Studies of Hadron Spectroscopy at Belle and Belle II

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Contents

Bottomonia below $B\overline{B}$ threshold

- Evidence for $h_b(2P) \to \Upsilon(1S)\eta$
- Search for $h_b(2P) \to \chi_{bJ}(1P)\gamma$

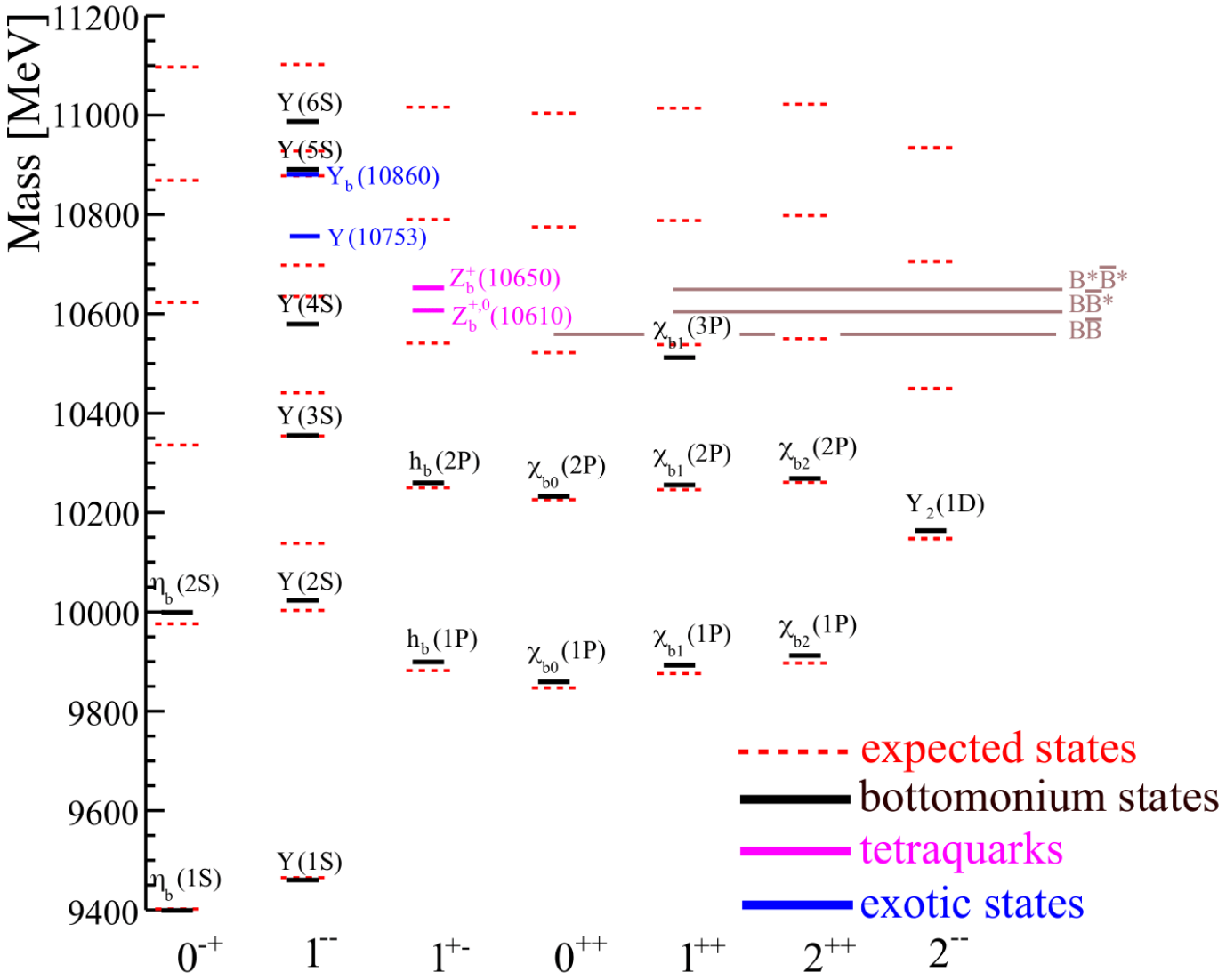
Bottomonium-like states above $B\overline{B}$ threshold

- Confirmation of $\Upsilon(10753) \to \Upsilon(nS)\pi^+\pi^-$
- Search for $\Upsilon(10753) \to \Upsilon(nS)\omega\eta_b(1S)$
- Search for $e^+e^- \to \omega\chi_{bJ}(1P)$
- Search for $e^+e^- \to h_b(1P)\eta$
- Search for $e^+e^- \to \Upsilon(1,2S)\eta$

$e^+e^- \to B^{(*)}\bar{B}^{(*)}$:

- Measurement of the $\sigma\left(e^+e^- \to B^{(*)}\bar{B}^{(*)}\right)$ energy dependence
- Measurements of the B^0 and B^+ meson mass difference

Bottomonium family



Bound state of $b\bar{b}$

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

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

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

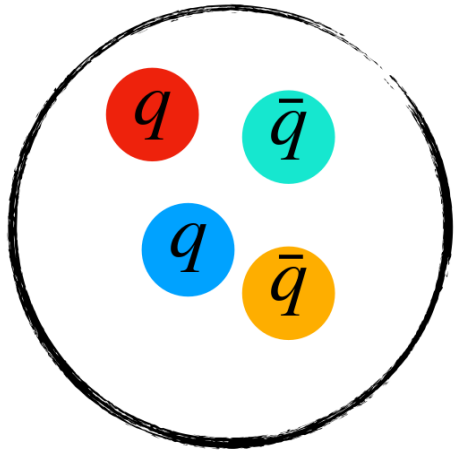
•Above BB - anomalous rate of $\pi^+\pi^-, \eta$ transitions:

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

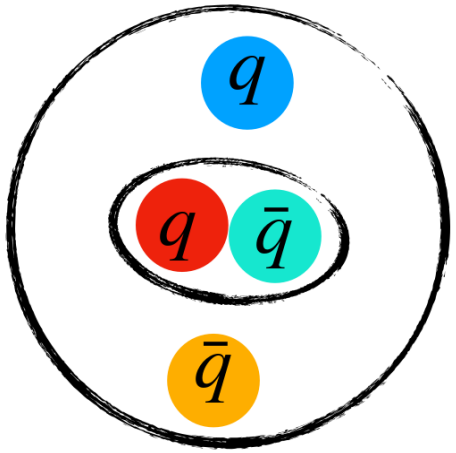
$$\Gamma(\Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^-) \sim 10^2\ \text{keV}$$

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

Structures above $B\overline{B}$ threshold

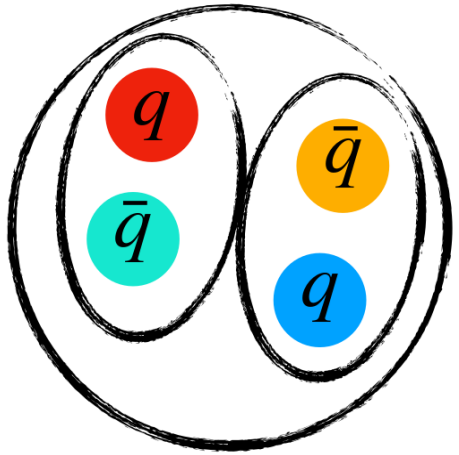


tetraquark

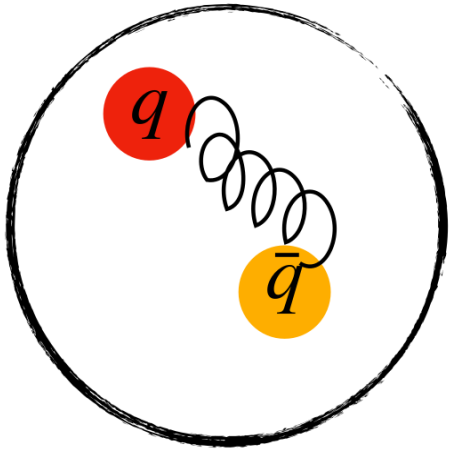


hadro-quarkonium

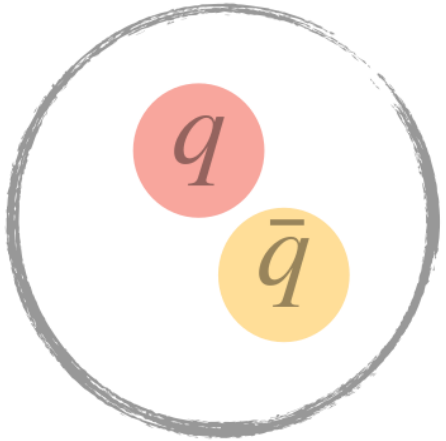
- Unexpected states observed similar with charmonium (X(3872), Y(4260))
- No definite interpretations
- Better understanding is needed



hadronic molecule



hybrid

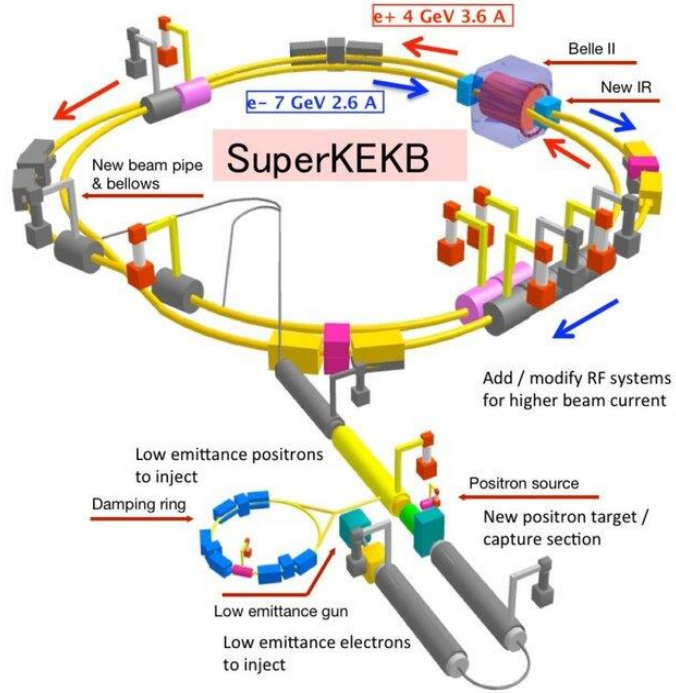


convensional meson (Including S-D state mixing)

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

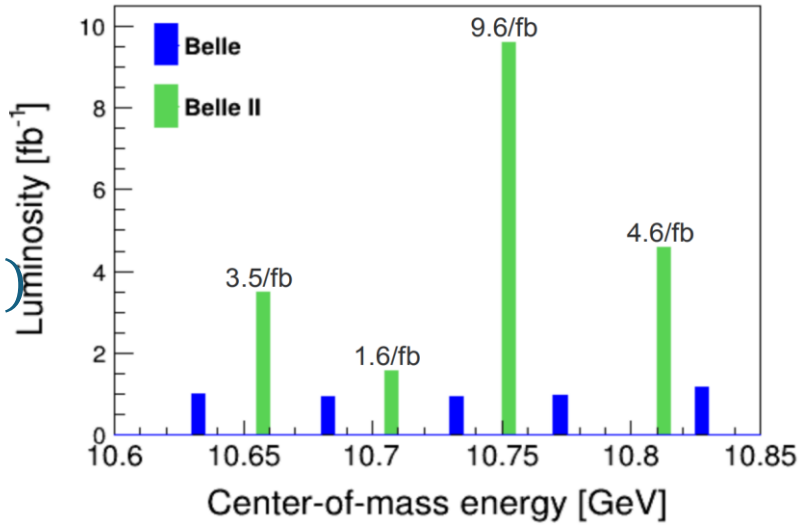
1999-2010

- $e^+\ (3.5\ \mathrm{GeV})\ e^-\ (8\ \mathrm{GeV})$
- $L_{peak} = 2.1 \times 10^{34} cm^{-2} s^{-1}$
- $\int Ldt = \begin{cases} 711\ fb^{-1}\ at\ \Upsilon(4S) \\ 21\ fb^{-1}\ scan\ data \\ 121\ fb^{-1}\ at\ \Upsilon(5S) \end{cases}$

SuperKEKB

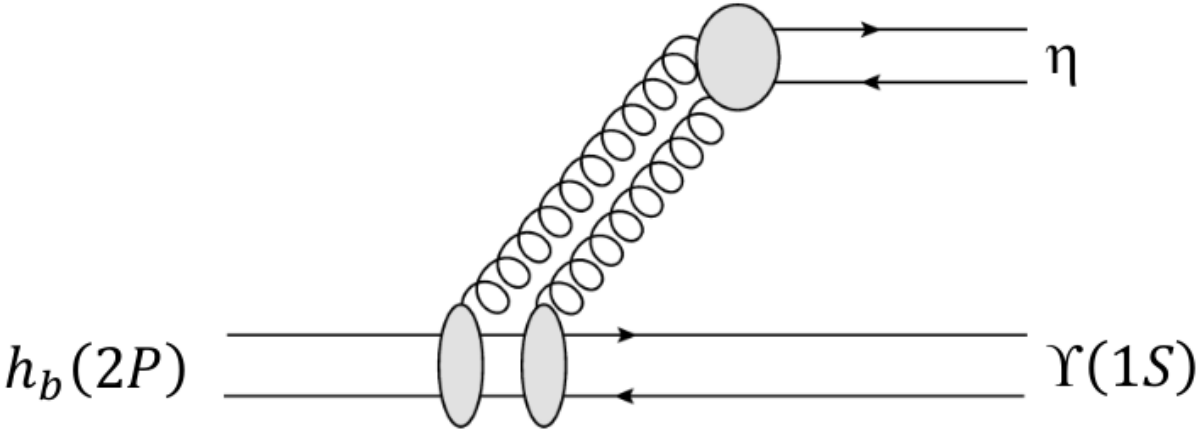
2018-current

- $e^+\ (4\ \mathrm{GeV})\ e^-\ (7.5\ \mathrm{GeV})$
- $L_{peak} = 5.1 \times 10^{34} cm^{-2} s^{-1}$
- $\int Ldt = \begin{cases} 365\ fb^{-1}\ at\ \Upsilon(4S) \\ 20\ fb^{-1}\ at\ \Upsilon(10753) \end{cases}$
- 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 ($\sim 1/m_b$)



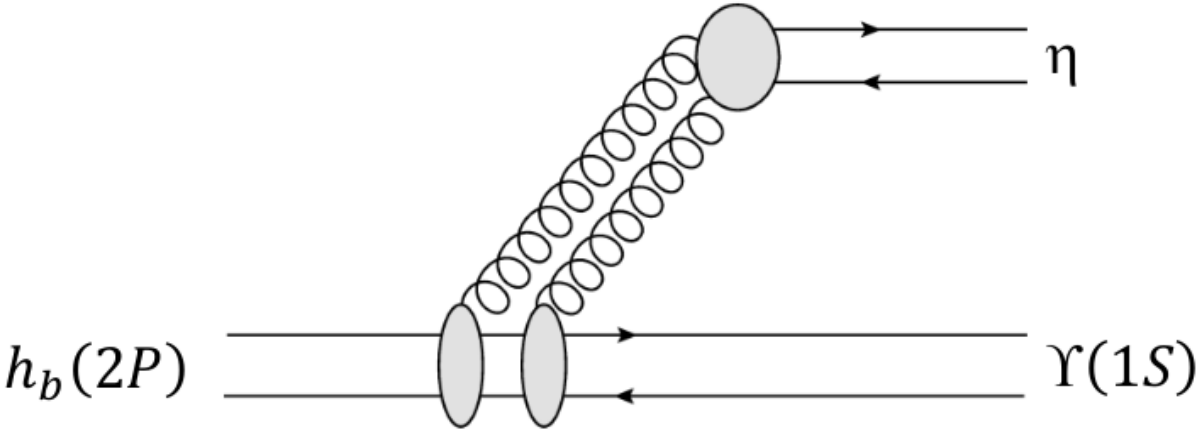
BaBar:

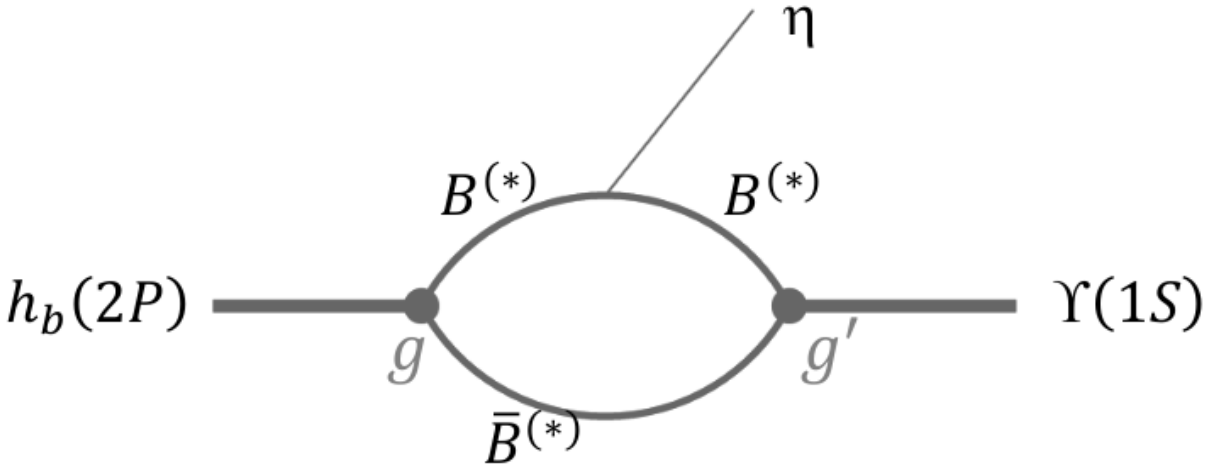
$\mathcal{B}(\Upsilon(3S) \to h_b(1P)\pi^0) \sim 10^{-3}$ with significance 3.1σ

PRD 84, 091101 (2011)

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:

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

PRD 84, 091101 (2011)

Prediction based on BaBar result:

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

PRD 86, 094013 (2012)

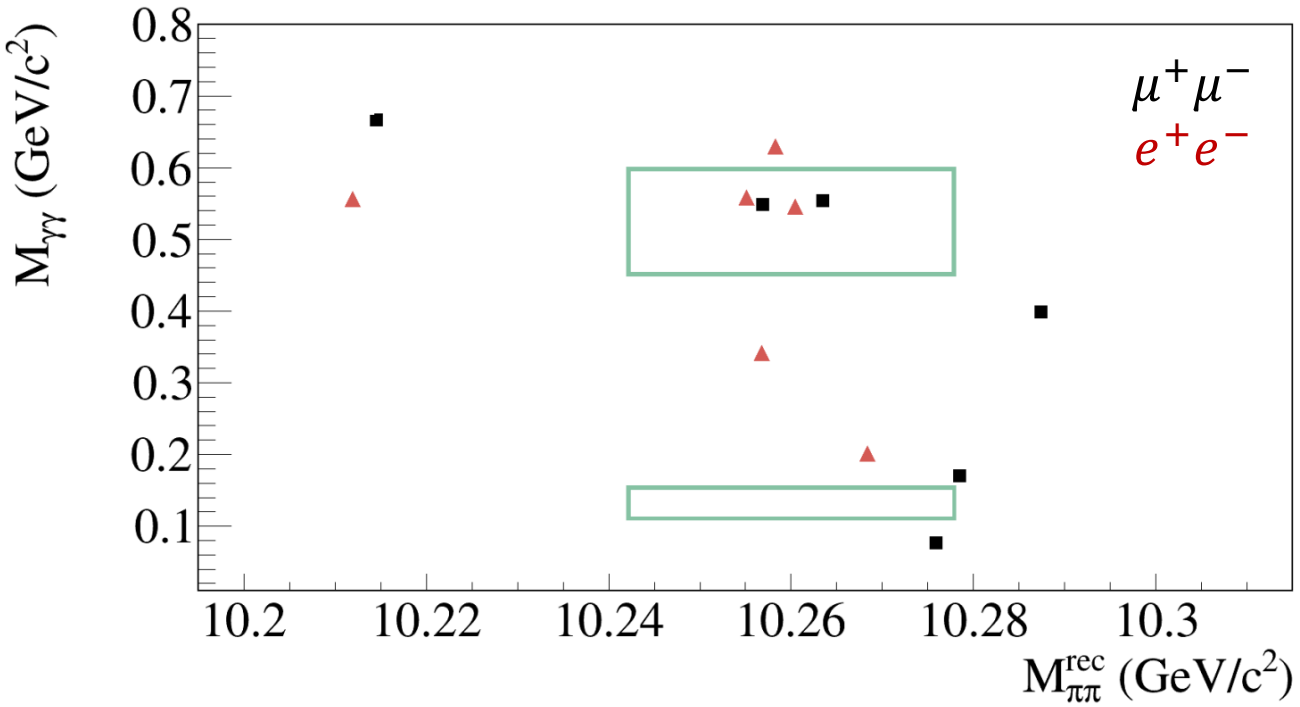
Evidence for $h_b(2P) \to \Upsilon(1S)\eta$

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

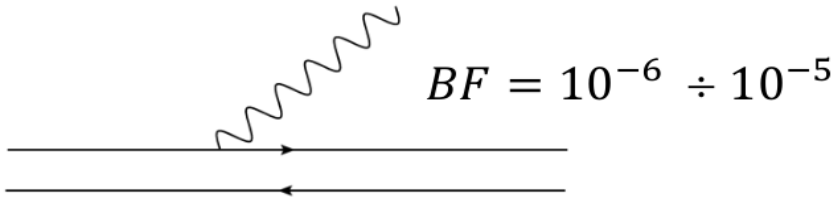
$\mathcal{B}(h_b(2P) \to \Upsilon(1S)\eta) = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$

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

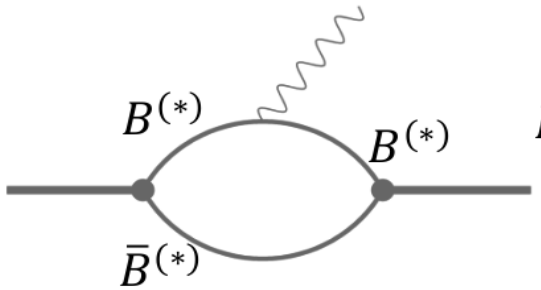
No signal of isospin violating decay $h_b(2P) \to \Upsilon(1S)\pi^0$

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

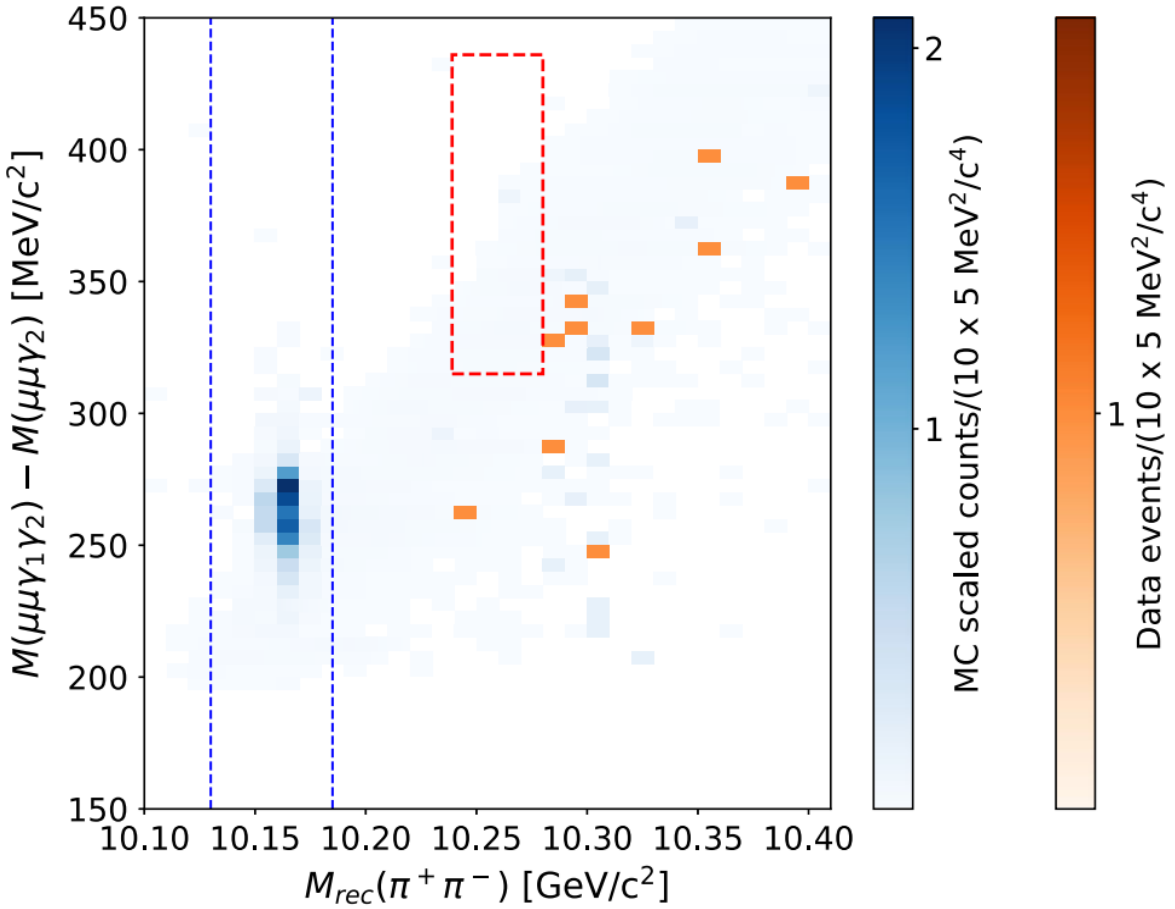
$h_b(2P) \to \chi_{bJ}(1P)\gamma_1 \to [\Upsilon(1S)\gamma_2]\gamma_1 \to$

$\to [(\mu^+\mu^-)\gamma_2]\gamma_1$

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



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

JHEP 07 2024, 116

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

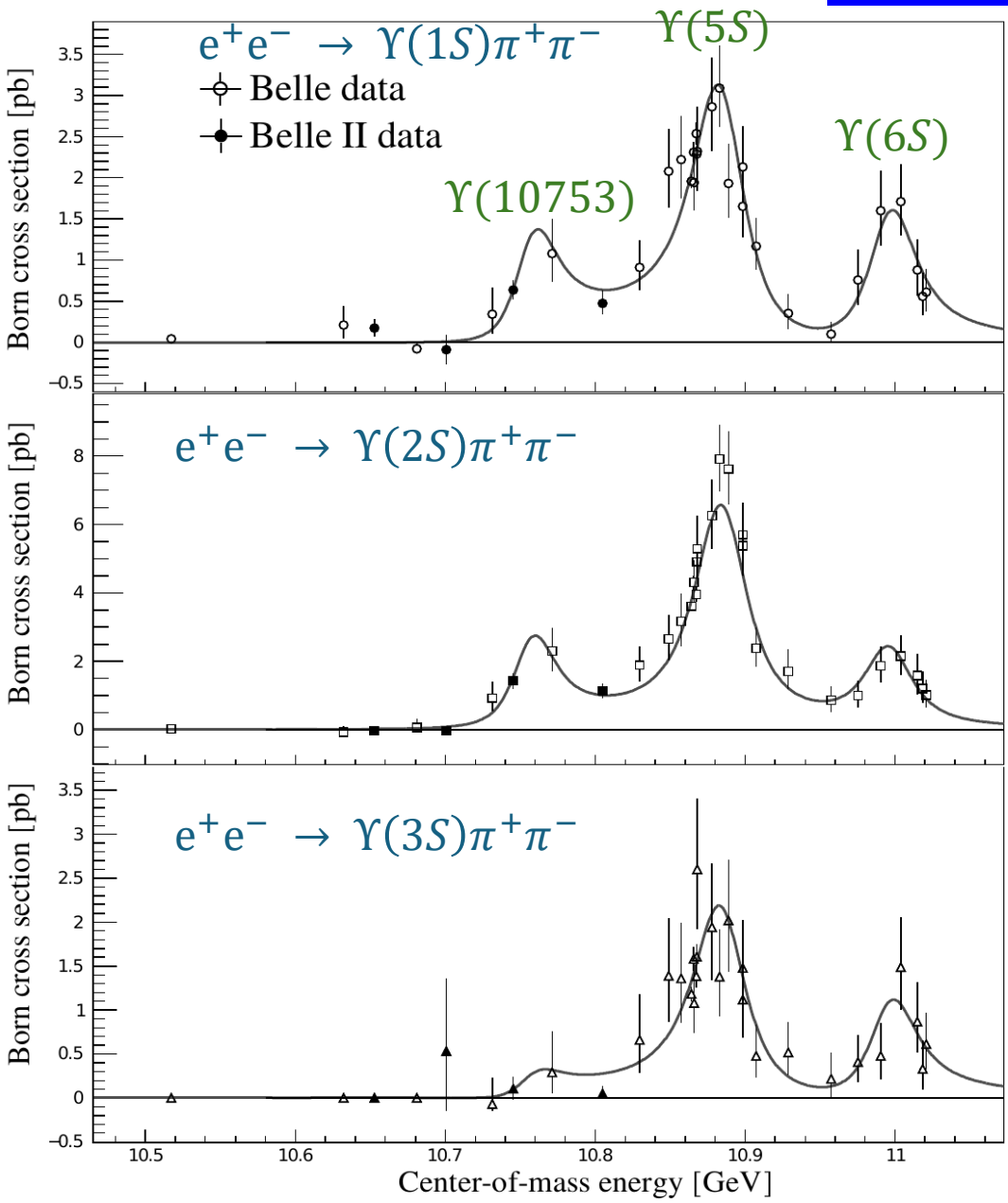
Significance

$\Upsilon(1S)\pi^+\pi^-$	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



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

PRD 109, 072013 (2024)

Predictions:

- Tetraquark: $\frac{\mathcal{B}(\Upsilon(10753)\to\omega\eta_b)}{\mathcal{B}(\Upsilon(10753)\to\Upsilon\pi^+\pi^-)} \sim 30$ CPC 43 (2019) 12, 123102
- 4S-3D mixed state: $\frac{\mathcal{B}(\Upsilon(10753)\to\omega\eta_b)}{\mathcal{B}(\Upsilon(10753)\to\Upsilon\pi^+\pi^-)} \sim (0.2 - 0.4)$ PRD 109, 014039 (2024)

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

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

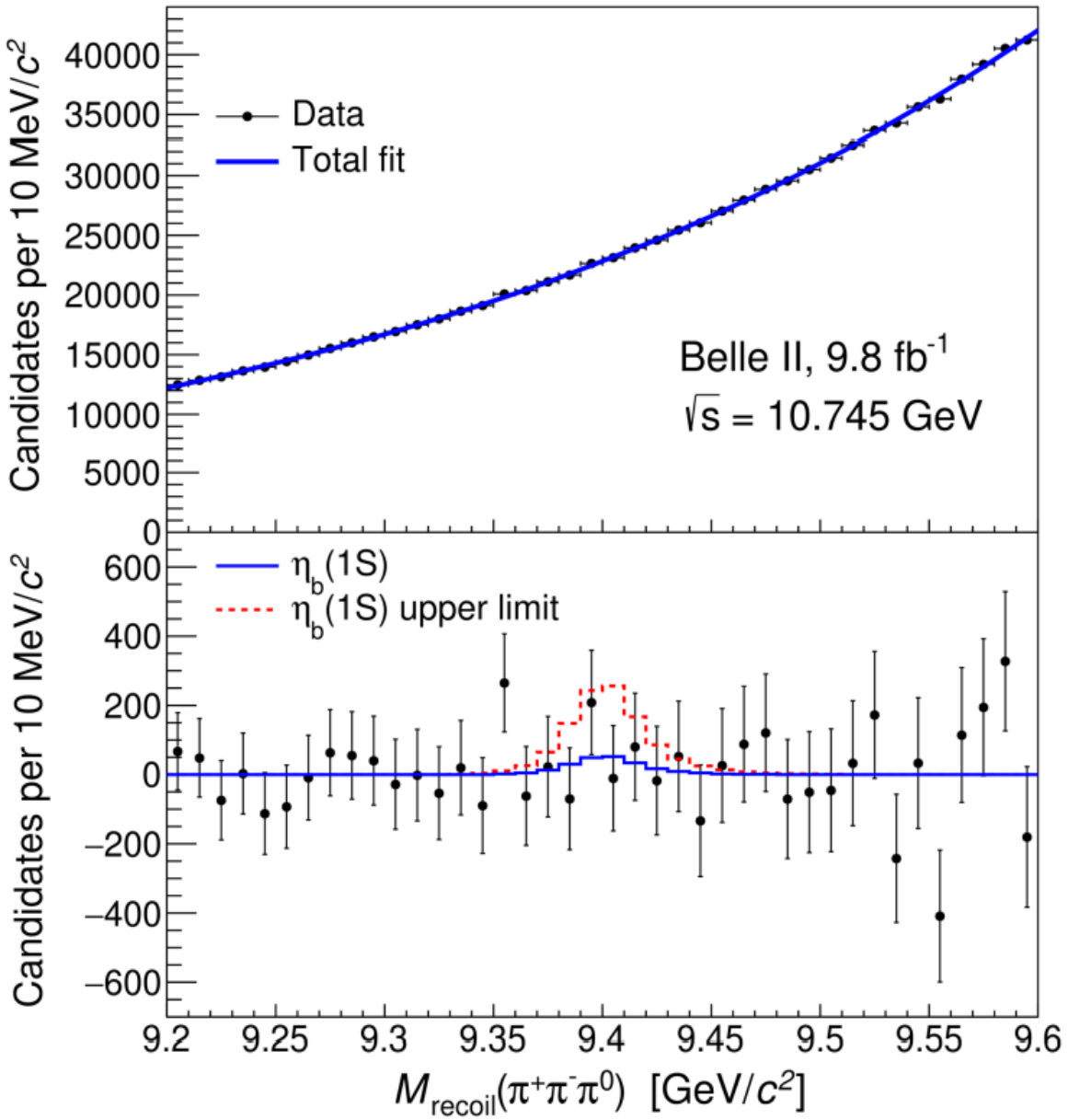
1D fit to $M_{recoil}(\pi^+\pi^-\pi^0)$

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



Search for $e^+e^- \to \omega\chi_{bJ}(1P)$

Preliminary

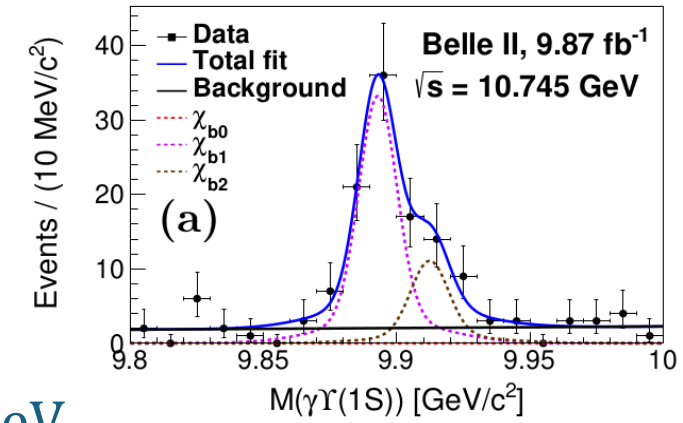
$\frac{\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b1})}{\mathcal{B}(\Upsilon(10753) \to \omega\chi_{b2})}$:

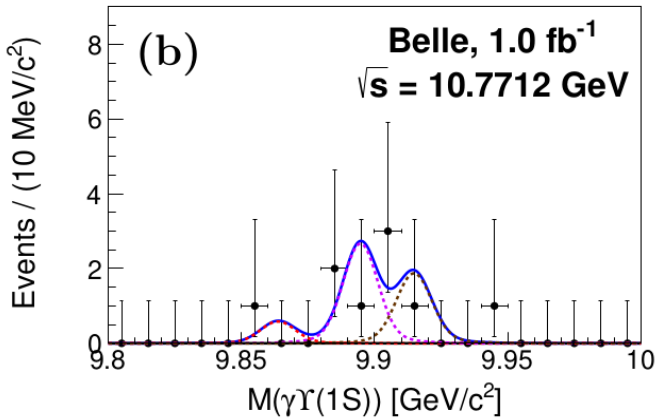
- ~ 15 for pure $\Upsilon(3D)$ state PLB 738, 172 (2014)
- ~ 0.2 for 4S-3D mixed state PRD 104, 034036 (2021)

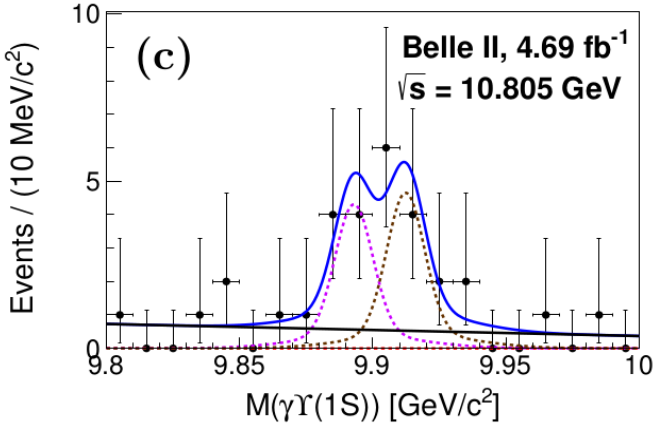
Scan Belle and Belle II data in $(10.43 - 11.02)$ GeV

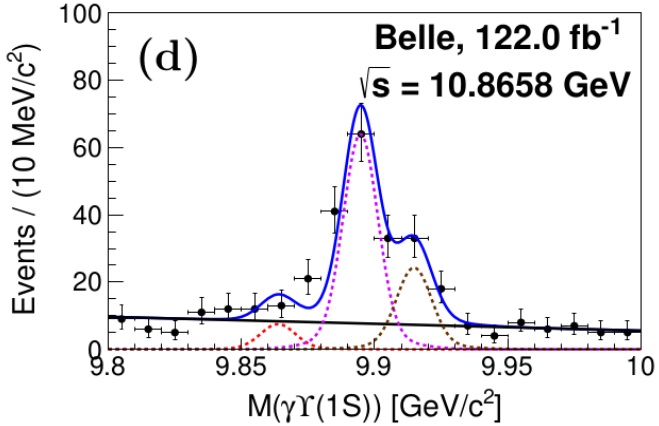
Full reconstruction: $e^+e^- \to \omega\chi_{bJ}(1P)$,
$\omega \to \pi^+\pi^-\pi^0, \chi_{bJ}(1P) \to \gamma\Upsilon(1S) \to \gamma(l^+l^-)$

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



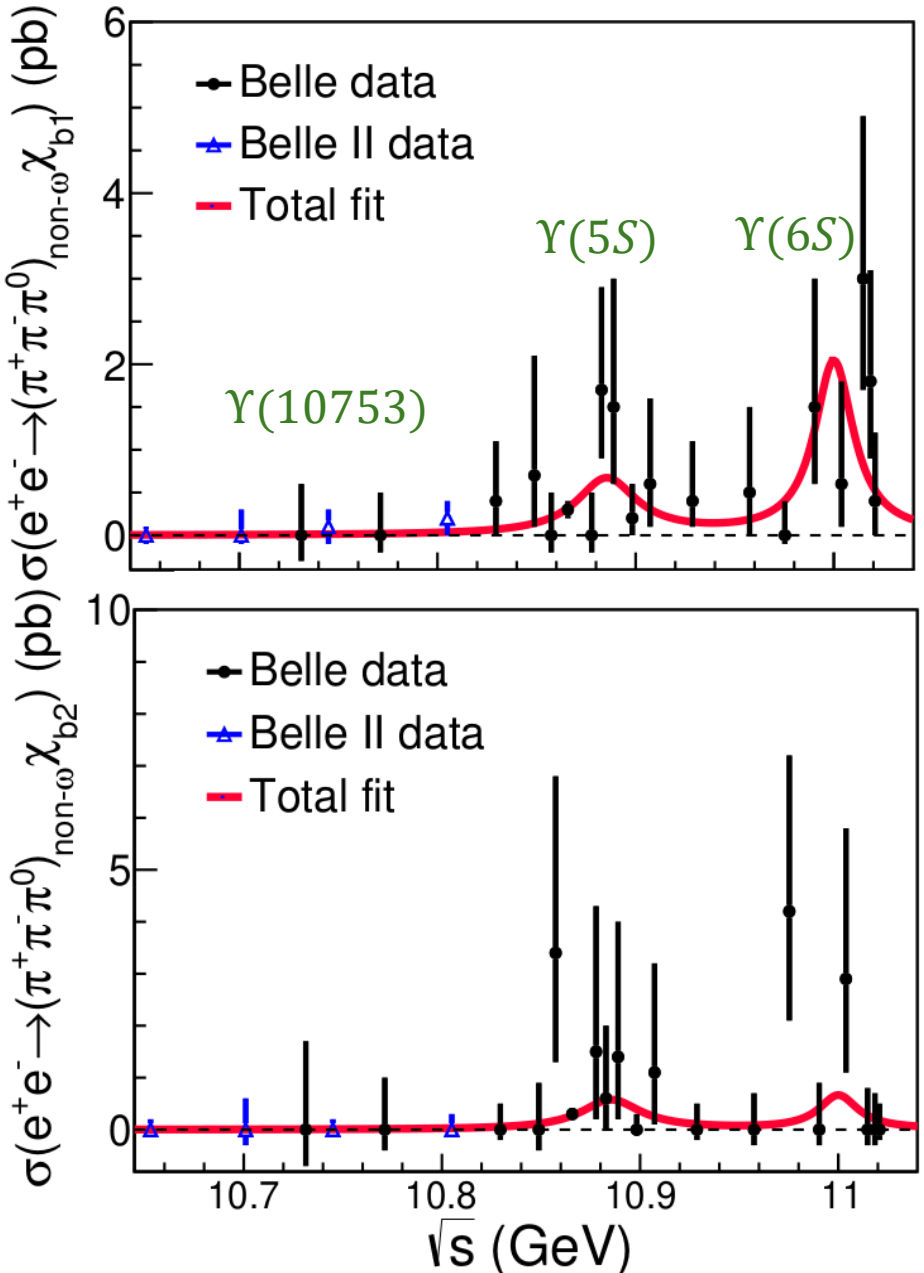






Search for $e^+e^- \to (\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}(1P)$

Preliminary



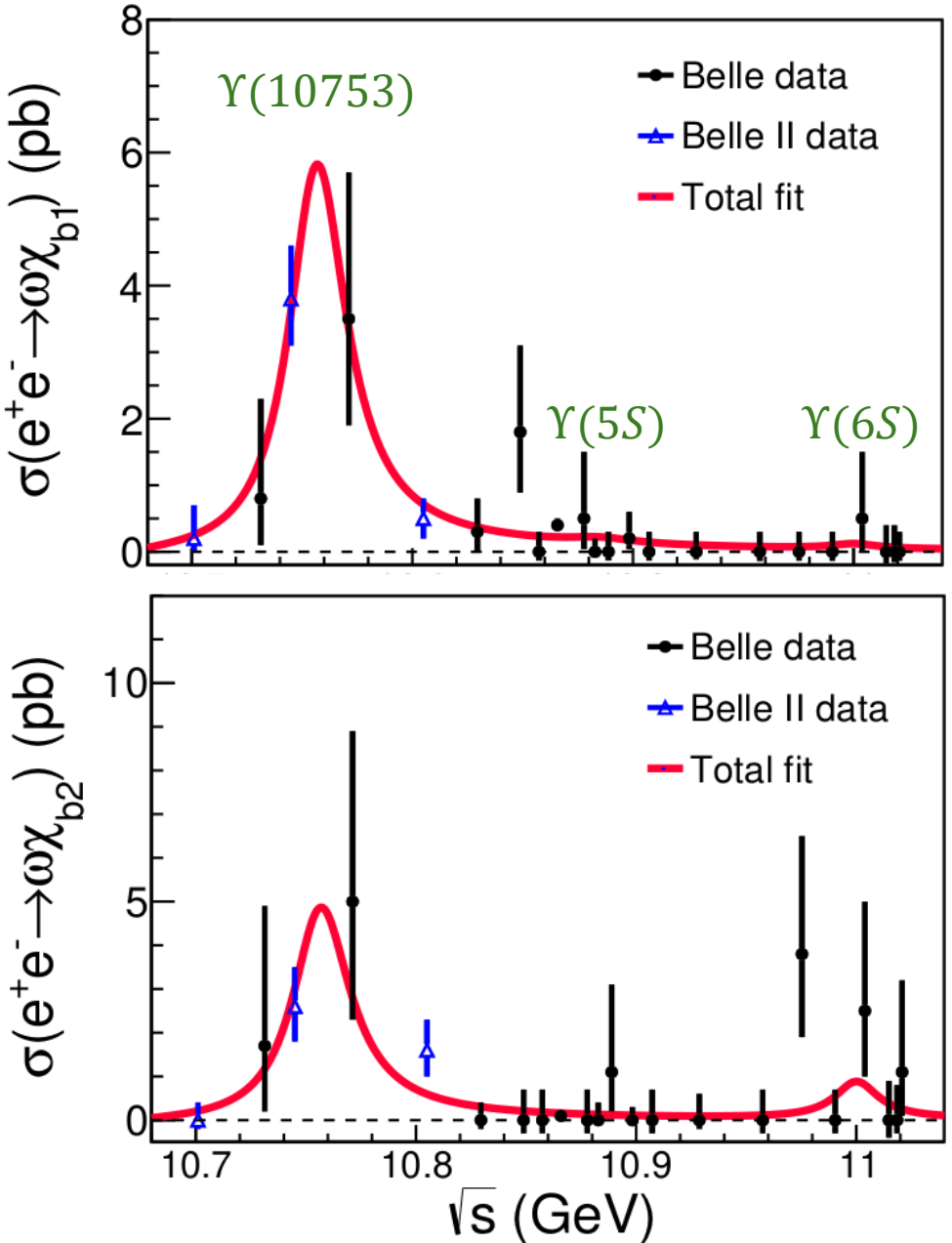
Decays of $\Upsilon(5S)$ and $\Upsilon(6S)$ into $(\pi^+\pi^-\pi^0)_{non-\omega}\chi_{bJ}(1P)$

$\Gamma_{ee}\mathcal{B}(\Upsilon(10753) \to (\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega}\chi_{b1})$	$(0.00 \pm 0.05 \pm 0.02)$ 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 $e^+e^- \to \omega\chi_{bJ}(1P)$

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 $e^+e^- \to \Upsilon(nS)\pi^+\pi^-$

$$\frac{\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b1})}{\mathcal{B}(\Upsilon(10753)\to\omega\chi_{b2})} = 1.1 \pm 0.4$$

Does not support pure 3D, 2.5σ 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?

Search for $e^+e^- \to h_b(1P)\eta$

Preliminary

Predictions:

- Hybrid: $\sigma(e^+e^- \to h_b(1P)\eta) \sim 30\ pb$
- 4S-3D mixed state: $\sigma(e^+e^- \to h_b(1P)\eta) \sim 0.3\ pb$

PRD 104, 034019 (2021)

PRD 104, 034036 (2021)

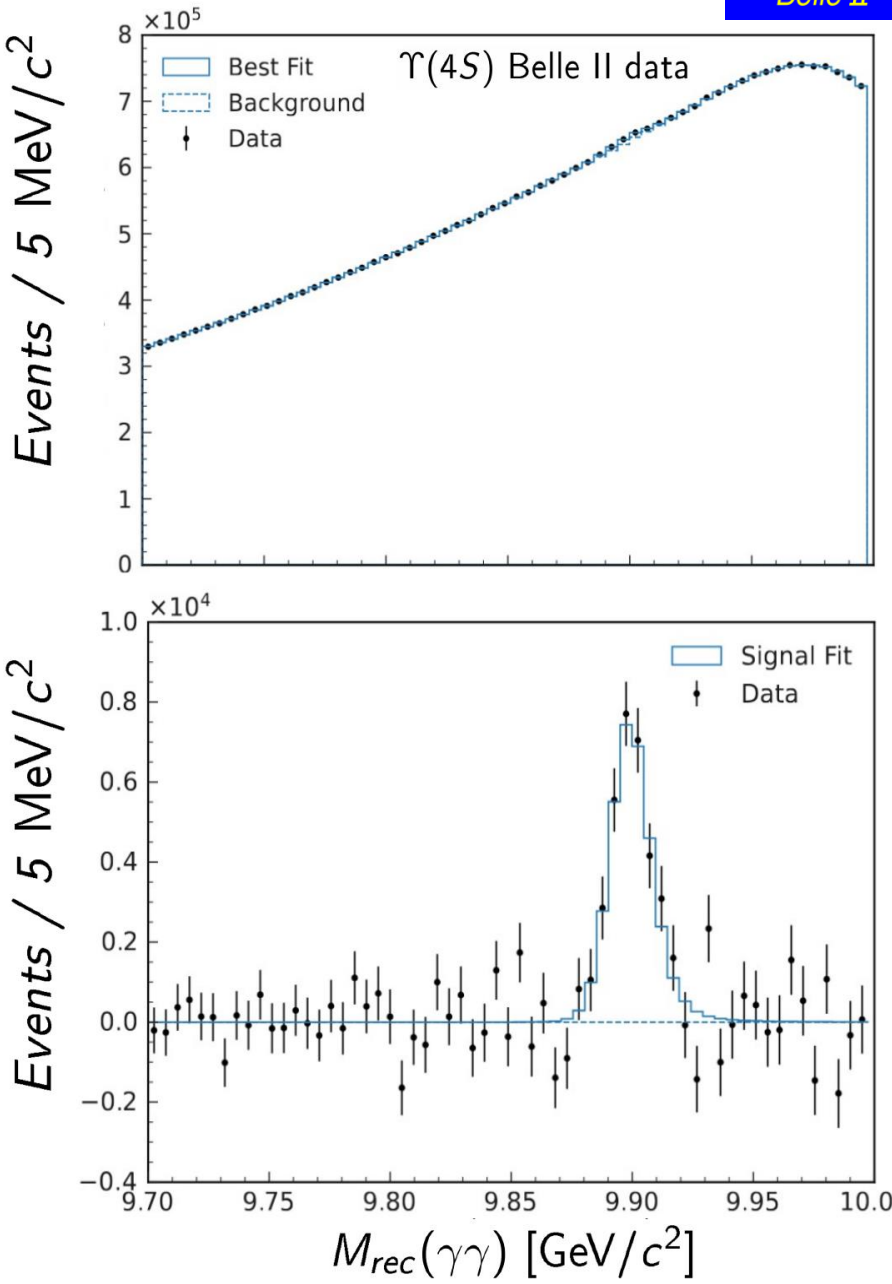
Partial reconstruction: $\eta \to \gamma\gamma$.
1D fit to $M_{rec}(\gamma\gamma)$

Control sample: $\Upsilon(4S) \to h_b(1P)\eta$ at Belle II

Agreement with Belle result:

Belle: $(2.18 \pm 0.11 \pm 0.18) \times 10^{-3}$

Belle II: $(1.80 \pm 0.15 \pm 0.18) \times 10^{-3}$

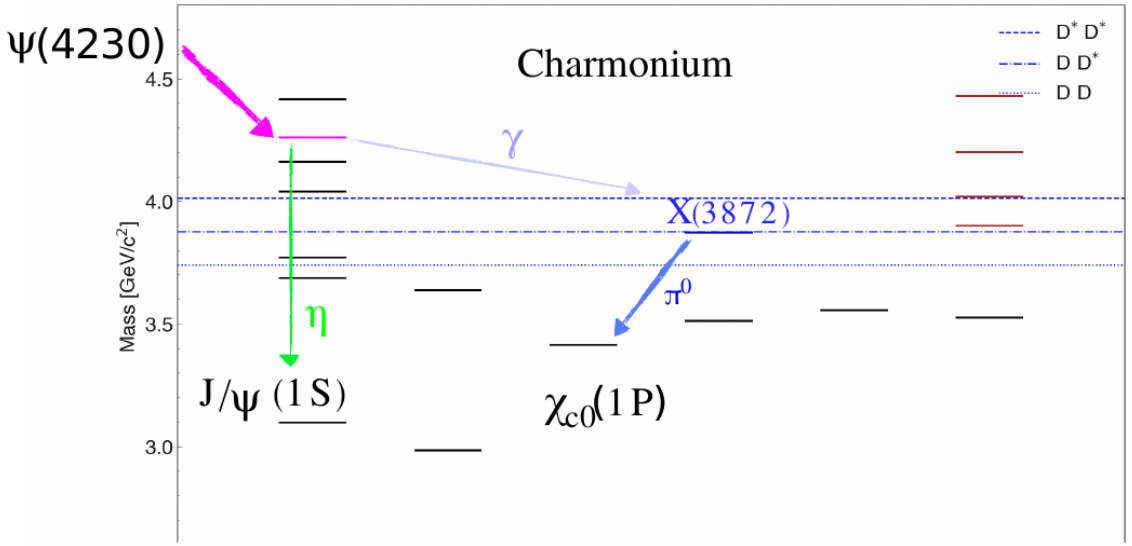


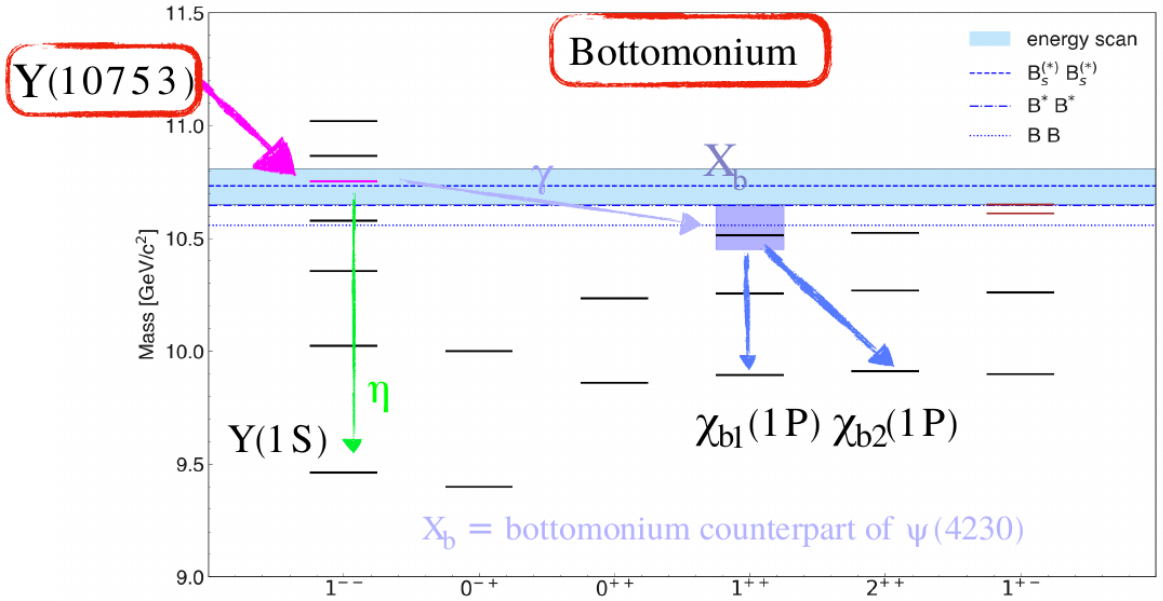
$\Upsilon(10753)$ as a bottomonium counterpart of $\psi(4230)$

$\psi(4230)$ was observed in $J/\psi(1S)\pi^+\pi^-$
by BaBar, BESIII, Belle

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

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





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

Belle II $\Upsilon(10753)$ scan data

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

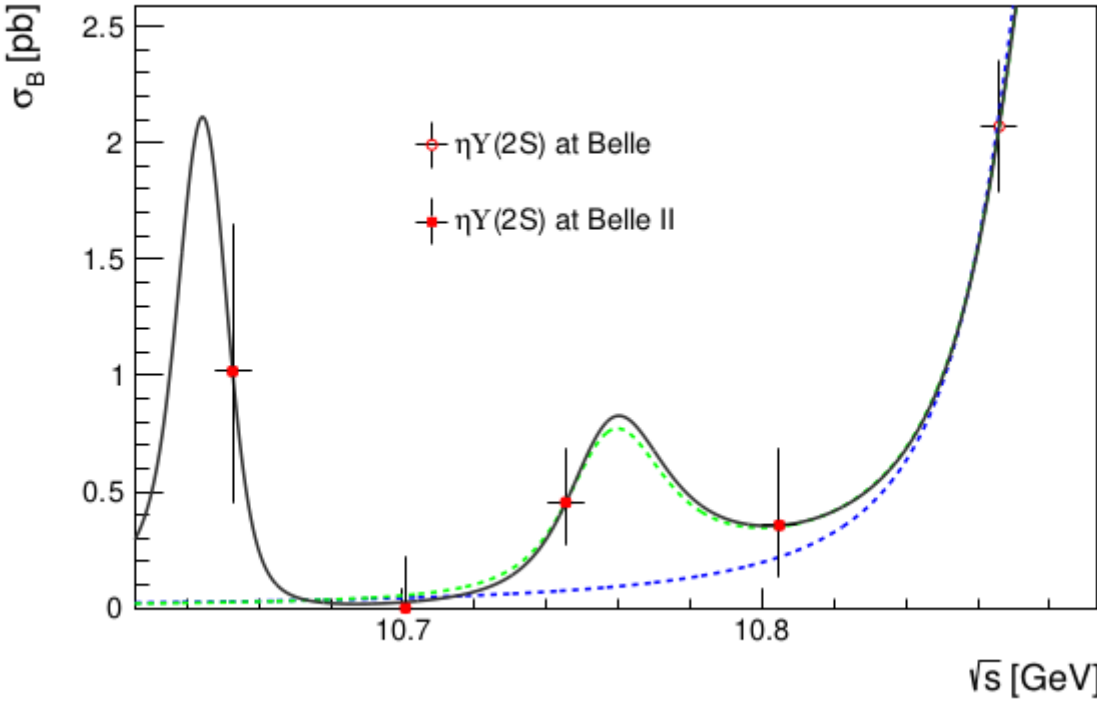
- $e^+e^- \to \eta(\to \gamma\gamma)\Upsilon(2S)\big(\to \pi^+\pi^-\Upsilon(1S)\big),\ \Upsilon(1S) \to l^+l^-$
- $e^+e^- \to \eta(\to \pi^+\pi^-\pi^0)\,\Upsilon(1,2S)(\to l^+l^-)$
- $e^+e^- \to \gamma X_b\big(\to \pi^+\pi^-\chi_{bJ}\big),\ \chi_{bJ} \to \gamma\Upsilon(1S) \to \gamma(l^+l^-)$

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

$e^+e^- \to \Upsilon(2S)\eta$ is observed with significance 6.6σ

Possible $B^*\bar{B}^*$ bound state at 10.65 GeV?

No evident signal of ηY (1S) nor the Xb, UL are set



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

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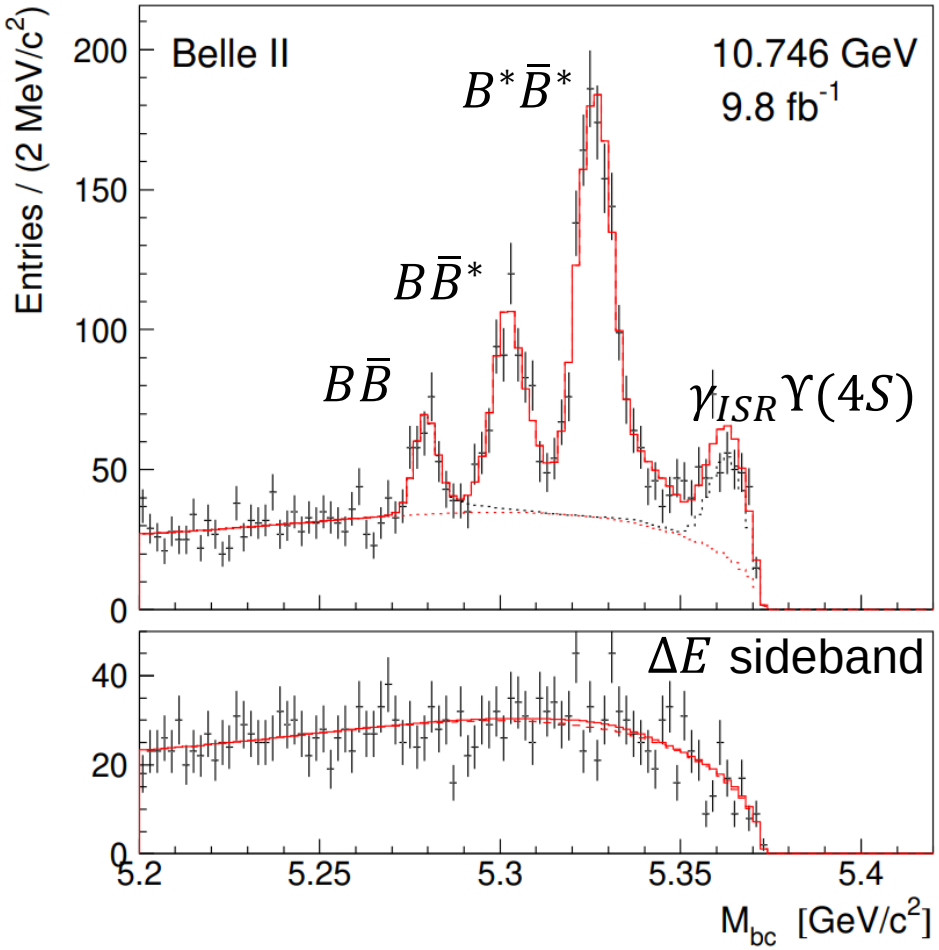
Full reconstruction of one B in the event



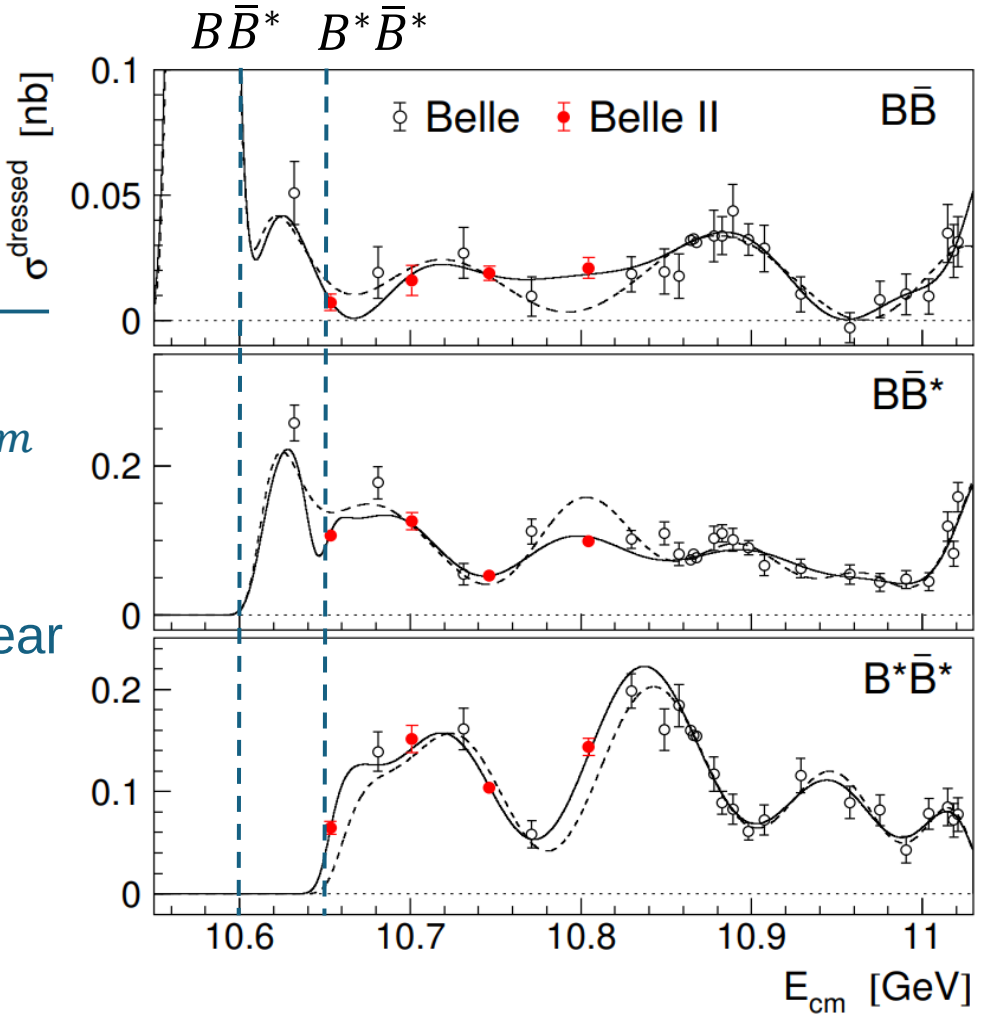
Process is identified by M_{bc} (p_{cm}):

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

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 (?)



Measurements of the B^0 and B^+meson mass difference

$$M_B = \sqrt{\left(\frac{\sqrt{s}}{2}\right)^2 - p_B^2}$$

$$\sigma_E \approx 5\ MeV, \quad R_{0+} = \frac{\sigma(e^+e^- \to B^0\bar{B}^0)}{\sigma(e^+e^- \to B^+B^-)}$$

Shift in Δm due to R_{0+} energy dependence:

$$\Delta(\Delta m) = \frac{\sigma_E^2}{2}\frac{\partial R_{0+}}{\partial E_{cm}}$$

Babar assumption: $R_{0+} = \left(\frac{p_{B^0}}{p_{B^+}}\right)^3$

PRD 78, 011103 (2008)

$\Delta m = (0.33 \pm 0.05 \pm 0.03)\ \mathrm{MeV}/c^2$

Isospin violation: $\Delta(\Delta m)$ up to $0.4\ \mathrm{MeV}/c^2$

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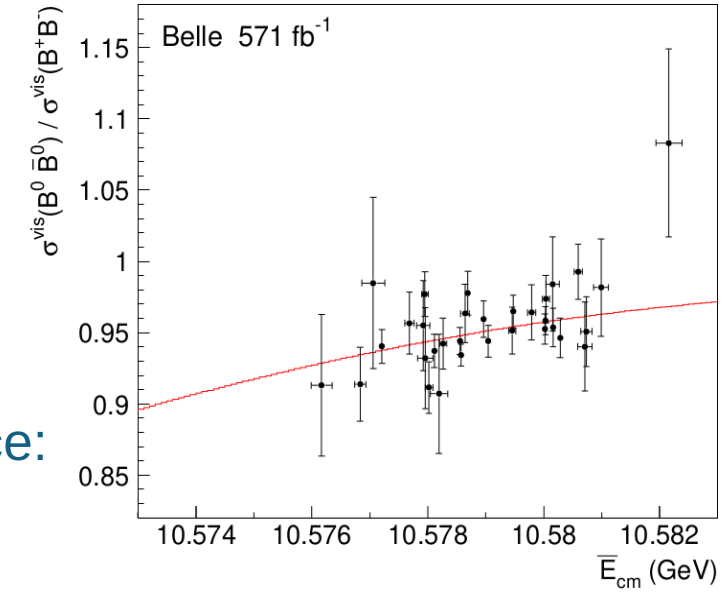
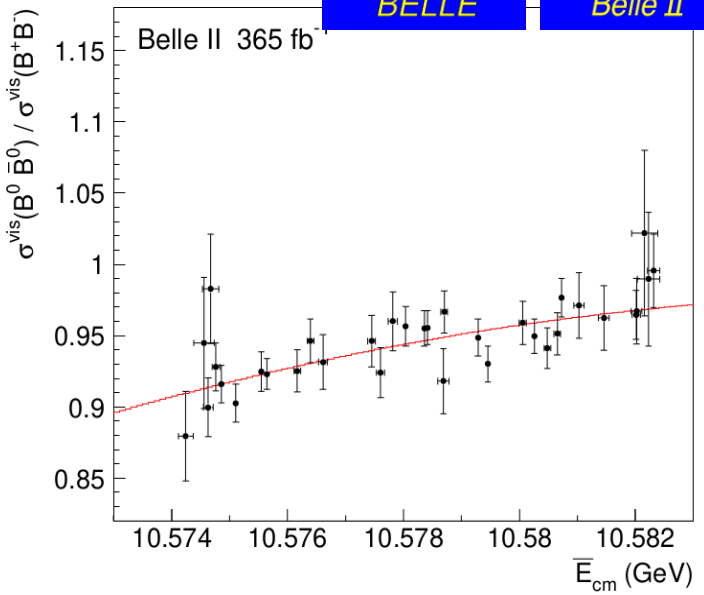
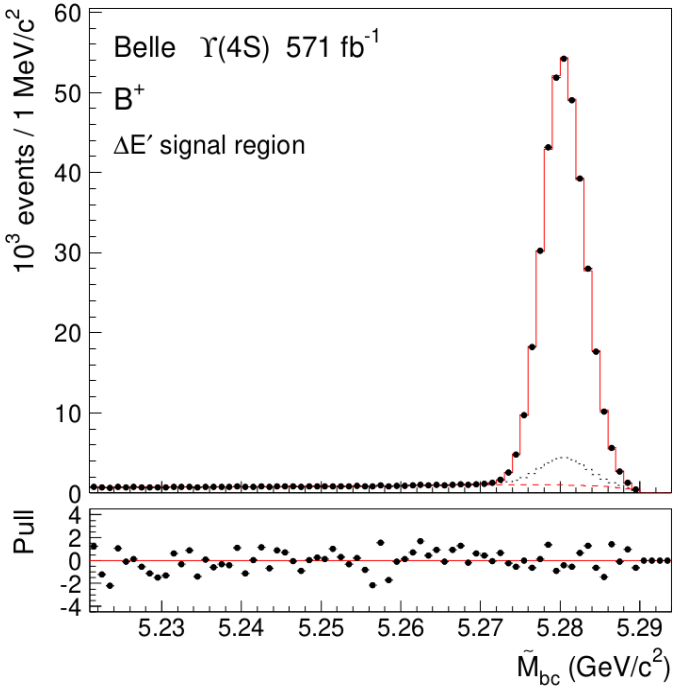
Measurement of R_{0+} dependence:

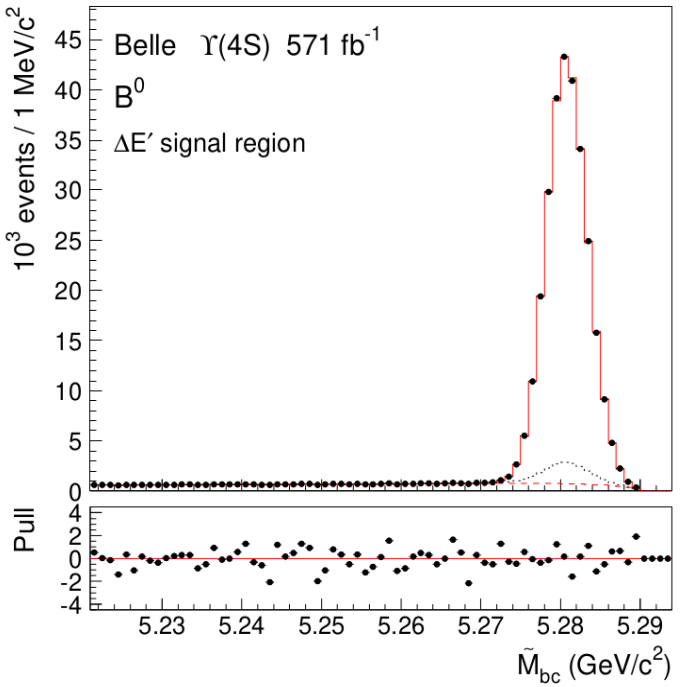
$\Delta m = (XX \pm 0.023 \pm 0.013)\ \mathrm{MeV}/c^2$

Preliminary









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:

  - No clear indication yet on its nature

  - Results in $\eta_b(1S)\omega$ consistent with S-D mixing, but not in $\chi_{bJ}(1P)\omega$

  - No enhancement in $\eta_b(1S)\omega$ as predicted by tetraquark model

  - Additional studies underway ($h_b(1P)\eta, h_b(1P)\pi^+\pi^-$, etc)
- The most precise measurement of B^0 and B^+ mass difference
- Only 0.5% of target integrated luminosity collected so far - much more to come!