Recent quarkonium results at Belle II

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On behalf of the Belle II Collaboration

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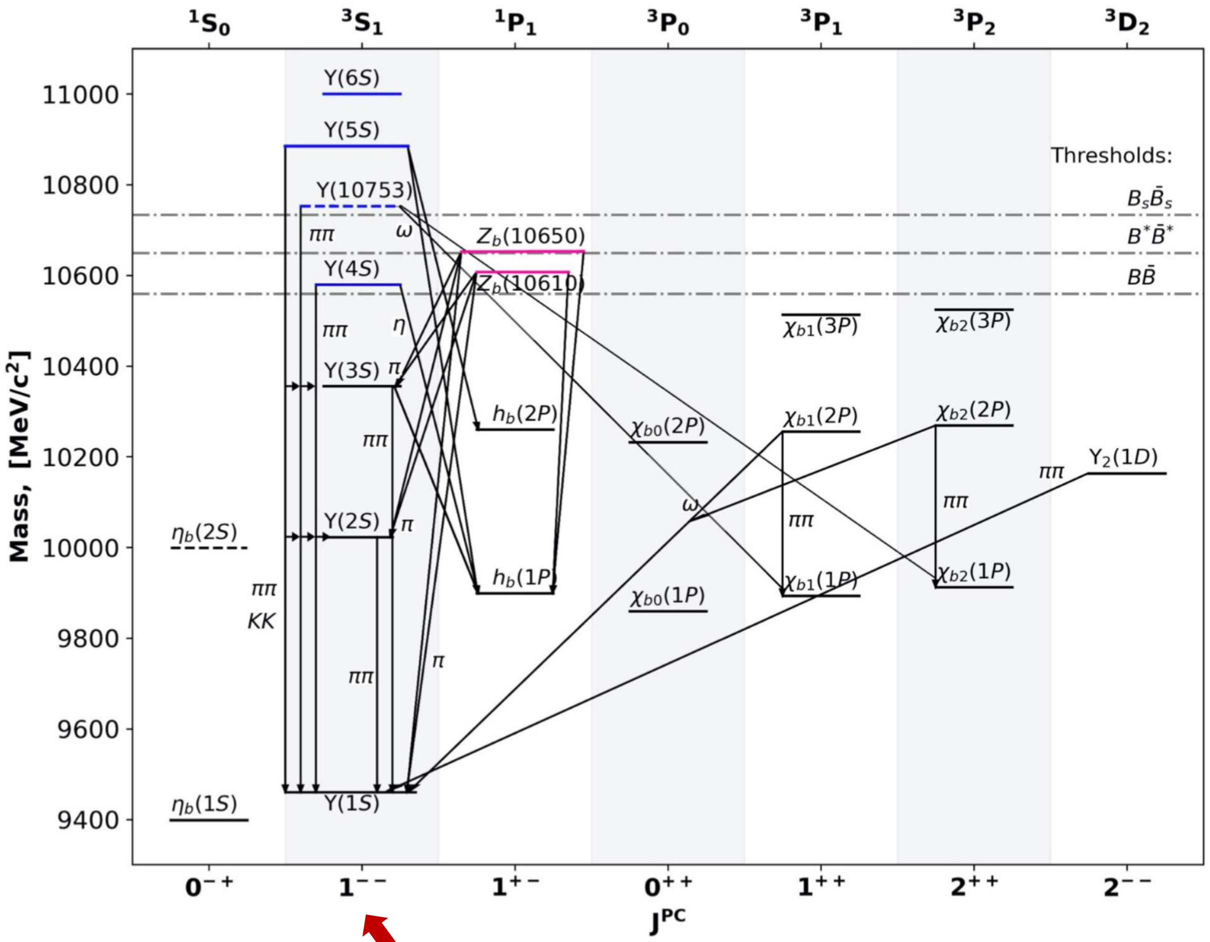
Bottomonium



$\Upsilon(nS)$ with 1^{--} can be produced in e^+e^- collisions

- The states with other quantum numbers can be produced via hadronic or radiative transitions.

Heavy quarkonium spectroscopy is an excellent laboratory to study non-perturbative QCD!

- Below $B\bar{B}$ threshold states are well described by the potential models.
- Above $B\bar{B}$ threshold states exhibit unexpected properties:
  - The transitions to lower bottomonium with the emission of light hadrons are not suppressed (violate OZI);
  - The η transitions are not suppressed compare to $\pi^+\pi^-$ transitions (violate HQSS);
  - Two charged Z_b^+ states are observed.

- Conventional bottomonium (pure $b\bar{b}$ states)
- Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)
- Purely exotic charged states (Z_b^+)

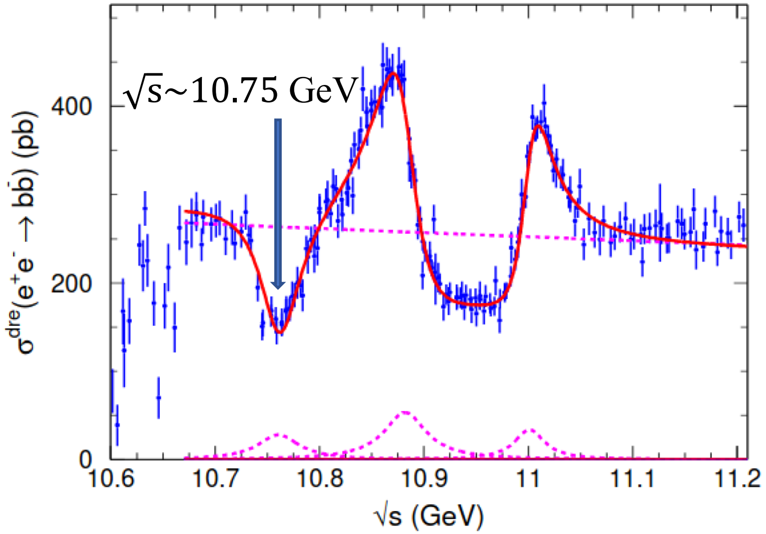
Discovery of $\Upsilon(10753)$

- The $\Upsilon(10753)$ was observed in the energy dependence of $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$ $(n = 1,2,3)$ cross sections by Belle.

[JHEP 10, 220 (2019)]

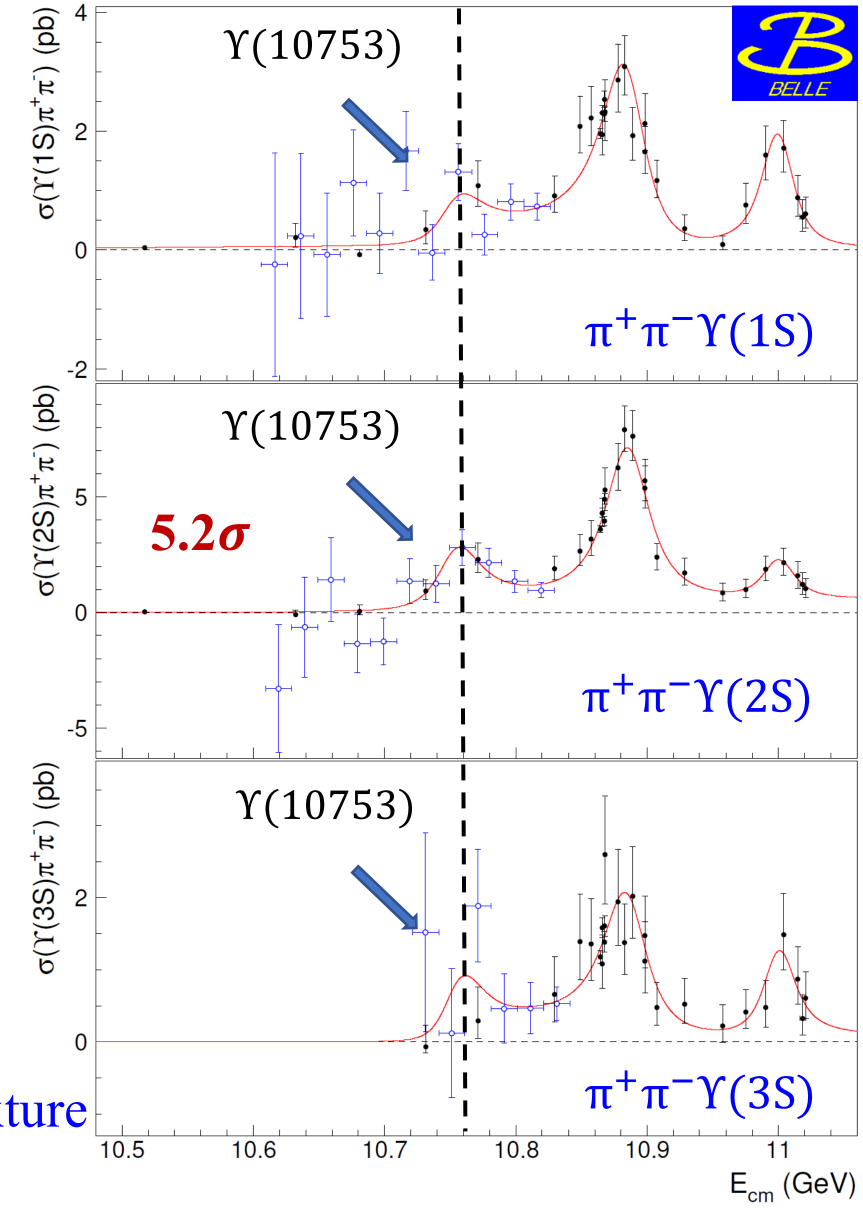
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\ ^{+2.2}_{-0.9}$	$11000.0^{+4.0\ +1.0}_{-4.5\ -1.3}$	$10752.7 \pm 5.9\ ^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\ +0.5}_{-3.9\ -1.1}$	$23.8^{+8.0\ +0.7}_{-6.8\ -1.8}$	$35.5^{+17.6\ +3.9}_{-11.3\ -3.3}$

- Refit of Babar and Belle $\sigma(e^+e^- \to b\bar{b})$ [CPC 44 (2020) 8, 083001]:



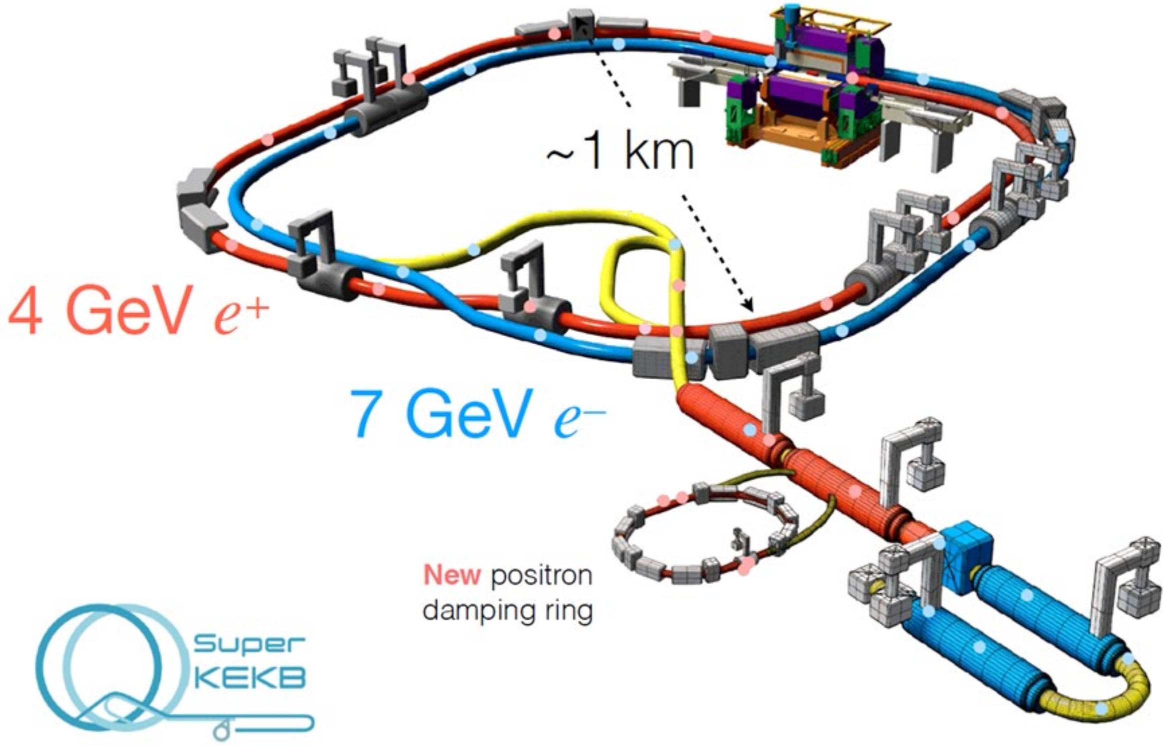
Dip near 10.75 GeV likely caused by interference between BW and smooth component.

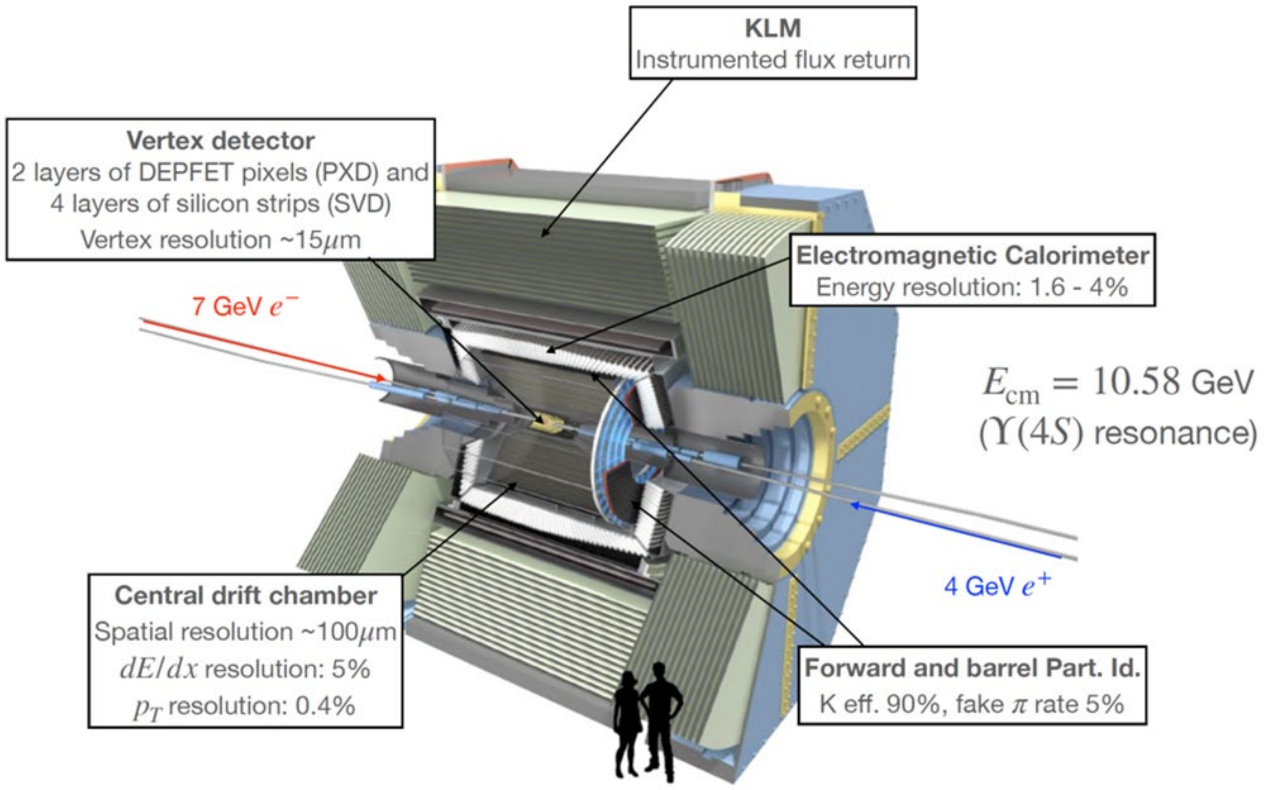
- **Possible interpretations:**
  - Conventional bottomonium?
  - Hybrid state?
  - Tetraquark state?
  - Hadronic molecule with a small admixture of a bottomonium?



Belle II experiment

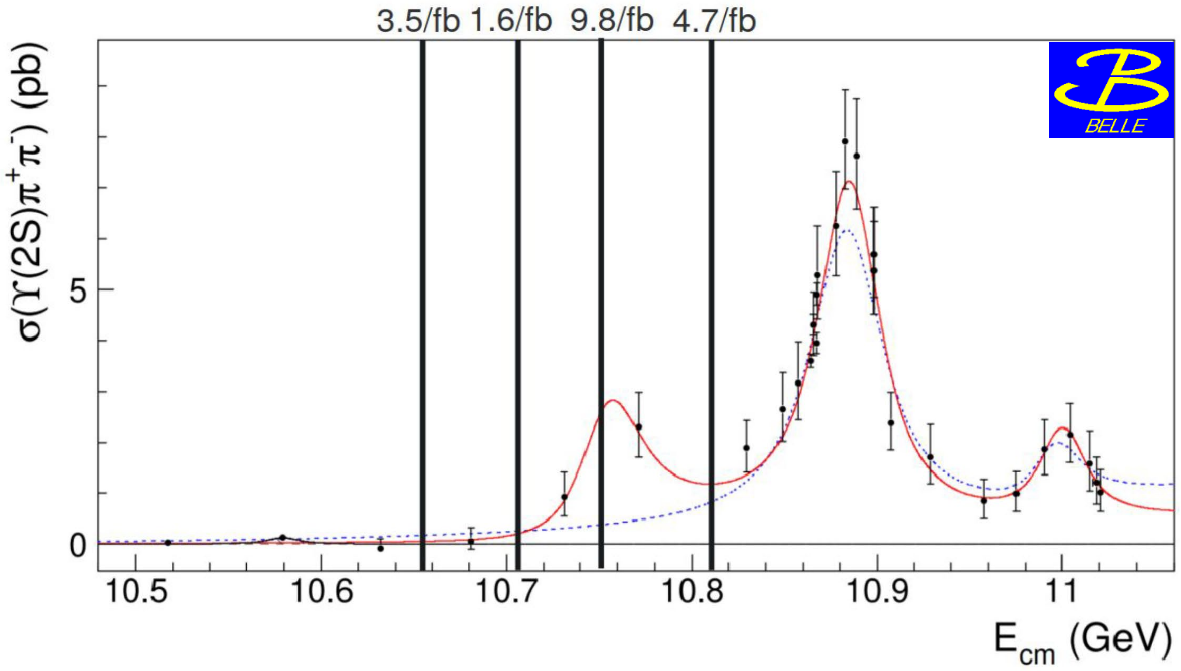
- Asymmetric e^+e^- collider at KEK provides unique clean environment.
- Upgraded detector (better vertex and particle identification performances).
- World-record instantaneous luminosity: $4.7 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$ ($\times$ 2 of the Belle peak luminosity).
- Total integrated luminosity: $424 \mathrm{fb}^{-1}$.

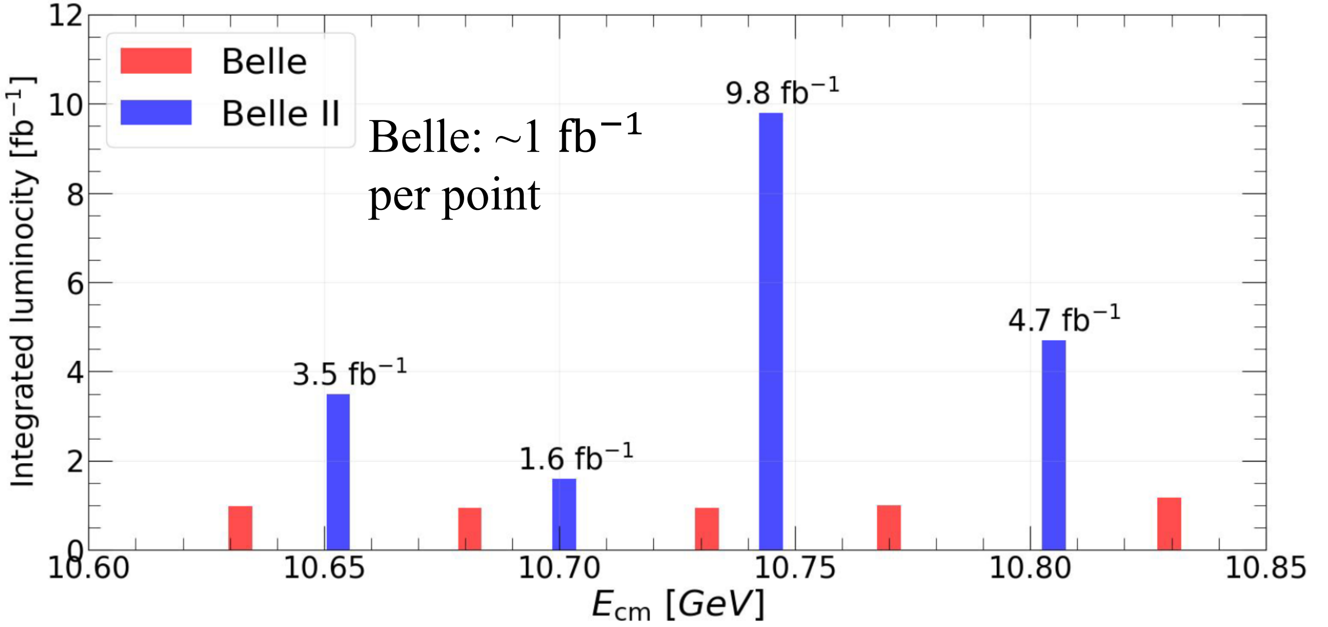




Unique scan data near $\sqrt{s} = 10.75$ GeV

- In November 2021, Belle II collected 19fb^{-1} of scan data at four energy points near 10.75 GeV.
- Physics goals: (1) understand the nature of the $\Upsilon(10753)$;
  (2) improve precision of exclusive cross-sections below $\Upsilon(5S)$.





Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ and search for $X_b \to \omega\Upsilon(1S)$ at $\sqrt{s}$ near 10.75 GeV

[PRL 130 091902 (2023)]

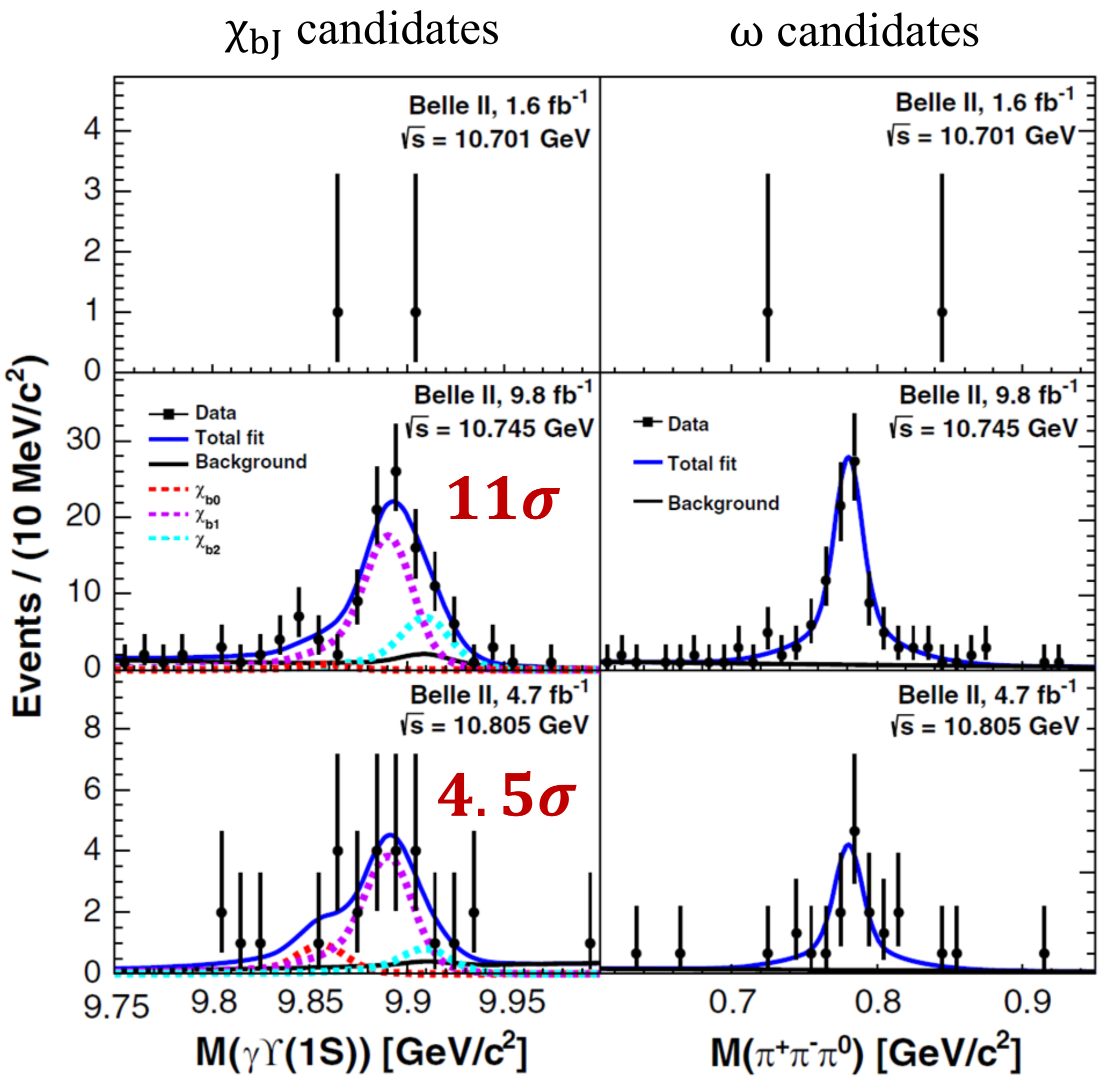
Observation of $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$

- Interpretations as an admixture of conventional 4S and 3D states predict comparable branching fractions of 10^{-3} for $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ and $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$.

[PRD104, 034036 (2021), PRD 105, 074007 (2022)]

Channel	$\sqrt{s}$ (GeV)	N^{sig}	$\Sigma(\sigma)$	σ_B (pb)
$e^+e^- \to \omega\chi_{b0}$	10.701	< 3.0	-	< 16.6
$e^+e^- \to \omega\chi_{b1}$		< 3.9	-	< 1.2
$e^+e^- \to \omega\chi_{b2}$		< 4.0	-	< 2.5
$e^+e^- \to \omega\chi_{b0}$	10.745	< 12.0	0.5	< 11.3
$e^+e^- \to \omega\chi_{b1}$		$68.9^{+13.7}_{-13.5}$	5.9	$3.6^{+0.7}_{-0.7} \pm 0.5$
$e^+e^- \to \omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	3.1	$2.8^{+1.2}_{-1.0} \pm 0.4$
$e^+e^- \to \omega\chi_{b0}$	10.805	< 9.9	1.2	< 11.4
$e^+e^- \to \omega\chi_{b1}$		$15.0^{+6.8}_{-6.2}$	2.7	< 1.7
$e^+e^- \to \omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	0.8	< 1.6

- We perform two dimensional un-binned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.

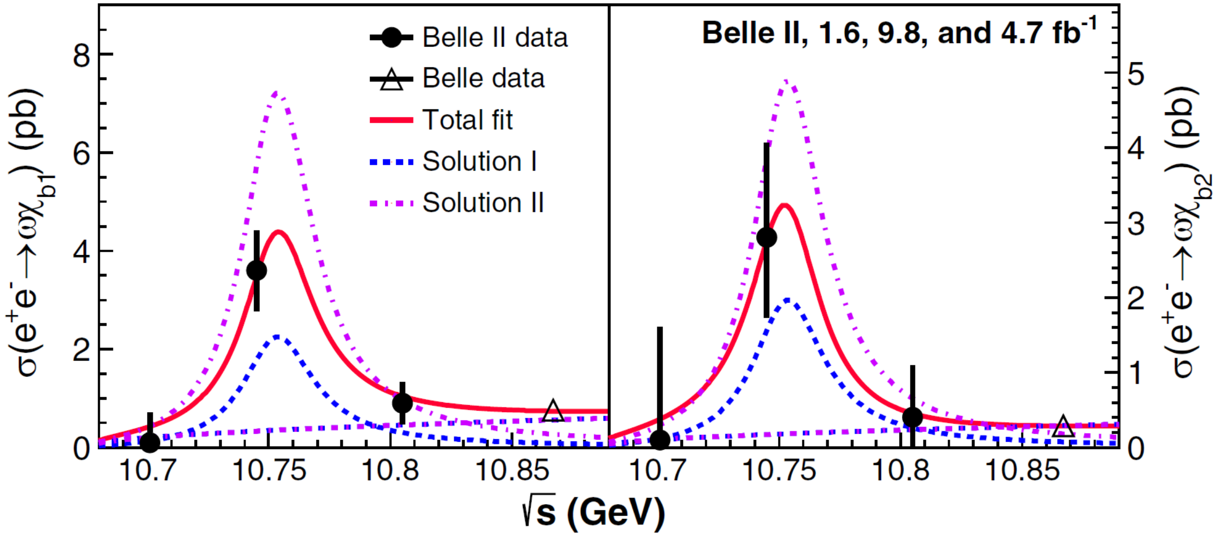


Observation of $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$

- The $e^+e^- \to \omega\chi_{bJ}(1P)$ [$J = 1,2$] cross sections are enhanced at $\Upsilon(10753)$.
- Combine Belle II measurements with Belle measurement [PRL 113, 142001(2014)] to fit cross sections:

$$\left| \sqrt{\Phi_2(\sqrt{s})} + \frac{\sqrt{12\pi\Gamma_{ee}\mathcal{B}_f\Gamma}}{s - M^2 - iM\Gamma}\sqrt{\frac{\Phi_2(\sqrt{s})}{\Phi_2(M)}}e^{i\phi} \right|^2$$

- The mass and width are fixed to the 10752.7 MeV/c^2 and 35.5 MeV. [JHEP 10, 220 (2019)]



Solution I: Constructive interference Solution II: Destructive interference

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

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

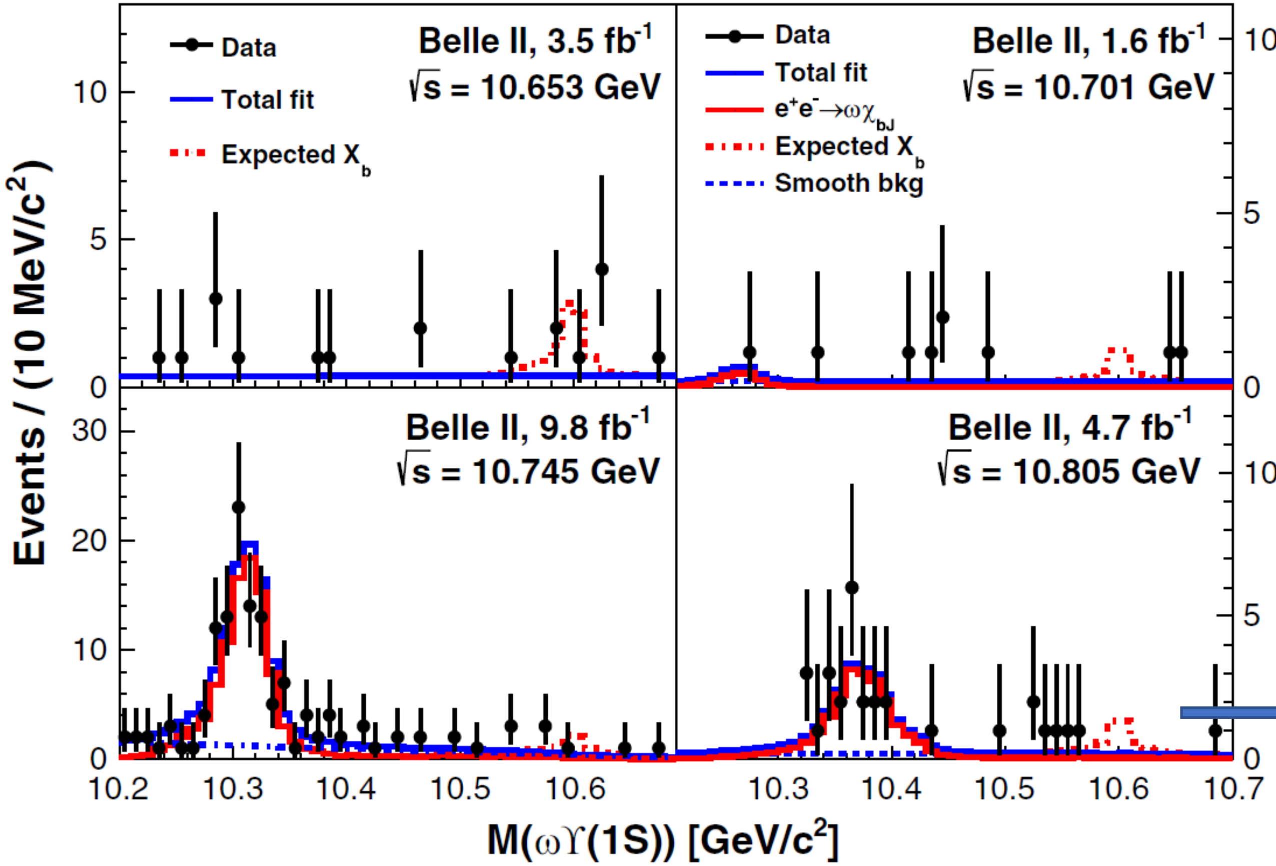
~0.15 at $\sqrt{s} = 10.867$ GeV

- It may indicate different internal structures for $\Upsilon(10753)$ and $\Upsilon(5S)$.

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

- Contradicts the expectation for a pure D-wave bottomonium state of 15 [PLB 738, 172 (2014)].
- A 1.8σ difference with the prediction for a S-D-mixed state of 0.2 [PRD 104, 034036 (2021)].

Search for $X_b \to \omega\Upsilon(1S)$



- The X_b is the posited bottomonium counterpart of the X(3872);
- No evidence of X_b signal;
- The peaks are the reflections of $e^+e^- \to \omega\chi_{bJ}$.
- Upper limits on cross sections are set for $M(X_b) \in [10.45, 10.65]$ GeV.

From simulated events with $m(X_b) = 10.6\ \mathrm{GeV}/c^2$
The yield is fixed at the upper limit at 90% C.L.

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

Search for $e^+e^- \to \omega\eta_b(1S)$ and $e^+e^- \to \omega\chi_{b0}(1P)$ at $\sqrt{s} = 10.745$ GeV with Belle II

[New for this conference]

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

- Tetraquark interpretation of the $\Upsilon(10753)$ predicts enhancement of the $\Upsilon(10753) \to \omega\eta_b(1S)$ transition:

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

[CPC 43, 123102 (2019)]

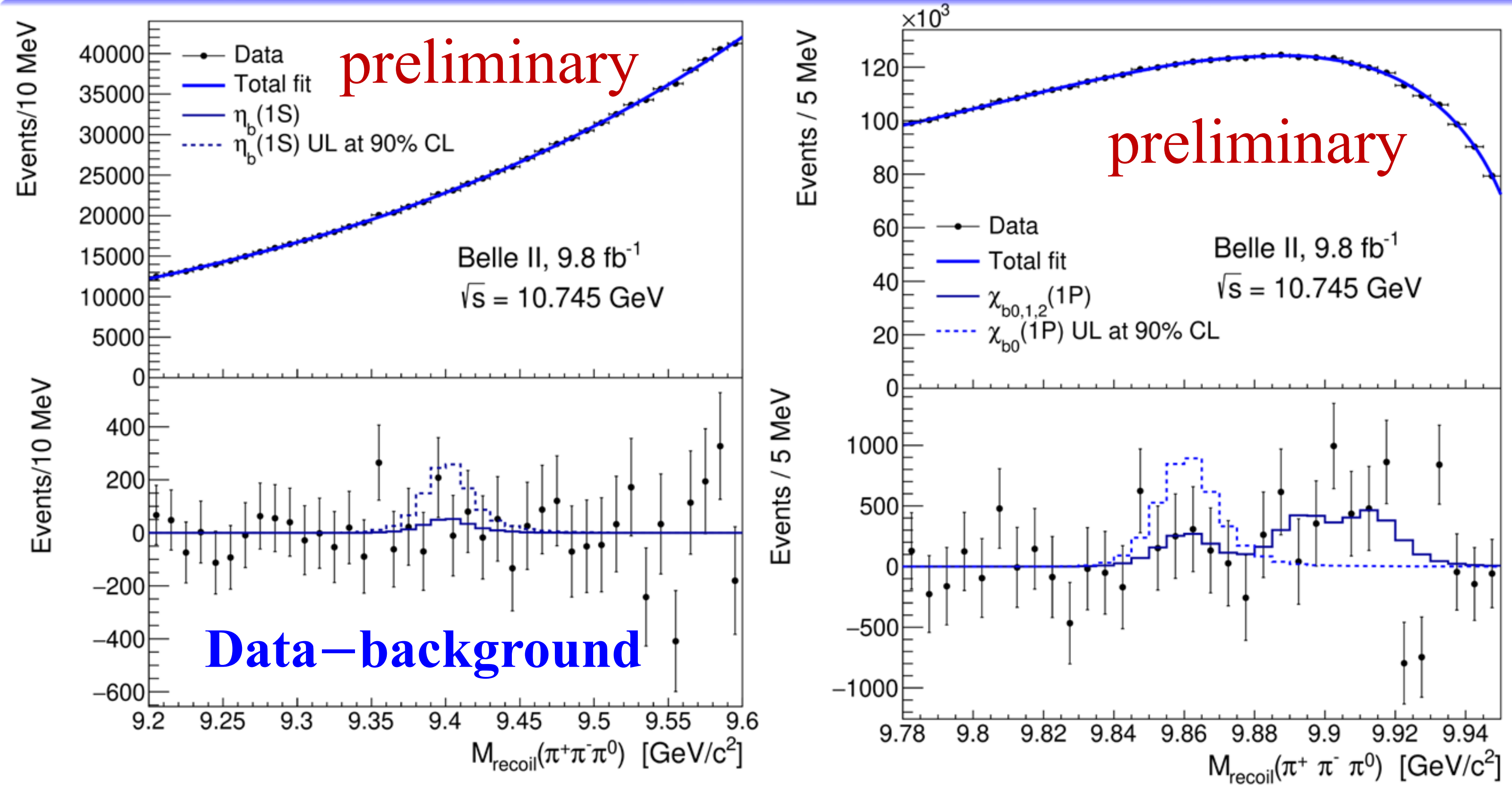
- The $e^+e^- \to \omega\chi_{bJ}(1P)(J = 1{,}2)$ was found to be enhanced at $\sqrt{s} = 10.745$ GeV. The $e^+e^- \to \omega\chi_{b0}(1P)$ transition was not observed due to low branching fraction $\mathcal{B}(\chi_{b0}(1P) \to \Upsilon(1S)\gamma) = (1.94 \pm 0.27)\%$.

[PRL 130 091902 (2023)]

- In this work, we reconstruct the ω meson via the $\pi^+\pi^-\pi^0$ mode, and then search for the $\eta_b(1S)$ and $\chi_{b0}(1P)$ states in the recoil mass spectrum of ω candidate.

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

$M_{recoil}(\pi^+\pi^-\pi^0)$



New

- No clear $\eta_b(1S)$ and $\chi_{b0}(1P)$ signals are observed.
- Upper limits at the 90% C.L. on the Born cross sections are set.

	$\eta_b(1S)\omega$	$\chi_{b0}(1P)\omega$
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 at 90% CL	< 2.5	< 8.6

This measurement and JHEP 10, 220 (2019):

$\sigma^B(e^+e^- \to \eta_b(1S)\omega) < 2.5$pb@10.745 GeV
$\sigma^B(e^+e^- \to \Upsilon(nS)\pi^+\pi^-) \sim 5$pb@10.75 GeV

- The measured cross-section contradicts the prediction of tetraquark model in Ref. [CPC 43, 123102 (2019)].

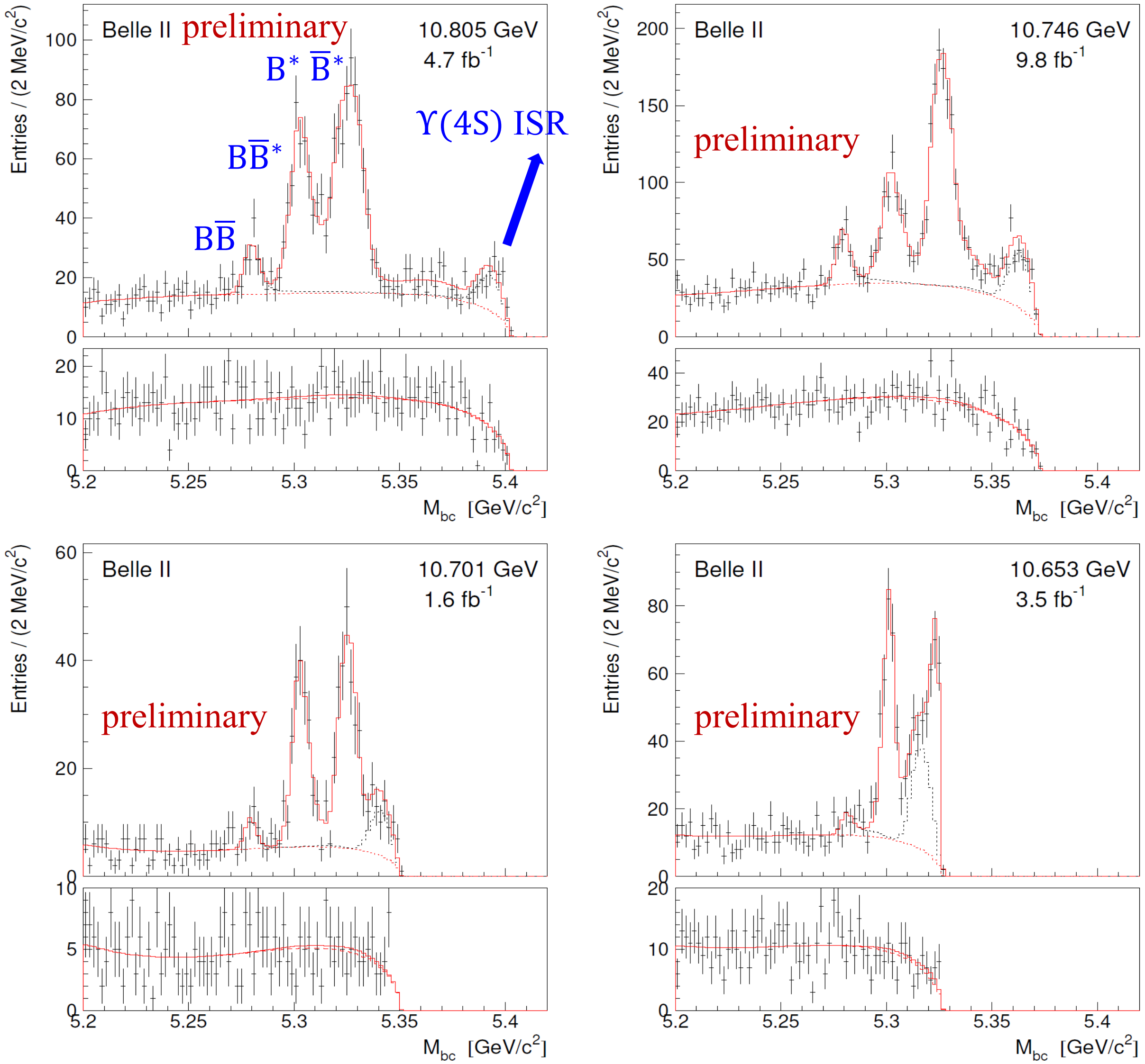
Measurement of the energy dependence of the $e^+e^- \to B^{(*)}\overline{B}^{(*)}$ cross sections at Belle II

$e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross sections

- ☐ The $B^{(*)}\bar{B}^{(*)}$ are expected to be dominant decay channels for excited bottomonium-like states.
- ☐ The measured cross sections can be used in the coupled channel analysis of all available scan data to extract the parameter of $\Upsilon(10753)$.
- ☐ Method:
  - Fully reconstruct one B in hadronic decays;
  - Identify signals with M_{bc}:

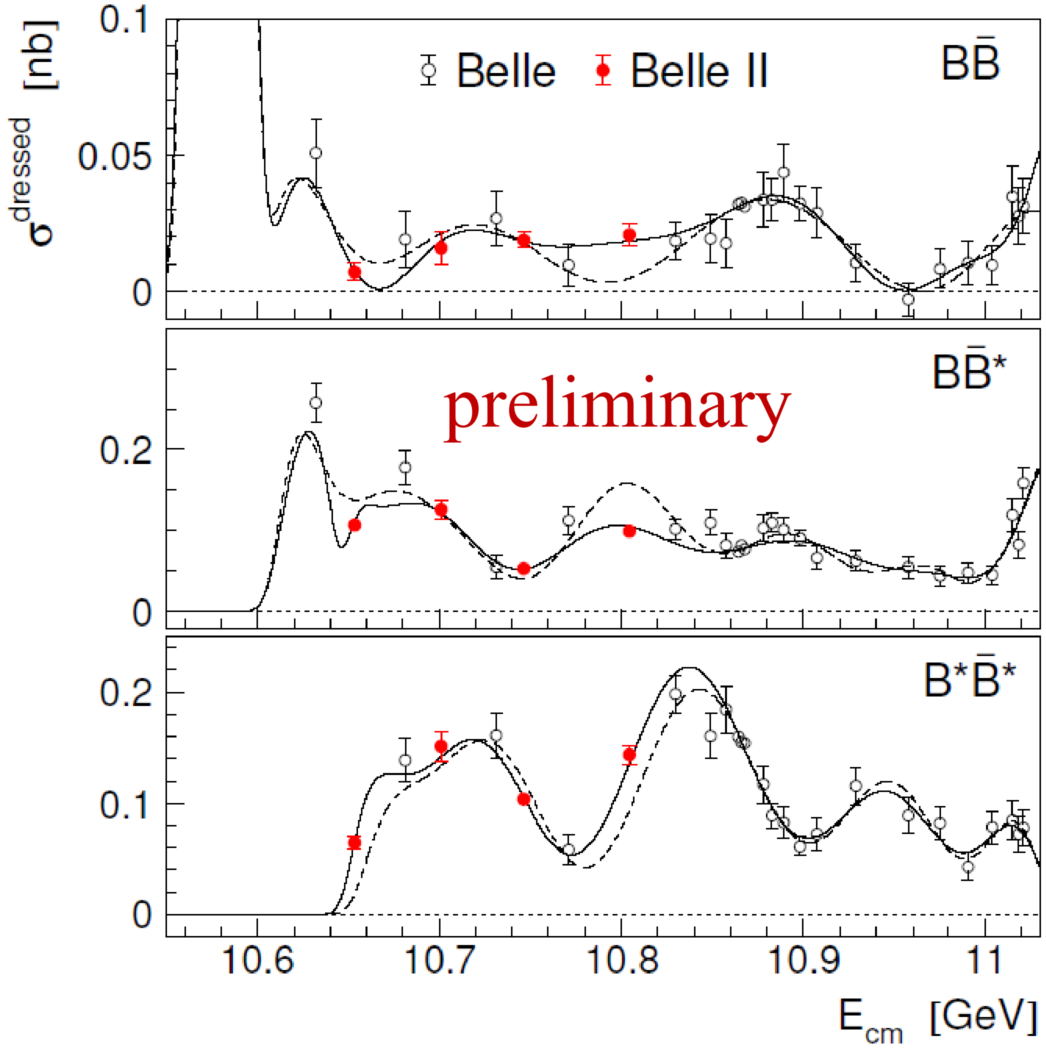
$$M_{bc} = \sqrt{(E_{cm}/2)^2 - p_B^2}$$

- ☐ Contribution of $\Upsilon(4S) \to B\bar{B}$ production via ISR is visible, well described by the fit.



$e^+e^- \to B^{(*)}\bar{B}^{(*)}$ cross sections

- $\sigma(e^+e^- \to B^*\bar{B}^*)$ increases rapidly above $B^*\bar{B}^*$ threshold. The energy of the nearby point is only 5MeV above the threshold. High value of the cross section is surprising since the phase space of this reaction grows as the 3/2 power of the difference between the beam energy and the threshold energy.
- **Possible interpretation:** resonance or bound state of $B^*\bar{B}^*$ (or $b\bar{b}$) near threshold [MPLA 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 $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$.
- The $\Upsilon(nS)\pi^+\pi^-$ and $h_b(1P)\eta$ final states could also be enhanced [PRD 87, 094033 (2013)].



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

Summary

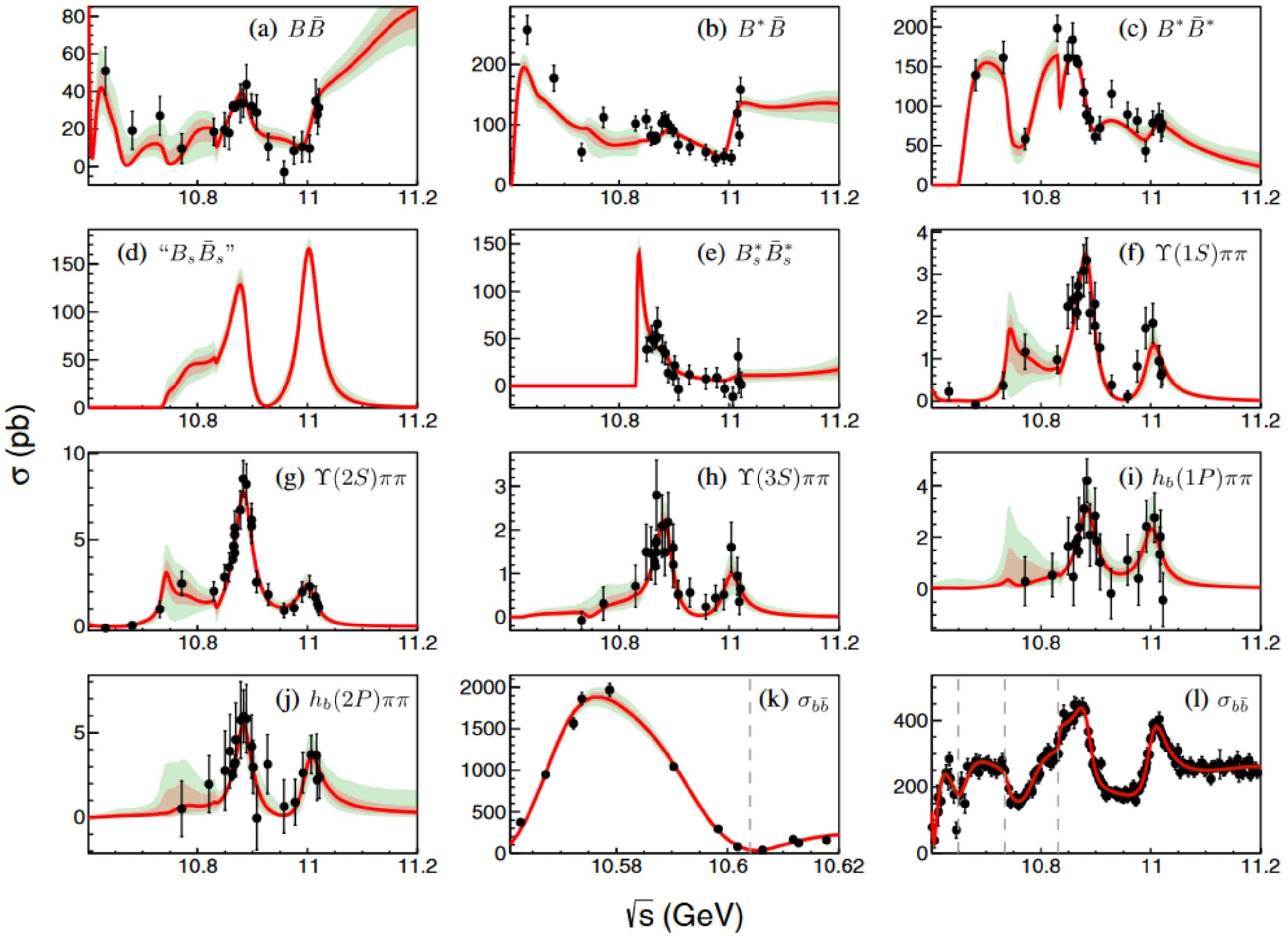
- **Observation of $e^+e^- \to \omega\chi_{bJ}(1P)$ near $\sqrt{s} = 10.75$ GeV:**
  - $\sigma(e^+e^- \to \omega\chi_{bJ}(1P))[J = 1,2]$ has a strong enhancement at 10.75 GeV;
  - Confirmation of $\Upsilon(10753)$ and observation of its new decay channel.
- **Search for $e^+e^- \to \omega\eta_b(1S)$ and $e^+e^- \to \omega\chi_{b0}(1P)$:**
  - No signals are observed, and upper limits on the Born cross sections are set;
  - The measured cross-section contradicts the prediction of tetraquark model.
- **Energy dependency of $e^+e^- \to B\bar{B}, B\bar{B}^*$, and $B^*\bar{B}^*$ cross sections:**
  - Confirmation of "oscillatory" behavior, improvement of the accuracy;
  - Rapid rise of $\sigma(e^+e^- \to B^*\bar{B}^*)$ above threshold–resonance or bound state of $B^*\bar{B}^*$?

Thanks for your attention!

Backup

- ☐ Uses the coupled-channel approach to perform a global fit to various cross section energy dependences.

N. HÜSKEN, R. E. MITCHELL, and E. S. SWANSON — PHYS. REV. D **106**, 094013 (2022)



[PRD 106 (2022) 9, 094013]

- ☐ Using data:
  - Two-body exclusive cross sections $\sigma\left(e^+e^- \to B_{(s)}^{(*)}\,\overline{B}_{(s)}^{(*)}\right)$;
  - Three-body exclusive cross sections $\sigma(e^+e^- \to \Upsilon(nS)/h_b(mP)\pi^+\pi^-)$ ($n = 1,2,3;\ m = 1,2$);
  - Combined Belle and Babar R_b measurements.
- ☐ Includes $\Upsilon(4S)$, $\Upsilon(10753)$, $\Upsilon(5S)$, and $\Upsilon(6S)$ poles.
- ☐ **Results:**

  pole positions (masses and widths) and energy dependence of scattering amplitudes.

Backup

- Good agreement at low energy.
- Deviation at higher energy is presumably due to $B_s^{(*)}$, multi-body $B^{(*)}\overline{B}^{(*)}\pi(\pi)$ and production of bottomonia with light hadrons.