Spectroscopy of Higher Bottomonia

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Introduction

The quark model (QM) reproduces a great quantity of observables:

magnetic moments, hadron spectra (especially lower part), strong couplings ...

QM neglects pair-creation effects, i.e. coupling to meson-meson channels → effect of sea pairs is neglected

Pair-creation effects introduced into the QM through the unquenched quark model (UQM) formalism

Calculation of bottomonium spectrum with self-energy corrections in the UQM

Calculation of open-flavor and electromagnetic decays

Quark nature of the $\chi_b(3P)$ system

Quark Models (QMs)

Effective degree of freedom of constituent quark is introduced

Dynamics described through non-relativistic Schrödinger equation

$$E\Psi(\mathbf{r}) = \left[\frac{-\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right]\Psi(\mathbf{r})$$

Several versions: Relativized QM [Phys. Rev. D **32**, 189 (1985)] (mesons); [Phys. Rev. D **34**, 2809 (1986)] (baryons). Isgur and Karl's [Phys. Rev. D **18**, 4187 (1978)] (baryons). Hypercentral [Eur. Phys. J. A **12**, 447 (2001)] (baryons). U(7) [Ann. Phys. **236**, 69 (1994)] (baryons)

Each version has its own characteristics. All models have in common:

1) Effective degrees of freedom of three constituent (valence) quarks (baryons) or a quark and an anti-quark (mesons) 2) Confining potential

Relativized QM (Mesons)

*Godfrey and Isgur, Phys. Rev. D **32**, 189 (1985)*

Describes q anti-q mesons

Light unflavored, strange, charmed, bottomed, c bar-c and b bar-b mesons treated in unified way

"Semi-relativistic" model: relativistic kinetic energy + introduction of relativistic effects treated in effective way

One-gluon exchange potential

$$H = \sqrt{q^2 + m_1^2} + \sqrt{q^2 + m_2^2} + V_{\rm conf} + V_{\rm hyp} + V_{\rm so}$$

$$V_{\rm conf} = -\left(\frac{3}{4}\,c + \frac{3}{4}\,br - \frac{\alpha_s(r)}{r}\right)\vec{F}_1 \cdot \vec{F}_2$$

$$\begin{aligned} V_{\rm so,cm} &= -\frac{\alpha_s(r)}{r^3}\left(\frac{1}{m_i} + \frac{1}{m_j}\right) \\ &\quad \left(\frac{\vec{S}_i}{m_i} + \frac{\vec{S}_j}{m_j}\right)\cdot\vec{L}\;\;\vec{F}_i \cdot \vec{F}_j \end{aligned}$$

$$\begin{aligned} V_{\rm hyp} &= -\frac{\alpha_s(r)}{m_1 m_2}\left[\frac{8\pi}{3}\vec{S}_1 \cdot \vec{S}_2\;\delta^3(\vec{r}) \right. \\ &\quad \left. + \frac{1}{r^3}\left(\frac{3\;\vec{S}_1\cdot\vec{r}\;\vec{S}_2\cdot\vec{r}}{r^2} - \vec{S}_1 \cdot \vec{S}_2\right)\right]\;\vec{F}_i \cdot \vec{F}_j \end{aligned}$$

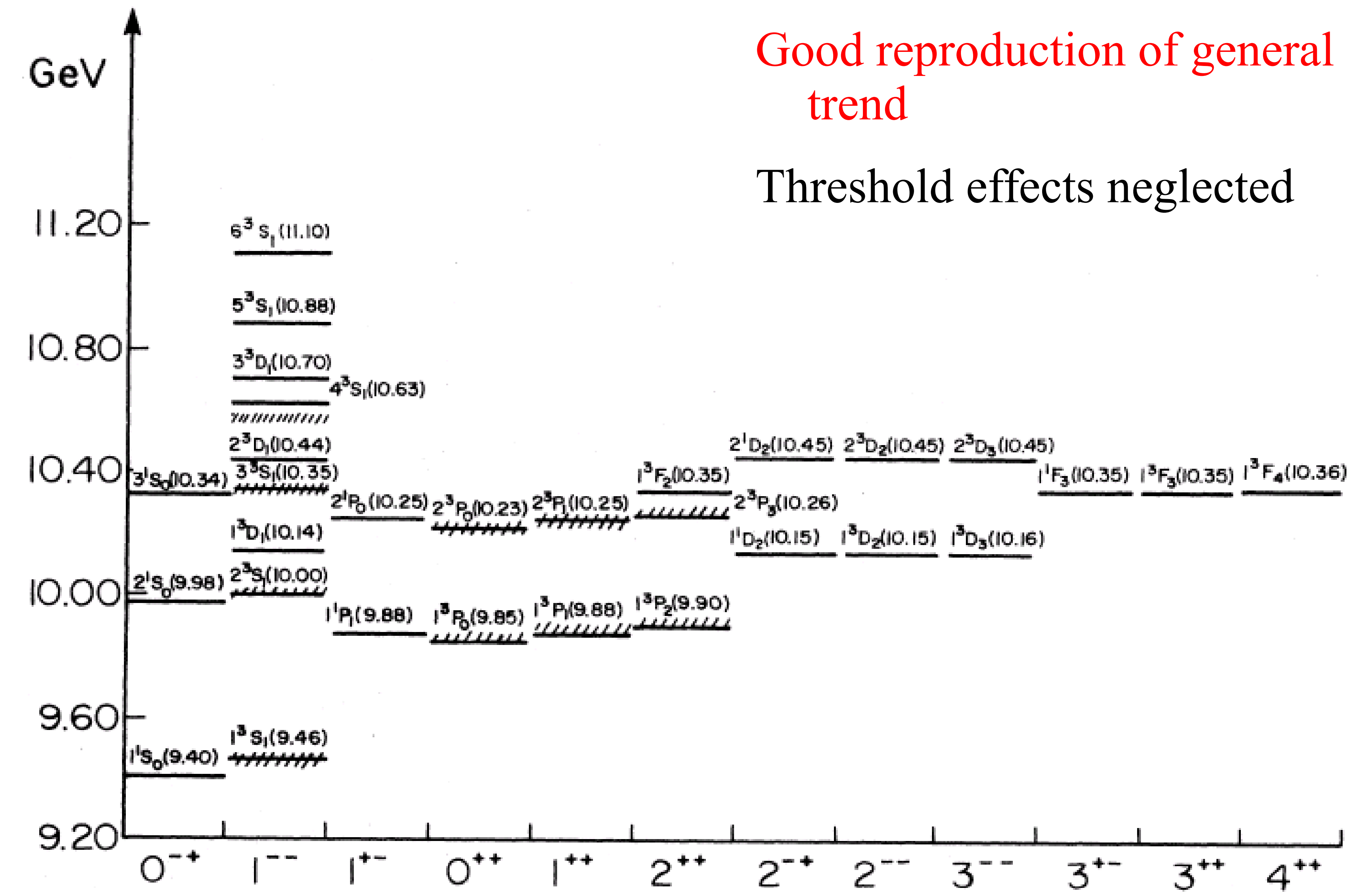
$$V_{\rm so,tp} = -\frac{1}{2r}\frac{\partial H_{ij}^{conf}}{\partial r}\left(\frac{\vec{S}_i}{m_i^2} + \frac{\vec{S}_j}{m_j^2}\right)\cdot\vec{L}$$

Relativized QM – Bottomonium

*Godfrey and Isgur, Phys. Rev. D **32**, 189 (1985)*

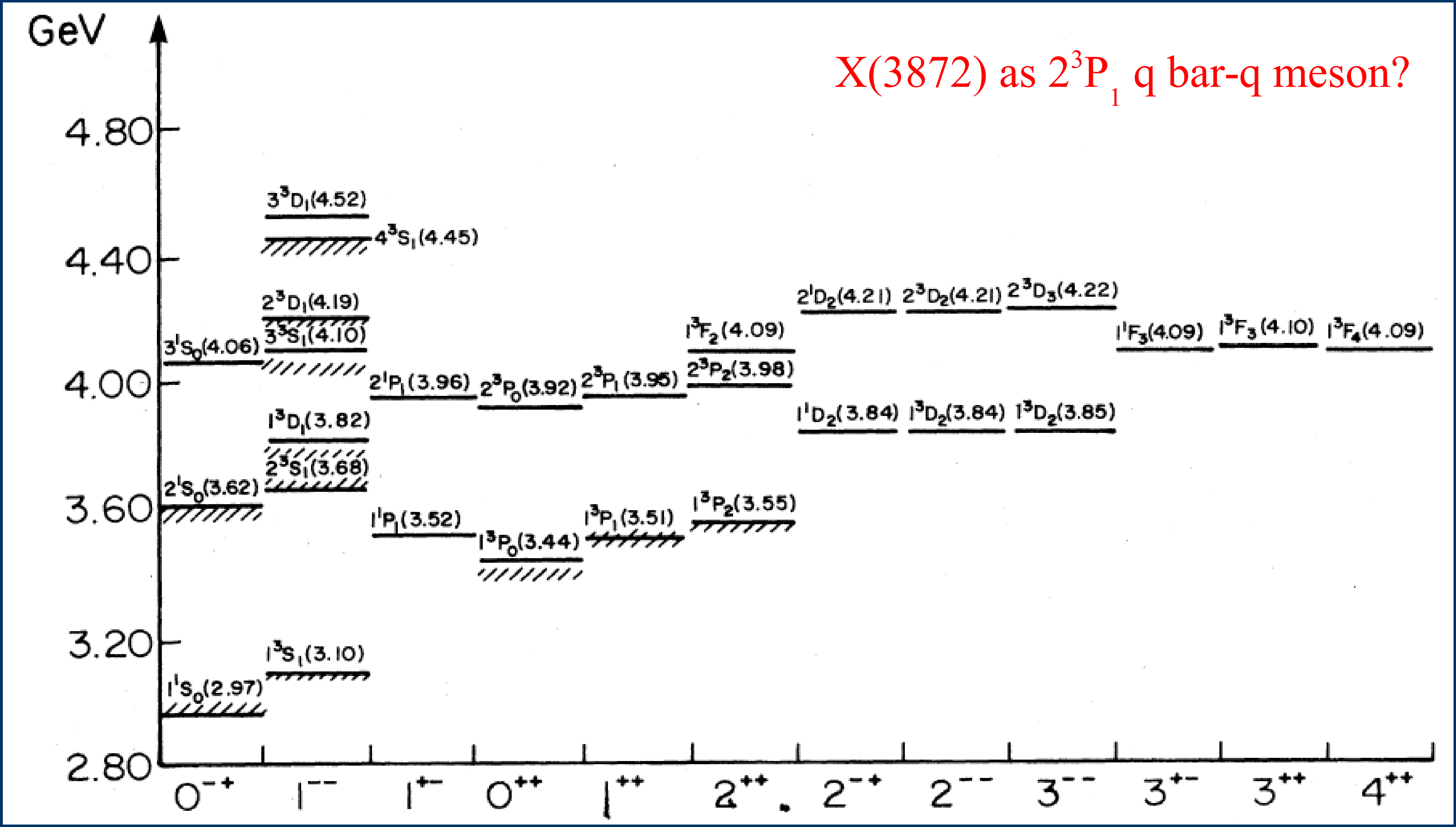
Good reproduction of general trend

Threshold effects neglected



Relativized QM – Charmonium

*Godfrey and Isgur, Phys. Rev. D **32**, 189 (1985)*



Nature of the X(3872)

Ferretti, Galata' and Santopinto, Phys. Rev. C **88**, 015207 (2013); D **90**, 054010 (2014)

Results used to study the problem of the **X(3872)** mass, meson with $J^{PC} = 1^{++}$, 2^3P_1 quantum numbers

Experimental mass: 3871.68 ± 0.17 MeV [PDG]

Larger QM predictions for X(3872)'s mass (relativized QM → 3.95 GeV)

X(3872) close to D bar-D* decay threshold. Continuum effects?

Several interpretations:

- pure c bar-c
- D bar-D* molecule
- tetraquark
- c bar-c + continuum effects

Necessary to study the decays (strong, e.m., hadronic, ...) of the meson to confirm one of the possible interpretations

UQM: why?

QM reproduces quite well many hadronic observables:

magnetic moments

baryon and meson spectra (lower part)

strong couplings

Some observables require corrections due to the coupling to the continuum

electromagnetic couplings

Some observables only give rise when the coupling to the continuum (loop effects) is taken into account

strangeness content of the nucleon

UQM: Formalism

Hadron wave function:

$$| \psi_A \rangle = \mathcal{N} \left[| A \rangle + \sum_{BC\ell J} \int d\vec{q} \, | BC\vec{q}\,\ell J \rangle \frac{\langle BC\vec{q}\,\ell J \, | \, T^\dagger \, | \, A \rangle}{E_a - E_b - E_c} \right]$$

valence component |A>

+

ediate states |BC>

Pair-creation operator (coupling to |BC> intermediate states):

$$T^\dagger = -3 \, \gamma_0^{\rm eff} \int d\vec{p}_4 \, d\vec{p}_5 \, \delta(\vec{p}_4 + \vec{p}_5) \, C_{45} \, F_{45} e^{-\frac{1}{8}\alpha_d^2 (\vec{p}_4 - \vec{p}_5)^2} \left[\chi_{45} \times \mathcal{Y}_1(\vec{p}_4 - \vec{p}_5) \right]_0^{(0)} b_4^\dagger(\vec{p}_4) \, d_5^\dagger(\vec{p}_5)$$

$^3P_0$ model

(reproduces well strong decays)

See: Bijker and Santopinto, Phys. Rev. C **80**, 065210 (2009); **82**, 062202 (2010); Bijker, Ferretti and Santopinto, Phys. Rev. C **85**, 035204 (2012); Ferretti *et al.*, Phys. Rev. C **86**, 015204 (2012); Ferretti, Galatà and Santopinto, Phys. Rev. C **88**, 015207 (2013); D **90**, 054010 (2014); Ferretti and Santopinto, arXiv: 1306.2874

$^3P_0$ Model

Micu, Nucl. Phys. B **10**, 521 (1969); Le Yaouanc *et al.*, Phys. Rev. D **8**, 2223 (1973)

Hadron decays proceed through q bar-q pair-creation

The created q bar-q pair has $^3P_0$ quantum numbers

Transition operator:

$$T^\dagger = -3\,\gamma_0 \int d\vec{p}_4\, d\vec{p}_5\, \delta(\vec{p}_4 + \vec{p}_5)\, C_{45}\, F_{45} \left[\chi_{45} \times \mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)\right]^{(0)}_0 b^\dagger_4(\vec{p}_4)\, d^\dagger_5(\vec{p}_5)$$

Quark & anti-quark creation operators: $b^\dagger_4(\vec{p}_4)$ $d^\dagger_5(\vec{p}_5)$

Color-singlet wave function: C_{45}

Flavor-singlet wave function: F_{45}

Spin-triplet wave function: χ_{45}

Solid spherical harmonic: $\mathcal{Y}_1(\vec{p}_4 - \vec{p}_5)$

UQM: Meson Self Energies

Hamiltonian:

$$H = H_0 + V$$

H_0 acts only in the bare meson space

V couples |A> to the continuum |BC>

Couplings between |A> and |BC> calculated in the $^3P_0$ model

Self-energy:

$$\Sigma(E_a) = \sum_{BC} \int_0^\infty q^2 dq \, \frac{\left|V_{a,bc}(q)\right|^2}{E_a - E_{bc}}$$

Bare energy E_a (H_0 eigenvalue) satisfies:

$$M_a = E_a + \Sigma(E_a)$$

M_a = physical mass of meson A. Fitted to experimental data

$\Sigma(E_a)$ = self energy of meson A

Intrinsic error of QM/UQM calculations: 30-50 MeV

UQM: bottomonium spectrum with self-energy corrections

Ferretti *et al*., Phys. Rev. C **86**, 015204 (2012); Ferretti and Santopinto, arXiv: 1306.2874

Parameters of the UQM ($^3P_0$ vertices)

Parameter	Value
γ_0	0.732
α	0.500 GeV
r_q	0.335 fm
m_n	0.330 GeV
m_s	0.550 GeV
m_c	1.50 GeV
m_b	4.70 GeV

Pair-creation strength γ_0 fitted to:

$$\begin{aligned}\Gamma_{\Upsilon(4S)\to B\bar{B}} &= 2\Phi_{A\to BC}\left|\langle BC\vec{q}_0\,\ell J|\,T^\dagger\,|A\rangle\right|^2 \\ &= 2\Phi_{\Upsilon(4S)\to B\bar{B}} \\ &\quad \left|\langle B\bar{B}\vec{q}_0\,11|\,T^\dagger\,|\Upsilon(4S)\rangle\right|^2 \\ &= 21 \text{ MeV}\end{aligned}$$

Relativized QM parameters (bare energies Ea)

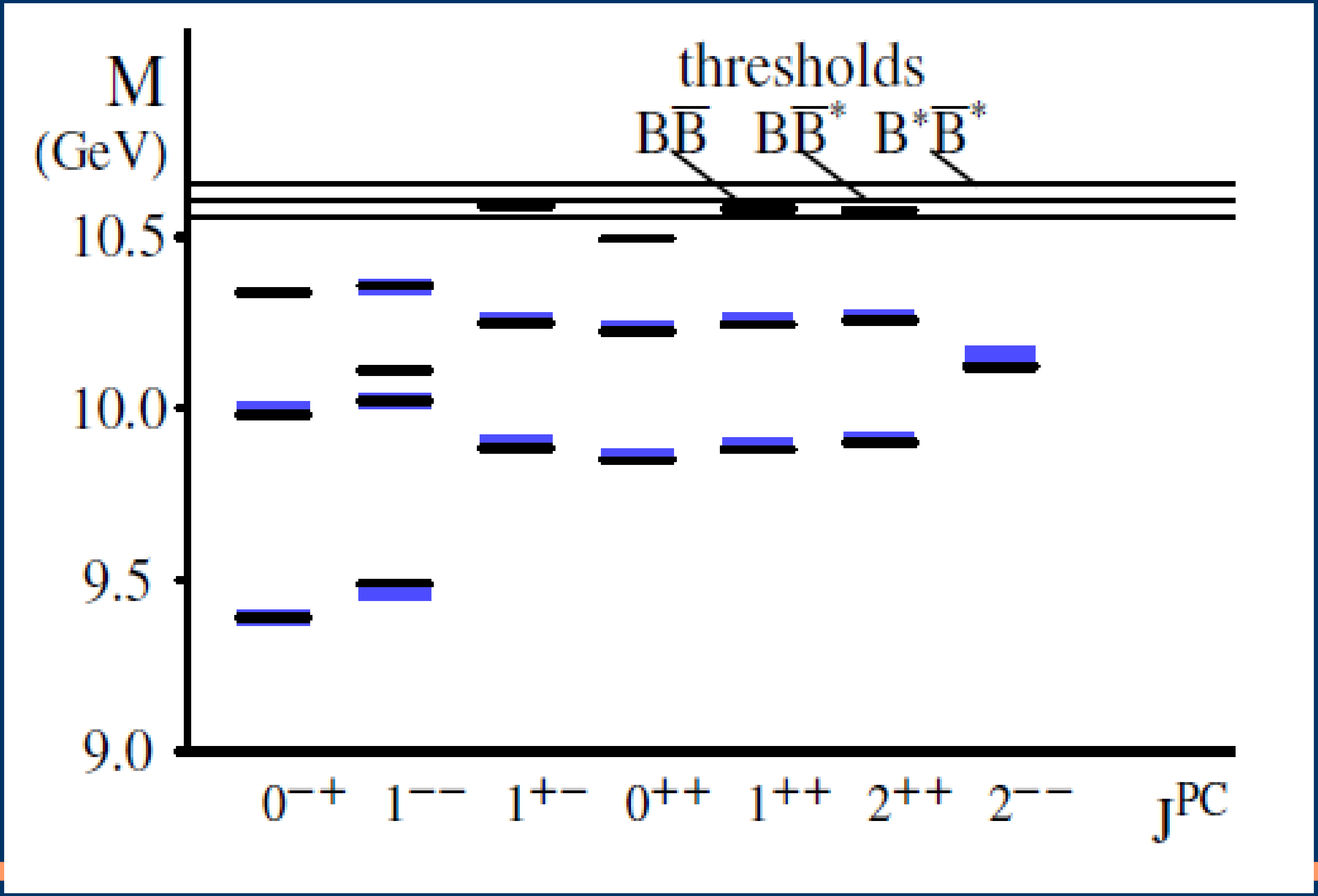
$m_b = 4.568$ GeV	$b = 0.1986$ GeV^2	$\alpha_s^{cr} = 0.600$
$\Lambda = 0.200$ GeV	$c = 0.628$ GeV	$\sigma_0 = 0.0127$ GeV
$s = 2.655$	$\epsilon_c = -0.2948$	$\epsilon_t = 0.0129$
$\epsilon_{so(V)} = -0.0715$	$\epsilon_{so(S)} = 0.0573$	

UQM: bottomonium spectrum with self-energy corrections

Ferretti *et al*., Phys. Rev. C **86**, 015204 (2012); Ferretti and Santopinto, arXiv: 1306.2874

Spectrum

Possible importance of continuum effects in $\chi_b(3P)$ system



UQM: bottomonium spectrum with self-energy corrections

Ferretti *et al.*, Phys. Rev. C **86**, 015204 (2012); Ferretti and Santopinto, arXiv: 1306.2874

UQM results compared with exp. data:

State	J^{PC}	$B\bar{B}$	$B\bar{B}^*$ $\bar{B}B^*$	$B^*\bar{B}^*$	$B_s\bar{B}_s$	$B_s\bar{B}_s^*$ $\bar{B}_sB_s^*$	$B_s^*\bar{B}_s^*$	$B_c\bar{B}_c$	$B_c\bar{B}_c^*$ $\bar{B}_cB_c^*$	$B_c^*\bar{B}_c^*$	$\eta_b\eta_b$	$\eta_b\Upsilon$	$\Upsilon\Upsilon$	$\Sigma(E_a)$	E_a	M_a	$M_{exp.}$
$\eta_b(1^1S_0)$	0^{-+}	–	-26	-26	–	-5	-5	–	-1	-1	–	–	0	-64	9455	9391	9391
$\Upsilon(1^3S_1)$	1^{--}	-5	-19	-32	-1	-4	-7	0	0	-1	–	0	–	-69	9558	9489	9460
$\eta_b(2^1S_0)$	0^{-+}	–	-43	-41	–	-8	-7	–	-1	-1	–	–	0	-101	10081	9980	9999
$\Upsilon(2^3S_1)$	1^{--}	-8	-31	-51	-2	-6	-9	0	0	-1	–	0	–	-108	10130	10022	10023
$\eta_b(3^1S_0)$	0^{-+}	–	-59	-52	–	-8	-8	–	-1	-1	–	–	0	-129	10467	10338	–
$\Upsilon(3^3S_1)$	1^{--}	-14	-45	-68	-2	-6	-10	0	0	-1	–	0	–	-146	10504	10358	10355
$h_b(1^1P_1)$	1^{+-}	–	-49	-47	–	-9	-8	–	-1	-1	–	0	–	-115	10000	9885	9899
$\chi_{b0}(1^3P_0)$	0^{++}	-22	–	-69	-3	–	-13	0	–	-1	0	–	0	-108	9957	9849	9859
$\chi_{b1}(1^3P_1)$	1^{++}	–	-46	-49	–	-8	-9	–	-1	-1	–	–	0	-114	9993	9879	9893
$\chi_{b2}(1^3P_2)$	2^{++}	-11	-32	-55	-2	-6	-9	0	-1	-1	0	–	0	-117	10017	9900	9912
$h_b(2^1P_1)$	1^{+-}	–	-66	-59	–	-10	-9	–	-1	-1	–	0	–	-146	10393	10247	10260
$\chi_{b0}(2^3P_0)$	0^{++}	-33	–	-85	-4	–	-14	0	–	-1	0	–	0	-137	10363	10226	10233
$\chi_{b1}(2^3P_1)$	1^{++}	–	-63	-60	–	-9	-10	–	-1	-1	–	–	0	-144	10388	10244	10255
$\chi_{b2}(2^3P_2)$	2^{++}	-16	-42	-72	-2	-6	-10	0	0	-1	0	–	0	-149	10406	10257	10269
$h_b(3^1P_1)$	1^{+-}	–	-18	-73	–	-11	-10	–	-1	-1	–	0	–	-114	10705	10591	–
$\chi_{b0}(3^3P_0)$	0^{++}	-4	–	-160	-6	–	-15	0	–	-1	0	–	0	-186	10681	10495	–
$\chi_{b1}(3^3P_1)$	1^{++}	–	-25	-74	–	-11	-10	–	0	-1	–	–	0	-121	10701	10580	–
$\chi_{b2}(3^3P_2)$	2^{++}	-19	-16	-79	-3	-8	-12	0	0	-1	0	–	0	-138	10716	10578	–
$\Upsilon_2(1^1D_2)$	2^{-+}	–	-72	-66	–	-11	-10	–	-1	-1	–	–	0	-161	10283	10122	–
$\Upsilon(1^3D_1)$	1^{--}	-24	-22	-90	-3	-3	-16	0	0	-1	–	0	–	-159	10271	10112	–
$\Upsilon_2(1^3D_2)$	2^{--}	–	-70	-68	–	-10	-11	–	-1	-1	–	0	–	-161	10282	10121	10164
$\Upsilon_3(1^3D_3)$	3^{--}	-18	-43	-78	-3	-8	-11	0	-1	-1	–	0	–	-163	10290	10127	–

Open-bottom decays

Ferretti *et al*., Phys. Rev. C **86**, 015204 (2012); Ferretti and Santopinto, arXiv: 1306.2874

Two-body strong decays. Results:

State	Mass [MeV]	J^{PC}	BB	BB^* $\bar{B}B^*$	B^*B^*	B_sB_s	$B_sB_s^*$ $\bar{B}_sB_s^*$	$B_s^*B_s^*$
$\Upsilon(4^3S_1)$	10.595 $10579.4 \pm 1.2^\dagger$	1^{--}	21	–	–	–	–	–
$\chi_{b2}(2^3F_2)$	10585	2^{++}	34	–	–	–	–	–
$\Upsilon(3^3D_1)$	10661	1^{--}	23	4	15	–	–	–
$\Upsilon_2(3^3D_2)$	10667	2^{--}	–	37	30	–	–	–
$\Upsilon_2(3^1D_2)$	10668	2^{-+}	–	55	57	–	–	–
$\Upsilon_3(3^3D_3)$	10673	3^{--}	15	56	113	–	–	–
$\chi_{b0}(4^3P_0)$	10726	0^{++}	26	–	24	–	–	–
$\Upsilon_3(2^3G_3)$	10727	3^{--}	3	43	39	–	–	–
$\chi_{b1}(4^3P_1)$	10740	1^{++}	–	20	1	–	–	–
$h_b(4^1P_1)$	10744	1^{+-}	–	33	5	–	–	–
$\chi_{b2}(4^3P_2)$	10751	2^{++}	10	28	5	1	–	–
$\chi_{b2}(3^3F_2)$	10800	2^{++}	5	26	53	2	2	–
$\Upsilon_3(3^1F_3)$	10803	3^{+-}	–	28	46	–	3	–
$\Upsilon(10860)$	$10876 \pm 11^\dagger$	1^{--}	1	21	45	0	3	1
$\Upsilon_2(4^3D_2)$	10876	2^{--}	–	28	36	–	4	4
$\Upsilon_2(4^1D_2)$	10877	2^{-+}	–	22	37	–	4	3
$\Upsilon_3(4^3D_3)$	10881	3^{--}	1	4	49	0	1	2
$\Upsilon_3(3^3G_3)$	10926	3^{--}	7	0	13	2	0	5
$\Upsilon(11020)$	$11019 \pm 8^\dagger$	1^{--}	0	8	26	0	0	2

Comparison with exp. data

State	Γ_{theor} ($^3P_0$) [MeV]	Γ_{exp} [MeV]
$\Upsilon(4^3S_1)$	21	20.5 ± 2.5
$\Upsilon(10860)$	71	42^{+29}_{-24}

χ_b(3P) system. Barycenter

Ferretti, Galatà and Santopinto, Phys. Rev. D **90**, 054010 (2014); Ferretti and Santopinto, arXiv: 1306.2874

Results used to study some properties of the χ_b(3P) system

χ_b(3P)'s close to first open bottom decay thresholds → possible importance of continuum effects?

"Further analysis is underway to determine whether this structure is due to the χ_b(3P) system or some exotic bottom-quark state." [Abazov *et al*. [D0 Coll.], Phys. Rev. D **86**, 031103 (2012)]

Mass barycenter (exp. data):

M = 10.530 ± 0.005 (stat.) ± 0.009 (syst.) GeV

Aad *et al*. [ATLAS Coll.], Phys. Rev. Lett. **108**, 152001 (2012)

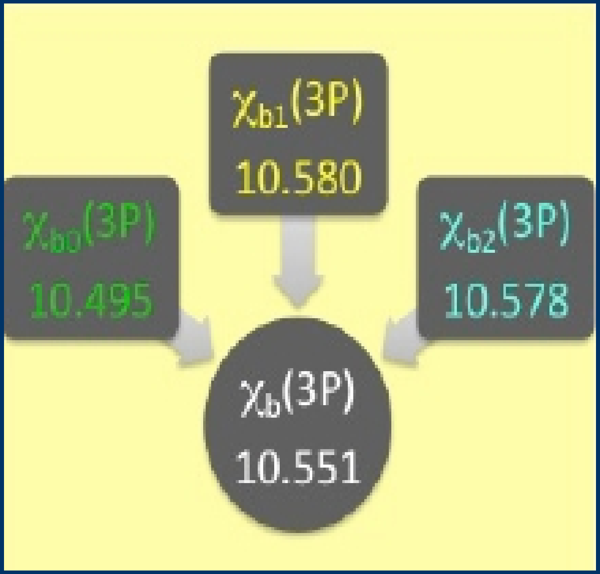
M = 10.551 ± 0.014 (stat.) ± 0.017 (syst.) GeV

Abazov *et al*. [D0 Coll.], Phys. Rev. D **86**, 031103 (2012)

Mass barycenter (relativized QM re-fit):

M = 10.51 GeV

Mass barycenter (UQM):



χ_b(3P) system. Radiative transitions

Ferretti, Galatà and Santopinto, Phys. Rev. D **90**, 054010 (2014)

QM formalism

$$\Gamma_{E1} = \frac{4}{3} C_{fi} \delta_{SS'} e_b^2 \alpha |\langle \psi_f | r | \psi_i \rangle|^2 E_\gamma^3 \frac{E_f^{(b\bar{b})}}{M_i^{(b\bar{b})}}$$

$$\langle \psi_f | r | \psi_i \rangle = \int_0^\infty r^2 dr \psi^*_{n_f, L_f}(r) r \psi_{n_i, L_i}(r)$$

$$C_{fi} = \max(L, L')(2J' + 1) \begin{Bmatrix} L' & J' & S \\ J & L & 1 \end{Bmatrix}^2$$

Transition	E_γ(QM) (MeV)	$\Gamma_{b\bar{b}}$(QM) (KeV)
$\chi_{b0}(3^3P_0) \to \Upsilon(1^3S_1)\gamma$	983	0.6
$\chi_{b0}(3^3P_0) \to \Upsilon(2^3S_1)\gamma$	460	1.2
$\chi_{b0}(3^3P_0) \to \Upsilon(3^3S_1)\gamma$	138	6.1
$\chi_{b0}(3^3P_0) \to \Upsilon(1^3D_1)\gamma$	344	0.2
$\chi_{b0}(3^3P_0) \to \Upsilon(2^3D_1)\gamma$	69	0.9
$\chi_{b1}(3^3P_1) \to \Upsilon(1^3S_1)\gamma$	971	2.1
$\chi_{b1}(3^3P_1) \to \Upsilon(2^3S_1)\gamma$	477	2.5
$\chi_{b1}(3^3P_1) \to \Upsilon(3^3S_1)\gamma$	155	7.4
$\chi_{b1}(3^3P_1) \to \Upsilon(1^3D_1)\gamma$	361	0
$\chi_{b1}(3^3P_1) \to \Upsilon(2^3D_1)\gamma$	86	0.4
$\chi_{b1}(3^3P_1) \to \Upsilon_2(1^3D_2)\gamma$	341	0
$\chi_{b1}(3^3P_1) \to \Upsilon_2(2^3D_2)\gamma$	79	1.0
$\chi_{b2}(3^3P_2) \to \Upsilon(1^3S_1)\gamma$	1010	3.9
$\chi_{b2}(3^3P_2) \to \Upsilon(2^3S_1)\gamma$	489	3.8
$\chi_{b2}(3^3P_2) \to \Upsilon(3^3S_1)\gamma$	168	8.2
$\chi_{b2}(3^3P_2) \to \Upsilon(1^3D_1)\gamma$	373	0
$\chi_{b2}(3^3P_2) \to \Upsilon(2^3D_1)\gamma$	99	0
$\chi_{b2}(3^3P_2) \to \Upsilon_2(1^3D_2)\gamma$	354	0
$\chi_{b2}(3^3P_2) \to \Upsilon_2(2^3D_2)\gamma$	92	0.3
$\chi_{b2}(3^3P_2) \to \Upsilon_3(1^3D_3)\gamma$	357	0
$\chi_{b2}(3^3P_2) \to \Upsilon_3(2^3D_3)\gamma$	86	1.4

Thank you for your attention!

Open-flavor decays. $^3P_0$ pair-creation Model

Micu, Nucl. Phys. B **10**, 521 (1969); Le Yaouanc *et al*., Phys. Rev. D **8**, 2223 (1973)

Hadron decays proceed through q bar-q pair-creation

The created q bar-q pair has $^3P_0$ quantum numbers

q bar-q pair produced by spatially constant pair-production strength γ_0

Quarks 1-2-3 are spectators