A plausible explanation of $\Upsilon(10860)$

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Outline

1. Introduction
2. The model
3. Results

Features of $\Upsilon(10860)$

Conventional features

- Mass.
- Width in e^+e^- channel.

Unconventional features

- Big decay width to lower-lying $\Upsilon(ns)$ and two pions.
- Big decay width to $h_b(np)$ and two pions.
- Decay widths to open-bottom, meson-meson states (?).

Model of strong interactions

Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \mathcal{H}^{(0)} + Q_a A_0^a - \boldsymbol{d}_a \cdot \boldsymbol{E}^a - \boldsymbol{m}_a \cdot \boldsymbol{B}^a$$

Schrödinger equation (Born-Oppenheimer framework)

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

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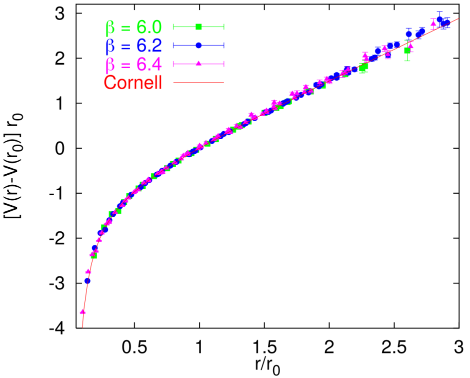


Credit: *Gunnar S. Bali, Phys.Rept. 343 (2001) 1-136.*

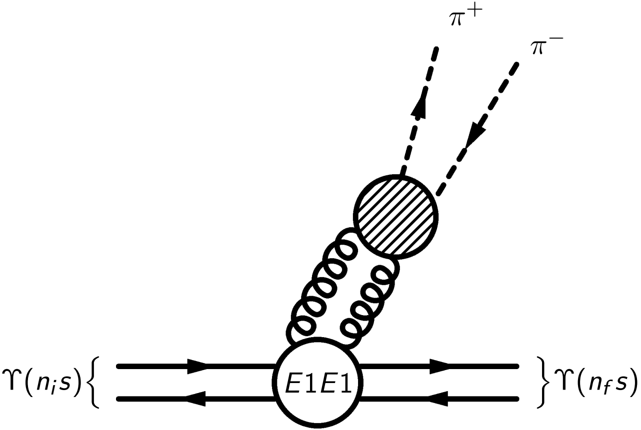
- On the left, quenched potential from lattice QCD vs.

Cornell potential

$$V_{\Sigma_g^+}(r) = \sigma r - \frac{\zeta}{r}$$

Two pion emission process

Pictorial representation



Transition operator

Transition amplitude

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

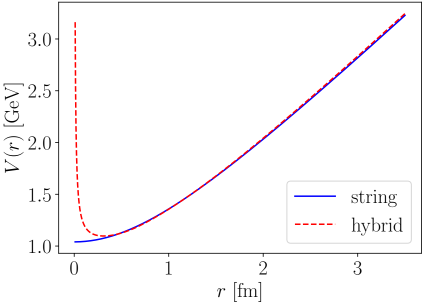
Evaluation

- Hadronization vertex: soft pion techniques and PCAC.
- Intermediate states: potential model.

Hybrid potential

- $V_{\Pi_u}(r)$ is defined as the minimal energy of excited gluon field configurations with $\Lambda = 1$ and $\eta = -1$.
- A good description at intermediate and long distances is given by the excited string potential.

$$V_{\Pi_u}(r) = \sqrt{\sigma^2 r^2 + \sigma h}$$



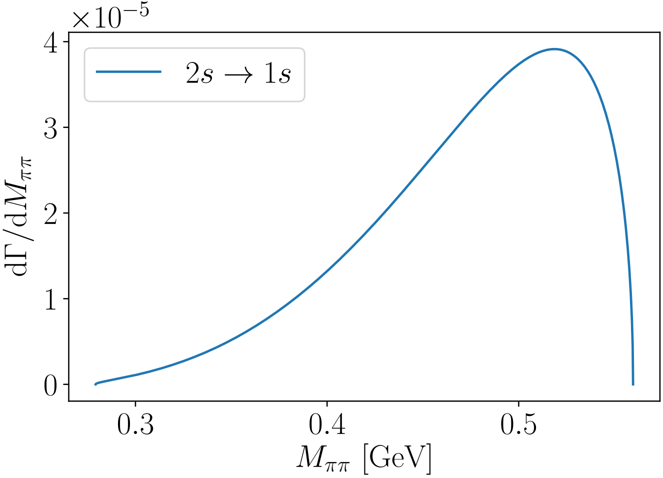
Gluelump energy

$$E_{\Pi_u} \approx 990 \text{ MeV}$$

Dipion transition rates

Process	Γ(keV)	PDG(keV)	
$2s \to 1s^{(*)}$	5.686	5.7	±0.6
$3s \to 1s$	0.936	0.89	±0.10
$3s \to 2s$	0.575	0.57	±0.09
$4s \to 1s$	6.932	1.7	±0.3
$4s \to 2s$	3.995	1.7	±0.4
$5s \to 1s$	655.7	270	±70
$5s \to 2s$	115.9	400	±120
$5s \to 3s$	20.6	240	±130

Dipion invariant mass distribution
$\Upsilon(n_i s) \to \Upsilon(1s)\pi^+\pi^-$



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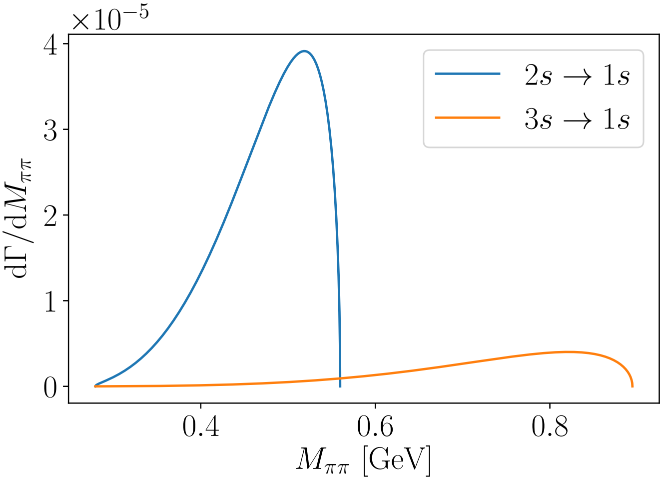

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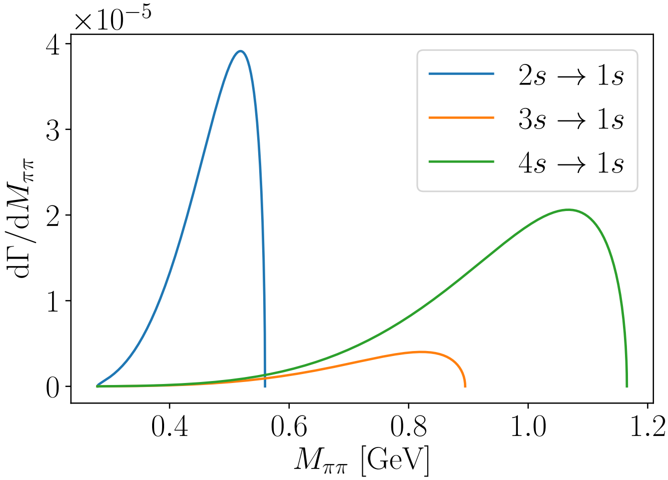

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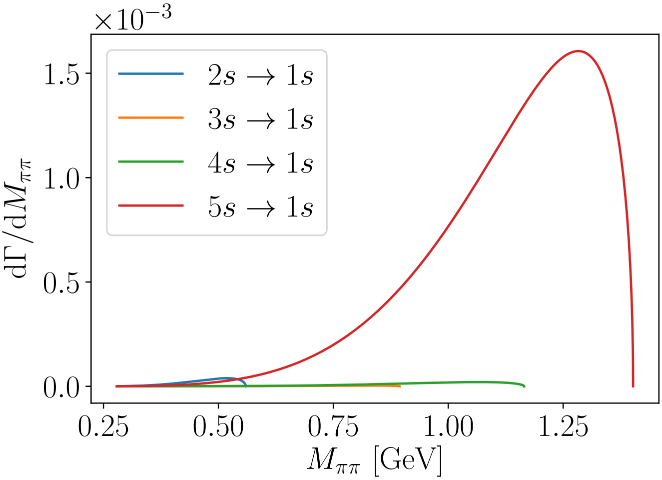

What is the nature of $\Upsilon(10860)$?

Features we understand from the $\Upsilon(5s)$ interpretation

- Mass.
- Width in e^+e^- channel.
- Big decay width to lower-lying $\Upsilon(ns)$ and two pions.

Features we do not understand from the $\Upsilon(5s)$ interpretation

- Big decay width to $h_b(np)$ and two pions.
- Big decay width to $B^*\bar{B}^*$.

Hybrid and quarkonium spectrum

Hybrid		Bottomonium			
nl	M_{nl} (MeV)	nl	M_{nl} (MeV)	M_{PDG} (MeV)	
		$1s$	9463	9460.30	± 0.26
		$2s$	10023	10 023.26	± 0.31
		$1d$	10169	10 163.7	± 1.4
		$3s$	10358	10 355.2	± 0.5
		$2d$	10455		
		$4s$	10628	10 579.4	± 1.2
		$3d$	10703		
$1p$	10888	$5s$	10865	10 889.9	$^{+3.2}_{-2.6}$
		$4d$	10926		
$2p$	11082	$6s$	11081	10 992.9	$^{+10.0}_{-3.1}$

The mixing picture

$\Upsilon(10860)$ may be a mixed state

All these features may be explained under the assumption that $\Upsilon(10860)$ is a mixing of the $\Upsilon(5s)$ with a small component of the ground-state hybrid $H_b(1p)$.

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

Plausible features of $H_b(1p)$

Quantum numbers

$$L_{Q\bar{Q}} = 1 \quad S_{Q\bar{Q}} = 0 \quad J_{\text{gluon}} = 1 \quad J^{PC} = 1^{--}$$

Small decay width to:

- lepton pair
- $\Upsilon(ns)$ and two pions

Big decay width to:

- $h_b(np)$ and two pions
- open bottom meson-meson states, in particular $B^*\bar{B}^*$

Summary

- $\Upsilon(10860)$ cannot be explained as pure $\Upsilon(5s)$
- A quantitative description of $\Upsilon(5s) \to \Upsilon(n_f s)\pi\pi$ requires a model for the hybrid spectrum
- The presence of an hybrid component in $\Upsilon(10860)$ may explain its exotic features

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References

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Details on the Born-Oppenheimer approximation

Adiabatic approximation

The motion of the heavy quarks is negligible with respect to the time scales of the gluon and light-quark fields.

Single channel approximation

The coupling between different configurations of the light degrees of freedom can be neglected.

Details on the B-O quantum numbers

Light fields quantum numbers

- $\Lambda = |\lambda|$, where λ is the eigenvalue of $\boldsymbol{J}_{\text{light}} \cdot \hat{\boldsymbol{r}}_{Q\bar{Q}}$.
- η, the eigenvalue of $(CP)_{\text{light}}$.
- ϵ, the eigenvalue of the reflection operator $(R)_{\text{light}}$.

Meson quantum numbers

- $l \geq \Lambda$, the eigenvalue of L^2, with $\boldsymbol{L} = \boldsymbol{L}_{Q\bar{Q}} + \boldsymbol{J}_{\text{light}}$.
- j, the eigenvalue of J^2, with $\boldsymbol{J} = \boldsymbol{L} + \boldsymbol{S}$.
- m, the eigenvalue of J_z.
- n, the radial quantum number.

Details on Schrödinger equation in B-O framework

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

$$\langle L^2_{Q\bar{Q}}\rangle_{\Gamma,\boldsymbol{r}} \approx \hbar^2\left[l(l+1) - 2\Lambda^2 + \langle J^2_{\text{light}}\rangle_{\Gamma,\boldsymbol{r}}\right]$$

$$\langle J^2_{\text{light}}\rangle_{\Gamma,\boldsymbol{r}} \approx \begin{cases} 0 & \text{for quarkonia} \\ 2 & \text{for hybrids} \end{cases}$$

$$\Lambda = \begin{cases} 0 & \text{for quarkonia} \\ 1 & \text{for hybrids} \end{cases}$$

Details on the B-O potential $V_{\Sigma_g^+}(r)$

Definition in QCD without light quarks

- $V_{\Sigma_g^+}(r)$ is defined as the ground state energy of the gluon field in presence of a $Q - \bar{Q}$ pair at a fixed distance r.
- A good description of the quarkonium potential calculated in quenched lattice QCD is given by the Cornell potential.

$$V_{\Sigma_g^+}(r) = \sigma r - \frac{\zeta}{r}$$

Values of the effective parameters

$$\sigma = 873\,\text{MeV/fm} \quad \zeta = 100\,\text{MeV fm} \quad m_Q = 4793\,\text{MeV}$$