Belle results on hyperon spectroscopy and future prospects at Belle II

Kiyoshi Tanida <kytanida@gmail.com>

(Japan Atomic Energy Agency)

Workshop on Hadron Spectroscopy
with Strangeness (@Glasgow U.)

3 April 2024

THE BELLE in Glasgow

Flavored Baryons in e^+e^- Collider

- Electron-positron colliders (CLEO, Belle, BaBar, BESIII…) are known to be useful for mesons, especially, quarkonia.

- Today, I will demonstrate they are also good for hyperons by showing some of the recent results by Belle.

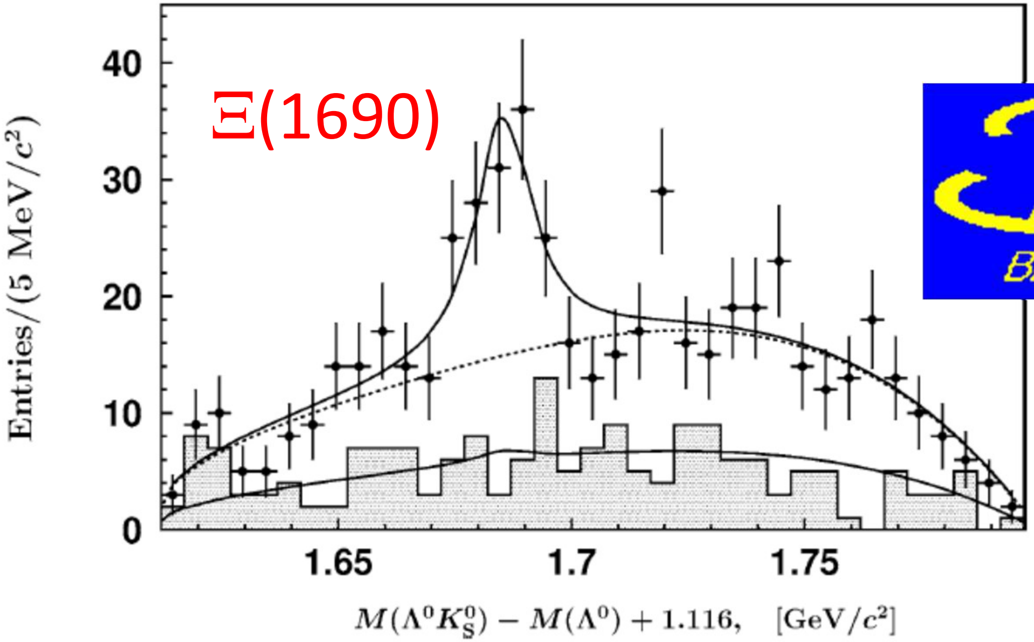
Why e^+e^- colliders?

- Small background
  - $e^+e^- \rightarrow Q\bar{Q}$ production is flavor blind.
    Only (charge)^2 matters → Good for heavy quarks.
- Missing mass spectroscopy is possible
  - Absolute branching fraction
  - Study of decays with missing particles (n, ν, …)
- Fragmentation+decays from bottom and charm
  - Abundant production of charmed baryons and hyperons.
  - Multi-strange baryons (Ξ & Ω) are also accessible.

Hyperons from charmed baryon decays

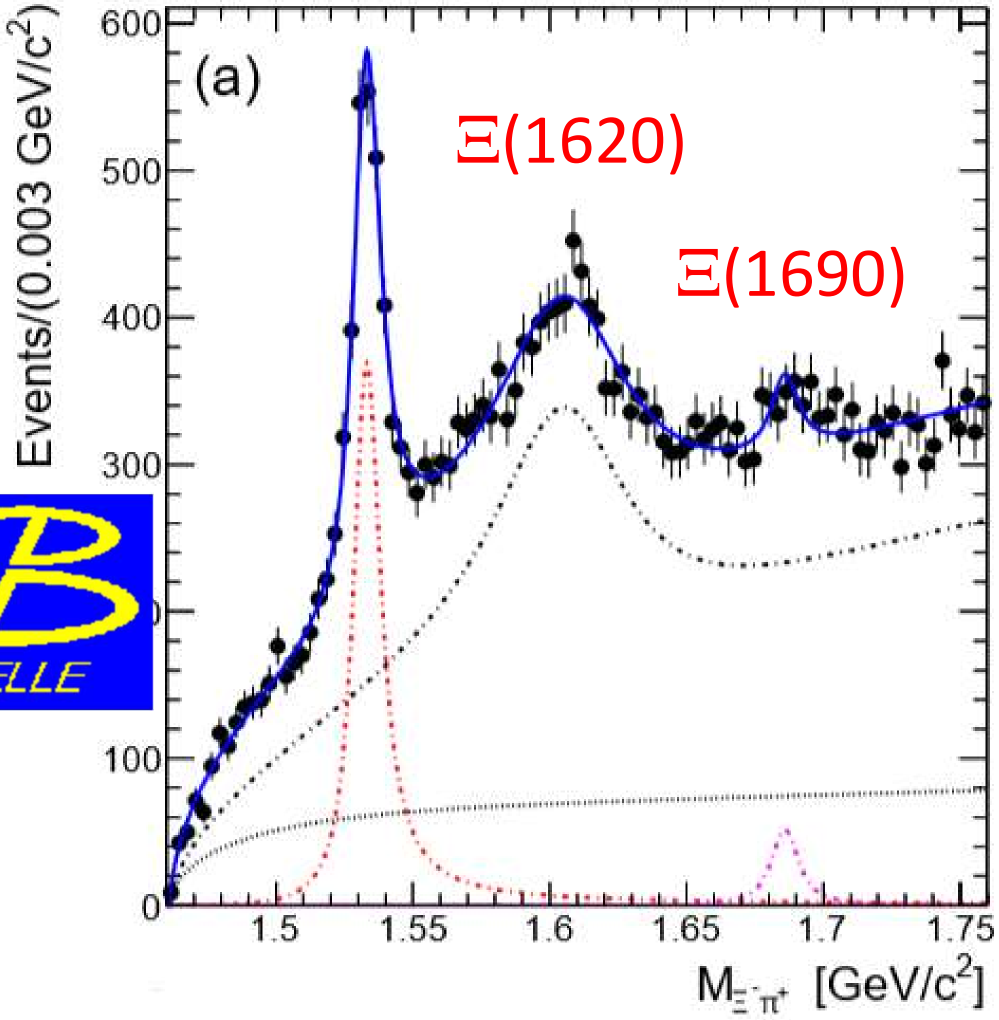
- New source for hyperon spectroscopy
  - New states?
  - Branching ratios

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



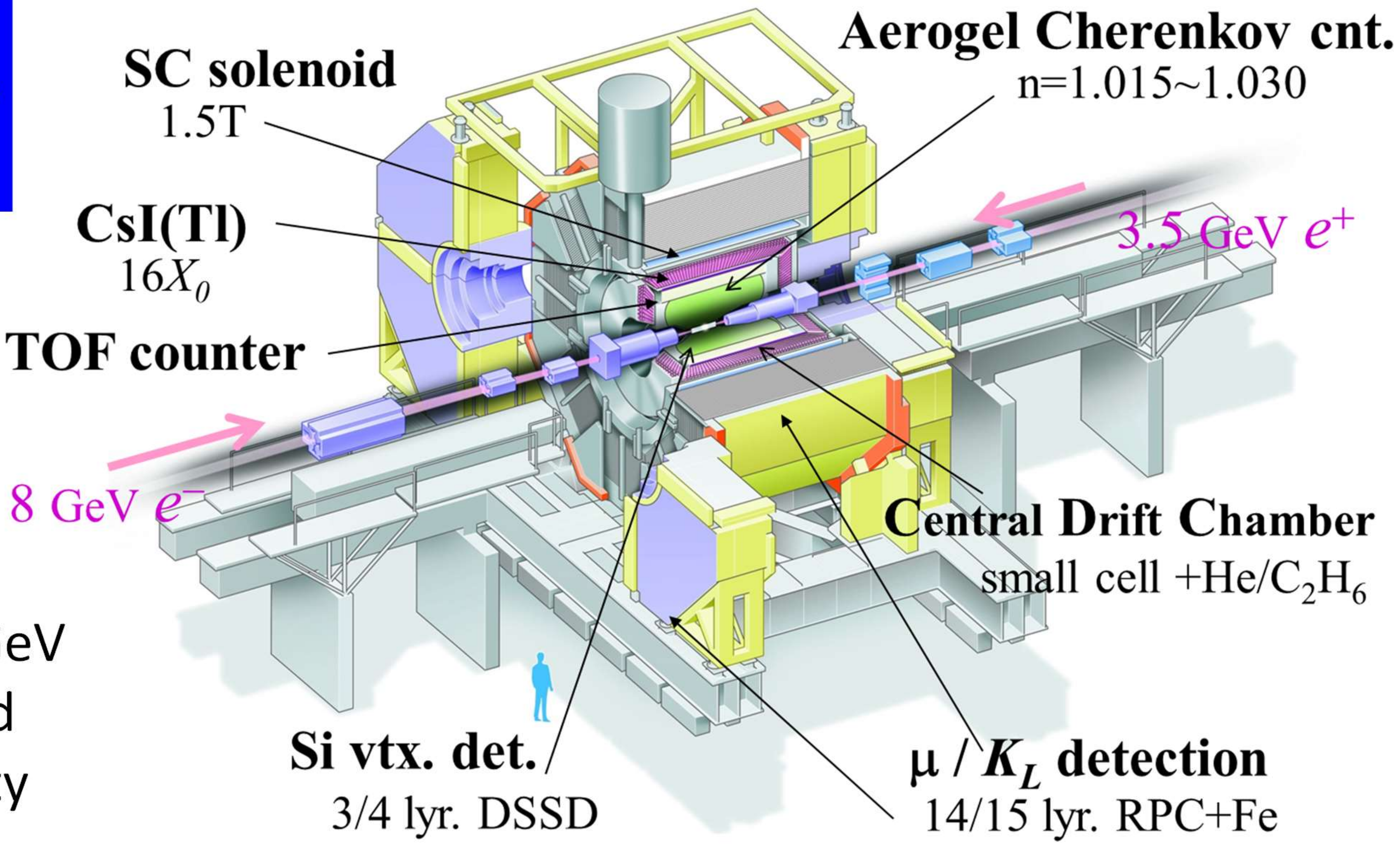
[Belle, PLB **524** (2002) 33-43]

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



[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

Topics of the day

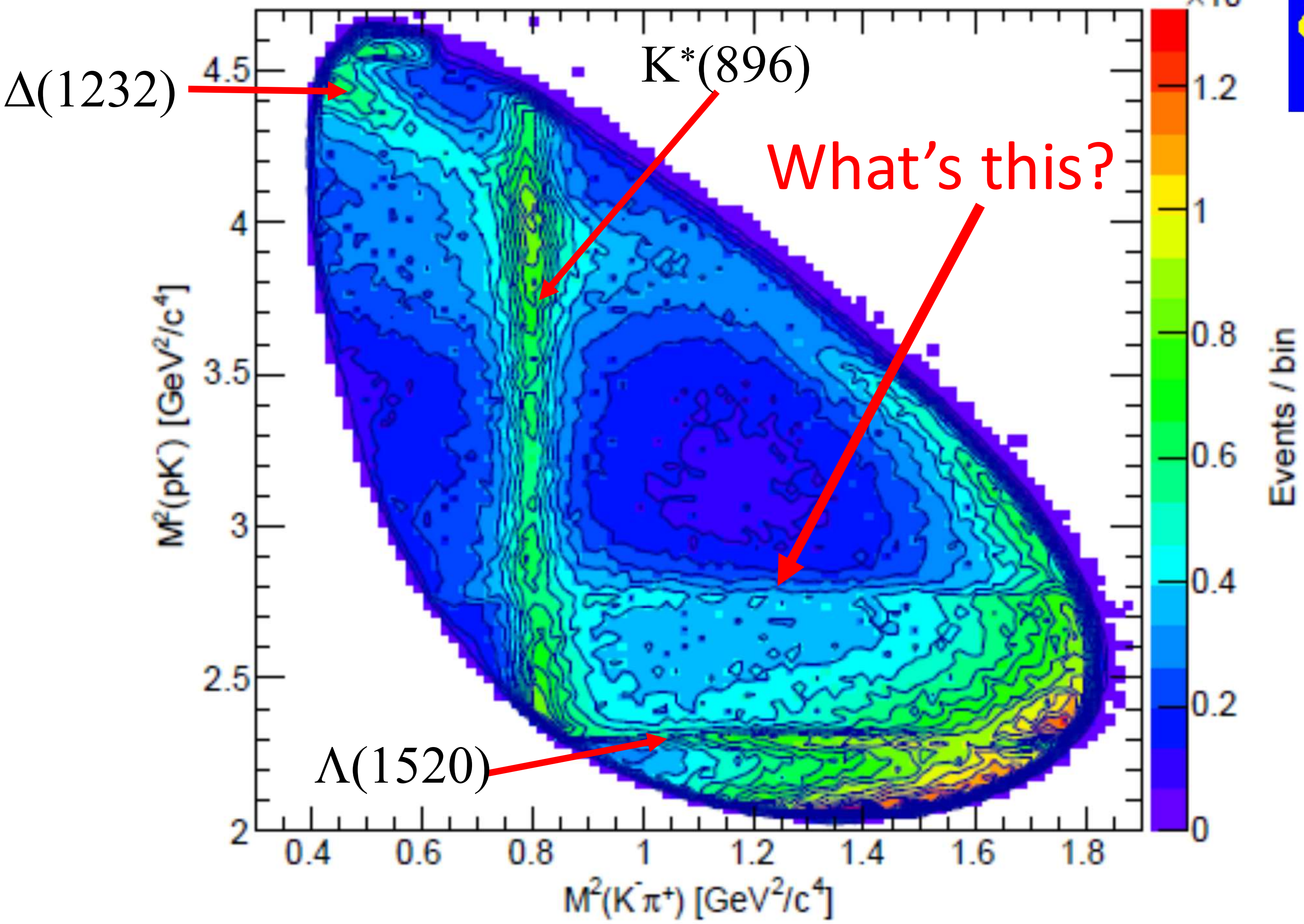
1. $\Lambda_c \to \Lambda\eta\pi^+$ and $\Lambda(1670)$[PRD103 (2021) 052005]
2. Identification of Threshold cusp in $\Lambda_c \to pK^-\pi^+$ [PRD108.L031104(2023)]
3. Peak at $\bar{K}N$ threshold in $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$ [PRL130(2023)151903]
4. $\Omega_c \to \Omega(2012)\pi^+$ [Belle, PRD104 (2021) 052005]
5. $\Omega(2012) \to \Xi(1530)\bar{K}$ [arXiv:2207.03090]
6. Belle II Prospects
7. Summary

1. $\Lambda_c \to \Lambda\eta\pi^+$ and $\Lambda(1670)$

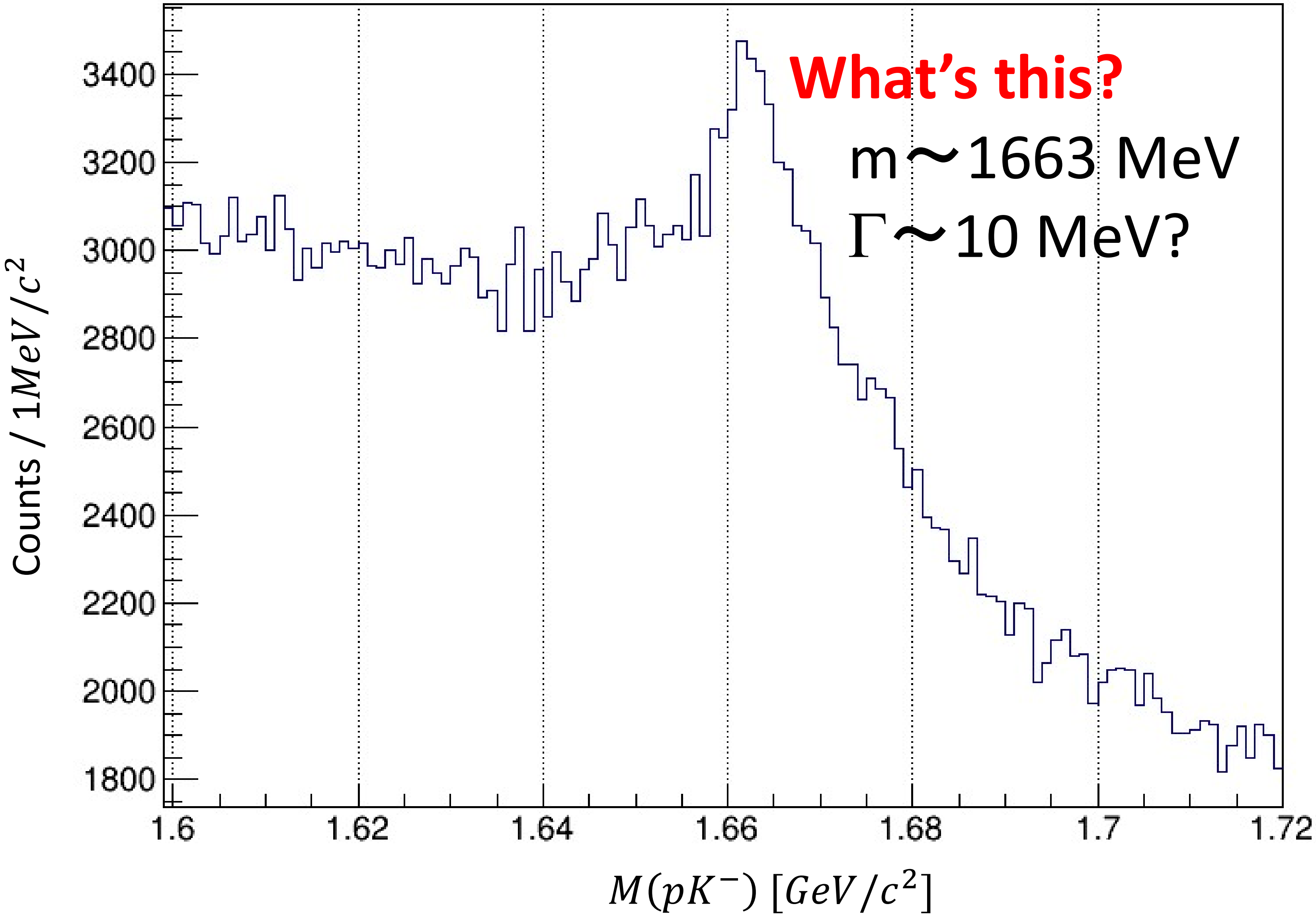
[PRD103 (2021) 052005]

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

[PRL117(2016)011801]



■ 1D projection -- $M(pK^-)$



What's this?

m ~ 1663 MeV

Γ ~ 10 MeV?

What’s this?

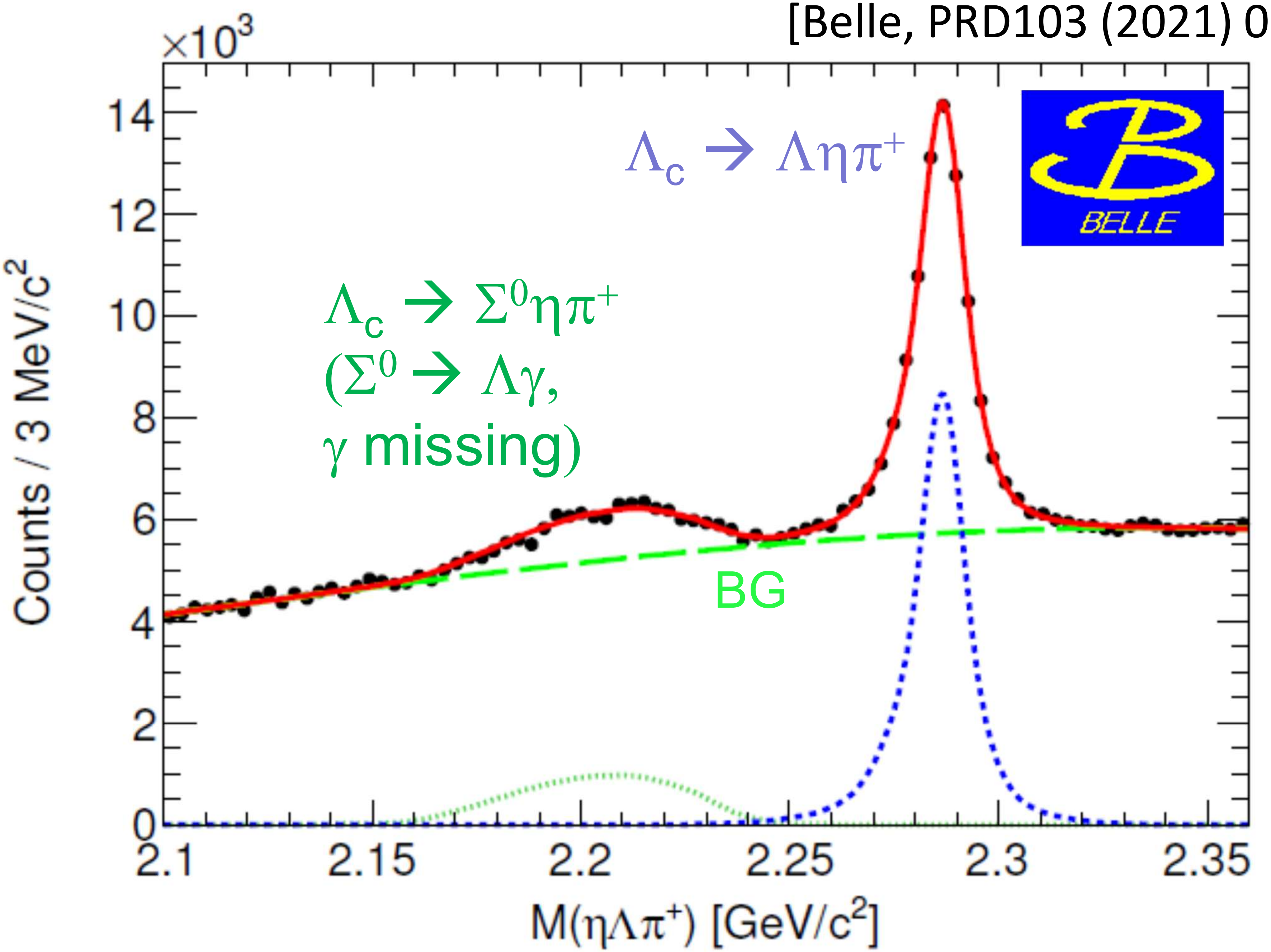
- The peak position is ~1663 MeV, near the Λη threshold (1663.5 MeV)
- Width is ~10 MeV, significantly narrower than Λ, Σ resonances in this region
  - Λ(1670): 25-50 MeV
  - Σ(1660): 40-200 MeV
  - Σ(1670): 40-80 MeV
  - Λ(1690): ~60 MeV
- No such narrow states are theoretically predicted in this region – new exotic resonance?

A new Λ resonance around 1670 MeV?

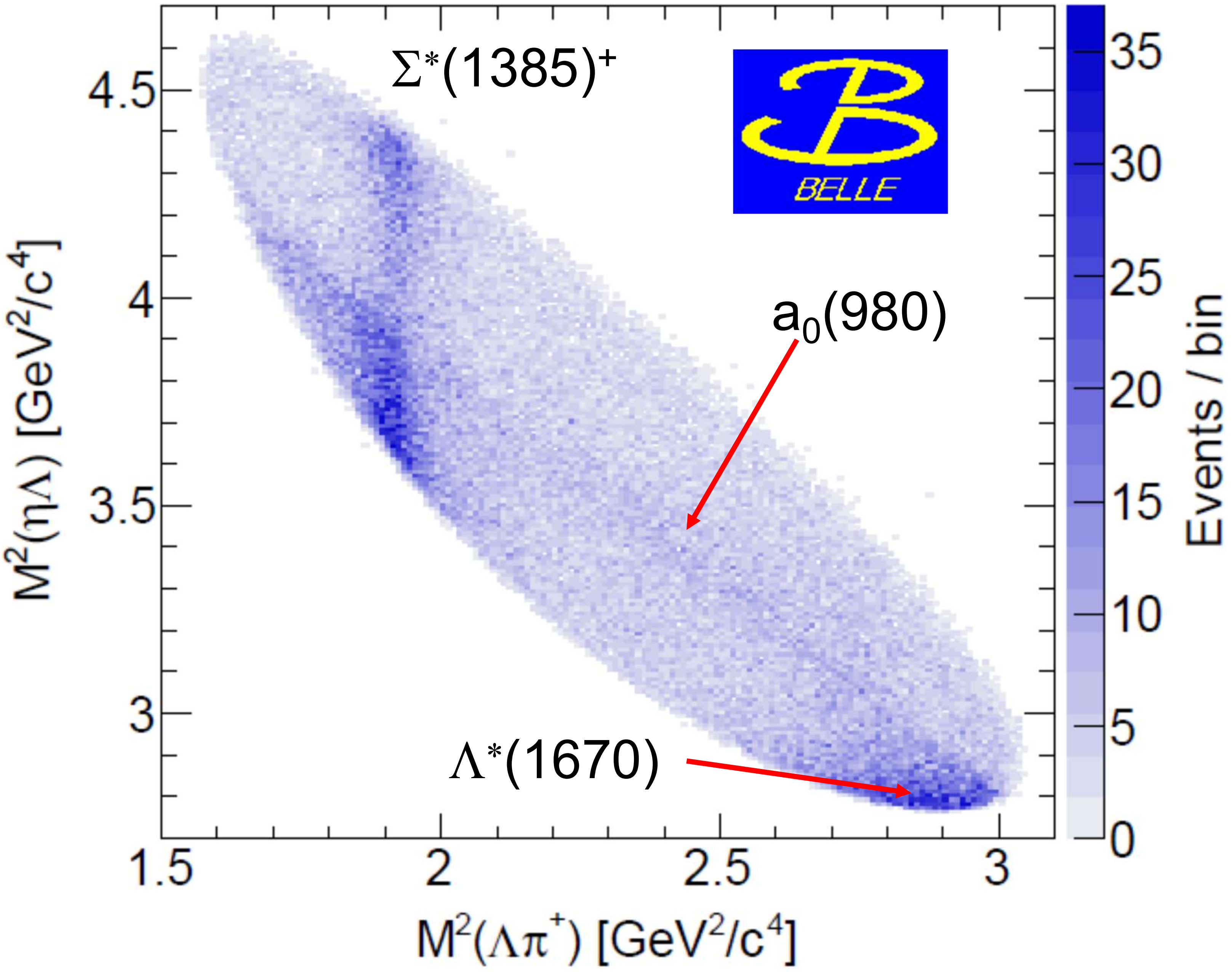
- 2 independent theory groups claim there is a new narrow Λ^* resonance around 1670 MeV with J=3/2
  - Kamano et al. [PRC90.065204, PRC92.025205]
    $J^P=3/2^+$ (P_{03}), M=1671+2-8 MeV, Γ=10+22-4 MeV
  - Liu & Xie [PRC85.038201, PRC86.055202]
    $J^P=3/2^-$ (D_{03}), M=1668.5±0.5 MeV, Γ=1.5±0.5 MeV
- 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
  - Might be also seen in the $\Lambda\eta\pi$ final state?

$\Lambda\eta\pi^+$ Invariant mass

[Belle, PRD103 (2021) 052005]



Dalitz plot

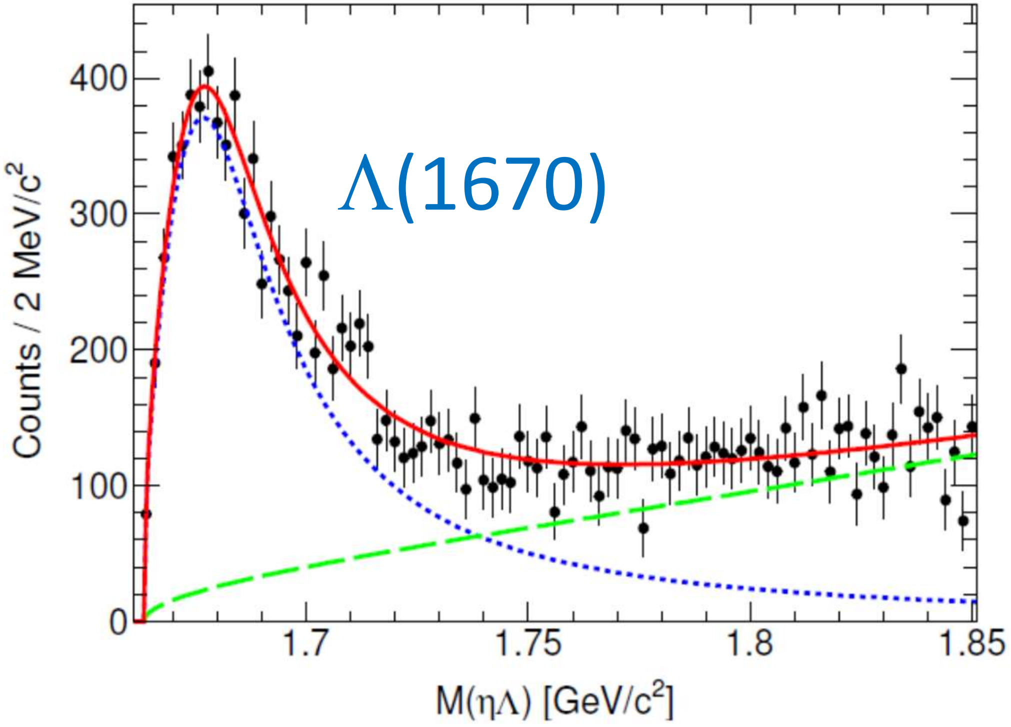


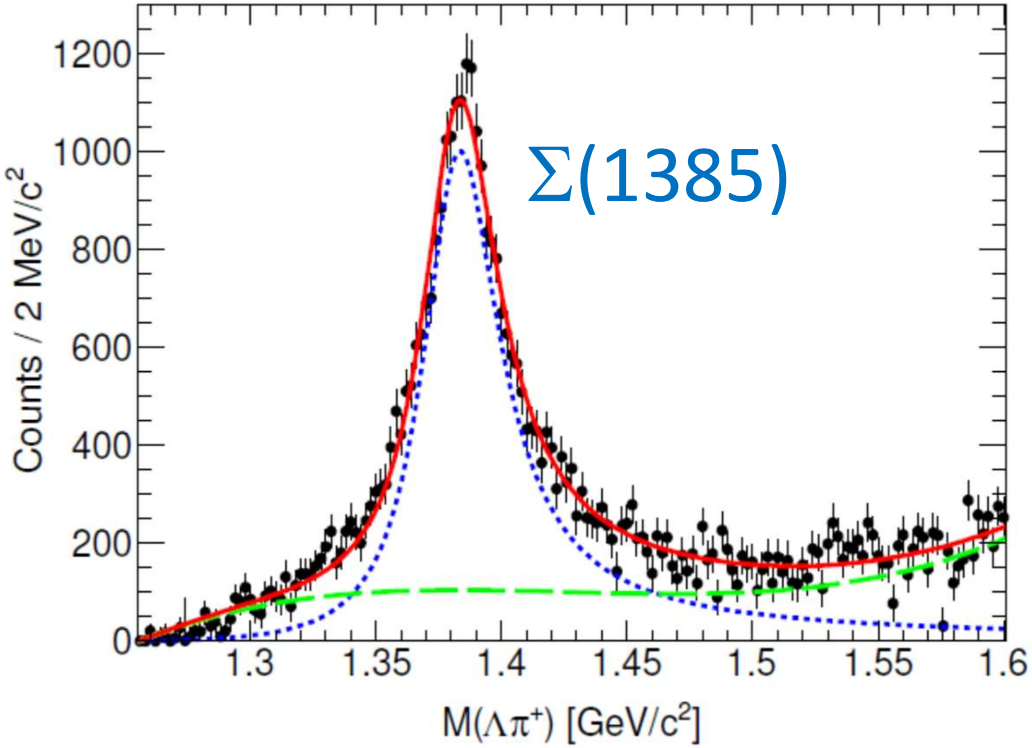
- Includes non-Λ_c BG
- Resonances are clearly seen

Resonances: $\Sigma(1385)$ & $\Lambda(1670)$

- For each $M(\Lambda\eta)/M(\Lambda\pi^+)$ bin, count Λ_c in the $\Lambda\eta\pi^+$ mass spectrum
  - Non-Λ_c background is excluded

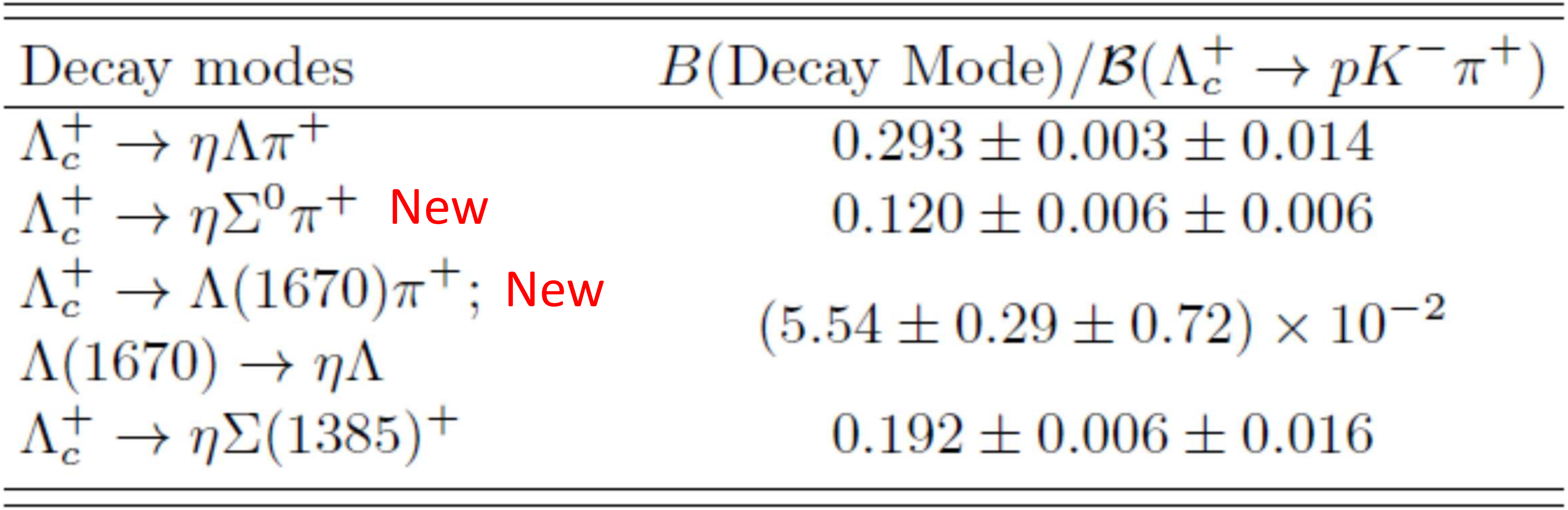
[Belle, PRD103 (2021) 052005]





No hint for a new resonance

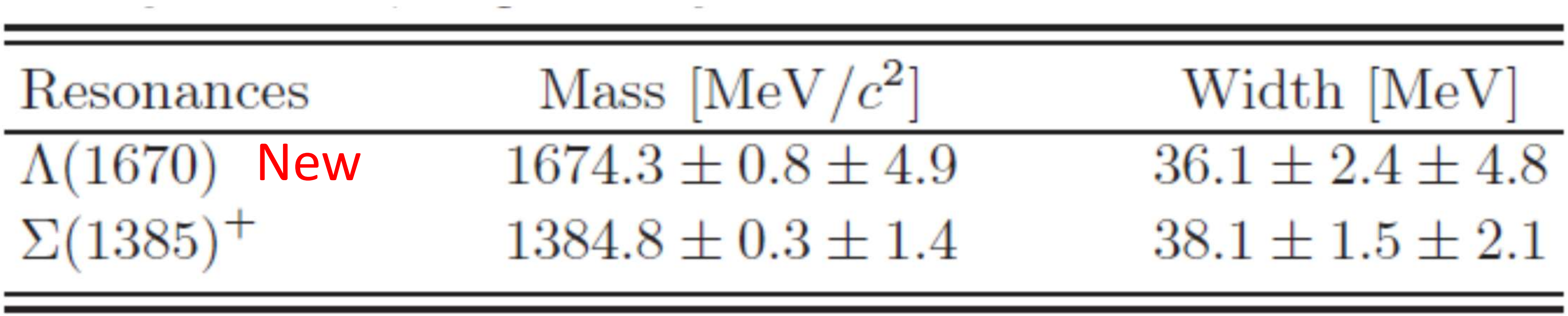
Results (1) – Branching ratios



Decay modes	$B(\text{Decay Mode})/\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)$
$\Lambda_c^+ \to \eta\Lambda\pi^+$	$0.293 \pm 0.003 \pm 0.014$
$\Lambda_c^+ \to \eta\Sigma^0\pi^+$ New	$0.120 \pm 0.006 \pm 0.006$
$\Lambda_c^+ \to \Lambda(1670)\pi^+$; New $\Lambda(1670) \to \eta\Lambda$	$(5.54 \pm 0.29 \pm 0.72) \times 10^{-2}$
$\Lambda_c^+ \to \eta\Sigma(1385)^+$	$0.192 \pm 0.006 \pm 0.016$

- $\Lambda(1670)\pi^+$, $\Sigma^0\eta\pi^+$ modes: first measurements
- $\Lambda\eta\pi^+$ and $\Sigma(1385)^+\eta$: consistent with PDG & more precise
  - $\Lambda\eta\pi^+$: (1.84±0.26)%/(6.28±0.32)%
  - $\Sigma(1385)^+\eta$: (0.91±0.20)%/(6.28±0.32)%

Results (2) – Mass & width



Resonances	Mass [MeV/c^2]	Width [MeV]
$\Lambda(1670)$ New	$1674.3 \pm 0.8 \pm 4.9$	$36.1 \pm 2.4 \pm 4.8$
$\Sigma(1385)^+$	$1384.8 \pm 0.3 \pm 1.4$	$38.1 \pm 1.5 \pm 2.1$

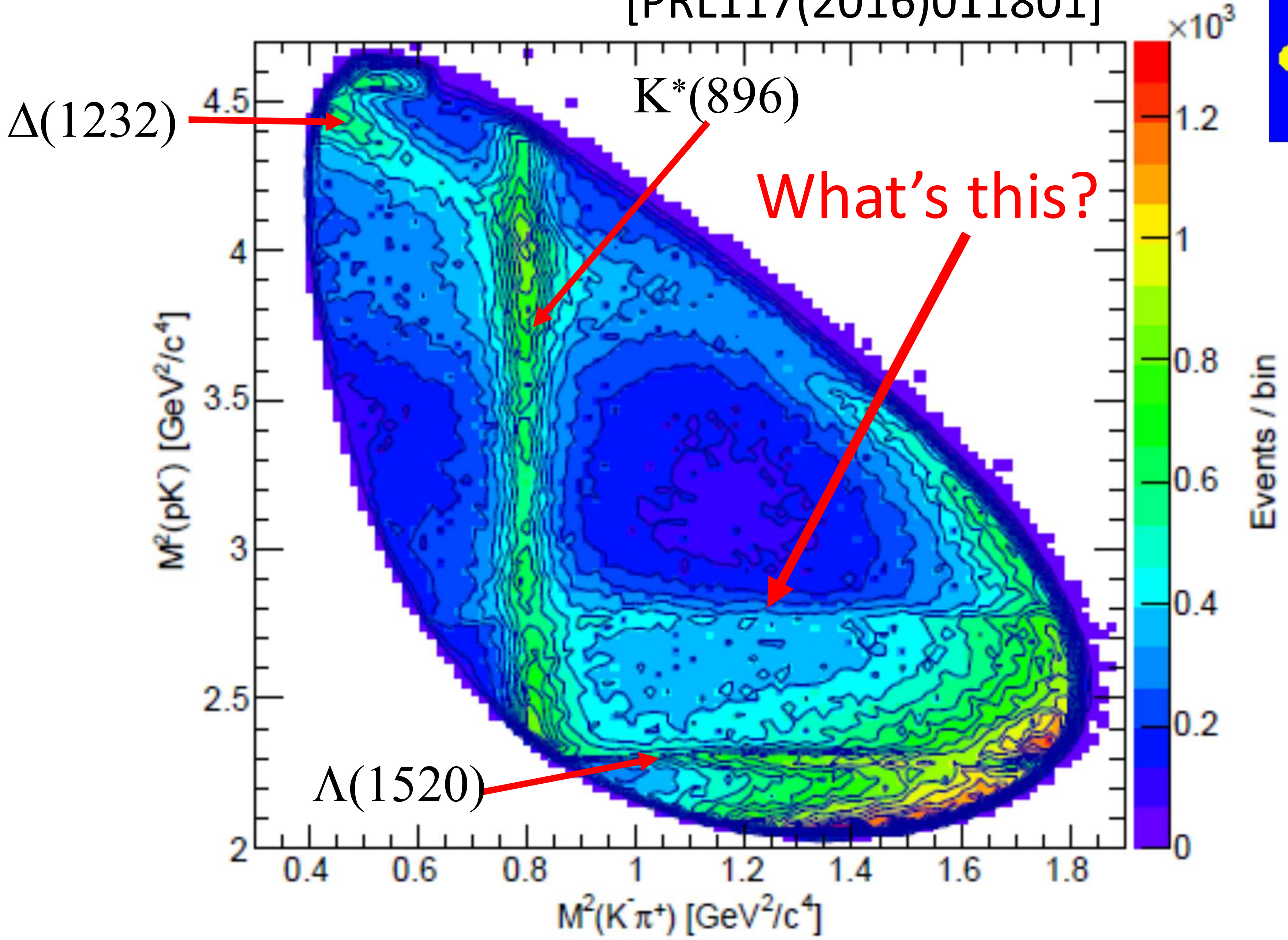
- $\Sigma(1385)^+$: consistent with PDG within uncertainty
- $\Lambda(1670)$: determined from peaking structure for the first time with a good accuracy.

2. Identification of Threshold cusp in $\Lambda_c \to pK^- \pi^+$

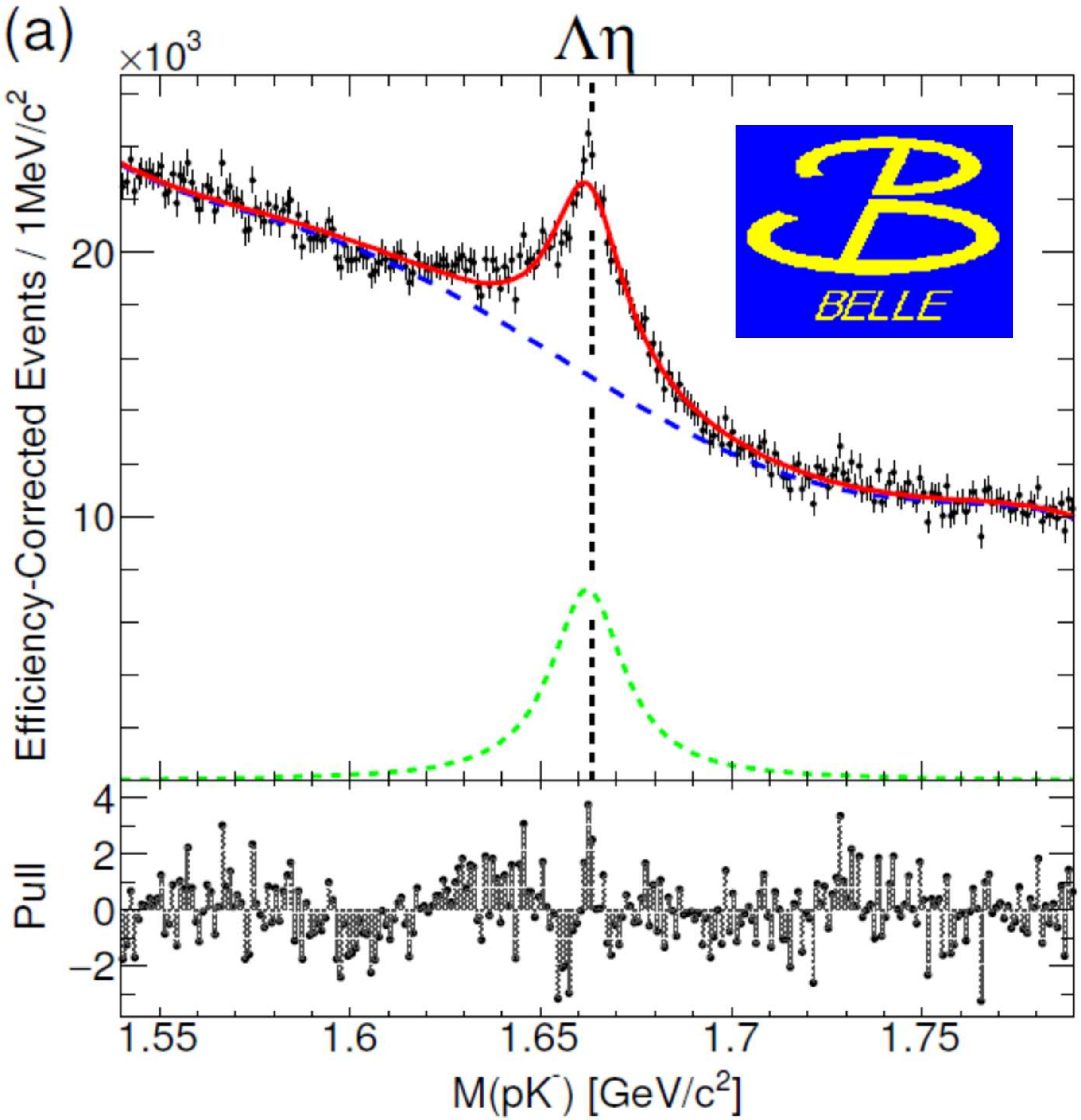
[PRD108.L031104(2023)]

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

[PRL117(2016)011801]



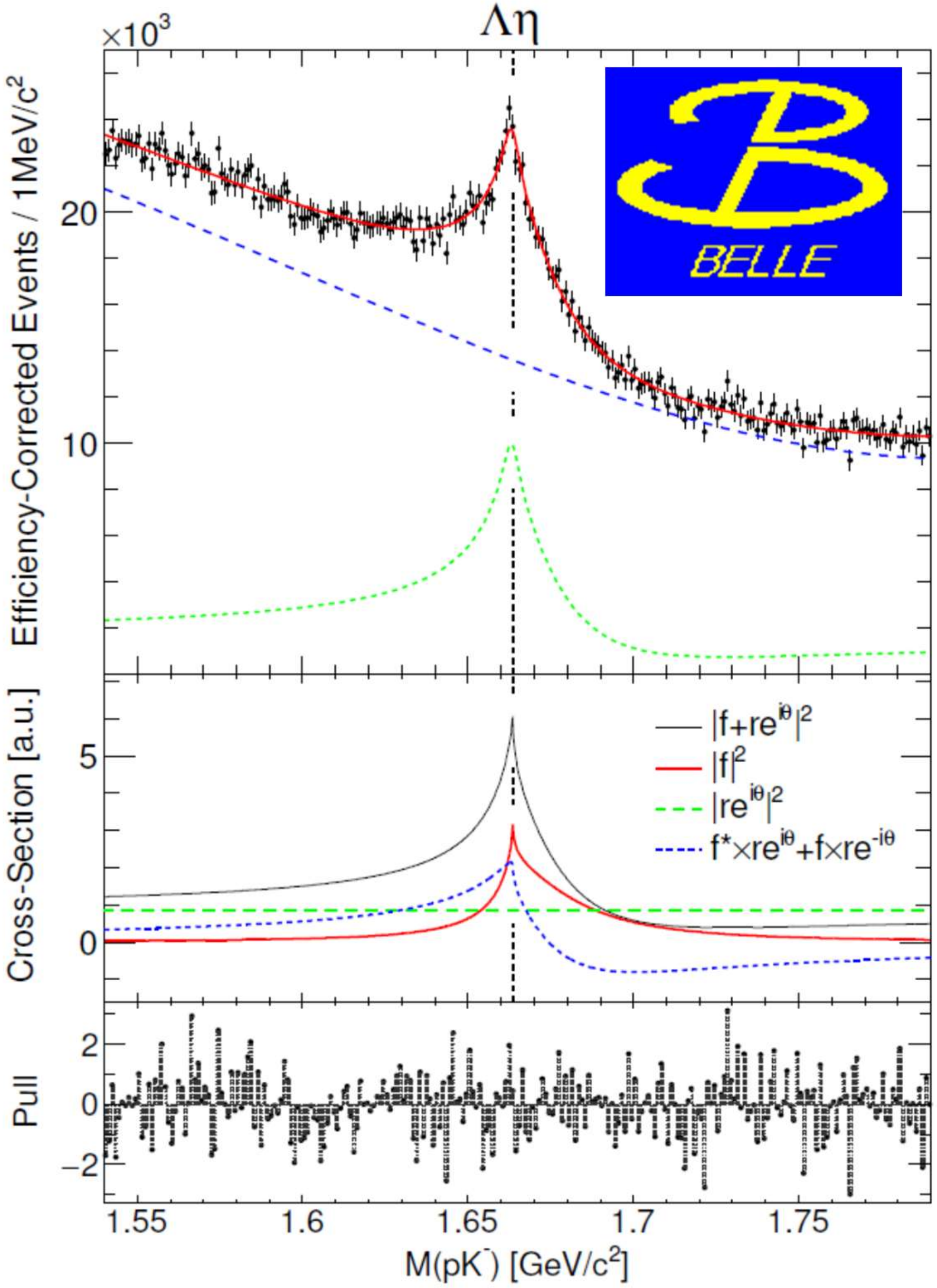
Fit to Breit-Wigner



- 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

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

- 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 Λ(1670)

  → First identification of a threshold cusp from the spectrum shape

- Obtained Λ(1670) parameters are consistent with those measured in $\Lambda_c \to \Lambda\eta\pi^+$

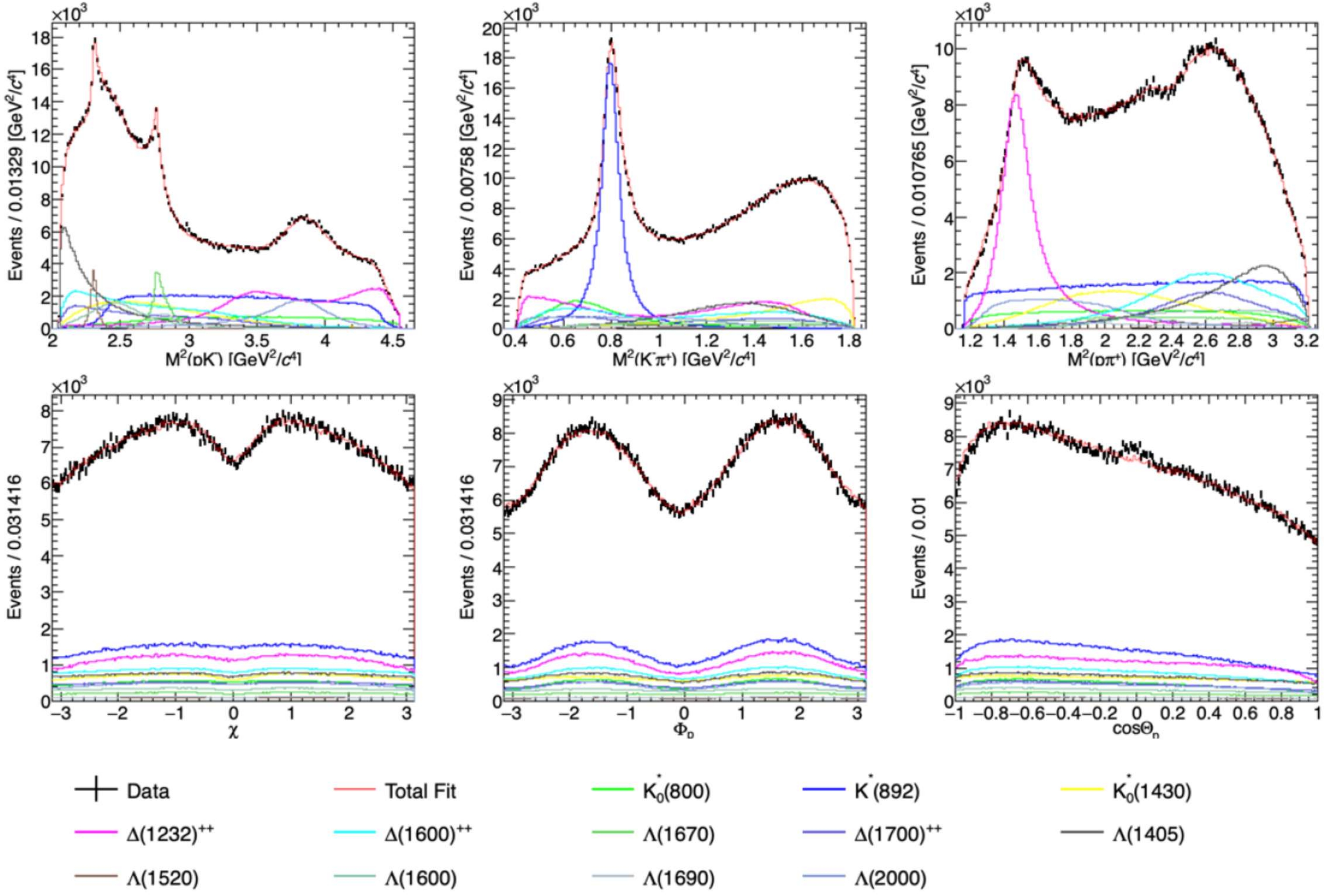
	Present result	**$\Lambda\eta\pi^+$ mode**
Mass (MeV/c²)	1674.4	$1674.3 \pm 0.8 \pm 4.9$
Width (MeV)	$50.3 \pm 2.9^{+4.2}_{-4.0}$	$36.1 \pm 2.4 \pm 4.8$

- How about other near-threshold exotic hadrons?
  - **They may be actually threshold cusps!** (e.g., X(3872))

Interference?

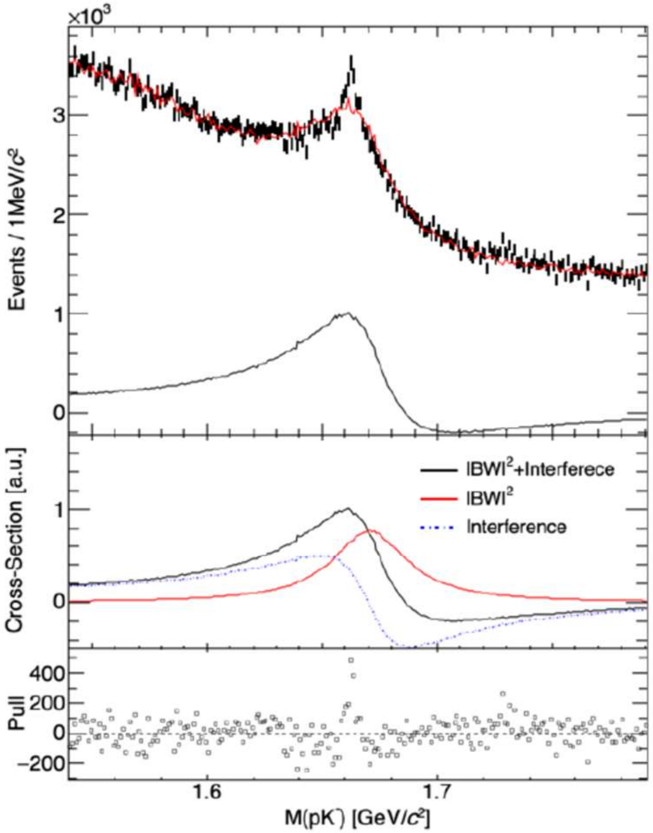
- Higher partial waves (P,D,…) would not affect the cusp shape because
  - Discontinuity in the higher partial waves appear only in the second or higher derivatives
  - The interference with different L vanishes with an integral over the solid angle
  - S-wave interference is approximately considered 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



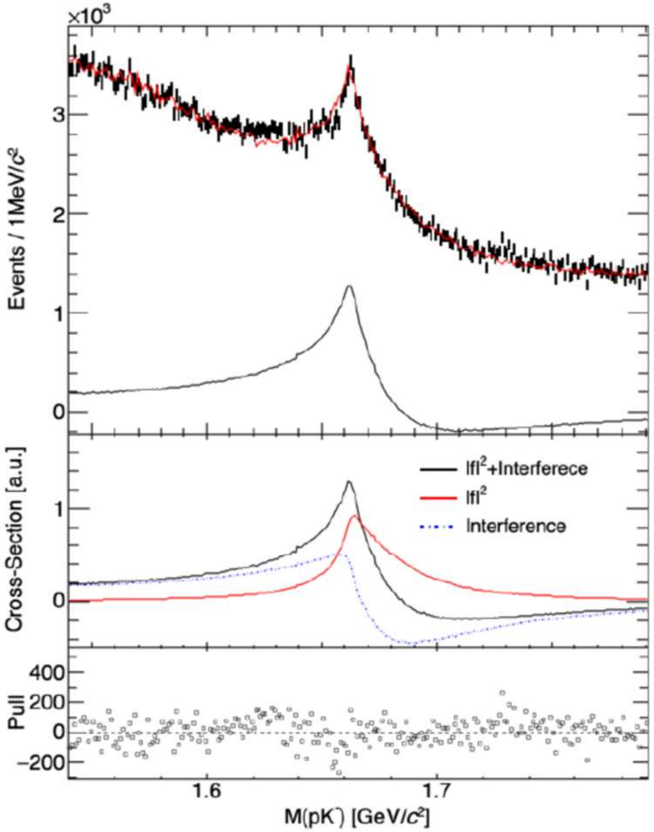
- Fit results projection to $M(pK^-)$ distribution

(a) BW model



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

(b) Flatté model



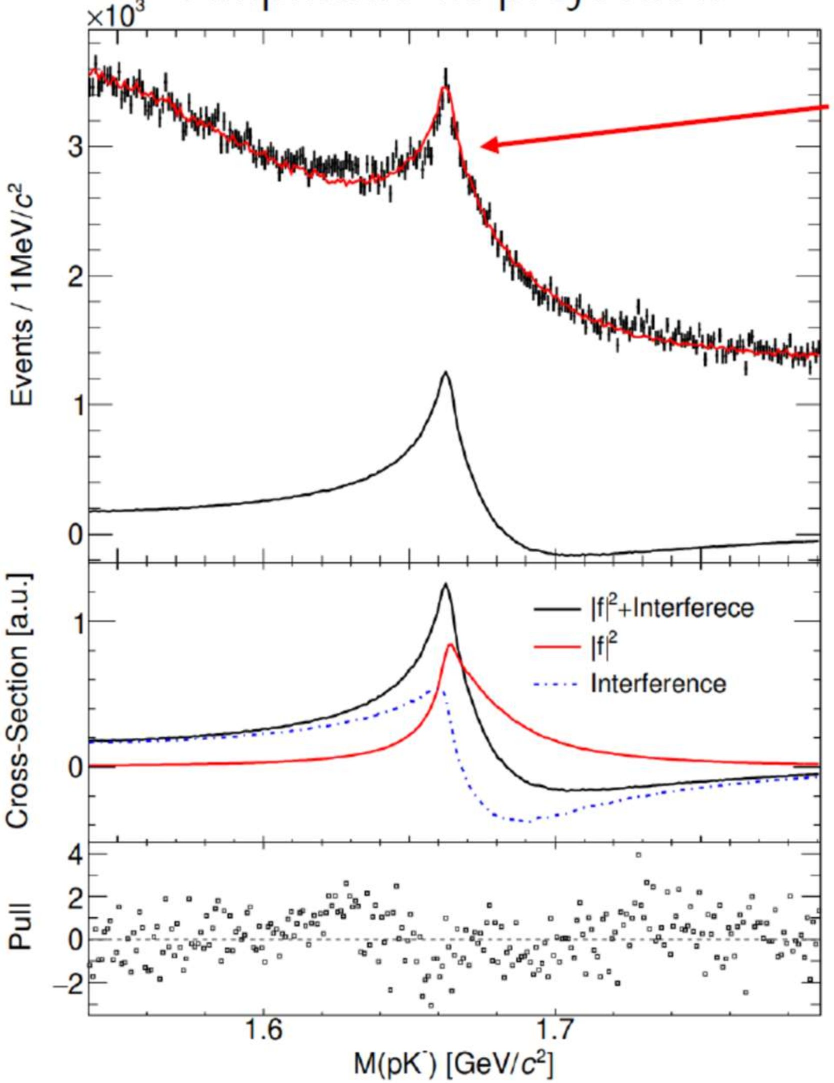
$\bar{g}_{pK} = 0.0437 \pm 0.0009$ corresponds to
$\Gamma' = 33.3 \pm 0.4$ MeV
$\bar{g}_{\Lambda\eta} = 0.218 \pm 0.003$
$\Gamma_{\mathrm{total}} = 52.8 \pm 0.6$ MeV
$\chi^2 = 17{,}827$
(16,384 bins and 60 free parameters)

- 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 $\Gamma_{\mathrm{total}} = 50.3\ \mathrm{MeV}$

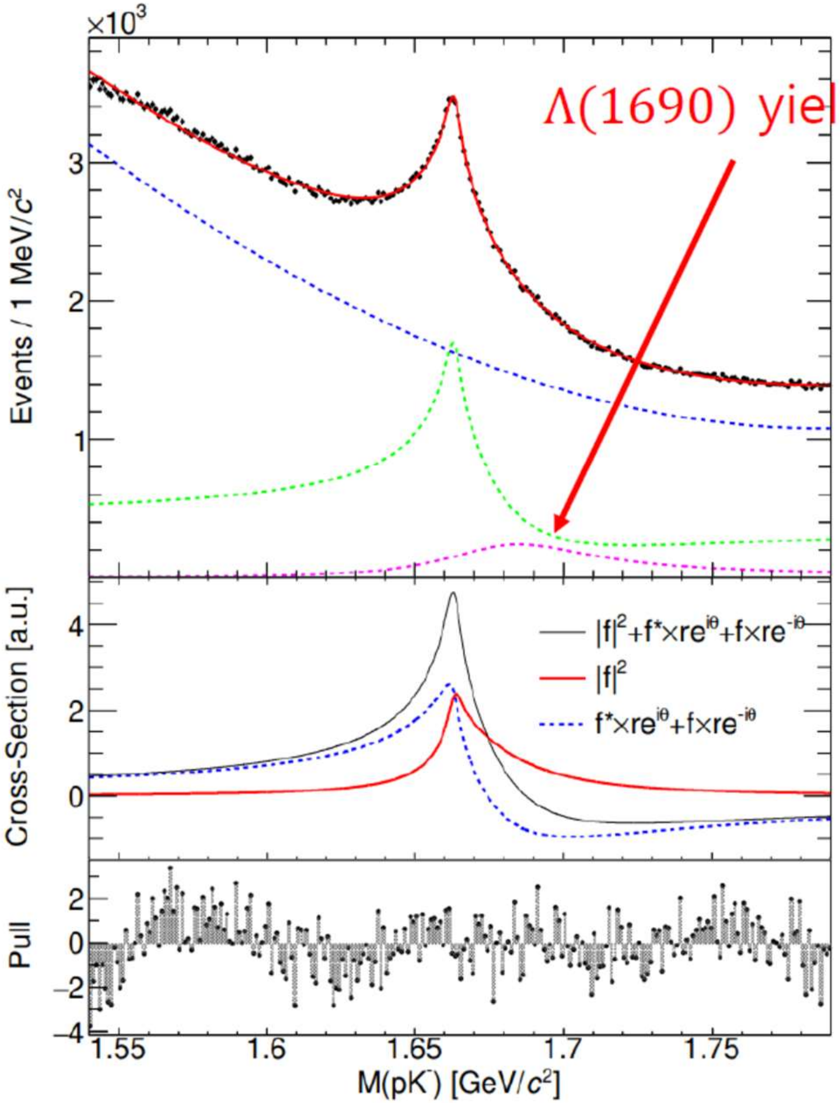
Amplitude fit projection



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.



Λ(1690) yield fixed

Parameter	Fit Results	$\frac{\text{Difference from the infiltrated value}}{\text{Systematical Uncertainty}}$
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

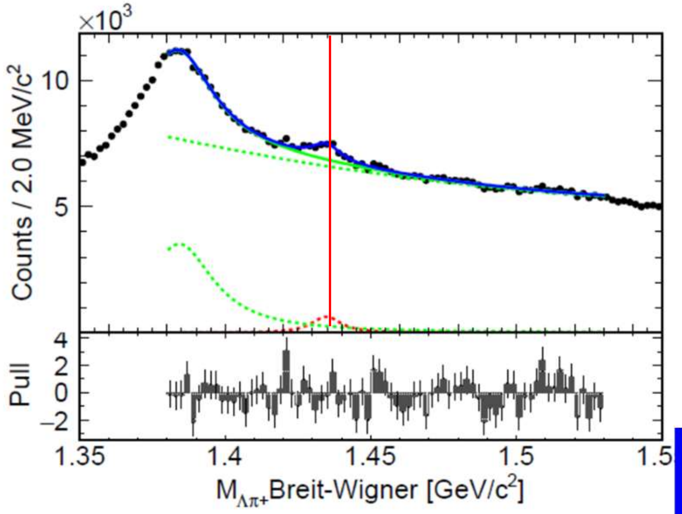
3. Peak at $\bar{K}N$ threshold in $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$

[PRL130(2023)151903]

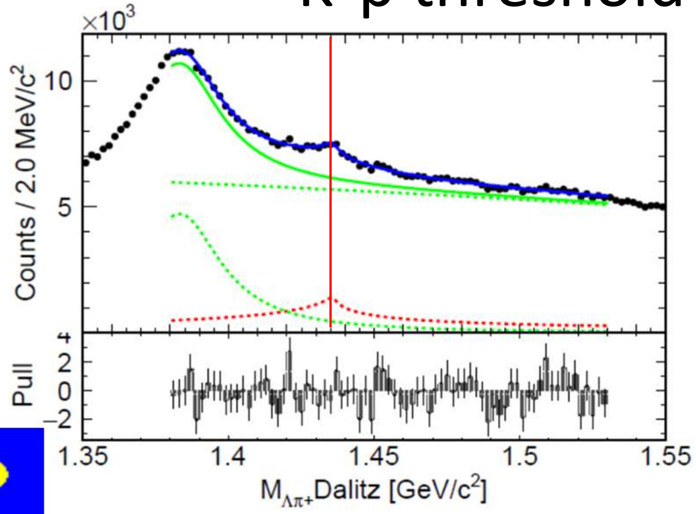
Peak at $\bar{K}N$ threshold in $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$

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

K^0p threshold

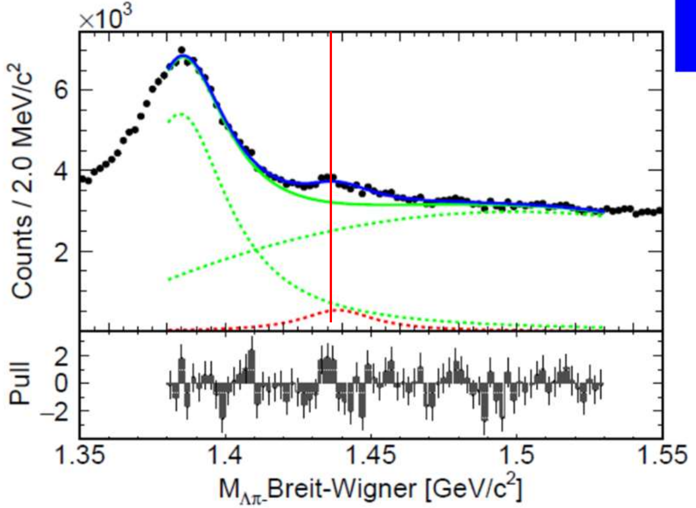


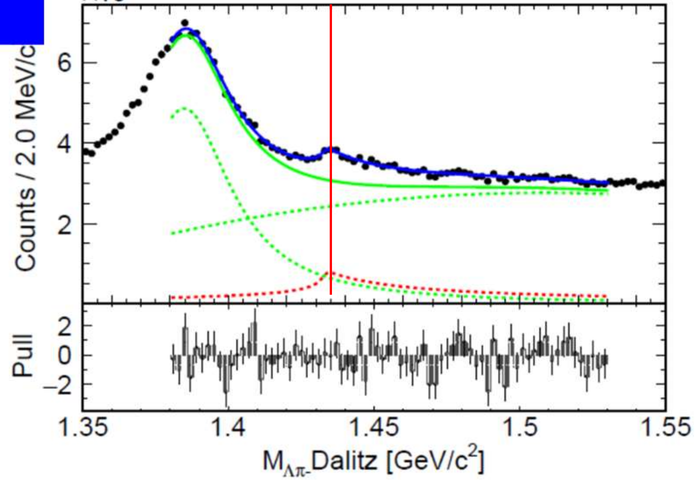
(a)

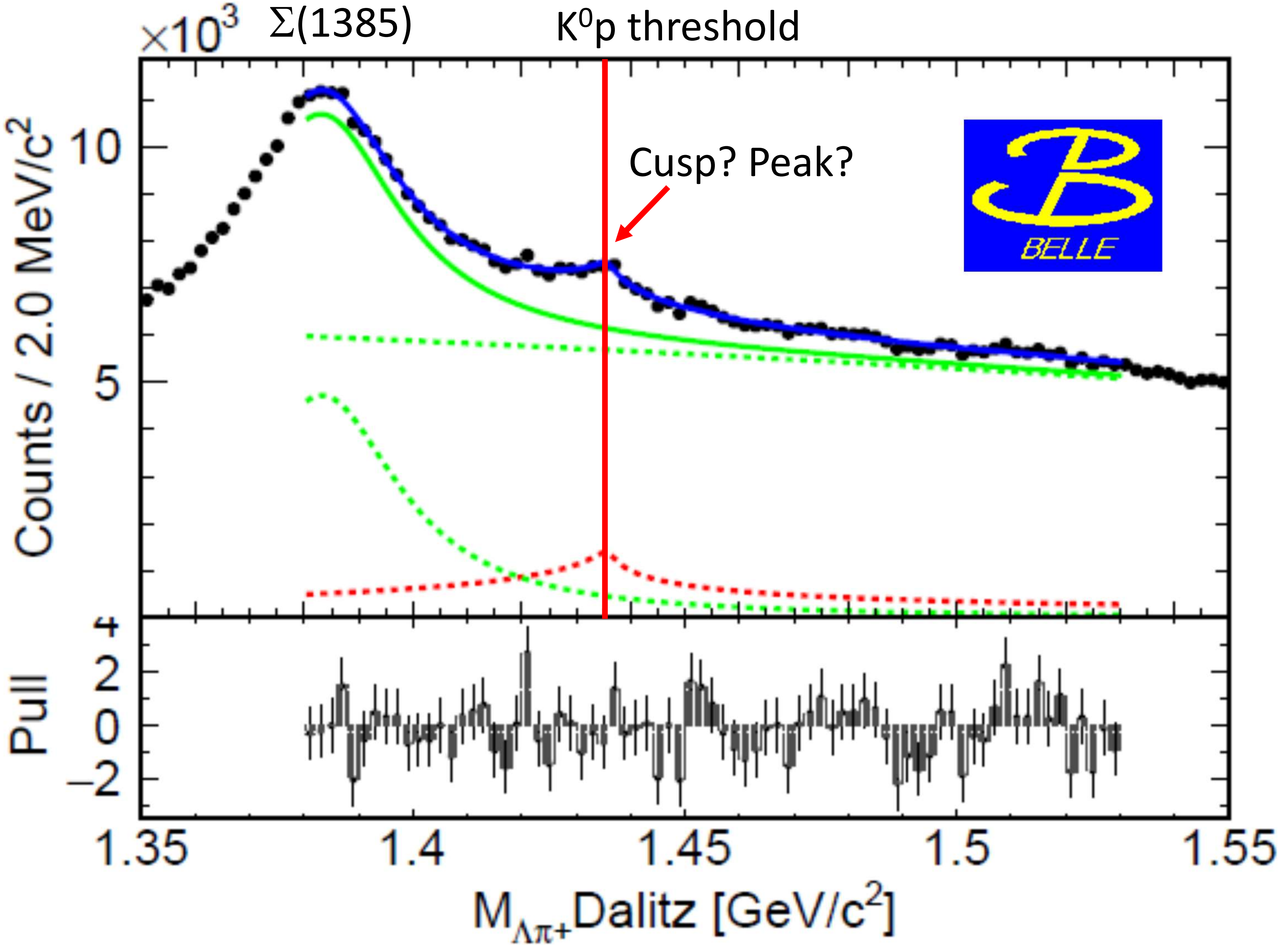


(a)

K^-n threshold







Σ(1385)

K^0p threshold

Cusp? Peak?

2 fitting models

1. Standard Breit-Wigner

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

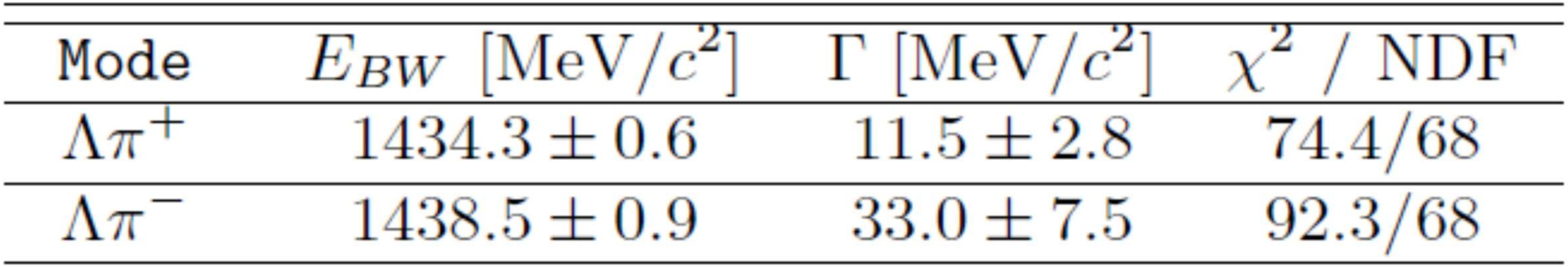
2. Dalitz model (cusp) [Czech. J. Phys. B**32**, 1021 (1982)]
For $\bar{K}N(I = 1)$ scattering length A=a+ib and decay momentum k/κ(=|k| below the threshold)

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

neglecting decay form factor

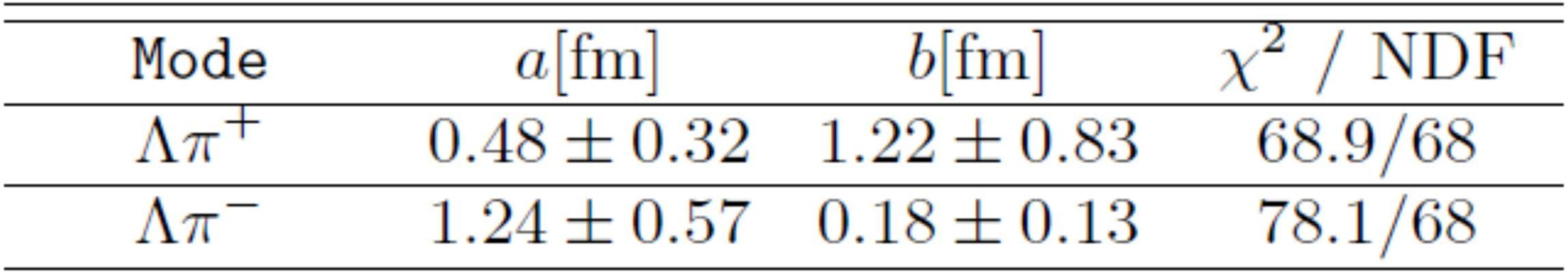
Fitting results

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, 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.)

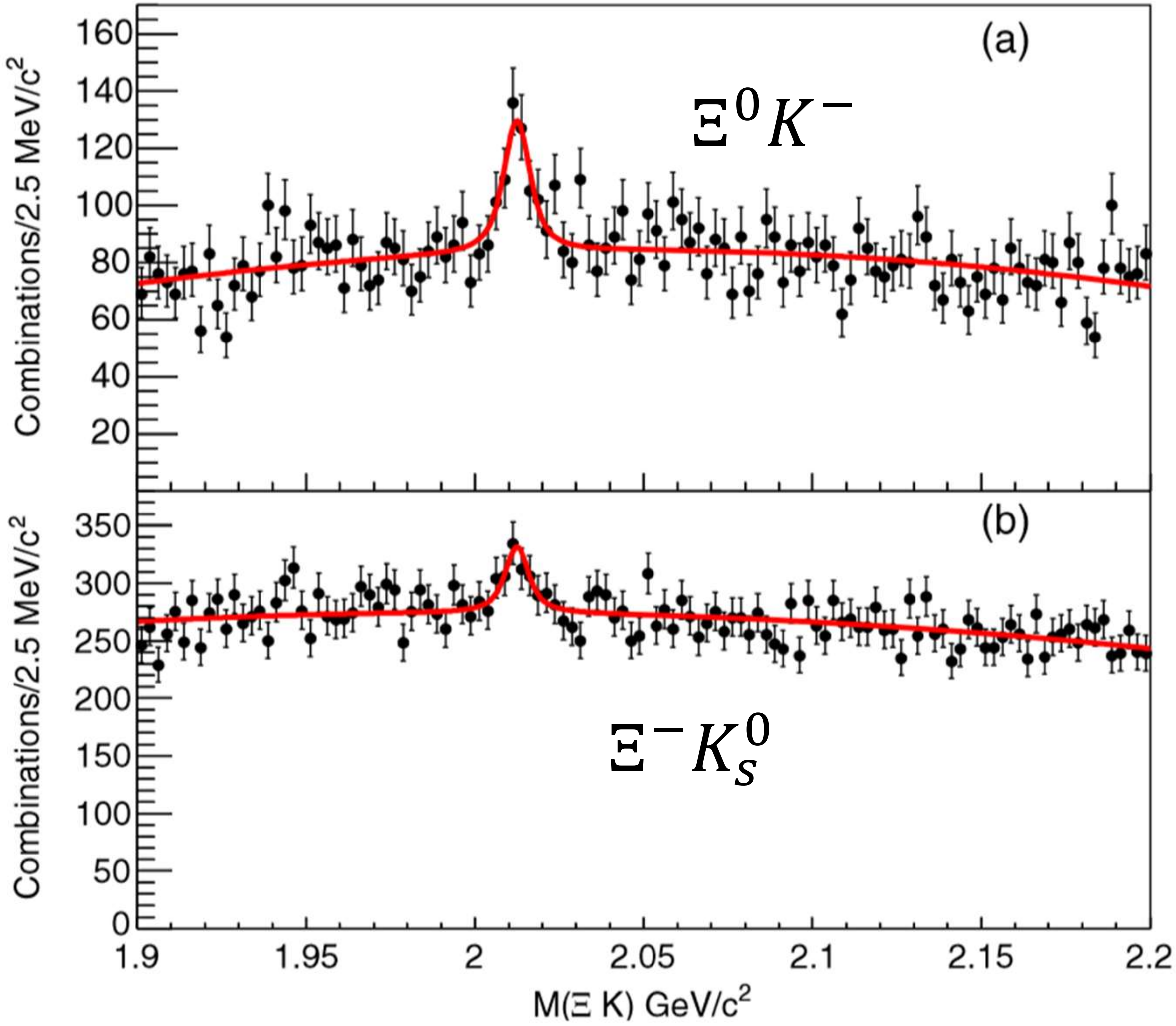
4. $\Omega_c \rightarrow \Omega(2012)\pi^+$

[Belle, PRD104 (2021) 052005]

$\Omega(2012)$

- Discovered in Υ(1-3S) decay.
- How about other channels?
  - E.g., $\Omega_c \rightarrow \Omega(2012)\pi^+$?

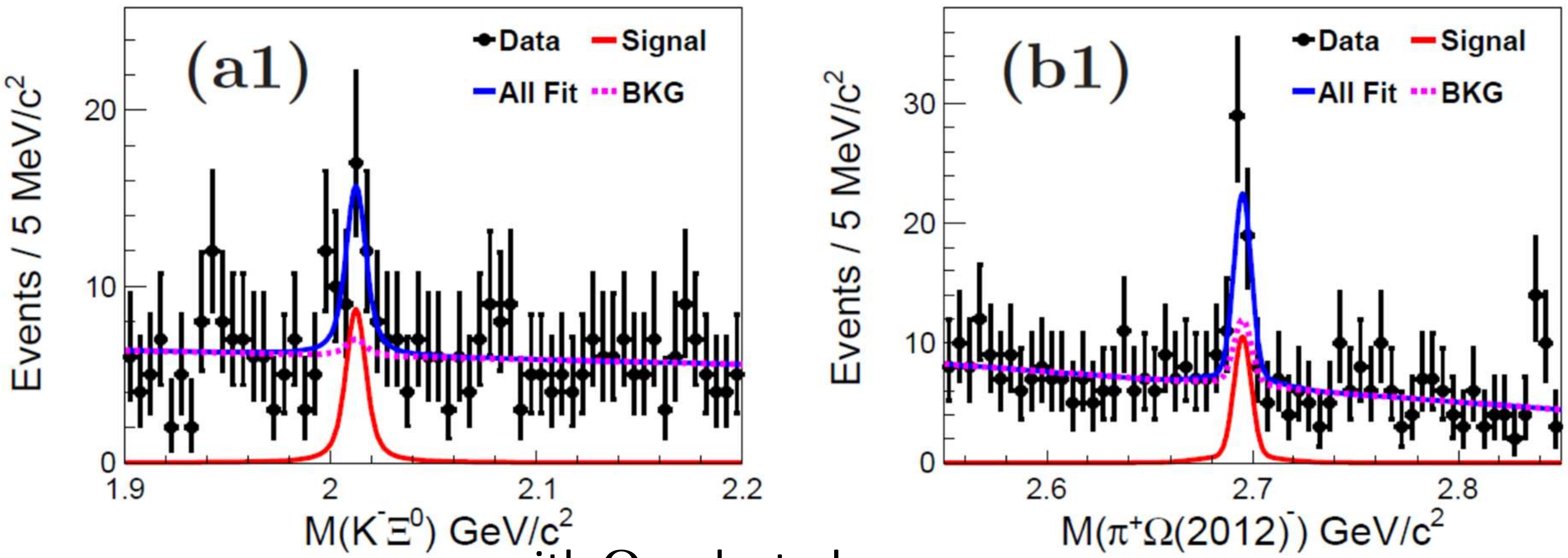
[Belle, PRL121 (2018) 052003]



$\Omega_c \rightarrow \Omega(2012)\pi^+$

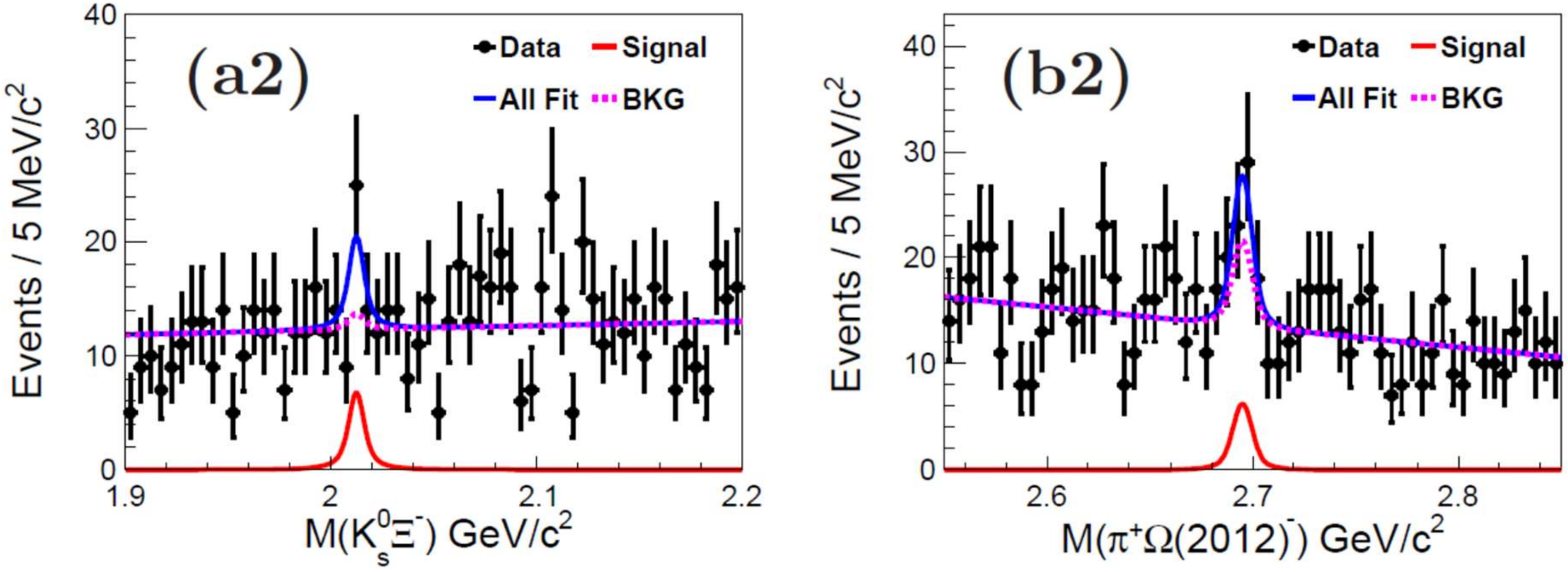
[Belle, PRD104 (2021) 052005]

- Decay mode: $\Omega_c \rightarrow (\Omega^*\pi^+) \rightarrow \Xi K\pi^+$



$K^-\Xi^0$

with Ω_c selected



$K^0_S\Xi^-$

Branching fractions

- $R_1 = \frac{BR\left(\Omega_c \to \pi^+ \Omega(2012)\right) BR\left(\Omega(2012) \to K^- \Xi^0\right)}{BR(\Omega_c \to \pi^+ K^- \Xi^0)}$
  $= 9.6 \pm 3.2 \pm 1.8\%$
- $R_2 = \frac{BR\left(\Omega_c \to \pi^+ \Omega(2012)\right) BR\left(\Omega(2012) \to K^0 \Xi^-\right)}{BR(\Omega_c \to \pi^+ K^0 \Xi^-)}$
  $= 5.5 \pm 2.8 \pm 0.7\%$
- $R_3 = \frac{BR\left(\Omega_c \to \pi^+ \Omega(2012)\right) BR\left(\Omega(2012) \to (K\Xi)^-\right)}{BR(\Omega_c \to \pi^+ \Omega)}$
  $= 22.0 \pm 5.9 \pm 3.5\%$

5. $\Omega(2012)$ → $\Xi(1530)\bar{K}$

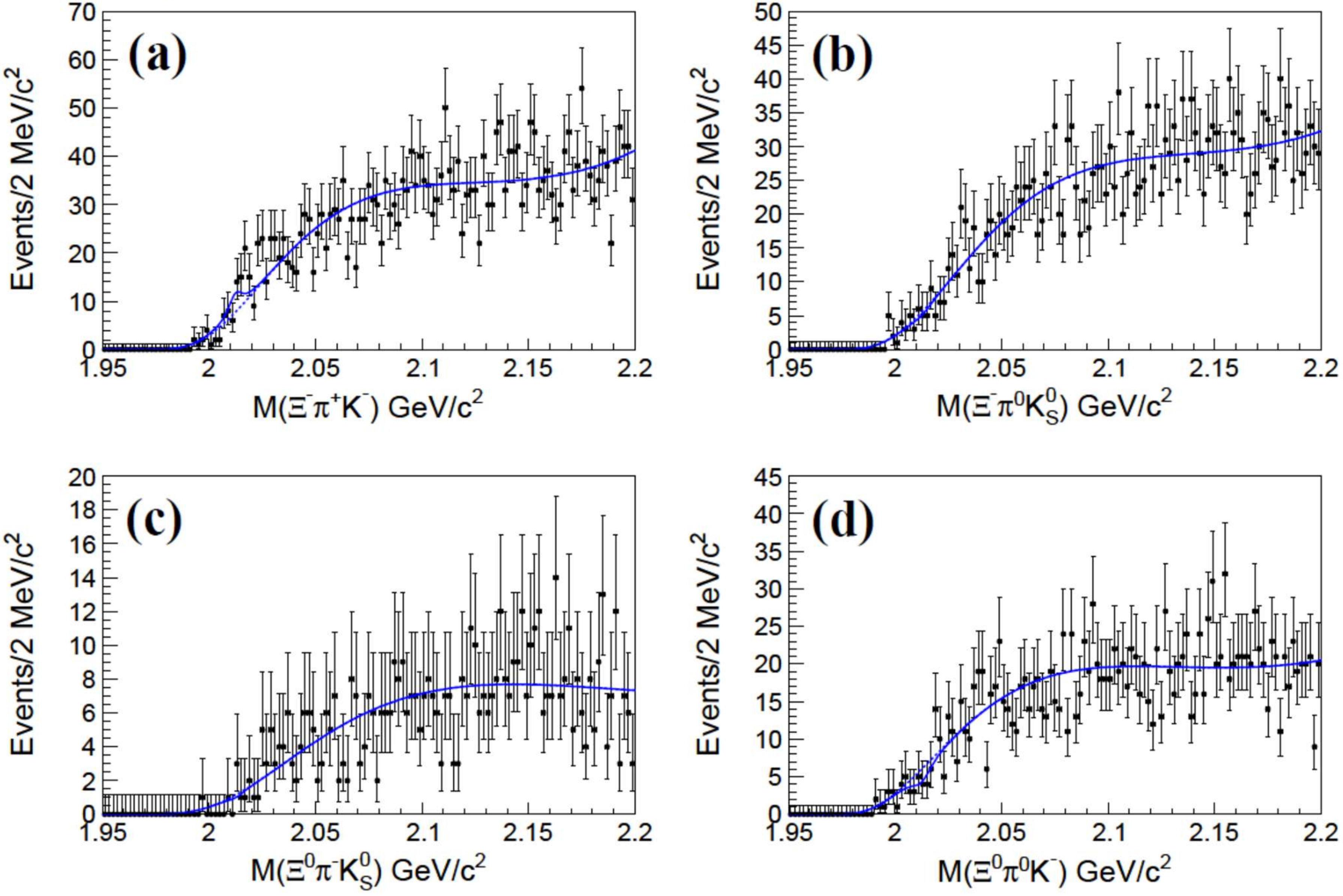
[arXiv:2207.03090]

$\Omega(2012) \rightarrow \Xi(1530)\bar{K}$

- Quark model: 1P orbital excited states expected in this mass region: $J^P=1/2^-$ and $3/2^-$
- The narrow width favors a $J^P=3/2^-$ state, of which decay to ΞK is D-wave and thus suppressed.
- However, there are claims that
  it could be a $\Xi(1530)K$ hadronic molecule
  [PRD **98** (2018) 054009, PRD **98** (2018) 056013, …]
- If this is the case, $\Xi(1530)K$ would be the main decay mode

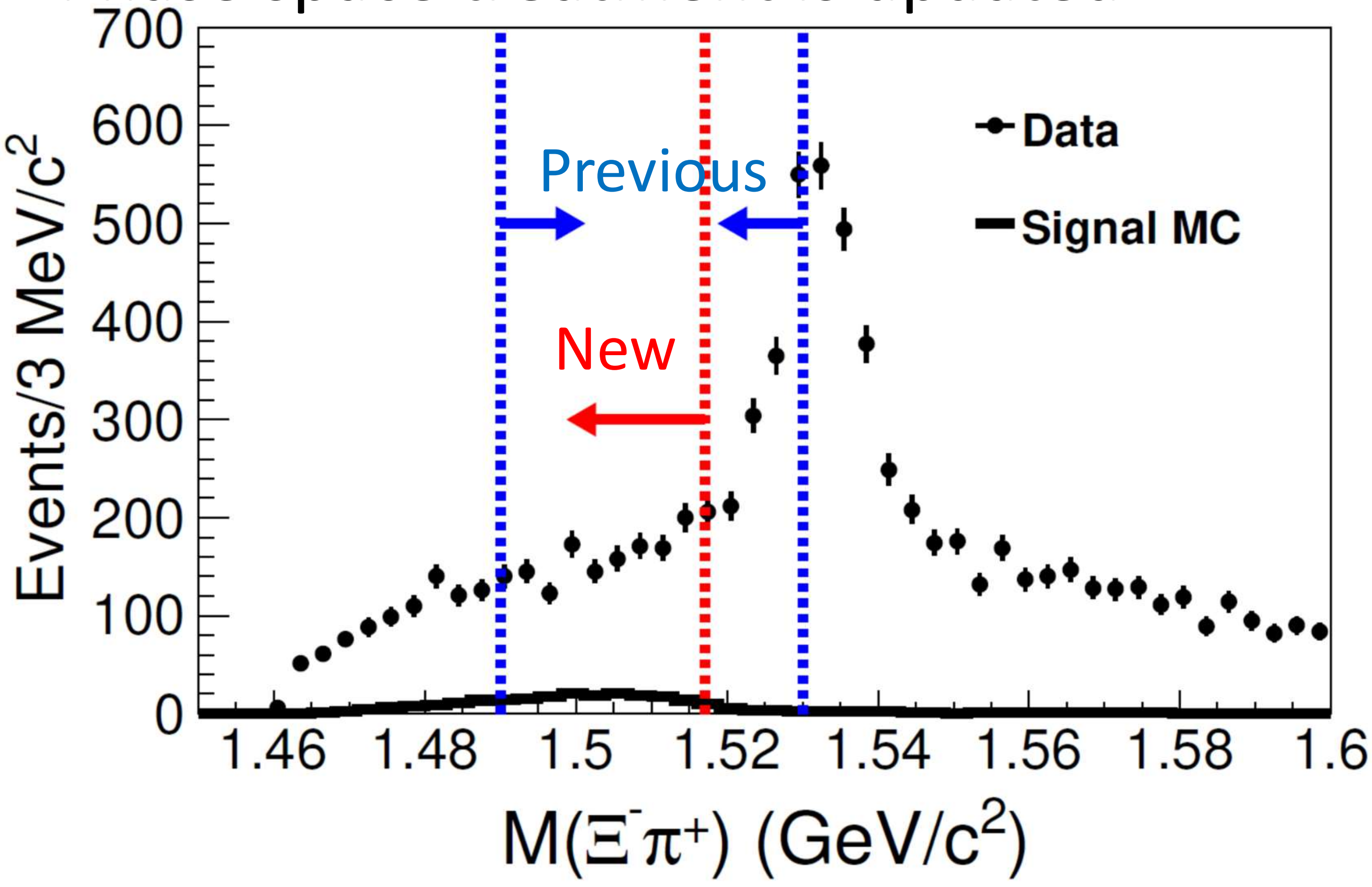
Previous study

[Belle, PRD 100 (2019) 032006]



What's the difference?

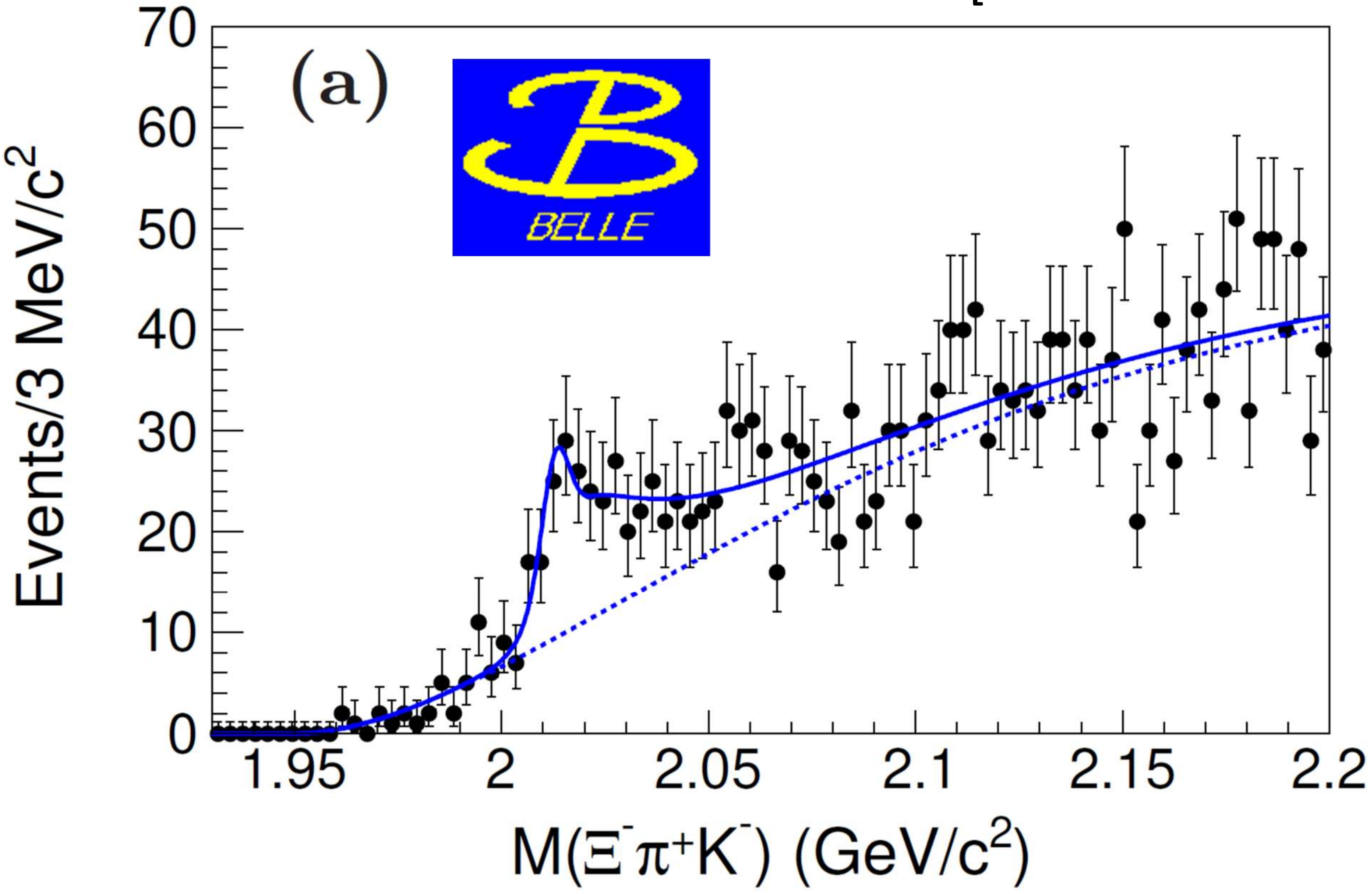
- Choice of Ξ(1530)
  - Phase space treatment is updated



- Additional cut on kaons from ϕ

New result

[arXiv:2207.03090]



Signal seen!

New result (cont.)

- Branching ratio: 3 body (ΞKπ) vs 2 body (ΞK)

$$R = 0.97 \pm 0.24 \pm 0.07$$

  - Consistent with molecular model
- Effective coupling=(partial width)/(phase space)

  ΞKπ: $(41.1 \pm 35.8 \pm 6.0) \times 10^{-2}$

  ΞK: $(1.7 \pm 0.3 \pm 0.3) \times 10^{-2}$

  → coupling to ΞKπ is much stronger

  (assuming no non-resonant contribution)

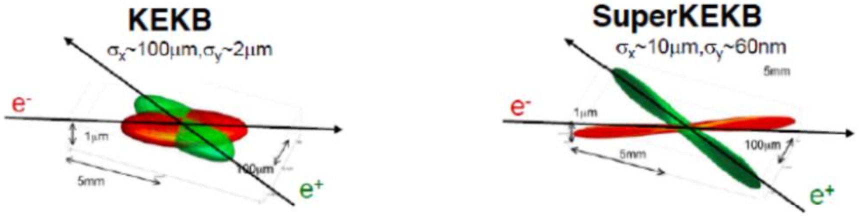
6. Belle II prospects

SuperKEKB and Belle II

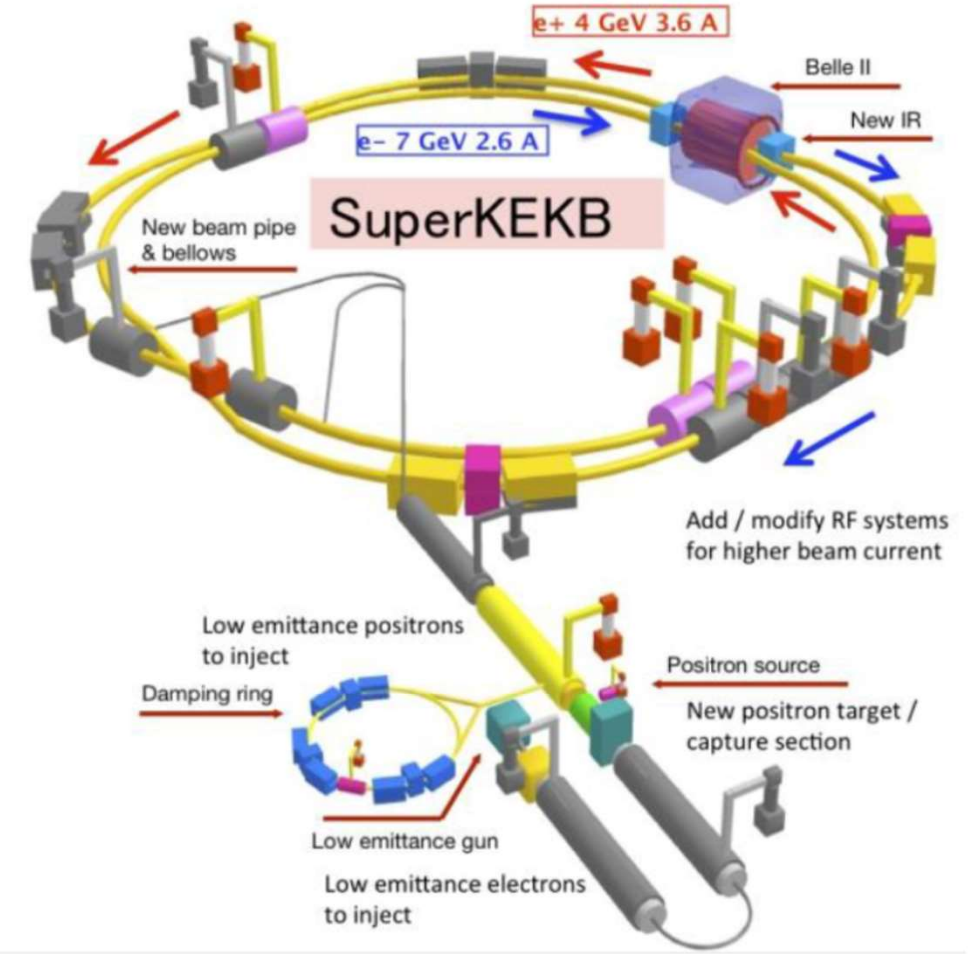
Upgrade for SuperKEKB and Belle II to achieve 30x peak $\mathcal{L}$

- Reduction in the beam size by 1/20 at the IP.
- Doubling the beam currents.

$$L = \frac{\gamma_{e\pm}}{2 e r_e}\left(1 + \frac{\sigma_y^*}{\sigma_x^*}\right)\left(\frac{I_{e\pm}\xi_y^{e\pm}}{\beta_y^*}\right)\left(\frac{R_L}{R_{\xi_y}}\right)$$



- ▶ *First turns achieved Feb. 2016*
- ▶ *Beam-background studies ongoing*

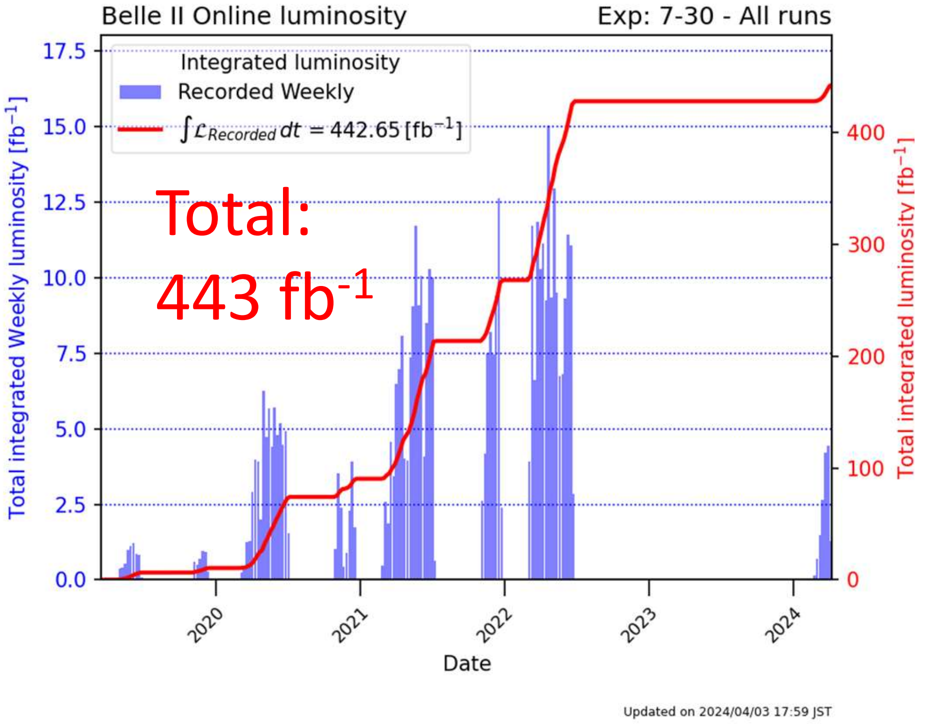


Goal: x50 more statistics than Belle

Belle II integrated luminosity

Achieved

Prospect



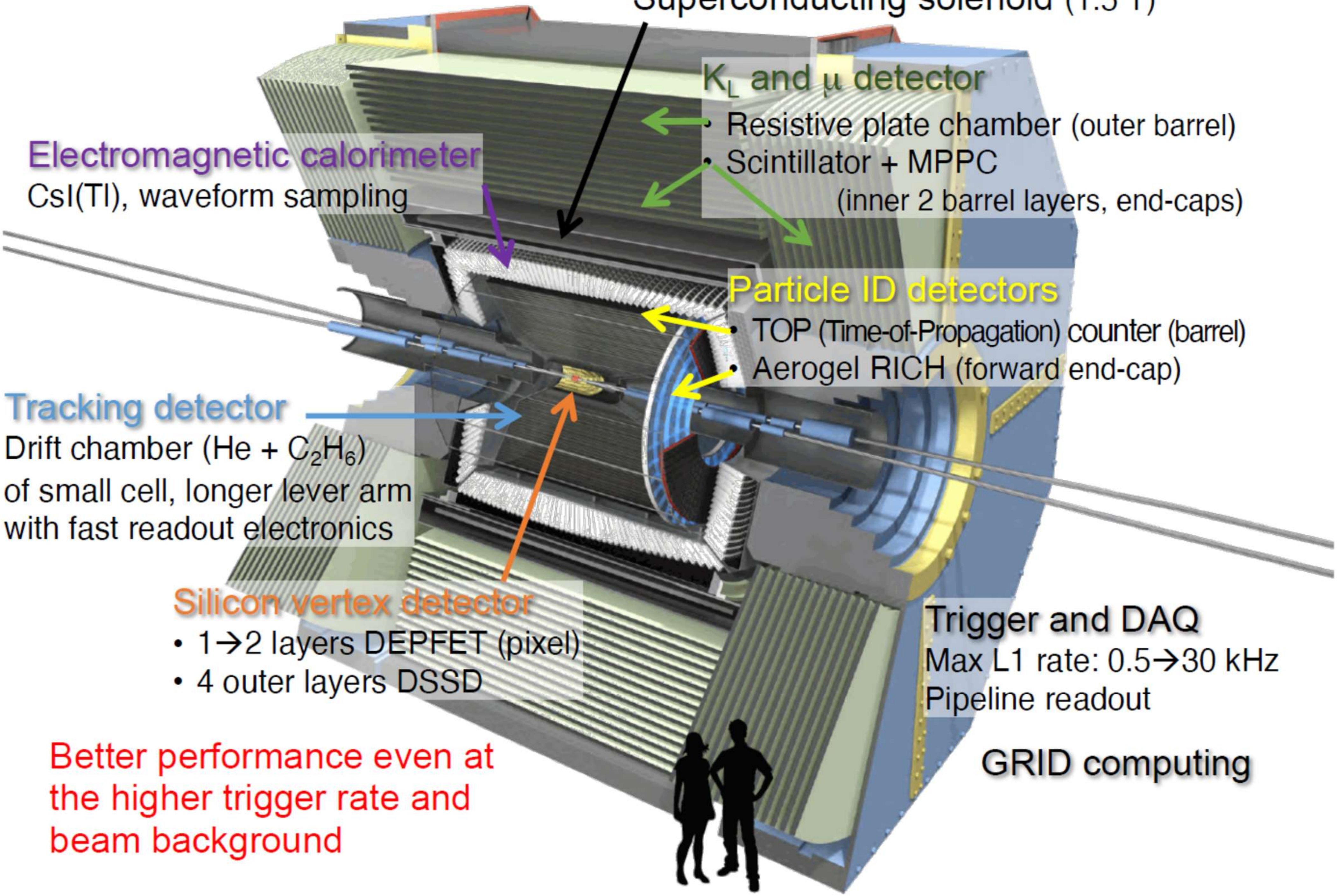
Total:
443 fb^{-1}

Now Run2
has begun!

- Instantaneous luminosity already exceeded Belle
  → New record: 4.7×10^{34} cm^{-2}s^{-1} in June 2022.
- Integrated luminosity will exceed Belle within a few years
- Goal: 50 ab^{-1} around 2035.

Belle II detector

Upgraded from Belle



Superconducting solenoid (1.5 T)

K_L and μ detector

- Resistive plate chamber (outer barrel)
- Scintillator + MPPC (inner 2 barrel layers, end-caps)

Electromagnetic calorimeter

CsI(Tl), waveform sampling

Particle ID detectors

- TOP (Time-of-Propagation) counter (barrel)
- Aerogel RICH (forward end-cap)

Tracking detector

Drift chamber (He + C_2H_6)
of small cell, longer lever arm
with fast readout electronics

Silicon vertex detector

- 1→2 layers DEPFET (pixel)
- 4 outer layers DSSD

Trigger and DAQ

Max L1 rate: 0.5→30 kHz
Pipeline readout

GRID computing

Better performance even at the higher trigger rate and beam background

Some possibilities

- Search for further states
  - Especially Ξ^* and Ω^*
  - Exotic states may be hidden
- Spin-parity determination
  - All the known states, i.e., $\Omega(2012)$, $\Xi(1620/1690)$, … are within Belle II reach
- Not only hyperons, but also strange mesons are in our scope
  - E.g., in $\tau \rightarrow K\pi\pi\nu_\tau$ decay

Summary & prospects

- Belle is not only for quarkonia, but for hyperons, too.
- Topics of the day
  - $\Lambda_c \to \Lambda\eta\pi^+$ and $\Lambda(1670)$
  - Identification of Threshold cusp in $\Lambda_c \to pK^-\pi^+$
  - Peak at $\bar{K}N$ threshold in $\Lambda_c \to \Lambda\pi^+\pi^+\pi^-$
  - $\Omega_c \to \Omega(2012)\pi^+$
  - $\Omega(2012) \to \Xi(1530)\bar{K}$
- **More results are expected from Belle II**
  - Instantaneous luminosity is already higher than Belle
  - Goal: 50 times higher statistics around 2035.

Backup