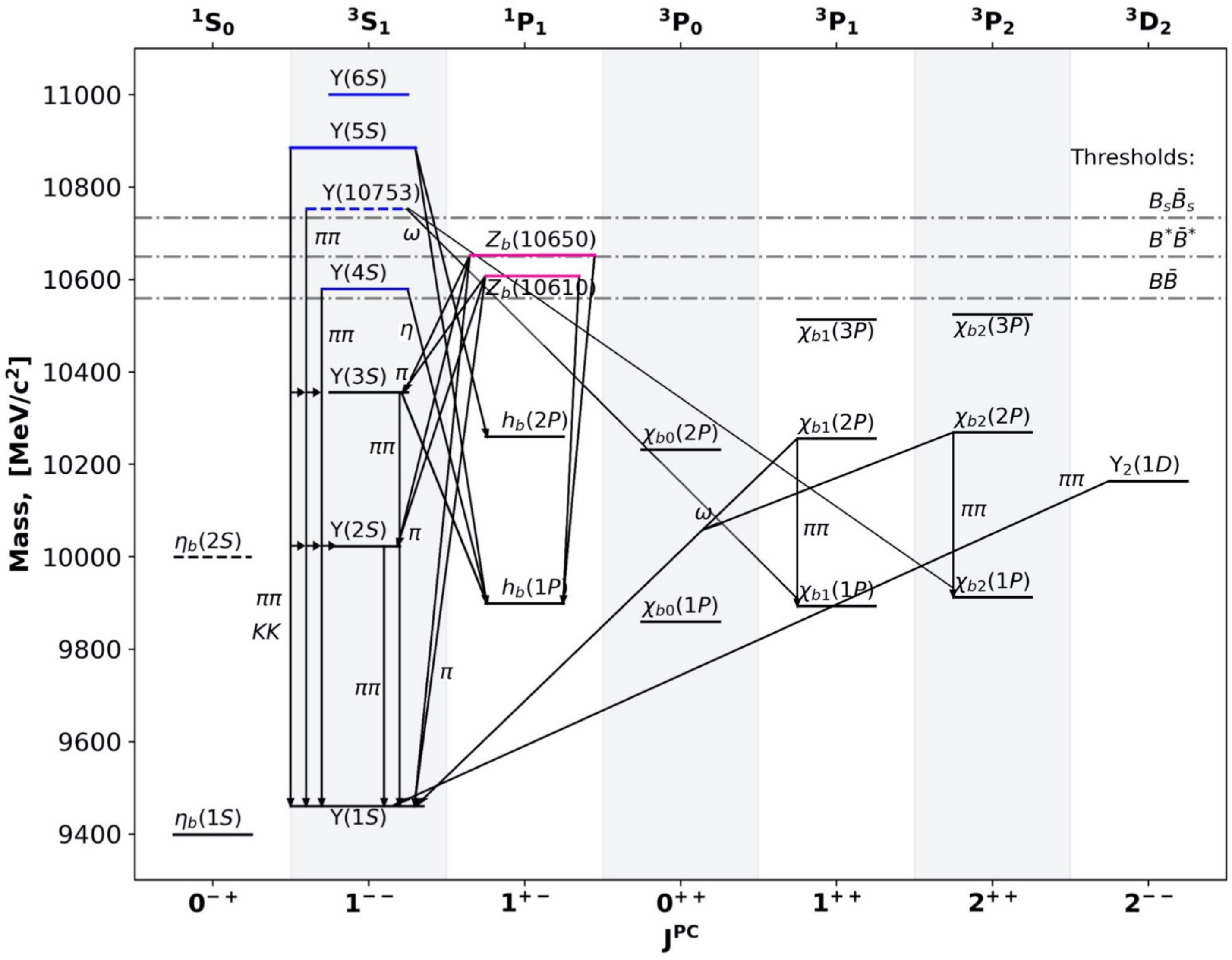
Quarkonium at Belle II

Sen Jia (Southeast University)
on behalf of the Belle II Collaboration

QCD23 26th HIGH-ENERGY PHYSICS INTERNATIONAL CONFERENCE IN QUANTUM CHROMODYNAMICS
MONTPELLIER 10 - 14 july 2023

Bottomonium

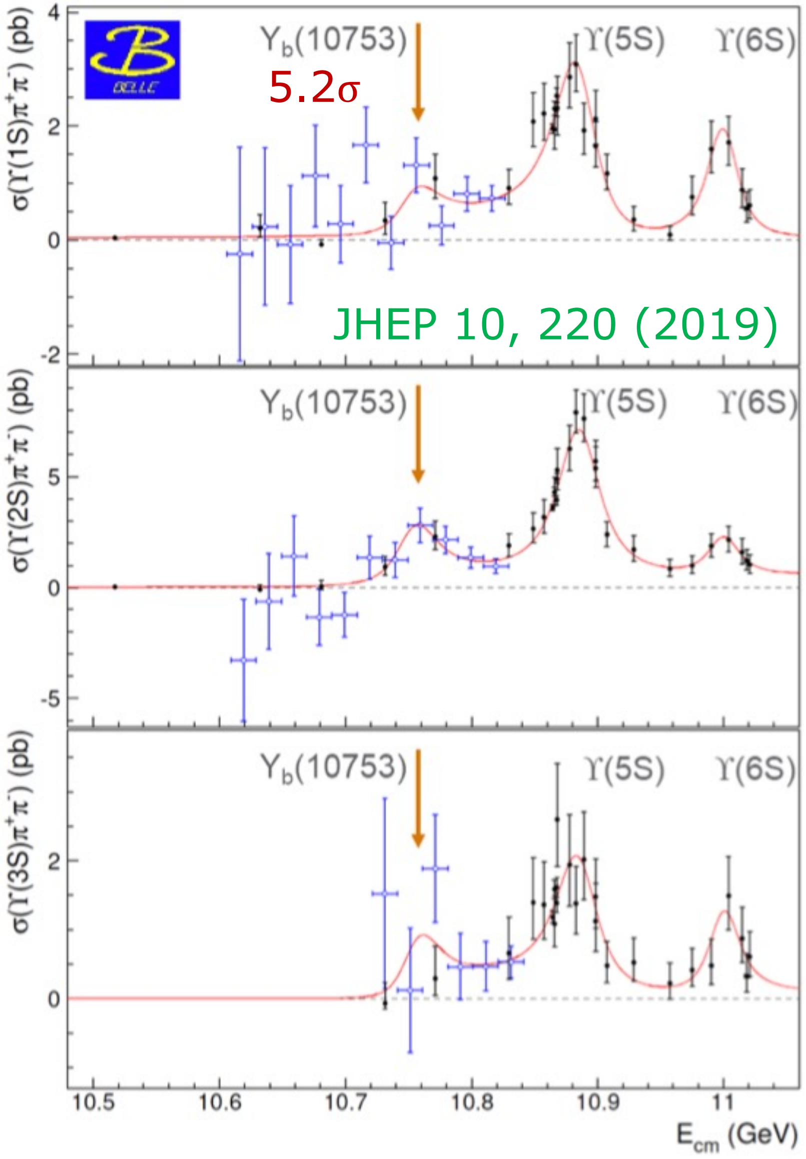


- Below $B\bar{B}$ thresholds – bottomonia are well described by the potential models.
- Above $B\bar{B}$ thresholds – bottomonia express unexpected properties:

- 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);

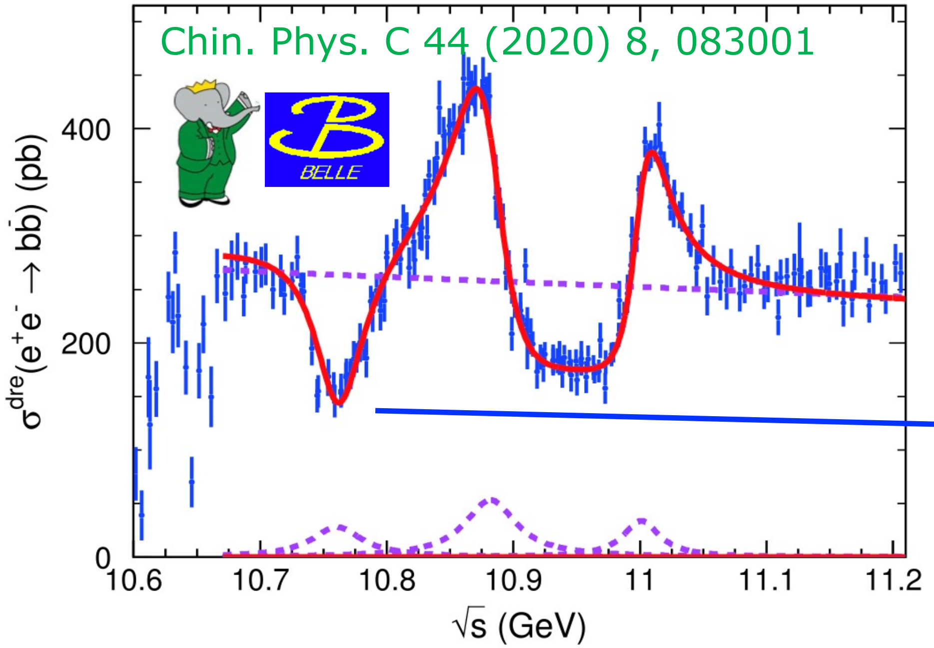
Conventional bottomonium (pure $b\bar{b}$ states)
Bottomonium-like states (mix of $b\bar{b}$ and $B\bar{B}$)
Exotic charged states (Z_b^+)

Discovery of $\Upsilon(10753)$



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

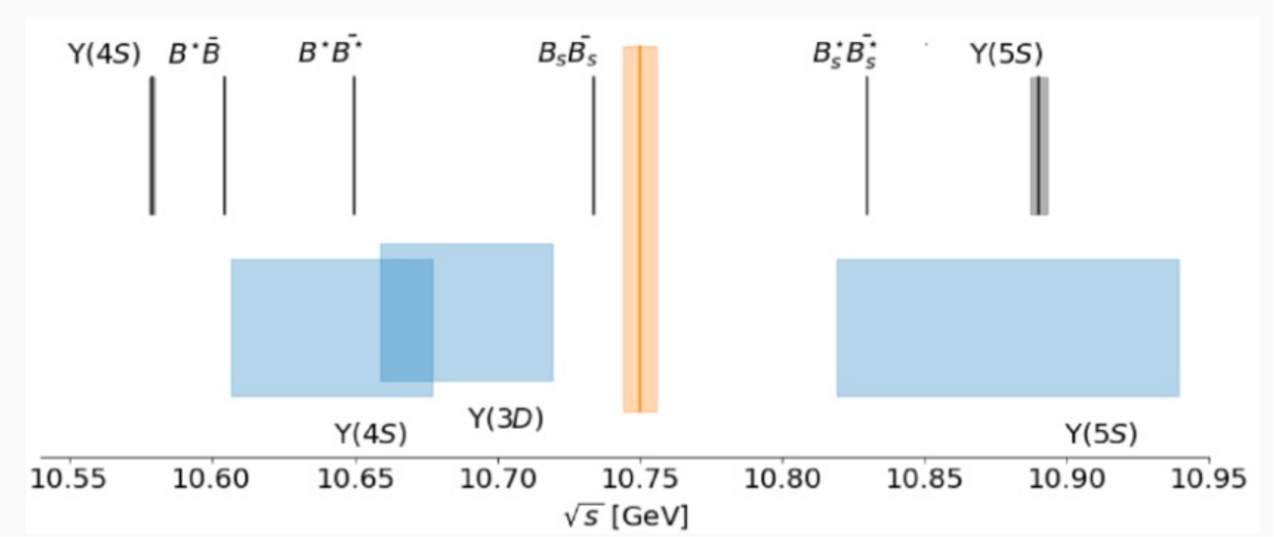
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0\,+1.0}_{-4.5\,-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5\,+0.5}_{-3.9\,-1.1}$	$23.8^{+8.0\,+0.7}_{-6.8\,-1.8}$	$35.5^{+17.6\,+3.9}_{-11.3\,-3.3}$



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

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

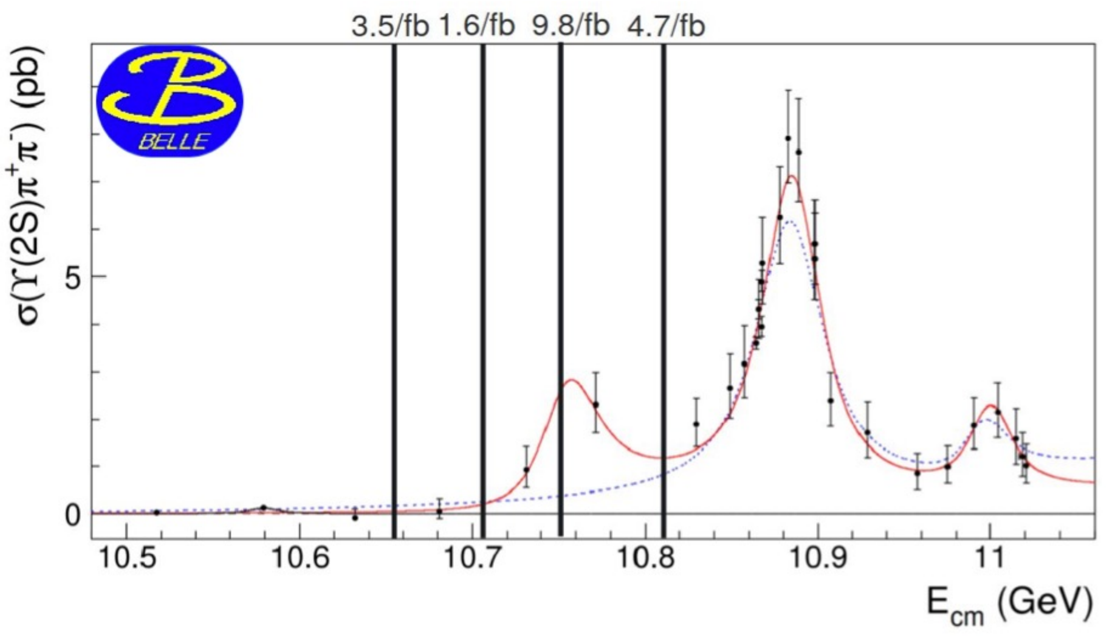
❑ Hybrid

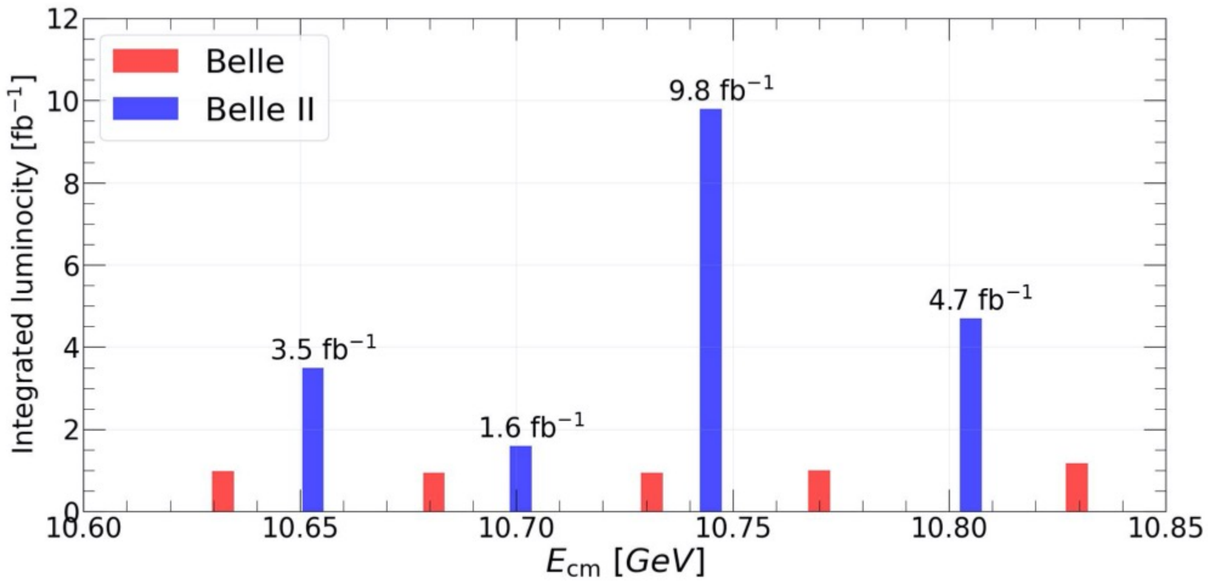
Phys. Rept. 873, 1 (2020)
Phys. Rev. D 104, 034019 (2021)

❑ Tetraquark

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

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 ϒ(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 ϒ(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 $X_b \to \omega\Upsilon(1S)$ [PRL 130, 091902 (2023)]
2. $e^+e^- \to$ $B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ [Preliminary]
3. $e^+e^- \to \omega\eta_b(1S)$ and $e^+e^- \to \omega\chi_{b0}(1P)$ [Preliminary]

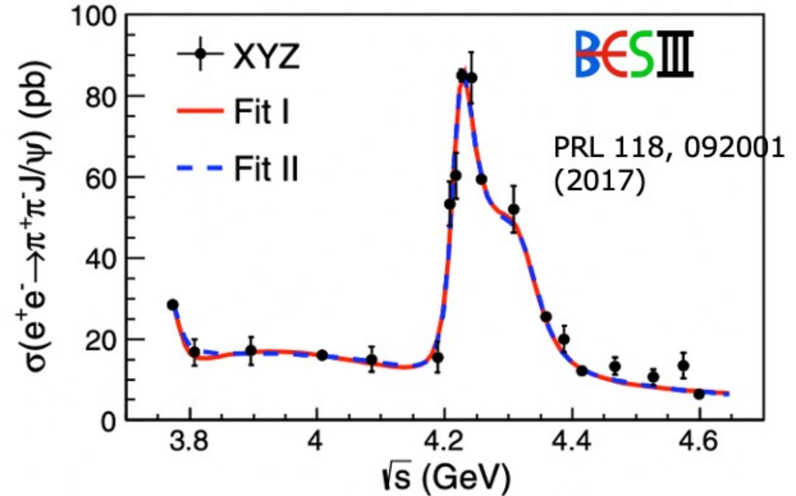
Motivation to search for $\Upsilon(10753) \to \omega\chi_{bJ}$

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

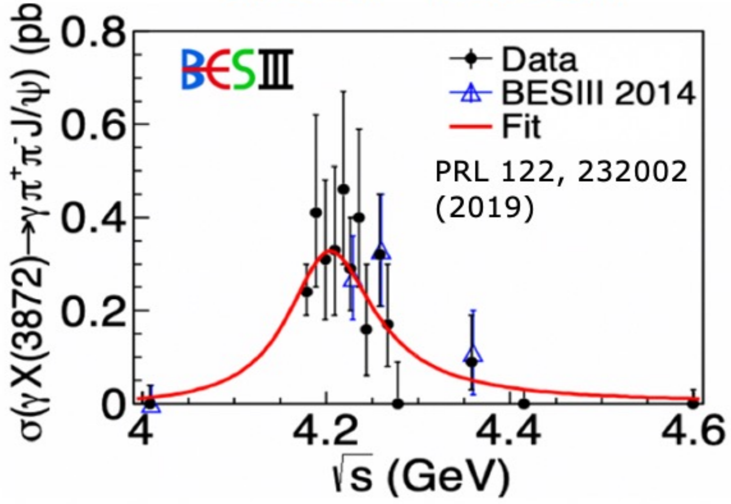
Charmonium sector:

- 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 observations of $\Upsilon(10753) \to \gamma X_b$ and $\omega\chi_{bJ}$.

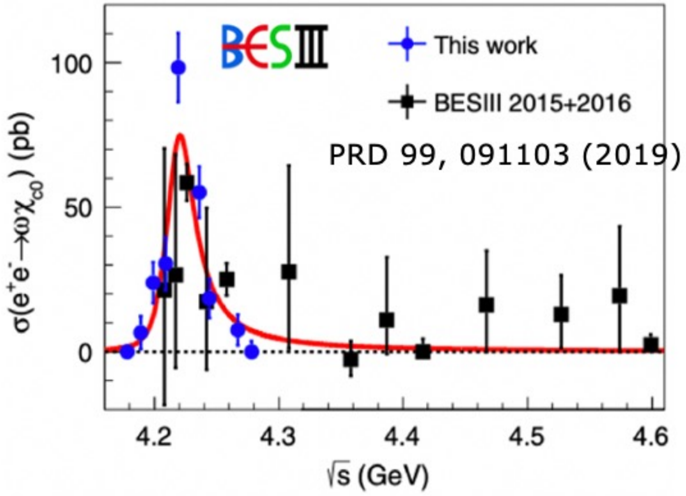
$Y(4220)/Y(4320) \to \pi^+\pi^- J/\psi$



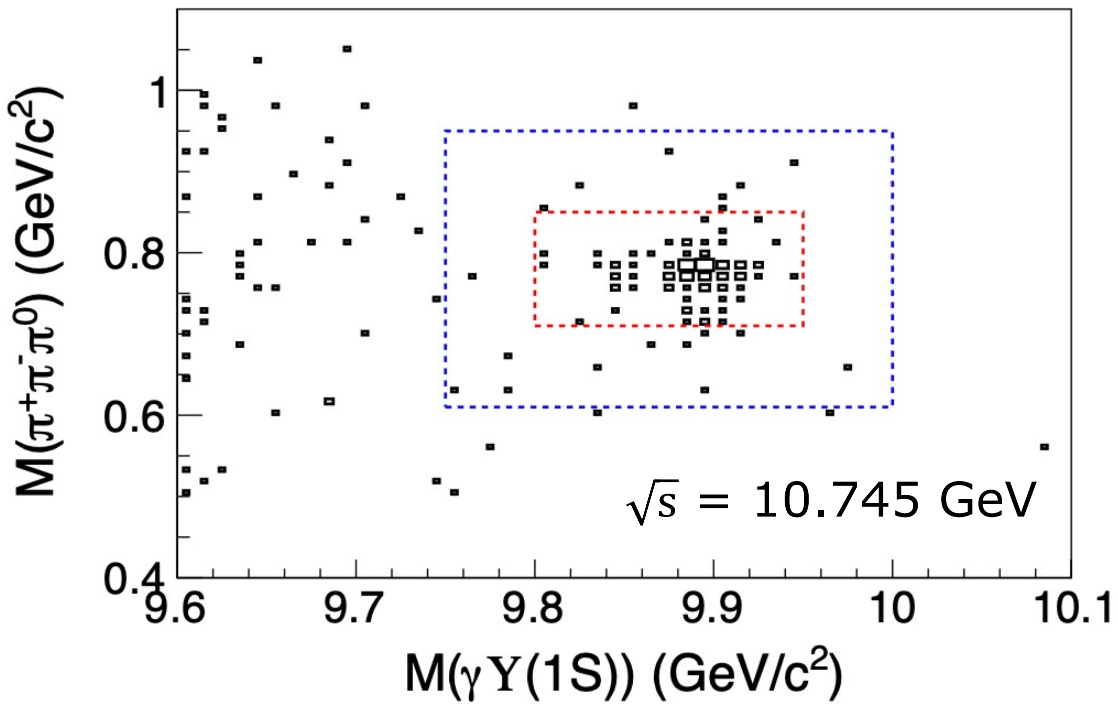
$Y(4220) \to \gamma X(3872)$

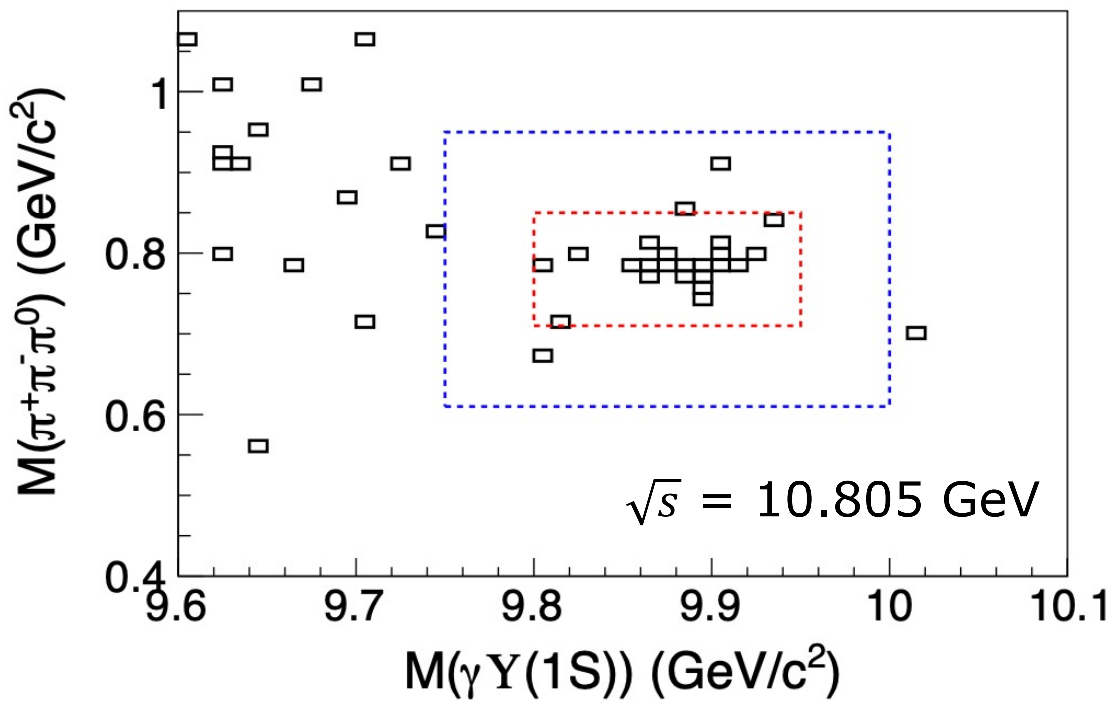


$Y(4220) \to \omega\chi_{c0}$



Mass distributions



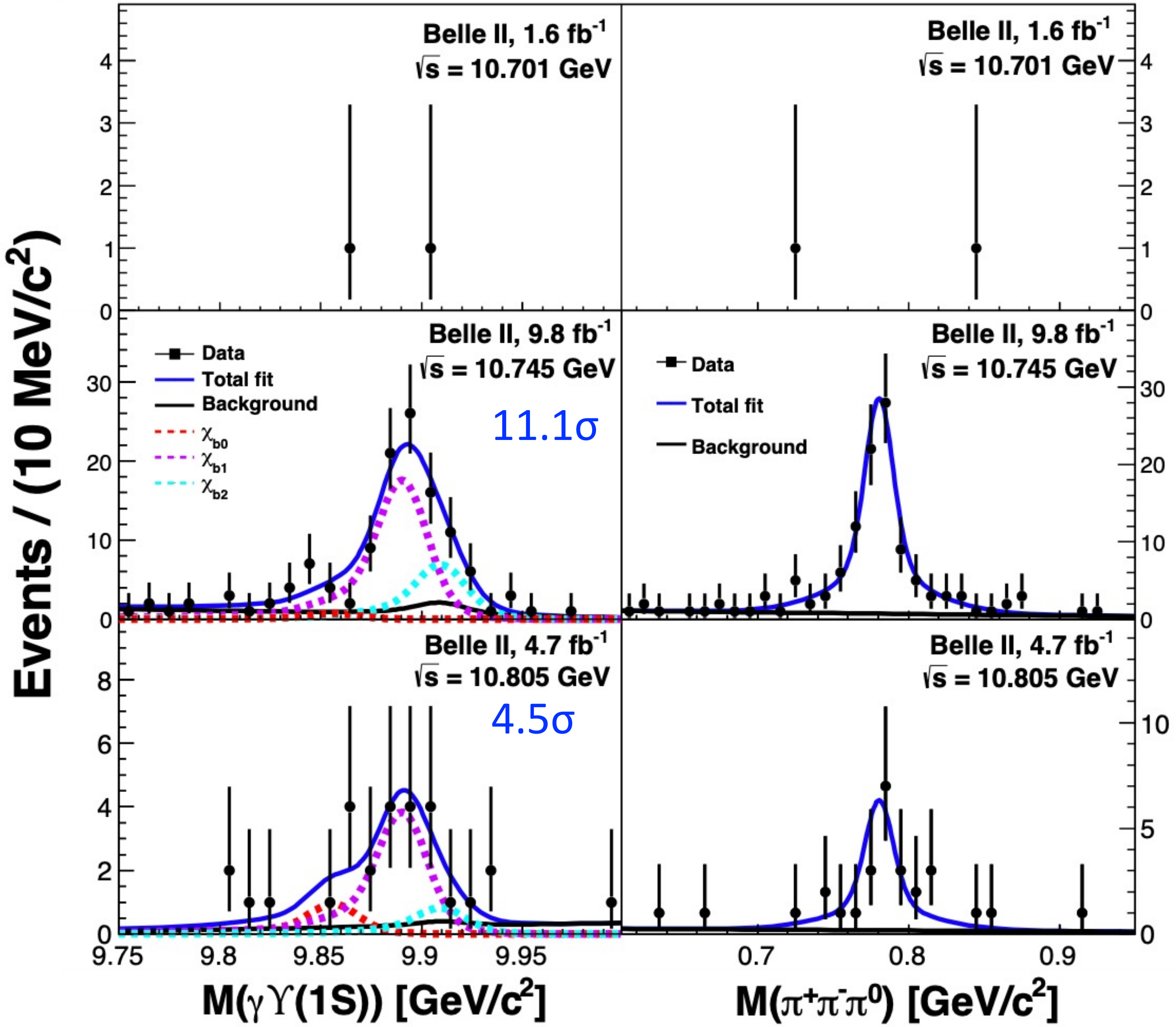


- Red boxes contains 95% of signals.
- Blue boxes show the fit ranges.

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

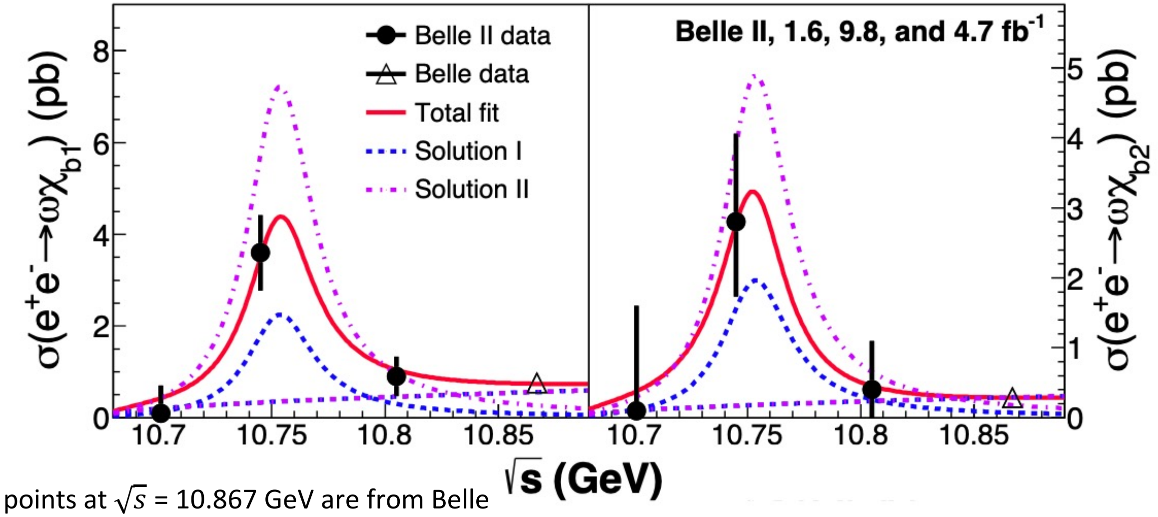
PRL 130, 091902 (2023)

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

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

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

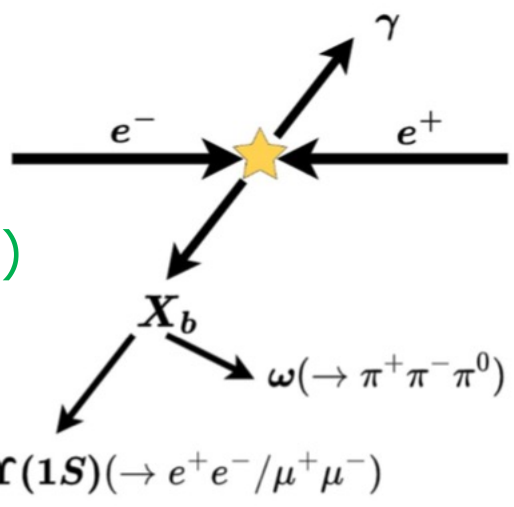
$\sim$ 0.15 at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001 (2014)]

- $\Upsilon(5S)$ 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**.

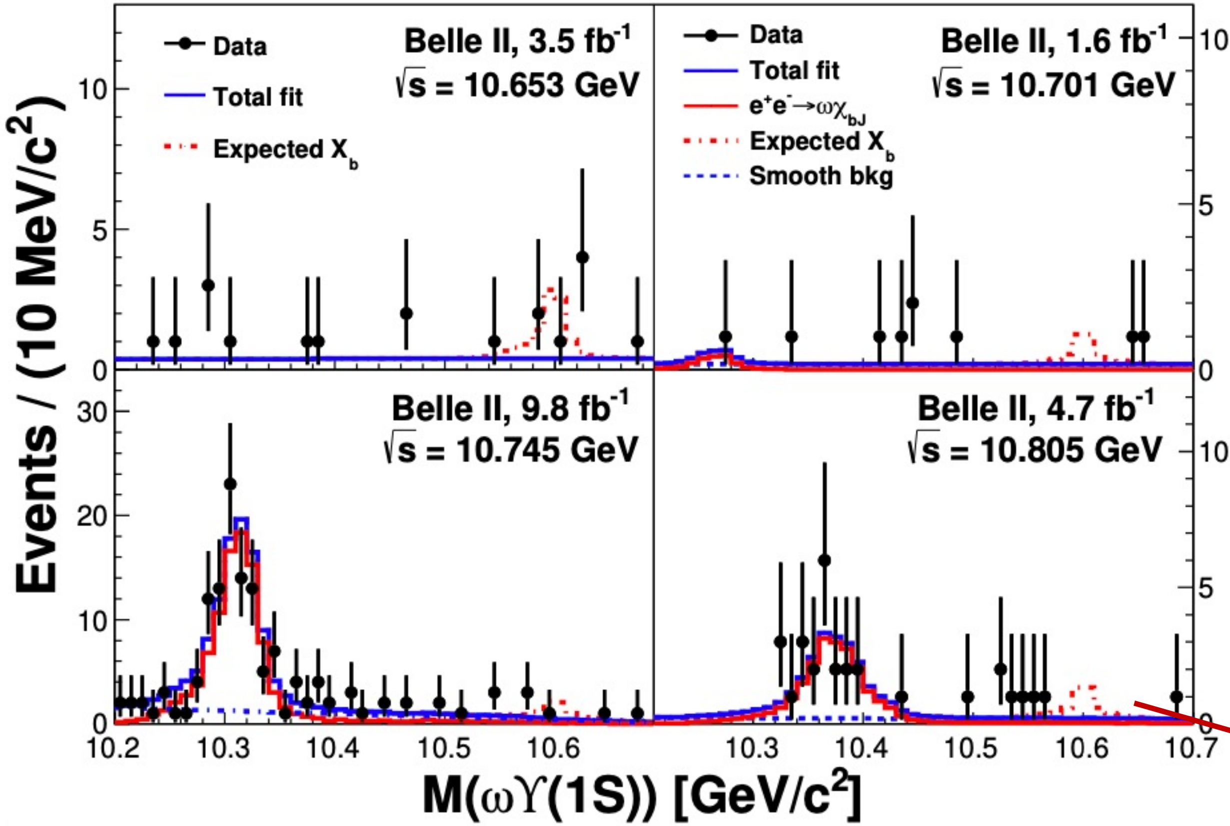
$$\frac{\sigma(e^+e^- \to \chi_{b1}(1P)\omega)}{\sigma(e^+e^- \to \chi_{b2}(1P)\omega)} = 1.3 \pm 0.6 \text{ at } \sqrt{s} = 10.745 \text{ GeV [PRL 130, 091902 (2023)]}$$

- **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)]

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/c^2
The yield is fixed at the upper limit at 90% C.L.

Upper limits at 90% C.L. on $\sigma_B(e^+e^- \to \gamma X_b) \cdot \mathcal{B}(X_b \to \omega\Upsilon(1S))$ (pb)	$\sqrt{s}$ (GeV)	10.653	10.701	10.745	10.805
	$m(X_b)$ = 10.6 GeV/c^2	0.46	0.33	0.10	0.14
	$m(X_b)$ = (10.45, 10.65) GeV/c^2	(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:

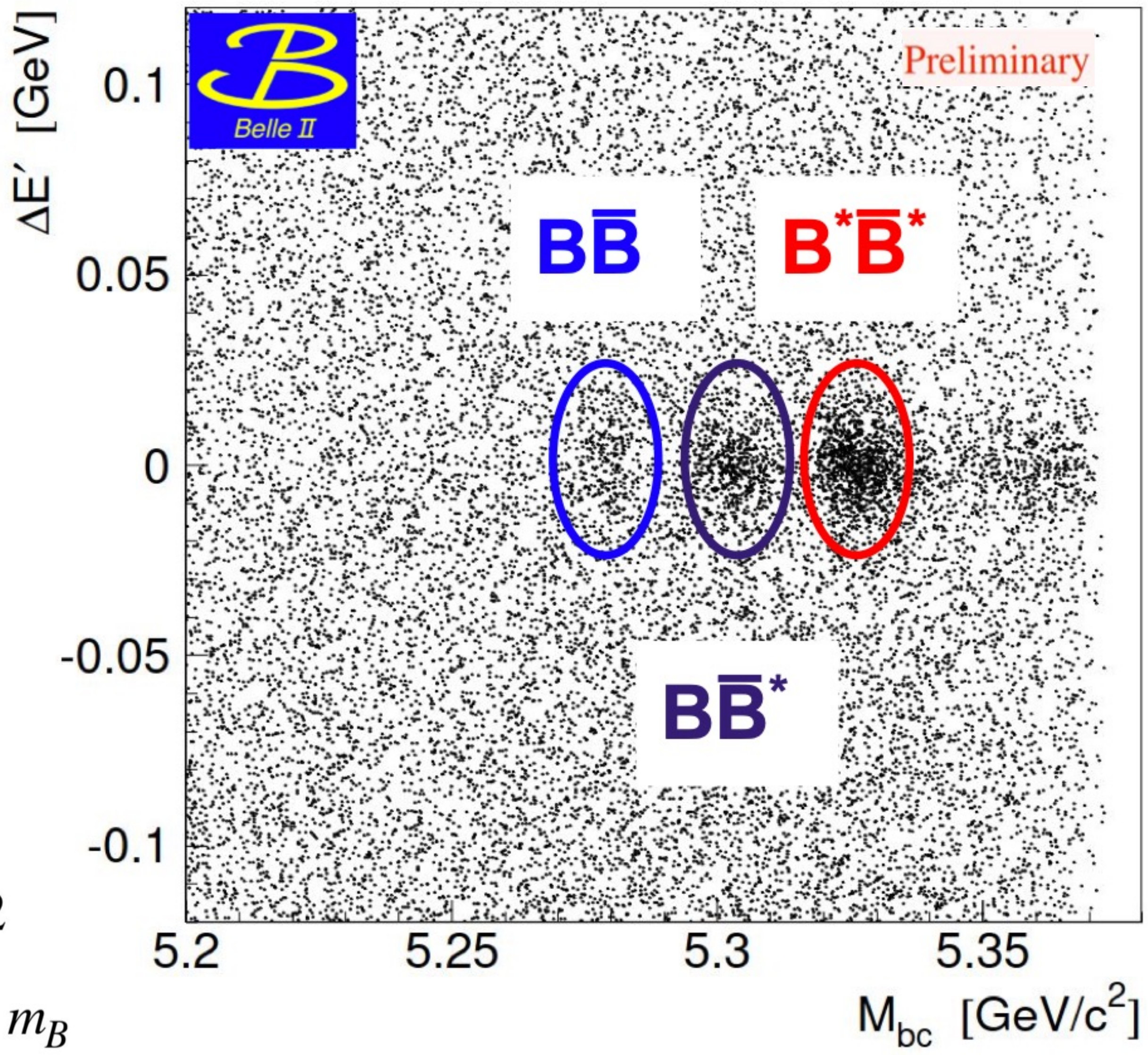
One B meson is reconstructed in hadronic channels, and signals are identified using

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

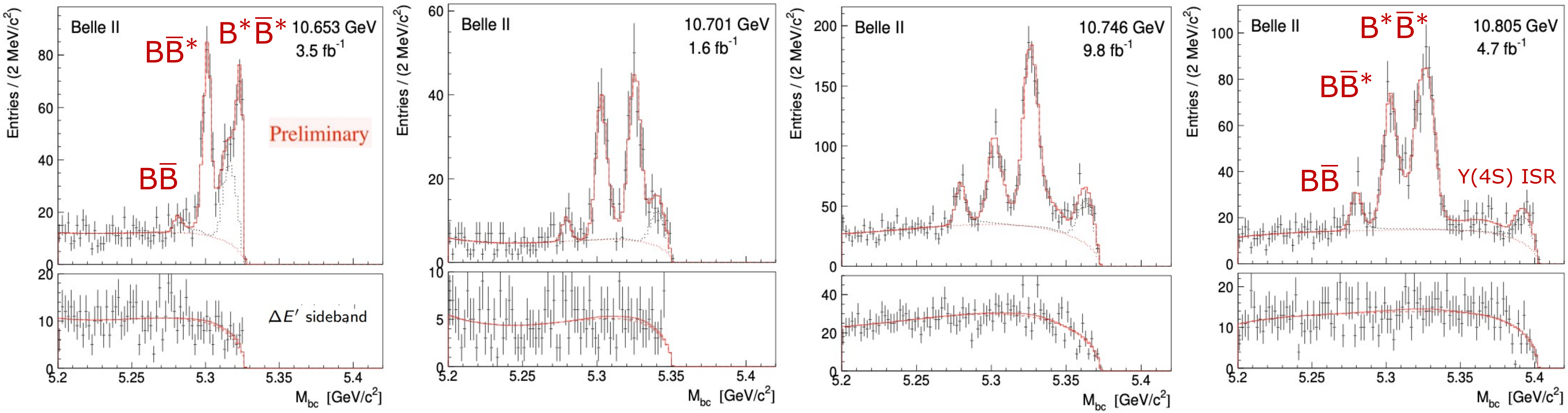
$$\Delta E = E_B - E_{cm}/2$$

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

$\sqrt{s} = 10.745$ GeV, 9.8 fb^{-1}

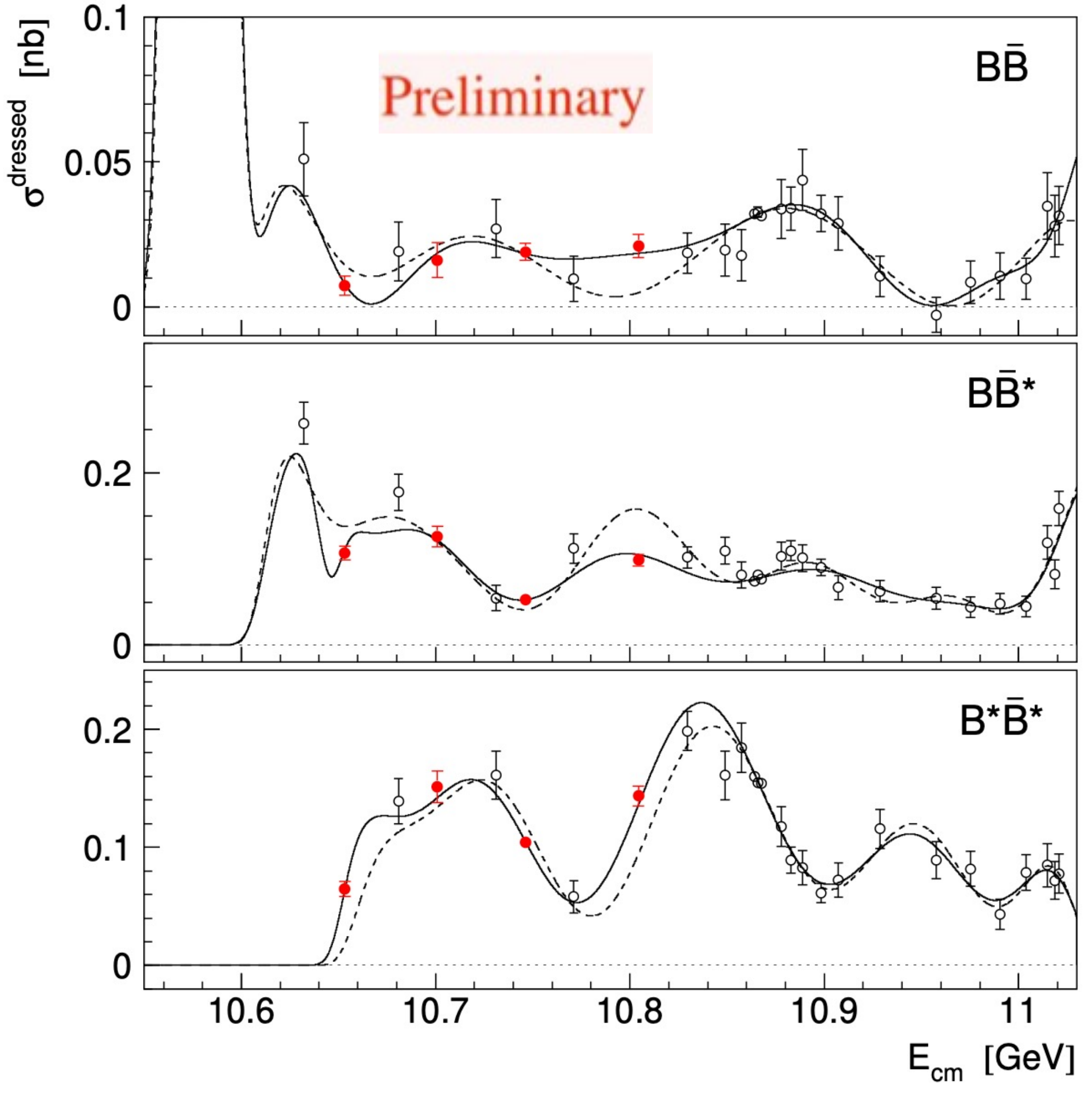


M_{bc} fit at scan energies



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

Energy dependence of the cross sections

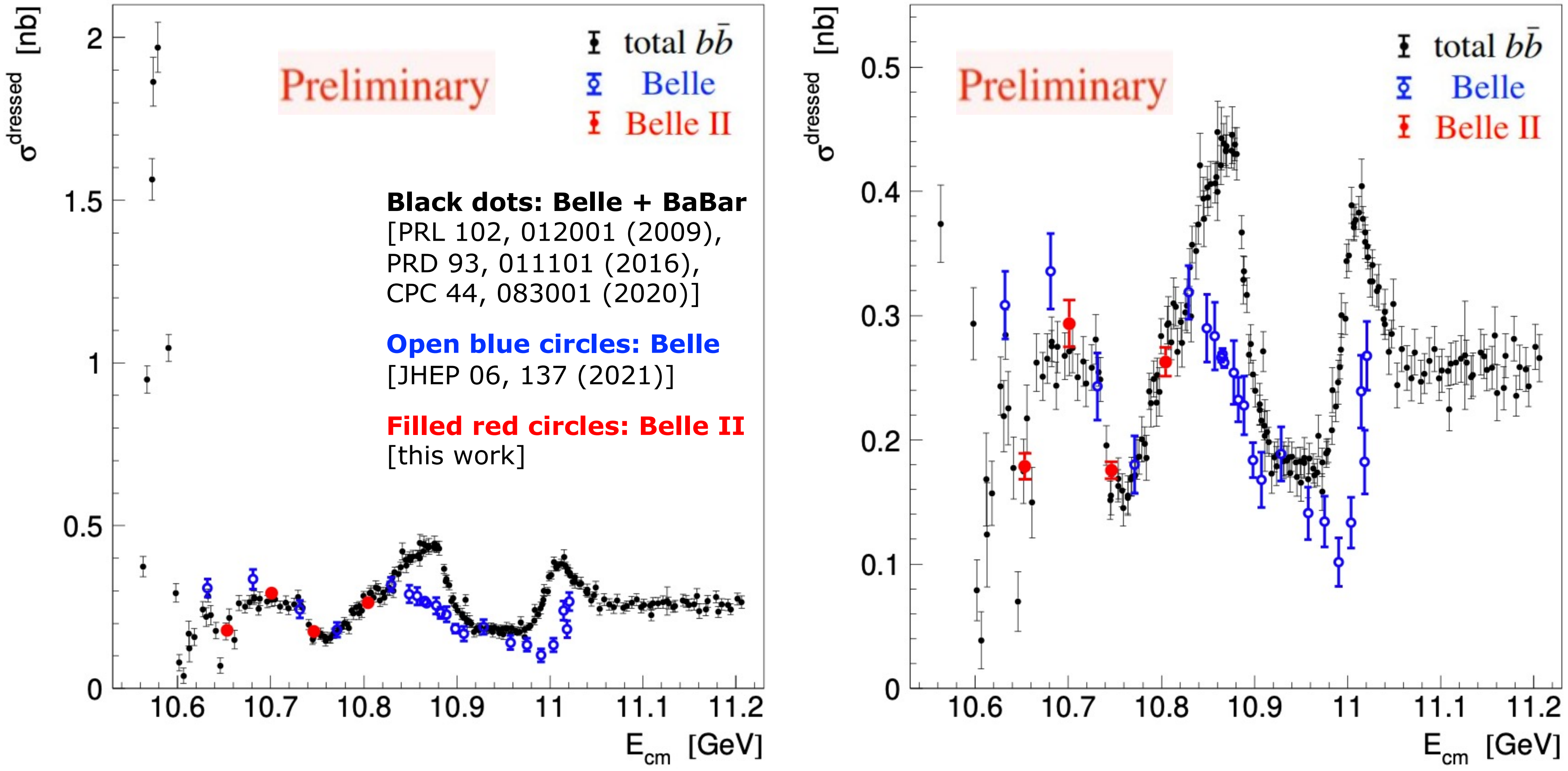


Solid curve – combined Belle + Belle II data fit
Dashed curve – Belle data fit only

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 is 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)].

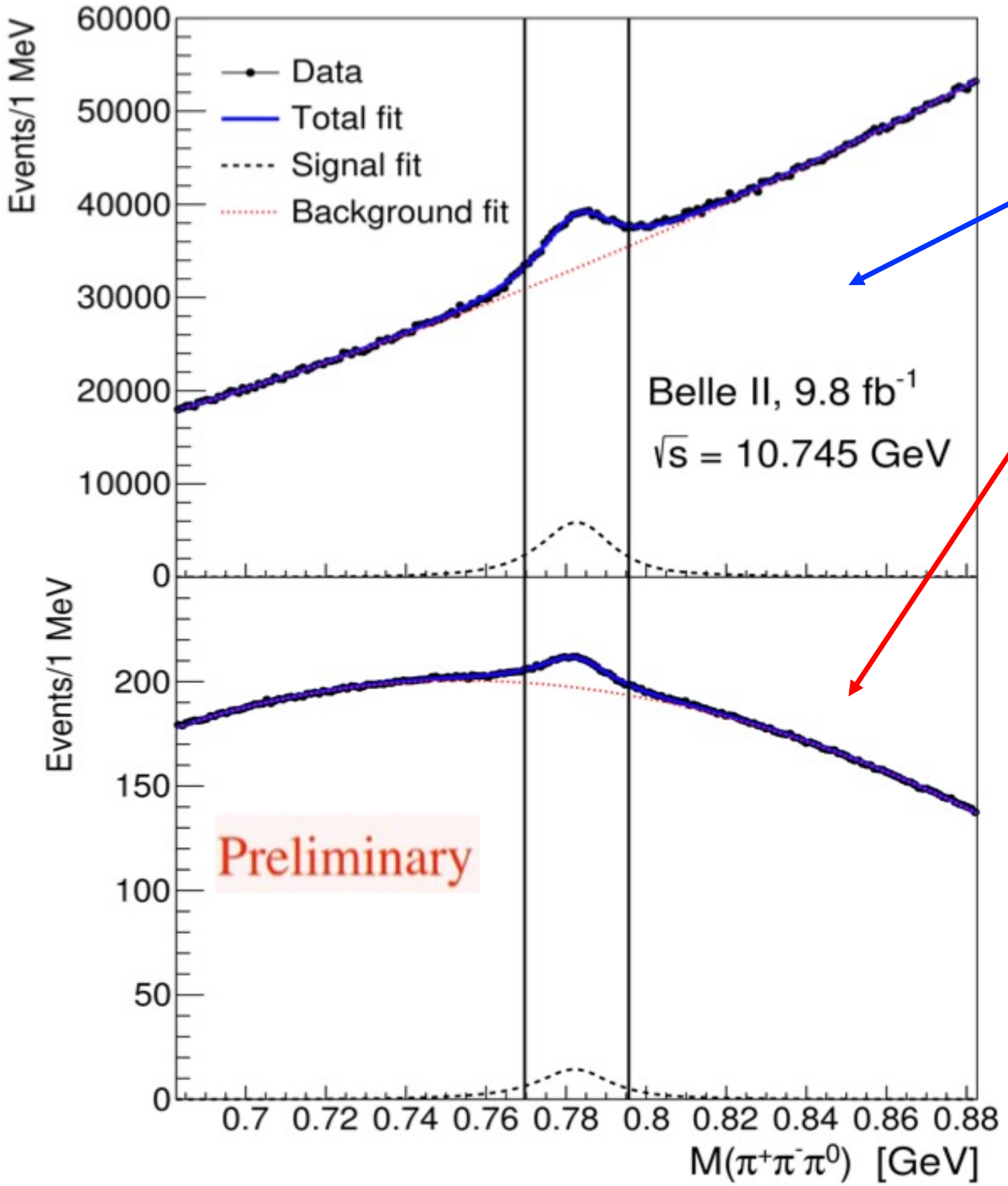
$$\frac{\Gamma(\eta_b\,\omega)}{\Gamma(\Upsilon\,\pi^+\pi^-)} \sim 30$$

- 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 $\mathcal{B}[\chi_{b0}(1P) \to \gamma\Upsilon(1S)] = (1.94 \pm 0.27)\%$.

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

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

Invariant mass distribution of $\pi^+\pi^-\pi^0$

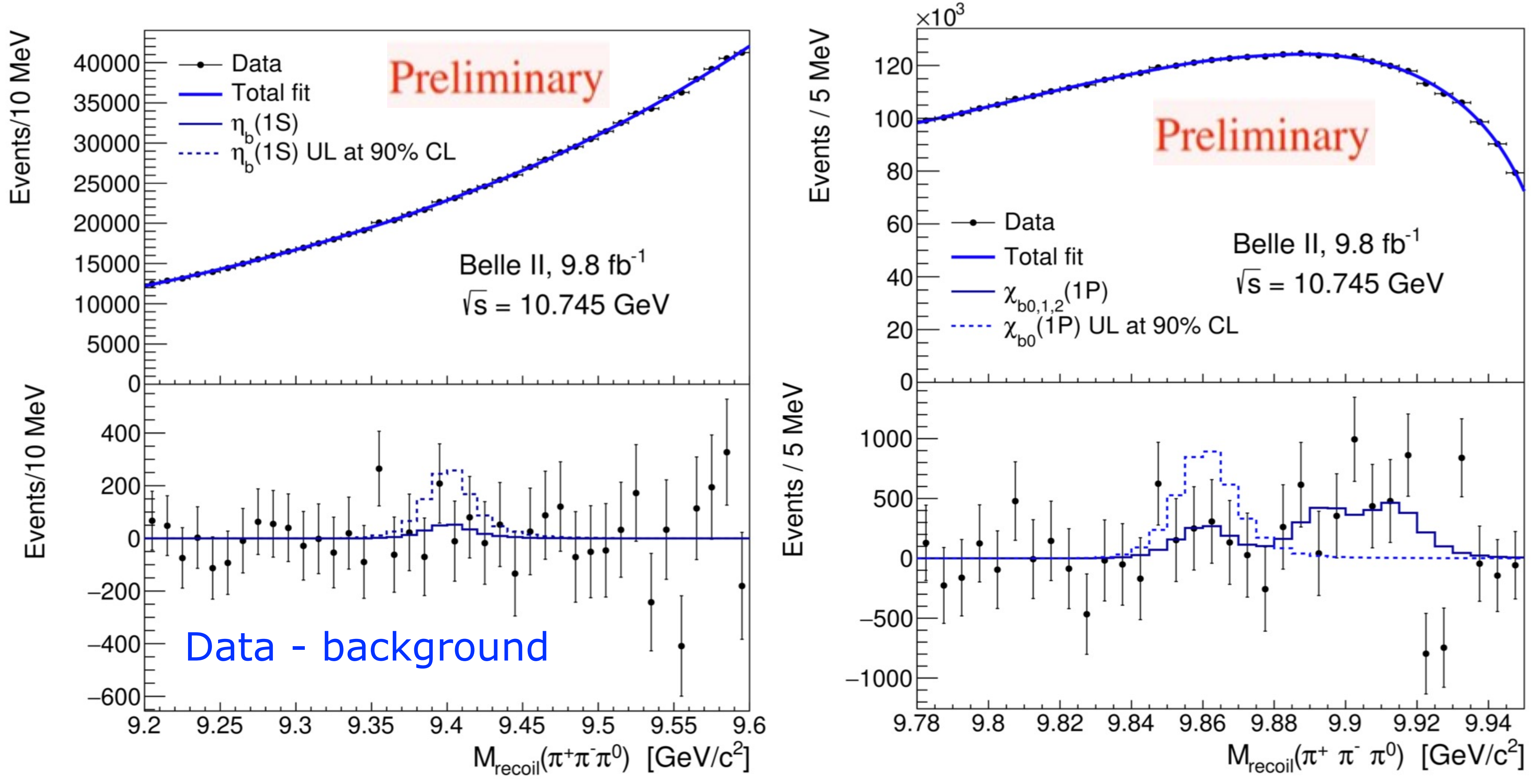


$9.2 < M_{rec}(\pi^+\pi^-\pi^0) < 9.6$ GeV/c²
($\eta_b(1S)$ included)

$9.78 < M_{rec}(\pi^+\pi^-\pi^0) < 9.95$ 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 purities of ω-meson signals are 12.9% for $\eta_b(1S)$ and 5.3% for $\chi_{bJ}(1P)$

Recoil mass spectra of $\pi^+\pi^-\pi^0$



- 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)].

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

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

Born cross sections

Preliminary

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

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 provides 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 [PRL 130, 091902 (2023)].
- 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!