Study of $\Upsilon(10753)$ at Belle II

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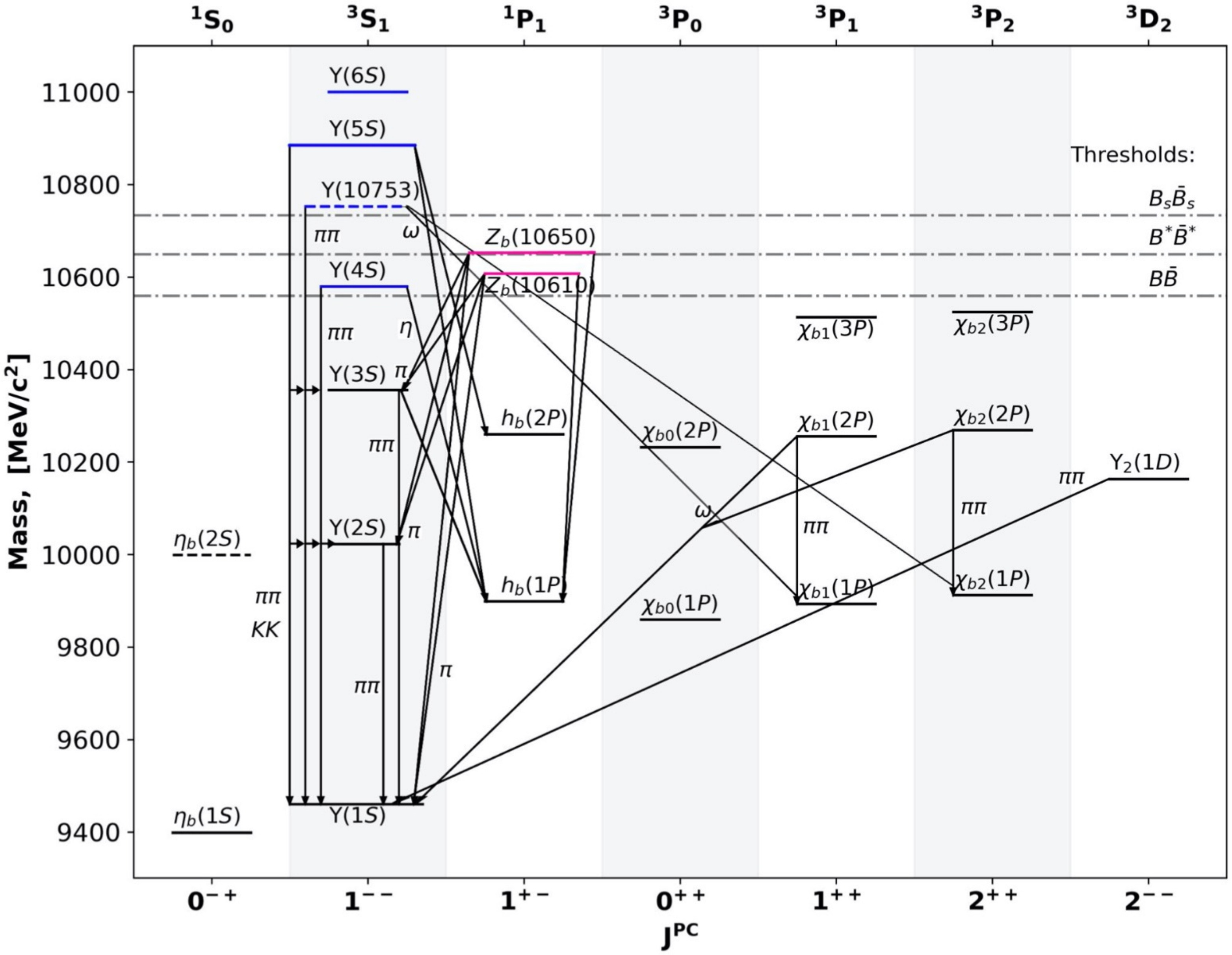
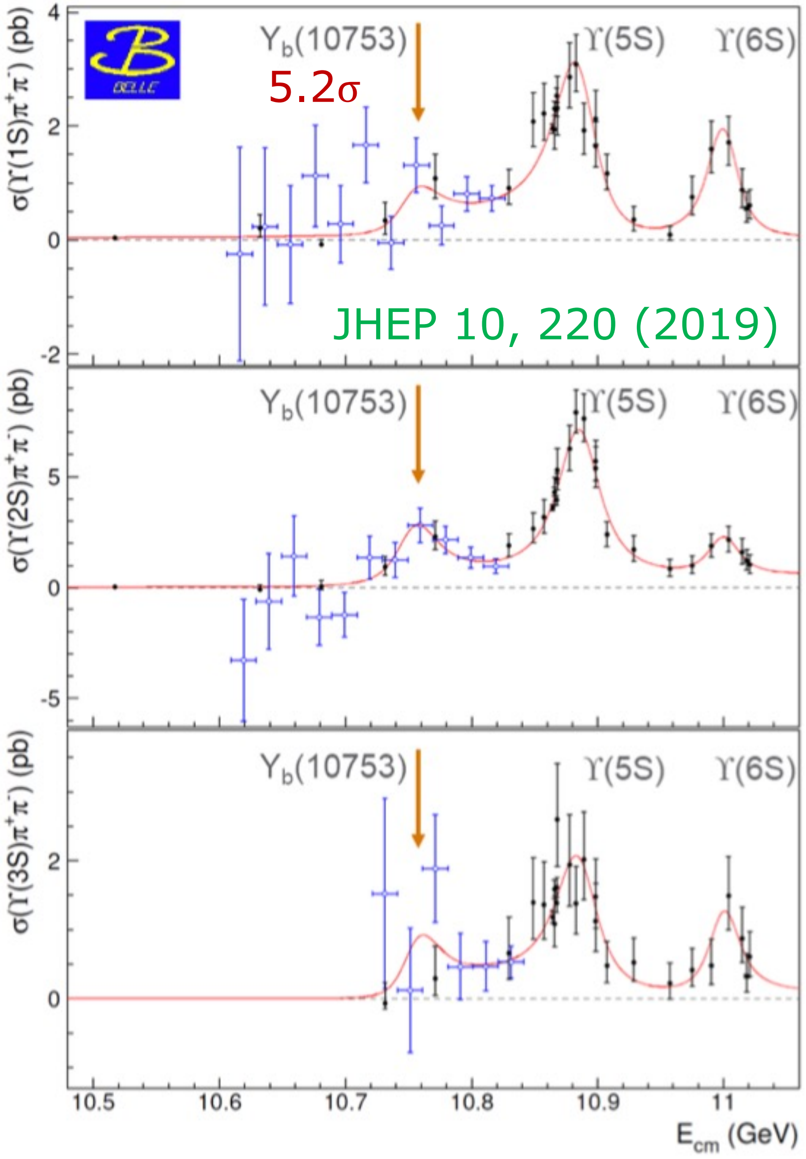
Bottomonium



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

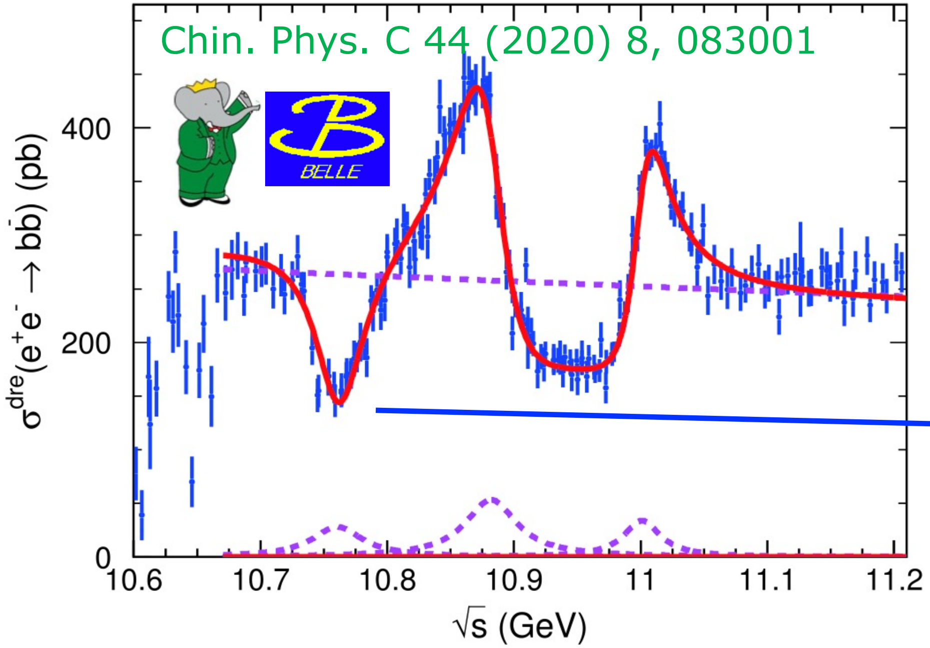
- Below $B\bar{B}$ thresholds – bottomonia are well described by the potential models.
- Above $B\bar{B}$ thresholds – bottomonia express unexpected properties.

Discovery of $\Upsilon(10753)$



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

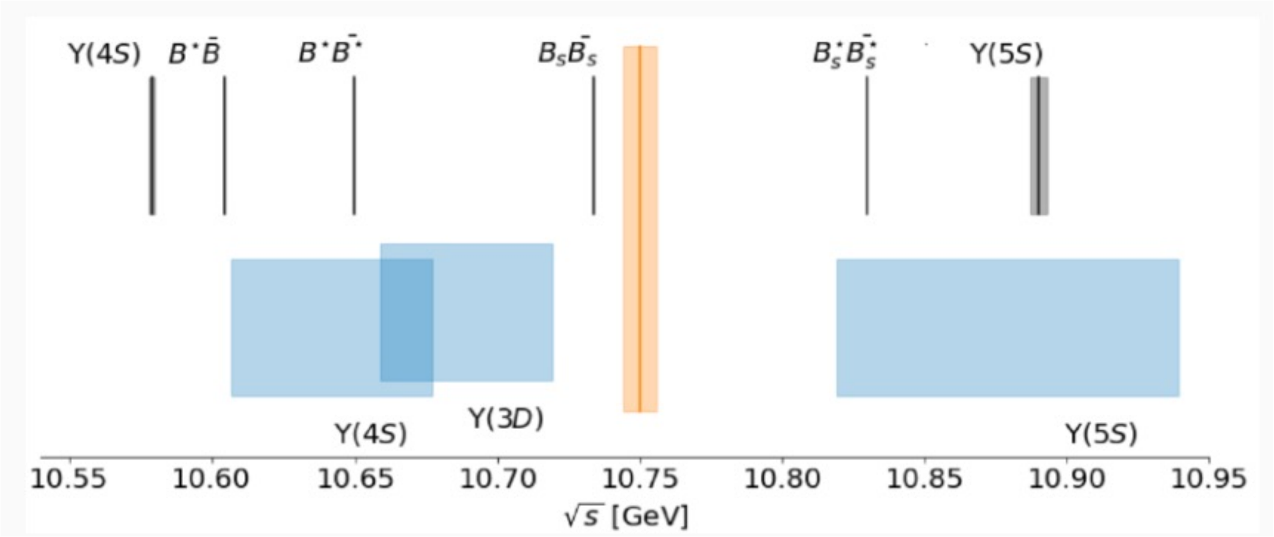
	$\Upsilon(10860)$	$\Upsilon(11020)$	New structure
M (MeV/c^2)	$10885.3 \pm 1.5\,^{+2.2}_{-0.9}$	$11000.0^{+4.0}_{-4.5}\,^{+1.0}_{-1.3}$	$10752.7 \pm 5.9\,^{+0.7}_{-1.1}$
Γ (MeV)	$36.6^{+4.5}_{-3.9}\,^{+0.5}_{-1.1}$	$23.8^{+8.0}_{-6.8}\,^{+0.7}_{-1.8}$	$35.5^{+17.6}_{-11.3}\,^{+3.9}_{-3.3}$



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)
Phys. Rev. D 109, 014039 (2024)

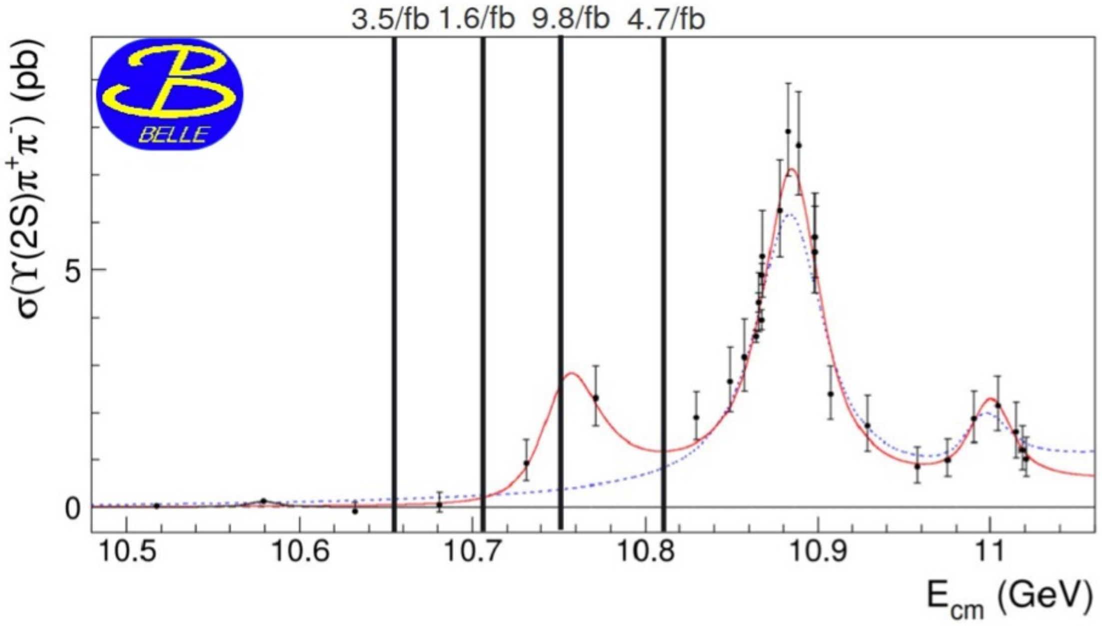
❑ Hybrid

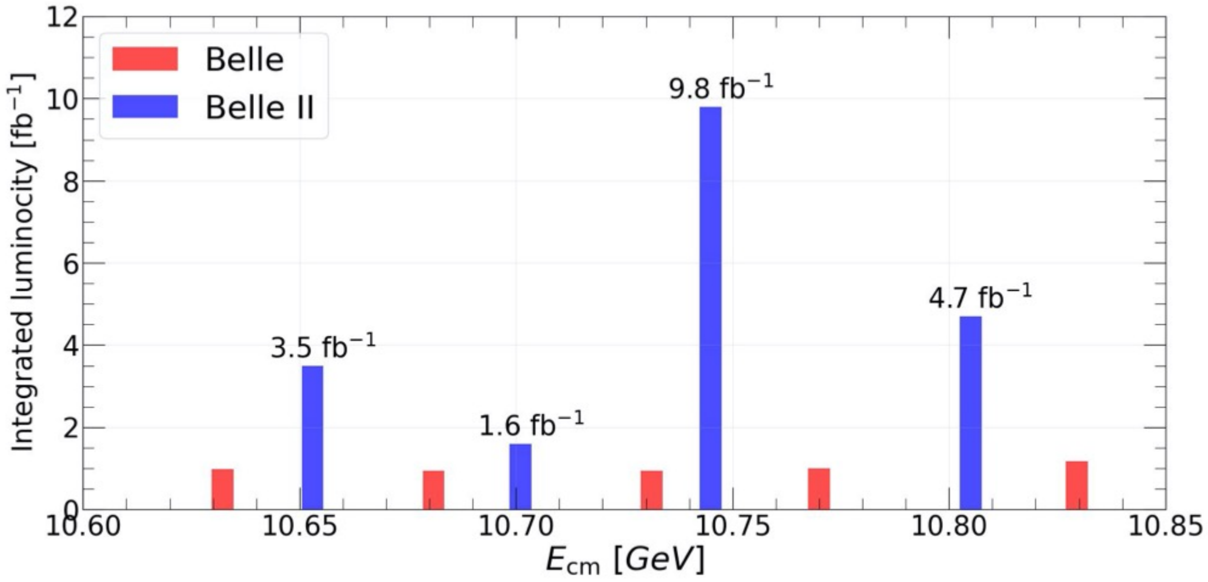
Phys. Rept. 873, 1 (2020)
Phys. Rev. D 104, 034019 (2021)

❑ 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 $\Upsilon(4S)$: 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.

Study of $\Upsilon(10753)$ at Belle II:

- $e^+e^-\to\omega\chi_{bJ}(1P)$ [PRL 130, 091902 (2023)]
- $e^+e^-\to B\bar{B}$, $B\bar{B}^*$, and $B^*\bar{B}^*$ [Preliminary results]
- $e^+e^-\to\omega\eta_b(1S)$ [PRD 109, 072013 (2024)]
- $e^+e^-\to\pi^+\pi^-\Upsilon(nS)$ [arXiv: 2401.12021]

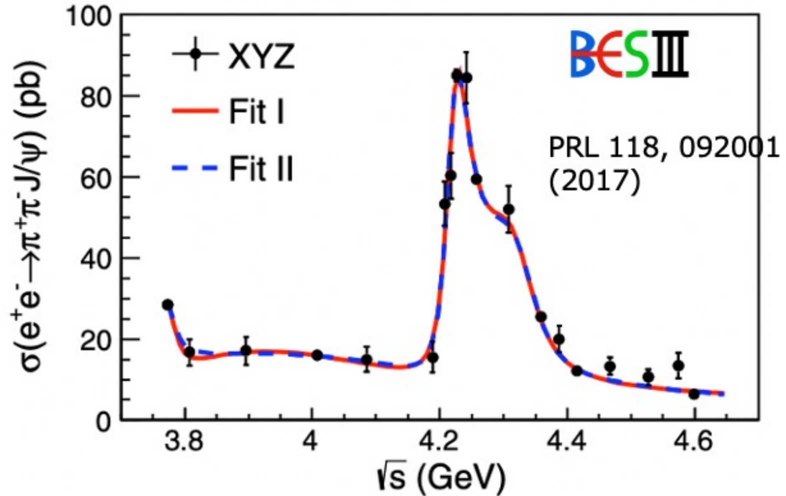
Motivation to search for $\Upsilon(10753) \to \omega\chi_{bJ}$

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 $\Upsilon(10753)$.

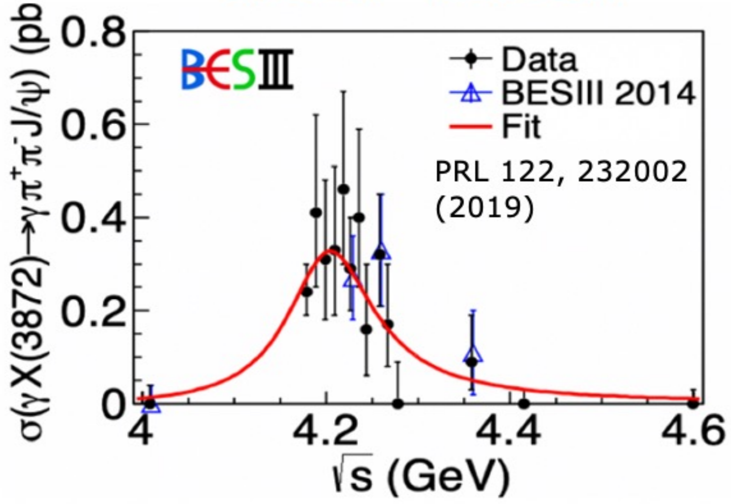
Charmonium sector:

- 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 $\omega\chi_{bJ}$.

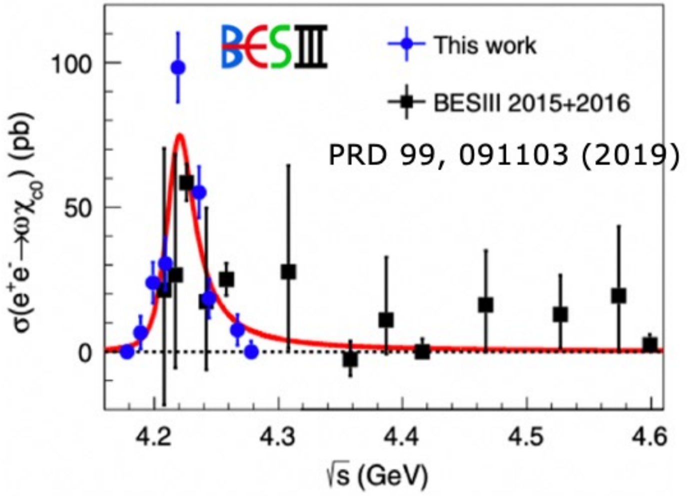
$Y(4220)/Y(4320) \to \pi^+\pi^- J/\psi$



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

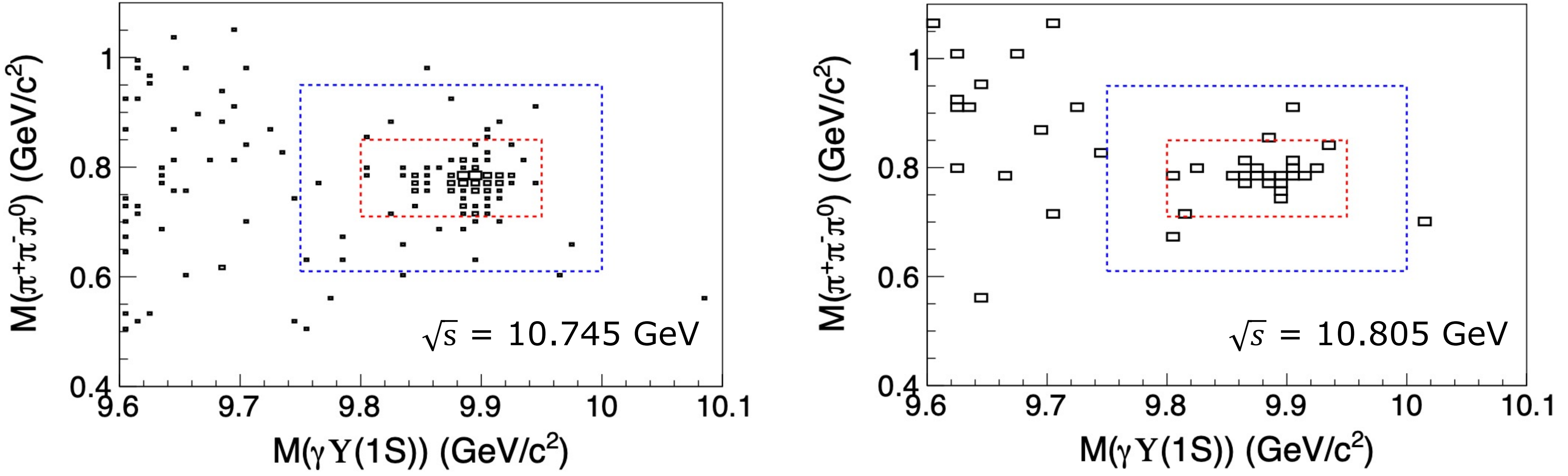


$Y(4220) \to \omega\chi_{c0}$



Mass distributions

[PRL 130, 091902 (2023)]

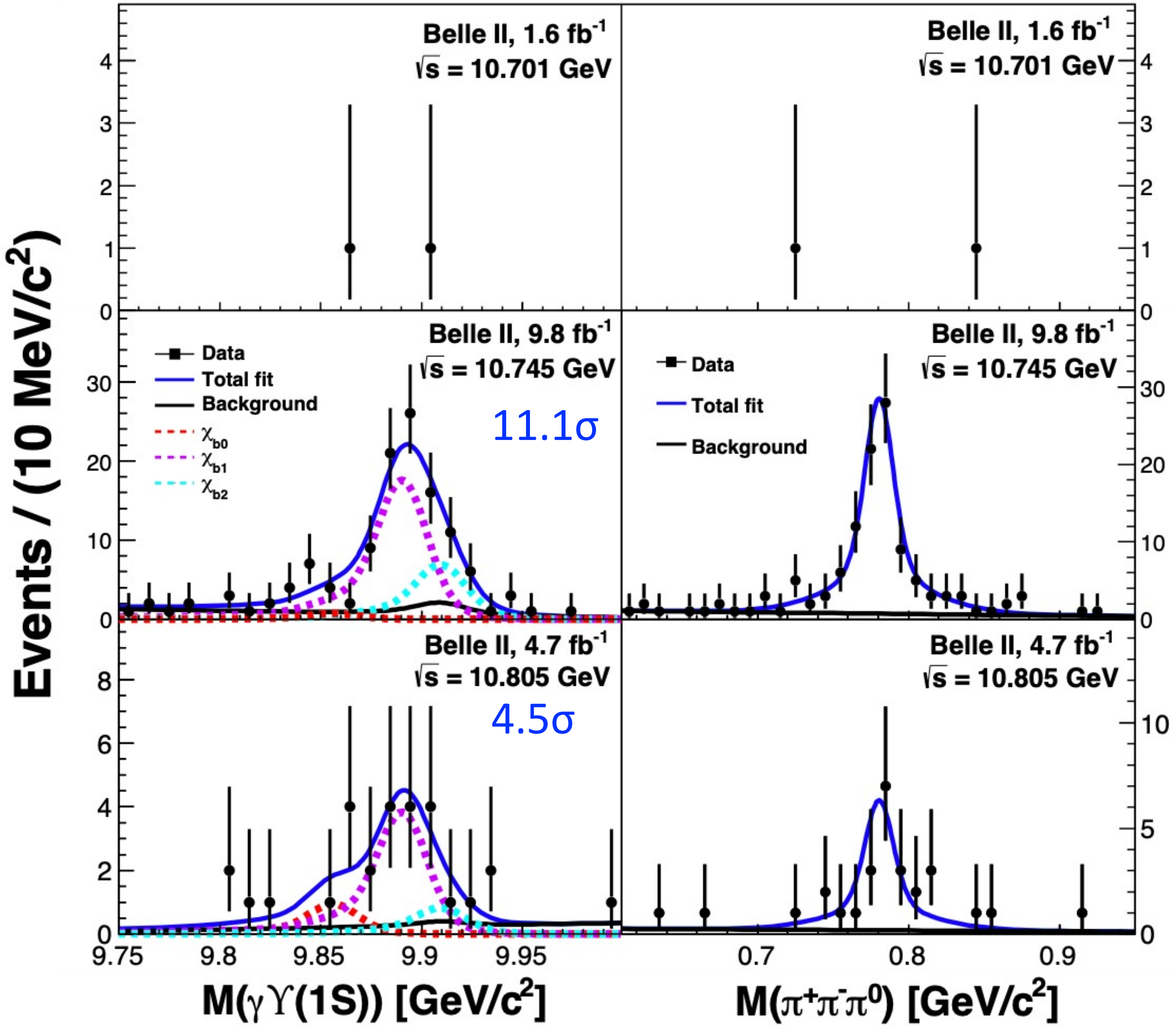


- Red boxes contains 95% of signals.
- Blue boxes show the fit ranges.

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

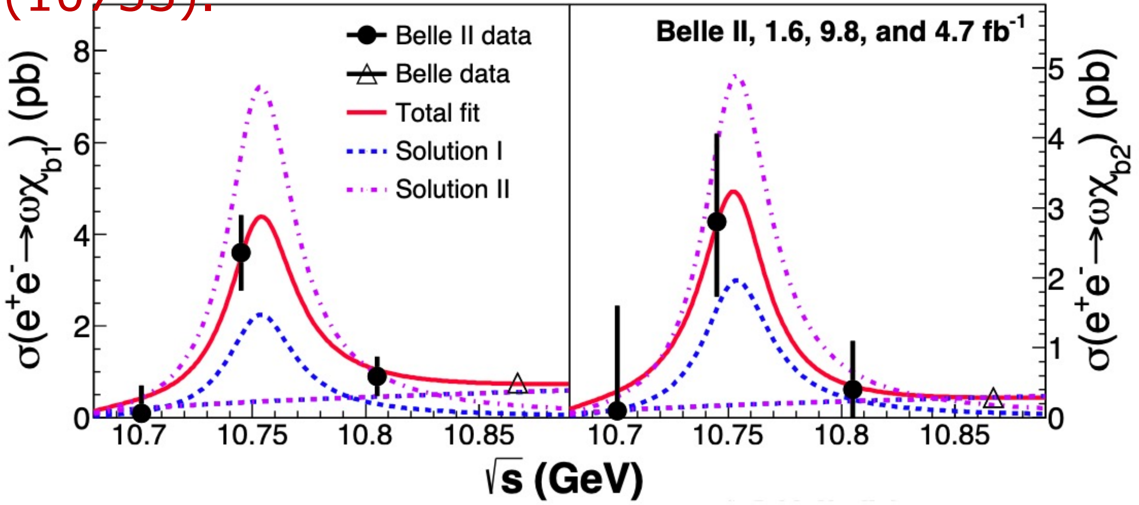
[PRL 130, 091902 (2023)]

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)]

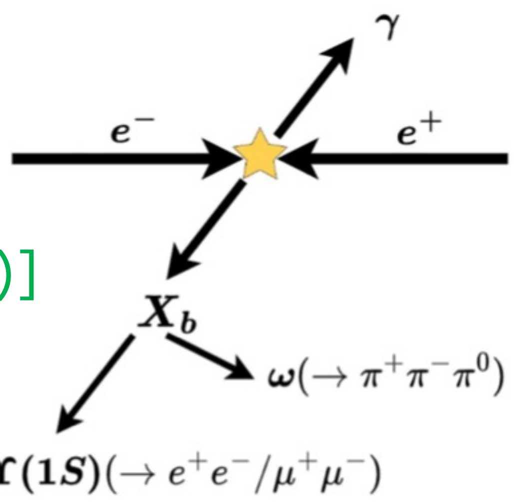
$\sim$ 0.15 at $\sqrt{s}$ = 10.867 GeV [PRL 113, 142001 (2014)]

- ϒ(5S) and ϒ(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**.

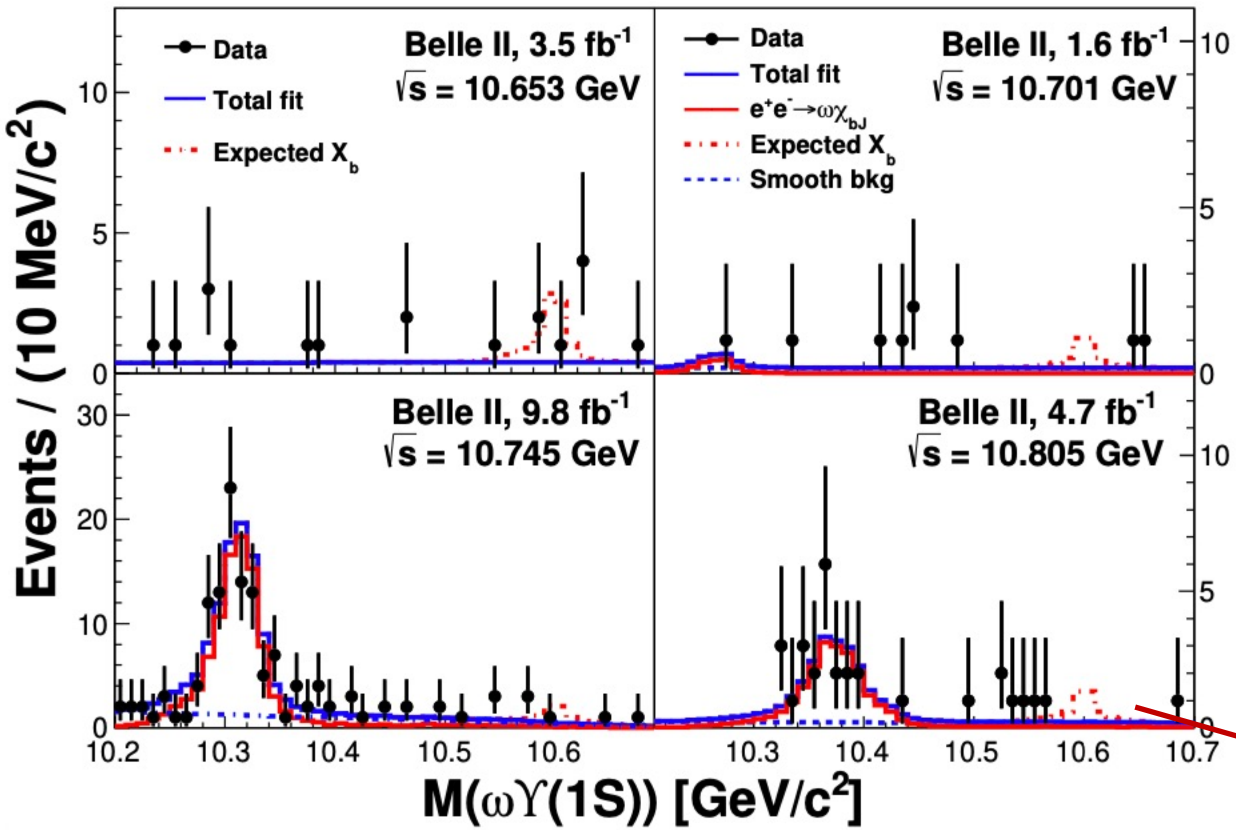
$$\frac{\sigma(e^+e^-\to\chi_{b1}(1P)\omega)}{\sigma(e^+e^-\to\chi_{b2}(1P)\omega)} = 1.3\pm0.6 \text{ at } \sqrt{s} = 10.745 \text{ GeV [PRL 130, 091902 (2023)]}$$

- **Contradicts the expectation for a pure D−wave bottomonium state of 15** [Phys. Lett. B 738, 172 (2014)]
- **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 $e^+e^- \to \omega\chi_{bJ}$.

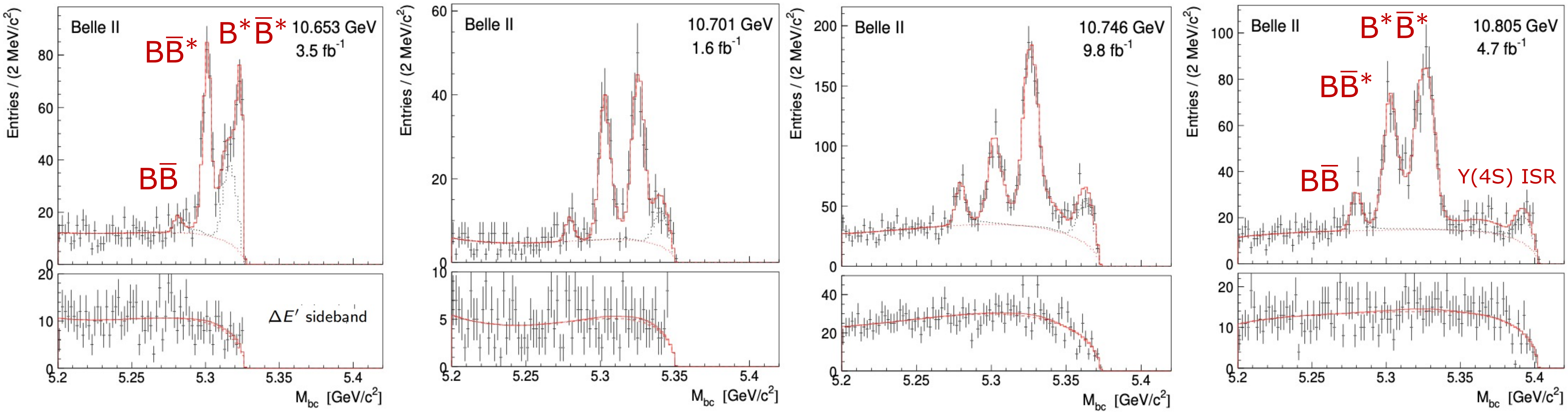
From simulated events with $m(X_b)$ = 10.6 GeV/c^2
The yield is fixed at the upper limit at 90% C.L.

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)

$e^+e^- \to B\bar{B}$, $B\bar{B}^*$ and $B^*\bar{B}^*$ cross sections

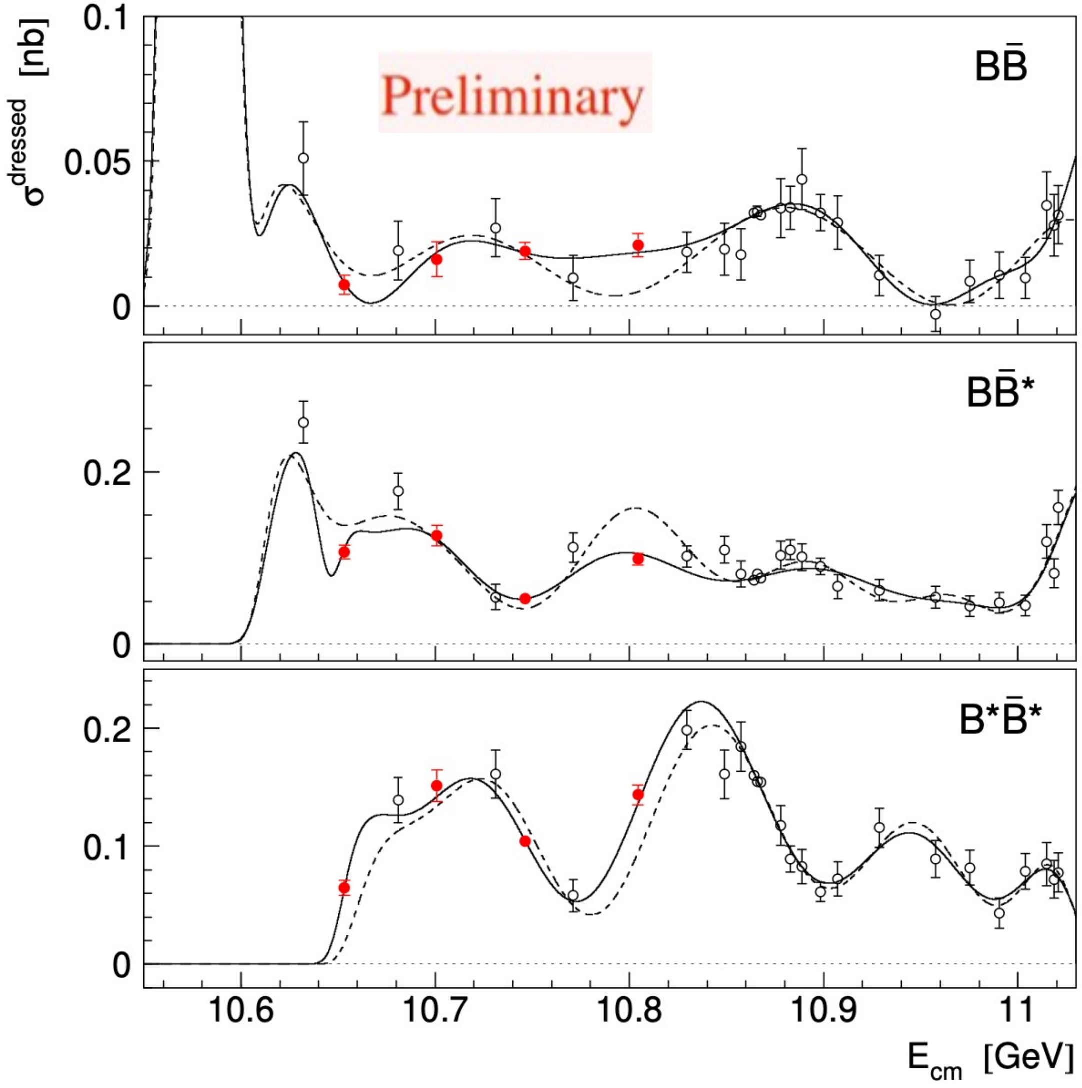
$M_{bc} = \sqrt{(E_{cm}/2)^2 - P_B^2}$

[Belle II preliminary]



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

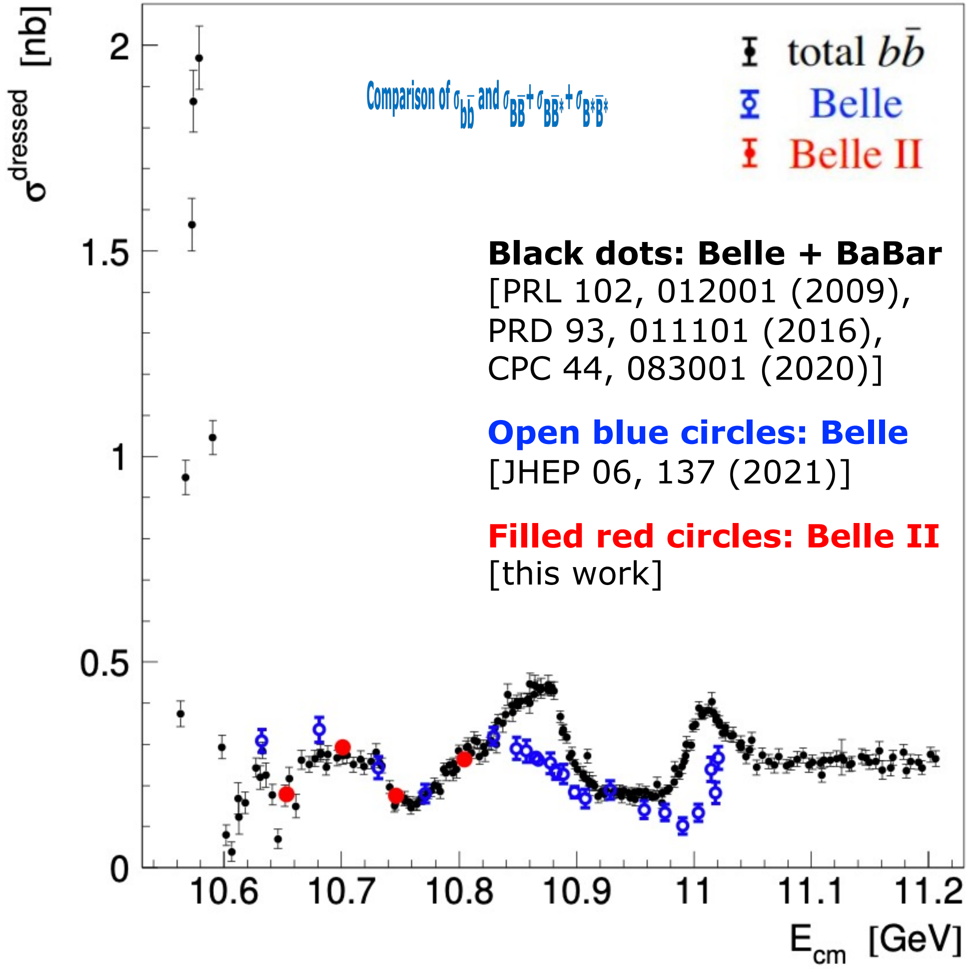
[Belle II preliminary]

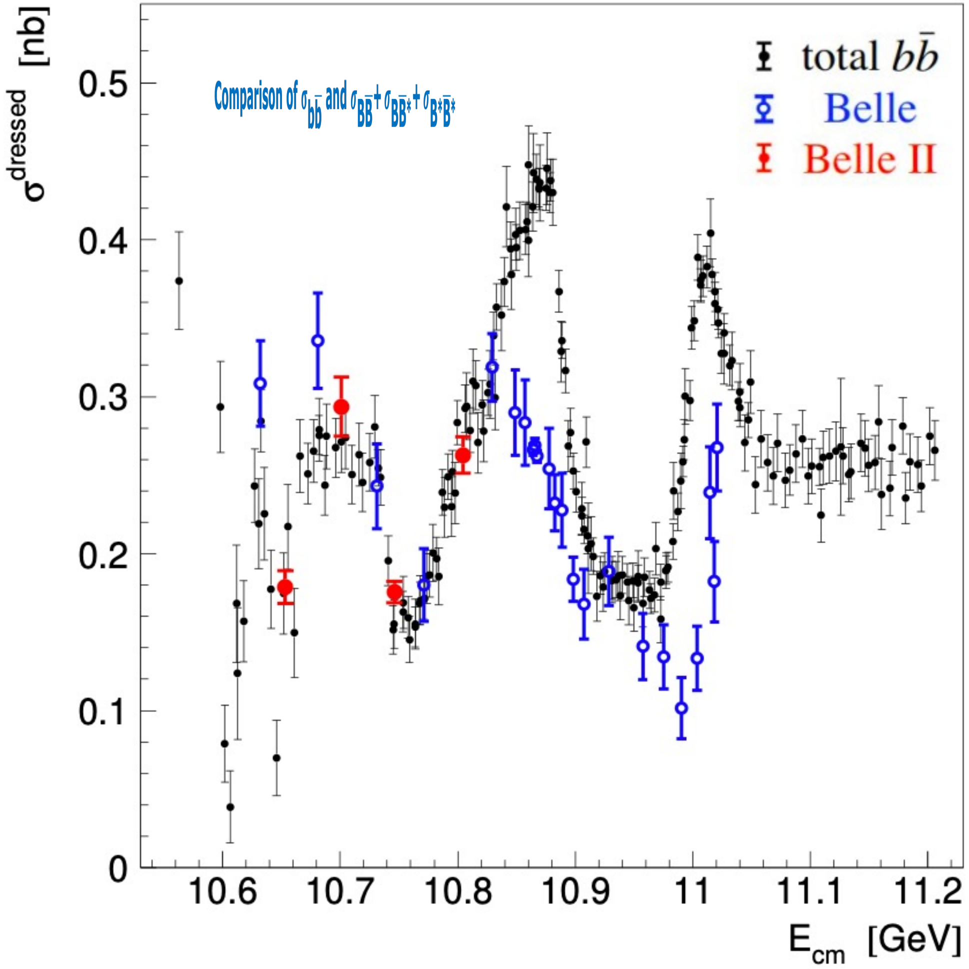
New: rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold

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

[Belle II preliminary]





- 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)].

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

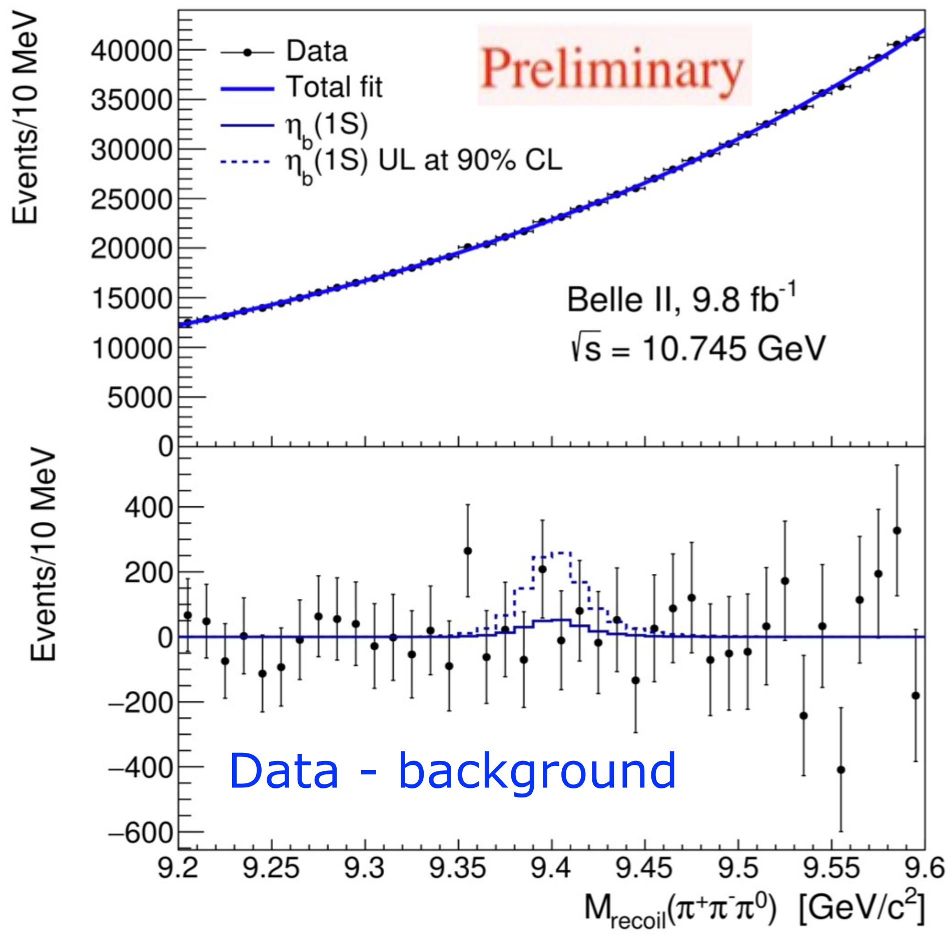
- The $e^+e^-\to\omega\chi_{bJ}(1P)$ (J = 1, 2) was found to be enhanced at $\sqrt{s}$ = 10.745 GeV (PRL 130, 091902 (2023)). The $e^+e^-\to\omega\chi_{b0}(1P)$ transition was not observed due to low $\mathcal{B}[\chi_{b0}(1P)\to\gamma\Upsilon(1S)]$ = (1.94±0.27)%.

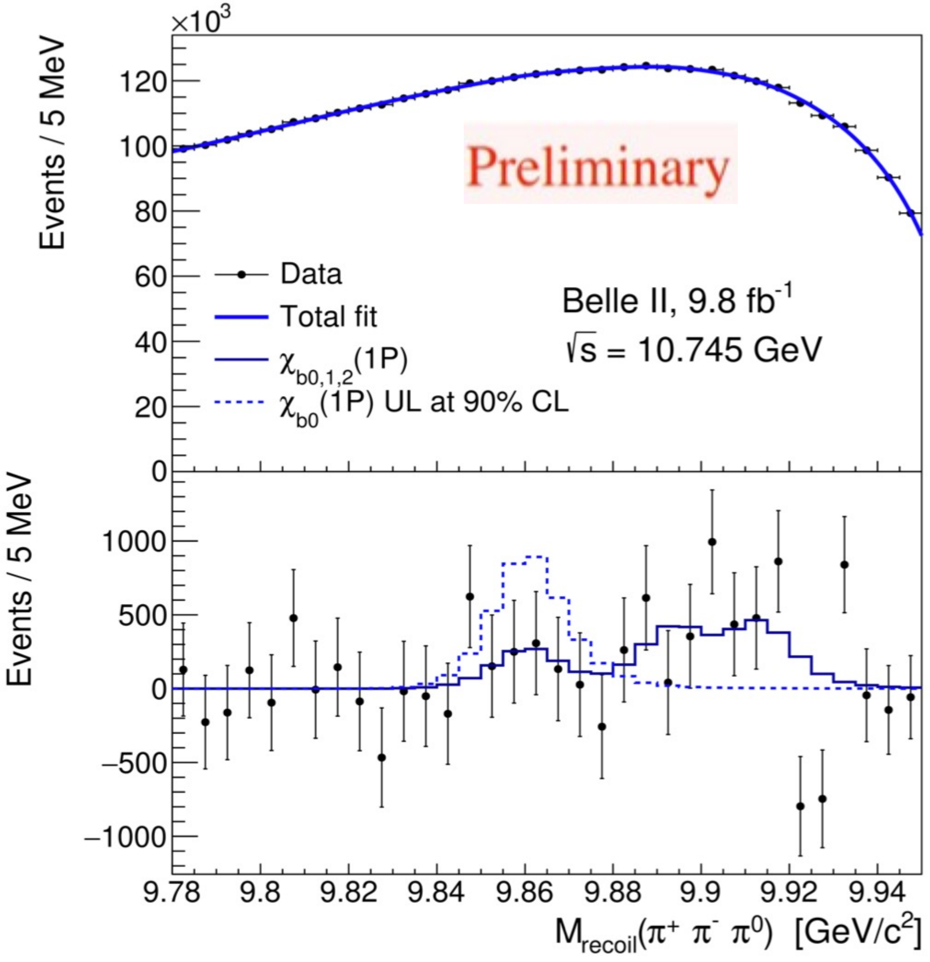
- We reconstruct only $\omega\to\pi^+\pi^-\pi^0$ and use its recoil mass to identify the signal.

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

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

[PRD 109, 072013 (2024)]





- Polynomial function for background shape
- 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

[PRD 109, 072013 (2024)]

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

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)]:

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

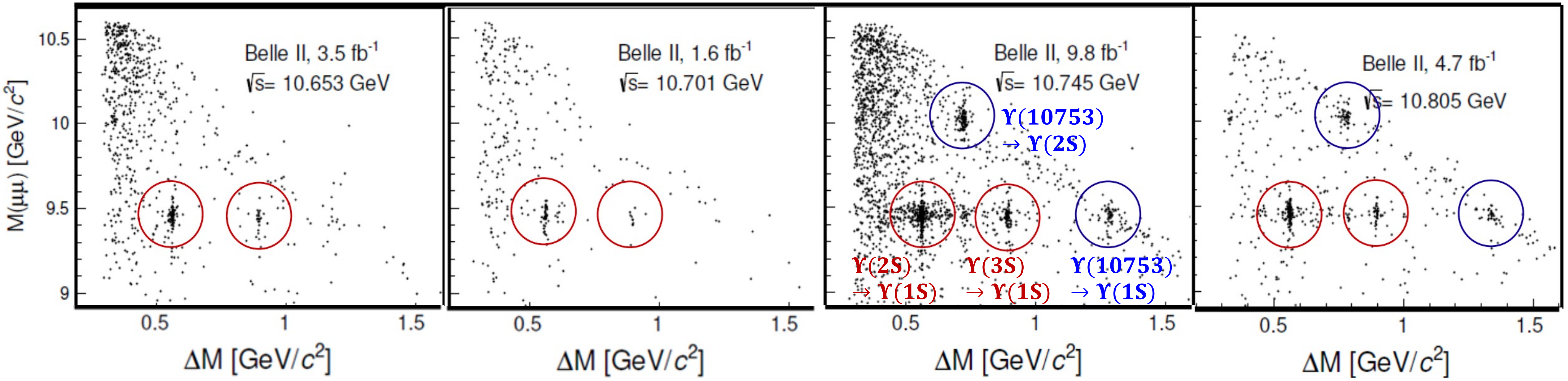
This measurement and JHEP 10, 220 (2019):

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

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

[arXiv: 2401.12021]

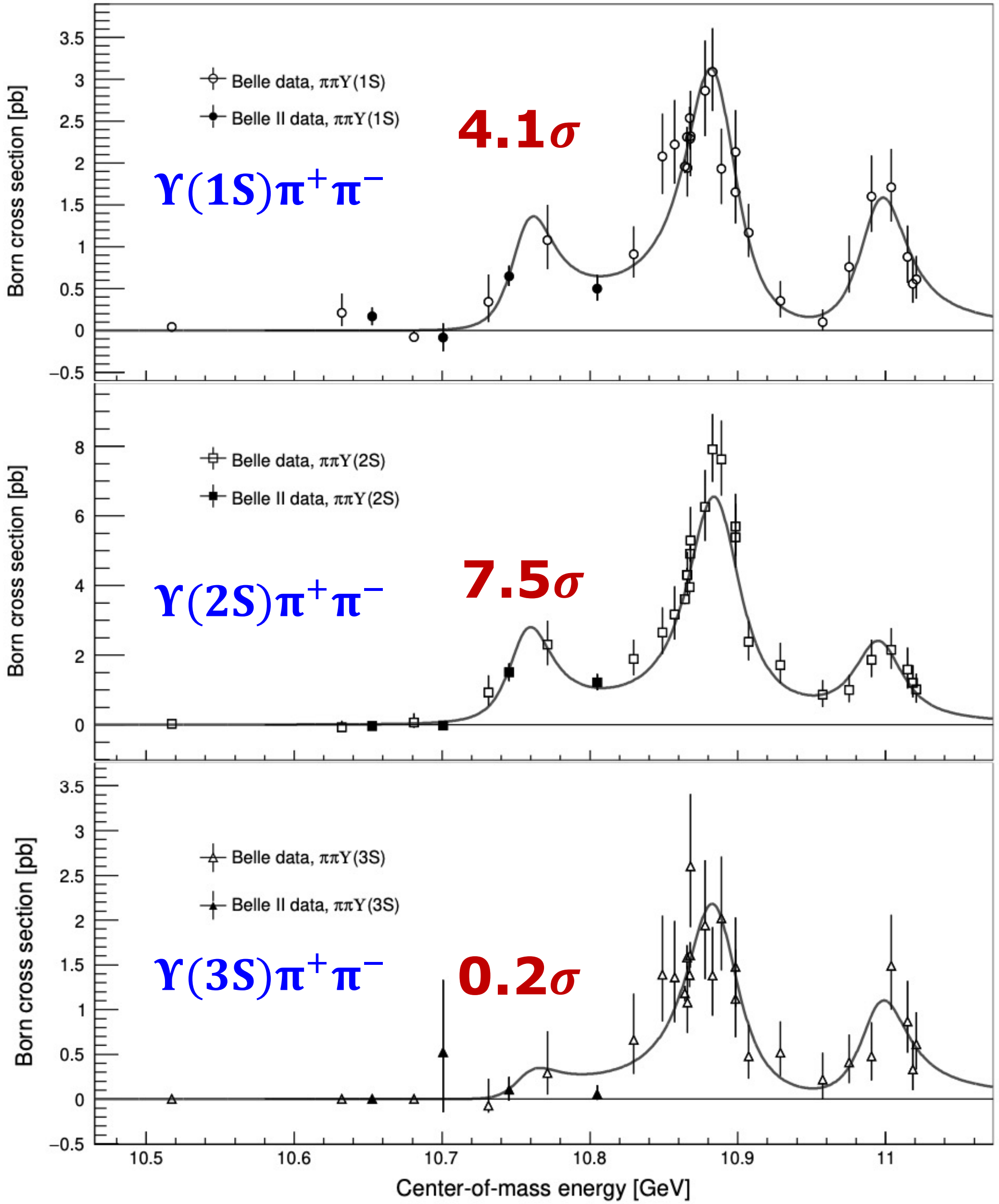
- The full reconstruction: $e^+e^- \to [\Upsilon(nS) \to \mu^+\mu^-]\pi^+\pi^-$
- $\Delta M = M(\mu^+\mu^-\pi^+\pi^-) - M(\mu^+\mu^-)$



ISR $\Upsilon(2S, 3S) \to \Upsilon(1S)\pi^+\pi^-$ **Signal: $e^+e^- \to [\Upsilon(nS) \to \mu^+\mu^-]\pi^+\pi^-$**

If we require $p^*(\pi^+\pi^-\mu^+\mu^-) < 100$ MeV/c, the background from non-prompt production of the $\Upsilon(10753)$ is suppressed.

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

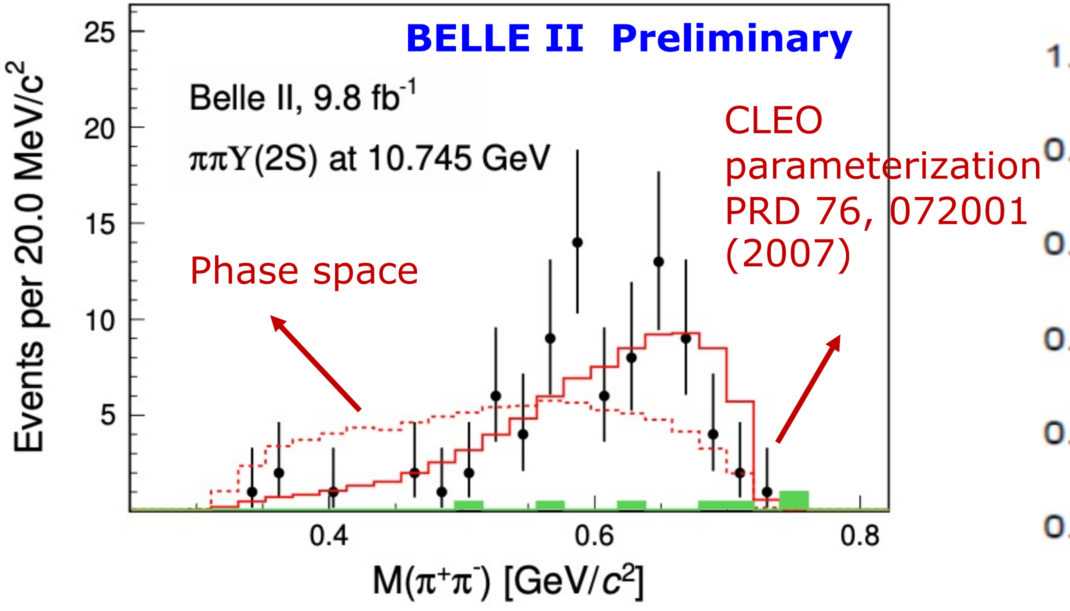


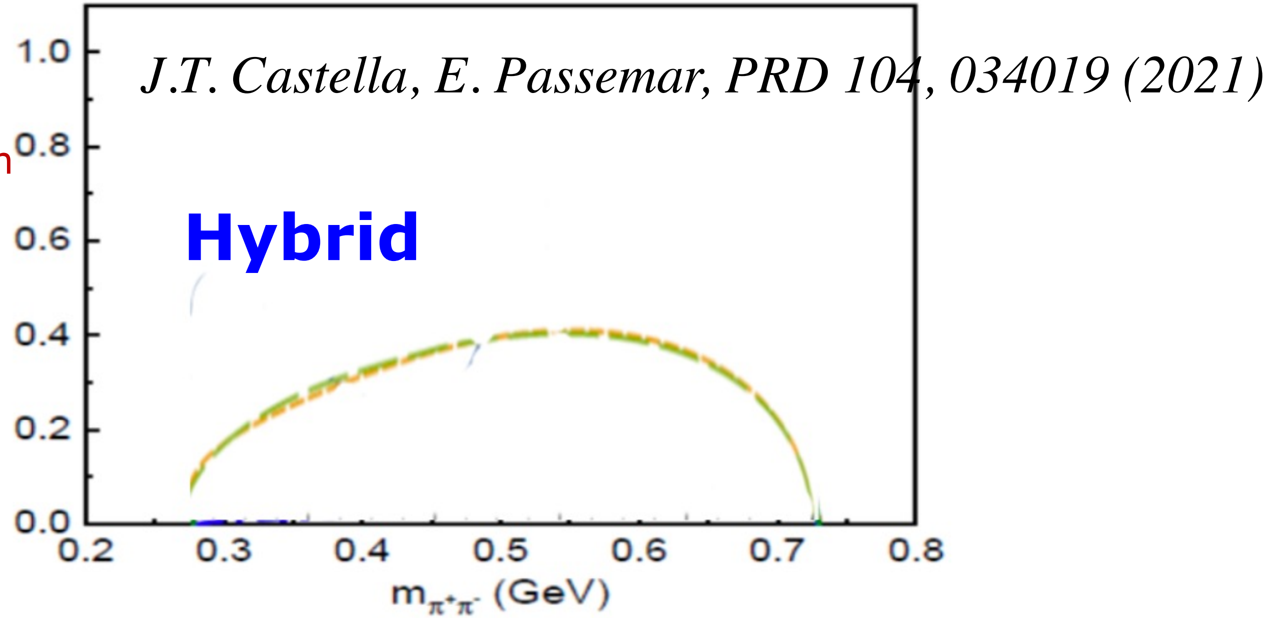
[arXiv: 2401.12021]

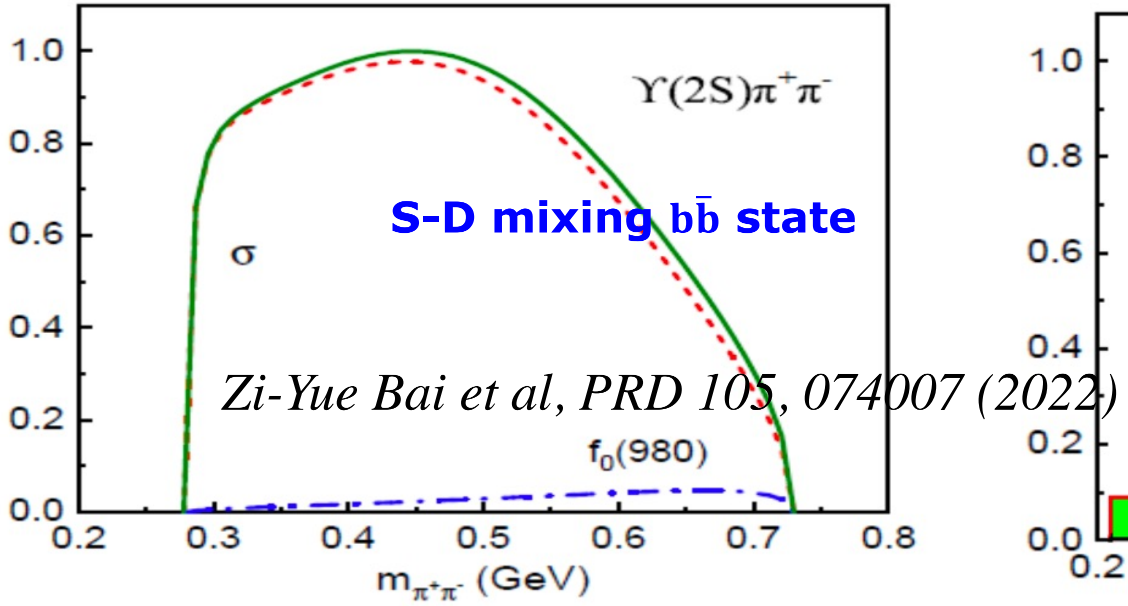
- New measurement confirms previous Belle result.
- Fit: Use coherent sum of Breit-Wigner amplitudes, convolve with a Gaussian to account for energy spread.

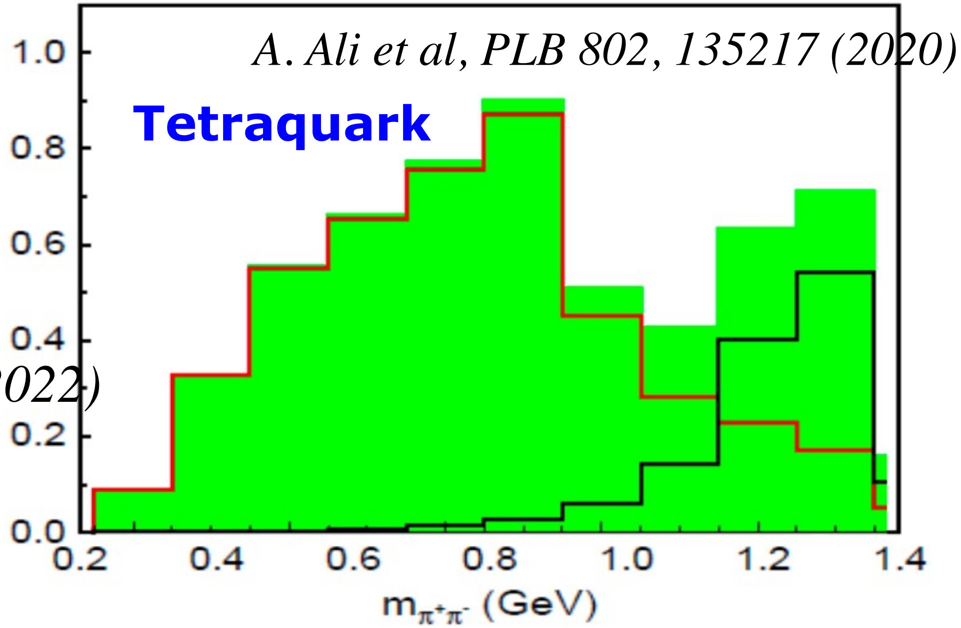
Mass	$(10756.3 \pm 2.7 \pm 0.6)$ MeV/c^2
Width	$(29.7 \pm 8.5 \pm 1.1)$ MeV
$\mathcal{R}^{\Upsilon(10753)}_{\sigma(1S/2S)}$	$0.46^{+0.15}_{-0.12}$
$\mathcal{R}^{\Upsilon(10753)}_{\sigma(3S/2S)}$	$0.10^{+0.05}_{-0.04}$

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









Summary

- Some new results from scan data around 10.75 GeV from Belle II help us understand the structure of $\Upsilon(10753)$.

- New decay mode of $\Upsilon(10753) \rightarrow \omega\chi_{bJ}$
- Rapid increase of $\sigma_{B^*\bar{B}^*}$ above the threshold
- A strengent upper limit for $e^+e^- \rightarrow \omega\eta_b(1S)$
- The mass and width of $\Upsilon(10753)$ with improved precision using $\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(nS)$

Thanks for your attention!