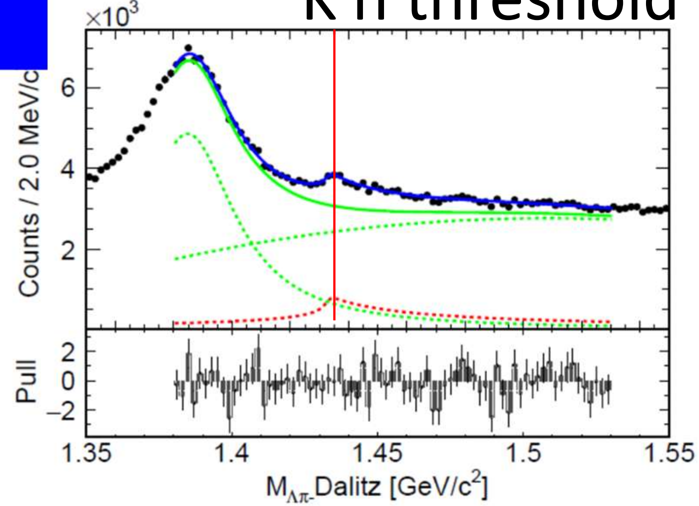
(a)



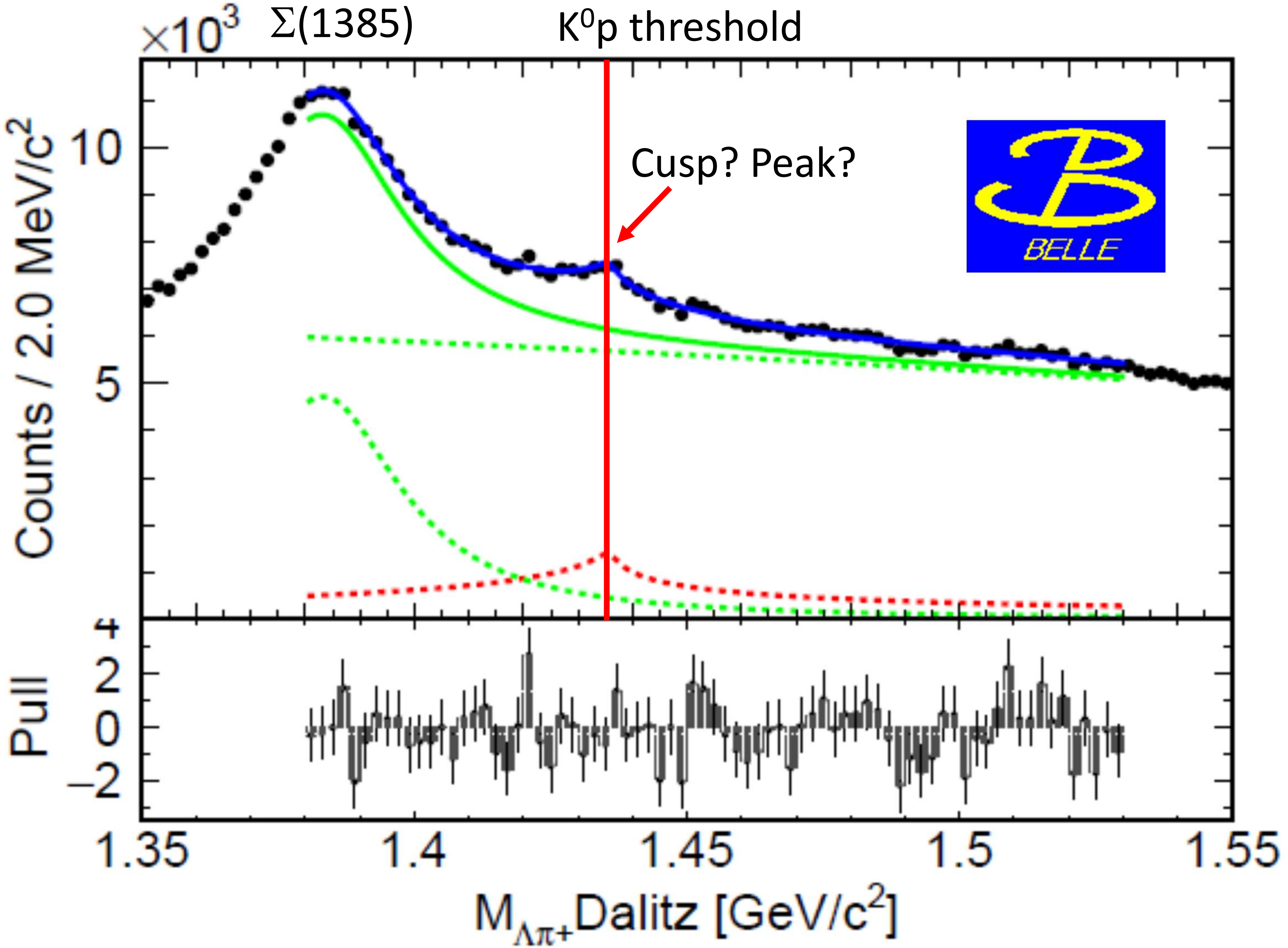
(a)

K$^-$n threshold





BELLE



×10³
Σ(1385)
K⁰p threshold
Cusp? Peak?
BELLE
Counts / 2.0 MeV/c²
10
5
Pull
4
2
0
−2
1.35
1.4
1.45
1.5
1.55
M_Λπ+ Dalitz [GeV/c²]

Two fitting models

1. Standard Breit-Wigner

$$f_{BW} = \frac{\Gamma/2}{(E - E_{BW})^2 + \Gamma^2/4},$$

2. Dalitz model (cusp) [Czech. J. Phys. B**32**, 1021 (1982)]
   For $\bar{K}N(I = 1)$ scattering length A=a+ib and decay momentum k/κ(=|k| below the threshold)

$$f_D = \frac{4\pi b}{(1 + kb)^2 + (ka)^2}, E > m_{\bar{K}N}$$

$$= \frac{4\pi b}{(1 + \kappa a)^2 + (\kappa b)^2}, E < m_{\bar{K}N},$$

neglecting decay form factor

Fitting results

1. Breit-Wigner

Mode	E_{BW} [MeV/c^2]	Γ [MeV/c^2]	χ^2 / NDF
$\Lambda\pi^+$	1434.3 ± 0.6	11.5 ± 2.8	74.4/68
$\Lambda\pi^-$	1438.5 ± 0.9	33.0 ± 7.5	92.3/68

2. Dalitz model (cusp)

Mode	a[fm]	b[fm]	χ^2 / NDF
$\Lambda\pi^+$	0.48 ± 0.32	1.22 ± 0.83	68.9/68
$\Lambda\pi^-$	1.24 ± 0.57	0.18 ± 0.13	78.1/68

Dalitz model gives slightly better χ^2, but the difference is not significant.

Results & discussions

1. Breit-Wigner

   Mass +: $1434.3 \pm 0.6^{+0.9}_{-0.0}$ MeV/c^2

   $-$: $1438.5 \pm 0.9^{+0.2}_{-2.5}$ MeV/c^2

   Width +: $11.5 \pm 2.8^{+0.1}_{-5.3}$ MeV

   $-$: $33.0 \pm 7.5^{+0.1}_{-23.6}$ MeV

- Significance 7.5(6.2)σ
- This interpretation implies the existence of an exotic state, Σ(1435).

Results & discussions

2. Dalitz (cusp) – scattering length A=a+ib

   a K^0p : $0.48 \pm 0.32^{+0.38}_{-0.01}$ fm

   K^-n : $1.24 \pm 0.57^{+1.56}_{-0.16}$ fm

   b K^0p : $1.22 \pm 0.83^{+2.54}_{-0.18}$ fm

   K^-n : $0.18 \pm 0.13^{+0.00}_{-0.20}$ fm

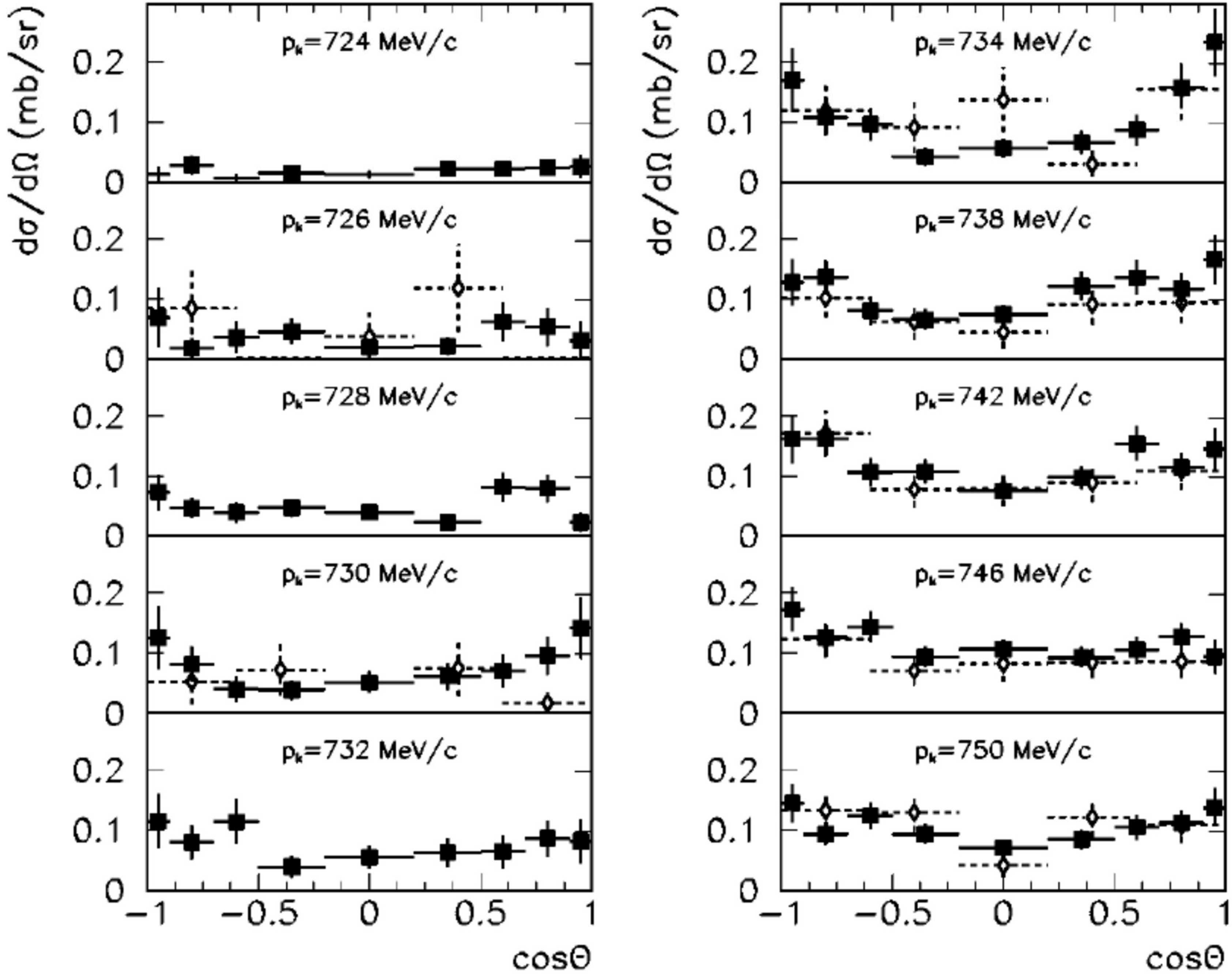
- Many theories predict a cusp here.
  [e.g., Y. Ikeda et al., NPA881.98(2012)]
  – Due to attraction between $\bar{K}$ and N in the I=1 channel
- Obtained center values for a are larger than most theories (e.g., a(K^-n)=0.3~0.6 fm for [*]), but with large uncertainties. (Also, form factor is ignored.)

II. J-PARC E72: Search for new narrow exotic Λ^* near the $\Lambda\eta$ threshold

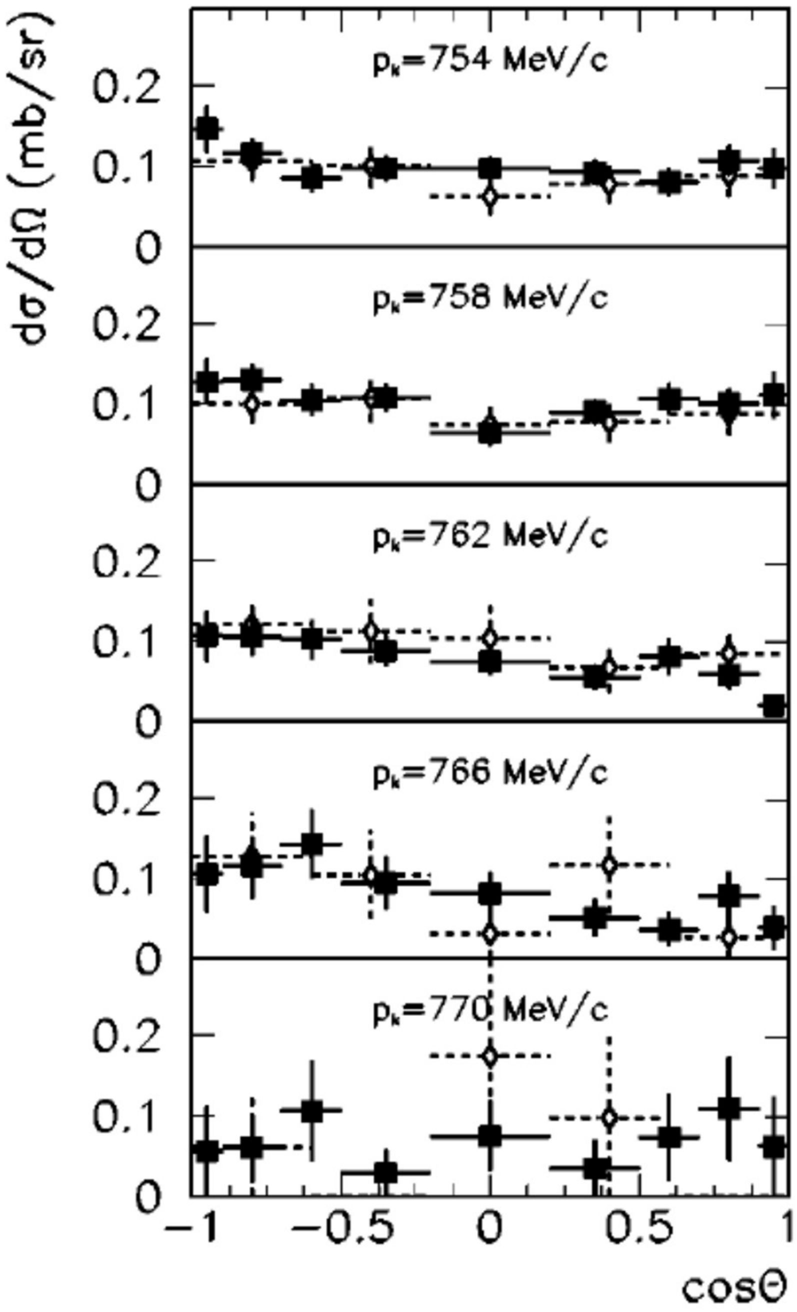
A new Λ resonance around 1670 MeV?

- 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.

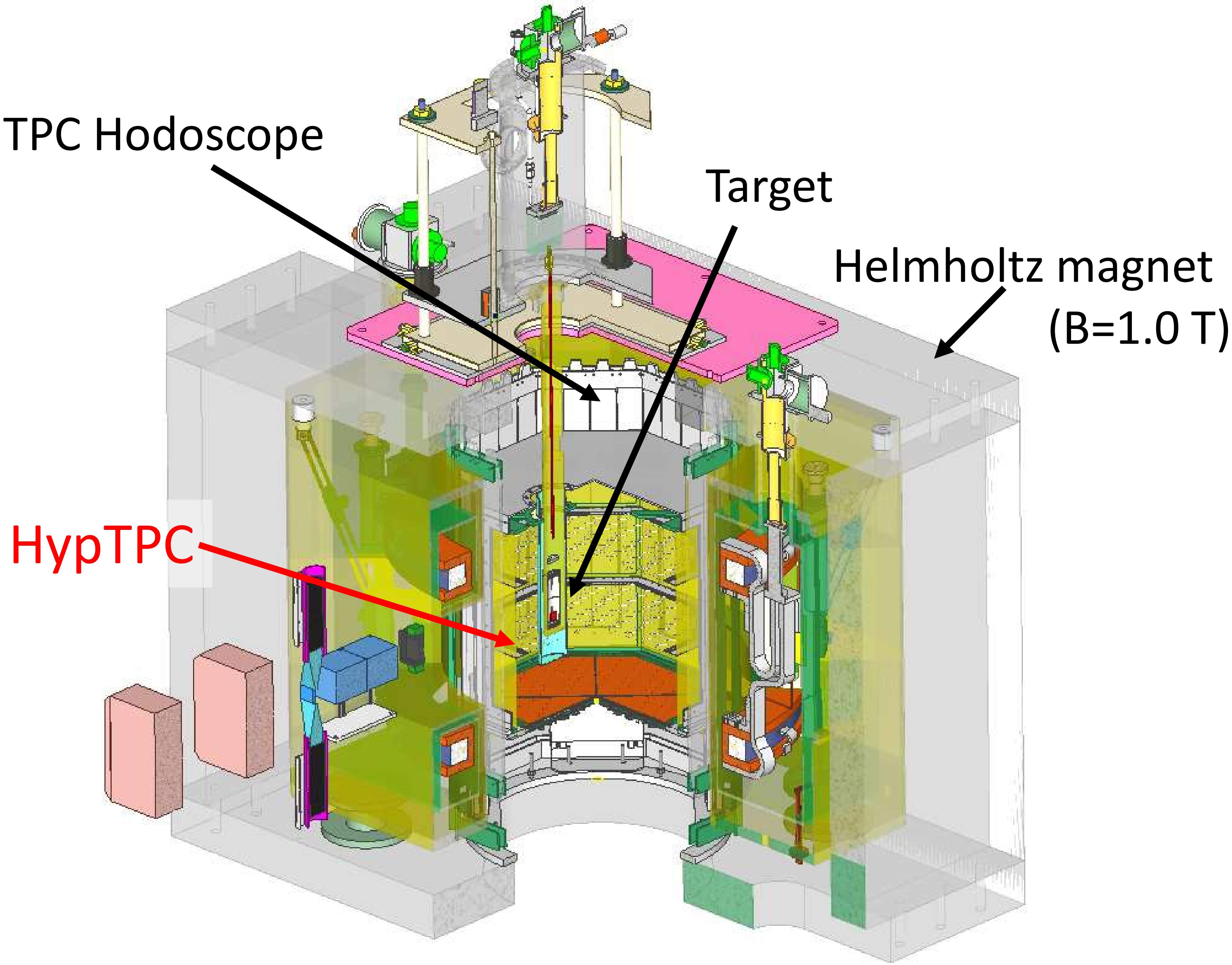
→ **It may be a new type of exotic state!**

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

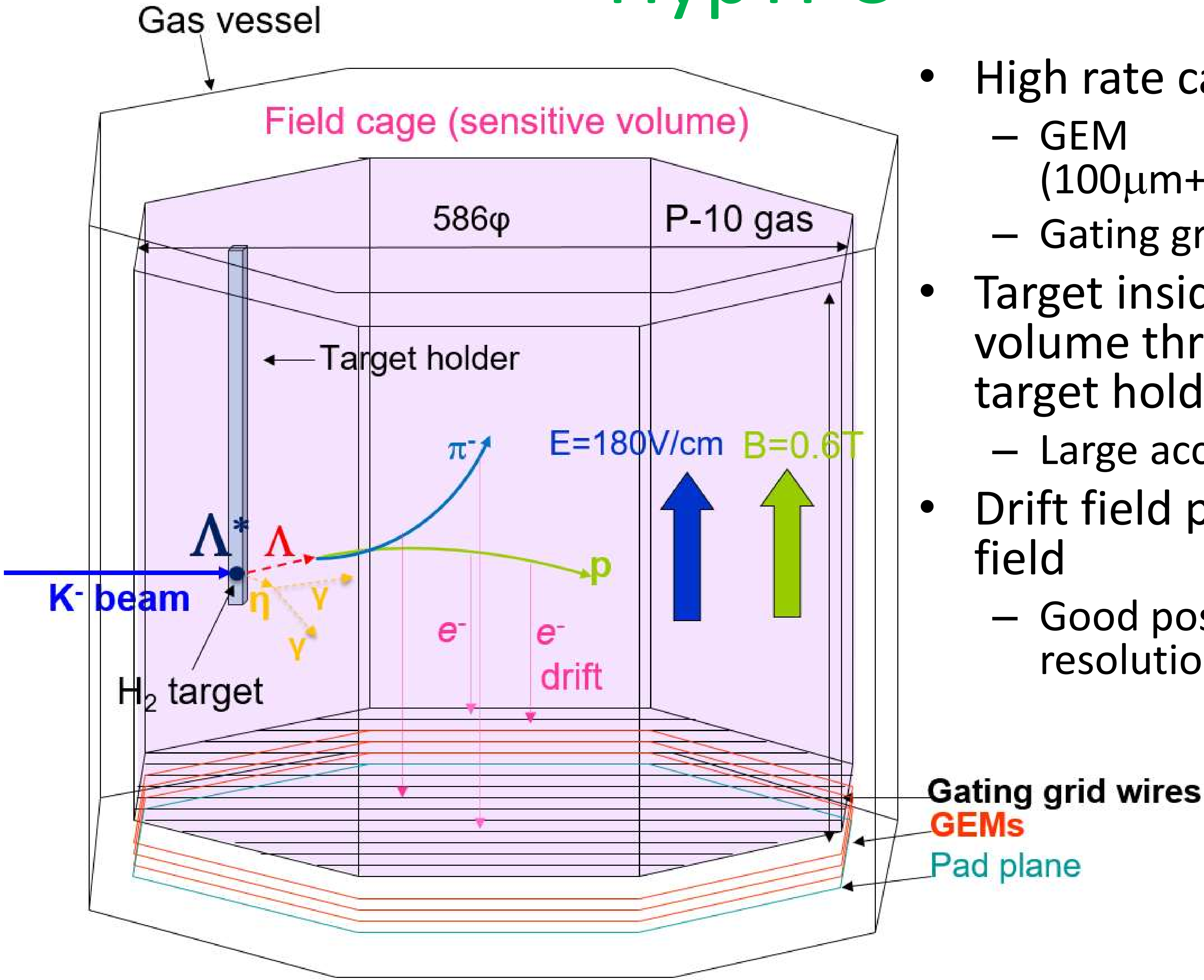
J-PARC E72

- 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
- Test run in this spring.
  Physics run expected in 2025.

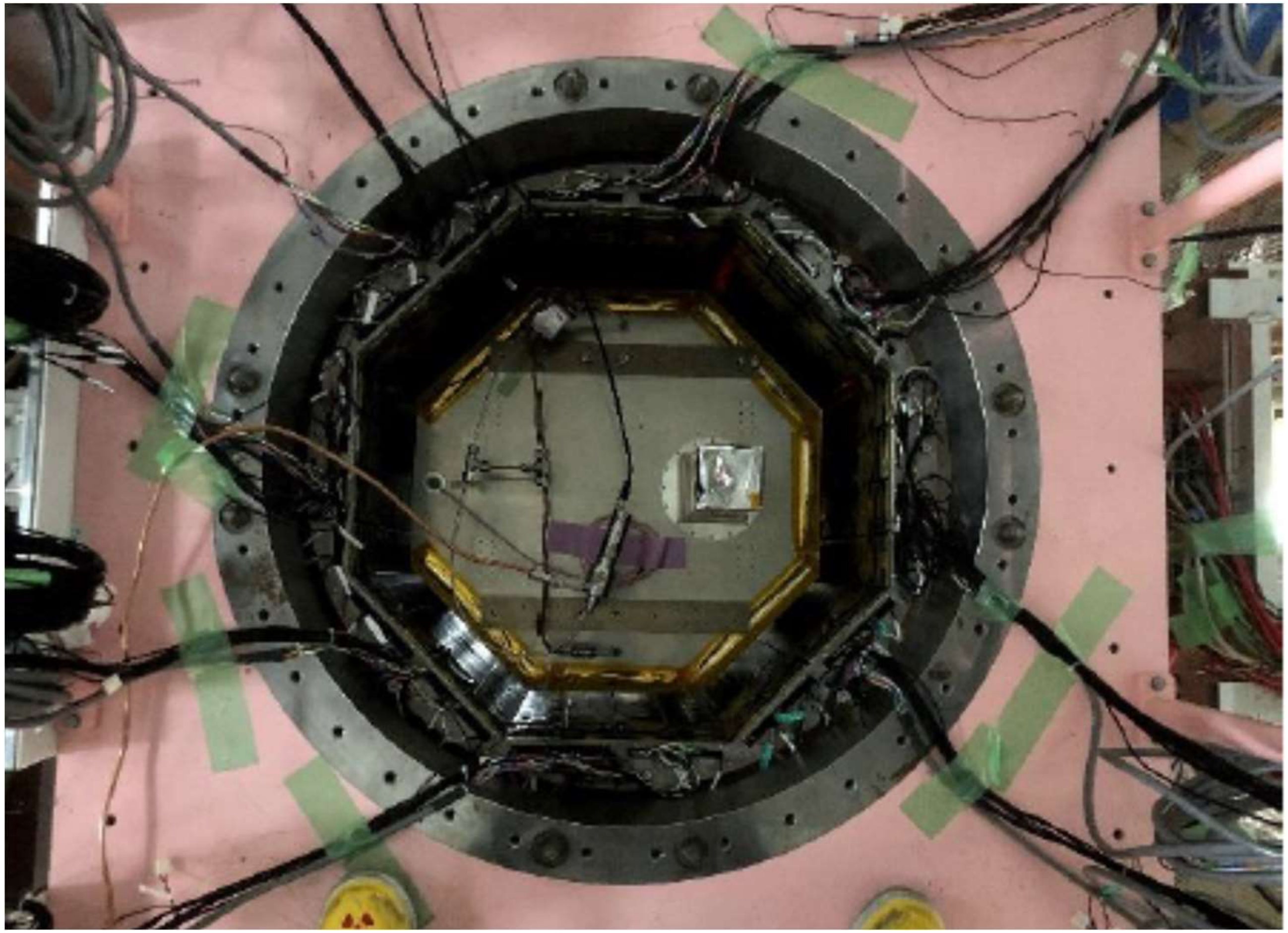
Hyperon Spectrometer



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

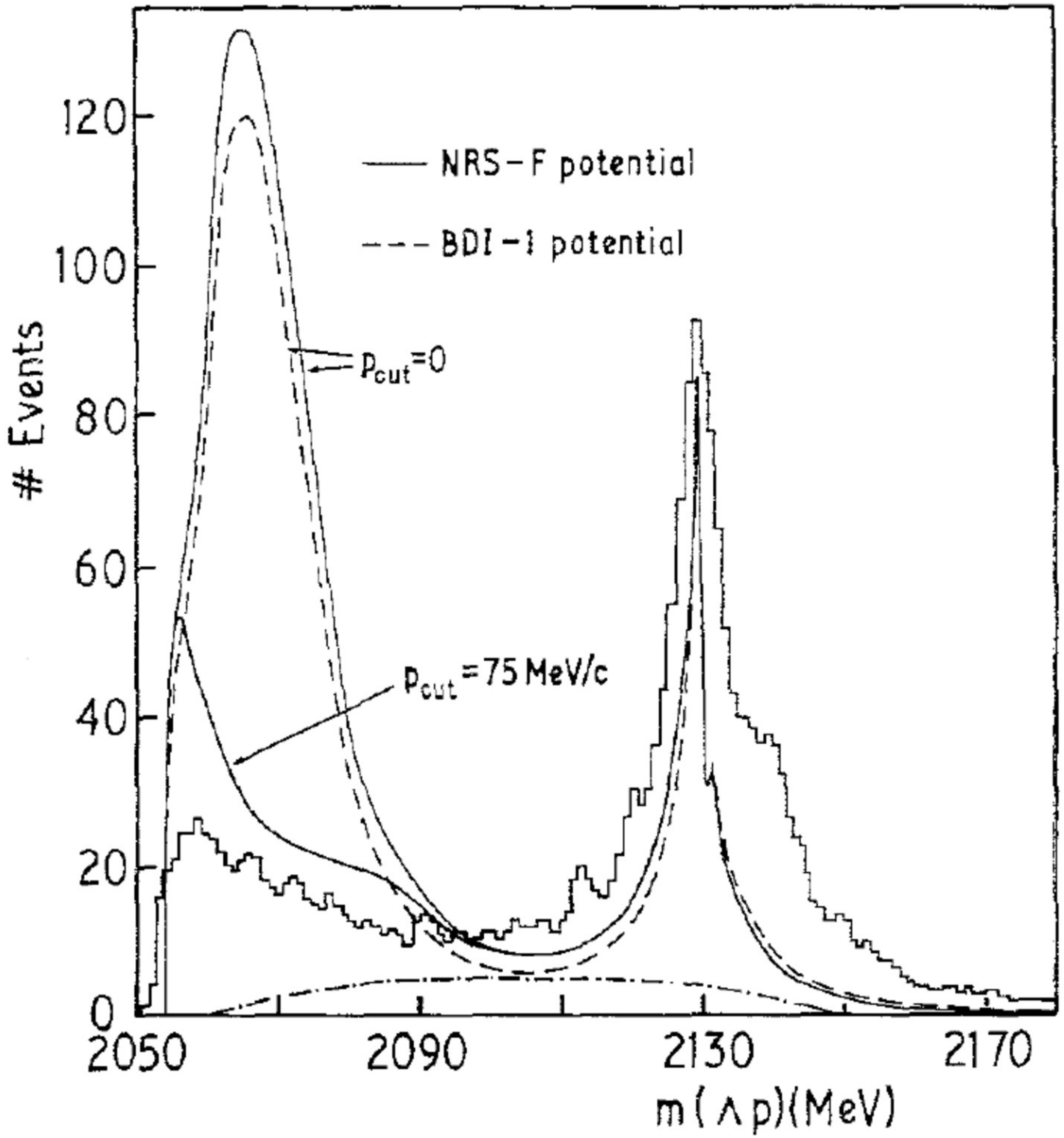


Byproduct – threshold behavior

- We can take data not only on $K^-p \rightarrow \Lambda\eta$, but most other reaction channels such as $K^-p \rightarrow K^-p$ (elastic), $K^0{}_S n$, $\Sigma\pi$, $\Lambda\pi^0$, etc.
  - Study threshold behavior
  - The same excellent mass resolution (0.5 MeV)
- Determine pole position for $\Lambda(1670)$ and $\Lambda\eta$ scattering length

III. J-PARC E90: ΣN scattering length via cusp spectroscopy (& beyond)

ΣN cusp



- Seen in K^{-}(stopped)+d → $\Lambda p \pi^{-}$ and many others
- Maybe the cleanest cusp ever seen, but not confirmed.
  - Because the resolution is not enough

What should we do?

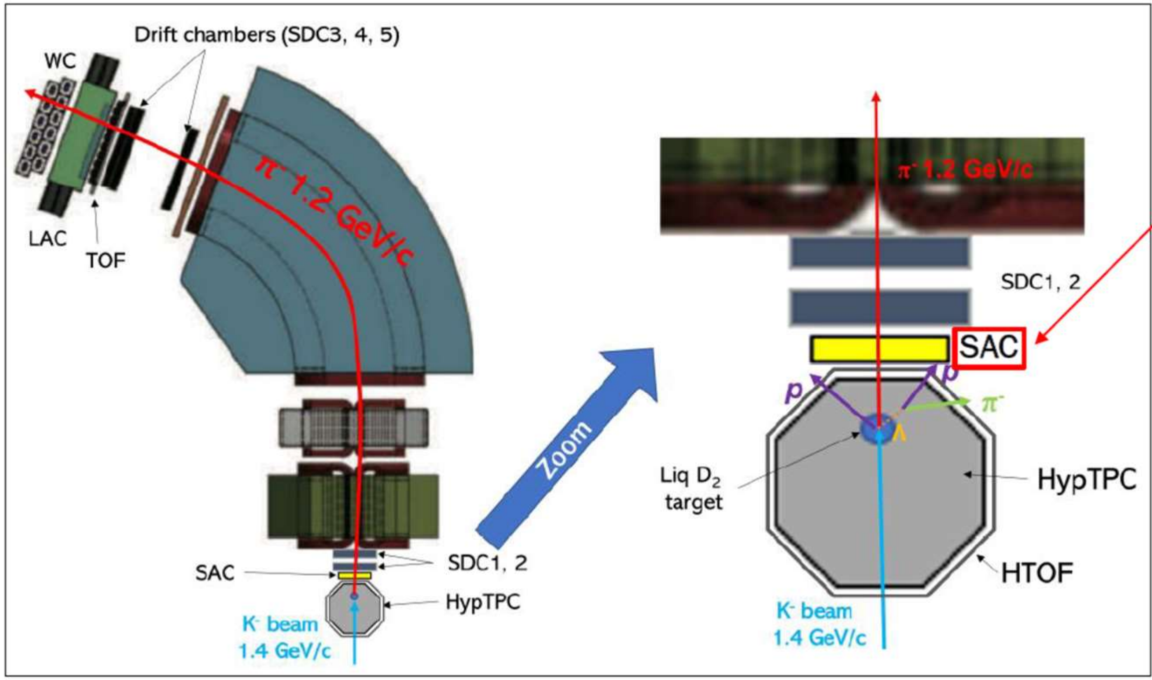
- Try even higher resolution
  - 0.4 MeV (σ) would be enough to see the cusp shape
- Tagging of the final state is necessary
  - Must be ΛN to derive ΣN(I=1/2) scattering length
  - ΣN(I=3/2) contaminate if not tagged
- J-PARC E90
  - 0.4 MeV resolution with d(K^-,p) reaction at $p_K \sim 1.4$ GeV/c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

E90 setup

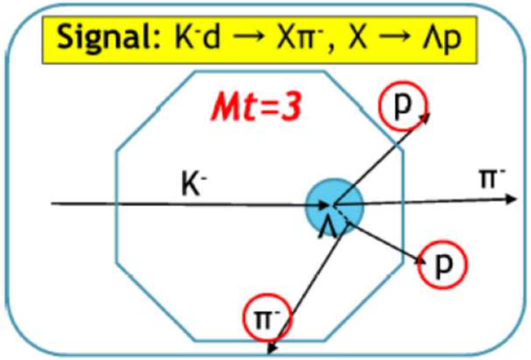
SET UP

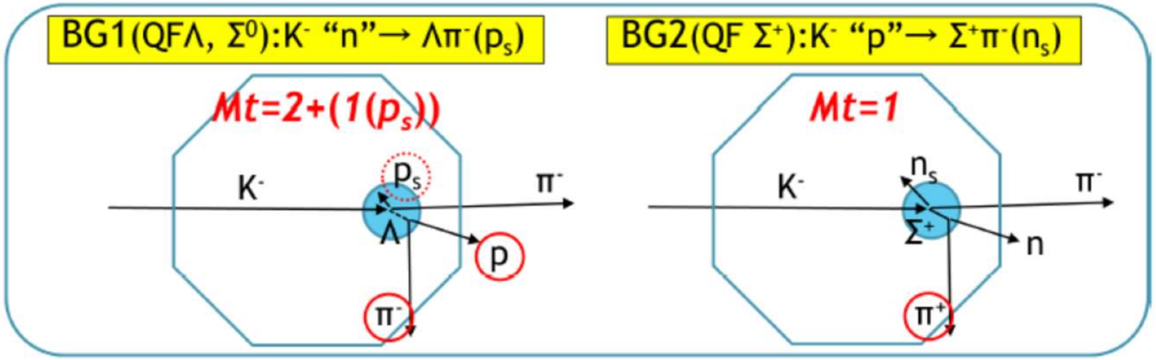
- Reaction: $K^- d \to \Lambda p \pi^-$ at 1.4 GeV/c
- S-2S(developed for E70): π^- measurements → measurement of missing mass spectrum
  - Good mass resolution: ΔM ~ 0.4 MeV (σ), ($\Delta p/p$(K18)=3.3×10^{-4}(FWHM), $\Delta p/p$(S-2S)=6.0×10^{-4}(FWHM))
- HypTPC(developed for E42): Final state (Λp) restriction and background suppression

Momentum transfer
~ 200 MeV/c



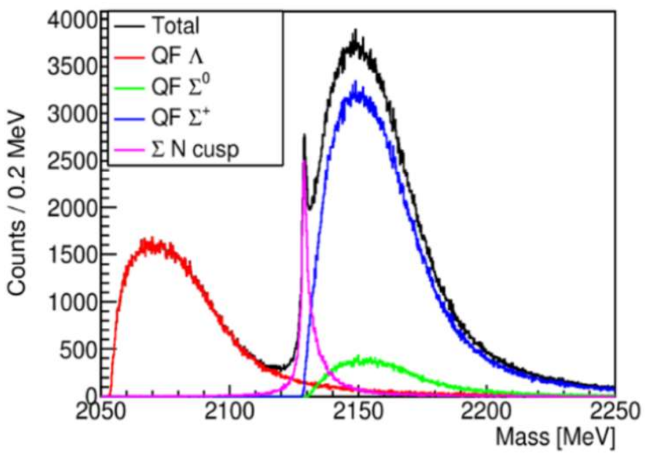
QF BACKGROUND SUPPRESSION BY HYPTPC





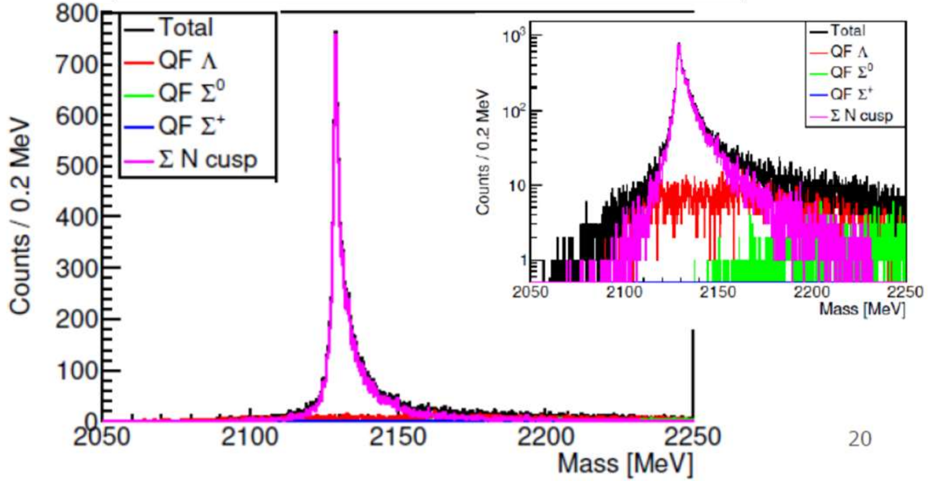
Simulated inclusive spectrum d(K⁻, π⁻)

Expected spectrum for the 15 days beam time



Multiplicity = 3

Multiplicity = 3 without (K⁻, π⁻)



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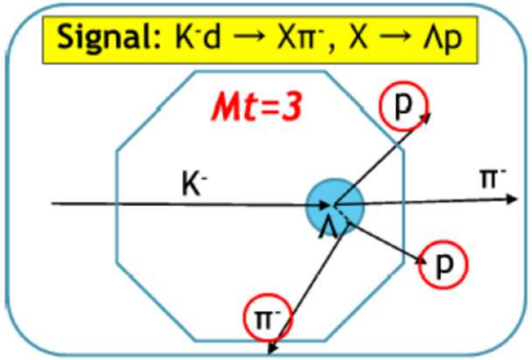
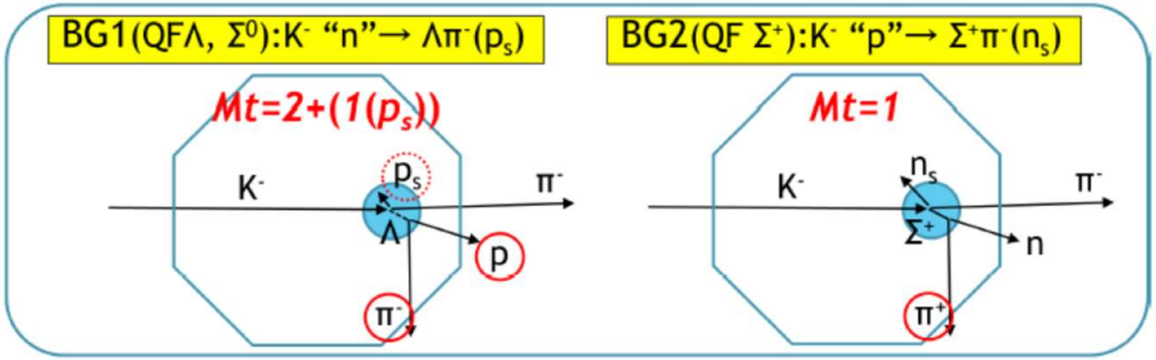
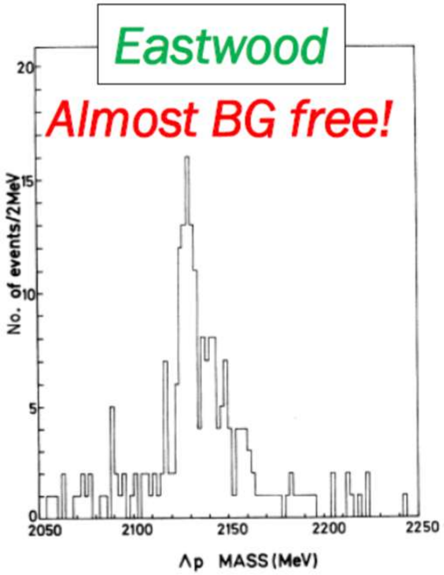
QF BACKGROUND SUPPRESSION BY HYPTPC

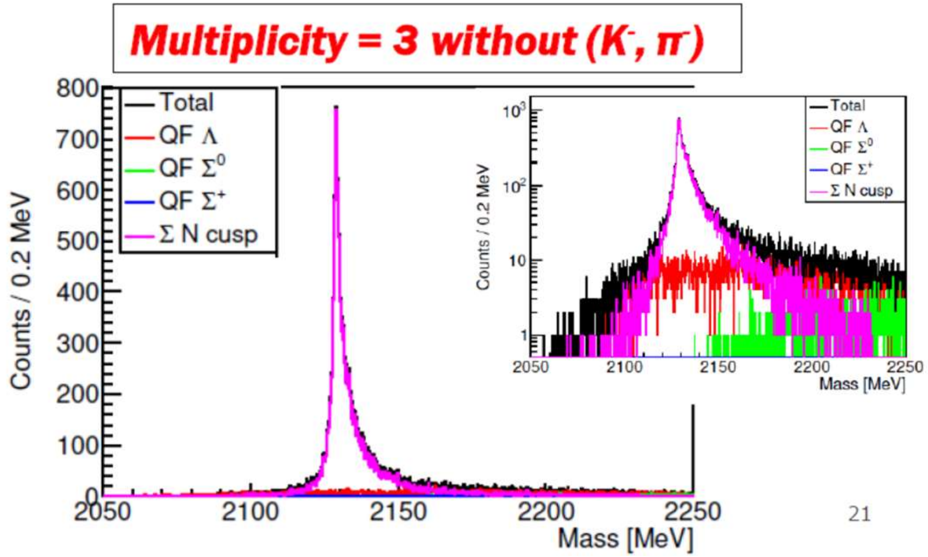




$K^{-}d \rightarrow \Lambda p \pi^{-}$
@1.45 and 1.65 GeV/c
(Bubble chamber)

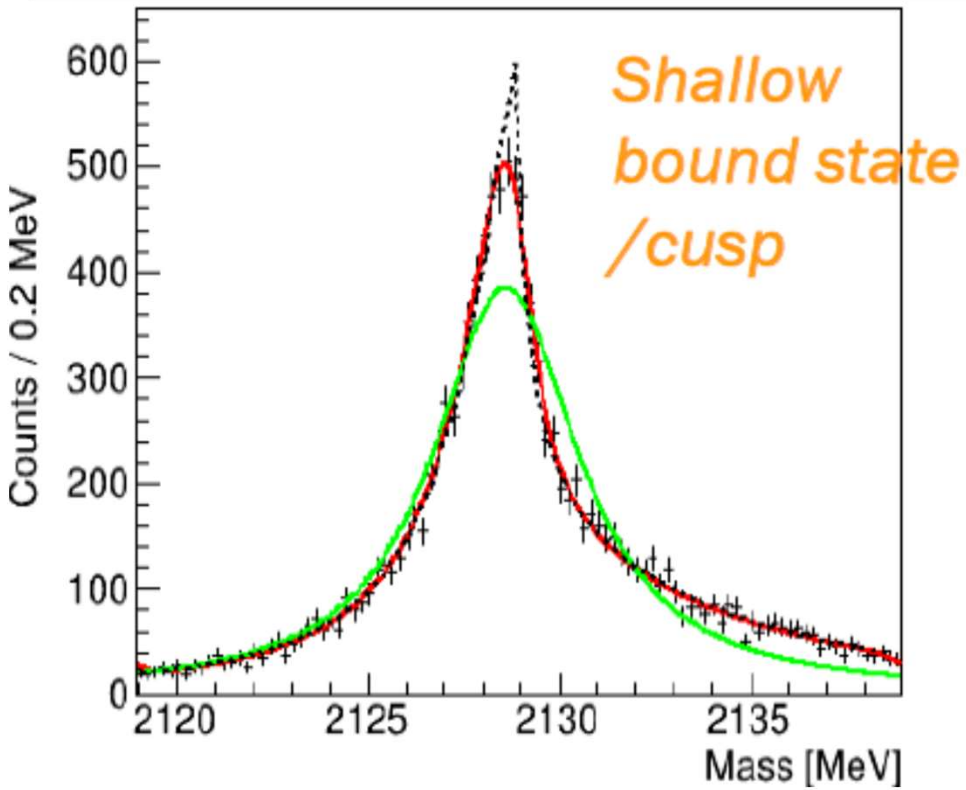
$\cos\theta_{CM} > 0.9$
$p_{proton} > 150$ MeV/c



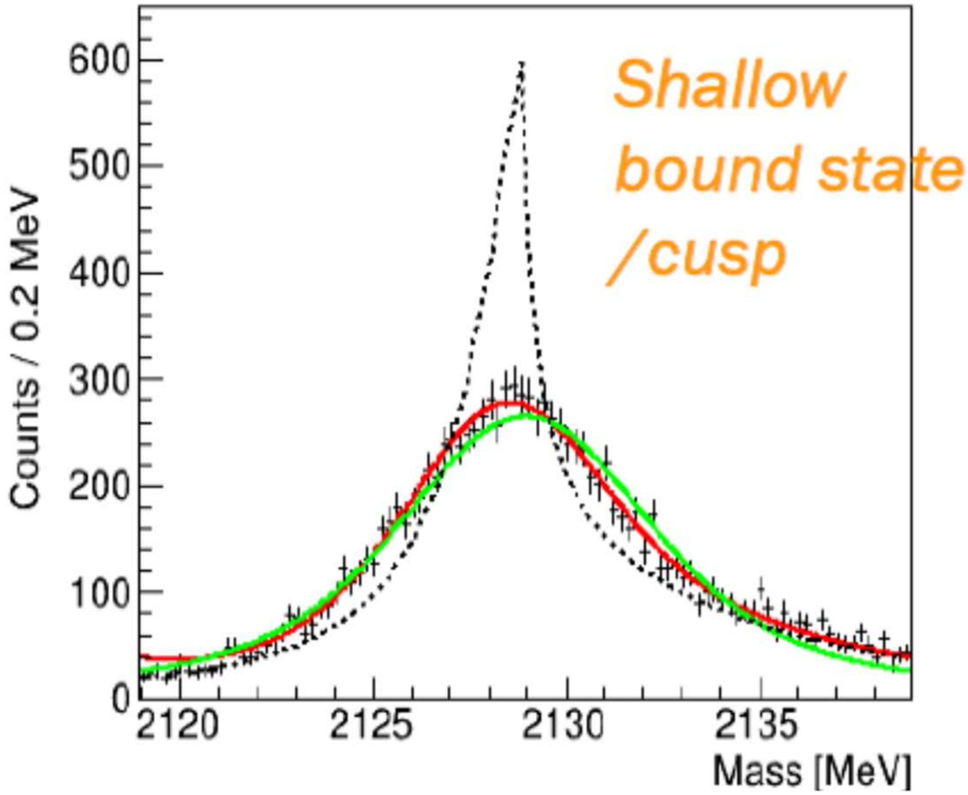


Importance of resolution

σ＝0.4 MeV



σ＝2 MeV



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

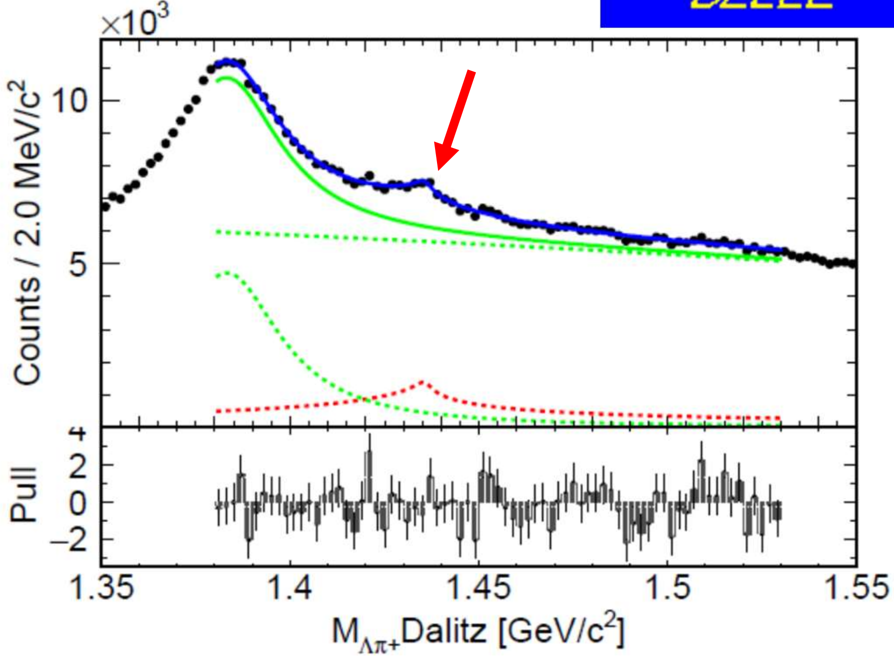
+α:
A new experiment to study $\bar{K}N(I=1)$ interaction via cusp spectroscopy

$\bar{K}N(I=1)$ scattering length

- Important, related to
  - Kaonic nuclei
  - Kaon condensation in neutron stars
- Dedicated experiments with a measurement of kaonic deuterium atom X rays.
  - J-PARC E57
  - Siddharta-2 at DAΦNE
- A new, independent measurement possible using threshold cusp.

$\Lambda\pi - \bar{K}N(I = 1)$ cusp at J-PARC?

- We already saw a hint in Λ_c decay@Belle
  - very poor S/N
  - Also unknown production mechanism



- Direct reaction is preferred
  - Two possibilities with $\Lambda\pi^{\pm}$ in the final state
    1. $p(K^{-},\pi^{\pm})\Lambda\pi^{\mp}$
    2. $d(K^{-},p)\Lambda\pi^{-}$
  - reaction 2: small momentum transfer & controlled reaction mechanism – the same mechanism as J-PARC E31 [PLB837(2023)137637]

Summary

- Virtual state
  → Cusp: sharp peak-like structure at threshold
- In Belle
  - $\Lambda\eta$ cusp is identified in Λ_c → $pK^-\pi^+$
  - Another candidate found in $\Lambda\pi$ at the $\bar{K}N$ threshold
- J-PARC E72: Search for an exotic $\Lambda(1665)$ and more data on $\Lambda\eta$ cusp
  → scattering length
- E90: ΛN-ΣN cusp study for ΣN scattering length
  - Can be applied to $\bar{K}N$(I=1) case
  - Even more: any thresholds such as ΛK, ΣK, N$\eta^{(\prime)}$, $\Lambda\eta'$, …