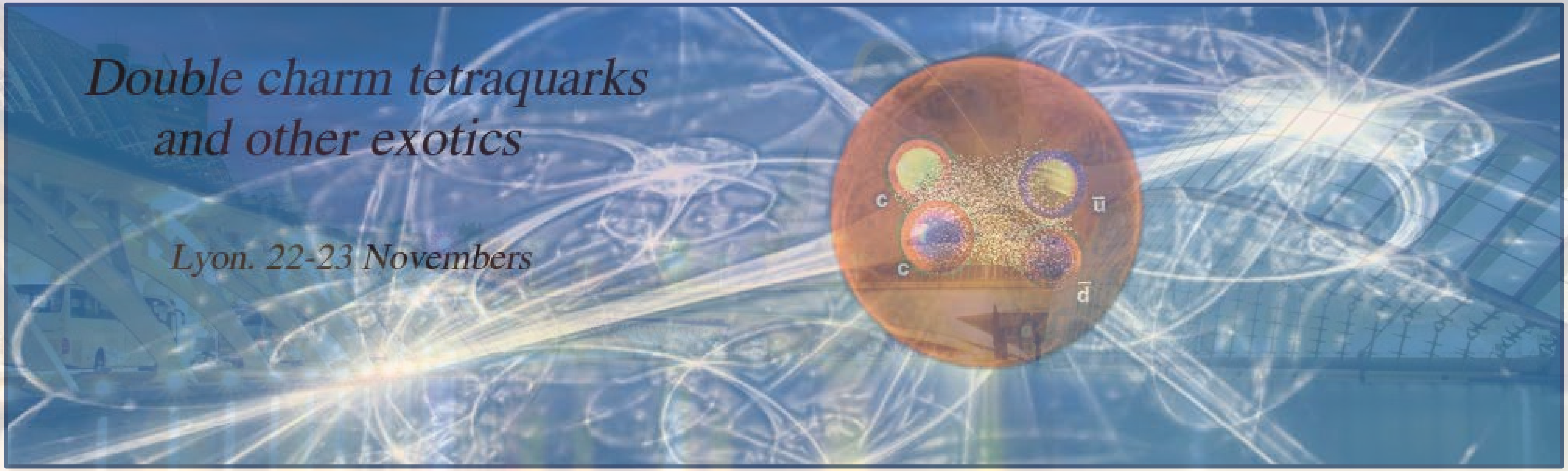
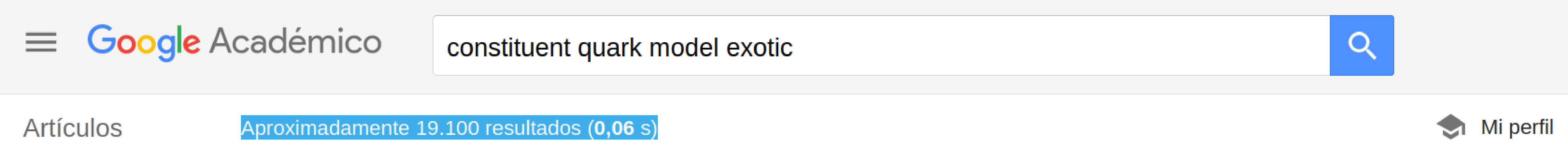
Constituent quark model. What have we learned?



J. Vijande PhD
University of Valencia, Spain

Double charm tetraquarks and other exotics

Double charm tetraquarks and other exotics



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Literature Authors Jo

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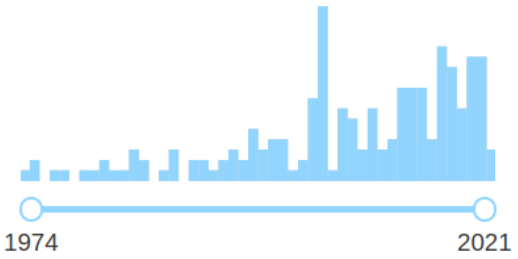

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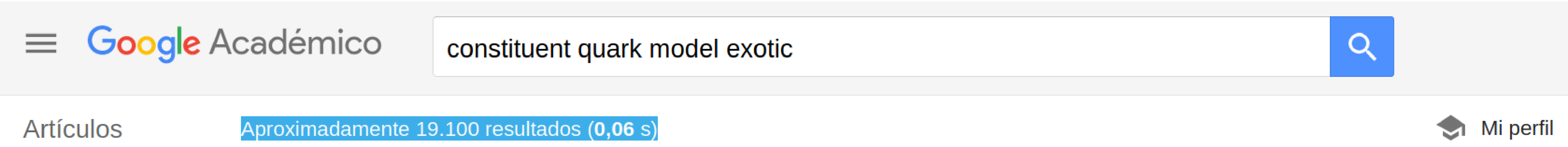
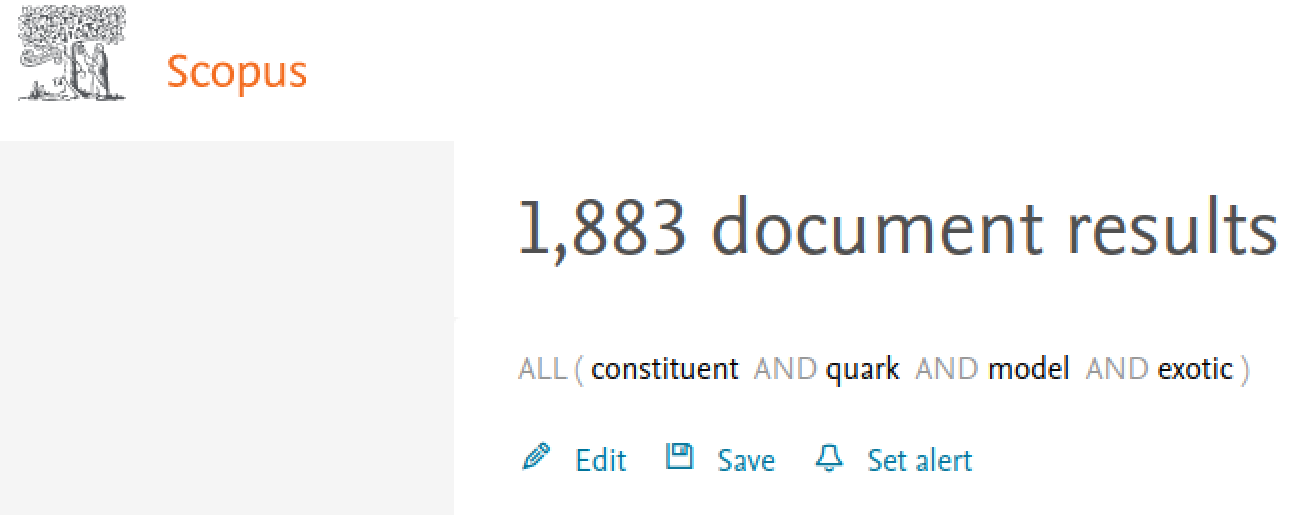
Double charm tetraquarks and other exotics





First, let me apologize if I do not quote your favorite paper.

Double charm tetraquarks and other exotics

- And second, I will mostly focus this talk on what can we learn from the constituent quark model approach in the double heavy four-quark sector.

- Topics I will not cover
  - QCD sum rules.
  - Lattice QCD.
  - Dinamically generated resonances.
  - Phenomenological mass-based relations.
  - etc…

Double *heavy* tetraquarks and *very little*, *if any*, *about* other exotics

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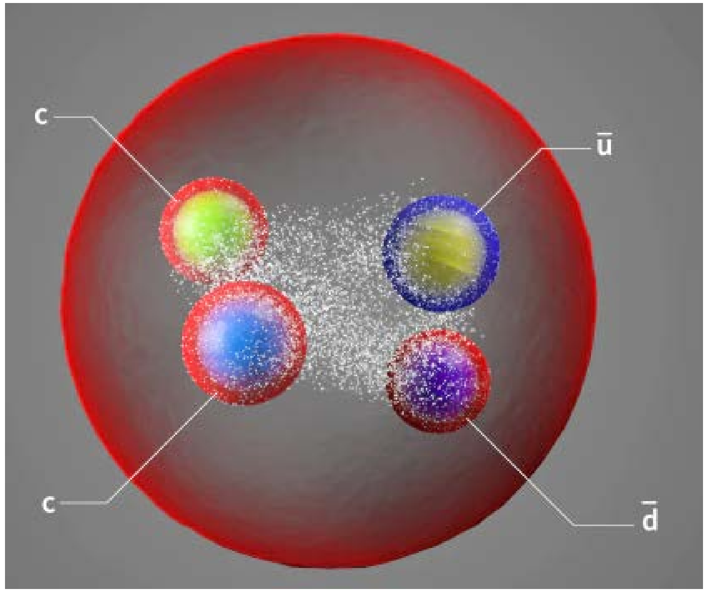
The basics

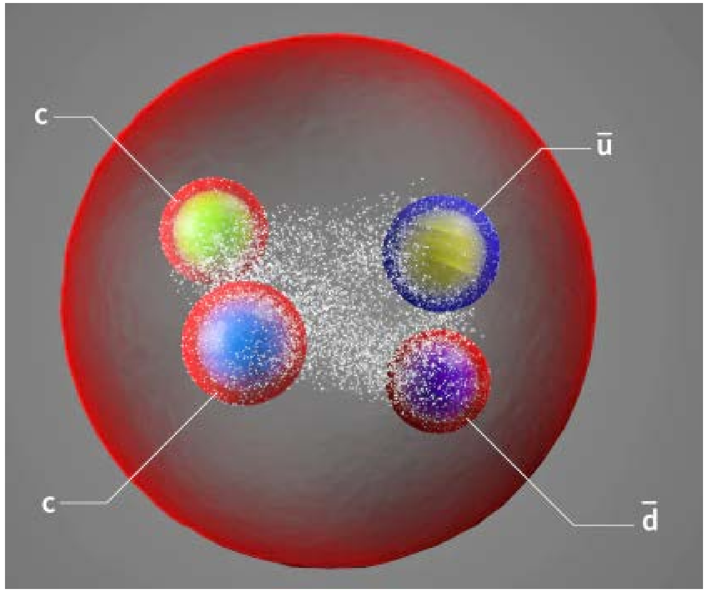


- The constituent quark model have (probably surprisingly) described rather well mesons and baryons as composite objects made of constituent valence quarks

$$m_c \approx 1.3\,GeV \qquad m_b \approx 5\,GeV \qquad m_u \approx 0.3\,GeV$$

interacting by means of a potential, normally pairwise, but not always.

The basics



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interacting by means of a potential, normally pairwise, but not always.

- A four-quark state is the simplest object with a non-trivial color structure.

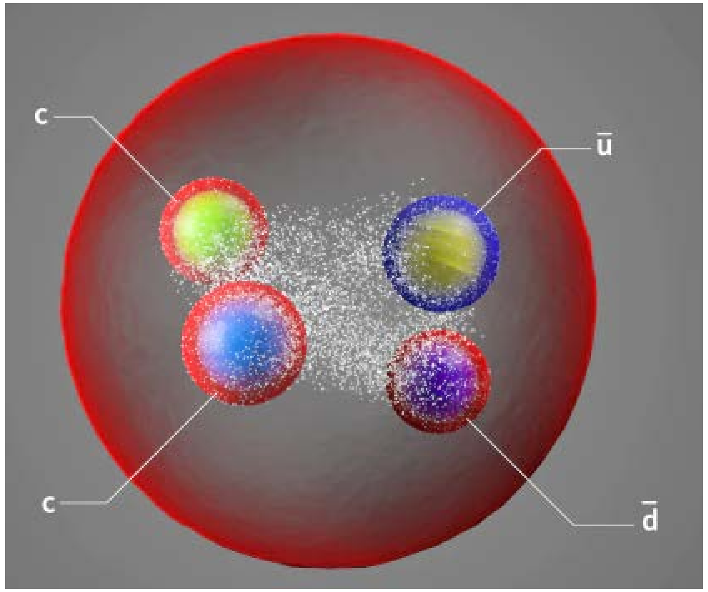
$$3 \otimes \bar{3} = 1$$

$$3 \otimes 3 \otimes \bar{3} \otimes \bar{3} \rightarrow \begin{cases} \bar{3}_{qq} \otimes 3_{\bar{q}\bar{q}} = 1 \\ 6_{qq} \otimes \bar{6}_{\bar{q}\bar{q}} = 1 \end{cases}$$

$$3 \otimes 3 \otimes 3 \otimes \bar{3} \otimes \bar{3} \otimes \bar{3} \rightarrow \begin{cases} 1_{q\bar{q}} \otimes 1_{q\bar{q}} \otimes 1_{q\bar{q}} = 1 & 1_{q\bar{q}} \otimes 8_{q\bar{q}} \otimes 8_{q\bar{q}} = 1 \\ 8_{q\bar{q}} \otimes 1_{q\bar{q}} \otimes 8_{q\bar{q}} = 1 & 8_{q\bar{q}} \otimes 8_{q\bar{q}} \otimes 1_{q\bar{q}} = 1 \\ 8_{q\bar{q}} \otimes 8_{q\bar{q}} \otimes 8_{q\bar{q}} = 1 & 8_{q\bar{q}} \otimes 8_{q\bar{q}} \otimes 8_{q\bar{q}} = 1 \end{cases}$$

$$|meson\rangle = \alpha_1 |q\bar{q}\rangle + \alpha_2 |qq\bar{q}\bar{q}\rangle + \alpha_3 |qqq\bar{q}\bar{q}\bar{q}\rangle + \ldots$$

The basics



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But for charm equal ±2 $\rightarrow$

$$|T_{cc}\rangle = \alpha_2 |cc\overline{qq}\rangle + \alpha_3 |ccq\overline{qqq}\rangle + \dots$$

VNIVERSITAT DE VALÈNCIA

In the begining. The year 1982

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PHYSICAL REVIEW D VOLUME 25, NUMBER 9 1 MAY 1982

Do narrow heavy multiquark states exist?

J.-P. Ader J.-M. Richard P. Taxil

(Received 11 August 1981)

We discuss the existence of states made of four heavy quarks in the context of potential models already used in the study of heavy mesons and baryons. [...]

$cc\bar{c}\bar{c}$ $cu\bar{c}\bar{d}$

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the α particle lies below the threshold for the decay into two deuterons. In quark physics, one of the most important problems today, experimentally and theoretically, is whether or not narrow multiquark states do exist. In this paper we do not in-

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The authors consider **linear+coulomb** and **power-law** potentials and a **variational approach** using a harmonic oscillator wave function .

More complex options are included for the all-heavy four-quark states (chromomagnetic interaction, bag model, negative parity states, etc…)

$$V^{\mathrm{I}}_{Q\bar{Q}}(r) = -\tfrac{16}{3} V^{\mathrm{I}}_{8}(r) = -\tfrac{4}{3}\frac{\alpha_s}{r} + \lambda r \, ,$$

$$V^{\mathrm{II}}_{Q\bar{Q}}(r) = -\tfrac{16}{3} V^{\mathrm{II}}_{8}(r) = A + B r^{\beta} \, .$$

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of the shape of the confining potential V_8. Using phenomenological interactions, we found for instance the first $cc\bar{c}\bar{c}$ state around 300 MeV above the threshold made of two charmonia, and the spin-independent corrections do not appreciably reduce this gap.

first threshold is ψX instead of $\eta_c\eta_c$. Even so, we did not find any narrow $cc\bar{c}\bar{c}$ P state emerging from our calculation.

our qualitative conclusions are certainly rather general. The cryptoexotic configuration $QQ'\bar{Q}\bar{Q}'$, lies above its lowest dissociation threshold $Q\bar{Q}+Q'\bar{Q}'$. On the other hand, the genuine exotic $QQ\bar{Q}'\bar{Q}'$ can be stable against dissociation if the ratio of the quark masses is large enough. Our predictions

Exploring numerical methods

Z. Phys. C – Particles and Fields 30, 457–468 (1986)

Zeitschrift für Physik C Particles and Fields

Four-Quark Bound States

S. Zouzou[1], B. Silvestre-Brac[2], C. Gignoux[2], J.M. Richard[3]*

[1] Laboratoire de Physique Théorique des Particules Elémentaires, Université Pierre et Marie Curie, F-75230 Paris, France and Division de Physique Théorique, IPN, F-91406 Orsay, France

[2] Institut des Sciences Nucléaires, F-38026 Grenoble, France

[3] Institut Laue-Langevin, F-38042 Grenoble, France

Received 29 October 1985

The authors search bound states with central forces only, by comparing **three methods**: a gaussian parametrization of the wave-function, the harmonic oscillator expansion and the hyperspherical expansion. They include **spin-spin** terms and virtual **meson-meson configurations**.

Exploring numerical methods

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seems hardly "defeatable" in our model. On the other hand, the genuine exotic $(QQ\bar{q}\bar{q})$ can take advantage of the asymmetry in the quark masses (with e.g. $r(QQ) \ll r(Q\bar{q}) \simeq r(\bar{q}\bar{q})$) and benefit from the strong attraction between the two heavy quarks, whereas in its threshold, $(Q\bar{q})+(Q\bar{q})$, the heavy quarks do not interact together. This is why we consider systems combining various flavours in our search for stable multiquarks.

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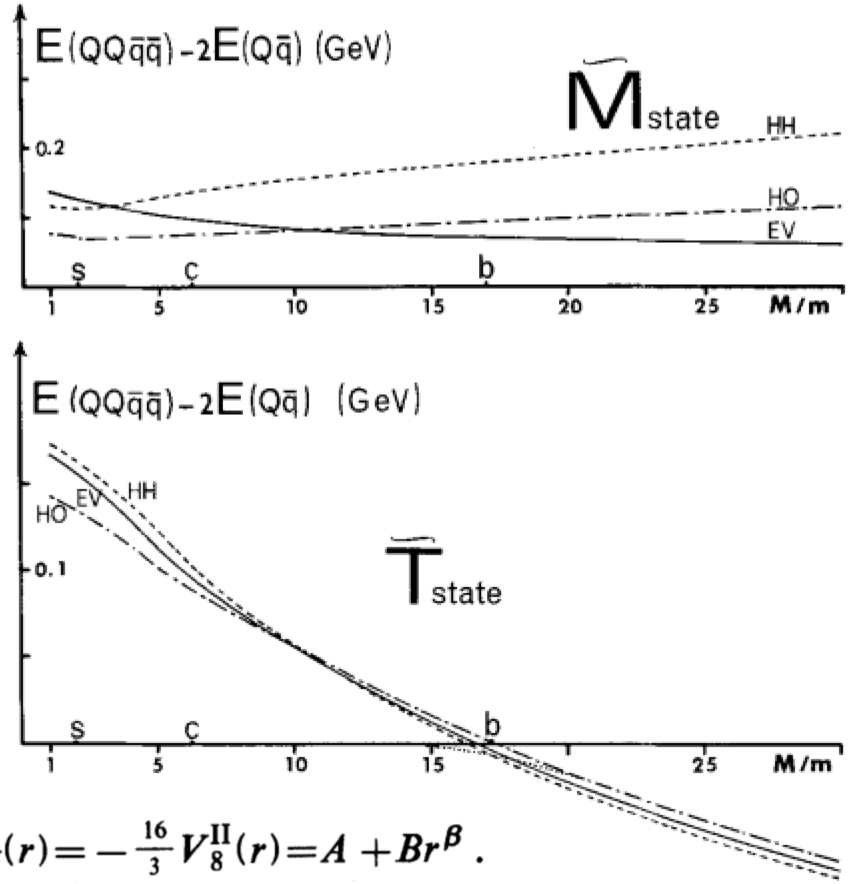

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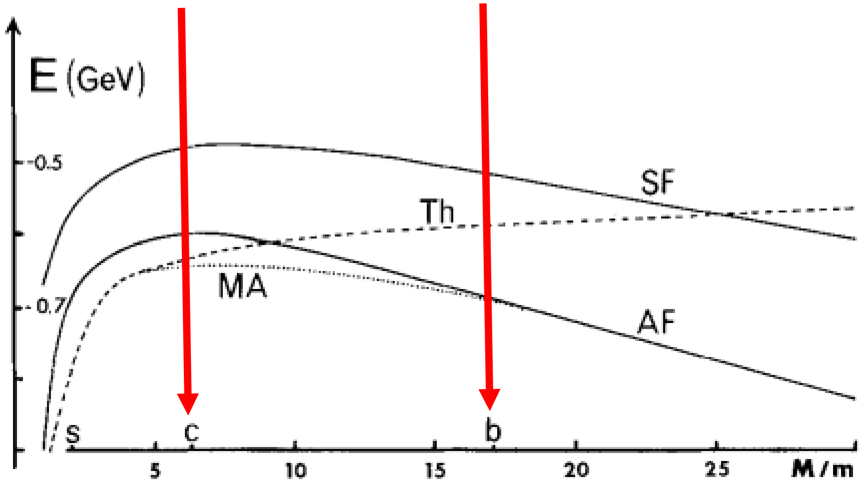

Using the Bhaduri potential they identified the ***S=1 I=0*** case as the most promising candidate for a bound state.

Potentials derived from the MIT Bag model

PHYSICAL REVIEW D VOLUME 35, NUMBER 3 1 FEBRUARY 1987

On the existence of stable dimesons

L. Heller
Theoretical Division, Los Alamos National Laboratory, University of California, Los Alamos, New Mexico 87545

J. A. Tjon
Theoretical Division, Los Alamos National Laboratory, University of California, Los Alamos, New Mexico 87545
*and Institute for Theoretical Physics, P.O. Box 80.006, 3508 TA Utrecht, The Netherlands**

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PHYSICAL REVIEW D VOLUME 37, NUMBER 3 1 FEBRUARY 1988

Stability of dimesons

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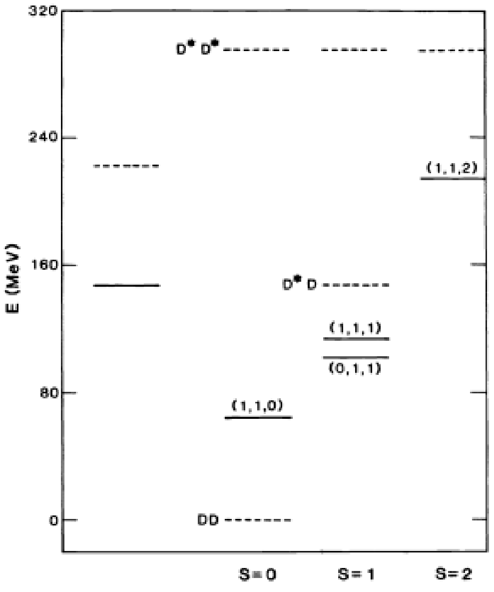
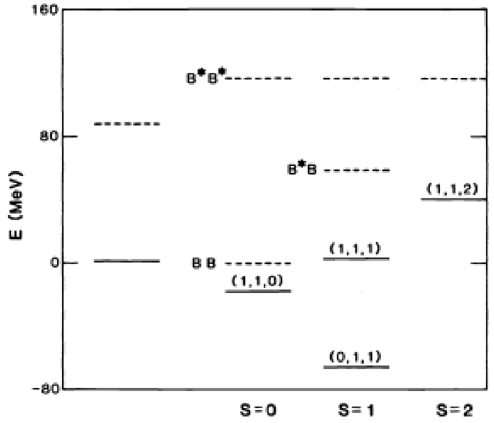
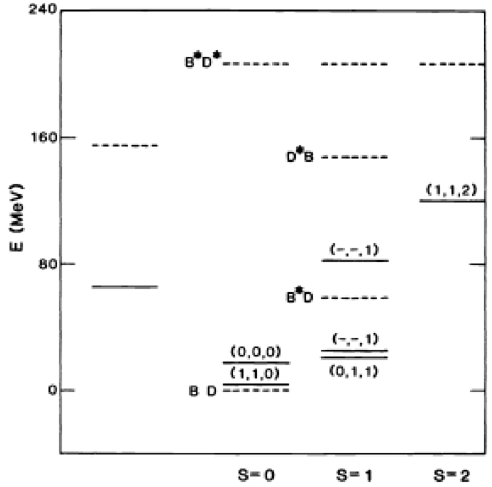




The bound-state problem of two- and four-quarks with coupled channels in color space is studied, using a potential derived from the MIT bag model.



$cc\bar{c}\bar{c}$

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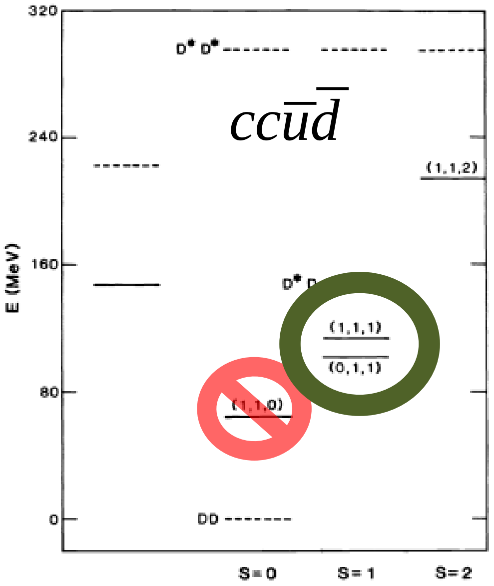

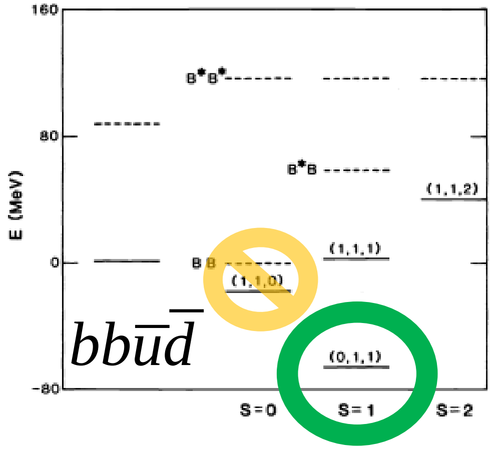

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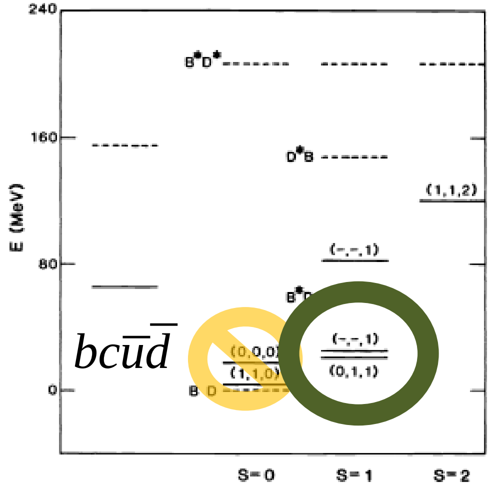

A systematic analysis

Z. Phys. C 57, 273–282 (1993)

Zeitschrift für Physik C **Particles and Fields**
© Springer-Verlag 1993

Systematics of $L=0$ $q^2\bar{q}^2$ systems

B. Silvestre-Brac[1], C. Semay[2,★]

Z. Phys. C 59, 457–470 (1993)

ZEITSCHRIFT FÜR PHYSIK C
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Spectrum and decay properties of diquonia

B. Silvestre-Brac[1], C. Semay[2,★]

Z. Phys. C 61, 271–275 (1994)

ZEITSCHRIFT FÜR PHYSIK C
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Diquonia and potential models

C. Semay[1,★], B. Silvestre-Brac[2]

Using the interquark potential due to Bhaduri *et al.*, the energies of all $L = 0,1,2,3$ four-quark states are calculated for any value of the total S and I and for q = u, d, s, c, b using a harmonic oscillator basis up to 7/8 quanta. Natural parity is considered.

This implies 924 combinations.

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C. Semay[1,*], B. Silvestre-Brac[2]

ZEITSCHRIFT FÜR PHYSIK C

Nature	I	$J=S$	E_d(MeV)	Δ(MeV)
$nn\bar{b}\bar{b}$	0	1	10525	−131
$ns\bar{b}\bar{b}$	1/2	1	10680	−40
$nn\bar{c}\bar{b}$	0	1	7244	1
$nn\bar{c}\bar{b}$	0	0	7206	11
$nn\bar{c}\bar{c}$	0	1	3931	19
$nn\bar{b}\bar{b}$	1	2	10735	30
$ns\bar{b}\bar{b}$	1/2	2	10816	48
$nn\bar{s}\bar{c}$	0	2	2975	49
$nn\bar{s}\bar{b}$	0	2	6306	49
$nn\bar{c}\bar{b}$	0	2	7422	49
$nn\bar{n}\bar{n}$	0	2	1605	51
$nn\bar{n}\bar{b}$	1/2	2	6181	52
$nn\bar{n}\bar{s}$	1/2	2	1734	52
$nn\bar{b}\bar{b}$	1	1	10712	56
$ns\bar{n}\bar{s}$	0, 1	2	1854	59
$ns\bar{c}\bar{b}$	1/2	2	7496	59

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Improving the numerical methods

A different approach based on Gaussian variational wave functions including combinations of three different radial coordinates is considered.

PHYSICAL REVIEW D VOLUME 57, NUMBER 11 1 JUNE 1998

Tetraquarks with heavy flavors

D. M. Brink
Dipartimento di Fisica, Università degli Studi di Trento, I-38050 Povo (Trento), Italy

Fl. Stancu
Université de Liège, Institut de Physique B5, Sart Tilman, B-4000 Liège 1, Belgium

	$E(qq\bar{b}\bar{b})$ (MeV)				
SI	1 Gaussian	5 Gaussians	Brac-Semay	Threshold	$E-E_T$
10	10 577.7	10 558.1	10 525	$B+B^*$	-98.9
01	10 802.4	10 766.2		$B+B$	156.2
11	10 812.1	10 774.1	10 712	$B+B^*$	117.1
21	10 831.5	10 789.8	10 735	B^*+B^*	85.8

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Few-Body Systems 35, 175–196 (2004)
DOI 10.1007/s00601-004-0068-9

Few-Body Systems
Printed in Austria

The $T_{cc}=DD^*$ Molecular State

D. Janc[1,*] and M. Rosina[1,2,**]

First detailed study of typical radii and radial properties.

$bb\bar{u}\bar{d}$

IS	Threshold [Bh]	$N_{max}=90$ [Bh]	Ref. [3] [Bh]	Threshold [AL1]	$N_{max}=90$ [AL1]	Ref. [4] [AL1]
01	10650.9	10518.9	10525	10644.1	10503.9	10509
10	10601.4	10601.4	>10642	10587.0	10587.0	–
11	10650.9	10650.9	10712	10644.1	10644.1	–

$cc\bar{u}\bar{d}$ $S=1\ I=0$

	Threshold	$N_{max}=140$	Ref. [3]
Bhaduri	3905.3	3904.7	3931
AL1	3878.6	3875.9	3892

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10	10 577.7	10 558.1	10 525	$B+B^*$	−98.9
01	10 802.4	10 766.2		$B+B$	156.2
11	10 812.1	10 774.1	10 712	$B+B^*$	117.1
21	10 831.5	10 789.8	10 735	B^*+B^*	85.8

Few-Body Systems 35, 175–196 (2004)
DOI 10.1007/s00601-004-0068-9

Few-Body Systems
Printed in Austria

The $T_{cc}=DD^*$ Molecular State

D. Janc[1,*] and M. Rosina[1,2,**]

First detailed study of typical radii and radial properties.

$bb\bar{u}\bar{d}$

IS	Threshold [Bh]	$N_{max}=90$ [Bh]	Ref. [3] [Bh]	Threshold [AL1]	$N_{max}=90$ [AL1]	Ref. [4] [AL1]
01	10650.9	10518.9	10525	10644.1	10503.9	10509
10	10601.4	10601.4	>10642	10587.0	10587.0	–
11	10650.9	10650.9	10712	10644.1	10644.1	–

$cc\bar{u}\bar{d}$ $S=1\ I=0$

	Threshold	$N_{max}=140$	Ref. [3]
Bhaduri	3905.3	3904.7	3931
AL1	3878.6	3875.9	3892

VNIVERSITAT DE VALÈNCIA

Exploring constituent quark models

6 February 1997

PHYSICS LETTERS B

ELSEVIER

Physics Letters B 393 (1997) 119–123

Tetraquarks with colour-blind forces in chiral quark models

S. Pepin [a,1], Fl. Stancu [a,2], M. Genovese [b,3], J.-M. Richard [b,4]

[a] Université de Liège, Institut de Physique, B.5, Sart Tilman, B-4000 Liège 1, Belgium

[b] Institut des Sciences Nucléaires, Université Joseph Fourier–IN2P3-CNRS, 53, avenue des Martyrs, F-38026 Grenoble Cedex, France

These systems were studied with a potential model fitted in the baryon spectrum that includes meson-exchange forces between quarks and entirely neglects the chromomagnetic interaction.

System	$(C_1)+$ OME	$(C_2)+$ OME	Ref. [4]
$cc\bar{q}\bar{q}$	−0.185	−0.332	0.019
$bb\bar{q}\bar{q}$	−0.226	−0.497	−0.135

Eur. Phys. J. C 49, 743–754 (2007)
DOI 10.1140/epjc/s10052-006-0142-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

Chromomagnetism, flavour symmetry breaking and S-wave tetraquarks

F. Buccella[1,a], H. Høgaasen[2,b], J.-M. Richard[3,c], P. Sorba[4,d]

A detailed formalism is presented to fully account for flavour-symmetry breaking in the chromomagnetic interaction together with its application to four-quark systems.

For $(QQ\bar{q}\bar{q})$ with identical heavy quarks, the chromomagnetic interaction is optimal for $J^P = 1^+$, since the Pauli principle forbids the 0^+ eigenstates with the lowest eigenvalue of H_{CM}. [...]

[...] The very large value of the mass ratio M_Q/m_n, where M_Q^{-1} is the average of the inverse masses m_c and m_b,[3] presumably gives binding or almost binding from the sole chromoelectric effects. The chromomagnetic interaction is also favourable, and, if alone, would give a binding of more than 100 MeV.

VNIVERSITAT DE VALÈNCIA

Exploring constituent quark models

Eur. Phys. J. A **19**, 383–389 (2004)
DOI 10.1140/epja/i2003-10128-9

THE EUROPEAN PHYSICAL JOURNAL A

Tetraquarks in a chiral constituent-quark model

J. Vijande[1,a], F. Fernández[1], A. Valcarce[1], and B. Silvestre-Brac[2]

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INSTITUTE OF PHYSICS PUBLISHING — JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **31** (2005) 481–506 doi:10.1088/0954-3899/31/5/017

Constituent quark model study of the meson spectra

J Vijande, F Fernández and A Valcarce

A different constituent quark model incorporating meson exchanges between light quarks on top of gluon exchange was explored

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$$R_s(1234) = \sum_{i=1}^{n} \beta_s^{(i)} R_s^{(i)} =$$

$$\sum_{i=1}^{n} \beta_s^{(i)} e^{-a_s^{(i)}\vec{x}^2 - b_s^{(i)}\vec{y}^2 - c_s^{(i)}\vec{z}^2 - d_s^{(i)}\vec{x}\vec{y} - e_s^{(i)}\vec{x}\vec{z} - f_s^{(i)}\vec{y}\vec{z}}$$

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THE EUROPEAN PHYSICAL JOURNAL A

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J. Vijande[1,a], F. Fernández[1], A. Valcarce[1], and B. Silvestre-Brac[2]

(S,I)		(0,0)	(0,1)	(1,0)	(1,1)	(2,0)	(2,1)
$nn\bar{s}\bar{s}$	E_T	2396	1858	1696	1934	2672	1993
	ΔE	+1404	+866	+291	+530	+852	+173
$nn\bar{c}\bar{c}$	E_T	4508	4155	3927	4176	4852	4195
	ΔE	+742	+389	+34	+283	+833	+175
$nn\bar{b}\bar{b}$	E_T	10975	10682	10424	10685	11321	10693
	ΔE	+413	+120	−178	+83	+679	+51

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Exploring constituent quark models

PHYSICAL REVIEW D **76**, 094027 (2007)

Are there compact heavy four-quark bound states?

J. Vijande,[1] E. Weissman,[2] A. Valcarce,[3] and N. Barnea[2,4]

PHYSICAL REVIEW D **79**, 074010 (2009)

Exotic meson-meson molecules and compact four-quark states

J. Vijande,[1,2] A. Valcarce,[2] and N. Barnea[3,4]

We revisit the same sector using more powerful numerical techniques:

- A variational method using generalized gaussians with all non-diagonal terms (relative $l \neq 0$)
- A hyperspherical harmonic formalism (up to $K = 30$)

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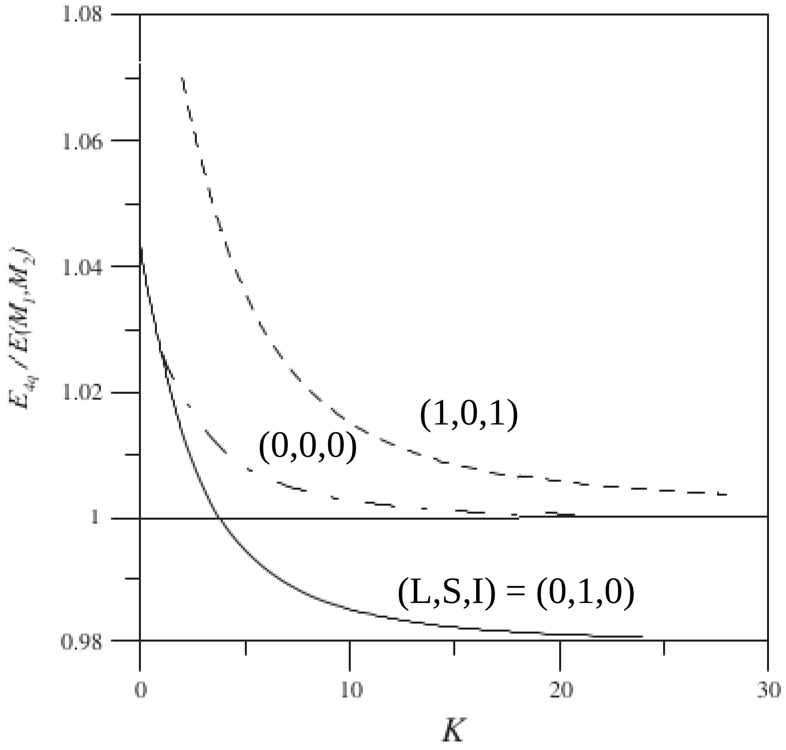

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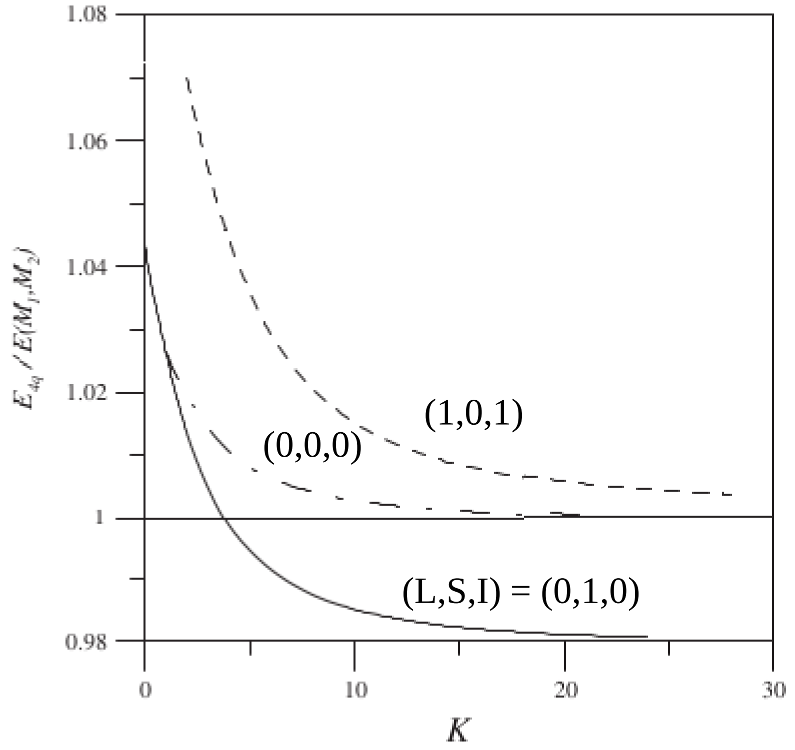
(L, S, I)	Reference [14]	HH ($\sum_i \ell_i = 0$)	HH
(0,0,1)	4155	4154	3911
(0,1,0)	3927	3926	3860
(0,1,1)	4176	4175	3975
(0,2,1)	4195	4193	4031



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It is bound!

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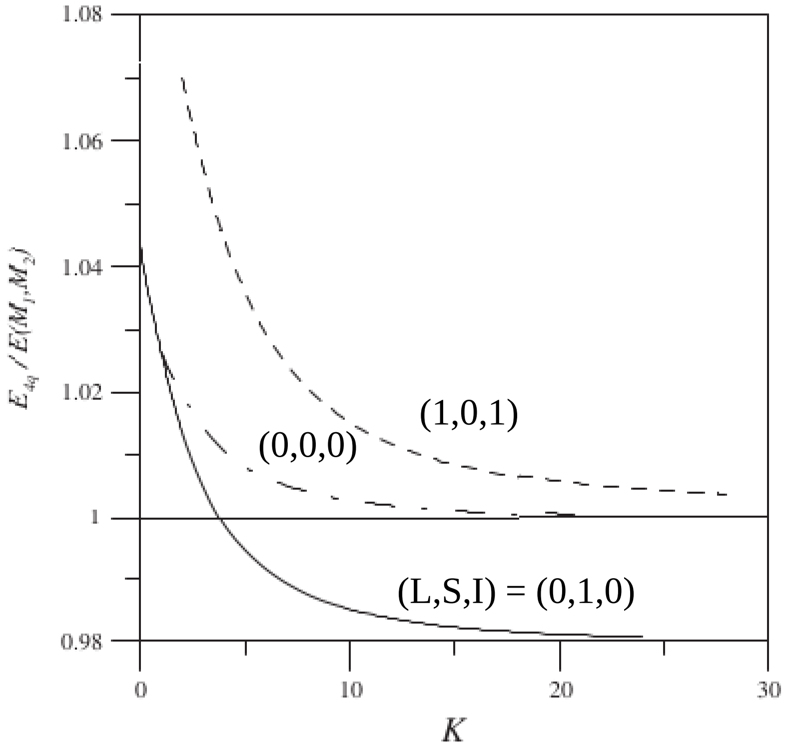

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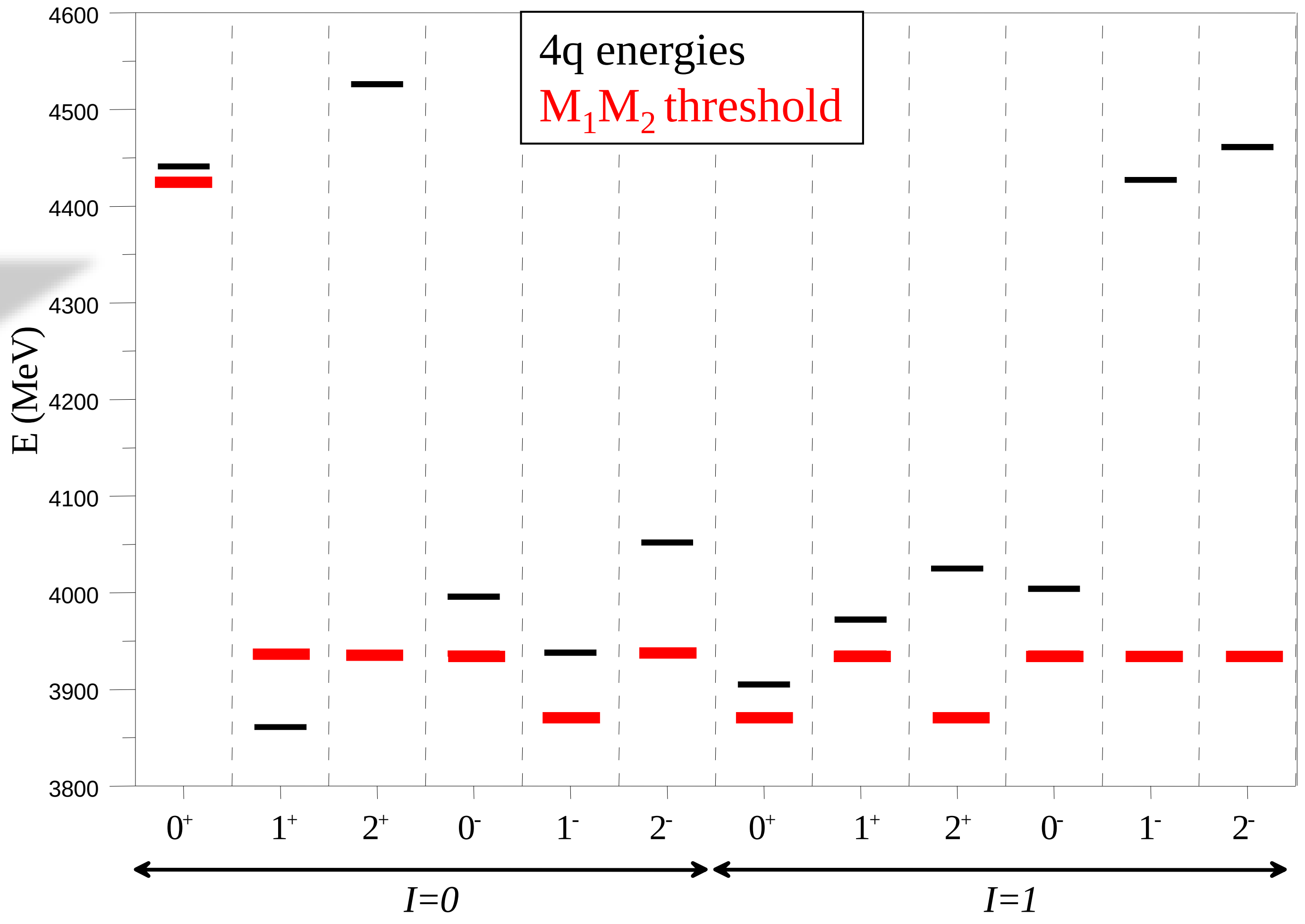

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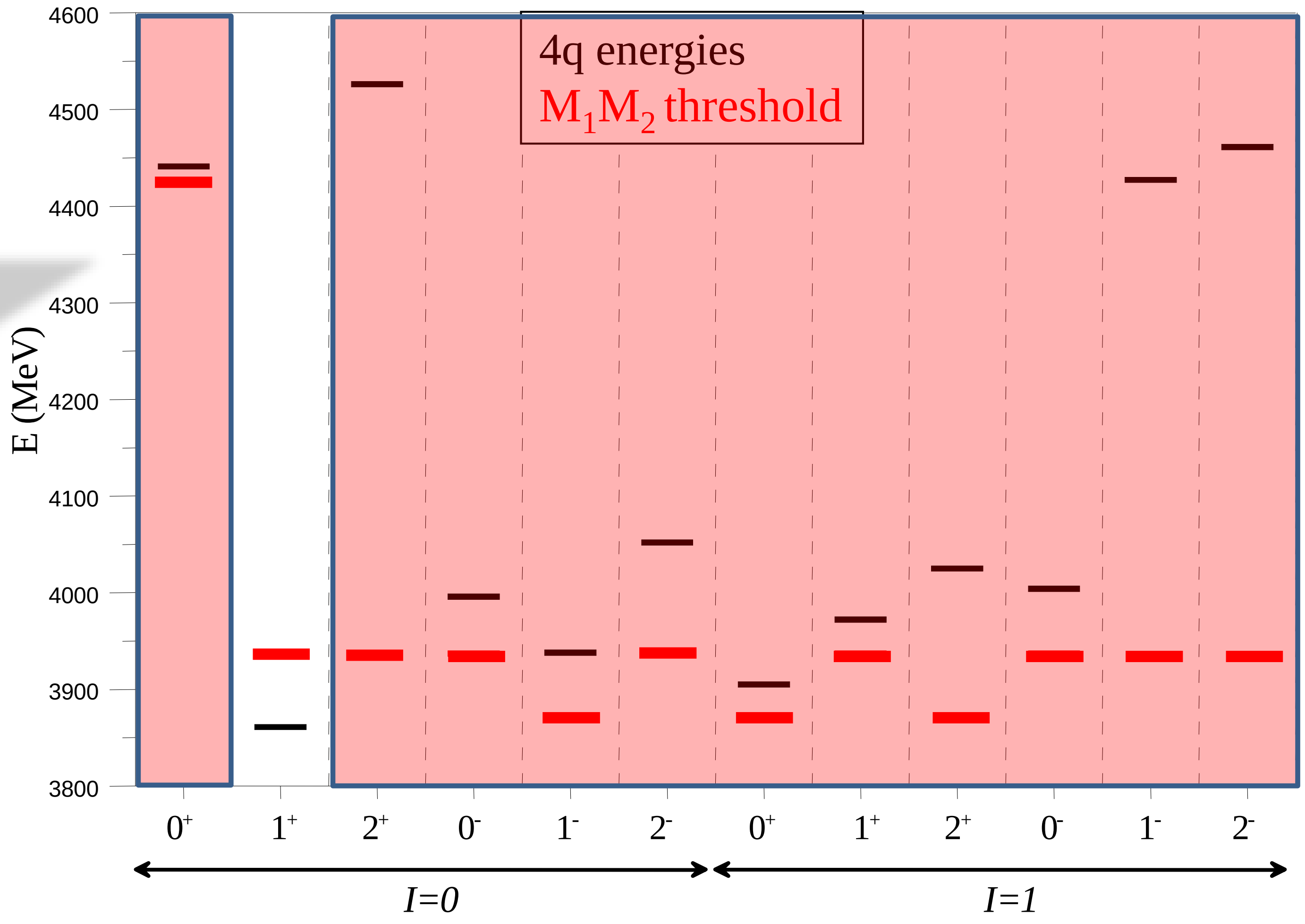

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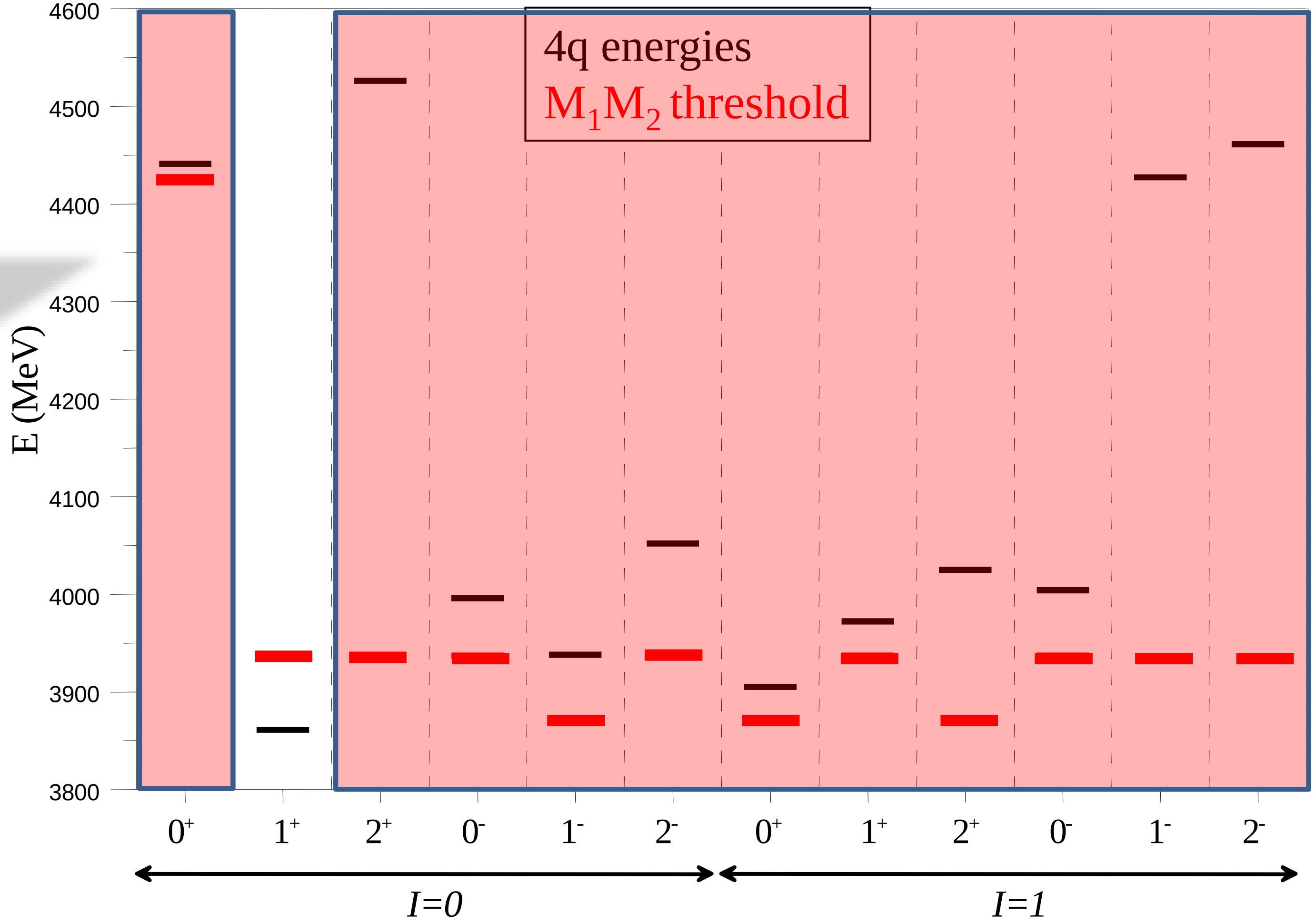
Quark content	$J^P(L, S, I)$	Model	Decay mode
$cc\bar{n}\,\bar{n}$	$1^+(0, 1, 0)$	CQC	Weak
		BCN	Electromagnetic
$bb\bar{n}\,\bar{n}$	$1^+(0, 1, 0)$	CQC	Weak
		BCN	Weak
	$3^-(1, 2, 1)$	CQC	Electromagnetic
		BCN	Electromagnetic
	$0^+(0, 0, 0)$	CQC	Electromagnetic
		BCN	Electromagnetic
	$1^-(1, 0, 0)$	CQC	Weak

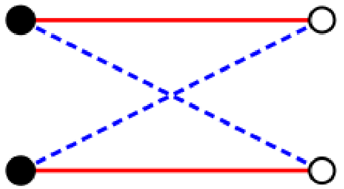


Beyond pairwise interactions

PHYSICAL REVIEW D **76**, 114013 (2007)

Stability of multiquarks in a simple string model

J. Vijande,[1,2,*] A. Valcarce,[2,†] and J.-M. Richard[3,‡]

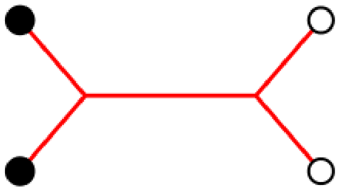


Flip-Flop model

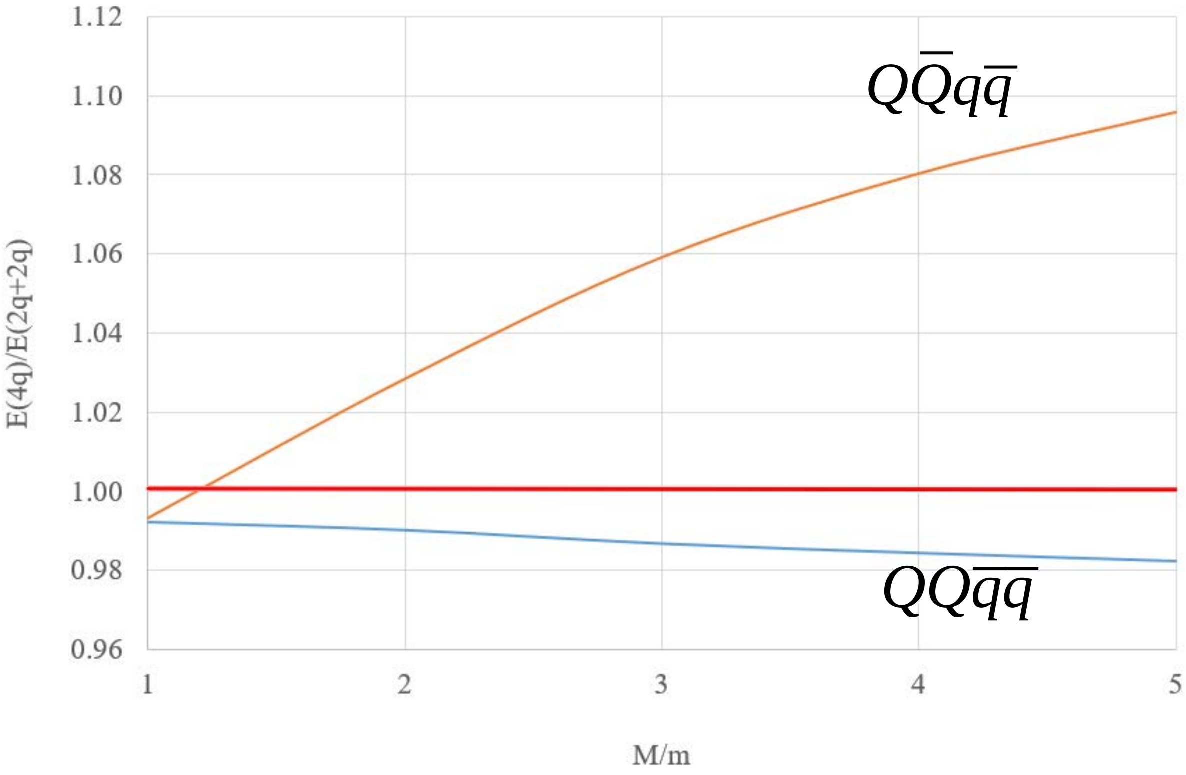
$$V_f = \lambda \min(r_{13} + r_{24}, r_{23} + r_{14})$$

$$V_s = \min(V_f, V_b).$$

$$V_b = \lambda \min_{k,\ell}(r_{1k} + r_{2k} + r_{k\ell} + r_{\ell 3} + r_{\ell 4})$$



Butterfly model



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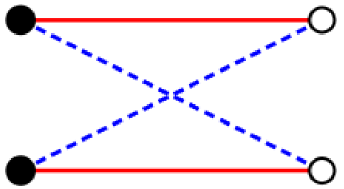

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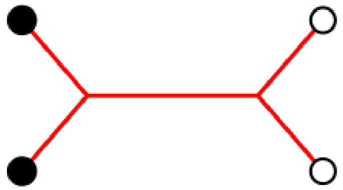


Butterfly model

Beyond pairwise interactions

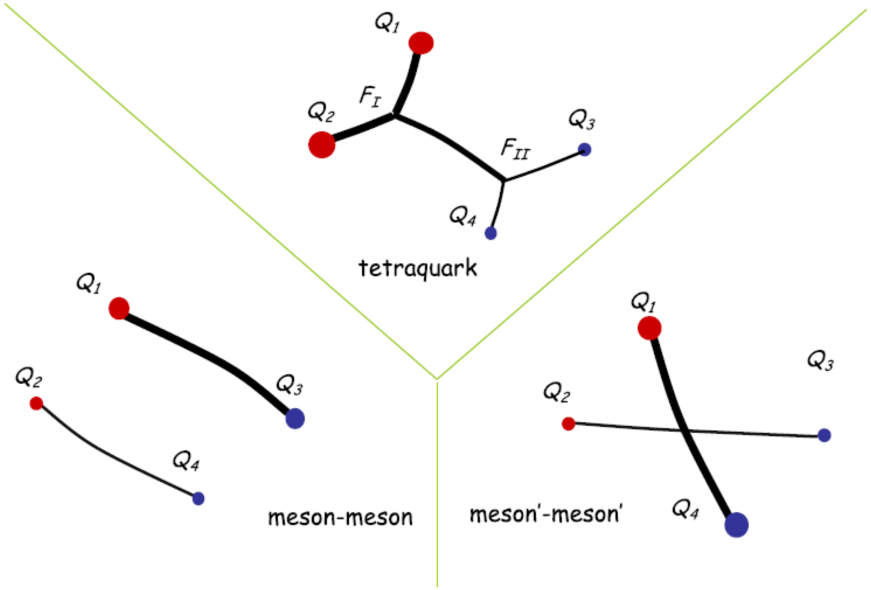
PHYSICAL REVIEW D **94,** 094032 (2016)

Tetraquark bound states and resonances in a unitary microscopic quark model: A case study of bound states of two light quarks and two heavy antiquarks

P. Bicudo[*] and M. Cardoso[†]

To summarize, we obtain tetraquark bound states on the $qq\bar{b}\bar{b}$ system, with quantum numbers 0^+ for s and c quarks, or light quarks with $I_{12} = 1$. For light quarks with $I_{12} = 0$, we obtain bound states with quantum numbers 1^+.

We also tried to find bound states for the $qq\bar{c}\bar{c}$ system, but we were unable to find them when the lightest quarks have constituent masses equal to or larger than the ones of light quarks $m_q \geq 400$ MeV.



The ground state potential for a system composed of two quarks and two antiquarks is well fitted by a string flip-flop potential.

$cc\bar{u}\bar{d}$

$bb\bar{u}\bar{d}$	$bb\bar{u}\bar{d}$	$bb\bar{s}\bar{s}$	$bb\bar{c}\bar{c}$
$(S=1, I=0)$	$(S=0, I=1)$	$(S=0, I=0)$	$(S=0, I=0)$

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What about the probabilities?

PHYSICAL REVIEW C **80**, 035204 (2009)

Probabilities in nonorthogonal bases: Four-quark systems

J. Vijande[1] and A. Valcarce[2]

$$\left[(q_1 q_2)(\bar{q}_3 \bar{q}_4)\right] \equiv \left\{ \left|\bar{3}_{12} 3_{34}\right\rangle, \left|6_{12} \bar{6}_{34}\right\rangle \right\} \equiv \left\{ \left|\bar{3}3\right\rangle_c^{12}, \left|6\bar{6}\right\rangle_c^{12} \right\}$$

$$\left[(q_1 \bar{q}_3)(q_2 \bar{q}_4)\right] \equiv \left\{ \left|1_{13} 1_{24}\right\rangle, \left|8_{13} 8_{24}\right\rangle \right\} \equiv \left\{ \left|11\right\rangle_c, \left|88\right\rangle_c \right\}$$

$$\left[(q_1 \bar{q}_4)(q_2 \bar{q}_3)\right] \equiv \left\{ \left|1_{14} 1_{23}\right\rangle, \left|8_{14} 8_{23}\right\rangle \right\} \equiv \left\{ \left|1'1'\right\rangle_c, \left|8'8'\right\rangle_c \right\}$$

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Calculations

$$\left[(q_1 \bar{q}_3)(q_2 \bar{q}_4)\right] \equiv \left\{ \left|1_{13} 1_{24}\right\rangle, \left|8_{13} 8_{24}\right\rangle \right\} \equiv \left\{ \left|11\right\rangle_c, \left|88\right\rangle_c \right\}$$

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Physical interpretation

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Physical interpretation

Journal of Mathematical Chemistry 5(1990)323–357

THEORY OF PROJECTED PROBABILITIES ON NON-ORTHOGONAL STATES: APPLICATION TO ELECTRONIC POPULATIONS IN MOLECULES

R.S. MANNING* and N. De LEON*†

$$\begin{aligned}
\left|\Psi\right\rangle &= \alpha\left|11\right\rangle_c + \beta\left|88\right\rangle_c \\
&= \alpha\left|11\right\rangle_c + \beta\left(\chi\left|1'1'\right\rangle_c + \delta\left|8'8'\right\rangle_c\right) \\
&= \alpha\left|11\right\rangle_c + \gamma\left|1'1'\right\rangle_c + \mu\left|8'8'\right\rangle_c \\
&= \alpha\left|11\right\rangle_c + \gamma\left|1'1'\right\rangle_c + \mu\left(\varpi\left|11\right\rangle_c + \varsigma\left|88\right\rangle_c\right) \\
&= \ldots\ldots = \wp_{\left|11\right\rangle_c}\left|\Psi\right\rangle + \wp_{\left|1'1'\right\rangle_c}\left|\Psi\right\rangle
\end{aligned}$$

What about the probabilities?

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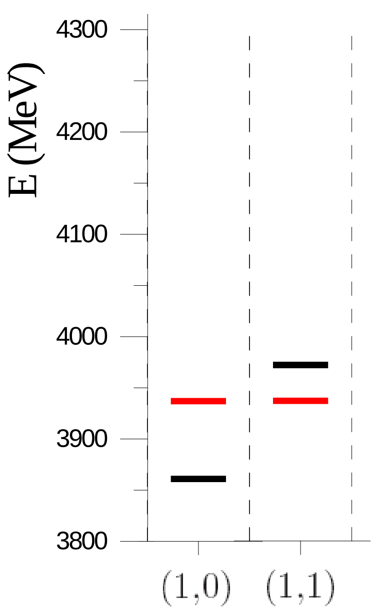

(S_T, I)	(0,1)	(1,1)	(1,0)	(1,0)	(0,0)
Flavor	$cc\bar{n}\bar{n}$	$cc\bar{n}\bar{n}$	$cc\bar{n}\bar{n}$	$bb\bar{n}\bar{n}$	$bb\bar{n}\bar{n}$
Energy	3877	3952	3861	10395	10948
Threshold	$DD\,\|_S$	$DD^*\,\|_S$	$DD^*\,\|_S$	$BB^*\,\|_S$	$B_1B\,\|_P$
Δ_E	+5	+15	−76	−217	−153
$P[\|\bar{3}3\rangle_c^{12}]$	0.333	0.333	0.881	0.974	0.981
$P[\|6\bar{6}\rangle_c^{12}]$	0.667	0.667	0.119	0.026	0.019
$P[\|\,11\rangle_c]$	0.556	0.556	0.374	0.342	0.340
$P[\|\,88\rangle_c]$	0.444	0.444	0.626	0.658	0.660
P_{MM}	1.000	–	–	–	0.254
P_{MM^*}	–	1.000	0.505	0.531	–
$P_{M^*M^*}$	0.000	0.000	0.495	0.469	0.746
$\langle x^2\rangle^{1/2}$	60.988	13.804	0.787	0.684	0.740
$\langle y^2\rangle^{1/2}$	60.988	13.687	0.590	0.336	0.542
$\langle z^2\rangle^{1/2}$	0.433	0.617	0.515	0.503	0.763
RMS_{4q}	30.492	6.856	0.363	0.217	0.330
Δ_R	69.300	11.640	0.799	0.700	0.885

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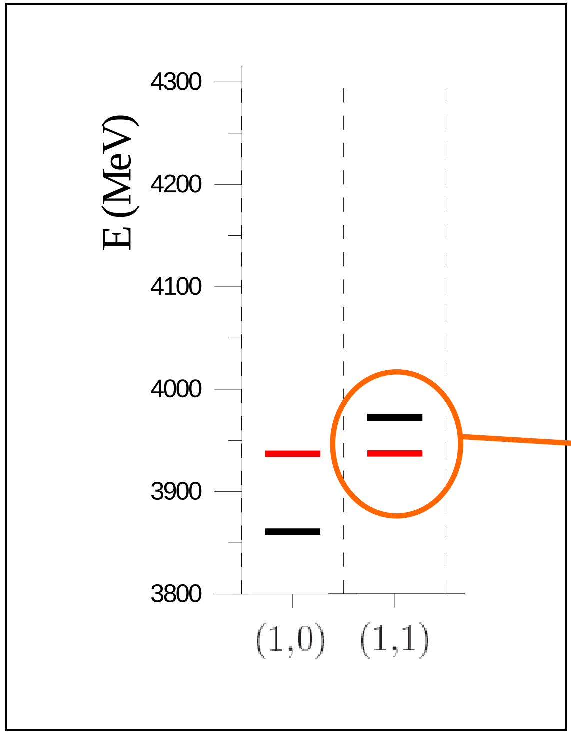
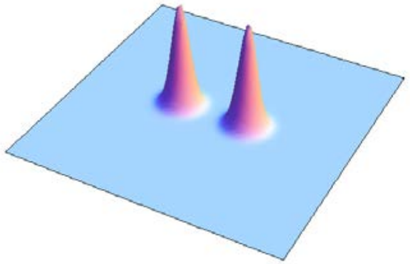
What about the probabilities?

PHYSICAL REVIEW C **80**, 035204 (2009)

Probabilities in nonorthogonal bases: Four-quark systems

J. Vijande[1] and A. Valcarce[2]





Unbound

(S_T, I)	(0,1)	(1,1)	(1,0)	(1,0)	(0,0)
Flavor	$cc\bar{n}\bar{n}$	$cc\bar{n}\bar{n}$	$cc\bar{n}\bar{n}$	$bb\bar{n}\bar{n}$	$bb\bar{n}\bar{n}$
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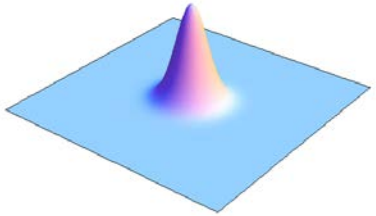

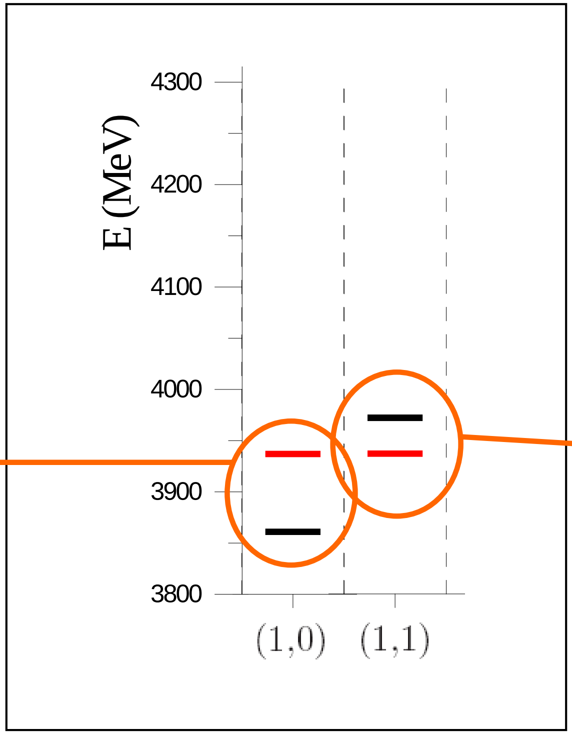

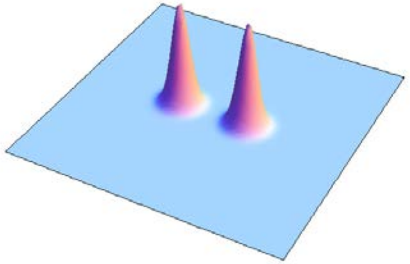

Bound

Unbound

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Compact or meson-meson configuration?

Physics Letters B 699 (2011) 291–295

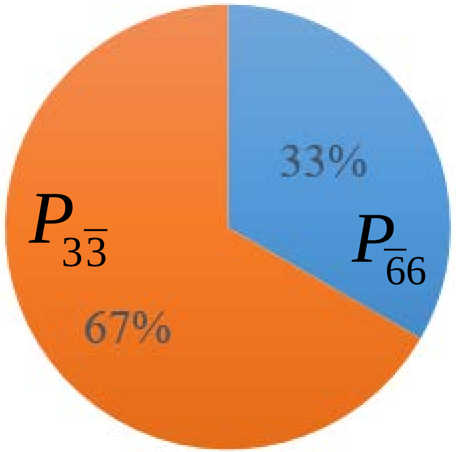
Doubly charmed exotic mesons: A gift of nature?

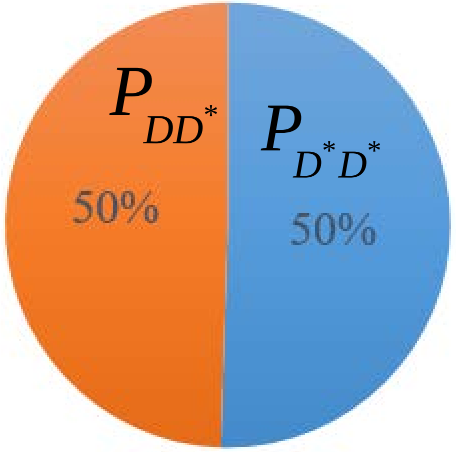
T.F. Caramés [a], A. Valcarce [a,*], J. Vijande [b]

$$|cc\bar{n}\bar{n}\rangle = \alpha_1 |\bar{3}3\rangle + \ldots + \alpha_2 |6\bar{6}\rangle + \ldots \overset{????}{=} \alpha_1 |DD^*\rangle + \alpha_2 |D^*D^*\rangle + \ldots$$

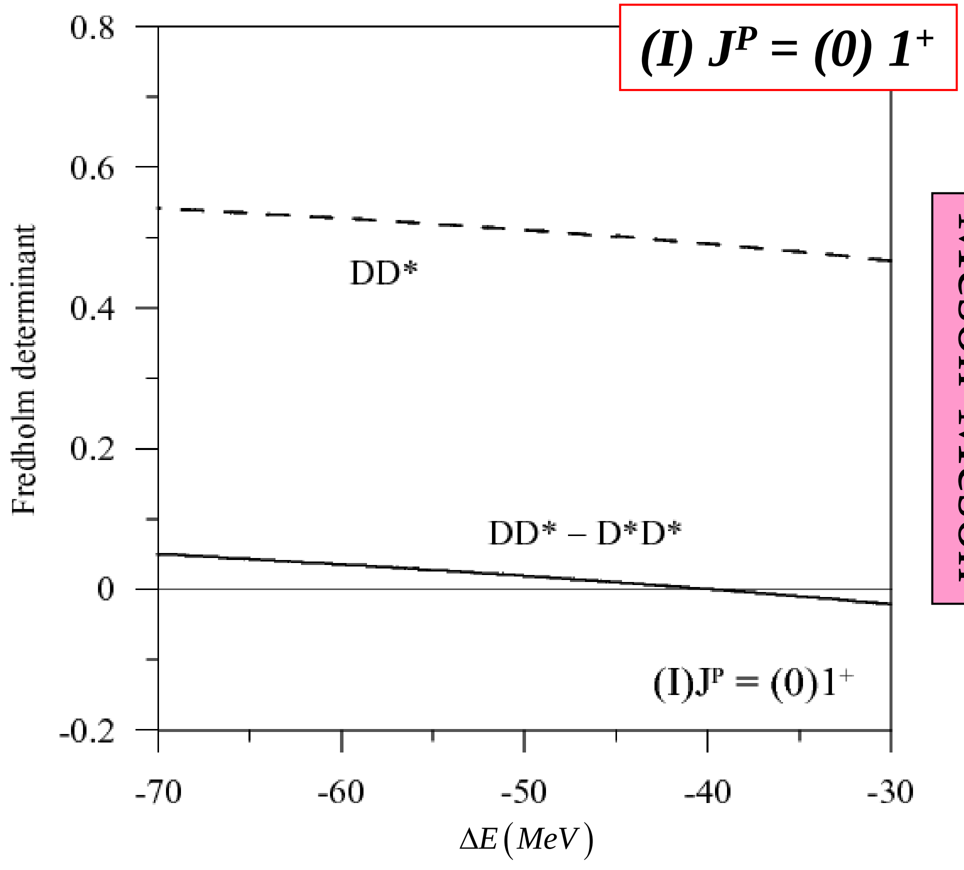
In this work the meson-meson configuration is solved by means of the Lippmann-Schwinger equation using the same interaction as the four-quark problem.

$$\Delta E = -76 MeV$$





Four-quark states



Meson-Meson

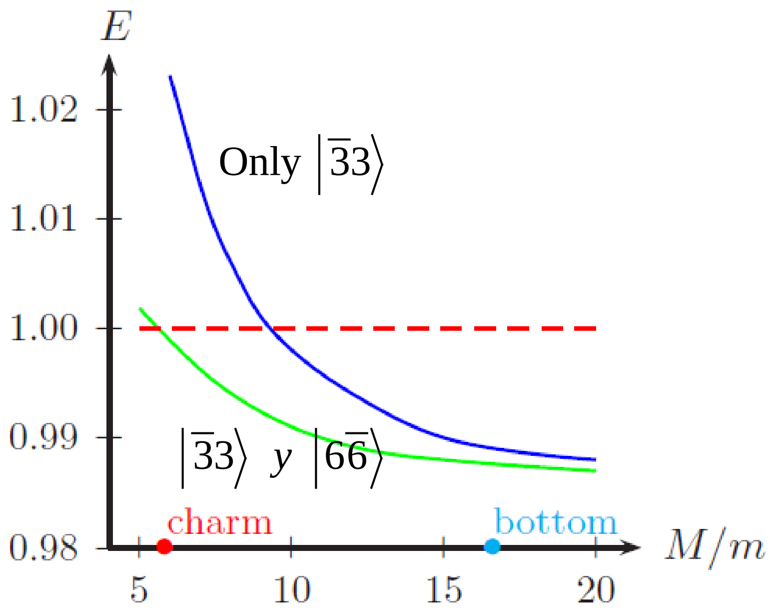
Few-body dynamics

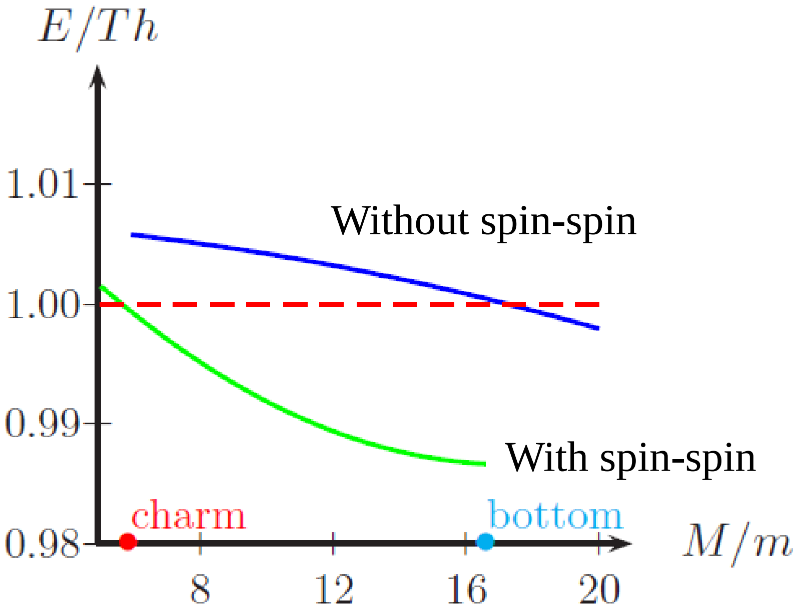
PHYSICAL REVIEW C **97**, 035211 (2018)

Few-body quark dynamics for doubly heavy baryons and tetraquarks

Jean-Marc Richard,[1,*] Alfredo Valcarce,[2,†] and Javier Vijande[3,‡]

A very delicate interplay between color and spin configurations.





$QQ\overline{qq}$ using the AL1 model

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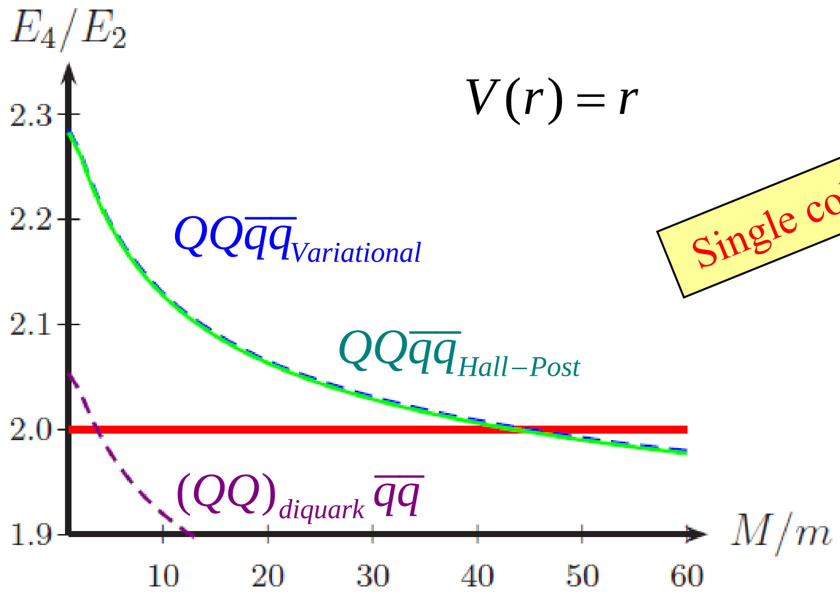
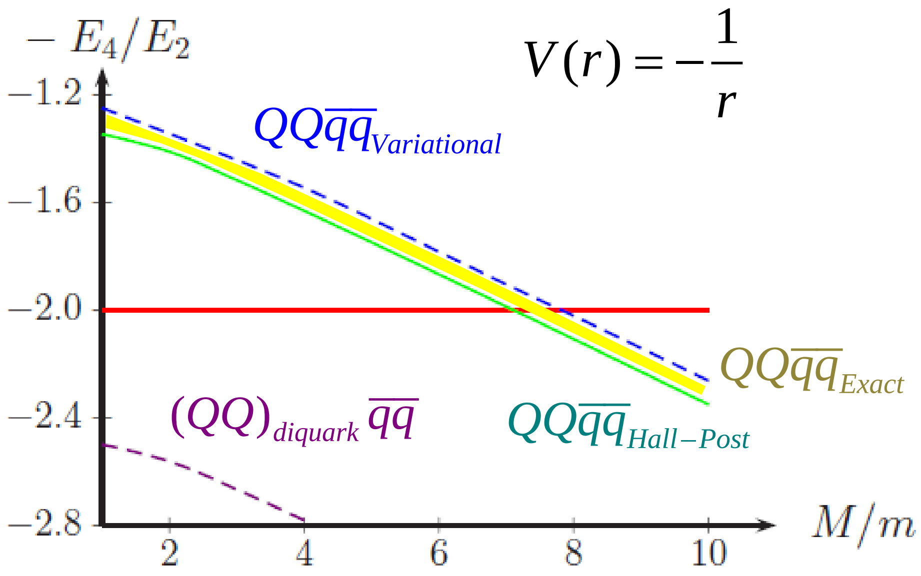
Few-body quark dynamics for doubly heavy baryons and tetraquarks

Jean-Marc Richard,[1,*] Alfredo Valcarce,[2,†] and Javier Vijande[3,‡]

The treatment of the four-body dynamics for double-charm tetraquarks is discussed. The **variational** and **Born-Oppenheimer** approximations together with the **Hall-Post** inequalities give energies very **close to the exact ones**, while the **diquark** approximation might be **more problematic**.



Single color channel



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Will the relativistic kinematics increase the number of stable multiquarks?

PHYSICAL REVIEW D **102**, 034012 (2020)

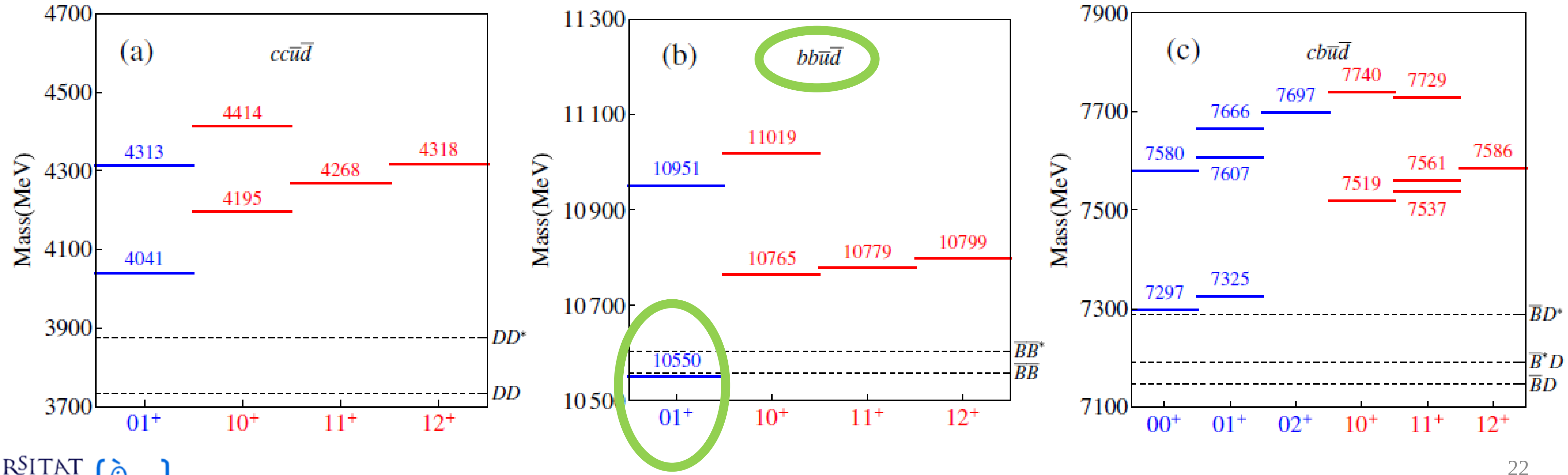
Masses of doubly heavy tetraquarks $T_{QQ'}$ in a relativized quark model

Qi-Fang Lü,[1,2,3,*] Dian-Yong Chen,[4,†] and Yu-Bing Dong[5,6,7,‡]

The authors investigate the mass spectra using the relativized quark model proposed by Godfrey, Capstick, and Isgur.

The spatial wave function is expanded in terms of a set of Gaussian basis functions where the Gaussian size parameters are taken in geometric progression

$QQ\bar{u}\bar{s}$ and $QQ\bar{s}\bar{s}$



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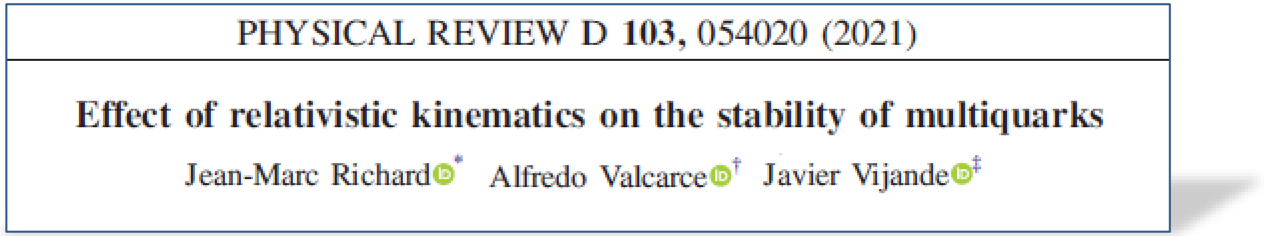


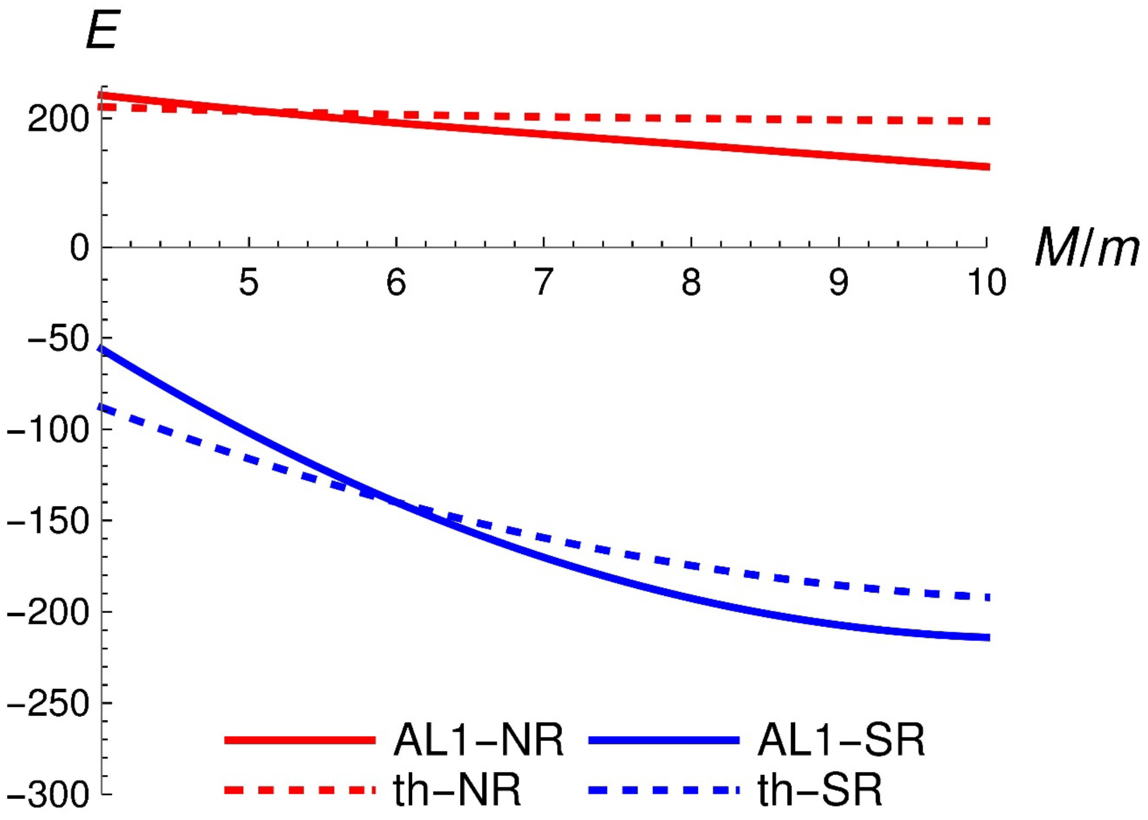
PHYSICAL REVIEW D **103**, 054020 (2021)

Effect of relativistic kinematics on the stability of multiquarks

Jean-Marc Richard[*] Alfredo Valcarce[†] Javier Vijande[‡]

In this case the threshold is made of two *(qQ)* mesons while in the four-quark state there are *(qq)*, *(QQ)* and four *(qQ)* interactions. Who will benefit more from the relativistic dynamics?

We consider the AL1 potential properly re-parametrized in the SR case for keeping the description of the meson spectra.



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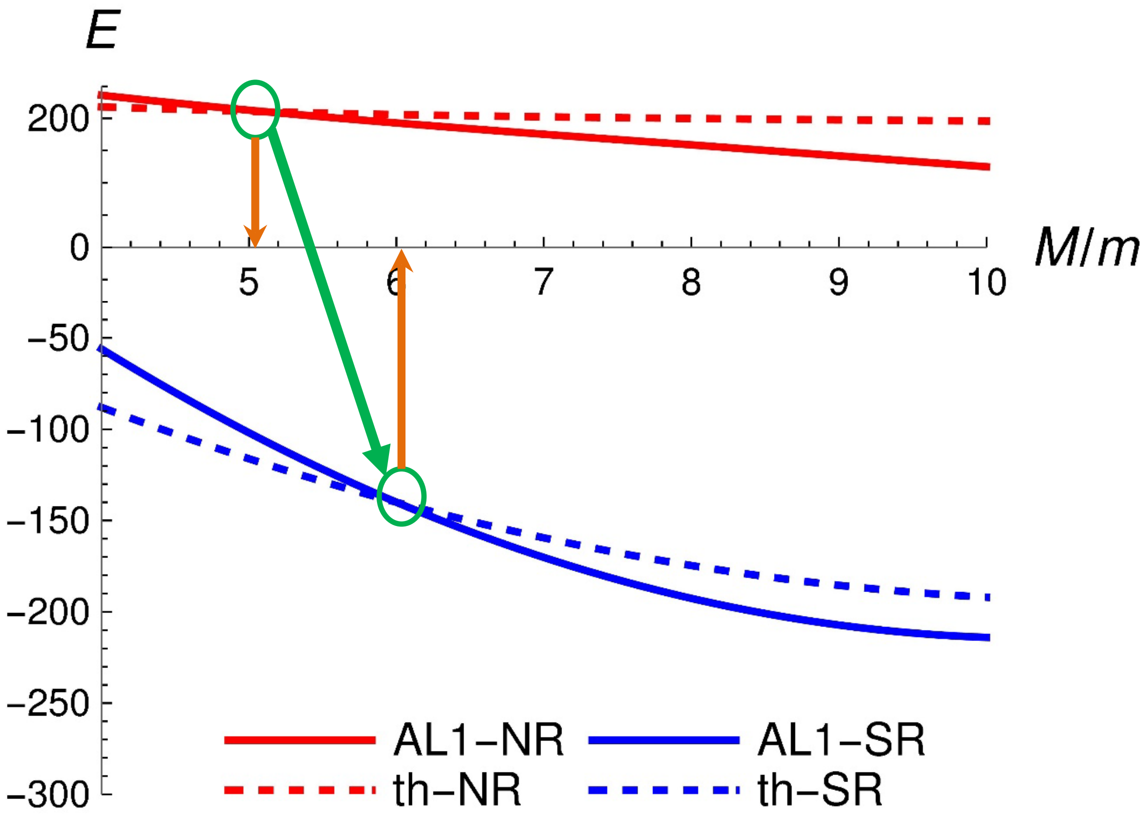

Conclusions

- The constituent quark model predicts a clear bound state, $bb\bar{u}\bar{d}$, and another one, $cc\bar{u}\bar{d}$, just below threshold with $(I)J^P=(0)1^+$. Some particular models may point to the existence of about five more bound states.
  - **There is not an overwhelming abundance of bound states within the constituent quark model.**
- The numerical methods required should be able to handle short- and long-range correlations, i.e. a meson-meson structures together with a more *clusterized* behaviour.
- Approximations and simplifications in the colour-spin structure should be done carefully.
  - **We should double check whether our findings are entirely due to our hypothesis and aproximations before extracting any general conclusion.**