Exotic hadrons at Belle and Belle II

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@HYP2022

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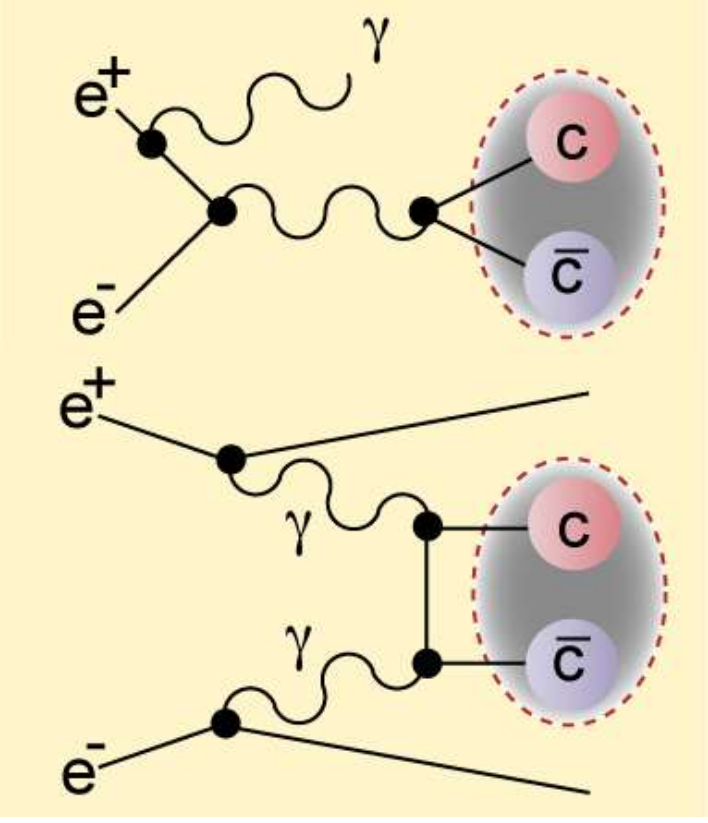
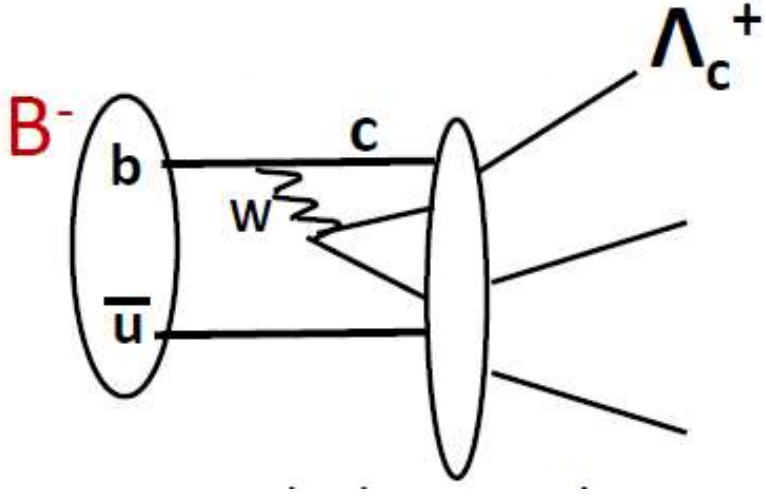
e^+e^- for hadron spectroscopy

- Small background
  - $e^+e^- \to Q\bar{Q}$ production is flavor blind.
    Only (charge)^2 matters → Production of heavy hadrons
- Missing mass spectroscopy is possible
  - Absolute branching fraction
  - Study of decays with missing particles (n, ν, …)
- Small production rate can be compensated by high luminosity
- Many exotic hadrons/candidates are found at e^+e^- machines

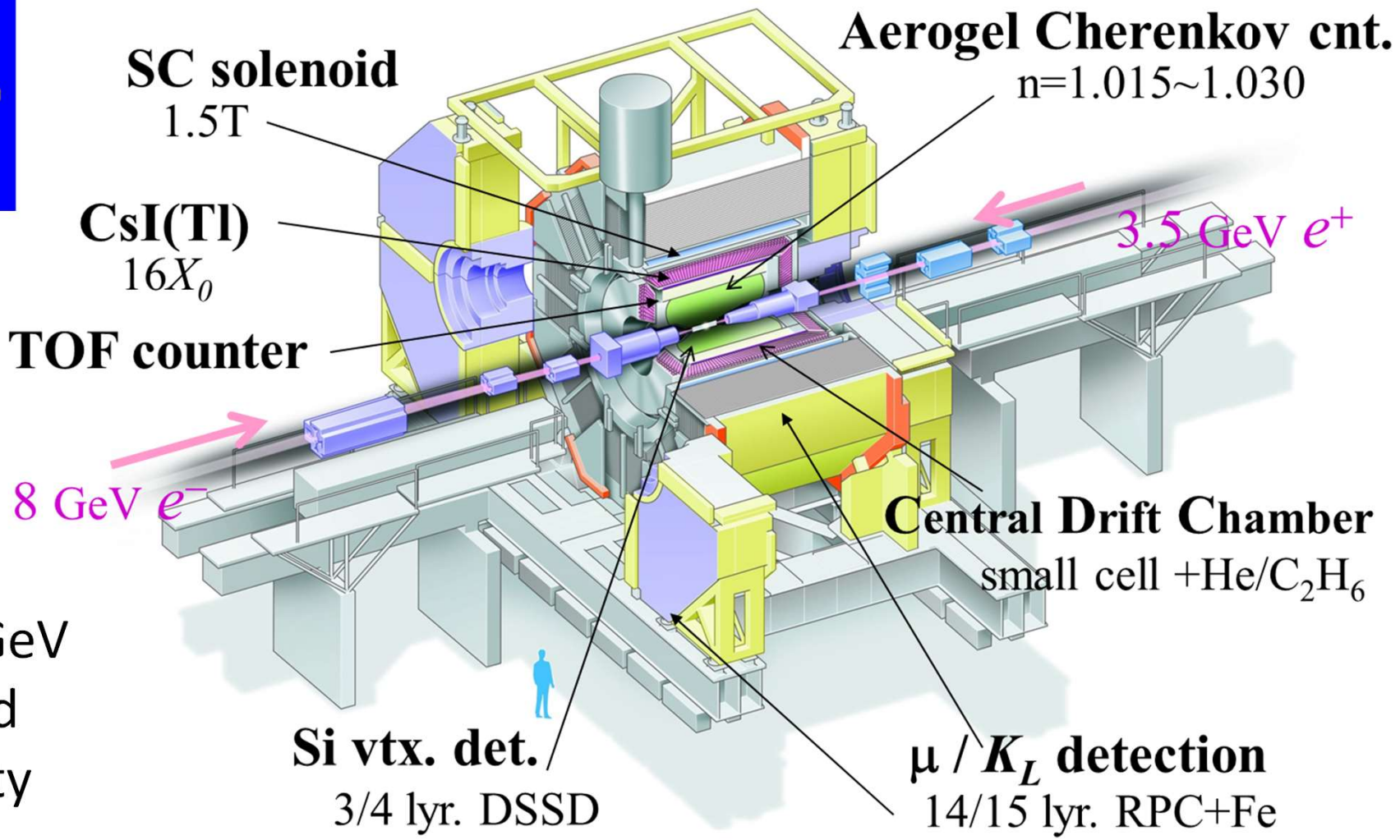
Hadron production in e^+e^-

- Direct resonance production
  - 1^{--} states: ψ, Υ, Y
  - Initial state radiation allows lower mass than √s
  - 2-photon process: 0^{++}, 2^{++} ,…
- Indirect production
  - Quark fragmentation from $Q\bar{Q}$
  - Cascade decays
    b → c, Υ decays, …





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

- $\Omega(2012) \rightarrow \Xi(1530)\bar{K}$ [to be submitted to PRL]
- $e^+e^- \rightarrow \eta\phi$ via ISR [to be submitted to PRD]
- $\Lambda_c \rightarrow \Sigma^+\gamma, \Xi_c^0 \rightarrow \Xi^0\gamma$ [to be submitted to PRD]
- Peak structure in $\Lambda_c \rightarrow pK^-\pi^+$ [to be submitted to PRL]
- $\gamma\gamma \rightarrow \chi_{c2}(1P) \rightarrow J/\psi\gamma$ [to be submitted to JHEP]
- New charm baryon in B decay [arXiv:2206.08822]
- $\Xi_c^0 \rightarrow \Lambda_c\pi^-$ [arXiv:2206.08527]
- Search for X(3872) $\rightarrow \pi^+\pi^-\pi^0$ [arXiv:2206.08592]
- Exotic candidates in $\gamma\gamma \rightarrow \gamma\psi(2S)$
  [arXiv:2105.06605, PRD in press]

Some of recent results (cont.)

- Search for $X_{cc\bar{s}\bar{s}}$ in $D_s^{(*)+}D_s^{(*)+}$ [PRD105 (2022) 032002]
- $\Lambda_c \rightarrow p\eta'$ [JHEP 03 (2022) 090]
- $\Xi_c^0 \rightarrow \Lambda K_S^0, \Sigma^0 K_S^0, \Sigma^+ K^-$ [PRD105 (2022) L011102]
- $e^+e^- \rightarrow \Upsilon(1,2S)\eta, \Upsilon(1S)\eta'$ [PRD104 (2021) 112006]
- $\Lambda_c \rightarrow p\omega$ [PRD104 (2021) 072008]
- $\Omega(2012)$ in Ω_c decay [PRD104 (2021) 052005]
- $\Xi_c^0 \rightarrow \Lambda \overline{K}^{*0}, \Sigma^0 \overline{K}^{*0}, \Sigma^+ K^{*-}$ [JHEP 06 (2021) 160]
- Mass and width of $\Sigma_c^{(*)+}$ [PRD104 (2021) 052003]
- $\Xi_c^0 \rightarrow \Xi^- \ell^+ \nu_\ell$ and $\Xi_c^0 \rightarrow \Xi^- \pi^+$ [PRL127 (2021) 121803]

Some of recent results (cont.)

- $\Xi_c^0 \to \Xi^0 K^+ K^-$ [PRD103 (2021) 112002]
- Search for $\eta_{c2}(1D)$ in $e^+e^- \to \gamma\eta_{c2}(1D)$
  [PRD103 (2021) 012012]
- Energy dependence of $e^+e^- \to B^{(*)}B^{(*)}$
  [JHEP 06 (2021) 137]
- $\Lambda_c \to p\eta$ and $p\pi^0$ [PRD103 (2021) 072004]
- Spin-parity measurement of $\Xi_c(2970)$
  [PRD103, L111101]
- $\Lambda_c \to \eta\Lambda\pi^+$ decay and $\Lambda(1670)$ [PRD103 (2021) 052005]
- Evidence of $\gamma\gamma^* \to X(3872)$ [PRL126 (2021) 122001]
- **More and more are coming!**

Topics of the day

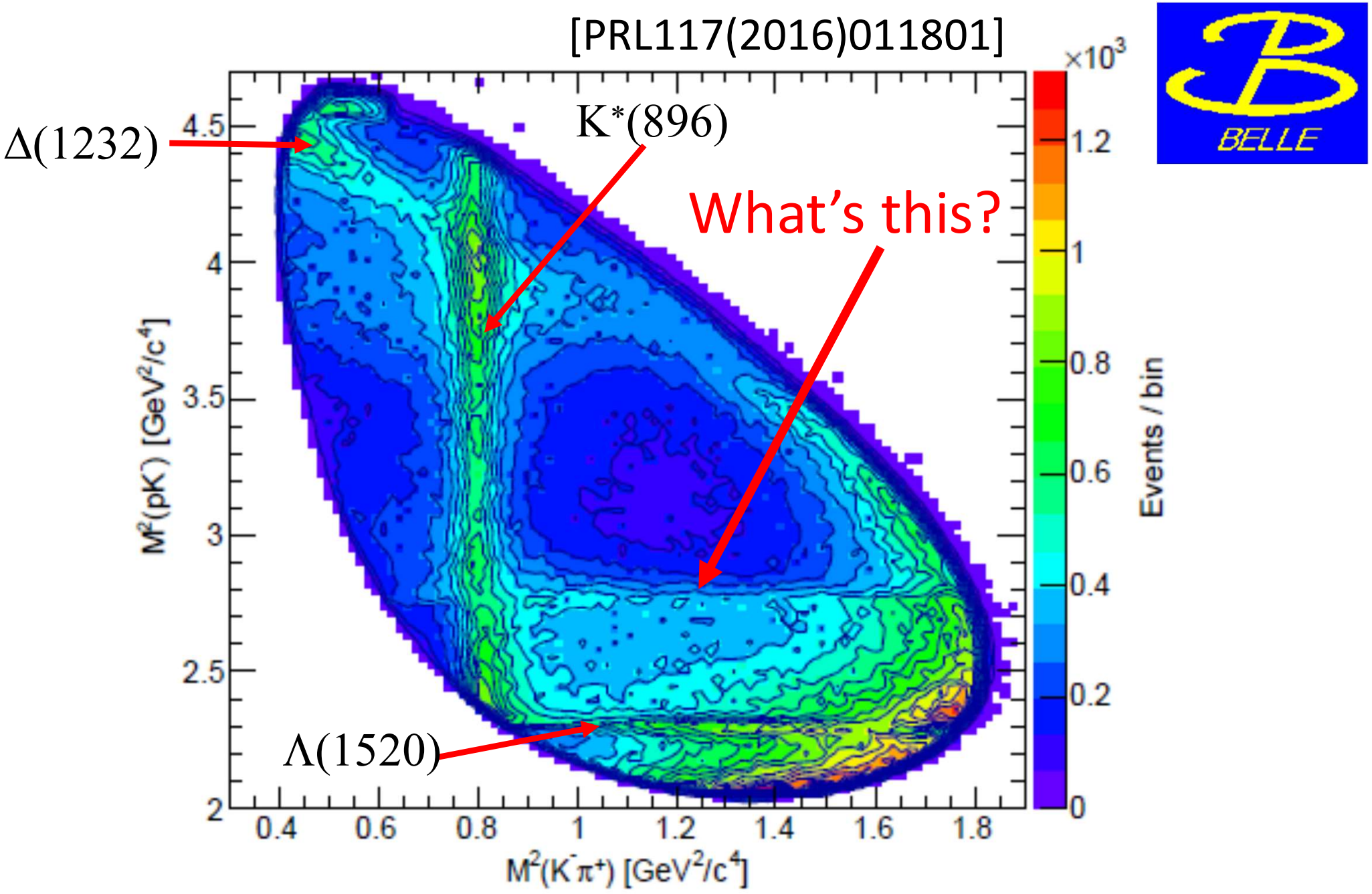
1. Baryons
   - Peak structure in $\Lambda_c \to pK^-\pi^+$
   - Spin-parity measurement of $\Xi_c(2970)$
   - New charm baryon in B decay
2. Mesons
   - Search for tetraquark $X_{cc\bar{s}\bar{s}}$
   - Exotic candidates in $\gamma\gamma \rightarrow \gamma\psi(2S)$
3. Belle II activities & future prospects
4. Summary

1. Baryons

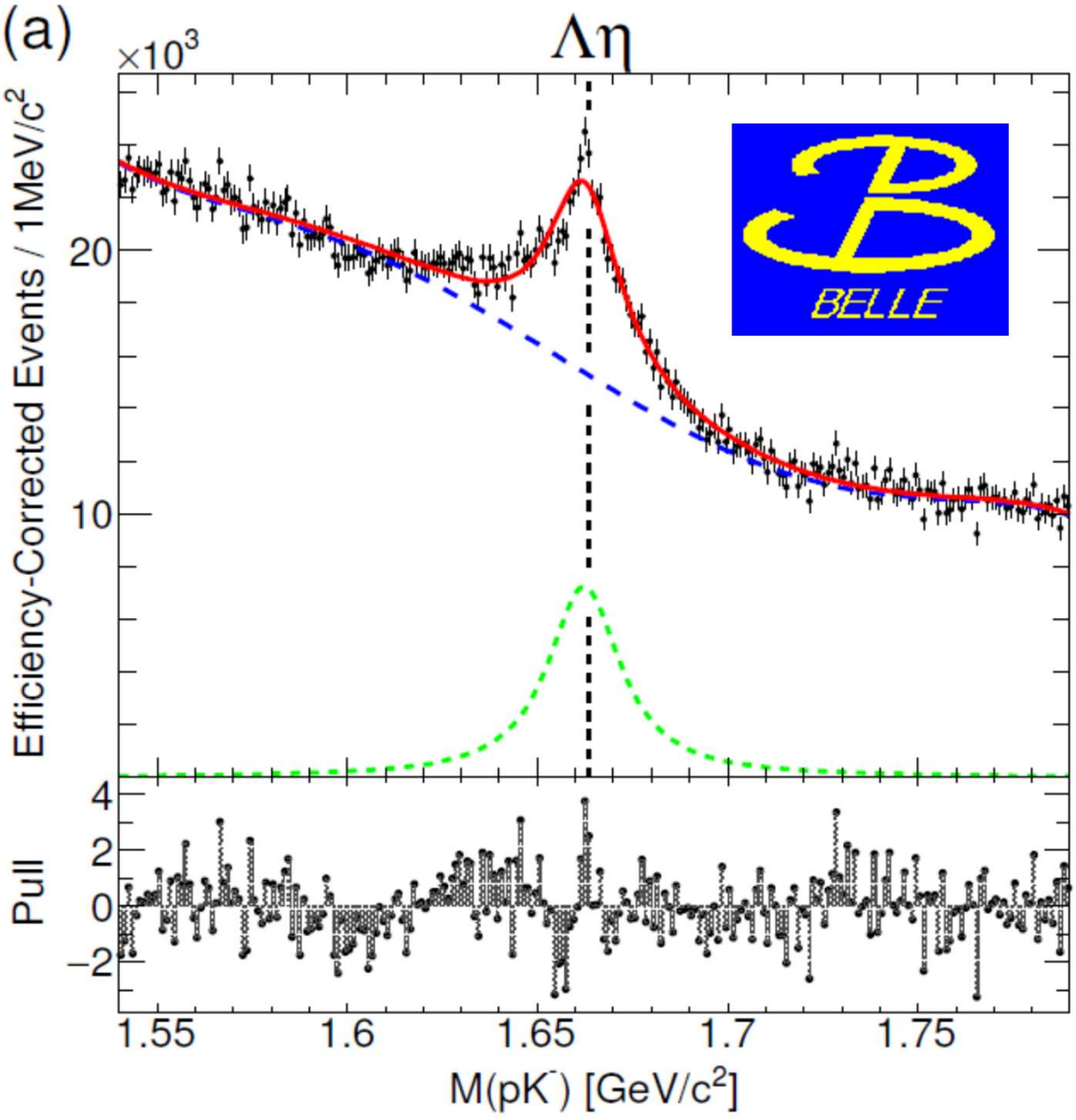
— We have more papers on baryons than mesons recently

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

[PRL117(2016)011801]

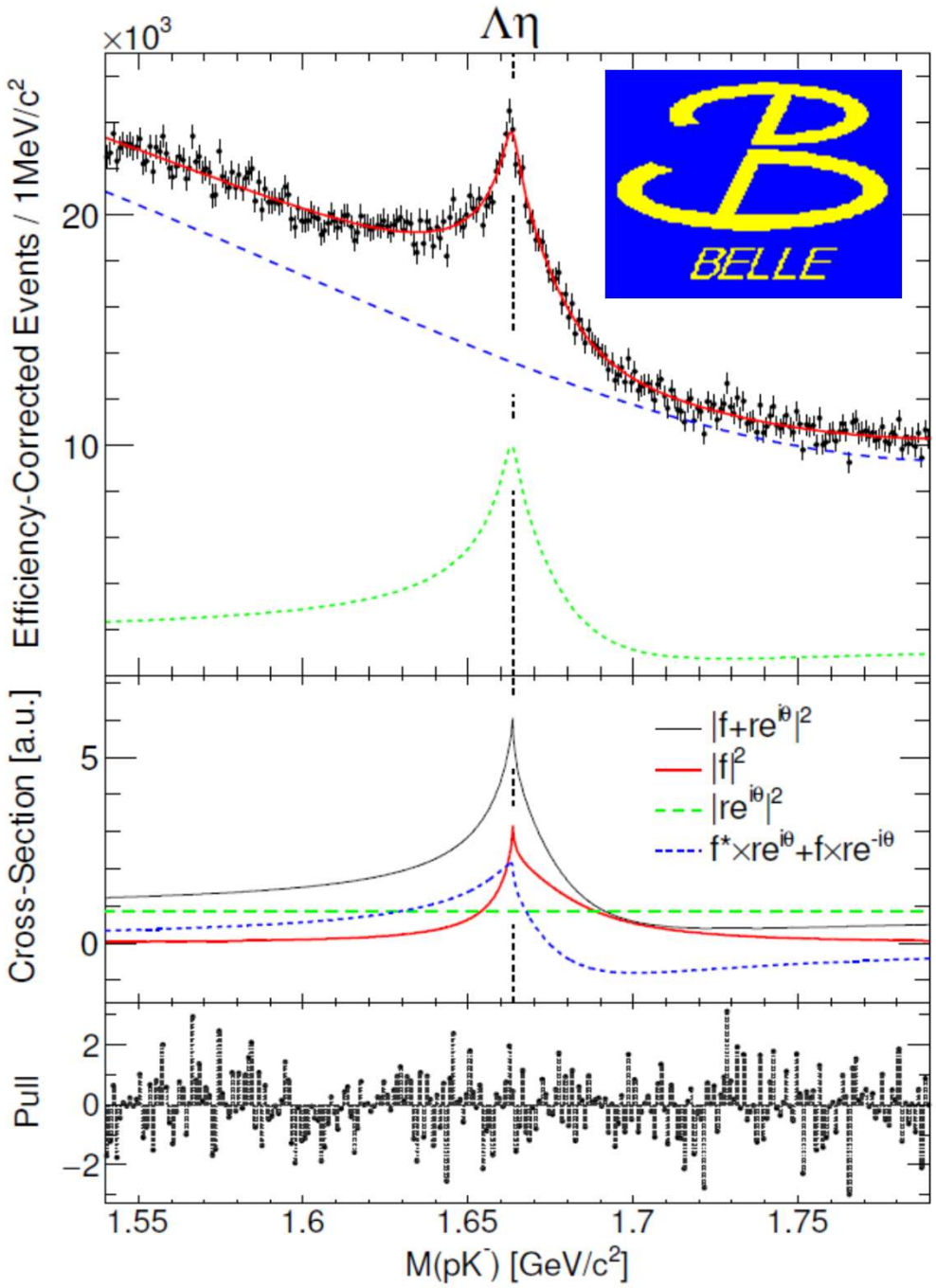


Fit to Breit-Wigner



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

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 $\Lambda(1670)$

  → **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	$50.3 \pm 2.9^{+4.2}_{-4.0}$	$36.1 \pm 2.4 \pm 4.8$

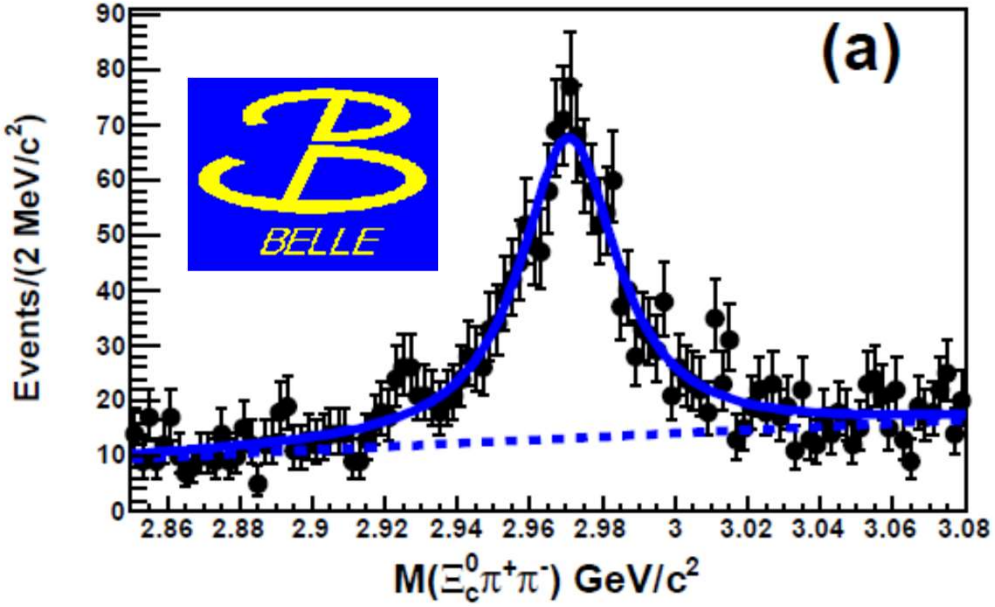
- How about other near-threshold exotic hadrons?

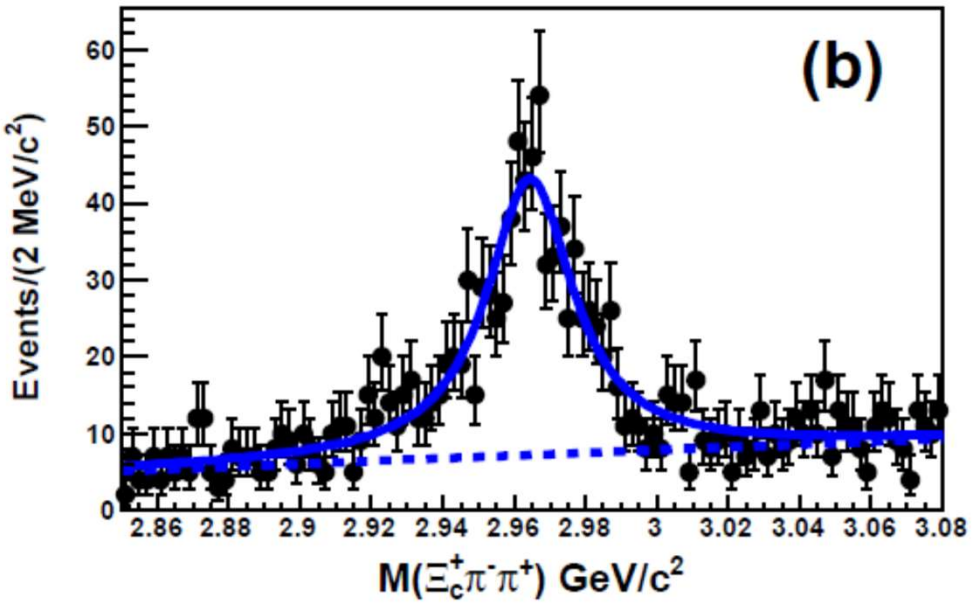
  – **They may be actually threshold cusps!**

$\Xi_c(2970)$

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

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



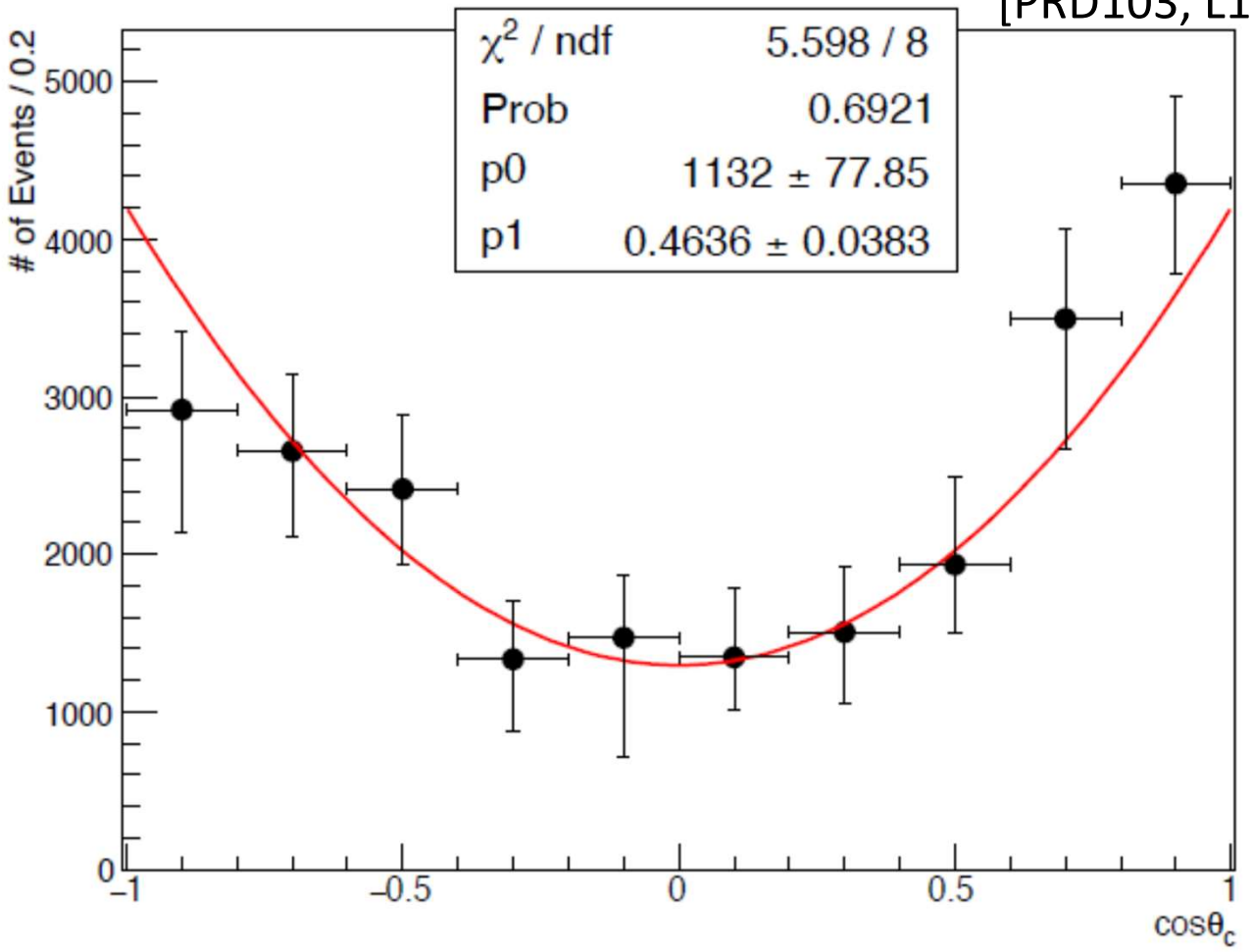


- Wide variety of theoretical predictions
- Important decay mode: $\Xi_c(2970) \rightarrow \Xi_c^*(2645)\pi$

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

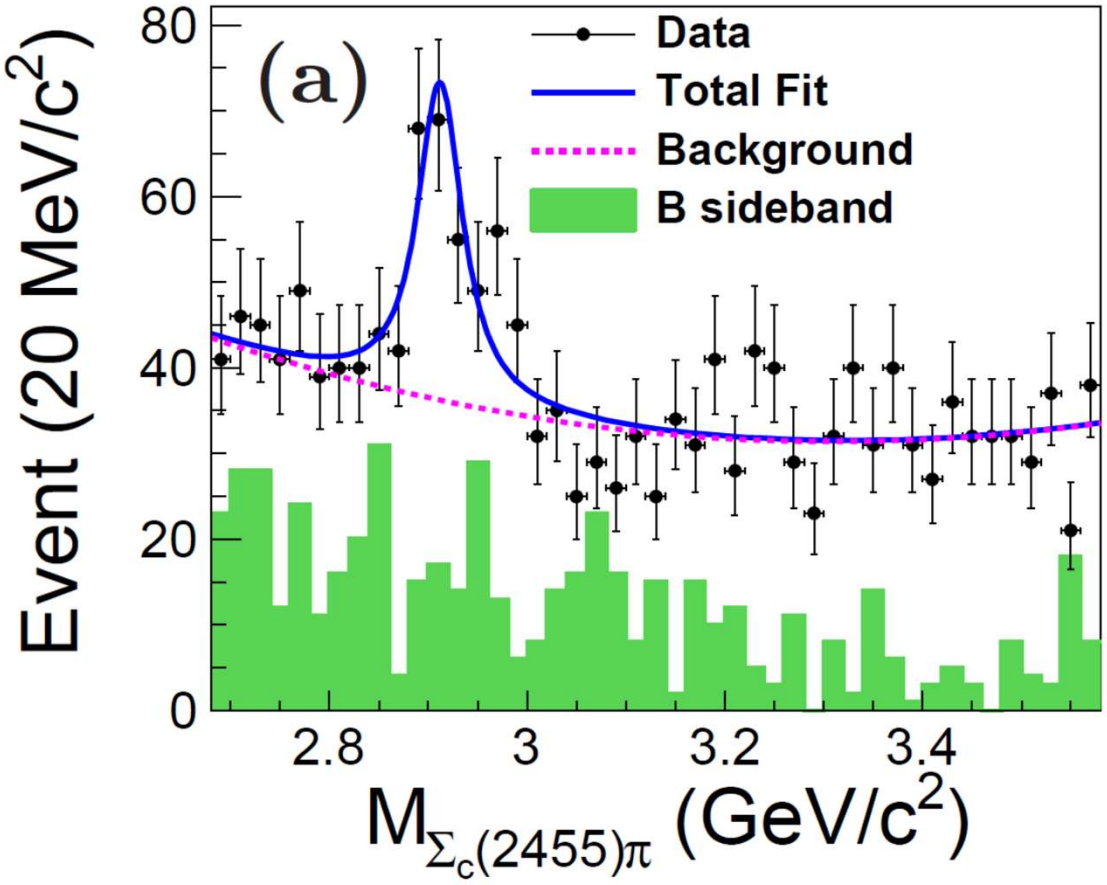
- We got $R = 1.67 \pm 0.29(\text{stat.})^{+0.15}_{-0.09}(\text{syst.}) \pm 0.25(\text{IS})$
  - Consistent with P=+ and brown-muck spin s_ℓ=0 only.

Discussion

- We got $J^P=1/2^+$. What can we say from this?
- This is the same as 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 $\Sigma_c(2455)^{0,++}\pi^{\pm}\bar{p}$



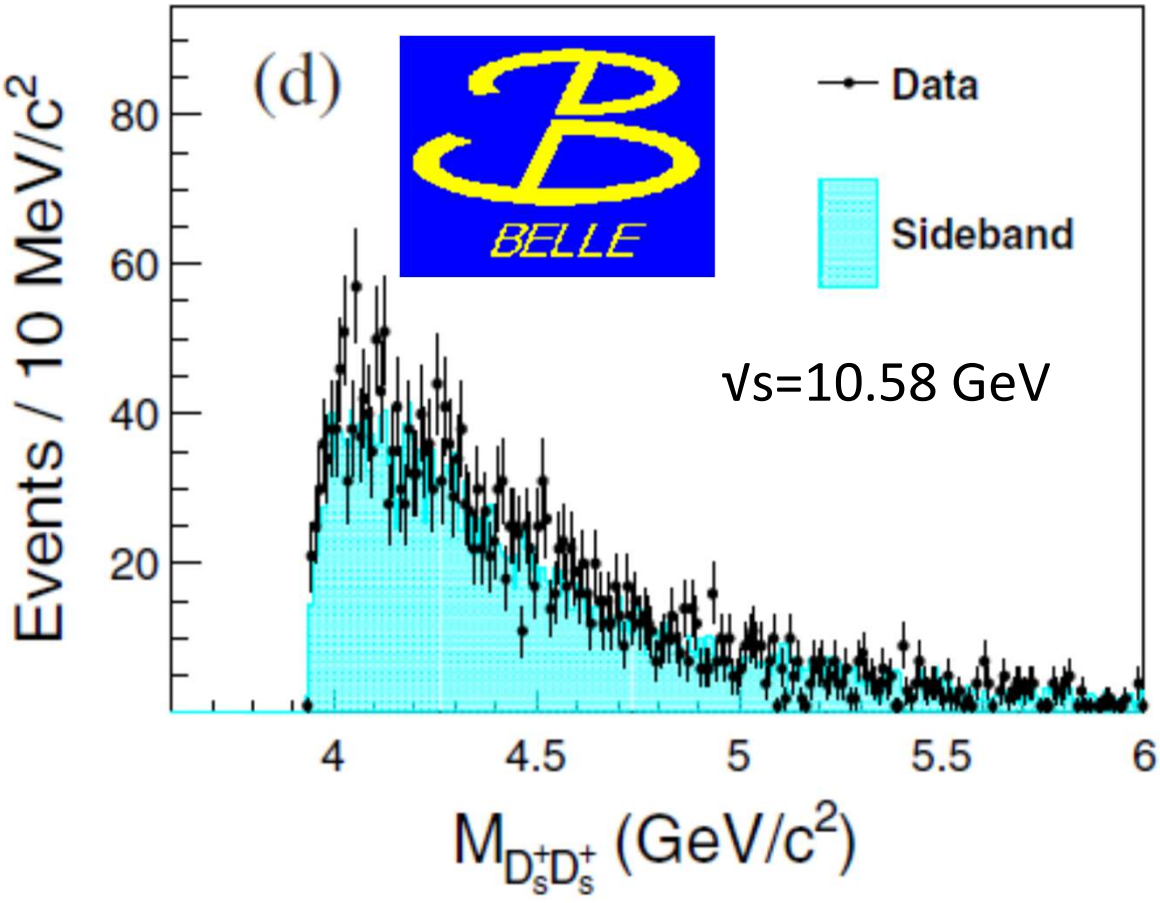
Known resonances [$\Lambda_c(2880)$ & $\Lambda_c(2940)$] are unlikely by 4.2σ

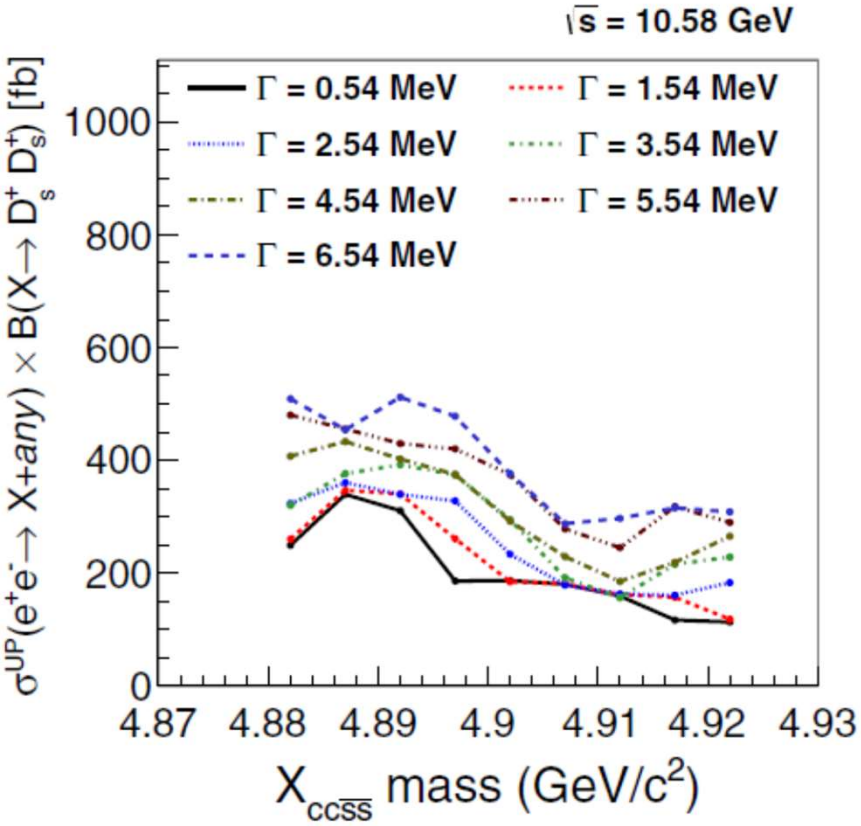
$M = 2913.8 \pm 5.6 \pm 3.8$ MeV/c²

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

2. Mesons

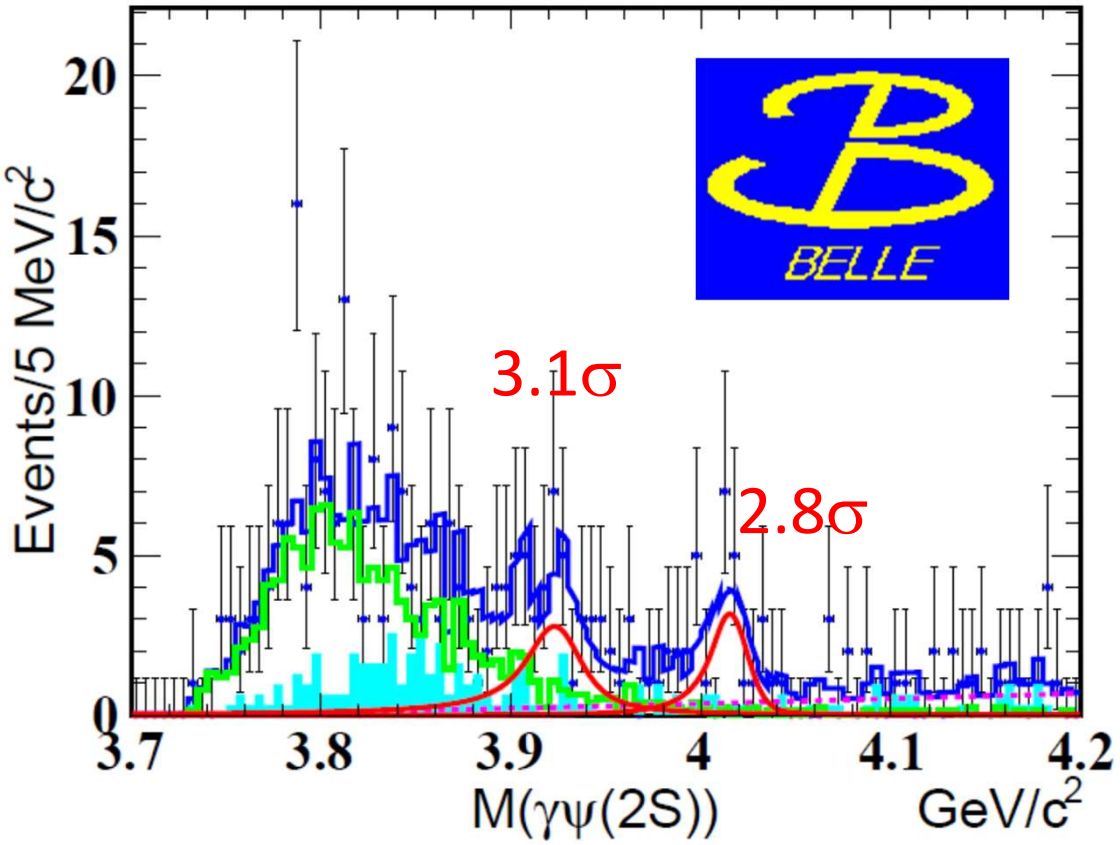
Search for tetraquark $X_{cc\bar{s}\bar{s}}$





- 5 energies: $\Upsilon(1S)$,$\Upsilon(2S)$, 10.52, 10.58 & 10.867 GeV
- No significant signals. Upper limits are set.

Exotic candidates in $\gamma\gamma \rightarrow \gamma\psi(2S)$



Resonant parameters	$J=0$	$J=2$
M_{R_1}	$3922.4 \pm 6.5 \pm 2.0$	
Γ_{R_1}	$22 \pm 17 \pm 4$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_1 \to \gamma\psi(2S))$	$9.8 \pm 3.6 \pm 1.2$	$2.0 \pm 0.7 \pm 0.2$
M_{R_2}	$4014.3 \pm 4.0 \pm 1.5$	
Γ_{R_2}	$4 \pm 11 \pm 6$	
$\Gamma_{\gamma\gamma}\mathcal{B}(R_2 \to \gamma\psi(2S))$	$6.2 \pm 2.2 \pm 0.8$	$1.2 \pm 0.4 \pm 0.2$

arXiv:2105.06605
PRD, in press.

- Hint for 2 resonances
  - Candidates for exotics
- $R_1(3921)$=X(3915)? $\chi_{c2}(3930)$?
- $R_2(4014)$??
  - Very near to the $D^*\overline{D}^*$ threshold

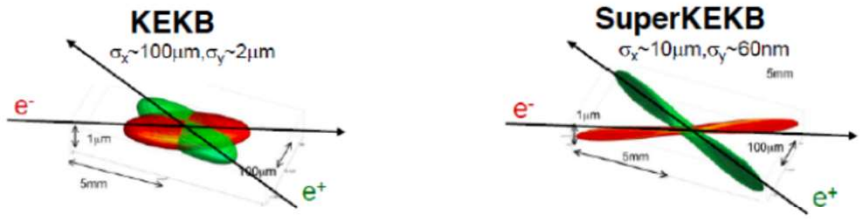
3. Belle II activities
&
future prospects

SuperKEKB and Belle II

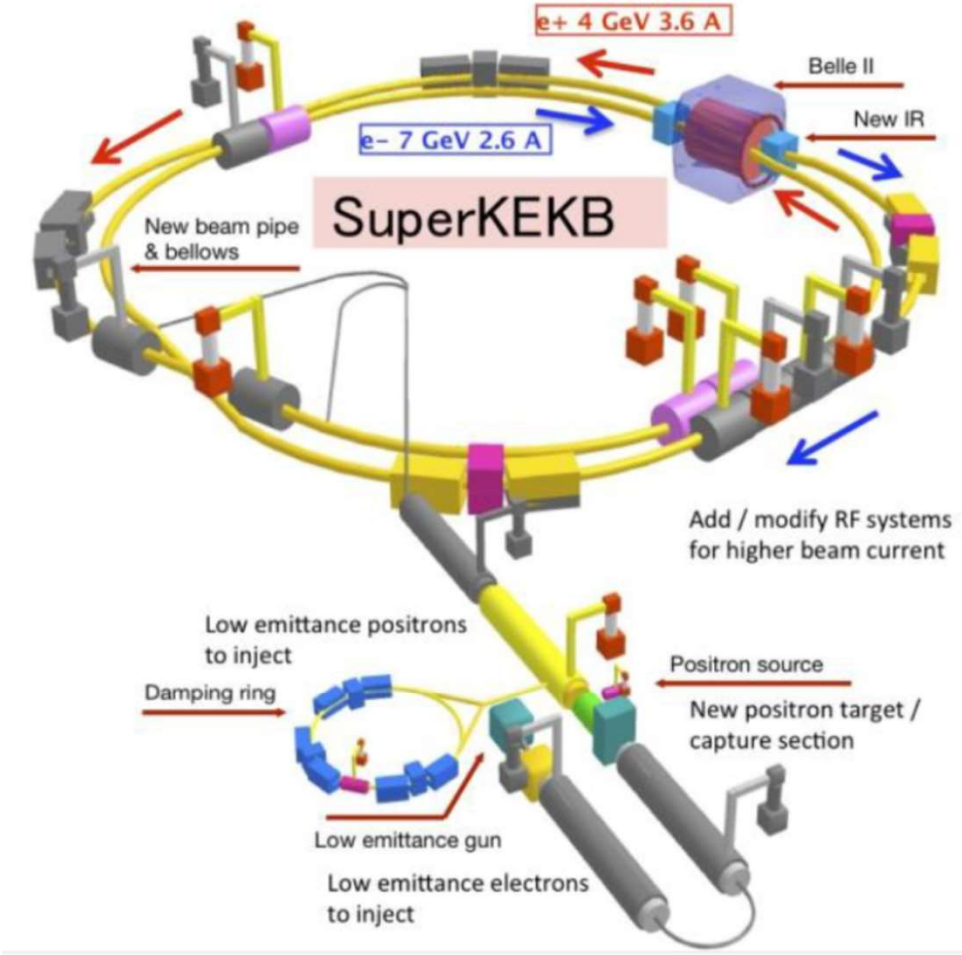
Upgrade for SuperKEKB and Belle II to achieve 30x peak $\mathcal{L}$

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

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



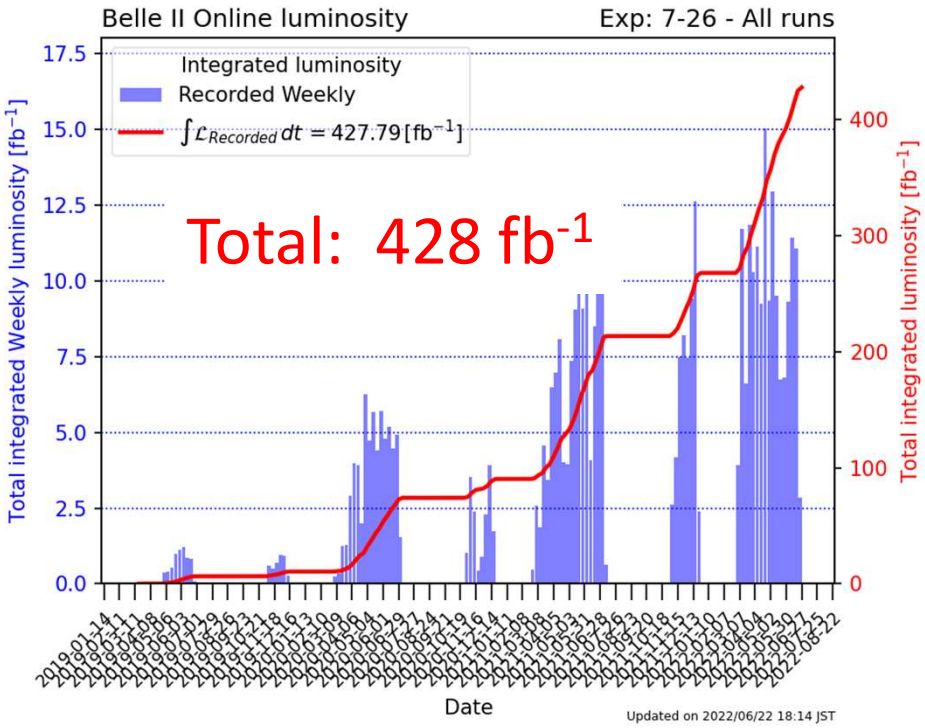
- *First turns achieved Feb. 2016*
- *Beam-background studies ongoing*



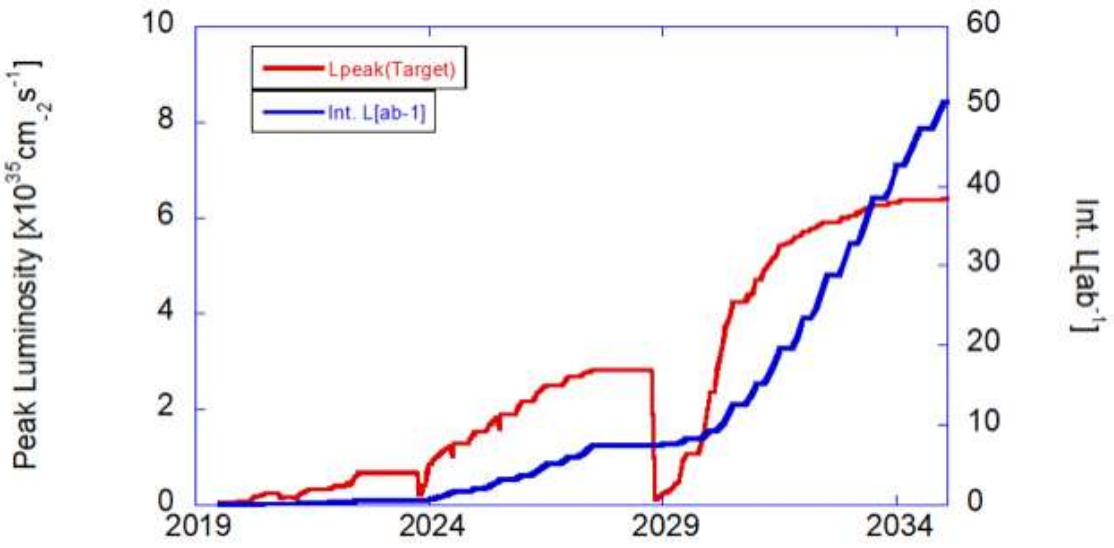
Goal: x50 more statistics than Belle

Belle II integrated luminosity

Achieved



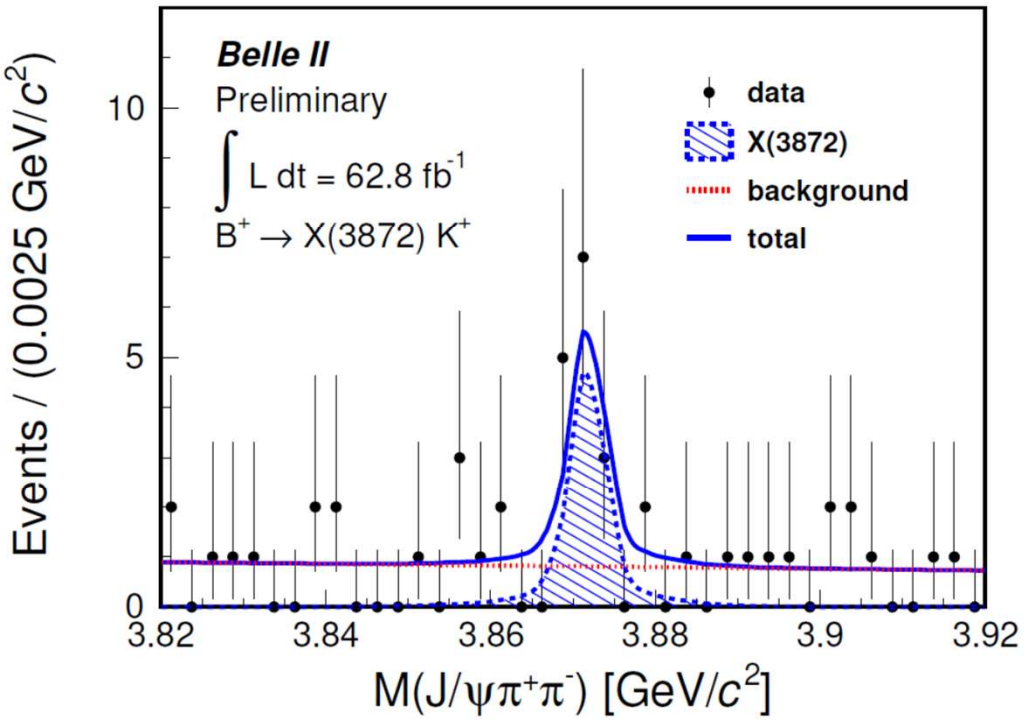
Prospect

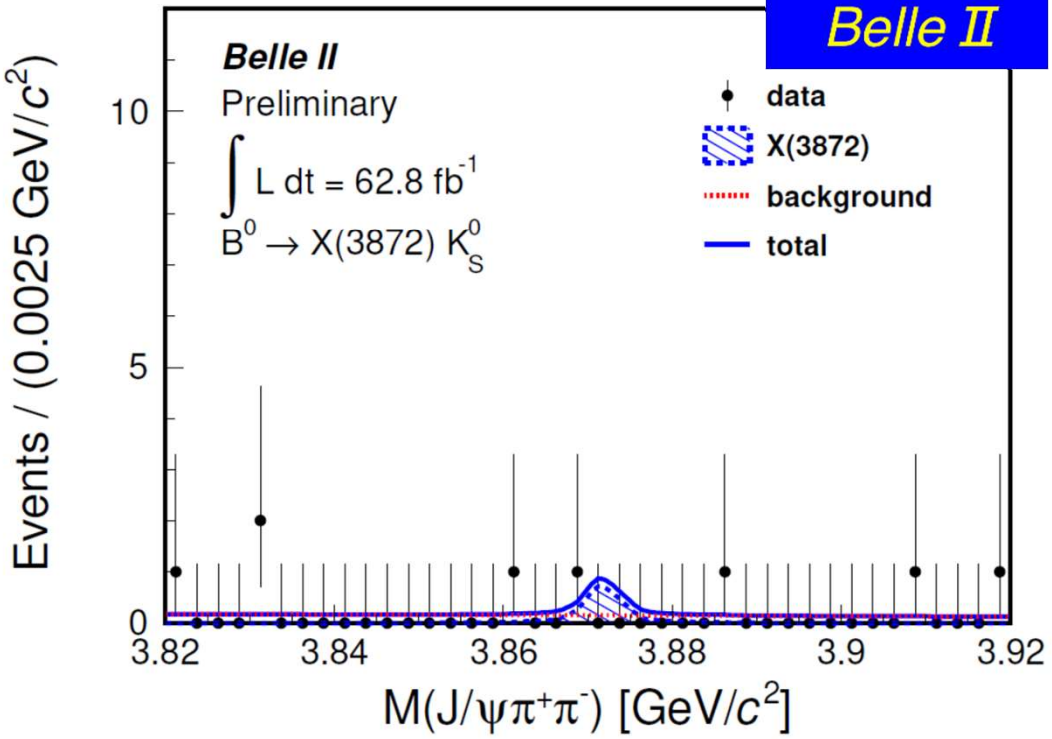


- Instantaneous luminosity already exceeded Belle
  → New record: 4.7×10^{34} $cm^{-2}s^{-1}$ on June 22nd.
- Integrated luminosity will exceed Belle within a few years
- Goal: 50 ab^{-1} around 2035.

X(3872)

- Rediscovery of X(3872) in B → X(3872)K → J/ψππK with 63 fb^{-1} (4.6σ significance)
  - ~20% higher efficiency than Belle



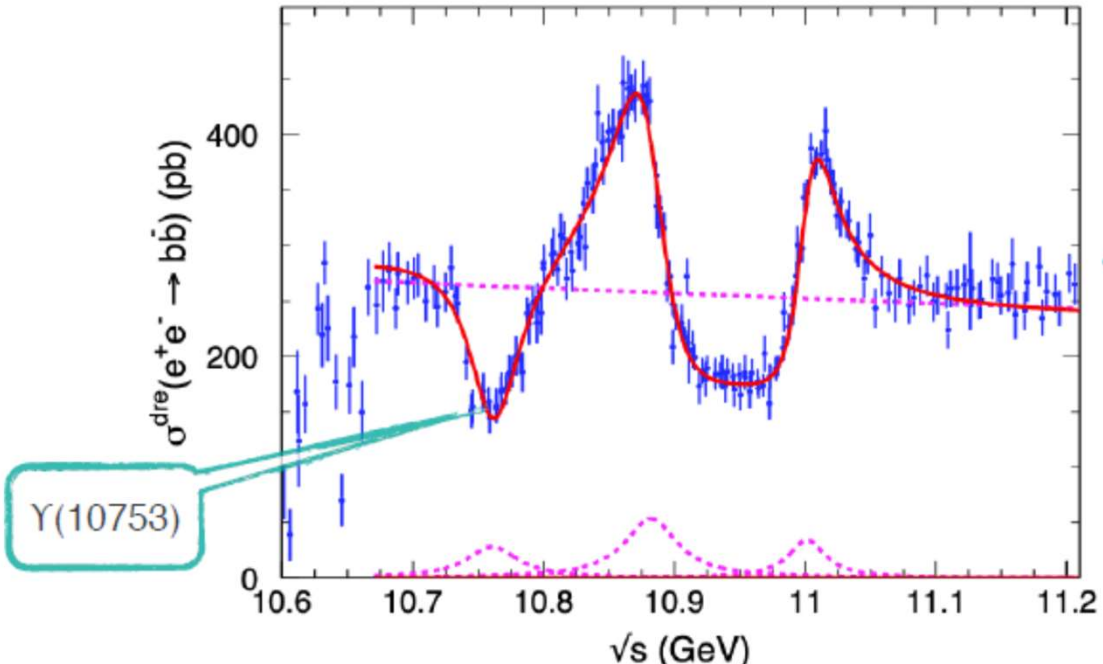


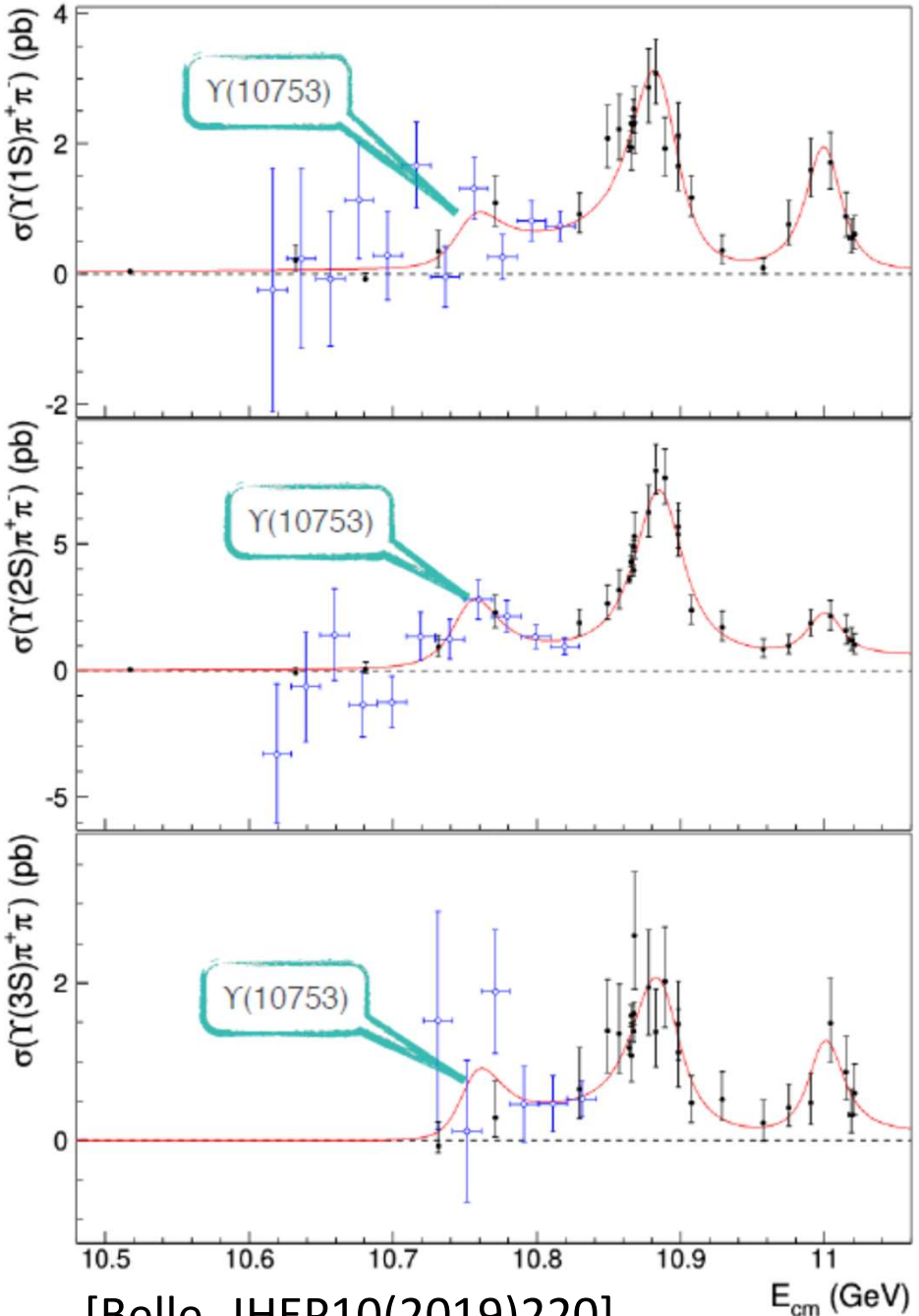
- Near future: Measurement of absolute BR with 1-5 ab^{-1} using missing mass in B → XK.

Energy scan ~10.751 GeV

- $\Upsilon(10753)$?
  - Hints in $\Upsilon(nS)\pi\pi$ & inclusive $b\bar{b}$ data
  - Significance 5.2σ
  - Exotic? Conventional?

[Chin. Phys. C 44 8, 083001 (2020)]

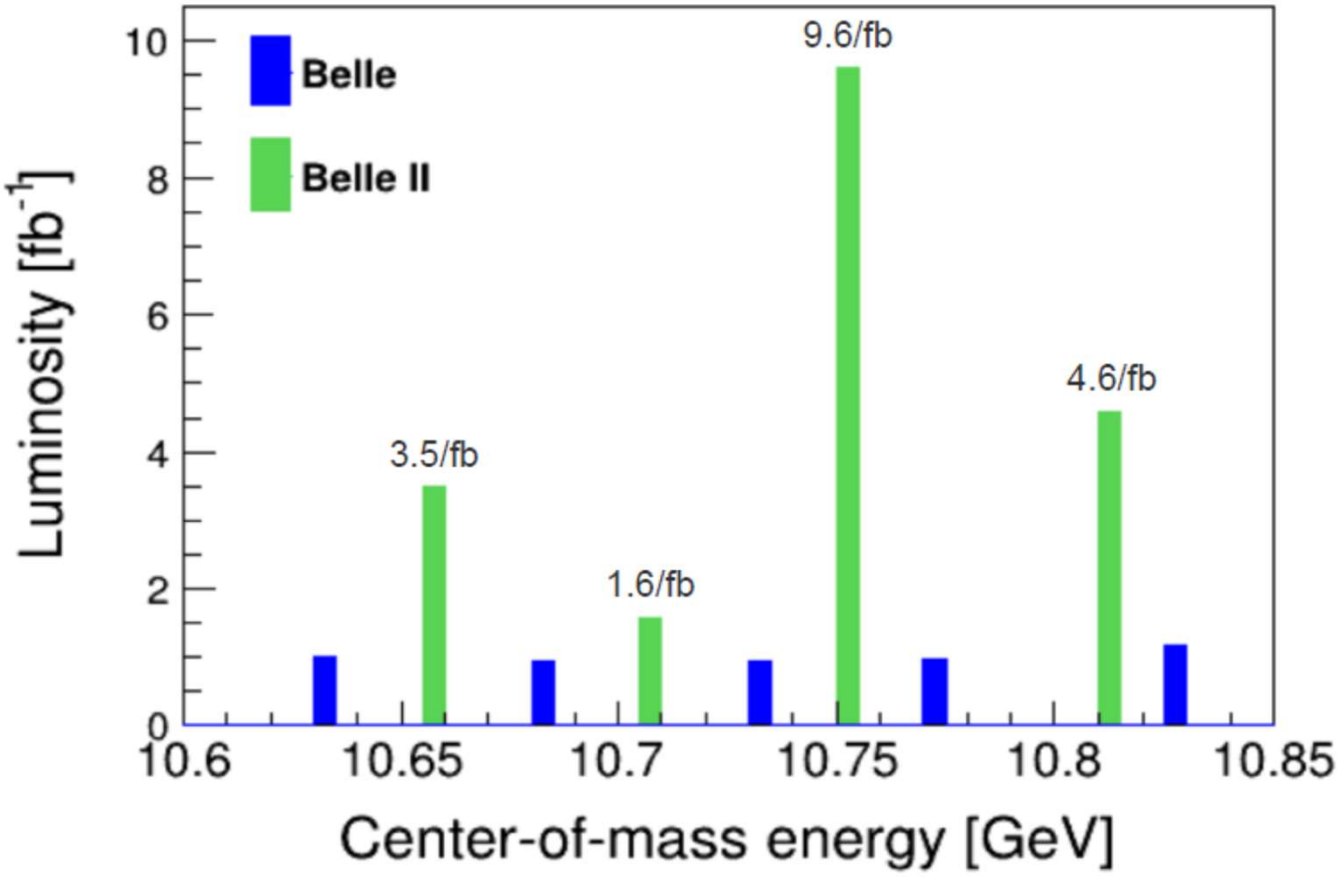




[Belle, JHEP10(2019)220]

Mini energy scan

- We took data at 4 points in Nov./Dec. 2021.
  - To establish the existence
  - Analysis ongoing



Summary

- Belle is still producing lots of interesting results
  - Observation of a threshold cusp
  - Spin-parity measurement of charmed baryon
  - And more. >10 hadron spectroscopy papers every year
- Belle II will acquire x50 more statistics than Belle
  - Instantaneous luminosity already surpassed
    → New record: 4.7×10^{34} $cm^{-2}s^{-1}$ achieved
  - Mini energy scan around 10.753 GeV
  - Expecting a lot of further discoveries