Hadronic decays of excited bottomonium states at Belle and Belle II

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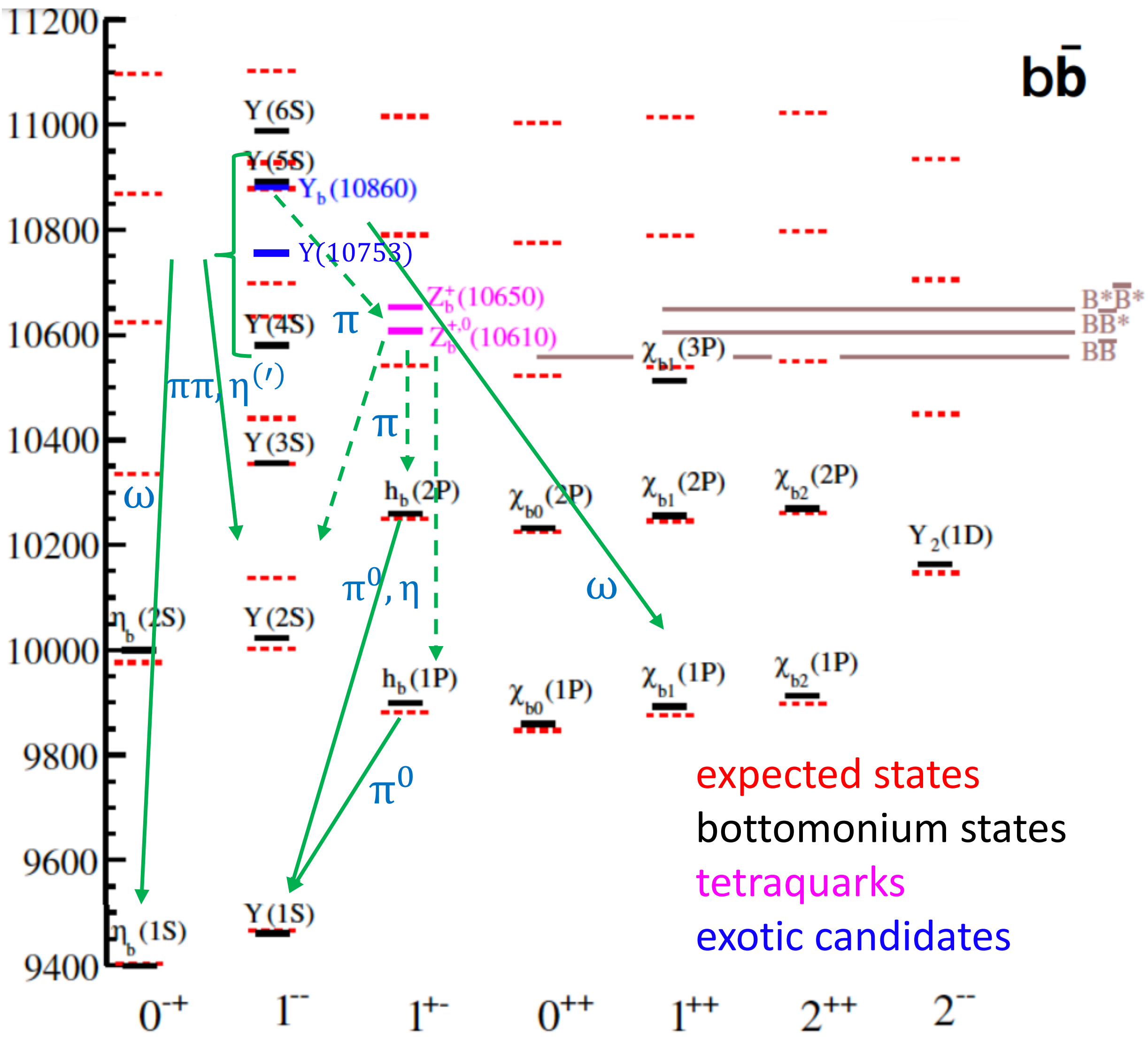
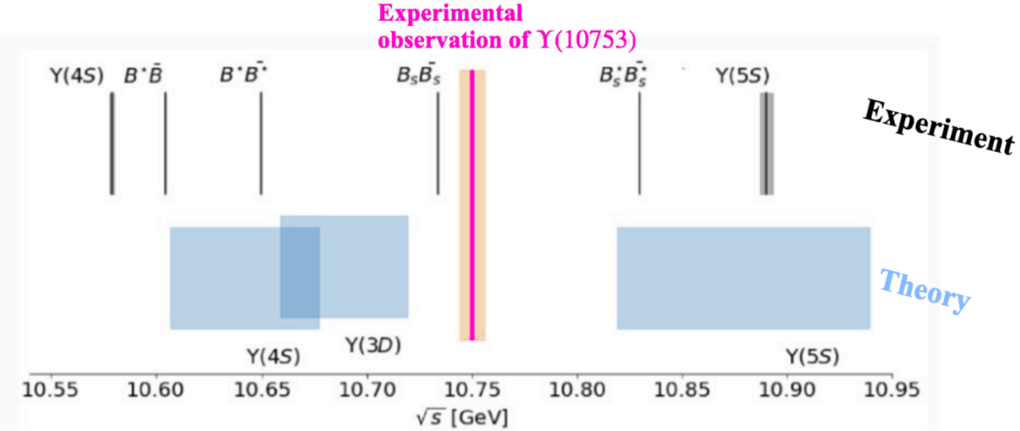
Bottomonium family

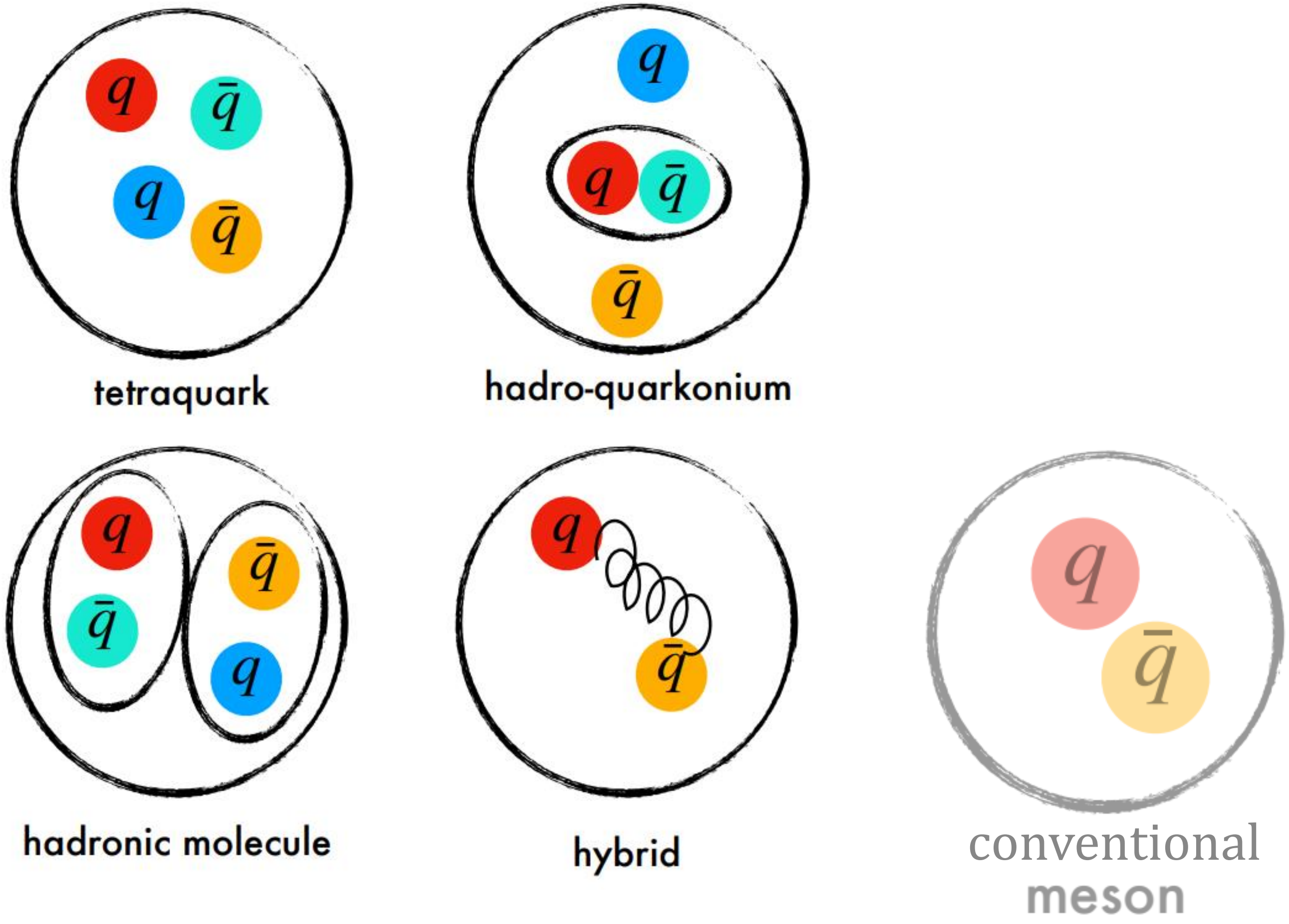


Bound state of $b\bar{b}$

- Properties below $B\bar{B}$ threshold are as expected
- Above $B\bar{B}$ - anomalous rate of $\pi\pi, \eta^{(\prime)}$ transitions
- Tetraquarks $Z_b(10610, 10650)$ $(T_{b\bar{b}1})$ observed in $\pi\pi$ transitions, with $I^G(J^{PC}) = 1^+(1^{+-})$
- $\Upsilon(10753)$ is observed - $\Upsilon(3D)$ or exotic?



Structure above $B\bar{B}$ threshold



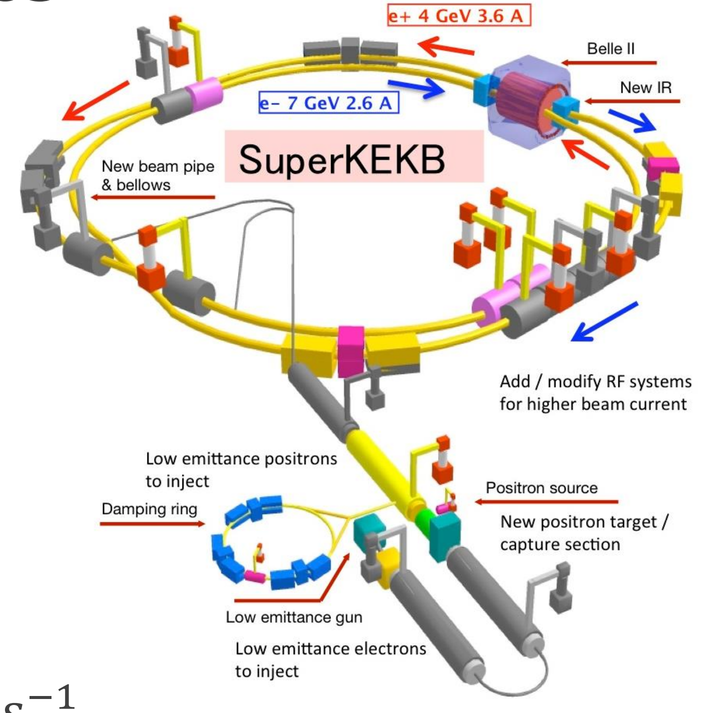
Including S-D state mixing

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

Belle and Belle II experiments

Conducted at KEKB/SuperKEKB colliders, Japan

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



KEKB

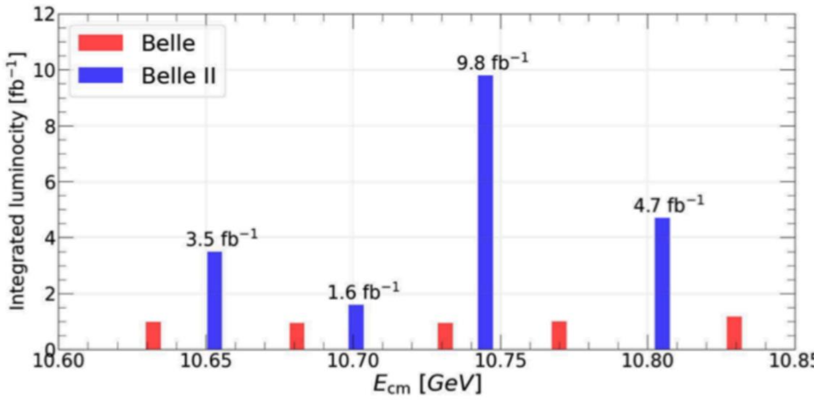
1999-2010

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

SuperKEKB

2018-current

- $e^+(4\ GeV)\ e^-(7\ GeV)$
- $L_{peak} = 4.7 \times 10^{34}\ cm^{-2}s^{-1}$
- $L_{target} = 6 \times 10^{35}\ cm^{-2}s^{-1}$
- $\int Ldt = \begin{cases} > 430\ fb^{-1}\ at\ \Upsilon(4S) \\ 20\ fb^{-1}\ at\ \Upsilon(10753) \end{cases}$
- Target $\int Ldt \sim 50\ ab^{-1}$

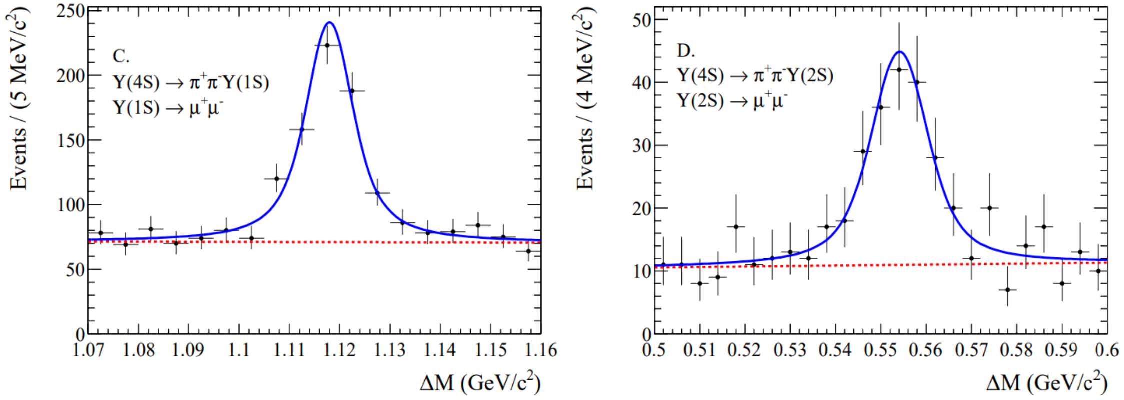


$\Upsilon(4S, 10753, 5S) \to \Upsilon(1S, 2S, 3S)\pi^+\pi^-$

- $\Upsilon(4S)$: compatible with $b\bar{b}$
- $\Upsilon(10753)$: resonance confirmed, no intermediate Z_b, structure - ?
- $\Upsilon(5S)$: intermediate Z_b was discovered

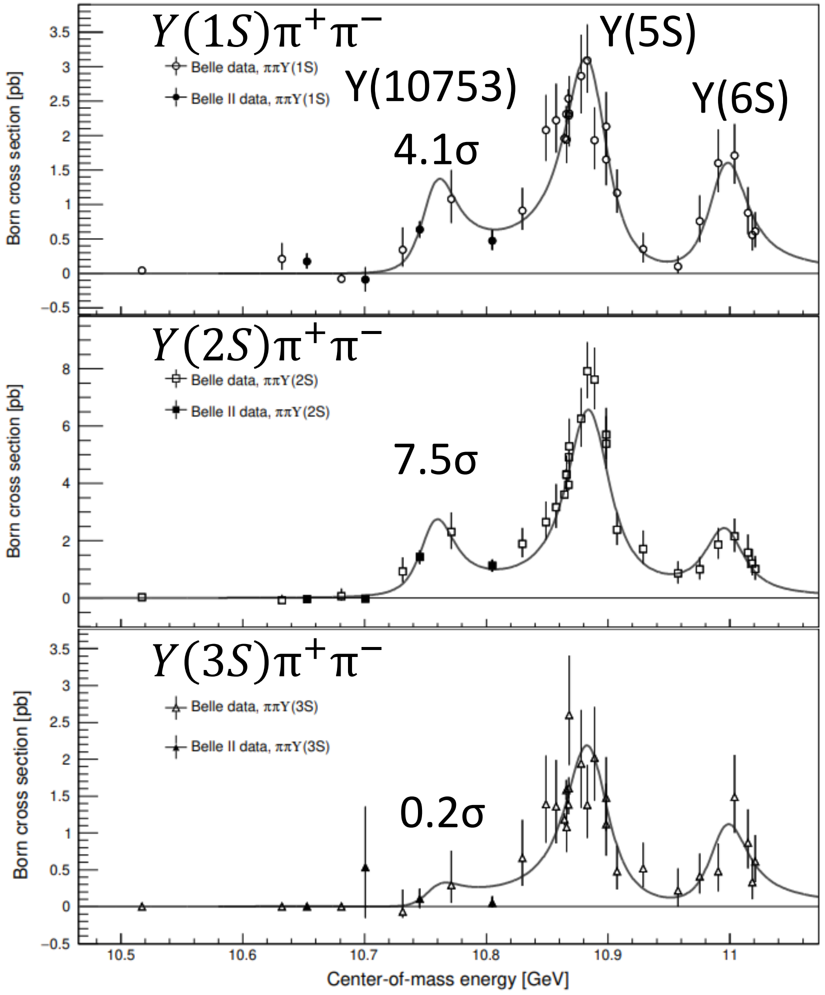
  Non-Z_b rate still does not support $b\bar{b}$ (x100)

$\Upsilon(4S) \to \Upsilon(1S, 2S)\pi^+\pi^-$



$M(\mu\mu\pi\pi) - M(\mu\mu)$ distribution at $\Upsilon(4S)$

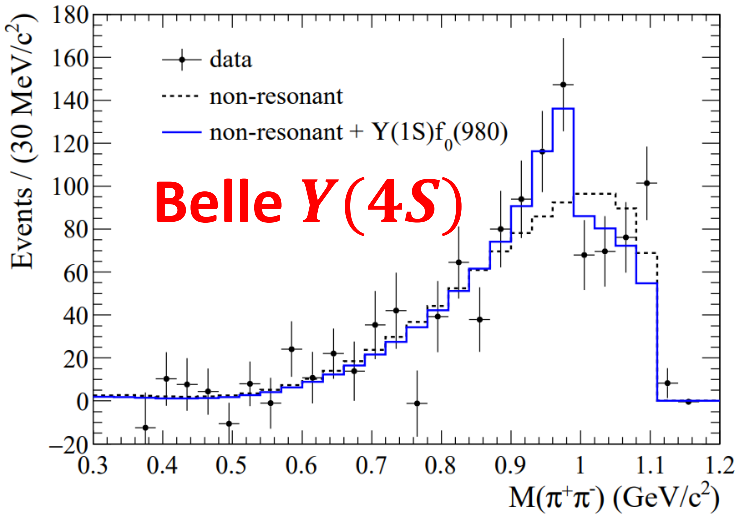
PRD 96 (2017) 5, 052005



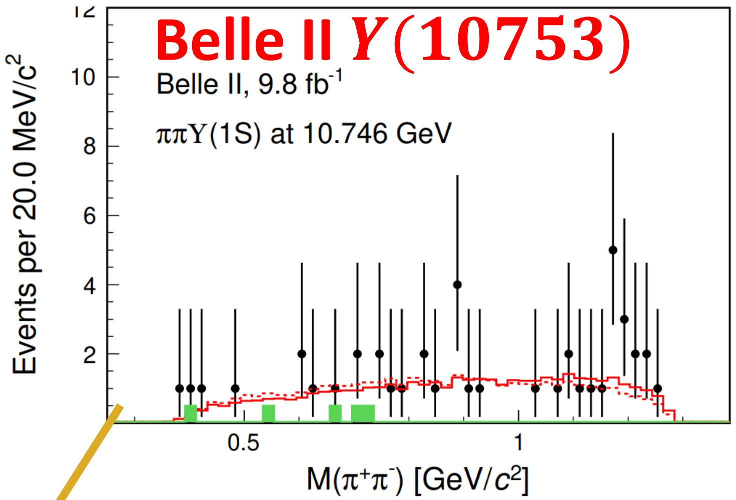
Cross section dependence above $\Upsilon(4S)$

JHEP 07 (2024) 116

Di-pion mass spectrum for $\Upsilon(1S)\pi^+\pi^-$



PRD 96 (2017) 5, 052005



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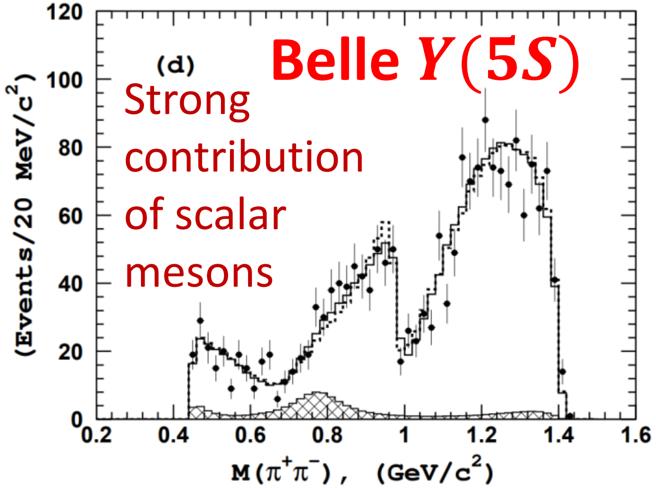
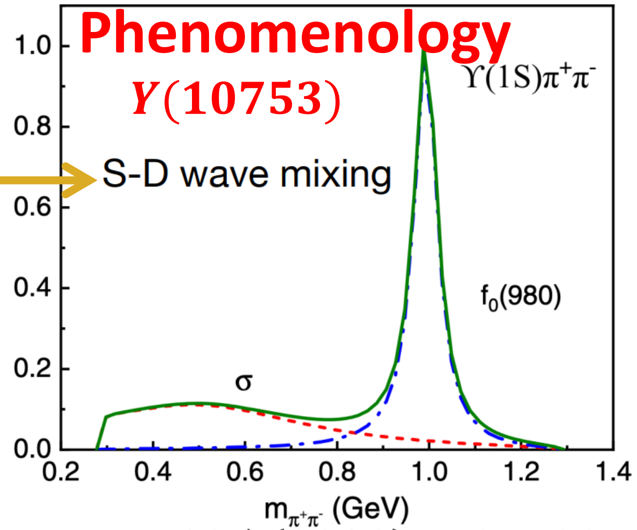
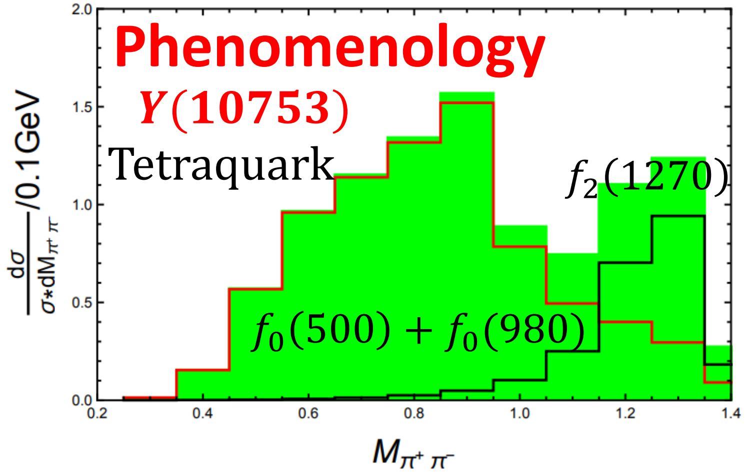


PRD 91 (2015) 7, 072003

- $\Upsilon(4S)$: indication of $f_0(980)$
- $\Upsilon(10753)$: no $f_0(980)$, no sign of S-D mixing, compatible with tetraquark?
- $\Upsilon(5S)$: Z_b, $f_0(980)$, $(\pi^+\pi^-)_{D\ wave}$



PRD 105 (2022) 7, 074007

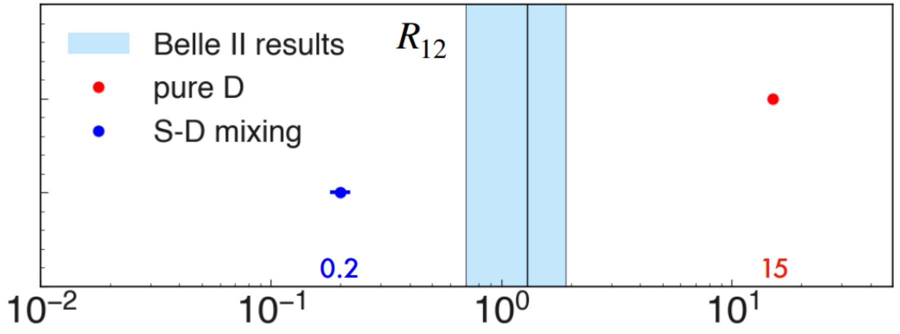


PLB 802 (2020) 135217

$\Upsilon(10753, 5S) \to \chi_{bJ}(1P)\omega$

- $\Upsilon(10753)$: observed ($J = 1,2$)

$$R_{12} = \frac{\Gamma_{ee}\times B[\Upsilon(10753)\to\chi_{b1}(1P)\omega]}{\Gamma_{ee}\times B[\Upsilon(10753)\to\chi_{b2}(1P)\omega]} = 1.3 \pm 0.6$$



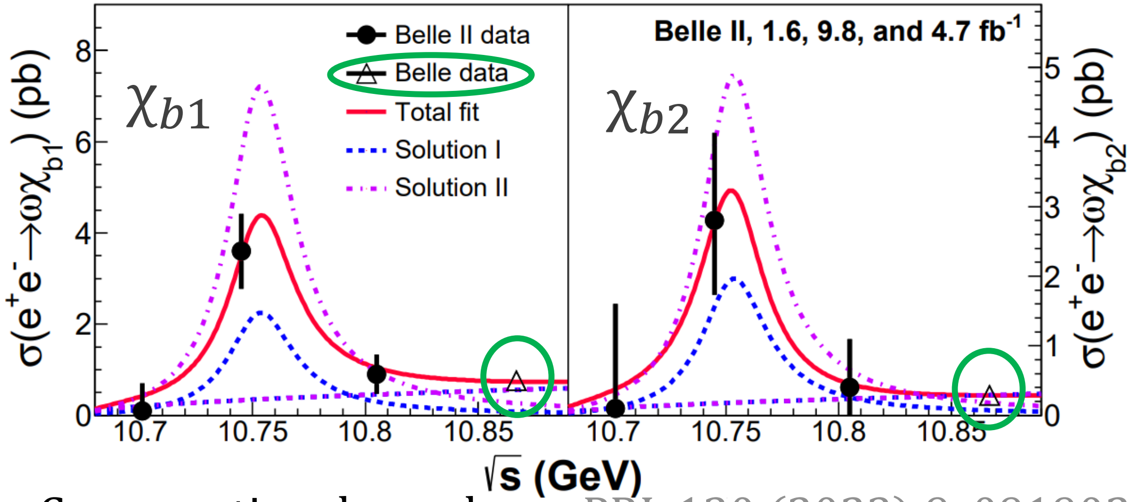
Does not support pure 3D, 1.8σ discrepancy from S-D mixing

- $\Upsilon(5S)$: observed ($J = 1,2$)

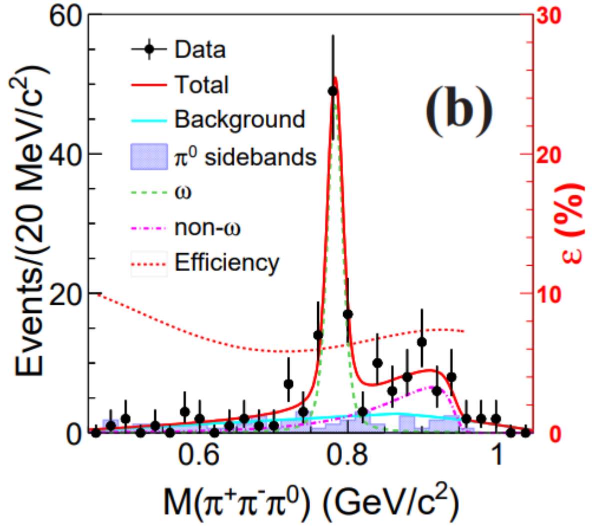
$$R_{12} = 2.6 \pm 1.1 \quad (0.63 \text{ is expected for } b\bar{b}\ 5S)$$

$$\frac{\sigma[e^+e^- \to \chi_{b1}(1P)\omega]}{\sigma[e^+e^- \to \Upsilon(1S)\pi^+\pi^-]} \approx \begin{cases} 5.6 \text{ at } \Upsilon(10753) \\ 0.3 \text{ at } \Upsilon(5S) \end{cases}$$

Different structure? Tail from $\Upsilon(10753)$?



Cross-section dependence PRL 130 (2023) 9, 091902



Distribution at $\Upsilon(5S)$ PRL 113 (2014) 14, 142001

$\Upsilon(4S, 10753, 5S) \to \eta_b(1S)\omega$

- $\Upsilon(4S)$: PRD 102 (2020) 9, 092011

  $B[\Upsilon(4S) \to \eta_b(1S)\omega] < 1.8 \times 10^{-4}$

  $R = \frac{\sigma(e^+e^- \to \eta_b(1S)\omega)}{\sigma(e^+e^- \to \Upsilon(1S)\pi^+\pi^-)} < 2.2$

- $\Upsilon(10753)$: PRD 109 (2024) 7, 072013

  $\sigma(e^+e^- \to \eta_b(1S)\omega) < 2.5\ pb$

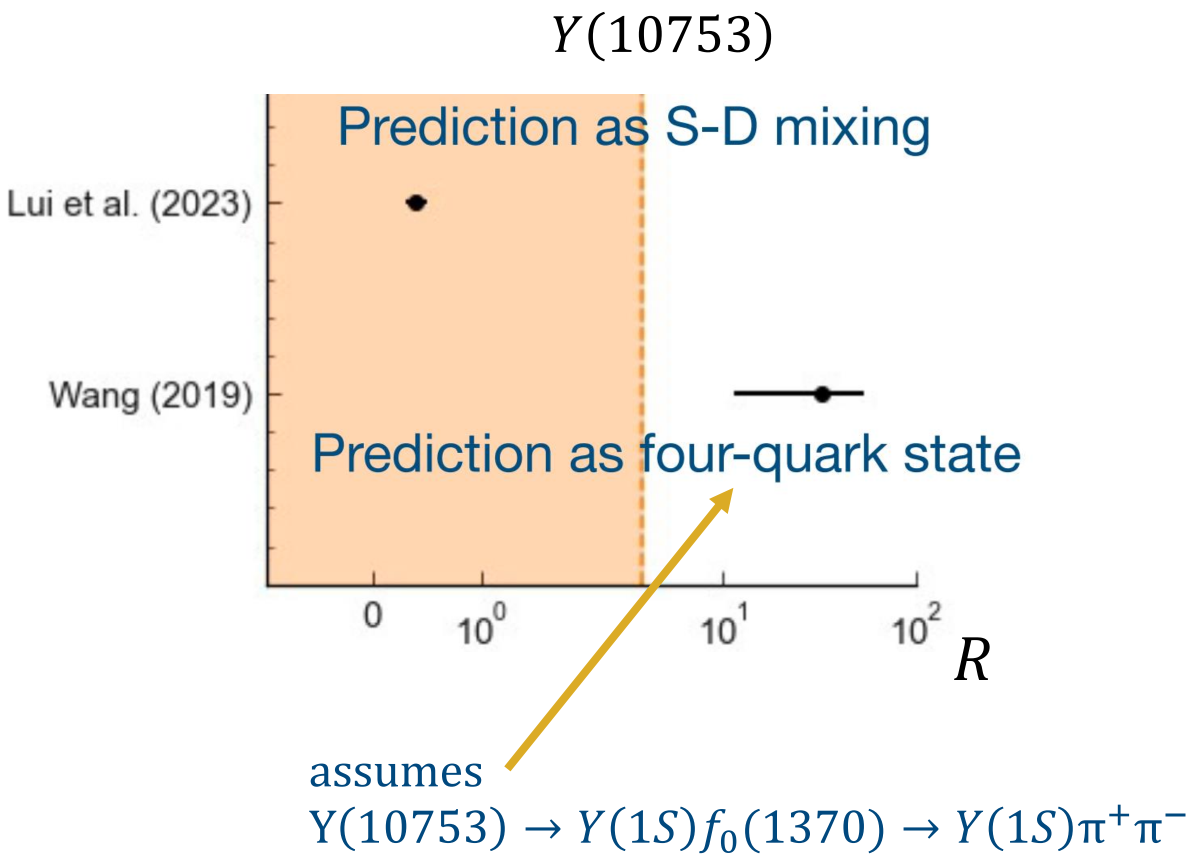
  $R < 1.25$

- $\Upsilon(5S)$: PRD 102 (2020) 9, 092011

  $B[\Upsilon(5S) \to \eta_b(1S)\omega] < 1.3 \times 10^{-3}$

  $B[\Upsilon(5S) \to \eta_b(2S)\omega] < 5.6 \times 10^{-3}$

  $R < 0.25$



Does not support tetraquark?

$\Upsilon(4S,5S) \to \Upsilon(1S,2S)\eta^{(\prime)}$

- $\Upsilon(4S)$:
  - $B[\Upsilon(4S) \to \Upsilon(1S)\eta] = (1.70 \pm 0.23 \pm 0.08) \times 10^{-4}$
  - $B[\Upsilon(4S) \to \Upsilon(1S)\eta'] = (3.43 \pm 0.88 \pm 0.21) \times 10^{-5}$
  - $R_{\eta/\pi\pi} = 2.07 \pm 0.24$ ($1/m_b$ suppression for pure $b\bar{b}$)
  - $R_{\eta'/\eta} = 0.20 \pm 0.06$ (≈ 5 for pure $b\bar{b}$)
- $\Upsilon(5S)$:
  - $B[\Upsilon(5S) \to \Upsilon(1S)\eta] = (8.5 \pm 1.7) \times 10^{-4}$
  - $B[\Upsilon(5S) \to \Upsilon(1S)\eta'] < 6.9 \times 10^{-5}$
  - $R_{\eta/\pi\pi} = 0.19 \pm 0.04$ ($1/m_b$ suppression for pure $b\bar{b}$)
  - $R_{\eta'/\eta} < 0.09$ (≈ 13 for pure $b\bar{b}$)

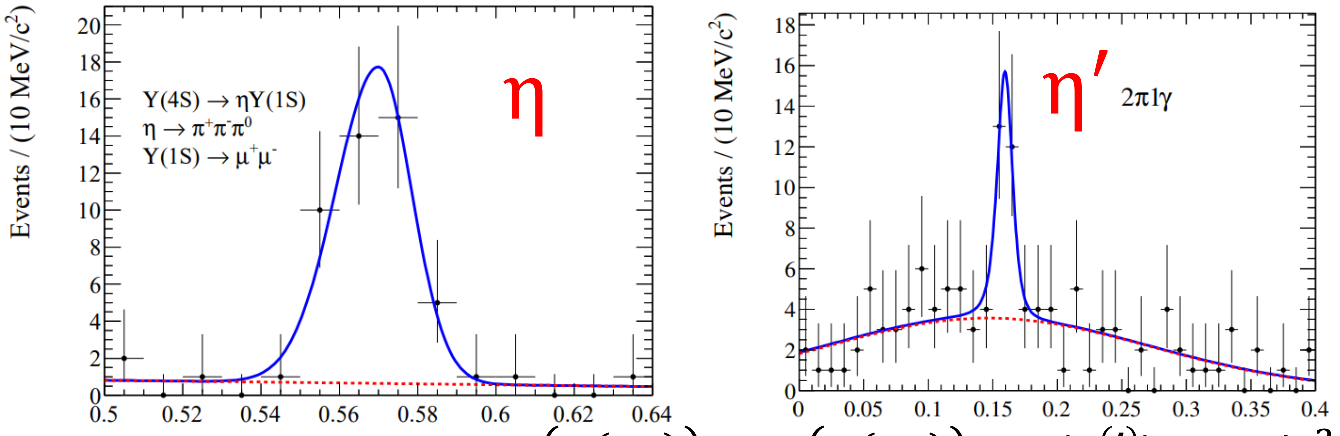
  $B[\Upsilon(5S) \to \Upsilon(2S)\eta] = (4.1 \pm 0.6) \times 10^{-4}$
  $R_{\eta/\pi\pi}(2S) = 0.51 \pm 0.06$ ($1/m_b$ suppression for pure $b\bar{b}$)

Does not support pure $b\bar{b}$

Could be explained by admixture of additional pair of light quarks

Or by B-meson loops

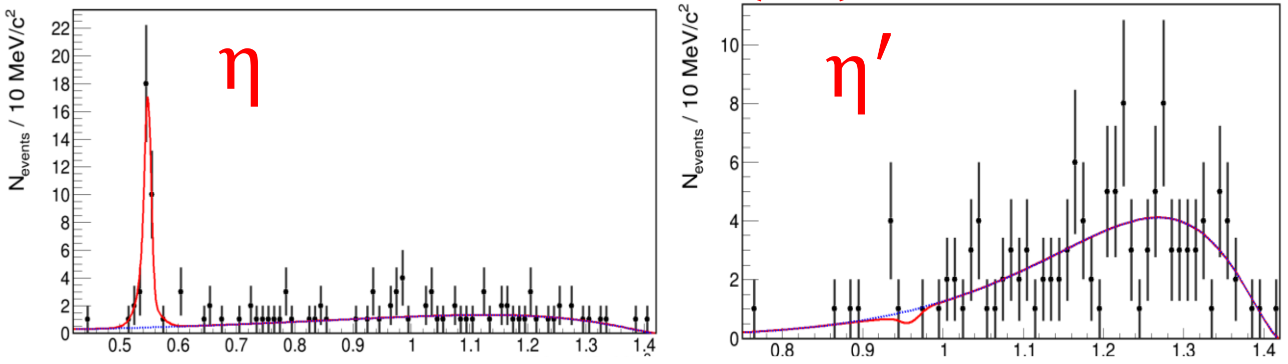
Belle $\Upsilon(4S)$



$\Delta M_{\eta^{(\prime)}} = M(\Upsilon(4S)) - M(\Upsilon(1S)) - M(\eta^{(\prime)}), GeV/c^2$

PRD 96 (2017) 5, 052005   PRL 121 (2018) 6, 062001

Belle $\Upsilon(5S)$

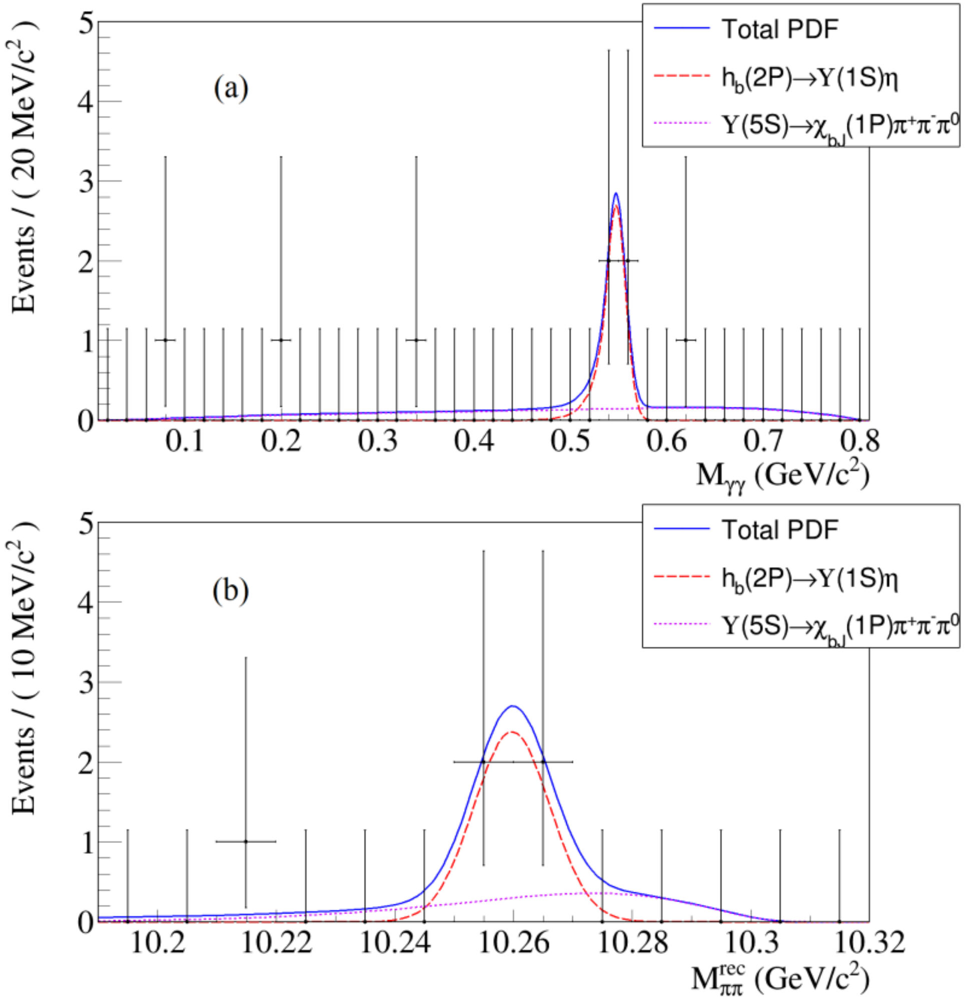


$M_{\pi\pi\gamma\gamma}, GeV/c^2$ $M_{\pi\pi\gamma\gamma}, GeV/c^2$

PRD 104 (2021) 11, 112006

$h_b(1P,2P) \to Y(1S)\eta(\pi^0)$

- Enhanced production in $Y(5S) \to h_b(1P,2P)\pi^+\pi^-$
- $\frac{\Gamma_{ann}[h_b(2P)]/\Gamma_{ann}[h_b(1P)]}{\Gamma_{ann}[\chi_{b1}(2P)]/\Gamma_{ann}[\chi_{b1}(1P)]} = 0.24^{+0.47}_{-0.24}$ (1 is expected) arxiv:2407.03783
- Contradiction gets stronger with expected $B(h_b(2P) \to \Upsilon(1S)\eta) \sim O(10\%)$ PRD 86 (2012) 094013
- First evidence of $h_b(2P) \to Y(1S)\eta$:
  $B(h_b(2P) \to \Upsilon(1S)\eta) = (7.1^{+3.7}_{-3.2} \pm 0.8) \times 10^{-3}$
  $\frac{\Gamma[h_b(2P)\to\Upsilon(1S)\eta]}{\Gamma[\Upsilon(3S)\to h_b(1P)\pi^0]} = 30^{+20}_{-18} \pm 10$ (140 − 320 is expected)
  PRD 84 (2011) 091101
- Also set upper limits:
  $B(h_b(1P) \to \Upsilon(1S)\pi^0) < 1.8 \times 10^{-3}$
  $B(h_b(2P) \to \Upsilon(1S)\pi^0) < 1.8 \times 10^{-3}$



arxiv:2407.03783

Conclusion

- Hadronic transitions between bottomonium states provides important information on its structure
- There are signs that states $Y(4S, 10753, 5S)$ above $B\bar{B}$ threshold might not be pure conventional $b\bar{b}$
- No clear explanation
- Additional efforts are required at this range of energies

  $e^+e^- \to Y(1S)K^+K^-$

  $e^+e^- \to Y(1S, 2S)\eta^{(\prime)}$

  Additional data taking around $Y(10753, 5S)$ energies

BACKUP

$\Upsilon(10753, 5S) \rightarrow [\Upsilon(1S, 2S, 3S)/h_b(1P, 2P)]\pi^+\pi^-$