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- Title: Hadron Spectroscopy at Belle & Belle II
- Time: 30 min. (presentation + Q&A)

Hadron Spectroscopy at Belle & Belle II

MENU 2023

October 16, 2023

Seongbae Yang (Korea University)

on behalf of Belle & Belle II Collaborations

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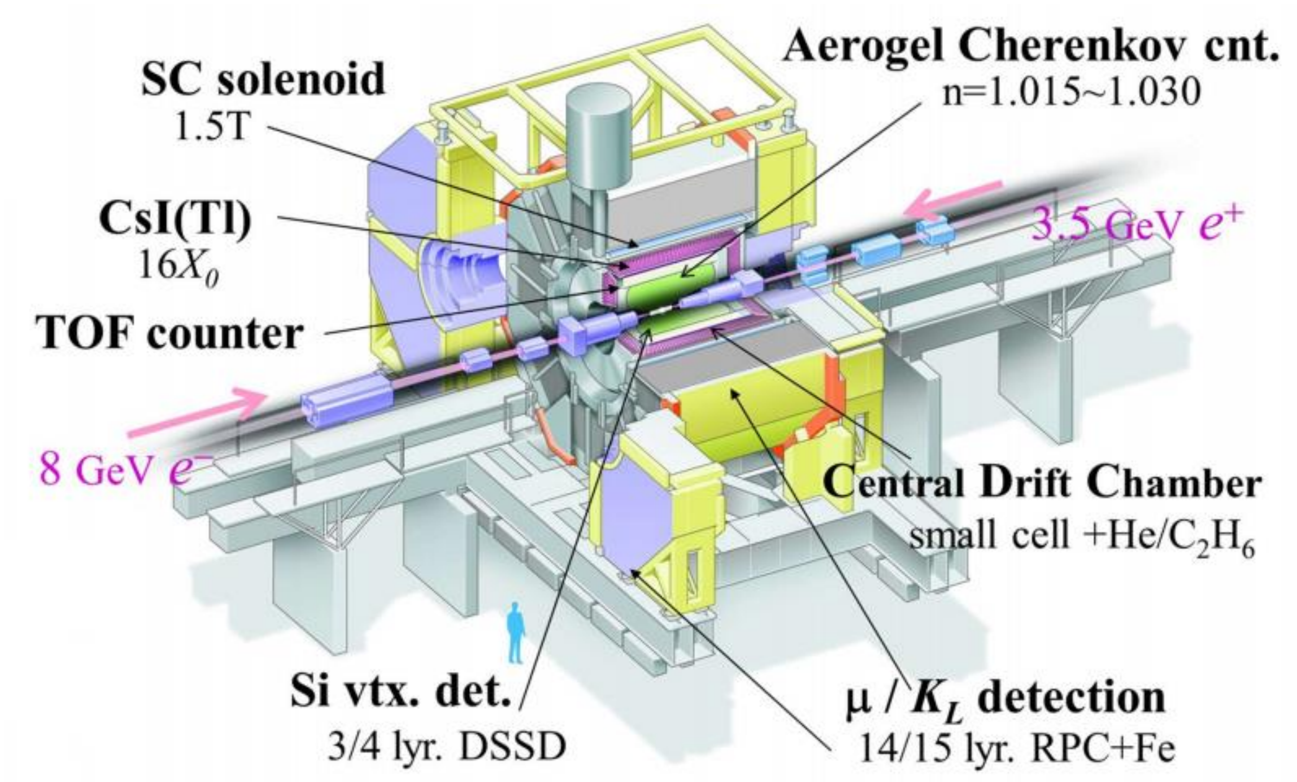
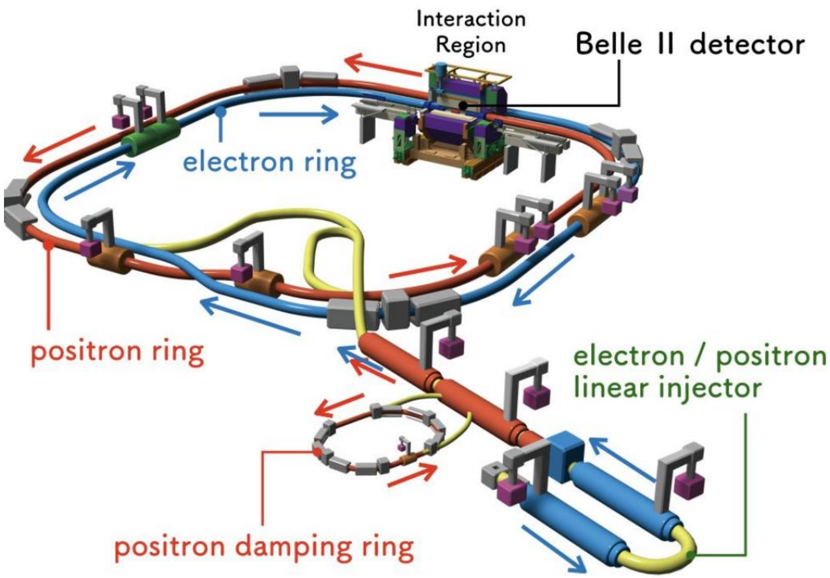
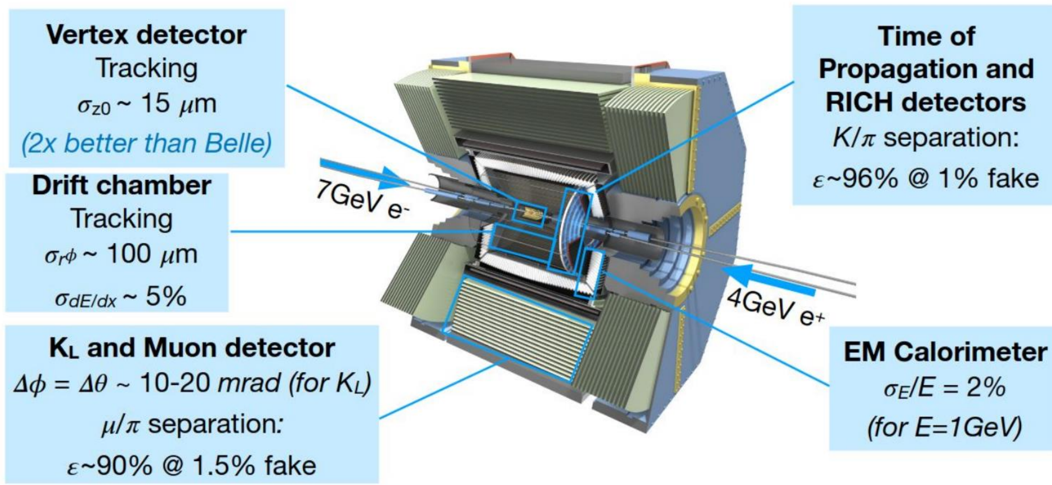
Belle



- Physics beamtime: 1999~2010 years
- $\sqrt{s}$= ~10.6 GeV
- Huge statistics, $\sim 10^9$ $B\bar{B}$ pairs, ~1 ab^{-1} integrated luminosity

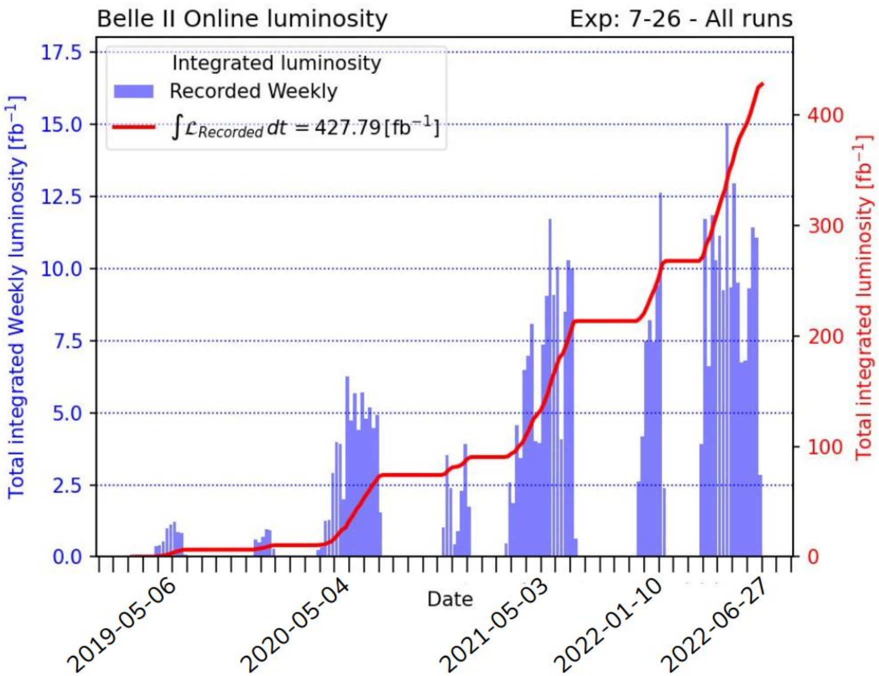
Belle II



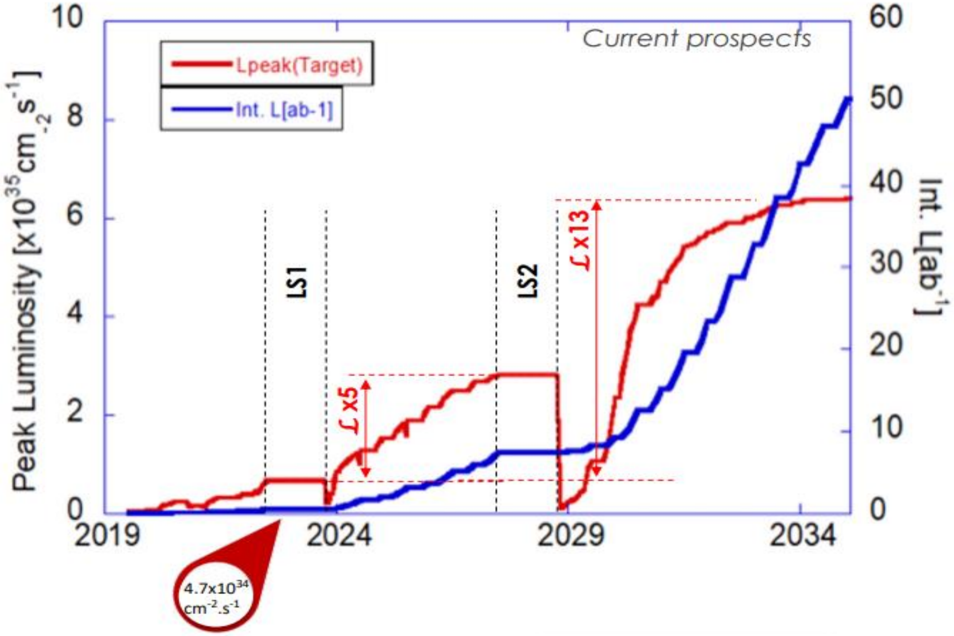


▪ SuperKEKB and Belle II upgrades

- Higher beam current ($\times$ 2) and smaller beam focus ($\times \frac{1}{20}$) at IR
- Upgrades in all parts of the detector
  (vertex, resolution, trigger, and DAQ, …)

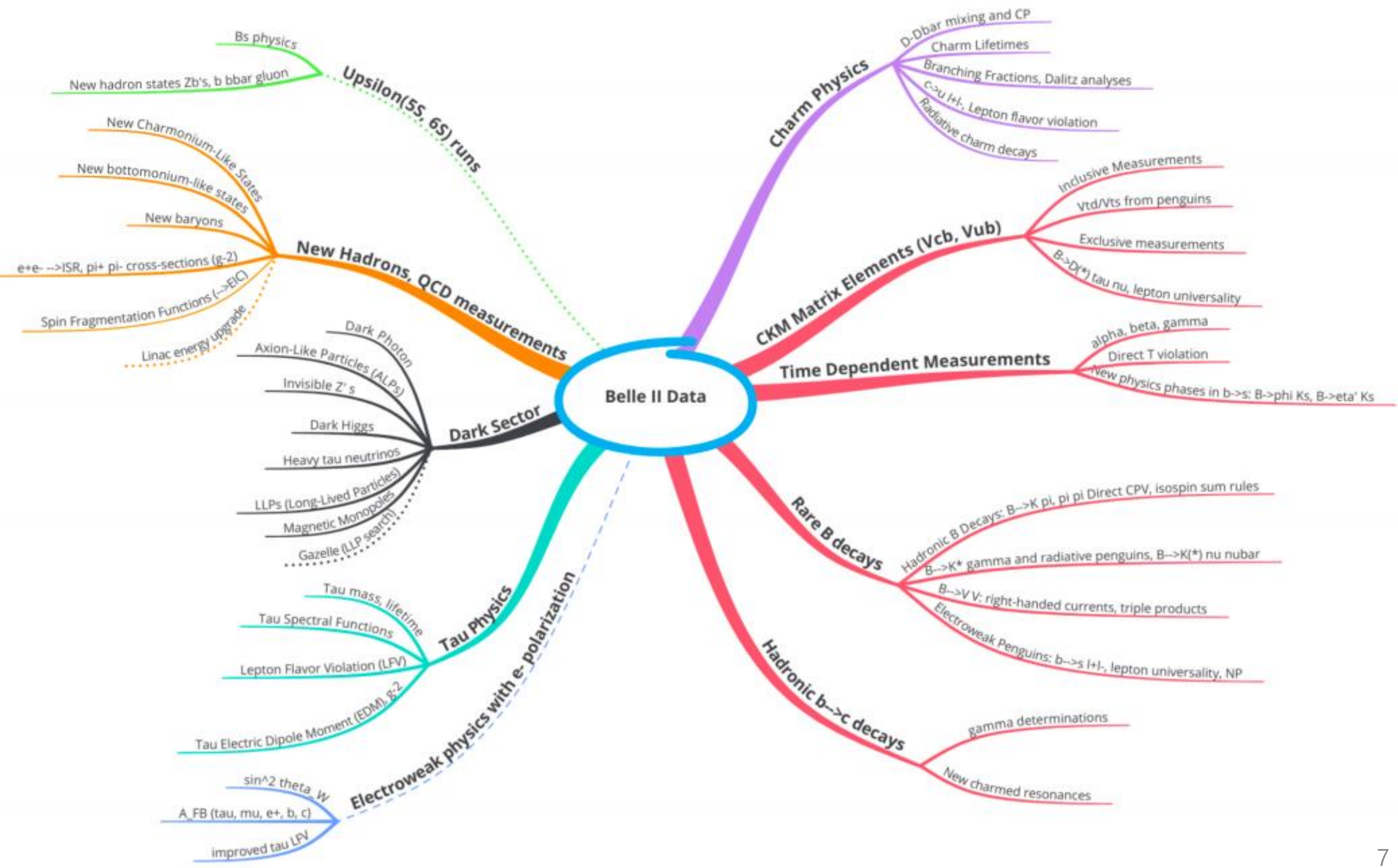


Long term plan



- Instantanesous luminosity record of $4.7 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$ (world record)
- Total integrated luminosity of $428\ \mathrm{fb^{-1}}$
- We plan to take 50 times more data ($50\ \mathrm{ab^{-1}}$) in the future

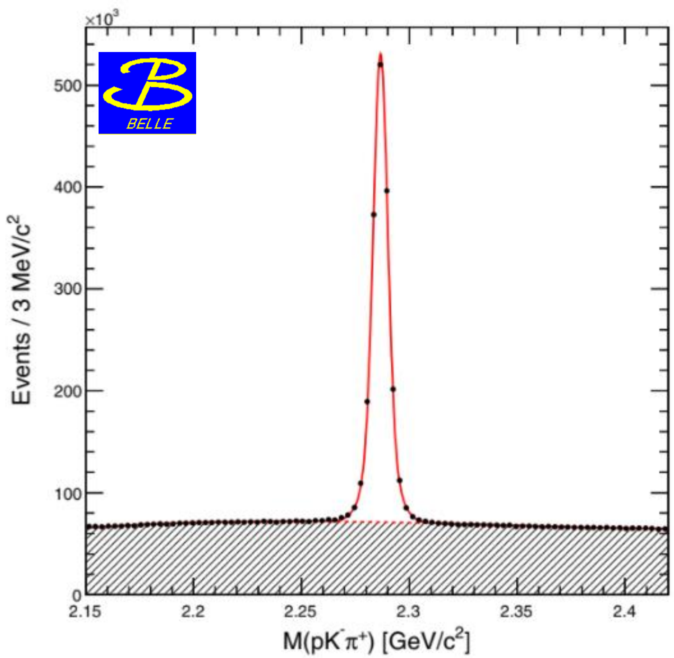
Physics Program



Hadron Spectroscopy at Belle & Belle II

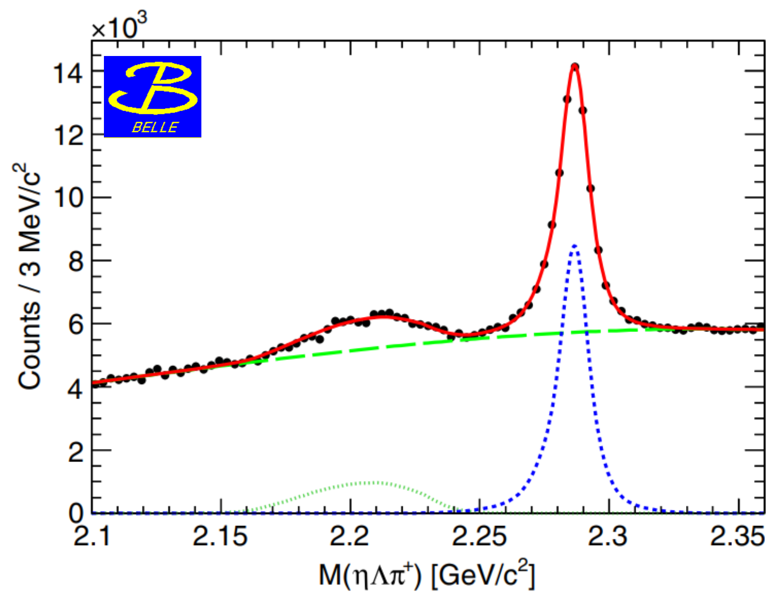
- Huge statistics, Belle + Belle II: $\sim 1.5\ \mathrm{ab}^{-1}$
- Excellent detector performance with 4π solid angle
- EM calorimeter for gamma detection ($\sigma_E/E = 2\%$ at 1 GeV)

$\Lambda_c^+ \to pK^-\pi^+$



*Belle, PRL 117, 011801 (2016)

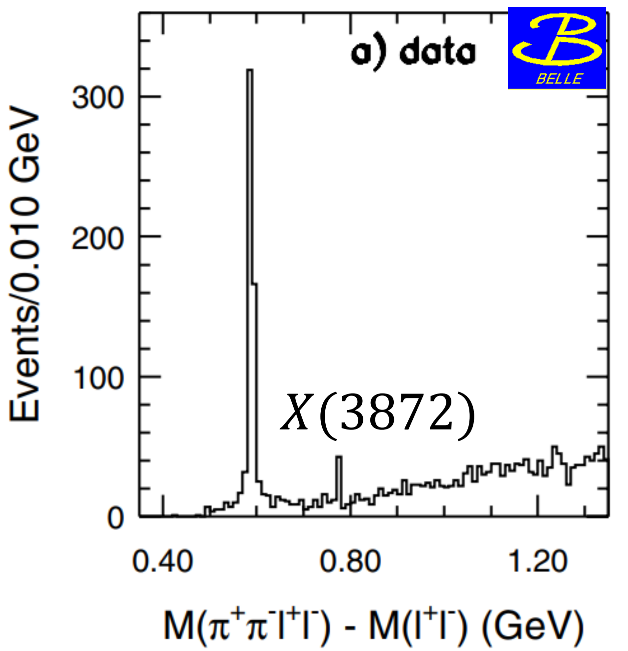
$\Lambda_c^+ \to \eta\Lambda\pi^+$



*Belle, PRD 103, 052005 (2021)

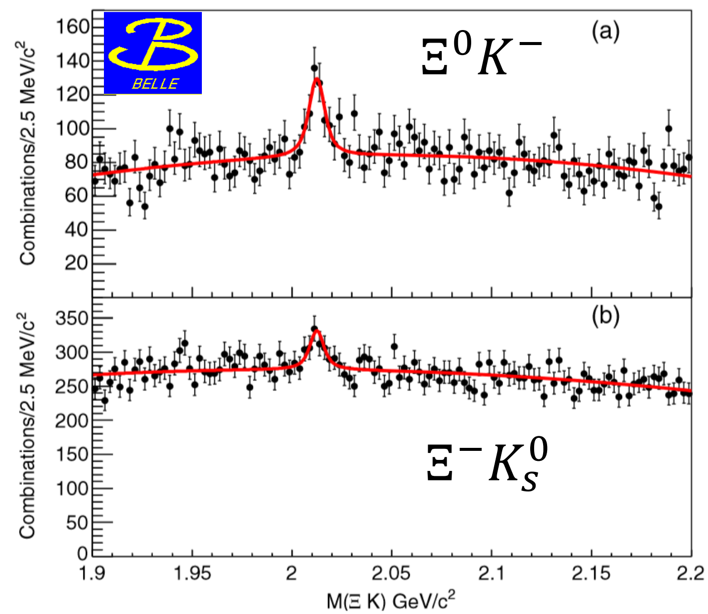
- Various channels for hadron spectroscopy
$e^+e^- \rightarrow q\bar{q}$, B decays, $\Upsilon(1S)$ decays, and charmed baryon decays (for hyperons)

$X(3872)$ in B decays



*Belle, PRL 91, 262001 (2003)

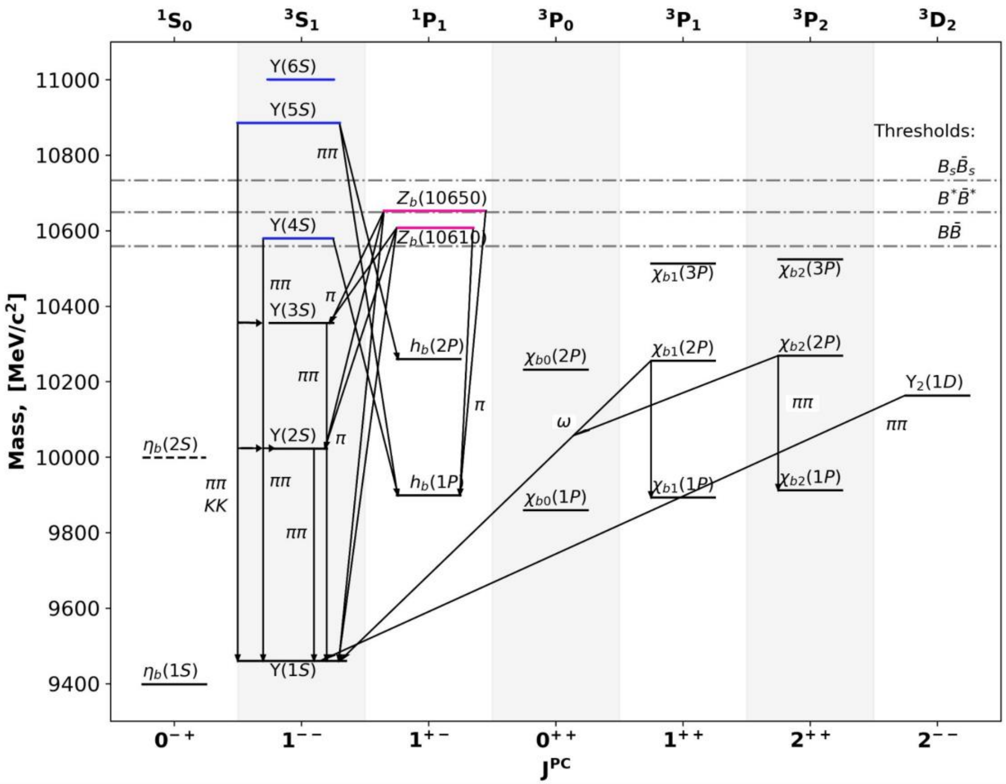
$\Omega(2012)^-$ in $\Upsilon(1S)$ decays



*Belle, PRL 121, 052003 (2018)

- Numerous significant results in hadron physics have been reported!!

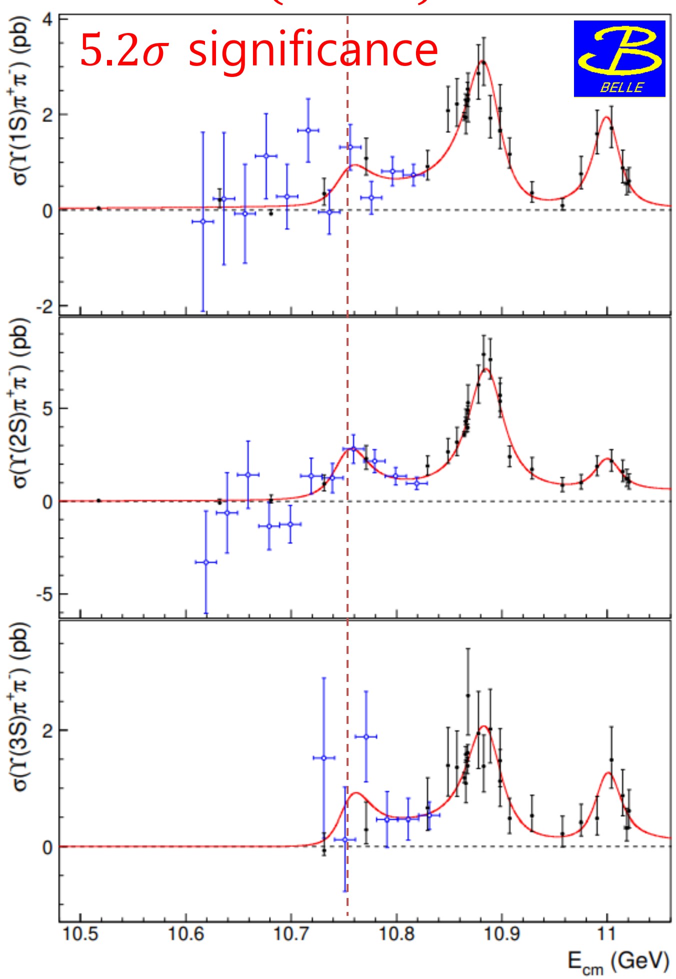
Bottomonium Scheme



- Below $B\bar{B}$ threshold: States are well described by potential models
- Above $B\bar{B}$ threshold: Unexpected properties are seen.
  - Two charged Z_b^+ states ($B^{(*)}\bar{B}$ molecular states?)
  - Hadronic transitions are strongly enhanced
  - η transitions are not suppressed compared to $\pi^+\pi^-$ transitions

Observation of $\Upsilon(10753)$

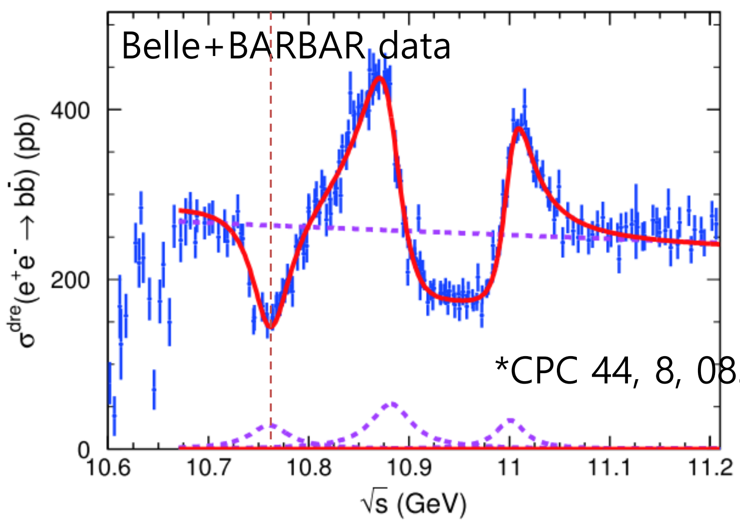
- Measurement of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ cross sections
- Belle energy scan data in the energy range from 10.63 GeV to 11.02 GeV



*Belle, JHEP 10 (2019) 220

	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$

- $e^+e^- \to B\bar{B}$ cross sections
  - A dip near 10.75 GeV

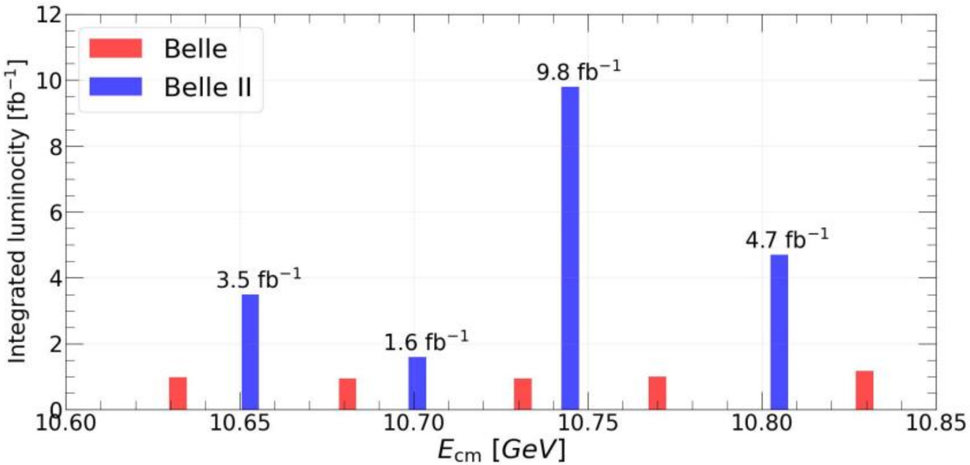


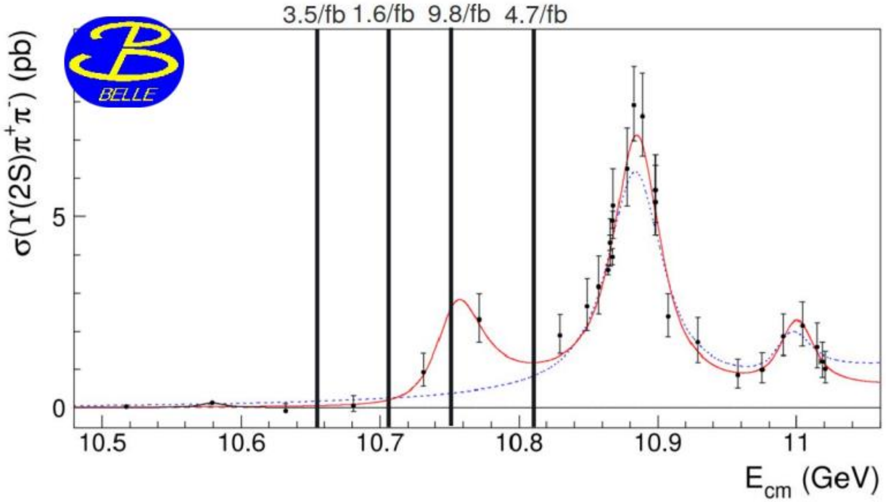
*CPC 44, 8, 083001 (2020)

Energy Scan for $\Upsilon(10753)$

- In November 2021, Belle II collected unique energy scan data around 10.75 GeV
- The main goal was to confirm and study $\Upsilon(10753)$

- Total integrated luminosity: 19 fb^{-1}
- Fill in the gaps between the Belle points

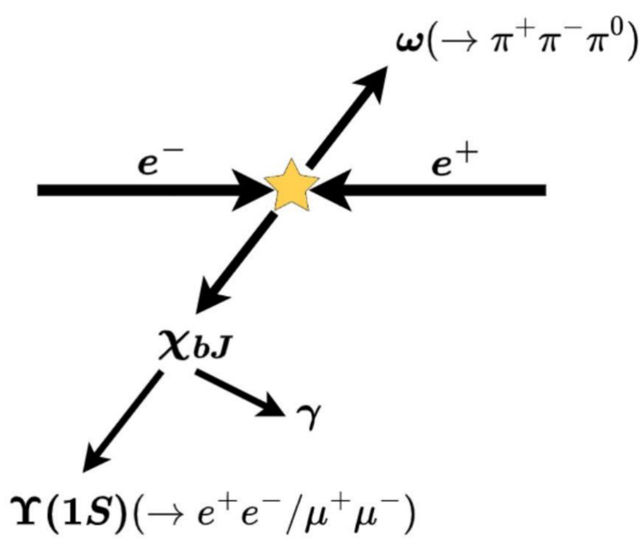


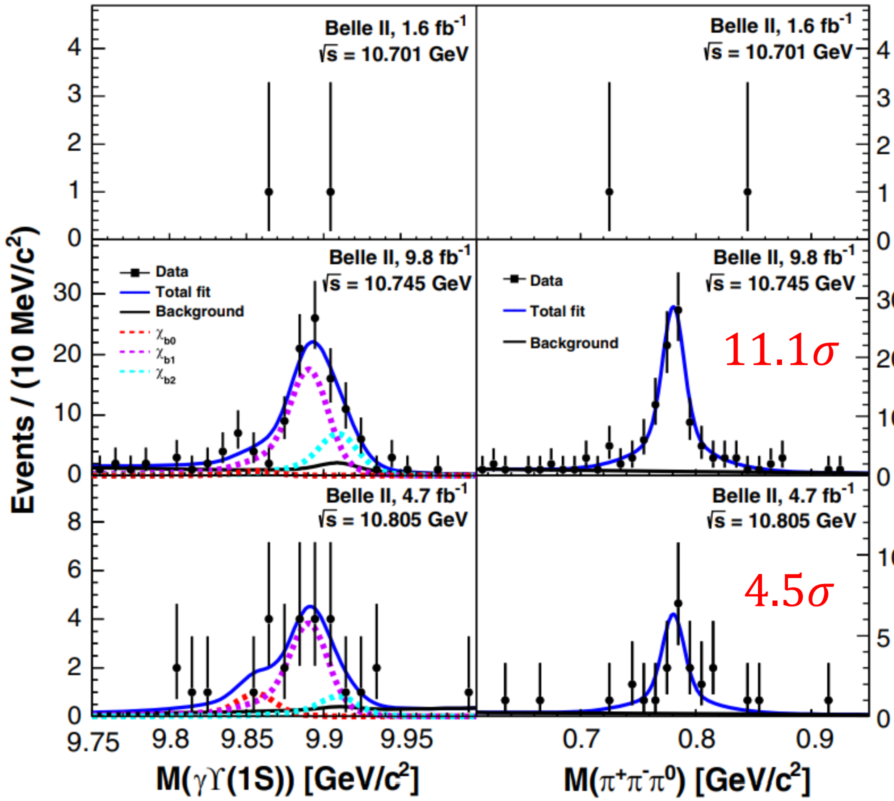


Observation of $\Upsilon(10753) \rightarrow \omega\chi_{bJ}$

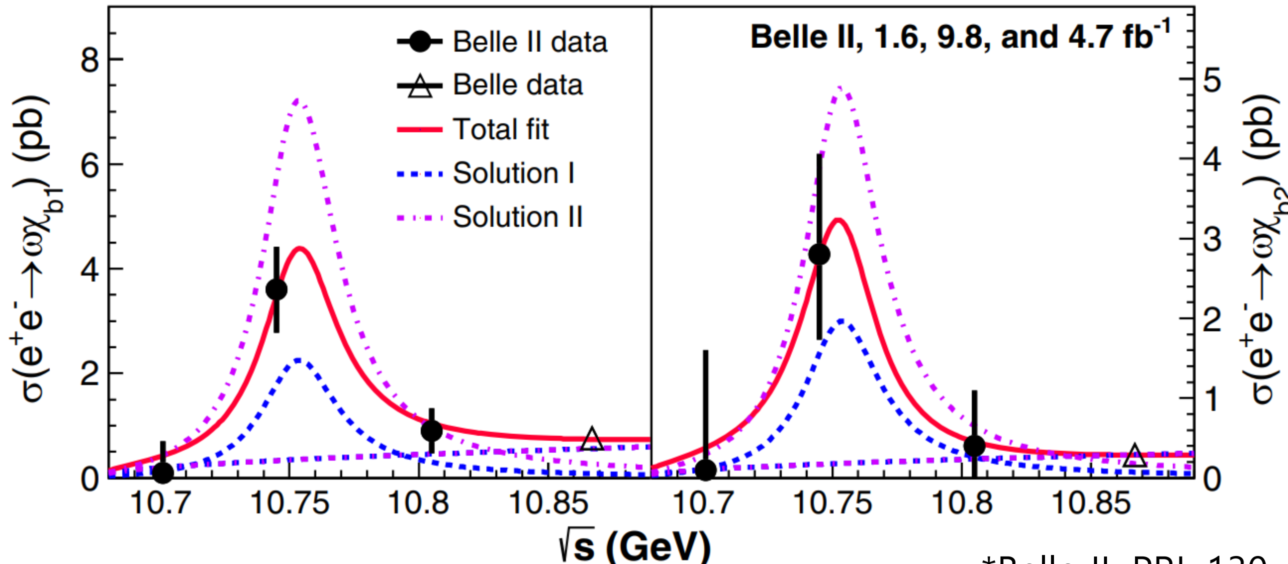
- $\Upsilon(10753) \rightarrow \omega\chi_{\mathrm{bJ}}$ and γX_b
  - $Y(4220) \rightarrow \omega\chi_{c0}$ and $\gamma X(3872)$ are observed → Similar nature with $Y(4220)$ in charmonium section
- 2D unbinned maximum likelihood fits to $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions

*Belle II, PRL 130, 091902 (2023)





- Cross sections of $e^+e^- \to \omega\chi_{b1}$ and $\omega\chi_{b2}$



*Belle II, PRL 130, 091902 (2023)

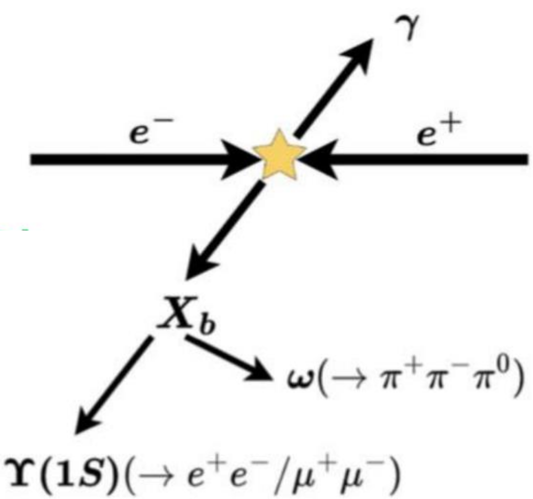
- $\frac{\sigma(e^+e^-\to\omega\chi_{bJ})}{\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)} = \sim 1.5$ at $\sqrt{s} = 10.745$ GeV
  - The ratio is significantly different with the ratio of $\Upsilon(5S)$ (~0.15)
  → Different internal structure with $\Upsilon(5S)$?

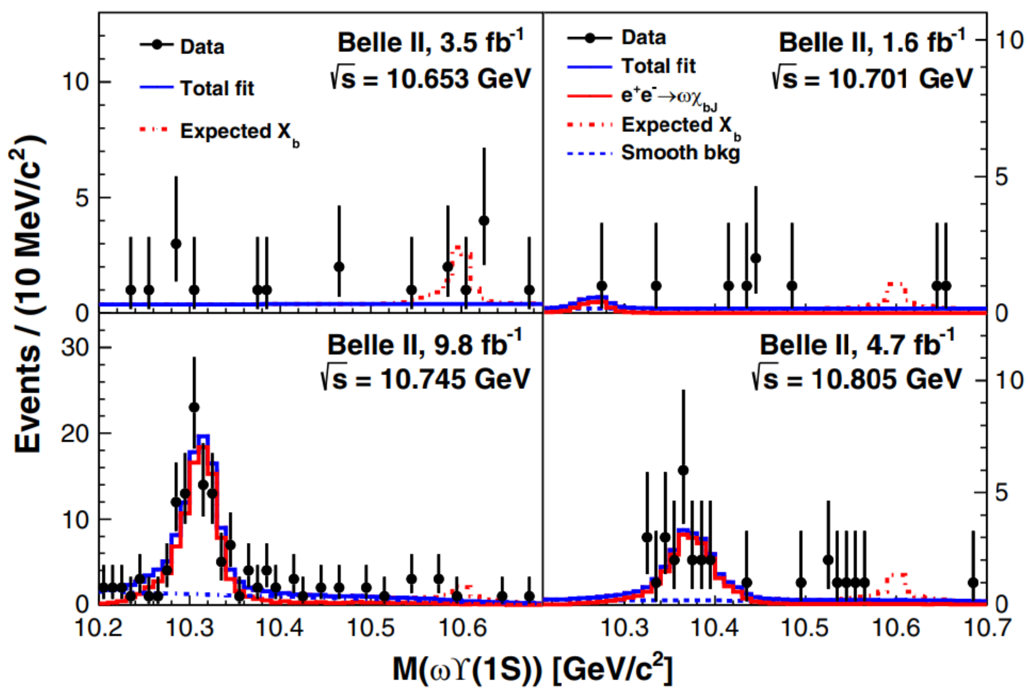
- $\frac{\sigma(e^+e^-\to\omega\chi_{b1}(1P))}{\sigma(e^+e^-\to\omega\chi_{b2}(1P))} = 1.3 \pm 0.6$ at $\sqrt{s} = 10.745$ GeV
  - Prediction for D-wave bottomonium state: 15
  - Prediction for S-D mixed state: 0.2
  → Close to S-D mixed state?

- Search for $\Upsilon(10753) \to \gamma X_b$
  - Search for X_b in $M(\omega\Upsilon(1S))$
    → Reflections from $\Upsilon(10753) \to \omega\chi_{b1}$ and $\omega\chi_{b2}$ are seen.
    → No significant signal of X_b is observed.

$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
Upper limits on $\sigma_B(e^+e^- \to \gamma X_b) \cdot B(X_b\omega\Upsilon(1S))$ (pb)	(10.14, 0.55)	(0.25, 0.84)	(0.06, 0.14)	(0.08, 0.37)

*with varying $M(X_b)$ from 10.45 to 10.65 GeV/c^2





*Belle II, PRL 130, 091902 (2023)

Search for $\Upsilon(10753) \to \omega\eta_b(1S)$ and $\omega\chi_{b0}$

- Tetraquark interpretation predicts a strong transition of $\omega\eta_\mathrm{b}(1s)$ compared to $\Upsilon\pi^+\pi^-$ transition.

$$\frac{\Gamma(\omega\eta_b)}{\Gamma(\Upsilon\pi^+\pi^-)} \sim 30$$

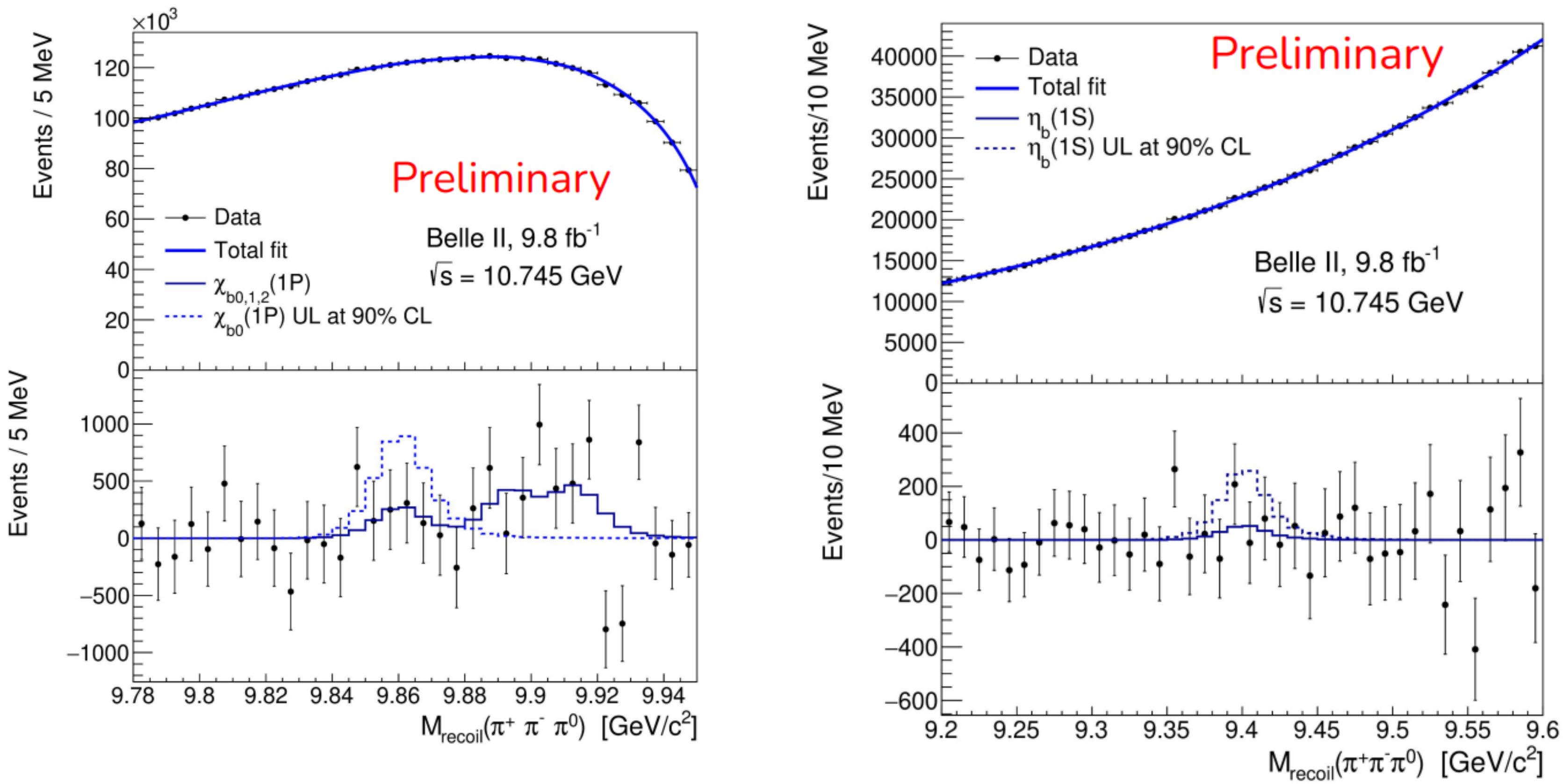
There is no convenient way to reconstruct η_b.

- In charmonium section, $Y(4220) \to \omega\chi_{\mathrm{c}0}$ transition is enhanced compared to $\omega\chi_{\mathrm{c}1}$ and $\omega\chi_{\mathrm{c}2}$. But $e^+e^- \to \omega\chi_{\mathrm{b}0}$ was not observed in the full reconstruction due to $\mathrm{B}\left(\chi_{\mathrm{b}0} \to \gamma\Upsilon(1S)\right) = (1.94 \pm 0.27)\%$.

- Search for these above transitions by the recoil mass of $\omega \to \pi^+\pi^-\pi^0$

$$M_{\mathrm{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{E_{c.m.} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}$$

- $\omega \to \pi^+\pi^-\pi^0$ recoil mass distributions



→ No significant χ_{b0} and $\eta_b(1s)$ signals are observed.

- $\sigma\left(e^+e^- \to \omega\eta_b(1s)\right) < 2.5$ pb   * $\sigma\left(e^+e^- \to \Upsilon(2S)\pi^+\pi^-\right) = \sim 3$ pb

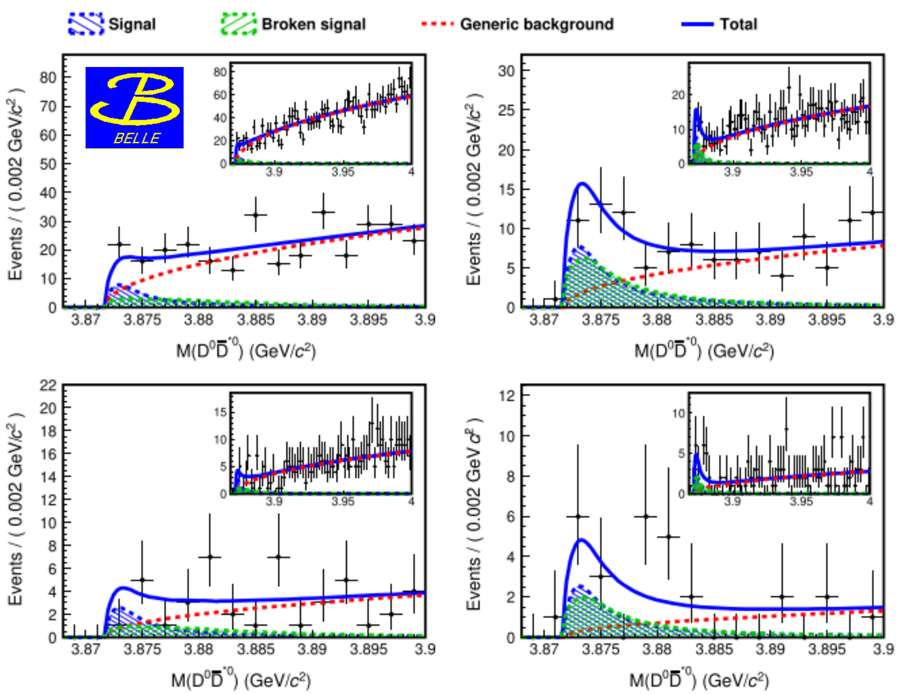
→ These results do not support the tetraquark prediction of $\Upsilon(10753)$.

New Peak Structures near the Mass Thresholds

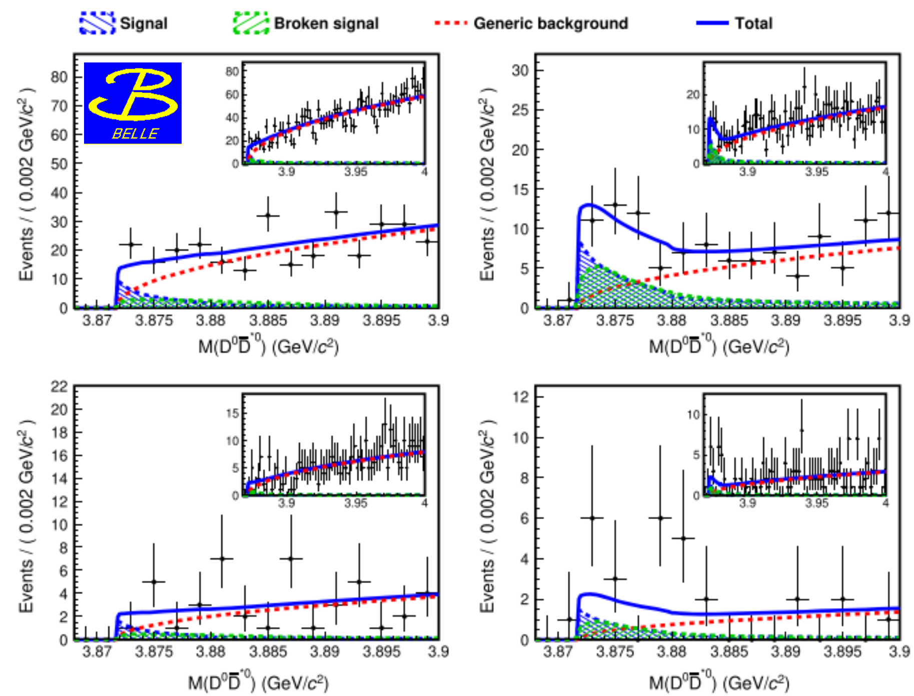
- New peak structures have been observed near the mass threshold.
  → They do not always indicate new hadron resonances.
  → Linesahpe analysis is required to identify the structure.

- $X(3872)$ structure near $D^0\bar{D}^{*0}$ threshold

Breit-Wigner model



Flatté model

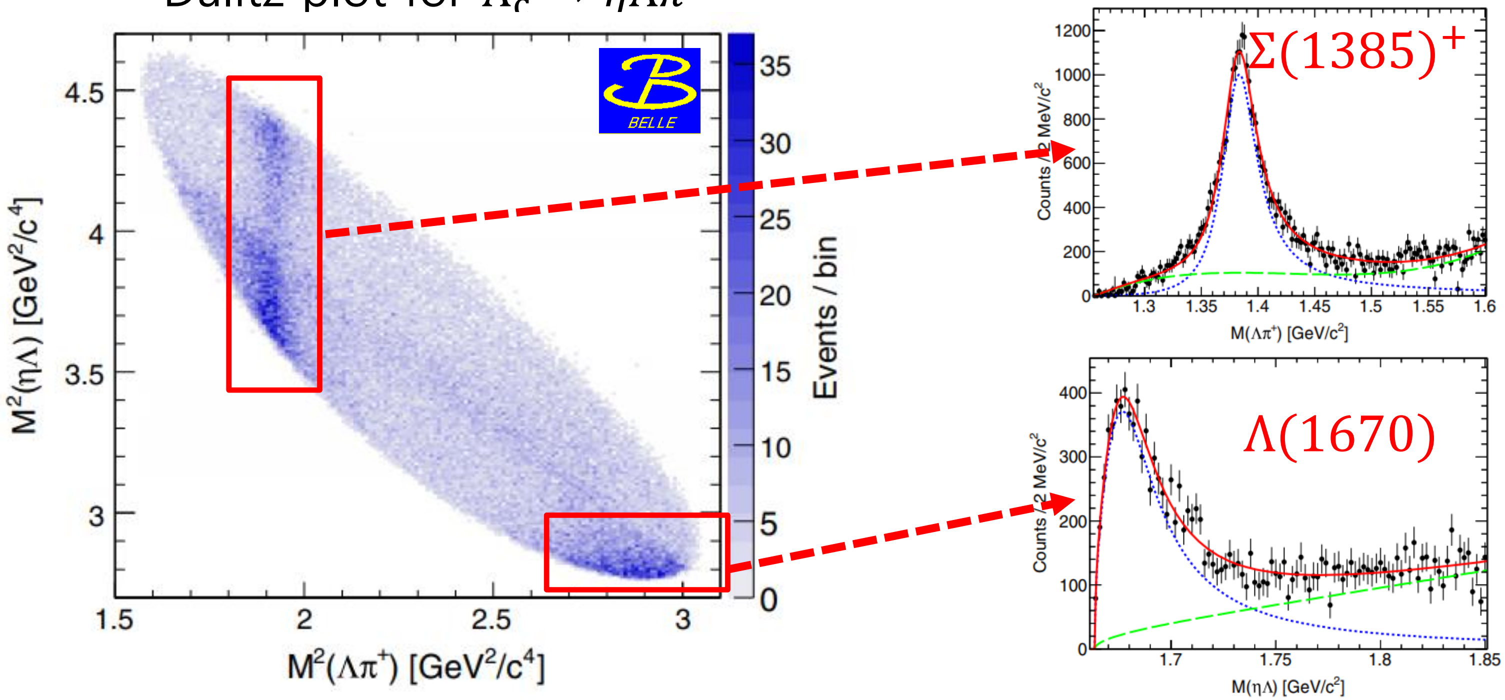


*Belle, PRD 107, 112011 (2023)

Hyperons in Charmed Baryon Decays

- Better S/N ratio compared to $e^+e^- \to q\bar{q}$ production.
- Possible to choose a suitable decay channel.
- $\Lambda(1670)$ in $\Lambda_c^+ \to \eta\Lambda\pi^+$ decays
  - First observation of a peak structure of $\Lambda(1670)$

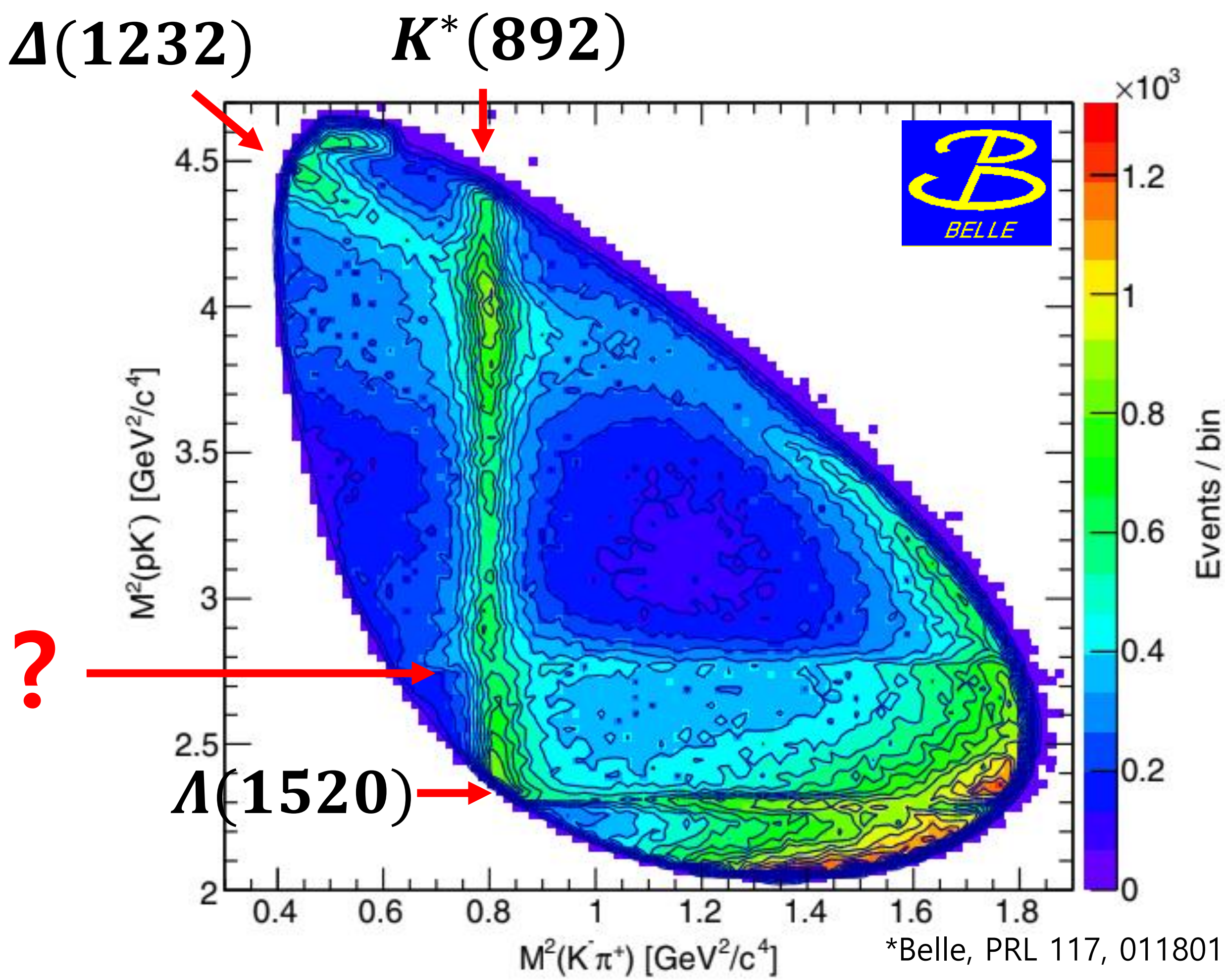
Dalitz plot for $\Lambda_c^+ \to \eta\Lambda\pi^+$



Belle, PRD 103, 052005 (2021)

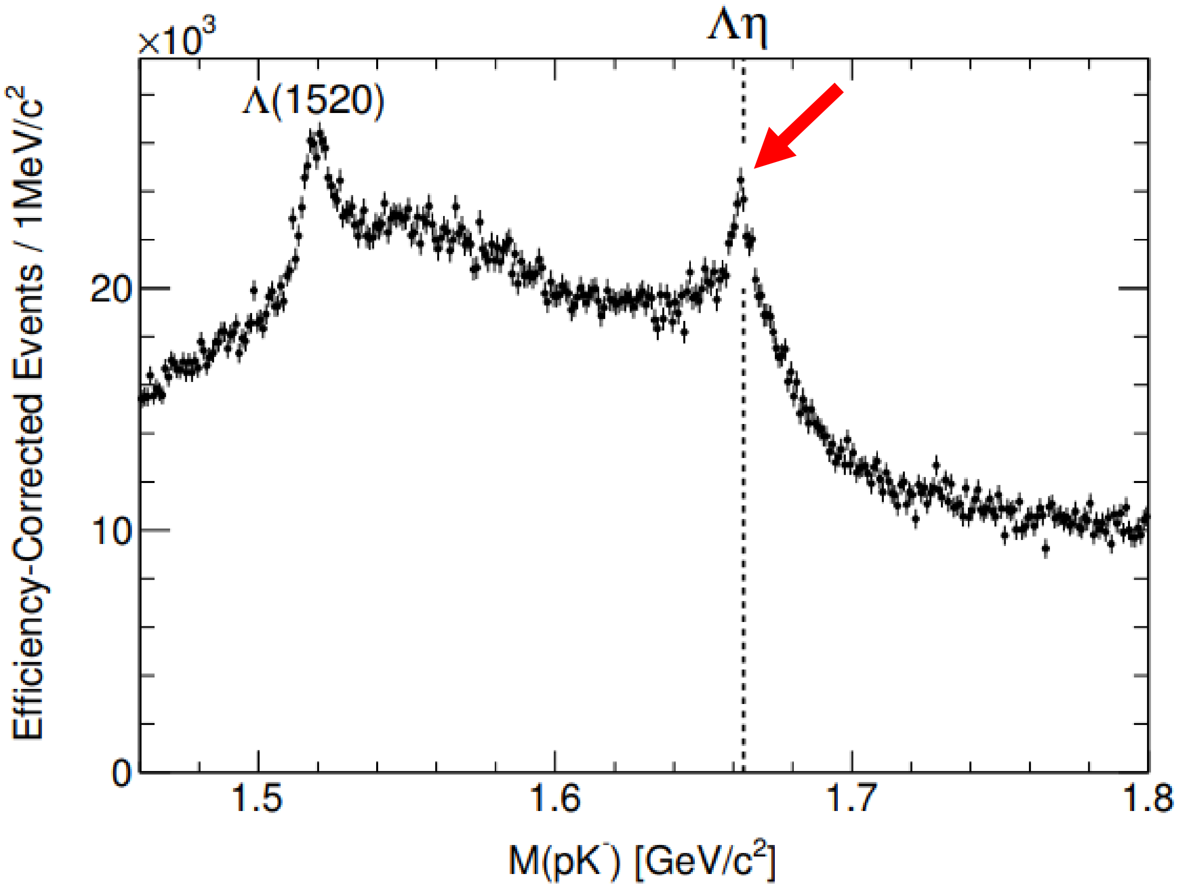
$\Lambda\eta$ Threshold Cusp in pK^- System

- Full data sample of Belle, 980 fb^{-1}
- Dalitz plot for $\Lambda_c^+ \to pK^-\pi^+$,



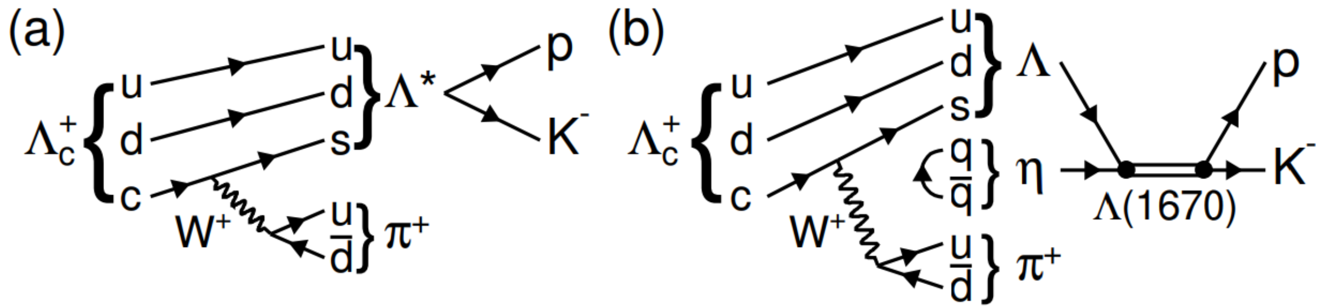
*Belle, PRL 117, 011801 (2016)

- $M(pK^-)$ Distribution of $\Lambda_c^+ \to pK^-\pi^+$ decays



→ A new narrow peak structure near the $\Lambda\eta$ threshold

- Two approaches to explain the narrow peaking structure.
  - (a) Breit-Wigner function: a new resonance
  - (b) Flatté function: a visible cusp enhanced by $\Lambda(1670)$ pole



- Flatté function

$$\frac{dN}{dm} \propto |f(m)|^2 = \left| \frac{1}{m - m_f + \frac{i}{2}\left(\Gamma' + \bar{g}_{\Lambda\eta} k\right)} \right|^2,$$

where m_f: Flatté mass

Γ': a sum of partial widths other than $\Lambda\eta$ decay

$\bar{g}_{\Lambda\eta}$: coupling constant of $\Lambda\eta$ channel

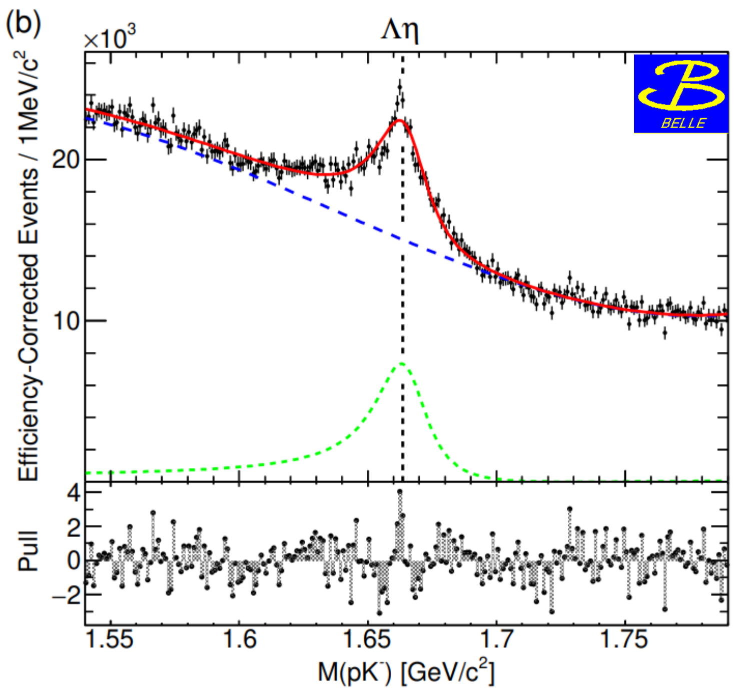
k: $\sqrt{2\mu_{\Lambda\eta}(m - m_\Lambda - m_\eta)}$, *$k$ is imaginary when $m < m_\Lambda + m_\eta$

- Breit-Wigner and Flatté functions with a constant coherently added
  - The cusp shape is unaffected by resonances in higher partial waves
  - The interference term with different L vanishes with an integral over the decay angle.
  - S-wave resonances such as $\Lambda(1405)$ can make an interference effect. As they are rather far away, and their effect are approximated as a constant

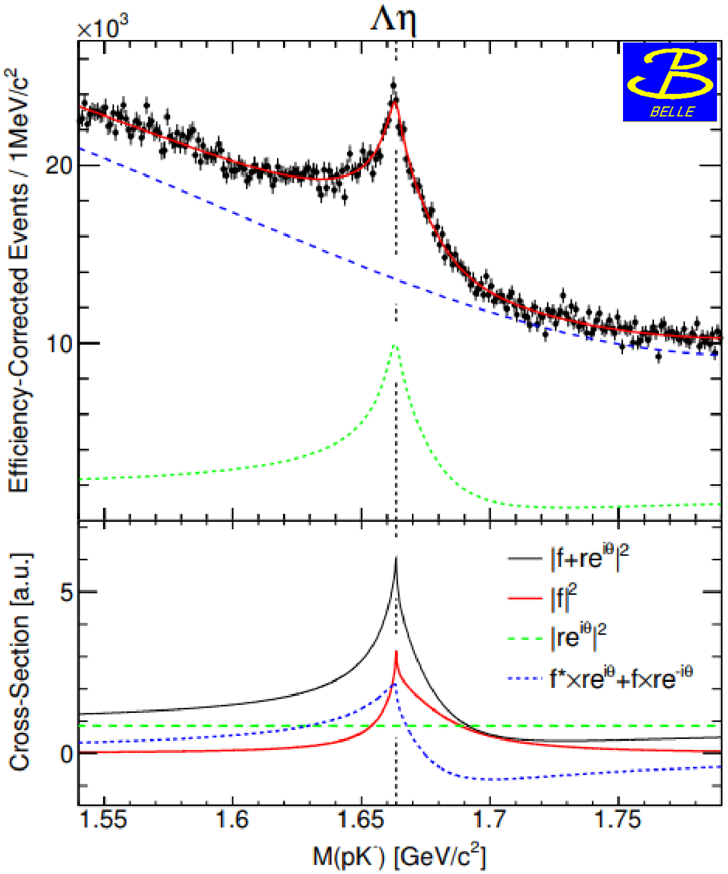
→ Then, $\frac{dN}{dm} \propto |f(m) + re^{i\theta}|^2$ is a reasonable choice.

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

- One-dimensional fit results



*Belle, PRD 108, L031104 (2023)



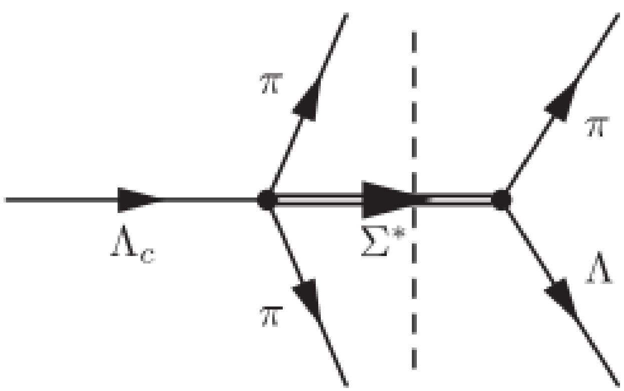
Mass $(\mathbf{MeV}/c^2)$	Width $(\mathbf{MeV})$	χ^2/ndf
1665.4±0.5	23.8±1.2	**1.27 (308/243)**

m_f $(\mathbf{MeV}/c^2)$	Γ' $(\mathbf{MeV})$	$\bar{g}_{\Lambda\eta}$	χ^2/ndf
1674.4 (fixed)	$27.2\pm1.9^{+5.0}_{-3.9}$	$0.258\pm0.023^{+61}_{-75}$	**1.06 (257/243)**

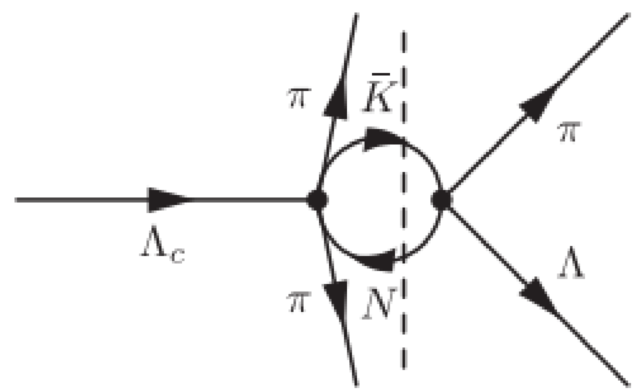
→ Flatté function is significantly favored than Breit-Wigner function.

New peak structures near $\bar{K}N$ threshold in $\Lambda\pi$ system

- New $\Lambda\pi$ peak structures near $\bar{K}N(I=1)$ threshold in $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$ decays
  - No prediction from standard quark model $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$
    → Exotic hadron?
    → Threshold cusp whose shape reflects the scattering length of $\bar{K}N(I=1)$ interaction?



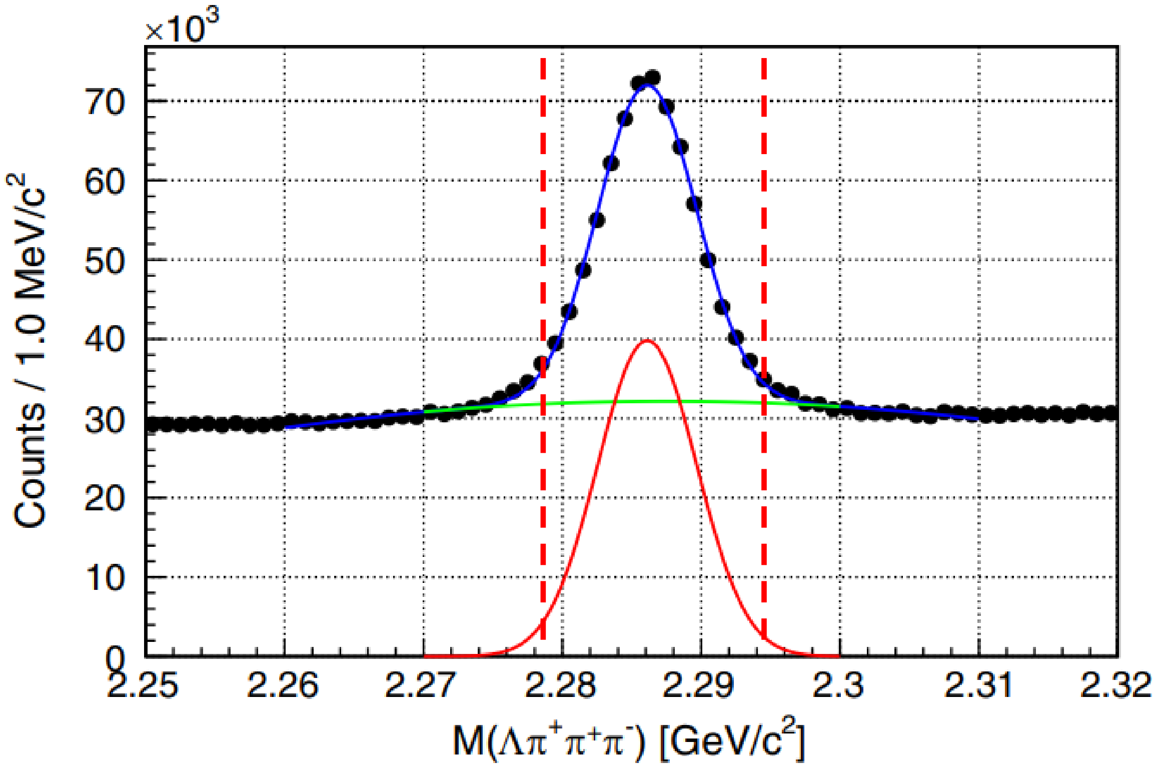
Σ^* resonance



$\bar{K}N$ scattering with a cusp

*Belle, PRL 130, 151903 (2023)

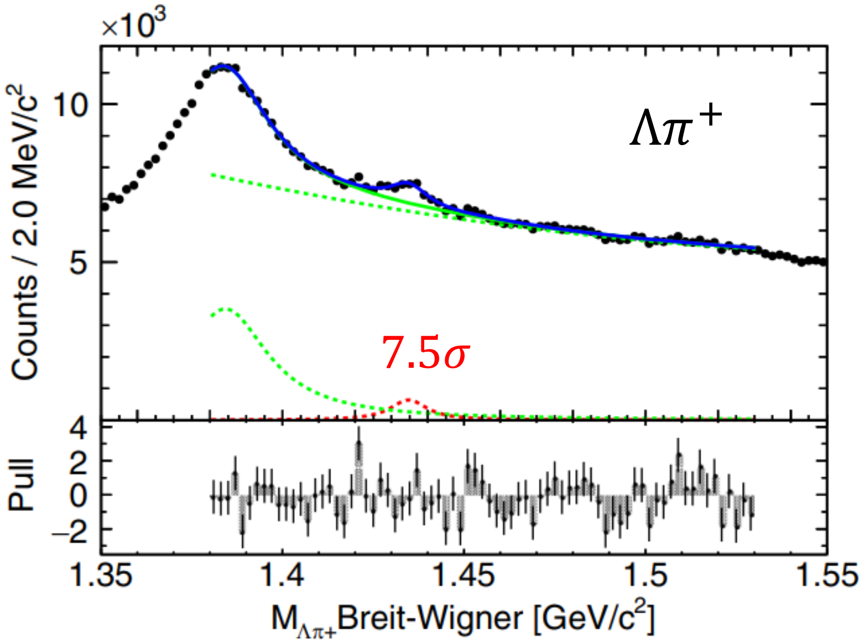
- Full data sample of Belle, 980 fb^{-1}
- Distribution of $M(\Lambda\pi^+\pi^-\pi^+)$
  - clear peak structure of Λ_c^+ is seen.
  - Mass window $\left|M(\Lambda\pi^+\pi^-\pi^+) - M_{\Lambda_c^+}\right| < 8\ \mathrm{MeV}/c^2$

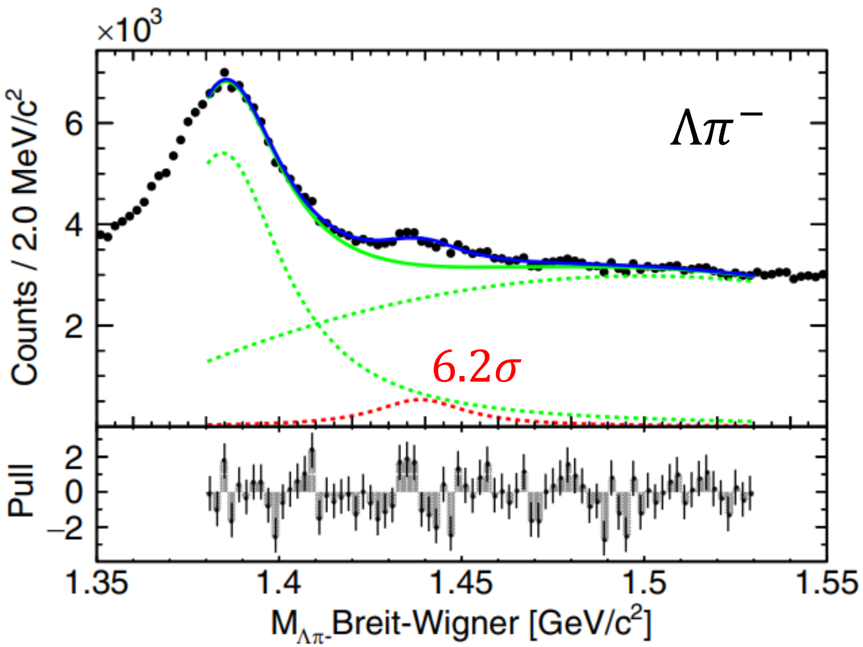


*Belle, PRL 130, 151903 (2023)

- Fit results with Breit-Wigner model

*Belle, PRL 130, 151903 (2023)





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

- Parameterization of Dalitz model
  - Neglecting the Λ_c^+ form factor
  - $\overline{K}$-N complex scattering length: $a + bi$

*Belle, PRL 130, 151903 (2023)

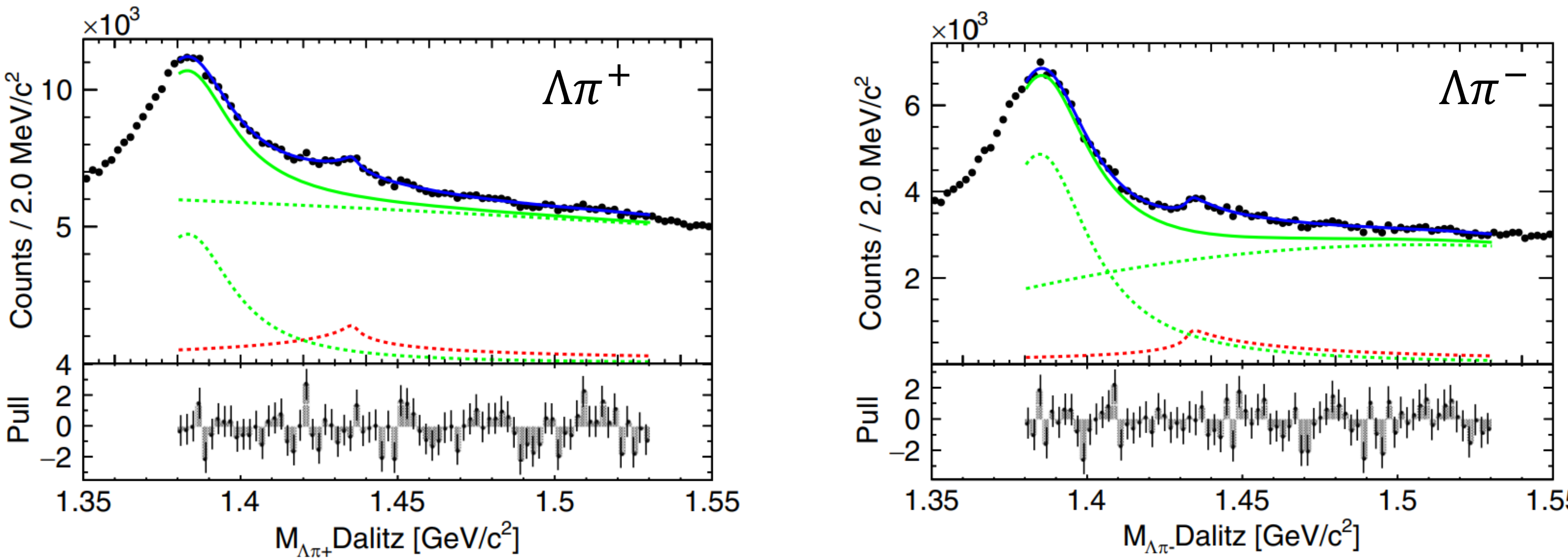
$$f_D = \frac{4\pi b}{(1+kb)^2 + (ka)^2}, \qquad E > m_{\bar{K}N}$$
$$= \frac{4\pi b}{(1+\kappa a)^2 + (\kappa b)^2}, \qquad E < m_{\bar{K}N},$$

where $\kappa = \sqrt{2\mu(E - m_{\overline{K}N})}$,
$k = \sqrt{2\mu_{\Lambda\eta}(m_{\overline{K}N} - E)}$,
$\mu = {m_{\overline{K}} m_N}/{(m_{\overline{K}} + m_N)}$.

- The Dalitz model is largely consistent with the Flatté model by fixing m_f far away from $\overline{K}N$ threshold.

- Fit results with Dalitz model

*Belle, PRL 130, 151903 (2023)



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	$78.1/68$

- The scattering length is larger than the previous results

→ The effect of the neglected decay form factor?

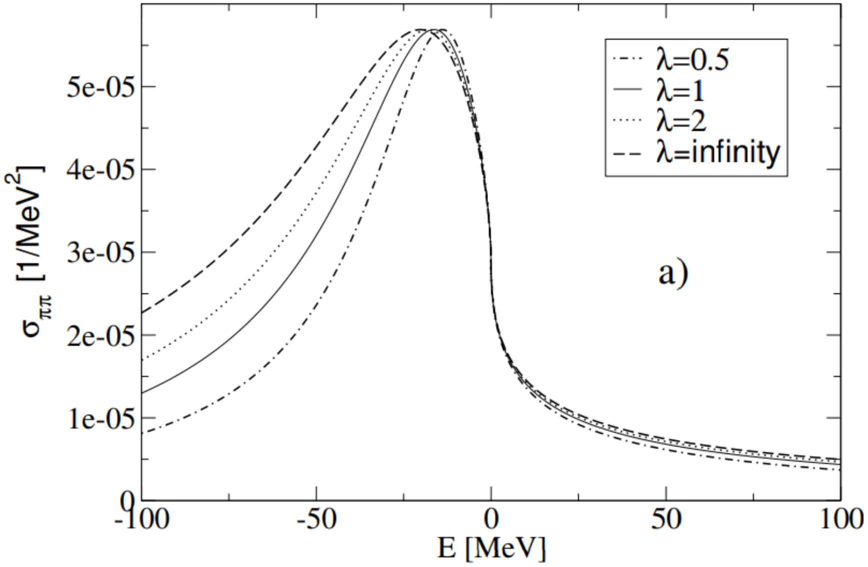
- Comparing to Breit-Wigner results, we can’t identity them.

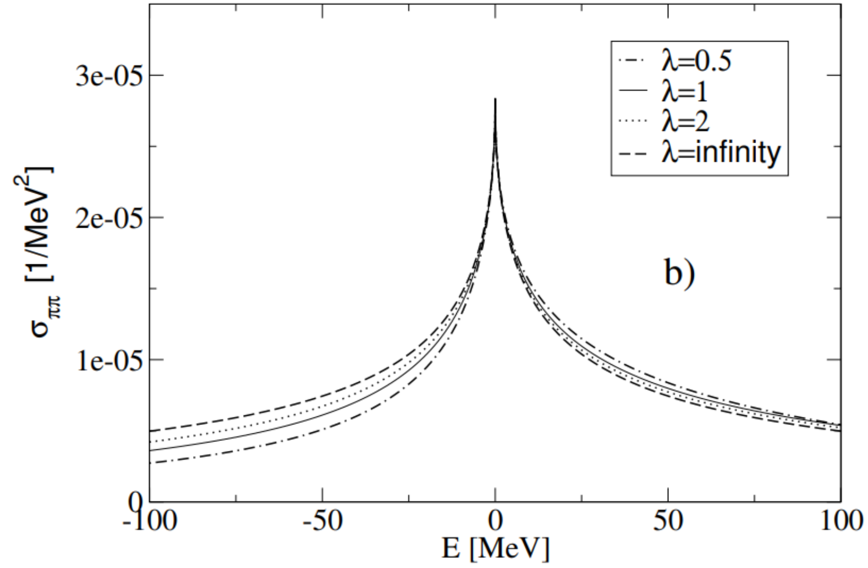
- Transitions of $\Upsilon(10753)$
  - $\Upsilon(10753) \to \chi_{bJ}(1P)\omega$ decays are observed.
  - No significant signals of $\Upsilon(10753) \to \chi_{b0}(1P)\omega$ and $\omega\eta_b(1S)$ decays are observed.

- New peak structures near the mass thresholds
  - A threshold cusp at the $\Lambda\eta$ threshold is observed in pK^- system. The peak structure favors the Flatté model significantly.
  - New $\Lambda\pi$ peak structures near the $\bar{K}N$ threshold are observed in $\Lambda_c^+ \to \Lambda\pi^+\pi^-\pi^+$ decays. They are not predicted by standard quark model.

*Backup Slides

- Flatté model





$$f_{\rm el} = -\frac{1}{2q}\frac{\Gamma_P}{E - E_{\rm BW} + i\frac{\Gamma_P}{2} + i\bar{g}_K\frac{k}{2}}$$

where, $k = \sqrt{m_K(\sqrt{s} - 2m_k)}$ *k is imaginary when $m < 2m_K$

*V. Baru et al., Eur. Phys. J. A 23, 523 (2005)