Peak-like structures observed in Λ_c decays at Belle

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@Hadron2023

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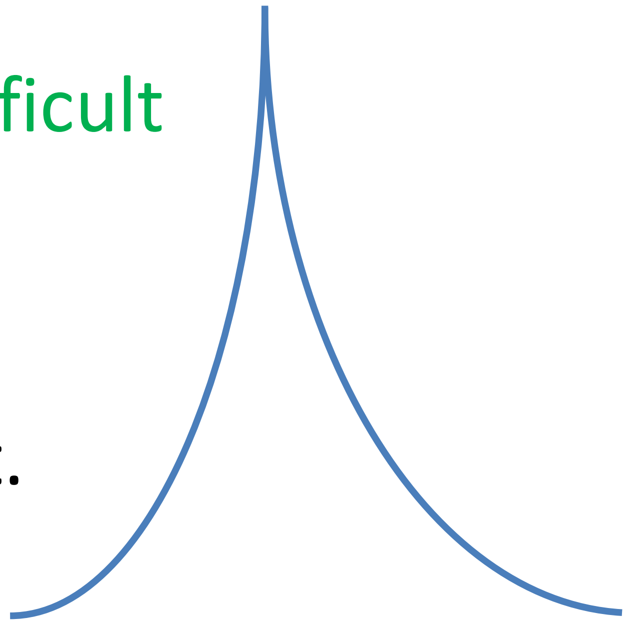
Introduction

- Baryons with flavors
  - Good playground for diquark correlation, especially with single heavy quark.
  - Also good to study meson-baryon correlation
    → Molecular type exotic state:
    Bound (Feshbach resonance) vs virtual?

Virtual state & threshold cusp

- Molecular type state -- when interaction is not strong enough to make a bound state, there would be a virtual state.
  - E < 0 (bound??), but in different Riemann sheet
  - Appears as threshold cusp instead of usual Breit-Wigner peak (in the narrow sense).
  - However, identification is rather difficult due to experimental resolution
- Are there really such states?
  - Pointing shape is not confirmed yet.



Introduction

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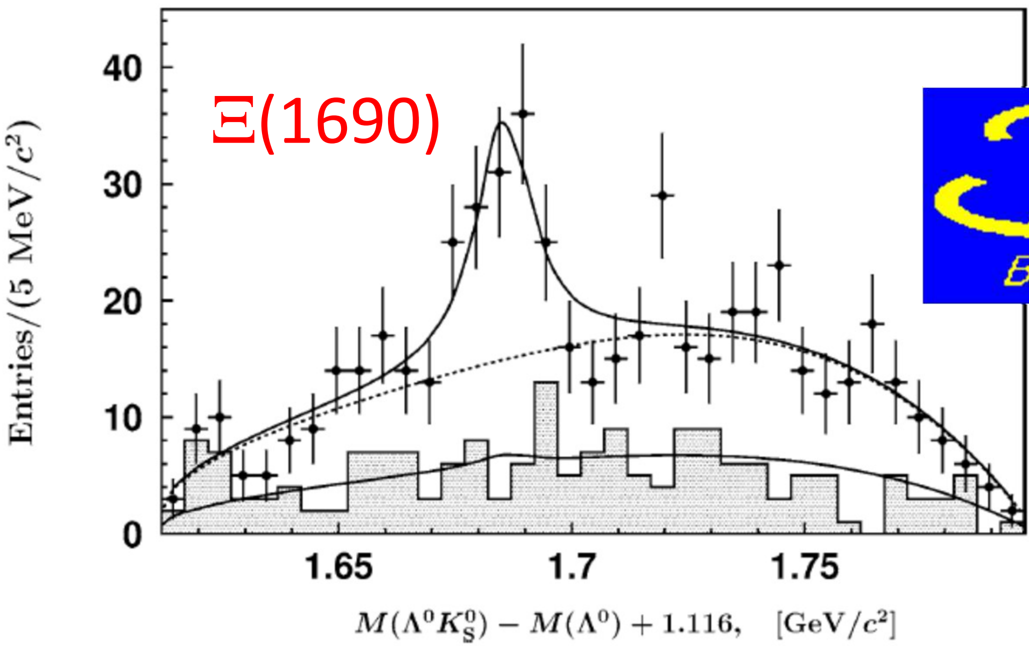
  - Good playground for diquark correlation, especially with single heavy quark.
  - Also good to study meson-baryon correlation
    → Molecular type exotic state:
    Bound (Feshbach resonance) vs virtual?
- Spectroscopy methods
  - Invariant mass
  - Scatterings with kaon beam
  - New mode: weak decay of heavy flavors

Hyperons from charmed baryon decays

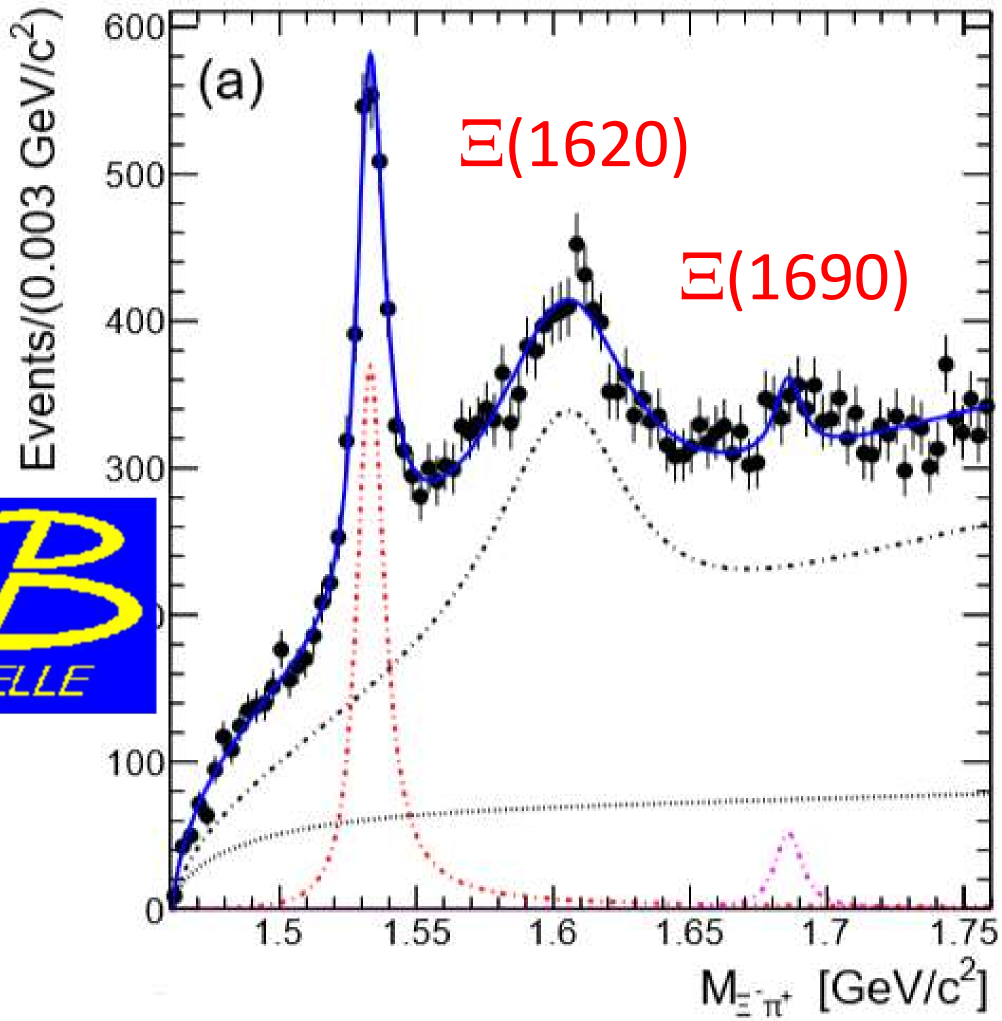
- New source for hyperon spectroscopy
  - New states?
  - Branching ratios

$\Lambda_c \rightarrow \Lambda K^0_S K^+$



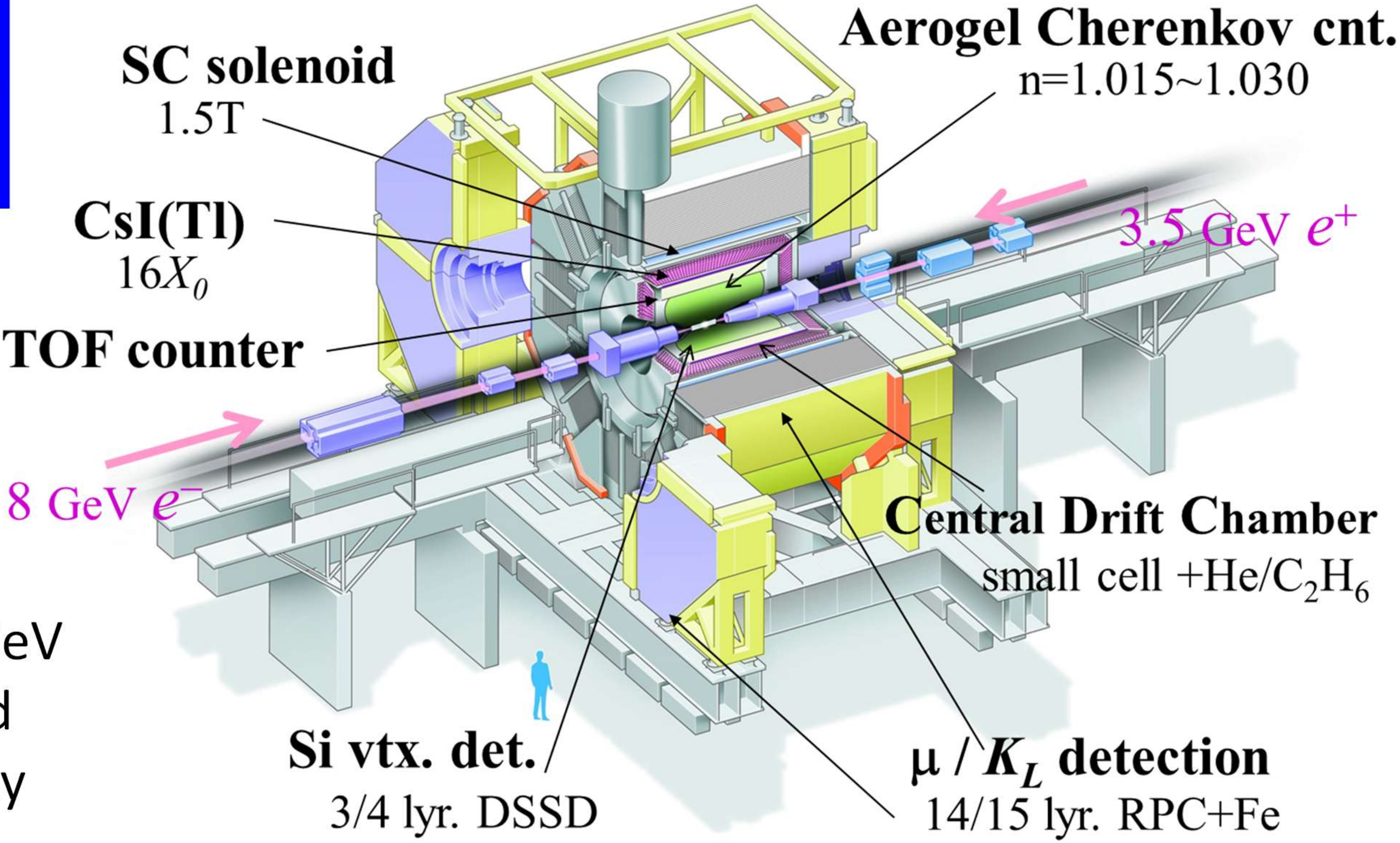
[Belle, PLB **524** (2002) 33-43]

$\Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+$



[Belle, PRL **122** (2019) 072501]

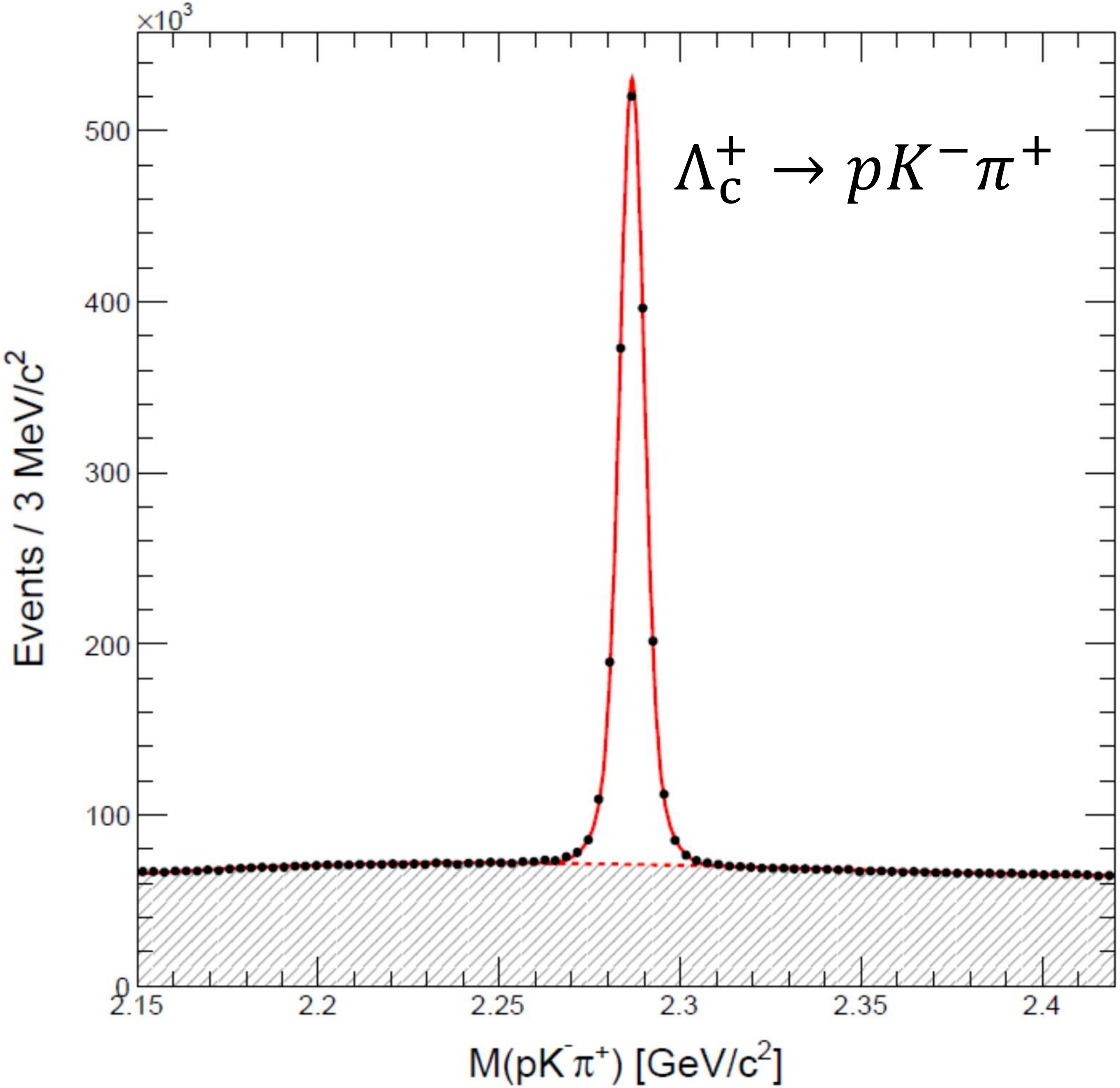
Belle experiment



- √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

Huge statistics, good quality



> 1 M events reconstructed

Resolution:
< 10 MeV FWHM

S/N ~ 10

Topics of the day

1. Threshold cusp in $\Lambda_c \rightarrow pK^-\pi^+$[arXiv:2209.00050]

2. Peak at $\bar{K}N$ threshold in $\Lambda_c \rightarrow \Lambda\pi^+\pi^+\pi^-$ [PRL130(2023)151903]

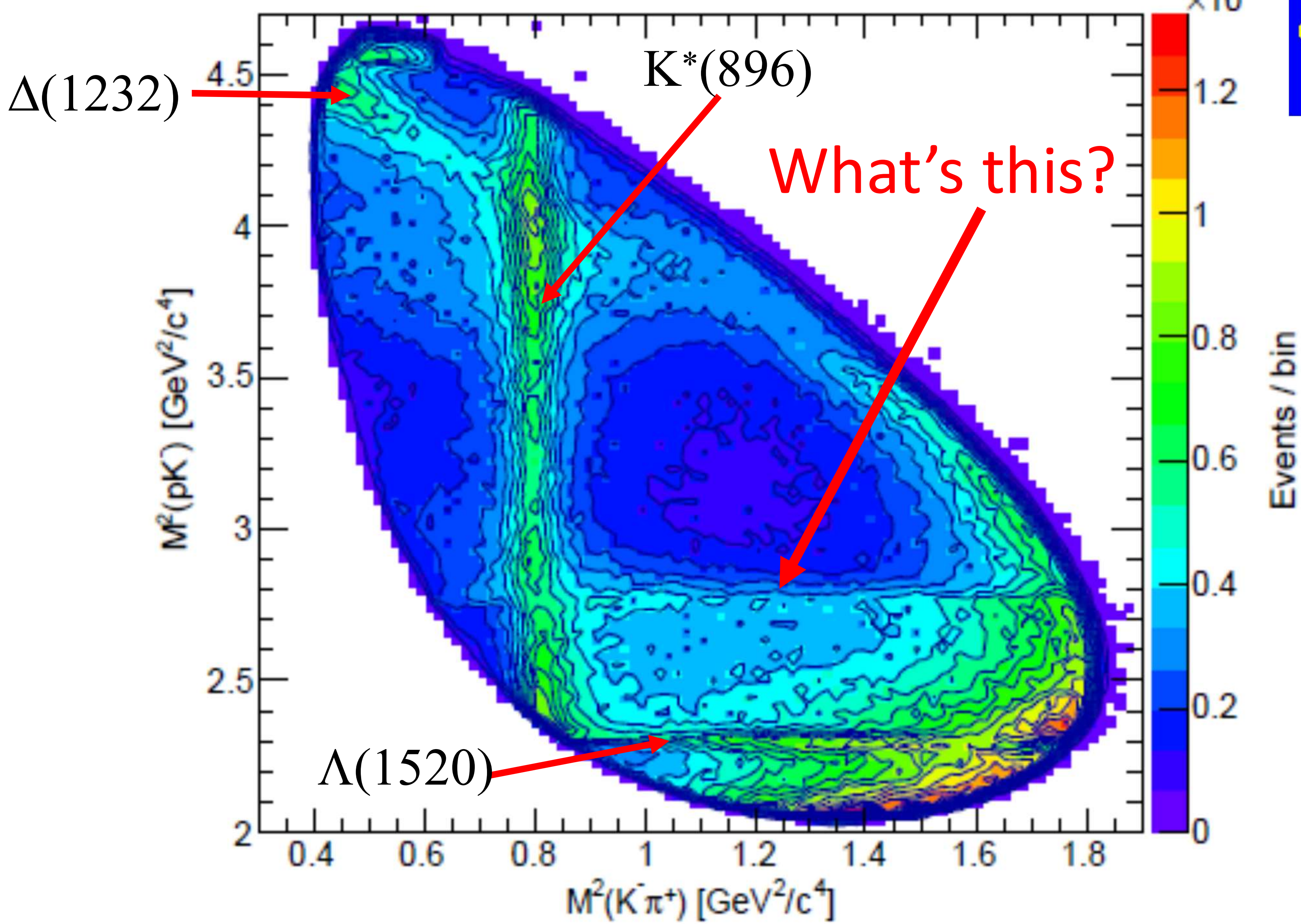
3. Summary

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

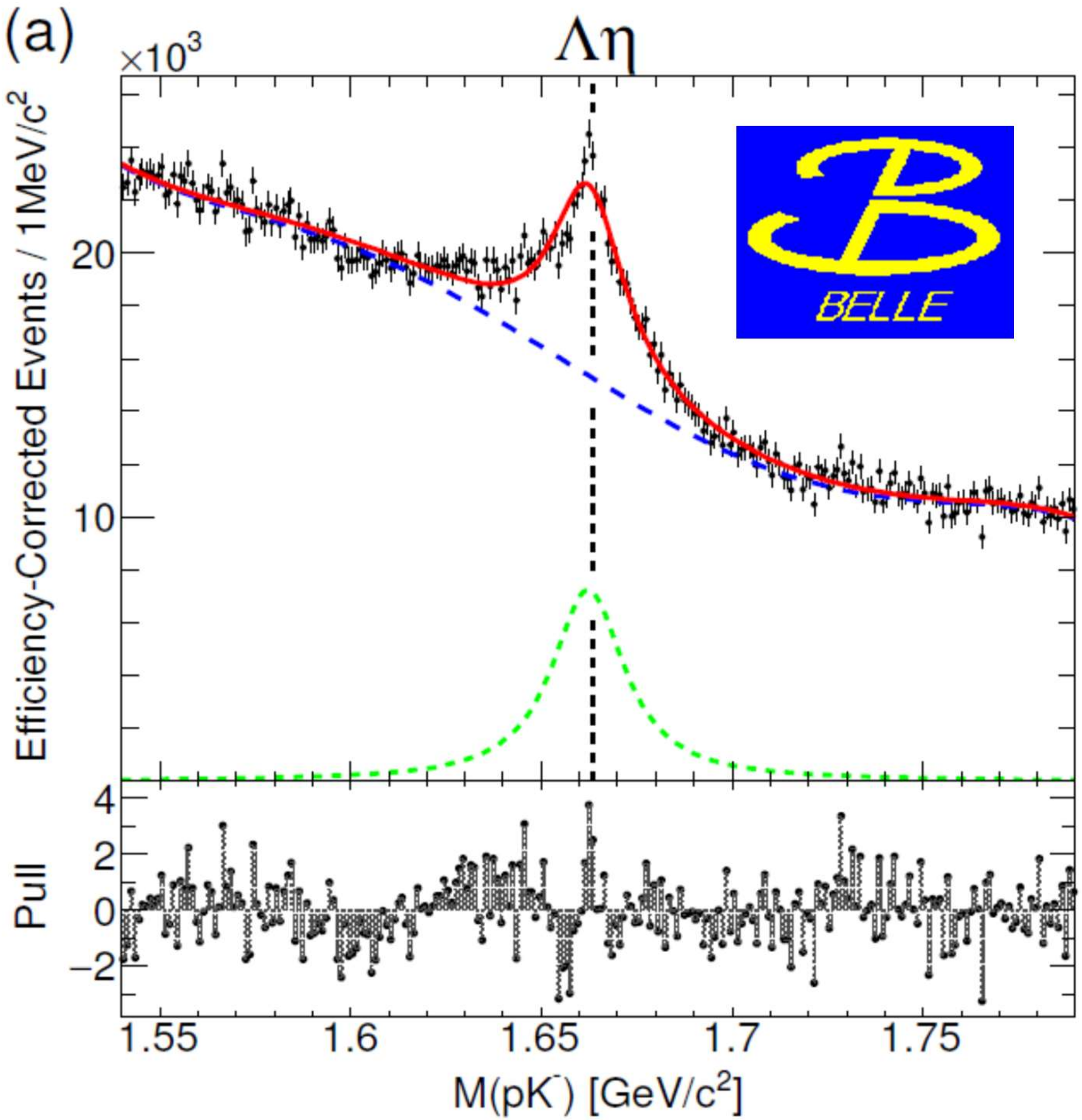
[arXiv:2209.00050, submitted to PRL]

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

[PRL117(2016)011801]



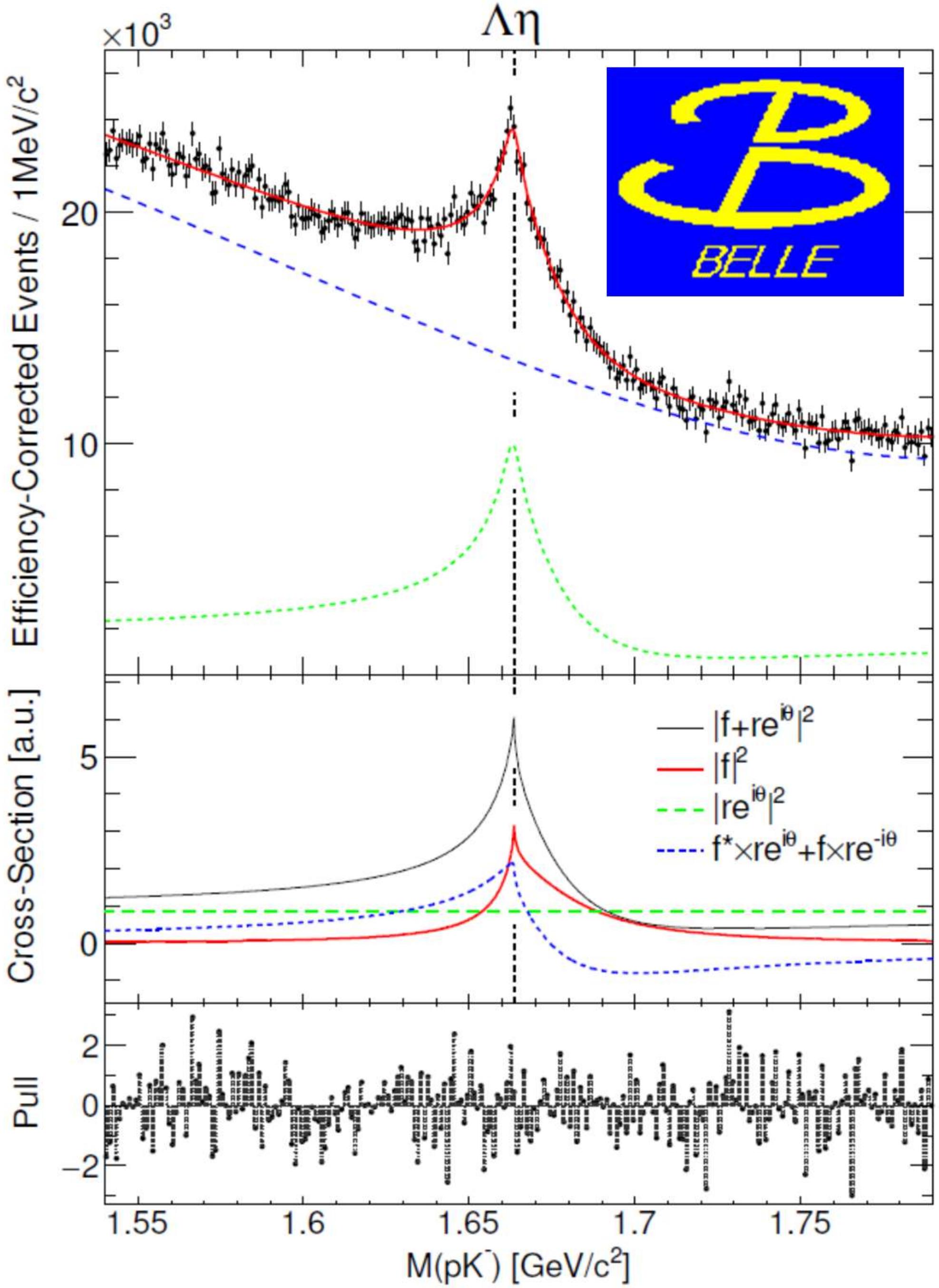
Fit to Breit-Wigner



- Not very good especially near the peak.
- Best χ^2/DOF: 308/243

[arXiv:2209.00050, submitted to PRL]

Fit to Flatte



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

f(m): non-relativistic Flatte

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

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

[arXiv:2209.00050, submitted to PRL]

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 $\Lambda_c \to \Lambda\eta\pi^+$
  [Belle, PRD103 (2021) 052005]

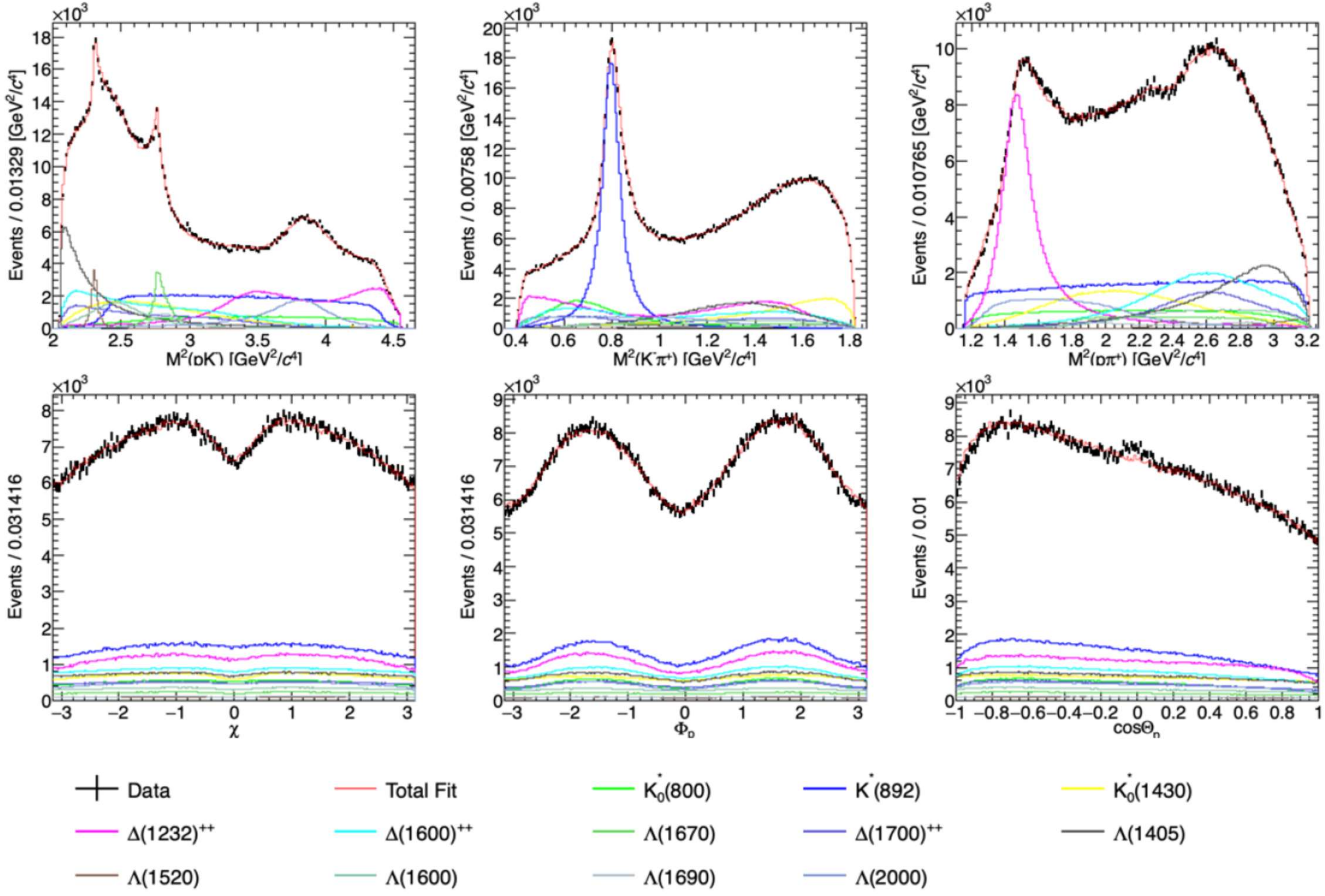
	Present result	**$\Lambda\eta\pi^+$ mode**
Mass	1674.4	$1674.3 \pm 0.8 \pm 4.9$
Width	$50.3 \pm 2.9^{+4.2}_{-7.1}$	$36.1 \pm 2.4 \pm 4.8$

- $\Lambda(1670)$ might be a $\Lambda\eta$ virtual state?

Interference?

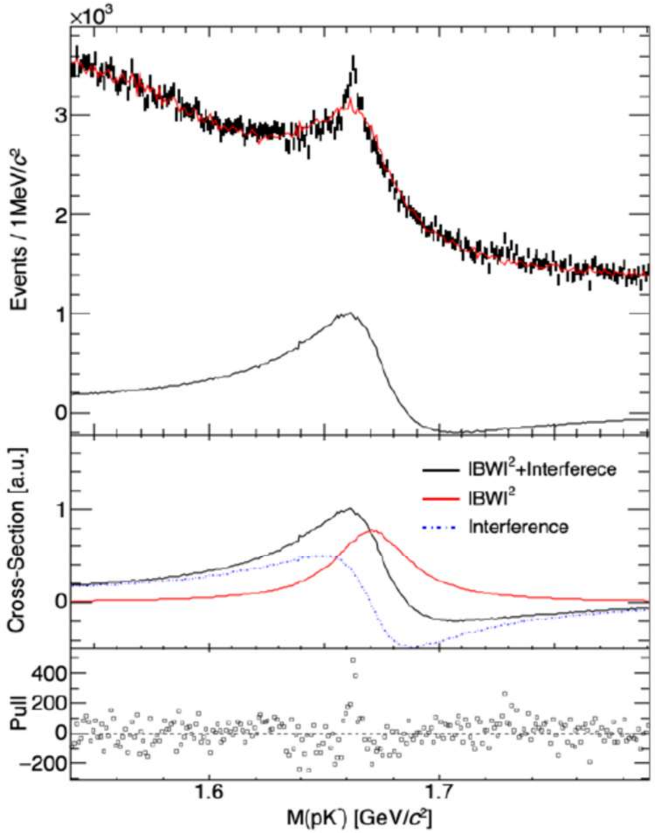
- Higher partial waves (P,D,…) would not affect the cusp shape because
  - Discontinuity in the higher partial waves appear only in the second or higher derivatives
  - The interference with different L vanishes with an integral over the solid angle
  - S-wave interference is approximately considered with a constant.
- This is confirmed by an amplitude analysis based on the LHCb result [arXiv:2208.03262]
  - Consistent results are obtained between the amplitude analysis & one-dimensional fit.

Amplitude analysis with Flatte

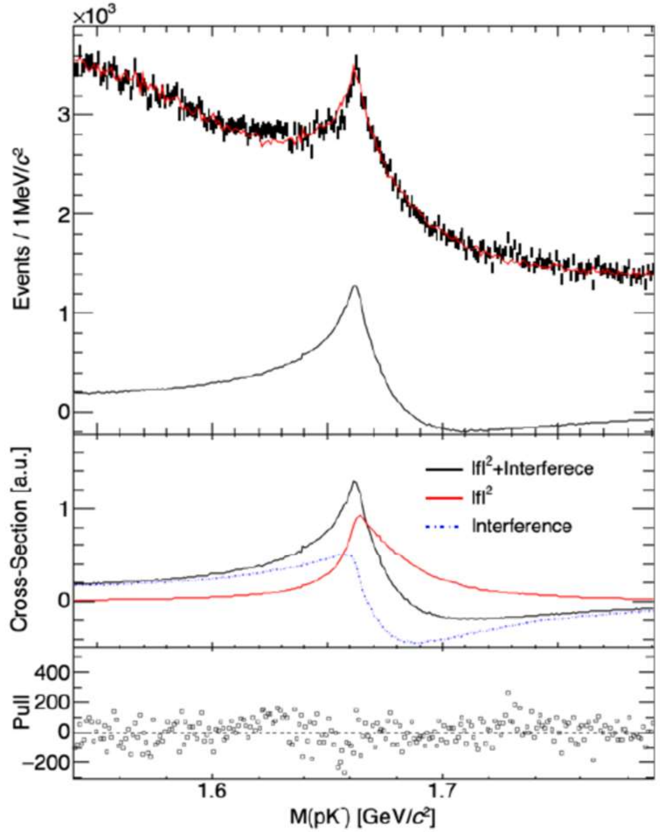


- Fit results projection to $M(pK^-)$ distribution

(a) BW model



(b) Flatté model



$m_0 = 1671.1 \pm 0.2\,\mathrm{MeV}/c^2$
$\Gamma_0 = 39.2 \pm 0.6$ MeV
$\chi^2 = 17{,}885$
(16,384 bins and 61 free parameters)

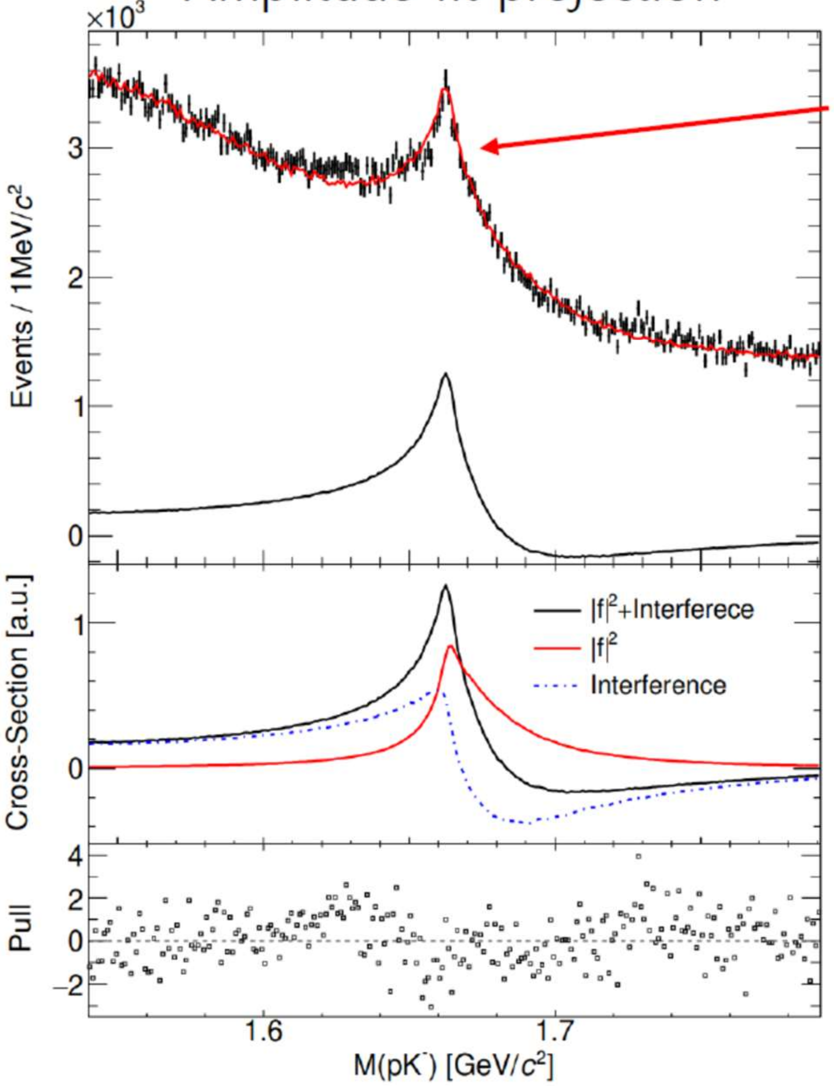
$\bar{g}_{pK} = 0.0437 \pm 0.0009$ corresponds to
$\Gamma' = 33.3 \pm 0.4$ MeV
$\bar{g}_{\Lambda\eta} = 0.218 \pm 0.003$
$\Gamma_{\text{total}} = 52.8 \pm 0.6$ MeV
$\chi^2 = 17{,}827$
(16,384 bins and 60 free parameters)

- Validation for one-dimensional fit
- Amplitude fit with all parameters of Flatté fixed,

$m_f = 1674.4\ \mathrm{MeV}/c^2$, $\Gamma_{\mathrm{others}} = 15\ \mathrm{MeV}$, $\bar{g}_{pK} = 0.028$, and $\bar{g}_{\Lambda\eta} = 0.253$

→ $\Gamma' = 27.2\ \mathrm{MeV}$, $\bar{g}_{\Lambda\eta} = 0.253$, and $\Gamma_{\mathrm{total}} = 50.3\ \mathrm{MeV}$

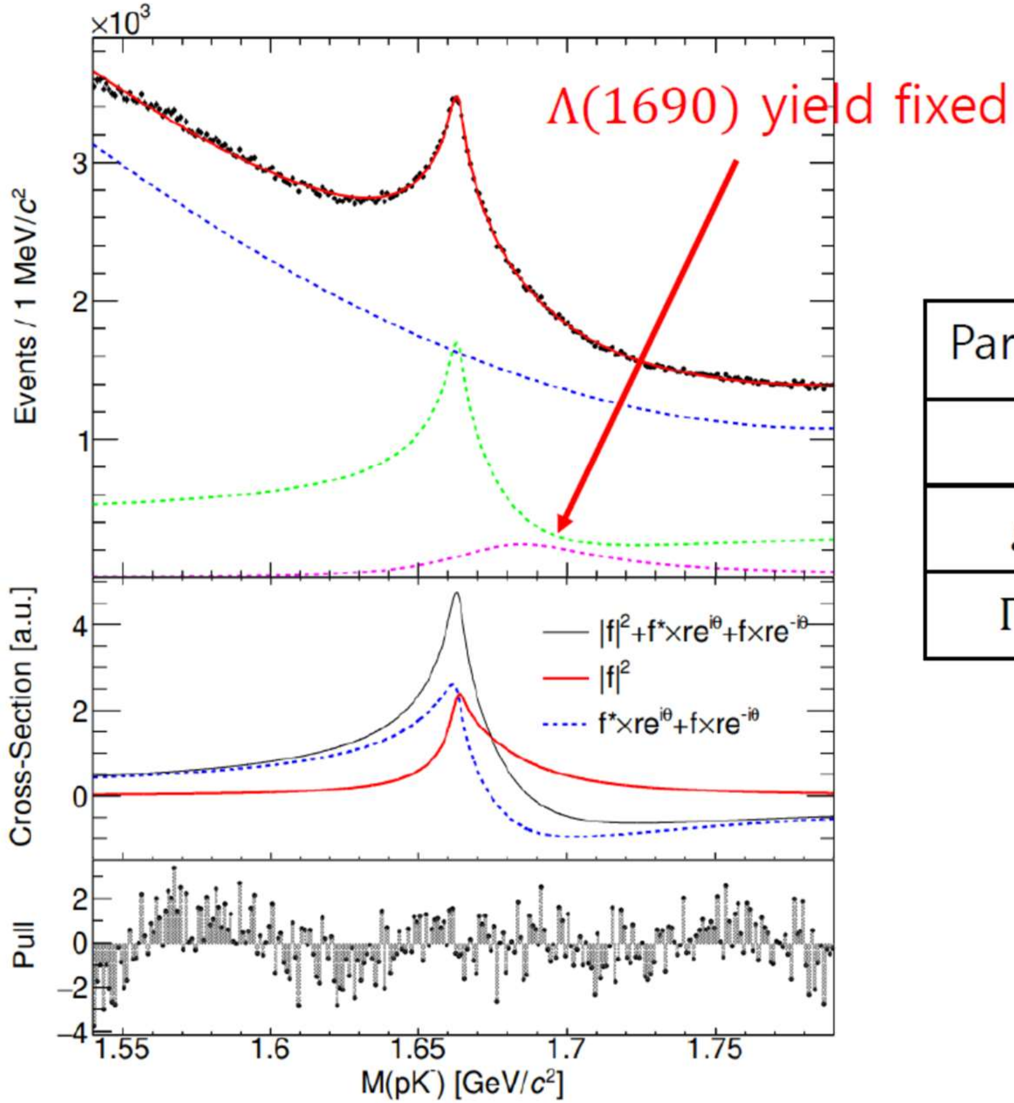
Amplitude fit projection



This line will be used for the validation test.

- Validation for one-dimensional fit

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



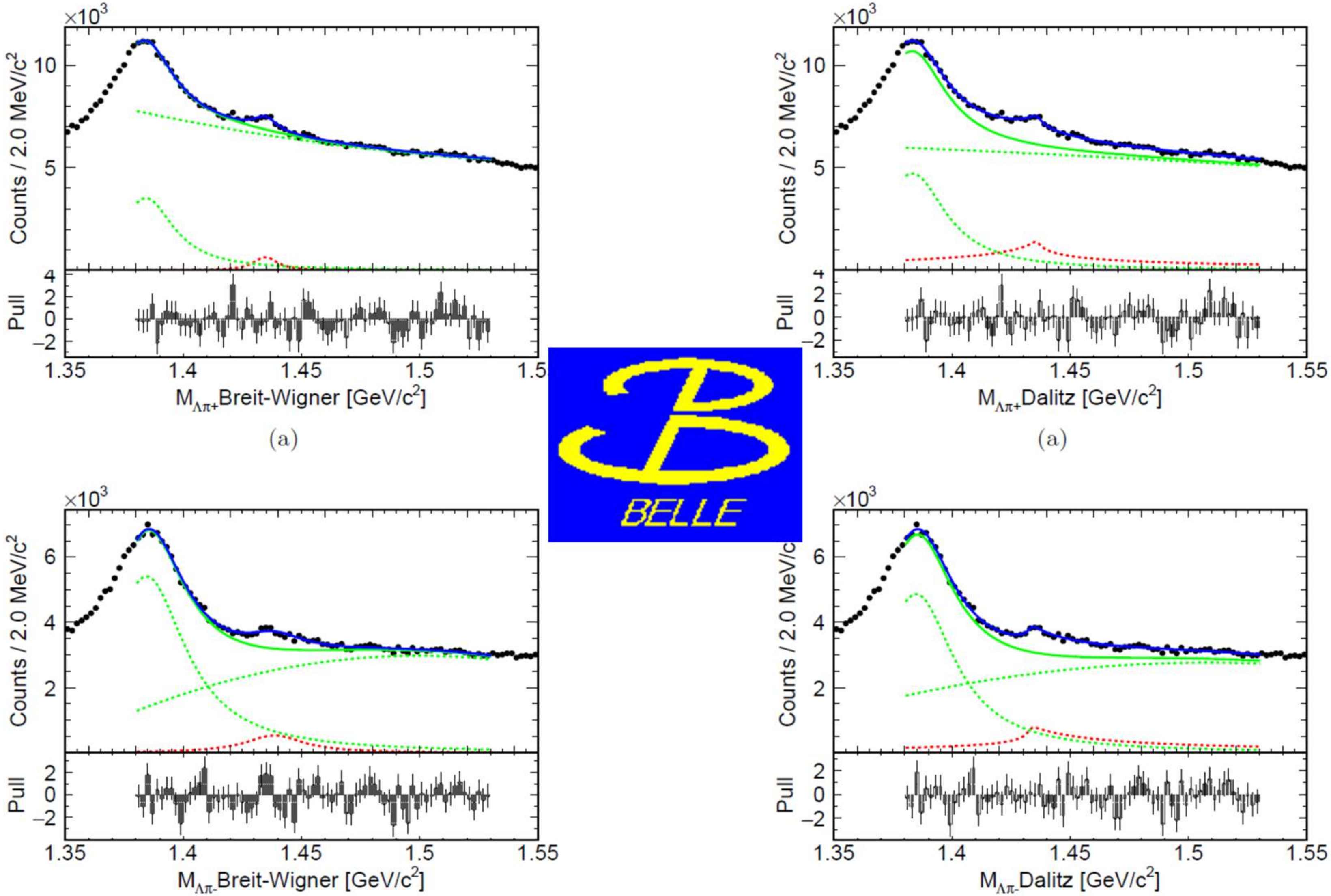
Parameter	Fit Results	Difference from the infiltrated value / Systematical Uncertainty
Γ'	27.8 ± 0.5 MeV	0.1σ
$\bar{g}_{\Lambda\eta}$	0.291 ± 0.007	0.6σ
Γ_{total}	53.9 ± 0.8 MeV	0.9σ

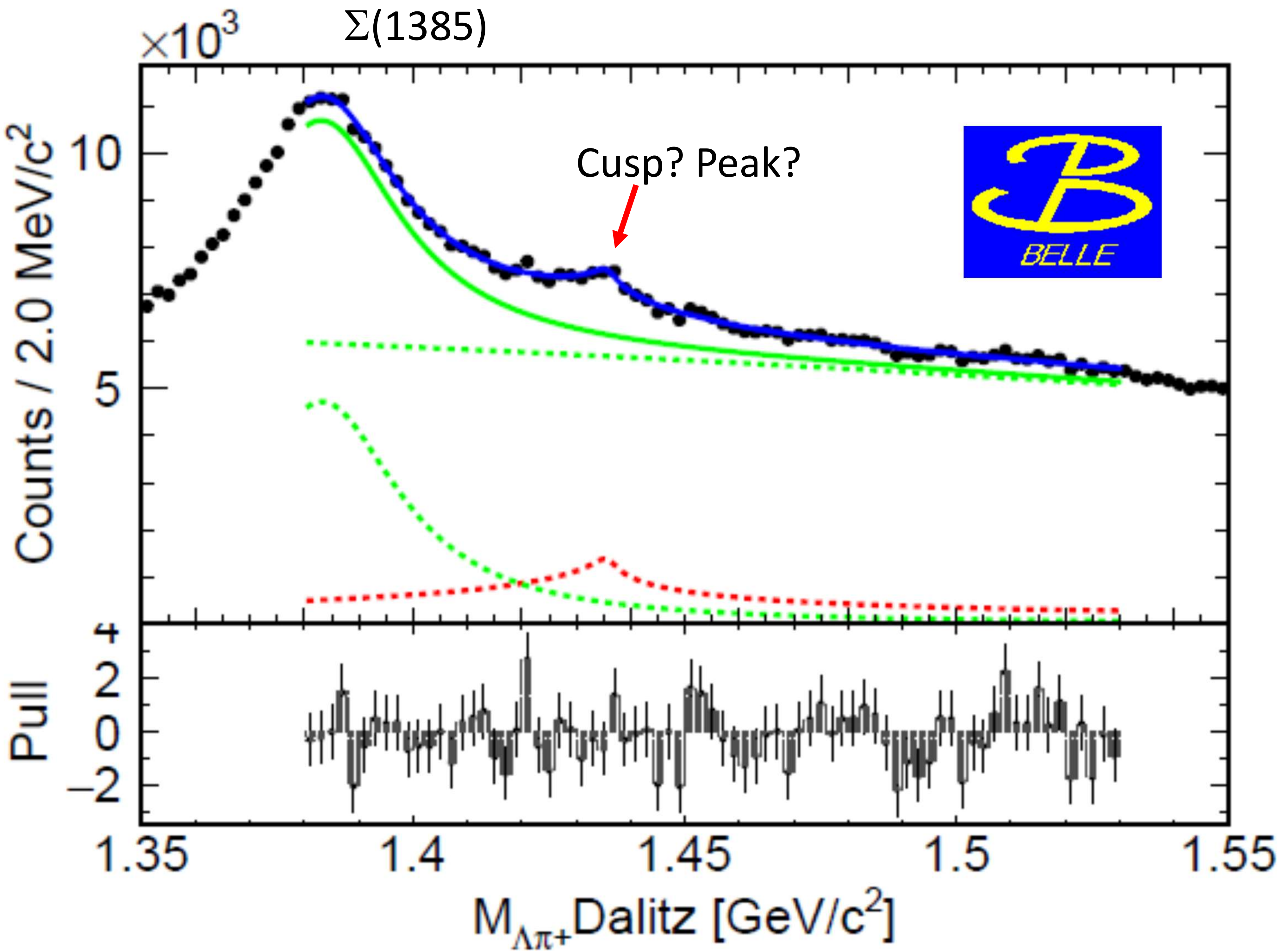
2. Peak at $\bar{K}N$ threshold in $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$

[PRL130(2023)151903]

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





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

2 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, $\Sigma(1435)$.

Results & discussions

2. Dalitz (cusp)

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

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

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

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

- Many theories predict a cusp here.
  - Due to the attraction between $\bar{K}$ and N in the I=1 channel
- Obtained scattering lengths are larger than most theories, but with large uncertainties
  (Also, form factor is ignored.)

Summary & Prospect

- Studies on exotic hyperons at Belle with Λ_c decay
- Observation of threshold cusp in $\Lambda_c \to pK^-\pi^+$
  - First identification of a threshold cusp from the spectrum shape
  - $\Lambda(1670)$ as a virtual state?
- Peak/cusp at $\bar{K}N$ threshold in $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$
  - Peak? Cusp?
  - Cannot be identified from the spectrum only due to poor S/N.
- More studies should be done with Belle II and other experiments.