Heavy mesons in the quark model

15th International Workshop on Mesons Physics

Meson 2018

MESON 2018

15th International Workshop on Meson Physics

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Organized by Jagiellonian University Kraków, Forschungszentrum Jülich, INFN-LNF Frascati, Institute of Nuclear Physics PAS

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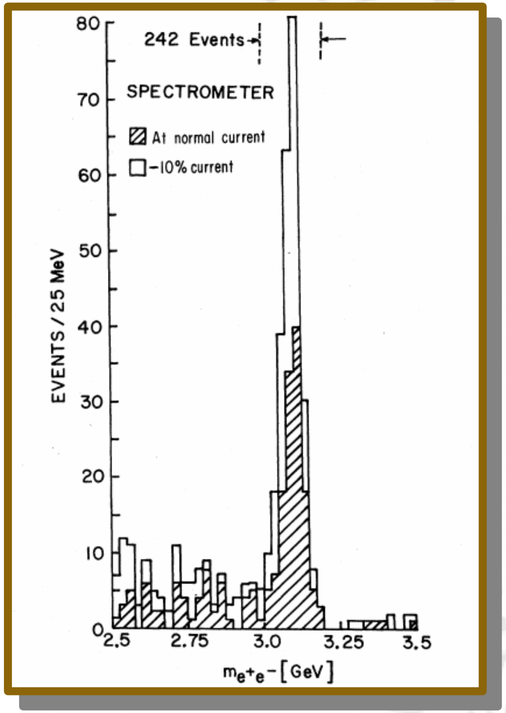
Outline

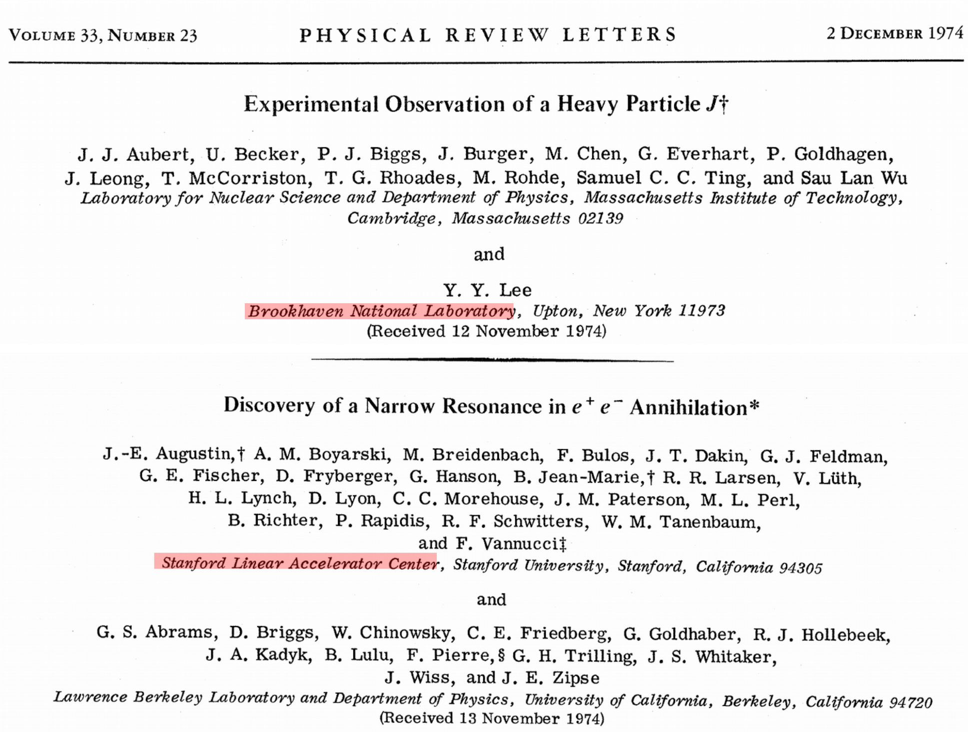
- *1974 - The November revolution*
- *The naive quark model - phenomenological potential models*
- *2003 - the discovery of the X(3872)*
- *Open charm and bottom meson dynamics – the Chiral Quark Model*
- *HQSS and HFS in the naive quark model and in the unquenched quark model*
- *The 3.9 GeV region – discrepancies from the naive quark model*
- *States above threshold – New resonances measured by LHCb*

The November revolution

The J

$p\mathrm{Be} \to e^+e^- X$





VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

Experimental Observation of a Heavy Particle J†

J. J. Aubert, U. Becker, P. J. Biggs, J. Burger, M. Chen, G. Everhart, P. Goldhagen,
J. Leong, T. McCorriston, T. G. Rhoades, M. Rohde, Samuel C. C. Ting, and Sau Lan Wu
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts 02139

and

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(Received 12 November 1974)

Discovery of a Narrow Resonance in e^+e^- Annihilation*

J.-E. Augustin,† A. M. Boyarski, M. Breidenbach, F. Bulos, J. T. Dakin, G. J. Feldman,
G. E. Fischer, D. Fryberger, G. Hanson, B. Jean-Marie,† R. R. Larsen, V. Lüth,
H. L. Lynch, D. Lyon, C. C. Morehouse, J. M. Paterson, M. L. Perl,
B. Richter, P. Rapidis, R. F. Schwitters, W. M. Tanenbaum,
and F. Vannucci‡
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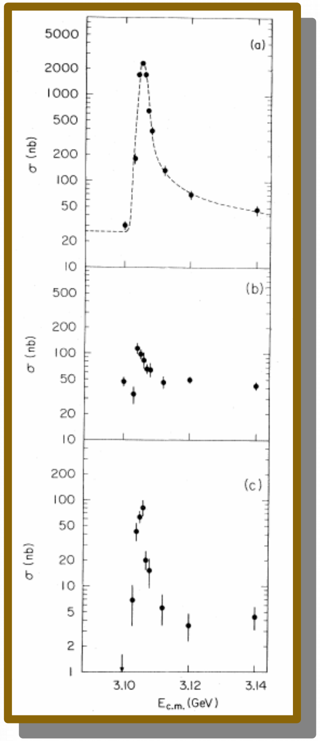
and

G. S. Abrams, D. Briggs, W. Chinowsky, C. E. Friedberg, G. Goldhaber, R. J. Hollebeek,
J. A. Kadyk, B. Lulu, F. Pierre,§ G. H. Trilling, J. S. Whitaker,
J. Wiss, and J. E. Zipse
Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

(Received 13 November 1974)



The ψ

$e^+e^- \to$ hadrons

The November revolution

- *The two particles were seen as the same*
- *The GIM mechanism (1970) required a new quark to explain the suppression of flavor-changing weak decays that were not observed, the c quark*
- *The* $\Upsilon(1S)$ *was discovered at Fermilab in* $p(\mathrm{Cu},\mathrm{Pt}) \to \mu^+\mu^- X$ *on the dimuon distribution at 9.5 GeV on 1977.*
- *Very soon after the Cornell model was developed*
  Phys. Rev. D ***17****, 3090 (1978)*

The Cornell model

- *Basic assumptions: basic interactions with SU(3) color gauge symmetry with flavor only broken by the quark masses.*
- *Heavy quarks are treated non-relativistically*
- *Interquark interaction assumed as*

$$V(r) = -\frac{\kappa}{r} + \frac{r}{a^2}$$

  - *Flavor independent*
  - *Spin independent HQSS symmetry*

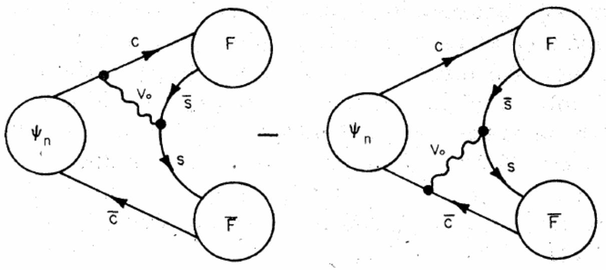
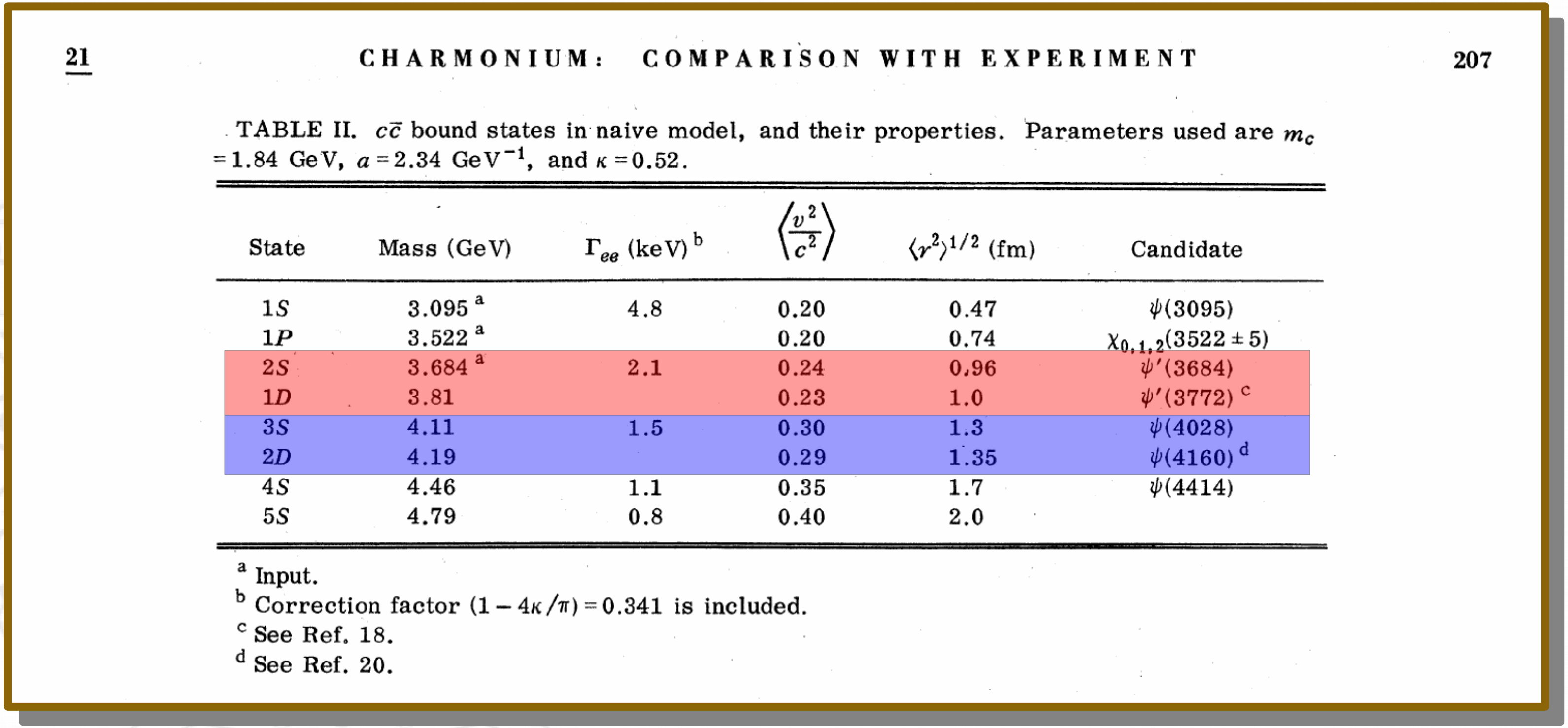


FIG. 6. This diagram depicts the decay of a $c\bar{c}$ state ψ_n into $F\bar{F}$. There are two terms, corresponding to $s\bar{s}$ creation by c or $\bar{c}$. The formula corresponding to this is Eq. (3.33).

- *Coupling to two meson states is considered*
- *The linear term dominates over the coulomb (small strong coupling constant α_s)*

The Cornell model



21 CHARMONIUM: COMPARISON WITH EXPERIMENT 207

TABLE II. $c\bar{c}$ bound states in naive model, and their properties. Parameters used are $m_c = 1.84$ GeV, $a = 2.34$ GeV^{-1}, and $\kappa = 0.52$.

State	Mass (GeV)	Γ_{ee} (keV)[b]	$\left\langle \frac{v^2}{c^2} \right\rangle$	$\langle r^2 \rangle^{1/2}$ (fm)	Candidate
$1S$	3.095[a]	4.8	0.20	0.47	$\psi(3095)$
$1P$	3.522[a]		0.20	0.74	$\chi_{0,1,2}(3522 \pm 5)$
$2S$	3.684[a]	2.1	0.24	0.96	$\psi'(3684)$
$1D$	3.81		0.23	1.0	$\psi'(3772)$[c]
$3S$	4.11	1.5	0.30	1.3	$\psi(4028)$
$2D$	4.19		0.29	1.35	$\psi(4160)$[d]
$4S$	4.46	1.1	0.35	1.7	$\psi(4414)$
$5S$	4.79	0.8	0.40	2.0	

[a] Input.
[b] Correction factor $(1 - 4\kappa/\pi) = 0.341$ is included.
[c] See Ref. 18.
[d] See Ref. 20.

The Cornell model

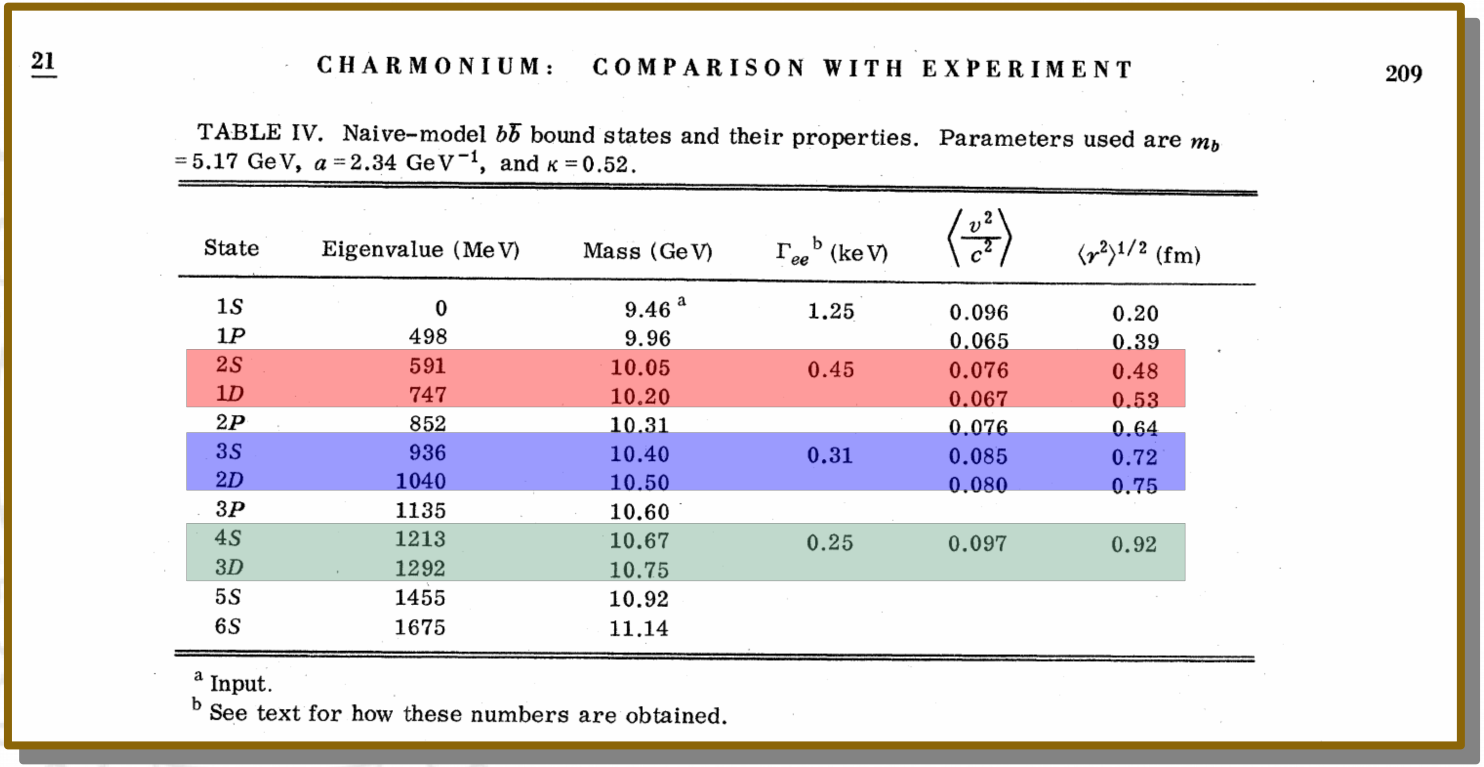


TABLE IV. Naive-model $b\bar{b}$ bound states and their properties. Parameters used are $m_b = 5.17$ GeV, $a = 2.34$ GeV^{-1}, and $\kappa = 0.52$.

State	Eigenvalue (MeV)	Mass (GeV)	Γ_{ee} [b] (keV)	$\left\langle \frac{v^2}{c^2} \right\rangle$	$\langle r^2 \rangle^{1/2}$ (fm)
$1S$	0	9.46 [a]	1.25	0.096	0.20
$1P$	498	9.96		0.065	0.39
$2S$	591	10.05	0.45	0.076	0.48
$1D$	747	10.20		0.067	0.53
$2P$	852	10.31		0.076	0.64
$3S$	936	10.40	0.31	0.085	0.72
$2D$	1040	10.50		0.080	0.75
$3P$	1135	10.60			
$4S$	1213	10.67	0.25	0.097	0.92
$3D$	1292	10.75			
$5S$	1455	10.92			
$6S$	1675	11.14			

[a] Input.
[b] See text for how these numbers are obtained.

PDG 1978

$c\bar{c}$ mesons

$J/\psi(3100)$	3097 ± 1	1^-
$\chi(3415)$	3414 ± 4	0^+
p_c or $\chi(3510)$	3507 ± 4	
$\chi(3550)$	3551 ± 5	
$\psi(3685)$	3685 ± 1	1^-
$\psi(3770)$	3768 ± 3	1^-
$\psi(4030)$	4030 ± 6	1^-
$\psi(4160)$	4159 ± 20	1^-
$\psi(4415)$	4415 ± 6	1^-

$b\bar{b}$ mesons

$\Upsilon(9460)$	9458 ± 6	1^-
$\Upsilon(10020)$	10016 ± 14	1^-

PDG 2003

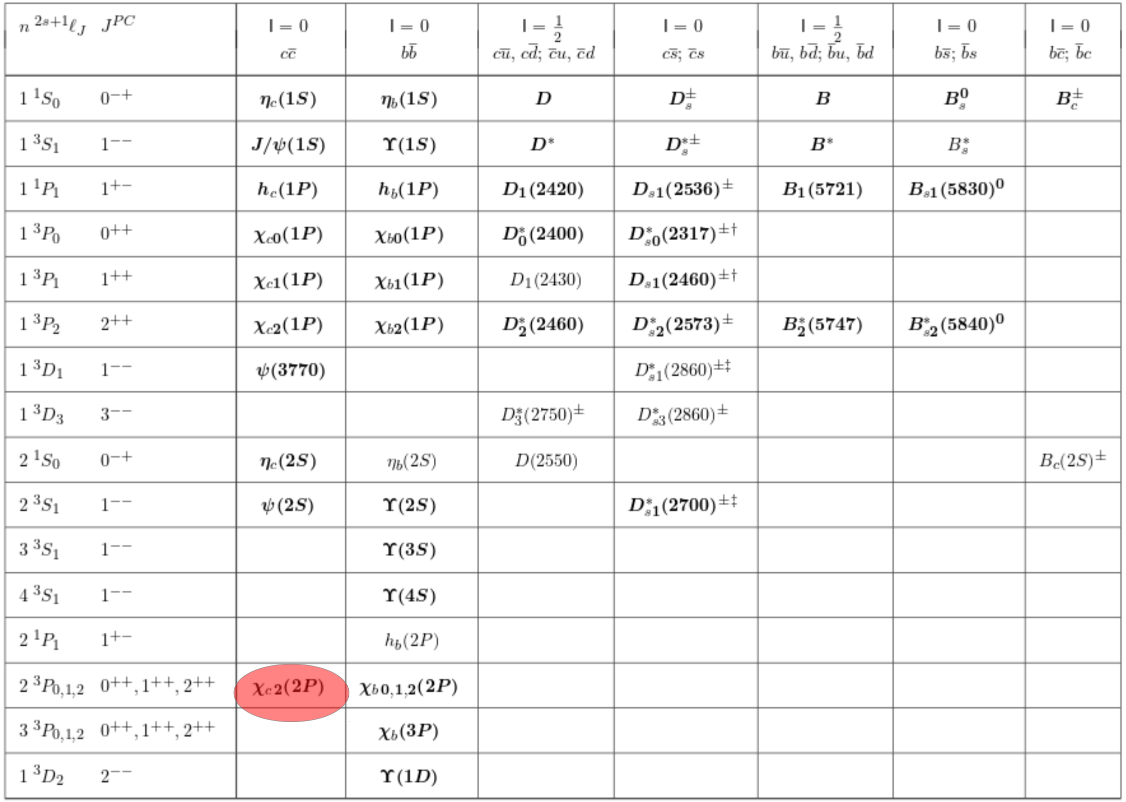
$c\bar{c}$ mesons

$\eta_c(1S)$	2979.2 ± 1.3	0^{-+}
$J/\psi(1S)$	3096.87 ± 0.04	1^{--}
$\chi_{c0}(1P)$	3415.3 ± 0.4	0^{++}
$\chi_{c1}(1P)$	3510.51 ± 0.12	1^{++}
$\chi_{c2}(1P)$	3556.18 ± 0.13	2^{++}
$h_c(1P)$	3526.14 ± 0.24	
$\eta_c(2S)$	3654 ± 10	0^{-+}
$\psi(2S)$	3685.96 ± 0.09	1^{--}
$\psi(3770)$	3769.9 ± 2.5	1^{--}
$\psi(3836)$	3836 ± 13	2^{--}
$\psi(4040)$	4040 ± 10	1^{--}
$\psi(4160)$	4159 ± 20	1^{--}
$\psi(4415)$	4415 ± 6	1^{--}

$b\bar{b}$ mesons

			Cornell
$\eta_b(1S)$	9300 ± 20	0^{-+}	
$\Upsilon(1S)$	9460.30 ± 0.26	1^{--}	
$\chi_{b0}(1P)$	9859.9 ± 1.0	0^{++}	
$\chi_{b1}(1P)$	9892.7 ± 0.6	1^{++}	$1P$ 9.96GeV
$\chi_{b2}(1P)$	9912.6 ± 0.5	2^{++}	
$\Upsilon(2S)$	10023.26 ± 0.31	1^{--}	
$\chi_{b0}(2P)$	10232.1 ± 0.6	0^{++}	
$\chi_{b1}(2P)$	10255.2 ± 0.5	1^{++}	$2P$ 10.31GeV
$\chi_{b2}(2P)$	10268.5 ± 0.4	2^{++}	
$\Upsilon(3S)$	10355.2 ± 0.5	1^{--}	$3S$ 10.4GeV
$\Upsilon(4S)$	10580 ± 3.5	1^{--}	$4S$ 10.67GeV
$\Upsilon(10860)$	10865 ± 8	1^{--}	$5S$ 10.92GeV
$\Upsilon(11020)$	11019 ± 8	1^{--}	

PDG 2017

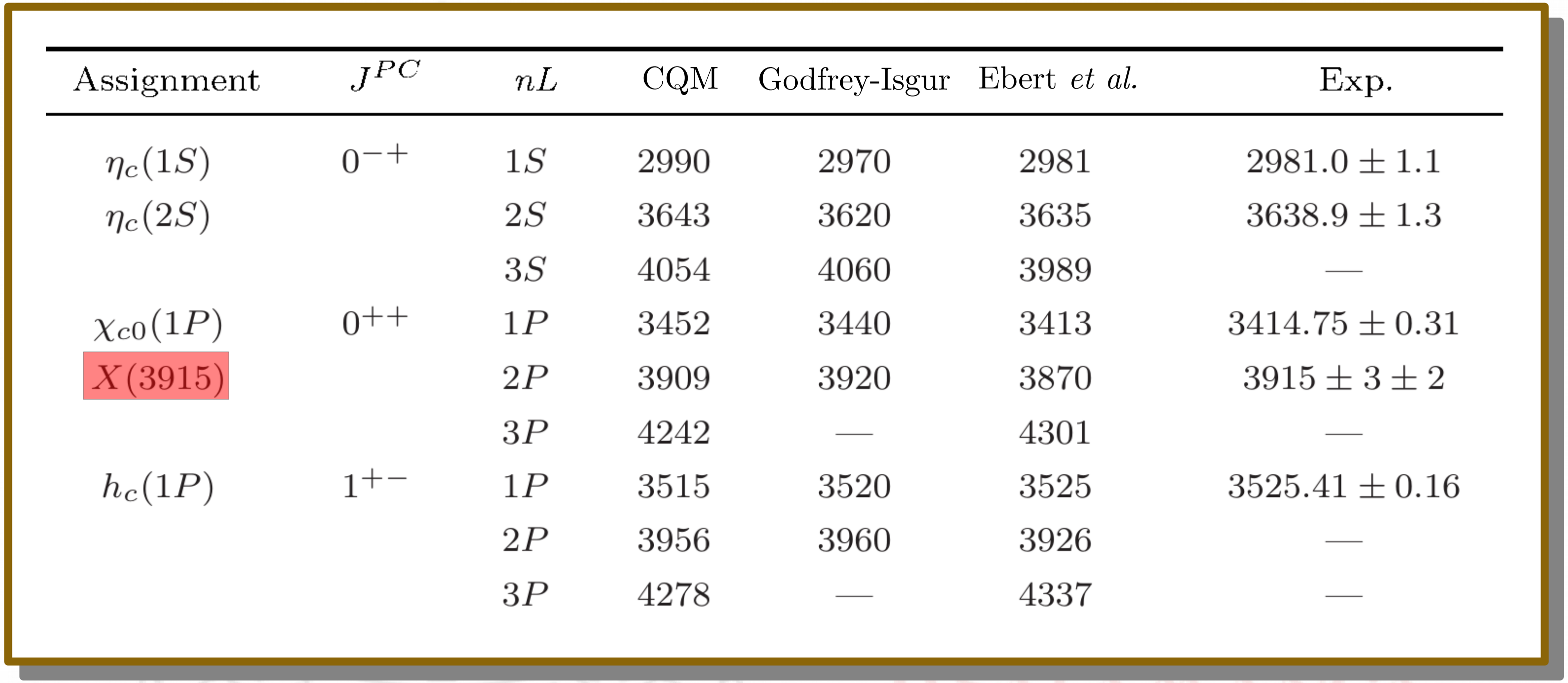


$n\,^{2s+1}\ell_J$ J^{PC}	$\mathrm{I}=0$ $c\bar{c}$	$\mathrm{I}=0$ $b\bar{b}$	$\mathrm{I}=\frac{1}{2}$ $c\bar{u}, c\bar{d}; \bar{c}u, \bar{c}d$	$\mathrm{I}=0$ $c\bar{s}; \bar{c}s$	$\mathrm{I}=\frac{1}{2}$ $b\bar{u}, b\bar{d}; \bar{b}u, \bar{b}d$	$\mathrm{I}=0$ $b\bar{s}; \bar{b}s$	$\mathrm{I}=0$ $b\bar{c}; \bar{b}c$
$1\,^1S_0$ 0^{-+}	$\boldsymbol{\eta_c(1S)}$	$\boldsymbol{\eta_b(1S)}$	$\boldsymbol{D}$	$\boldsymbol{D_s^\pm}$	$\boldsymbol{B}$	$\boldsymbol{B_s^0}$	$\boldsymbol{B_c^\pm}$
$1\,^3S_1$ 1^{--}	$\boldsymbol{J/\psi(1S)}$	$\boldsymbol{\Upsilon(1S)}$	$\boldsymbol{D^*}$	$\boldsymbol{D_s^{*\pm}}$	$\boldsymbol{B^*}$	B_s^*	
$1\,^1P_1$ 1^{+-}	$\boldsymbol{h_c(1P)}$	$\boldsymbol{h_b(1P)}$	$\boldsymbol{D_1(2420)}$	$\boldsymbol{D_{s1}(2536)^\pm}$	$\boldsymbol{B_1(5721)}$	$\boldsymbol{B_{s1}(5830)^0}$	
$1\,^3P_0$ 0^{++}	$\boldsymbol{\chi_{c0}(1P)}$	$\boldsymbol{\chi_{b0}(1P)}$	$\boldsymbol{D_0^*(2400)}$	$\boldsymbol{D_{s0}^*(2317)^{\pm\dagger}}$			
$1\,^3P_1$ 1^{++}	$\boldsymbol{\chi_{c1}(1P)}$	$\boldsymbol{\chi_{b1}(1P)}$	$D_1(2430)$	$\boldsymbol{D_{s1}(2460)^{\pm\dagger}}$			
$1\,^3P_2$ 2^{++}	$\boldsymbol{\chi_{c2}(1P)}$	$\boldsymbol{\chi_{b2}(1P)}$	$\boldsymbol{D_2^*(2460)}$	$\boldsymbol{D_{s2}^*(2573)^\pm}$	$\boldsymbol{B_2^*(5747)}$	$\boldsymbol{B_{s2}^*(5840)^0}$	
$1\,^3D_1$ 1^{--}	$\boldsymbol{\psi(3770)}$			$D_{s1}^*(2860)^{\pm\ddagger}$			
$1\,^3D_3$ 3^{--}			$D_3^*(2750)^\pm$	$D_{s3}^*(2860)^\pm$			
$2\,^1S_0$ 0^{-+}	$\boldsymbol{\eta_c(2S)}$	$\eta_b(2S)$	$D(2550)$				$B_c(2S)^\pm$
$2\,^3S_1$ 1^{--}	$\boldsymbol{\psi(2S)}$	$\boldsymbol{\Upsilon(2S)}$		$\boldsymbol{D_{s1}^*(2700)^{\pm\ddagger}}$			
$3\,^3S_1$ 1^{--}		$\boldsymbol{\Upsilon(3S)}$					
$4\,^3S_1$ 1^{--}		$\boldsymbol{\Upsilon(4S)}$					
$2\,^1P_1$ 1^{+-}		$h_b(2P)$					
$2\,^3P_{0,1,2}$ $0^{++}, 1^{++}, 2^{++}$	$\boldsymbol{\chi_{c2}(2P)}$	$\boldsymbol{\chi_{b0,1,2}(2P)}$					
$3\,^3P_{0,1,2}$ $0^{++}, 1^{++}, 2^{++}$		$\boldsymbol{\chi_b(3P)}$					
$1\,^3D_2$ 2^{--}		$\boldsymbol{\Upsilon(1D)}$					

Charmonium: A total of 37 states

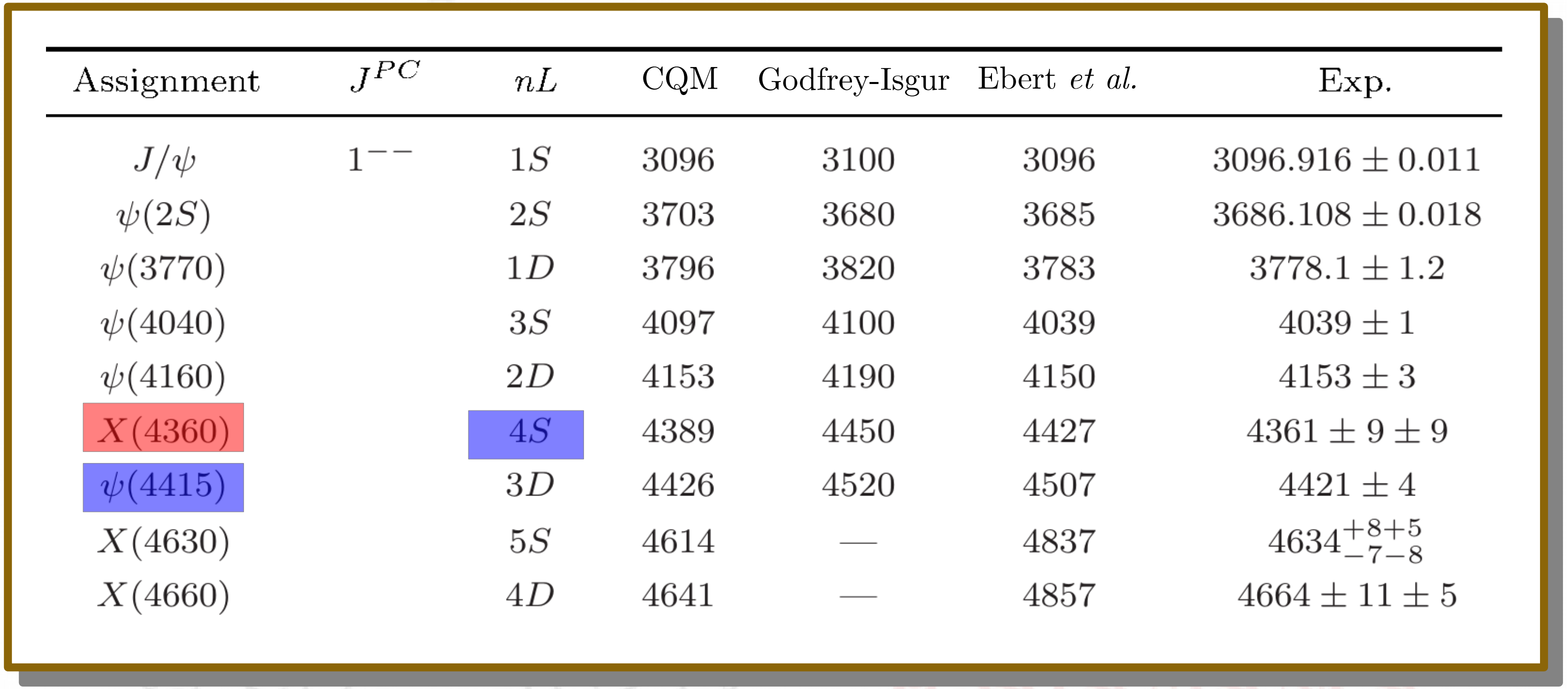
Bottomonium: A total of 20 states

Charmonium



Assignment	J^{PC}	nL	CQM	Godfrey-Isgur	Ebert *et al.*	Exp.
$\eta_c(1S)$	0^{-+}	$1S$	2990	2970	2981	2981.0 ± 1.1
$\eta_c(2S)$		$2S$	3643	3620	3635	3638.9 ± 1.3
		$3S$	4054	4060	3989	—
$\chi_{c0}(1P)$	0^{++}	$1P$	3452	3440	3413	3414.75 ± 0.31
$X(3915)$		$2P$	3909	3920	3870	$3915 \pm 3 \pm 2$
		$3P$	4242	—	4301	—
$h_c(1P)$	1^{+-}	$1P$	3515	3520	3525	3525.41 ± 0.16
		$2P$	3956	3960	3926	—
		$3P$	4278	—	4337	—

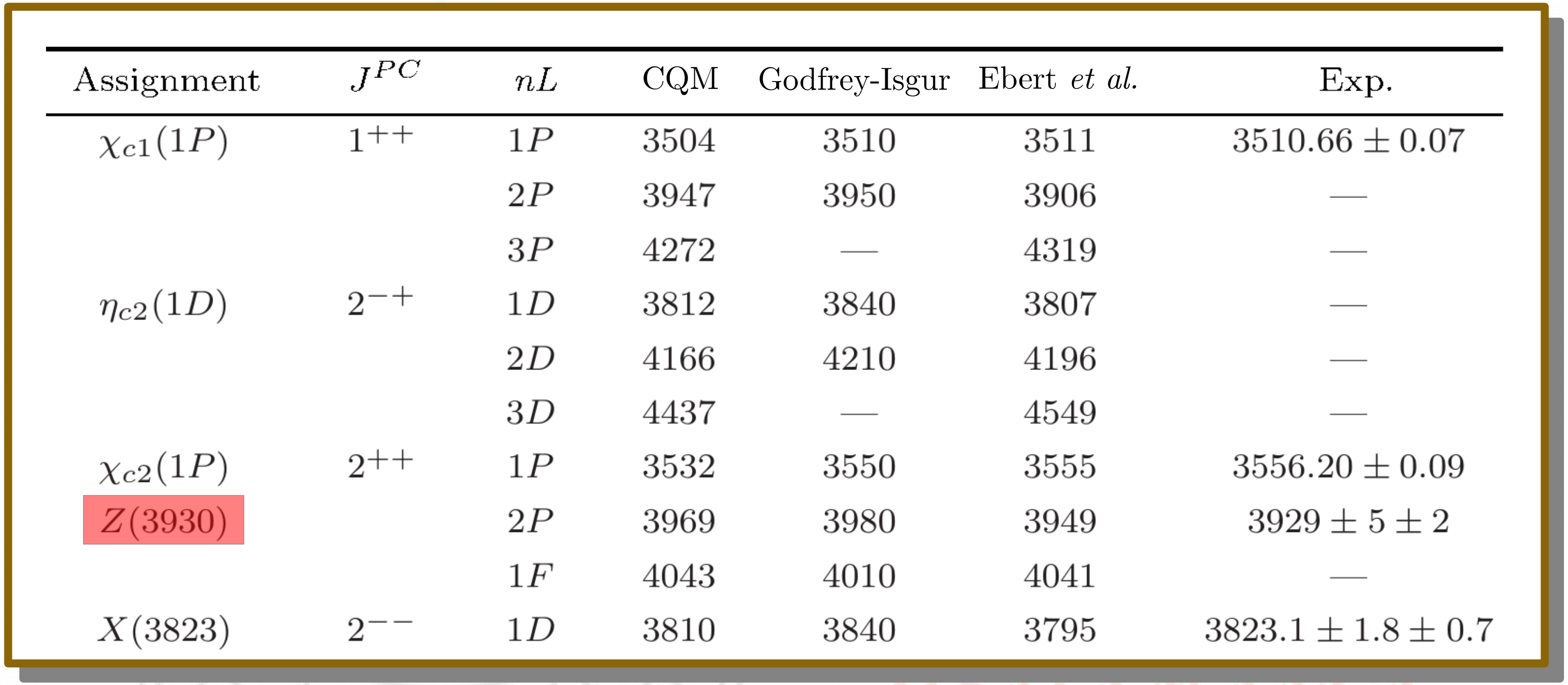
Charmonium



Assignment	J^{PC}	nL	CQM	Godfrey-Isgur	Ebert *et al.*	Exp.
J/ψ	1^{--}	$1S$	3096	3100	3096	3096.916 ± 0.011
$\psi(2S)$		$2S$	3703	3680	3685	3686.108 ± 0.018
$\psi(3770)$		$1D$	3796	3820	3783	3778.1 ± 1.2
$\psi(4040)$		$3S$	4097	4100	4039	4039 ± 1
$\psi(4160)$		$2D$	4153	4190	4150	4153 ± 3
$X(4360)$		$4S$	4389	4450	4427	$4361 \pm 9 \pm 9$
$\psi(4415)$		$3D$	4426	4520	4507	4421 ± 4
$X(4630)$		$5S$	4614	—	4837	4634^{+8+5}_{-7-8}
$X(4660)$		$4D$	4641	—	4857	$4664 \pm 11 \pm 5$

$$\left\{ \begin{array}{l} D^{(*)}\bar{D}^{(*)} \sim 7\% \\ D\bar{D}_1 \sim 48\% \\ D\bar{D}_2^* \sim 25\% \end{array} \right.$$

Charmonium



Assignment	J^{PC}	nL	CQM	Godfrey-Isgur	Ebert *et al.*	Exp.
$\chi_{c1}(1P)$	1^{++}	$1P$	3504	3510	3511	3510.66 ± 0.07
		$2P$	3947	3950	3906	—
		$3P$	4272	—	4319	—
$\eta_{c2}(1D)$	2^{-+}	$1D$	3812	3840	3807	—
		$2D$	4166	4210	4196	—
		$3D$	4437	—	4549	—
$\chi_{c2}(1P)$	2^{++}	$1P$	3532	3550	3555	3556.20 ± 0.09
$Z(3930)$		$2P$	3969	3980	3949	$3929 \pm 5 \pm 2$
		$1F$	4043	4010	4041	—
$X(3823)$	2^{--}	$1D$	3810	3840	3795	$3823.1 \pm 1.8 \pm 0.7$

Charmonium

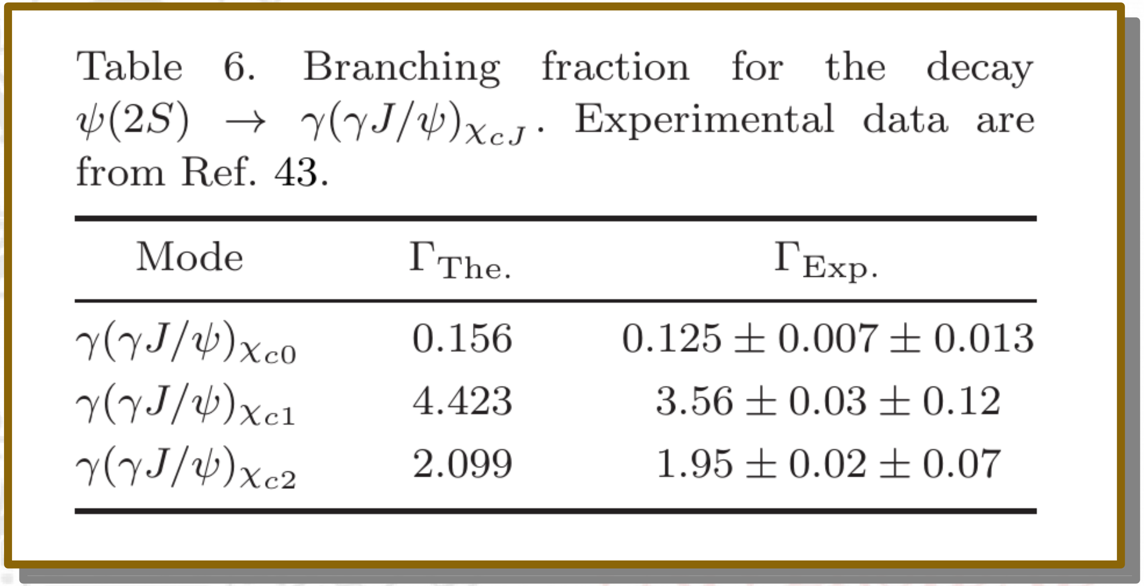


Table 6. Branching fraction for the decay $\psi(2S) \to \gamma(\gamma J/\psi)_{\chi_{cJ}}$. Experimental data are from Ref. 43.

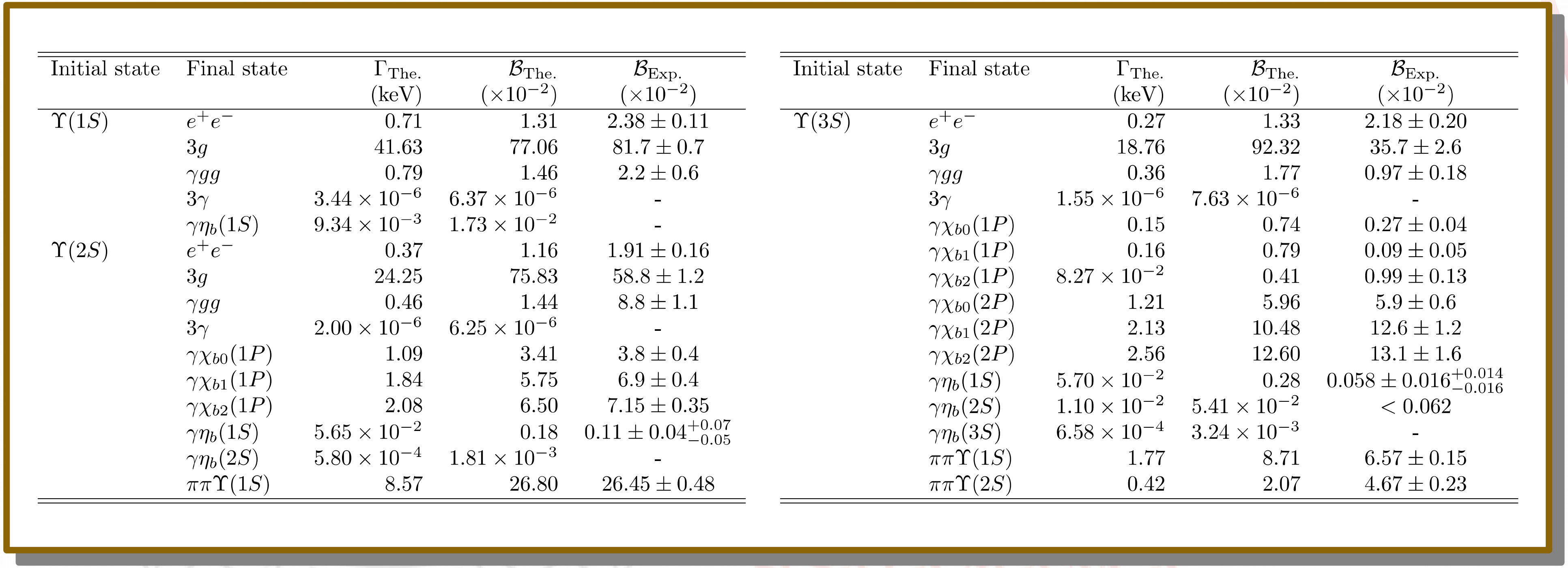
Mode	$\Gamma_{\text{The.}}$	$\Gamma_{\text{Exp.}}$
$\gamma(\gamma J/\psi)_{\chi_{c0}}$	0.156	$0.125 \pm 0.007 \pm 0.013$
$\gamma(\gamma J/\psi)_{\chi_{c1}}$	4.423	$3.56 \pm 0.03 \pm 0.12$
$\gamma(\gamma J/\psi)_{\chi_{c2}}$	2.099	$1.95 \pm 0.02 \pm 0.07$

Bottomonium

State	J^{PC}	nL	The. (MeV)	Exp. (MeV)
η_b	0^{-+}	$1S$	9455	9398.0 ± 3.2
		$2S$	9990	$9999.0 \pm 3.5^{+2.8}_{-1.9}$
		$3S$	10330	-
χ_{b0}	0^{++}	$1P$	9855	$9859.44 \pm 0.42 \pm 0.31$
		$2P$	10221	$10232.5 \pm 0.4 \pm 0.5$
		$3P$	10500	-
h_b	1^{+-}	$1P$	9879	9899.3 ± 1.0
		$2P$	10240	$10259.8 \pm 0.5 \pm 1.1$
		$3P$	10516	-
χ_{b1}	1^{++}	$1P$	9874	$9892.78 \pm 0.26 \pm 0.31$
		$2P$	10236	$10255.46 \pm 0.22 \pm 0.50$
		$3P$	10513	$1513.42 \pm 0.41 \pm 0.18$
χ_{b2}	2^{++}	$1P$	9886	$9912.21 \pm 0.26 \pm 0.31$
		$2P$	10246	$10268.65 \pm 0.22 \pm 0.50$
		$1F$	10315	-
		$3P$	10521	$10524.02 \pm 0.57 \pm 0.18$
		$2F$	10569	-

State	J^{PC}	nL	The. (MeV)	Exp. (MeV)
Υ	1^{--}	$1S$	9502	9460.30 ± 0.26
		$2S$	10015	10023.26 ± 0.31
		$1D$	10117	-
		$3S$	10349	10355.2 ± 0.5
		$2D$	10414	-
		$4S$	10607	10579.4 ± 1.2
		$3D$	10653	-
		$5S$	10818	10876 ± 11
		$4D$	10853	-
		$6S$	10995	11019 ± 8
		$5D$	11023	-
Υ_2	2^{--}	$1D$	10122	10163.7 ± 1.4
		$2D$	10418	-
		$3D$	10657	-
h_{b3}	3^{+-}	$1F$	10322	-
		$2F$	10573	-
		$3F$	10785	-

Bottomonium



Initial state	Final state	$\Gamma_{\text{The.}}$ (keV)	$\mathcal{B}_{\text{The.}}$ $(\times 10^{-2})$	$\mathcal{B}_{\text{Exp.}}$ $(\times 10^{-2})$
$\Upsilon(1S)$	e^+e^-	0.71	1.31	2.38 ± 0.11
	$3g$	41.63	77.06	81.7 ± 0.7
	γgg	0.79	1.46	2.2 ± 0.6
	3γ	3.44×10^{-6}	6.37×10^{-6}	-
	$\gamma\eta_b(1S)$	9.34×10^{-3}	1.73×10^{-2}	-
$\Upsilon(2S)$	e^+e^-	0.37	1.16	1.91 ± 0.16
	$3g$	24.25	75.83	58.8 ± 1.2
	γgg	0.46	1.44	8.8 ± 1.1
	3γ	2.00×10^{-6}	6.25×10^{-6}	-
	$\gamma\chi_{b0}(1P)$	1.09	3.41	3.8 ± 0.4
	$\gamma\chi_{b1}(1P)$	1.84	5.75	6.9 ± 0.4
	$\gamma\chi_{b2}(1P)$	2.08	6.50	7.15 ± 0.35
	$\gamma\eta_b(1S)$	5.65×10^{-2}	0.18	$0.11 \pm 0.04^{+0.07}_{-0.05}$
	$\gamma\eta_b(2S)$	5.80×10^{-4}	1.81×10^{-3}	-
	$\pi\pi\Upsilon(1S)$	8.57	26.80	26.45 ± 0.48

Initial state	Final state	$\Gamma_{\text{The.}}$ (keV)	$\mathcal{B}_{\text{The.}}$ $(\times 10^{-2})$	$\mathcal{B}_{\text{Exp.}}$ $(\times 10^{-2})$
$\Upsilon(3S)$	e^+e^-	0.27	1.33	2.18 ± 0.20
	$3g$	18.76	92.32	35.7 ± 2.6
	γgg	0.36	1.77	0.97 ± 0.18
	3γ	1.55×10^{-6}	7.63×10^{-6}	-
	$\gamma\chi_{b0}(1P)$	0.15	0.74	0.27 ± 0.04
	$\gamma\chi_{b1}(1P)$	0.16	0.79	0.09 ± 0.05
	$\gamma\chi_{b2}(1P)$	8.27×10^{-2}	0.41	0.99 ± 0.13
	$\gamma\chi_{b0}(2P)$	1.21	5.96	5.9 ± 0.6
	$\gamma\chi_{b1}(2P)$	2.13	10.48	12.6 ± 1.2
	$\gamma\chi_{b2}(2P)$	2.56	12.60	13.1 ± 1.6
	$\gamma\eta_b(1S)$	5.70×10^{-2}	0.28	$0.058 \pm 0.016^{+0.014}_{-0.016}$
	$\gamma\eta_b(2S)$	1.10×10^{-2}	5.41×10^{-2}	< 0.062
	$\gamma\eta_b(3S)$	6.58×10^{-4}	3.24×10^{-3}	-
	$\pi\pi\Upsilon(1S)$	1.77	8.71	6.57 ± 0.15
	$\pi\pi\Upsilon(2S)$	0.42	2.07	4.67 ± 0.23

Bottomonium

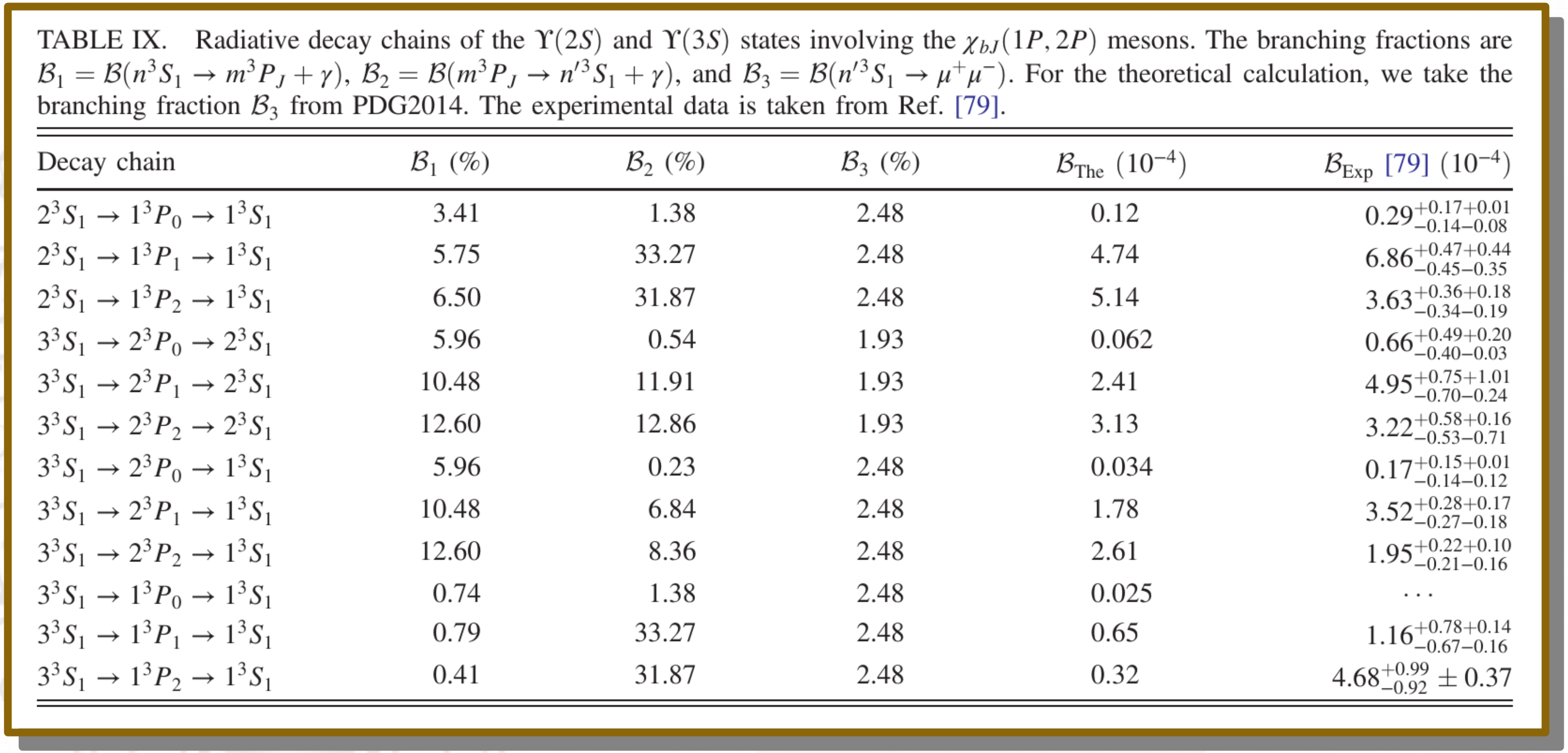
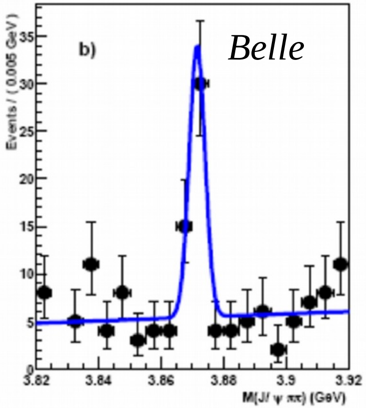


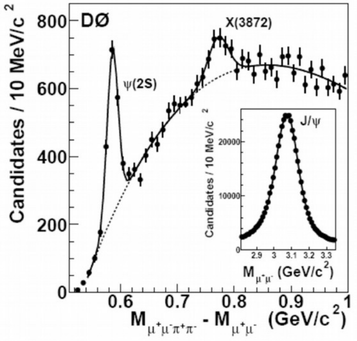
TABLE IX. Radiative decay chains of the $\Upsilon(2S)$ and $\Upsilon(3S)$ states involving the $\chi_{bJ}(1P,2P)$ mesons. The branching fractions are $\mathcal{B}_1 = \mathcal{B}(n^3S_1 \to m^3P_J + \gamma)$, $\mathcal{B}_2 = \mathcal{B}(m^3P_J \to n'^3S_1 + \gamma)$, and $\mathcal{B}_3 = \mathcal{B}(n'^3S_1 \to \mu^+\mu^-)$. For the theoretical calculation, we take the branching fraction $\mathcal{B}_3$ from PDG2014. The experimental data is taken from Ref. [79].

Decay chain	$\mathcal{B}_1$ (%)	$\mathcal{B}_2$ (%)	$\mathcal{B}_3$ (%)	$\mathcal{B}_{\text{The}}$ (10^{-4})	$\mathcal{B}_{\text{Exp}}$ [79] (10^{-4})
$2^3S_1 \to 1^3P_0 \to 1^3S_1$	3.41	1.38	2.48	0.12	$0.29^{+0.17+0.01}_{-0.14-0.08}$
$2^3S_1 \to 1^3P_1 \to 1^3S_1$	5.75	33.27	2.48	4.74	$6.86^{+0.47+0.44}_{-0.45-0.35}$
$2^3S_1 \to 1^3P_2 \to 1^3S_1$	6.50	31.87	2.48	5.14	$3.63^{+0.36+0.18}_{-0.34-0.19}$
$3^3S_1 \to 2^3P_0 \to 2^3S_1$	5.96	0.54	1.93	0.062	$0.66^{+0.49+0.20}_{-0.40-0.03}$
$3^3S_1 \to 2^3P_1 \to 2^3S_1$	10.48	11.91	1.93	2.41	$4.95^{+0.75+1.01}_{-0.70-0.24}$
$3^3S_1 \to 2^3P_2 \to 2^3S_1$	12.60	12.86	1.93	3.13	$3.22^{+0.58+0.16}_{-0.53-0.71}$
$3^3S_1 \to 2^3P_0 \to 1^3S_1$	5.96	0.23	2.48	0.034	$0.17^{+0.15+0.01}_{-0.14-0.12}$
$3^3S_1 \to 2^3P_1 \to 1^3S_1$	10.48	6.84	2.48	1.78	$3.52^{+0.28+0.17}_{-0.27-0.18}$
$3^3S_1 \to 2^3P_2 \to 1^3S_1$	12.60	8.36	2.48	2.61	$1.95^{+0.22+0.10}_{-0.21-0.16}$
$3^3S_1 \to 1^3P_0 \to 1^3S_1$	0.74	1.38	2.48	0.025	...
$3^3S_1 \to 1^3P_1 \to 1^3S_1$	0.79	33.27	2.48	0.65	$1.16^{+0.78+0.14}_{-0.67-0.16}$
$3^3S_1 \to 1^3P_2 \to 1^3S_1$	0.41	31.87	2.48	0.32	$4.68^{+0.99}_{-0.92} \pm 0.37$

The X(3872)

- *Discovered by Belle in 2003*
- *Confirmed by CDFII, D0 and BaBar*
- *LHCb set the quantum numbers to* $J^{PC}=1^{++}$ *in 2014*
- $\frac{\Gamma(\omega J/\psi)}{\Gamma(\pi^+\pi^- J/\psi)} = 0.8 \pm 0.3$ *Difficult to explain as a* $c\bar{c}$ *state*
- *Mass very close to* $D^0\bar{D}^{*0}$ *threshold*
- *Ratio can be easily explained on the molecular picture due to the mass difference between* $D^0\bar{D}^{*0}$ *and* $D^+\bar{D}^{*-}$
- *Possible explanations*
  - *Pure molecule*
  - *Mixed* $c\bar{c} - D\bar{D}^*$ *molecule*
  - *Tetraquark*
  - *Hybrid*





Molecular picture

Use symmetries of QCD:

- *Heavy Quark Spin Symmetry*

  Hidden-charm sector:

  A $D^*\bar{D}^*\ 2^{++}$ *should appear as a bound state X(4012)*

  Other states depends on additional assumptions

- *Heavy Flavor Symmetry*

  Hidden-bottom sector

  $B\bar{B}^*\ 1^{++}$ *and* $B^*\bar{B}^*\ 2^{++}$ *analogs as bound states*

  Other states depends on additional assumptions

$$\boxed{V(D\bar{D}^*\,1^{++}) \quad = \quad V(D^*\bar{D}^*\,2^{++})}$$

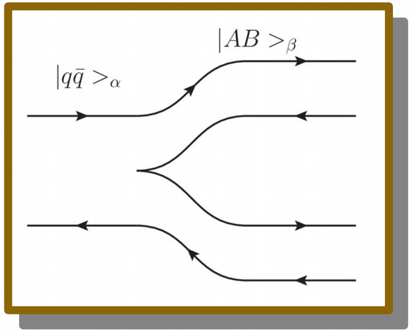
$$\boxed{V(B^{(*)}\bar{B}^{(*)}) \quad = \quad V(D^{(*)}\bar{D}^{(*)})}$$

Molecular picture

Bottom partner of the X(3872):

- *Not found by CMS, Phys. Lett. B 727, 57 (2013)* $\Upsilon(1S)\pi^+\pi^-$
- *Not found by ATLAS, Phys. Lett. B 740, 199 (2015)*
- *Not found by Belle, Phys. Rev. Lett. 113, 142001 (2014)* $\Upsilon(1S)\omega$

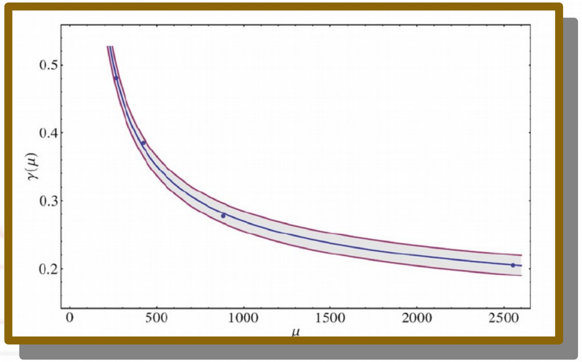
Quark model



- *Strong decays* ► *one meson and two-meson states are coupled*
- *On the quark model means that $q\bar{q}$ and $qq\bar{q}\bar{q}$ should be mixed*
- *Coupling:*
  - *Microscopic model (like Cornell)*
  - *Phenomenological 3P0 model, OZI allowed decays*
- *On the 3P0 model there is only one parameter*

$$\gamma(\mu) = \frac{\gamma_0}{\log(\frac{\mu}{\mu_0})}$$

$$\gamma_0 = 0.81 \pm 0.02$$



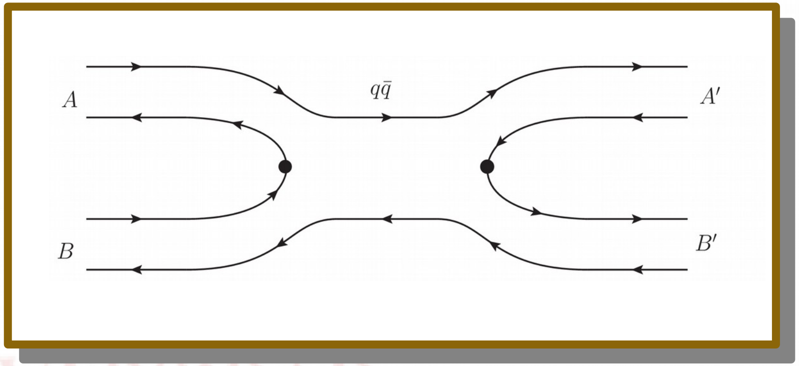
J. Segovia, DRE, F. Fernández, Phys. Lett. B 715, 322 (2012)

Two meson dynamics

Hadronic state: $|\Psi\rangle = \sum_\alpha c_\alpha |\psi\rangle + \sum_\beta \chi_\beta(P) |\phi_{M1}\phi_{M2}\beta\rangle$

Two meson dynamics: $\sum_\beta \int \left(H^{M_1 M_2}_{\beta'\beta}(P',P) + V^{eff}_{\beta'\beta}(P',P) \right) \chi_\beta(P) P^2 dP = E\chi_{\beta'}(P')$

$$V^{eff}_{\beta'\beta}(P',P) = \sum_\alpha \frac{h_{\beta'\alpha}(P')h_{\alpha\beta}(P)}{E - M_\alpha}$$



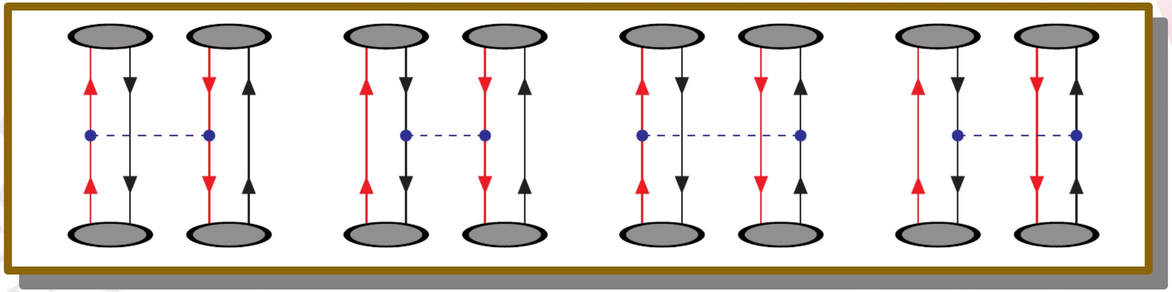
The effective potential is:

- *Attractive for states above threshold*
- *Repulsive for states below threshold*

Two meson dynamics

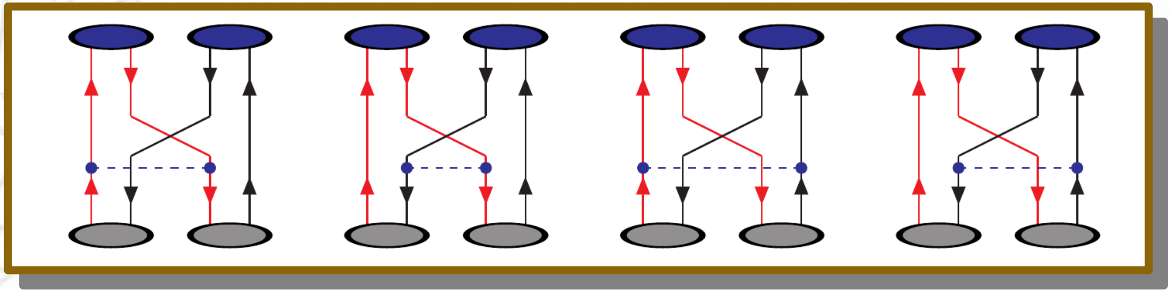
Direct terms:

- *No change of quark content*
- *Cancel for color interactions*



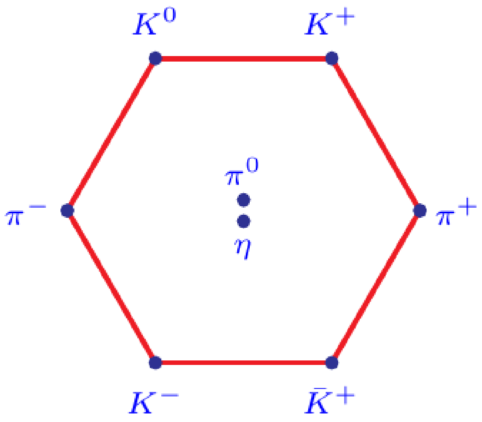
Rearrangement process:

- *Change quark content*
- *Color interactions contribute*
- *Suppressed*



The Quiral Quark Model

- *Spontaneous Chiral Symmetry Breaking*
  Pseudo-goldstone boson exchange
- *One gluon exchange*
- *Confinement*



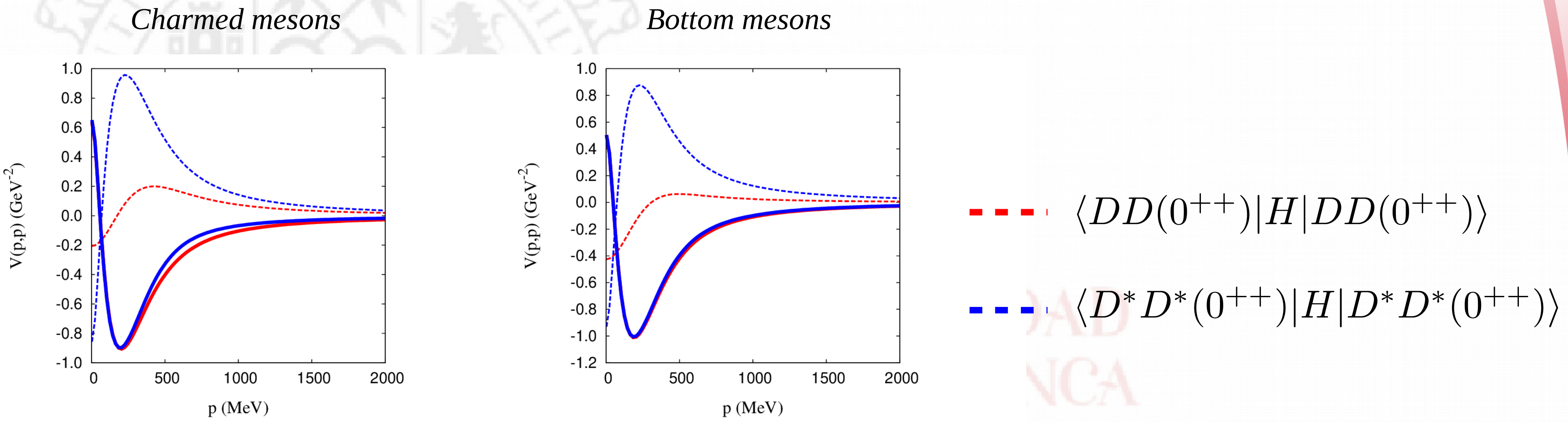
$$V_{q_i q_j} = \begin{cases} q_i q_j = nn \Rightarrow V_{CON} + V_{OGE} + V_{GBE} + V_{SBE} \\ q_i q_j = nQ \Rightarrow V_{CON} + V_{OGE} \\ q_i q_j = QQ \Rightarrow V_{CON} + V_{OGE} \end{cases}$$

A. Manohar and H. Georgi, Nucl. Phys. B 324 (1984)
F. Fernández et al., J. Phys. G 19 (1993)

HQSS and HFS

Heavy Quark Spin Symmetry and Heavy Flavor Symmetry is fulfilled by the model

$$\frac{2}{\sqrt{3}}\langle D^*D^*(0^{++})|H_I|DD(0^{++})\rangle \;=\; \langle DD(0^{++})|H_I|DD(0^{++})\rangle - \langle D^*D^*(0^{++})|H_I|D^*D^*(0^{++})\rangle$$



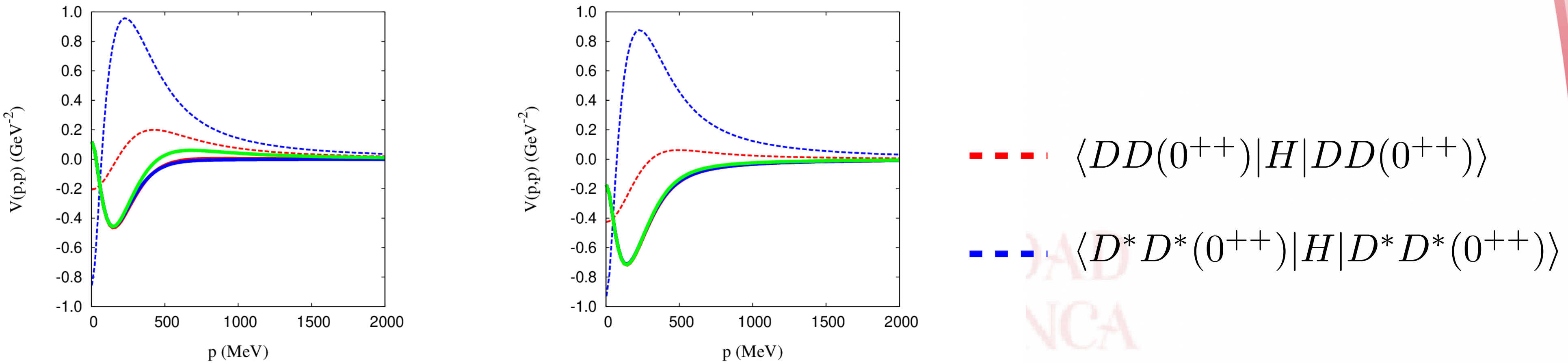
Charmed mesons

Bottom mesons

HQSS and HFS

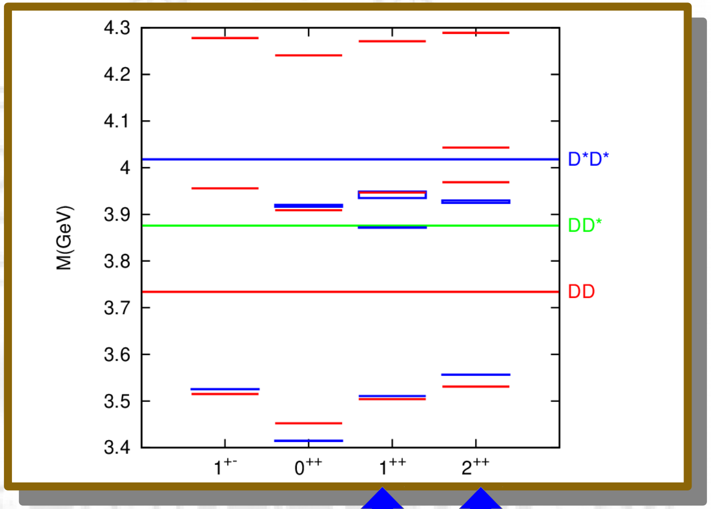
Heavy Quark Spin Symmetry and Heavy Flavor Symmetry is fulfilled by the model

$$
\begin{aligned}
\langle DD^*(1^{++})|H_I|DD^*(1^{++})\rangle &= \langle D^*D^*(2^{++})|H_I|D^*D^*(2^{++})\rangle \\
&= \frac{3}{2}\left[\langle DD(0^{++})|H_I|DD(0^{++})\rangle - \frac{1}{3}\langle D^*D^*(0^{++})|H_I|D^*D^*(0^{++})\rangle\right]
\end{aligned}
$$

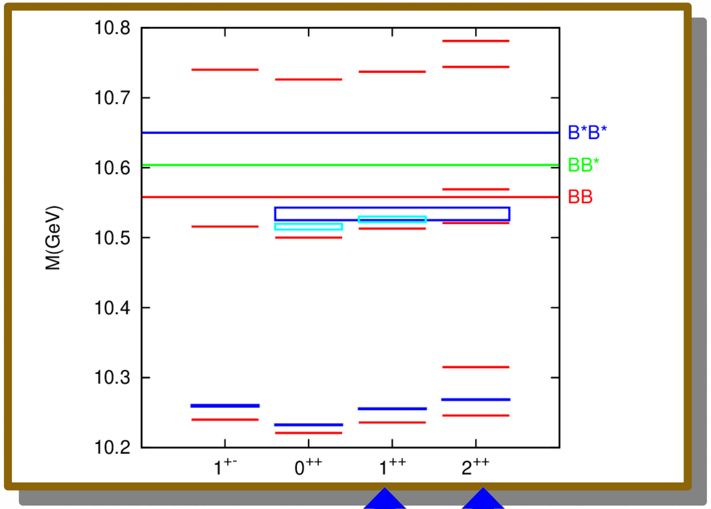


HQSS and HFS breaking

Charmonium



Bottomonium



$D\bar{D}^*$ $D^*\bar{D}^*$

$B\bar{B}^*$ $B^*\bar{B}^*$

Two meson thresholds can generate deviations from HQSS and HFS expectations

Deviations from HQSS and HFS

- *The 1^{++} channel does not bind without coupling to the $\chi_{c1}(2P)$*
- *We get an additional state, the X(3872), when we couple to the $\chi_{c1}(2P)$ and the $\chi_{c1}(2P)$ state appears as a candidate to the X(3940)*
- *We don't get a bound state for the 2^{++} channels. Differs from HQSS expectations*
- *We don't get the the 1^{++} bottom analog although is close to bind. Differs from HFS*
- *We get a 2^{++} bottom analog.*

The 3.9 GeV region

- *The X(3872) Belle 2003. LHCb determined to be a 1^{++} state in 2014*
- *The Y(3940) Belle 2005.*
  - *BaBar confirmed it in 2008 with a mass around 3914*
  - *Belle in 2010 reported a state with mass 3915 and possible 0^{++} or 2^{++} quantum numbers the X(3915) that was relabeled $\chi_{c0}(2P)$*
  - *Guo and Meissner, and Olsen challenged this assignment*
    - $X(3915) \to \omega J/\psi$ Too large
    - *Not seen on* $D\bar{D}$
    - *Mass splitting with the 2^{++} too small*
  - *Zhou reanalyzed the data finding a 2^{+} assignment*
  - *Relabeled as X(3915)*
- *The X(3930) Belle 2006. J=2 was assigned to be the $\chi_{c2}(2P)$ although lower in mass expected in the naive quark model.*
- *The X(3940) Belle 2007. $J^{PC}=?^{??}$ not seen on $D\bar{D}$ and seen on $D\bar{D}^*$. Suggests 1^{++}*
- *The X(3860) Belle 2017. 0^{++} favored*

The 3.9 GeV region

$J^{PC}=0^{++}$	$2^3P_0(c\bar{c})$	$D\bar{D}$	$\omega J/\psi$	$D_s\bar{D}_s$	$D^*\bar{D}^*$
		3724	3880	3937	4017

$J^{PC}=2^{++}$	$2^3P_2(c\bar{c})$	$D\bar{D}$	$\omega J/\psi$	$D_s\bar{D}_s$	$D^*\bar{D}^*$	$D\bar{D}^*+D^*\bar{D}$
		3724	3880	3937	4017	3877

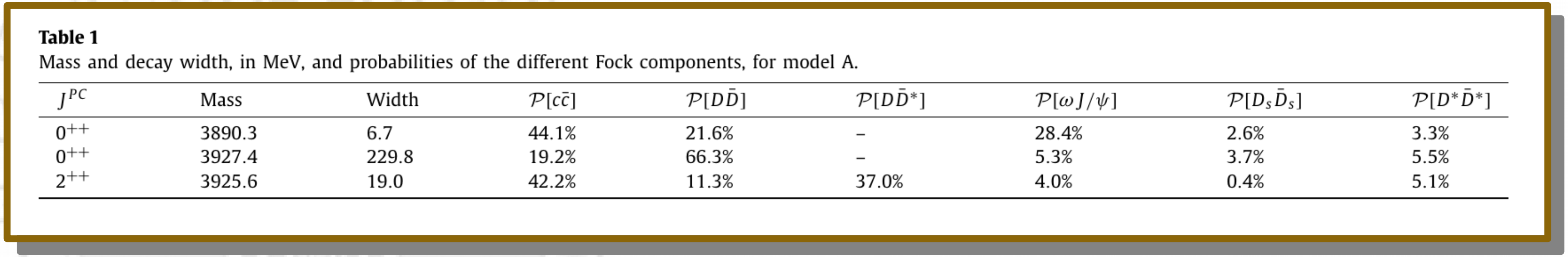


Table 1

Mass and decay width, in MeV, and probabilities of the different Fock components, for model A.

J^{PC}	Mass	Width	$\mathcal{P}[c\bar{c}]$	$\mathcal{P}[D\bar{D}]$	$\mathcal{P}[D\bar{D}^*]$	$\mathcal{P}[\omega J/\psi]$	$\mathcal{P}[D_s\bar{D}_s]$	$\mathcal{P}[D^*\bar{D}^*]$
0^{++}	3890.3	6.7	44.1%	21.6%	–	28.4%	2.6%	3.3%
0^{++}	3927.4	229.8	19.2%	66.3%	–	5.3%	3.7%	5.5%
2^{++}	3925.6	19.0	42.2%	11.3%	37.0%	4.0%	0.4%	5.1%

Width of the first 0^{++} state with high uncertainty G.L. Yu et al. Arxiv: 1704.06763

Two possible scenarios:

- *X(3860) second 0^{++}, no Y(3940) and X(3915)/X(3930) with the 2^{++}*
- *X(3860) first 0^{++}, Y(3940) second 0^{++} and X(3915)/X(3930) with the 2^{++}*

Hyperfine splitting differs from naive quark model

The 3.9 GeV region

$J^{PC}=0^{++}$	$2^3P_0(c\bar{c})$	$D\bar{D}$	$\omega J/\psi$	$D_s\bar{D}_s$	$D^*\bar{D}^*$
		3724	3880	3937	4017

$J^{PC}=2^{++}$	$2^3P_2(c\bar{c})$	$D\bar{D}$	$\omega J/\psi$	$D_s\bar{D}_s$	$D^*\bar{D}^*$	$D\bar{D}^*+D^*\bar{D}$
		3724	3880	3937	4017	3877

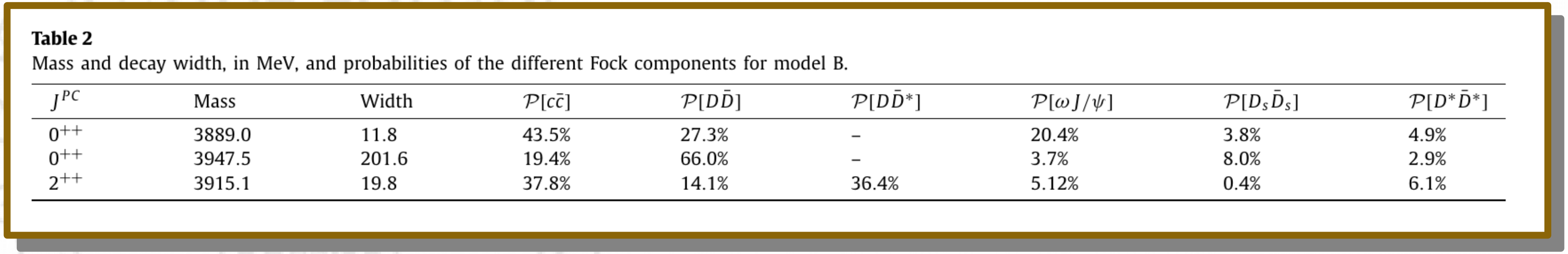


Table 2

Mass and decay width, in MeV, and probabilities of the different Fock components for model B.

J^{PC}	Mass	Width	$\mathcal{P}[c\bar{c}]$	$\mathcal{P}[D\bar{D}]$	$\mathcal{P}[D\bar{D}^*]$	$\mathcal{P}[\omega J/\psi]$	$\mathcal{P}[D_s\bar{D}_s]$	$\mathcal{P}[D^*\bar{D}^*]$
0^{++}	3889.0	11.8	43.5%	27.3%	–	20.4%	3.8%	4.9%
0^{++}	3947.5	201.6	19.4%	66.0%	–	3.7%	8.0%	2.9%
2^{++}	3915.1	19.8	37.8%	14.1%	36.4%	5.12%	0.4%	6.1%

Slight change of the parameters better agreement for the second hypothesis

Hyperfine splitting in distorted by the coupling with two meson channels

Hyperfine splitting differs from naive quark model

The 3.9 GeV region

$J^{PC}=0^{++}$	$2^3P_0(c\bar{c})$	$D\bar{D}$	$\omega J/\psi$	$D_s\bar{D}_s$	$D^*\bar{D}^*$
		3724	3880	3937	4017

$J^{PC}=2^{++}$	$2^3P_2(c\bar{c})$	$D\bar{D}$	$\omega J/\psi$	$D_s\bar{D}_s$	$D^*\bar{D}^*$	$D\bar{D}^*+D^*\bar{D}$
		3724	3880	3937	4017	3877

$X(3915)$

$X(3930)$

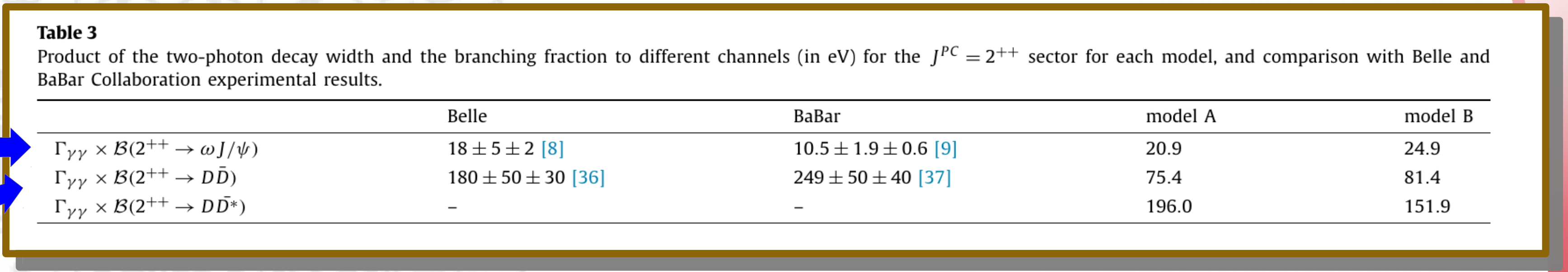


Table 3

Product of the two-photon decay width and the branching fraction to different channels (in eV) for the $J^{PC}=2^{++}$ sector for each model, and comparison with Belle and BaBar Collaboration experimental results.

	Belle	BaBar	model A	model B
$\Gamma_{\gamma\gamma}\times\mathcal{B}(2^{++}\to\omega J/\psi)$	$18\pm5\pm2$ [8]	$10.5\pm1.9\pm0.6$ [9]	20.9	24.9
$\Gamma_{\gamma\gamma}\times\mathcal{B}(2^{++}\to D\bar{D})$	$180\pm50\pm30$ [36]	$249\pm50\pm40$ [37]	75.4	81.4
$\Gamma_{\gamma\gamma}\times\mathcal{B}(2^{++}\to D\bar{D}^*)$	–	–	196.0	151.9

Test the X(3915)/X(3930) hypothesis:

- *Data for the X(3915) can be understand with the 2^{++} assignment (0^{++} would be too high)*
- *Data for the X(3940) in agreement if we consider final DD states through DD**

Some new resonances

- *LHCb measured the X(4140), X(4274), X(4500) and X(4700)*
- *X(4140) measured previously by CDF, D0, CMS, Belle and BaBar*
- *X(4140) and X(4274) are* 1^{++}
- *X(4500) and X(4700) are* 0^{++}
- *For the X(4140)*
  - *Multiquark models (Lebeled and Polosa) expected the X(4140) but the X(4274) expected as a* 0^{-+}
  - *Molecular interpretation expected X(4140) as a* 0^{++} *or* 2^{++} $D_s^*\bar{D}_s^*$ *molecule*
  - *Tetraquark models expected* 0^{-+}, 1^{-+} *or* 0^{++}, 2^{++} *states*
- *For the X(4500) and X(4700)*
  - *A virtual state at 4.48 GeV is predicted by Wang et al.*
- *Naive quark model also has states in this energy region*

The χ_{c1}(3P)

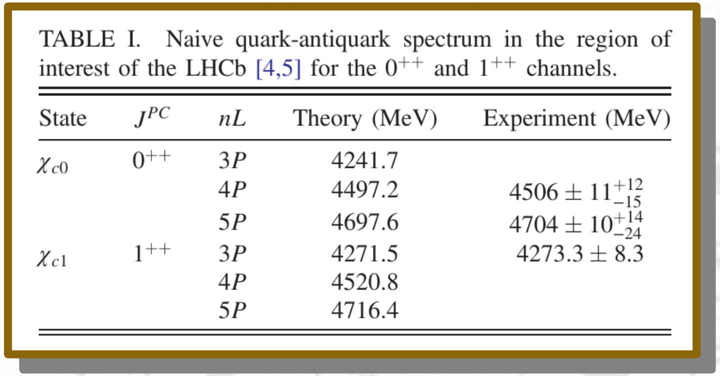


TABLE I. Naive quark-antiquark spectrum in the region of interest of the LHCb [4,5] for the 0^{++} and 1^{++} channels.

State	J^{PC}	nL	Theory (MeV)	Experiment (MeV)
χ_{c0}	0^{++}	$3P$	4241.7	
		$4P$	4497.2	$4506 \pm 11^{+12}_{-15}$
		$5P$	4697.6	$4704 \pm 10^{+14}_{-24}$
χ_{c1}	1^{++}	$3P$	4271.5	4273.3 ± 8.3
		$4P$	4520.8	
		$5P$	4716.4	

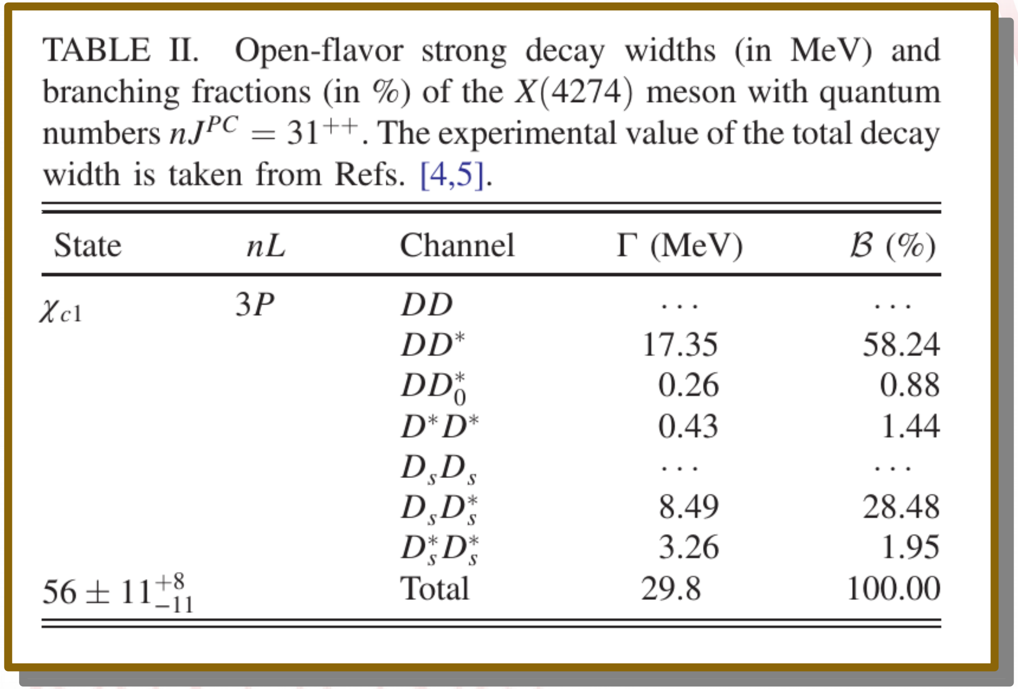


TABLE II. Open-flavor strong decay widths (in MeV) and branching fractions (in %) of the $X(4274)$ meson with quantum numbers $nJ^{PC} = 31^{++}$. The experimental value of the total decay width is taken from Refs. [4,5].

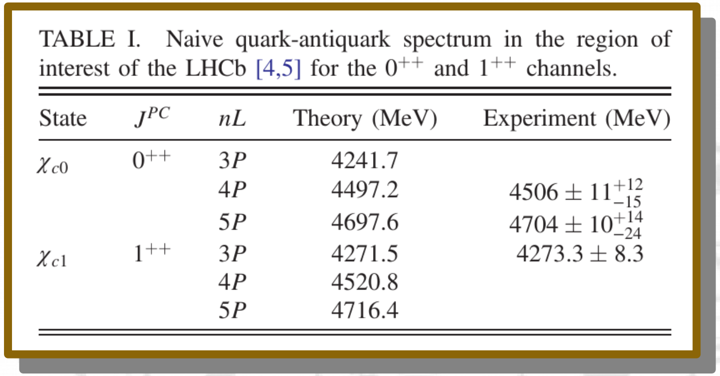
State	nL	Channel	Γ (MeV)	$\mathcal{B}$ (%)
χ_{c1}	$3P$	DD	...	...
		DD^*	17.35	58.24
		DD_0^*	0.26	0.88
		D^*D^*	0.43	1.44
		D_sD_s	...	...
		$D_sD_s^*$	8.49	28.48
		$D_s^*D_s^*$	3.26	1.95
$56 \pm 11^{+8}_{-11}$		Total	29.8	100.00

The χ_{c1}(3P) has a mass compatible with the X(4274)

The width is close to the experimental Value. However other experiment found evidences of the X(4274)

- *CDF* $\Gamma = 32^{+22}_{-15} \pm 8$ MeV
- *CMS* $\Gamma = 38^{+30}_{-15} \pm 16$ MeV

The χ_{c0}(4P)



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χ_{c0}	0^{++}	$3P$	4241.7	
		$4P$	4497.2	$4506 \pm 11^{+12}_{-15}$
		$5P$	4697.6	$4704 \pm 10^{+14}_{-24}$
χ_{c1}	1^{++}	$3P$	4271.5	4273.3 ± 8.3
		$4P$	4520.8	
		$5P$	4716.4	

The χ_{c0}(4P) has a mass and width compatible with the X(4500)

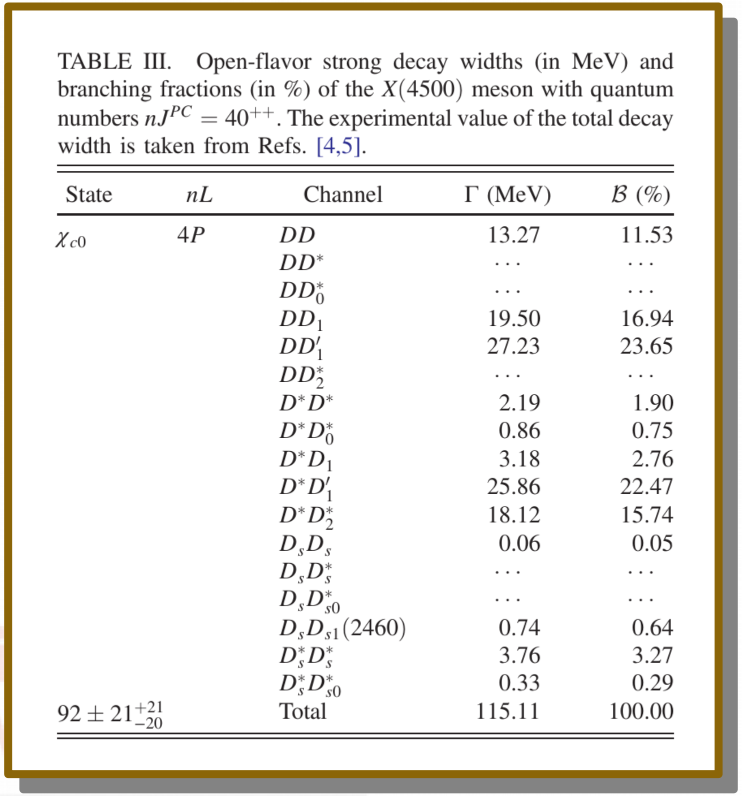

TABLE III. Open-flavor strong decay widths (in MeV) and branching fractions (in %) of the $X(4500)$ meson with quantum numbers $nJ^{PC} = 40^{++}$. The experimental value of the total decay width is taken from Refs. [4,5].

State	nL	Channel	Γ (MeV)	$\mathcal{B}$ (%)
χ_{c0}	$4P$	DD	13.27	11.53
		DD^*	⋯	⋯
		DD_0^*	⋯	⋯
		DD_1	19.50	16.94
		DD_1'	27.23	23.65
		DD_2^*	⋯	⋯
		D^*D^*	2.19	1.90
		$D^*D_0^*$	0.86	0.75
		D^*D_1	3.18	2.76
		D^*D_1'	25.86	22.47
		$D^*D_2^*$	18.12	15.74
		D_sD_s	0.06	0.05
		$D_sD_s^*$	⋯	⋯
		$D_sD_{s0}^*$	⋯	⋯
		$D_sD_{s1}(2460)$	0.74	0.64
		$D_s^*D_s^*$	3.76	3.27
		$D_s^*D_{s0}^*$	0.33	0.29
$92 \pm 21^{+21}_{-20}$		Total	115.11	100.00

The χ_{c0}(5P)

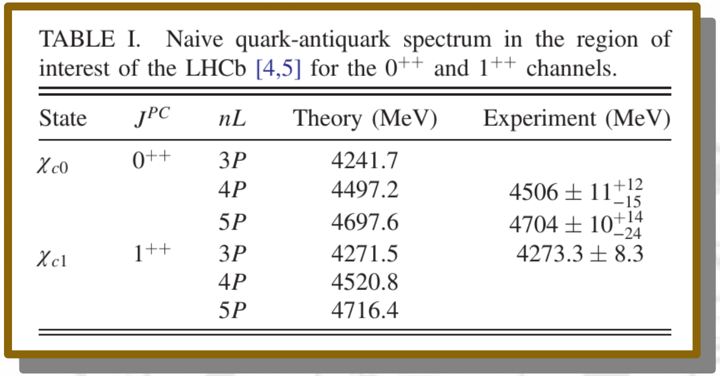

TABLE I. Naive quark-antiquark spectrum in the region of interest of the LHCb [4,5] for the 0^{++} and 1^{++} channels.

State	J^{PC}	nL	Theory (MeV)	Experiment (MeV)
χ_{c0}	0^{++}	$3P$	4241.7	
		$4P$	4497.2	$4506 \pm 11^{+12}_{-15}$
		$5P$	4697.6	$4704 \pm 10^{+14}_{-24}$
χ_{c1}	1^{++}	$3P$	4271.5	4273.3 ± 8.3
		$4P$	4520.8	
		$5P$	4716.4	

The χ_{c0}(5P) has a mass and width compatible with the X(4700)

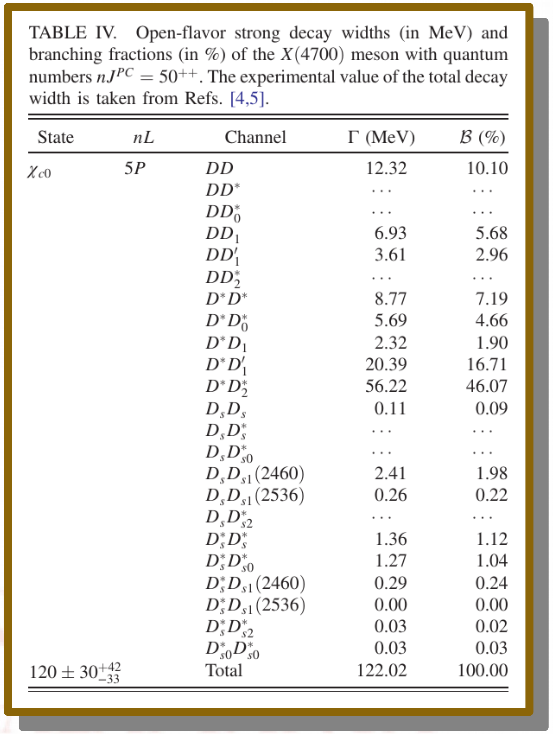

TABLE IV. Open-flavor strong decay widths (in MeV) and branching fractions (in %) of the $X(4700)$ meson with quantum numbers $nJ^{PC} = 50^{++}$. The experimental value of the total decay width is taken from Refs. [4,5].

State	nL	Channel	Γ (MeV)	$\mathcal{B}$ (%)
χ_{c0}	$5P$	DD	12.32	10.10
		DD^*	$\cdots$	$\cdots$
		DD_0^*	$\cdots$	$\cdots$
		DD_1	6.93	5.68
		DD_1'	3.61	2.96
		DD_2^*	$\cdots$	$\cdots$
		D^*D^*	8.77	7.19
		$D^*D_0^*$	5.69	4.66
		D^*D_1	2.32	1.90
		D^*D_1'	20.39	16.71
		$D^*D_2^*$	56.22	46.07
		D_sD_s	0.11	0.09
		$D_sD_s^*$	$\cdots$	$\cdots$
		$D_sD_{s0}^*$	$\cdots$	$\cdots$
		$D_sD_{s1}(2460)$	2.41	1.98
		$D_sD_{s1}(2536)$	0.26	0.22
		$D_sD_{s2}^*$	$\cdots$	$\cdots$
		$D_s^*D_s^*$	1.36	1.12
		$D_s^*D_{s0}^*$	1.27	1.04
		$D_s^*D_{s1}(2460)$	0.29	0.24
		$D_s^*D_{s1}(2536)$	0.00	0.00
		$D_s^*D_{s2}^*$	0.03	0.02
		$D_{s0}^*D_{s0}^*$	0.03	0.03
$120 \pm 30^{+42}_{-33}$		Total	122.02	100.00

The X(4140)

The naive quark model does not have a 1^{++} state at 4140 Maybe a molecule?

1^{++} $D_s\bar{D}_s^*$, $D_s^*\bar{D}_s^*$, and $J/\psi\phi$

0^{++} $D^*\bar{D}_1^{(\prime)}$, $D_s\bar{D}_s$, $D_s^*\bar{D}_s^*$, and $J/\psi\phi$

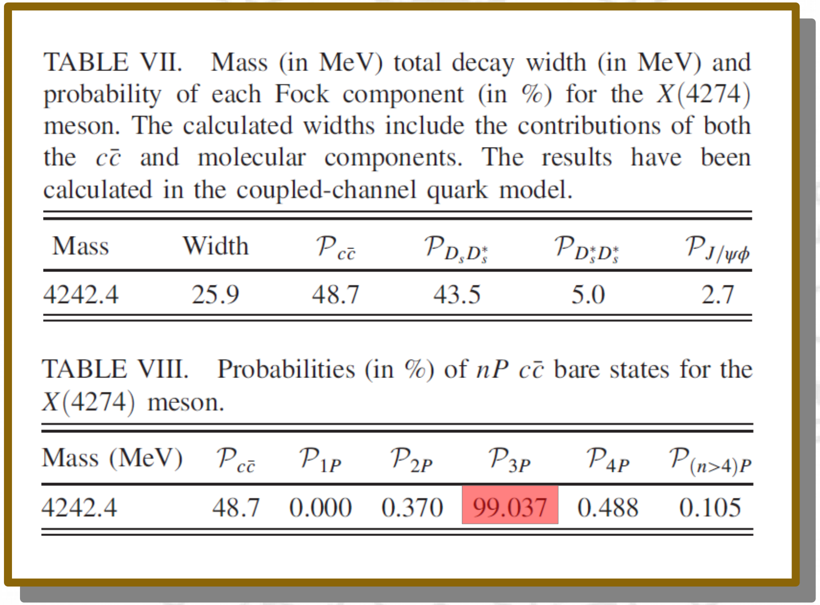

TABLE VII. Mass (in MeV) total decay width (in MeV) and probability of each Fock component (in %) for the $X(4274)$ meson. The calculated widths include the contributions of both the $c\bar{c}$ and molecular components. The results have been calculated in the coupled-channel quark model.

Mass	Width	$\mathcal{P}_{c\bar{c}}$	$\mathcal{P}_{D_sD_s^*}$	$\mathcal{P}_{D_s^*D_s^*}$	$\mathcal{P}_{J/\psi\phi}$
4242.4	25.9	48.7	43.5	5.0	2.7

TABLE VIII. Probabilities (in %) of nP $c\bar{c}$ bare states for the $X(4274)$ meson.

Mass (MeV)	$\mathcal{P}_{c\bar{c}}$	$\mathcal{P}_{1P}$	$\mathcal{P}_{2P}$	$\mathcal{P}_{3P}$	$\mathcal{P}_{4P}$	$\mathcal{P}_{(n>4)P}$
4242.4	48.7	0.000	0.370	99.037	0.488	0.105

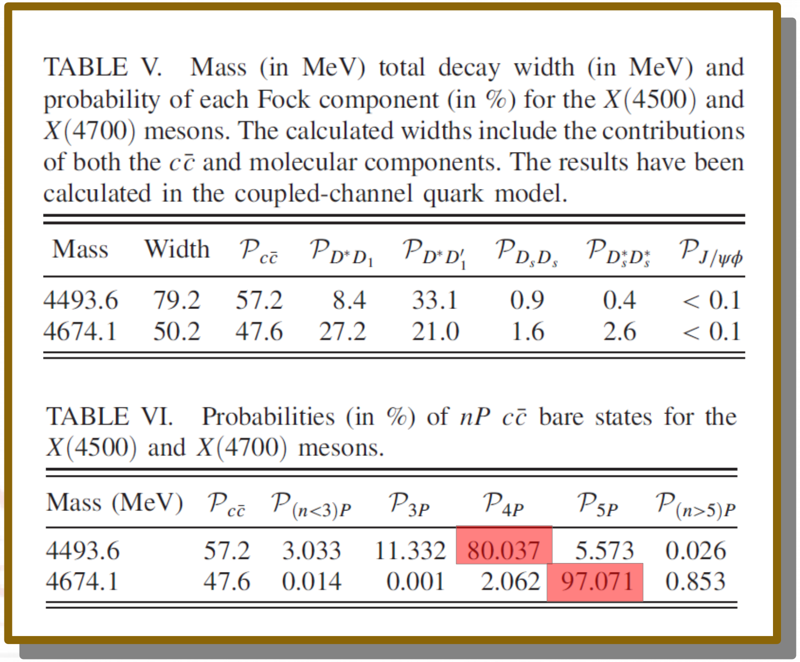

TABLE V. Mass (in MeV) total decay width (in MeV) and probability of each Fock component (in %) for the $X(4500)$ and $X(4700)$ mesons. The calculated widths include the contributions of both the $c\bar{c}$ and molecular components. The results have been calculated in the coupled-channel quark model.

Mass	Width	$\mathcal{P}_{c\bar{c}}$	$\mathcal{P}_{D^*D_1}$	$\mathcal{P}_{D^*D_1'}$	$\mathcal{P}_{D_sD_s}$	$\mathcal{P}_{D_s^*D_s^*}$	$\mathcal{P}_{J/\psi\phi}$
4493.6	79.2	57.2	8.4	33.1	0.9	0.4	< 0.1
4674.1	50.2	47.6	27.2	21.0	1.6	2.6	< 0.1

TABLE VI. Probabilities (in %) of nP $c\bar{c}$ bare states for the $X(4500)$ and $X(4700)$ mesons.

Mass (MeV)	$\mathcal{P}_{c\bar{c}}$	$\mathcal{P}_{(n<3)P}$	$\mathcal{P}_{3P}$	$\mathcal{P}_{4P}$	$\mathcal{P}_{5P}$	$\mathcal{P}_{(n>5)P}$
4493.6	57.2	3.033	11.332	80.037	5.573	0.026
4674.1	47.6	0.014	0.001	2.062	97.071	0.853

Conclusions

- *The naive quark model gives a good guidance to heavy meson spectroscopy*
- *One meson and two meson channels should be coupled*
  - *HQSS and HFS expectations for molecules can change by nearby* $c\bar{c}$ *or* $b\bar{b}$ *states*
  - *Hyperfine splittings on naive quark model expectations can change by nearby two meson channels*
- *Some states above threshold can be understood within the naive quark model with small influence of nearby thresholds.*