Enhanced heavy quark spin symmetry breaking in $\Upsilon(10860)$ transitions

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Based on: FKG, U.-G. Meißner and C.-P. Shen, Phys.Lett. B **738** (2014) 172 [arXiv:1406.6543]

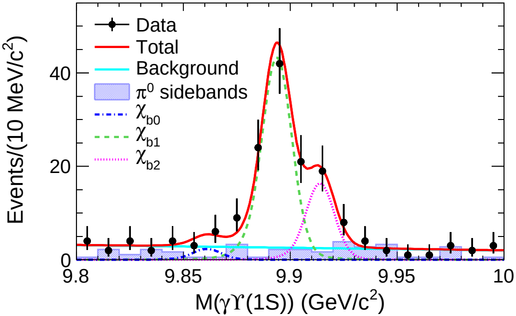
- In the limit of infinitely heavy quarks, heavy quark spin symmetry (HQSS)
- Examples in radiative transitions: Cho, Wise, PPLB346(1995)129

$$\Gamma({}^3S_1 \to {}^3P_J\gamma) \propto \frac{2J+1}{9}E_\gamma^3, \qquad \Gamma({}^3P_J \to {}^3S_1\gamma) \propto E_\gamma^3$$

$\Gamma_0 : \Gamma_1 : \Gamma_2$	HQSS predictions	Data
$\Upsilon(2S) \to \chi_{bJ}\gamma$	$1 : 1.5 : 1.6$	$1 : (1.9 \pm 0.2) : (1.8 \pm 0.2)$
$\psi(2S) \to \chi_{cJ}\gamma$	$1 : 0.84 : 0.58$	$1 : (0.96 \pm 0.04) : (0.91 \pm 0.04)$
$\chi_{cJ} \to J/\psi\,\gamma$	$1 : 2.12 : 2.85$	$1 : (2.14 \pm 0.16) : (2.78 \pm 0.16)$

The agreement is generally quite good, but there are exceptions …

Experimental data on the $\Upsilon(10860) \to \omega\chi_{bJ}$



Belle, PRL113(2014)142001

- Measured branching fractions

$$\begin{aligned} \mathcal{B}\left(\Upsilon(10860) \to \chi_{b0}\omega\right) &< 3.9 \times 10^{-3}, \\ \mathcal{B}\left(\Upsilon(10860) \to \chi_{b1}\omega\right) &= (1.57 \pm 0.22_{\text{stat.}} \pm 0.21_{\text{sys.}}) \times 10^{-3}, \\ \mathcal{B}\left(\Upsilon(10860) \to \chi_{b2}\omega\right) &= (0.60 \pm 0.23_{\text{stat.}} \pm 0.15_{\text{sys.}}) \times 10^{-3}. \end{aligned}$$

A large breaking of HQSS

- Define two ratios

$$R_{02} \equiv \frac{\Gamma(\Upsilon(10860) \to \chi_{b0}\omega)}{\Gamma(\Upsilon(10860) \to \chi_{b2}\omega)}, \qquad R_{12} \equiv \frac{\Gamma(\Upsilon(10860) \to \chi_{b1}\omega)}{\Gamma(\Upsilon(10860) \to \chi_{b2}\omega)}$$

- Comparing with the HQSS predictions if $\Upsilon(10860)$ is the $5S$ state,

HQSS:	$R_{02}^{S} = 0.23,$	$R_{12}^{S} = 0.64$
Data:	$R_{02} < 13.3,$	$R_{12} = 2.62 \pm 1.30$

Large discrepancy in R_{12} $\Rightarrow$ large breaking of HQSS

- The ratios for a D-wave Υ with a mass of $\Upsilon(10860)$:

$$R_{02}^{D} = 22.9, \qquad R_{12}^{D} = 15.8$$

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A possible explanation of the Belle observation

- The measured ratio R_{12} is between the values for a pure S- and D-wave Υ
- The $\Upsilon(10860)$ has both S-wave and D-wave components
  ☞ according to the NRQCD power counting, Bodwin et al, PRD51(1995)1125

$$S\text{-}D \text{ mixing} = \mathcal{O}\left(v_Q^2\right)$$

- The total decay amplitude

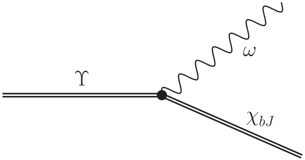
$$\mathcal{A}(\Upsilon(10860) \to \chi_{bJ}\omega) = \cos\theta\,\mathcal{A}_S + \sin\theta\,\mathcal{A}_D$$

- The ratios could differ a lot from those for a pure S-wave Υ even for a small mixing if

$$|\mathcal{A}_D| \gg |\mathcal{A}_S|$$

Decay mechanism for the D-wave component

- Direct transition



☞ $b\bar{b} \to b\bar{b}\,\omega$: OZI suppressed

- Bottom meson loops

☞ $s_\ell^P = \frac{3}{2}^+ :\ B_1, B_2;\ \ s_\ell^P = \frac{1}{2}^- :\ B,\ B^*$

☞ All vertices are individually OZI allowed, S-wave

☞ $2M_B - M_{b\bar{b}} \ll M_B$: bottom mesons are nonrelativistic

☞ Power counting:

$$\mathcal{A}_D^{\text{loop}} \sim \frac{v^5}{(v^2)^3} = \mathcal{O}\left(\frac{1}{v}\right)$$

$\Rightarrow$ the loop effect is most prominent close to thresholds

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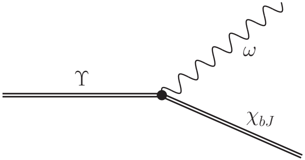

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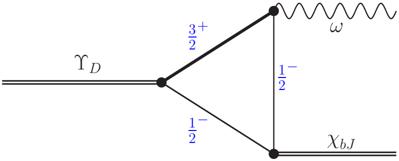

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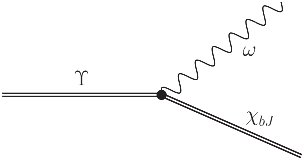

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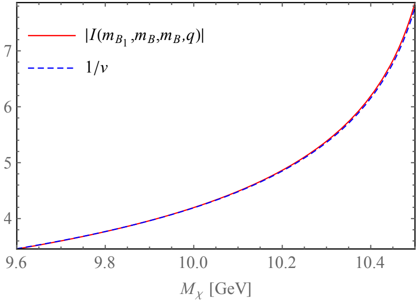

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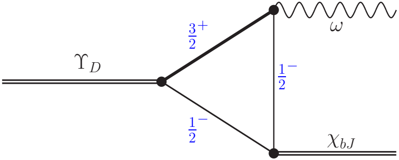

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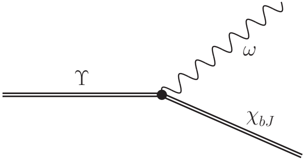

☞ $b\bar{b} \to b\bar{b}\,\omega$: OZI suppressed

- Loops with a $\frac{1}{2}^+$ bottom meson

The $\frac{1}{2}^+$ states are broad
$\Rightarrow$ little enhancement

- Loops with S-wave bottom mesons

☞ two P-wave vertices $\Rightarrow$

$$\mathcal{A}_S^{\rm loop} \sim \frac{v^5}{(v^2)^3} v^2 = \mathcal{O}(v)$$

☞ divergent, needs a counterterm

- If all the couplings take natural values, we expect $|\mathcal{A}_D| \gg |\mathcal{A}_S|$

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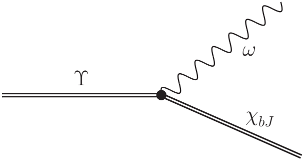

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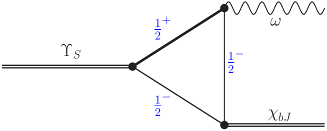

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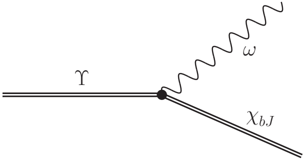

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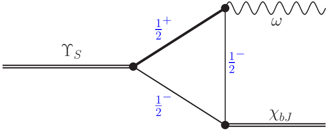

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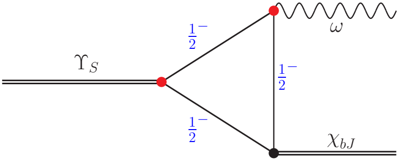

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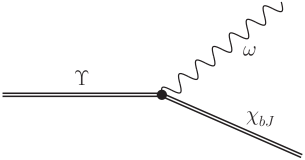

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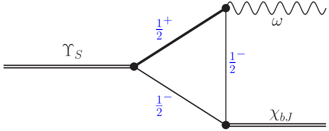

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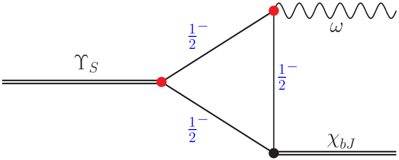

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How do meson loops change the ratios?

- When the meson loops are neglected
  - ☞ For $\Upsilon_S \to \chi_{bJ}\omega$, $\Gamma_0^S : \Gamma_1^S : \Gamma_2^S = 1 : 2.8 : 4.4$
  - ☞ For $\Upsilon_D \to \chi_{bJ}\omega$, $\Gamma_0^D : \Gamma_1^D : \Gamma_2^D = 22.9 : 15.8 : 1$

Data:

$$\frac{\Gamma_1}{\Gamma_2} = 2.62 \pm 1.30$$

- For meson loops
  - ☞ All the vertices respect HQSS
  - ☞ If we let the bottom mesons in the same spin multiplet to be degenerate, $\Rightarrow$ the same ratios
  - ☞ Dependence of $\Gamma_0^D : \Gamma_2^D$ on the mass of Υ_D

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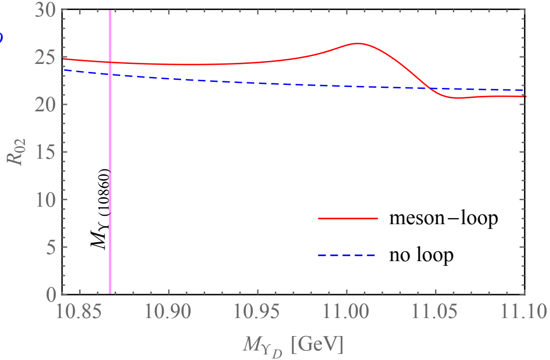
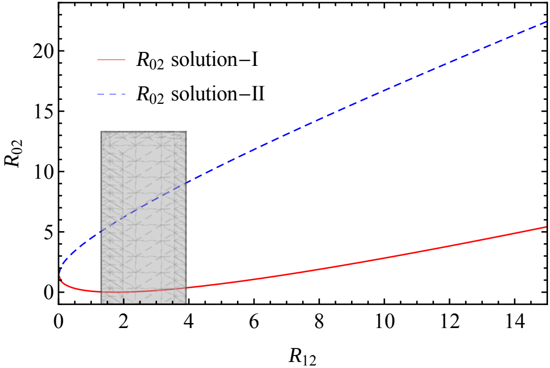


Quantitative prediction



Bell data: PRL113(2014)142001

$R_{02} < 13.3$

$R_{12} = 2.62 \pm 1.30$

- Results of the ratios depend on two parameters: mixing angle and relative strength of the decay amplitudes $|\mathcal{A}_S/\mathcal{A}_D|$
- For each value of R_{12}, there are two solutions for R_{02}.
  Prediction for R_{02}:

$$R_{02} = 7.1 \pm 2.8, \quad \text{or} \quad R_{02} = 0.19 \pm 0.18$$

Qualitative prediction

- For the $\Upsilon(11020)$, ratios from pure S-wave and D-wave components:
  - ☞ For $\Upsilon_S \to \chi_{bJ}\omega, \quad \Gamma_0^S : \Gamma_1^S : \Gamma_2^S = 1 : 2.9 : 4.6$
  - ☞ For $\Upsilon_D \to \chi_{bJ}\omega, \quad \Gamma_0^D : \Gamma_1^D : \Gamma_2^D = 21.7 : 15.5 : 1$ (no loop)

    $27.5 : 18.4 : 1$ (pure loops)
- The $\Upsilon(11020)$ is much closer to the thresholds of $\frac{3}{2}^+$-$\frac{1}{2}^-$ pairs:

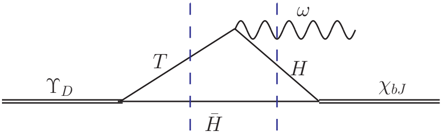
  $B_1\bar{B}[11003]$, $B_1\bar{B}^*[11049]$ and $B_2\bar{B}^*[11068]$

  $\Rightarrow$ the decays of the D-wave component are more enhanced
- We expect the HQSS breaking for the $\Upsilon(11020) \gtrsim$ that for the $\Upsilon(10860)$

Conclusions

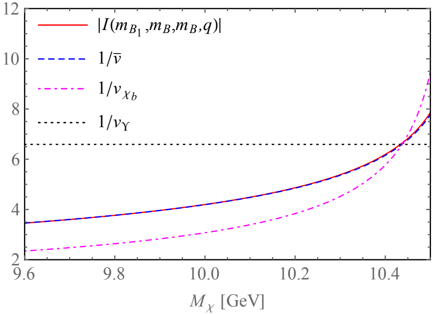
- A small S-D mixing could result in a much larger breaking of HQSS in transitions
- This requires the decay rate for the D-wave component to be much larger than the S-wave one
  ☞ To avoid a too large width for the D-wave component $\Rightarrow \theta \gtrsim 5^\circ$
- More precise measurements in future experiments such as Belle-II are necessary to understand
  ☞ the origin of the HQSS breaking
  ☞ structure of the $\Upsilon(10860)$ and $\Upsilon(11020)$

Two cuts

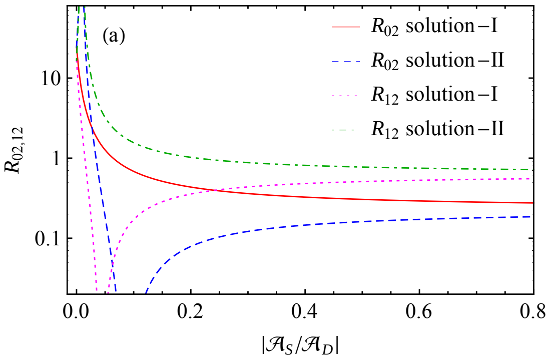


- There are two cuts, and each cut can be used to define a velocity
- v in the power counting corresponds to the average of the two

FKG, Meißner, PRL109(2012)062001



Dependence of the ratio on the ratio $\mathcal{A}_S/\mathcal{A}_D$



assuming a 5° mixing angle

Width effect

- Strong enhancement due to Landau singularity of the triangle diagram
- Finite width of the intermediate meson will reduce the enhancement
- If one of the intermediate meson decay in an S-wave $\Rightarrow$ a large width
  $\Rightarrow$ the enhancement could be erased