Hadroquarkonium

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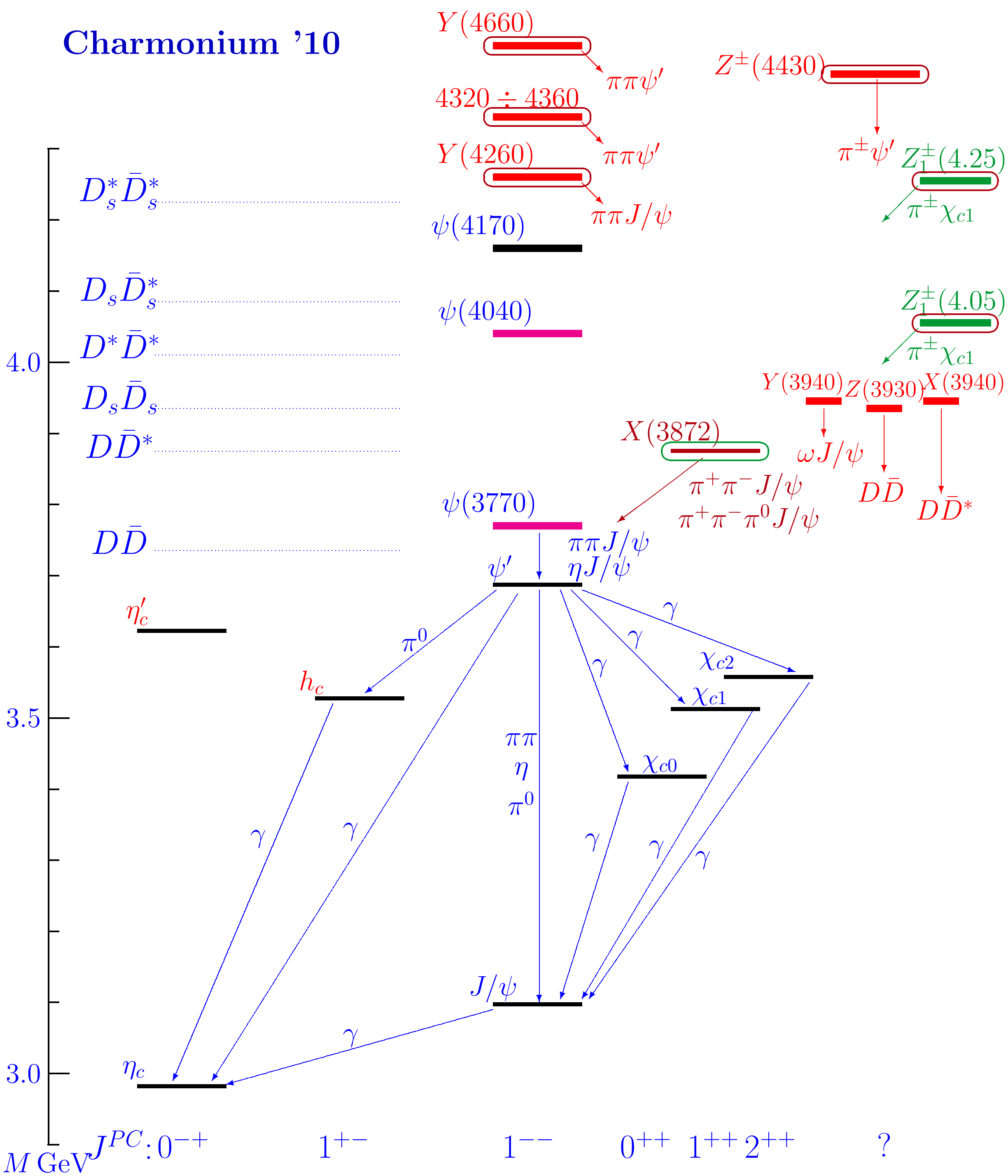


Charmonium '10
Y(4660)
ππψ′
4320 ÷ 4360
ππψ′
Y(4260)
ππJ/ψ
Z±(4430)
π±ψ′
Z1±(4.25)
π±χc1
ψ(4170)
Z1±(4.05)
π±χc1
ψ(4040)
Ds* D̄s*
Ds D̄s*
D* D̄*
Ds D̄s
D D̄*
D D̄
Y(3940)
Z(3930)
X(3940)
ωJ/ψ
DD̄
DD̄*
X(3872)
π+π−J/ψ
π+π−π0J/ψ
ψ(3770)
ππJ/ψ
ηJ/ψ
ψ′
η′c
π0
γ
χc2
χc1
hc
ππ
η
π0
χc0
J/ψ
ηc
4.0
3.5
3.0
M GeV
JPC: 0−+
1+−
1−−
0++
1++
2++
?

$Y(4.26)$, $Y(4.32-4.36)$, $Y(4.66)$

- $Y(4260)$: Confirmed by Belle, CLEO, CLEO-c. Also seen in $B \to \pi^+\pi^- J/\psi K$.

$Y(4260) \to \pi^+\pi^- J/\psi$: $M = 4264^{+10}_{-12}\,\text{MeV}$, $\Gamma = 83^{+20}_{-17}\,\text{MeV}$

Other decay modes seen: $\pi^0\pi^0 J/\psi$, $K^+K^- J/\psi$. $\frac{\Gamma(Y\to K^+K^- J/\psi)}{\Gamma(Y\to\pi^+\pi^- J/\psi)} \approx 0.15$

No decays with $D\bar{D}$ in the final state were seen. In particular:

$\frac{\Gamma(Y\to D\bar{D})}{\Gamma(Y\to\pi^+\pi^- J/\psi)} \lesssim 1.0$, $\quad \frac{\Gamma(Y\to D\bar{D}+pions)}{\Gamma(Y\to\pi^+\pi^- J/\psi)} \lesssim 1.0$

Impossible to explain if $Y(4260)$ is a pure charmonium state!

Compare e.g. with $\Gamma(\psi(3770) \to D\bar{D})/\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) \approx 400$

- $Y(4.32-4.36)$:

"Broad structure" in (ISR) $e^+e^- \to \pi^+\pi^-\psi'$ (not J/ψ!)

BaBar: $M = 4324 \pm 24\,\text{MeV}$, $\Gamma = 172 \pm 33\,\text{MeV}$ Belle: $M = 4361 \pm 9 \pm 9\,\text{MeV}$, $\Gamma = 74 \pm 15 \pm 10\,\text{MeV}$ and additionally:

- $Y(4.66)$

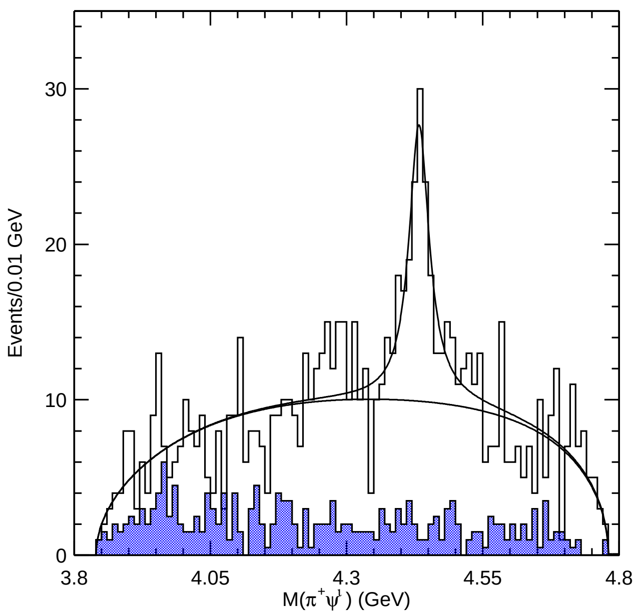
Peak in $\pi^+\pi^-\psi'$ at $M = 4664 \pm 11 \pm 5\,\text{MeV}$, $\Gamma = 48 \pm 15 \pm 3\,\text{MeV}$.

$Z(4430)$ Manifestly Exotic

Belle '07: Peak in $\pi^+\psi'$ inv. mass in the decays $B \to \pi^+\psi' K$. ($6.5\,\sigma$ significance).

Z(4430): $M = 4333 \pm 4 \pm 2\,\text{MeV}$, $\Gamma = 45^{+18}_{-15}{}^{+30}_{-13}\,\text{MeV}$.

$\mathcal{B}(B^0 \to KZ^\pm)\,\mathcal{B}(Z^\pm \to \pi^\pm\psi') \approx 4 \times 10^{-5}$ (similar to $B \to KX(3872)$ followed by $X \to \pi^+\pi^- J/\psi$)



BaBaR did not confirm ...

- Suggested explanations:

\- Y's:

- Hybrids: $c\bar{c} + glue$ F.Close and P.Page, E.Kou and O.Pene
- Di-diquarks: $[cs][\bar{c}\bar{s}]$ L.Miani *et.al.*

Enhanced strangeness not likely in view of $\frac{\Gamma(Y\to K^+K^-J/\psi)}{\Gamma(Y\to\pi^+\pi^-J/\psi)} \approx 0.15$
Why a hybrid would chose to go into a particular charmonium state J/ψ or ψ'?
Why no very strong $D\bar{D}$ decays?

\- $Z(4430)$:

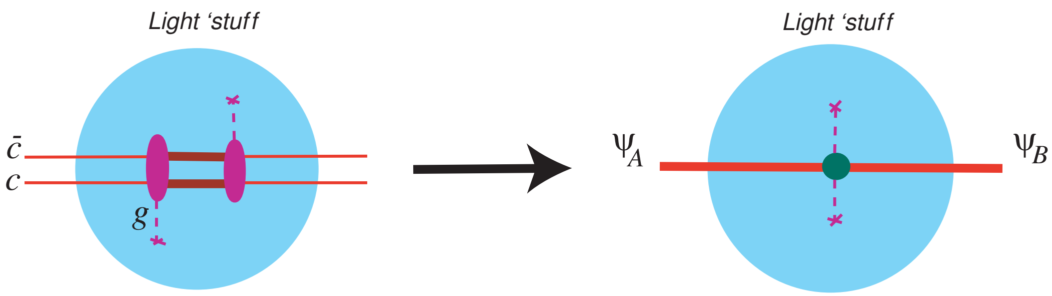
- Molecule/threshold cusp $D_1^+\bar{D}^{*0} + \xi\, D^{*+}\bar{D}_1^0$. Rosner, … D_1: 1^+,
  $M(D_1^0) = 2422.3 \pm 1.3\,\mathrm{MeV}$, $\Gamma = 20.4 \pm 1.7\,\mathrm{MeV}$.
  $M(D^{*+}D_1^0) \approx 4430\,\mathrm{MeV}$. For S-wave $1^+ \otimes 1^-$ possible J^P are 0^-, 1^-, and 2^-.
  Rosner argues $J^P = 0^-$ (small energy release in $B \to ZK$).
  $Z \to D^*\bar{D}^*\pi$ should be much stronger than $Z \to \pi\psi'$.
  Other charmonium+pions modes? Why $\pi\psi'$, rather than $\pi J/\psi$?
  I have hard time understanding a resonance with the width $20\,\mathrm{MeV}$ having a binding energy $\sim 3\,\mathrm{MeV}$ (decays faster than binds).
- Tetraquark: $[cu] + [\bar{c}\bar{d}]$ Miani et.al., Gershtein et.al.
  Not many new predictions. Same questions as for the molecule.

• If you ask me...

To me $Y(4260)$, $Y(4.32-4.36)$, $Y(4.66)$, $Z(4430)$ all look like 'a charmonium stuck in a light hadron'. At least this can explain why dominantly a specific charmonium state e.g. J/ψ or ψ' appears in the decay.

Here's what I mean:

Van der Waals interaction of charmonium with light hadronic matter



$$\langle B|H_{eff}|A\rangle = -\frac{1}{2}\,\alpha_{AB}\,\vec{E}^a\cdot\vec{E}^a$$

Chromo-polarizability: α_{AB}. Chromo-electric field $\vec{E}^a$.

$|\alpha_{\psi' J/\psi}| \approx 2\,GeV^{-3}$ is known from $\psi' \to \pi\pi\, J/\psi$.

Schwartz inequality: $\alpha_{J/\psi}\alpha_{\psi'} \geq \alpha^2_{\psi' J/\psi}$, so that either $\alpha_{J/\psi}$ or $\alpha_{\psi'}$ or both should be bigger than $2\,GeV^{-3}$.

$$\langle X|\vec{E}^a\cdot\vec{E}^a\;|X\rangle \geq \langle X|\vec{E}^a\cdot\vec{E}^a-\vec{B}^a\cdot\vec{B}^a|X\rangle = -\frac{1}{2}\langle X|(F^a_{\mu\nu})^2|X\rangle = \frac{32\pi^2}{9}\,M_X^2$$

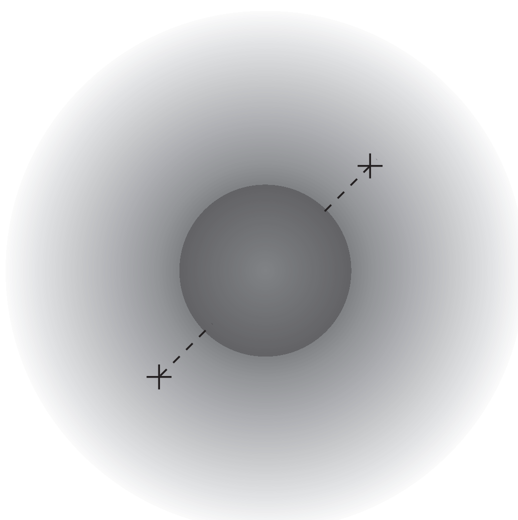
X=(Light hadron) $\Rightarrow$ strong interaction with heavier hadronic states made of light quarks and gluons.

E.g. J/ψ binding potential V in heavy nuclei:

$$|V| \geq \frac{8\pi^2}{9}\,\alpha_{J/\psi}\,m_N\,\rho_N$$

$V < -27\,\mathrm{MeV}$ at $\rho_N = 0.16\,\mathrm{fm}^{-3}$.

The interaction with the light quark-gluon matter within an excited hadron should be $few\times$ stronger due to higher ρ.



If charmonium — light-hadron interaction is described by potential $V(x)$, the low-energy theorem implies that

$$\int V(x)\, d^3x \le -\frac{8\pi^2}{9}\, \alpha^{(\psi)}\, M_X$$

The existence of bound state depends on relation between the mass M_X and the size of the hadron R:

$$\alpha^{(\psi)}\, \frac{M_X \bar{M}}{R} \ge O(1)$$

($\bar{M} = M_X M_\psi / (M_X + M_\psi)$ - reduced mass.)

If with excitation R grows slower than M_X then binding necessarily occurs at sufficiently high excitation. E.g. in bag model $R \propto M^{1/3}$.

Linear Regge trajectories: $R \propto M$ and a better analysis is needed.

In a holographic (soft wall) model with linear Regge behavior binding necessarily occurs at a high excitation.

(S. Dubynskiy, A. Gorsky, M.B.V.)

Spin S meson masses: eigenvalues of

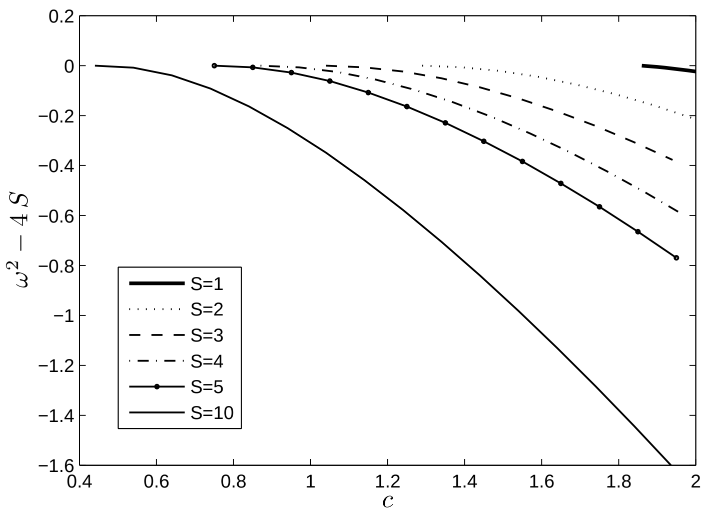
$$\left(-\frac{\mathrm{d}^2}{\mathrm{d}z^2}+z^2+2\,S-2+\frac{S^2-1/4}{z^2}\right)\psi_n(z)=m_n^2\,\psi_n(z) \qquad \Rightarrow \qquad m_n^2=4(n+S)$$

$H_{eff}=-C\,\theta_\mu^\mu$ - source η of dilaton (localized at $\vec{x}=0,\ z=0$).

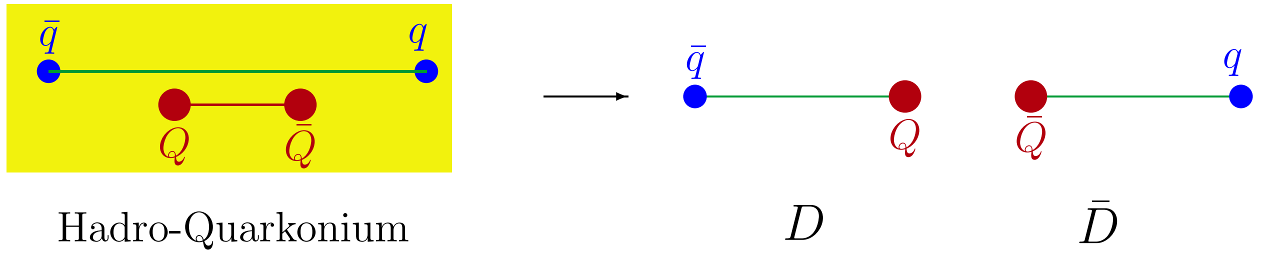
$V(z,\vec{x})=g(z)\,D(z,\vec{x})\,\eta$ - extra potential in the eigenvalue problem:

$$V(z,\vec{x})=-c\,z^6\int_0^\infty \mathrm{d}\tau\,\left(\frac{1}{2\pi\tau}\right)^{3/2}\exp\left(-\frac{x^2}{2\tau}\right)\,\frac{e^{-\tau}}{\sinh^3\tau}\,\exp\left(-\frac{z^2}{2}\,\frac{e^{-\tau}}{\sinh\tau}\right)$$

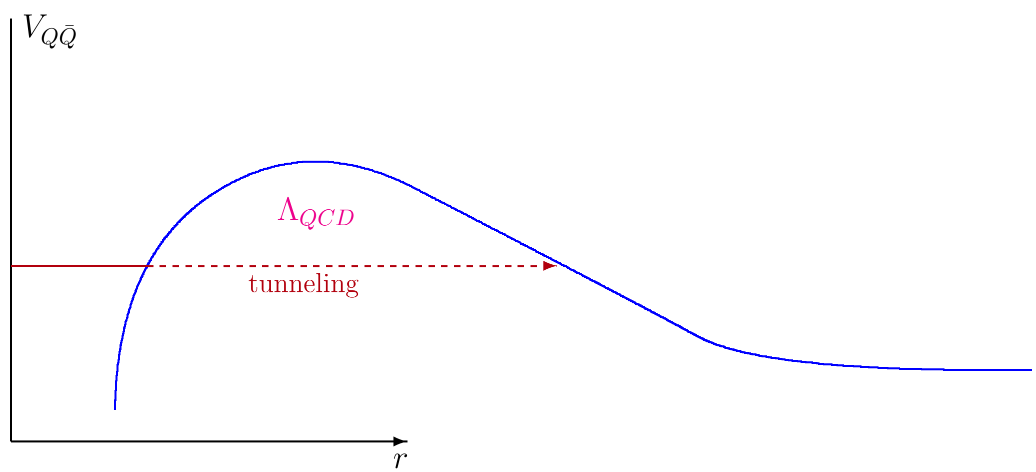
$c=C\,(\text{string tension})^{3/2}$ - dimensionless; $c\approx 1$ at $\alpha^{(\psi)}=2\,\mathrm{Gev}^{-3}$.



- Decay to open heavy flavor mesons



If approximated by an effective potential for heavy $Q\bar{Q}$:



The tunneling momentum $|p_Q| = \sqrt{M_Q\,(V_{Q\bar{Q}} - E)} \sim \sqrt{M_Q\,\Lambda_{QCD}} \Rightarrow$

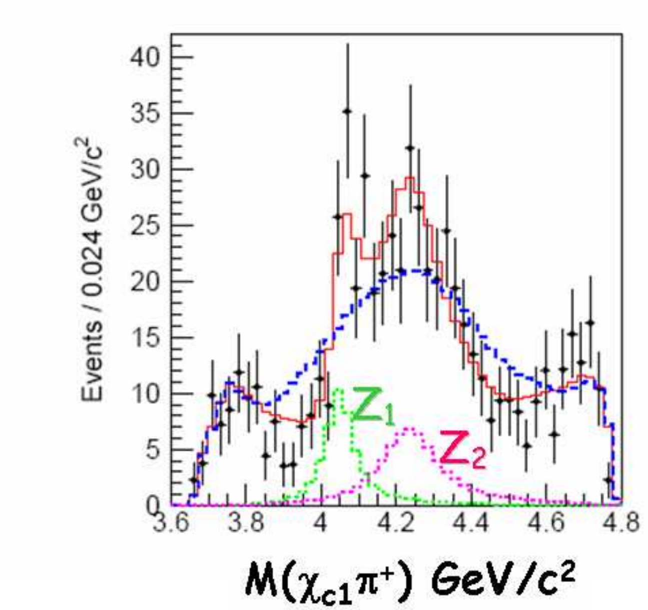
$$\Gamma(Y, Z \to D\bar{D}\ldots) \sim \exp\left(-\int |p_Q(r)|\,dr\right) \sim \exp\left(-\sqrt{\frac{M_Q}{\Lambda_{QCD}}}\right)$$

If such interpretation of Y's and Z has anything to do with reality, there should be:

- bound states of J/ψ and/or ψ' with light nuclei and with baryonic resonances, i.e. baryo-charmonium decaying to e.g. pJ/ψ (+ pions).
- resonances containing χ_{cJ} charmonium, i.e. in χ_{cJ}+pion(s)
- decays (moderately suppressed) into non-preferred charmonium states, e.g. $Y(4260) \to \pi\pi\psi'$, or $Y(4.3) \to \pi\pi J/\psi$
- resonances containing excited bottomonium, $\Upsilon(3S)$, $\chi_b(2P)$, $\Upsilon(1D)$ in the mass range around 11 - 11.5 GeV

• Latest experimental additions

Belle 08: $Z^+_{1,2} \to \pi^+\chi_{c1}$. (Observed in $B \to K\pi^+\chi_{c1}$)



Z_1 : $M \approx 4.05\,\mathrm{GeV}$, $\Gamma \approx 80\,\mathrm{MeV}$. Z_2 : $M \approx 4.25\,\mathrm{GeV}$, $\Gamma \approx 180\,\mathrm{MeV}$.

Notice: $Z(4430) - Z_2(4.25) \approx \psi' - \chi_{c1} \approx 180\,\mathrm{MeV}$.

Could it be that they have the same hosting light-meson resonance?

However $\Gamma_{Z_2} \approx 4\,\Gamma_{Z(4430)}$ (???)

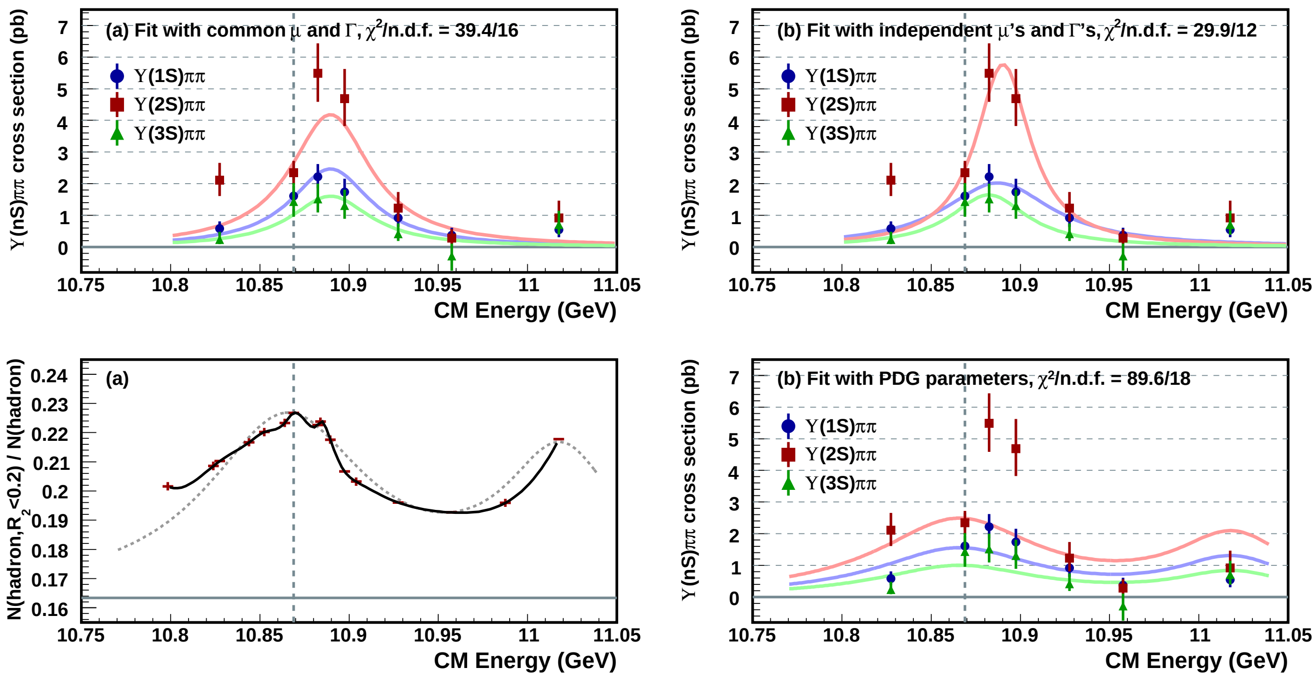
• Belle '08: $e^+e^- \to X(4630) \to \Lambda_c\bar{\Lambda}_c$ (???) Not well established. Is this $Y(4.66)$?

$\Upsilon(5S)$ region in e^+e^-.

Belle '07: $\Gamma(\Upsilon(5S) \to \pi\pi\Upsilon(1S,2S)) \gtrsim 100\,\Gamma_{typical}$, (0.6 – 0.8 MeV vs. few keV)

More detailed study: Belle 8/08 [ArXive 0808.2445]

Unexplained enhancement of e^+e^- to $\pi^+\pi^-\Upsilon$, $\pi^+\pi^-\Upsilon(2S)$ and $\pi^+\pi^-\Upsilon(3S)$ around 10.89 GeV



The shapes are not compatible with $\Upsilon(5S)$, neither can be explained by a single resonance, either common or individual for all three channels.

Notice the relative enhancement of $\pi\pi\Upsilon(2S)$. $\Rightarrow$ Hadro-bottomonium with dominantly $\Upsilon(2S)$?

Conclusion

I am not entirely sure that the hadroquarkonium picture will pass further testing. But I belive that it has a chance and IMHO it is worth testing!