Continuum-coupling effects in heavy meson spectroscopy

Jacopo Ferretti
Università di Roma "Sapienza"

TNPI2016 – XV Conference on Theoretical Nuclear Physics in Italy
Pisa, April 20-22 2016

Outline

* Why introducing higher Fock components in QM formalism
* The Unquenched Quark Model (UQM) formalism
* Calculation of meson observables in the UQM
* Charmonium and bottomonium spectra with self-energy corrections
* The X(3872): quark structure and decays

Introduction of higher Fock components

- ⋆ The QM reproduces quite well several observables: magnetic moments, baryon and meson spectra (lower parts), strong couplings
- ⋆ Some observables may require corrections due to the coupling to the continuum, e.g. electromagnetic couplings
- ⋆ Some observables necessarily require coupling to the continuum: strangeness content of nucleon e.m. form factors, flavor asymmetry of nucleon sea
- ⋆ Coupling to the continuum → Higher Fock components are introduced in meson ($q\bar{q} - q\bar{q}$) and baryon ($qqq - q\bar{q}$) wave functions via a quark-antiquark pair-creation mechanism

Higher Fock components and meson spectroscopy

- ⋆ Potential models reproduce very well meson spectrum (lower part)
- ⋆ Example: Relativized QM's global fit (isoscalars, vectors, strange, D, B, charmonium, …) with a single set of parameters

  Godfrey and Isgur, PRD **32**, 189 (1985)

- ⋆ A few exceptions:

State	Exp. Mass [MeV]	Rel. QM Mass [MeV]
X(3872)	3871.69±0.17	3950
D_0^*(2400)	2318±29	2398
D_{s0}^*(2317)	2317.7±0.6	2482
B_2^*(5747)	5743±5	5796

- ⋆ Several interpretations: meson-meson molecules, tetraquarks, quarkonium + continuum components
- ⋆ Necessary to estimate main decay modes within different interpretations to distinguish between them

Unquenched quark model (UQM) formalism

* Hadron wave function in the UQM

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

Valence component $\left|A\right\rangle$ + sum over continuum components $\left|BC\right\rangle$

* Coupling to continuum provided by $^3P_0$ model (open-flavor decays)

$$T^\dagger = -3\gamma_0^{\mathrm{eff}} \int d\vec{p}_3 d\vec{p}_4 \delta(\vec{p}_3 + \vec{p}_4) C_{34} F_{34} e^{-r_q^2(\vec{p}_3 - \vec{p}_4)^2/6} \times \left[\chi_{34} \times \mathcal{Y}_1(\vec{p}_3 - \vec{p}_4)\right]_0^{(0)} b_3^\dagger(\vec{p}_3) d_4^\dagger(\vec{p}_4),$$

C_{34} = color-singlet WF; F_{34} = flavor-singlet WF; χ_{34} spin-triplet WF; b_3^+ and d_4^+ = quark and antiquark creation operators

The created quark-antiquark pair (34) has $^3P_0$ quantum numbers

Quark form factor (created pair not point-like)

Effective paircreation strength γ_0^{eff} (heavy pair-creation suppressed)

Hadron observables in the UQM

- ⋆ Expectation value of an observable *O*, $<\Psi_A|O|\Psi_A>$, on the wave function

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

- ⋆ Continuum + valence contributions

Santopinto and Bijker, PRC **80**, 065210 (2009); Bijker and Santopinto, PRC **82**, 062202 (2010); Bijker, Ferretti and Santopinto, PRC **85**, 035204 (2012)

Meson spectrum with self-energy corrections

* Hamiltonian

$$H = H_0 + V$$

Bare spectrum (H_0) + coupling to meson-meson continuum (V)

* Bare meson spectrum (E_a) calculated in the relativized QM

$$H_0 = \sqrt{q^2 + m_1^2} + \sqrt{q^2 + m_2^2} + V_{\text{conf}} + V_{\text{hyp}} + V_{\text{so}}$$

Godfrey and Isgur, PRD **32**, 189 (1985)

* Self-energy corrections calculated in the UQM

$$\Sigma(E_a) = \sum_{BC\ell J} \int_0^\infty q^2 dq \frac{|\langle BC\vec{q}\ell J|T^\dagger|A\rangle|^2}{E_a - E_b - E_c}$$

Ferretti, Galatà, Santopinto and Vassallo, PRC **86**, 015204 (2012); Ferretti, Galatà and Santopinto, PRC **88**, 015207 (2013); PRD **90**, 054010 (2014); Ferretti and Santopinto PRD **90**, 094022 (2014)

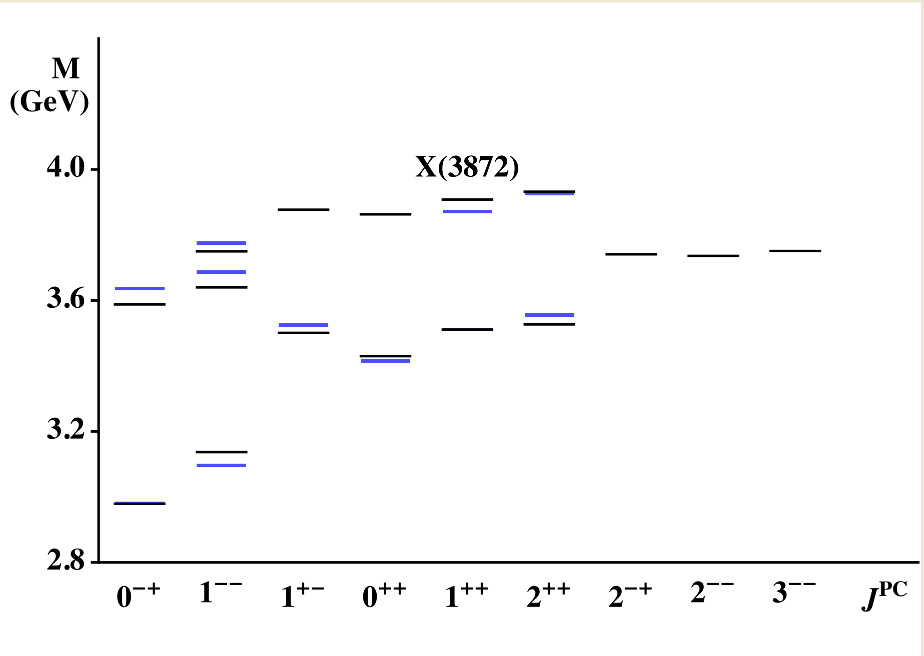
* Physical masses: $M_a = E_a + \Sigma(E_a)$

* Relativized QM parameters fitted to experimental masses

UQM parameters fitted to open-flavor strong decays

Charmonium spectrum with self-energy corrections

* Ferretti, Galatà and Santopinto, PRC **88**, 015207 (2013)



$m_c = 1.562$ GeV	$b = 0.1477$ GeV^2	$\alpha_s^{cr} = 0.600$
$\Lambda = 0.200$ GeV	$c = 0.069$ GeV	$\sigma_0 = 1.463$ GeV
$s = 2.437$	$\epsilon_c = -0.2500$	$\epsilon_t = 0.0300$
$\epsilon_{so(V)} = -0.0314$	$\epsilon_{so(S)} = 0.0637$	

Relativized QM parameters

Parameter	Value
γ_0	0.510
α	0.500 GeV
r_q	0.335 fm
m_n	0.330 GeV
m_s	0.550 GeV
m_c	1.50 GeV

$^3P_0$ model parameters

State	Exp. Mass [MeV]	Rel. QM Mass [MeV]	UQM Mass [MeV]
X(3872)	3871.69±0.17	3950	3908

Charmonium spectrum with self-energy corrections

* Ferretti, Galatà and Santopinto, PRC **88**, 015207 (2013)

State	J^{PC}	$D\bar{D}$	$\bar{D}D^*$ $D\bar{D}^*$	$\bar{D}^*D^*$	$D_s\bar{D}_s$	$D_s\bar{D}_s^*$ $\bar{D}_sD_s^*$	$D_s^*\bar{D}_s^*$	$\eta_c\eta_c$	$\eta_c J/\Psi$	$J/\Psi\ J/\Psi$	$\Sigma(E_a)$	E_a	M_a	$M_{\text{expt.}}$
$\eta_c(1^1S_0)$	0^{-+}	–	−34	−31	–	−8	−8	–	–	−2	−83	3062	2979	2980
$J/\Psi(1^3S_1)$	1^{--}	−8	−27	−41	−2	−6	−10	–	−2	–	−96	3233	3137	3097
$\eta_c(2^1S_0)$	0^{-+}	–	−52	−41	–	−9	−8	–	–	−1	−111	3699	3588	3637
$\Psi(2^3S_1)$	1^{--}	−18	−42	−54	−2	−7	−10	–	−1	–	−134	3774	3640	3686
$h_c(1^1P_1)$	1^{+-}	–	−59	−48	–	−11	−10	–	−2	–	−130	3631	3501	3525
$\chi_{c0}(1^3P_0)$	0^{++}	−31	–	−72	−4	–	−15	0	–	−3	−125	3555	3430	3415
$\chi_{c1}(1^3P_1)$	1^{++}	–	−54	−53	–	−9	−11	–	–	−2	−129	3623	3494	3511
$\chi_{c2}(1^3P_2)$	2^{++}	−17	−40	−57	−3	−8	−10	0	–	−2	−137	3664	3527	3556
$h_c(2^1P_1)$	1^{+-}	–	−55	−76	–	−12	−8	–	−1	–	−152	4029	3877	–
$\chi_{c0}(2^3P_0)$	0^{++}	−23	–	−86	−1	–	−13	0	–	−1	−124	3987	3863	–
$\chi_{c1}(2^3P_1)$	1^{++}	–	−30	−66	–	−11	−9	–	–	−1	−117	4025	3908	3872
$\chi_{c2}(2^3P_2)$	2^{++}	−2	−42	−54	−4	−8	−10	0	–	−1	−121	4053	3932	3927
$\eta_{c2}(1^1D_2)$	2^{-+}	–	−99	−62	–	−12	−10	–	–	−1	−184	3925	3741	–
$\Psi(3770)(1^3D_1)$	1^{--}	−11	−40	−84	−4	−2	−16	–	0	–	−157	3907	3750	3775
$\Psi_2(1^3D_2)$	2^{--}	–	−106	−61	–	−11	−11	–	−1	–	−190	3926	3736	–
$\Psi_3(1^3D_3)$	3^{--}	−25	−49	−88	−4	−8	−10	–	−1	–	−185	3936	3751	–

X(3872). Radiative transitions

- ⋆ Ferretti, Galatà and Santopinto, PRD **90**, 054010 (2014)

- ⋆ QM calculation with relativized QM wave functions

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

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

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

e_c = c-quark charge; α = fine structure constant; E_f = energy of final charmonium state; M_i = mass of initial charmonium state

- ⋆ Results

Transition	E_γ (MeV)	$\Gamma_{c\bar{c}}$ (KeV) present paper	Molecular model: $\Gamma_{D\bar{D}^*}$ (KeV) Ref. [7]	Molecular model: $\Gamma_{D\bar{D}^*}$ (KeV) Ref. [8]	Molecular model: $\Gamma_{D\bar{D}^*}$ (KeV) Ref. [63]	Molecule + quarkonium component: $\Gamma_{c\bar{c}+D\bar{D}^*}$ (KeV) Ref. [64]	Γ_{exp} (KeV) PDG [43]
$X(3872) \to J/\Psi\gamma$	697	11	8	64–190	125–251	2–17	≈7
$X(3872) \to \Psi(2S)\gamma$	181	70	0.03			7–59	≈36
$X(3872) \to \Psi(3770)\gamma$	101	4.0	0				
$X(3872) \to \Psi_2(1^3D_2)\gamma$	34	0.35	0				

[7] Swanson, Phys. Lett. B **588**, 189 (2004); [8] Aceti, Molina and Oset, PRD **86**, 113007 (2012); Dong *et al.*, PRD **77**, 094013 (2008); Dong *et al.*, J. Phys. G **38**, 015001 (2011).

X(3872). Open-flavor decays

- Ferretti, Galatà and Santopinto, PRD **90**, 054010 (2014)
- Consider the process $\boldsymbol{X(3872) \to D^0 (\bar{D}^0 \pi^0)_{\bar{D}^{0*}}}$
- Quasi two-body decay width: Phase-space available for D^{0*} to decay into $D^0\pi^0$

$$\Gamma_{X(3872)}^{QTB} = \int_0^{q_{\max}} dq q^2 \frac{2\sum_{\ell,J} |\langle D^0 \bar{D}^{0*} \vec{q} \ell J | T^\dagger | X(3872)\rangle|^2 \Gamma_{\bar{D}^{0*} \to \bar{D}^0 \pi^0}(q)}{[M_a - E_b(q) - E_c(q)]^2 + \frac{1}{4}\Gamma^2_{\bar{D}^{0*}}}$$

$\langle D^0 \bar{D}^{0*} \vec{q}_0 \ell J | T^\dagger | X(3872)\rangle$: $X(3872) \to D^0 \bar{D}^{0*}$ decay width

Factor of 2: $X(3872)$ decays into $D^0 \bar{D}^{0*}$ or $\bar{D}^0 D^{0*}$

$\Gamma_{\bar{D}^{0*} \to \bar{D}^0 \pi^0}(q)$: energy-dependent width of unstable $\bar{D}^{0*}$ to decay into $\bar{D}^0 \pi^0$

Result: $\Gamma_{X(3872) \to D(\bar{D}\pi)_{\bar{D}^*}} = 0.54 - 0.70 \text{ MeV}$

in accordance with $\Gamma_{X(3872)} < 1.2 \text{ MeV}$ (PDG)

X(3872). Continuum components

- Ferretti, Galatà and Santopinto, PRD **90**, 054010 (2014)
- X(3872) WF has a 45% charmonium component PLUS

$D\bar{D}^*$	$D^*\bar{D}^*$	$D_s\bar{D}_s^*$	$D_s^*\bar{D}_s^*$	$J/\Psi J/\Psi$
0.13	0.35	0.06	0.01	0.0003

continuum components

- Continuum components calculated via

$$P_a^{BC} = \sum_{BC\ell J} \int_0^\infty q^2 dq \frac{|\langle BC\vec{q}\ell J|T^\dagger|A\rangle|^2}{(E_a - E_b - E_c)^2 + \frac{1}{4}\Gamma_{D^*}^2}$$

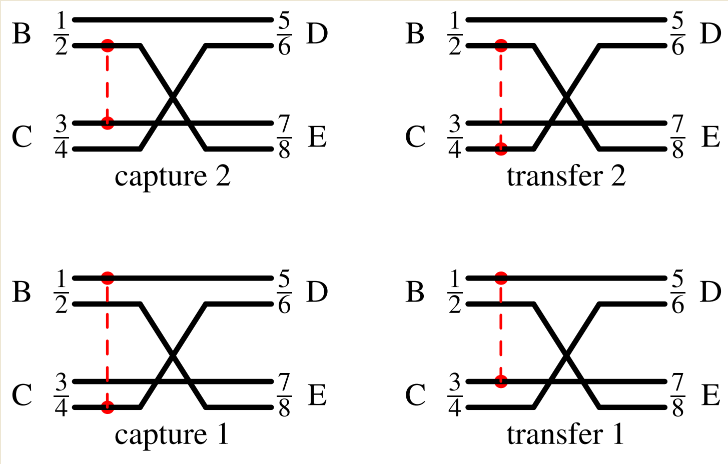
X(3872). Hidden-flavor decays

- ⋆ Ferretti, Guerrieri, Pilloni and Santopinto, in preparation
- ⋆ X(3872) → J/Ψ ω and J/Ψ ρ hidden-flavor decays calculated in the UQM formalism + meson-meson low-energy scattering in a non-relativistic potential
- ⋆ UQM provides weight of $D^0 \bar{D}^{0*}$ component in X(3872)'s WF
- ⋆ $D^0 \bar{D}^{0*}$ component dissociates in J/Ψ ω or J/Ψ ρ
- ⋆ Dissociation matrix elements calculated as low-energy scattering of $D^0 \bar{D}^{0*}$ in a nonrelativistic potential model

Barnes and Swanson, PRD **46**, 131 (1992); Barnes et al., PRC **68**, 014903 (2003).

X(3872). Hidden-flavor decays

- ⋆ Ferretti, Guerrieri, Pilloni and Santopinto, in preparation
- ⋆ Diagrams:



Hamiltonian:

$$H_{ij} = \frac{\lambda_i^a}{2}\frac{\lambda_j^a}{2}\left[\frac{\alpha_s}{r_{ij}} - \frac{3\beta}{4} r_{ij} - \frac{8\pi\alpha_s}{3m_i m_j} \vec{S}_i \cdot \vec{S}_j \delta(\vec{r}_{ij})\right]$$

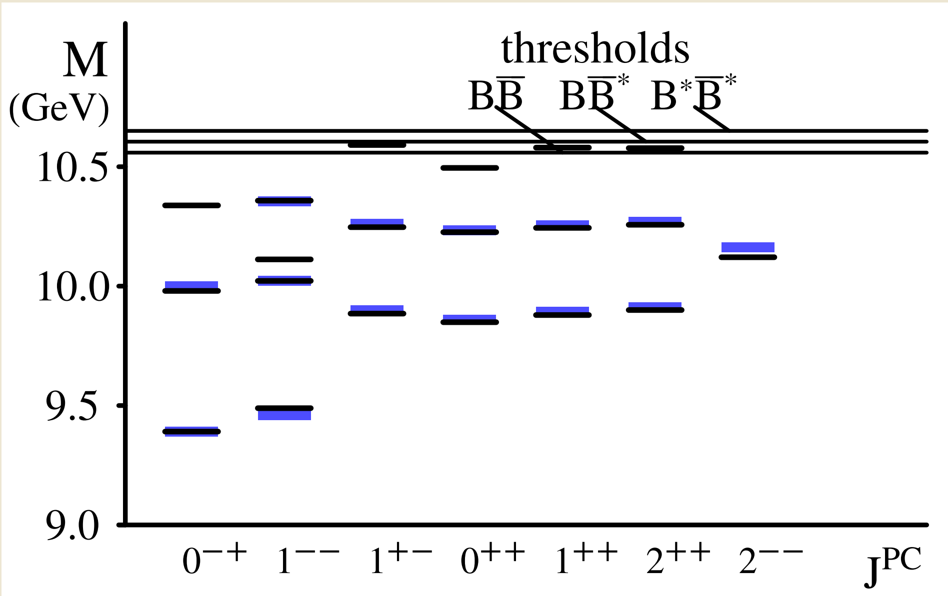
- ⋆ Results:

Transition	Γ^{UQM} (KeV)	Γ^{exp} (KeV)
$X(3872) \to J/\Psi\rho$	10	≈ 31
$X(3872) \to J/\Psi\omega$	6	≈ 22

Source	Value of $\frac{\Gamma_{X(3872)\to J/\Psi\omega}}{\Gamma_{X(3872)\to J/\Psi\rho}}$
Experiment [3]	0.8 ± 0.3
Ref. [25]	≈ 2
Ref. [37]	1.0 ± 0.3
Ref. [50]	$5.5 - 6.6$
Ref. [51]	0.42
Ref. [52]	$1.27 - 2.24$
Present work	0.6

Bottomonium spectrum with self-energy corrections

* Ferretti and Santopinto, PRD **90**, 094022 (2014)



m_b = 5.024 GeV	b = 0.156 GeV^2	α_s^{cr} = 0.60
Λ = 0.200 GeV	c = −0.280 GeV	σ_0 = 0.146 GeV
s = 4.36	ϵ_c = −0.242	ϵ_t = 0.030
$\epsilon_{so(V)}$ = −0.053	$\epsilon_{so(S)}$ = 0.019	

Relativized QM parameters

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

$^3P_0$ model parameters

* Threshold effects for $\chi_b(3P)$ states

Ferretti, Galatà and Santopinto, PRD **90**, 054010 (2014)

Bottomonium spectrum with self-energy corrections

* Ferretti and Santopinto, PRD **90**, 094022 (2014)

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	$M_{\text{exp.}}$
$\eta_b(1^1S_0)$	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	—

Conclusion

* Importance of introducing higher Fock components in QM formalism
* The Unquenched Quark Model (UQM)
* Calculation of meson observables in the UQM
* Charmonium and bottomonium spectra with self-energy corrections
* The X(3872): quark structure and decays

Thank you for your attention!