CONFXI

XIth Quark Confinement and the Hadron Spectrum

Saint Petersburg, September 2014

HEAVY QUARKONIA DESCRIPTION

FROM A

GENERALIZED SCREENED POTENTIAL MODEL

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Motivation

12 New Neutral Charmonium States

since PDG 2000

10 X States (7 unconventional)

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

$X\ (3823)$

$\chi_{c0}\ (2p)$

J. Beringer *et al.* (PDG) PRD 86, 010001 (2012)

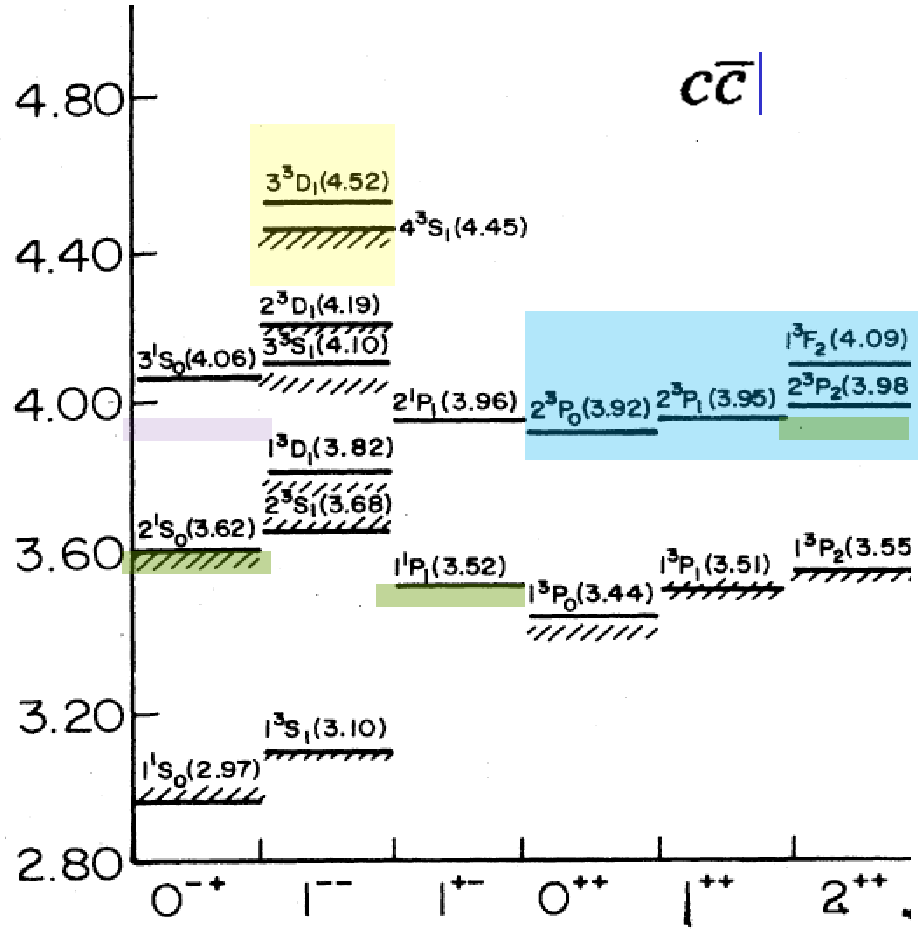
K. A. Olive *et al.* (PDG) Chin. Phys. C38, 090001 (2014)

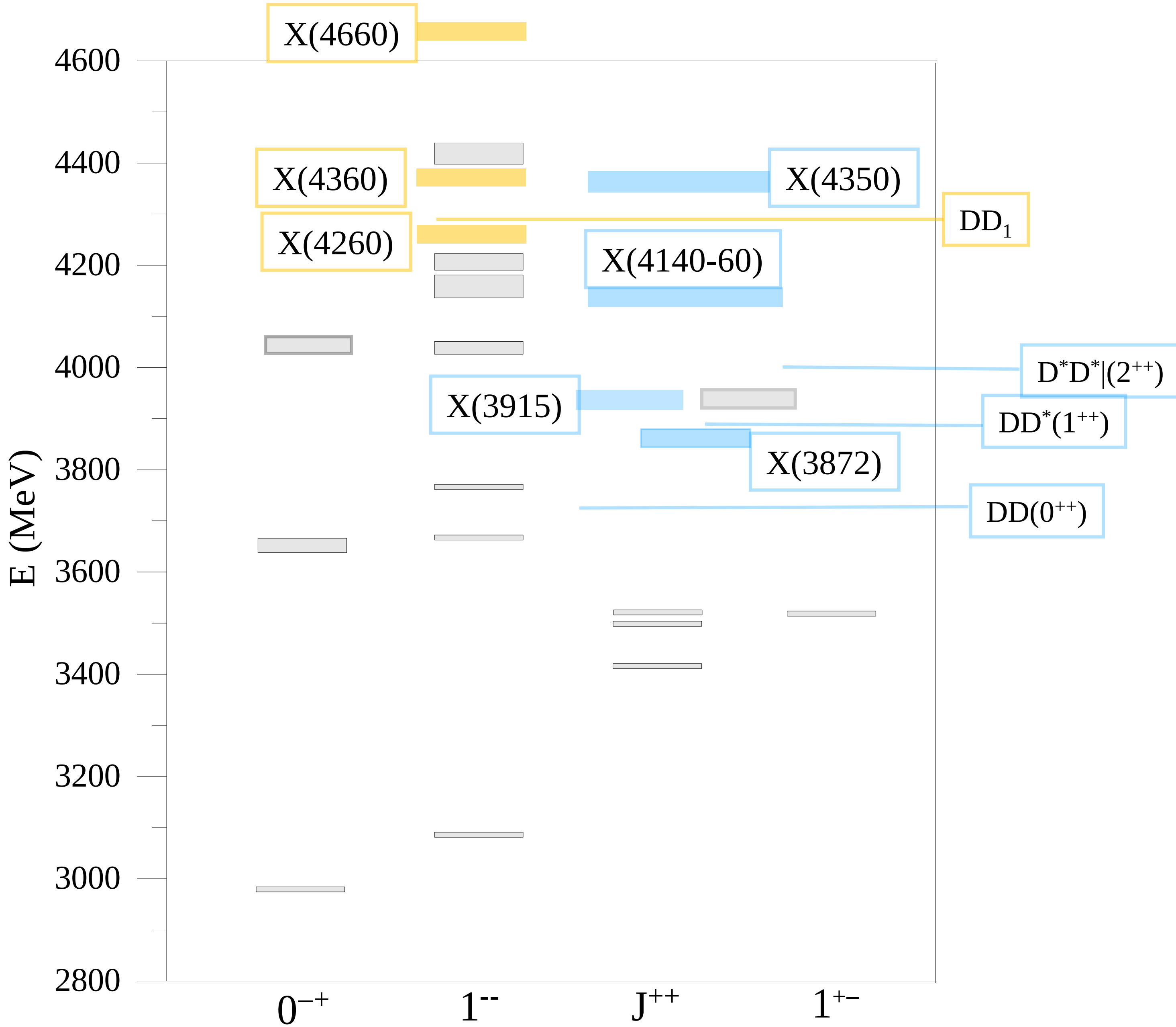
Conventional States

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

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

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





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

Decay properties of some X states very different from conventionally expected.

$X(3872): 0^{+}(1^{++})$

Conventional description: $\chi_{c1}(2p)$ with parallel properties to $\chi_{b1}(2p)$

However decay properties completely different

$X(4260): 0^{-}(1^{--})$

Conventional description: $\psi(3D)$ or $\psi(4S)$

However $X(4260) \longrightarrow J/\psi\pi\pi$ an order of magnitude higher than expected

What are they ?

Hybrid (Quark-Antiquark + Gluon) States ?

Molecular Sates ?

Tetraquarks (compact states) ?

Quark-Antiquark + Molecular States ?

What is the effect of Meson-Meson Thresholds ?

Can we implement threshold effects within a quark-antiquark model framework?

Quark-Antiquark effective potential description implicitly incorporating molecular components.

INDEX

i) Quenched versus Threshold-Unquenched Quark-Antiquark Energy from Lattice. Static Potential.

ii) Generalized Screened Potential Model (GSPM).

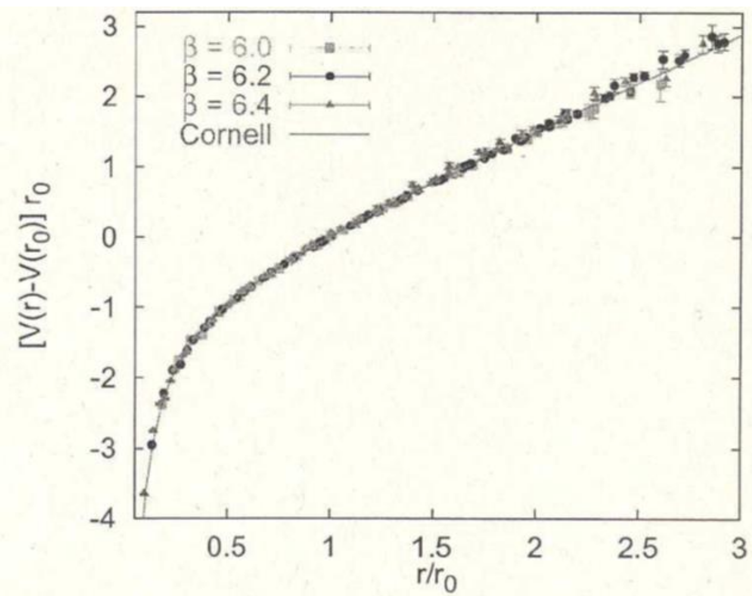
iii) Heavy Quarkonia Spectrum Description from the GSPM.

iv) Summary.

Quenched vs Threshold-Unquenched Quark-Antiquark Energy

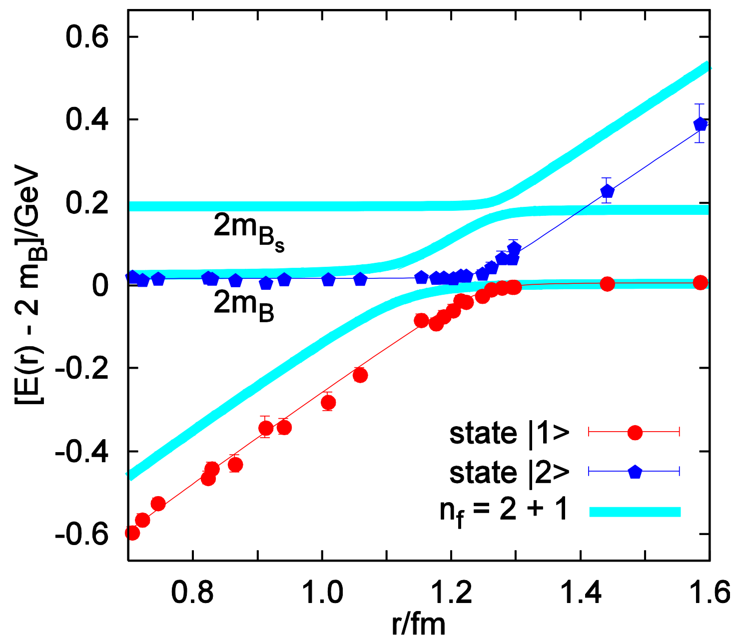
$$E(r) = V(r) + m_Q + m_{\overline{Q}}$$

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



$$V_{Q_0\overline{Q}_0}(r) \equiv V_{Cor}(r) = \sigma r - \frac{\chi}{r} + C$$

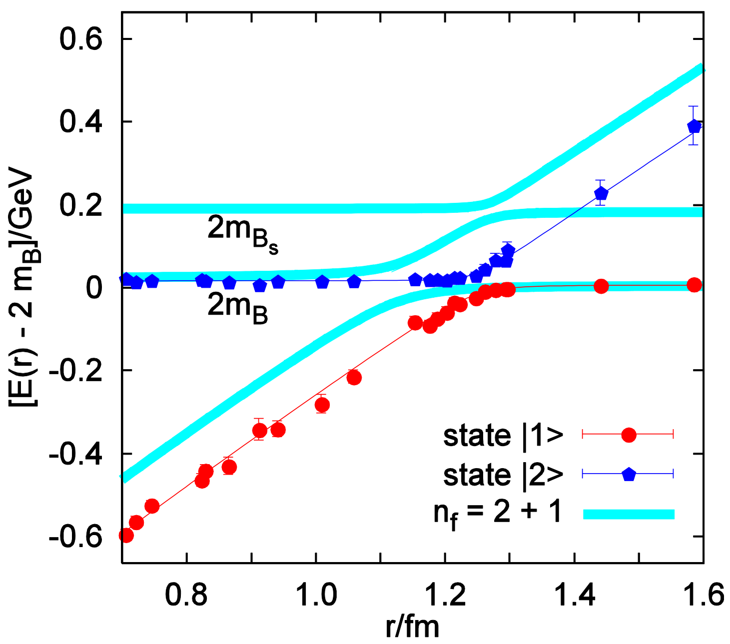
G. S. Bali *et al.*, PRD 71, 11453 (2005)

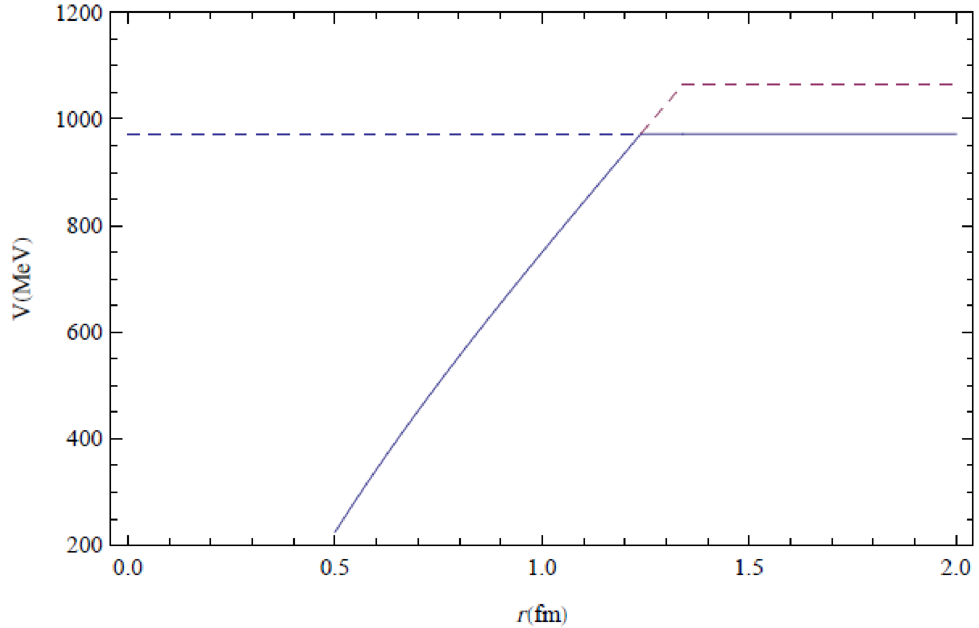


$$V_{Q\overline{Q}}(r) \equiv V_{E_{Q\overline{Q}}}(r)$$

Generalized Screened Potential Model (GSPM)

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

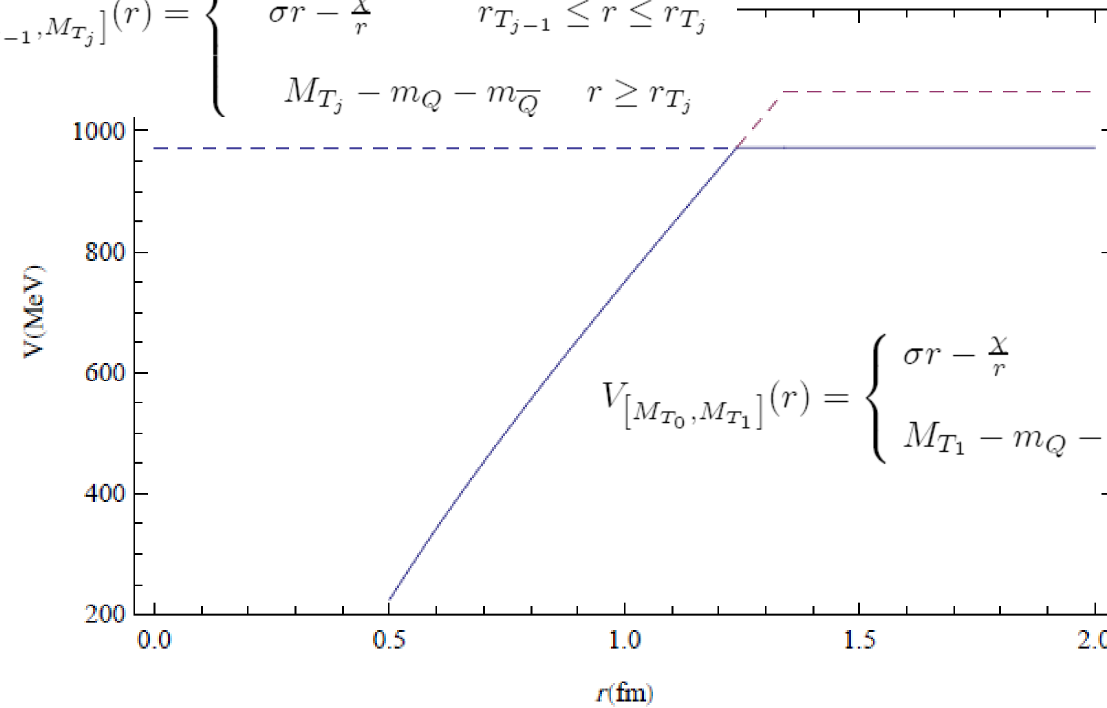




$$\sigma r_{T_{j-1}} - \frac{\chi}{r_{T_{j-1}}} = M_{T_{j-1}} - m_Q - m_{\overline{Q}}$$

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

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



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

Cornell potential modulated by thresholds

Possible Shortcomings

- Non relativistic potential (effective).
- No spin dependent terms in the Cornell potential.
- Only screening from meson-meson channels.
- No thresholds widths.

Heavy Quarkonia Description

The lowest lying spectrum is described by the Cornell potential

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

$$\sigma = 850 \text{ MeV/fm } \left(0.17 \text{ GeV}^2\right)$$
$$\chi = 100 \text{ MeV.fm}$$
$$m_b = 4793 \text{ MeV}$$
$$m_c = 1348.5 \text{ MeV}$$

$$\alpha_s = \frac{3\chi}{4\hbar} \simeq 0.38$$

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

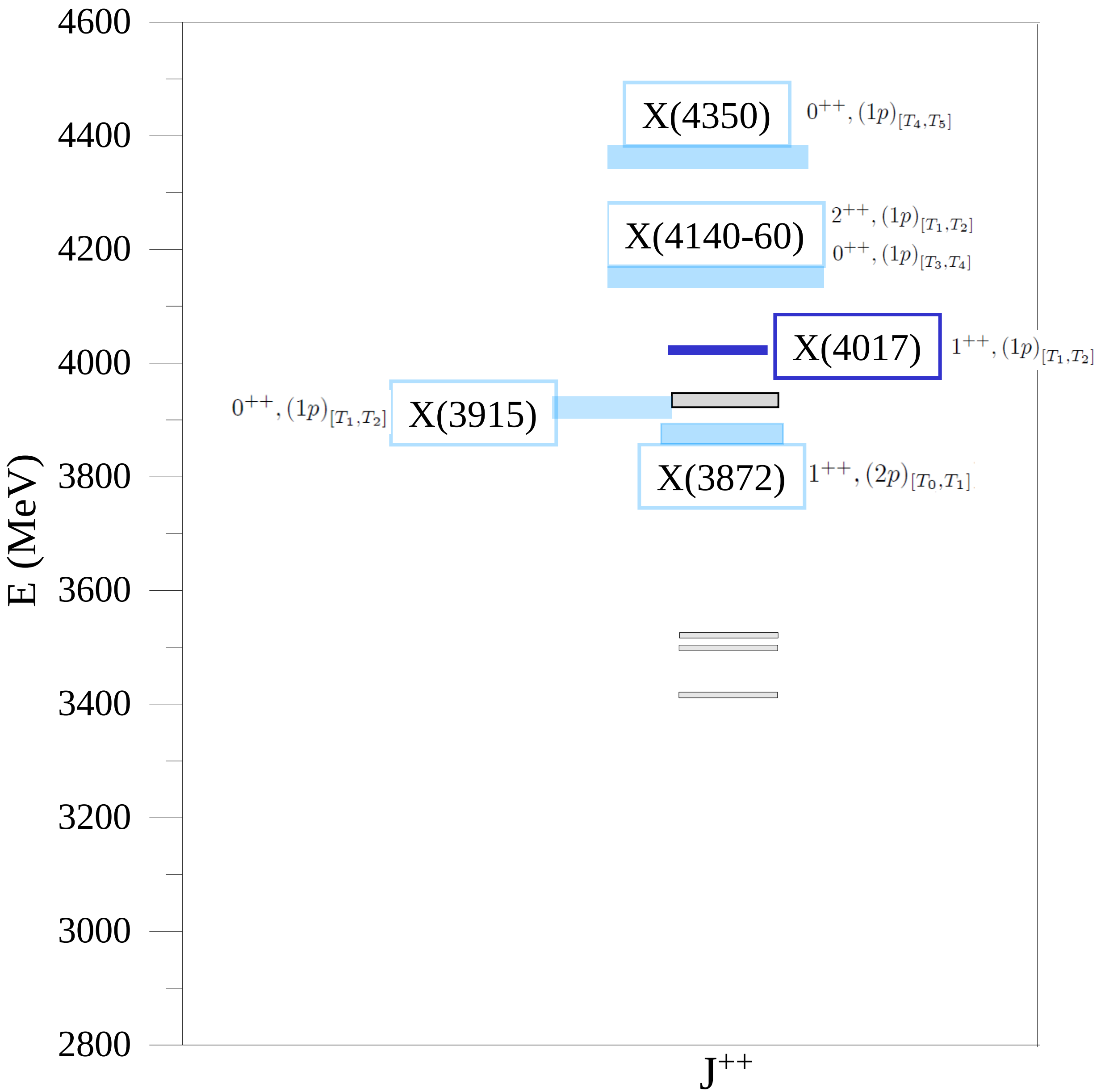
Charmonium

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

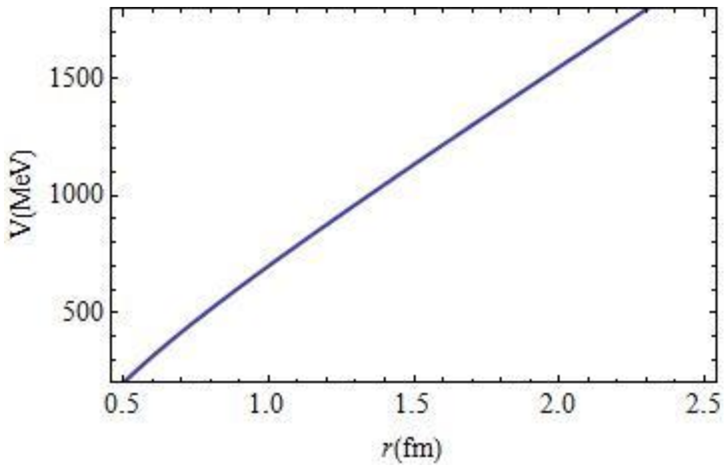
GSPM J++ Spectrum

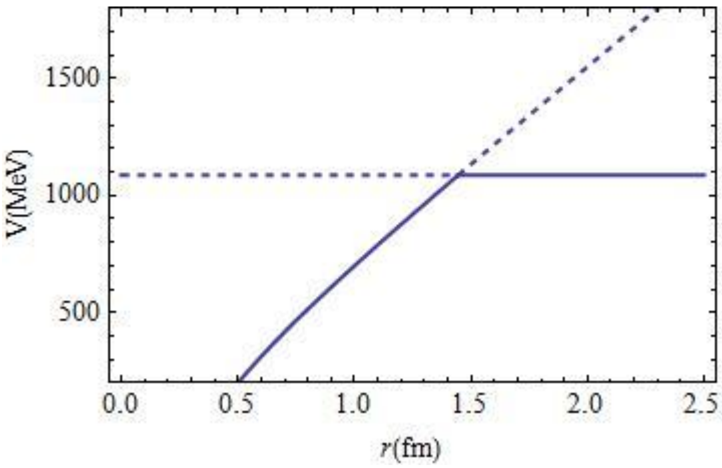
J^{PC}	GSPM States $k_{[T_{i-1},T_i]}$	M_{GSPM} MeV	M_{PDG} MeV	M_{Cor} MeV
0^{++}	$1p_{[T_0,T_1]}$	3456	3414.75 ± 0.31	3456
1^{++}	$1p_{[T_0,T_1]}$	3456	3510.66 ± 0.07	3456
2^{++}	$1p_{[T_0,T_1]}$	3456	3556.20 ± 0.09	3456
1^{++}	$2p_{[T_0,T_1]}$	3871.7	3871.68 ± 0.17	3911
0^{++}	$1p_{[T_1,T_2]}$	3898	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


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

Threshold Effect

1^{++}





Additional States

$c\bar{c}\,(1^{++})$

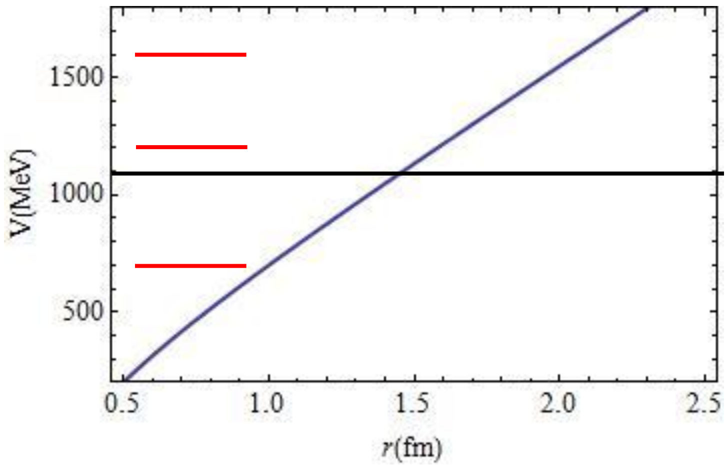
T_1	$D^0\overline{D^*(2007)}^0$	$(0^-, 1^-)$	3872
T_2	$D_s^+ D_s^{*-}$	$(0^-, 1^-)$	4080

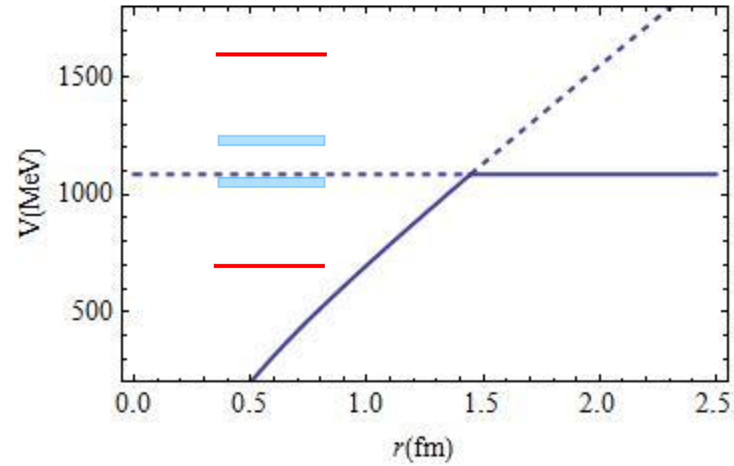
GSPM States $k_{[T_{i-1},T_i]}$	M_{GSPM} MeV	M_{Cor} MeV	Cornell States
$1p_{[T_0,T_1]}$	3456	3456	$1p$
$2p_{[T_0,T_1]}$	3871.7	3911	$2p$
$1p_{[T_1,\infty]}$	4029		
$2p_{[T_1,\infty]}$	4303	4295	$3p$

$X(3872)$ results from the interaction between T_1 and the Cornell state

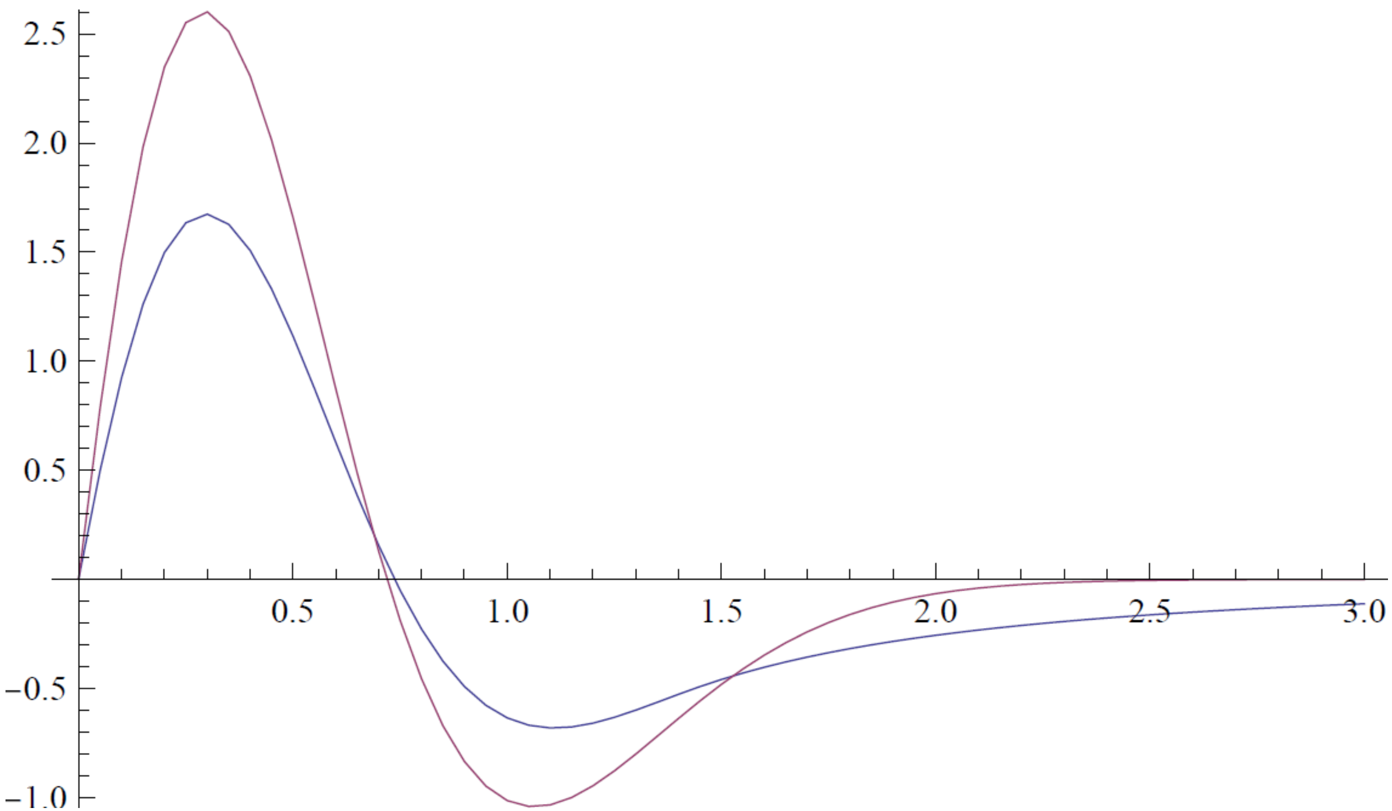
Additionally a new state $X(4029)$ appears.

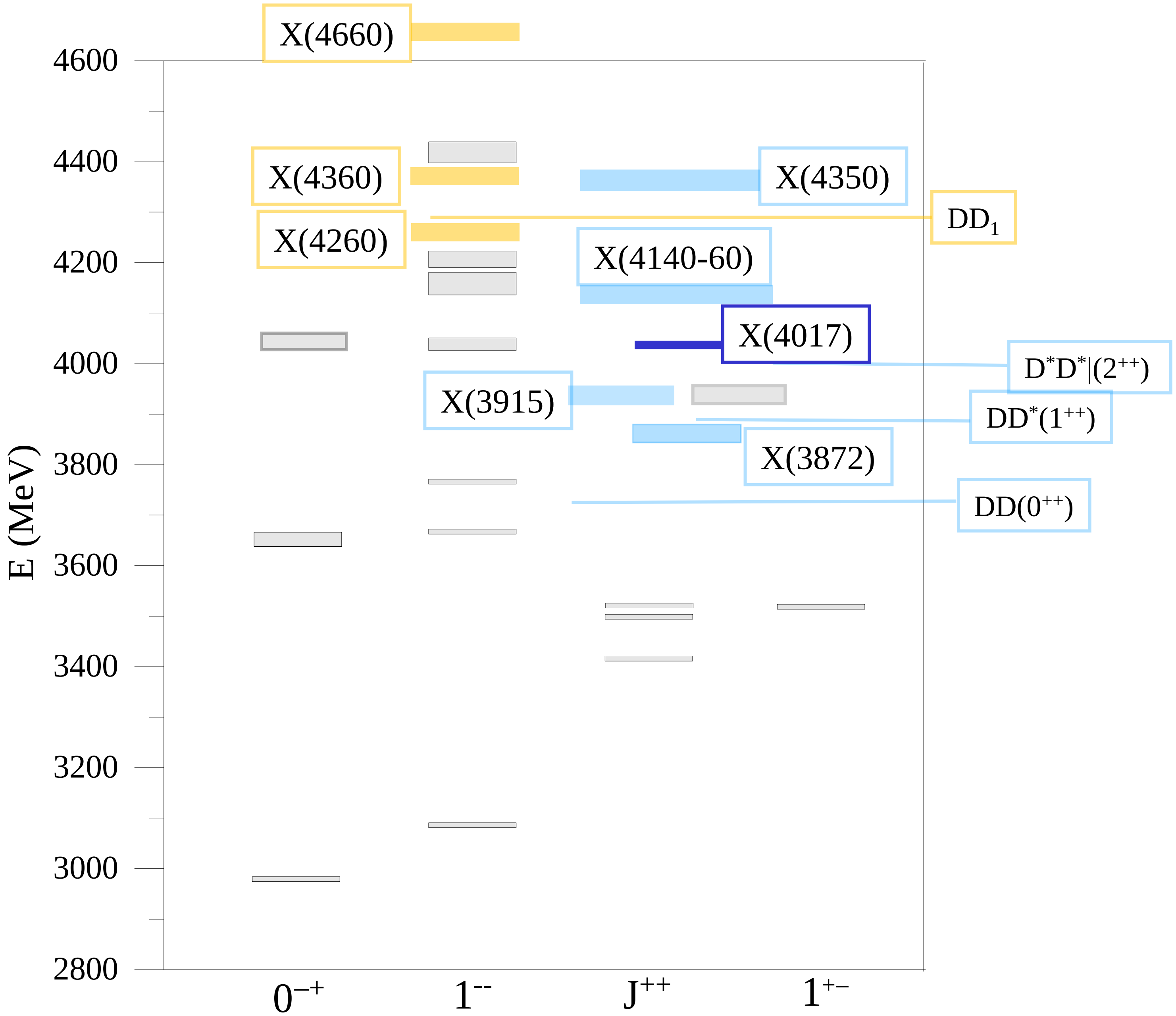
Additional States





$X3872) : 1^{++}\,(2p)_{[T_0,T_1]}$ vs $\chi_{c1}\,(2p)$





E (MeV)
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800
0−+
1--
J++
1+−
X(4660)
X(4360)
X(4260)
X(4350)
DD1
X(4140-60)
X(4017)
D*D*|(2++)
X(3915)
DD*(1++)
X(3872)
DD(0++)

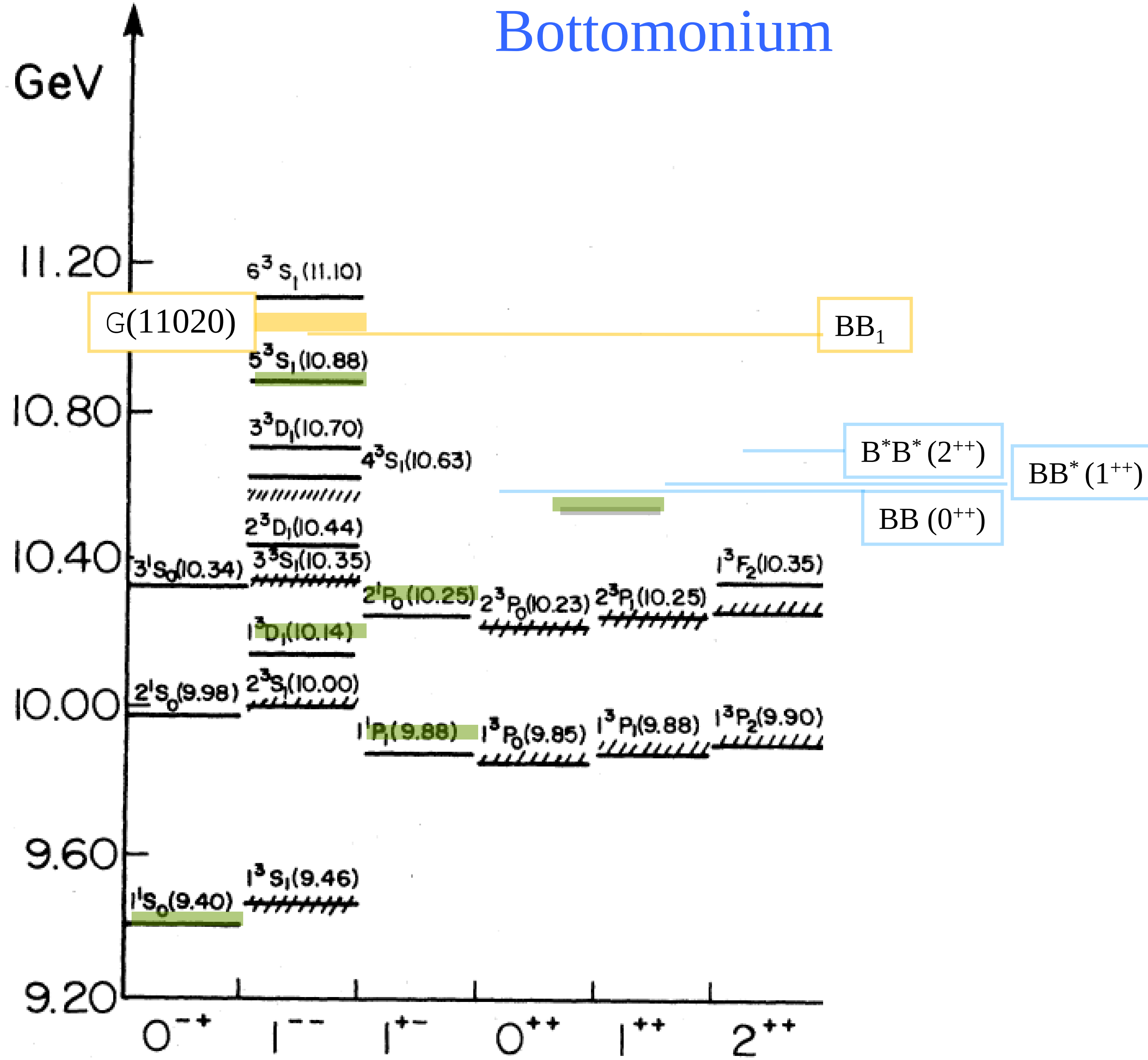
1-- Thresholds

J^{PC}	T_i	$Meson1 - Meson2$	(J_1^P, J_2^P)	M_{T_i}
1^{--}				
	T_1	$D^0 \overline{D_1(2420)}^0$ $D^0 \overline{D_1(2430)}^0$	$(0^-, 1^+)$	4287
	T_2	$D^*(2007)^0 \overline{D_0^*(2400)}^0$	$(1^-, 0^+)$	4325
	T_3	$D^*(2007)^0 \overline{D_1(2420)}^0$ $D^*(2007)^0 \overline{D_1(2430)}^0$ $D_s^+ D_{s1}(2460)^-$ $D_s^{*+} D_{s0}^*(2317)^-$	$(1^-, 1^+)$ $(1^-, 1^+)$ $(0^-, 1^+)$ $(1^-, 0^+)$	4429
	T_4	$D^*(2007)^0 \overline{D_2^*(2460)}^0$	$(1^-, 2^+)$	4470
	T_5	$D_s^+ D_{s1}(2536)^-$	$(0^-, 1^+)$	4504
	T_6	$D_s^{*+} D_{s1}(2460)^-$	$(1^-, 1^+)$	4572
	T_7	$D_s^{*+} D_{s1}(2536)^-$	$(1^-, 1^+)$	4648
	T_8	$D_s^{*+} D_{s2}^*(2573)^-$	$(1^-, 2^+)$	4685

Overlapping Thresholds

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

Bottomonium



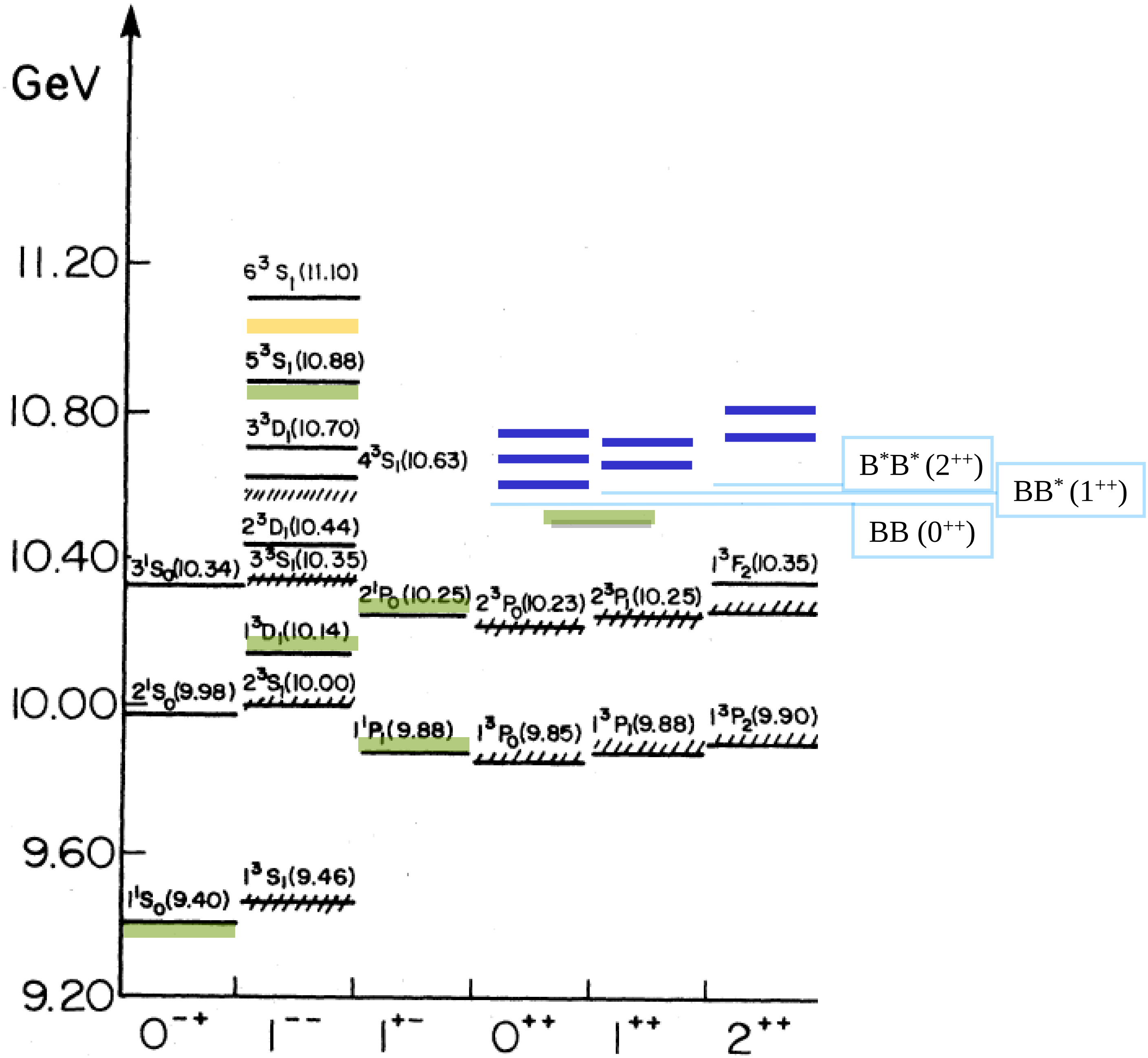
J++ States

$b\overline{b}$

J^{PC}	T_i	$Meson1 - Meson2$	(J_1^P, J_2^P)	M_{T_i}
0^{++}				
	T_1	$B^0\overline{B}^0$	$(0^-, 0^-)$	10558
	T_2	$B^{*0}\overline{B^*}^0$	$(1^-, 1^-)$	10650
	T_3	$B_s^0\overline{B_s}^0$	$(0^-, 0^-)$	10734
	T_4	$B_s^*\overline{B_s^*}$	$(1^-, 1^-)$	10830
1^{++}				
	T_1	$B^0\overline{B^*}^0$	$(0^-, 1^-)$	10604
	T_2	$B_s^0\overline{B_s^*}$	$(0^-, 1^-)$	10782
2^{++}				
	T_1	$B^{*0}\overline{B^*}^0$	$(1^-, 1^-)$	10650
	T_2	$B_s^*\overline{B_s^*}$	$(1^-, 1^-)$	10830

J^{PC}	GSPM States $k_{[T_{i-1},T_i]}$	M_{GSPM} MeV	M_{PDG} MeV	M_{Cor} MeV
0^{++}	$1p_{[T_0,T_1]}$	9920	$9859.44 \pm 0.42 \pm 0.31$	9920
1^{++}	$1p_{[T_0,T_1]}$	9920	$9892.78 \pm 0.26 \pm 0.31$	9920
2^{++}	$1p_{[T_0,T_1]}$	9920	$9912.21 \pm 0.26 \pm 0.31$	9920
0^{++}	$2p_{[T_0,T_1]}$	10259	$10232.5 \pm 0.4 \pm 0.5$	10259
1^{++}	$2p_{[T_0,T_1]}$	10259	$10255.46 \pm 0.22 \pm 0.50$	10259
2^{++}	$2p_{[T_0,T_1]}$	10259	$10268.65 \pm 0.22 \pm 0.50$	10259
0^{++}	$3p_{[T_0,T_1]}$	10521		10531
1^{++}	$3p_{[T_0,T_1]}$	10526		10531
			$10530 \pm 5 \pm 9$	
2^{++}	$3p_{[T_0,T_1]}$	10528		10531
0^{++}	$1p_{[T_1,T_2]}$	10620		
1^{++}	$1p_{[T_1,T_2]}$	10668		
0^{++}	$1p_{[T_2,T_3]}$	10704		
2^{++}	$1p_{[T_1,T_2]}$	10710		
				10768
1^{++}	$2p_{[T_1,T_2]}$	10776		
0^{++}	$1p_{[T_3,T_4]}$	10784		
2^{++}	$2p_{[T_1,T_2]}$	10815		

P. González, J. Phys. G 41 (2014) 095001


GeV
11.20
10.80
10.40
10.00
9.60
9.20
6^3S_1(11.10)
5^3S_1(10.88)
3^3D_1(10.70)
4^3S_1(10.63)
2^3D_1(10.44)
3^1S_0(10.34)
3^3S_1(10.35)
2^1P_0(10.25)
2^3P_0(10.23)
2^3P_1(10.25)
1^3F_2(10.35)
1^3D_1(10.14)
2^1S_0(9.98)
2^3S_1(10.00)
1^1P_1(9.88)
1^3P_0(9.85)
1^3P_1(9.88)
1^3P_2(9.90)
1^3S_1(9.46)
1^1S_0(9.40)
0^{-+}
1^{--}
1^{+-}
0^{++}
1^{++}
2^{++}
B^*B^* (2^{++})
BB^* (1^{++})
BB (0^{++})

Summary

i) There is a spectral puzzle concerning experimentally unconventional charmonium states.

ii) There is a plausible explanation for this puzzle based on an Energy Dependent Quark-antiQuark Potential from threshold effects.

iii) The Generalized Screened Potential Model (GSPM) based on this potential allows for a reasonable spectral description of J++ charmonium.

iv) New higher energy states in charmonium and bottomonium are predicted.

THE END