Recent quarkonium(-like) measurements at Belle and Belle II

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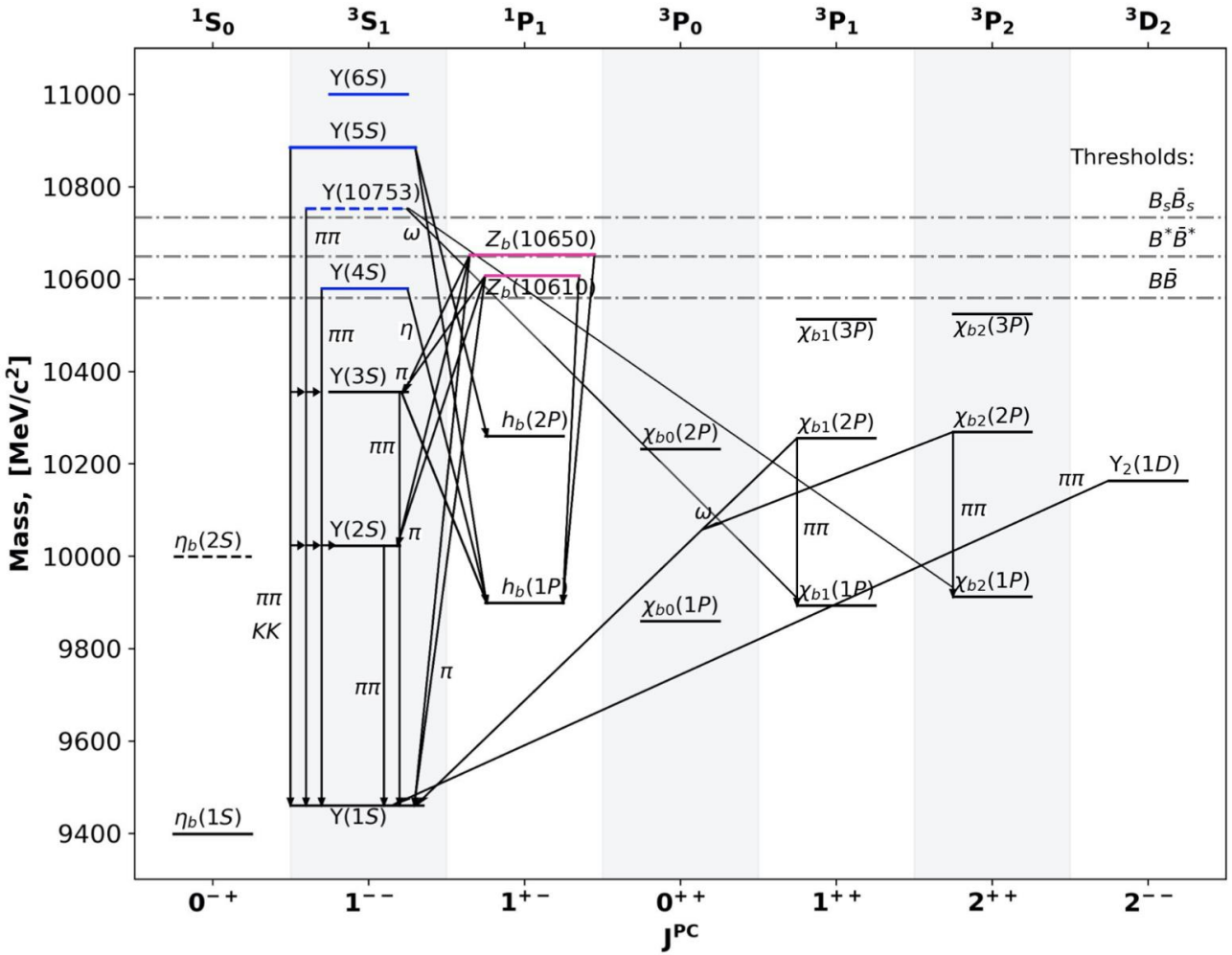
第三届高能物理理论与实验融合发展研讨会
2024年11月3日，大连

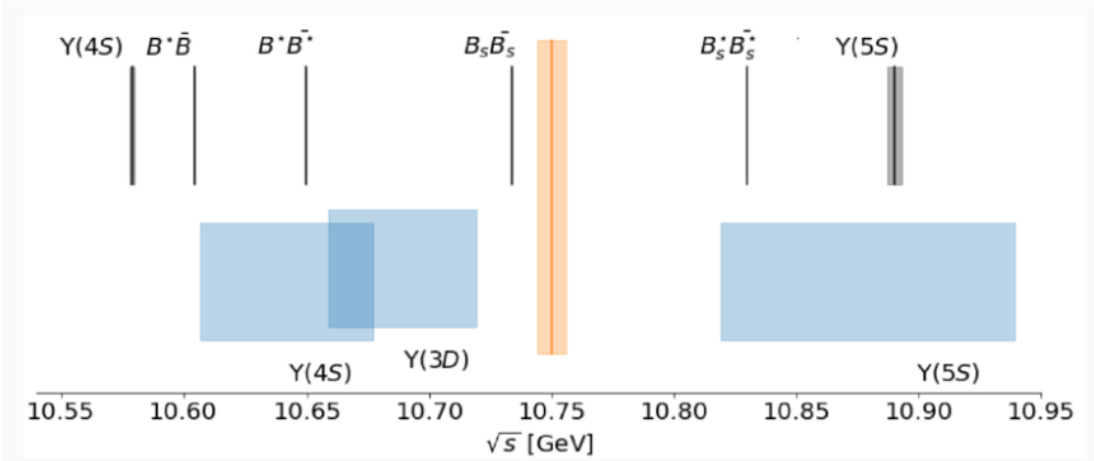
Outline

- Study of $\Upsilon(10753)$
- Evidence of $P_{cs}(4459)$
- Bottomonium transitions
- Summary

Motivation: $\Upsilon(10753)$

The $\Upsilon(10753)$ was first discovered in $\pi^+\pi^-\Upsilon(nS)$ final states using $\Upsilon(10860)$ scan data by Belle [JHEP 10, 220 (2019)].

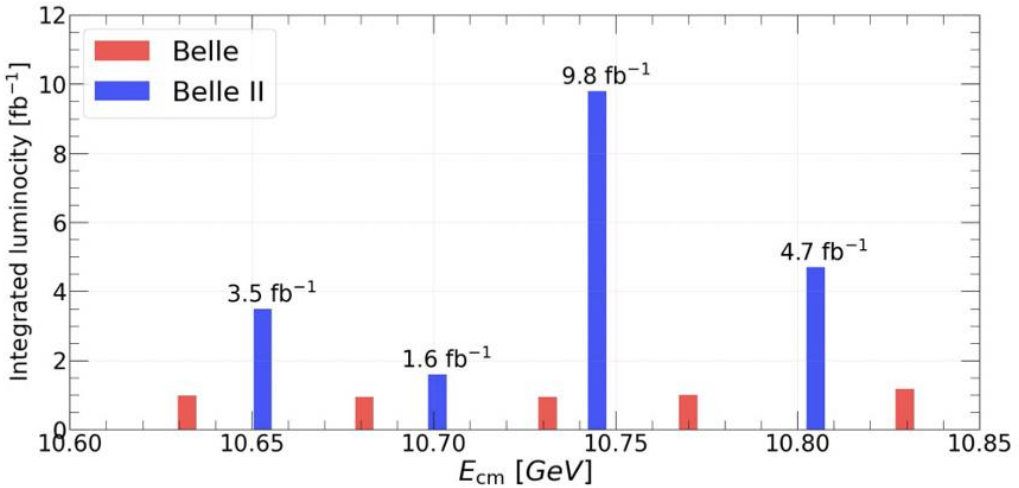




[Godfrey and Moats, PRD 92, 054034 (2015)]

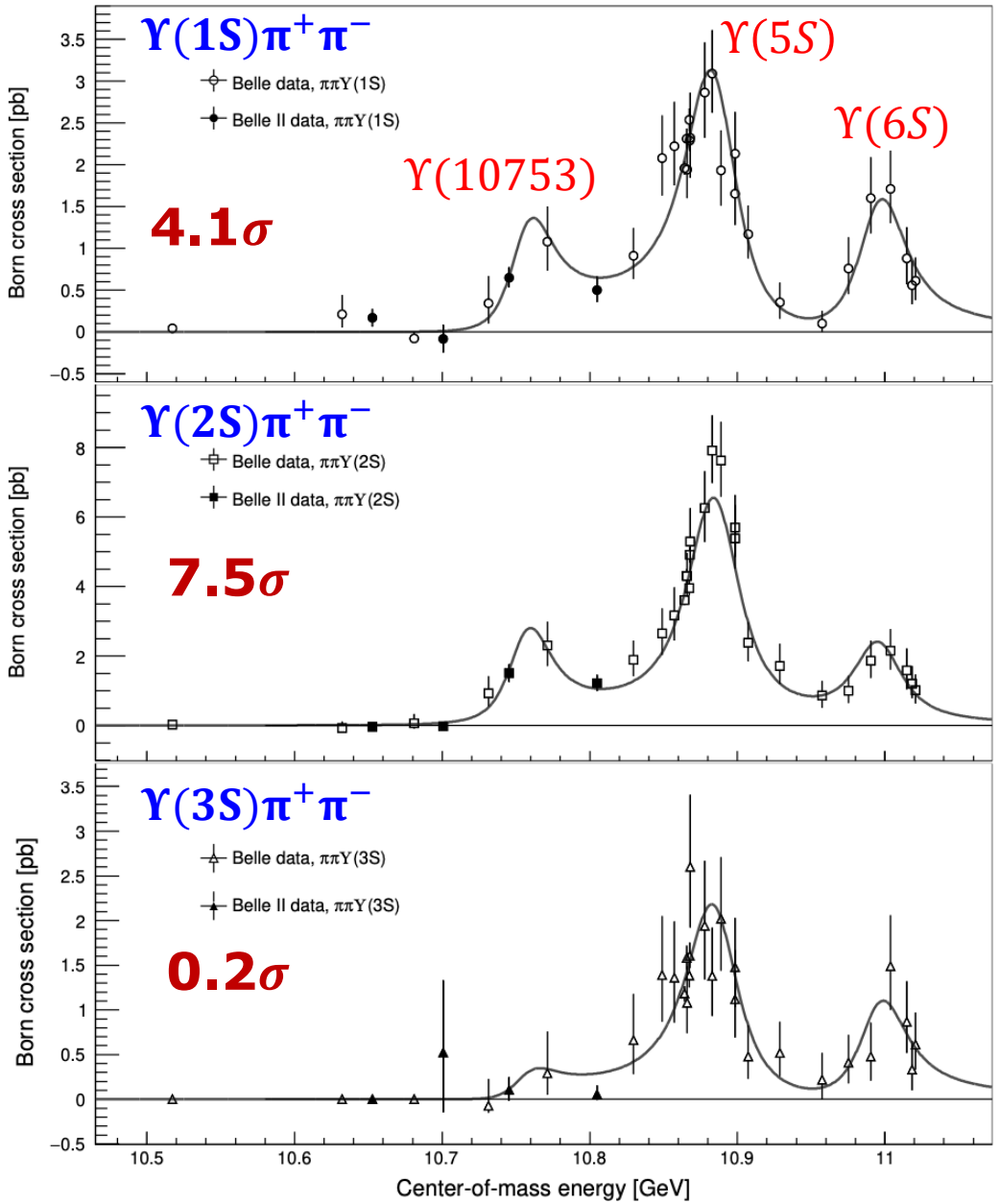
The nature of $\Upsilon(10753)$ is unclear.

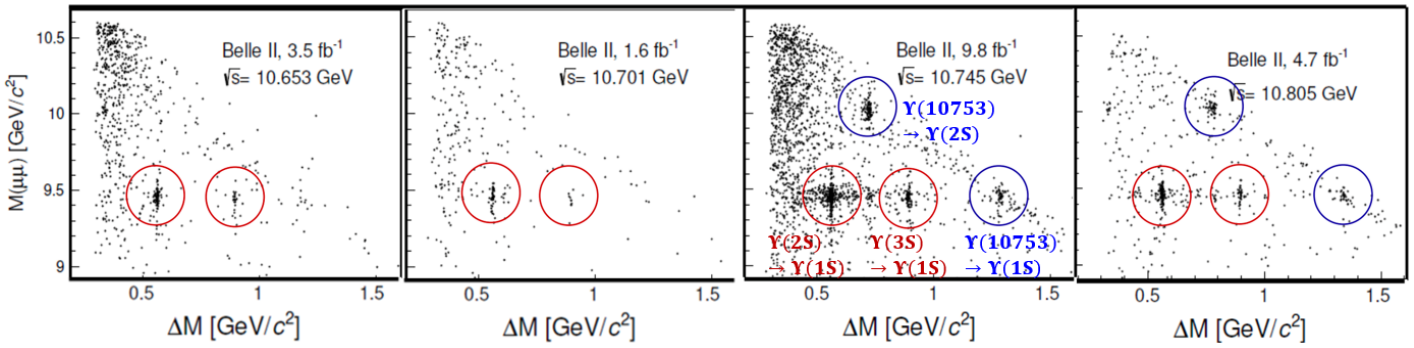
Recently, Belle II collected 19 fb^{-1} of unique data around $\sqrt{s}$ ~ 10.75 GeV:



Confirmation: $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ at Belle II

[JHEP 07 (2024) 116]





- Full reconstruction: $e^+e^- \to [\Upsilon(nS) \to \mu^+\mu^-]\pi^+\pi^-$

$$\Delta M = \mathrm{M}(\mu^+\mu^-\pi^+\pi^-) - \mathrm{M}(\mu^+\mu^-)$$

- Combined fit to Belle + Belle II

$$M = (10756.6 \pm 2.7 \pm 0.6)\ \mathrm{MeV}/c^2$$

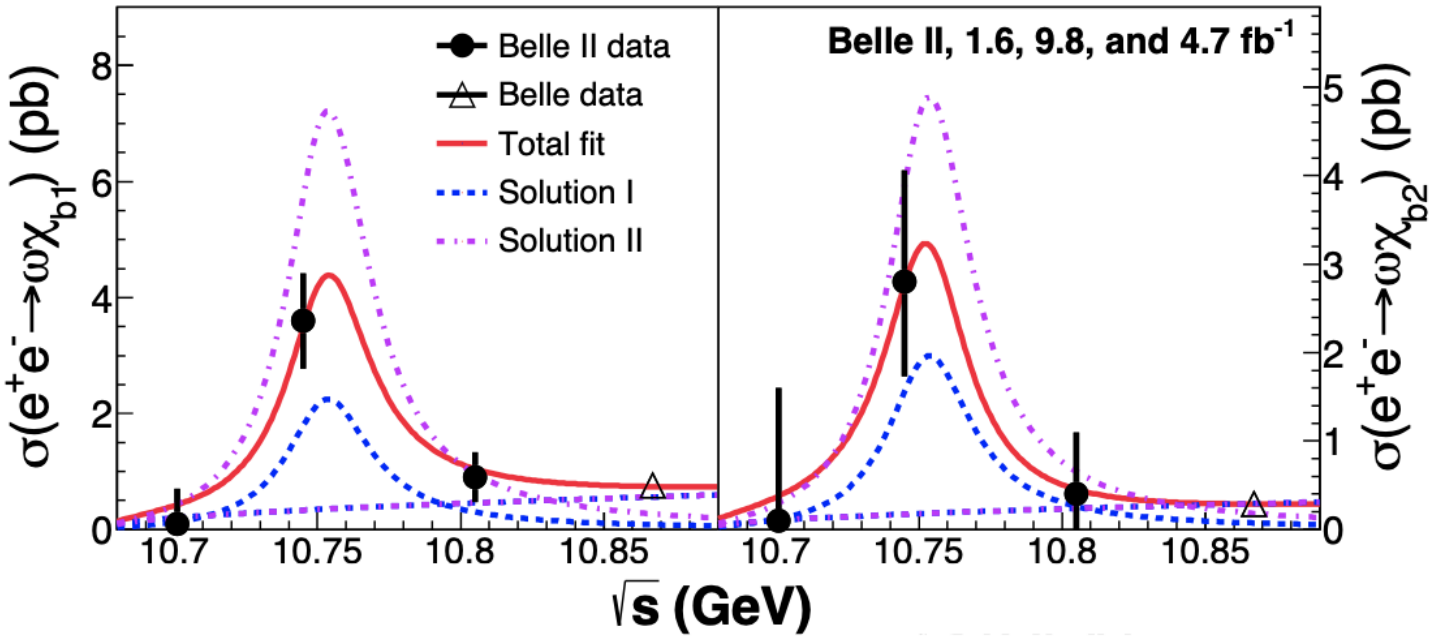
$$\Gamma = (29.0 \pm 8.8 \pm 1.2)\ \mathrm{MeV}/c^2$$

	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(5S)}_{\sigma(3S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(1S/2S)}$	$\mathcal{R}^{\Upsilon(6S)}_{\sigma(3S/2S)}$
Ratio	$0.46^{+0.15}_{-0.12}$	$0.10^{+0.05}_{-0.04}$	$0.45^{+0.04}_{-0.04}$	$0.32^{+0.04}_{-0.03}$	$0.64^{+0.23}_{-0.13}$	$0.41^{+0.16}_{-0.12}$

- No significant substructure is found.

Observation: $\Upsilon(10753) \to \omega\chi_{bJ}$ at Belle II

The $e^+e^- \to \omega\chi_{bJ}$ (J = 1, 2) cross sections peak at $\Upsilon(10753)$. [PRL 130, 091902 (2023)]



$$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.3\pm0.6 \text{ at } \sqrt{s} = 10.745 \text{ GeV}$$

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

~1.5 at $\sqrt{s}$ = 10.745 GeV

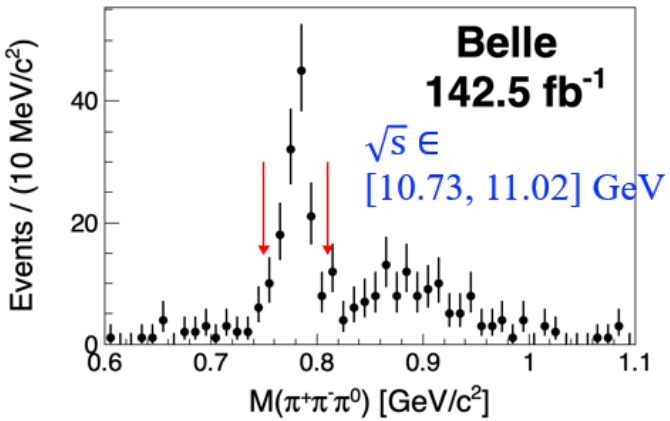
~ 0.15 at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001 (2014)]

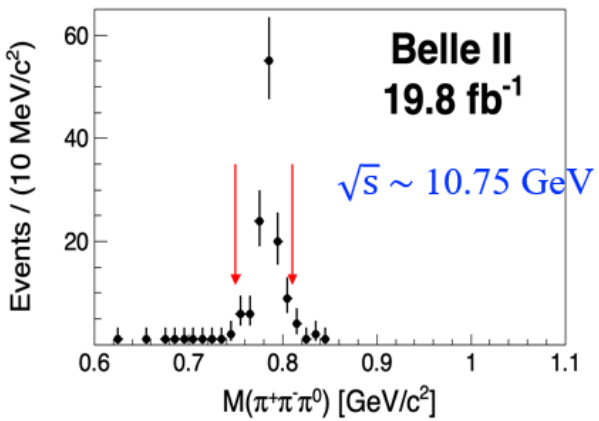
- $\Upsilon(5S)$ and $\Upsilon(10753)$ have same quantum numbers and similar masses, but the difference on the above ratio is large. This may indicate **the difference in the internal structures of these two states**.

- 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)]

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

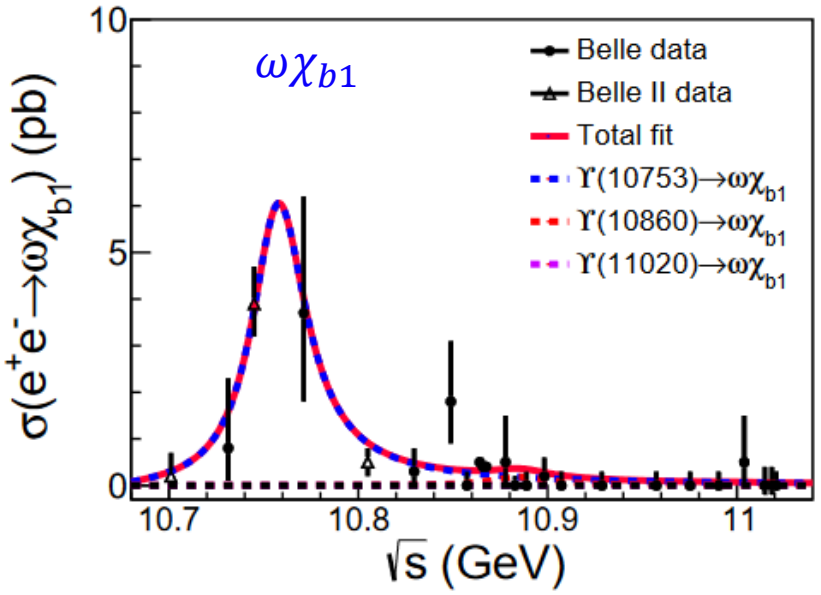
[Preliminary results at Belle and Belle II]

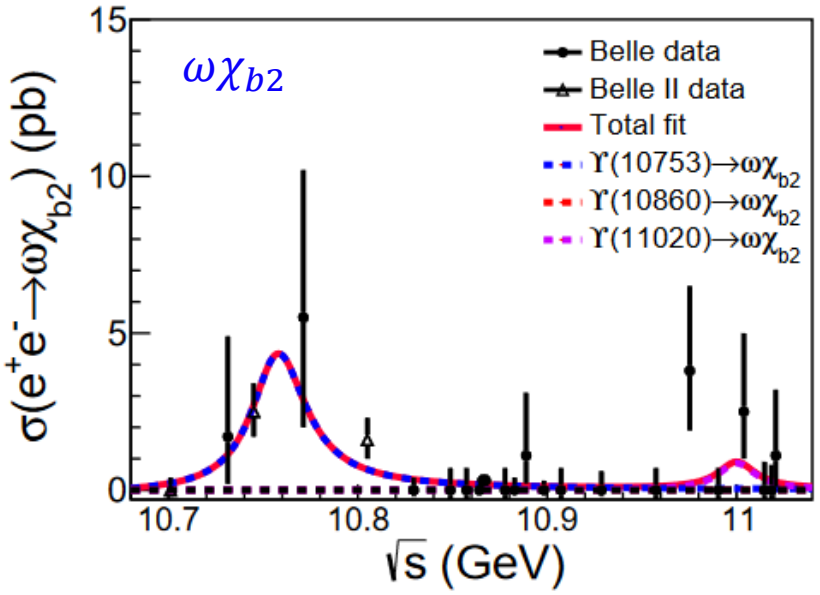




In addition to ω signal candidates, there are some events from non-resonant decays at Belle.

A coherent sum of 3BWs of $\Upsilon(10753)$, $\Upsilon(10860)$, and $\Upsilon(11020)$ to fit the energy dependences of Born cross sections for $e^+e^- \to \omega\chi_{bJ}$ and $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega\chi_{bJ}}$.

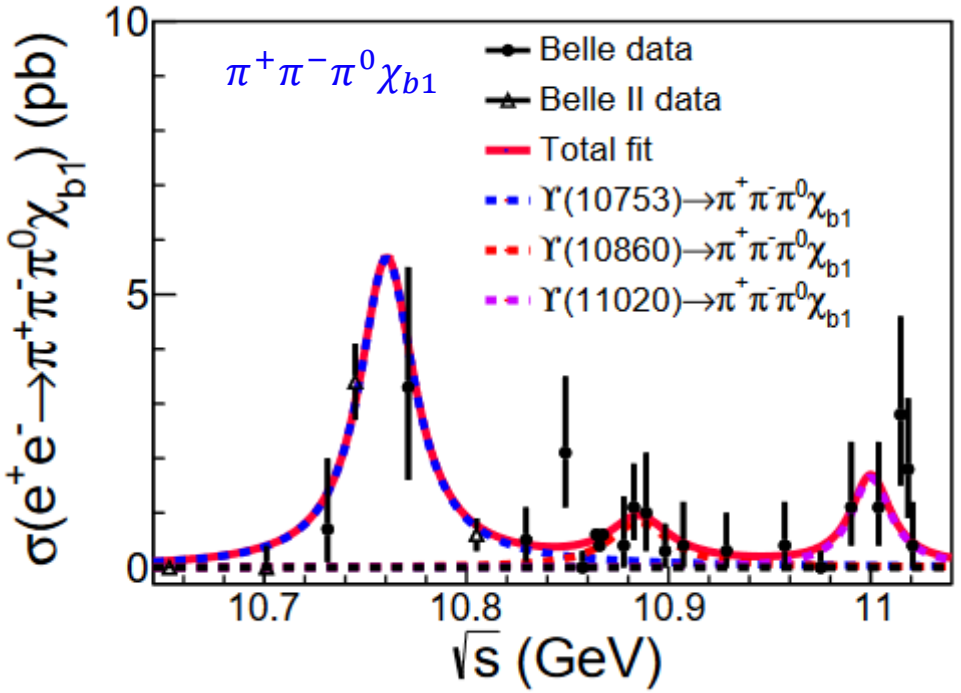


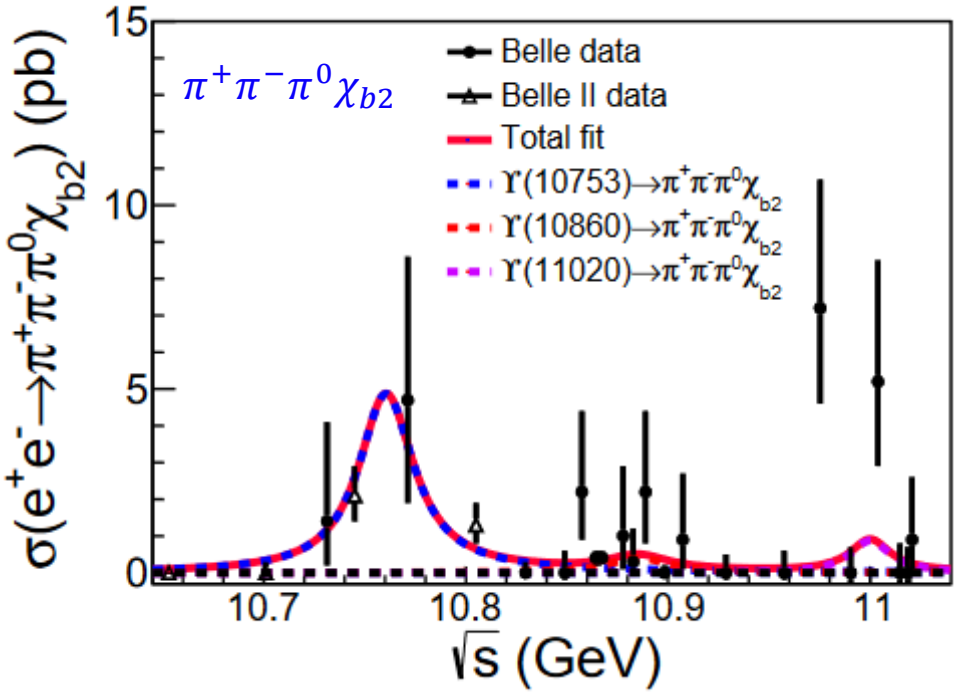


$M(\Upsilon(10753))$	$(10757.1 \pm 5.3 \pm 3.0)$ MeV/c^2
$\Gamma(\Upsilon(10753))$	$(35.3 \pm 14.1 \pm 16.4)$ MeV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$	$(1.7 \pm 0.3 \pm 0.1)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$	$(1.2 \pm 0.4 \pm 0.2)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \omega\chi_{b1})$	$(0.1 \pm 0.1 \pm 0.1)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \omega\chi_{b2})$	$(0.0 \pm 0.1 \pm 0.1)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \omega\chi_{b1})$	$(0.0 \pm 0.1 \pm 0.1)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \omega\chi_{b2})$	$(0.2 \pm 0.1 \pm 0.1)$ eV

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

[Preliminary results at Belle and Belle II]





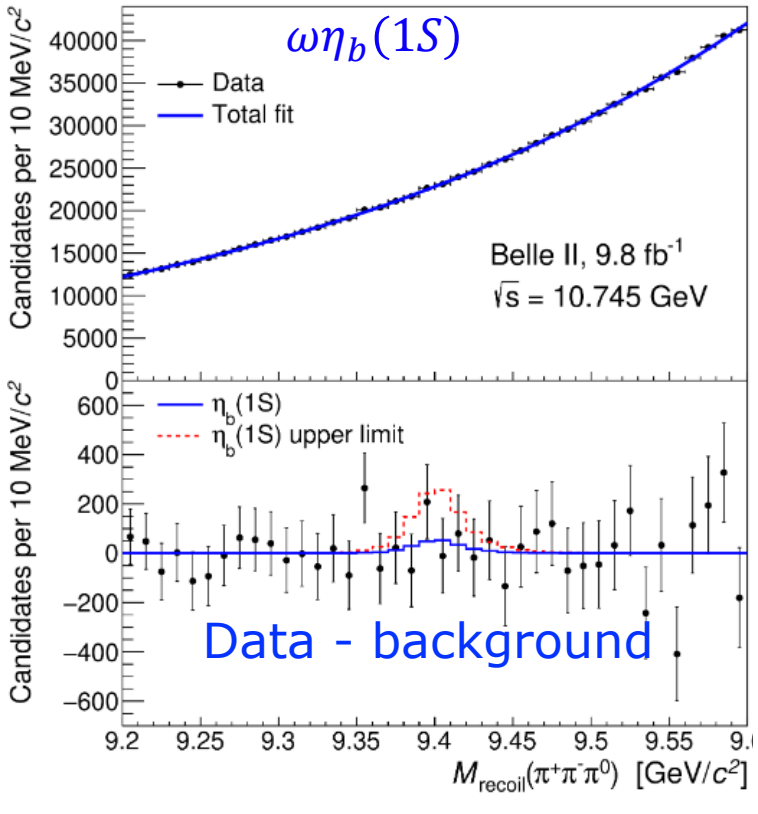
- The measured mass and width of $\Upsilon(10753)$ are consistent with the previous analyses [JHEP 10 (2019) 220, JHEP 07 (2024) 116].
- The $\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})$ and $\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})$ are compatible with those measured in [PRL 130, 091902 (2023)].
- The $(\pi^+\pi^-\pi^0)_{non-\omega\chi_{bJ}}$ is a consequence of the cascade decay of $\Upsilon(10860,11020) \to Z_b\pi \to \chi_{bJ}\rho\pi$ [PRD 90, 014036 (2014)].

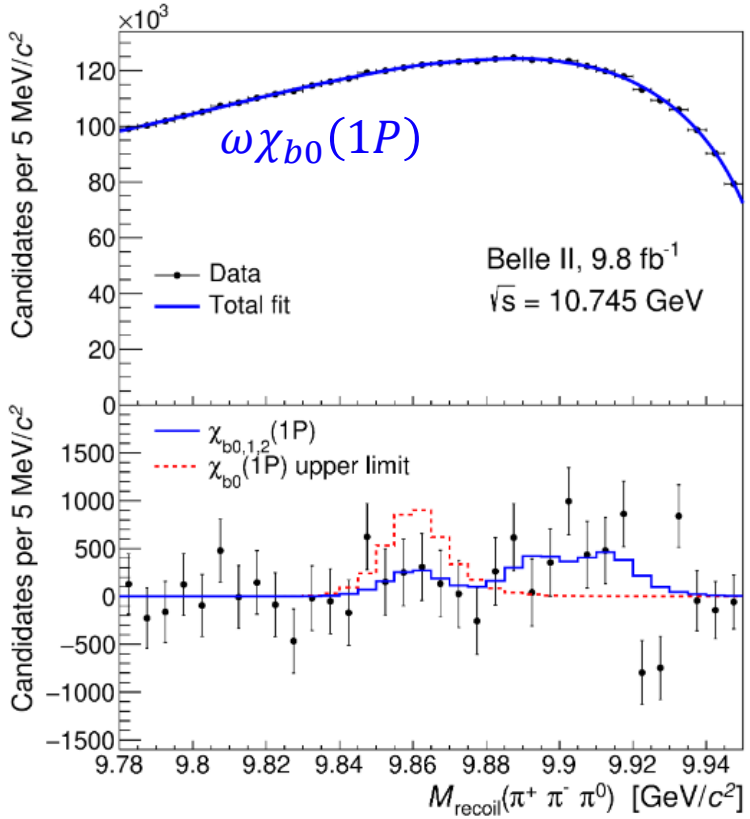
$M(\Upsilon(10753))$	$(10760.4 \pm 3.6 \pm 5.5)$ MeV/c^2
$\Gamma(\Upsilon(10753))$	$(33.5 \pm 14.0 \pm 17.5)$ MeV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \pi^+\pi^-\pi^0\chi_{b1})$	$(1.5 \pm 0.3 \pm 0.3)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to \pi^+\pi^-\pi^0\chi_{b2})$	$(1.3 \pm 0.4 \pm 0.1)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \pi^+\pi^-\pi^0\chi_{b1})$	$(0.2 \pm 0.1 \pm 0.2)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to \pi^+\pi^-\pi^0\chi_{b2})$	$(0.1 \pm 0.1 \pm 0.1)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \pi^+\pi^-\pi^0\chi_{b1})$	$(0.3 \pm 0.1 \pm 0.1)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to \pi^+\pi^-\pi^0\chi_{b2})$	$(0.2 \pm 0.1 \pm 0.1)$ eV

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

- The $\Upsilon(10753) \to \omega\eta_b(1S)$ transition is enhanced in tetraquark interpretation [CPC 43, 123102 (2019)]

[PRD 109, 072013 (2024)]





	$\eta_b(1S)\omega$	$\chi_{b0}(1P)\omega$
Yield (10^3)	$0.23 \pm 0.49 \pm 0.25$	$1.2 \pm 1.4 \pm 0.9$
Born cross section (pb)	$0.5 \pm 1.1 \pm 0.6$	$2.6 \pm 3.1 \pm 2.0$
Upper limit (pb)	< 2.5	< 8.7

- No significant signals are observed in ω recoil

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

- Set the upper limits at $\sqrt{s}$ =10.745 GeV

$$\sigma_B(e^+e^- \to \omega\eta_b(1S)) < 2.5 \text{ pb}$$

combined with [PRL 130, 091902 (2023)]

$$\sigma_B(e^+e^- \to \omega\chi_{b0}(1P)) < 7.8 \text{ pb}$$

in ref. [JHEP 10, 220 (2019)]

$$\sigma_B\left(e^+e^- \to \pi^+\pi^-\Upsilon(nS)\right) \sim (1-3) \text{ pb}$$

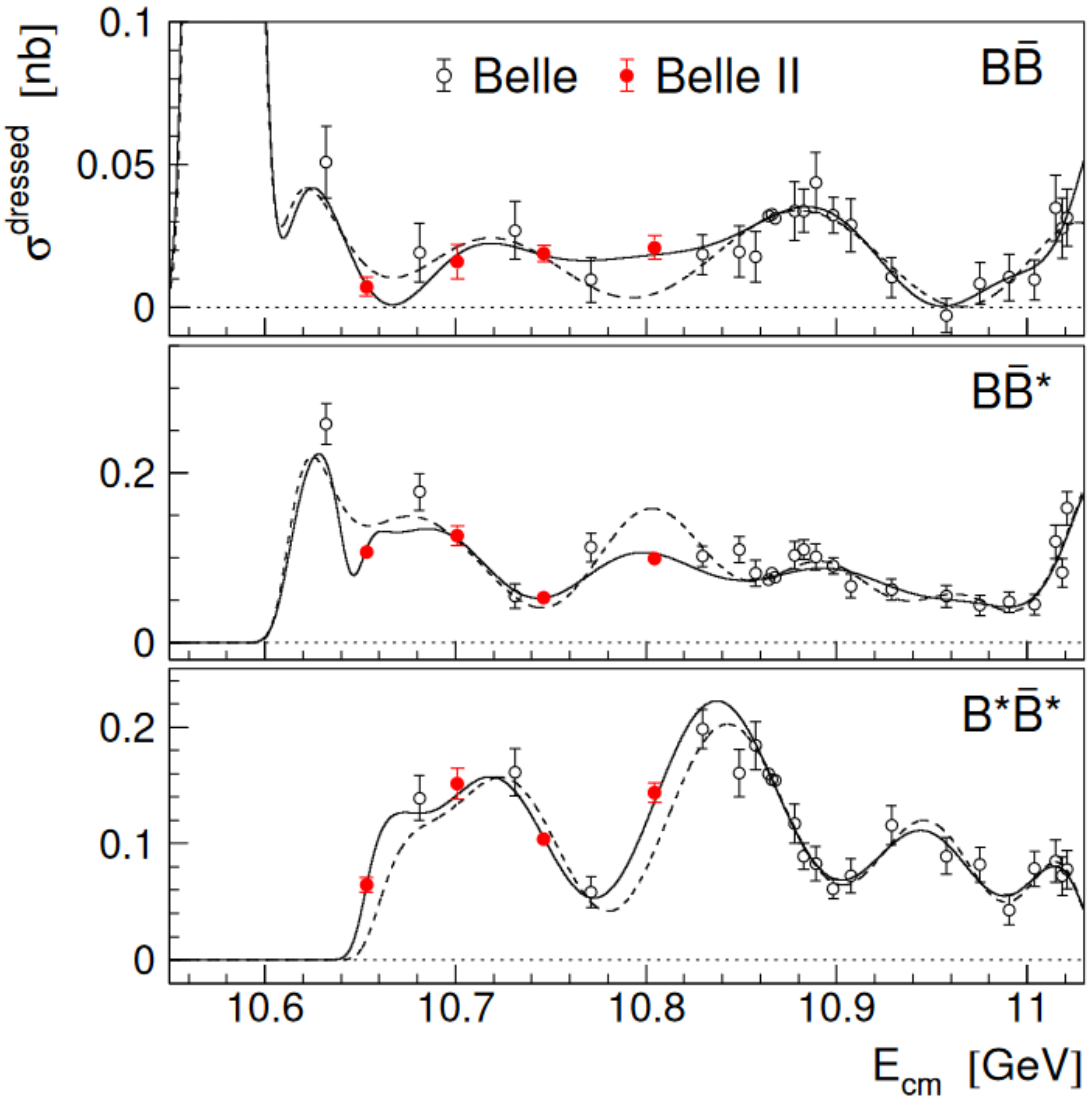
- Predictions of tetraquark model [CPC 43, 123102 (2019)]

$$\Gamma(\Upsilon(10753) \to \omega\eta_b) = 2.64^{+4.70}_{-1.69} \text{ MeV}$$

$$\Gamma(\Upsilon(10753) \to \pi^+\pi^-\Upsilon) = 0.08^{+0.20}_{-0.06} \text{ MeV}$$

Energy dependence $\sigma\left(e^+e^- \to B^{(*)}\bar{B}^{(*)}\right)$

[JHEP 07 (2024) 116]

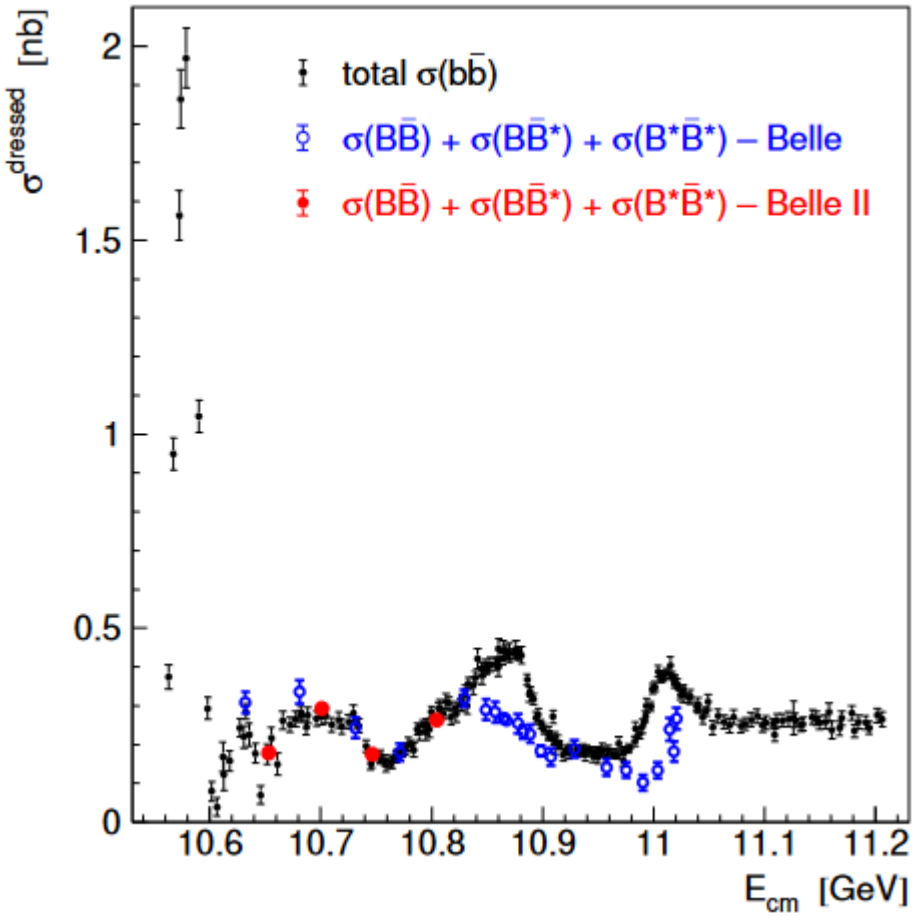


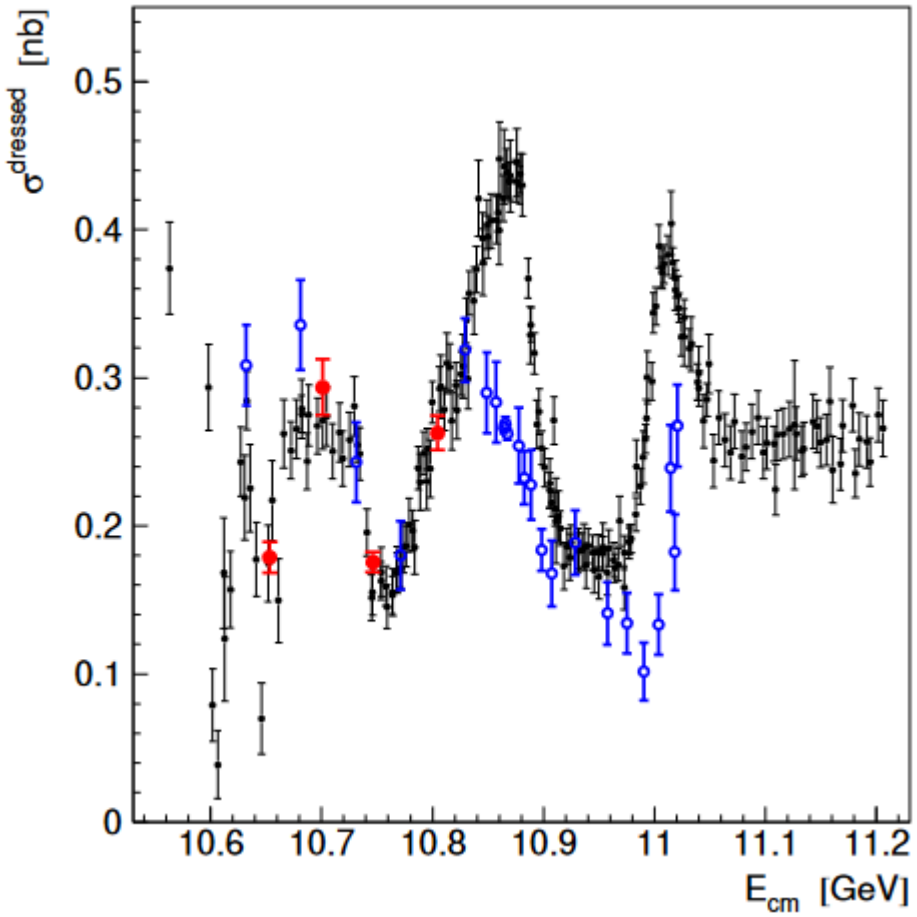
New: rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold

- 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 $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$

Energy dependence $\sigma\left(e^+e^- \to B^{(*)}\bar{B}^{(*)}\right)$

[JHEP 07 (2024) 116]





Black dots: Belle + BaBar
[PRL 102, 012001 (2009), PRD 93, 011101 (2016), CPC 44, 083001 (2020)]

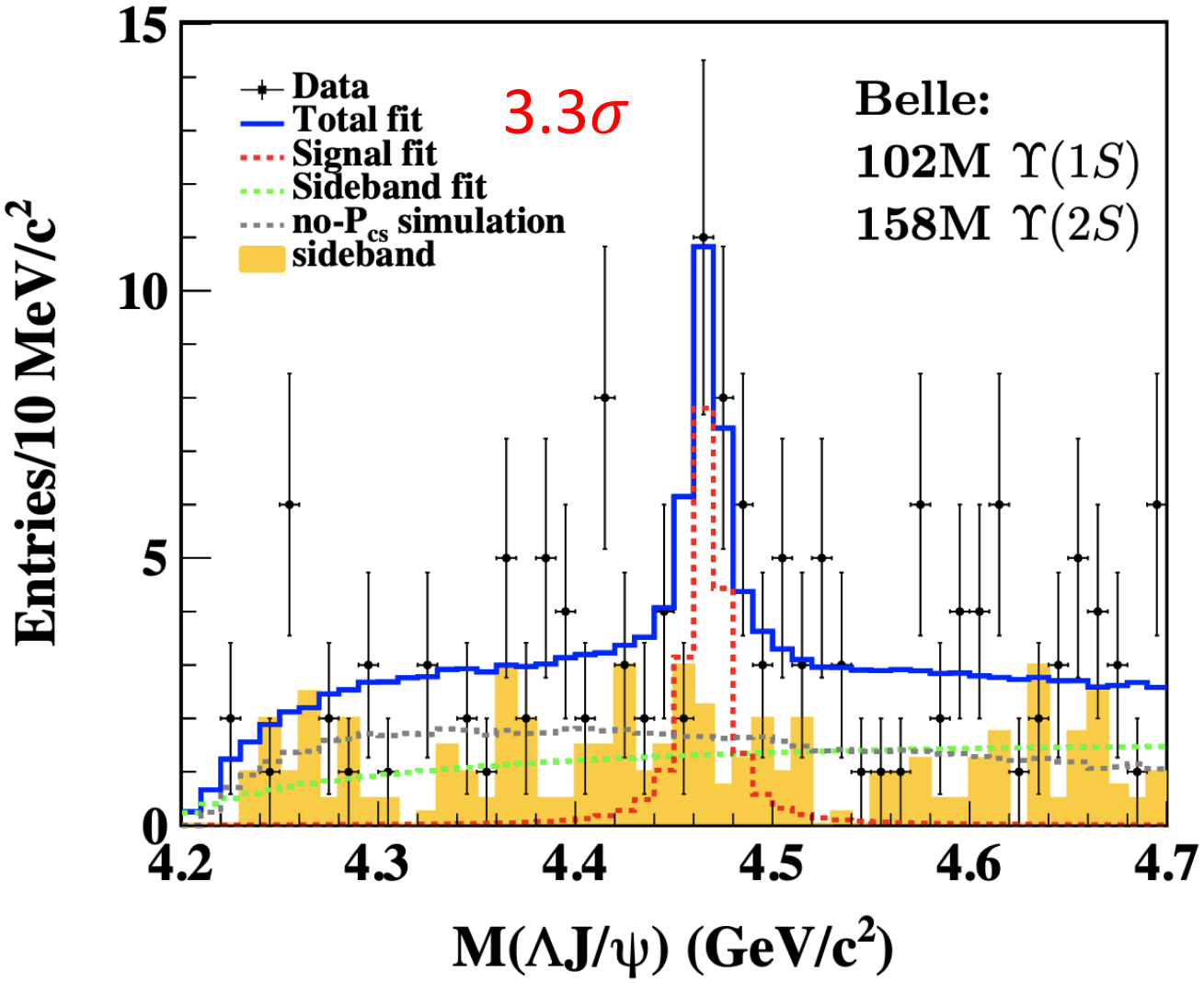
Open blue circles: Belle
[JHEP 06, 137 (2021)]

Filled red circles: Belle II
[this work]

- Agreement at low energy
- Departure at high energy is due to $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, and bottomonia

Evidence of $P_{cs}(4459)$ in $\Upsilon(1S, 2S)$ decays

[Preliminary results]



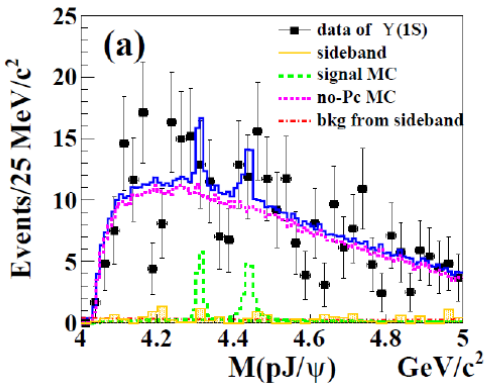
- Select inclusive $\Upsilon(1S, 2S) \to J/\psi\Lambda + X$ decays, then search for $P_{cs} \to J/\psi\Lambda$ in $M(J/\psi\Lambda)$
- Enhancements near $P_{cs}(4459)$ mass
- 4.0σ local significance with free mass and width

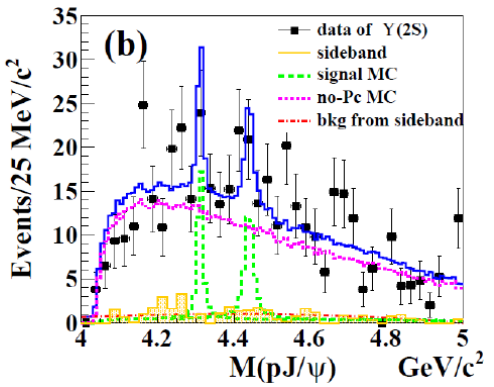
$$M = 4469.5 \pm 4.1 \pm 4.1 \text{ MeV}$$

$$\Gamma = 14.3 \pm 9.2 \pm 6.3 \text{ MeV}$$

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

- No significant P_c state in pJ/ψ final state

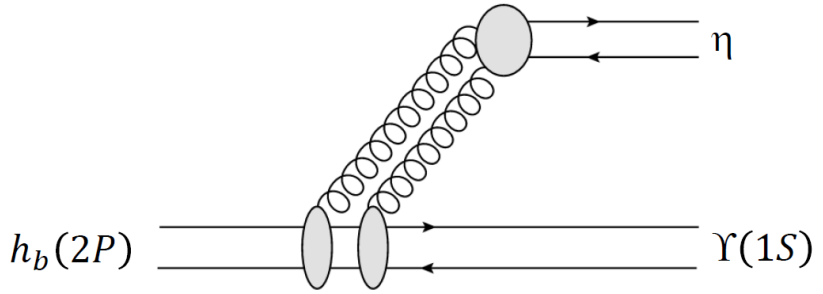


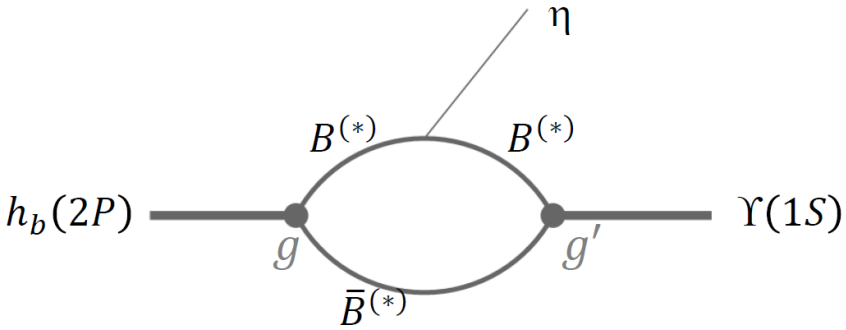


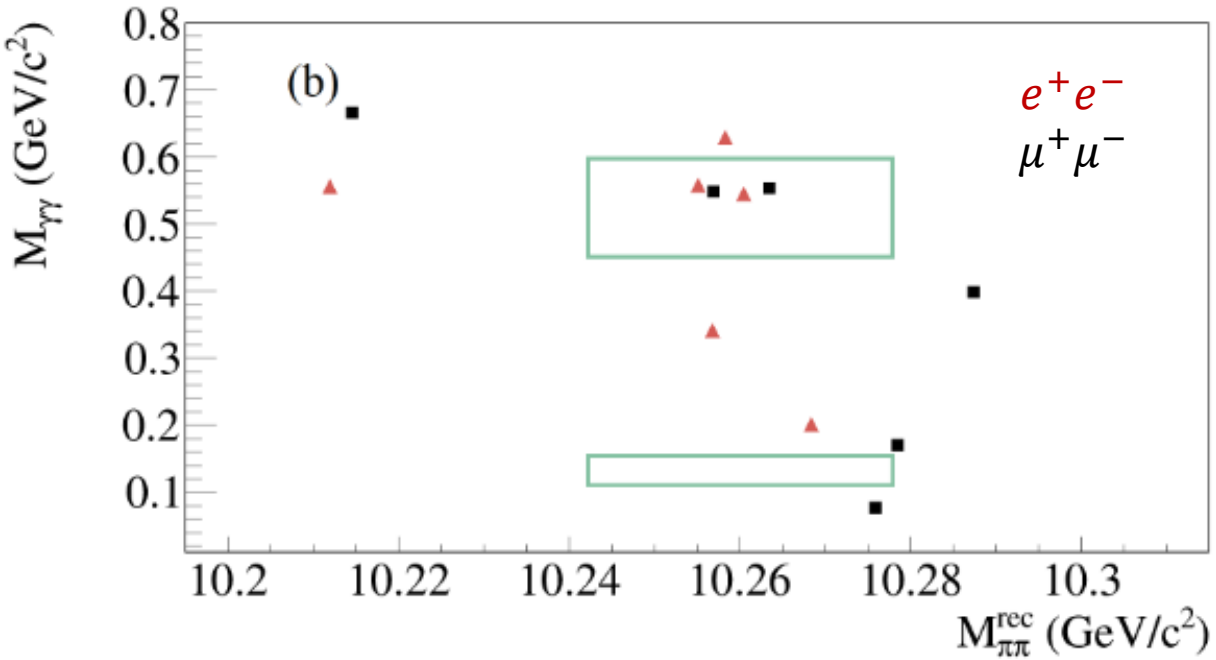
Bottomonium transitions: $h_b \to \pi^0/\eta\Upsilon(1S)$

[arXiv:2407.03783]

- Transitions between spin-singlet $S = 0$ and spin-triplet $S = 1$ bottomonium are suppressed, $\mathcal{A} \propto 1/m_b$
- The suppression might be lifted due to hadron loops
- Prediction: $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] \sim 10\%$ [PRD 86, 094013 (2012)] based on previous BaBar result $\mathcal{B}[\Upsilon(3S) \to \mathrm{h_b(1P)}\pi^0] \sim 10^{-3}$ [PRD 84, 091101 (2011)]







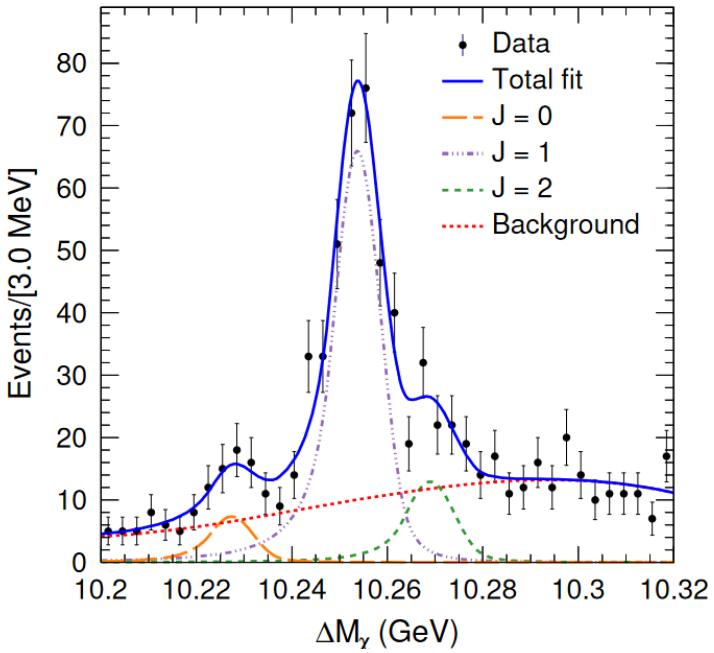
- First evidence of $h_b(2P) \to \Upsilon(1S)\eta$ with 3.5σ
  $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\eta] = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$
- Upper limits on π^0 transitions
  $\mathcal{B}[h_b(1P) \to \Upsilon(1S)\pi^0] < 1.8 \times 10^{-3}$
  $\mathcal{B}[h_b(2P) \to \Upsilon(1S)\pi^0] < 1.8 \times 10^{-3}$

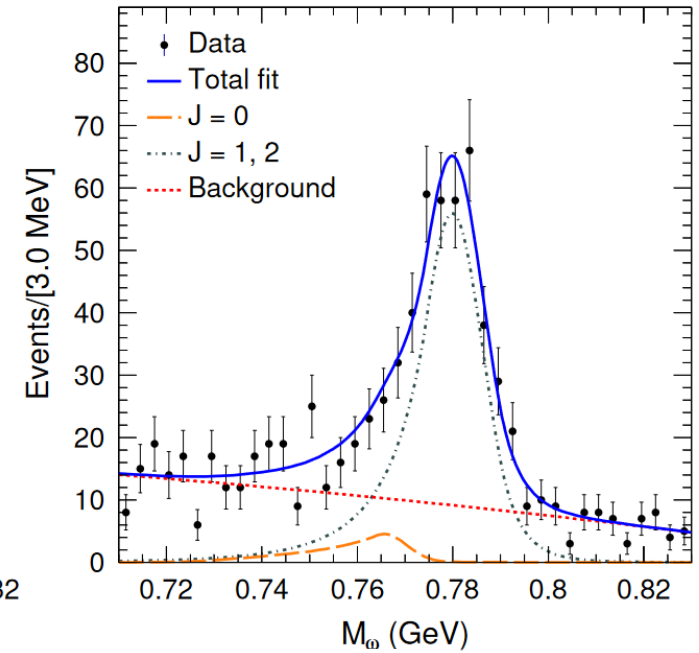
Belle $\Upsilon(5S)$ data
Full reconstruction: $e^+e^- \to h_b\pi^+\pi^-$

Bottomonium transitions: $\chi_{bJ}(2P) \to \omega\Upsilon(1S)$

[arXiv:2407.00879]

- First observation of $\chi_{b1,2}(2P) \to \omega\Upsilon(1S)$ was reported by CLEO, $\mathcal{B}\sim 1\%$ [PRL PRL 92, 222002 (2004)]
- No $\chi_{b0}(2P) \to \omega\Upsilon(1S)$ was observed





$$\Delta M_\chi = M(\pi^+\pi^-\pi^0\ell^+\ell^-) - M(\ell^+\ell^-) + m\big(\Upsilon(1S)\big),$$

❑ First evidence of $\chi_{b0}(2P) \to \omega\Upsilon(1S)$ with 3.2σ

$$\mathcal{B}\big(\chi_{b0}(2P) \to \omega\Upsilon(1S)\big) = (0.55 \pm 0.19 \pm 0.07)\%$$

$$\mathcal{B}\big(\chi_{b1}(2P) \to \omega\Upsilon(1S)\big) = (2.39^{+0.20}_{-0.19} \pm 0.24)\%$$

$$\mathcal{B}\big(\chi_{b2}(2P) \to \omega\Upsilon(1S)\big) = (0.47^{+0.13}_{-0.12} \pm 0.06)\%$$

❑ Confirm previous measurement of $J = 1,2$ Belle $\Upsilon(3S)$ data, $\Upsilon(3S) \to \gamma\chi_{bJ}$

❑ The ratio for $J = 2$ to $J = 1$ transitions is found to differ by 3.3σ with QCD multipole expansion [Mod. Phys. Lett. A 18, 1067 (2003)]

$$r_{J/1} = \frac{\mathcal{B}\big(\Upsilon(3S) \to \gamma\chi_{bJ}(2P) \to \gamma\omega\Upsilon(1S)\big)}{\mathcal{B}\big(\Upsilon(3S) \to \gamma\chi_{b1}(2P) \to \gamma\omega\Upsilon(1S)\big)},$$

Summary

- New results from scan data around 10.75 GeV from Belle II help to understand the structure of $\Upsilon(10753)$
  - Improved mass and width using $\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(nS)$
  - New decay mode $\Upsilon(10753) \rightarrow \omega\chi_{bJ}$
  - Study of $e^+e^- \rightarrow \omega\chi_{bJ}, \pi^+\pi^-\pi^0\chi_{bJ}$
  - Upper limits on $e^+e^- \rightarrow \omega\eta_b(1S), \omega\chi_{b0}$
  - Cross sections $\sigma[e^+e^- \rightarrow B^{(*)}\bar{B}^{(*)}]$
- Evidence of $\mathrm{P}_{cs}(4459)$ in $\Upsilon(1S, 2S)$
- Evidence of bottonium transitions $h_b(2P) \rightarrow \Upsilon(1S)\eta$ and $\chi_{b0}(2P) \rightarrow \omega\Upsilon(1S)$

Thank you for your attention!