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Quark Model explanation of $\Upsilon(10860)$

P. González and R. Bruschini
Universitat de València and IFIC (SPAIN)

Motivation

Although the mass of the $0\,(1^{--})\,\Upsilon\,(10860)$ is close to the conventional $5\ {}^3S_1\,(b\bar{b})$ or $\Upsilon(5s)$ quark model state, its decay properties point out to a non conventional nature:

i) Anomalous dipion production: $\Upsilon\,(10860) \rightarrow \pi^+\pi^-\Upsilon(ns)\ \ (n = 1,2,3)$

widths two order of magnitude larger than $\Upsilon(n's) \rightarrow \pi^+\pi^-\Upsilon(1s)\ \ (n' = 2,3,4)$

ii) Heavy Quark Spin Symmetry : $\Upsilon(10860) \rightarrow \pi^+\pi^- h_b(np)$ has a non

expected similar production rate to $\Upsilon(10860) \rightarrow \pi^+\pi^-\Upsilon(n_f s)$

iii) Non conventional ratios for decays to open bottom mesons :

$$\left(\frac{\Gamma\left(\Upsilon(10860)\rightarrow B^*\overline{B}^*\right)}{\Gamma\left(\Upsilon(10860)\rightarrow B\overline{B}^*+h.c.\right)} \right)_{Exp} = 2.8 \pm 0.6$$

versus

$$\left(\frac{\Gamma\left(\Upsilon(5s)\rightarrow B^*\overline{B}^*\right)}{\Gamma\left(\Upsilon(5s)\rightarrow B\overline{B}^*+h.c.\right)} \right)_{3P_0 \text{ or } CDM} \lesssim 1$$

$$\left(\frac{\Gamma\left(\psi(4040)\rightarrow D^*\overline{D}^*\right)}{\Gamma\left(\psi(4040)\rightarrow D\overline{D}^*+h.c.\right)} \right)_{Exp} = 0.18 \pm 0.14 \pm 0.03$$

$$\frac{\Gamma\left(\Upsilon(10860)\rightarrow B^*\overline{B}^*\right)}{\Gamma(\Upsilon(10860))} = (38.1 \pm 3.4)\,\%$$

$$\frac{\Gamma\left(\Upsilon(10860)\rightarrow B_s^*\overline{B}_s^*\right)}{\Gamma(\Upsilon(10860))} = (17.6 \pm 2.7)\,\%$$

$$\left(\frac{\Gamma\left(\Upsilon(10860)\rightarrow B_s^*\overline{B}_s^*\right)}{\Gamma\left(\Upsilon(10860)\rightarrow B_s\overline{B}_s^*+h.c.\right)} \right)_{Exp} = 2.2 \pm 0.6$$

What is the nature of $\Upsilon(10860)$?

Mixed $5s-4d$ state: it does not help to explain dipion decays.

Mixing with the first S – wave $0(1^{--})$ threshold $B\overline{B}_1$ (more than 100 MeV above in energy) : not expected.

$B^*\overline{B}^*$ or $B_s^*\overline{B}_s^*$ P-wave resonance: $B^*\overline{B}^* \not\leftrightarrow B_s^*\overline{B}_s^*$ OZI suppressed.

$\Upsilon(5s)$ + $B_s^*\overline{B}_s^*$: nonconventional ratios ? M. B. Voloshin, PRD 85, 034024 (2012)

$\Upsilon(5s)$ + First Hybrid : from LQCD both states could be close in mass.

E. Braaten, C. Langmack, D. Hudson Smith, PRD 90, 014044 (2014)

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vi) Summary.

Bottomonium Spectrum

Nonrelativistic Static Quark-Antiquark Potential

E. Eichten *et al.*, PRD 17, 3090 (1978) : Cornell Potential

$$V_C(r) = \sigma r - \frac{\zeta}{r}$$

$\sigma = 873\ \mathrm{MeV/fm}$

$\zeta = 100\ \mathrm{MeV\ fm}$

$m_b = 4793\ \mathrm{MeV}$

nl States	M_{nl} (MeV)	M_{PDG} (MeV)
$1s$	9463	9460.30 ± 0.26
$2s$	10023	10023.26 ± 0.31
$1d$	10169	10163.7 ± 1.4
$3s$	10358	10355.2 ± 0.5
$2d$	10455	
$4s$	10628	10579.4 ± 1.2
$3d$	10703	$10752.7 \pm 5.9^{+0.7}_{-1.1}$
$5s$	10865	$10889.9^{+3.2}_{-2.6}$
$4d$	10926	
$6s$	11081	$10992.9^{+10.0}_{-3.1}$

Belle: arXiv: 1905.06610

Natural assignment from spectroscopy : $\Upsilon(10860) : \Upsilon(5s)$

This assignment allows for a good description of the leptonic width ratios

$$\mathcal{R}(n) \equiv \frac{\Gamma(\Upsilon(5s) \to e^+e^-)}{\Gamma(\Upsilon(ns) \to e^+e^-)} = \frac{|R_{\Upsilon(5s)}(0)|^2}{|R_{\Upsilon(ns)}(0)|^2} \frac{M^2_{\Upsilon(ns)}}{M^2_{\Upsilon(5s)}}$$

n	$\mathcal{R}(n)$	$\mathcal{R}(n)_{\text{Exp}}$
1	0.19	0.23 ± 0.05
2	0.51	0.52 ± 11
3	0.71	0.70 ± 0.16

Dipion transitions $\Upsilon(n_i s) \to \pi^+\pi^-\Upsilon(n_f s)$

M. Tanabashi *et al*. (PDG), PRD 98, 030001 (2018)

Process	PDG(keV)	Error(keV)
$2s \to 1s$	5.7	0.6
$3s \to 1s$	0.89	0.10
$3s \to 2s$	0.57	0.09
$4s \to 1s$	1.7	0.3
$4s \to 2s$	1.7	0.4
$5s \to 1s$	270	70
$5s \to 2s$	400	120
$5s \to 3s$	240	130

$\Upsilon(10860) : \Upsilon(5s)$

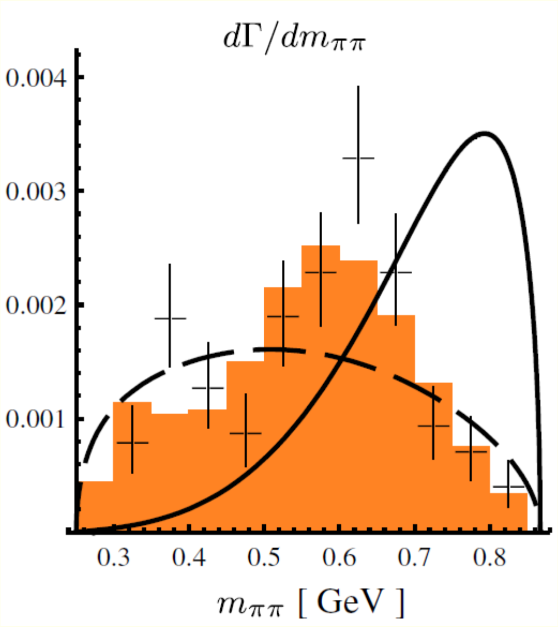
Large dipion production from $\Upsilon(10860)$ as compared to $\Upsilon(n_i s)$ $(n_i < 5)$

Dipion transitions $\Upsilon(n_i s) \to \pi^+\pi^-\Upsilon(n_f s)$

A. Ali, C. Hambrock, PRL 104, 162001 (2010)

Nonresonant + Resonant contributions to $\frac{d\Gamma}{dM_{\pi\pi}}$

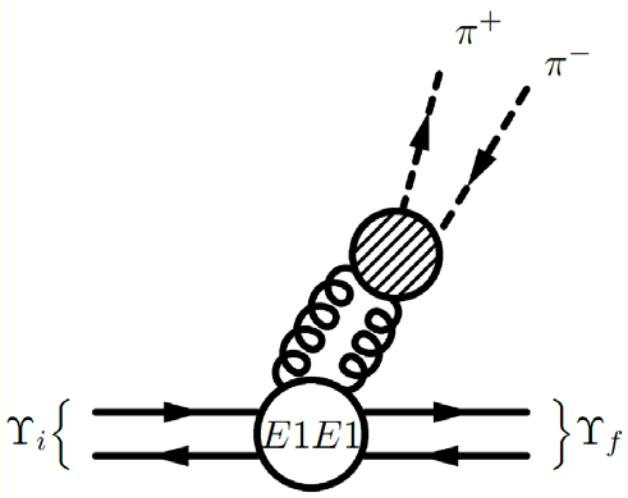
By assuming a nonresonant amplitude with the same form that for conventional states but two orders of magnitude bigger, data may be reasonably fitted through the implementation of $0^+(0^{++}, 2^{++})$ resonances.



Dipion transitions $\Upsilon(n_i s) \to \pi^+\pi^-\Upsilon(n_f s)$

Y-P. Kuang, Int. J. Mod. Phys. A24S1, 327 (2009)

QCD Multipole Expansion



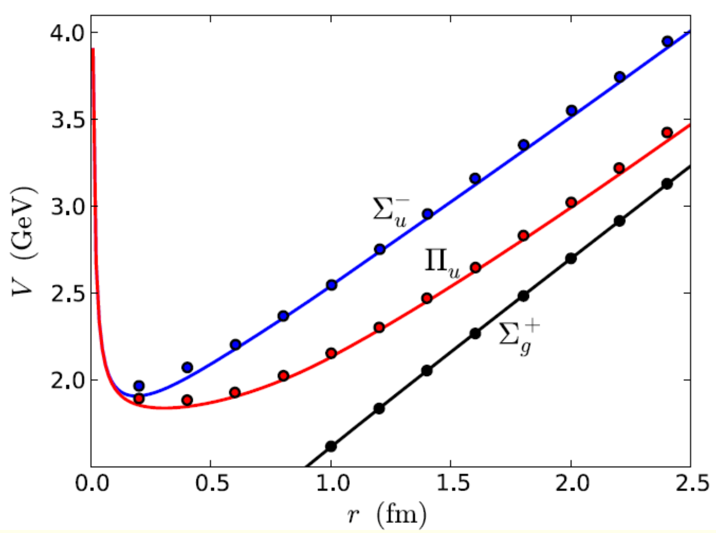
$$\mathcal{M} = i\frac{g_E^2}{6}\langle\pi^+\pi^-|\boldsymbol{E}\boldsymbol{E}|0\rangle\sum_{np}\frac{\langle n_f s|\boldsymbol{r}|np\rangle\,\langle np|\boldsymbol{r}|n_i s\rangle}{M_{n_i s} - M_{np}}$$

Hybrid Spectrum : $(Q\bar{Q})_8 + g$

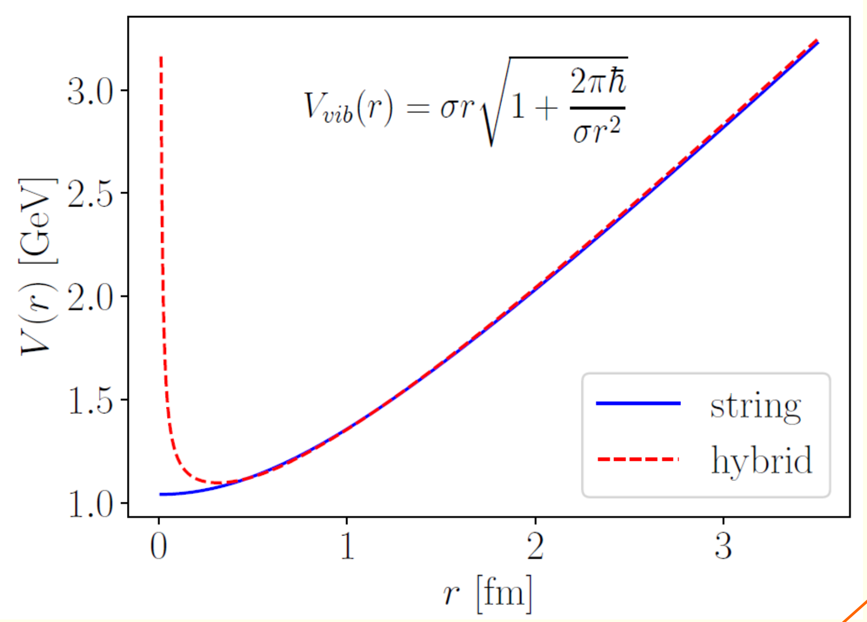
K. J. Juge, J. Kuti, C. J. Morningstar, PRL 82, 4400 (1999)
E. Braaten, C. Langmack, D. Hudson Smith, PRD 90, 014044 (2014)

Energy levels of $Q\bar{Q}$ in the excited flavor singlet BO potentials

$$\left[-\frac{\hbar^2}{m_Q}\left(\frac{\mathrm{d}}{\mathrm{d}r}\right)^2 + \frac{\langle L^2_{Q\bar{Q}}\rangle_{\Gamma,r}}{m_Q r^2} + V_\Gamma(r)\right]\psi_n(r) = \mathcal{E}_n\psi_n(r)$$



Hybrid Spectrum



Hybrid		Bottomonium		PDG
nl	M_{nl} (MeV)	nl	M_{nl}(MeV)	M(MeV)
		1s	9463.2	9460.3
		2s	10 022.9	10 023.3
		1d	10 168.9	10 163.7
		3s	10 357.8	10 355.2
		2d	10 454.7	
		4s	10 628.4	10 579.4
		3d	10 702.6	
1p	10 887.9	5s	10 865.4	10 889.9
		4d	10 926.4	
2p	11 082.2	6s	11 080.9	10 992.9

Lowest energy hybrid: $H_b(1p)$

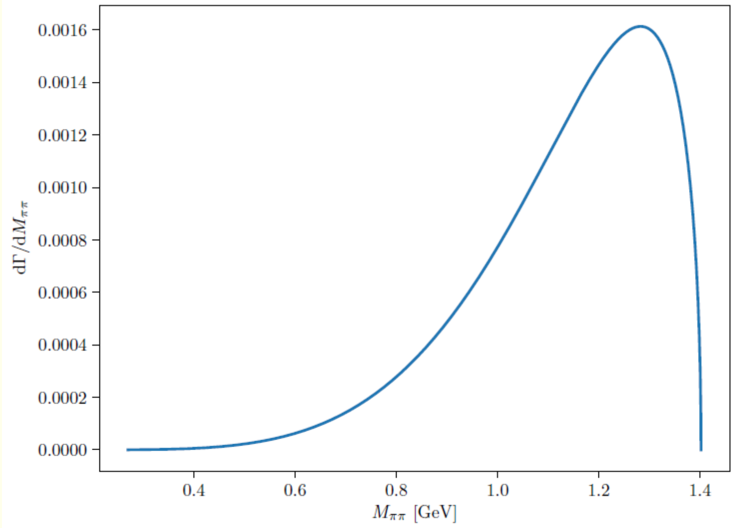
$$\mathcal{M} = i\frac{g_E^2}{6}\langle\pi^+\pi^-|\boldsymbol{EE}|0\rangle\sum_{np}\frac{\langle n_f s|\boldsymbol{r}|np\rangle\ \langle np|\boldsymbol{r}|n_i s\rangle}{M_{n_i s}-M_{np}}$$

$$\Upsilon(n_i s) \to \pi^+\pi^-\Upsilon(n_f s)$$

Γ(keV) : Calculated non resonant widths

Process	$\Gamma(\text{keV})$	PDG(keV)	Error(keV)
$2s \to 1s$	5.7	5.7	0.6
$3s \to 1s$	0.94	0.89	0.10
$3s \to 2s$	0.58	0.57	0.09
$4s \to 1s$	6.9	1.7	0.3
$4s \to 2s$	4.0	1.7	0.4
$5s \to 1s$	660	270	70
$5s \to 2s$	120	400	120
$5s \to 3s$	20	240	130

$\Upsilon(5s) \to \pi^+\pi^-\Upsilon(1s)$



Dominant resonant contribution in $5s \to 3s$ $\quad M(5s) - M(3s) = M_{f_0(500)}$

The order of magnitude of these dipion decays may be understood from $\Upsilon(10860) : \Upsilon(5s)$ through the intermediate hybrid contributions to the nonresonant amplitude.

$\Upsilon(10860) \to \pi^+\pi^- h_b(np)$ decays

$E1 - M1$ transitions

Y-P. Kuang, T-M. Yan, PRD 24, 2874 (1981)

$$\frac{\Gamma(\Upsilon(5s) \to \pi^+\pi^- h_b(1p))}{\Gamma(\Upsilon(3s) \to \pi^+\pi^- h_b(1p))} \approx \frac{\Gamma(\Upsilon(5s) \to gg\, h_b(1p))}{\Gamma(\Upsilon(3s) \to gg\, h_b(1p))} = \frac{(M_{5s} - M_{1p})^7}{(M_{3s} - M_{1p})^7} \frac{|\mathfrak{g}_{5,1}|^2}{|\mathfrak{g}_{3,1}|^2}$$

$$\mathfrak{g}_{n_i,1} \equiv \sum_{n_{hyb}} \frac{\int \mathrm{d}r\, r^2 R_{n_i s}(r) r R_{n_{hyb}p}(r) \int \mathrm{d}r'\, r'^2 R_{n_{hyb}p}(r') R_{h_b(1p)}(r')}{M_{n_i s} - \mathcal{M}_{n_{hyb}p}}$$

$$\frac{\Gamma(\Upsilon(5s) \to \pi^+\pi^- h_b(1p))}{\Gamma(\Upsilon(3s) \to \pi^+\pi^- h_b(1p))} \approx 1.1 \times 10^2 \qquad \frac{\Gamma(\Upsilon(10860) \to \pi^+\pi^- h_b(1p))_{\mathrm{Exp}}}{\Gamma(\Upsilon(3s) \to \pi^+\pi^- h_b(1p))_{\mathrm{Exp}}} > 7.3 \times 10^4$$

These decays cannot be understood from $\Upsilon(10860) : \Upsilon(5s)$ in accord with HQSS violation

$$(S_{b\bar{b}})_{h_b(1p)} = 0 \neq (S_{b\bar{b}})_{\Upsilon(ns)} = 1$$

Nature of $\Upsilon(10860)$

Simplest alternative : $\Upsilon(5s)$ - $H_b(1p)$ mixing

$$|\Upsilon(10860)\rangle \approx \cos\theta\,|\Upsilon(5s)\rangle + \sin\theta\,|H_b(1p)\rangle$$

From the leptonic widths : $\sin^2\theta \leq 0.1$

HQSS: $(S_{b\bar{b}})_{H_b(1p)} = (S_{b\bar{b}})_{h_b(1p)} = 0$

$$\Gamma(\Upsilon(10860) \to \pi^+\pi^- h_b(np)) \approx \sin^2\theta\,\Gamma(H_b(1p) \to \pi^+\pi^- h_b(np))$$

$$\Gamma(H_b(1p) \to \pi^+\pi^- h_b(1p)) \geq 1.8 \pm 0.9\,\mathrm{MeV}$$
$$\Gamma(H_b(1p) \to \pi^+\pi^- h_b(2p)) \geq 2.9 \pm 1.5\,\mathrm{MeV}$$

Two-body decays to open bottom mesons

$$\left(\frac{\Gamma\left(\Upsilon(10860)\to B^*\overline{B}^*\right)}{\Gamma\left(\Upsilon(10860)\to B\overline{B}^*+h.c.\right)}\right)_{Exp} = 2.8 \pm 0.6$$

$$\left(\frac{\Gamma\left(\Upsilon(10860)\to B^*\overline{B}^*\right)}{\Gamma\left(\Upsilon(10860)\to B\overline{B}\right)}\right)_{Exp} = 6.9 \pm 2.3$$

From the Cornell potential model :

$$\left(\frac{\Gamma\left(\Upsilon(5s)\to B^*\overline{B}^*\right)}{\Gamma\left(\Upsilon(5s)\to B\overline{B}^*+h.c.\right)}\right)_{3P_0 \text{ or } CDM} \lesssim 1$$

$$\left(\frac{\Gamma\left(\Upsilon(5s)\to B^*\overline{B}^*\right)}{\Gamma\left(\Upsilon(5s)\to B\overline{B}\right)}\right)_{3P_0 \text{ or } CDM} \lesssim 1$$

The hybrid should have a significant $B^*\overline{B}^*$ two-body decay : not through spin 1 pair creation P. R. Page, PLB 402, 183 (1997)

Summary

Dipion decay properties of $\Upsilon(10860)$ suggest a non conventional nature.

$\Upsilon(n_i s) \to \pi^+\pi^-\Upsilon(n_f s)$ decays may be explained from $\Upsilon(10860) : \Upsilon(5s)$ and consistently obtained intermediate hybrid states.

$\Upsilon(10860) \to \pi^+\pi^- h_b(np)$ decays cannot be explained from $\Upsilon(5s)$ in accord with HQSS expectations.

$|\Upsilon(10860)\rangle \approx \cos\theta\,|\Upsilon(5s)\rangle + \sin\theta\,|H_b(1p)\rangle$ $\sin^2\theta \leq 0.1$ could give account of the observed dipion decay properties.

A reliable study of hybrid two-body decays is needed.

THE END