TWENTY-SECOND LOMONOSOV CONFERENCE **August, 21-27, 2025**
ON ELEMENTARY PARTICLE PHYSICS
MOSCOW STATE UNIVERSITY

Quarkonium Physics at Belle and Belle II

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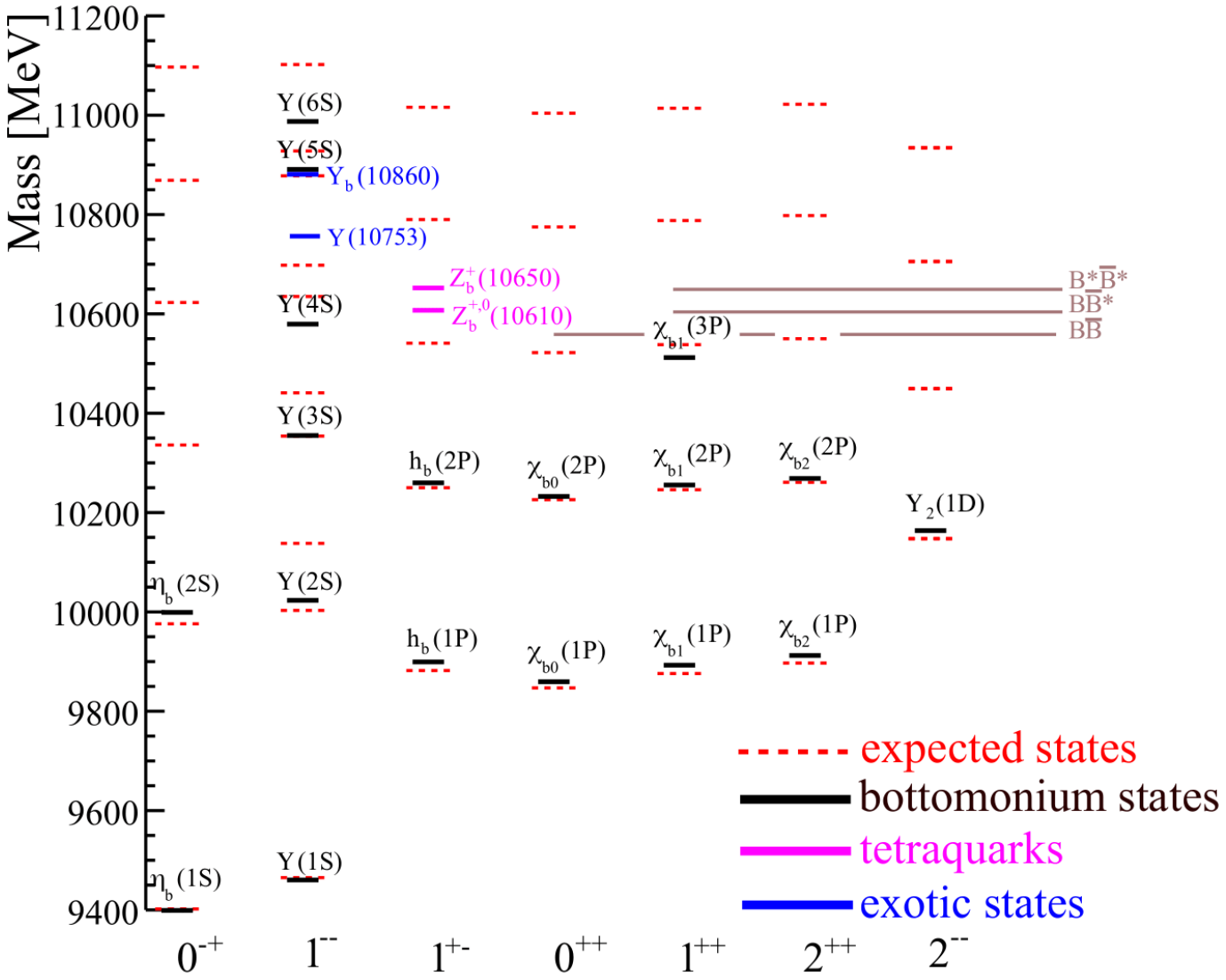
on behalf of Belle II collaboration

Bottomonium family



Bound state of $b\bar{b}$

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

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

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

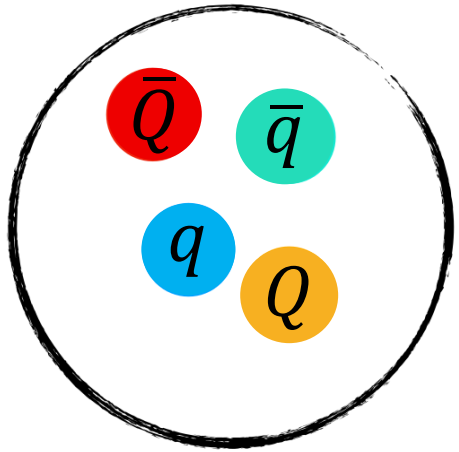
- Above $B\bar{B}$ – anomalous rate of $\pi^+\pi^-, \eta$ transitions:

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

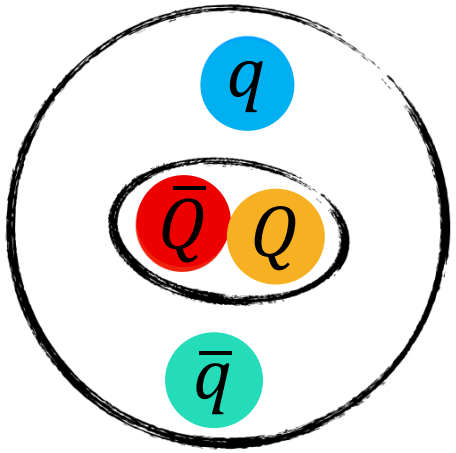
$$\frac{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\eta)}{\Gamma(\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-)} = 2.41 \pm 0.42$$

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

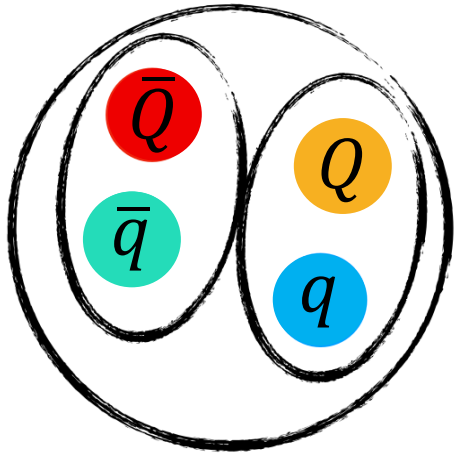
Structures above $B\overline{B}$ threshold



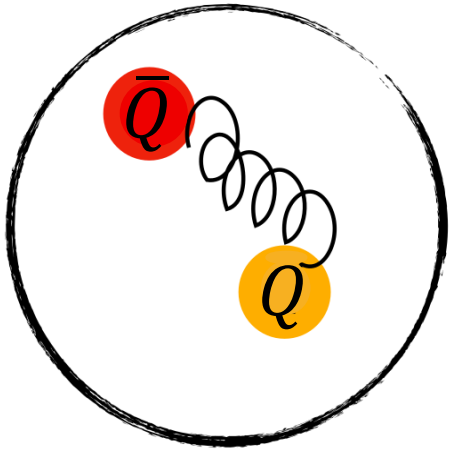
tetraquark



hadro-quarkonium

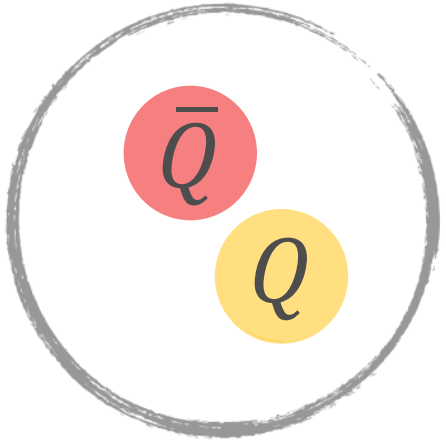


hadronic molecule



hybrid

- Unexpected states observed similar with charmonium: $X(3872)$, $Y(4230)$
- No definite interpretations
- Better understanding is needed

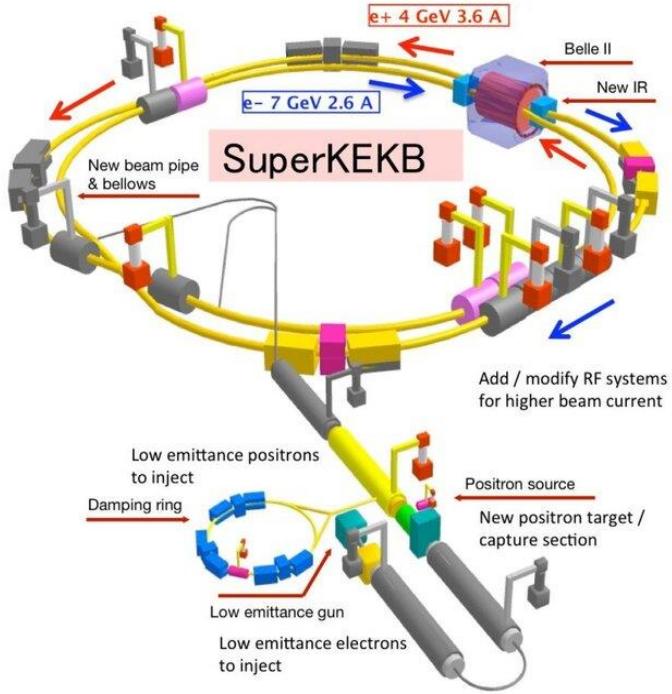


convensional meson (Including S-D state mixing)

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

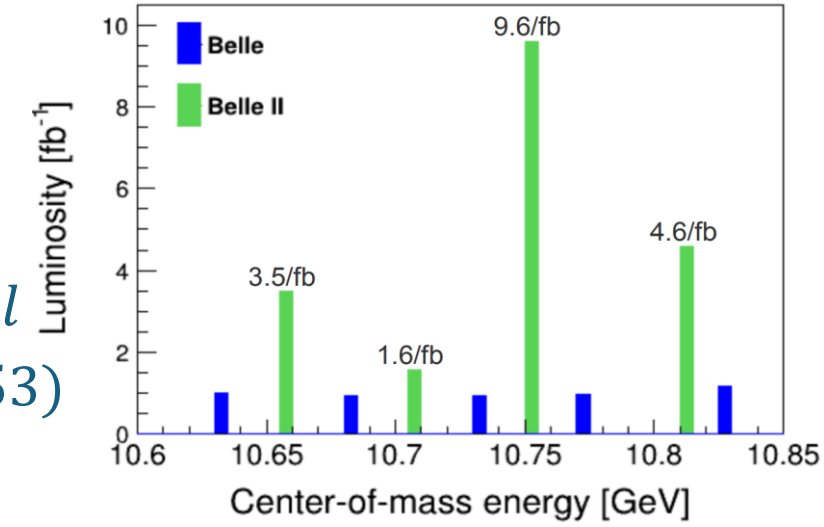
1999-2010

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

SuperKEKB

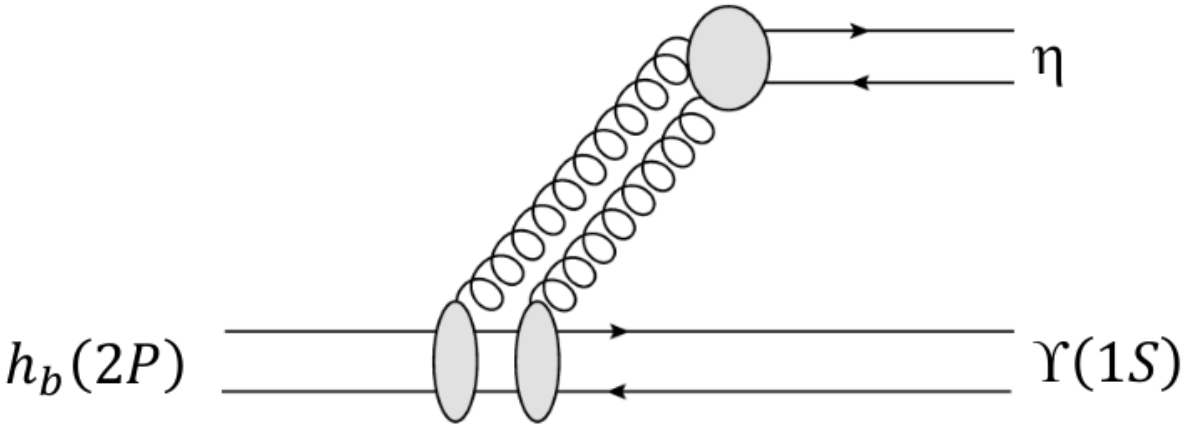
2018-current

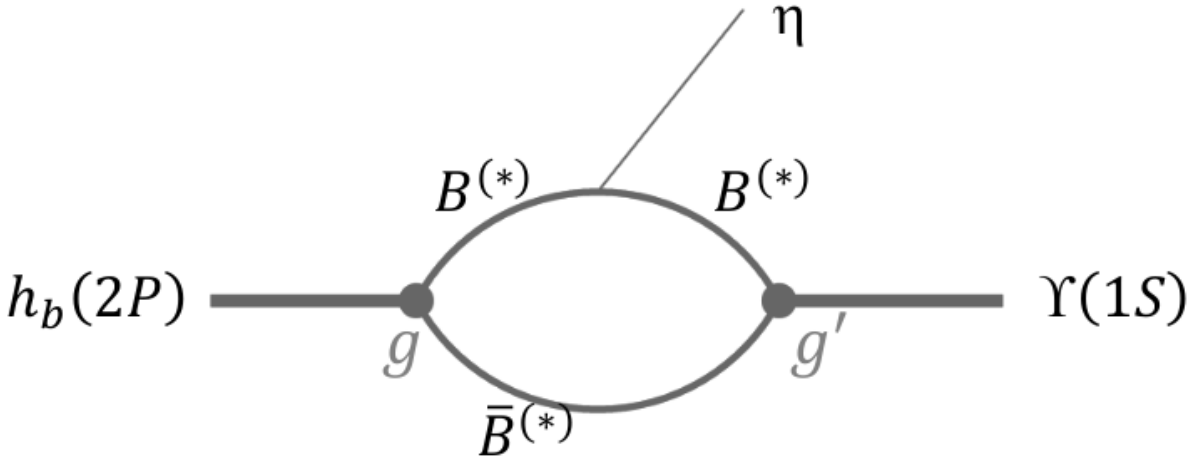
- $e^+\ (4\ \mathrm{GeV})\ e^-\ (7\ \mathrm{GeV})$
- $L_{peak} = 5.1 \times 10^{34} cm^{-2} s^{-1}$
- $\int Ldt = \begin{cases} 575\ fb^{-1}\ in\ total \\ 20\ fb^{-1}\ at\ \Upsilon(10753) \end{cases}$
- Target $\int Ldt \sim 50\ ab^{-1}$



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

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

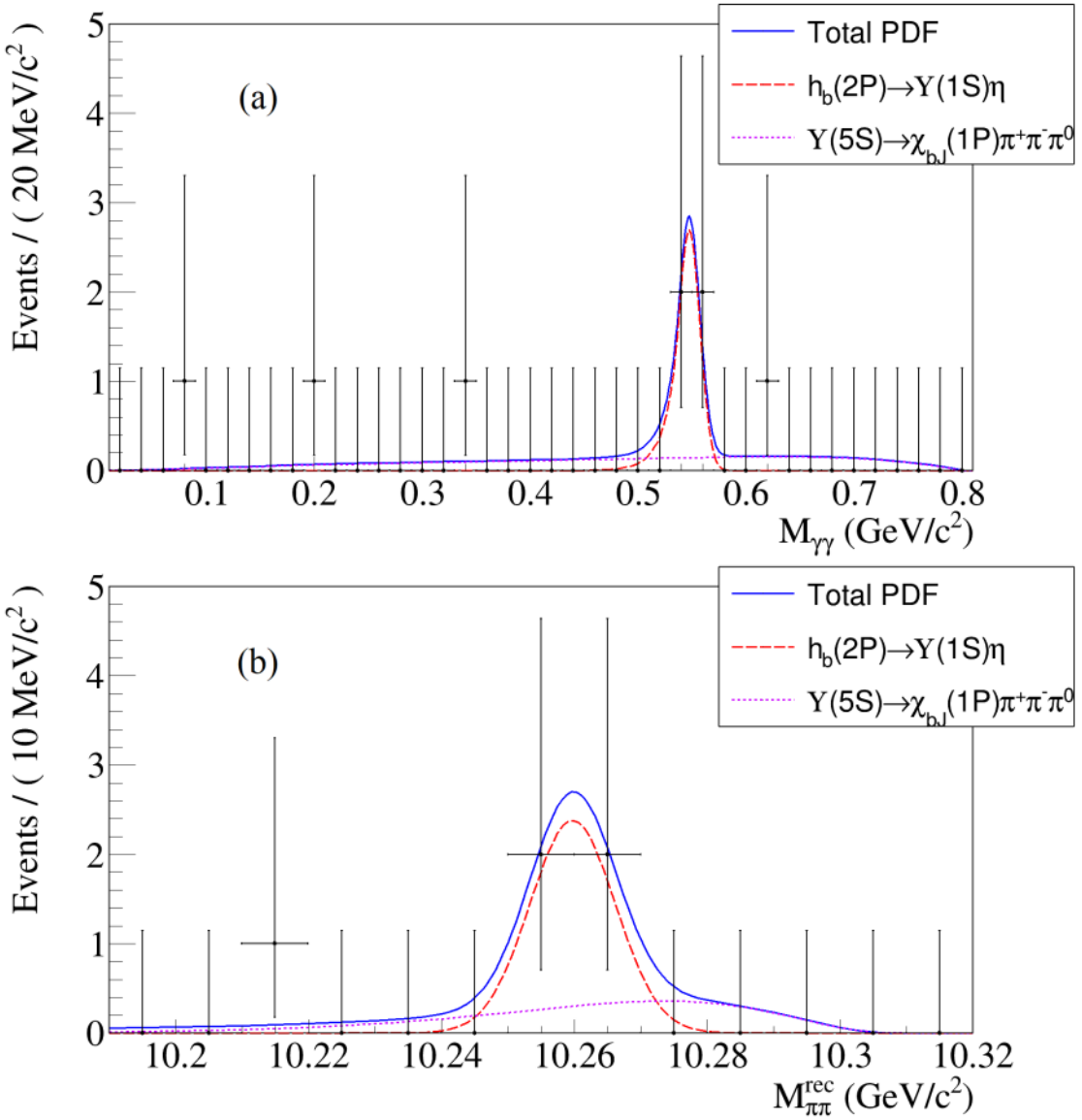
2D fit to $M_{rec}(\pi^+\pi^-)\ vs.\ M(\gamma\gamma)$

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

Significance: 3.5σ including systematics

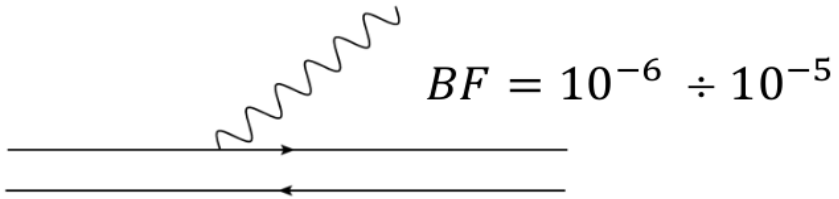
$\mathcal{B}(h_b(2P) \to \Upsilon(1S)\eta) = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$

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

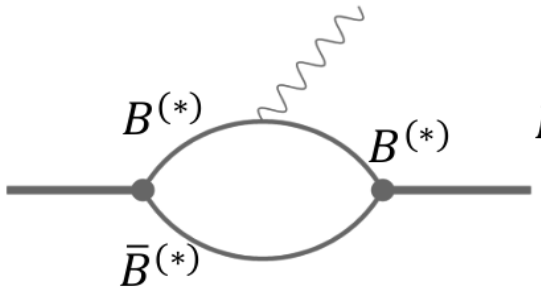


Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

PRD 111, L011102 (2025)



PRD 32, 189 (1985)



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

PLB 760, 417 (2016)

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

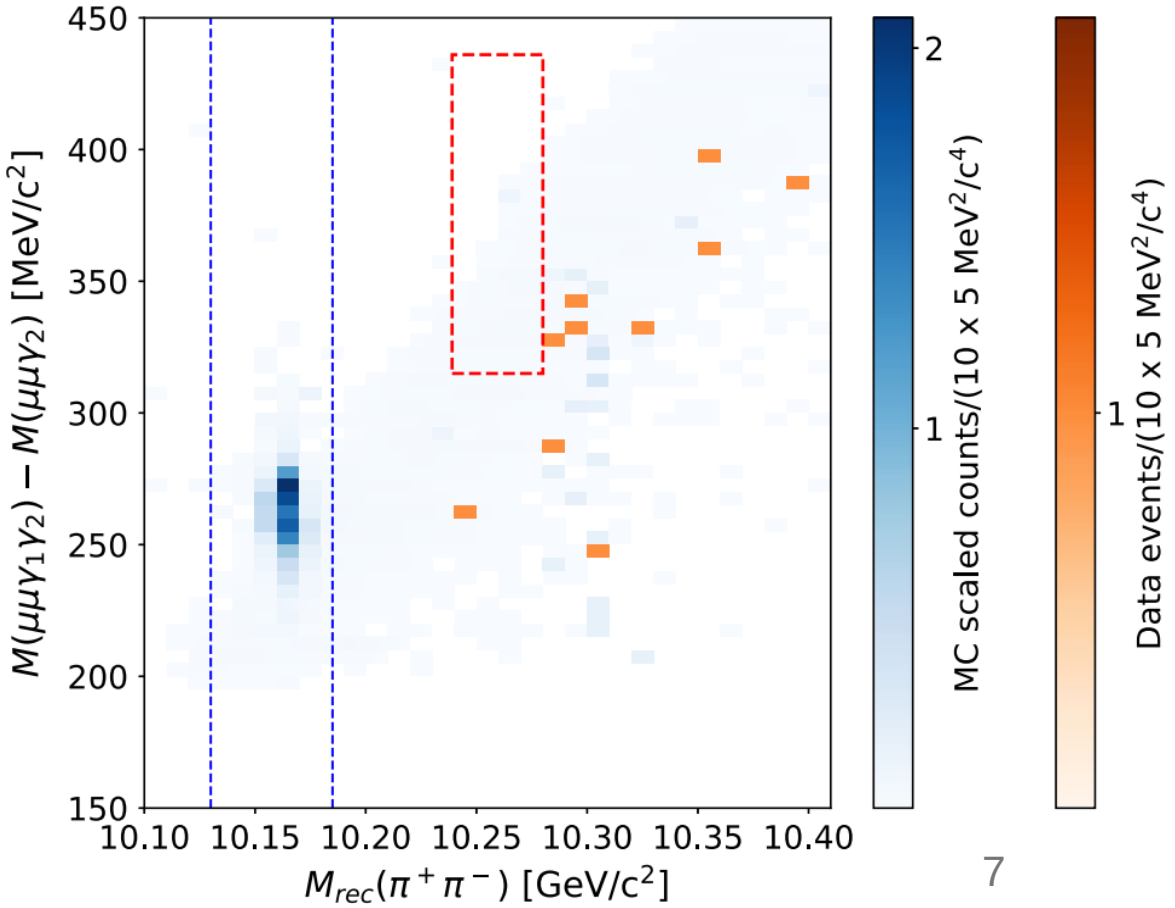
Full reconstruction: $\Upsilon(5S) \to Z_b^+\pi^- \to h_b(2P)\pi^+\pi^-$

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

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

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

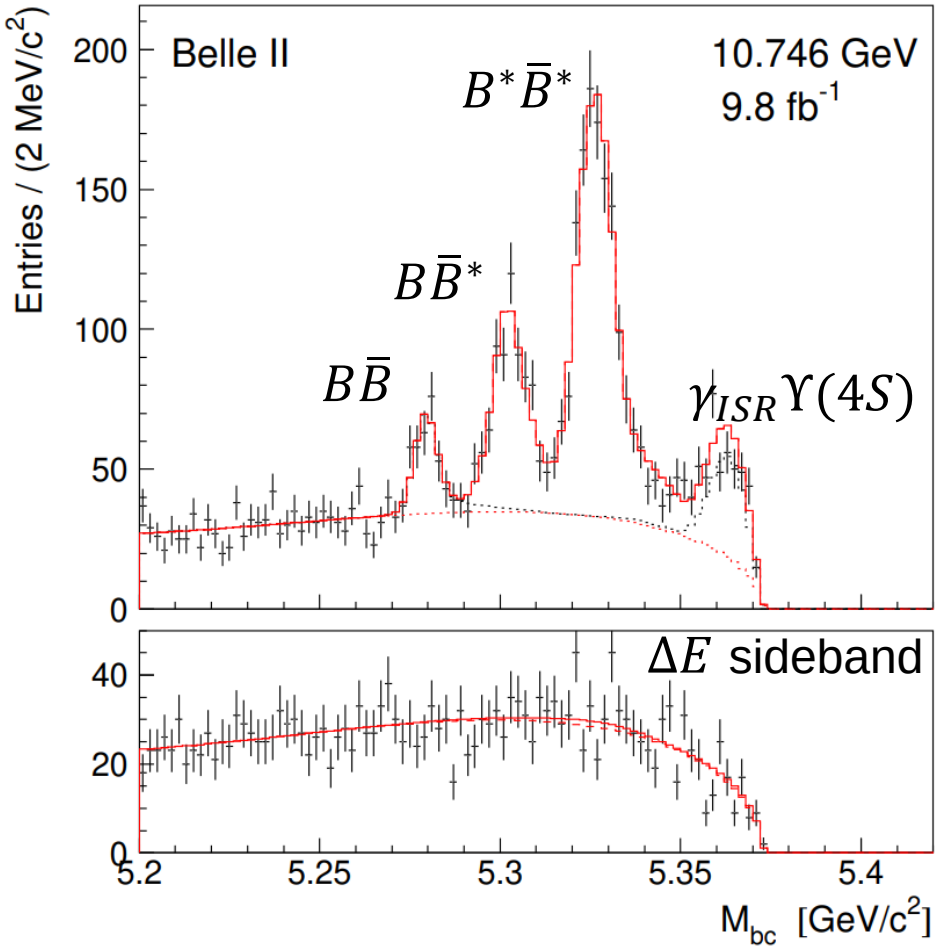
ULs are consistent with expectations



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

JHEP 10 2024, 114

Full reconstruction of one B in the event

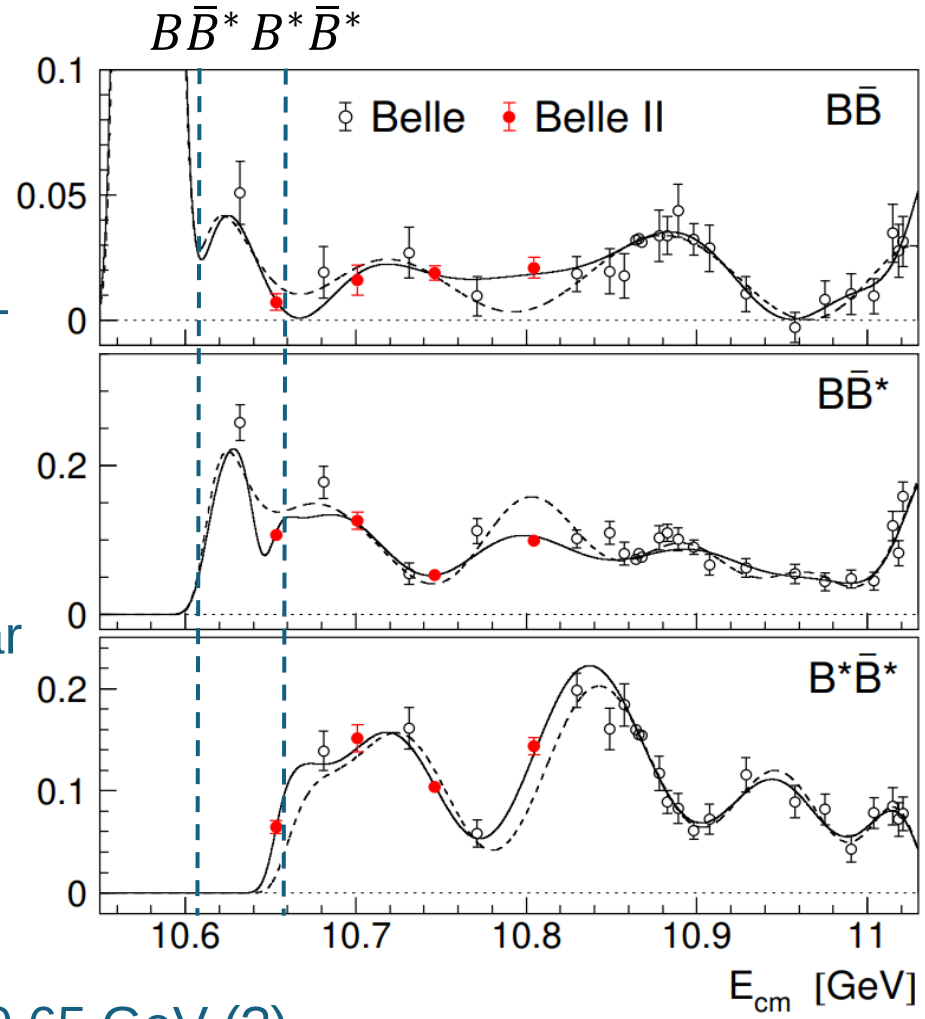


Process is identified by M_{bc} (p_{cm}):

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

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 at 10.65 GeV (?)

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

JHEP 07 2024, 116

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

Significance

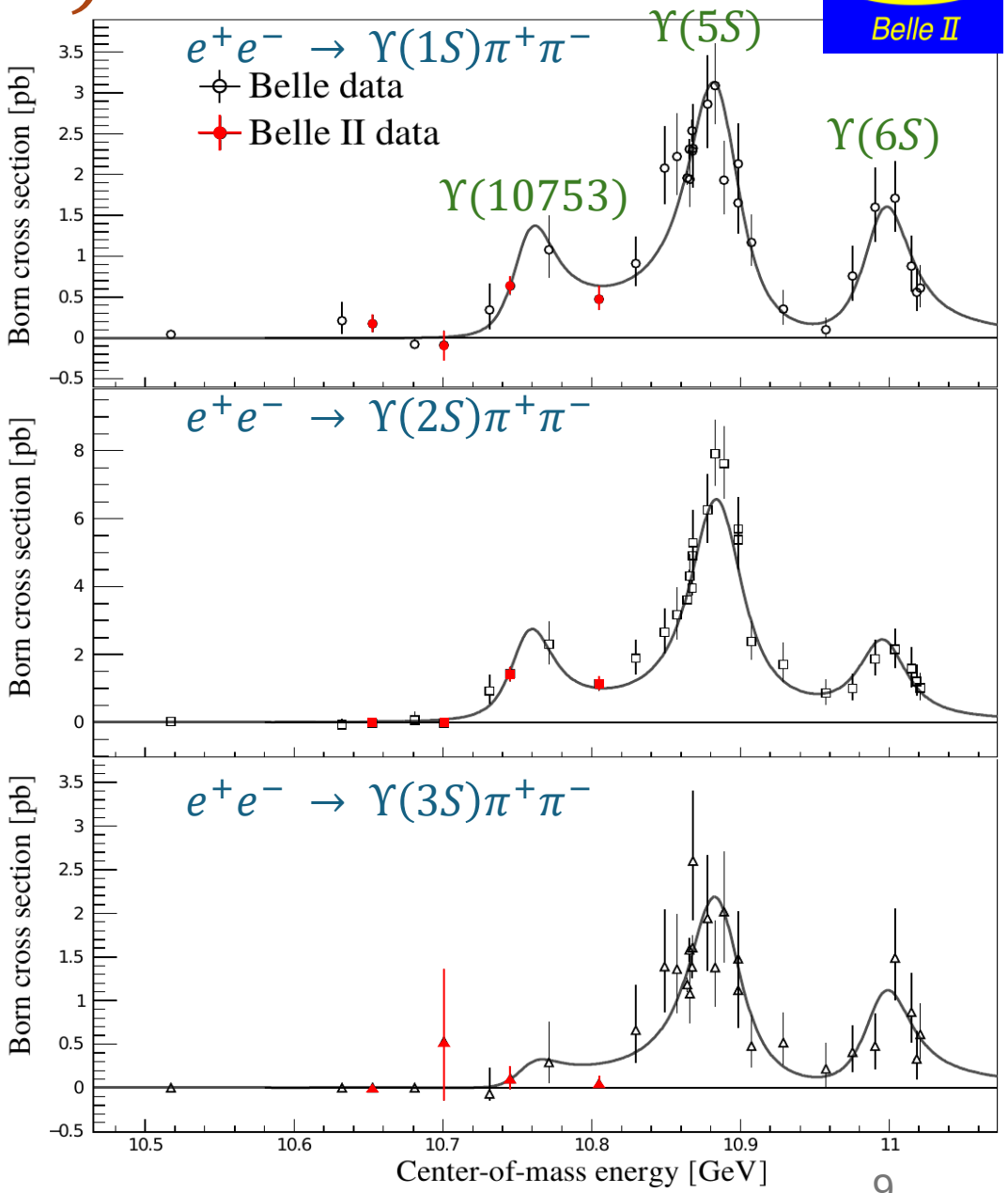
$\Upsilon(1S)\pi^+\pi^-$ 4.1σ

$\Upsilon(2S)\pi^+\pi^-$ 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



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

Preliminary

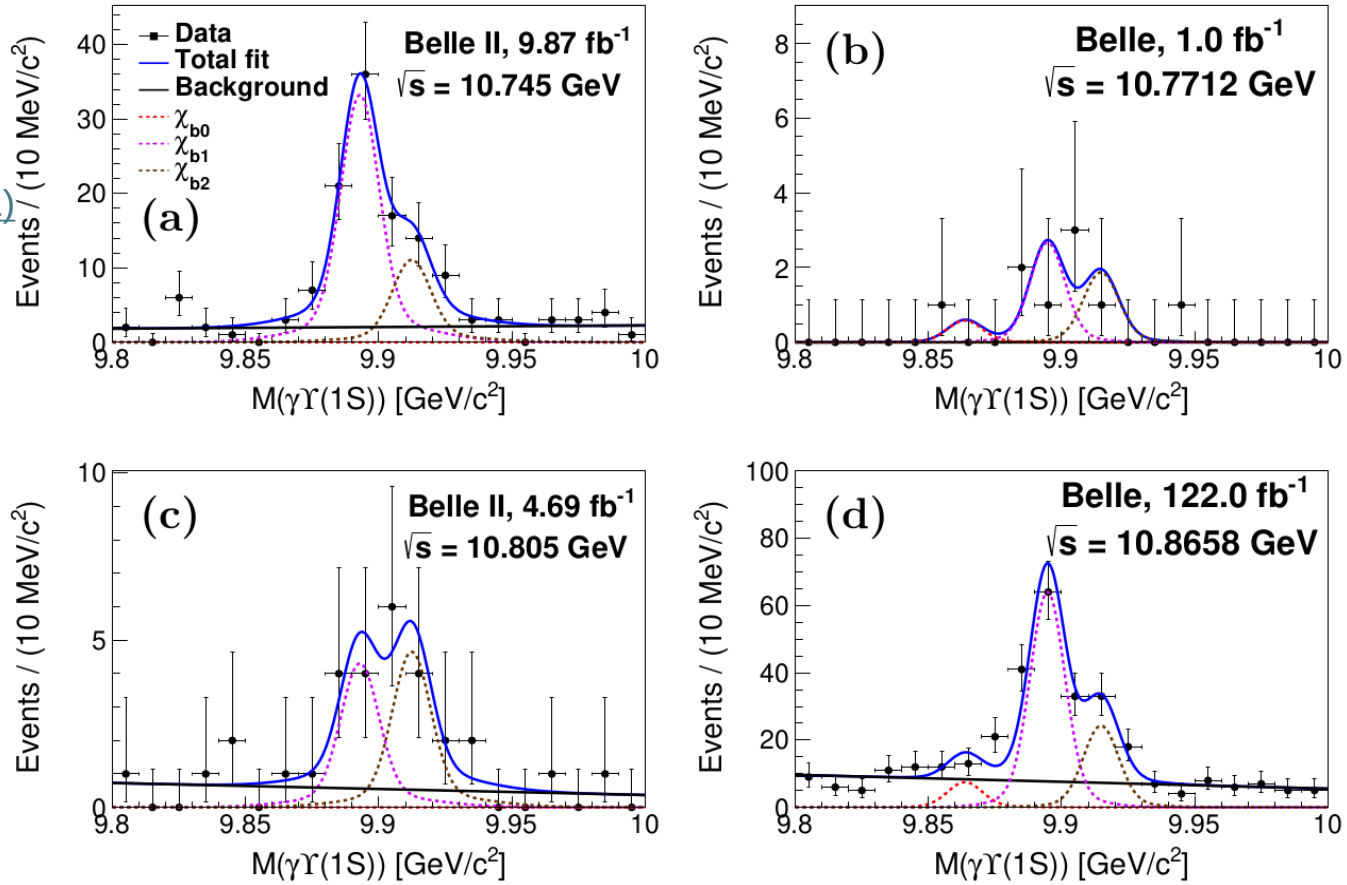
$\frac{\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b1})}{\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b2})}$ predictions:

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

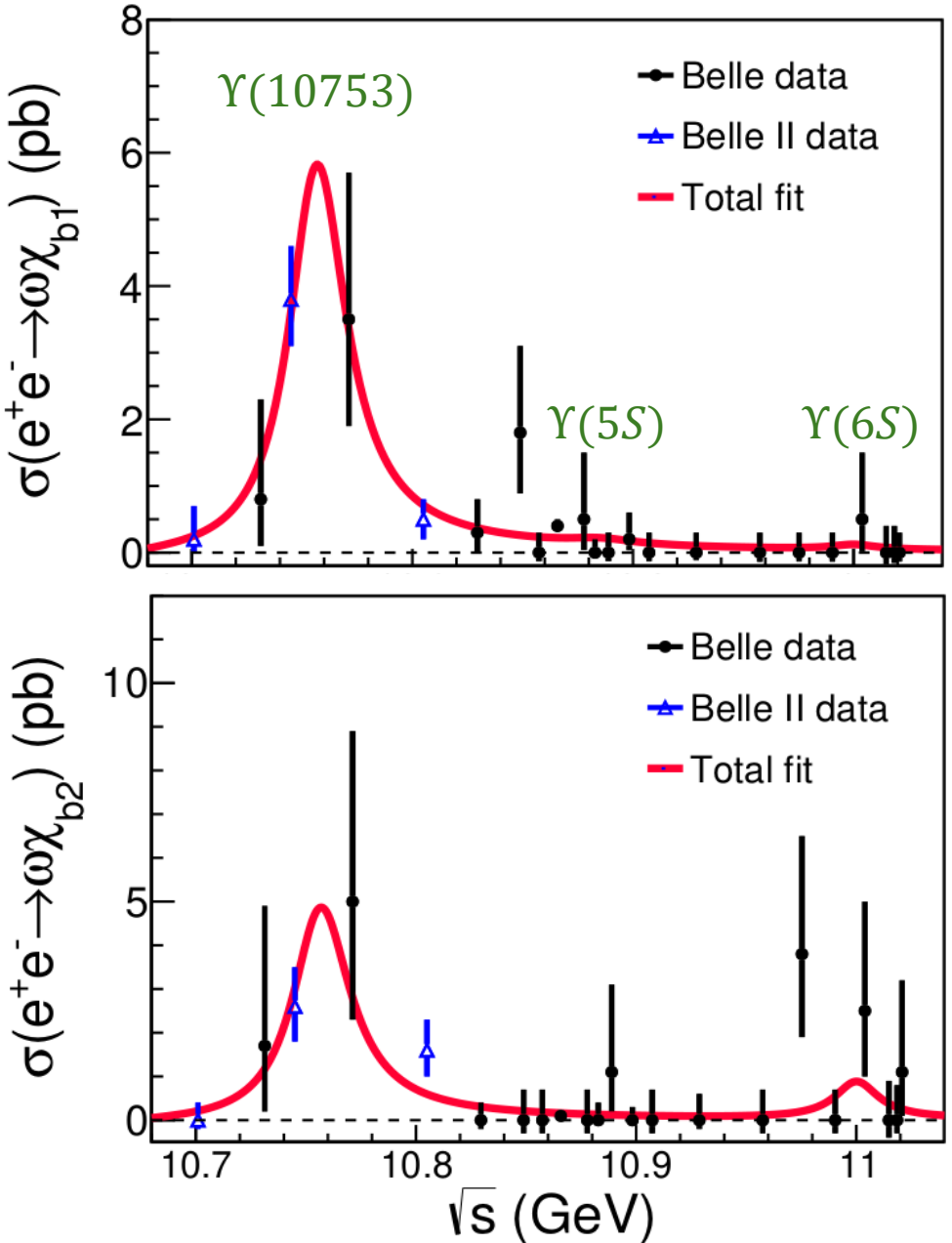
Scan Belle and Belle II data
In $(10.652 - 11.02)$ GeV

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 in backup



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?

$\Upsilon(10753)$ as a bottomonium counterpart of $Y(4230)$

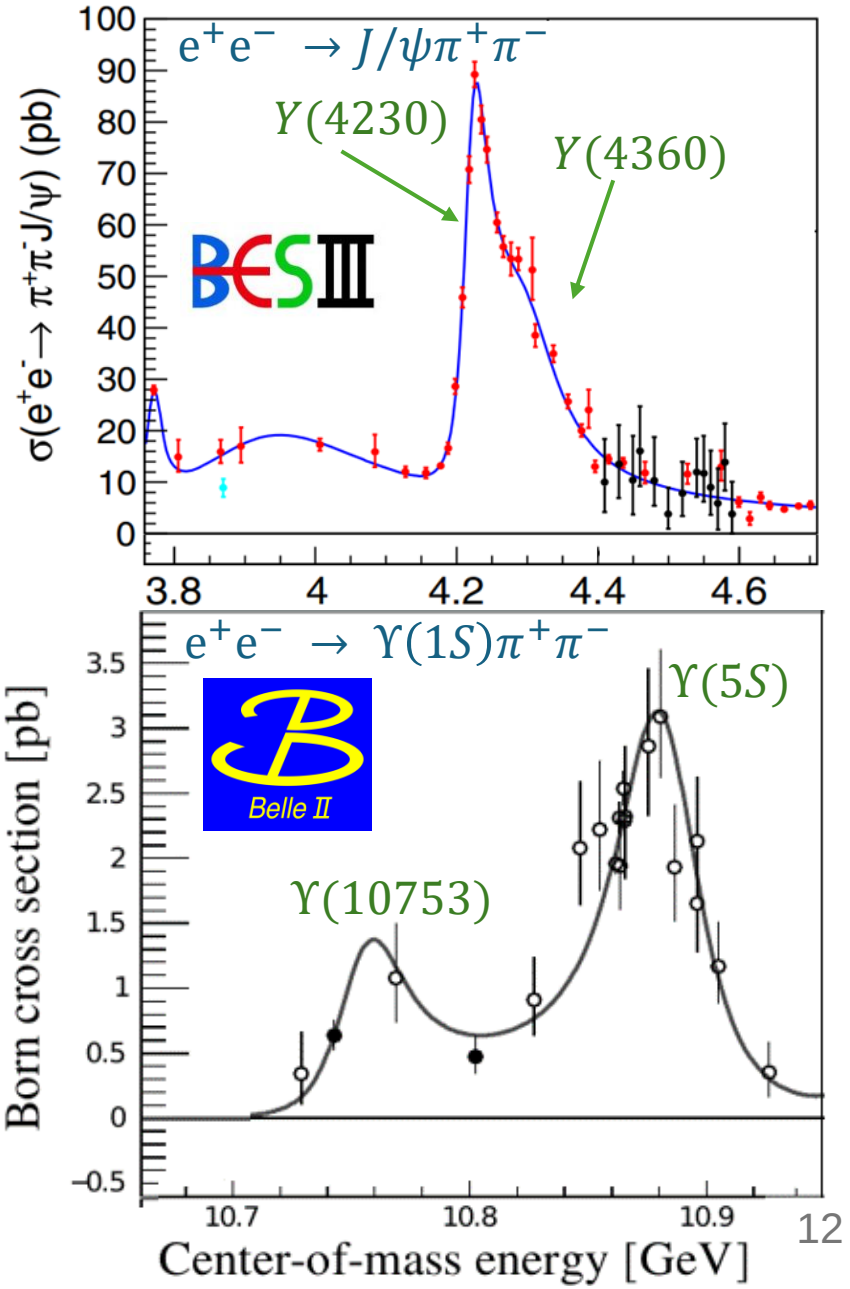
$Y(4230)$ was observed in $J/\psi\ \pi^+\pi^-$
by BaBar, Belle, BESIII

Hypothesis: $\Upsilon(10753)$ is similar in nature

- the same quantum numbers – 1^{--}
- two close peaks from $Y(4230)$ and $Y(4360)$ in $\sigma(e^+e^- \to J/\psi\ \pi^+\pi^-)$, similar with $\Upsilon(10753)$ and $\Upsilon(5S)$
  Phys. Rev. Lett. **118**, 092001 (2017)

$Y(4230)$ transitions:
$\to \omega\ \chi_{cJ}(1P)$
$\to \eta\ J/\psi(1P)$
$\to \gamma\ X(3872)$
$\to \gamma\ \chi_{cJ}(1P)$

Search for similar decays of $\Upsilon(10753)$



Search for $e^+e^- \to \Upsilon(1,2S)\eta$

Preliminary

Belle II $\Upsilon(10753)$ scan data

Full reconstruction: $e^+e^- \to \gamma\gamma\pi^+\pi^- l^+l^-$

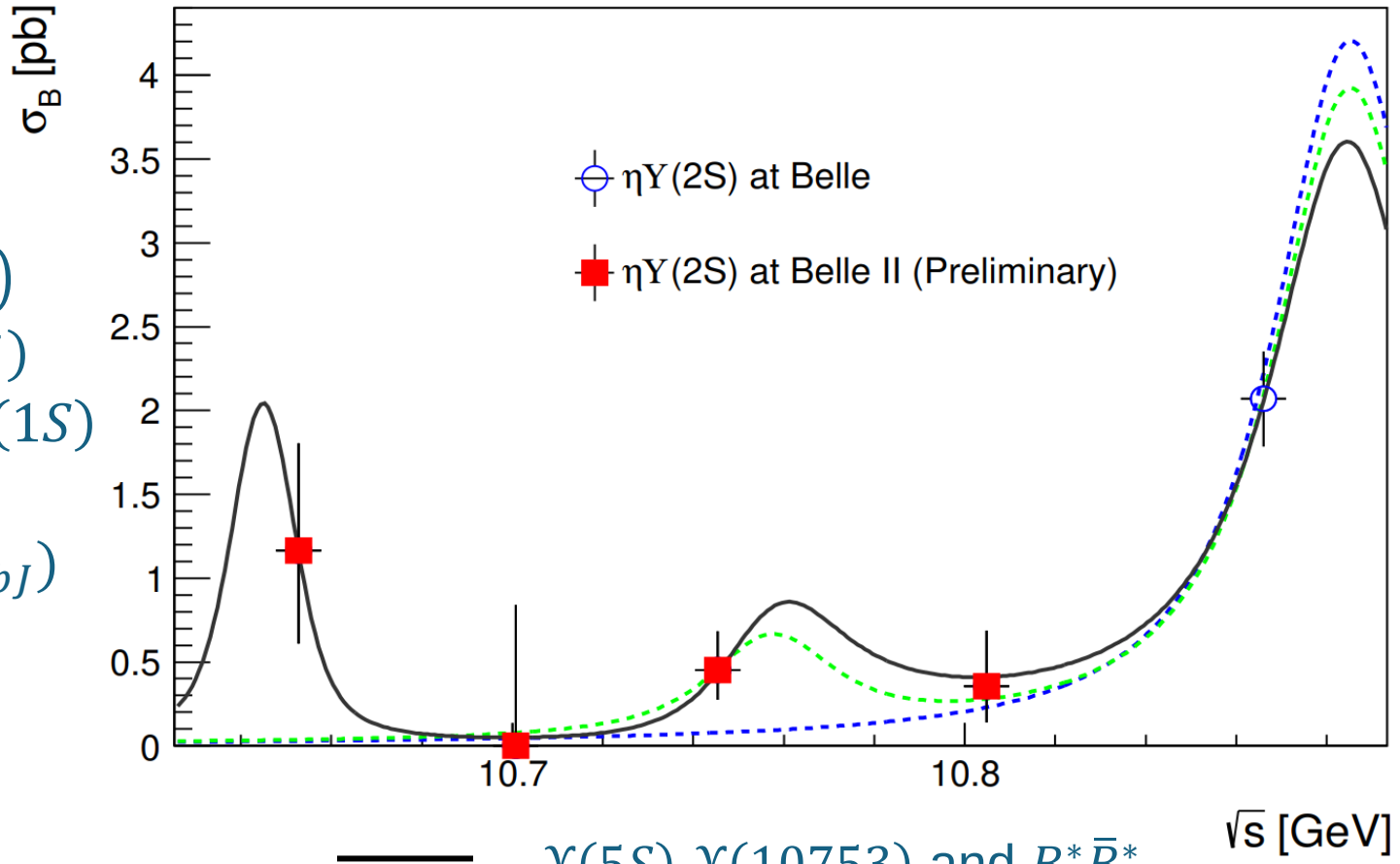
- $e^+e^- \to \eta(\to \gamma\gamma)\,\Upsilon(2S)\big(\to \pi^+\pi^-\Upsilon(1S)\big)$
- $e^+e^- \to \eta(\to \pi^+\pi^-\pi^0)\,\Upsilon(1,2S)(\to\ l^+l^-)$
- $e^+e^- \to \gamma X_b\big(\to \pi^+\,\pi^-\,\chi_{bJ}\big),\ \ \chi_{bJ} \to \gamma\Upsilon(1S)$

1D fit to $M(\gamma\gamma)$, $M(\pi^+\pi^-\pi^0)$ or $M(\pi^+\pi^-\chi_{bJ})$

No evident signal of $\Upsilon(1S)\eta$ nor γX_b,
UL are set

$e^+e^- \to \Upsilon(2S)\eta$: significance greater than 6.6σ

$B^*\bar{B}^*$ bound state at 10.65 GeV: significance greater than 3.2σ



Summary and conclusions

- Continued studies of conventional and potentially exotic states at Belle and Belle II
- Much higher significance confirmation of the $\Upsilon(10753)$ by Belle II:
  - Improved results for mass and width using $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$
  - New $\Upsilon(10753) \to \omega\chi_{bJ}(1P)$ decay channel is observed
  - Current experimental and theoretical accuracy does not allow drawing conclusions
- Only 1% of target integrated luminosity collected so far – much more to come!

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

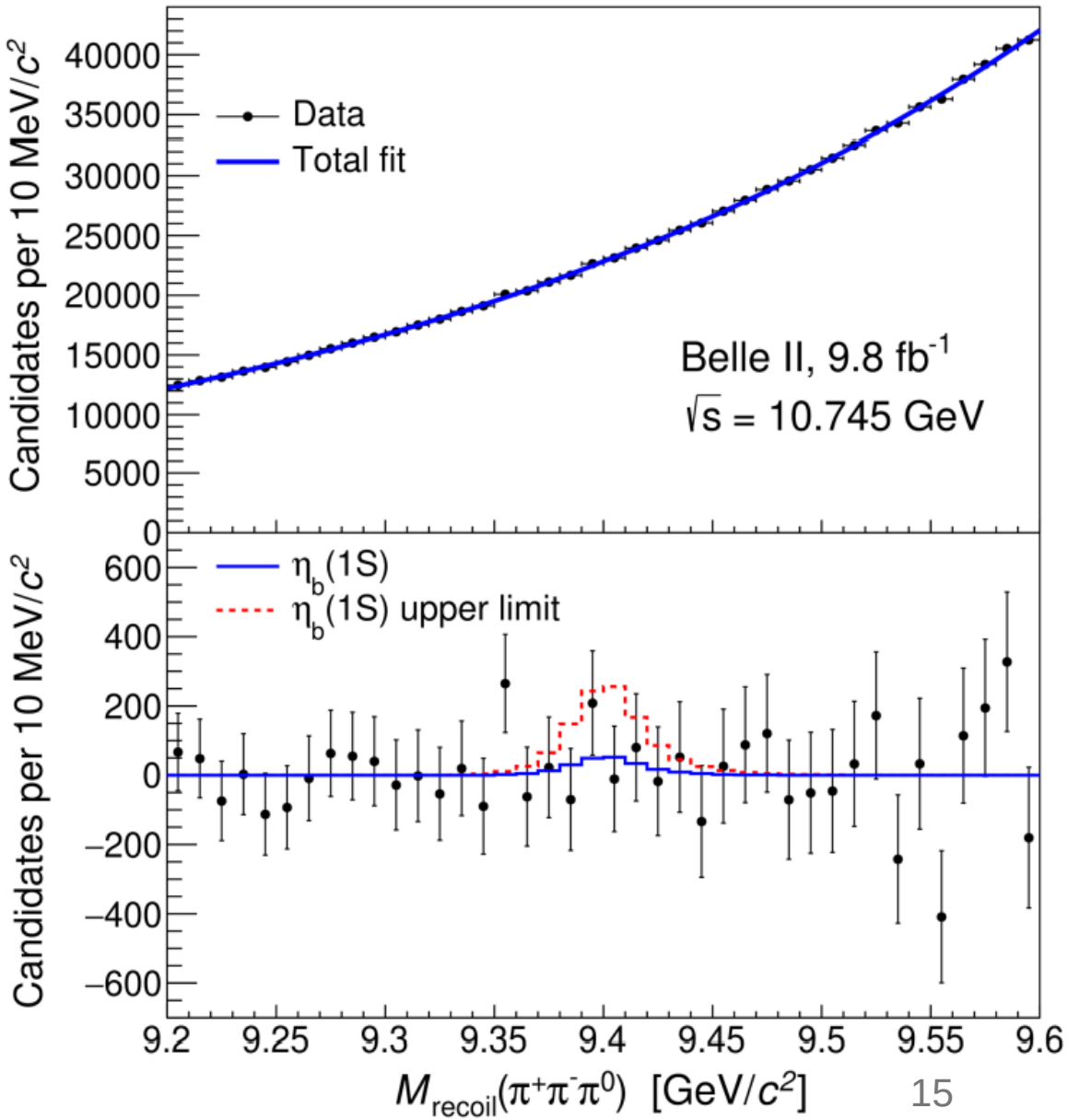
1D fit to $M_{recoil}(\pi^+\pi^-\pi^0)$

No significant signal is observed

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

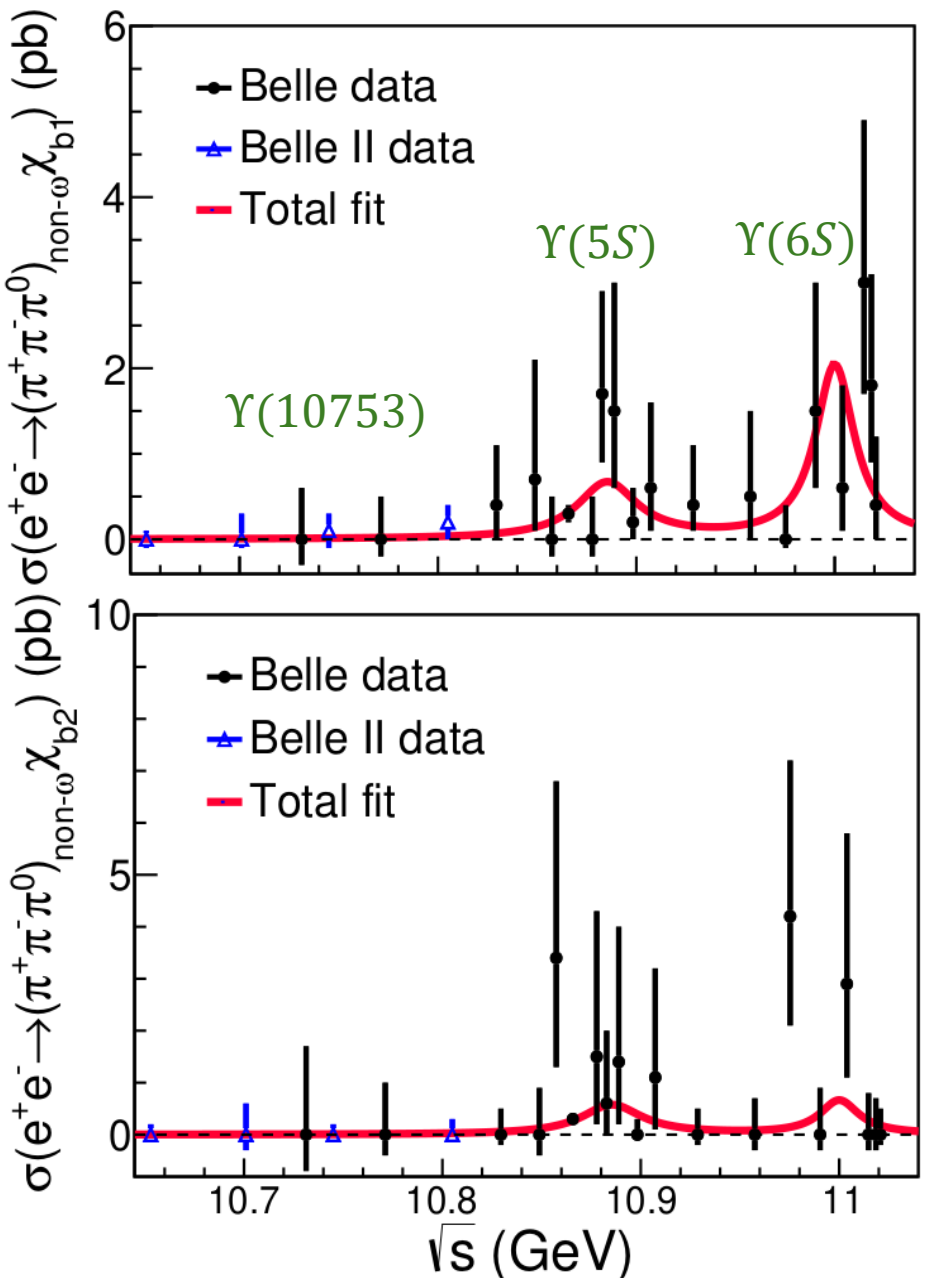
Evidence against the tetraquark model predictions.

Compatible with S − D mixed model



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

Search for $\Upsilon(10753) \to \gamma\chi_{bJ}$

Preliminary

$Y(4230) \to \gamma\chi_{c1}$ and $Y(4230) \to \gamma\chi_{c2}$:
observed by BESIII with 3.0σ and 3.4σ
Chin.Phys.C 39, 041001 (2015)

Full reconstruction: $e^+e^- \to \gamma_h\chi_{bJ} \to \gamma_h\gamma_l\ell^+\ell^-$

1D fit to $M(\Upsilon(1S)\gamma)$

Upper limits at the 90% C.L.:

$o(e^+e^- \to \gamma\chi_{b1}) < 0.26$ pb at 10.746 GeV