Charmed baryons and excited hyperons at Belle

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Flavored Baryons in e^+e^- Collider

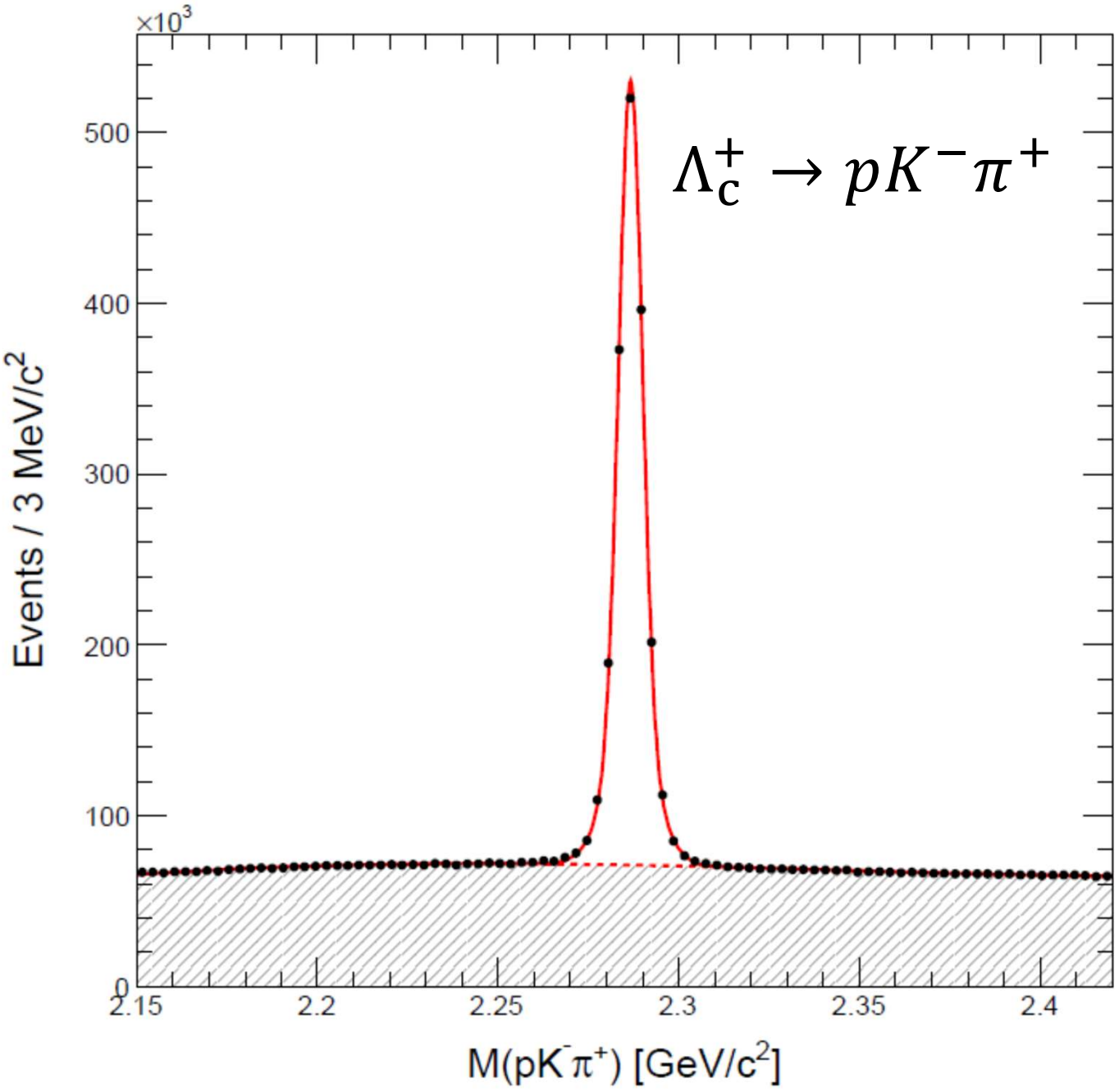
- Electron-positron colliders (CLEO, Belle, Babar, BESIII…) are known to be useful for mesons, especially, quarkonia.

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

Why e^+e^- colliders?

- Small background
  - $e^+e^- \to Q\bar{Q}$ production is flavor blind.
    Only (charge)^2 matters.
- 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.

Huge statistics, good quality

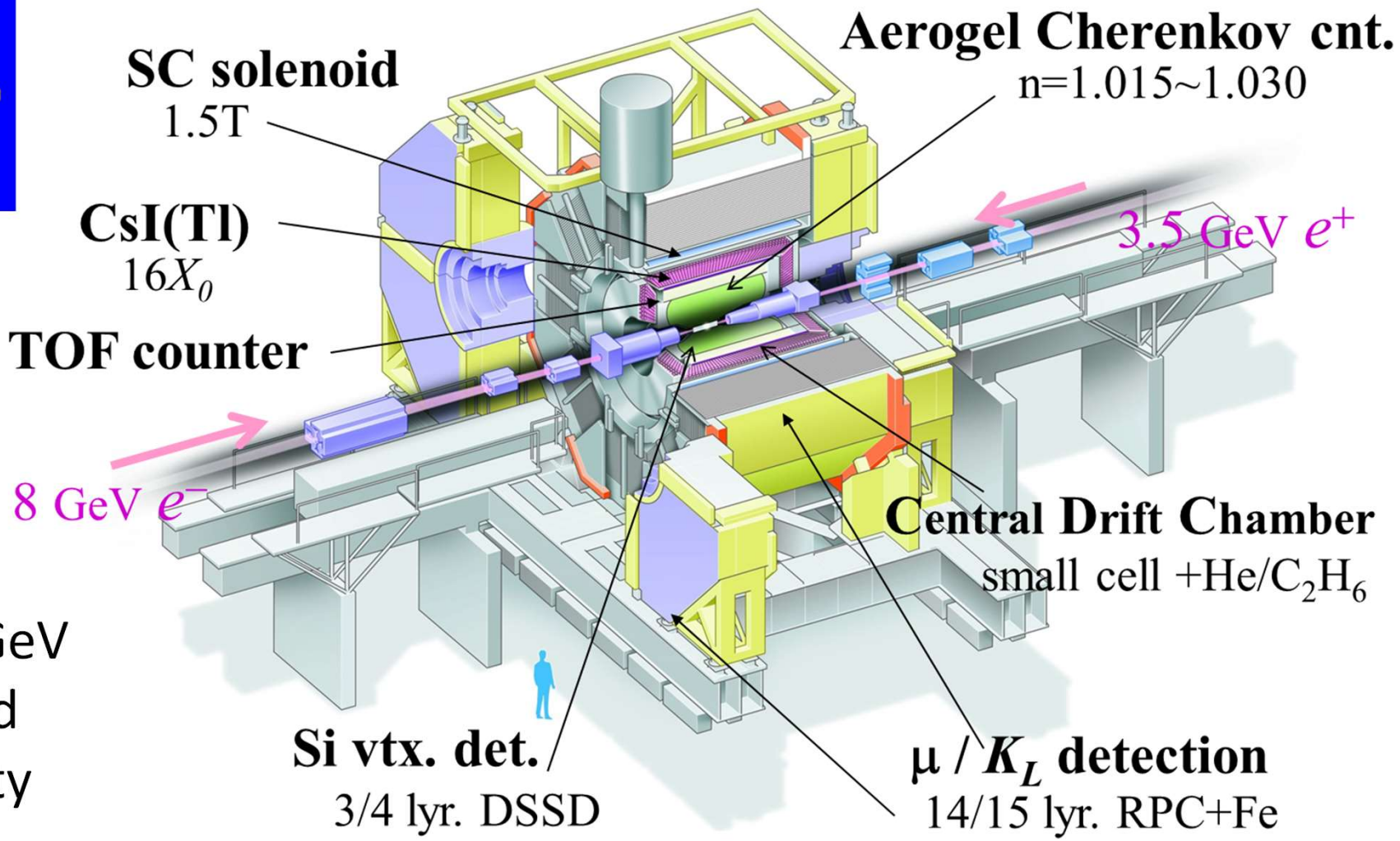


> 1 M events reconstructed

Resolution:
< 10 MeV FWHM

S/N ~ 10

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

Some of recent (~ 1 year) results

- $\Lambda_c \to \Sigma^+\eta^{(\prime)}$ [arXiv:2208.10825]
- CP violation in $\Lambda_c \to \Lambda h^+, \Lambda_c \to \Sigma^0 h^+$ [arXiv:2208.08695]
- $\Omega(2012) \to \Xi(1530)\bar{K}$ [arXiv:2207.03090]
- $\Lambda_c \to \Sigma^+\gamma, \Xi_c^0 \to \Xi^0\gamma$ [arXiv:2206.12517, PRD in press]
- Threshold cusp in $\Lambda_c \to pK^-\pi^+$ [arXiv:2209.00050]
- New charm baryon in B decay [arXiv:2206.08822, PRL in press]
- $\Xi_c^0 \to \Lambda_c\pi^-$ [arXiv:2206.08527, PRD in press]
- $\Lambda_c \to p\eta'$ [JHEP 03 (2022) 090]
- $\Xi_c^0 \to \Lambda K_S^0, \Sigma^0 K_S^0, \Sigma^+ K^-$ [PRD105 (2022) L011102]
- $\Lambda_c \to p\omega$ [PRD104 (2021) 072008]

Some of recent results (cont.)

- $\Omega(2012)$ in Ω_c decay [PRD104 (2021) 052005]
- $\Xi_c^0 \to \Lambda \bar{K}^{*0}, \Sigma^0 \bar{K}^{*0}, \Sigma^+ K^{*-}$ [JHEP 06 (2021) 160]
- Mass and width of $\Sigma_c^{(*)+}$ [PRD104 (2021) 052003]
- $\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$ and $\Xi_c^0 \to \Xi^- \pi^+$ [PRL127 (2021) 121803]
- $\Xi_c^0 \to \Xi^0 K^+ K^-$ [PRD103 (2021) 112002]
- $\Lambda_c \to p\eta$ and $p\pi^0$ [PRD103 (2021) 072004]
- Spin-parity measurement of $\Xi_c(2970)$ [PRD103 (2021) L111101]
- $\Lambda_c \to \eta\Lambda\pi^+$ decay and $\Lambda(1670)$ [PRD103 (2021) 052005]

More and more are coming!

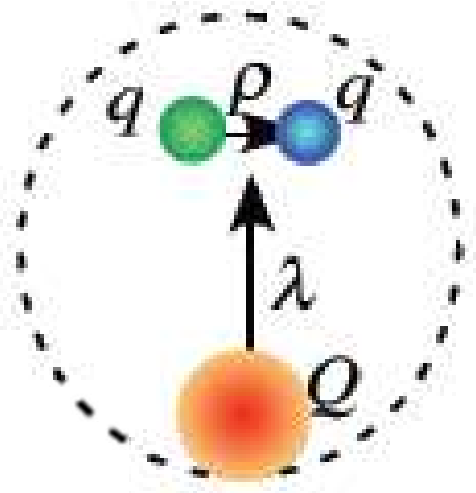
Topics of the day

1. Charmed baryons
   - Spin-parity measurement of $\Xi_c(2970)$
   - New charm baryon in B decay
2. Hyperons
   - $\Lambda_c \to \Lambda\eta\pi^+$ and $\Lambda(1670)$
   - Threshold cusp in $\Lambda_c \to pK^-\pi^+$
   - $\Omega_c \to \Omega(2012)\pi^+$
   - $\Omega(2012) \to \Xi(1530)\bar{K}$
3. Summary

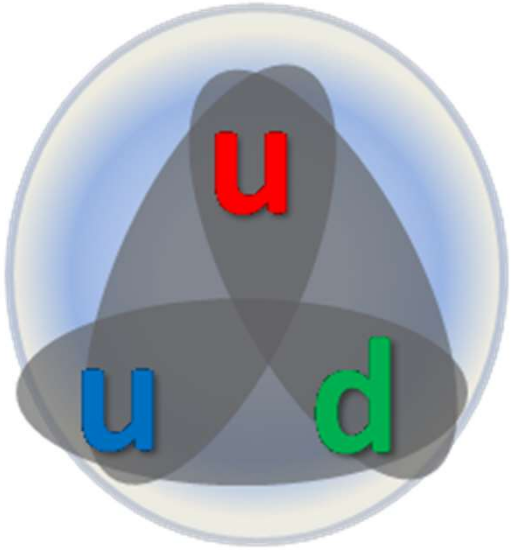
1. Charmed baryons

Introduction – Heavy quark baryons

- Heavy quark in Baryon
  - Bare quark ≒ constituent quark
  - Makes a “static core”, light quarks play around
    → Diquark correlation enhanced?
  - New symmetry – heavy quark symmetry
    → Hyperfine doublet for heavy quark spin.

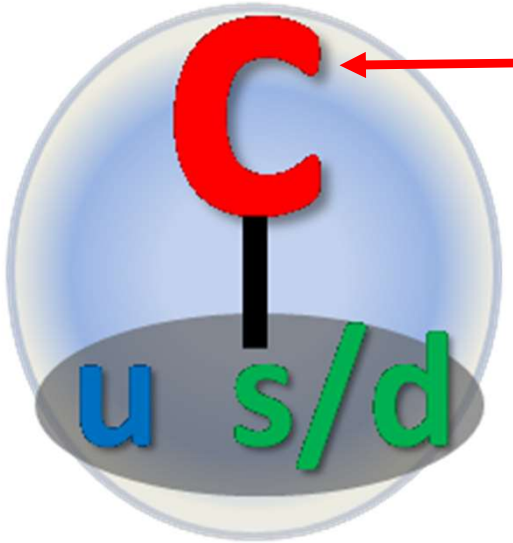


Nucleon



Indistinguishable pairs

Charmed baryon



HQS: spin Approximately conserved

Light di-quark with inert charm?

Introduction – Heavy quark baryons

- Heavy quark in Baryon
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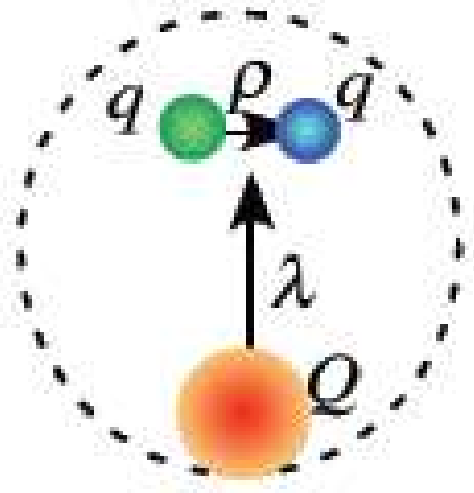
    → Hyperfine doublet for heavy quark spin.

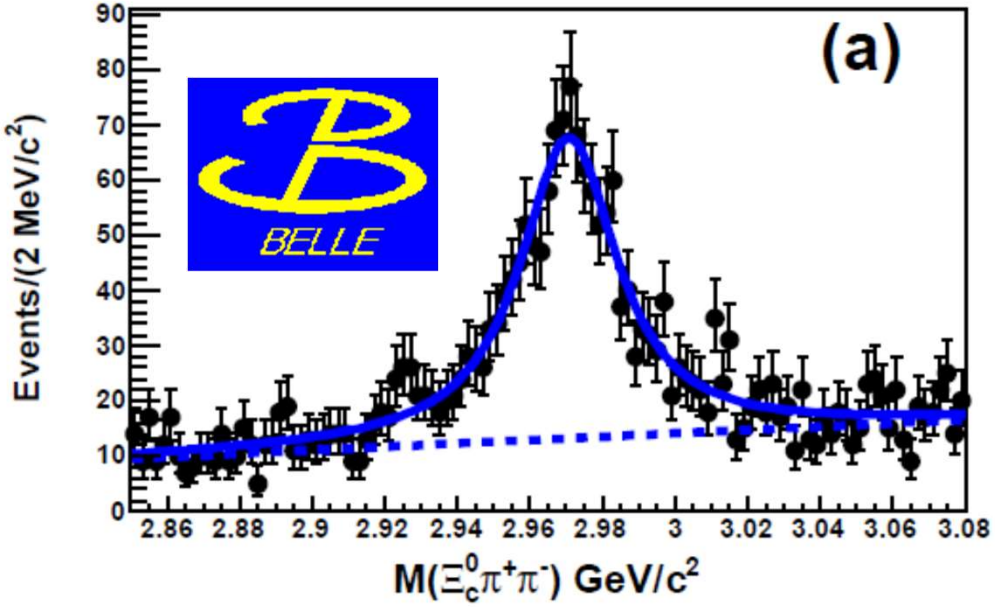


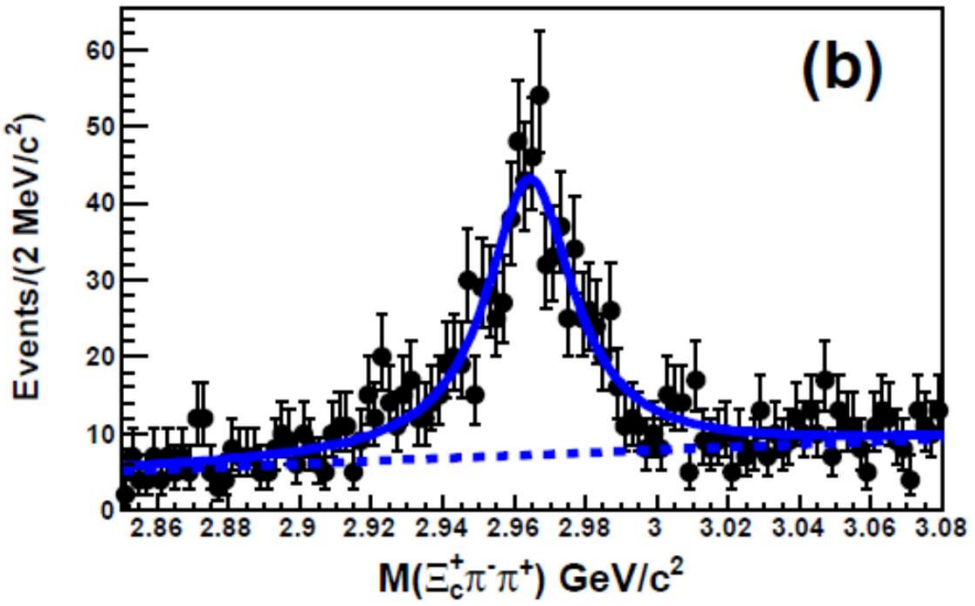
- How analog states appear?
  - Comparison with strange baryons is interesting
  - $\Lambda(1405)$ → ?, Roper resonance → ?
  - Helps to understand the nature of those states.
- Missing resonances?
- New exotic states? E.g., DN bound state, pentaquarks, ...

Spin-parity of $\Xi_c(2970)$

- Relatively low excitation energy
  - Good statistics & S/N ratio

Belle, PRD**94**, 052011 (2016)



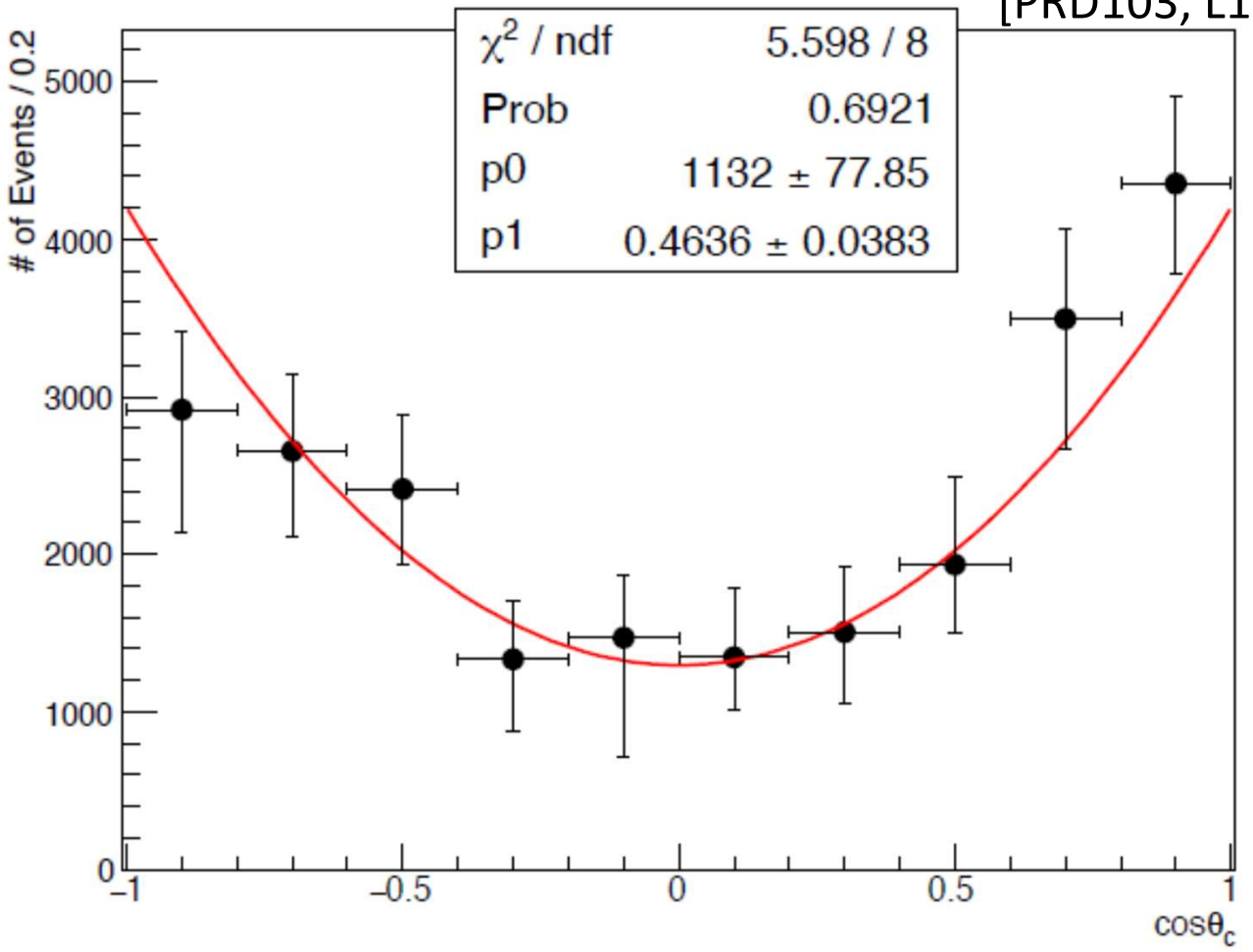


- Wide variety of theoretical predictions
- Important decay mode: $\Xi_c(2970) \rightarrow \Xi_c^*(2645)\pi$

SPIN: Angular correlation of

$\Xi_c(2970) \rightarrow \Xi_c^*(2645)\pi_1 \rightarrow \Xi_c\pi_1\pi_2$

[PRD103, L111101]



- Consistent with $1+3\cos^2\theta \rightarrow$ J = 1/2

  [see also: Arifi, Hosaka, Nagahiro, and Tanida, PRD101, 111502(R)(2020)]

PARITY: Decay to Ξ_c^* and Ξ_c'

- $R = \frac{\Gamma(\Xi_c(2970) \to \Xi_c^* \pi)}{\Gamma(\Xi_c(2970) \to \Xi_c' \pi)}$ is expected to be small for negative parity:
  - $\Xi_c(2970) \to \Xi_c' \pi$ is in S-wave, while $\Xi_c(2970) \to \Xi_c^* \pi$ is in D-wave.
- For positive parity, calculable based on HQS

Parity	+	+
Diquark spin s_ℓ	0	1
R	1.06	0.26

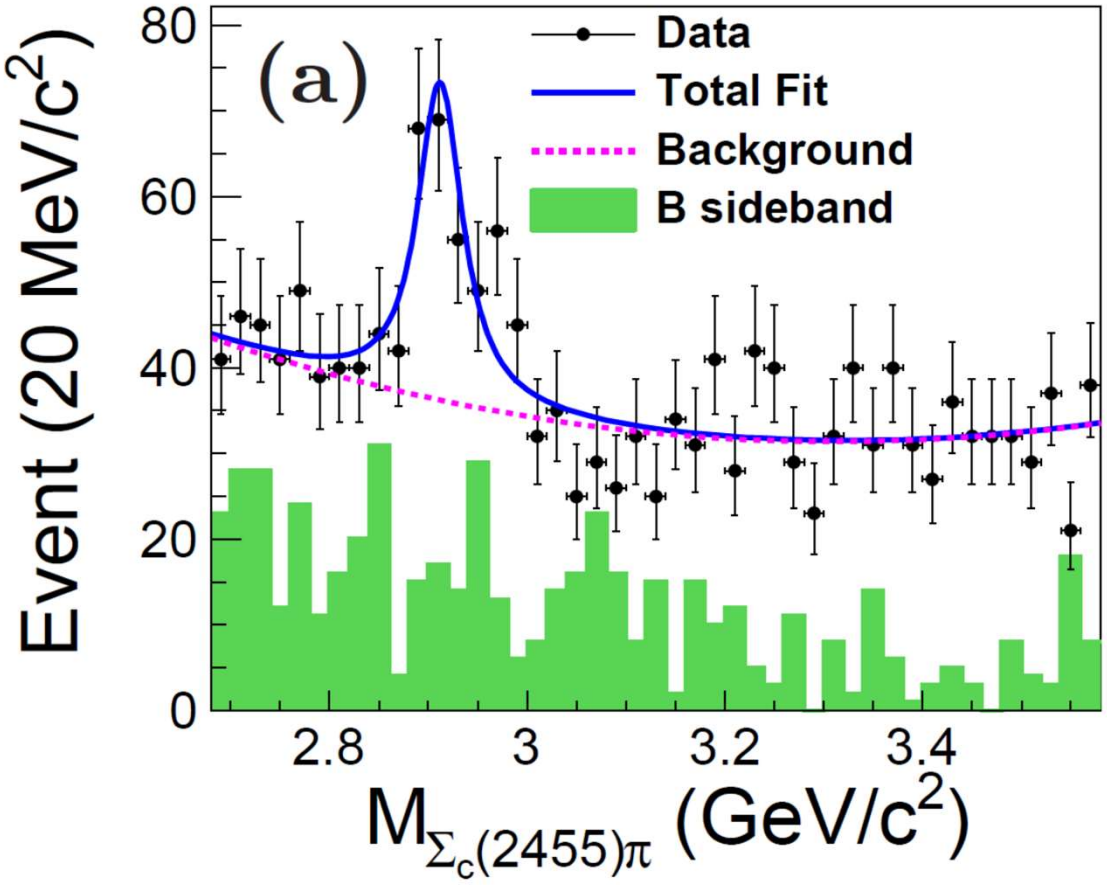
- We got $R = 1.67 \pm 0.29(\text{stat.})^{+0.15}_{-0.09}(\text{syst.}) \pm 0.25(\text{IS})$
  - Consistent with P=+ and brown-muck spin s_ℓ=0 only.

Discussion

- We got $J^P=1/2^+$. What can we say from this?
- This is the same as the infamous Roper resonance, N(1440), the first excited state of nucleon.
  - Excitation energy (~500 MeV) is also the same.
- Difficult to explain Roper in quark model
  - Single quark excitation: 1st excited state should be a negative parity state (ex. N(1530)).
  - Surprisingly, difficult even in Lattice QCD.
  - The present measurement may give a hint.

New charm baryon in B decay

- A search in B^0 decay to $\Sigma_c(2455)^{0,++}\pi^{\pm}\bar{p}$



[arXiv:2206.08822, PRL, in press]

Known resonances [$\Lambda_c(2880)$ & $\Lambda_c(2940)$] are unlikely by 4.2σ

$M = 2913.8 \pm 5.6 \pm 3.8$ MeV/c^2

$\Gamma = 52 \pm 20 \pm 19$ MeV

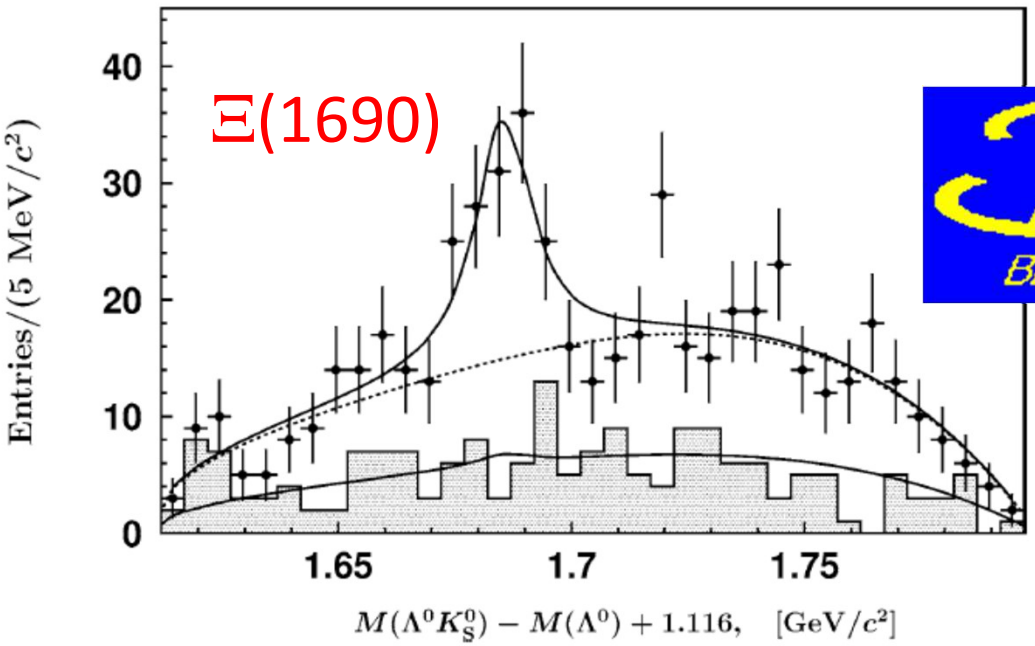
2. Hyperons

especially from
charmed baryon decays

Hyperons from charmed baryon decays

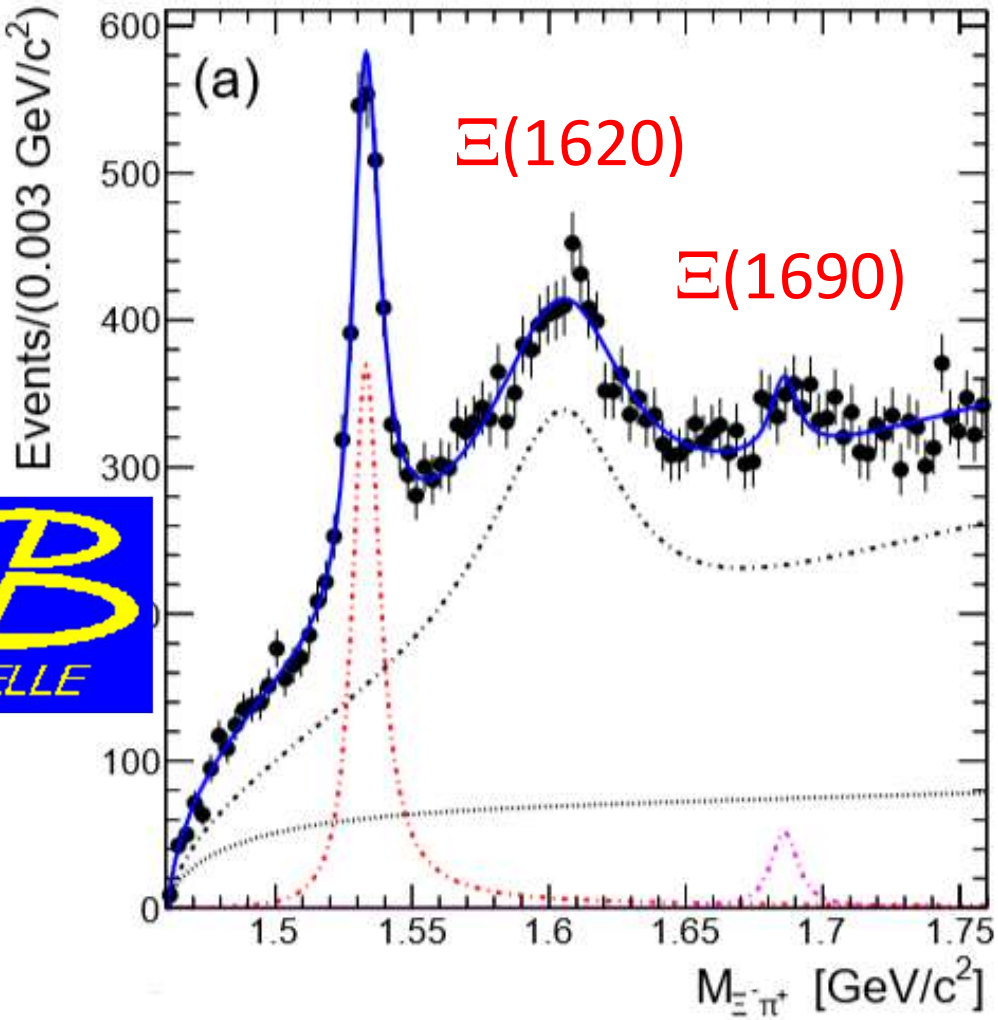
- New source for hyperon spectroscopy
  - New states?
  - Branching ratios

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



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

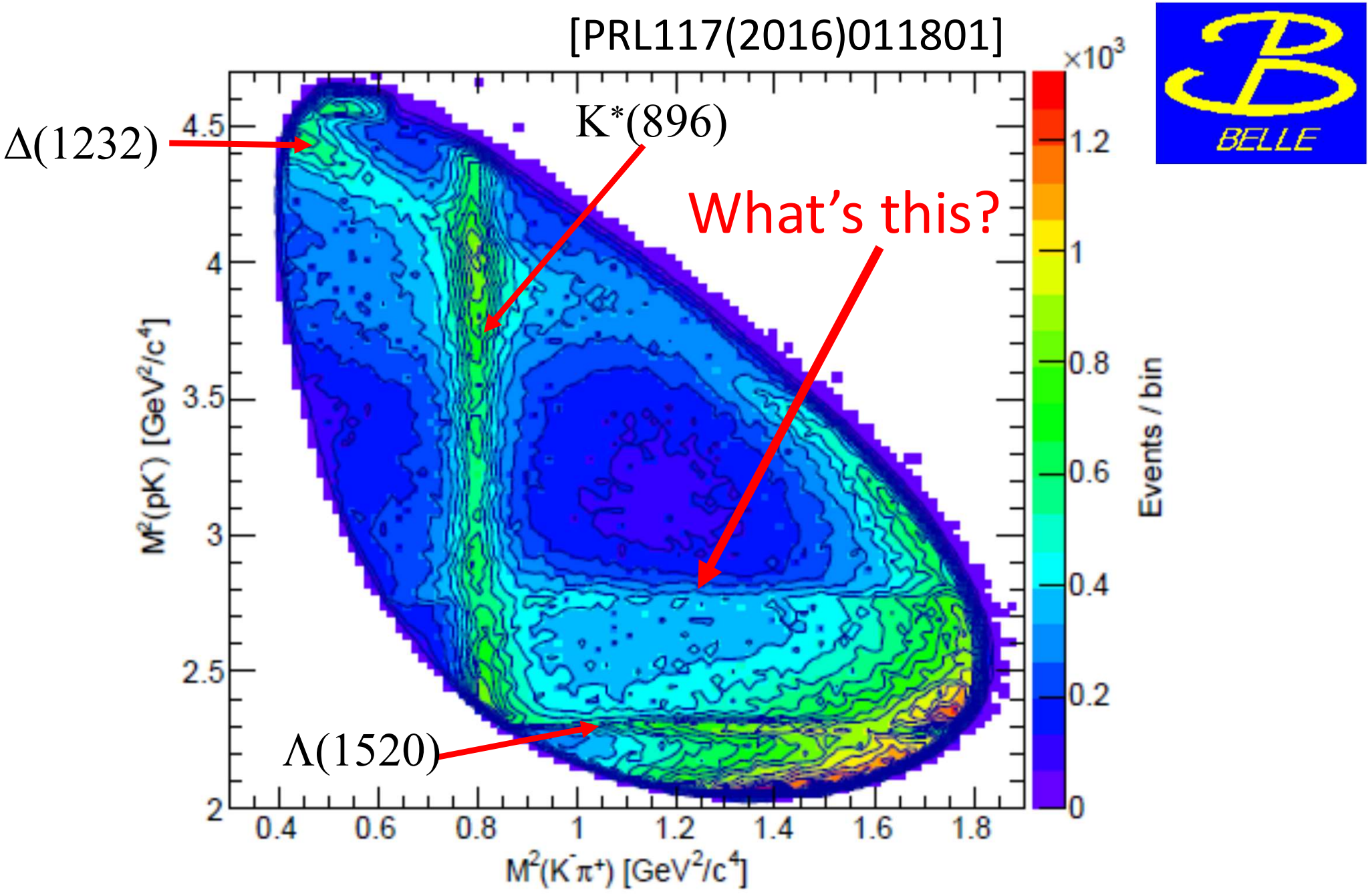
$\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+$



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

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

[PRL117(2016)011801]

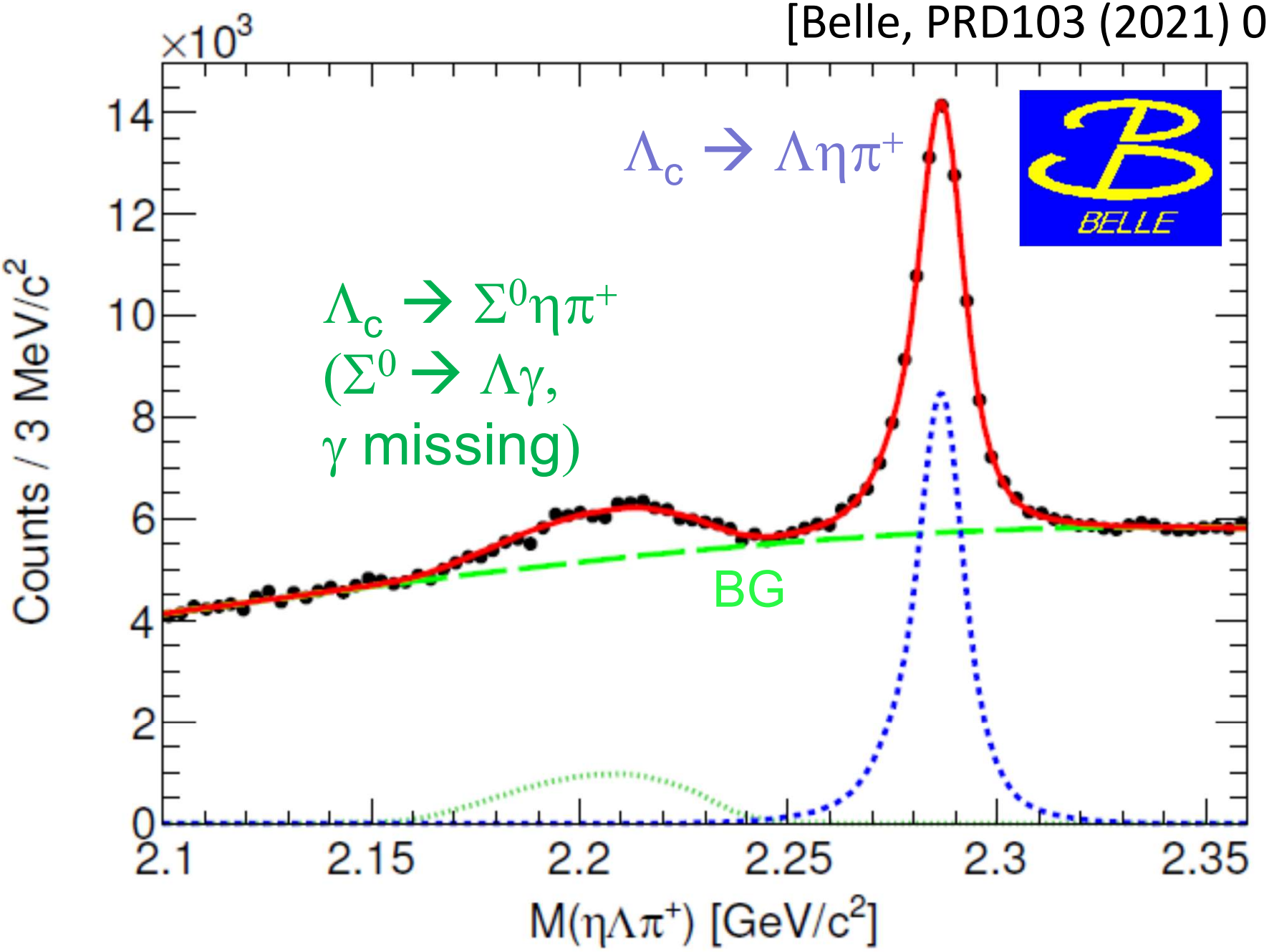


What's this?

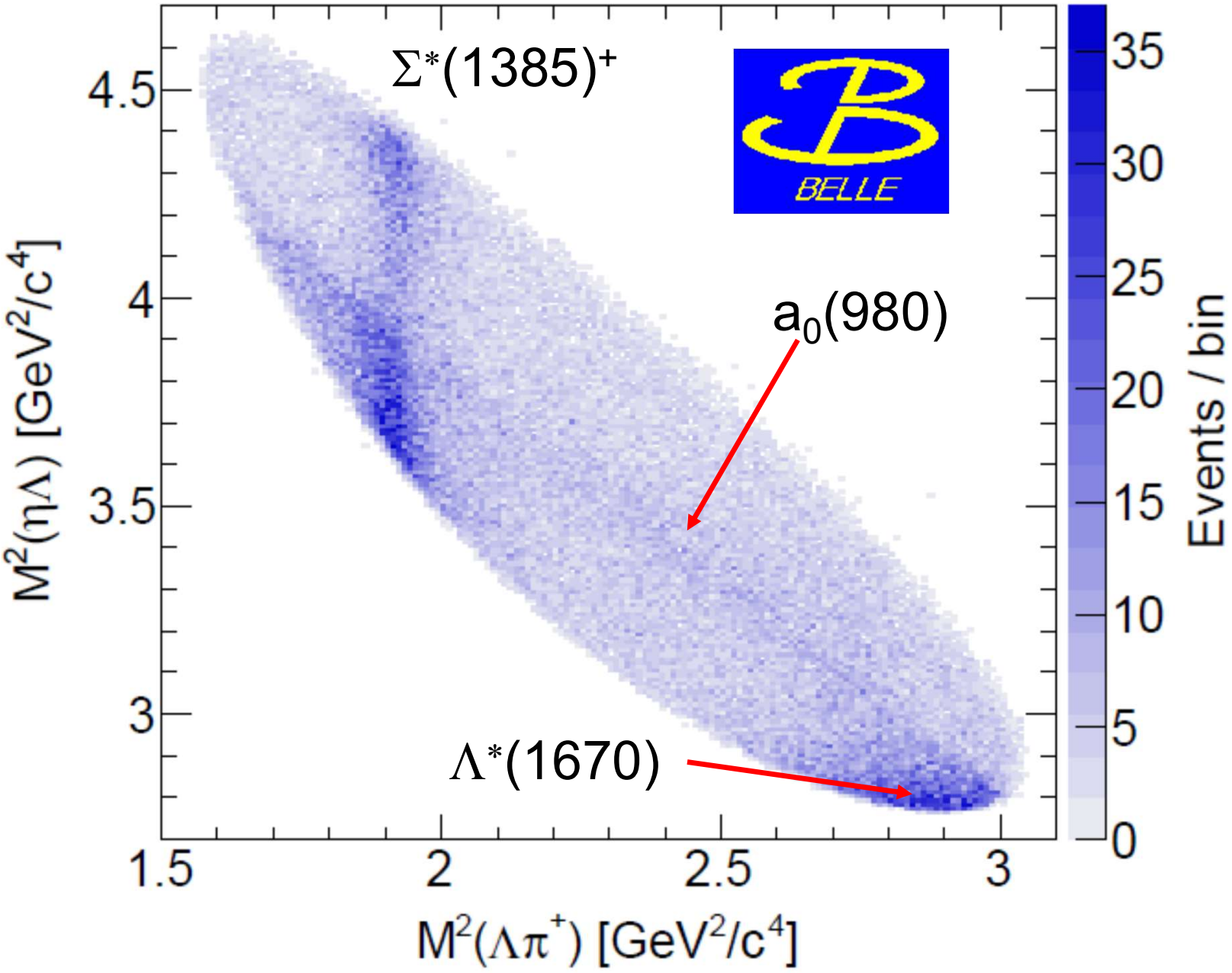
- The peak position is ~1663 MeV, near the $\Lambda\eta$ threshold (1663.5 MeV)
- Width is ~10 MeV, significantly narrower than Λ, Σ resonances in this region
  - $\Lambda(1670)$: 25-50 MeV
  - $\Sigma(1660)$: 40-200 MeV
  - $\Sigma(1670)$: 40-80 MeV
  - $\Lambda(1690)$: ~60 MeV
- No such narrow states are theoretically predicted in this region – new exotic resonance?
- Is it seen in other channels? E.g., $\Lambda\eta\pi$

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

[Belle, PRD103 (2021) 052005]



Dalitz plot

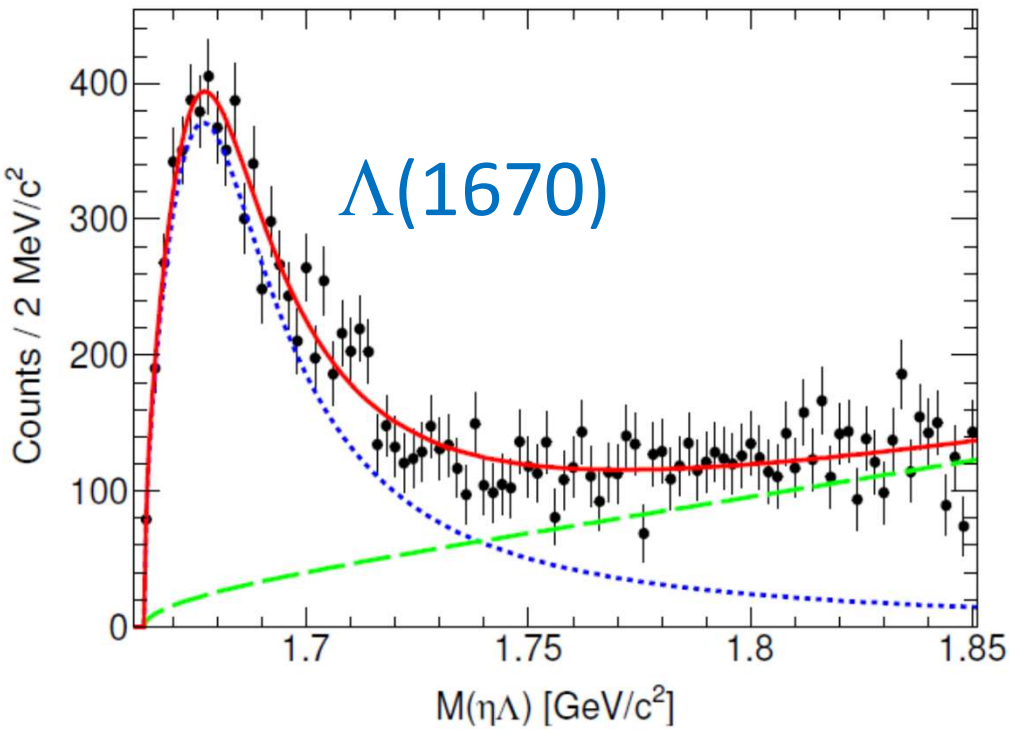


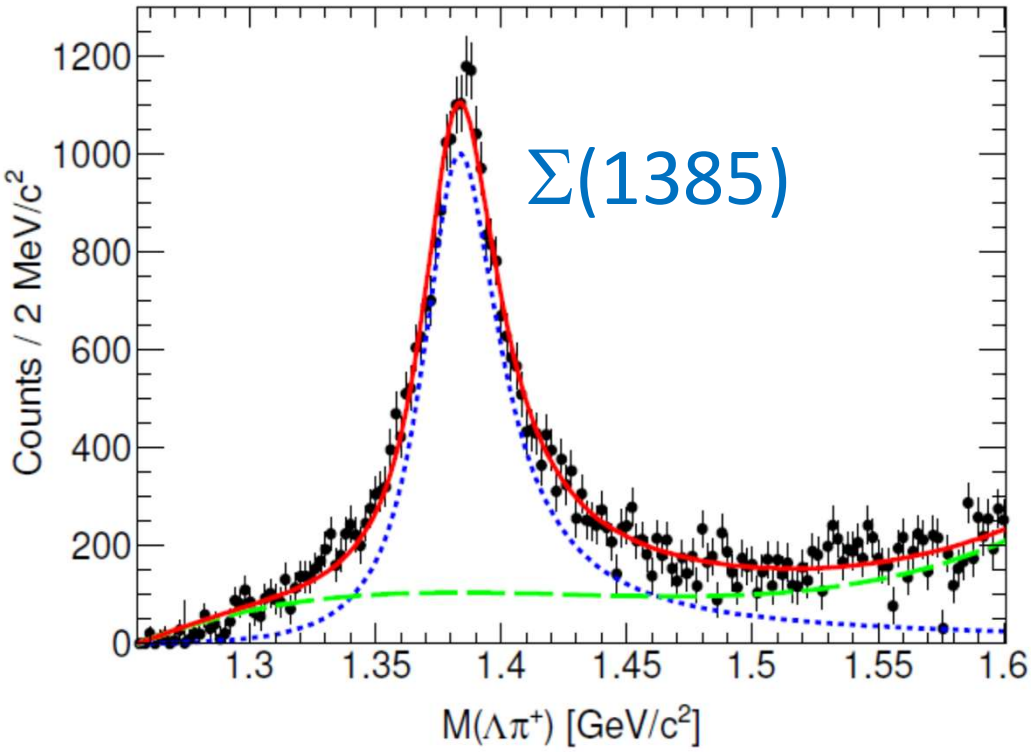
- Includes non-Λ_c BG
- Reso-nances are clearly seen

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	$0.120 \pm 0.006 \pm 0.006$
$\Lambda_c^+ \to \Lambda(1670)\pi^+$; $\Lambda(1670) \to \eta\Lambda$ New	$(5.54 \pm 0.29 \pm 0.72) \times 10^{-2}$
$\Lambda_c^+ \to \eta\Sigma(1385)^+$	$0.192 \pm 0.006 \pm 0.016$

- $\Lambda(1670)\pi^+$, $\Sigma^0\eta\pi^+$ 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)%

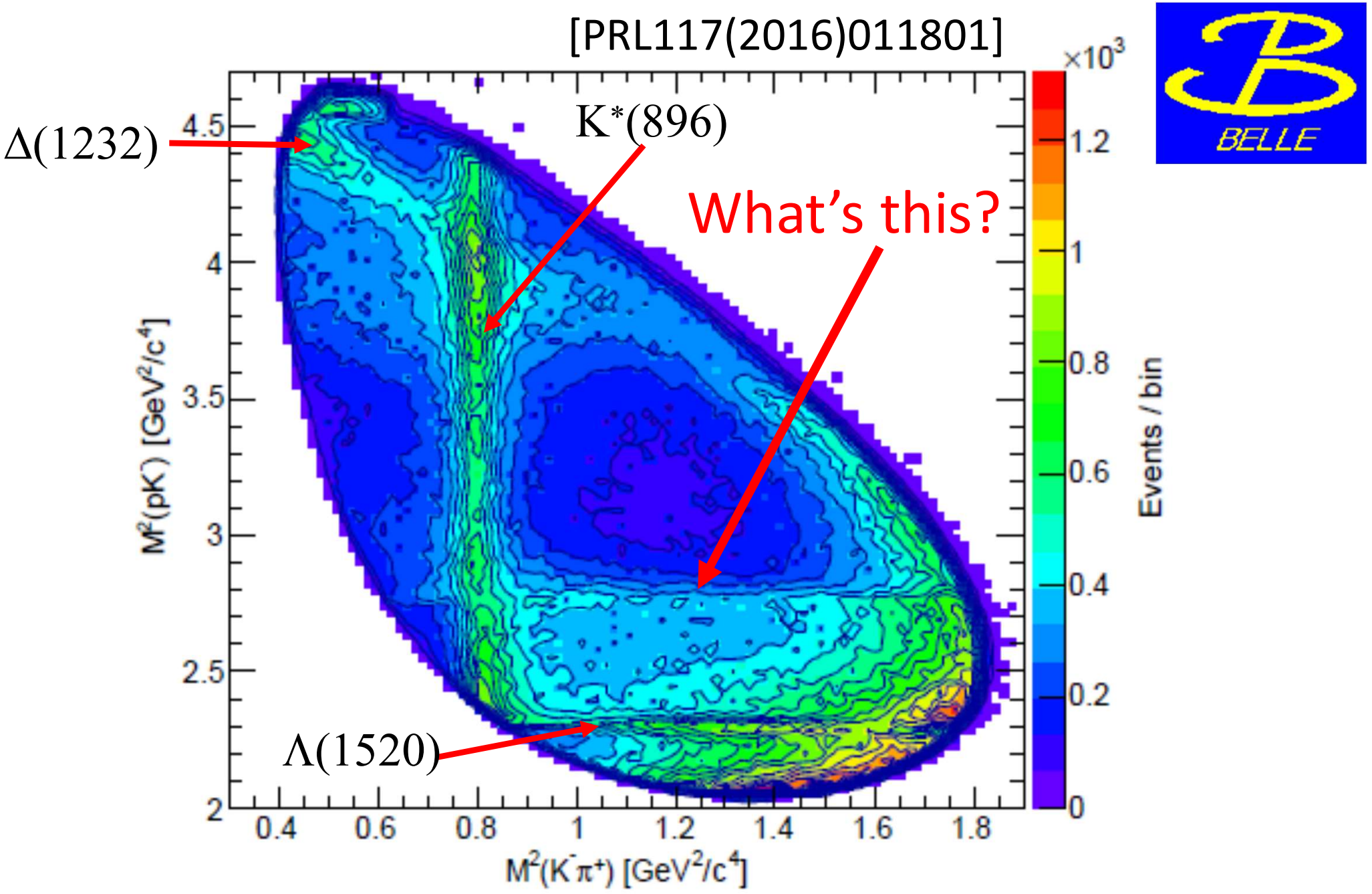
Results (2) – Mass & width

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

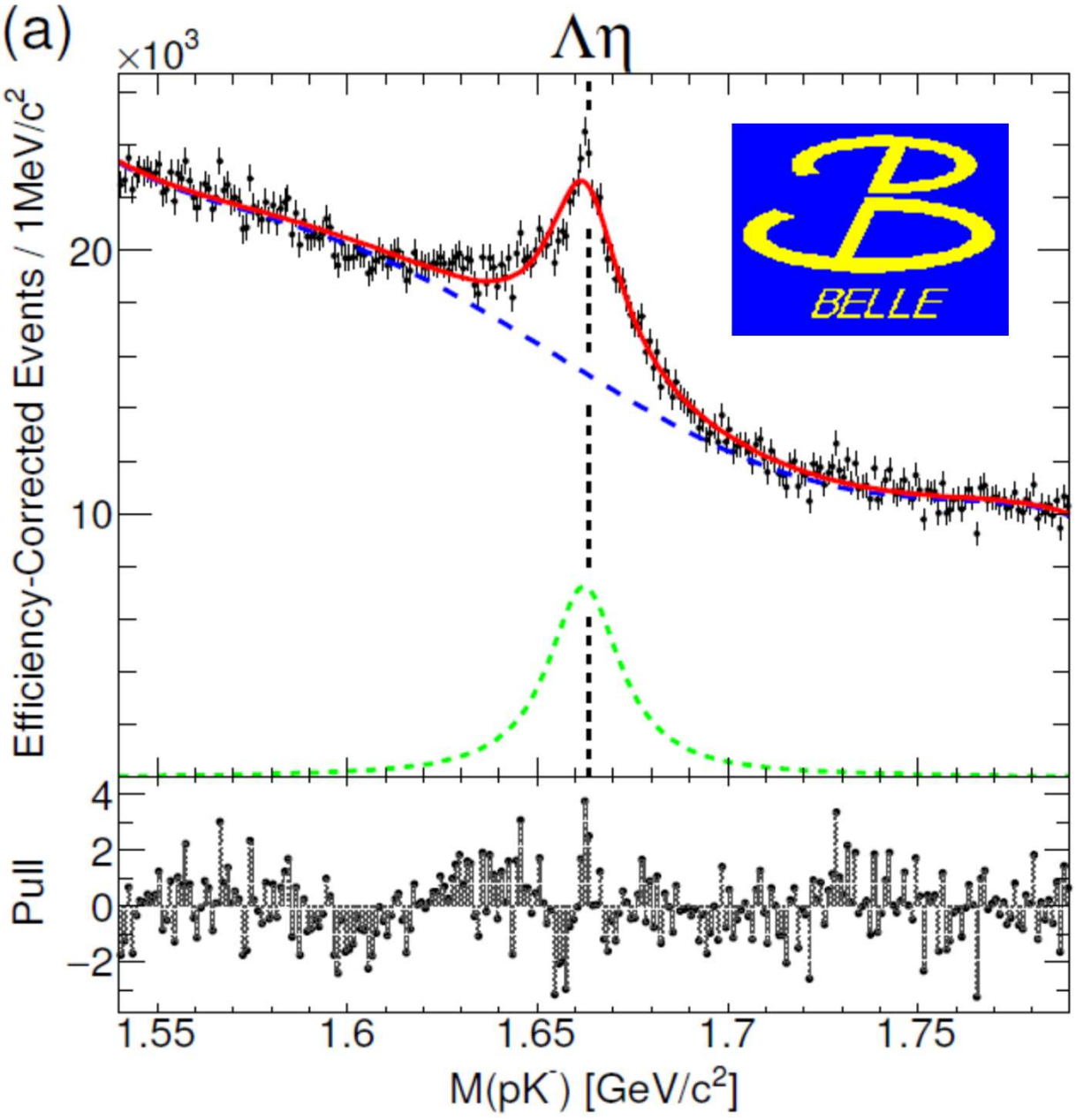
- $\Sigma(1385)^+$: consistent with PDG within uncertainty
- $\Lambda(1670)$: determined from peaking structure for the first time with a good accuracy.

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

[PRL117(2016)011801]



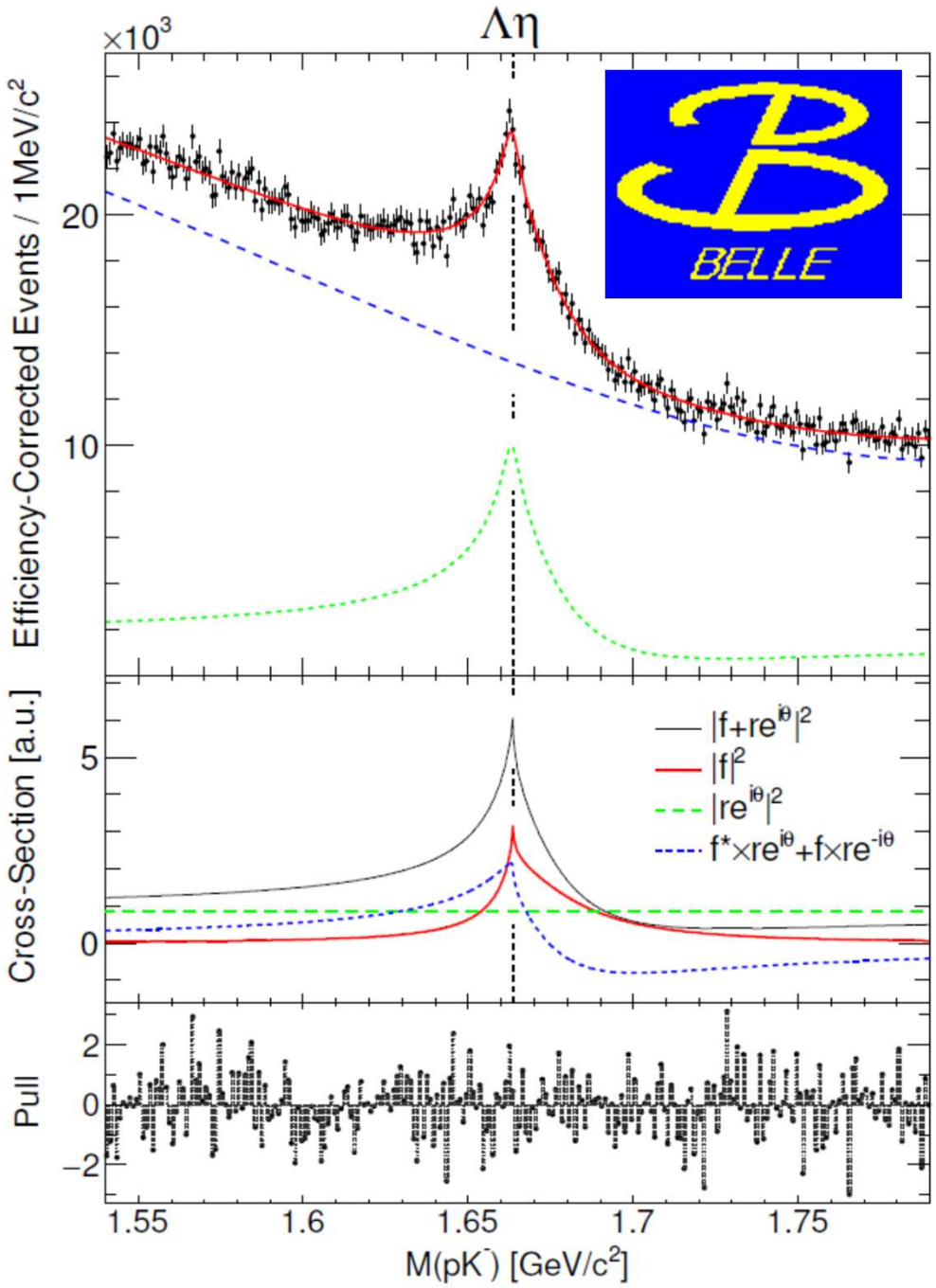
Fit to Breit-Wigner



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

[arXiv:2209.00050, submitted to PRL]

Fit to Flatte



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

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 $\Lambda_c \to \Lambda\eta\pi^+$

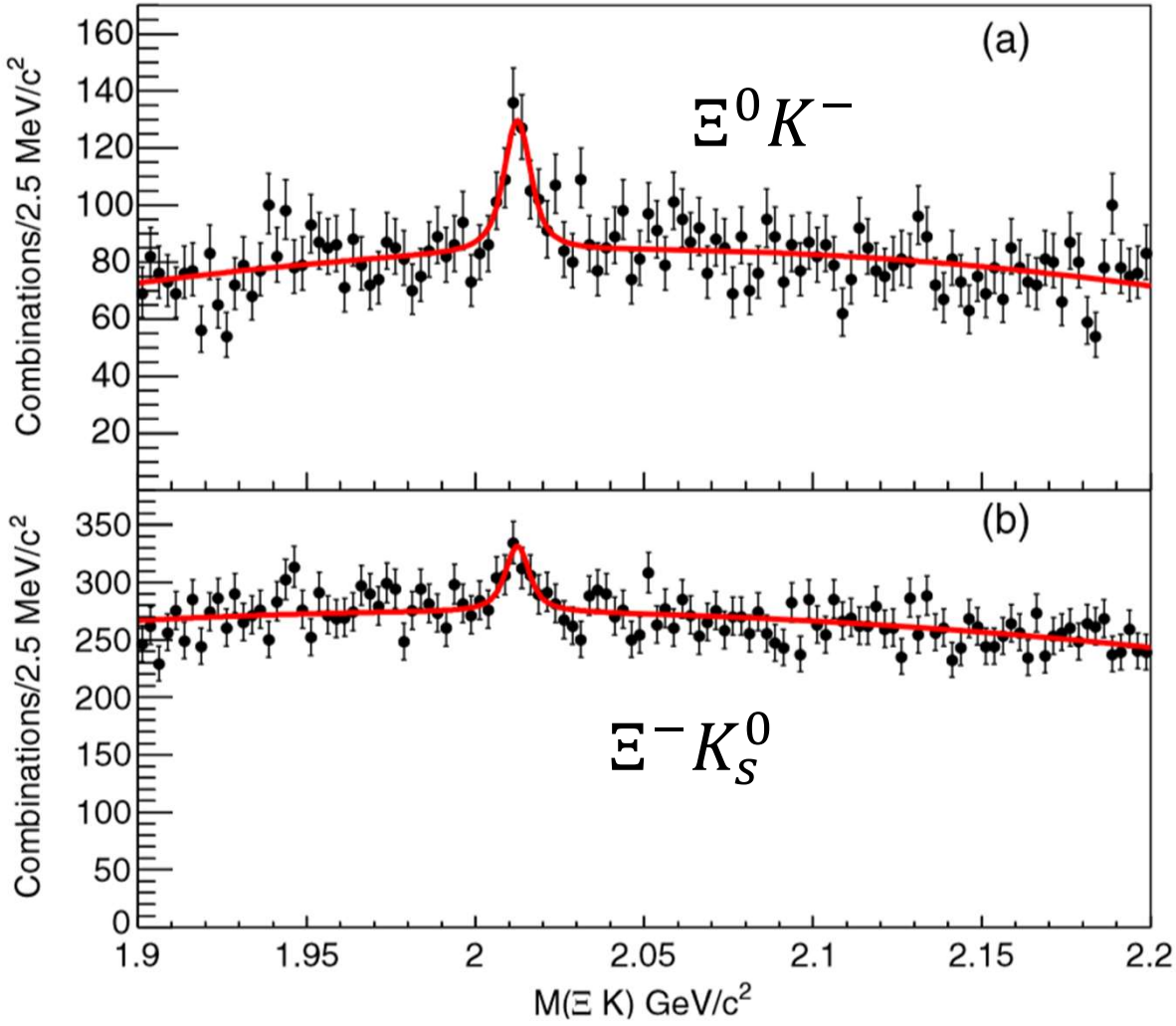
	Present result	$\Lambda\eta\pi^+$ mode
Mass	1674.4	$1674.3 \pm 0.8 \pm 4.9$
Width	$50.3 \pm 2.9^{+4.2}_{-4.0}$	$36.1 \pm 2.4 \pm 4.8$

- How about other near-threshold exotic hadrons?
  - **They may be actually threshold cusps!**

$\Omega(2012)$

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

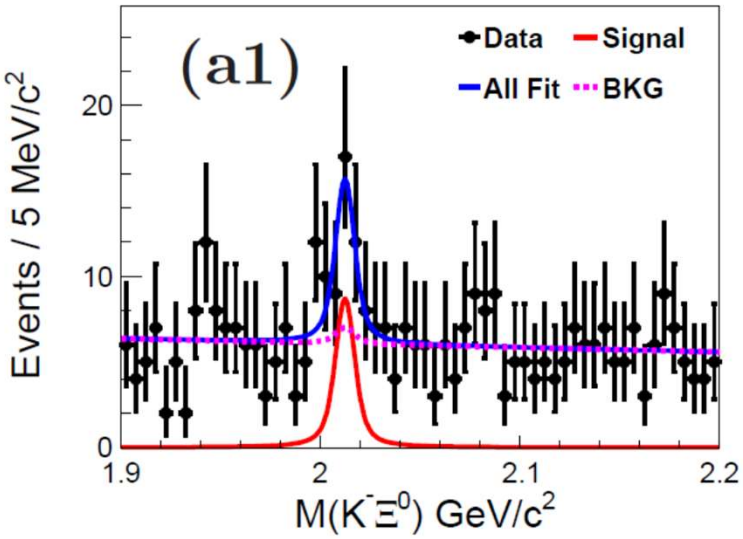
[Belle, PRL121 (2018) 052003]

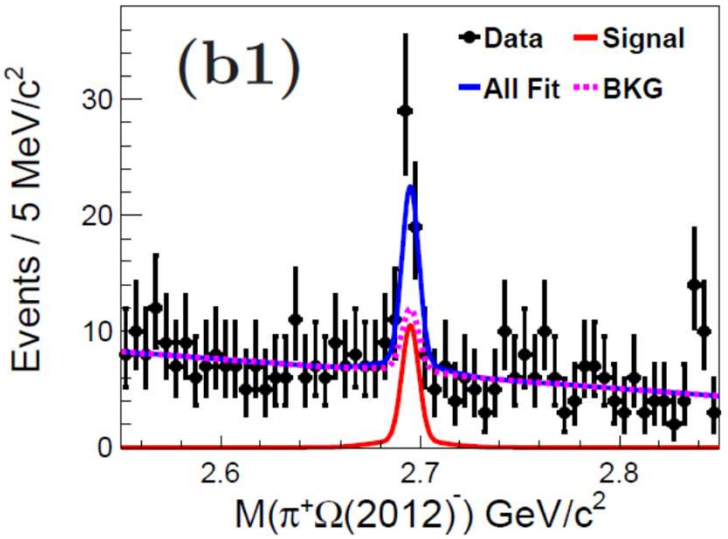


$\Omega_c \rightarrow \Omega(2012)\pi^+$

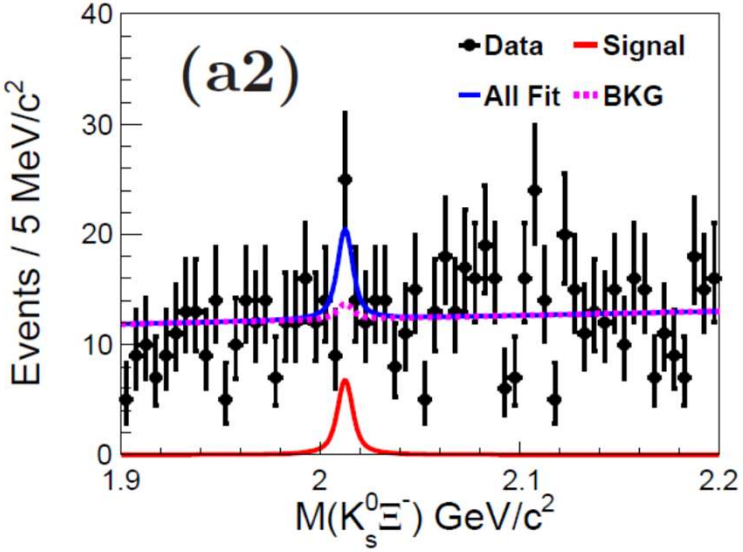
- Decay mode: $\Omega_c \rightarrow (\Omega^*\pi^+) \rightarrow \Xi K\pi^+$

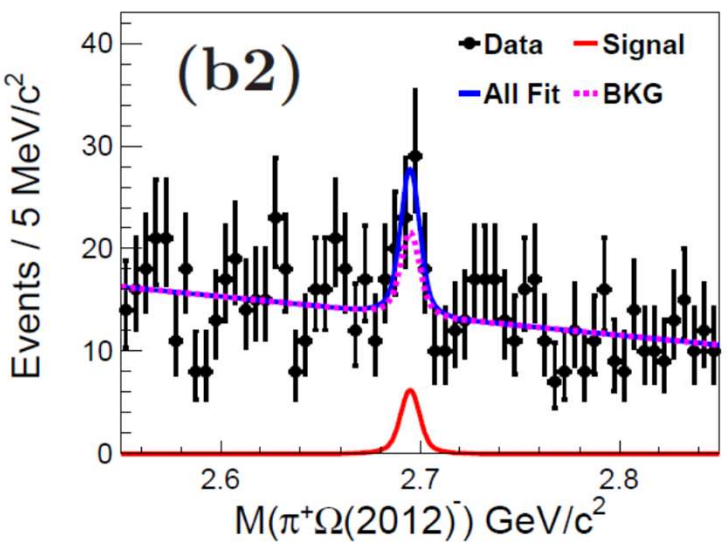
[Belle, PRD104 (2021) 052005]





$K^-\Xi^0$





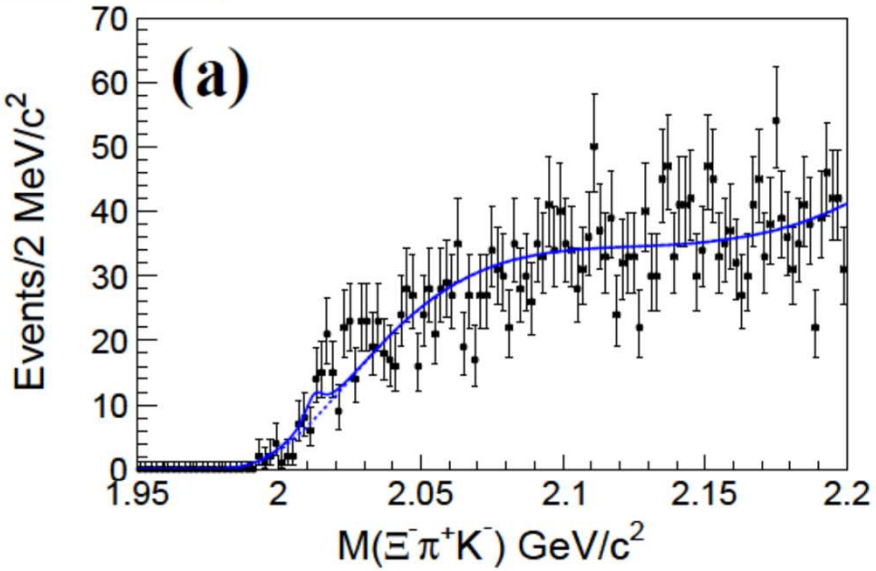
$K^0_S\Xi^-$

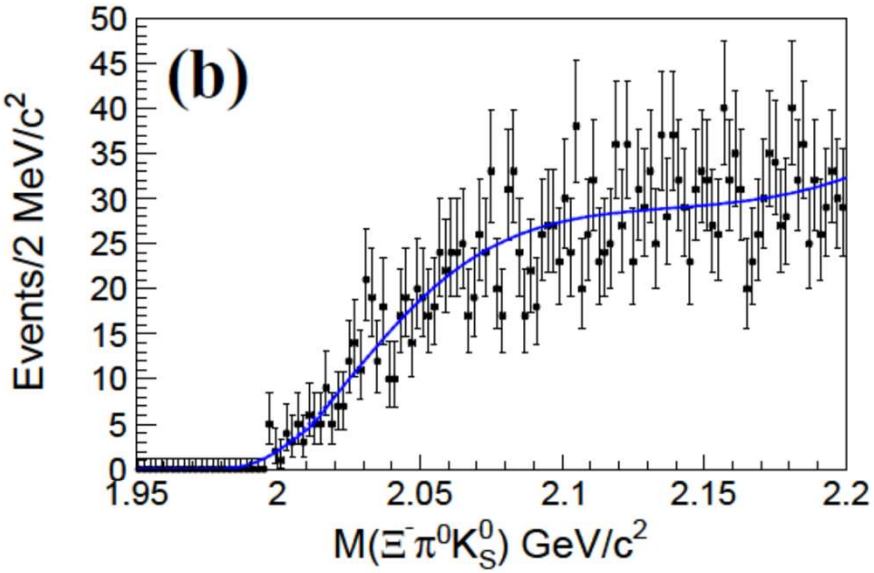
$\Omega(2012) \rightarrow \Xi(1530)\overline{K}$

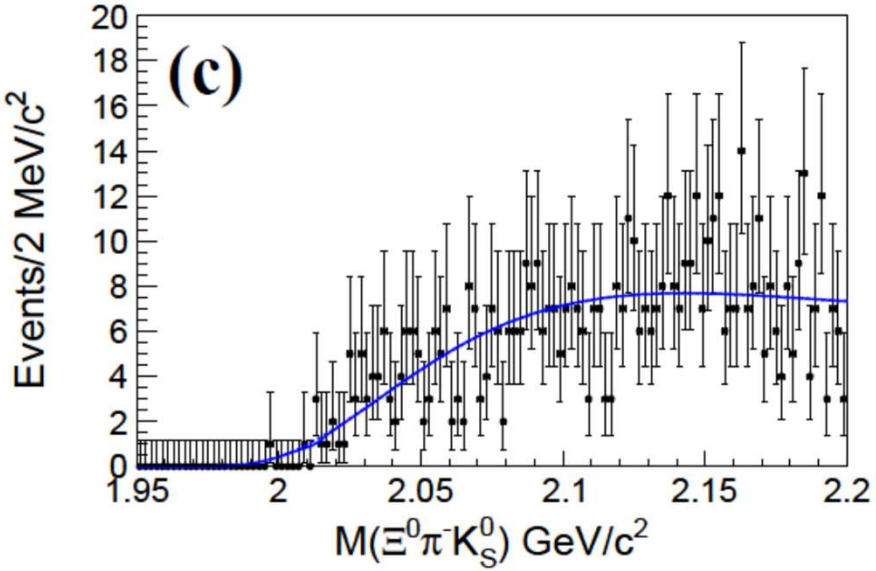
- Quark model: 1P orbital excited states expected in this mass region: J^P=1/2$^-$ and 3/2$^-$
- The narrow width favors a J^P=3/2$^-$ state, of which decay to ΞK is D-wave and thus suppressed.
- However, there are claims that
  it could be a $\Xi(1530)K$ hadronic molecule
  [PRD **98** (2018) 054009,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

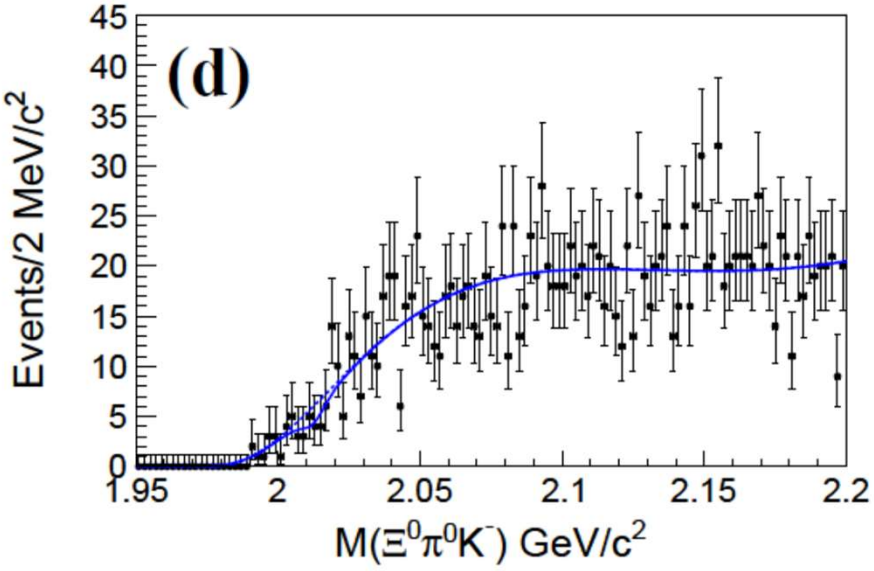
Previous study

[Belle, PRD 100 (2019) 032006]



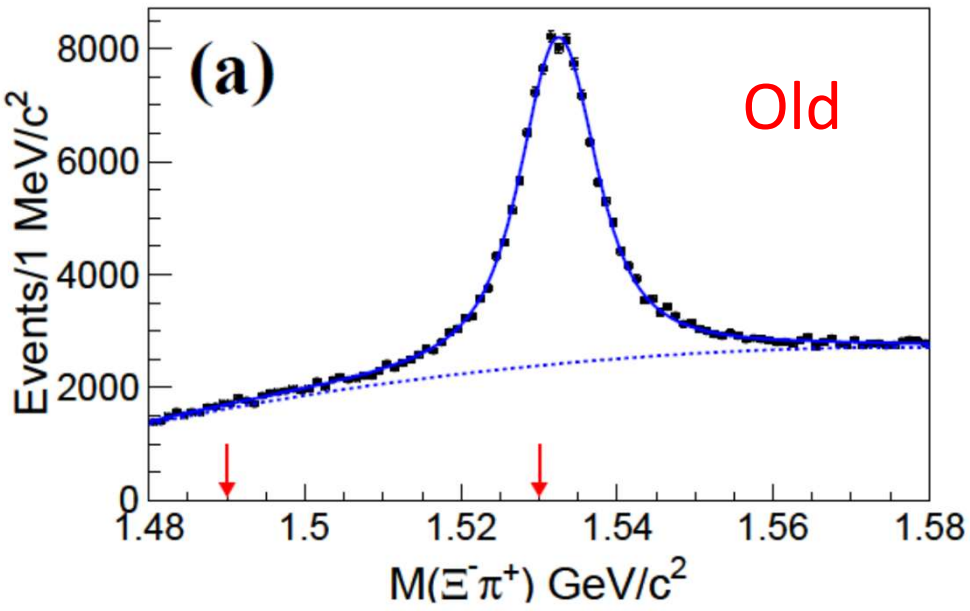


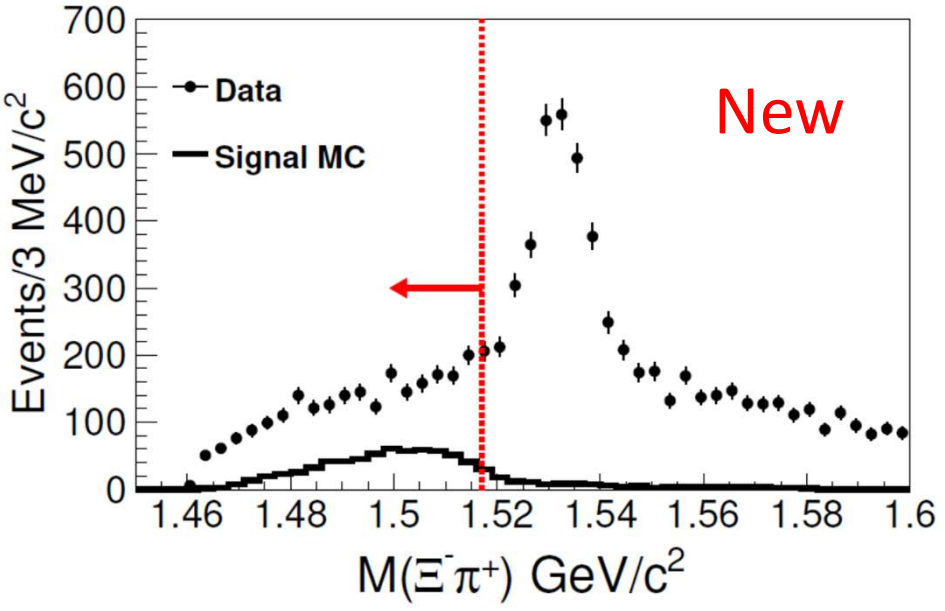




What's the difference?

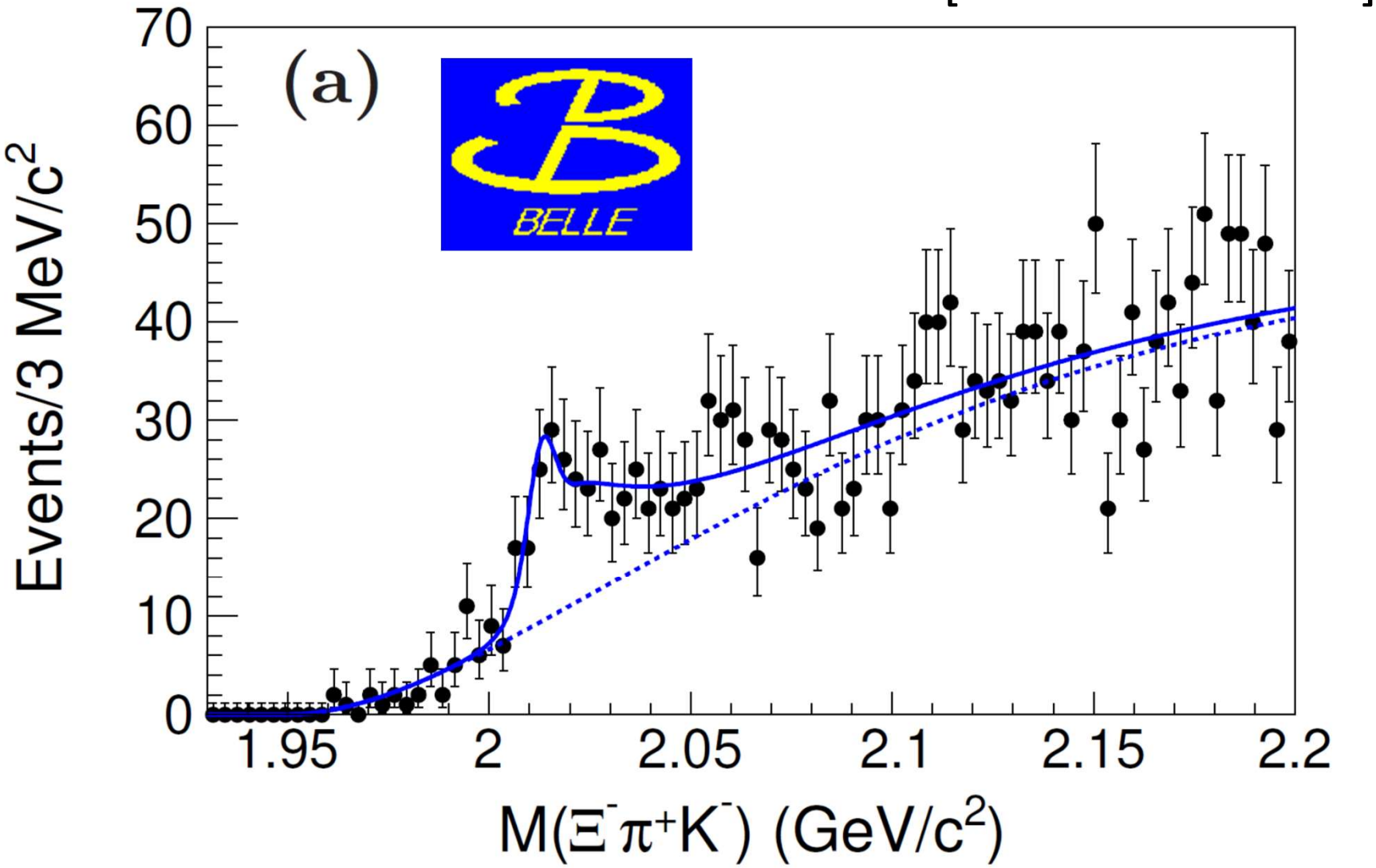
- Choice of Ξ(1530)
  - Phase space is very limited
  - Lighter mass region has larger phase space
  - The region chosen is now completely off-peak





New result

[arXiv:2207.03090]



Signal seen!

New result (cont.)

- Branching ratio: 3 body ($\Xi K\pi$) vs 2 body (ΞK)

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

  – Consistent with molecular model

- Effective coupling=(partial width)/(phase space)

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

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

  → coupling to $\Xi K\pi$ is much stronger

  (assuming no non-resonant contribution)

Summary & prospects

- Belle is still producing lots of interesting results
  ~10 baryon papers every year
- Topics of the day
  - Spin-parity measurement of $\Xi_c(2970)$
  - Evidence for a new charmed baryon, $\Lambda_c(2910)$
  - $\Lambda(1670)$ and a cusp at the $\Lambda\eta$ threshold
  - $\Omega(2012)$: $\Xi(1530)$K molecule?
- **More results are coming!**
- Taking more data with Belle II
  → See J. Yelton's talk (earlier today in parallel 1)