

Tetraquark Interpretation and Production Mechanism of the Belle $Y_b(10750)$ -Resonance

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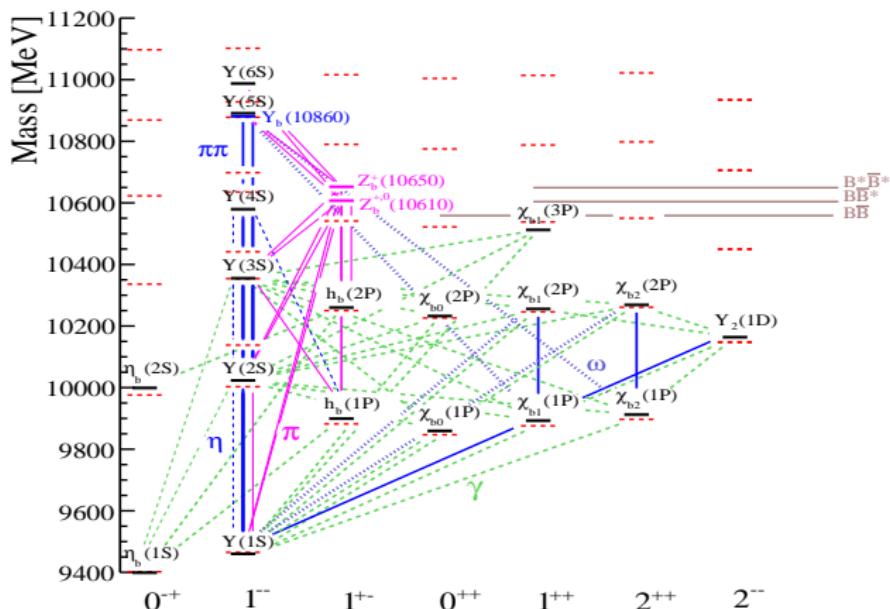
based on the paper [PLB 802 \(2020\) 135217 \[arXiv:1910.07671\]](#)

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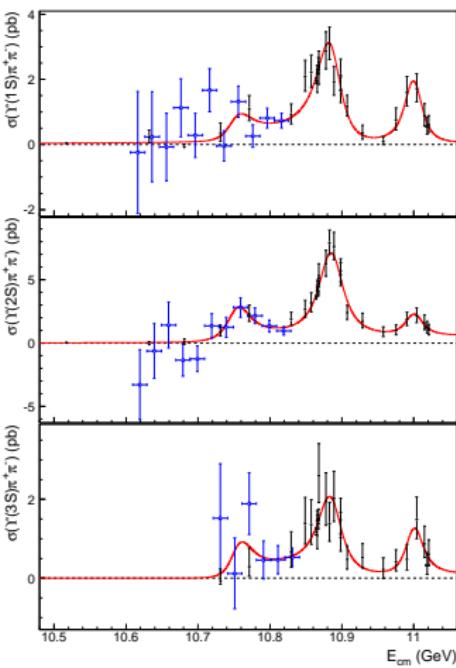
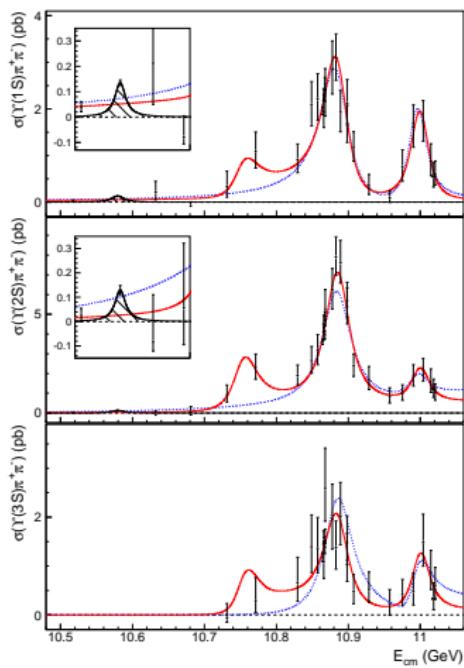
Y_b , Z_b , and Bottomonium States

[S. L. Olsen, T. Skwarnicki, D. Zieminska, Rev. Mod. Phys. 90 (2018) 015003]



Energy Scan in the $e^- e^+$ -Annihilation by the Belle Collab.

[R. Mizuk et al., JHEP 1910 (2019) 220; arXiv:1905.05521]



Experimental Data on $\Upsilon(10860)$, $\Upsilon(11020)$, and $Y_b(10750)$

[R. Mizuk et al., JHEP 1910 (2019) 220; arXiv:1905.05521]

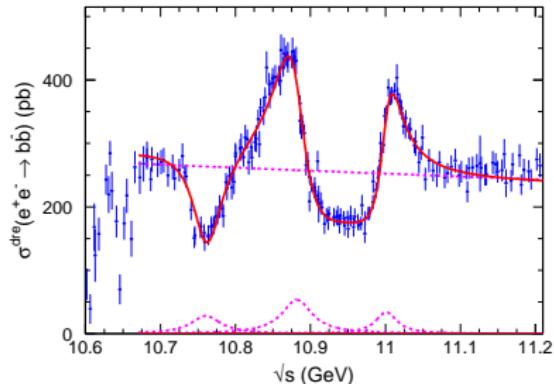
- Measured masses and decay widths (in MeV), and ranges of $\Gamma_{ee} \times \mathcal{B}$ (in eV) of $\Upsilon(10860)$, $\Upsilon(11020)$, and $Y_b(10750)$

State	$\Upsilon(10860)$	$\Upsilon(11020)$	$Y_b(10750)$
Mass	$10885.3 \pm 1.5^{+2.2}_{-0.9}$	$11000.0^{+4.0+1.0}_{-4.5-1.3}$	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
Width	$36.6^{+4.5+0.5}_{-3.9-1.1}$	$23.8^{+8.0+0.7}_{-6.8-1.8}$	$35.5^{+17.6+3.9}_{-11.3-3.3}$
$\Upsilon(1S)\pi^+\pi^-$	0.75 – 1.43	0.38 – 0.54	0.12 – 0.47
$\Upsilon(2S)\pi^+\pi^-$	1.35 – 3.80	0.13 – 1.16	0.53 – 1.22
$\Upsilon(3S)\pi^+\pi^-$	0.43 – 1.03	0.17 – 0.49	0.21 – 0.26

- Global significance of $Y_b(10750)$ is 5.2σ

Hadronic Cross Section of e^-e^+ -Annihilation from Belle & BaBar

[X.-K. Dong et al., Chin. Phys. C 44 (2020) 083001; arXiv:2002.09838]

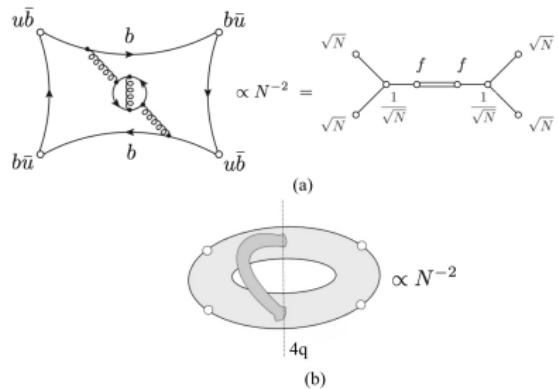


- M , Γ_{tot} , $\Gamma_{e^-e^+}$, and ϕ are free parameters
- 8 solutions with identical fit quality are found

Solution	Parameter	$Y_b(10750)$	$\Upsilon(5S)$	$\Upsilon(6S)$
1-8	Mass (MeV/c^2)	10761 ± 2	10882 ± 1	11001 ± 1
	Width (MeV)	48.5 ± 3.0	49.5 ± 1.5	35.1 ± 1.2
1	$\Gamma_{e^-e^+}$ (eV)	10.7 ± 0.9	21.3 ± 1.0	9.8 ± 0.5
	ϕ (degree)	260 ± 3	144 ± 2	34 ± 3

Possible Interpretations of $Y_b(10750)$

- Conventional interpretation: $Y_b(10750)$ and $\Upsilon(10680)$ are the mixture of $\Upsilon(5S)$ and $\Upsilon(4D)$
- Our interpretation: $Y_b(10750)$ and $\Upsilon(10680)$ are the mixture of $\Upsilon(5S)$ and hidden-bottom tetraquark
- Tetraquark-Bottomonium mixing exists in the large- N_c approach with the mixing coefficient $f \sim N_c^{-3/2}$
- Should be sizable at $N_c = 3$



Mixing Formalism. I

- Define the tetraquark states Y_b^I ($I = 0, 1$) in the isospin basis, with $Y_b^0 \equiv (Y_{[bu]} + Y_{[bd]}) / \sqrt{2}$ and $Y_b^1 \equiv (Y_{[bu]} - Y_{[bd]}) / \sqrt{2}$
- Their mass difference due to the isospin breaking is ignored
- Production is via the isosinglet $b\bar{b}$ -component, so only Y_b^0 -state is considered
- Observed mass differences are
 $M[\Upsilon(10860)] - M[Y_b(10750)] \simeq 133$ MeV and
 $M[\Upsilon(11020)] - M[Y_b(10750)] \simeq 247$ MeV, so the mixing between $\Upsilon(10860)$ and $Y_b(10750)$ should be more pronounced

$$\begin{pmatrix} Y_b(10750) \\ \Upsilon(10860) \end{pmatrix} = \begin{pmatrix} \cos \tilde{\theta} & \sin \tilde{\theta} \\ -\sin \tilde{\theta} & \cos \tilde{\theta} \end{pmatrix} \begin{pmatrix} Y_b^0 \\ \Upsilon(5S) \end{pmatrix}$$

- Mixing angle $\tilde{\theta}$ is estimated phenomenologically
- Mixing can be generalized to the case of all three states

Mixing Formalism. II

- This mixing relates $\Gamma_{ee}[Y_b(10750)]$ and $\Gamma_{ee}[\Upsilon(5S)]$

$$\frac{\Gamma_{ee}[Y_b(10750)]}{\Gamma_{ee}[\Upsilon(10860)]} = \tan^2 \tilde{\theta} \left[\frac{M[\Upsilon(10860)]}{M[Y_b(10750) \pm 13.7 \text{ eV}]} \right]^4 \simeq 1.04 \tan^2 \tilde{\theta}$$

- LHS can be determined numerically, using
 $\Gamma_{ee}[\Upsilon(10860)] = (310 \pm 70) \text{ eV}$ [PDG, 2018]
 $\Gamma_{ee}[Y_b(10750)] = (13.7 \pm 1.8) \text{ eV}$ [C.-Z. Yuan, XVth Rencontre du Vietnam, 2019]
- Estimate of the mixing angle

$$\tan^2 \tilde{\theta} = 0.044 \pm 0.006 \implies \tilde{\theta} \simeq 12^\circ$$

- This supports the prediction from the large- N_c approach that the mixing angle between the pure bottomonium and hidden-bottom tetraquark state is relatively large

Hadroproduction Cross Sections at the LHC. I

- Hadroproduction cross sections for $\Upsilon(5S)$ and $\Upsilon(6S)$ in $p\bar{p}$ (Tevatron) and pp (LHC) collisions were calculated, using NRQCD framework [A. Ali, C. Hambrock, W. Wang, PRD 88 (2013) 054026]
- Calculation has adopted a factorization ansatz to separate the short- and long-distance effects
- Cross-sections for $Y_b(10750)$ are scaled from the ones for $\Upsilon(5S)$, since in both cases the production takes place via the $b\bar{b}$ -component
- The cross-section ratio is determined by the mixing angle

$$\frac{\sigma(pp \rightarrow Y_b(10750) + X) \mathcal{B}_f(Y_b(10750))}{\sigma(pp \rightarrow \Upsilon(10860) + X) \mathcal{B}_f(\Upsilon(10860))} \\ \simeq \frac{\Gamma_{ee}(Y_b(10750)) \mathcal{B}_f(Y_b(10750))}{\Gamma_{ee}(\Upsilon(10860)) \mathcal{B}_f(\Upsilon(10860))} \simeq 1.04 \tan^2 \tilde{\theta} \frac{\mathcal{B}_f(Y_b(10750))}{\mathcal{B}_f(\Upsilon(10860))}$$

- $\mathcal{B}_f(Y_b(10750)) = \mathcal{B}(Y_b(10750) \rightarrow \Upsilon(nS)\pi^+\pi^-)$ and $\mathcal{B}_f(\Upsilon(10860)) = \mathcal{B}(\Upsilon(10860) \rightarrow \Upsilon(nS)\pi^+\pi^-)$ with $n = 1, 2, 3$
- RHS of this equation has been measured by Belle

Hadroproduction Cross Sections at the LHC. II

- Absolute cross sections for $\Upsilon(10860)$ are estimated in NRQCD [A. Ali, C. Hambrock, W. Wang, PRD 88 (2013) 054026]

$$\begin{aligned}\sigma(pp \rightarrow \Upsilon(10860) + X) &= \sum_Q \sigma_Q \\ &= \sum_Q \int dx_1 dx_2 \sum_{i,j} f_i(x_1) f_j(x_2) \hat{\sigma}(ij \rightarrow \langle \bar{b}b \rangle_Q + X) \langle O[Q] \rangle\end{aligned}$$

- $f_i(x_1)$ is the parton distribution function (PDF) of a generic i -th parton inside a proton
- Label $Q = {}^{2S+1}L^c_J$ denotes the $b\bar{b}$ -pair quantum number (color c , spin S , and orbital L and total J angular momenta)
- $\langle O[Q] \rangle$ are long-distance matrix elements (LDMEs)
- $\hat{\sigma} = \sigma / \langle O[Q] \rangle$ is a normalized partonic cross section
- Leading-order partonic processes for the S -wave configurations

$$\begin{array}{ll} g + g \rightarrow \Upsilon[{}^3S_1^1] + g, & g + g \rightarrow \Upsilon[{}^1S_0^8, {}^3S_1^8] + g \\ g + q \rightarrow \Upsilon[{}^1S_0^8, {}^3S_1^8] + q, & q + \bar{q} \rightarrow \Upsilon[{}^1S_0^8, {}^3S_1^8] + g \end{array}$$

Hadroproduction and Drell-Yan Cross Sections at the LHC

- Total cross sections (in pb) at $\sqrt{s} = 14 \text{ TeV}$ for
 $pp \rightarrow Y_b(10750) + X \rightarrow \Upsilon(nS)(\rightarrow \mu^+ \mu^-) \pi^+ \pi^- + X$
 $(n = 1, 2, 3)$ at the LHC, assuming the transverse momentum range $3 \text{ GeV} < p_T < 50 \text{ GeV}$
- Rapidity ranges are $|y| < 2.5$ for ATLAS and CMS (called LHC 14) and $2.0 < y < 4.5$ for the LHCb
- Error estimates in the QCD production are from the variation of the central values of the Color-Octet LDMEs and the various decay branching ratios, as discussed in [A. Ali, C. Hamrock, W. Wang, PRD 88 (2013) 054026]
- Contributions from $\Upsilon(1S, 2S, 3S)$ are added together in the Drell-Yan production mechanism [A. Ali & W. Wang, PRL 106 (2011) 192001]

	QCD (gg)			Drell-Yan DY
	$n = 1$	$n = 2$	$n = 3$	
LHC 14	[0.29, 3.85]	[0.70, 4.78]	[0.45, 3.10]	[0.002, 0.004]
LHCb 14	[0.08, 1.21]	[0.20, 1.51]	[0.13, 0.99]	[0.001, 0.002]

Differential Cross Section in $Y_b(10750) \rightarrow \Upsilon(nS)\pi^+\pi^-$

- Differential cross section can be written as [A. Ali, C. Hambrock, S. Mishima, PRL 106 (2011) 092002]

$$\frac{d^2\sigma_{\Upsilon(1S)PP'}}{dm_{PP'} d\cos\theta} = \frac{\lambda^{1/2}(s, m_\Upsilon^2, m_{PP'}^2) \lambda^{1/2}(m_{PP'}^2, m_P^2, m_{P'}^2)}{384\pi^3 s m_{PP'} \left[(s - m_{Y_b}^2)^2 + m_{Y_b}^2 \Gamma_{Y_b}^2 \right]} \\ \times \left\{ \left(1 + \frac{(q \cdot p)^2}{2s m_\Upsilon^2} \right) |S|^2 + 2 \operatorname{Re} \left[S^* \left(\mathcal{D}' + \frac{(q \cdot p)^2}{2s m_\Upsilon^2} \mathcal{D}'' \right) \right] \left(\cos^2 \theta - \frac{1}{3} \right) \right. \\ + |\mathcal{D}|^2 \sin^2 \theta \left[\sin^2 \theta + 2 \left(\frac{q_0^2}{s} + \frac{p_0^2}{m_\Upsilon^2} \right) \cos^2 \theta \right] \\ \left. + \left(|\mathcal{D}'|^2 + \frac{(q \cdot p)^2}{2s m_\Upsilon^2} |\mathcal{D}''|^2 \right) \left(\cos^2 \theta - \frac{1}{3} \right)^2 \right\}$$

- m_{Y_b} , m_Υ , m_P and $m_{P'}$ are the masses of Y_b , $\Upsilon(nS)$, P and P'
- s and $m_{PP'}$ are invariant masses squared of e^+e^- and PP' -pairs
- θ is the angle between Y_b and P momenta in the PP' rest frame
- $\lambda(x, y, z) \equiv (x - y - z)^2 - 4yz$ is the kinematical function
- q_0 and p_0 are energies of the Y_b and $\Upsilon(nS)$ in the PP' rest frame
- Γ_{Y_b} is the decay width of Y_b

S - and D -Wave Amplitudes in $Y_b(10750) \rightarrow \Upsilon(nS)\pi^+\pi^-$

- S -wave amplitude for PP' system, \mathcal{S} , and D -wave amplitudes, \mathcal{D} , \mathcal{D}' and \mathcal{D}'' , are the sums over possible isospin states
[A. Ali, C. Hamrock, S. Mishima, PRL 106 (2011) 092002]

$$\mathcal{M} = \sum_I \mathcal{M}_I \quad \text{for } \mathcal{M} = \mathcal{S}, \mathcal{D}, \mathcal{D}', \mathcal{D}''$$

- For the $\pi^+\pi^-$ -pair, isospin $I = 0$
- In $Y_b(10750) \rightarrow \Upsilon(1S)\pi^+\pi^-$ process, scalar $f_0(500)$ - and $f_0(980)$ - and tensor $f_2(1270)$ -resonances contribute
- $I = 0$ amplitudes are given by the combinations of the resonance amplitudes, \mathcal{M}_0^S and $\mathcal{M}_0^{f_2}$, and the non-resonating continuum amplitudes, \mathcal{M}_0^{1C} and \mathcal{M}_0^{2C}

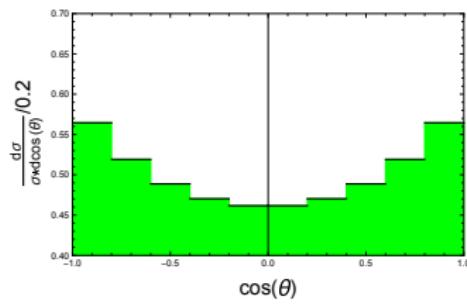
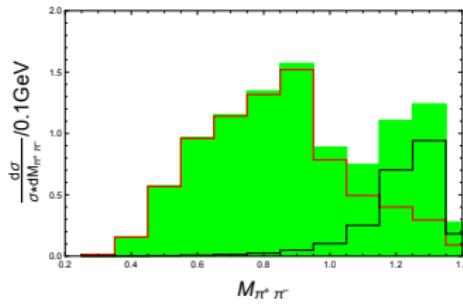
$$\mathcal{S}_0 = \mathcal{M}_0^{1C} + (\mathbf{k}_1 \cdot \mathbf{k}_2) \sum_S \mathcal{M}_0^S, \quad \mathcal{D}_0 = |\mathbf{k}|^2 \mathcal{M}_0^{f_2},$$

$$\mathcal{D}'_0 = \mathcal{M}_0^{2C} - \mathcal{D}_0, \quad \mathcal{D}''_0 = \mathcal{M}_0^{2C} + \frac{2q_0 p_0}{(\mathbf{q} \cdot \mathbf{p})} \mathcal{D}_0,$$

- $|\mathbf{k}|$ is the π^+ -meson momentum magnitude in $\pi^+\pi^-$ rest frame

$\pi^+\pi^-$ Invariant Mass and Angular Distributions

- $m_{\pi^+\pi^-}$ and $\cos\theta$ distributions for the process $e^+e^- \rightarrow Y_b + X \rightarrow \Upsilon(1S)\pi^+\pi^- + X$ are calculated
- They normalized by $\sigma_{\Upsilon(1S)\pi^+\pi^-}^{\text{Belle}} = (1.61 \pm 0.16) \text{ pb}$ measured by the Belle Collab. [K. F. Chen et al., PRL 100 (2008) 112001]
- Only resonant contributions are plotted, using relevant input parameters [A. Ali, C. Hambrock, S. Mishima, PRL 106 (2011) 092002]
- Anticipated spectral shapes will be modified in detail as a non-resonant contribution is included
- A fit can only be undertaken as experimental measurements become available



Branching Fractions of $Y_b(10750) \rightarrow \Upsilon(nS)\pi^+\pi^-$ Decays

- The products $\Gamma_{ee} \times \mathcal{B}$ are measured by Belle [R. Mizuk et al., JHEP 1910 (2019) 220; arXiv:1905.05521]
- $\Gamma_{ee}[Y_b(10750)] = (13.7 \pm 1.8) \text{ eV}$ from the Belle and BaBar data on R_b [C.-Z. Yuan, XVth Rencontres du Vietnam, 2019]
- Corresponding ranges of the branching fractions

$$\mathcal{B}_{\Upsilon(1S)\pi^+\pi^-} = (0.9 - 3.4)\%$$

$$\mathcal{B}_{\Upsilon(2S)\pi^+\pi^-} = (3.9 - 8.9)\%$$

$$\mathcal{B}_{\Upsilon(3S)\pi^+\pi^-} = (1.5 - 1.9)\%$$

- Note that due to the dominant tetraquark nature of $Y_b(10750)$, and its quark content, $Y_b(10750) \rightarrow B_s^{(*)}\bar{B}_s^{(*)}$ decays are not anticipated, in agreement with the data from the Belle Collab. [A. Abdesselam et al., arXiv:1609.08749]

Summary

- The tetraquark-based interpretation of the Belle data on the new structure $Y_b(10750)$ in the e^+e^- annihilation is presented
- The $Y_b(10750)$ - and $\Upsilon(10860)$ -states are assumed to be the tetraquark- $b\bar{b}$ -mixing states, anticipated in the large- N_c limit
- The $b\bar{b}$ -component is used to predict the hadroproduction and Drell-Yan cross sections at the LHC
- A crucial test of our model is in the $m_{\pi^+\pi^-}$ and $\cos\theta$ distributions, whose resonant contribution is worked out, which is not expected in other dynamical schemes
- The tetraquark- $Q\bar{Q}$ mixing scheme suggested has wider implications