Studies of Hadron Spectroscopy at Belle and Belle II

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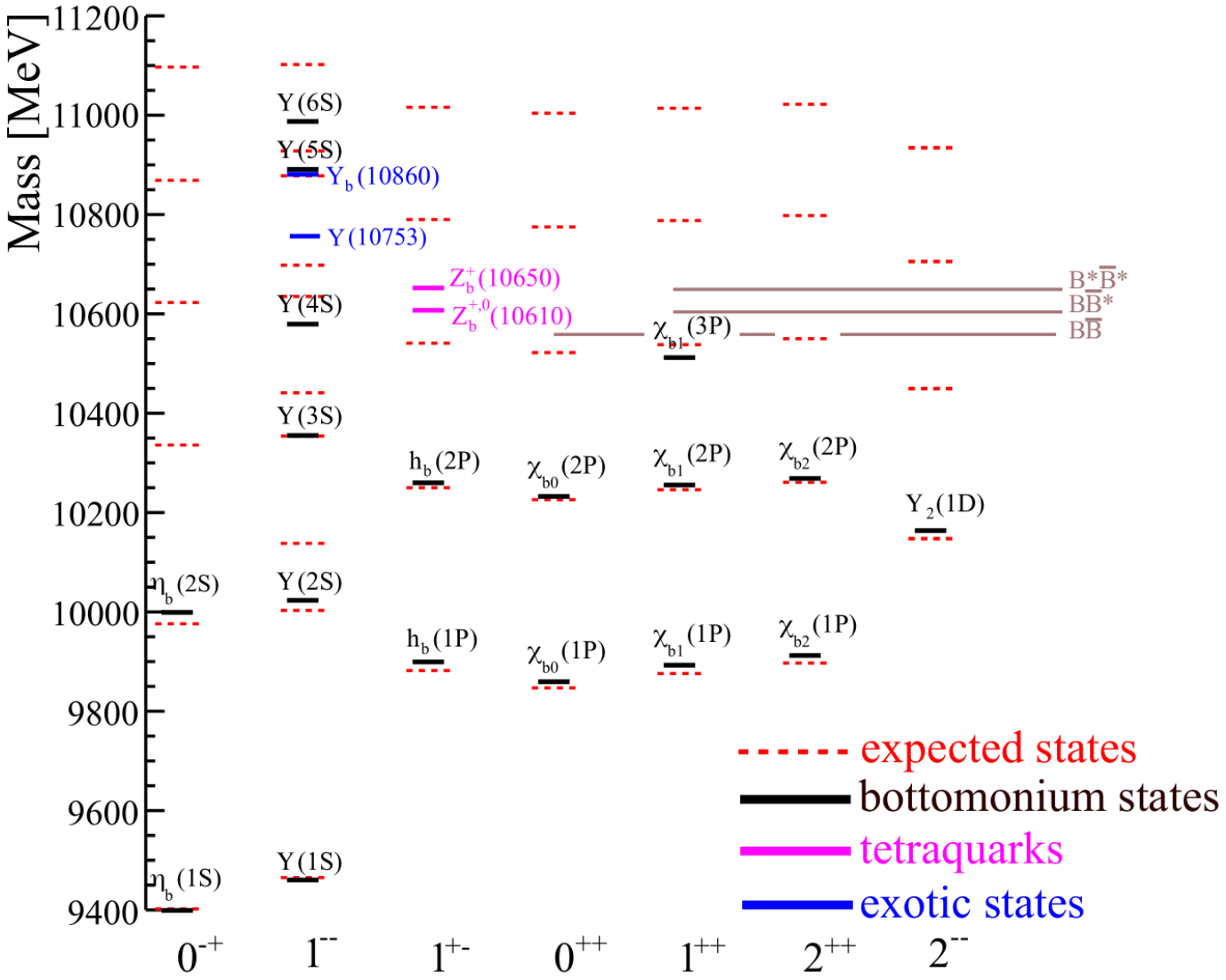
Bottomonium family



Bound state of $b\bar{b}$

•Below the $B\overline{B}$ threshold states are well described by potential models:

$$\Gamma(\Upsilon(2,3S) \to \Upsilon(1S)\pi^+\pi^-) \sim \text{keV}$$

$$\Gamma(\Upsilon(2,3S) \to \Upsilon(1S)\eta) \sim 10^{-3}\ \text{keV}$$

•Above $B\overline{B}$ – anomalous rate of $\pi^+\pi^-, \eta$ transitions:

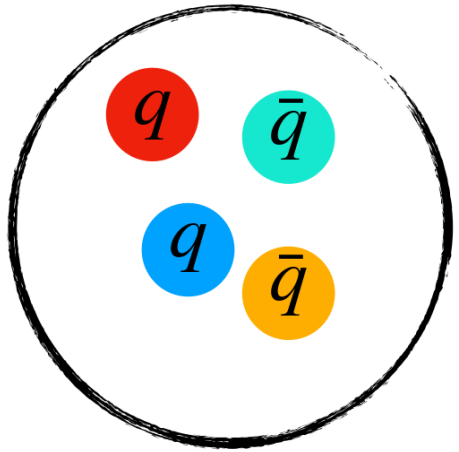
$$\Gamma(\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-) \sim 10^2\ \text{keV}$$

$$\frac{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\eta)}{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-)} = 2.41 \pm 0.42$$

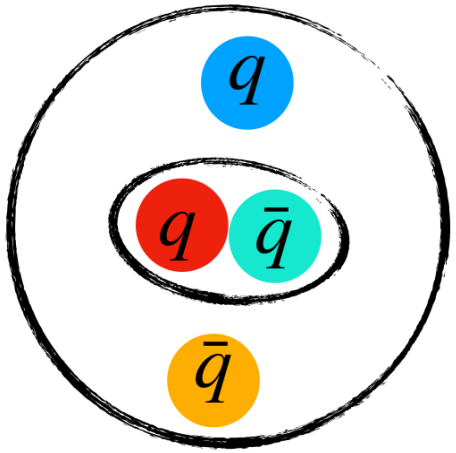
•Unexpected states:

tetraquarks $Z_b(10610, 10650)$ with $I^G(J^{PC}) = 1^+(1^{+-})$, $\Upsilon(10753)$

Structures above $B\overline{B}$ threshold

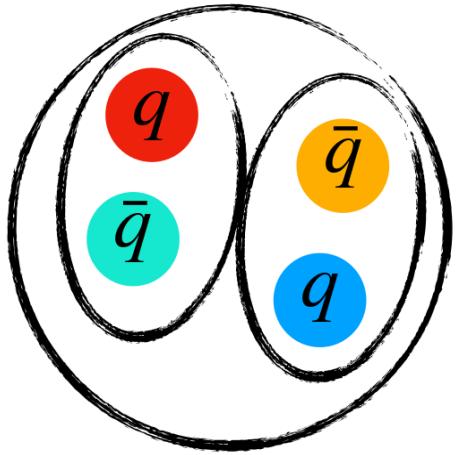


tetraquark

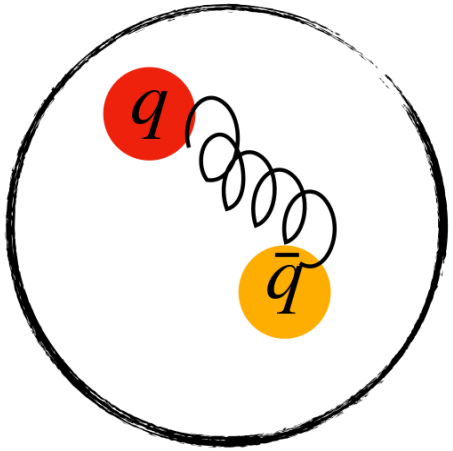


hadro-quarkonium

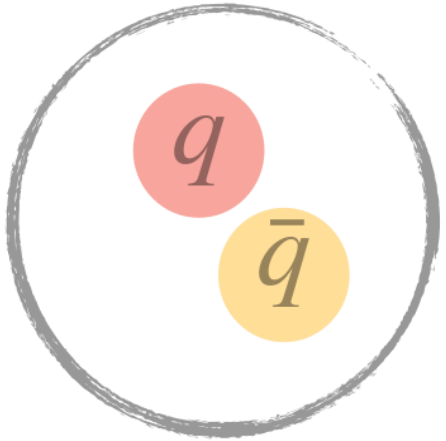
- Unexpected states observed similar with charmonium (X(3872), Y(4260))
- No definite interpretations
- Better understanding is needed



hadronic molecule



hybrid

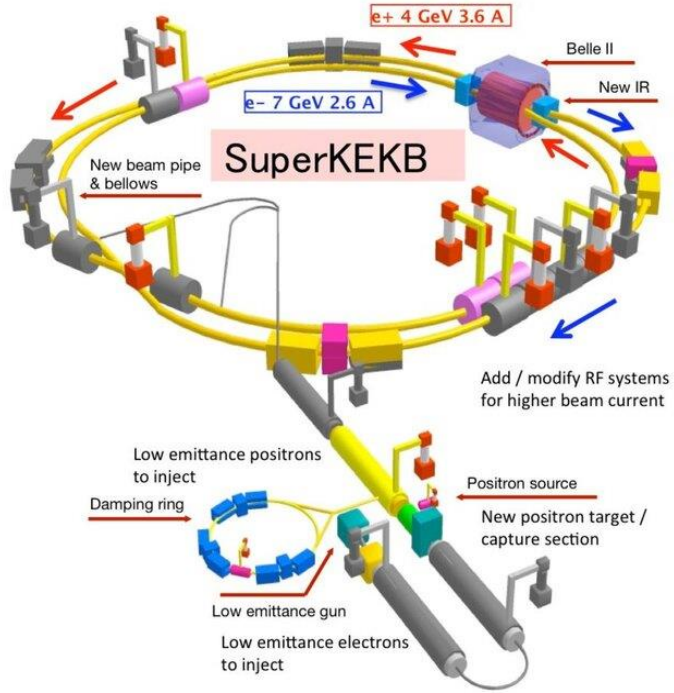


convensional meson (Including S-D state mixing)

Belle and Belle II experiments

Conducted at KEKB/SuperKEKB colliders, Japan

- Asymmetric e^+e^- colliders
- Center-of-Mass energy mostly at $10.58\ \mathrm{GeV}$ $(\Upsilon(4S))$



KEKB

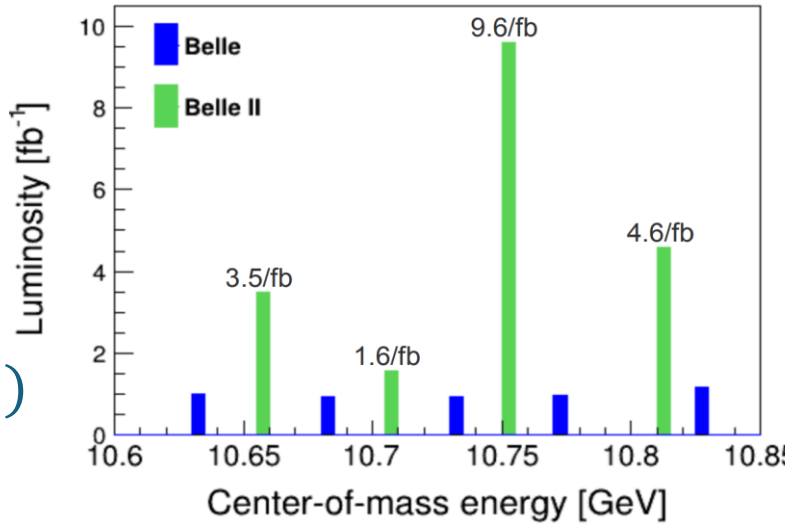
1999-2010

- $e^+\ (3.5\ \mathrm{GeV})\ e^-\ (8\ \mathrm{GeV})$
- $L_{peak} = 2.1 \times 10^{34} cm^{-2} s^{-1}$
- $\int Ldt = \begin{cases} 988\ fb^{-1}\ in\ total \\ 21\ fb^{-1}\ scan\ data \\ 121\ fb^{-1}\ at\ \Upsilon(5S) \end{cases}$

SuperKEKB

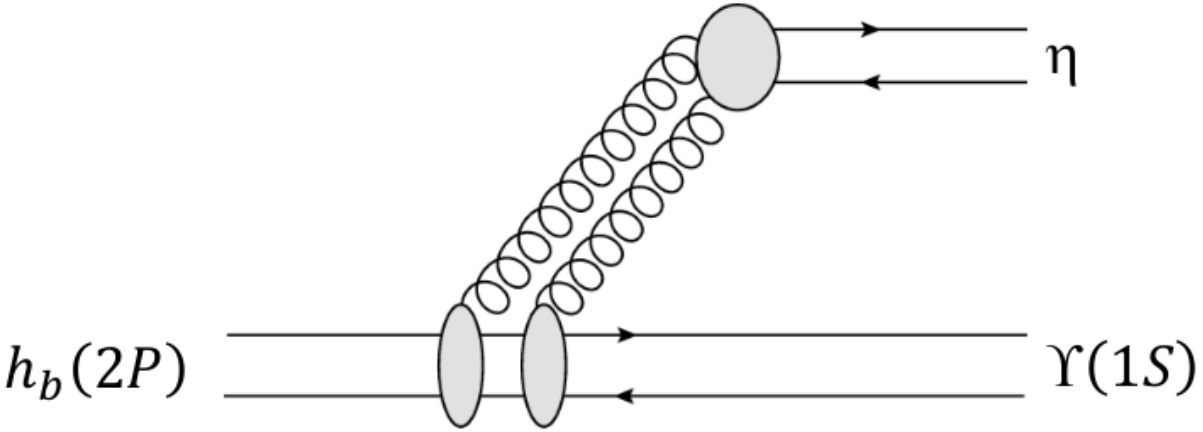
2018-current

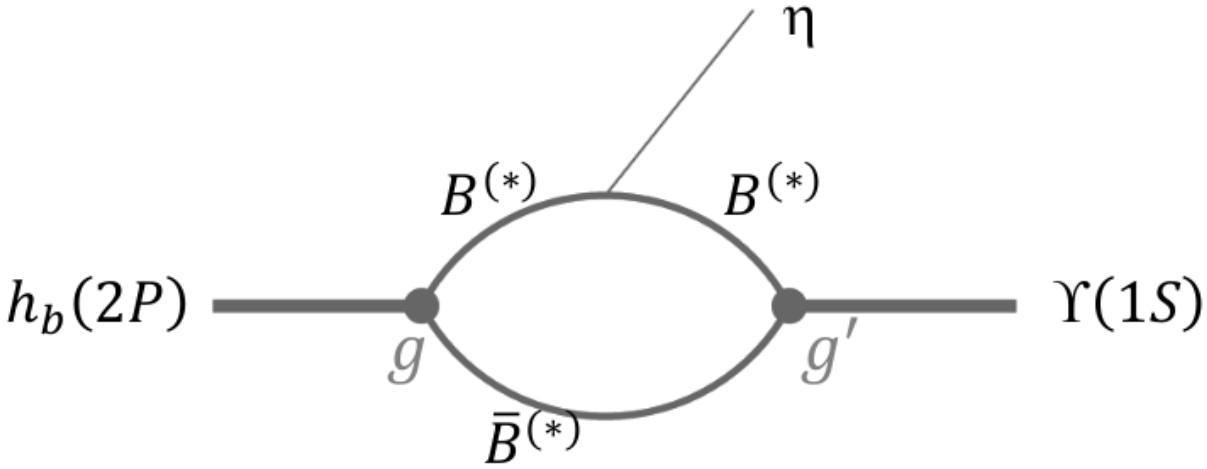
- $e^+\ (4\ \mathrm{GeV})\ e^-\ (7\ \mathrm{GeV})$
- $L_{peak} = 5.1 \times 10^{34} cm^{-2} s^{-1}$
- $\int Ldt = \begin{cases} 575\ fb^{-1}\ in\ total \\ 20\ fb^{-1}\ at\ \Upsilon(10753) \end{cases}$
- Target $\int Ldt \sim 50\ ab^{-1}$



Search for $h_b(2P) \to \Upsilon(1S)\eta$

Transitions between spin-singlet ($S_{q\bar{q}} = 0$) and spin-triplet ($S_{q\bar{q}} = 1$) are suppresed ($\sim 1/m_b$)





Suppression might be lifted due to hadron loops (coupled-channel effect)

BaBar: PRD 84, 091101 (2011)

$\mathcal{B}(\Upsilon(3S) \to h_b(1P)\pi^0) \sim 10^{-3}$ with significance 3.1σ

Prediction based on BaBar result: PRD 86, 094013 (2012)

$\mathcal{B}(h_b(2P) \to \Upsilon(1S)\eta) \sim 10\%$

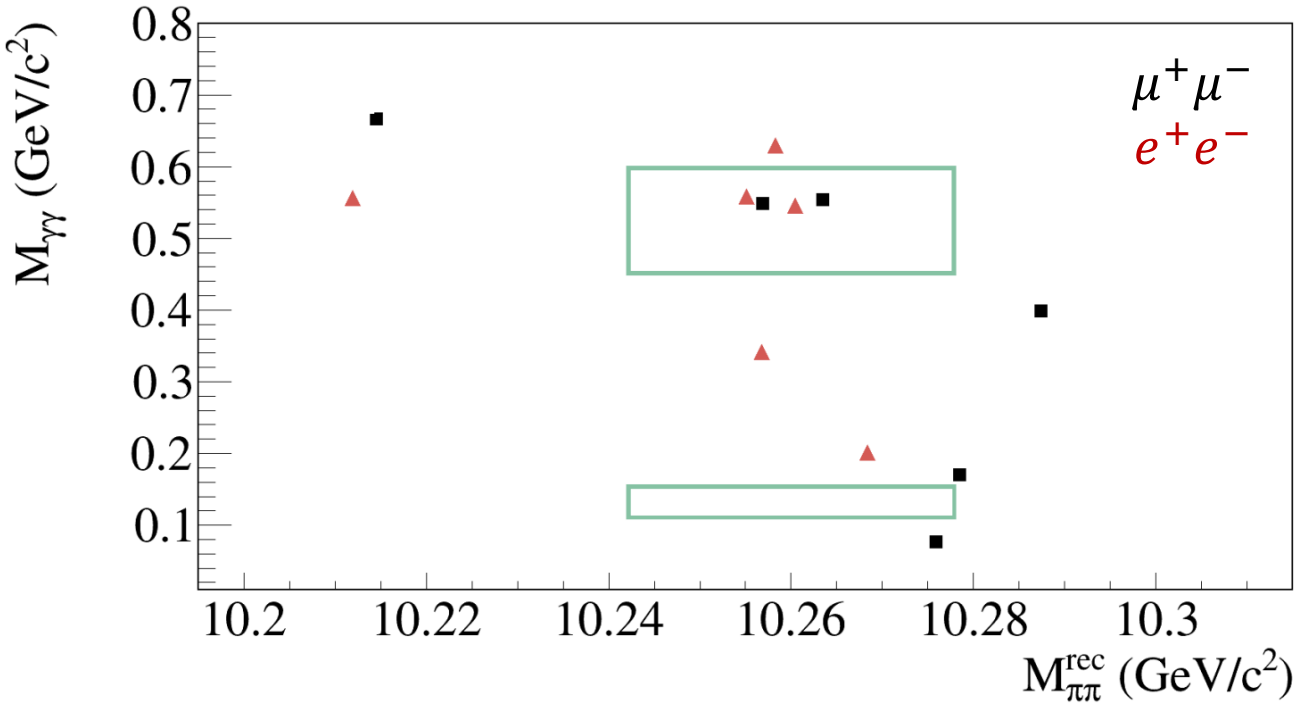
Evidence for $h_b(2P) \to \Upsilon(1S)\eta$

PRL 133, 261901 (2024)

$\Upsilon(5S)$ Belle data: $121\ fb^{-1}$.

Full reconstruction: $\Upsilon(5S) \to Z_b^+\pi^- \to h_b(2P)\pi^+\pi^-$

$h_b(2P) \to \Upsilon(1S)\eta \to (e^+e^-, \mu^+\mu^-)\,(\gamma\,\gamma)$



2D fit to $M_{rec}(\pi^+\pi^-)\ vs.\ M(\gamma\gamma)$

$$M_{rec}(\pi^+\pi^-) = \sqrt{\left(\frac{\sqrt{s}}{2} - E_{\pi^+\pi^-}\right)^2 - p^2_{\pi^+\pi^-}}$$

Significance: 3.5σ including systematics

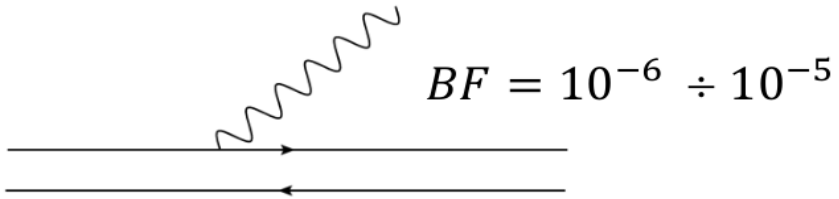
$\mathcal{B}(h_b(2P) \to \Upsilon(1S)\eta) = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$

10× lower than the expectations based on experimental $\mathcal{B}(\Upsilon(3S) \to h_b(1P)\pi^0)$.

No signal of isospin violating decay $h_b(2P) \to \Upsilon(1S)\pi^0$: $\mathcal{B} < 1.8 \times 10^{-3}$

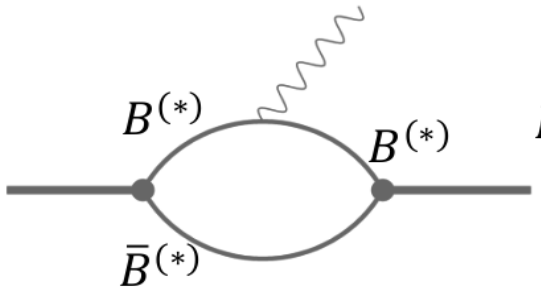
Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

PRD 111, L011102 (2025)



$BF = 10^{-6} \div 10^{-5}$

PRD 32, 189 (1985)



$BF = 10^{-2} \div 10^{-1}$

PLB 760, 417 (2016)

$\Upsilon(5S)$ Belle data: $121\ fb^{-1}$.

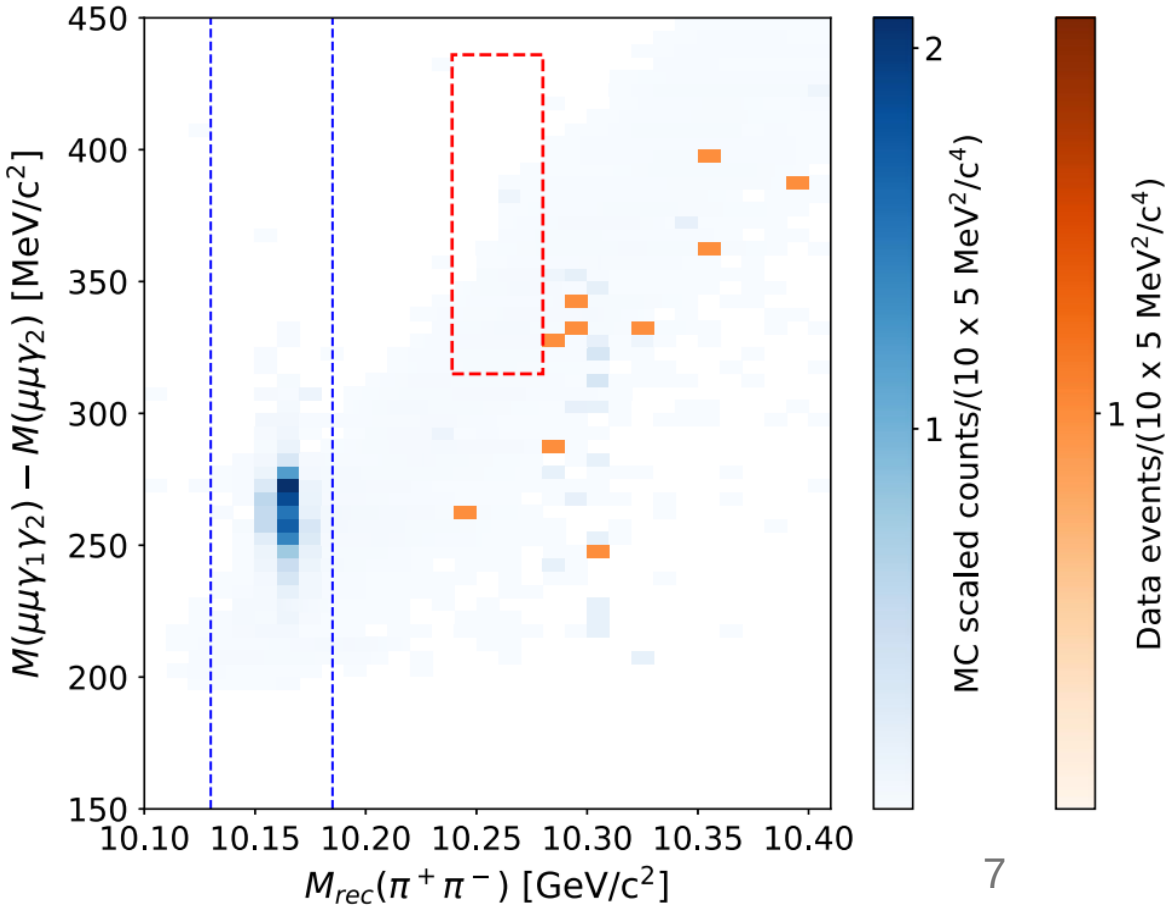
Full reconstruction: $\Upsilon(5S) \to Z_b^+\pi^- \to h_b(2P)\pi^+\pi^-$

$h_b(2P) \to \chi_{bJ}(1P)\gamma_1 \to [\Upsilon(1S)\gamma_2]\gamma_1 \to$
$\to [(\mu^+\mu^-)\gamma_2]\gamma_1$

No events in the signal region:
upper limits at the 90% C.L. are set

Channel	$\mathcal{B}$
$h_b(2P) \to \gamma\chi_{b2}(1P)$	$<1.3 \times 10^{-2}$
$h_b(2P) \to \gamma\chi_{b1}(1P)$	$<5.4 \times 10^{-3}$
$h_b(2P) \to \gamma\chi_{b0}(1P)$	$<2.7 \times 10^{-1}$

ULs are consistent with expectations



Confirmation of $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$

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$\Upsilon(10753)$: observed by Belle, confirmed by Belle II

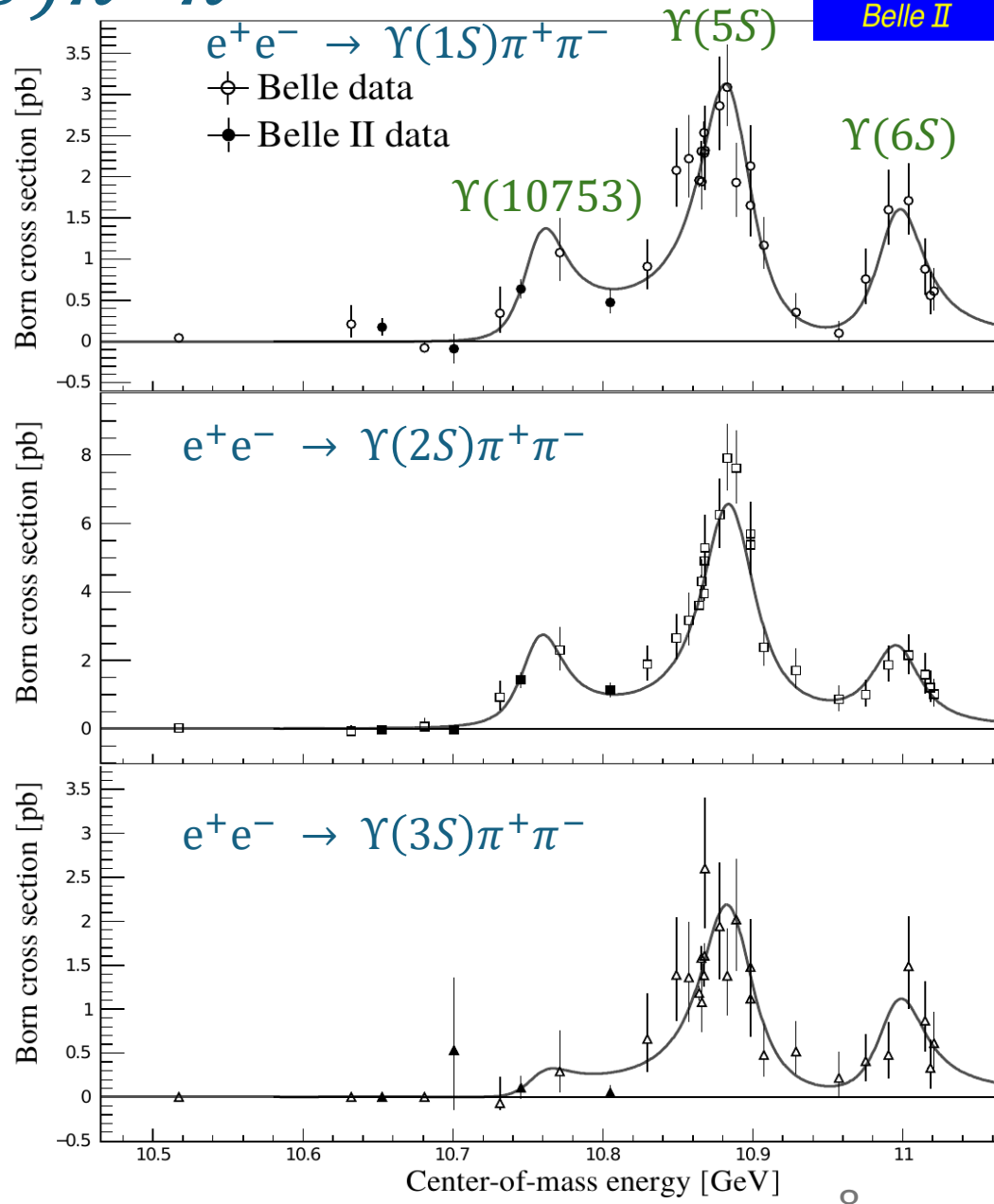
Significance

$\Upsilon(1S)\pi^+\pi^-$	4.1σ
$\Upsilon(2S)\pi^+\pi^-$	7.5σ

$$M = 10756.6 \pm 2.7 \pm 0.9\,\text{MeV}$$
$$\Gamma = 29.0 \pm 8.8 \pm 1.2\,\text{MeV}$$

Interpretations:

- $\Upsilon(3D)$ mixed with $\Upsilon(4S)$ via hadron loops
- hybrid
- compact tetraquark



Resonant substructure in $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$

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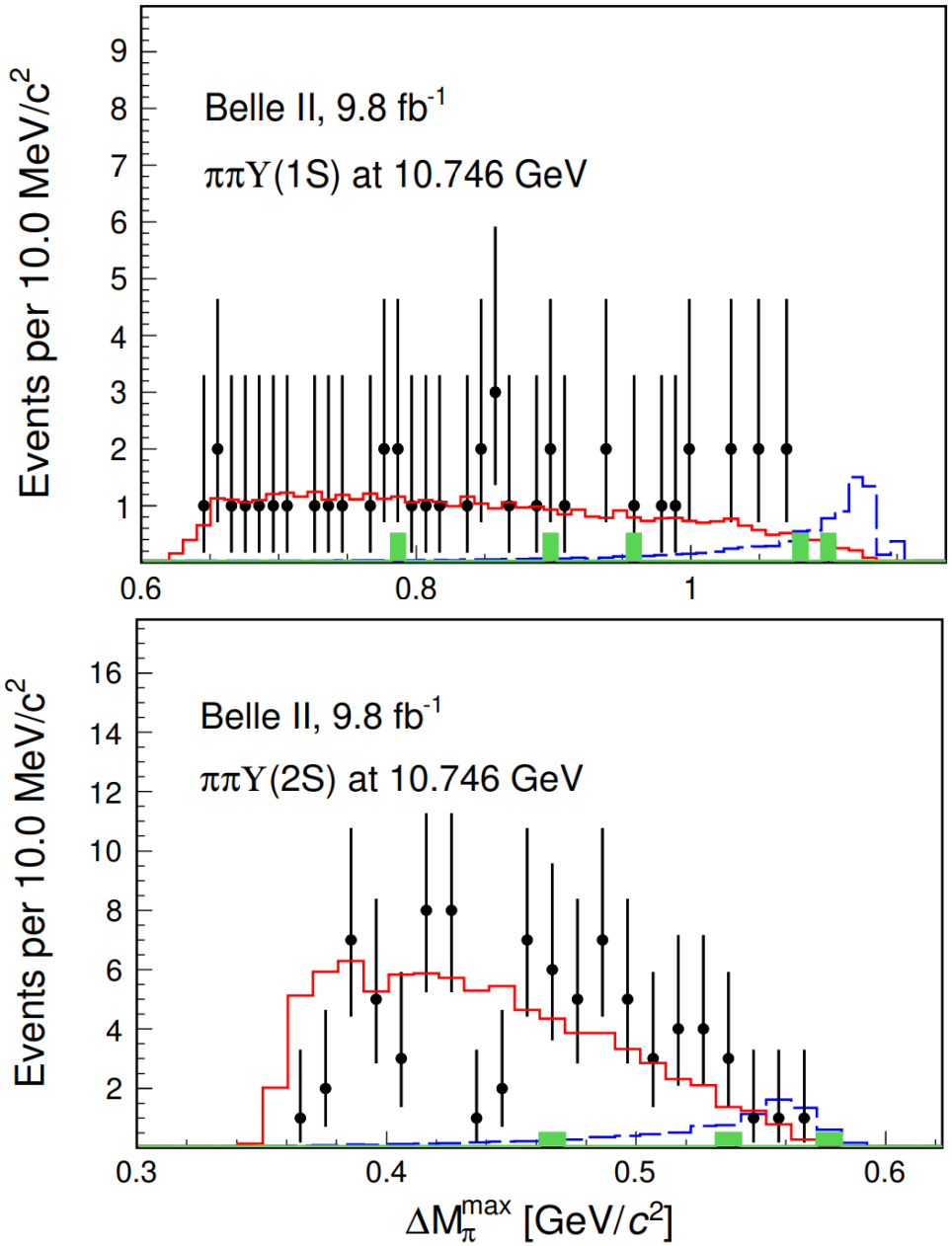

- No signal of intermediate $Z_b^+(10610)$ or $Z_b^+(10650)$ resonances are observed in $M[\Upsilon(nS)\pi^+]$

- ΔM_π distribution is consistent with phase space

$$\Delta M_\pi = M(\pi\mu^+\mu^-) - M(\mu^+\mu^-)$$

Resonant substructure in $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$

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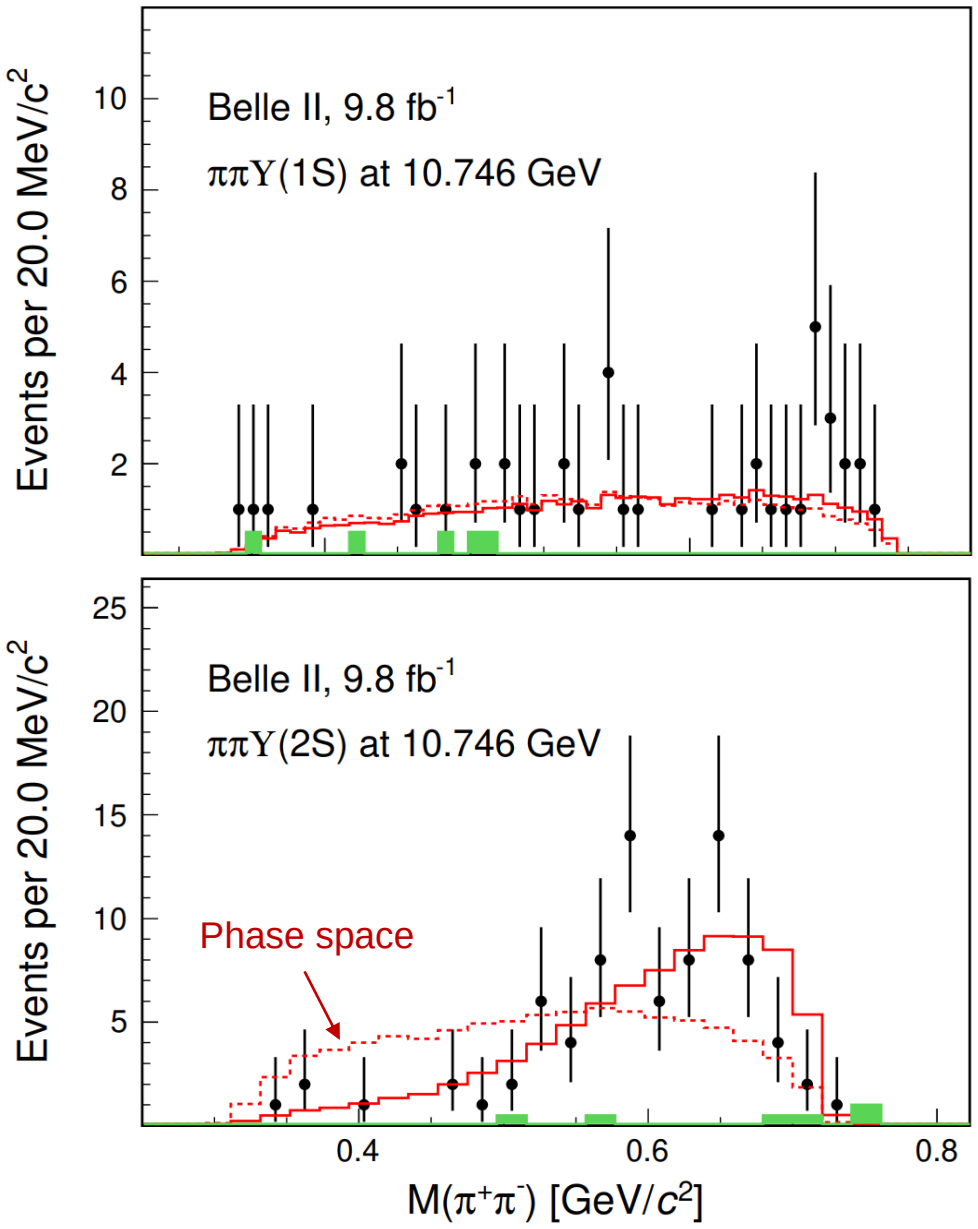
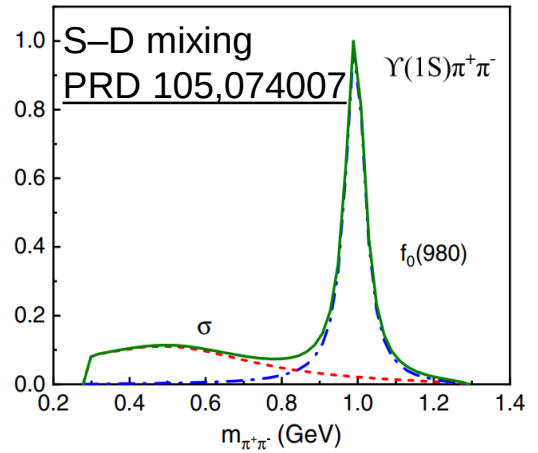
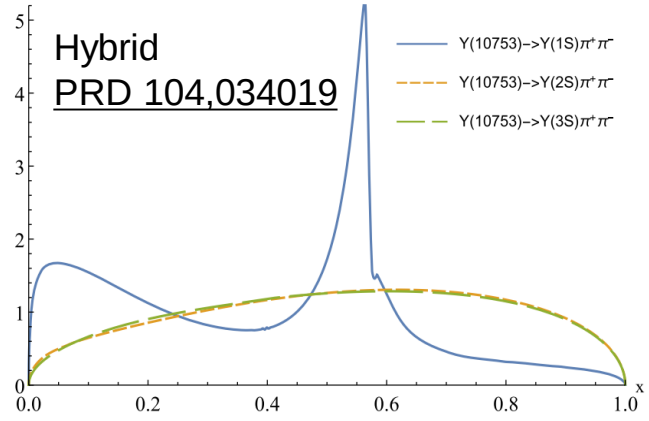
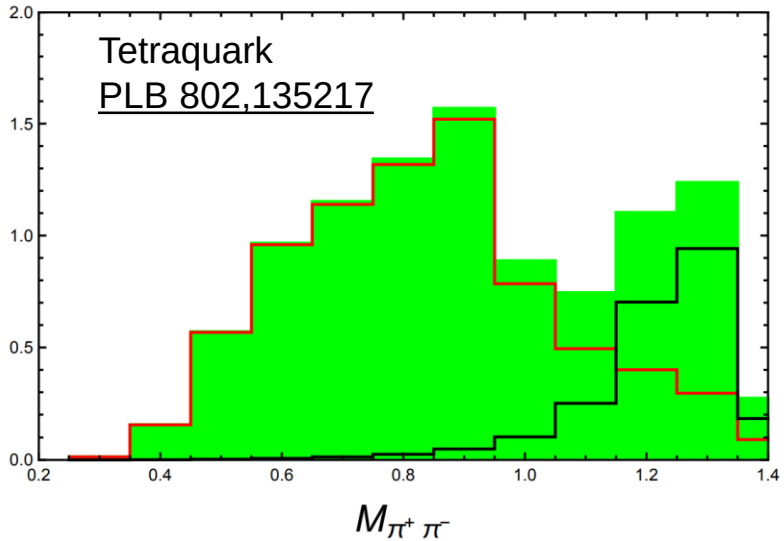


- $\pi^+\pi^-\,\Upsilon(1S)$: models predict production of $f_0(980)$
- $\pi^+\pi^-\,\Upsilon(2S)$: larger values of $M(\pi^+\pi^-)$ enhanced







Search for $\Upsilon(10753) \to \omega\eta_b(1S)$

PRD 109, 072013 (2024)

$\frac{\mathcal{B}(\Upsilon(10753)\to\omega\eta_b)}{\mathcal{B}(\Upsilon(10753)\to\Upsilon\pi^+\pi^-)}$ predictions:

- ~ 30 for tetraquark — CPC 43 (2019) 12, 123102
- $\sim (0.2 - 0.4)$ for 4S-3D mixed state — PRD 109, 014039 (2024)

$\Upsilon(10753)$ Belle II data: $9.8\ fb^{-1}$

Partial reconstruction: $\omega \to \pi^+\pi^-\pi^0$.

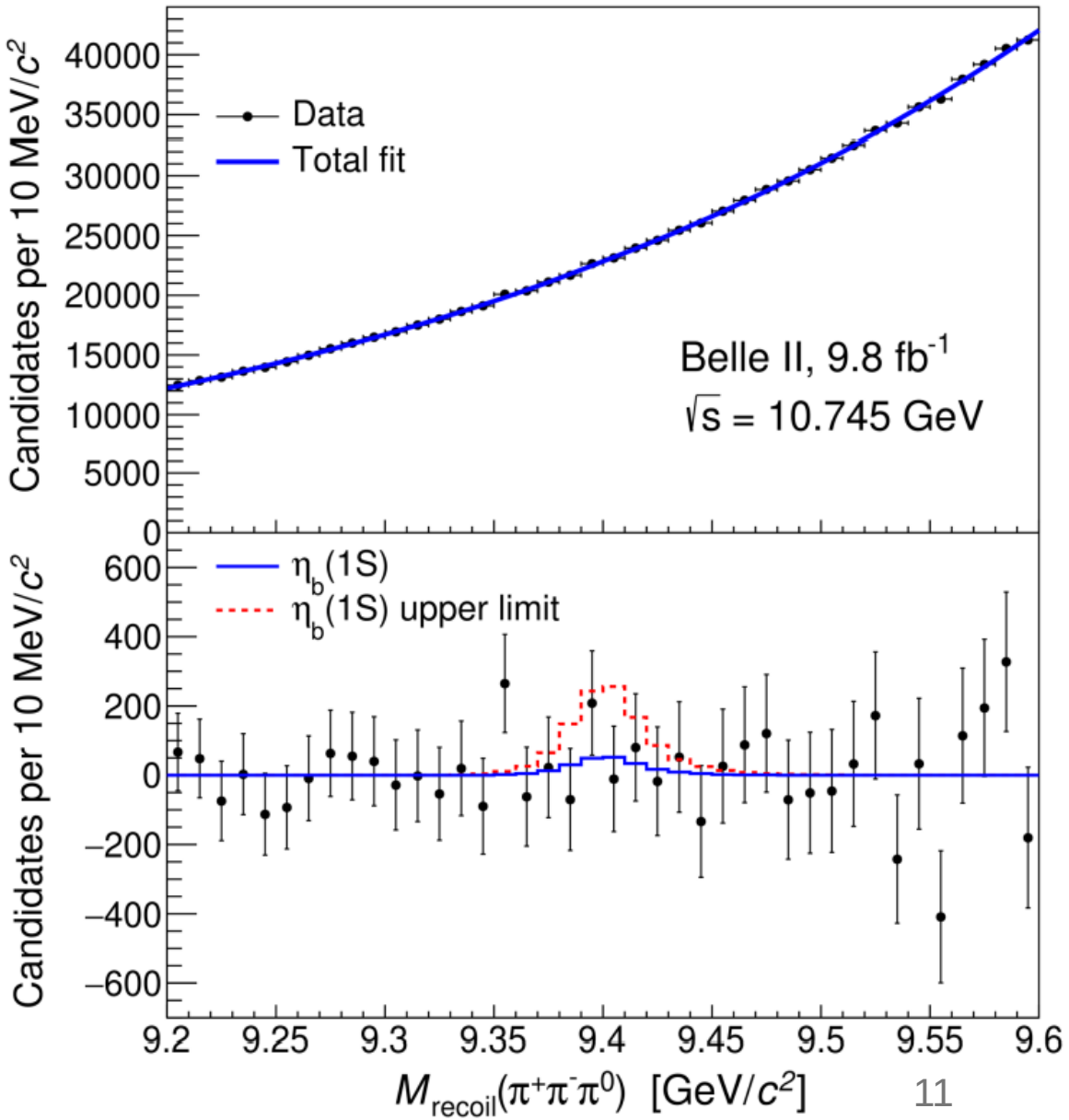
1D fit to $M_{recoil}(\pi^+\pi^-\pi^0)$

No significant signal is observed

$\sigma(e^+e^- \to \omega\eta_b(1S))/\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-) < 1.25$

Evidence against the tetraquark model predictions.

Compatible with S − D mixed model



Energy dependence of $\sigma(e^+e^- \to \omega\chi_{bJ}(1P))$

Preliminary

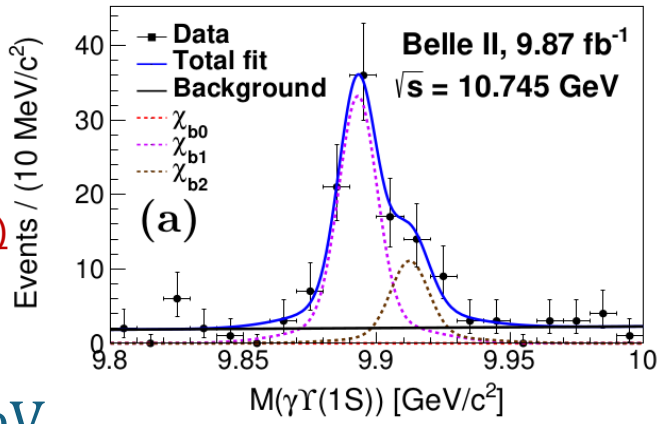
$\frac{\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b1})}{\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b2})}$ predictions:

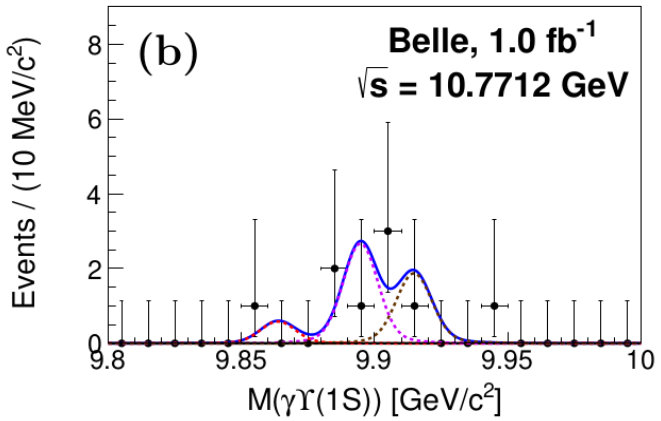
- ~ 15 for pure $\Upsilon(3D)$ state PLB 738, 172 (2014)
- ~ 0.2 for 4S-3D mixed state PRD 104, 034036 (2021)

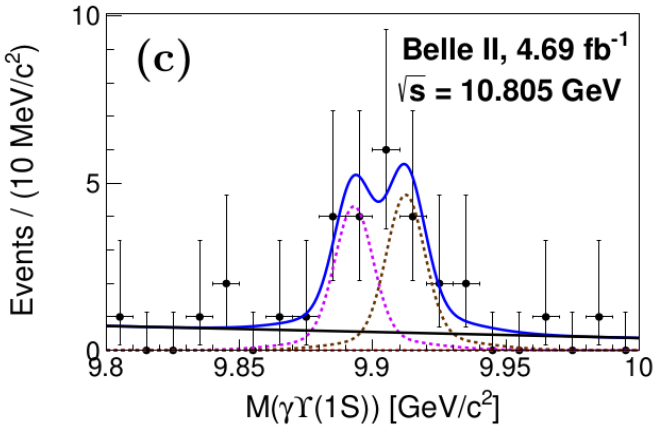
Scan Belle and Belle II data in $(10.73 - 11.02)$ GeV

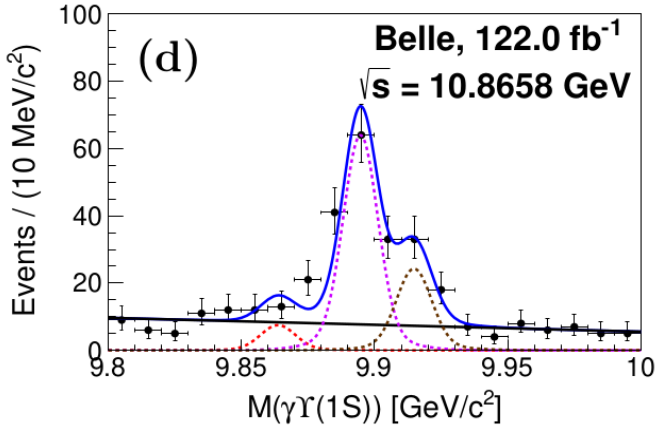
Full reconstruction: $e^+e^- \to \omega\chi_{bJ}(1P)$,
$\omega \to \pi^+\pi^-\pi^0, \chi_{bJ}(1P) \to \gamma\Upsilon(1S) \to \gamma(l^+l^-)$

Search for $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}(1P)$
with the same final state



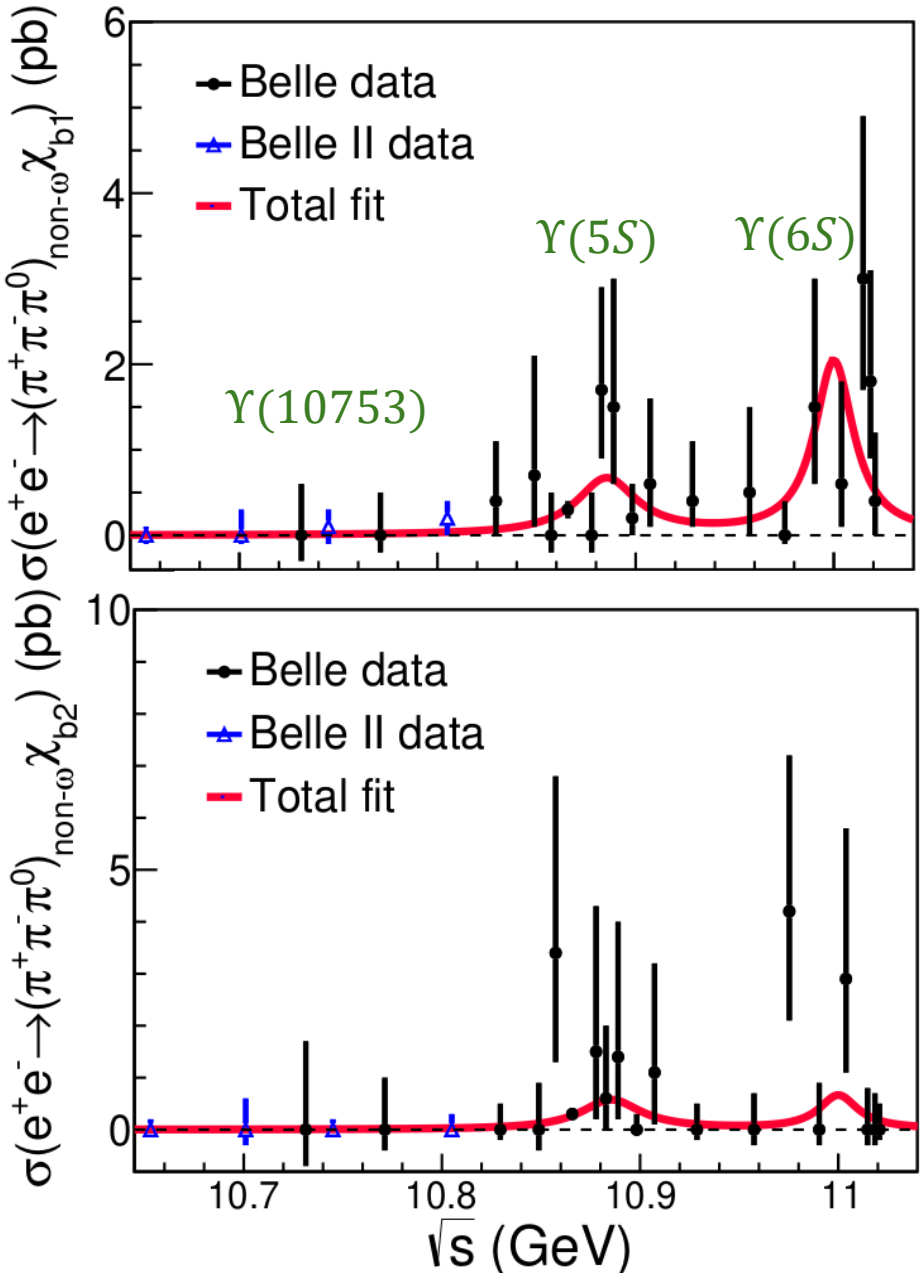






Dependence of $\sigma(e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega\chi_{bJ}}(1P))$

Preliminary

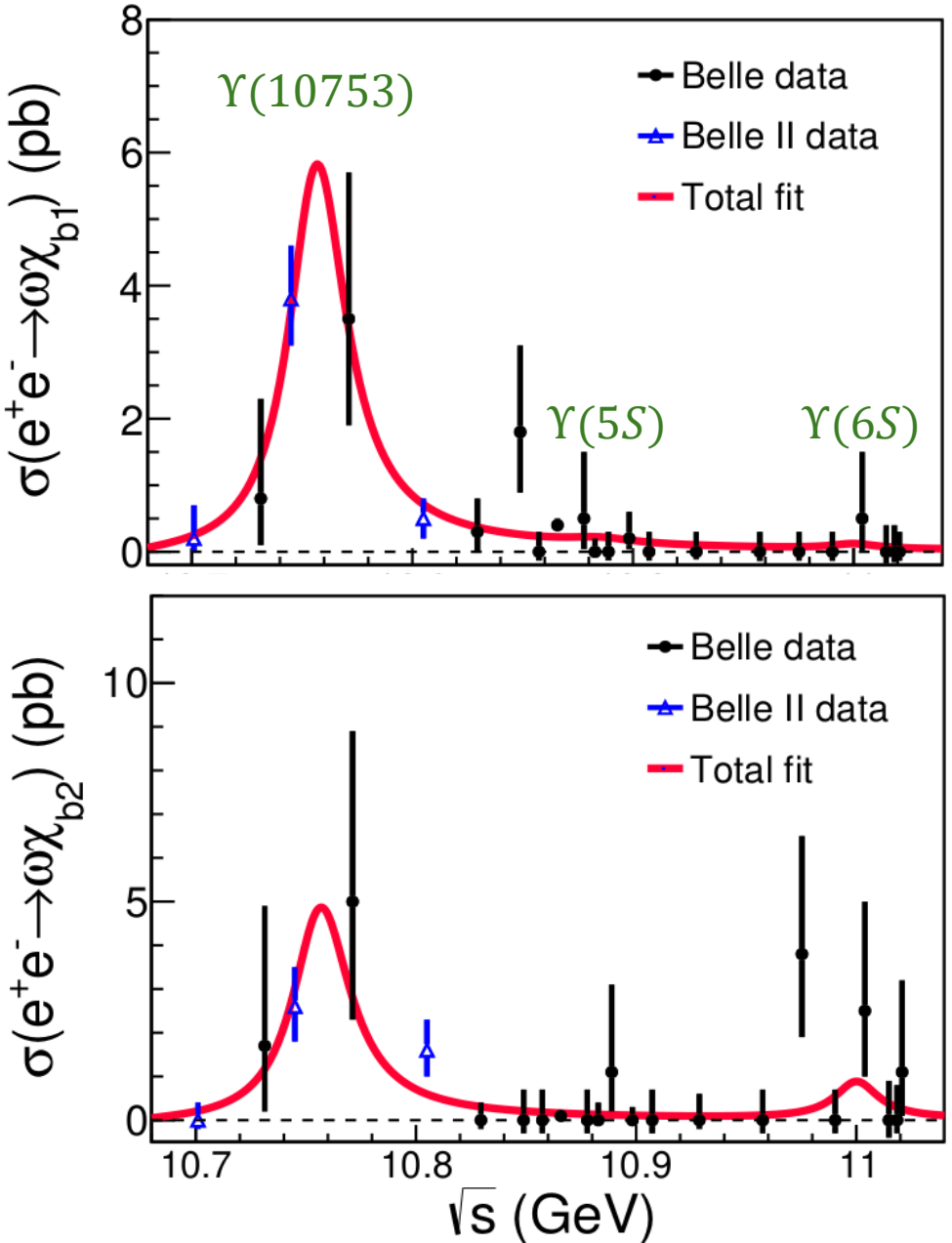


Decays of $\Upsilon(5S)$ and $\Upsilon(6S)$ into $(\pi^+\pi^-\pi^0)_{non-\omega\chi_{bJ}}(1P)$

$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to (\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega\chi_{b1}})$	$(0.00 \pm 0.05 \pm 0.02)$ eV (<0.08 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to (\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega\chi_{b2}})$	$(0.00 \pm 0.03 \pm 0.02)$ eV (<0.07 eV)
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to (\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega\chi_{b1}})$	$(0.26 \pm 0.08 \pm 0.12)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(10860) \to (\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega\chi_{b2}})$	$(0.17 \pm 0.05 \pm 0.04)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to (\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega\chi_{b1}})$	$(0.48 \pm 0.19 \pm 0.18)$ eV
$\Gamma_{ee}\mathcal{B}(\Upsilon(11020) \to (\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega\chi_{b2}})$	$(0.14 \pm 0.12 \pm 0.10)$ eV

Predicted $\Upsilon(10860, 11020) \to Z_b\pi \to \chi_{bJ}(1P)\rho\pi$ (?)

Energy dependence of $\sigma(e^+e^- \to \omega\chi_{bJ}(1P))$



Preliminary

$$M = 10756.1 \pm 3.4 \pm 2.7\ \text{MeV}$$
$$\Gamma = 32.2 \pm 11.3 \pm 14.9\ \text{MeV}$$

Mass and width are consistent with $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$

$$\left.\frac{\sigma(e^+e^- \to \omega\chi_{b1})}{\sigma(e^+e^- \to \omega\chi_{b2})}\right|_{\Upsilon(10753)} = 1.5 \pm 0.6$$

Does not support pure 3D, 2.2σ discrepancy from S-D mixing

$$\frac{\Gamma(\Upsilon(nS)\pi^+\pi^-)}{\Gamma(\omega\chi_{bJ})} = \begin{cases} < 0.9\ at\ \Upsilon(10753) \\ > 28.1\ at\ \Upsilon(5S) \end{cases}$$

Different structure?

Energy dependence of $B^{(*)}\bar{B}^{(*)}$ cross sections at Belle II

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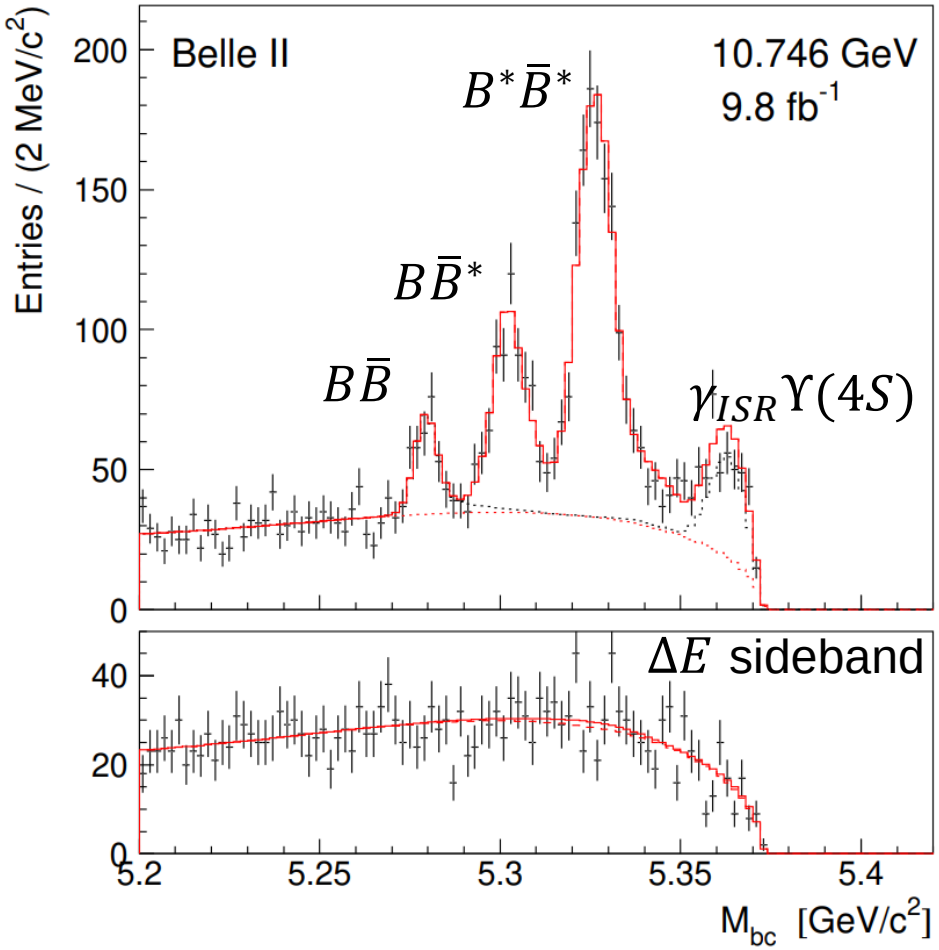
Full reconstruction of one B in the event



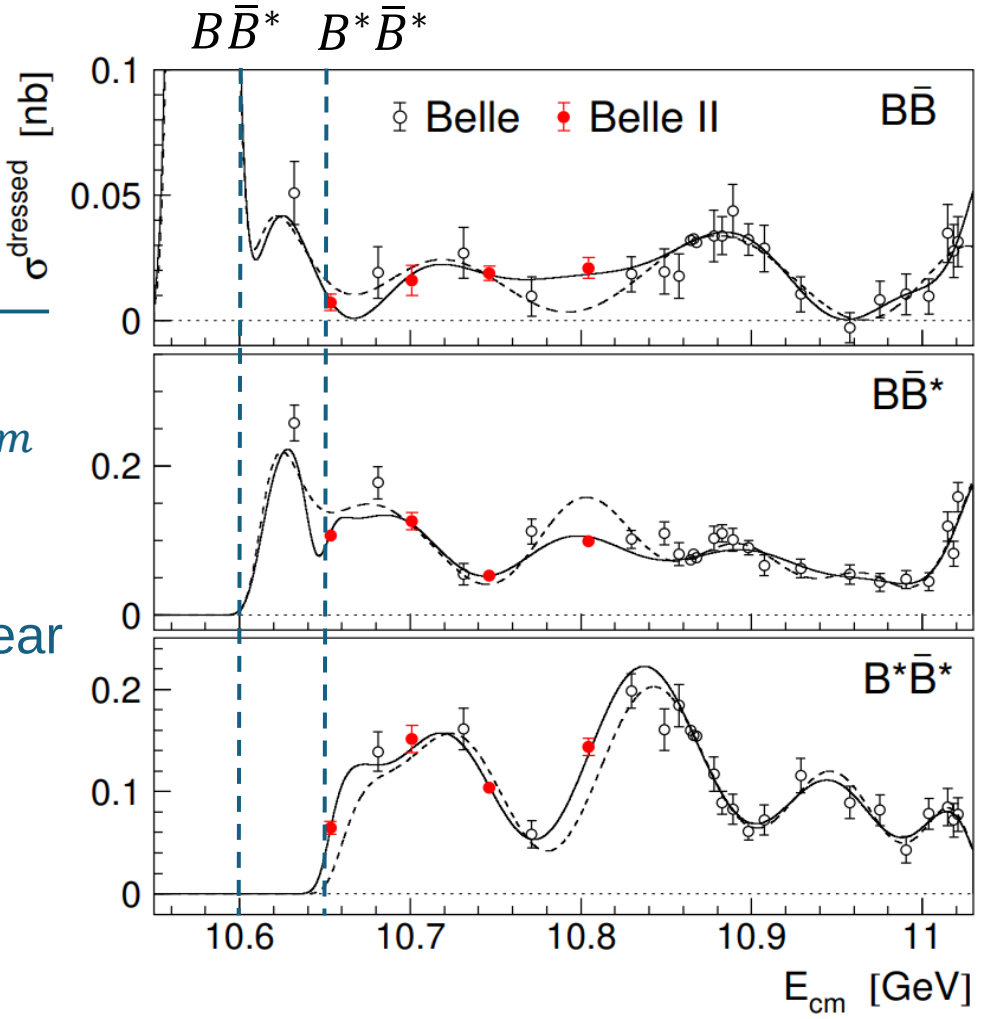
Process is identified by M_{bc} (p_{cm}):

$$M_{bc} = \sqrt{\left(\frac{E_{cm}}{2}\right)^2 - p_{cm}^2}$$

Rapid rise of $\sigma(B^*\bar{B}^*)$ near threshold.

$B^*\bar{B}^*$ are in P-wave: $PHSP \sim p_B^3$

$B^*\bar{B}^*$ molecular state (?)



Summary and conclusions

- Continued studies of conventional and potentially exotic states at Belle and Belle II (with growing datasets)
- Much higher significance confirmation of the $\Upsilon(10753)$ by Belle II:

  - Improved results for mass and width using $\Upsilon(10753) \rightarrow \Upsilon(nS)\pi^+\pi^-$
  - Current experimental and theoretical accuracy does not allow drawing conclusions on the $\Upsilon(10753)$ nature
  - Additional studies underway ($h_b(1P)\eta$, $\Upsilon(nS)\eta$, etc)

- Only 1% of target integrated luminosity collected so far – much more to come!