Results on Hadron Spectroscopy from the Belle and Belle II Experiments

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on behalf of the Belle and Belle II Collaboration

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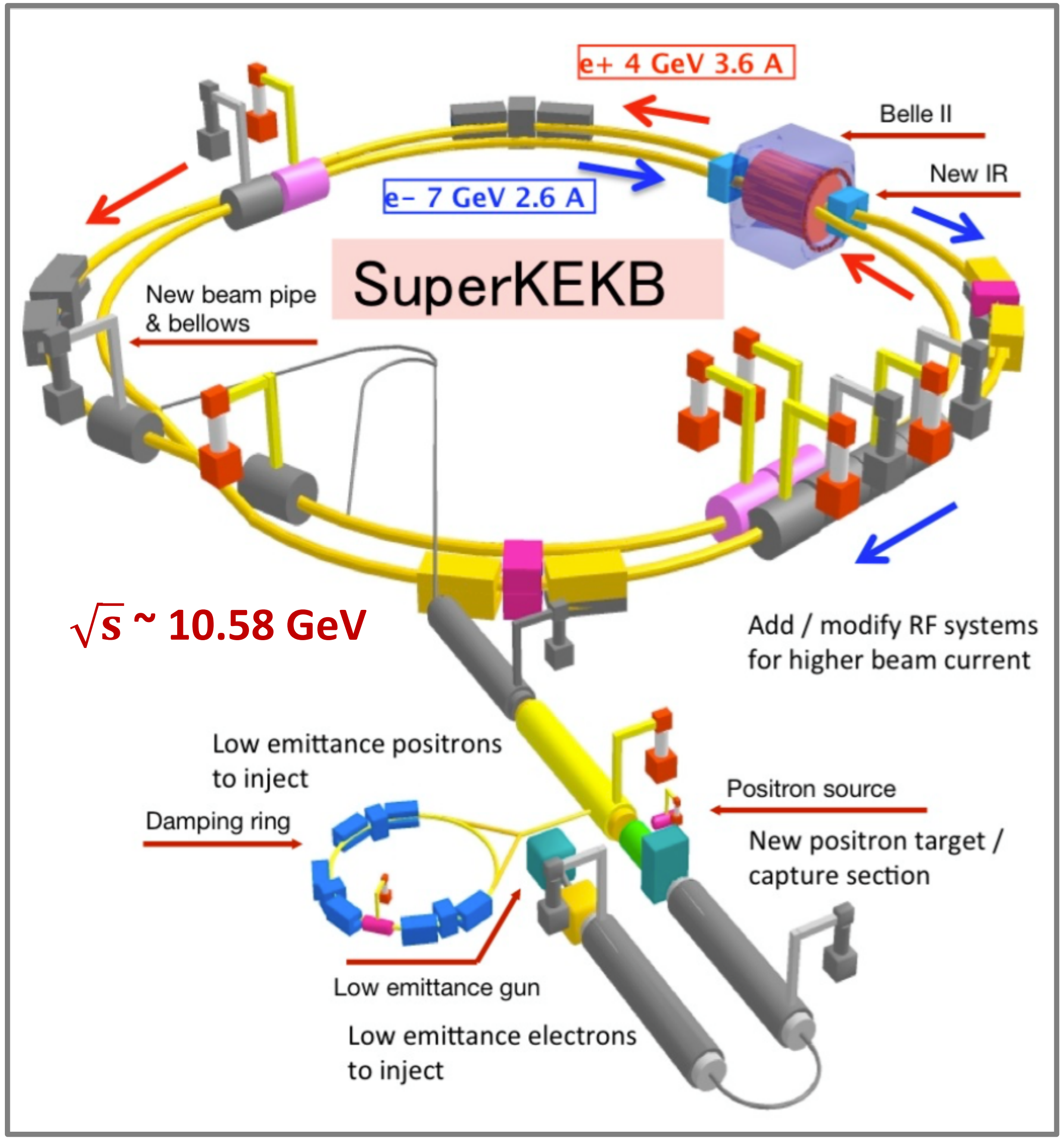
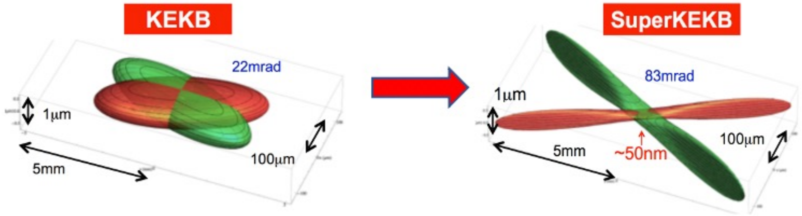
SuperKEKB and Belle II

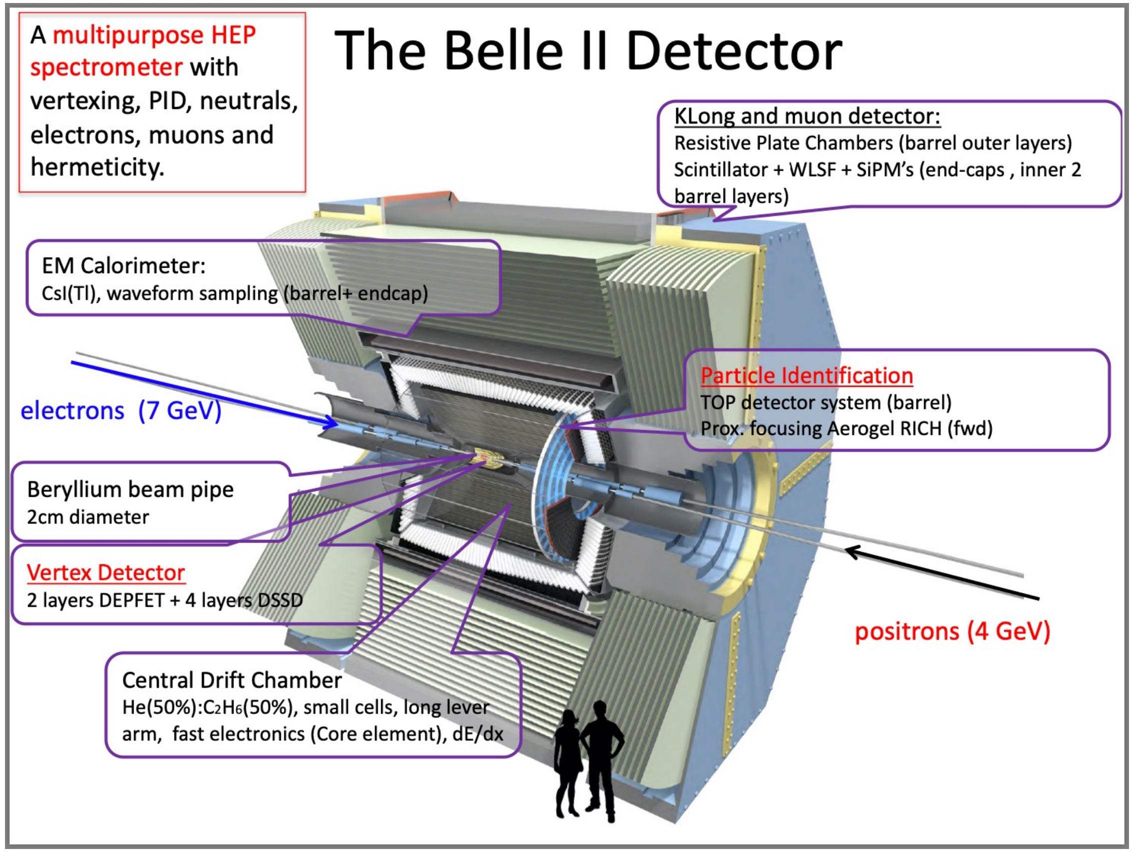




Nano-beam design:

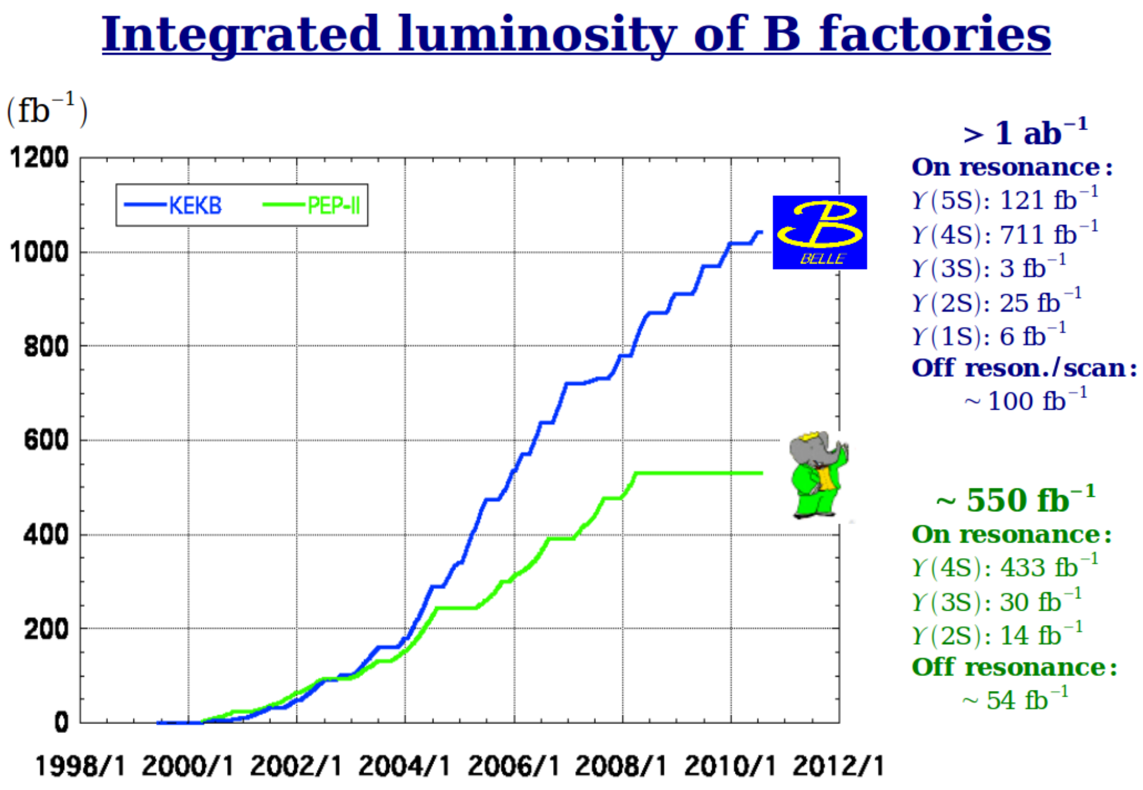
Beam squeezing: ×20 smaller; Beam current: ×2 larger

Target peak luminosity: KEKB×30



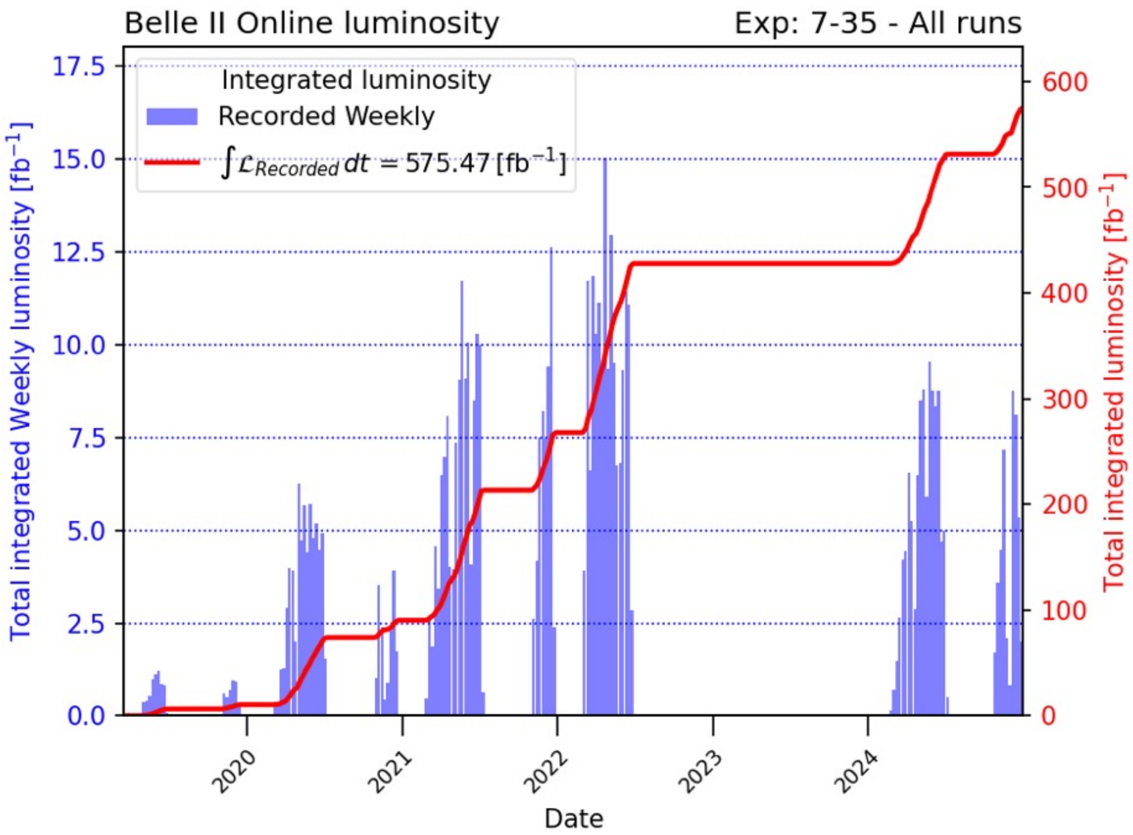
Belle and Belle II Datasets

- **Belle (1999 - 2012)**
- **Belle II RUN-I (2019 - 2023)**
- **Belle II RUN-II (2014 - 2025)**



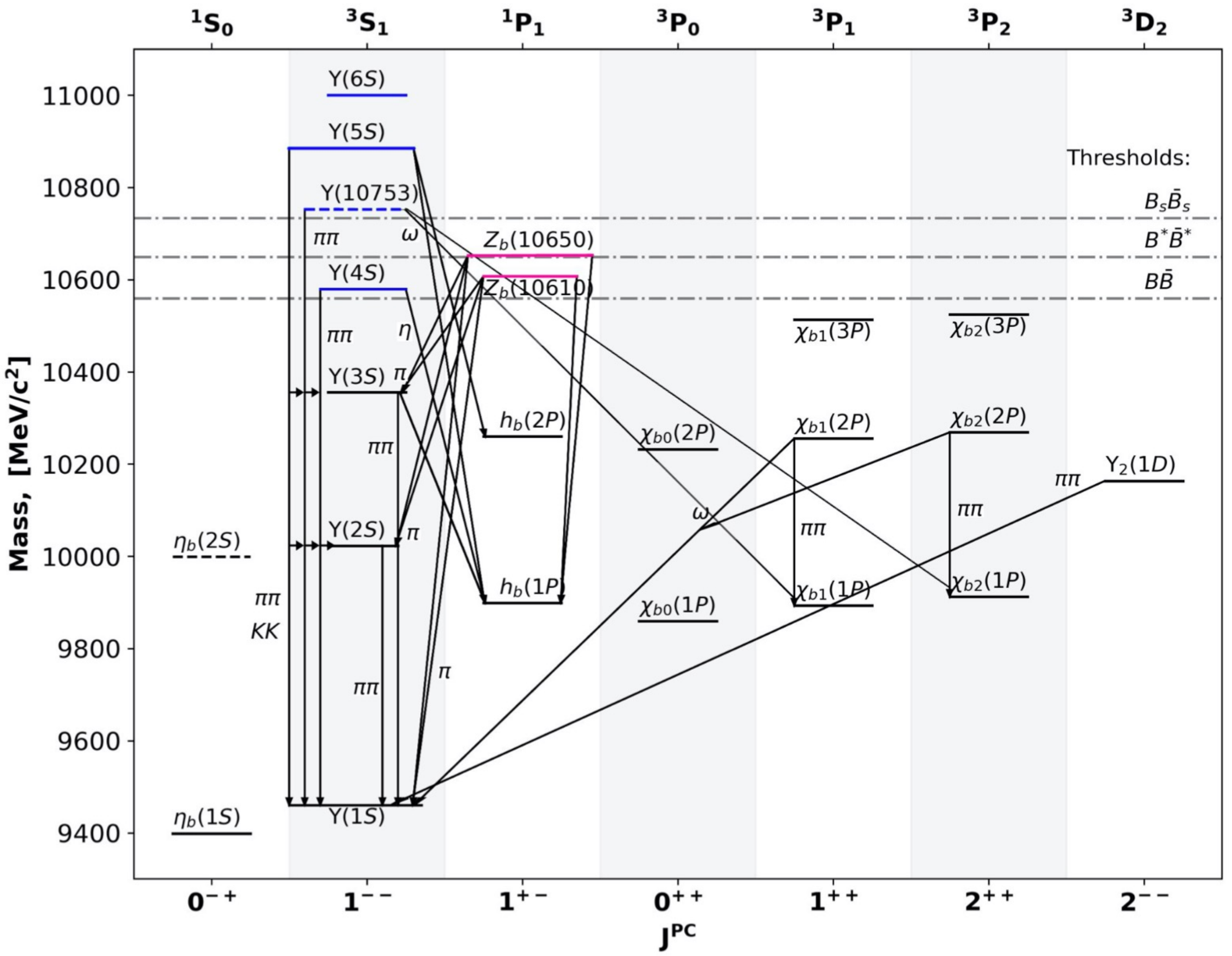
In December 2024

WORLD RECORD: $5.1\times10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$



Most data at or near the $\Upsilon(4S)$ resonance, and 19.6 fb^{-1} near $\Upsilon(10753)$.

Bottomonium



Conventional bottomonium (pure $b\bar{b}$ states)

Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)

Exotic charged states (Z_b^+)

- Below $B\bar{B}$ thresholds – bottomonia are well described by the potential models.

- Above $B\bar{B}$ thresholds – bottomonia express unexpected properties.

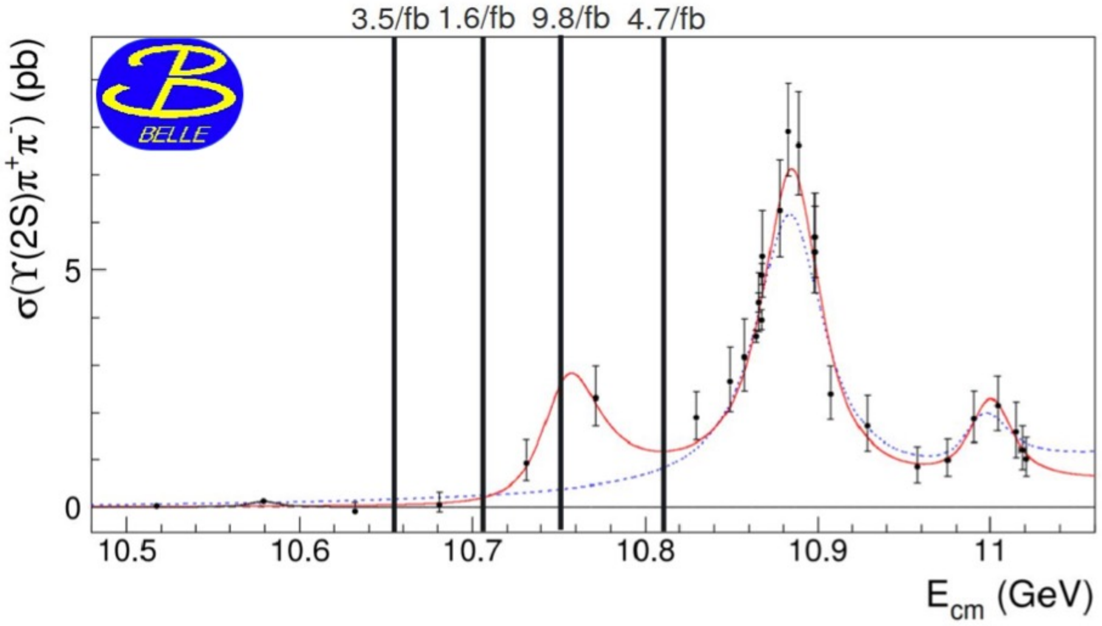
Outline:

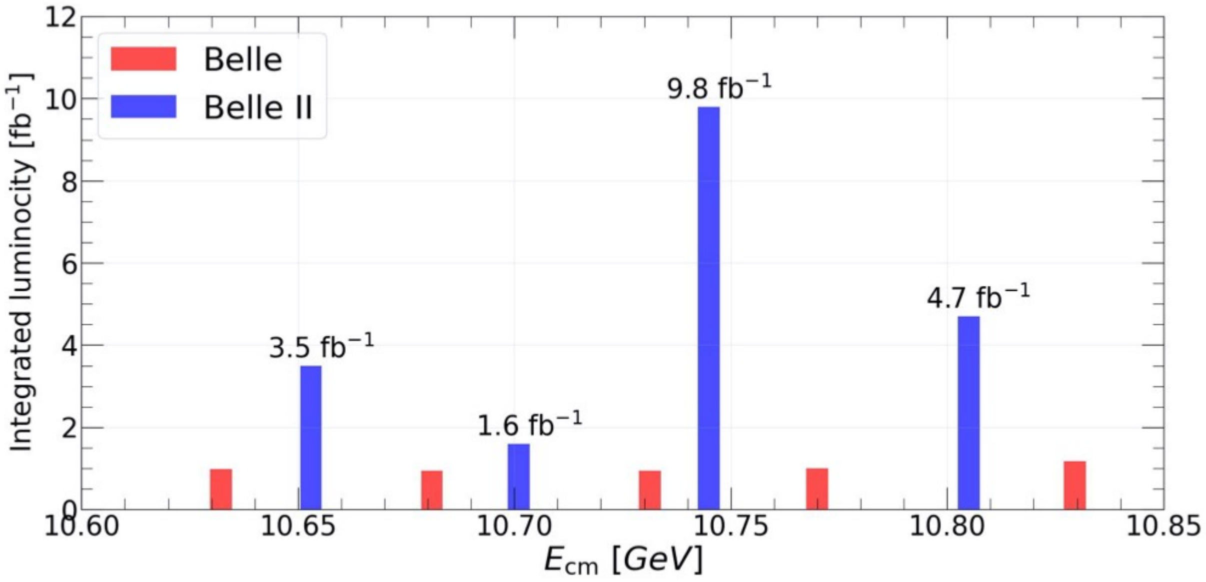
- **The study of $\Upsilon(10753)$ at Belle II**
  - $e^+e^-\to\pi^+\pi^-\Upsilon(nS)$ [JHEP 07, 116 (2024)]
  - $e^+e^-\to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ [JHEP 10, 114 (2024)]
  - $e^+e^-\to\omega\eta_b(1S)$ [PRD 109, 072013 (2024)]
  - $e^+e^-\to\omega\chi_{bJ}$ and $e^+e^-\to(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ [New]
  - $e^+e^-\to\eta\Upsilon(1S,2S)$ [New]
- **Search for pentaquark states in $\Upsilon(1S,2S)$ decays at Belle**
  - $P_c\to pJ/\psi$ [arXiv: 2403.04340]
  - $P_{c\bar{c}s}\to\Lambda J/\psi$ [arXiv: 2502.09951]
- **Bottomonium transitions**
  - $h_b(2P)\to\eta\Upsilon(1S)$ [PRL 133, 261901 (2024)]
  - $h_b(2P)\to\gamma\chi_{bJ}(1P)$ [PRD 111, 011102 (2025)]
- $\boldsymbol{\Omega(2012)^-\to\Xi(1530)\bar{K}\to\Xi\pi\bar{K}}$ [PLB 860, 139224 (2025)]
- **Prospects at Belle II**

The study of $\Upsilon(10753)$ at Belle II

More details can be found in Junhao's talk: $\Upsilon(10753)$ results at Belle II

Unique scan data near $\sqrt{s}$ = 10.75 GeV

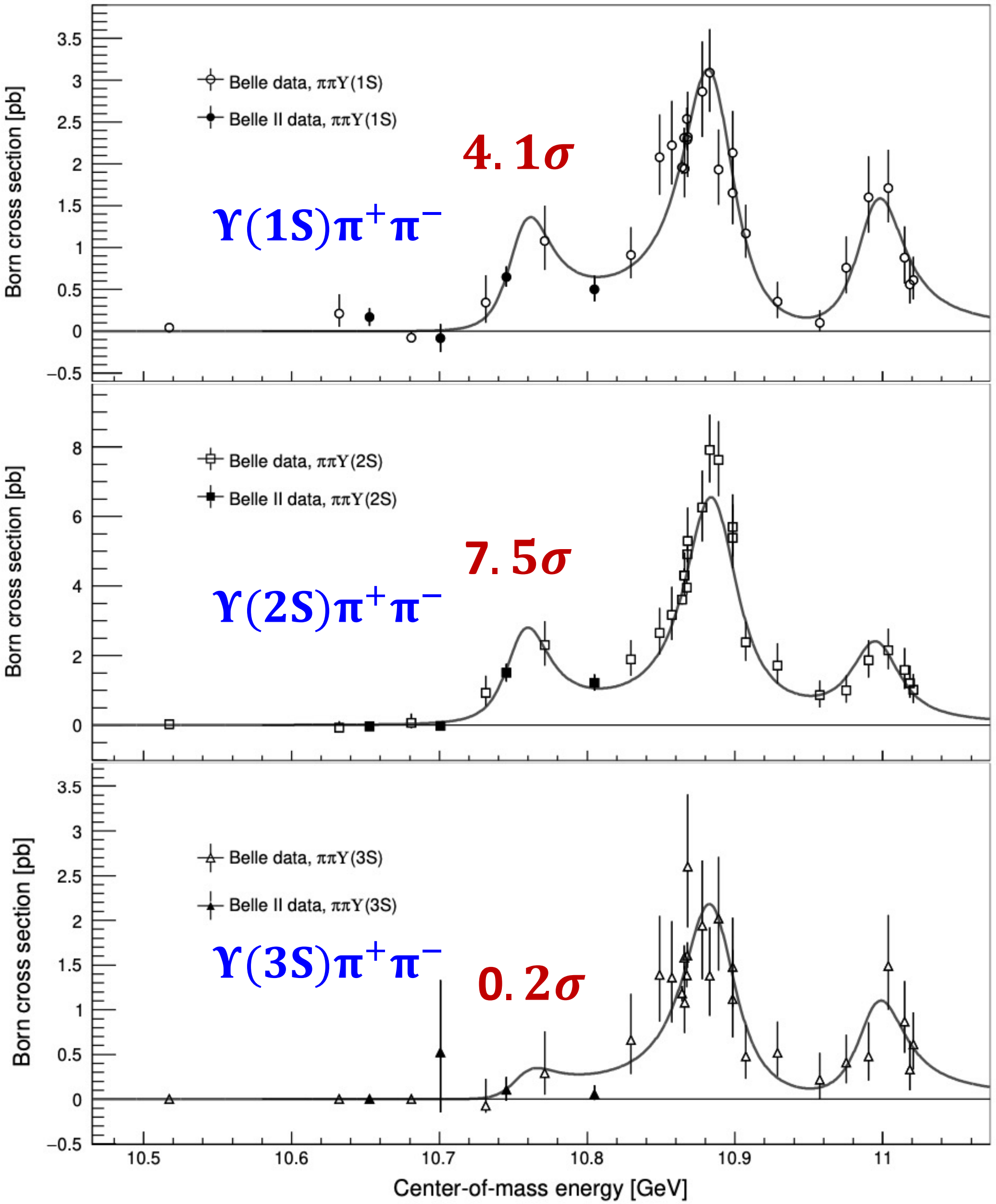




- In November 2021, Belle II collected 19 fb^{-1} of unique data at energies above the $\Upsilon(4S)$: four energy scan points around 10.75 GeV.
- Belle II collected the data in the gaps between Belle energy scan points.
- Physics goal: understand the nature of the $\Upsilon(10753)$ energy region.

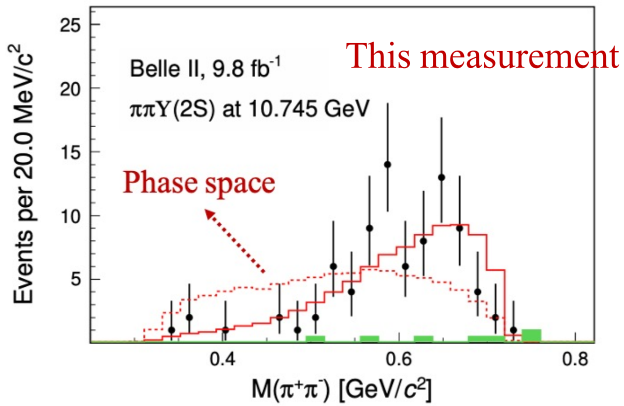
Updated measurement of $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ at Belle II

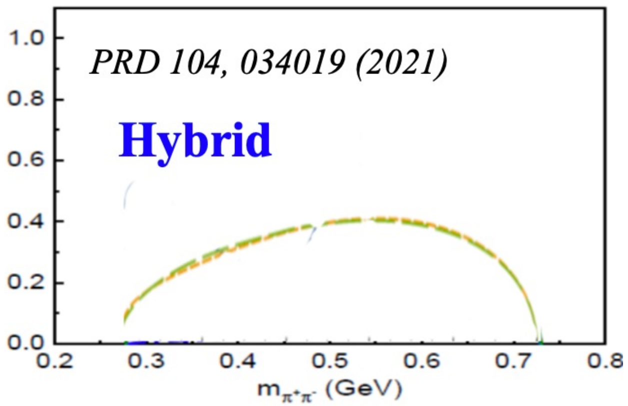
[JHEP 07, 116 (2024)]

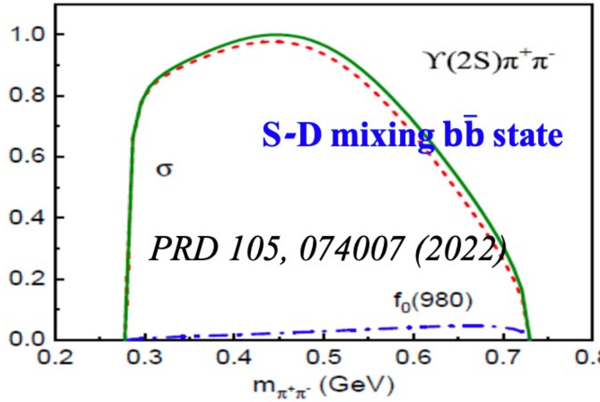


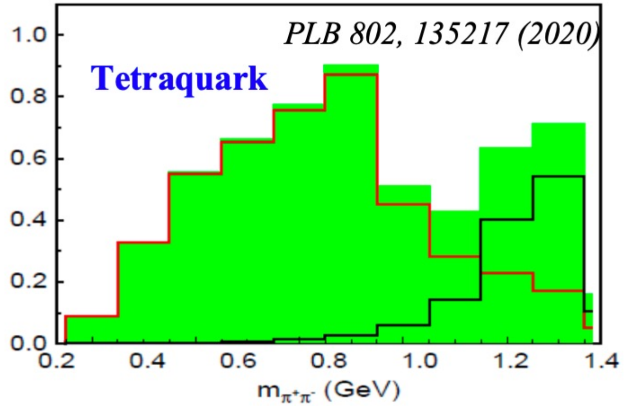
Belle II confirm this peak!

	Belle + Belle II (MeV)	Belle (MeV)
Mass	$10756.6 \pm 2.7 \pm 0.9$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Width	$29.0 \pm 8.8 \pm 1.2$	$35.5^{+17.6+3.9}_{-11.3-3.3}$





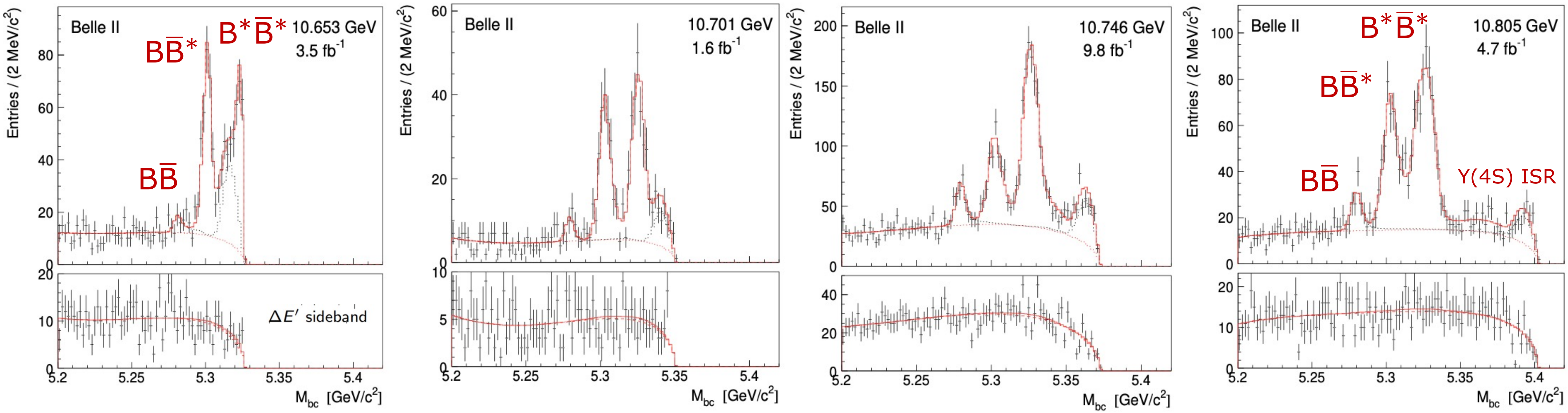




Measurement of the energy dependence of the $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ cross sections

$M_{bc} = \sqrt{(E_{cm}/2)^2 - P_B^2}$

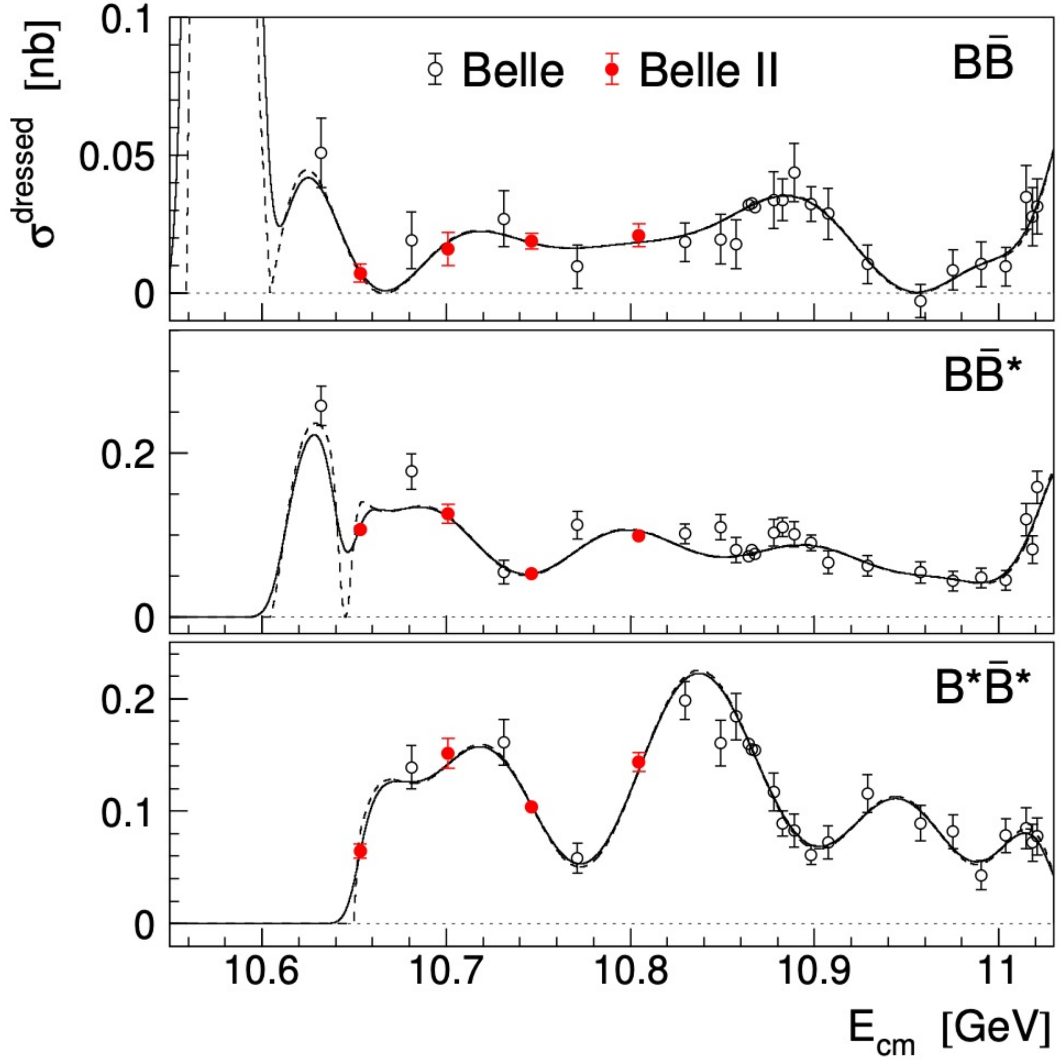
[JHEP 10, 114 (2024)]



- $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ signals at $\sqrt{s} \sim 10.75$ GeV can be clearly observed
- Contribution of $\Upsilon(4S) \to B\bar{B}$ production via ISR is visible well (black dotted histograms)
- At $\sqrt{s}$ =10.653 GeV, the sharp cut of the data at right edge is due to threshold effect

Energy dependence of the cross sections

[JHEP 10, 114 (2024)]



Solid curve – combined Belle + Belle II data fit
Dashed curve – Belle data fit only

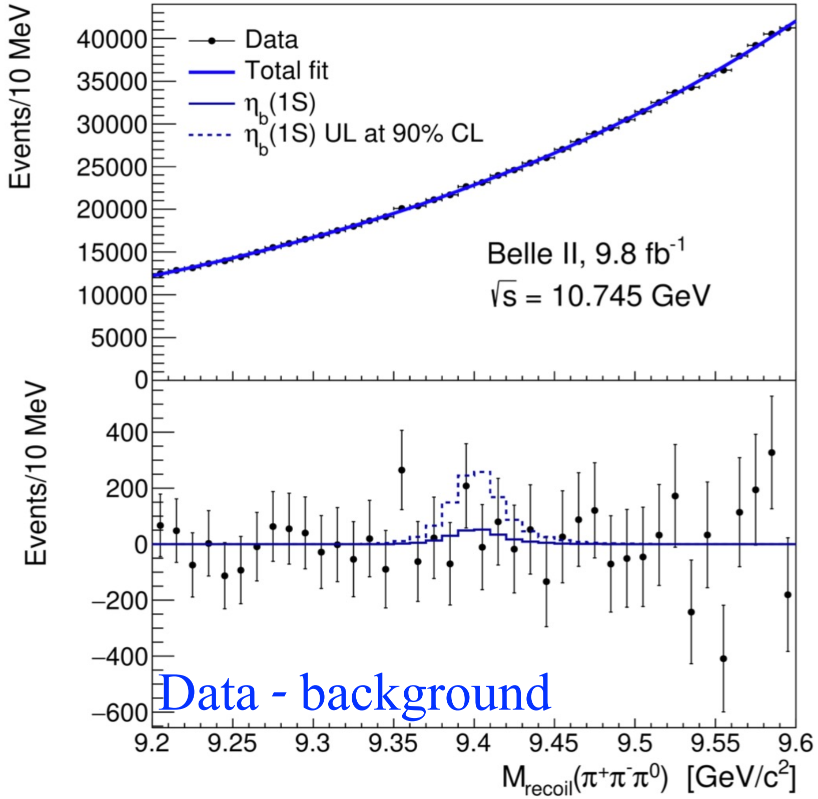
New: rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold

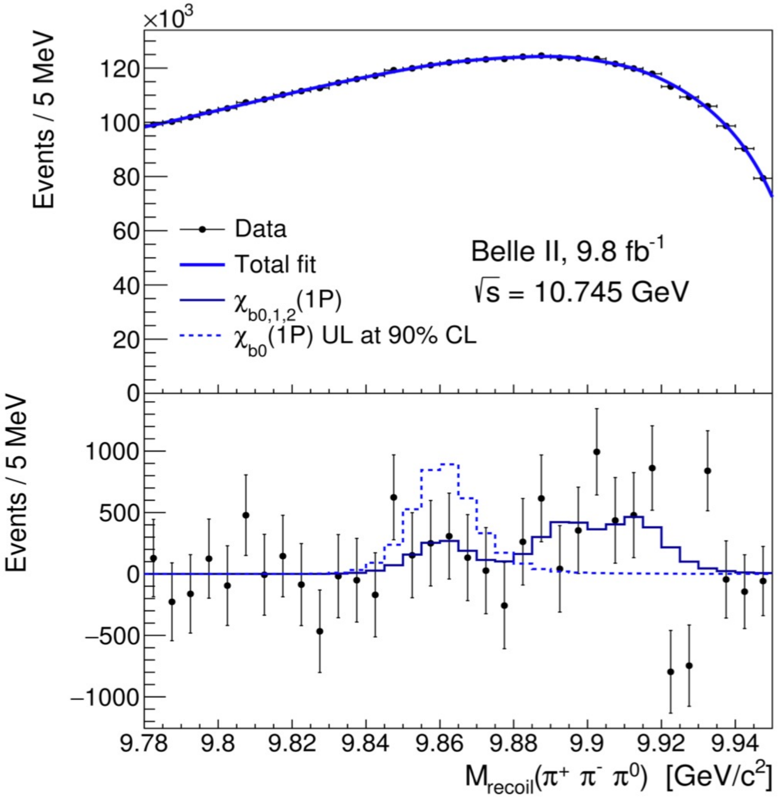
- Similar behaviour was seen for $D^*\bar{D}^*$ cross section (PRD 97, 012002 (2018))
- Possible interpretation: resonance or bound state ($B^*\bar{B}^*$ or $b\bar{b}$) near threshold (MPL A 21, 2779 (2006))
- Also explains a narrow dip in $\sigma(e^+e^- \to B\bar{B}^*)$ near $B^*\bar{B}^*$ threshold by destructive interference between $e^+e^- \to B\bar{B}^*$ and $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$
- Expect channels [$\pi^+\pi^-\Upsilon(nS)$, $\Upsilon(nS)\eta$, and $h_b(1P)\eta$] could also be enhanced

Search for $e^+e^-\to\omega\eta_b(1S)$ and $e^+e^-\to\omega\chi_{b0}(1P)$

No clear $\eta_b(1S)$ and $\chi_{b0}(1P)$ signals are observed.

[PRD 109, 072013 (2024)]





- A 3rd polynomial for $\eta_b(1S)$
- A product of a 4th polynomial and a square root function for $\chi_{b0}(1P)$
- Polynomial orders are chosen with maximum p-values
- The yields for $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ are fixed [PRL 130, 091902 (2023)].

Tetraquark model in Ref. [CPC 43, 123102 (2019)]:

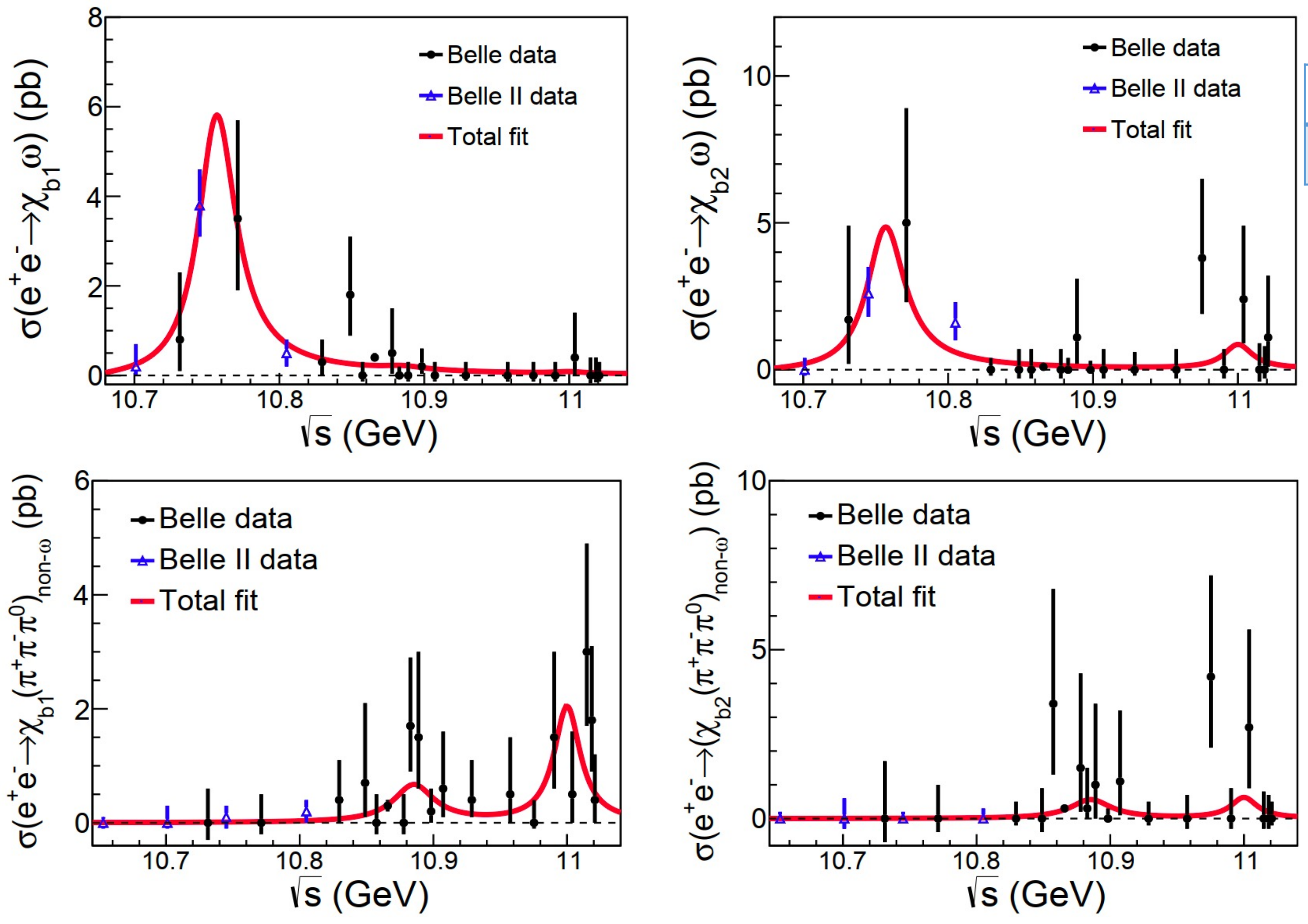
$$\Gamma(\Upsilon(10753)\to\eta_b(1S)\omega) = 2.64^{+4.70}_{-1.69}\ \text{MeV}$$
$$\Gamma(\Upsilon(10753)\to\Upsilon\pi^+\pi^-) = 0.08^{+0.20}_{-0.06}\ \text{MeV}$$

This measurement and JHEP 10, 220 (2019):

$$\sigma^B(\Upsilon(10753)\to\eta_b(1S)\omega) < 2.5\ \text{pb}$$
$$\sigma^B(\Upsilon(10753)\to\Upsilon(2S)\pi^+\pi^-) \approx (3\pm1)\ \text{pb}$$

$e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ at Belle and Belle II

[Preliminary results]



$\Upsilon(10753)$ mass	(10756.1 ± 4.3) MeV/c^2
$\Upsilon(10753)$ width	(32.2 ± 18.7) MeV

- The mass and width are consistent with those from $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ measuremnt [JHEP 07, 116 (2024)].

$$\frac{\sigma(e^+e^-\to\chi_{bJ}(1P)\omega)}{\sigma(e^+e^-\to\Upsilon(nS)\pi^+\pi^-)}$$

1.5 at $\sqrt{s}\sim 10.75$ GeV **0.15 at $\sqrt{s}\sim 10.867$ GeV**

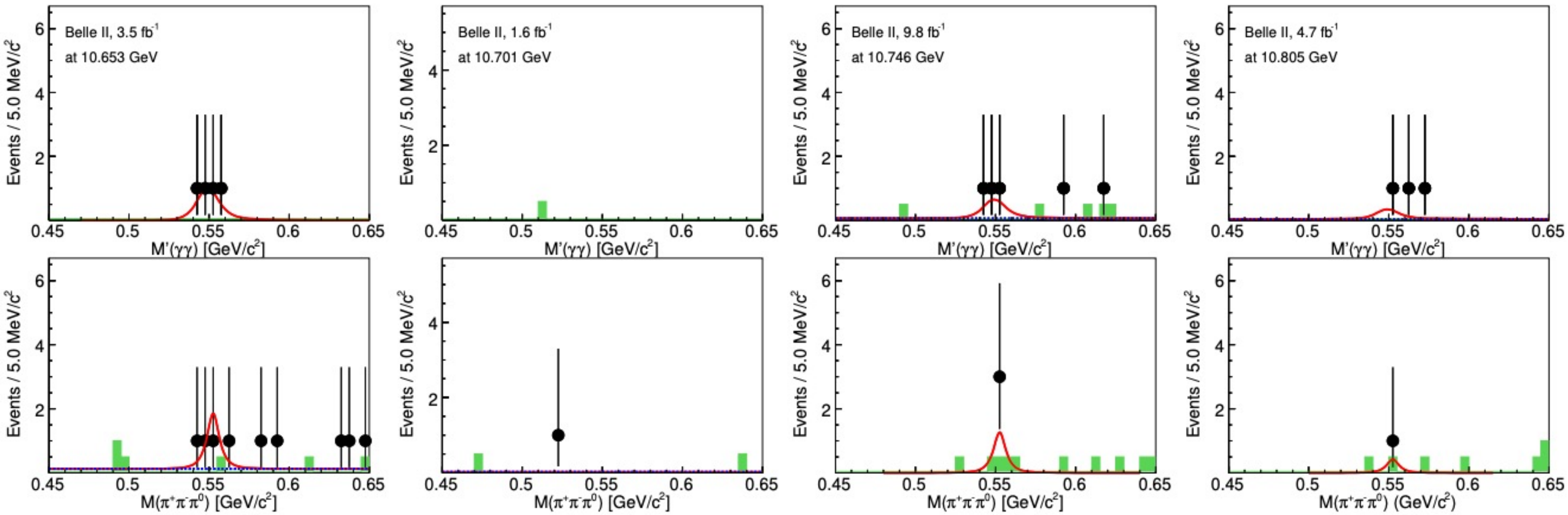
This may indicate the difference in the internal structures of $\Upsilon(10753)$ and $\Upsilon(5S)$.

- The $(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}$ excess maybe due the cascade decay of $\Upsilon(10860,11020) \to Z_b\pi \to \chi_{bJ}\rho\pi$ [PRD 90, 014036 (2014)].

$e^+e^- \to \eta\Upsilon(1S, 2S)$ at $\sqrt{s} \sim 10.75$ GeV

After requiring $\Upsilon(2S)$ signal region, simultaneous fit to M($\gamma\gamma$) and M($\pi^+\pi^-\pi^0$) for each energy point.

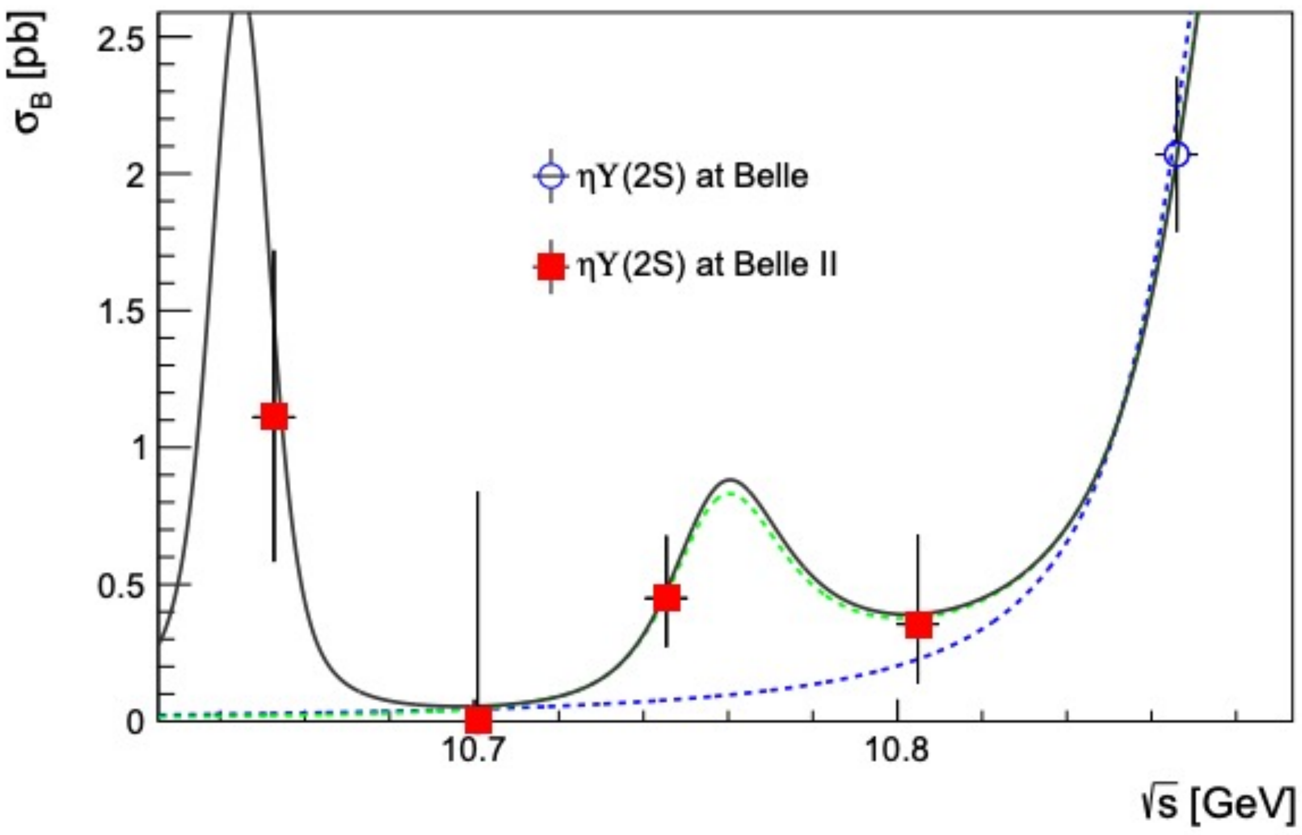
[Preliminary results]



- Combining all of the energy points, the signal yields for $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ are $6.0^{+1.7}_{-1.5}$ and $11.5^{+3.3}_{-2.8}$.
- **The statistical significance is 6.4σ for $e^+e^- \to \eta\Upsilon(2S)$ at $\sqrt{s} \sim 10.75$ GeV.**
- No clear signal is observed for $e^+e^- \to \eta\Upsilon(1S)$.

Energy dependence of Born crosss for $e^+e^- \to \eta\Upsilon(2S)$

[Preliminary results]



The Born cross section of $e^+e^- \to \eta\Upsilon(2S)$ around $B^*\bar{B}^*$ mass is relatively large.

Fit the with 3 different hypotheses:

H_1: only $\Upsilon(5S)$ [blue curve]

H_2: $\Upsilon(10753)$ + $\Upsilon(5S)$ [Green curve]

H_3: $B^*\bar{B}^*$ bound state + $\Upsilon(10753)$ + $\Upsilon(5S)$ [Black curve]

The masses and widths of $B^*\bar{B}^*$ bound state, $\Upsilon(10753)$, and $\Upsilon(5S)$ are fixed [JHEP 10 (2024) 114].

The statistical significance of $B^*\bar{B}^*$ bound state is 4.3σ [H_3 comapred to H_1].

Search for pentaquark states in $\Upsilon(1S, 2S)$ decays at Belle

More details can be found in Shiming's talk: Exotic states from Υ(1S,2S) decays

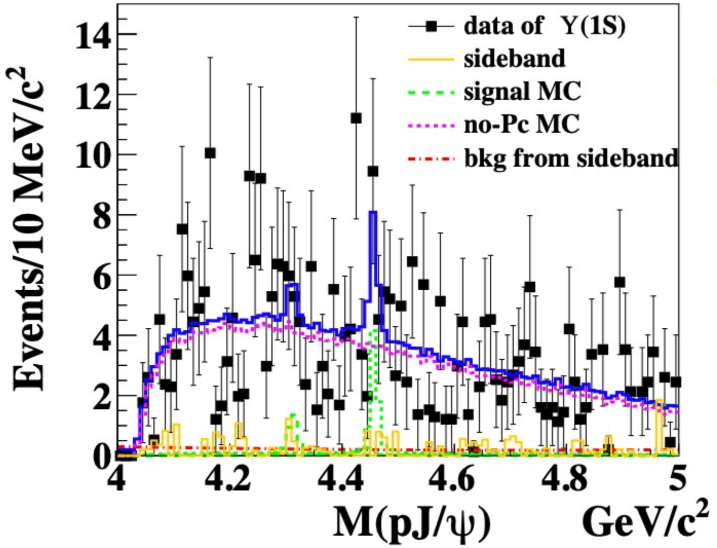
Search for $P_c \to pJ/\psi$ in $\Upsilon(1S, 2S)$ decays at Belle

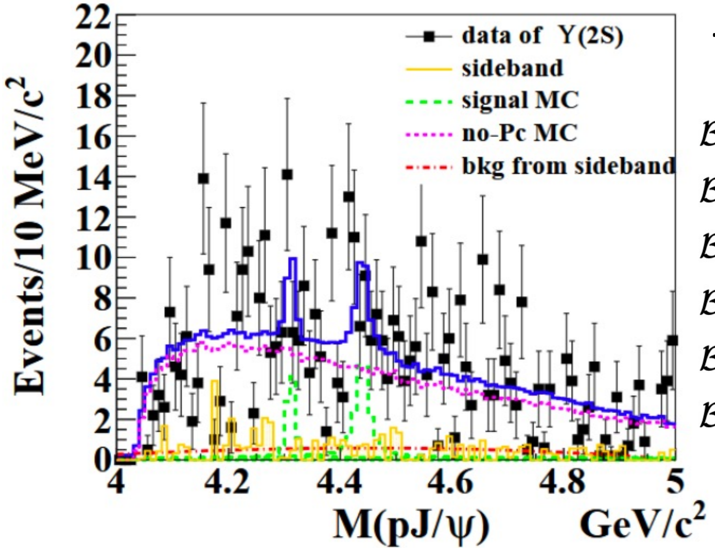
[arXiv:2403.04340]

- OZI suppressed decays of $\Upsilon(1S)$ and $\Upsilon(2S)$ rich in gluons:
  - enhanced baryon production
  - Pentaquarks?
- Select inclusive $\Upsilon(1S, 2S) \to pJ/\psi + X$ decays, then search for $P_c \to pJ/\psi$ in $M(pJ/\psi)$

No pentaquarks are found.

— only very slight excesses in the place of the LHCb results [PRL 122, 222001 (2019)].



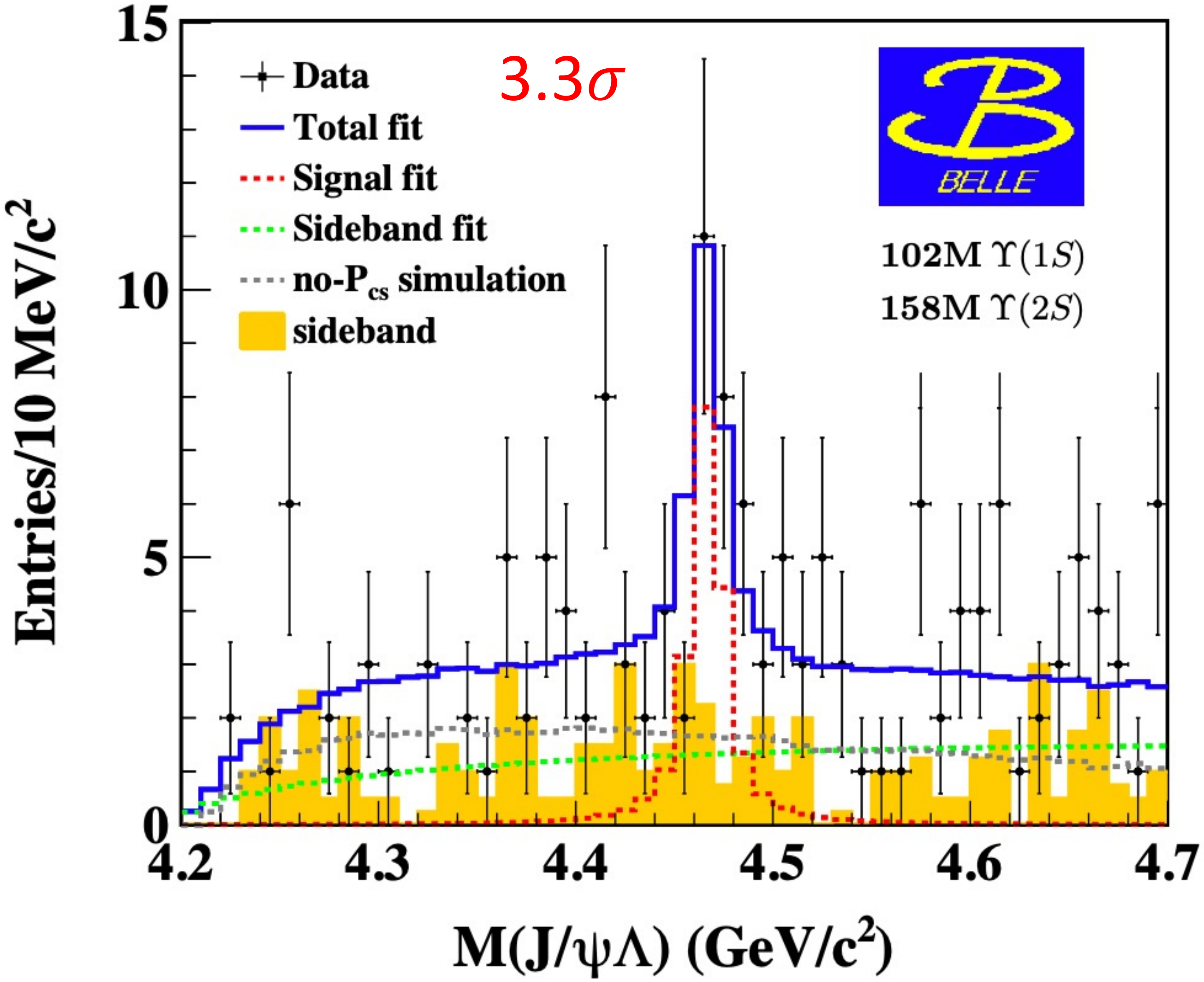


The upper limits at 90% C.L.

$$\mathcal{B}[\Upsilon(1S) \to P_c(4312)^+ + anything] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 3.9 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(1S) \to P_c(4440)^+ + anything] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 6.2 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(1S) \to P_c(4457)^+ + anything] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 5.5 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4312)^+ + anything] \cdot \mathcal{B}[P_c(4312)^+ \to pJ/\psi] < 4.7 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4440)^+ + anything] \cdot \mathcal{B}[P_c(4440)^+ \to pJ/\psi] < 7.2 \times 10^{-6},$$
$$\mathcal{B}[\Upsilon(2S) \to P_c(4457)^+ + anything] \cdot \mathcal{B}[P_c(4457)^+ \to pJ/\psi] < 2.6 \times 10^{-6},$$

Evidence of $P_{c\bar{c}s}(4459)$ at Belle

[arXiv:2502.09951]



- Select inclusive $\Upsilon(1S,2S) \to J/\psi\Lambda + X$ decays, then search for $P_{cs} \to J/\psi\Lambda$ in M(J/ψΛ)
- 4.0σ local significance with free mass and width

Mass	(4471.7±4.8±0.6) MeV/c^2
Width	(21.9±13.1±2.7) MeV

- 3.3σ significance with the Gaussian constraints from LHCb measurement [Sci. Bull. 66, 1278 (2021)]

$$-2\ln\mathcal{L} + \frac{(m-m_0)^2}{\sigma_{m_0}^2} + \frac{(\Gamma-\Gamma_0)^2}{\sigma_{\Gamma_0}^2}$$

Bottomonium transitions

Evidence of $h_b(2P) \to \Upsilon(1S)\eta$ decay and search for $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$

[PRL 13, 261901 (2024)]

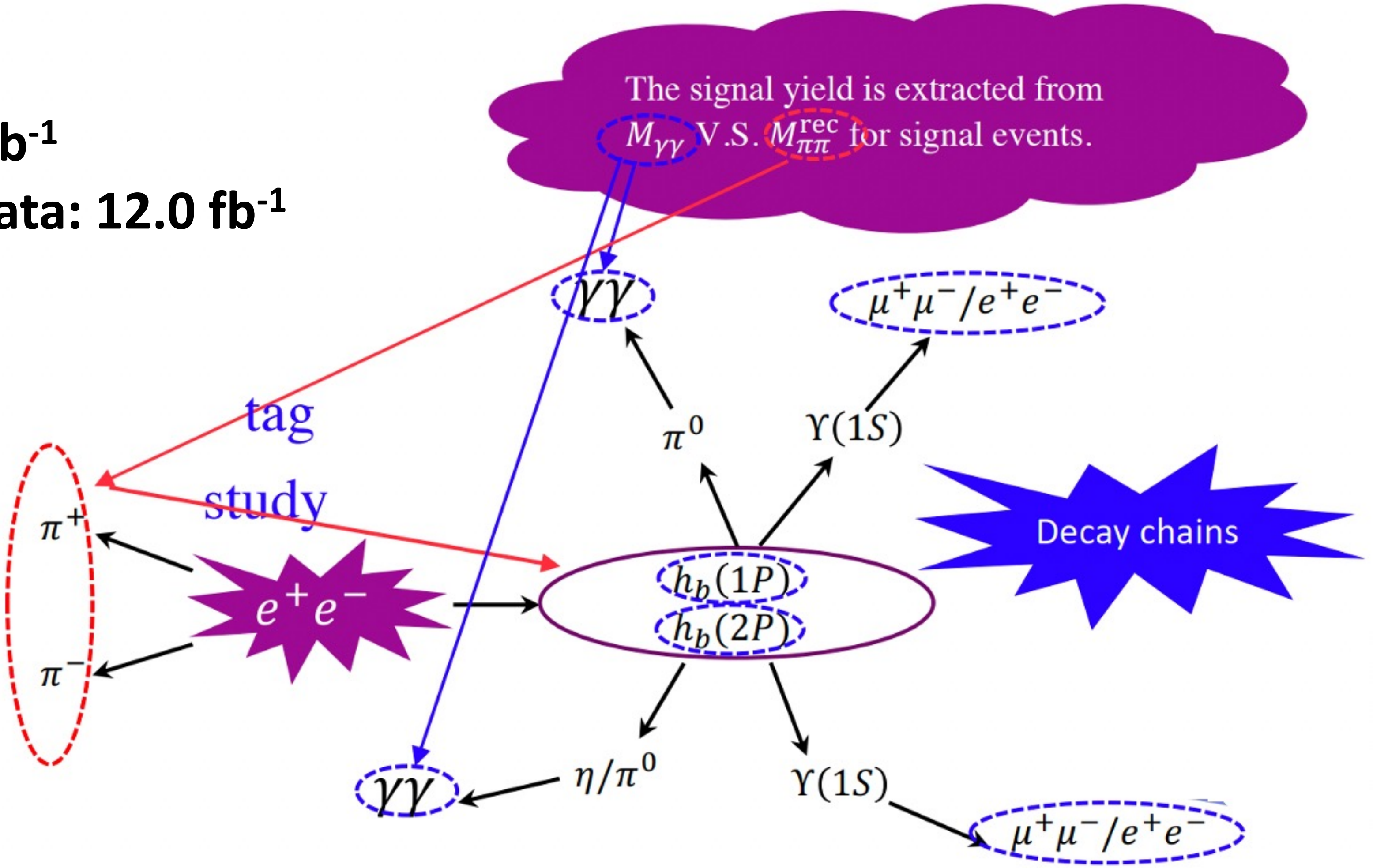
Motivation:

Based on the QCD multipole expansion, $h_b(2P) \to \Upsilon(1S)\eta$ decay is of great interest as its rate is suppressed by the heavy quark spin symmetry.

Data samples:

$\Upsilon(5S)$: 121.4 fb^{-1}

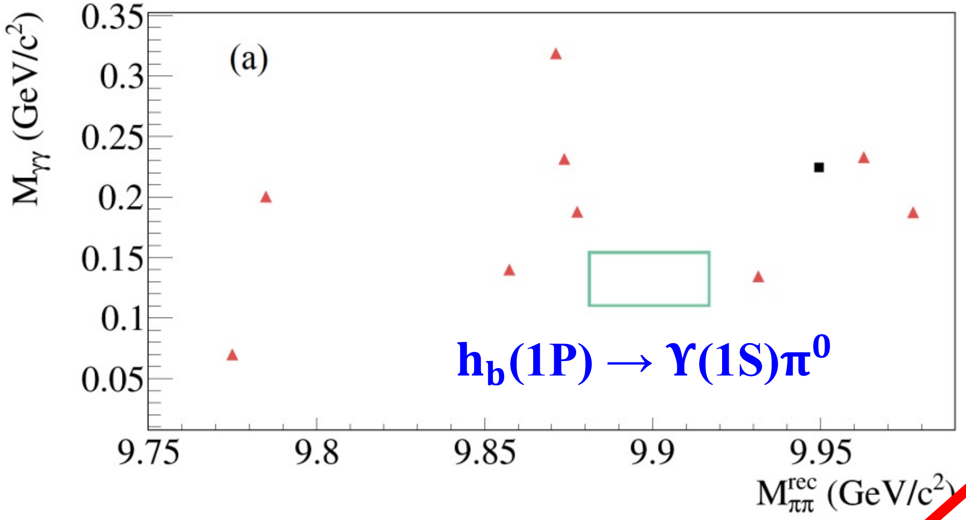
Energy-scan data: 12.0 fb^{-1}

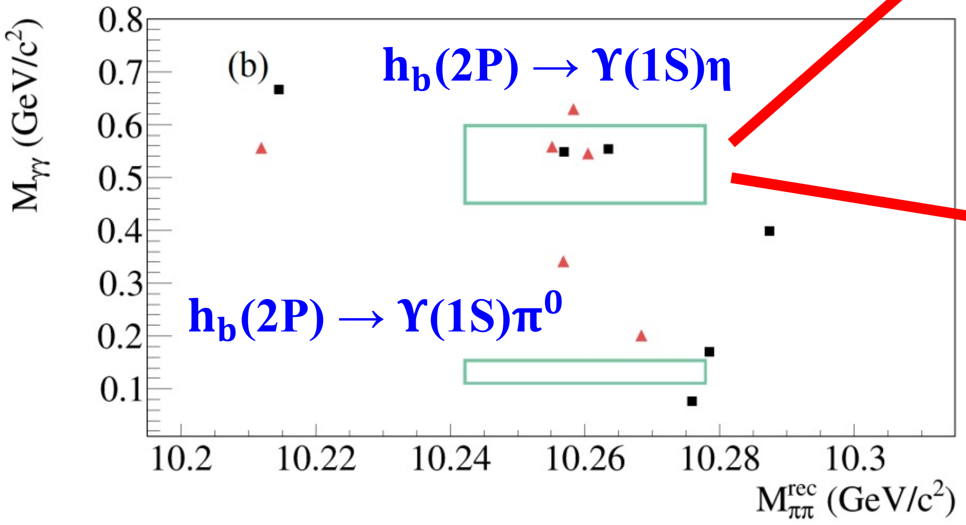


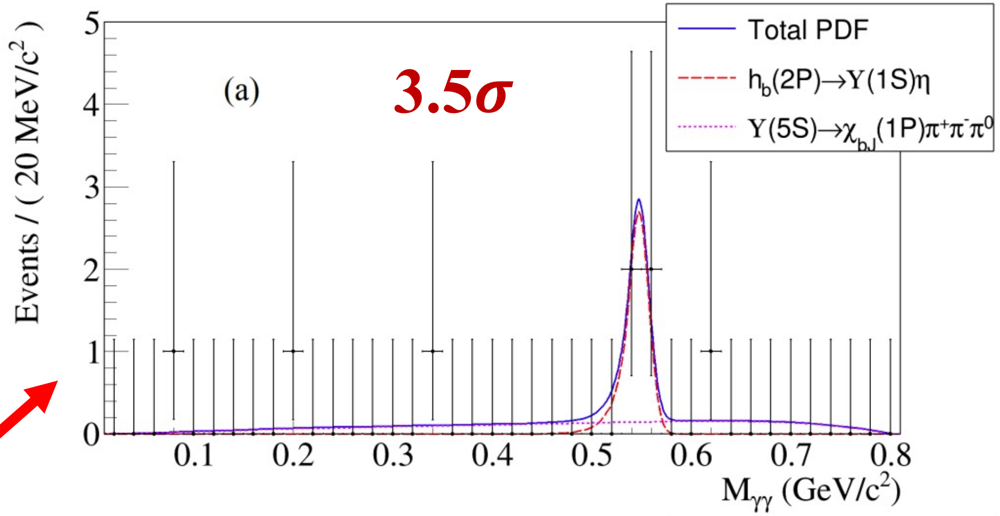
Evidence of $h_b(2P) \to \Upsilon(1S)\eta$ decay and search for $h_b(1P, 2P) \to \Upsilon(1S)\pi^0$

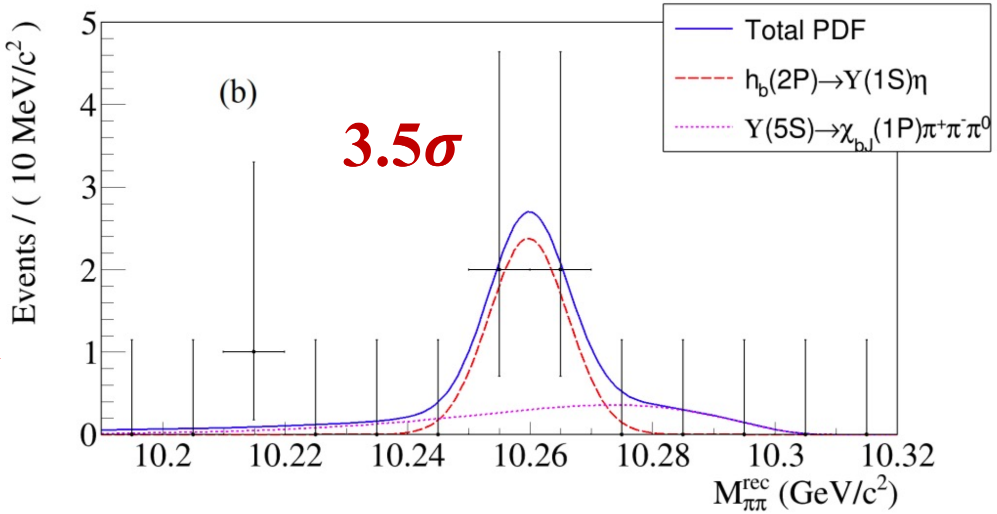
[PRL 13, 261901 (2024)]

Results:









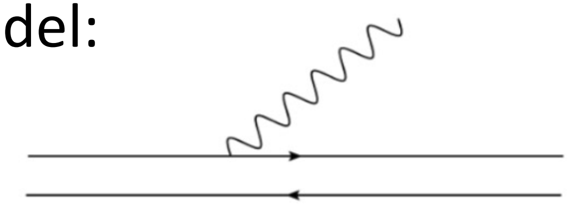
$$\mathcal{B}(h_b(2P) \to \Upsilon(1S)\eta) = \left(7.1^{+3.7}_{-3.2} \pm 0.8\right) \times 10^{-3}$$

Search for $h_b(2P) \to \gamma\chi_{bJ}(1P)$

The relativized quark model:

BF = $10^{-6} - 10^{-5}$

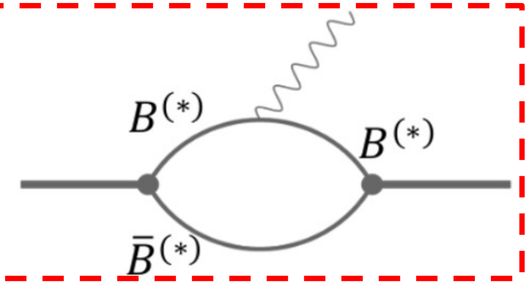
[PRD 32, 189 (1985)]



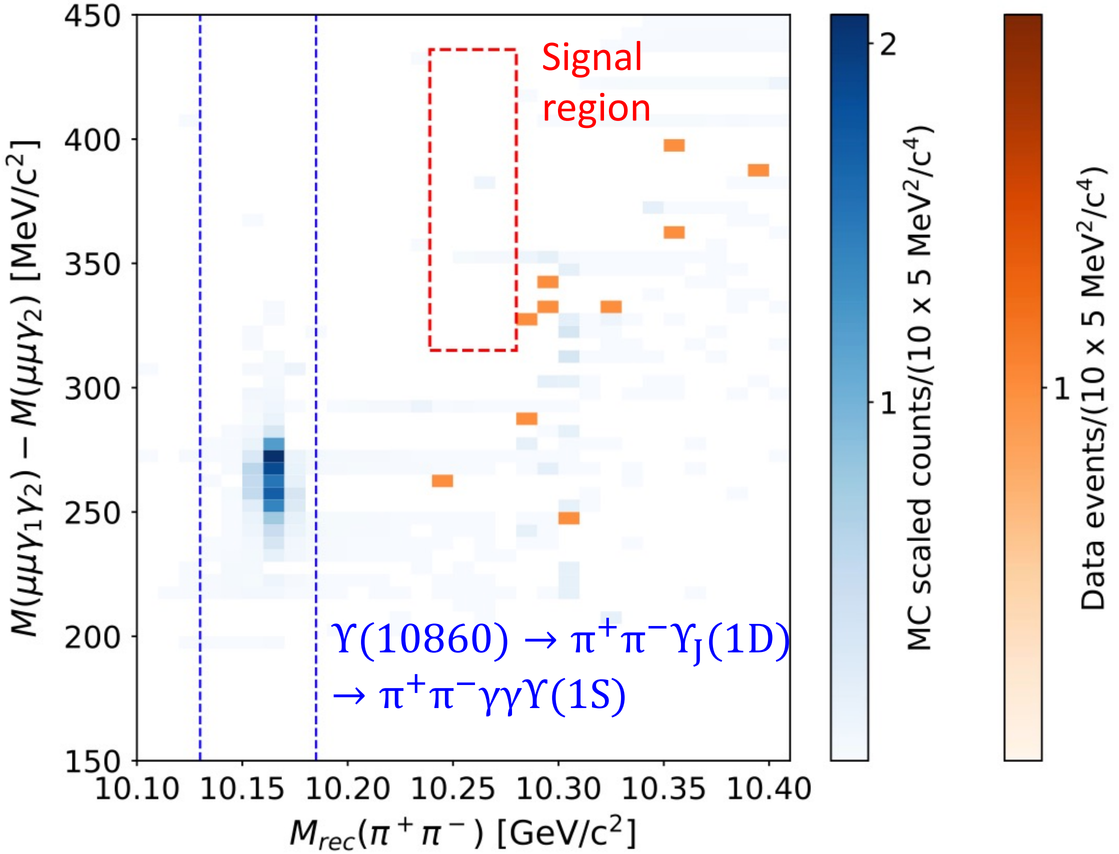
Coupled-channel effects:

BF = $10^{-2} - 10^{-1}$

[PLB 760, 417 (2016)]



[PRD 111, L011102 (2025)]



Full reconstruction: $\Upsilon(10860) \to \pi^+\pi^- h_b(2P)$, $h_b(2P) \to \gamma_1\chi_{bJ}(1P)$, $\chi_{bJ}(1P) \to \gamma_2\Upsilon(1S)$, $\Upsilon(1S) \to \mu^+\mu^-$

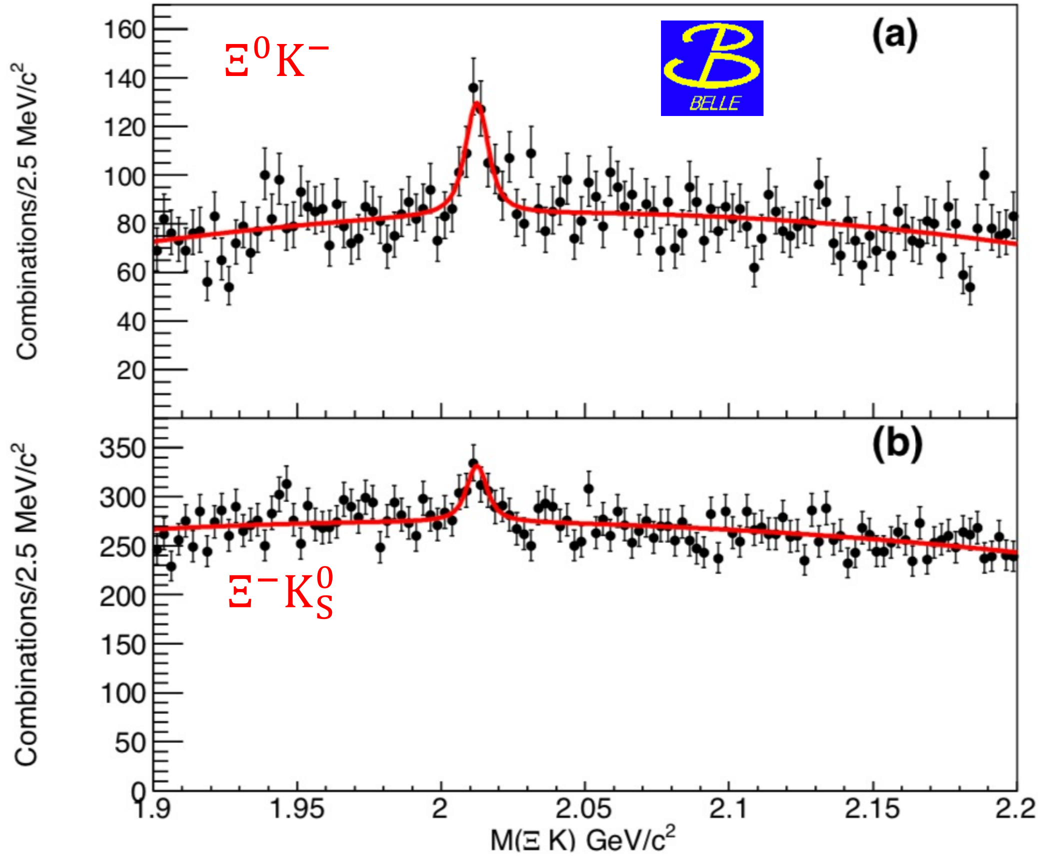
The upper limits at 90% C.L.

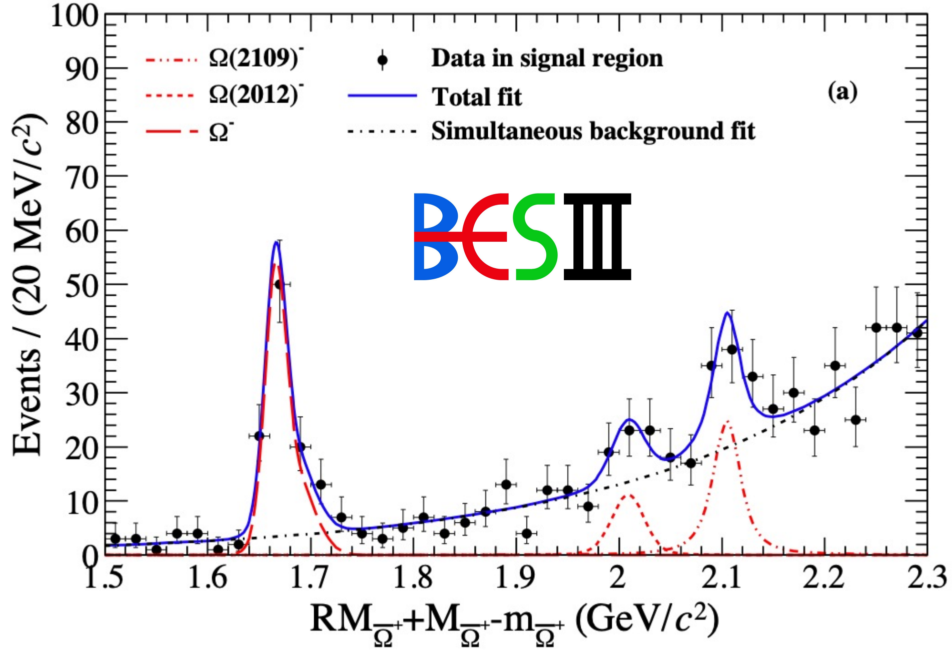
Channel	$\mathcal{B}$
$h_b(2P) \to \gamma\chi_{b2}(1P)$	$<1.3 \times 10^{-2}$
$h_b(2P) \to \gamma\chi_{b1}(1P)$	$<5.4 \times 10^{-3}$
$h_b(2P) \to \gamma\chi_{b0}(1P)$	$<2.7 \times 10^{-1}$

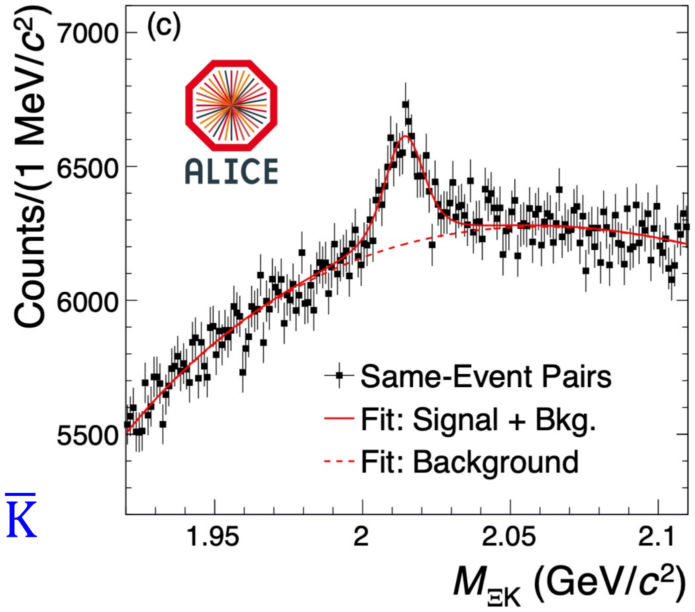
$$\boldsymbol{\Omega(2012)^{-} \rightarrow \Xi(1530)\overline{K} \rightarrow \Xi\pi\overline{K}}$$

Discovery of $\Omega(2012)^-$

The $\Omega(2012)$ was first observed by Belle in $\Xi\overline{K}$ final states [PRL 121, 052003 (2018)], and was confirmed by BESIII [PRL 134, 131903 (2025)] and ALICE [arXiv: 2502.18063].







The $\Omega(2012)^-$ was interpreted as a standard baryon or a $\Xi(1530)\overline{K}$ molecule.

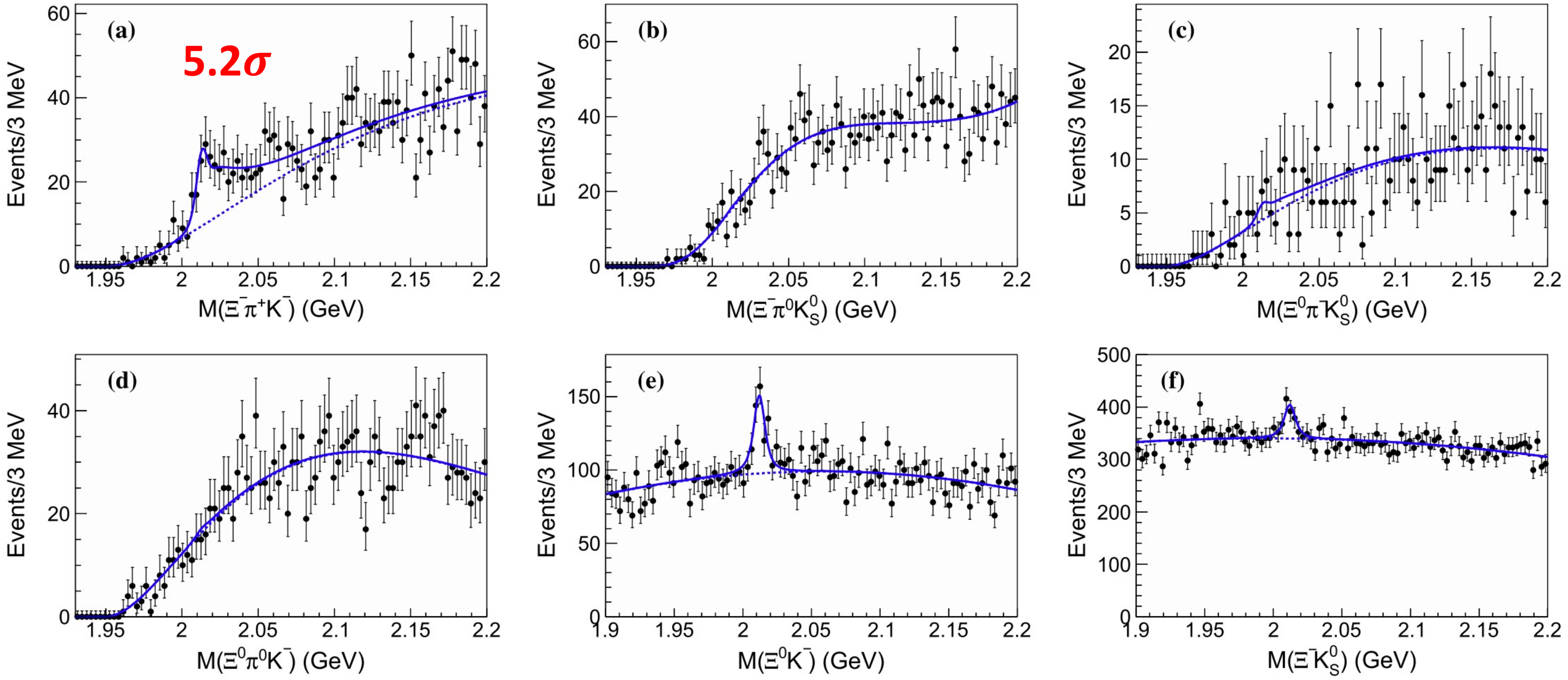
$\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K}$

[PLB 860, 139224 (2025)]

The Flatté-like function [PRD 81, 094028 (2010)]

$$T_n(M) = \frac{g_n k_n(M_n)}{|M_n - m_{\Omega(2012)} + \frac{1}{2}\sum_{j=2,3} g_j[\kappa_j(M_j) + ik_j(M_j)]|^2}$$

- g_n is the effective coupling of to the n–body final state.
- k_n and κ_n parameterize the real and imaginary parts of the $\Omega(2012)^-$ self-energy.



The mass and ratio of effective couplings :

$\Omega(2012)^-$ mass	(2012.5±0.7±0.5) MeV
g_3/g_2	$22.9^{+17.9}_{-22.4}\pm2.2$

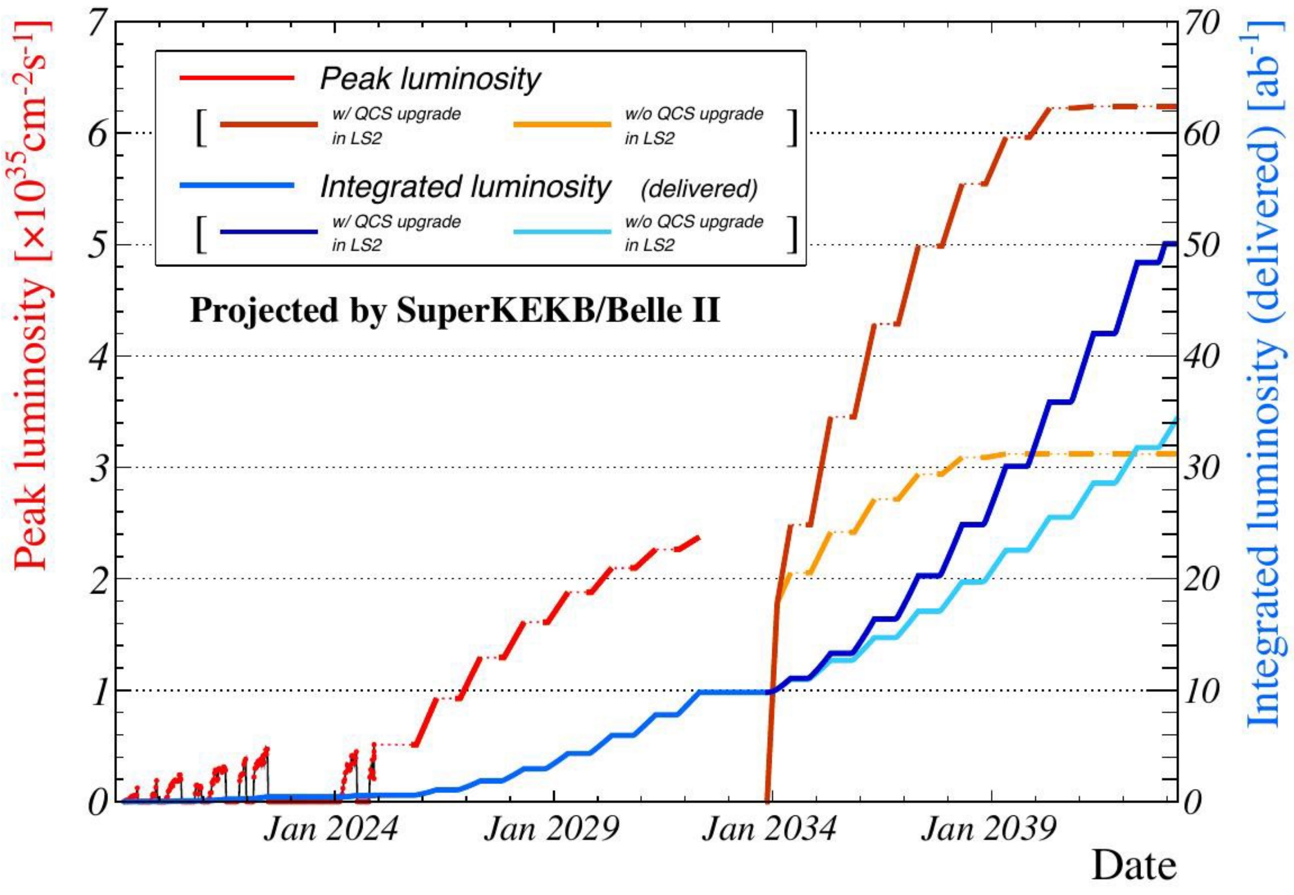
$$\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}} = \frac{\mathcal{B}(\Omega(2012)^- \to \Xi(1530)\bar{K} \to \Xi\pi\bar{K})}{\mathcal{B}(\Omega(2012)^- \to \Xi\bar{K})}$$

0.99±0.26±0.06

Mode	ε (%)	Y
$\Omega(2012)^- \to \Xi(1530)^0 K^- \to \Xi^-\pi^+K^-$	6.97 ± 0.07	267 ± 60
$\Omega(2012)^- \to \Xi(1530)^- \bar{K}^0 \to \Xi^-\pi^0\bar{K}^0$	1.06 ± 0.01	7 ± 2
$\Omega(2012)^- \to \Xi(1530)^- \bar{K}^0 \to \Xi^0\pi^-\bar{K}^0$	1.74 ± 0.02	23 ± 5
$\Omega(2012)^- \to \Xi(1530)^0 K^- \to \Xi^0\pi^0K^-$	0.63 ± 0.01	12 ± 3

Our result is consistent with the molecular model of $\Omega(2012)^-$, which predicts comparable rates for $\Omega(2012)^-$ decay to $\Xi(1530)\bar{K}$ and $\Xi\bar{K}$ [PRD 98 (2018) 054009, PRD 98 (2018) 056013, PRD 98 (2018) 076012].

Data-taking plan and prospects



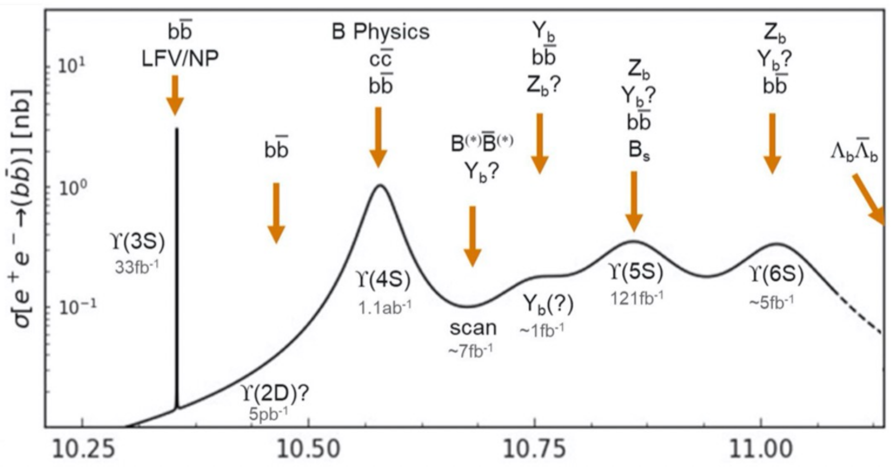
- *Until 2026, about 1 ab^{-1} data, comparable to Belle*
- *Until 2029, about 4 ab^{-1} data.*

Charmonium-like states:

- B decay (B → K$X_{c\bar{c}}$)
- Initial-state radiation (ISR)
- Two-photon process
- Double charmonium

Bottomonium-like states:

- Decays of higher mass states (e.g. Υ(5S,6S))
- Direct production via operation at a lower center-of-mass energy.



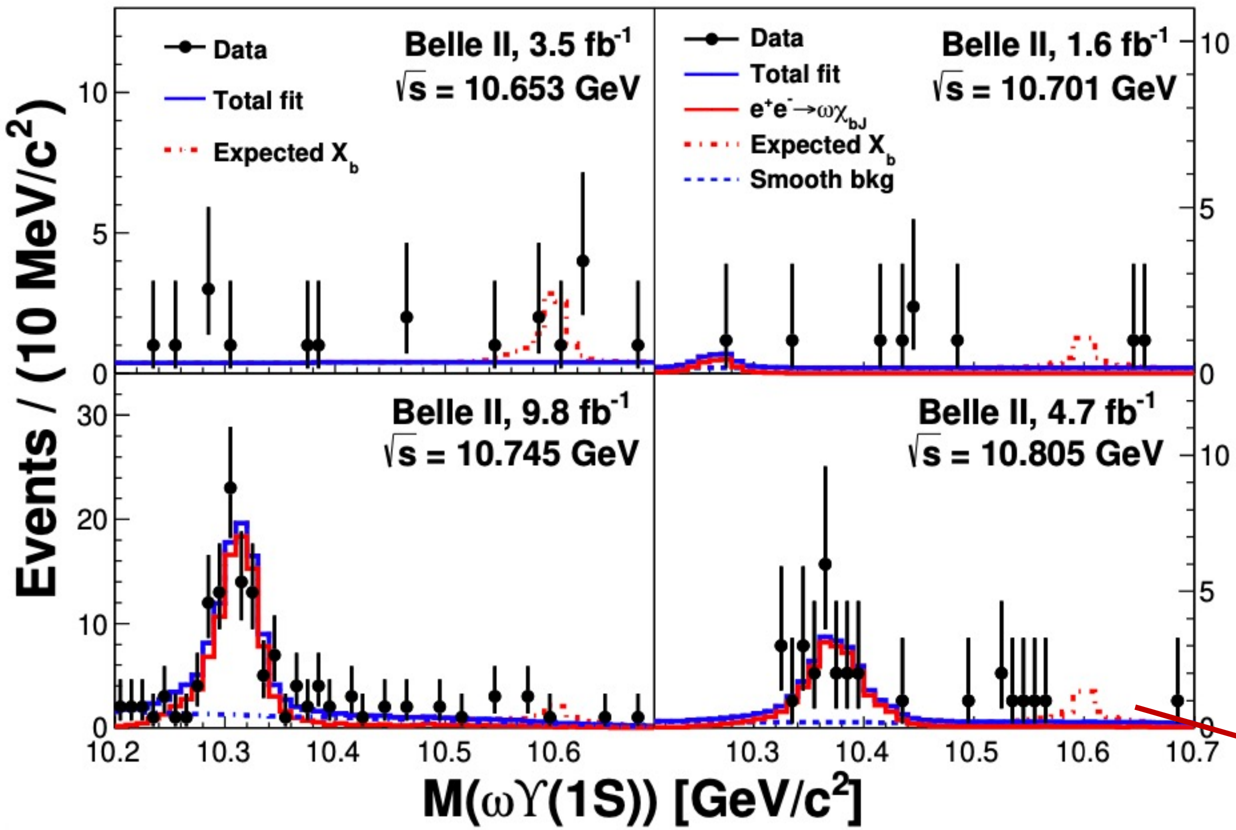
Summary

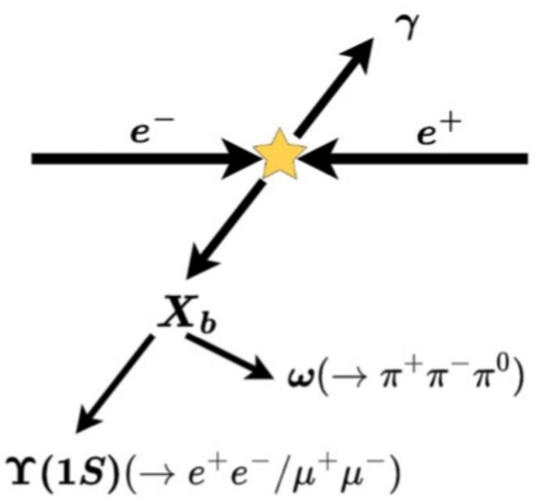
- Belle II started operation in 2019, and the peak luminosity has achieved $\sim 0.5\times10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$.
- Belle II is getting more exciting hadron physics results, especially on Υ(10753) and bottomonium transitions.
- The Belle dataset has not been surpassed by Belle II but now analyses combine the two data from the two experiments.
- Stay tuned for many results on spectroscopy from Belle II in the next few years.

Thanks for your attention!

Backup

Search for X_b





[PRL 130, 091902 (2023)]

- No significant X_b signal is observed.
- The peaks are the reflections of $e^+e^- \to \omega\chi_b$

From simulated events with $m(X_b) = 10.6$ GeV/c²
The yield is fixed at the upper limit at 90% C.L.

Upper limits at 90% C.L. on $\sigma_B(e^+e^- \to \gamma X_b) \cdot \mathcal{B}(X_b \to \omega\Upsilon(1S))$ (pb)	$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
	$m(X_b) = 10.6$ GeV/c²	0.46	0.33	0.10	0.14
	$m(X_b) = (10.45, 10.65)$ GeV/c²	(0.14, 0.55)	(0.25, 0.84)	(0.06, 0.14)	(0.08, 0.37)

Discussion

[PRL 130, 091902 (2023)]

$$\frac{\sigma(e^+e^- \to \chi_{bJ}(1P)\omega)}{\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)} \sim$$

~ 1.5 at $\sqrt{s} = 10.745$ GeV [PRL 130, 091902 (2023)]

~ 0.15 at $\sqrt{s} = 10.867$ GeV [PRL 113, 142001 (2014)]

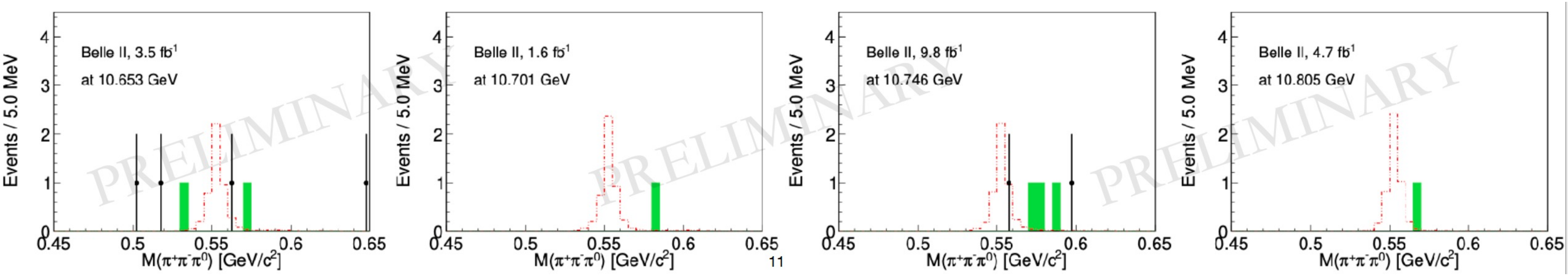
- $\Upsilon(5S)$ and $\Upsilon(10753)$ have same quantum numbers and similar masses, but the difference on the above ratio is large. This may indicate **the difference in the internal structures of these two states**.

$$\frac{\sigma(e^+e^- \to \chi_{b1}(1P)\omega)}{\sigma(e^+e^- \to \chi_{b2}(1P)\omega)} = 1.3 \pm 0.6 \text{ at } \sqrt{s} = 10.745 \text{ GeV [PRL 130, 091902 (2023)]}$$

- **Contradicts the expectation for a pure D−wave bottomonium state of 15** [Phys. Lett. B 738, 172 (2014)]
- **An observation of 1.8σ difference with the prediction for a S−D−mixed state of 0.2** [Phys. Rev. D 104, 034036 (2021)]

Signal yields

$$e^+e^- \to \eta\Upsilon(1S)$$



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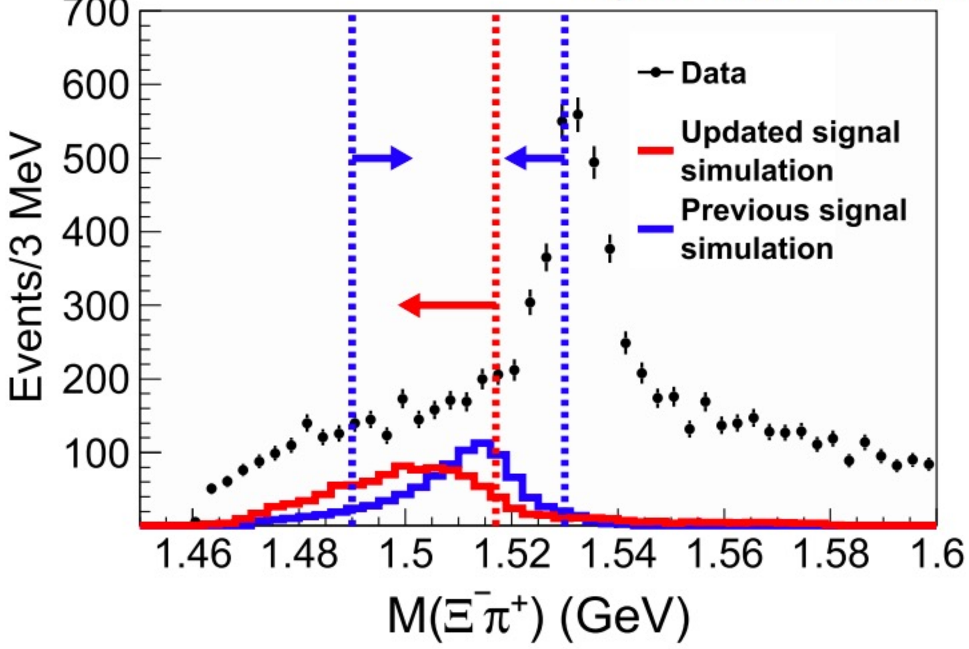

Fig. 1. The $\Xi^-\pi^+$ mass distributions in $\Xi^-\pi^+K^-$ events in data (points) and in simulations using the models of the previous analysis [41] (solid blue line) and this work (solid red line), with each simulation normalized to have an exaggerated $\mathcal{R}^{\Xi\pi\bar{K}}_{\Xi\bar{K}}$ value of 4. The red arrow shows the mass requirement of this analysis; the blue arrows show the mass requirement of the previous analysis [41].