Quarkonium at Belle II

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on behalf of the Belle II Collaboration

QCD23
26th HIGH-ENERGY PHYSICS
INTERNATIONAL CONFERENCE
IN QUANTUM CHROMODYNAMICS
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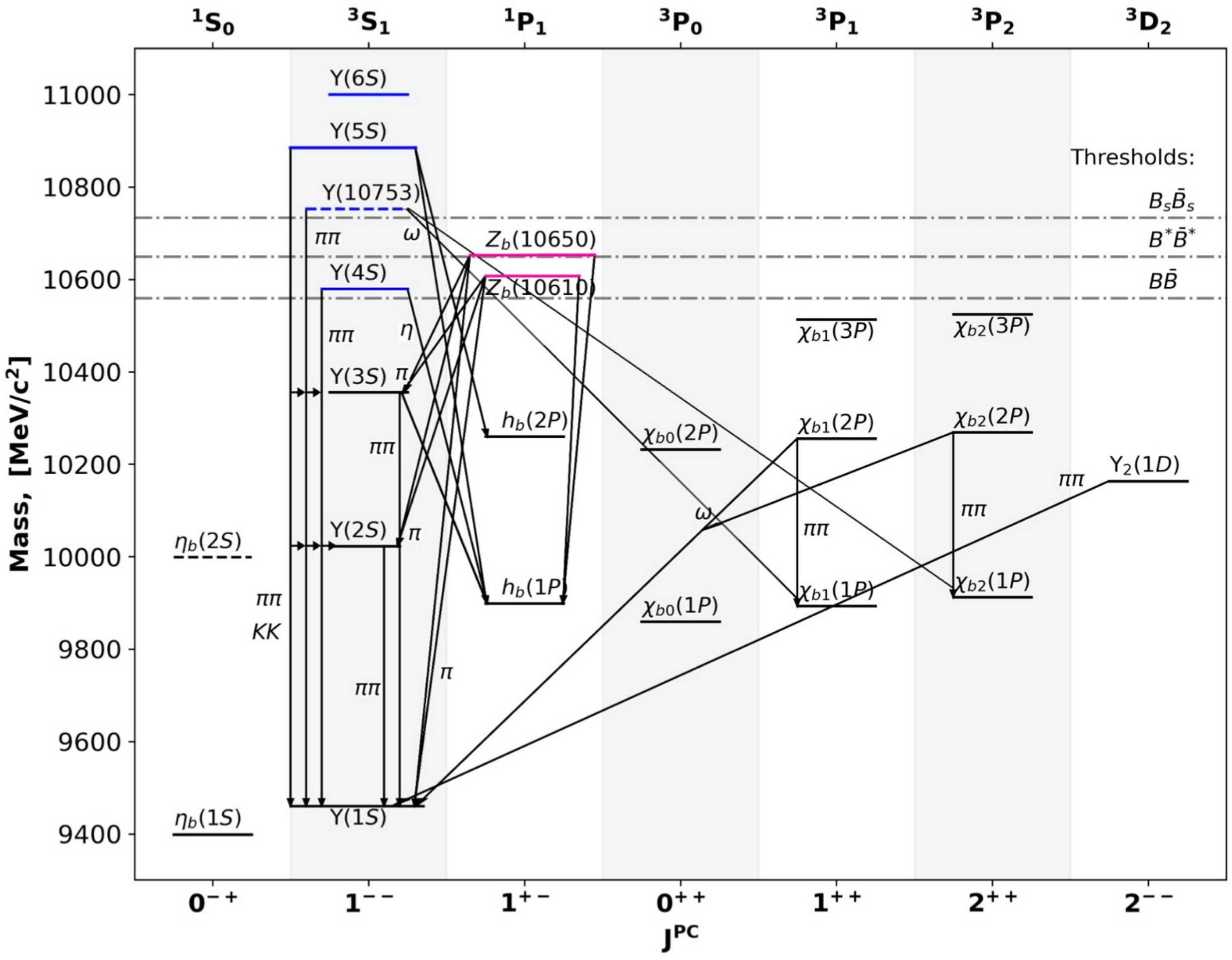
Bottomonium

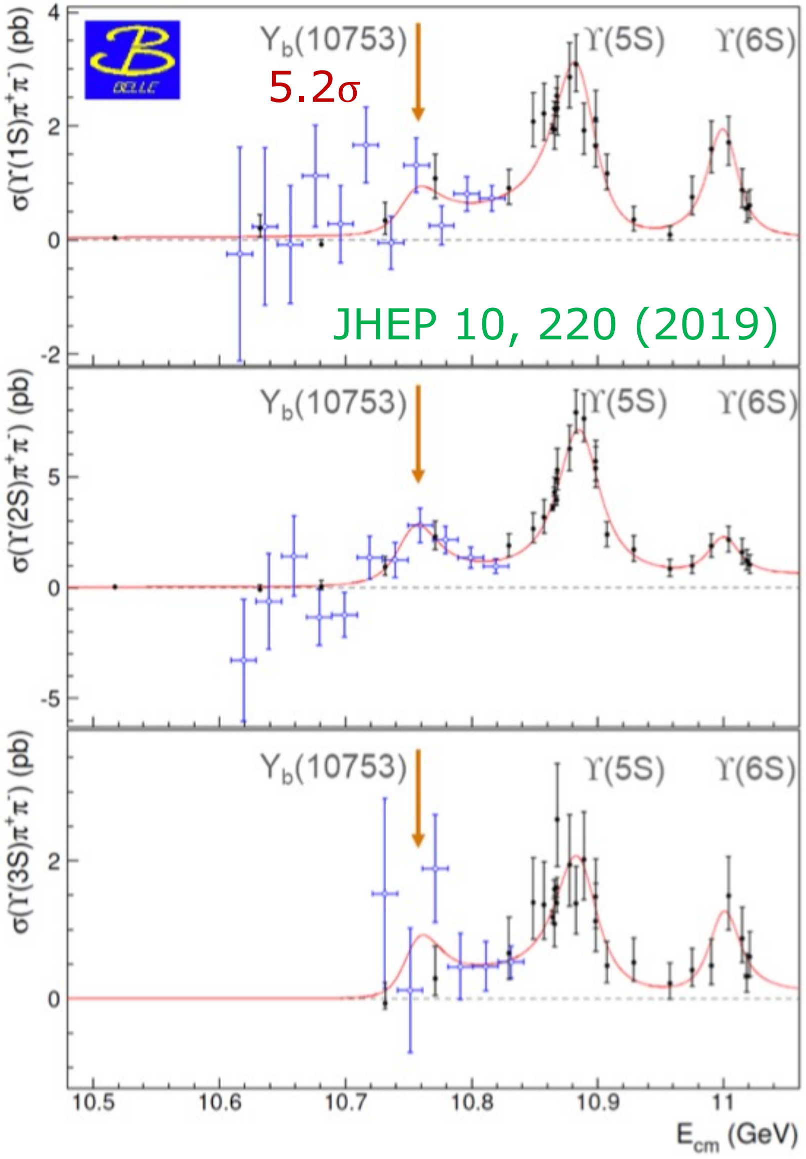


- Below $B\bar{B}$ thresholds – bottomonia are well described by the potential models.
- Above $B\bar{B}$ thresholds – bottomonia express unexpected properties:

- Two charged Z_b^+ states are observed ($B^{(*)}\bar{B}^*$ molecular?)
- Hadronic transitions are strongly enhanced (OZI rule violation);
- η transitions are not suppressed compare to $\pi^+\pi^-$ transitions (heavy quark spin-symmetry violation);

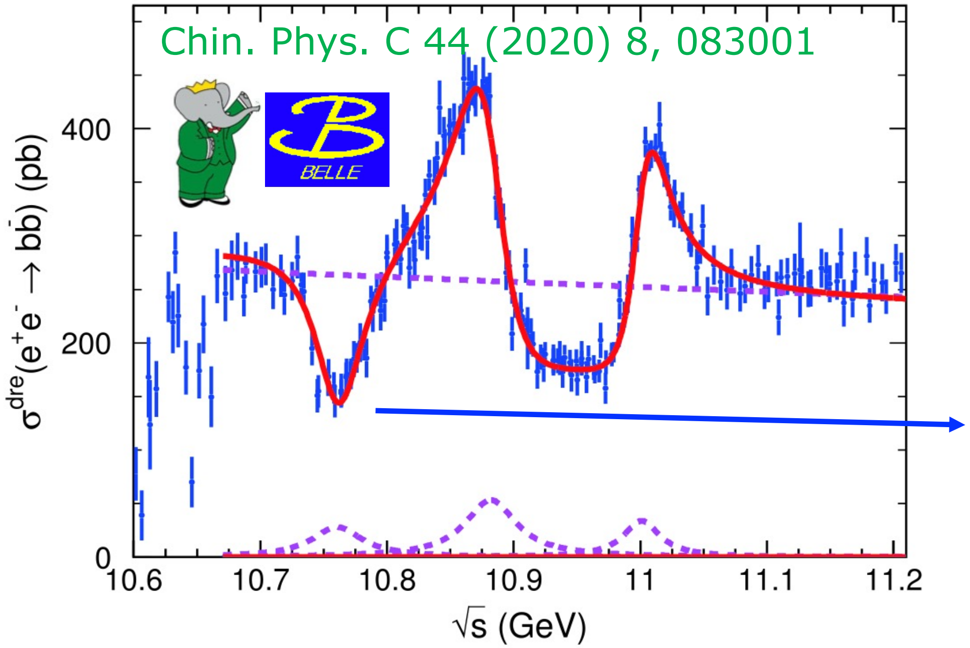
Conventional bottomonium (pure $b\bar{b}$ states)
Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)
Exotic charged states (Z_b^+)

Discovery of $\Upsilon(10753)$



- Belle: several ~1fb^{-1} scan points below $\Upsilon(5S)$
- New structure observed in $\pi^+\pi^-\Upsilon(nS)$ transitions

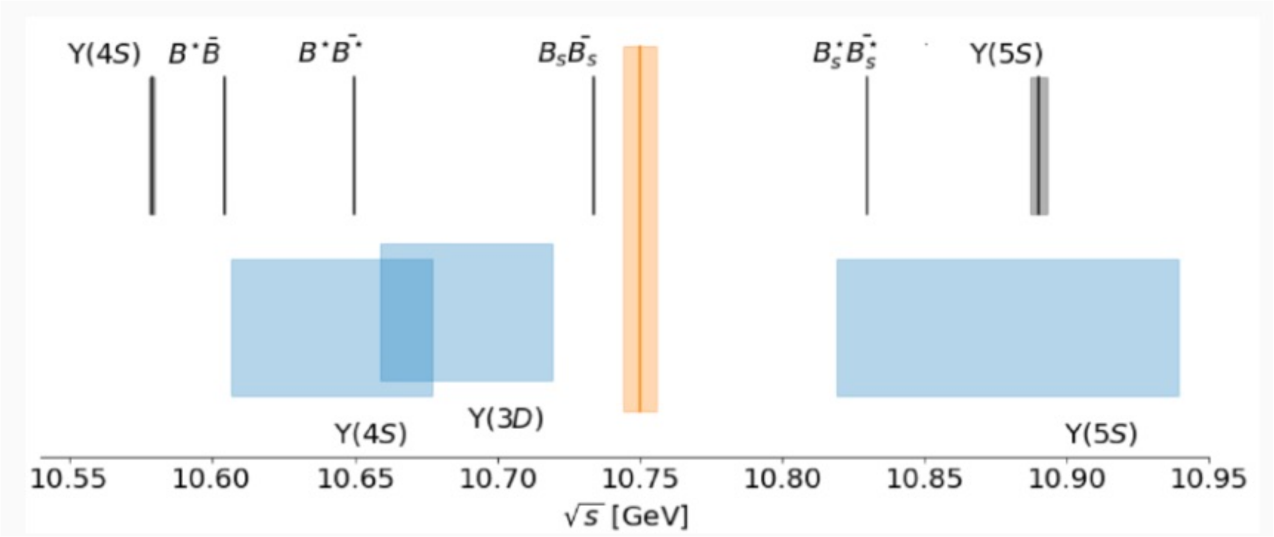
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$	$23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$	$35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$



A dip at 10.75 GeV may correspond to $\Upsilon(10753)$.

Theoretical interpretations

Godfrey and Moats, PRD 92, 054034 (2015)



- Mass does not match Υ(3D) theoretical predictions, and D-wave states are not seen in e^+e^- collisions.
- Υ(4S) - Υ(3D) mixing can be enhanced due to hadron loops.

❑ Conventional bottomonium

Phys. Rev. D 105, 074007 (2022)
Phys. Rev. D 104, 034036 (2021)
Eur. Phys. J. C 80, 59 (2020)
Phys. Rev. D 101, 014020 (2020)
Phys. Rev. D 102, 014036 (2020)
Eur. Phys. J. Plus 137, 357 (2022)
Phys. Rev. D 105, 114041 (2022)
Phys. Lett. B 803, 135340 (2020)
Phys. Rev. D 106, 094013 (2022)
Prog. Part. Nucl. Phys. 117, 103845 (2021)

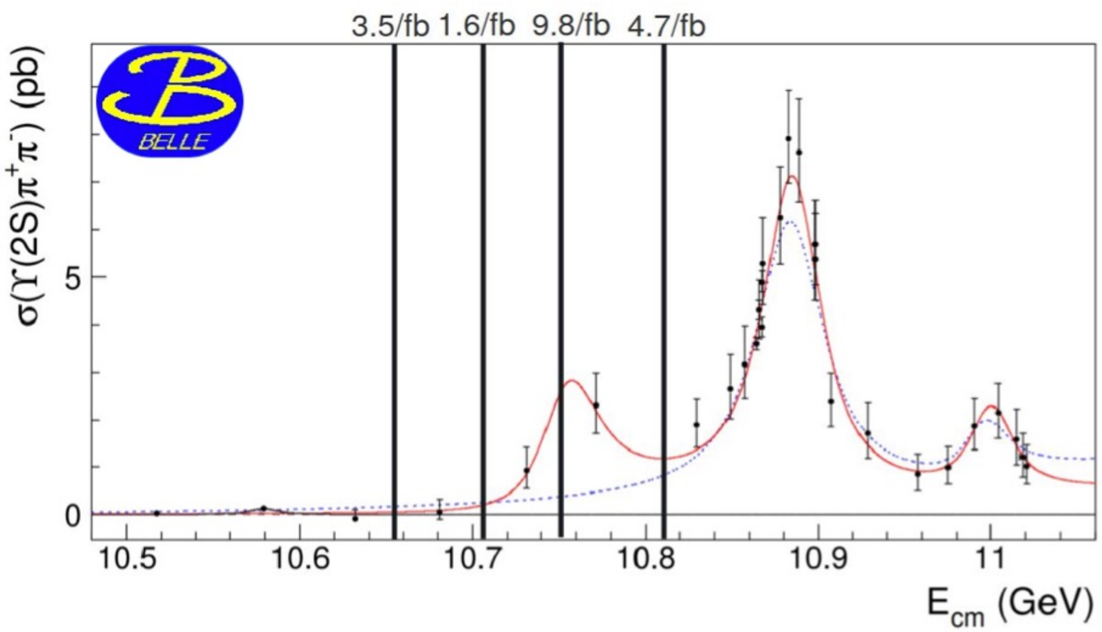
❑ Hybrid

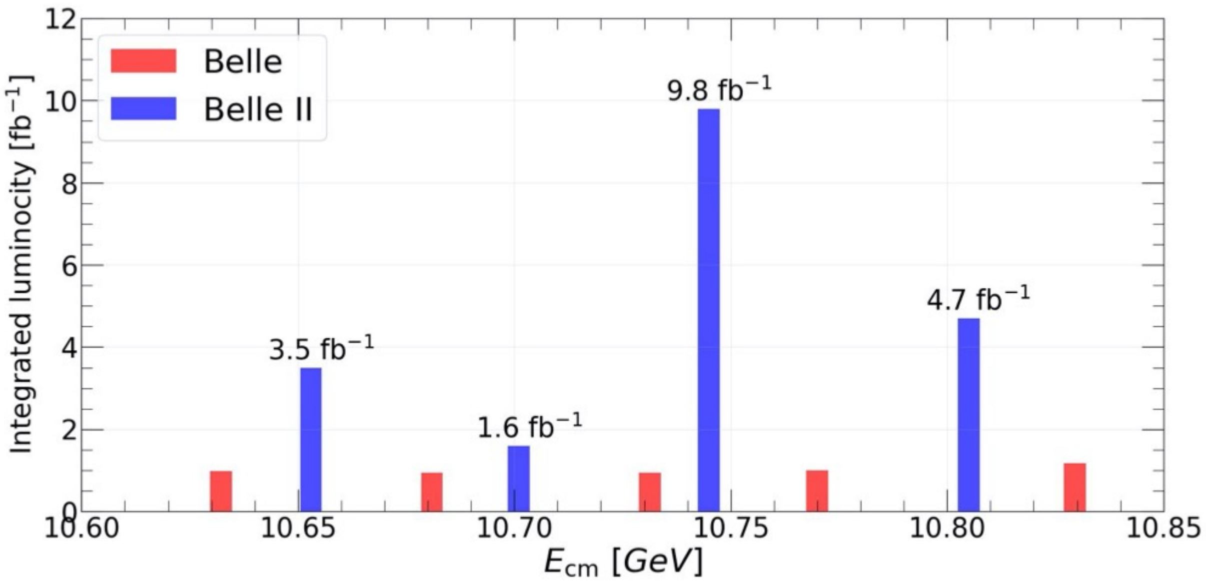
Phys. Rev. D 104, 034019 (2021)
Phys. Rept. 873, 1 (2020)

❑ Tetraquark

Phys. Lett. B 802, 135217 (2020)
Phys. Rev. D 103, 074507 (2021)
Phys. Rev. D 107, 094515 (2023)
Chin. Phys. C 43, 123102 (2019)

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.

For the details on the SuperKEKB and Belle II detectors, please see Renu's report "Recent highlights from Belle II".

Three Belle II results will be presented:

1. $e^+e^- \to \omega\chi_{bJ}$ and $X_b \to \omega\Upsilon(1S)$
2. $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$
3. $e^+e^- \to \omega\eta_b(1S)$ and $e^+e^- \to \omega\chi_{b0}(1P)$

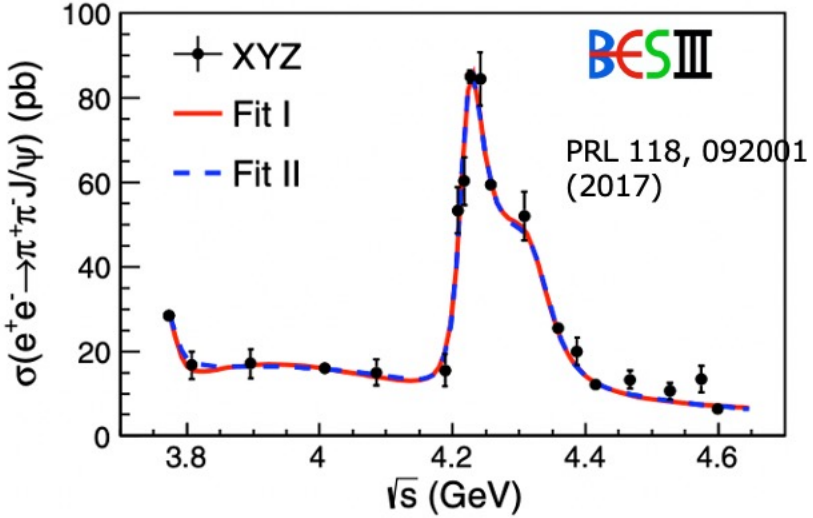
Motivation to search for $\Upsilon(10753) \to \omega\chi_{bJ}$

Theory: A branching fraction of 10^{-3} for $\Upsilon(10753) \to \omega\chi_{bJ}$ and $\Upsilon(10753) \to \pi^+\pi^-\Upsilon(nS)$ assuming Υ(4S) - Υ(3D) mixing state for Υ(10753) [PRD 105, 074007 (2022), PRD 104, 034036 (2021)].

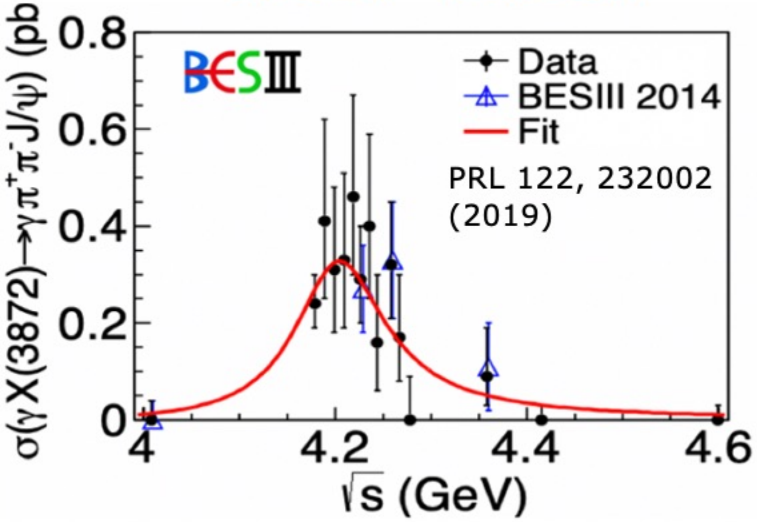
Charmonium sector:

- Two close peaks observed in the cross sections for $e^+e^- \to \pi^+\pi^- J/\psi$ by BESIII and $e^+e^- \to \pi^+\pi^-\Upsilon(nS)$ by Belle, respectively, may suggest similar nature.
- Y(4220) $\to \gamma X(3872)$ and $\omega\chi_{c0}$ observed by BESIII.
- So we expect the $\Upsilon(10753) \to \gamma X_b$ and $\omega\chi_{bJ}$.

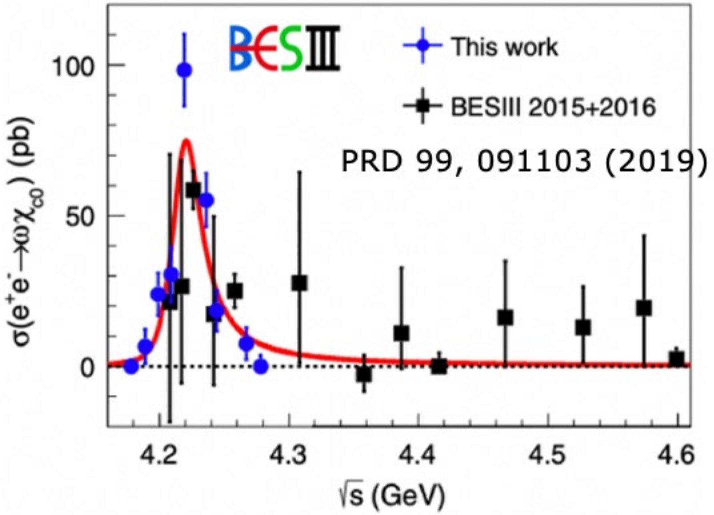
Y(4220)/Y(4320) $\to \pi^+\pi^- J/\psi$



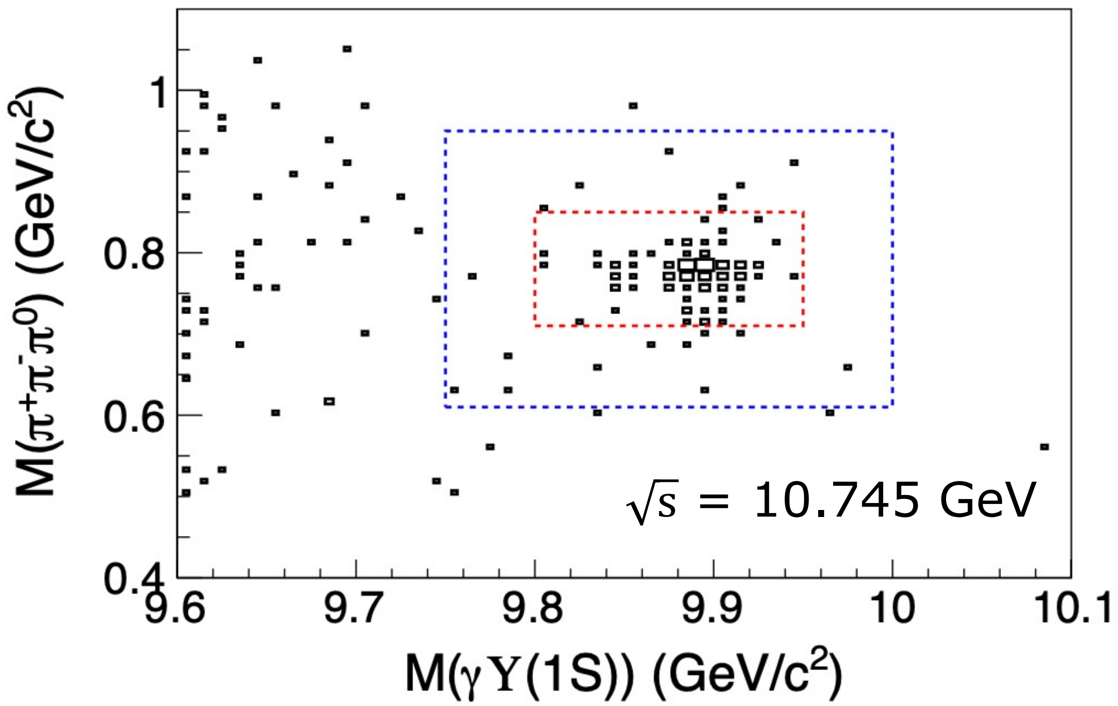
Y(4220) $\to \gamma X(3872)$

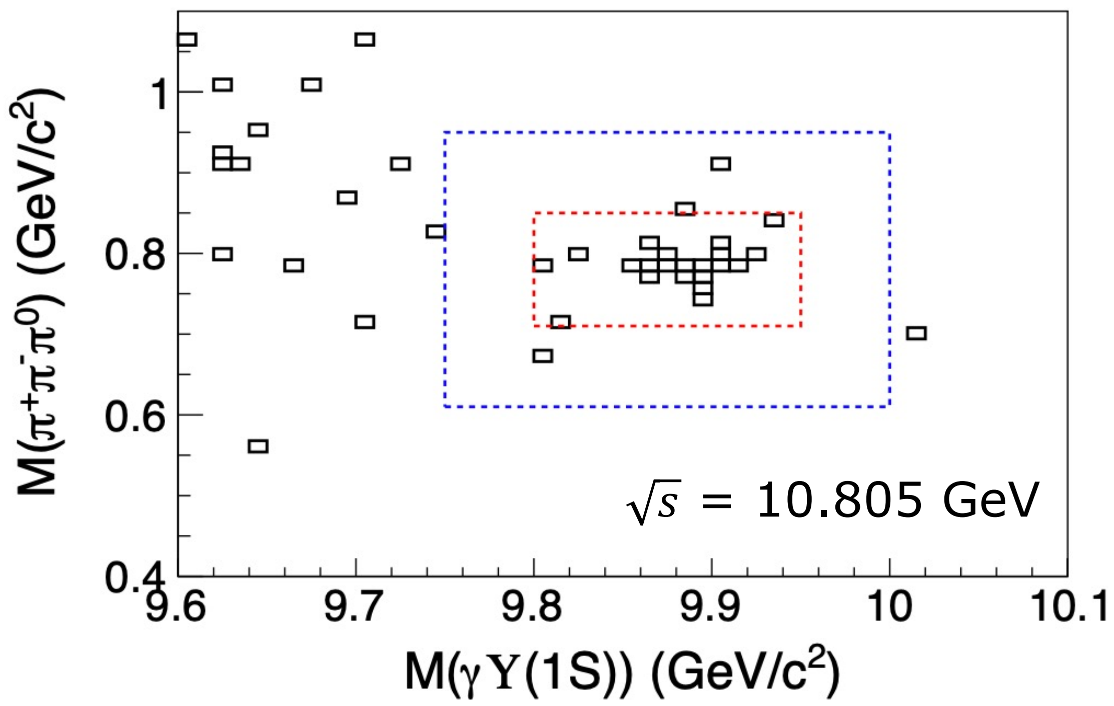


Y(4220) $\to \omega\chi_{c0}$



Mass distributions



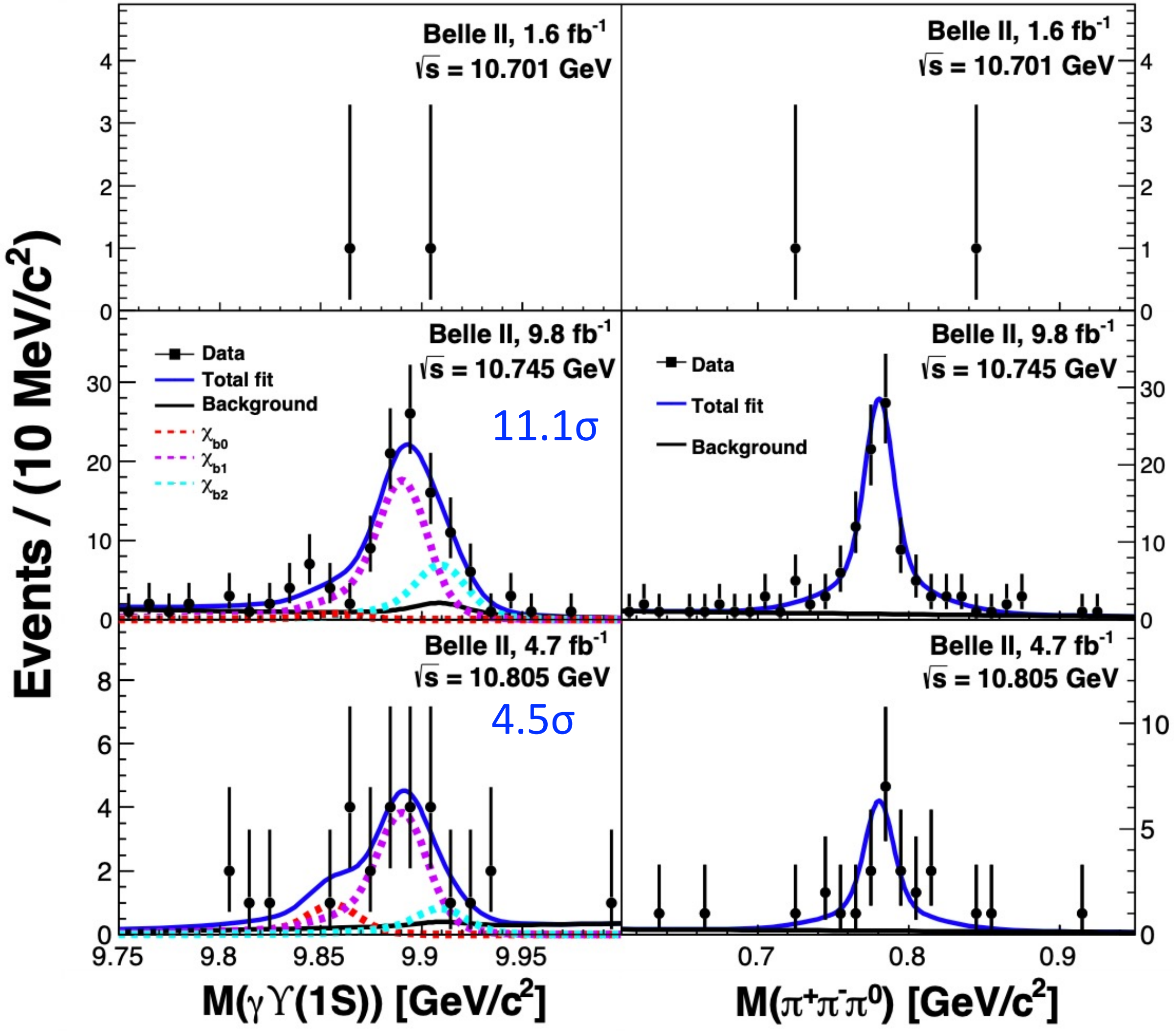


- Red boxes contains 95% of signals.
- Blue boxes show the fit ranges.

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

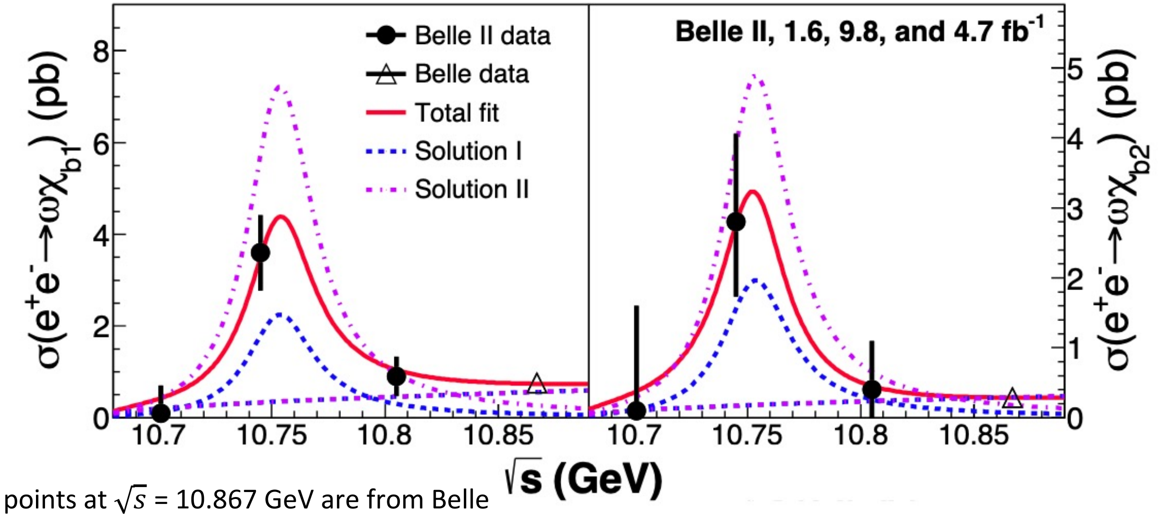
PRL 130, 091902 (2023)

Two dimensional unbinned maximum likelihood fits to the $M(\gamma\Upsilon(1S))$ and $M(\pi^+\pi^-\pi^0)$ distributions.



Channel	$\sqrt{s}$ (GeV)	N^{sig}	$\sigma_{Born}^{(UL)}$ (pb)
$\omega\chi_{b1}$	10.745	$68.9^{+13.7}_{-13.5}$	$3.6^{+0.7}_{-0.7} \pm 0.4$
$\omega\chi_{b2}$		$27.6^{+11.6}_{-10.0}$	$2.8^{+1.2}_{-1.0} \pm 0.5$
$\omega\chi_{b1}$	10.805	$15.0^{+6.8}_{-6.2}$	1.6 @90% C.L.
$\omega\chi_{b2}$		$3.3^{+5.3}_{-3.8}$	1.5 @90% C.L.

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



The points at $\sqrt{s}$ = 10.867 GeV are from Belle measurements [PRL 113, 142001 (2014)].

Discussion

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

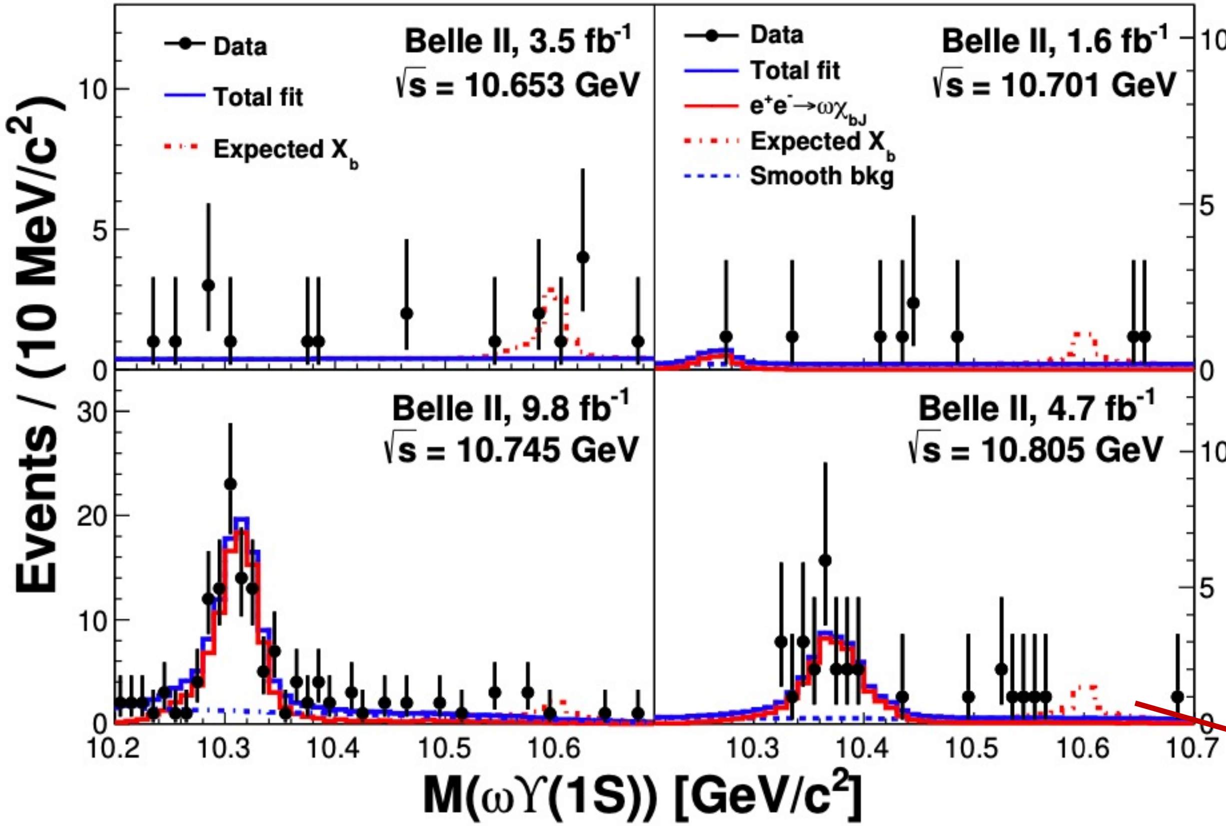
- ~ 1.5 at $\sqrt{s}$ = 10.745 GeV [PRL 130, 091902 (2023)]
- ~ 0.15 at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001 (2014)]

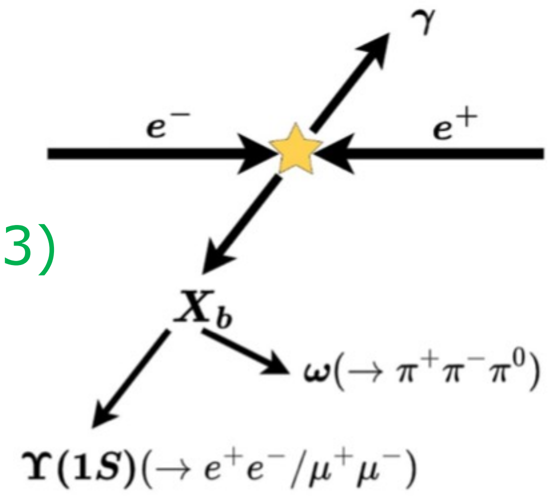
- ❑ $\Upsilon(5S)$ and $\Upsilon(10753)$ have same quantum numbers and similar masses, but the difference on the above ratio is large. This may indicate **the difference in the internal structures of these two states**.

$$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.3\pm0.6 \text{ at } \sqrt{s} = 10.745 \text{ GeV [PRL 130, 091902 (2023)]}$$

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

Search for X_b





PRL 130, 091902 (2023)

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

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)

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

- The $B^{(*)}\bar{B}^{(*)}$ are expected to be dominant decay channels for excited bottomonium-like states. Their measurements are critical for understanding these states.

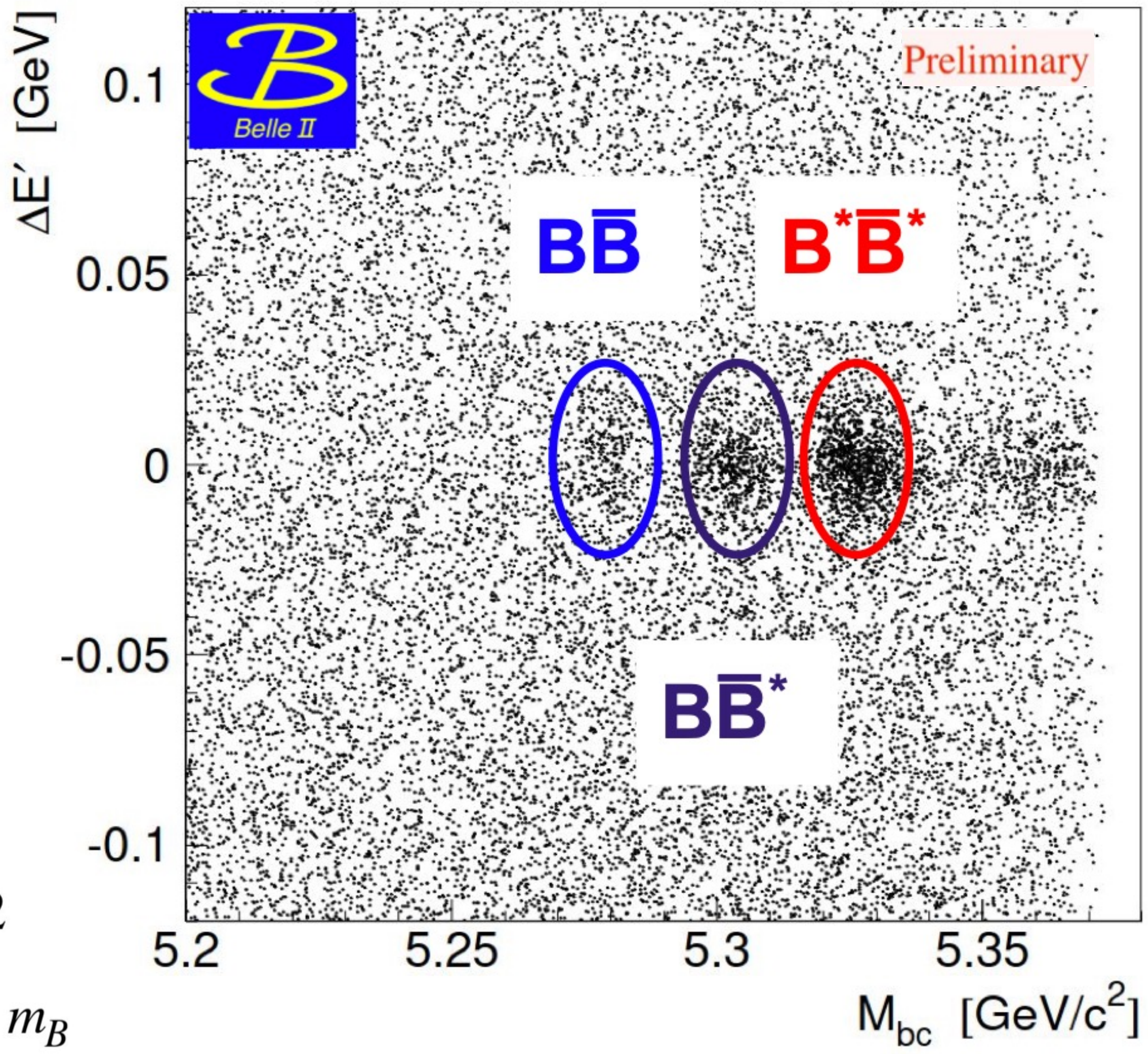
Method:

One B meson is reconstructed in hadronic channels, and signals are identified using

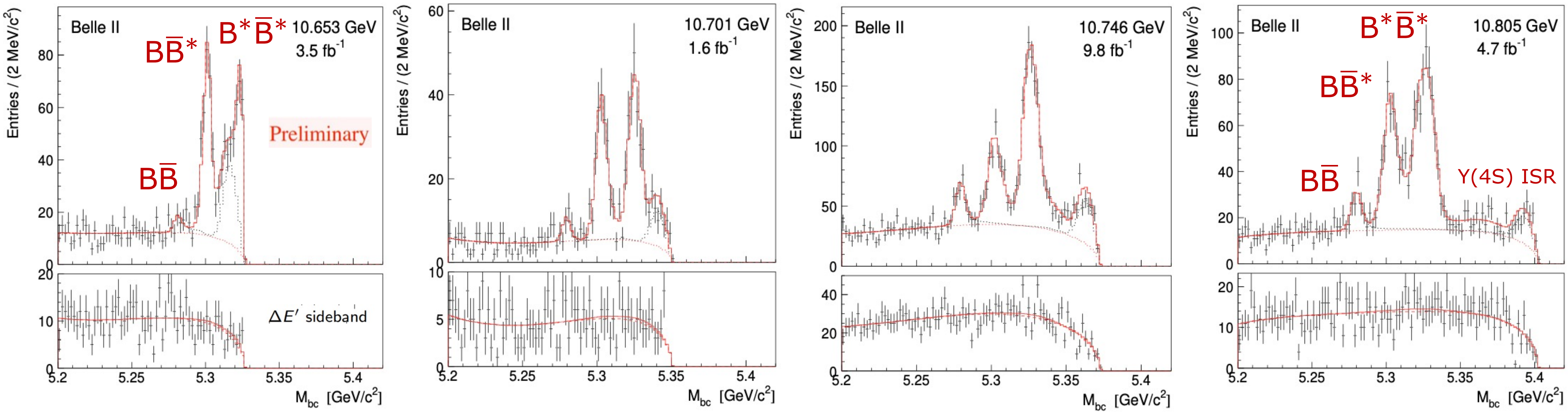
$$M_{bc} = \sqrt{(E_{cm}/2)^2 - P_B^2}$$

$$\Delta E = E_B - E_{cm}/2$$

$$\Delta E' = \Delta E + M_{bc} - m_B$$

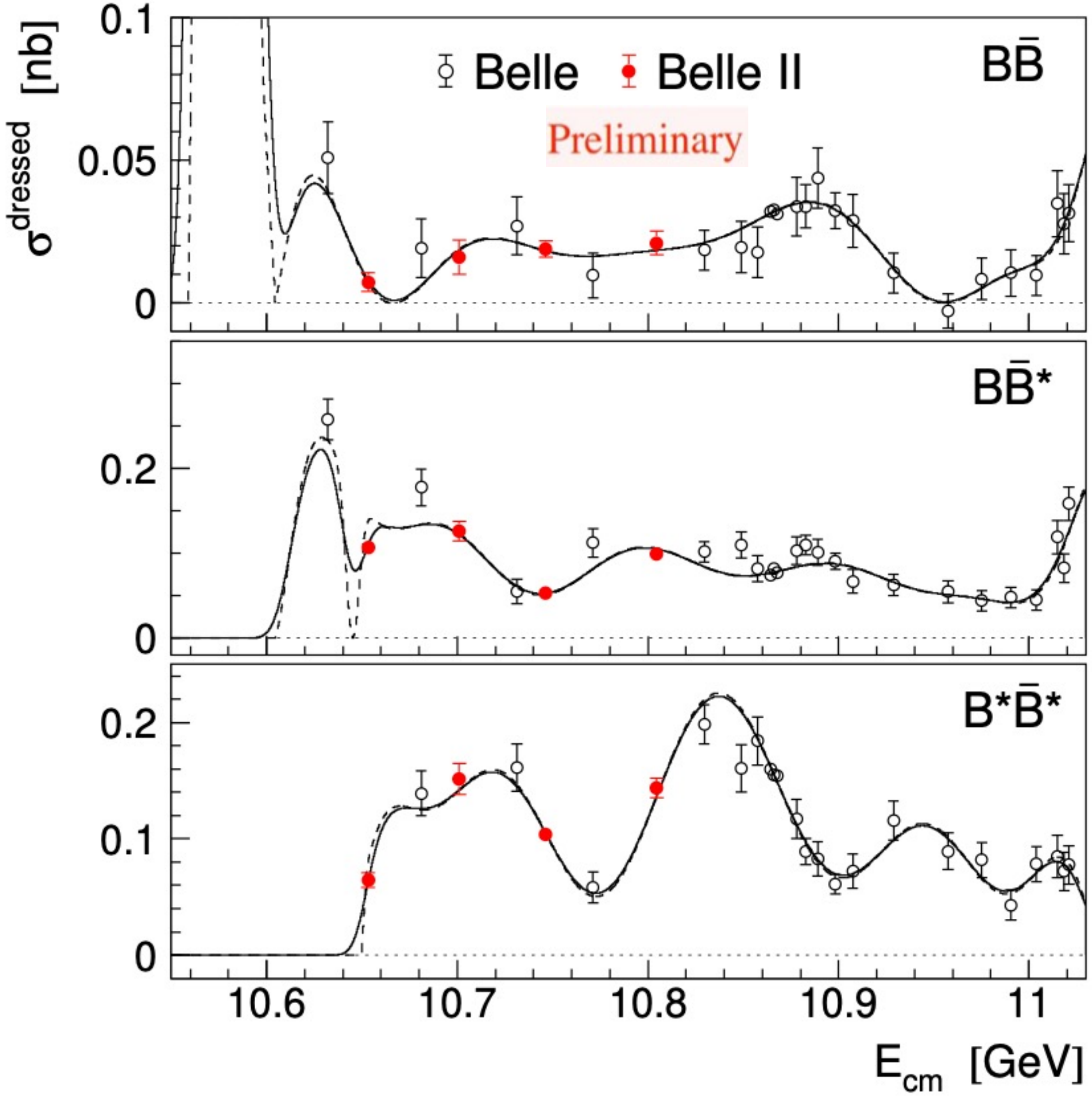


M_{bc} fit at scan energies



- $e^+e^- \to B\bar{B}$, $B\bar{B}^*$ 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 due to threshold effect

Energy dependence of the cross sections

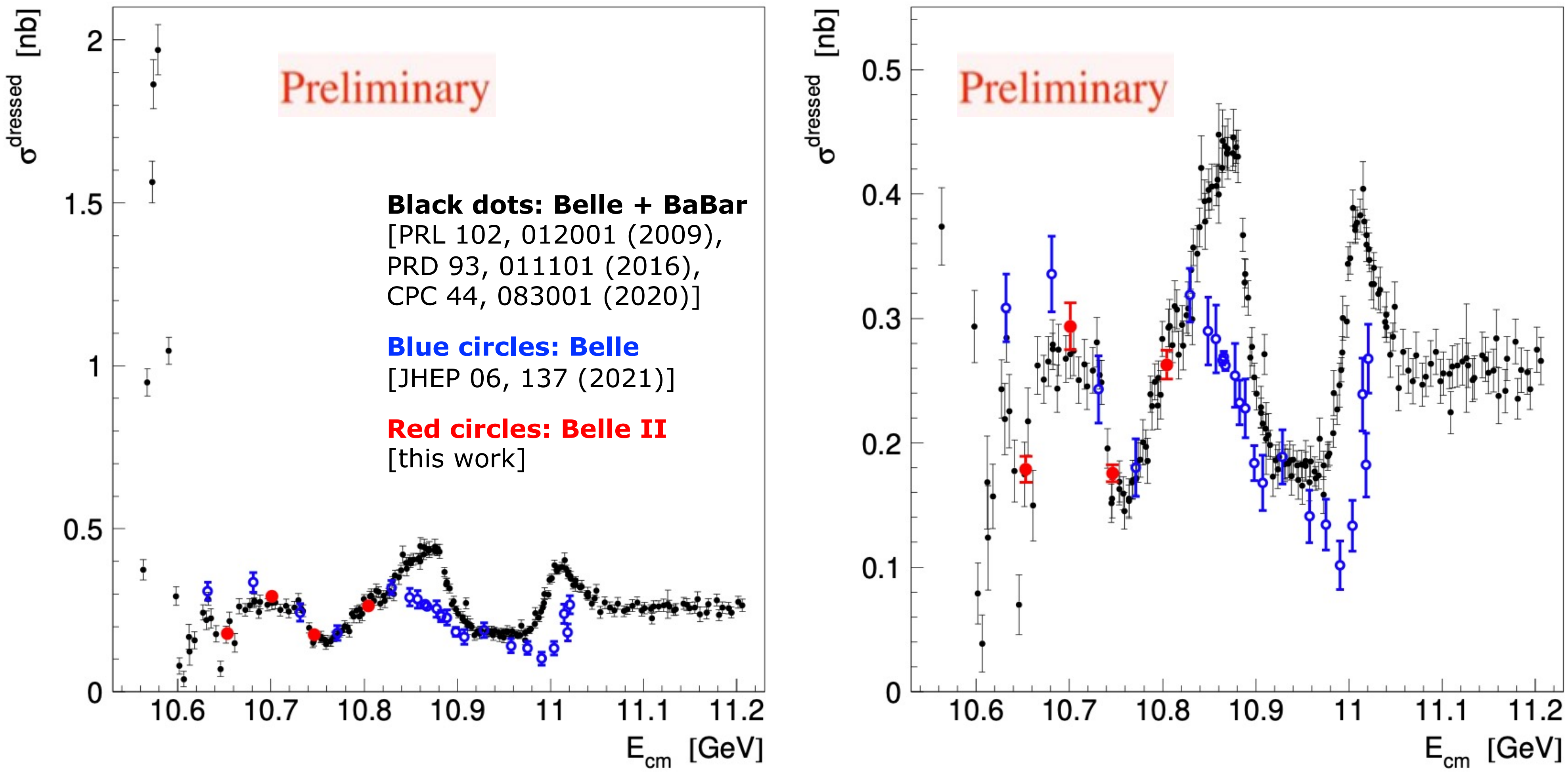


Solid curve – combined Belle + Belle II data fit
Dashed curve – Belle data fit only

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 $e^+e^- \to B^*\bar{B}^* \to B\bar{B}^*$
- Inelastic channels $[\pi^+\pi^-\Upsilon(nS)$ and $h_b(1P)\eta]$ could also be enhanced (PRD 87, 094033 (2013))

Comparison of $\sigma_{b\bar{b}}$ and $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$



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

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

- Tetraquark (diquark-antidiquark) interpretation of this state predicts enhancement of $\Upsilon(10753)\to\omega\eta_b(1S)$ transition [Chin. Phys. C 43, no.12, 123102 (2019)].

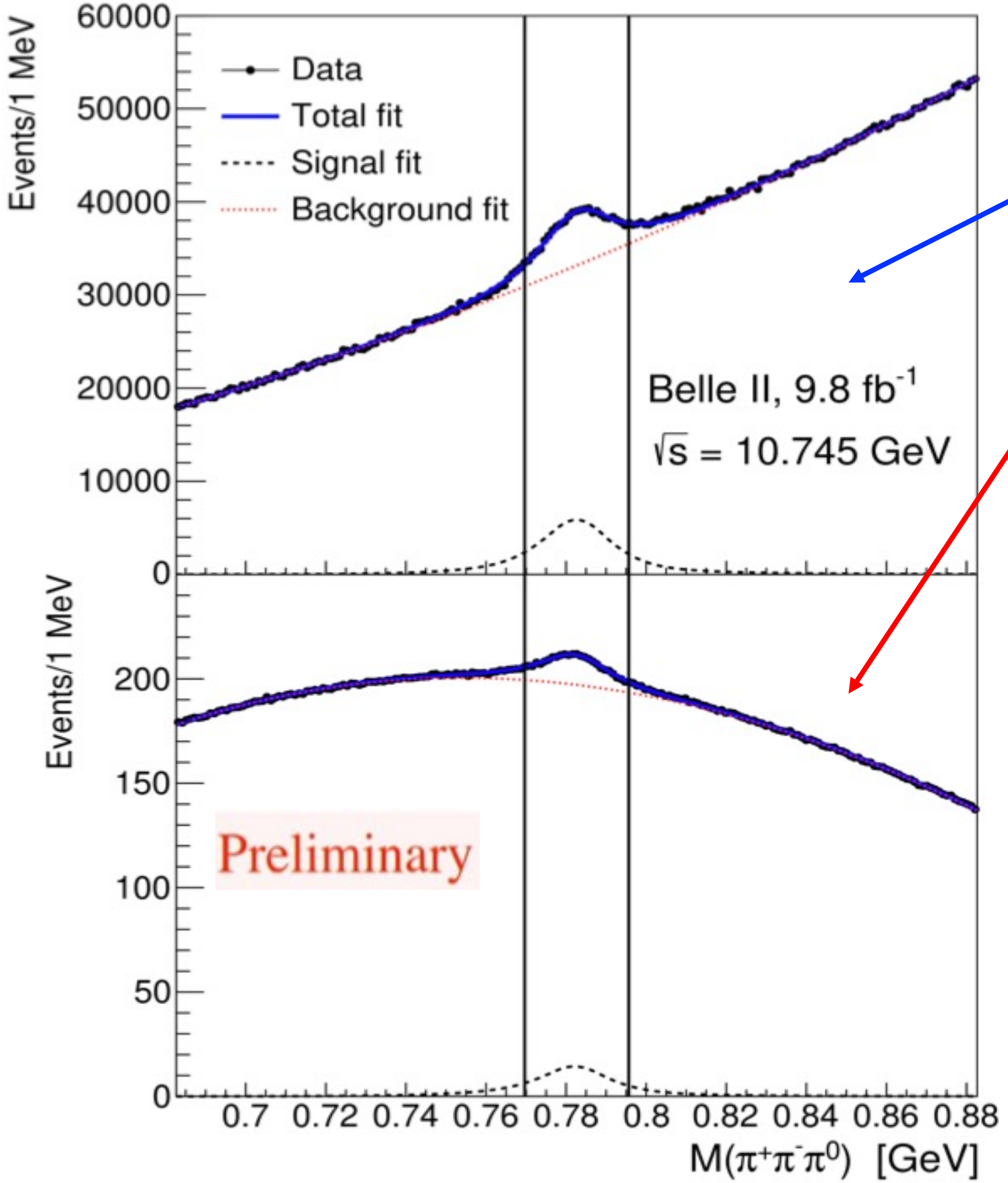
$$\frac{\Gamma(\eta_b\,\omega)}{\Gamma(\Upsilon\,\pi^+\pi^-)}\sim 30$$

- The $e^+e^-\to\omega\chi_{bJ}(1P)$ $(J = 1, 2)$ was found to be enhanced at $\sqrt{s} = 10.745$ GeV (PRL 130, 091902 (2023)). The $e^+e^-\to\omega\chi_{b0}(1P)$ transition was not observed due to low $\mathcal{B}[\chi_{b0}(1P)\to\gamma\Upsilon(1S)] = (1.94\pm0.27)\%$.

- We reconstruct only $\omega\to\pi^+\pi^-\pi^0$ and use its recoil mass to identify the signal.

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

The invariant mass of $\pi^+\pi^-\pi^0$

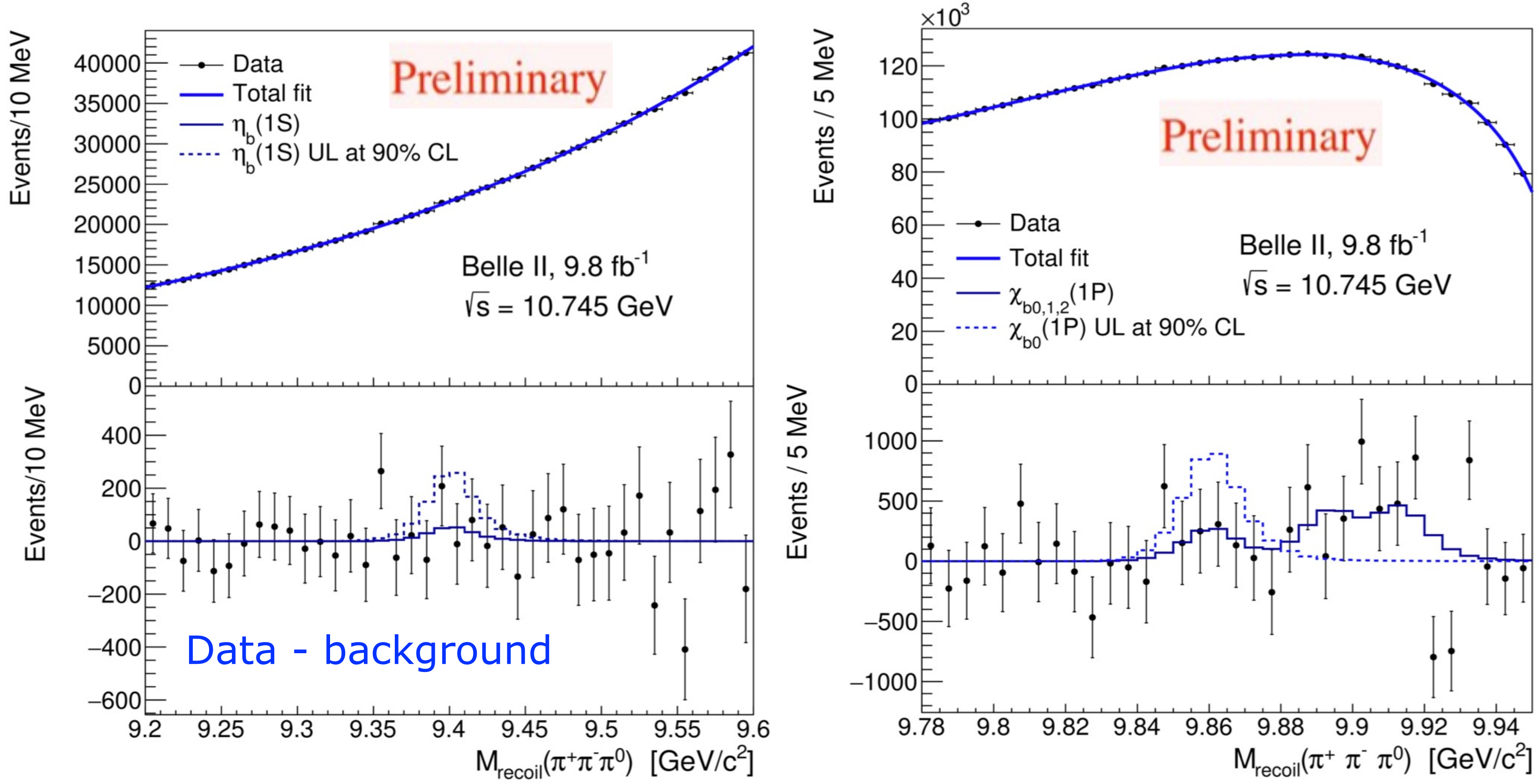


$9.2 < M_{rec}(\pi^+\pi^-\pi^0) < 9.6$ GeV/c² ($\eta_b(1S)$ included)

$9.78 < M_{rec}(\pi^+\pi^-\pi^0) < 9.95$ GeV/c² ($\chi_{bJ}(1P)$ included)

- A double-sided Crystal Ball + a Gaussian for ω signal
- 2nd or 3rd order Chebyshev polynomials for backgrounds
- The purity of the ω-meson signal: 12.9% and 5.3%

The recoil mass spectra of $\pi^+\pi^-\pi^0$



- The polynomial orders (3rd for $\eta_b(1S)$ and 4th for $\chi_{b0}(1P)$) are chosen with the maximum p-values for the fits.
- The yields for $\chi_{b1}(1P)$ and $\chi_{b2}(1P)$ are fixed [PRL 130, 091902 (2023)].
- No clear $\eta_b(1S)$ and $\chi_{b0}(1P)$ signals are observed.

Channel	$e^+e^- \to \eta_b(1S)\omega$	$e^+e^- \to \chi_{b0}(1P)\omega$
Yield	$(0.23 \pm 0.49 \pm 0.25) \cdot 10^3$	$(1.2 \pm 1.4 \pm 0.9) \cdot 10^3$

Born cross sections

$$\sigma_B[e^+e^- \to X\omega] = \frac{N \cdot |1-\Pi|^2}{\varepsilon \cdot \mathcal{L} \cdot (1+\delta_{ISR}) \cdot \mathcal{B}_{int}}$$

Preliminary

Channel	$e^+e^- \to \eta_b(1S)\omega$	$e^+e^- \to \chi_{b0}(1P)\omega$
Yield (10^3)	$0.23 \pm 0.49 \pm 0.25$	$1.2 \pm 1.4 \pm 0.9$
Born section section (pb)	$0.5 \pm 1.1 \pm 0.6$	$2.6 \pm 3.1 \pm 2.1$
Upper limit at 90% C.L. (pb)	<2.5	<8.7

Upper limits at the 90% CL are set using the Feldman-Cousins method [Phys. Rev. D 57, 3873 (1998)]

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):

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

Our results do not support the prediction within the tetraquark model that the $\Upsilon(10753) \to \omega\eta_b(1S)$ decay is enhanced.

Summary

- We are at the beginning of a long program of quarkonium physics.
- The unique scan data near $\sqrt{s}$ = 10.75 GeV at Belle II provide an opportunity to understand the nature of the $\Upsilon(10753)$ energy region, as well as the quarkonium spectroscopy.
- New decay modes of $\Upsilon(10753) \to \omega\chi_{bJ}$ are observed for the first time.
- The rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold may imply a resonance of $B^*\bar{B}^*$ or $b\bar{b}$.
- The stringent upper limit is set for the $e^+e^-\to\omega\eta_b(1S)$ at $\sqrt{s}$ = 10.745 GeV.

Thanks for your attention!