

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.)

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Flavored Baryons in e^+e^- Collider

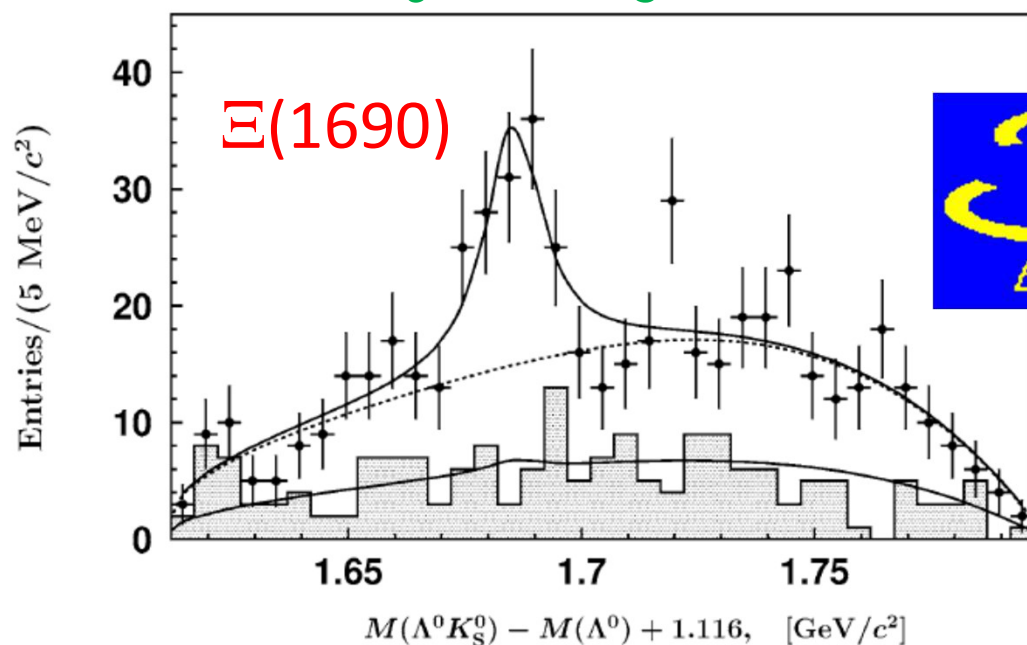
- Electron-positron colliders (CLEO, Belle, Babar, BESIII...) are known to be useful for mesons, especially, quarkonia.
- Today, I will demonstrate **they are also good for hyperons** by showing some of the recent results by Belle.

Why e^+e^- colliders?

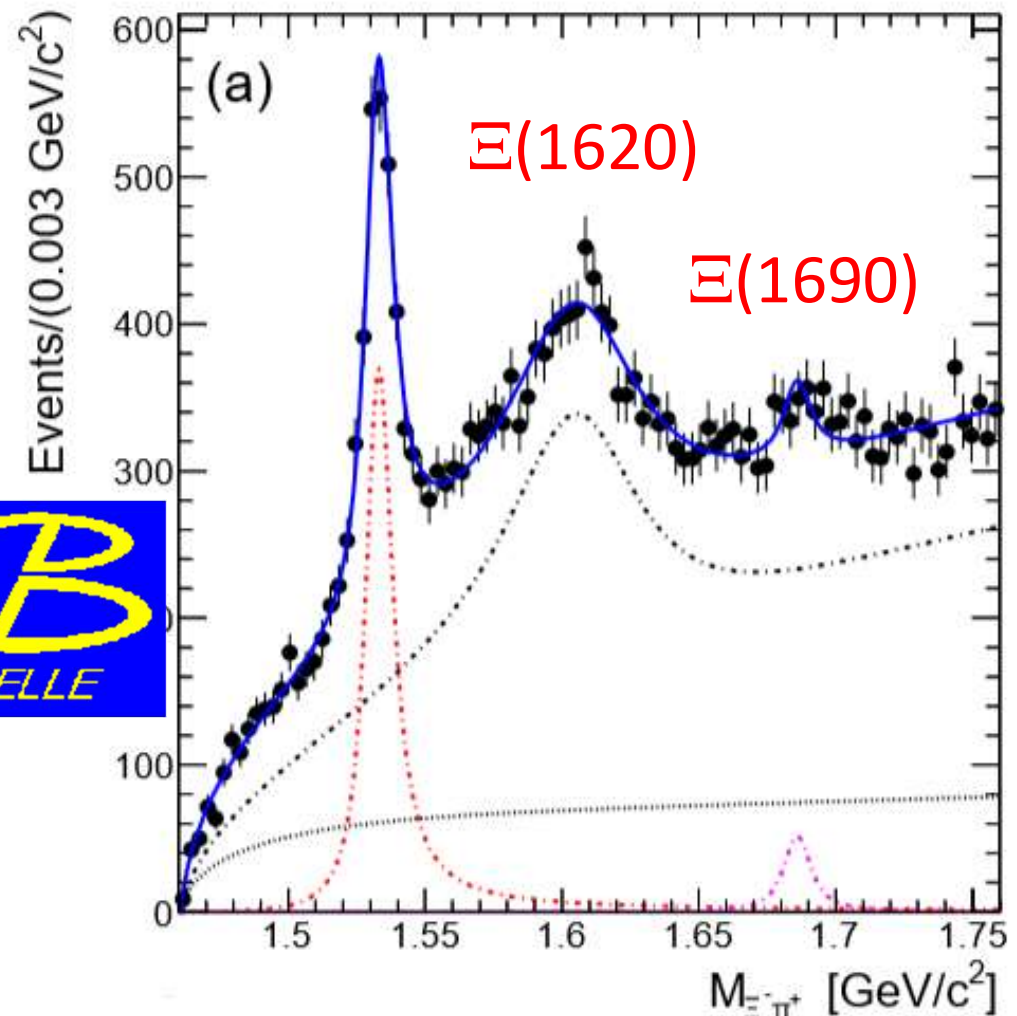
- Small background
 - $e^+e^- \rightarrow Q\bar{Q}$ production is flavor blind.
Only (charge)² matters \rightarrow Good for heavy quarks.
- Missing mass spectroscopy is possible
 - Absolute branching fraction
 - Study of decays with missing particles (n, ν , ...)
- Fragmentation+decays from bottom and 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

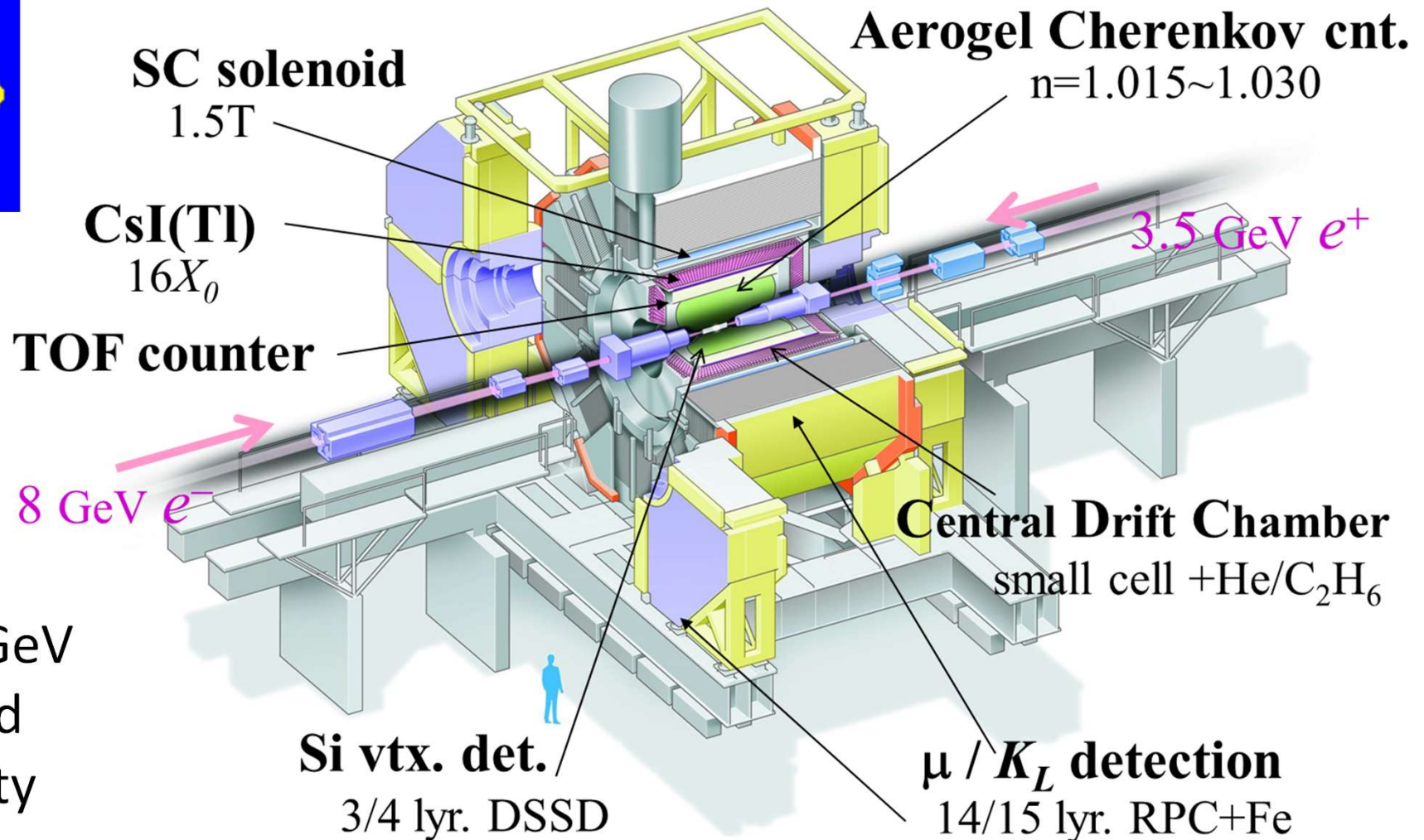


[Belle, PLB **524** (2002) 33-43]



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

Belle experiment



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

Topics of the day

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

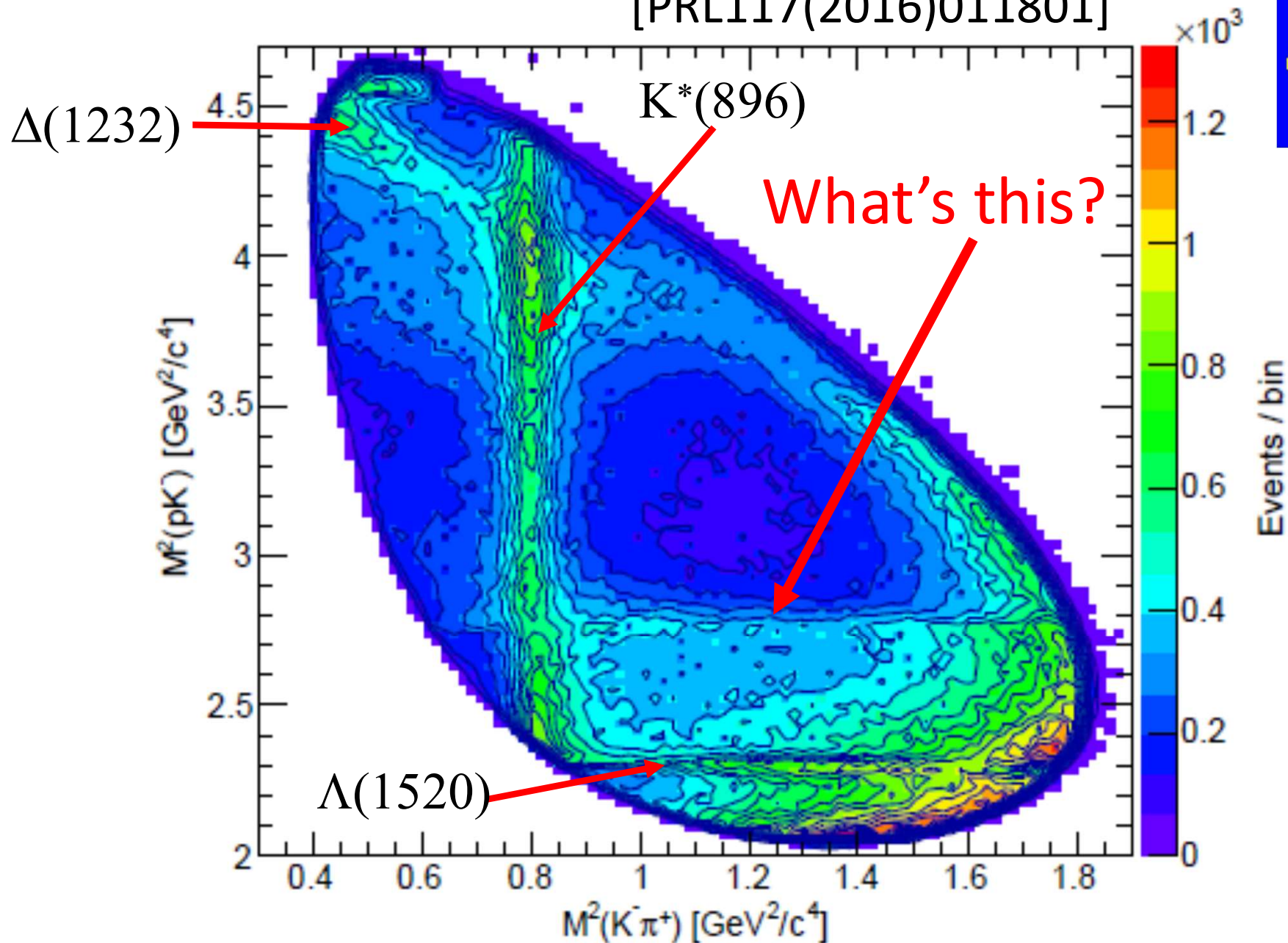
1. $\Lambda_c \rightarrow \Lambda \eta \pi^+$ and

$\Lambda(1670)$

[PRD103 (2021) 052005]

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

[PRL117(2016)011801]

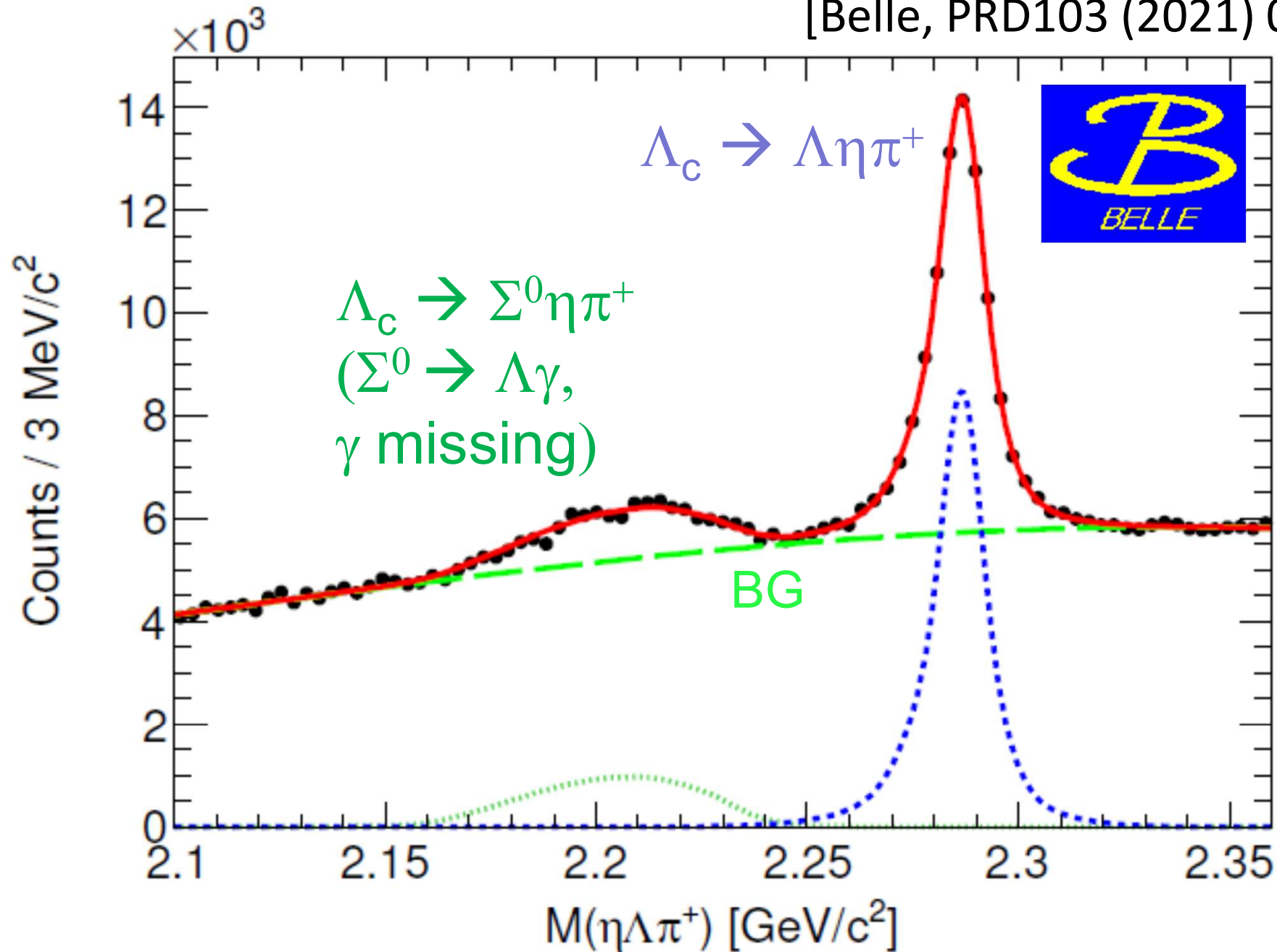


What's this?

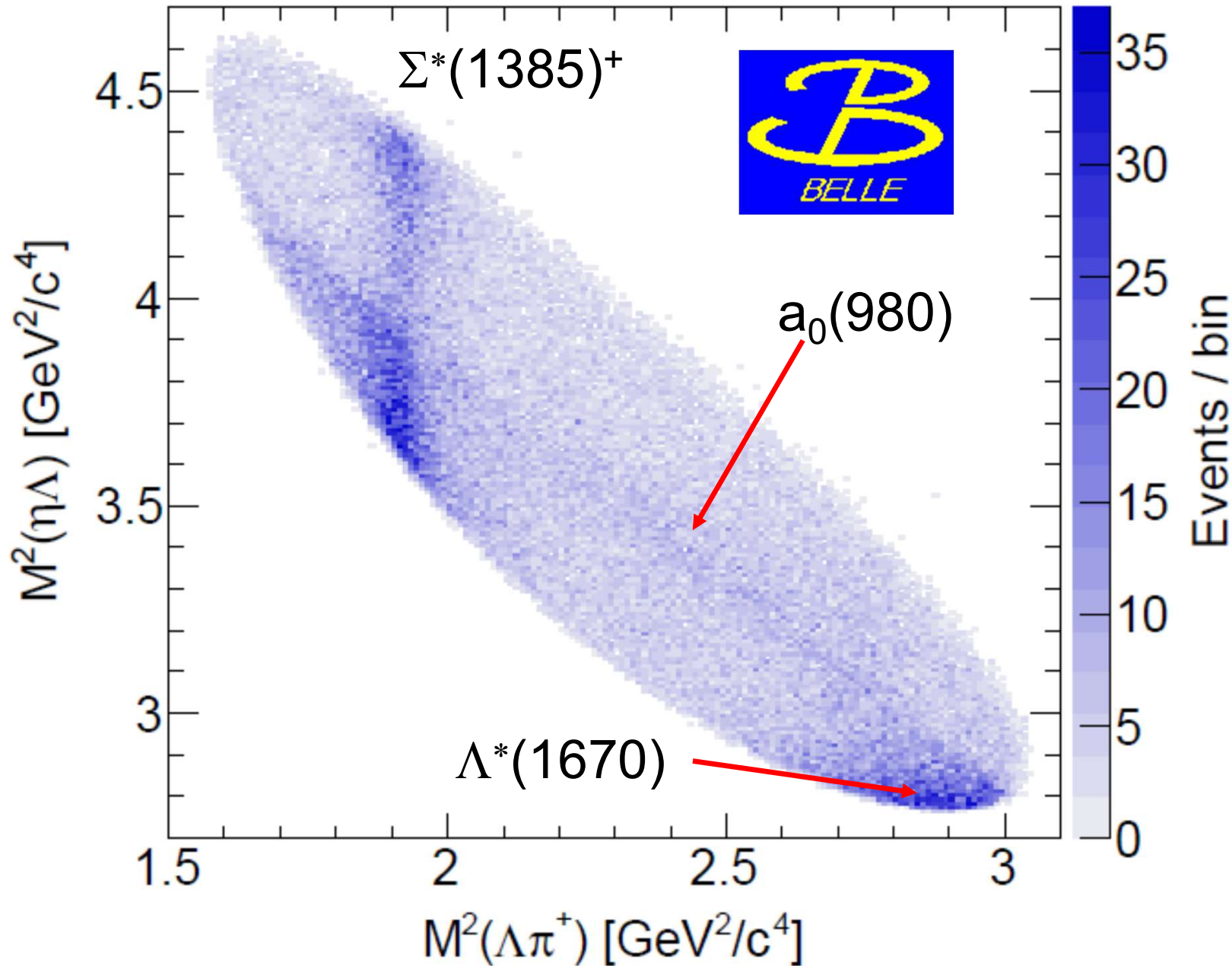
- The peak position is ~ 1663 MeV, near the $\Lambda\eta$ threshold (1663.5 MeV)
- Width is ~ 10 MeV, significantly narrower than Λ , Σ resonances in this region
 - $\Lambda(1670)$: 25-50 MeV
 - $\Sigma(1660)$: 40-200 MeV
 - $\Sigma(1670)$: 40-80 MeV
 - $\Lambda(1690)$: ~ 60 MeV
- No such narrow states 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



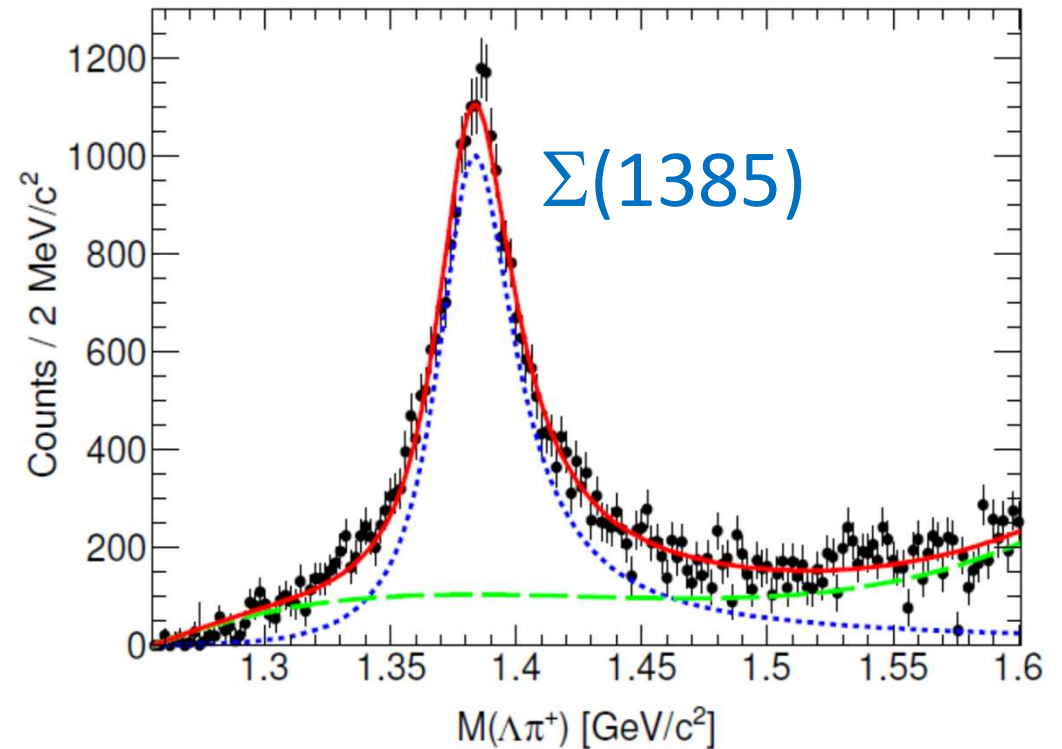
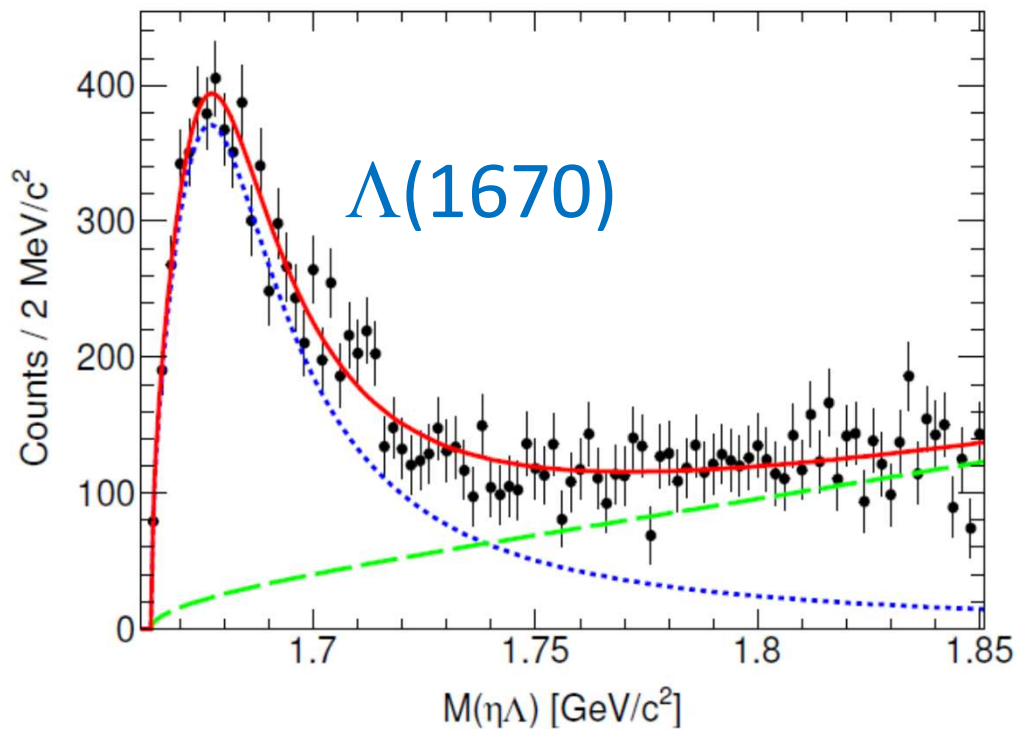
- Includes non- Λ_c BG
- Resonances are clearly seen

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

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

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.

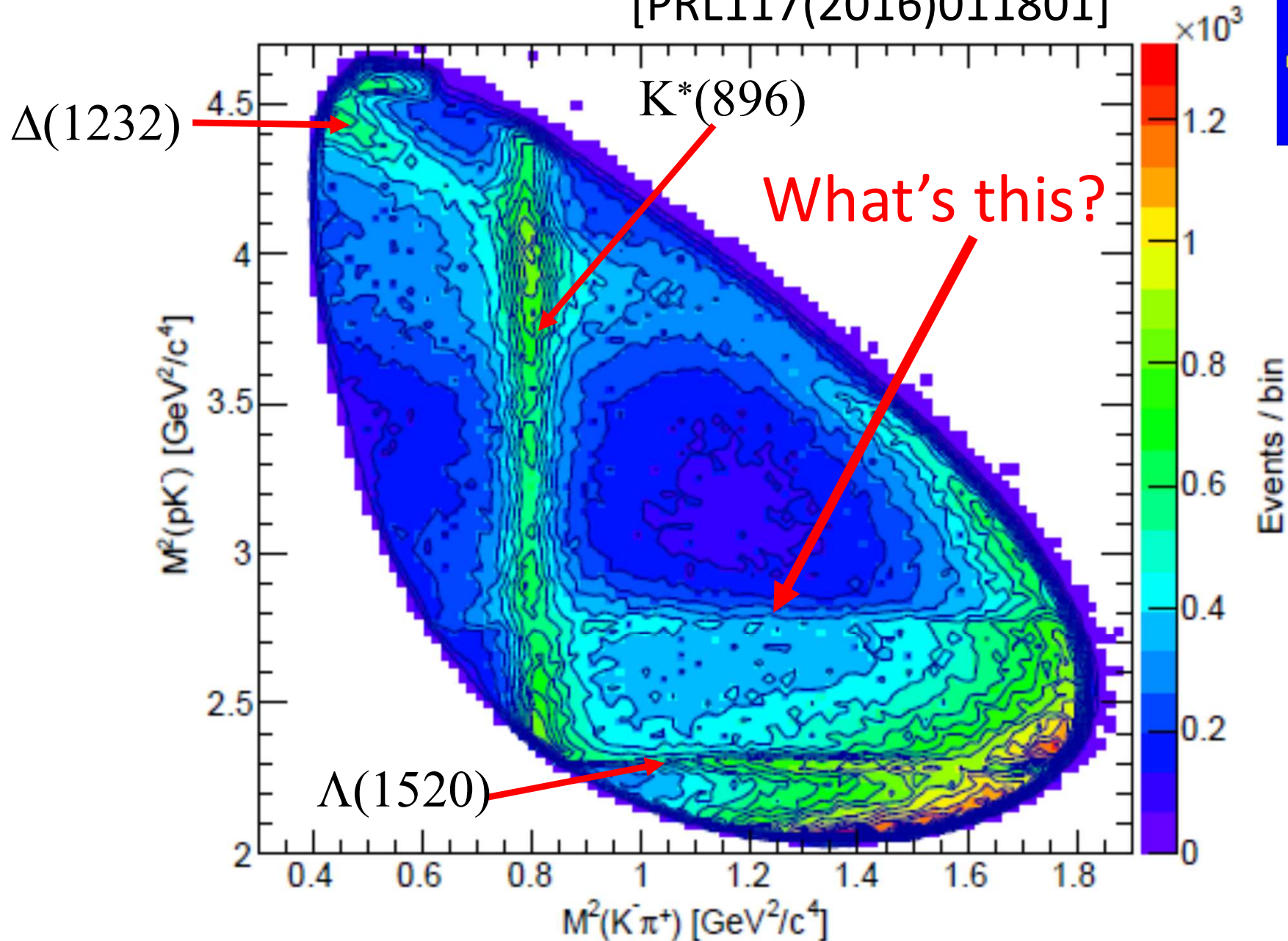
2. Identification of Threshold cusp in

$$\Lambda_c \rightarrow p K^- \pi^+$$

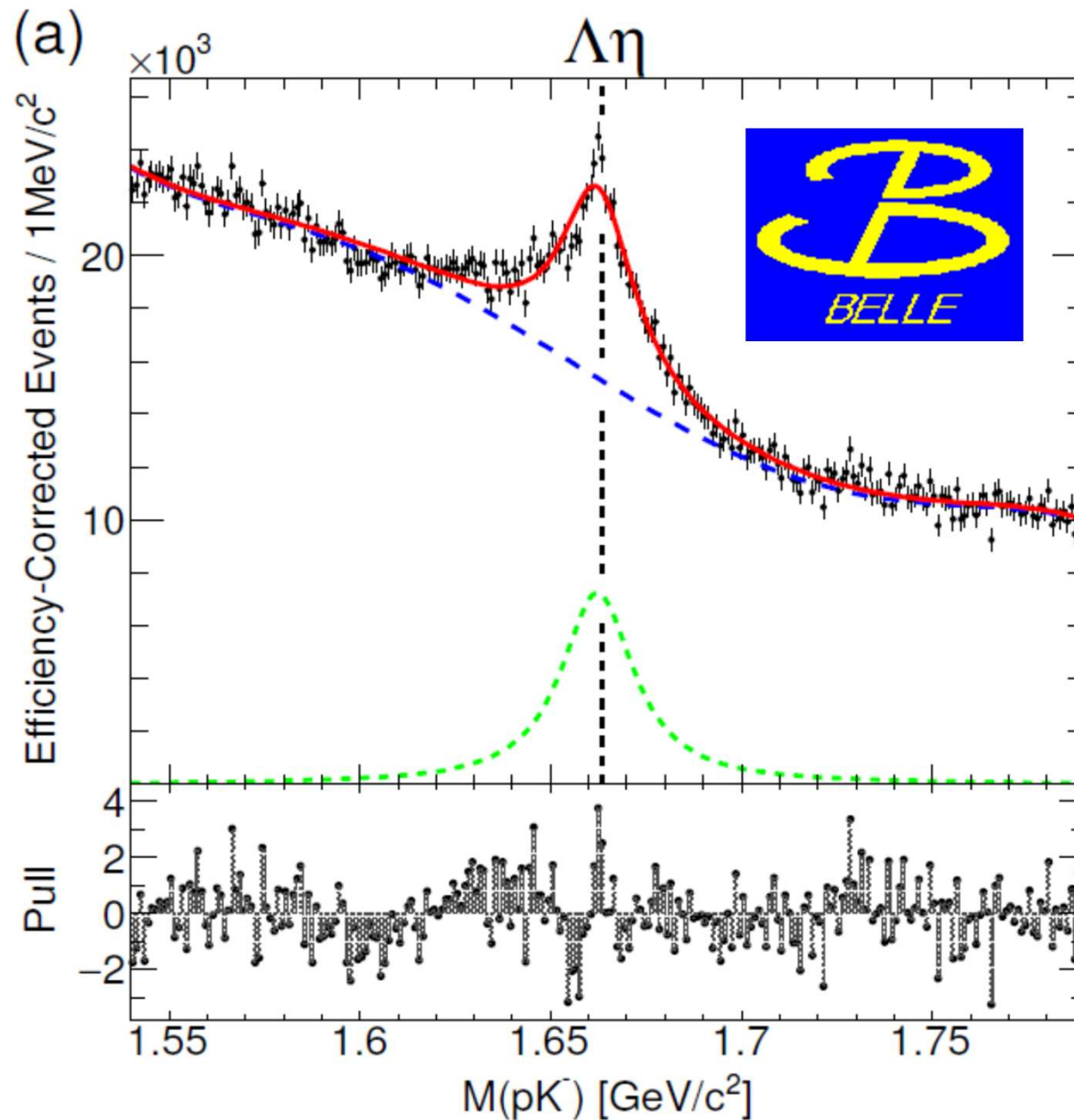
[PRD108.L031104(2023)]

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

[PRL117(2016)011801]



Fit to Breit-Wigner

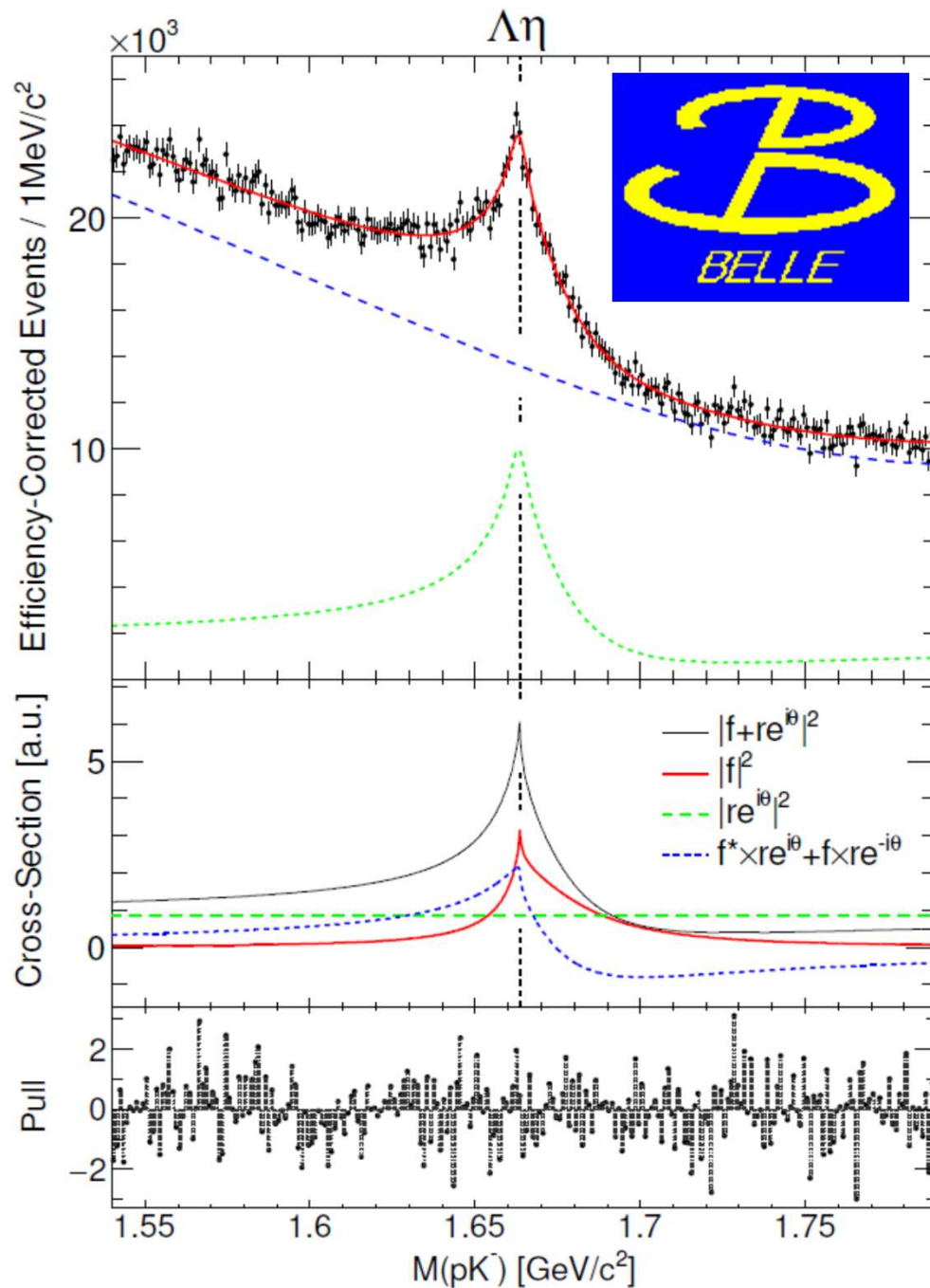


- Not very good especially near the peak.

- 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

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

- 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 $\Lambda_c \rightarrow \Lambda\eta\pi^+$

	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!**

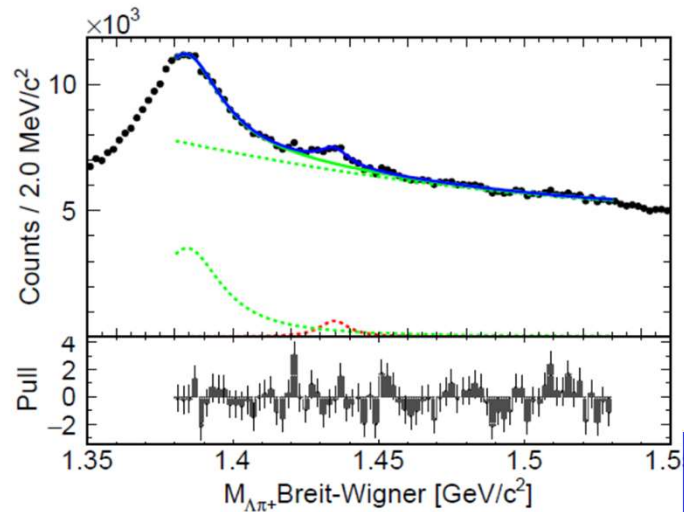
3. Peak at $\bar{K}N$
threshold in

$$\Lambda_c \rightarrow \Lambda \pi^+ \pi^+ \pi^-$$

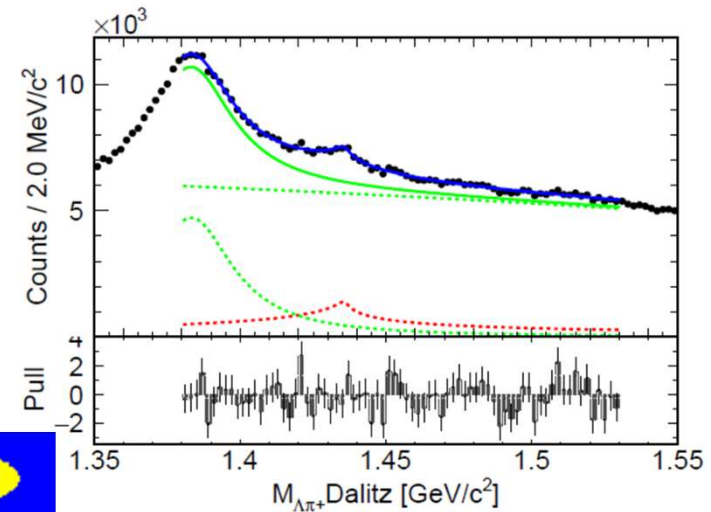
[PRL130(2023)151903]

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

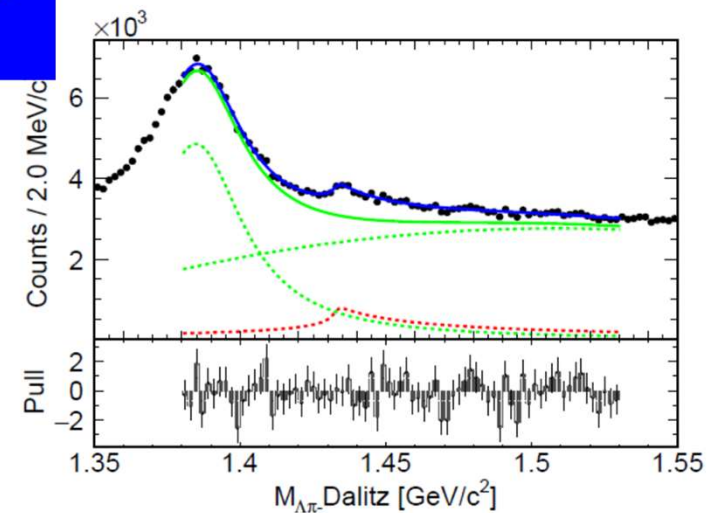
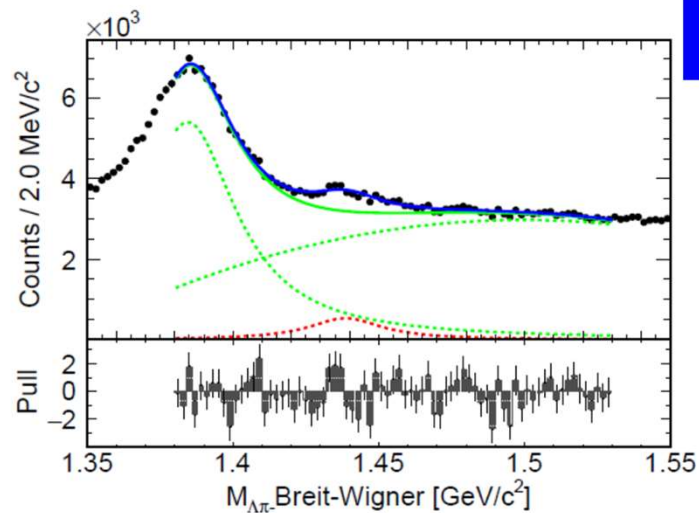
- Cusp candidates are observed in $\Lambda\pi^\pm$ invariant mass spectra, from Λ_c decay

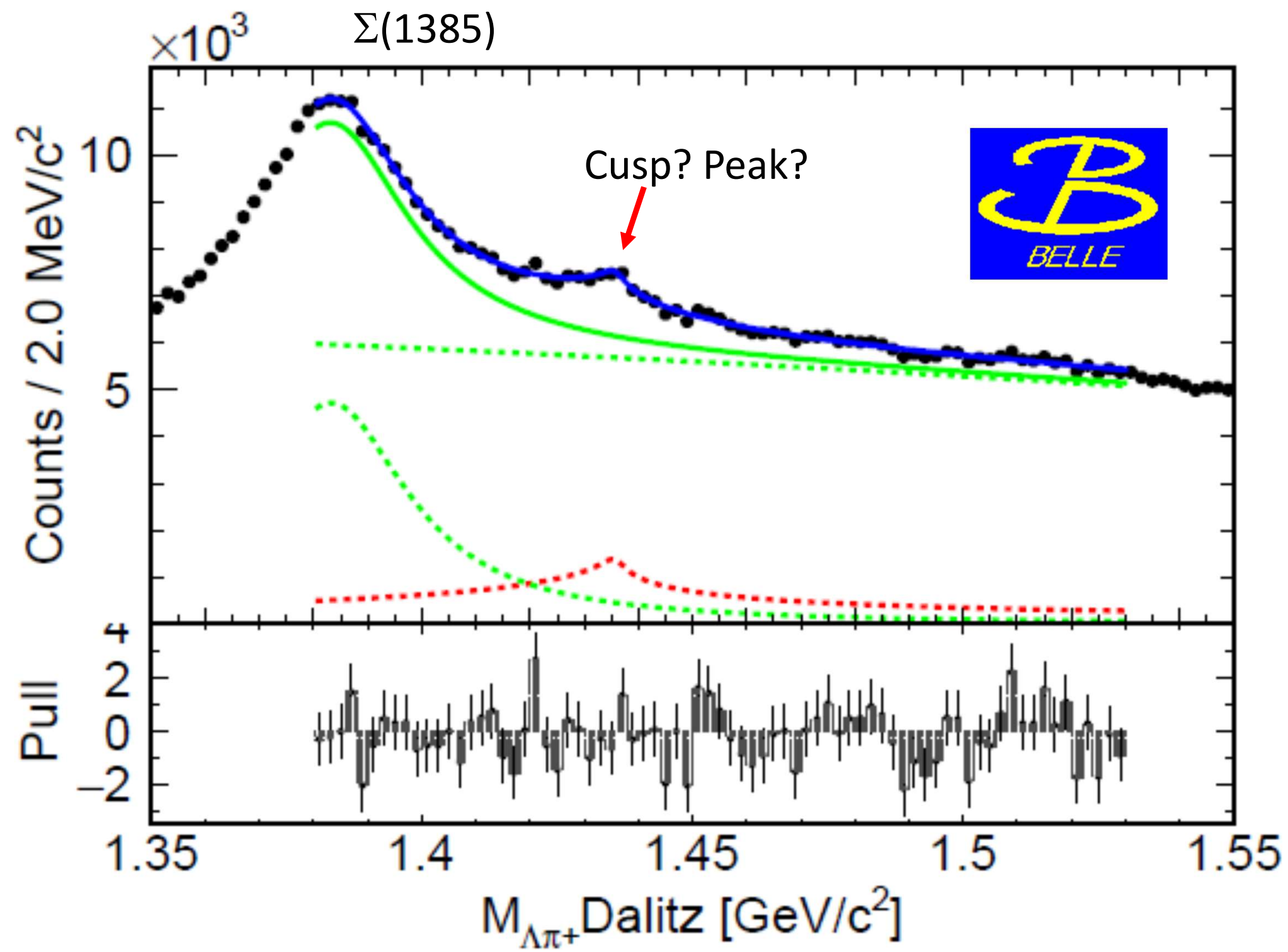


(a)



(a)





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. B32, 1021 (1982)]

For $\bar{K}N(I = 1)$ scattering length $A = a + ib$ and decay momentum $k/\kappa (= |k|$ 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

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

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

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

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

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

Results & discussions

2. Dalitz (cusp)

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

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

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

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

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

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

[Belle, PRD104 (2021) 052005]

$\Omega(2012)$

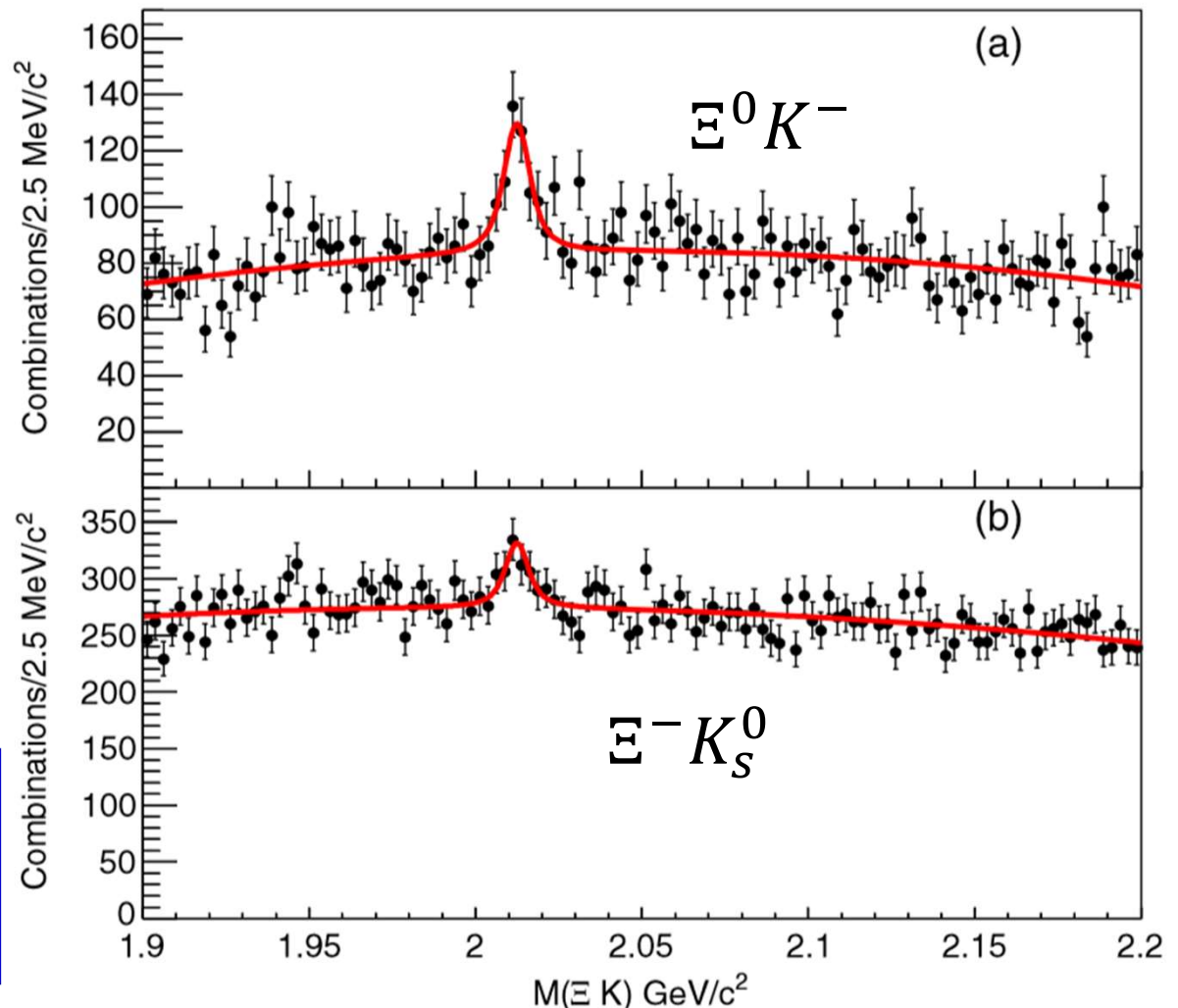
- Discovered in $\Upsilon(1-3S)$ decay.

- How about other channels?

– E.g.,

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

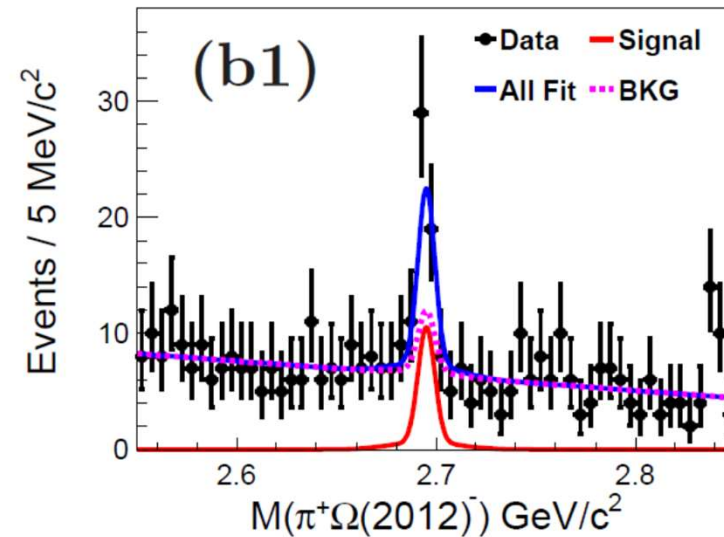
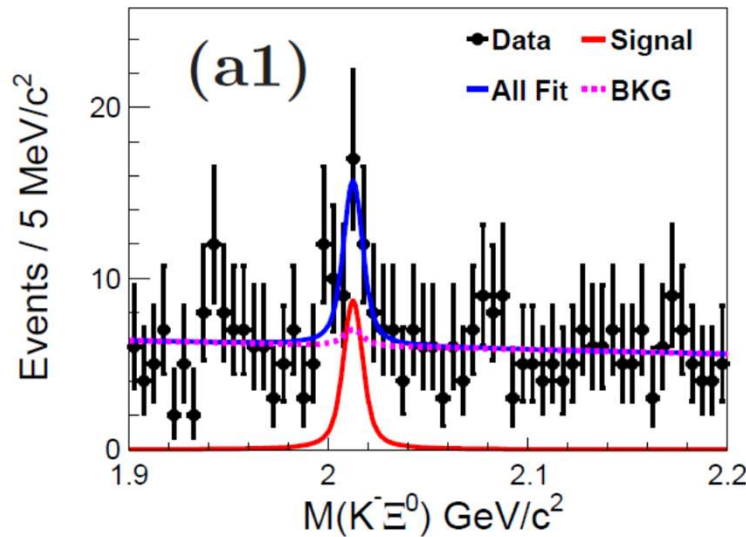
[Belle, PRL121 (2018) 052003]



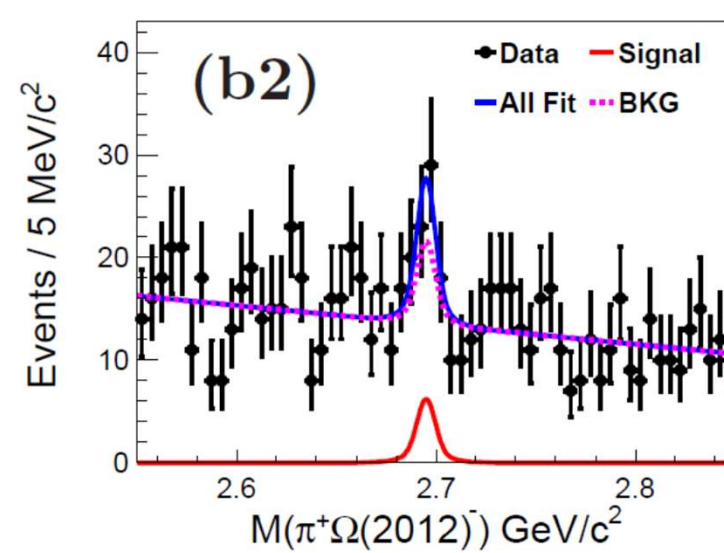
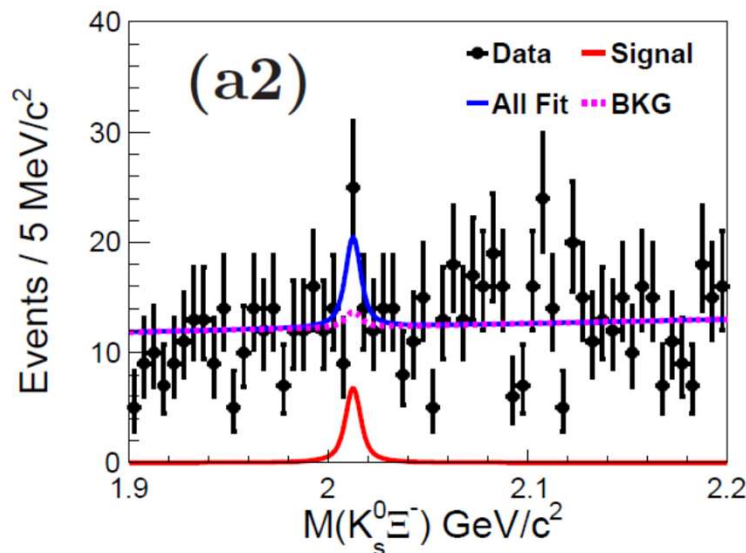
$$\Omega_c \rightarrow \Omega(2012)\pi^+$$

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

[Belle, PRD104 (2021) 052005]



$K^-\Xi^0$



$K_s^0\Xi^-$

5. $\Omega(2012)$
 $\rightarrow \Xi(1530)\bar{K}$
[arXiv:2207.03090]

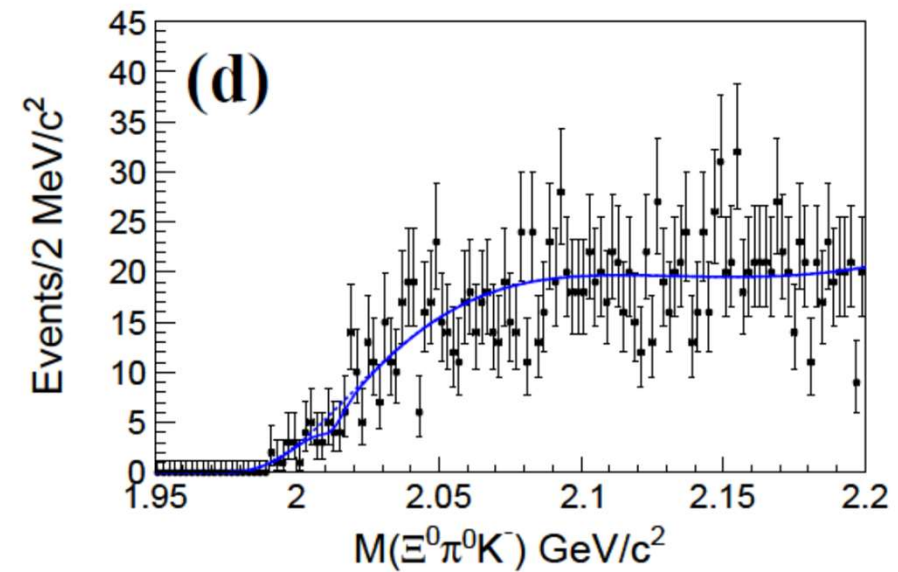
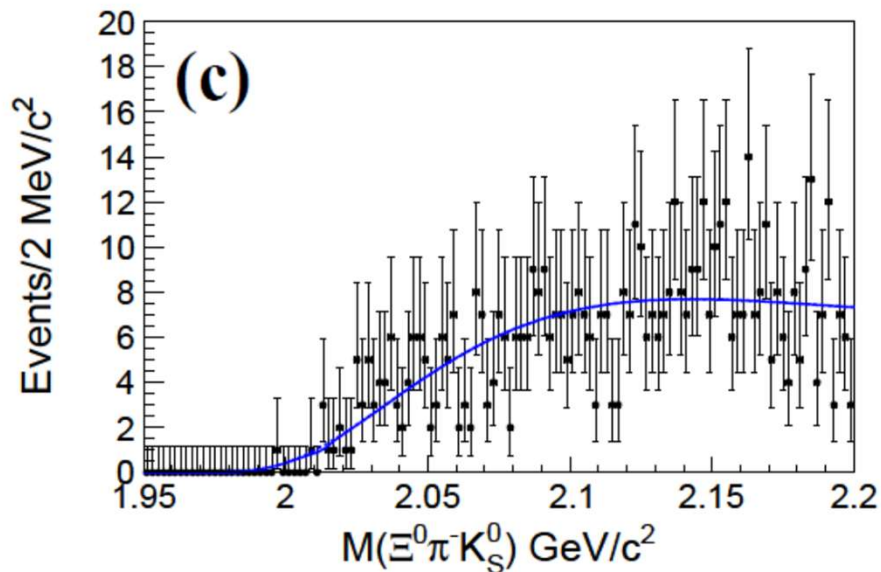
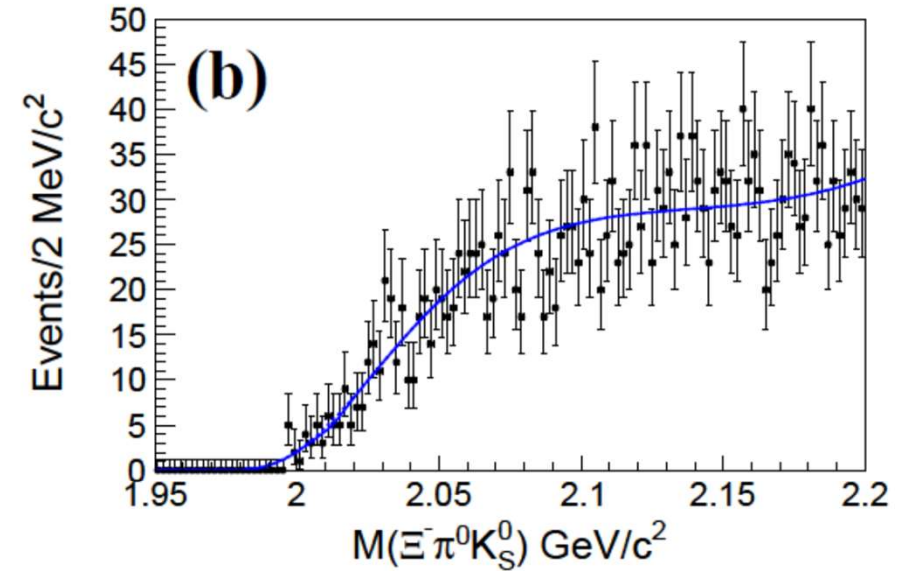
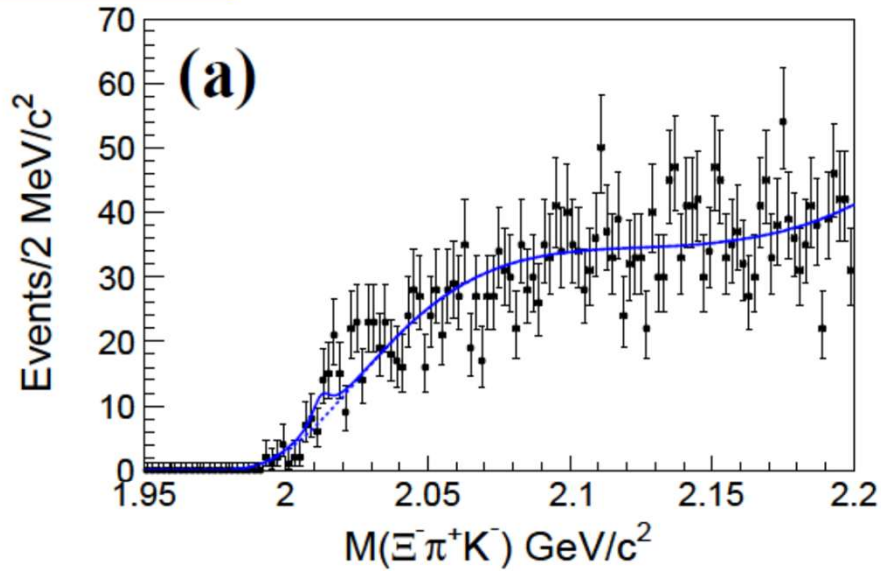
$\Omega(2012) \rightarrow \Xi(1530)\bar{K}$

- 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

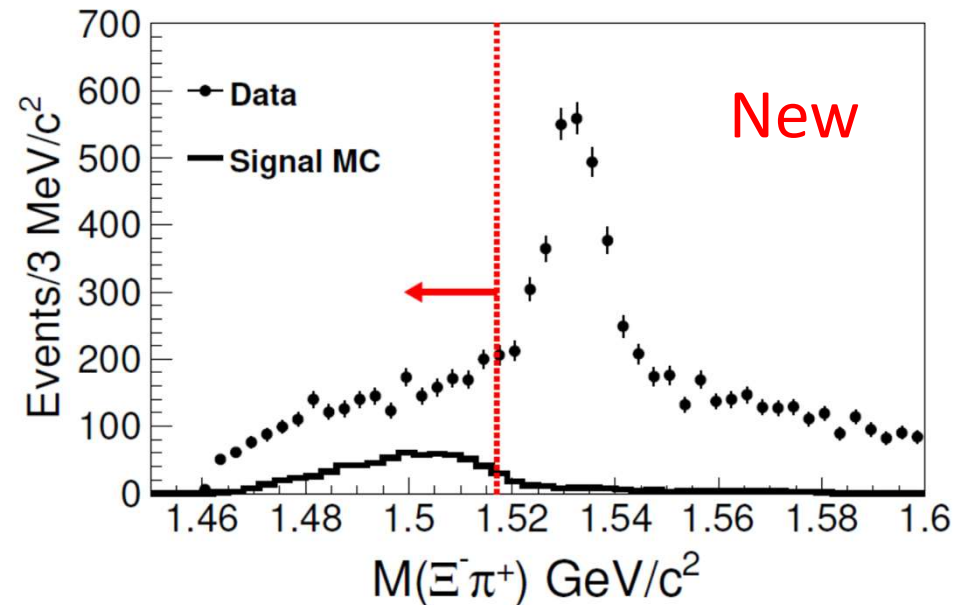
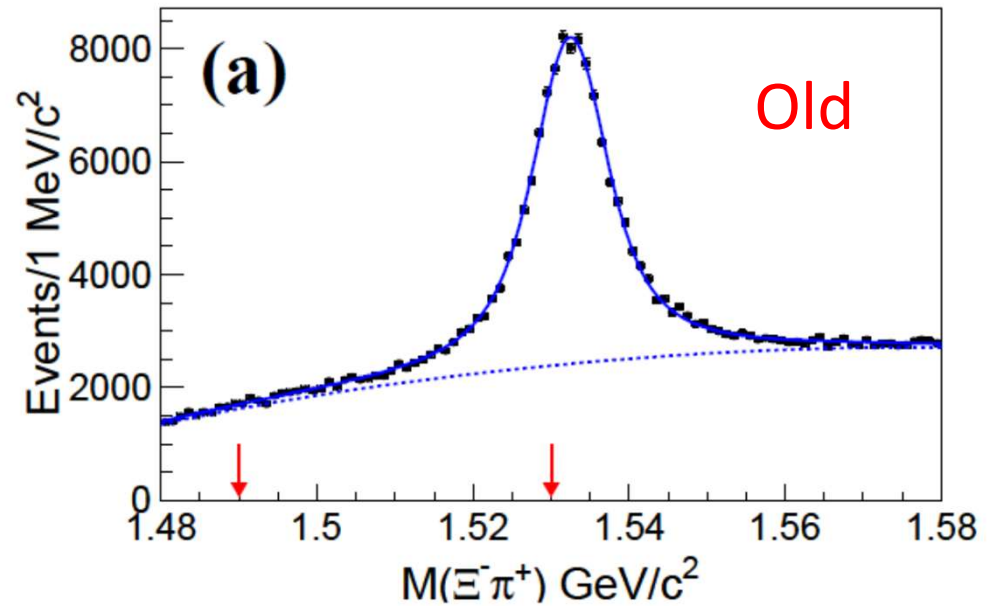


[Belle, PRD 100 (2019) 032006]



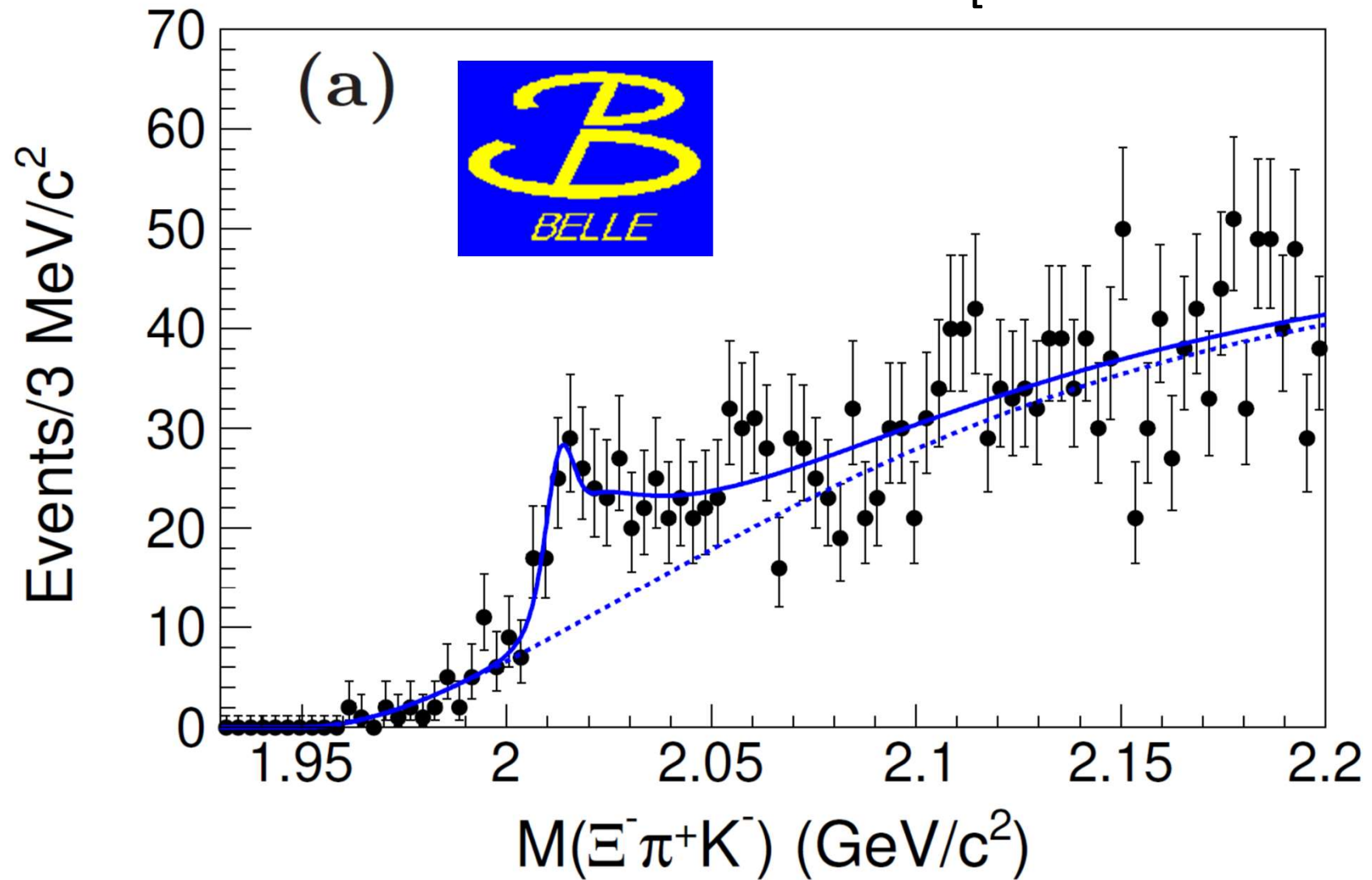
What's the difference?

- Choice of $\Xi(1530)$
 - 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)

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

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

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

(assuming no non-resonant contribution)

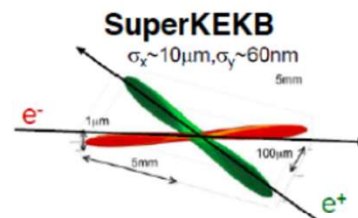
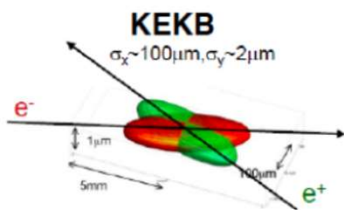
6. Belle II prospects

SuperKEKB and Belle II

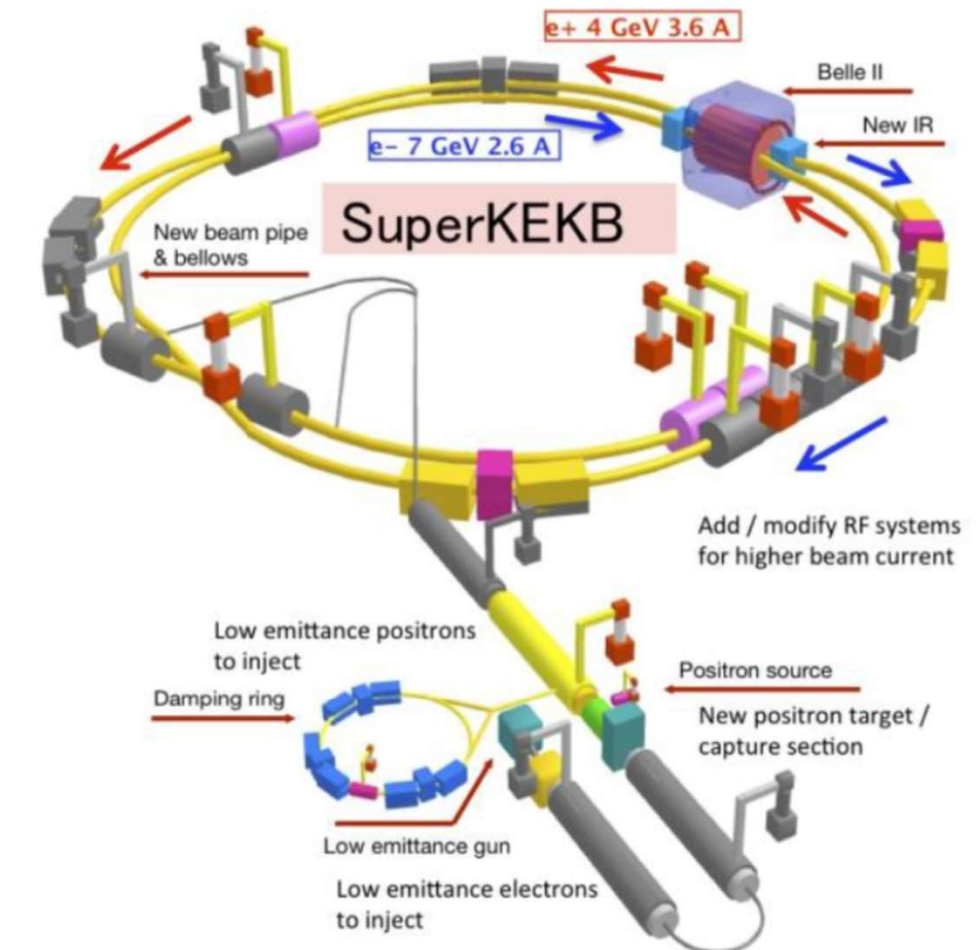
Upgrade for SuperKEKB and Belle II to achieve **30x peak \mathcal{L}**

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

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



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

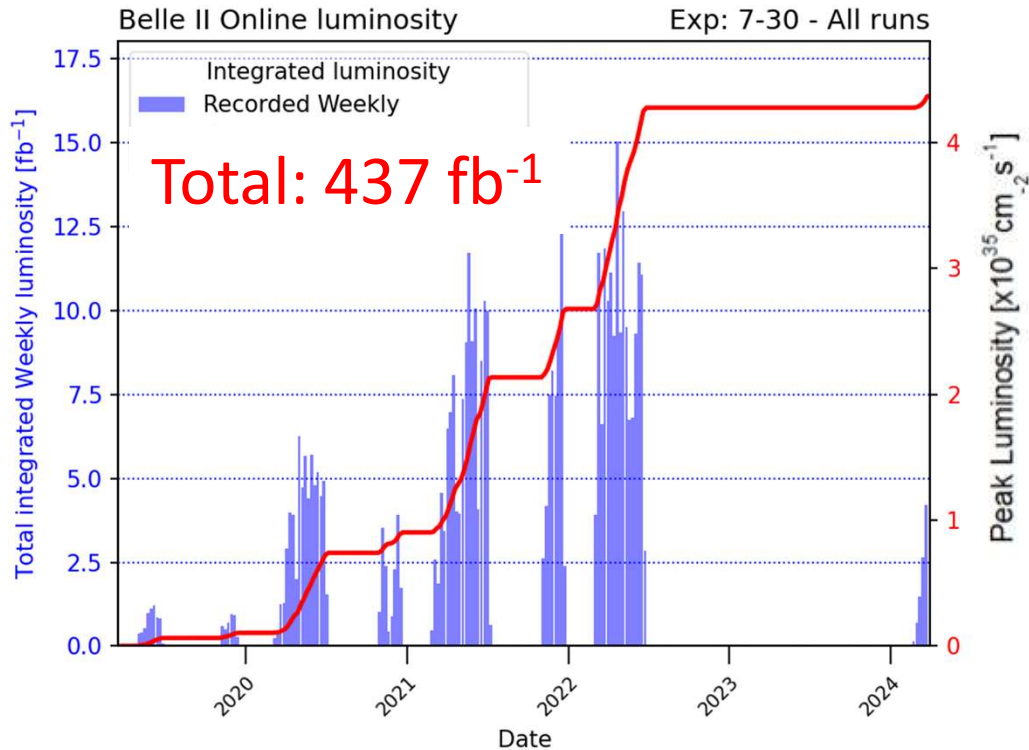


Goal: x50 more statistics than Belle

Belle II integrated luminosity

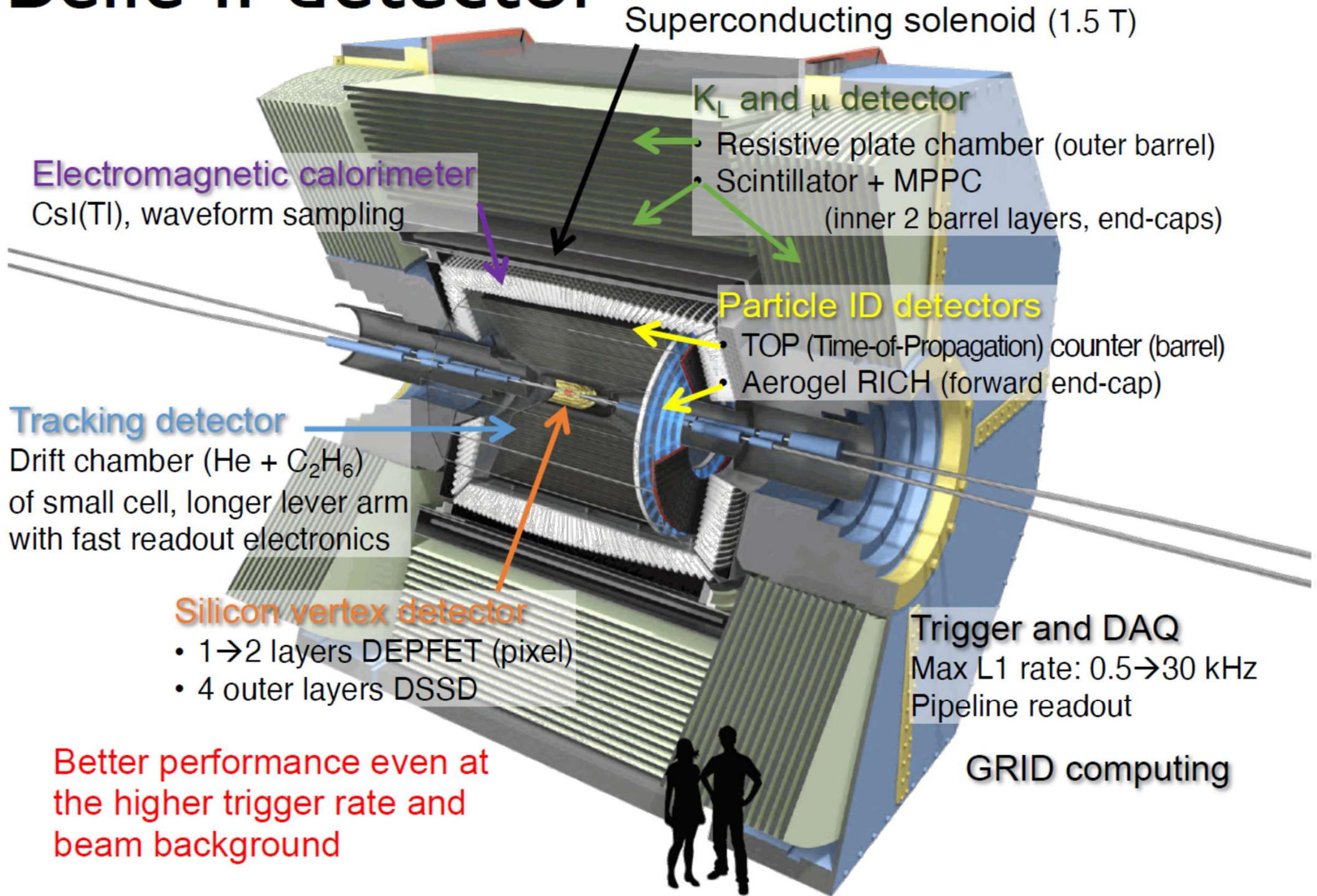
Achieved

Prospect



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

Belle II detector



Summary & prospects

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