CHARM 2016

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CONVENTIONAL VERSUS UNCONVENTIONAL

NATURE OF X(3915)

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Motivation

J. Beringer *et al.* 2012
Phys. D86, 010001

$c\bar{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
• $X(3915)$	**$0^+(?^{?+})$**
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(?^?)$
• $X(4660)$	$?^?(1^{--})$

K. A.Olive *et al.* 2014
Ch. Phys. C86, 090001

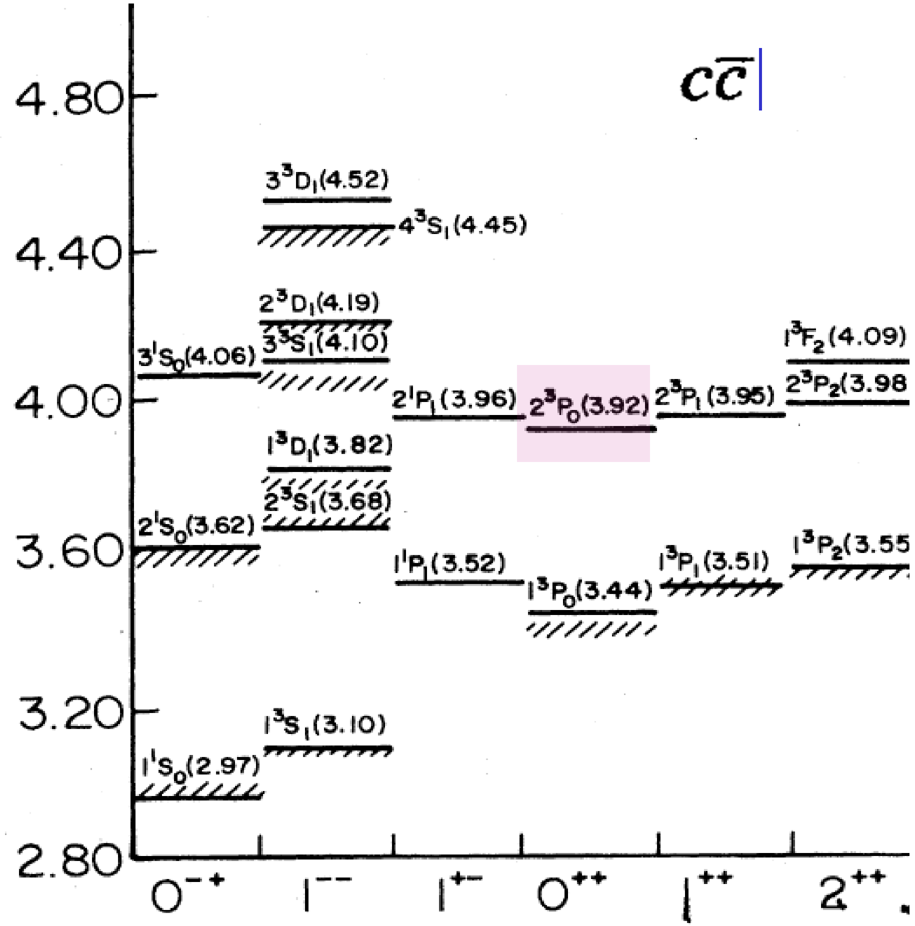
$c\bar{c}$	$I^G(J^{PC})$
• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
• $h_c(1P)$	$?^?(1^{+-})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
$X(3823)$	$?^?(?^{?-})$
• $X(3872)$	$0^+(1^{++})$
• $X(3900)^\pm$	$?(1^+)$
$X(3900)^0$	$?(?^?)$
• $\chi_{c0}(2P)$	**$0^+(0^{++})$**
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$X(3940)$	$?^?(?^{??})$
$X(4020)^\pm$	$?(?^?)$
• $\psi(4040)$	$0^-(1^{--})$
$X(4050)^\pm$	$?(?^?)$
$X(4140)$	$0^+(?^{?+})$
• $\psi(4160)$	$0^-(1^{--})$
$X(4160)$	$?^?(?^{??})$
$X(4250)^\pm$	$?(?^?)$
• $X(4260)$	$?^?(1^{--})$
$X(4350)$	$0^+(?^{?+})$
• $X(4360)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$
$X(4430)^\pm$	$?(1^+)$
• $X(4660)$	$?^?(1^{--})$

Conventional States

$$H = T(Q) + T(\overline{Q}) + V_{conf} + V_{Coul} + V_{Sd}$$

$$V_{conf} = \sigma r \qquad V_{Coul} = -\frac{\chi}{r} \qquad \chi = \frac{4}{3}\alpha_s \hbar$$

S. Godfrey, N. Isgur
PRD 32, 189 (1985)



Decay properties and production rates of X(3915) may be incompatible with a conventional description

F. K. Guo and U. G. Meissner, Phys. D86, 091501 (2012)
S. L. Olsen, Phys. D91, 057501 (2015)

$$\mathcal{B}\left(B^+ \to K^+ X(3915)\right) \mathcal{B}\left(X(3915) \to J/\psi\omega\right) = 3.0^{+0.6+0.5}_{-0.5-0.3} \times 10^{-5}$$

$$\Gamma\left(X(3915) \to \gamma\gamma\right) \mathcal{B}\left(X(3915) \to J/\psi\omega\right) = 54 \pm 9 \text{ eV}$$

OZI allowed $X(3915) \to D\overline{D}$ but suppressed

Non quark-antiquark structure?

H-X. Chen, W. Chen, X. Liu, S-L. Zhu, Phys. Rep. 639, 1-121 (2016)

- Meson-antimeson molecule
- Tetraquark
- Mixed charmonium-molecule
- …

No full compatibility with current data

INDEX

i) Conventional versus unconventional quark-antiquark model description of $X(3915)$.

ii) Decay models for $X(3915) \to D\overline{D}$.

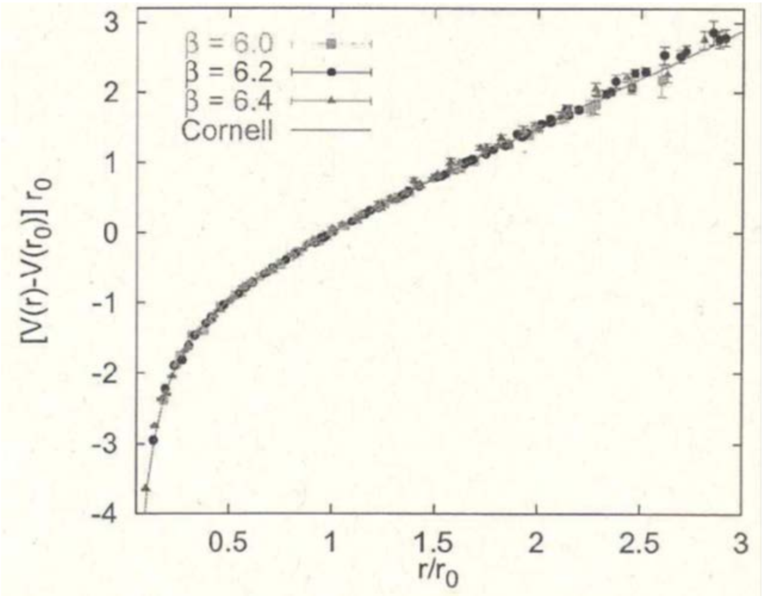
iii) The $X(3915) \to J/\psi\omega$ decay.

iv) The production process $B^+ \to K^+ X(3915)$.

v) Summary.

Conventional description: the Cornell Model.

G. S. Bali, Phis. Rep. 343,1 (2001)



$$V_{Cor}(r) \equiv \sigma r - \frac{\chi}{r}$$

$$\sigma = 850 \text{ MeV/fm } (0.17 \text{ GeV}^2)$$

$$\chi = 100 \text{ MeV.fm} \quad \alpha_s = \frac{3\chi}{4\hbar} \simeq 0.38$$

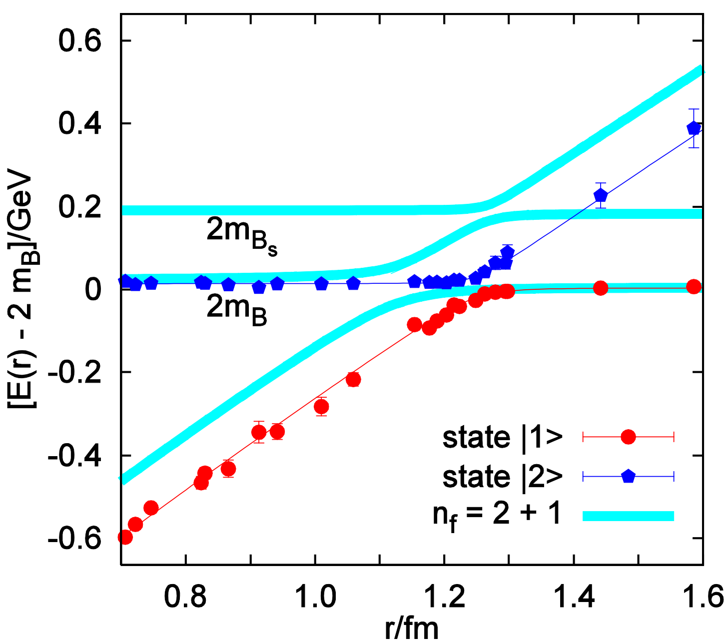
$$m_b = 4793 \text{ MeV}$$

$$m_c = 1348.5 \text{ MeV}$$

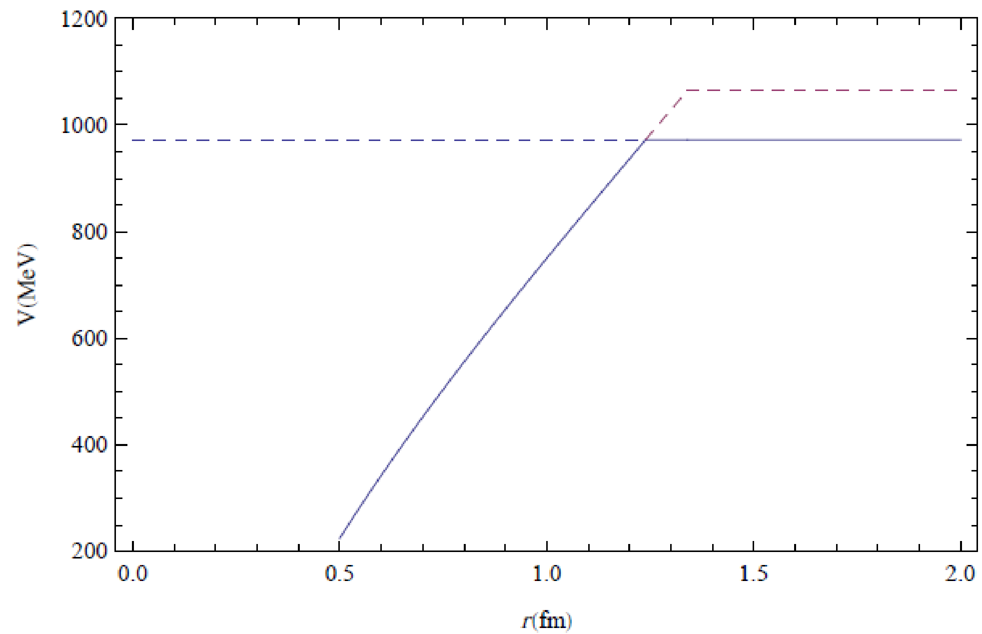
Calculated masses for the lowest lying spin triplet states differing at most 30 MeV (60 MeV) for bottomonium (charmonium).

Unconventional description:
Generalized Screened Potential Model (GSPM)

$$V_{E_{Q\overline{Q}}}(r) = V_{[M_{T_{i-1}}, M_{T_i}]}(r) \quad \text{if} \quad M_{T_{i-1}} < E_{Q\overline{Q}} \leq M_{T_i} \qquad M_{T_0} \equiv 0$$



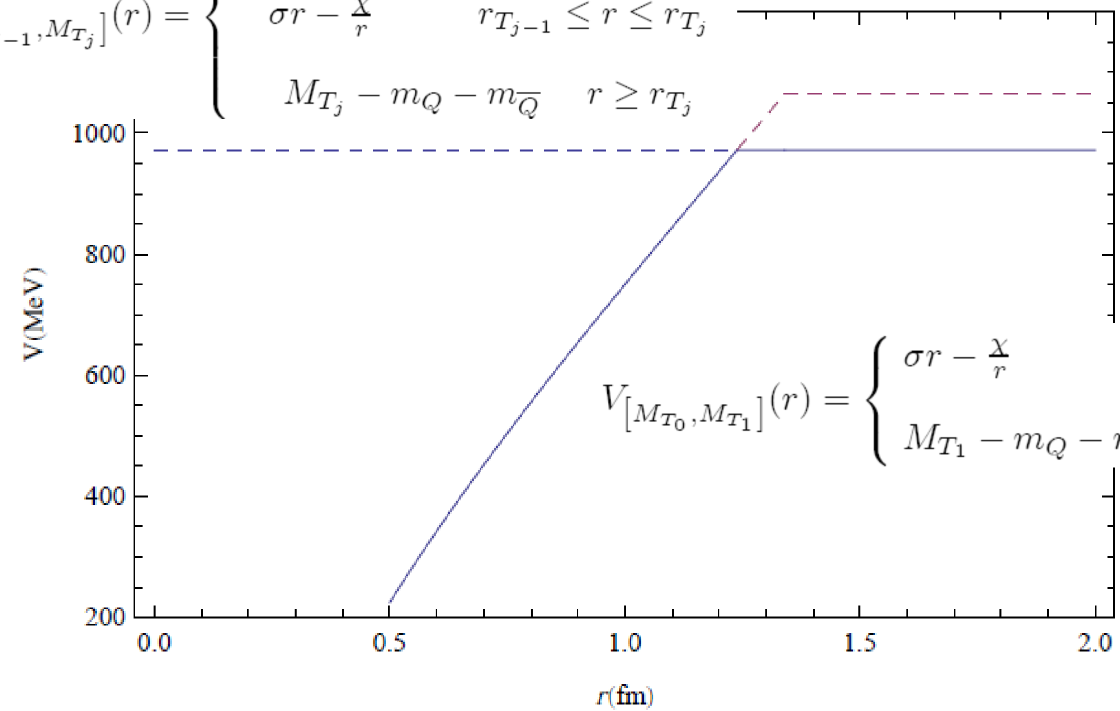
G. S. Bali *et al.*, PRD 71, 11453 (2005)



$$\sigma r_{T_{j-1}} - \frac{\chi}{r_{T_{j-1}}} = M_{T_{j-1}} - m_Q - m_{\overline{Q}}$$

$$V_{E_{Q\overline{Q}}}(r) = V_{[M_{T_{i-1}}, M_{T_i}]}(r) \qquad \text{if} \;\; M_{T_{i-1}} < E_{Q\overline{Q}} \leq M_{T_i}$$

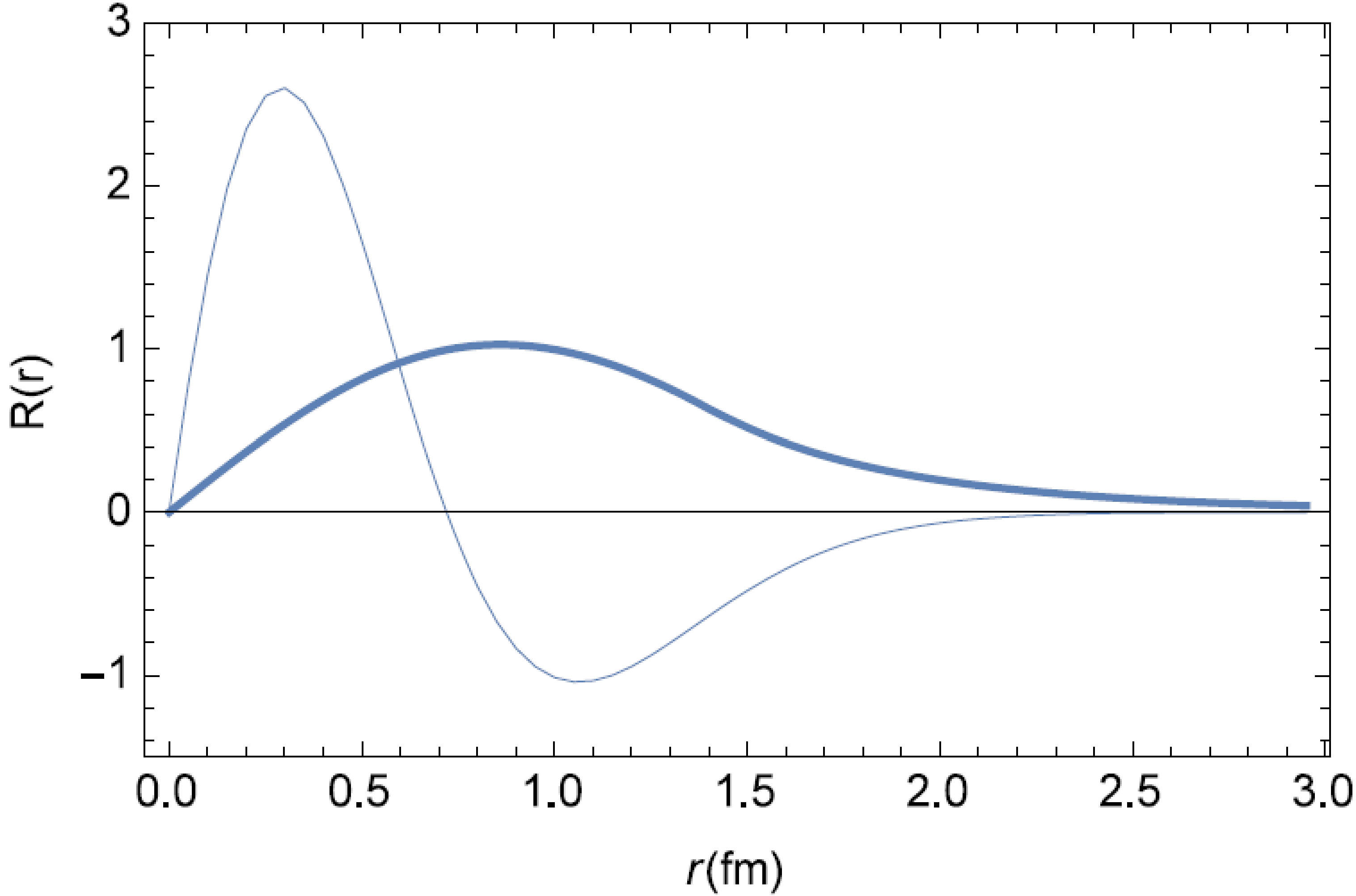
$$V_{[M_{T_{j-1}}, M_{T_j}]}(r) = \begin{cases} M_{T_{j-1}} - m_Q - m_{\overline{Q}} & r \leq r_{T_{j-1}} \\ \sigma r - \frac{\chi}{r} & r_{T_{j-1}} \leq r \leq r_{T_j} \\ M_{T_j} - m_Q - m_{\overline{Q}} & r \geq r_{T_j} \end{cases}$$



$$V_{[M_{T_0}, M_{T_1}]}(r) = \begin{cases} \sigma r - \frac{\chi}{r} & r \leq r_{T_1} \\ M_{T_1} - m_Q - m_{\overline{Q}} & r \geq r_{T_1} \end{cases}$$

Cornell potential modulated by thresholds

J^{PC}	GSPM States $k_{[T_{i-1},T_i]}$	M_{GSPM} MeV	M_{PDG} MeV	M_{Cor} MeV
0^{++}	$1p_{[T_0,T_1]}$	3456	3414.75 ± 0.31	3456
1^{++}	$1p_{[T_0,T_1]}$	3456	3510.66 ± 0.07	3456
2^{++}	$1p_{[T_0,T_1]}$	3456	3556.20 ± 0.09	3456
1^{++}	$2p_{[T_0,T_1]}$	3871.7	3871.68 ± 0.17	3911
0^{++}	$1p_{[T_1,T_2]}$	3898	3918.4 ± 1.9	3911
2^{++}	$2p_{[T_0,T_1]}$	3903	3927.2 ± 2.6	3911
1^{++}	$1p_{[T_1,T_2]}$	4017		
0^{++}	$1p_{[T_3,T_4]}$	4140	$4143.0 \pm 2.9 \pm 1.2$	
2^{++}	$1p_{[T_1,T_2]}$	4140	$4156^{+25}_{-20} \pm 15$	
0^{++}	$1p_{[T_4,T_5]}$	4325	$4350.6^{+4.6}_{-5.1} \pm 0.7$	4295


3
2
1
0
-1
R(r)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
r(fm)

$$X(3915) \to D\overline{D}$$

OZI allowed but exprimentally suppressed

$$\Gamma = 2\pi \frac{E_D E_{\overline{D}}}{M_{X(3915)}} k_D |A|^2$$

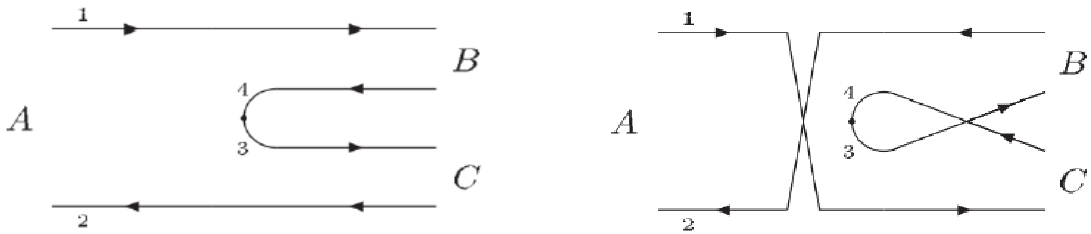
$$k_D = 599.6 \text{ MeV}$$

$$\psi_D(r_D) = \frac{2}{\pi^{\frac{1}{4}} R_D^{\frac{3}{2}}} e^{-\frac{r_D^2}{2R_D^2}} \qquad R_D = 0.54 \text{ fm}$$

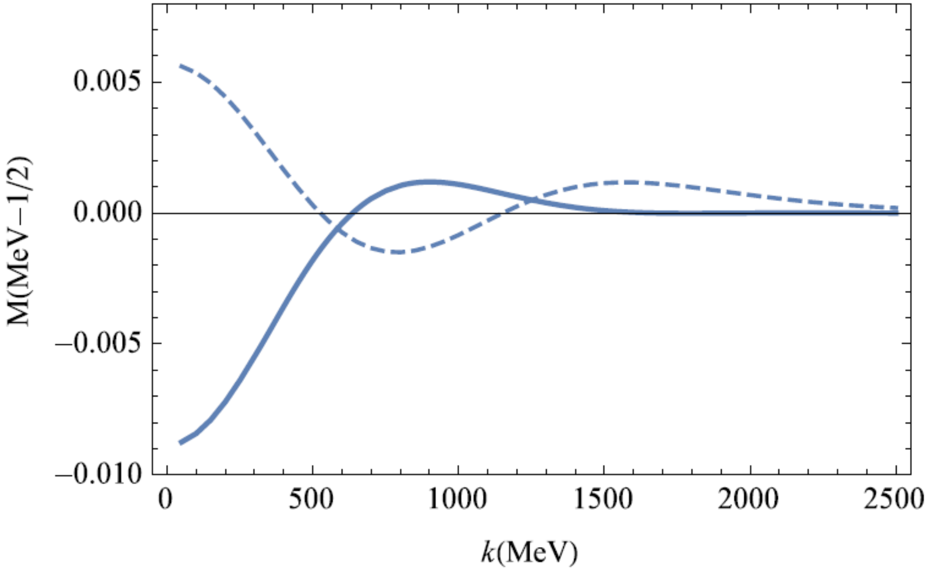
${}^3P_0$ Decay Model

$$H_{pair} = \gamma \sum_{i,j} a_i^\dagger(\vec{p})\, b_j^\dagger(\vec{p}\,')\, \frac{\vec{\sigma}\cdot(\vec{p}-\vec{p}\,')}{2\sqrt{2}\,\pi}\, (2\pi)^3\, \delta(\vec{p}+\vec{p}\,') + h.c.$$

$$|A|^2_{{}^3P_0} \equiv \gamma^2\, |M|^2$$



Solid line: GSPM
Dashed line: Cornell

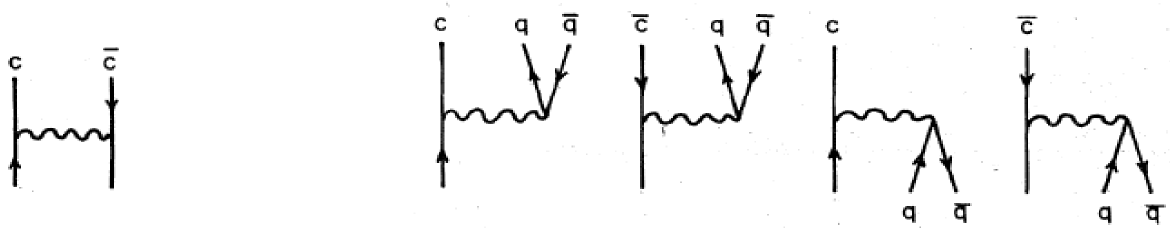


The suppression of the decay might be explained from a decay model ${}^3P_0$ with the GSPM description.

C^3 Decay Model

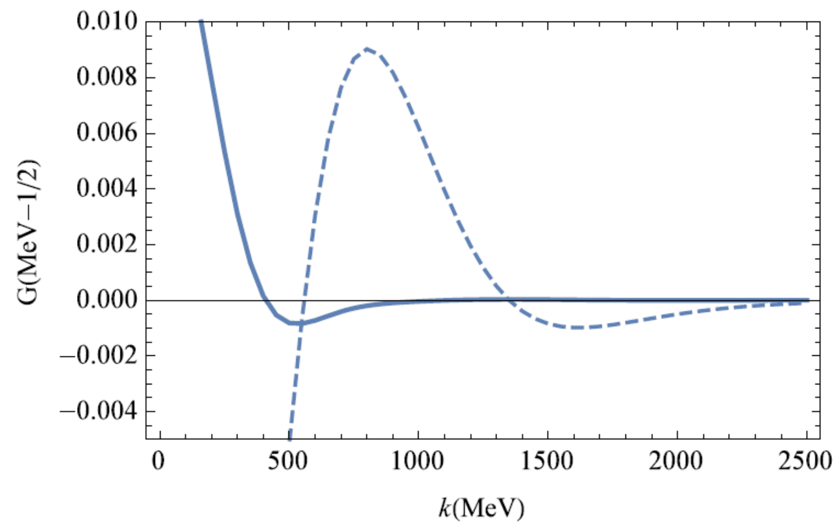
$$H_I = \frac{1}{2}\int d^3x\, d^3y : \rho_a(\vec{x})\, \frac{3}{4}\, V(\vec{x}-\vec{y})\, \rho_a(\vec{y}) :$$

$$\rho_a(\vec{x}) = \sum_{\text{flavors}} \psi^\dagger(\vec{x})\, \frac{1}{2}\lambda_a\, \psi(\vec{x})$$



$$|A|^2_{Cor} \equiv |G|^2$$

Solid line: GSPM
Dashed line: Cornell



The suppression of the decay might be explained from a C^3 decay model with the Cornell description.

$$X(3915) \rightarrow J/\psi\omega$$

$$\Gamma\left(X(3915) \rightarrow \gamma\gamma\right) \mathcal{B}\left(X(3915) \rightarrow J/\psi\omega\right) = 54 \pm 9 \text{ eV}$$

Cornell description

$$\frac{\left(\Gamma\left(\chi_{c0}\left(2p\right) \rightarrow \gamma\gamma\right)\right)}{\left(\Gamma\left(\chi_{c0}\left(1P\right) \rightarrow \gamma\gamma\right)\right)} = \frac{\left|R'_{0^{++}(2p)}\left(0\right)\right|^2}{\left|R'_{0^{++}(1p)}\left(0\right)\right|^2} = 1.4$$

$$\Gamma\left(\chi_{c0}\left(1P\right) \rightarrow \gamma\gamma\right) = 2.3 \pm 0.4 \text{ KeV}$$

$$\Gamma\left(\chi_{c0}\left(2p\right) \rightarrow \gamma\gamma\right) \sim 3.3 \pm 0.6 \text{ KeV}$$

$$\mathcal{B}\left(\chi_{c0}\left(2p\right) \rightarrow J/\psi\omega\right) \sim 0.017 \pm 0.006$$

GSPM description

$$\frac{\Gamma\left(1p_{[T_1,T_2]} \rightarrow \gamma\gamma\right)}{\Gamma\left(\chi_{c0}\left(1P\right) \rightarrow \gamma\gamma\right)} = \frac{\left|R'_{0^{++}\left(1p_{[T_1,T_2]}\right)}\left(0\right)\right|^2}{\left|R'_{0^{++}\left(1p_{[T_0,T_1]}\right)}\left(0\right)\right|^2} = 0.02$$

$$\Gamma\left(\chi_{c0}\left(1P\right) \rightarrow \gamma\gamma\right) = 2.3 \pm 0.4 \text{ KeV}$$

$$\Gamma\left(0^{++}\left(1p_{[T_1,T_2]}\right) \rightarrow \gamma\gamma\right) \sim 46 \pm 8 \text{ eV}$$

$$\mathcal{B}\left(1p_{[T_1,T_2]} \rightarrow J/\psi\omega\right) > 0.83$$

$$\mathcal{B}\left(B^+ \to K^+ X(3915)\right) \mathcal{B}\left(X(3915) \to J/\psi\omega\right) = 3.0^{+0.6+0.5}_{-0.5-0.3} \times 10^{-5}$$

Cornell description

$$\mathcal{B}\left(B^+ \to K^+ \chi_{c0}(2p)\right) \sim 1.8 \times 10^{-3}$$

GSPM description

$$\mathcal{B}\left(B^+ \to K^+ 0^{++}\left(1p_{[T_1,T_2]}\right)\right) < 3.6 \times 10^{-5}$$

$$B^+ \to K^+ X(3915)$$

G. Bodwin, E. Braaten, T. C. Yuan, G. P. Lepage, PRD 46, R3703, 1992

The decay rate of a B+-meson to 0++ charmonium is given by the decay rate of the b antiquark with the light quark as a noninteracting spectator.

$$\Gamma_{\left(\bar{b}\to 0^{++},\bar{s}\right)} = H_8'\left(m_b\right)\Gamma_{8\left(\bar{b}\to c\bar{c}\left({}^3S_1\right),\bar{s}\right)}$$

$$H_8'\left(m_b\right) = a + eH_1$$

$$e \approx 0.2 \qquad H_1 \approx \frac{1}{m_c^4}\left(\frac{9}{2\pi}\right)\left|R_{0^{++}}'(0)\right|^2$$

Cornell description

$$\mathcal{B}\left(B^+ \to K^+\chi_{c0}\left(2p\right)\right) \sim 1.8 \times 10^{-3}$$

$$\frac{\mathcal{B}\left(B^+ \to K^+\chi_{c0}\left(2p\right)\right)}{\mathcal{B}\left(B^+ \to K^+\chi_{c0}\left(1p\right)\right)} \sim \frac{1}{F}\left(\frac{a + 0.2\left(H_1\right)_{\chi_{c0}(2p)}}{a + 0.2\left(H_1\right)_{\chi_{c0}(1p)}}\right)$$

$$\mathcal{B}\left(B^+ \to K^+\chi_{c0}\left(2p\right)\right) \lesssim \mathcal{B}\left(B^+ \to K^+\chi_{c0}\left(1p\right)\right)$$

$$\mathcal{B}\left(B^+ \to K^+\chi_{c0}\left(1p\right)\right) = 1.5^{+0.15}_{-0.14} \times 10^{-4}$$

Incompatibility

GSPM description

$$\mathcal{B}\left(B^+ \to K^+ 0^{++}\left(1p_{[T_1,T_2]}\right)\right) < 3.6 \times 10^{-5}$$

$$\frac{\mathcal{B}\left(B^+ \to K^+ 0^{++}_{1p_{[T_1,T_2]}}\right)}{\mathcal{B}\left(B^+ \to K^+ \chi_{c0}\left(2p\right)\right)} = \frac{a + e\left(H_1\right)_{1p_{[T_1,T_2]}}}{a + e\left(H_1\right)_{\chi_{c0}(2p)}}$$

$$\mathcal{B}\left(B^+ \to K^+ 0^{++}_{1p_{[T_1,T_2]}}\right) \lesssim \left(\frac{a + e\left(H_1\right)_{1p_{[T_1,T_2]}}}{a + e\left(H_1\right)_{\chi_{c0}(2p)}}\right) \mathcal{B}\left(B^+ \to K^+ \chi_{c0}\left(1p\right)\right)$$

$a \sim 2.1$ MeV

Compatibility

Summary

i) Strong decays of $X(3915)$ have been analyzed from a conventional as well as from an unconventional quark model description.

ii) The $X(3915) \to D\overline{D}$ decay can not discriminate between both descriptions once momentum dependent corrections are taken into account.

iii) The $X(3915) \to J/\psi\omega$ decay can not be consistently explained from a Cornell description. However, an unconventional description may accommodate all the experimental information predicting a quite big branching ratio for this OZI non allowed decay.

iv) The PDG assignment of $X(3915)$ as a conventional state should not be taken for granted.

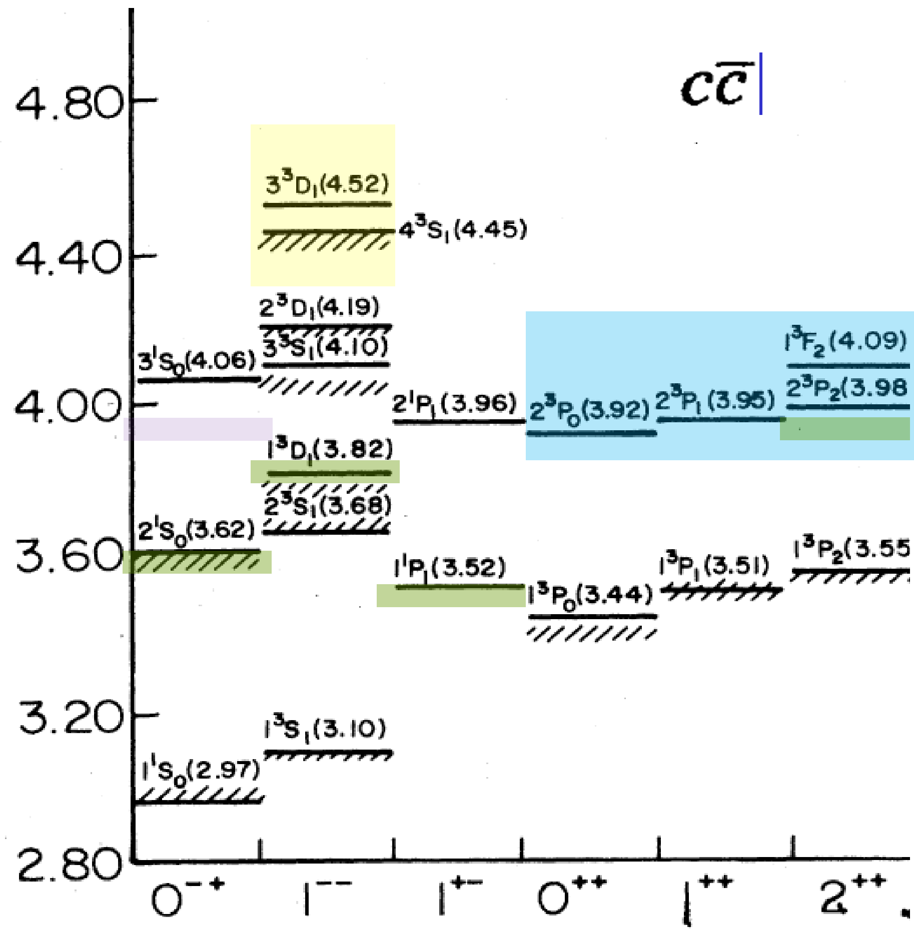
THE END

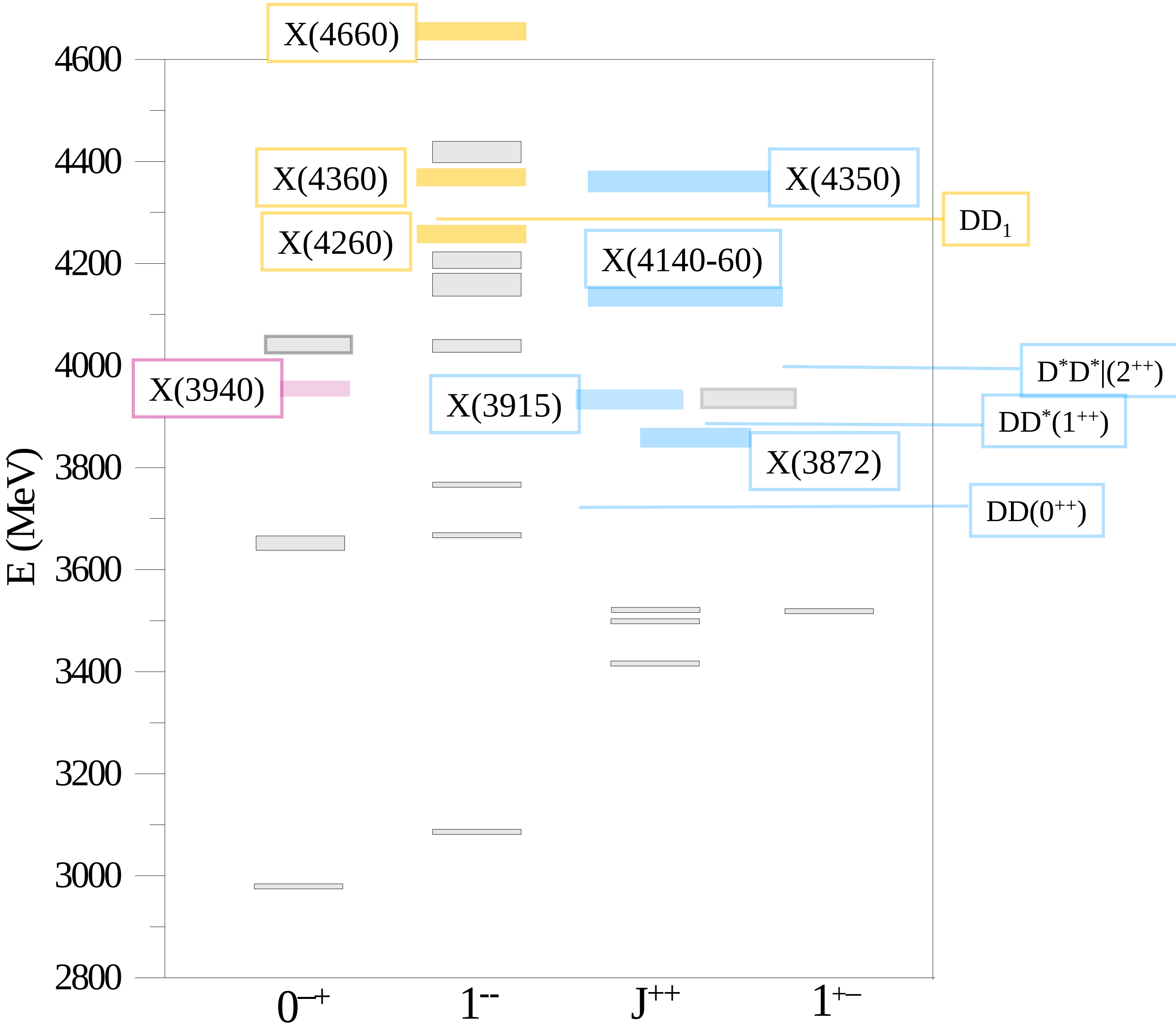
Conventional States

$$H = T(Q) + T(\overline{Q}) + V_{conf} + V_{Coul} + V_{Sd}$$

$$V_{conf} = \sigma r \qquad V_{Coul} = -\frac{\chi}{r} \qquad \chi = \frac{4}{3}\alpha_s \hbar$$

S. Godfrey, N. Isgur
PRD 32, 189 (1985)





X states : Close-below or Above their First S-wave M-M Threshold

Charmonium

J++ Thresholds

J^{PC}	T_i	$Meson1 - Meson2$	(J_1^P, J_2^P)	M_{T_i}
0^{++}				
	T_1	$D^0\overline{D}^0$	$(0^-, 0^-)$	3730
	T_2	$D_s^+ D_s^-$	$(0^-, 0^-)$	3937
	T_3	$D^*(2007)^0\overline{D^*(2007)}^0$	$(1^-, 1^-)$	4014
	T_4	$D_s^{*+} D_s^{*-}$	$(1^-, 1^-)$	4224
	T_5	$D^0\overline{D(2550)}^0$	$(0^-, 0^-)$	4405
1^{++}				
	T_1	$D^0\overline{D^*(2007)}^0$	$(0^-, 1^-)$	3872
	T_2	$D_s^+ D_s^{*-}$	$(0^-, 1^-)$	4080
2^{++}				
	T_1	$D^*(2007)^0\overline{D^*(2007)}^0$	$(1^-, 1^-)$	4014
	T_2	$D_s^{*+} D_s^{*-}$	$(1^-, 1^-)$	4224

GSPM J++ Spectrum

J^{PC}	GSPM States $k_{[T_{i-1},T_i]}$	M_{GSPM} MeV	M_{PDG} MeV	M_{Cor} MeV
0^{++}	$1p_{[T_0,T_1]}$	3456	3414.75 ± 0.31	3456
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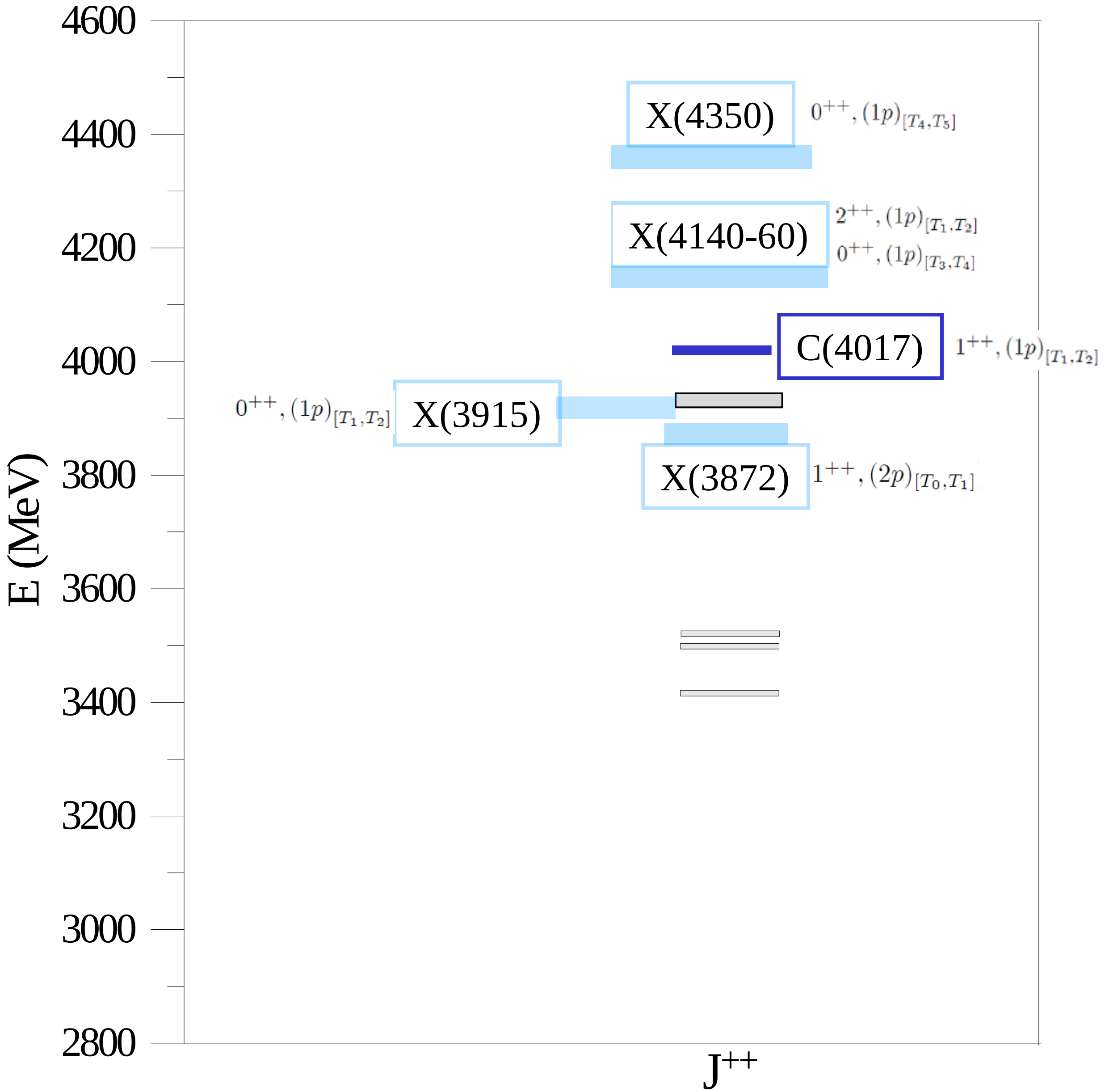
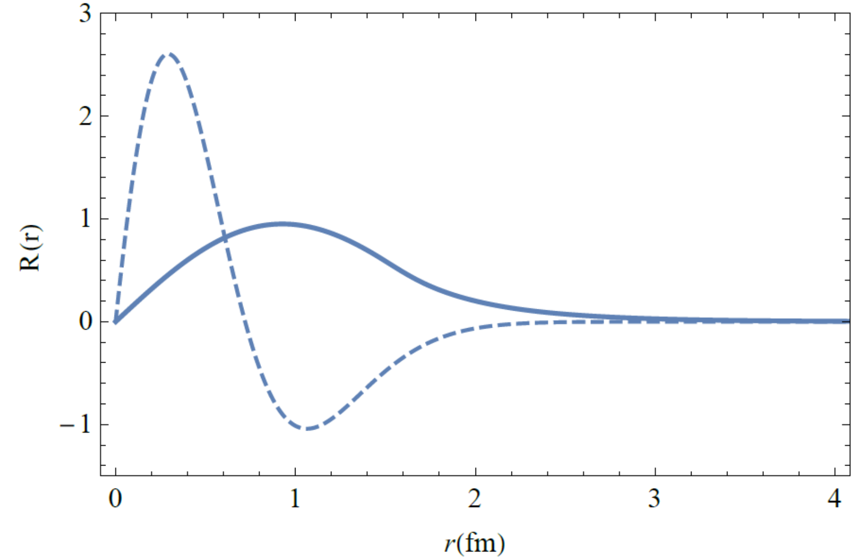
2^{++}	$1p_{[T_1,T_2]}$	4140	$4156^{+25}_{-20} \pm 15$	
0^{++}	$1p_{[T_4,T_5]}$	4325	$4350.6^{+4.6}_{-5.1} \pm 0.7$	4295



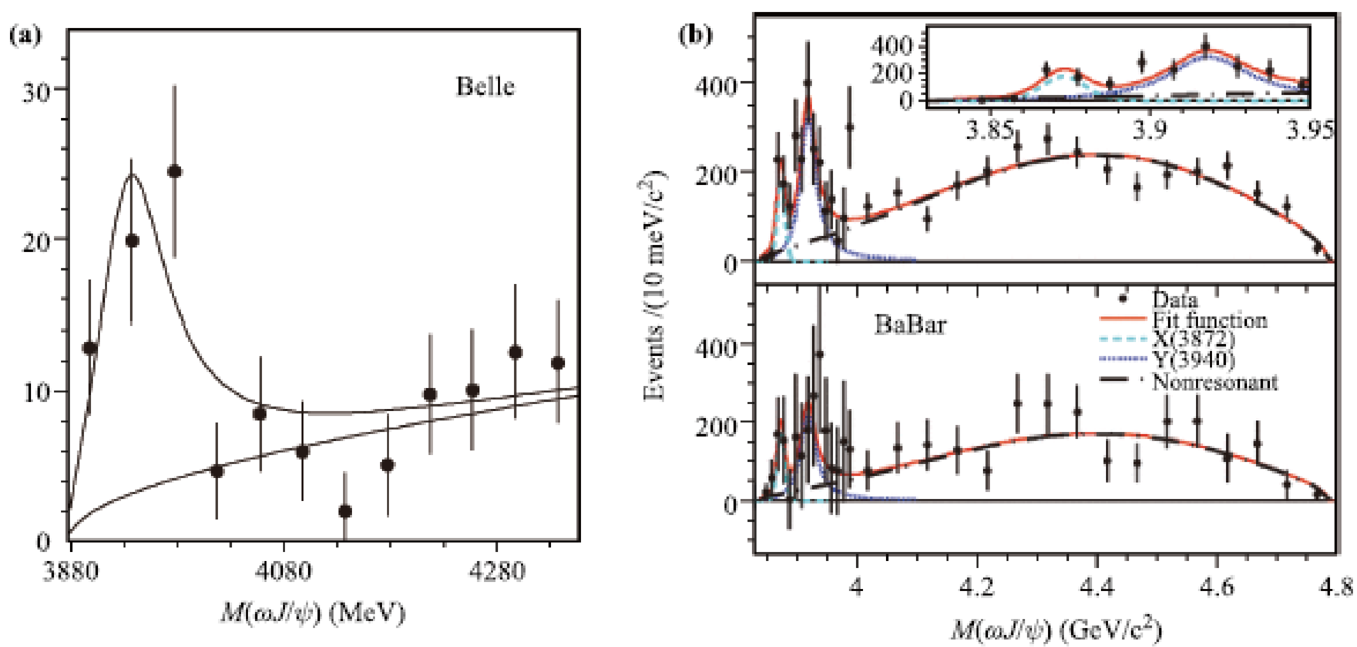
E (MeV)
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800
X(4350)
$0^{++}, (1p)_{[T_4,T_5]}$
X(4140-60)
$2^{++}, (1p)_{[T_1,T_2]}$
$0^{++}, (1p)_{[T_3,T_4]}$
C(4017)
$1^{++}, (1p)_{[T_1,T_2]}$
$0^{++}, (1p)_{[T_1,T_2]}$
X(3915)
X(3872)
$1^{++}, (2p)_{[T_0,T_1]}$
J^{++}

$C(4017)$

$1^{++}\,(1p)_{[T_1,T_3]}$ vs $\chi_{c1}\,(2p)$



$B \to K\omega J/\psi$



J^{PC}	GSPM States $k_{[T_{i-1},T_i]}$	M_{GSPM} MeV	M_{PDG} MeV	M_{Cor} MeV	Cornell States k
0^{++}	$1p_{[T_0,T_1]}$	3456.1	3414.75 ± 0.31	3456.2	$1p$
1^{++}	$1p_{[T_0,T_1]}$	3456.1	3510.66 ± 0.07	3456.2	$1p$
2^{++}	$1p_{[T_0,T_1]}$	3456.1	3556.20 ± 0.09	3456.2	$1p$
1^{++}	$2p_{[T_0,T_1]}$	3871.7	3871.69 ± 0.17	3910.9	$2p$
0^{++}	$1p_{[T_1,T_2]}$	3897.9	3918.4 ± 1.9	3910.9	$2p$
2^{++}	$2p_{[T_0,T_1]}$	3903.0	3927.2 ± 2.6	3910.9	$2p$
1^{++}	$1p_{[T_1,T_2]}$	4017.3			
0^{++}	$1p_{[T_3,T_4]}$	4140.2			
			$X\,(4140)$		
2^{++}	$1p_{[T_1,T_2]}$	4140.2			
0^{++}	$1p_{[T_4,T_5]}$	4325.1	$X\,(4350)$	4294.6	$3p$

$B^+ \to K^+ X(3915)$

$$\mathcal{B}\left(B^+ \to K^+ X(3915)\right) \mathcal{B}\left(X(3915) \to J/\psi\omega\right) = 3.0^{+0.6+0.5}_{-0.5-0.3} \times 10^{-5}$$

Cornell description

$$\mathcal{B}\left(B^+ \to K^+ \chi_{c0}(2p)\right) \sim 1.8 \times 10^{-3}$$

G. Bodwin, E. Braaten,
T. C. Yuan, G. P. Lepage,
PRD 46, R3703, 1992

$$\frac{\mathcal{B}\left(B^+ \to K^+ \chi_{c0}(2p)\right)}{\mathcal{B}\left(B^+ \to K^+ \chi_{c0}(1p)\right)} \sim \frac{1}{F}\left(\frac{a + 0.2\left(H_1\right)_{\chi_{c0}(2p)}}{a + 0.2\left(H_1\right)_{\chi_{c0}(1p)}}\right)$$

$$H_1 \approx \frac{1}{m_c^4}\left(\frac{9}{2\pi}\right)\left|R'_{0^{++}}(0)\right|^2$$

$$\mathcal{B}\left(B^+ \to K^+ \chi_{c0}(2p)\right) \lesssim \mathcal{B}\left(B^+ \to K^+ \chi_{c0}(1p)\right)$$

$$\mathcal{B}\left(B^+ \to K^+ \chi_{c0}(1p)\right) = 1.5^{+0.15}_{-0.14} \times 10^{-4}$$

Incompatibility

$$B^+ \to K^+ X(3915)$$

$$\mathcal{B}\left(B^+ \to K^+ X(3915)\right) \mathcal{B}\left(X(3915) \to J/\psi\omega\right) = 3.0^{+0.6+0.5}_{-0.5-0.3} \times 10^{-5}$$

GSPM description

$$\mathcal{B}\left(B^+ \to K^+ 0^{++}\left(1p_{[T_1,T_2]}\right)\right) < 3.6 \times 10^{-5}$$

G. Bodwin, E. Braaten, T. C. Yuan, G. P. Lepage, Phys. Rev. D46, R3703

$$\frac{\mathcal{B}\left(B^+ \to K^+ 0^{++}_{1p_{[T_1,T_2]}}\right)}{\mathcal{B}\left(B^+ \to K^+ \chi_{c0}(2p)\right)} = \frac{a + e\left(H_1\right)_{1p_{[T_1,T_2]}}}{a + e\left(H_1\right)_{\chi_{c0}(2p)}}$$

$$\mathcal{B}\left(B^+ \to K^+ 0^{++}_{1p_{[T_1,T_2]}}\right) \lesssim \left(\frac{a + e\left(H_1\right)_{1p_{[T_1,T_2]}}}{a + e\left(H_1\right)_{\chi_{c0}(2p)}}\right) \mathcal{B}\left(B^+ \to K^+ \chi_{c0}(1p)\right)$$

$$a \sim 2.1\ \mathrm{MeV}$$

Compatibility