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Heavy Quarkonia: the Beauty and the Beasts

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I. Introduction: proliferation of charmonium-like states

II. Why χ_{c1}**(3872)** is so unique

III. Modelling non-resonant ψ**(4260)**, ψ**(4660)**, Υ**(10580)**

IV. Conclusions

I. Introduction: proliferation of charmonium-like states

- Since 2004 there has been a steep increase in mostly hidden-charm states listed by the PDG, starting with **X(3872)** now designated **χ_{c1}(3872)**.
- Charged charmonium-like states appeared in the PDG in 2010 and charged bottomonium like states in 2012.
- In the 2018 PDG edition a state with possibly exotic $J^{PC} = 0^{--}$ called **R_{c0}(4240)** has been included.
- Several states changed their masses and names over the years, and a few states even disappeared.
- The interpretation of several "XYZ" states is hotly disputed, ranging from tetraquarks, via hadronic molecules, to non-resonant enhancements due to triangle singularities. For a short review, see e.g. X. Liu, D.-Y. Chen, and T. Matsuki, JPS Conf. Proc. **17** (2017) 111004.
- **χ_{c1}(3872)** maintains its unique position of a very well determined charmonium-like state just below or even on top of its lowest OZI-allowed hadronic decay mode.

Charmonium

2002:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P) chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) psi(3836) psi(4040) psi(4160) psi(4415)

2004:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P) chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) psi(3836) X(3872) psi(4040) psi(4160) psi(4415)

2006:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P) chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) (psi(3836)) X(3872) chi(c2)(2P) X(3940) psi(4040) psi(4160) Y(4260) psi(4415)

2008:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P) chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) X(3872) chi(c2)(2P) X(3940) X(3945) psi(4040) psi(4160) X(4260) X(4360) psi(4415)

2010:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P)
chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) X(3872)
chi(c2)(2P) X(3940) X(3945) psi(4040) X(4050)+- X(4140)
psi(4160) X(4160) X(4250)+- X(4260) X(4350) X(4360)
psi(4415) X(4430)+- X(4660)

2012:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P)
chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) X(3872) X(3915)
chi(c2)(2P) X(3940) (X(3945)) psi(4040) X(4050)+-
X(4140) psi(4160) X(4160) X(4250)+- X(4260) X(4350)
X(4360) psi(4415) X(4430)+- X(4660)

2014:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P)
chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) X(3823) X(3872)
X(3900)+- X(3900)0 X(3915) chi(c0)(2P) chi(c2)(2P)
X(3940) X(4020)+- psi(4040) X(4050)+- X(4140) psi(4160)
X(4160) X(4250)+- X(4260) X(4350) X(4360) psi(4415)
X(4430)+- X(4660)

2016:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P) chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) psi(3823) X(3872) X(3900)+- (X(3900)0) X(3915) (chi(c0)(2P)) chi(c2)(2P) X(3940) X(4020)+- psi(4040) X(4050)+- X(4055)+- X(4140) psi(4160) X(4160) X(4200)+- X(4230) X(4240)+- X(4250)+- X(4260) X(4350) X(4360) psi(4415) X(4430)+- X(4660)

2018:

eta(c)(1S) J/psi(1S) chi(c0)(1P) chi(c1)(1P) h(c)(1P) chi(c2)(1P) eta(c)(2S) psi(2S) psi(3770) psi(2)(3823) chi(c0)(3860) chi(c1)(3872) Z(c)(3900) X(3915) chi(c2)(3930) X(3940) X(4020)+- psi(4040) X(4050)+- X(4055)+- chi(c1)(4140) psi(4160) X(4160) Z(c)(4200) psi(4230) R(c0)(4240) X(4250)+- psi(4260) chi(c1)(4274) X(4350) psi(4360) psi(4390) psi(4415) Z(c)(4430) chi(c0)(4500) psi(4660) chi(c0)(4700)

Bottomonium

2002:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) chi(b2)(1P) Upsilon(2S) chi(b0)(2P) chi(b1)(2P) chi(b2)(2P) Upsilon(3S) Upsilon(4S) Upsilon(10860) Upsilon(11020)

2004:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) chi(b2)(1P) Upsilon(2S) chi(b0)(2P) chi(b1)(2P) chi(b2)(2P) Upsilon(3S) Upsilon(4S) Upsilon(10860) Upsilon(11020)

2006:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) chi(b2)(1P) Upsilon(2S) Upsilon(1D) chi(b0)(2P) chi(b1)(2P) chi(b2)(2P) Upsilon(3S) Upsilon(4S) Upsilon(10860) Upsilon(11020)

2008:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) chi(b2)(1P) Upsilon(2S) Upsilon(1D) chi(b0)(2P) chi(b1)(2P) chi(b2)(2P) Upsilon(3S) Upsilon(4S) Upsilon(10860) Upsilon(11020)

2010:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) chi(b2)(1P) Upsilon(2S) Upsilon(1D) chi(b0)(2P) chi(b1)(2P) chi(b2)(2P) Upsilon(3S) Upsilon(4S) Upsilon(10860) Upsilon(11020)

2012:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) h(b)(1P) chi(b2)(1P) Upsilon(2S) Upsilon(1D) chi(b0)(2P) chi(b1)(2P) h(b)(2P) chi(b2)(2P) Upsilon(3S) chi(b)(3P) Upsilon(4S) X(10610)+- X(10650)+- Upsilon(10860) Upsilon(11020)

2014:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) h(b)(1P) chi(b2)(1P) eta(b)(2S) Upsilon(2S) Upsilon(1D) chi(b0)(2P) chi(b1)(2P) h(b)(2P) chi(b2)(2P) Upsilon(3S) chi(b)(3P) Upsilon(4S) X(10610)+- X(10610)0 X(10650)+- Upsilon(10860) Upsilon(11020)

2016:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) h(b)(1P) chi(b2)(1P) eta(b)(2S) Upsilon(2S) Upsilon(1D) chi(b0)(2P) chi(b1)(2P) h(b)(2P) chi(b2)(2P) Upsilon(3S) chi(b)(3P) Upsilon(4S) X(10610)+- X(10610)0 X(10650)+- Upsilon(10860) Upsilon(11020)

2018:

eta(b)(1S) Upsilon(1S) chi(b0)(1P) chi(b1)(1P) h(b)(1P) chi(b2)(1P) eta(b)(2S) Upsilon(2S) Upsilon(2)(1D) chi(b0)(2P) chi(b1)(2P) h(b)(2P) chi(b2)(2P) Upsilon(3S) chi(b)(3P) Upsilon(4S) Z(b)(10610) Z(b)(10650) Upsilon(10860) Upsilon(11020)

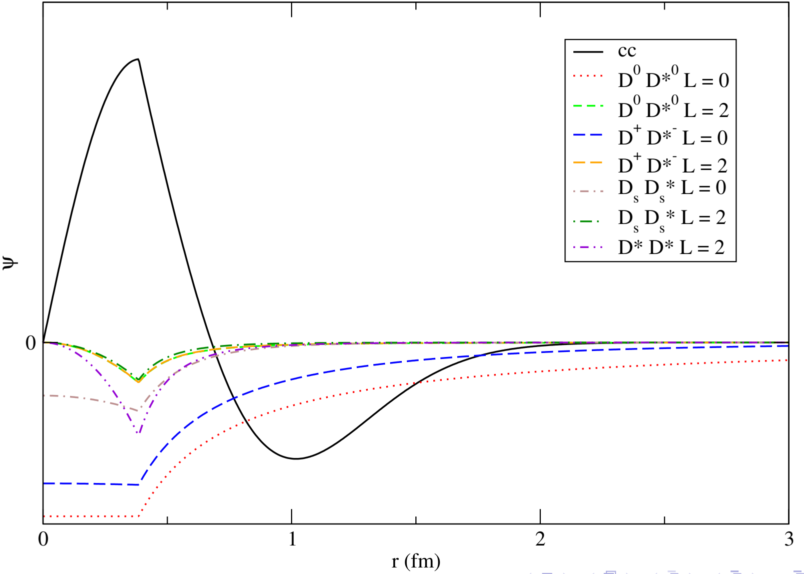
II. Why $\chi_{c1}(3872)$ is so unique

- PDG-2018 average mass: $\mathbf{m_{\chi_{c1}(3872)} = 3871.69 \ \pm 0.17\ MeV}$. Average $\mathbf{D^0\bar{D}^{\star 0}}$ threshold: $\mathbf{m_{D^0\bar{D}^{\star 0}} = 3871.696 \pm 0.08\ MeV}$.
- This mass difference has been shrinking over the years and is now probably smaller than the $\mathbf{D^{\star 0}}$ width.
- The other hadronic decay modes $\omega \mathbf{J}/\psi$ and $\rho^{\mathbf{0}}\mathbf{J}/\psi$ are both OZI-suppressed, the latter also isospin-breaking. Therefore, the $\chi_{c1}(3872)$ width is very small.
- The quantum numbers $\mathbf{I^G J^{PC} = 0^+ 1^{++}}$ have been firmly established.
- For many purposes, $\chi_{c1}(3872)$ can be treated as a (quasi-)bound state, allowing very detailed model calculations.
- Future experiments (e.g. PANDA) will be able to pin down $\chi_{c1}(3872)$'s properties with unprecedented precision, such as electromagnetic transitions.
- $\chi_{c1}(3872)$ is an ideal laboratory for both experimentalists and theorists to improve their methods of analysis.

Wave function of χ_{c1}**(3872)** as a unitarised $2\,^3P_1$ $c\bar{c}$ state

M. Cardoso, G. Rupp, and E. van Beveren

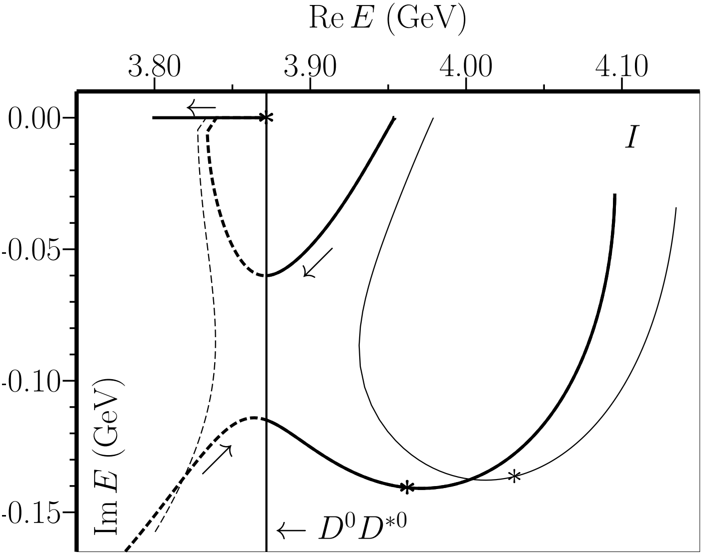
Eur. Phys. J. C **75** (2015) 26 [arXiv:1411.1654 [hep-ph]]



χ_{c1}(3872) as an intrinsic or a dynamical unitarised $2\,{}^3P_1$ $c\bar{c}$ state

S. Coito, G. Rupp, and E. van Beveren

Eur. Phys. J. C **73** (2013) 2351 [arXiv:1212.0648 [hep-ph]]



M. Padmanath, C. B.Lang, and S. Prelovsek Phys. Rev. D **92** (2015) 034501

We perform a lattice study of charmonium-like mesons with $J^{PC} = 1^{++}$ and three quark contents $\bar{c}c\bar{d}u$, $\bar{c}c(\bar{u}u+\bar{d}d)$ and $\bar{c}c\bar{s}s$, where the later two can mix with $\bar{c}c$. This simulation with $N_f = 2$ and $m_\pi \simeq 266$ MeV aims at the possible signatures of four-quark exotic states. We utilize a large basis of $\bar{c}c$, two-meson and diquark-antidiquark interpolating fields, with diquarks in both antitriplet and sextet color representations. A lattice candidate for $X(3872)$ with $I = 0$ is observed very close to the experimental state only if both $\bar{c}c$ and $D\bar{D}^*$ interpolators are included; the candidate is not found if diquark-antidiquark and $D\bar{D}^*$ are used in the absence of $\bar{c}c$. No candidate for neutral or charged $X(3872)$, or any other exotic candidates are found in the $I = 1$ channel. We also do not find signatures of exotic $\bar{c}c\bar{s}s$ candidates below 4.2 GeV, such as $Y(4140)$. Possible physics and methodology related reasons for that are discussed. Along the way, we present the diquark-antidiquark operators as linear combinations of the two-meson operators via the Fierz transformations.

> . . . *“In the physical world with* $\mathbf{N_c = 3}$*, it is argued that tetraquarks could exist at subleading orders [46] of large* $\mathbf{N_c}$ *QCD. However, in the presence of the leading order two-meson terms, one should take caution in interpreting the nature of the levels purely based on their overlap factors onto various four-quark interpolators.”* . . .

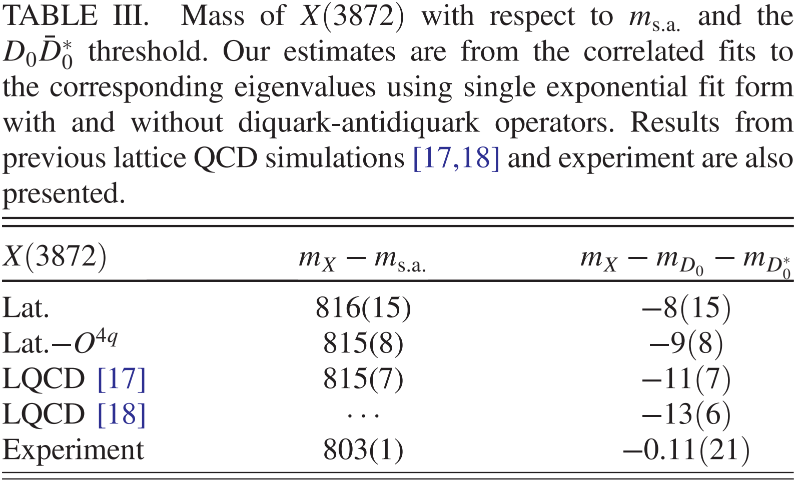


TABLE III. Mass of $X(3872)$ with respect to $m_{\text{s.a.}}$ and the $D_0\bar{D}_0^*$ threshold. Our estimates are from the correlated fits to the corresponding eigenvalues using single exponential fit form with and without diquark-antidiquark operators. Results from previous lattice QCD simulations [17,18] and experiment are also presented.

$X(3872)$	$m_X - m_{\text{s.a.}}$	$m_X - m_{D_0} - m_{D_0^*}$
Lat.	816(15)	−8(15)
Lat.−O^{4q}	815(8)	−9(8)
LQCD [17]	815(7)	−11(7)
LQCD [18]	⋯	−13(6)
Experiment	803(1)	−0.11(21)

> . . . *"These results are in agreement with a possible interpretation of* **X(3872)**, *where its properties are due to the accidental alignment of a* $\mathbf{c\bar{c}}$ *state with the* $\mathbf{D^0\bar{D}^{\star 0}}$ *threshold [49,50], but we cannot rule out other options."*
>
> . . .

$\psi(4260)$ decay modes in the PDG-2018 Meson Listings

M. Tanabashi *al.* (Particle Data Group)

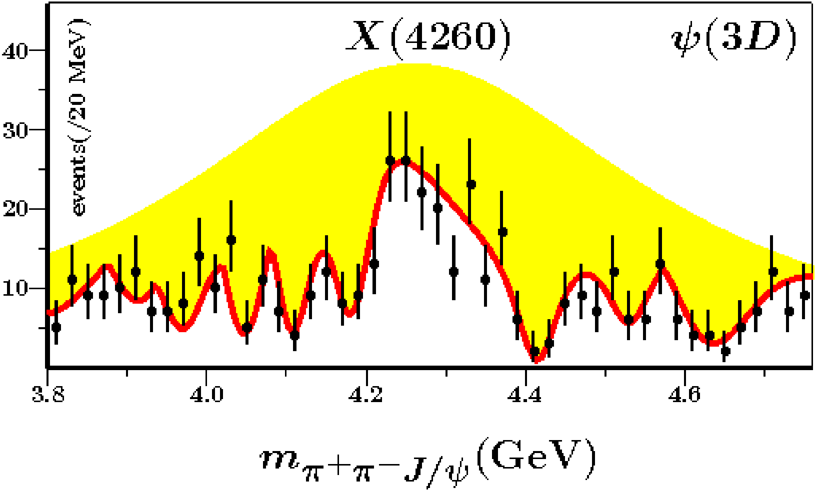
Phys. Rev. D **98** (2018) 030001

	Mode	Fraction (Γ_i/Γ)
Γ_1	$e^+ e^-$	
Γ_2	$J/\psi \pi^+ \pi^-$	seen
Γ_3	$J/\psi f_0(980),\ f_0(980) \to \pi^+ \pi^-$	seen
Γ_4	$Z_c(3900)^\pm \pi^\mp,\ Z_c^\pm \to J/\psi \pi^\pm$	seen
Γ_5	$J/\psi \pi^0 \pi^0$	seen
Γ_6	$J/\psi K^+ K^-$	seen
Γ_7	$J/\psi K^0_S K^0_S$	not seen
Γ_8	$J/\psi \eta$	not seen
Γ_9	$J/\psi \pi^0$	not seen
Γ_{10}	$J/\psi \eta'$	not seen
Γ_{11}	$J/\psi \pi^+ \pi^- \pi^0$	not seen
Γ_{12}	$J/\psi \eta \pi^0$	not seen
Γ_{13}	$J/\psi \eta \eta$	not seen
Γ_{14}	$\psi(2S) \pi^+ \pi^-$	not seen
Γ_{15}	$\psi(2S) \eta$	not seen
Γ_{16}	$\chi_{c0} \omega$	not seen
Γ_{17}	$\chi_{c1} \pi^+ \pi^- \pi^0$	not seen
Γ_{18}	$\chi_{c2} \pi^+ \pi^- \pi^0$	not seen
Γ_{19}	$h_c(1P) \pi^+ \pi^-$	not seen
Γ_{20}	$\phi \pi^+ \pi^-$	not seen
Γ_{21}	$\phi f_0(980) \to \phi \pi^+ \pi^-$	not seen
Γ_{22}	$D \overline{D}$	not seen
Γ_{23}	$D^0 \overline{D}{}^0$	not seen
Γ_{24}	$D^+ D^-$	not seen
Γ_{25}	$D^* \overline{D}$ +c.c.	not seen
Γ_{26}	$D^*(2007)^0 \overline{D}{}^0$ +c.c.	not seen
Γ_{27}	$D^*(2010)^+ D^-$ +c.c.	not seen
Γ_{28}	$D^* \overline{D}{}^*$	not seen
Γ_{29}	$D^*(2007)^0 \overline{D}{}^*(2007)^0$	not seen
Γ_{30}	$D^*(2010)^+ D^*(2010)^-$	not seen
Γ_{31}	$D \overline{D} \pi$ +c.c.	
Γ_{32}	$D^0 D^- \pi^+$ +c.c. (excl. $D^*(2007)^0 \overline{D}{}^{*0}$ +c.c., $D^*(2010)^+ D^-$ +c.c.)	not seen
Γ_{33}	$D \overline{D}{}^* \pi$ +c.c. (excl. $D^* \overline{D}{}^*$)	not seen
Γ_{34}	$D^0 D^{*-} \pi^+$ +c.c. (excl. $D^*(2010)^+ D^*(2010)^-$)	not seen
Γ_{35}	$D^0 D^*(2010)^- \pi^+$ +c.c.	not seen
Γ_{36}	$D^* \overline{D}{}^* \pi$	not seen
Γ_{37}	$D_s^+ D_s^-$	not seen
Γ_{38}	$D_s^{*+} D_s^-$ +c.c.	not seen
Γ_{39}	$D_s^{*+} D_s^{*-}$	not seen
Γ_{40}	$p \overline{p}$	not seen
Γ_{41}	$p \overline{p} \pi^0$	not seen
Γ_{42}	$K^0_S K^\pm \pi^\mp$	not seen
Γ_{43}	$K^+ K^- \pi^0$	not seen
	Radiative decays	
Γ_{44}	$\eta_c(1S) \gamma$	possibly
Γ_{45}	$\chi_{c1} \gamma$	not seen
Γ_{46}	$\chi_{c2} \gamma$	not seen
Γ_{47}	$\chi_{c1}(3872) \gamma$	seen

ψ**(4260)** as a non-resonant **c$\bar{\text{c}}$** structure from inelasticities

E. van Beveren, G. Rupp, and J. Segovia

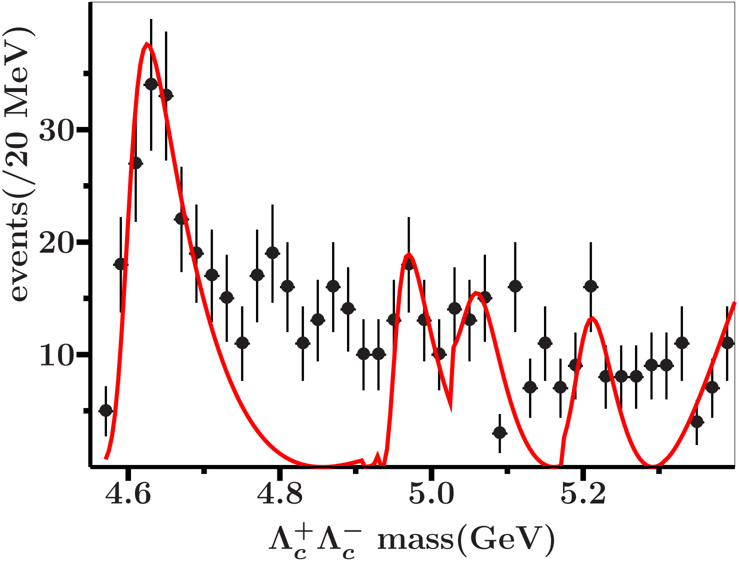
Phys. Rev. Lett. **105** (2010) 102001 [arXiv:1005.1010 [hep-ph]]



$\psi(4660)$ as a $\Lambda_c\bar{\Lambda}_c$ threshold enhancement in BABAR data

E. van Beveren, X. Liu, R. Coimbra, and G. Rupp

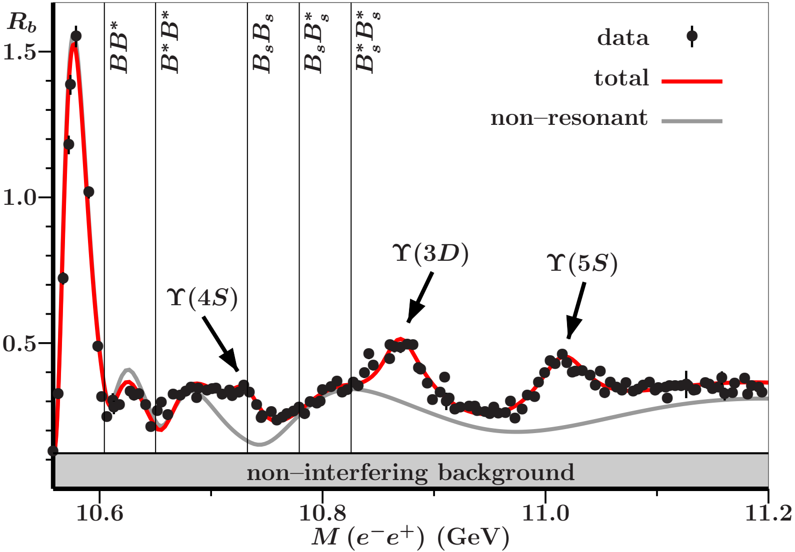
Europhys. Lett. **85** (2009) 61002 [arXiv:0809.1151 [hep-ph]]



Alternative vector **$b\bar{b}$** spectrum from threshold enhancements

E. van Beveren and G. Rupp, arXiv:0910.0967 [hep-ph]

Also see: EvB & GR, Phys. Rev. D **80** (2009) 074001



IV. Conclusions

- A modern lattice calculation seems to confirm $\chi_{c1}(3872)$ as an axial-vector charmonium state with a sizeable $D^0\bar{D}^{\star 0}$ component. Both $c\bar{c}$ and $D^0\bar{D}^{\star 0}$ turn out to be crucial for its existence, in contrast with a largely negligible diquark-antidiquark component.
- As the (putative) $\chi_{b1}(3P)$ state lies way below the $B\bar{B}^{\star}$ threshold, the $\chi_{c1}(3872)$ case appears to be unique as a lucky accident.
- The large unitarisation effects found for $\chi_{c1}(3872)$ should be a warning to model builders who treat new charmonium-like and bottomonium-like states as static tetraquarks or molecules.
- Experimentalists should be very careful in trying to distinguish between genuine resonance and possible non-resonant threshold effects. They should also not make assignments of new heavy quarkonium states above open-charm/bottom threshold based on predictions of static quark models.
- In my opinion, the PDG people should be more selective in including new charmonium-like states in the listings, lest the heavy-quarkonium panorama become increasingly confusing.