The 21st Particles & Nuclei International Conference

1-5 September 2017, IHEP, Beijing, China

A few certainties and many uncertainties about multiquarks

J. Vijande (Univ. Valencia)

A. Valcarce , J.-M. Richard

Experiment: The first charmed “exotic” states (1974)

VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

BNL Experimental Observation of a Heavy Particle J†

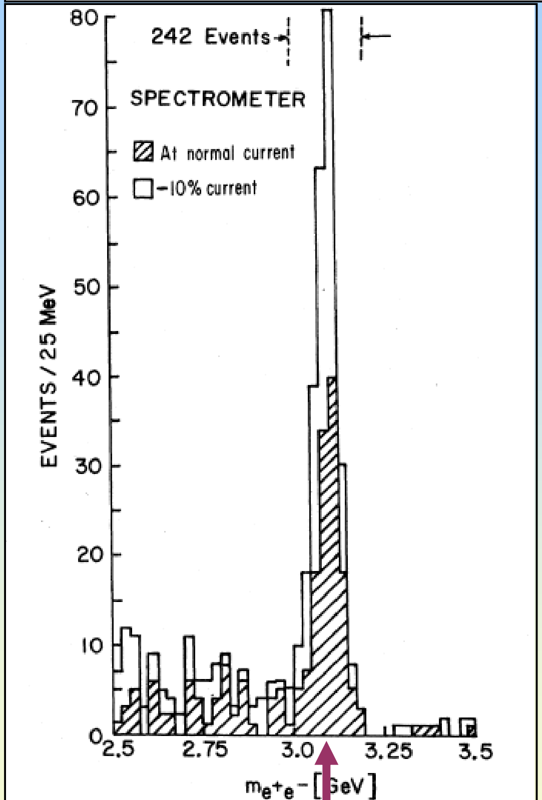


FIG. 2. Mass spectrum showing the existence of J.

M = 3.1 GeV

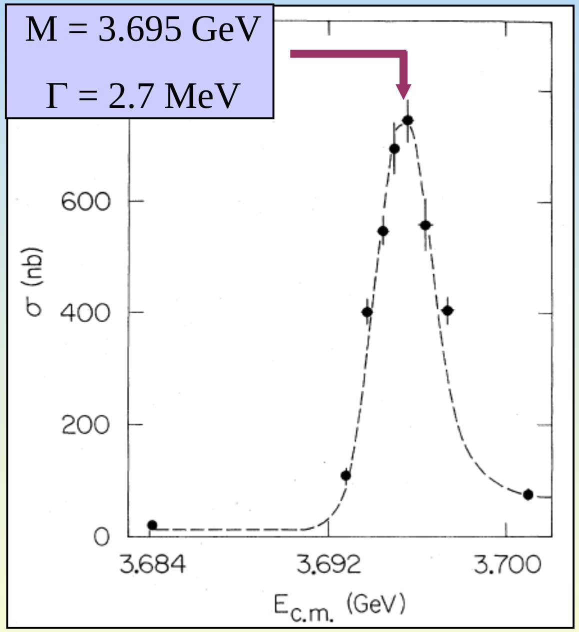
Γ ~ 0 MeV

VOLUME 33, NUMBER 24 PHYSICAL REVIEW LETTERS 9 DECEMBER 1974

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

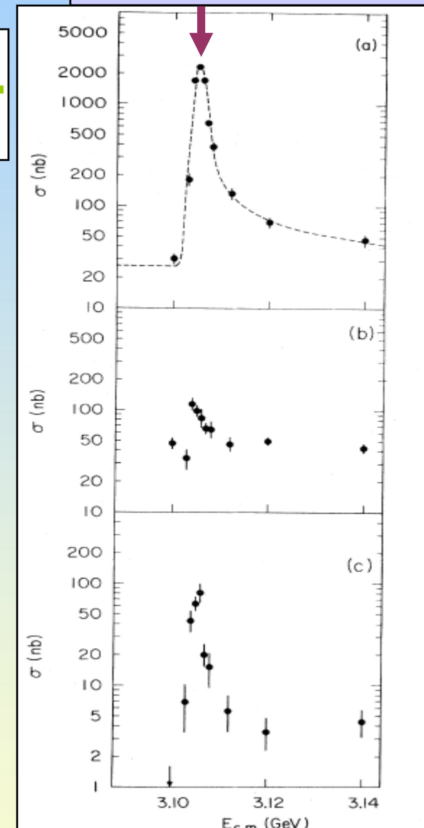
M = 3.695 GeV

Γ = 2.7 MeV



M = 3.105 GeV

Γ < 1.3 MeV



VOLUME 33, NUMBER 23 PHYSICAL REVIEW LETTERS 2 DECEMBER 1974

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

Theory: Predictions

VOLUME 34, NUMBER 6 PHYSICAL REVIEW LETTERS 10 FEBRUARY 1975

Spectroscopy of the New Mesons*

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and

VOLUME 34, NUMBER 6 PHYSICAL REVIEW LETTERS 10 FEBRUARY 1975

Spectrum of Charmed Quark-Antiquark Bound States*

E. Eichten, K. Gottfried, T. Kinoshita, J. Kogut, K. D. Lane, and T.-M. Yan†
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York 14853

The interpretation of the narrow boson resonances at 3.1 and 3.7 GeV as charmed quark-antiquark bound states implies the existence of other states. Some of these should

be copiously produced in the radiative decays of the 3.7-GeV resonance. We estimate the masses and decay rates of these states and emphasize the importance of γ-ray spectroscopy.

tum numbers and estimate masses and decay widths of these states. Their existence should be revealed by γ-ray transitions among them.

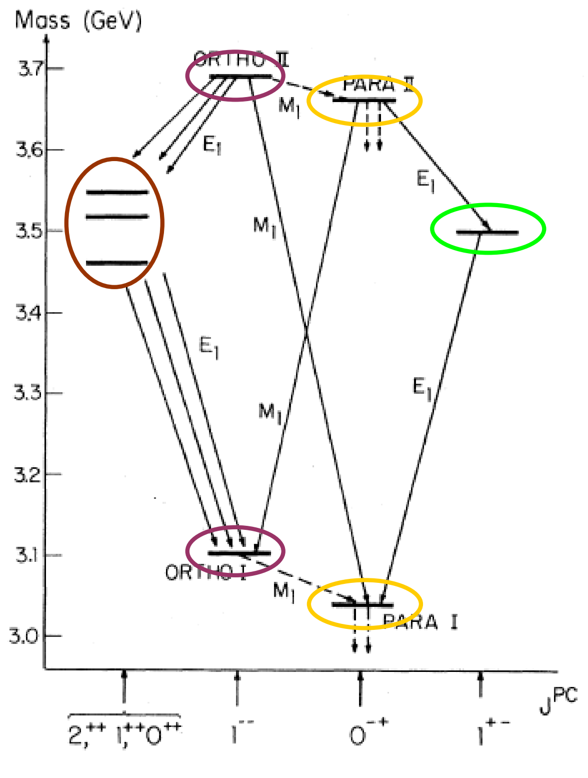


FIG. 1. Masses and radiative transitions of charmonium.

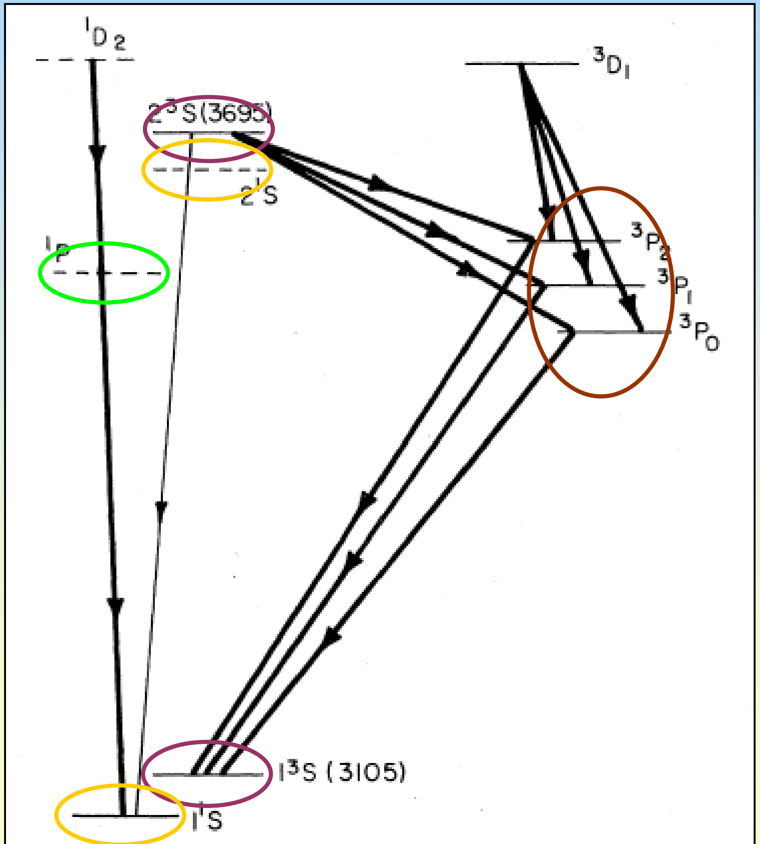


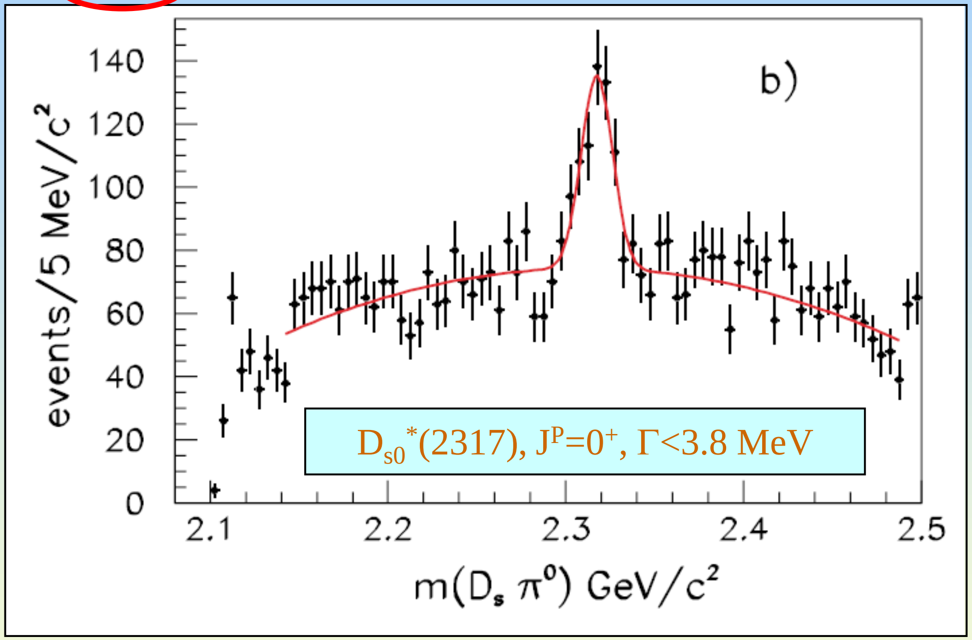
FIG. 1. The spectrum of charmonium. The vertical

New experimental challenges (2003)

VOLUME 90, NUMBER 24 PHYSICAL REVIEW LETTERS week ending 20 JUNE 2003

Observation of a Narrow Meson State Decaying to $D_s^+\pi^0$ at a Mass of 2.32 GeV/c^2

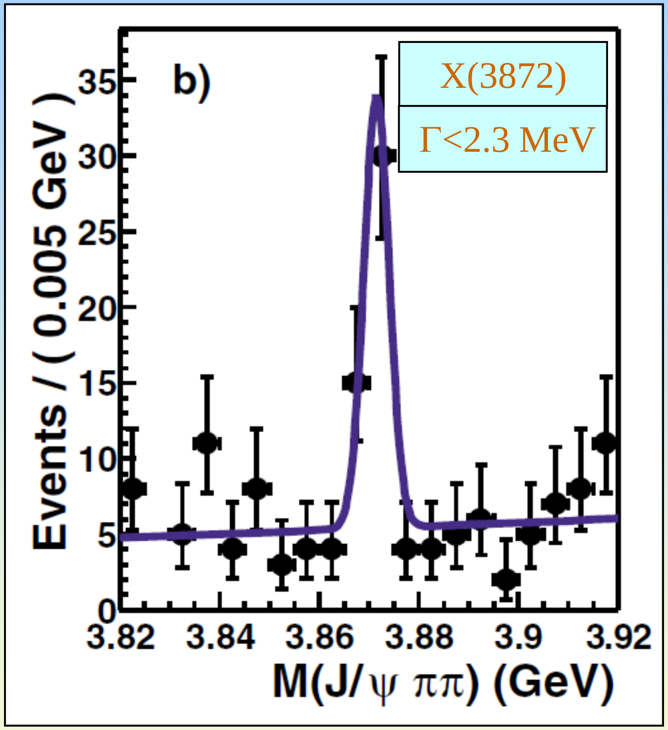
We have observed a narrow state near 2.32 GeV/c^2 in the inclusive $D_s^+\pi^0$ invariant mass distribution from e^+e^- annihilation data at energies near 10.6 GeV. The observed width is consistent with the experimental resolution. The small intrinsic width and the quantum numbers of the final state indicate that the decay violates isospin conservation. The state has natural spin-parity and the low mass suggests a $J^P = 0^+$ assignment. The data sample corresponds to an integrated luminosity of 91 fb^{-1} recorded by the BABAR detector at the SLAC PEP-II asymmetric-energy e^+e^- storage ring.



$D_s^*(2112)^+\gamma$, or $D_s^+\gamma\gamma$. Since a $c\bar{s}$ meson of this mass contradicts current models of charm meson spectroscopy [6–8], either these models need modification or the observed state is of a different type altogether, such as a four-quark state.

$D_{s1}(2460)$, $J^P=1^+$, Γ < 3.5 MeV

This mass value and the absence of a strong signal in the $\gamma\chi_{c1}$ decay channel are in some disagreement with potential model expectations for the $^3D_{c2}$ charmonium state. The mass is within errors at the $D^0\bar{D}^{*0}$ mass threshold (3871.1 ± 1.0 MeV) [9]), which is suggestive of a loosely bound $D\bar{D}^*$ multiquark "molecular state," as



VOLUME 91, NUMBER 26 PHYSICAL REVIEW LETTERS week ending 31 DECEMBER 2003

Observation of a Narrow Charmoniumlike State in Exclusive $B^\pm \to K^\pm\pi^+\pi^-J/\psi$ Decays

We report the observation of a narrow charmoniumlike state produced in the exclusive decay process $B^\pm \to K^\pm\pi^+\pi^-J/\psi$. This state, which decays into $\pi^+\pi^-J/\psi$, has a mass of 3872.0 ± 0.6(stat) ± 0.5(syst) MeV, a value that is very near the $M_{D^0} + M_{D^{*0}}$ mass threshold. The results are based on an analysis of 152M B-$\bar{B}$ events collected at the Υ(4S) resonance in the Belle detector at the KEKB collider. The signal has a statistical significance that is in excess of 10σ.

XYZ mesons

LHCb pentaquarks

WASA dibaryons

Baryonia

………?

Are all these resonances (if they really exist!) multiquark states and/or hadron-hadron molecules?

Back to 1974: A challenge for theory!!

$|\,\text{Meson (B=0)}\rangle \Rightarrow |q\bar{q}\rangle\,,\ |qq\bar{q}\bar{q}\rangle$ → $|cc\bar{n}\bar{n}\rangle$

$|\,\text{Baryon (B=1)}\rangle \Rightarrow |qqq\rangle\,,\ |qqqq\bar{q}\rangle$ → $|nnnn\bar{c}\rangle$

Predictions: An experimental challenge!!

All-heavy tetraquarks

J.-M.R., A.V., J.V.,

Phys. Rev. D 95, 054019 (2017)

Many speculations about the stability of $(Q_1Q_2Q_3Q_4)$: $(cc\underline{cc})$, $(bb\underline{cc})$, $(bc\underline{cc})$, …

- Extrapolation of quarkonium dynamics to higher configurations
- New color substructures: 3- or 4-body forces / Role of antisymmetry

Chromoelectric (CE) limit (Two-body forces and color as a global operator)

Limit of very heavy constituents: Neglect chromomagnetic terms $\propto (m_i\, m_j)^{-1}$

$$H = \sum_i \frac{\vec{p}_i^{\,2}}{2\, m_i} - \frac{16}{3} \sum_{i<j} \vec{\lambda}_i \cdot \vec{\lambda}_j\, V(r_{ij}) \quad \Leftrightarrow_{\text{QED}} \quad H = \sum_i \frac{\vec{p}_i^{\,2}}{2\, m_i} - \sum_{i<j} \frac{e_i\, e_j}{r_{ij}}$$

QED

- ✓ $(e^+ e^+ e^- e^-) \equiv Ps_2$ positronium molecule, stable although with tiny binding
- ✓ $(p\, p\, e^- e^-) \equiv H_2$ hydrogen molecule, stable with a comfortable binding
- ✓ $(M^+ M^+ m^- m^-)$ more stable than $(m^+ m^+ m^- m^-)$. Stability depends critically on the masses involved
- ✓ But $(M^+ m^+ M^- m^-)$ unstable if $M/m \geq 2.2$

QCD

- $(QQ\underline{qq})$ stable for large M/m ratio
- $(QQ\underline{QQ})$ unstable in naive CE limit
- Delicate four-body problem
- Approximations, like diquarks or restricting the Hilbert space, **artificially** favor binding

Improved chromoelectric model: Many-body confining forces

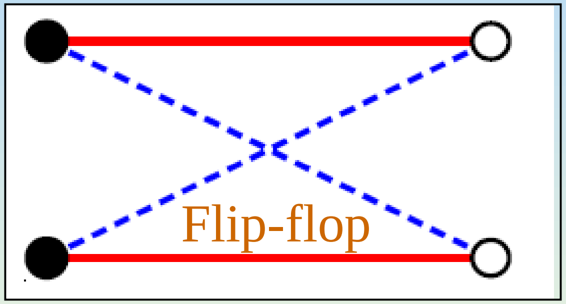
$$V_s = \min(V_f, V_b).$$

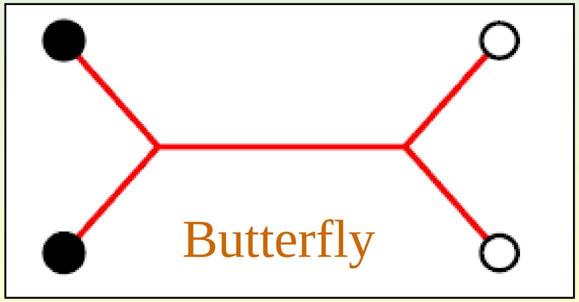
V_f stands for the so-called "flip-flop" model

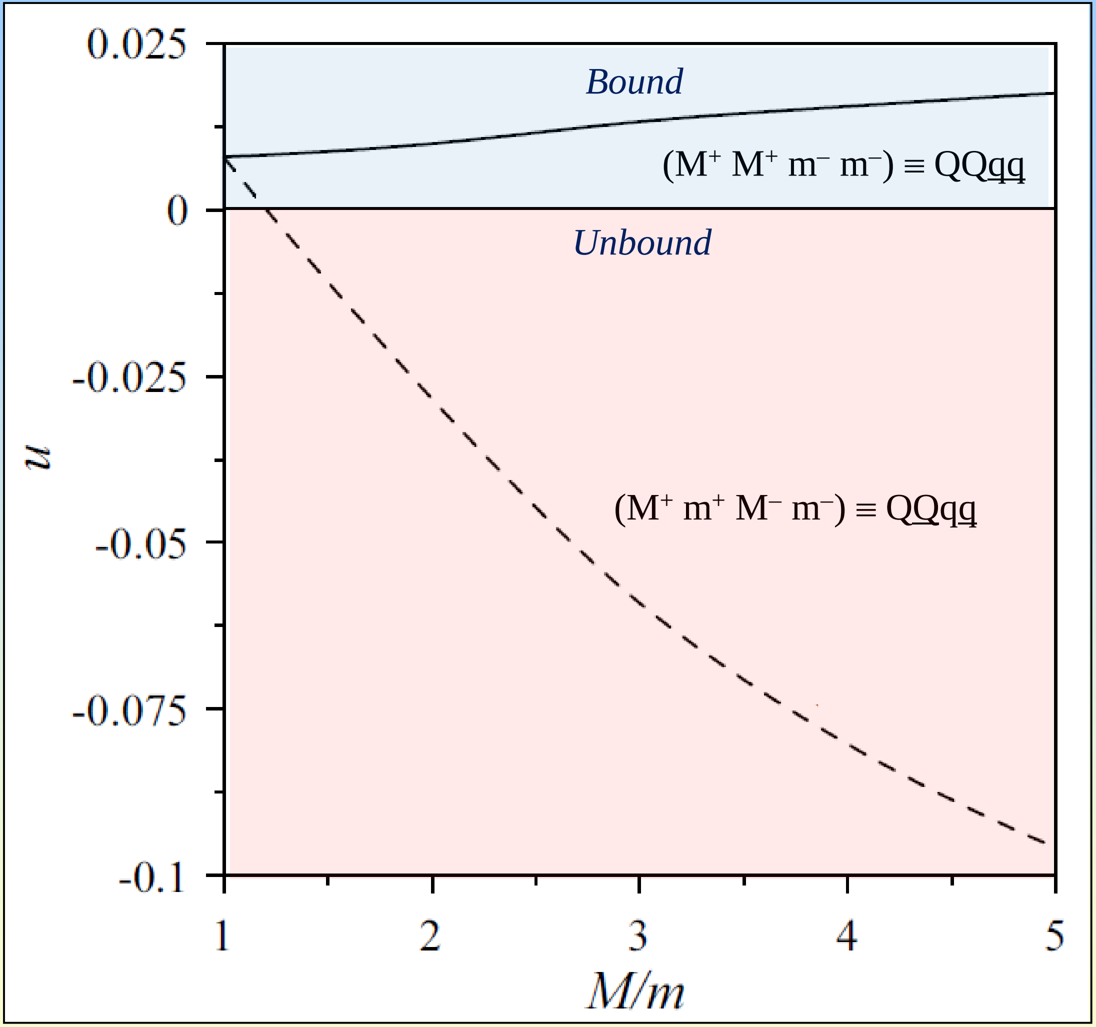
$$V_f = \lambda \min(r_{13} + r_{24}, r_{23} + r_{14}),$$

V_b is the butterflylike configuration,

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







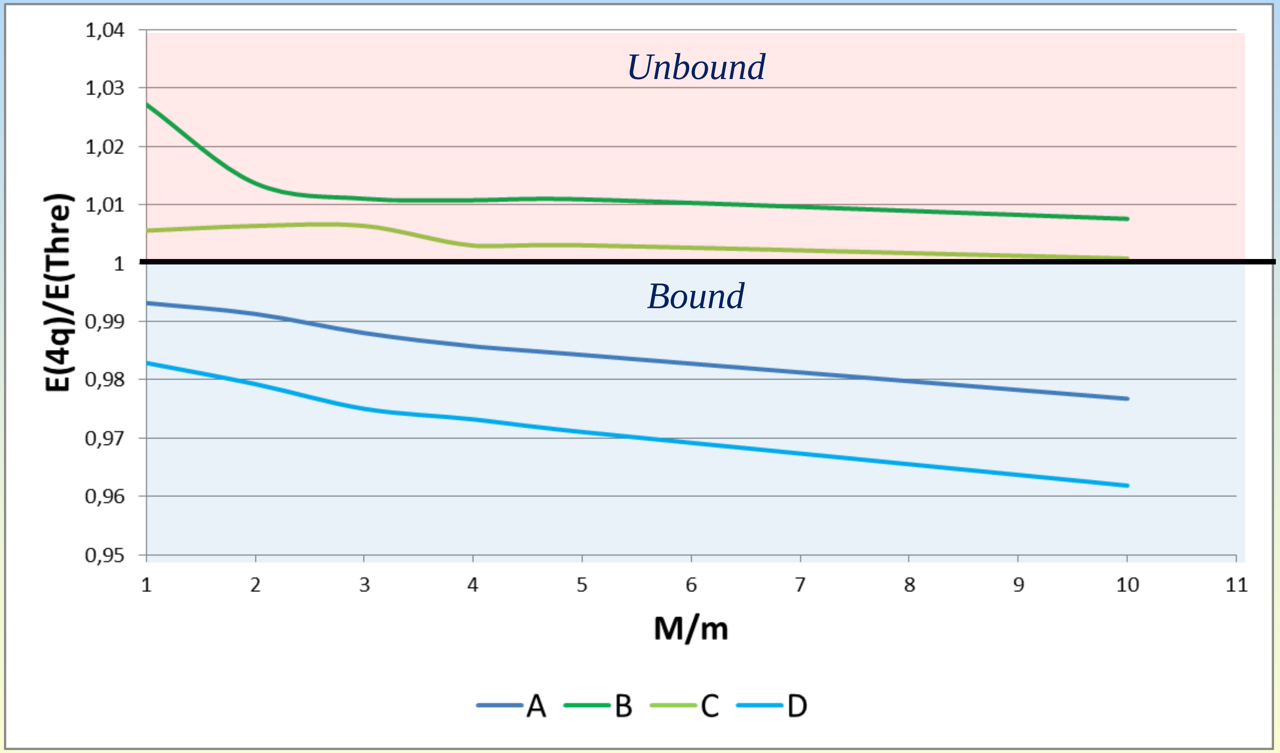
J.V., A.V., J.-M.R., Phys. Rev. D 76, 114013 (2007), Phys. Rev. D 87, 034040 (2013)

Improved chromoelectric model: Many-body confining forces

$$V = -\frac{3}{16}\sum_{i<j}\tilde{\lambda}_i.\tilde{\lambda}_j v(r_{ij}).$$

$$\Psi = \psi_T|T\rangle + \psi_M|M\rangle,$$

A $\Rightarrow$ String model with $|T\rangle$
B $\Rightarrow$ String model with $|T\rangle$ and $|M\rangle$
C $\Rightarrow$ Pairwise with $|T\rangle$ and $|M\rangle$
D $\Rightarrow$ Adiabatic limit of C



A,D (adiabatic) bound !! BUT B,C (color+antisymmetry) unbound

All-heavy tetraquarks

- (bb$\underline{bb}$) and (cc$\underline{cc}$) are **unstable** in serious 4-body estimates in naive **CE models**. They follow the trends of (++––) in QED, but less favorable due to the non-Abelian algebra of charges.

- (bc$\underline{bc}$) might have some opportunities as compared to (bb$\underline{bb}$) and (cc$\underline{cc}$)

  (b$\underline{c}$)(c$\underline{b}$) ≡ M$\underline{M}$

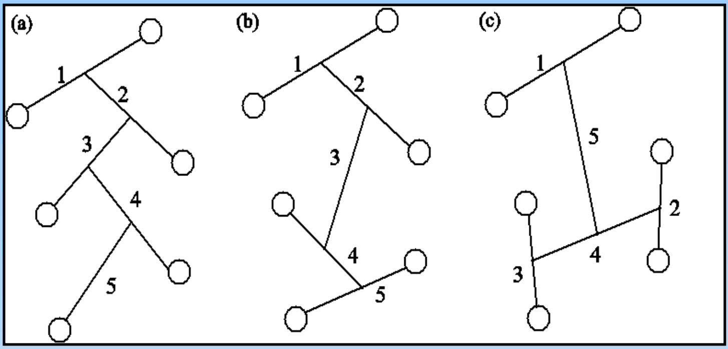
  BUT (bc$\underline{bc}$) there are two-different thresholds

  (b$\underline{b}$)(c$\underline{c}$) ≡ Υ J/ψ

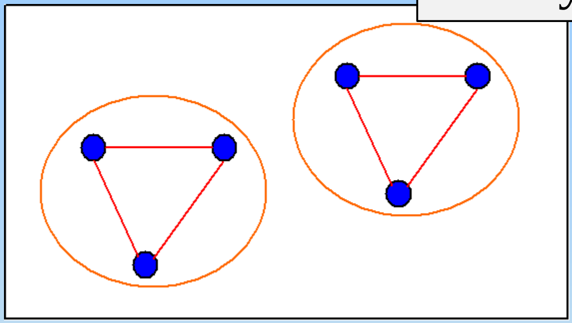
  THUS it may present **metastability** below the M$\underline{M}$ threshold

- (**bb$\underline{cc}$**) although more delicate:
  - ✓ Benefits from symmetry breaking
  - ✓ There is a single threshold
  - ✓ For non-identical quarks and antiquarks, string potentials offer good opportunities
  - ✓ (QQ$\underline{qq}$) favored in the CE limit due to the striking M/m dependence

Similar findings: Baryonia ($Q^3\underline{q}^3$) and dibaryons (Q^3q^3)

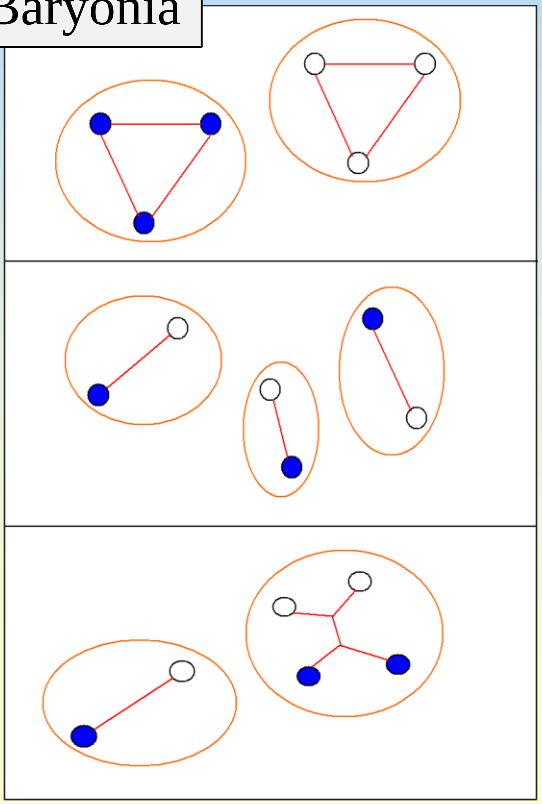


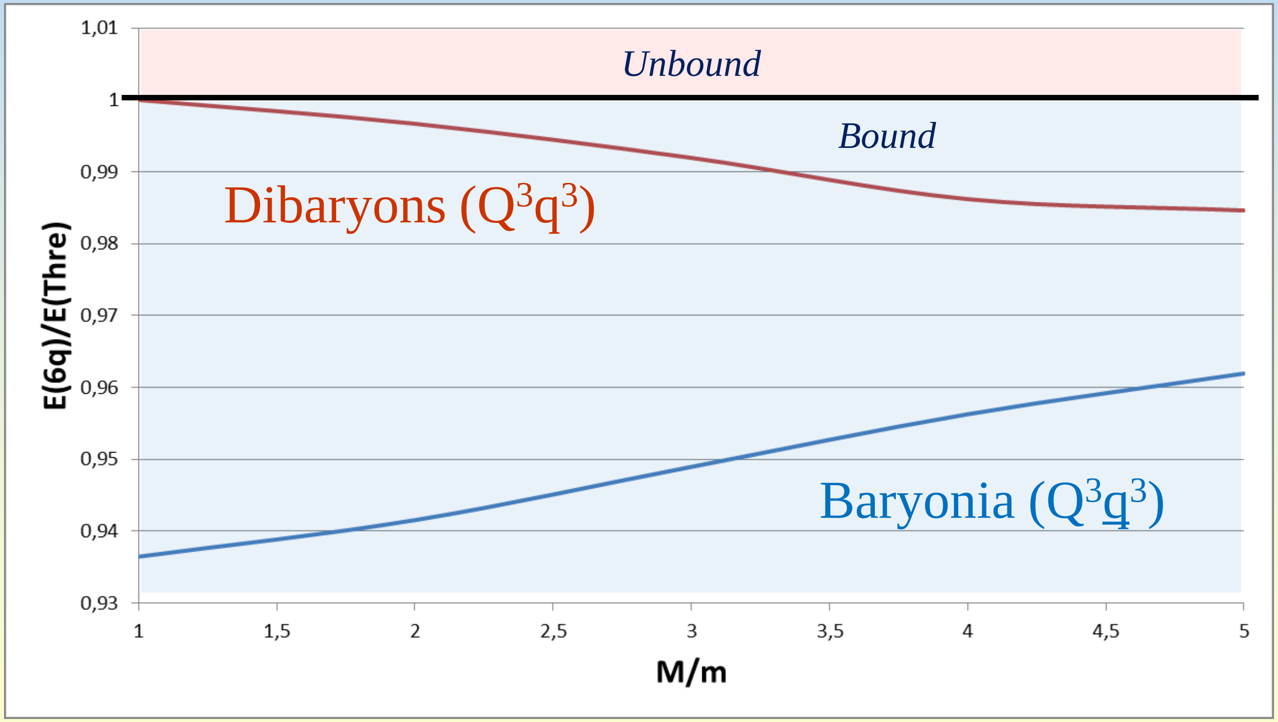
Dibaryons



J.V., A.V., J.-M.R., Phys. Rev. D 85, 014019 (2012)

Baryonia





Chromomagnetic term: Dibaryons (qqqq'QQ')

J.V., A.V., J.-M.R., P.S., Phys. Rev. D 94, 034038 (2016)

Color + Antisymmetry

$$V = -\frac{3}{16}\sum_{i<j}\tilde{\lambda}_i.\tilde{\lambda}_j\left(-\frac{a}{r_{ij}} + b\,r_{ij} + \frac{c}{m_i\,m_j}\left(\frac{\mu}{\pi}\right)^{3/2}\exp(-\mu\,r_{ij}^2)\,\boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j\right)$$

$$S_1 = (000)\ ,\quad S_2 = (011)\ ,\quad S_3 = (101)\ ,\quad S_4 = (110)\ ,\quad S_5 = (111)\ .$$

$$C_1 = (666)\ ,\quad C_2 = (6\bar{3}\bar{3})\ ,\quad C_3 = (\bar{3}6\bar{3})\ ,\quad C_4 = (\bar{3}\bar{3}6)\ ,\quad C_5 = (\bar{3}\bar{3}\bar{3})\ .$$

$J^P=0^+$

Color-spin vector	E (GeV)
C_1S_1	3.079
C_2S_1	2.829
C_3S_4	2.831
C_2S_2	3.030
C_3S_3	3.030
C_3S_5	2.908
C_1S_2	2.995
C_4S_3	2.835
C_4S_4	3.080
C_4S_5	3.016
C_5S_3	2.891
C_5S_4	2.997
C_5S_5	3.034
Coupled	2.767
Thresholds	2.570, 2.630

TABLE III: Probabilities of the different six-body channels contributing to the $J^P = 0^+$ six-quark state.

Channel	C_1S_2	C_2S_1	C_3S_4	C_4S_3
Probability	0.004	0.539	0.456	0.001

Conflict between CE and CM

It goes against binding

TABLE I: Energy (in GeV) of the baryons involved in the thresholds within the model (1). Σ stands for a baryon where the first two quarks are in a spin 1 state, and Λ in a spin 0 state.

$qqQ(\Sigma)$	$qqQ'(\Lambda)$	$qqq(\Sigma)$	$QQ'q(\Sigma)$
1.372	1.258	1.461	1.109

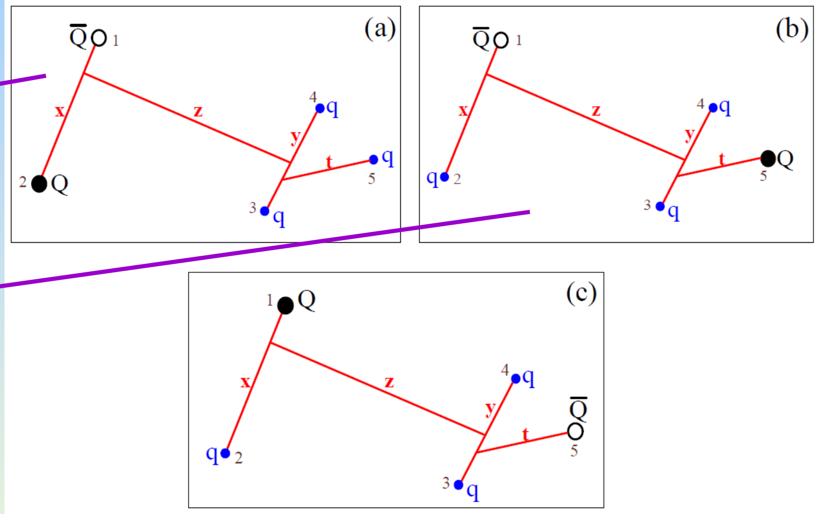
What about pentaquarks?: (QQqqq)

AL1

$$V(r) = -\frac{3}{16}\,\tilde{\lambda}_i \cdot \tilde{\lambda}_j \left[\lambda\, r - \frac{\kappa}{r} - \Lambda + \frac{V_{SS}(r)}{m_i\, m_j}\, \vec{\sigma}_i \cdot \vec{\sigma}_j\right] ,$$

$$V_{SS} = \frac{2\,\pi\,\kappa'}{3}\,\frac{1}{\pi^{3/2}\, r_0^3}\, \exp(-r^2/r_0^2) \ , \quad r_0(m_i, m_j) = A\left(\frac{2 m_i m_j}{m_i + m_j}\right)^{-B}$$

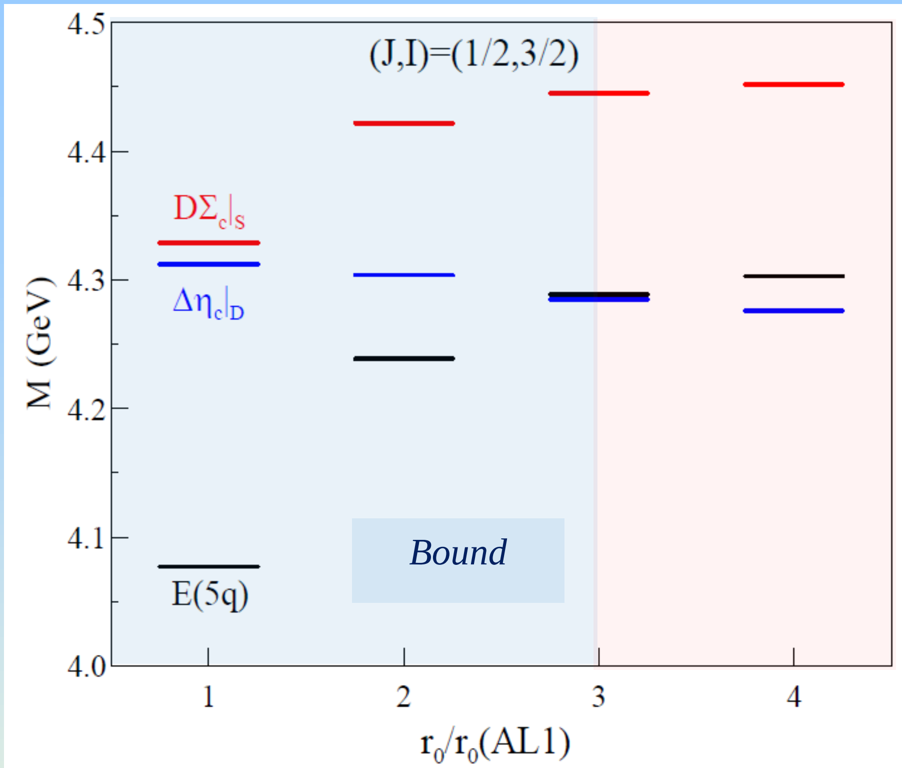
$I=1/2$					$I=3/2$				
J	1/2	3/2	5/2	Mass	J	1/2	3/2	5/2	Mass
$N\eta_c$	S	D	D	4.001	$\Delta\eta_c$	D	S	D	4.312
NJ/ψ	S	S	D	4.097	$D\Sigma_c$	S	D	D	4.329
$D\Lambda_c$	S	D	D	4.154	$D\Sigma_c^*$	D	S	D	4.408
$D^*\Lambda_c$	S	S	D	4.308	$\Delta J/\psi$	S	S	S	4.408
$D\Sigma_c$	S	D	D	4.329	$D^*\Sigma_c$	S	S	D	4.483
$D\Sigma_c^*$	D	S	D	4.408	$D^*\Sigma_c^*$	S	S	S	4.562
$D^*\Sigma_c$	S	S	D	4.483					
$D^*\Sigma_c^*$	S	S	S	4.562					



(J,I)	$(\bar{c}cqqq)$	Lowest threshold
(1/2, 1/2)	4.077	4.001 (S) / 4.408 (D)
(3/2, 1/2)	4.161	4.001 (D) / 4.097 (S)
(5/2, 1/2)	4.429	4.001 (D) / 4.562 (S)
(1/2, 3/2)	4.077	4.312 (D) / 4.329 (S)
(3/2, 3/2)	4.161	4.312 (S) / 4.329 (D)
(5/2, 3/2)	4.429	4.312 (D) / 4.408 (S)

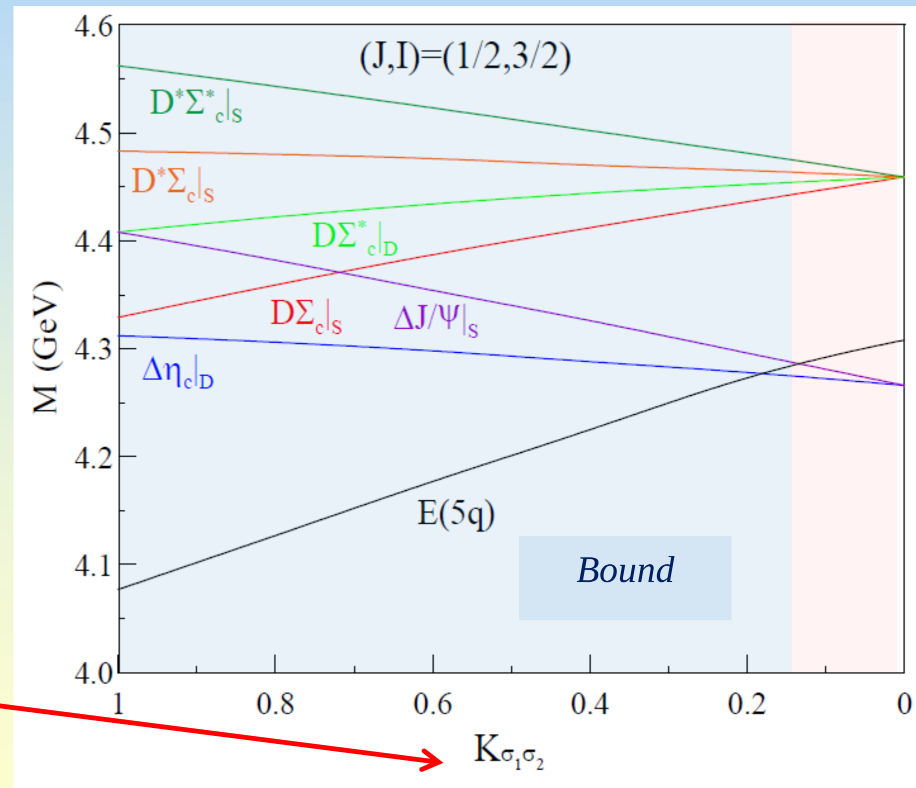
Not so Stable! Above D-wave threshold and below S-wave one.

Stable! Below S- and D-wave thresholds



$$V(r) = -\frac{3}{16}\,\tilde{\lambda}_i \cdot \tilde{\lambda}_j \left[\lambda r - \frac{\kappa}{r} - \Lambda + \frac{V_{SS}(r)}{m_i m_j}\,\vec{\sigma}_i \cdot \vec{\sigma}_j\right],$$

$$V_{SS} = \frac{2\pi\kappa'}{3}\,\frac{1}{\pi^{3/2} r_0^3}\,\exp(-r^2/r_0^2)\,, \quad r_0(m_i, m_j) = A\left(\frac{2 m_i m_j}{m_i + m_j}\right)^{-B}$$



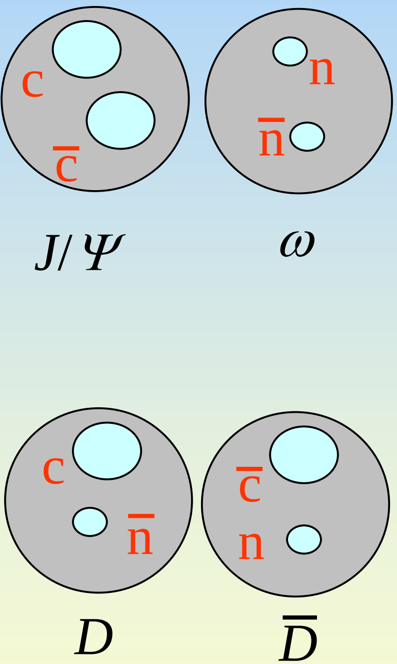
Summary of four-quark states: BCN and CQC

$Q \equiv c$

	$Qn\underline{Qn}$ (Non exotic)	$QQ\underline{nn}$ (Exotic)
Compact	No states *Phys. Rev. D 76, 094022 (2007)*	$J^P=1^+$ *Phys. Rev. D 79, 074010 (2009)*
Molecular	$(I)J^{PC}=(0)1^{++} \Rightarrow X(3872)$ $(I)J^{PC}=(1)2^{++}$ (Exotic) *Phys. Rev. Lett. 103, 222001 (2009)* *Phys. Rev. D 82, 054032 (2010)*	

How the molecular $Qn\underline{Qn}$ states are formed in a quark model framework?

Coupled channel effect ⇔ Hidden color vectors



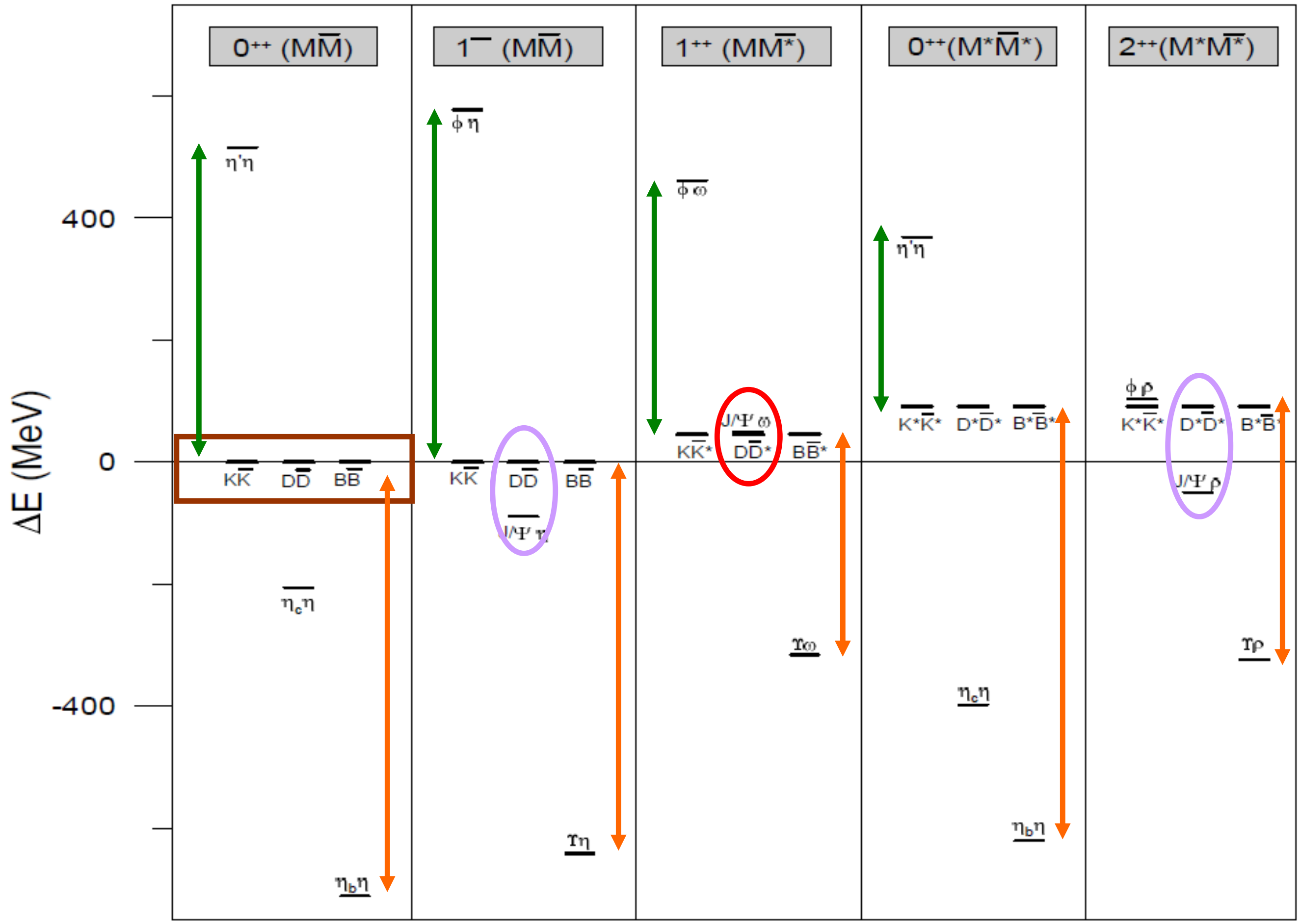
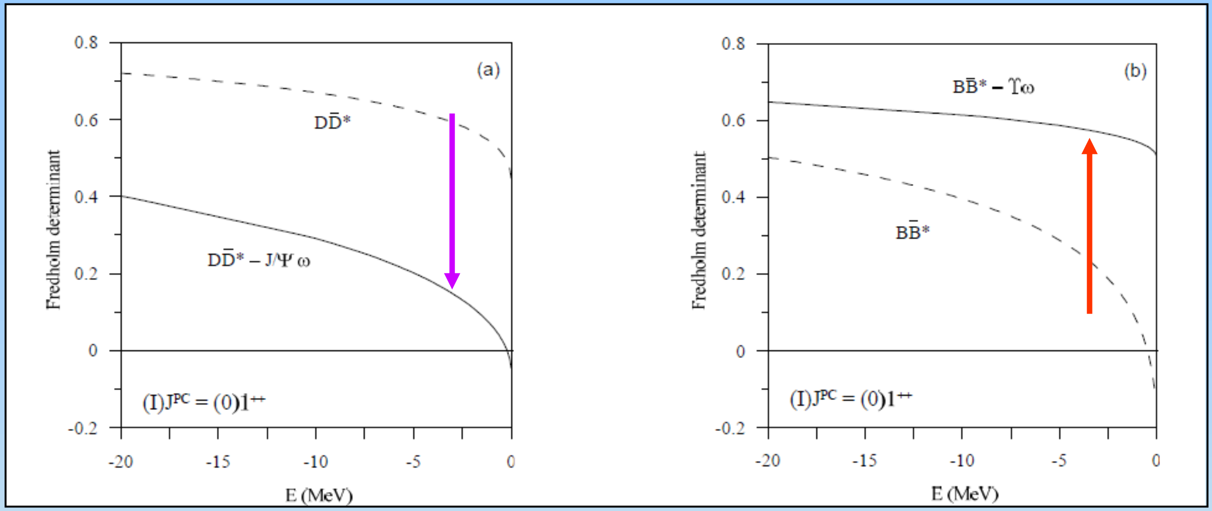


FIG. 1: Experimental masses of the different two-meson systems made of a heavy and a light quark and their corresponding antiquarks, $Qn\bar{Q}\bar{n}$ with $Q = s, c$, or b, for several sets of quantum numbers, J^{PC}. We have set as our origin of energies the $K\bar{K}$, $D\bar{D}$ and $B\bar{B}$ masses for the hidden strange, charm and bottom sectors, respectively.

T.F.C., A.V., J.V., Phys. Lett. B 709, 358 (2012)

T.F.C., A.V., Phys. Lett. B 758, 244 (2016)

QnQn

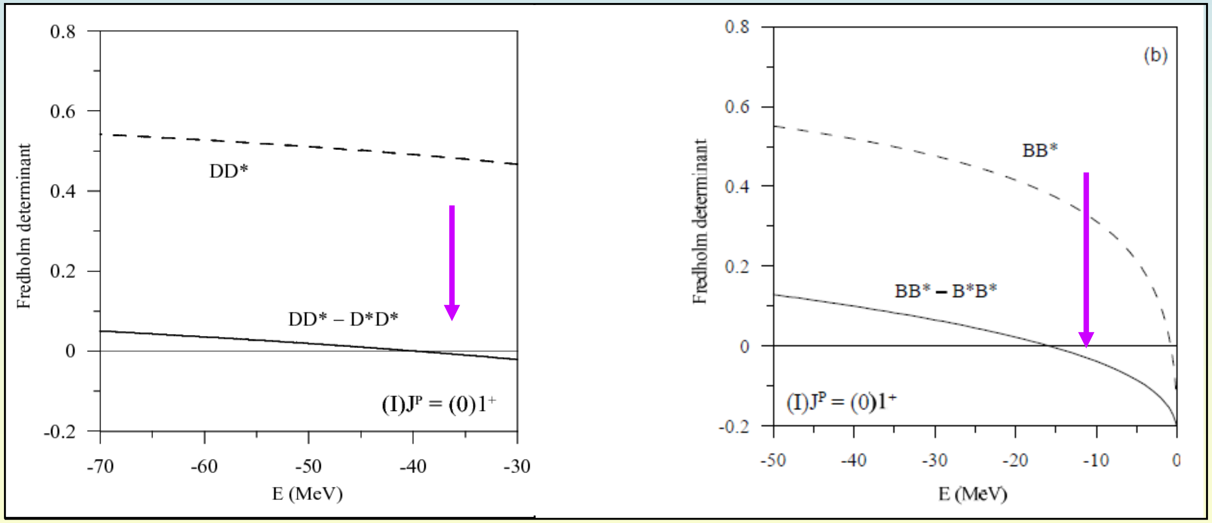


There should not be a partner of the X(3872) in the bottom sector

$Q \equiv c$

$Q \equiv b$

QQnn



There should be a $J^P=1^+$ bound state in the exotic bottom sector

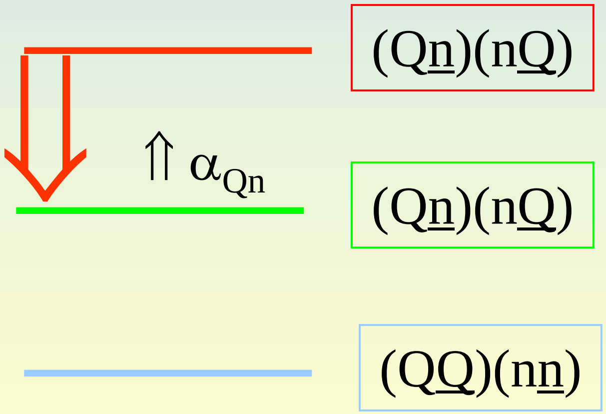
A quark-model mechanism for the XYZ mesons

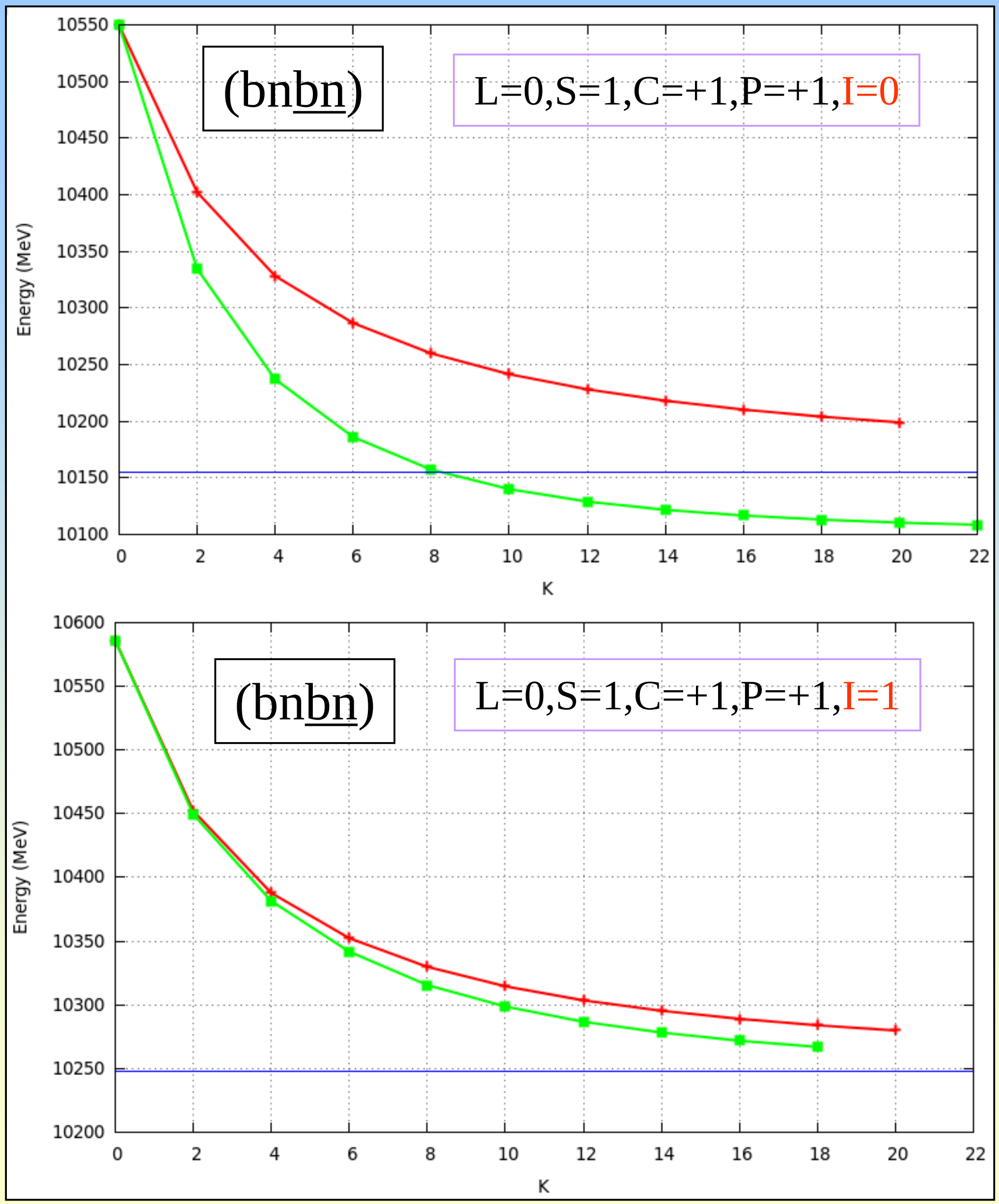
$(Qn\underline{Q}\underline{n})$

$(QQ)(\underline{n}\underline{n})$ — $(Q\underline{n})(n\underline{Q})$

Central — Spin-spin

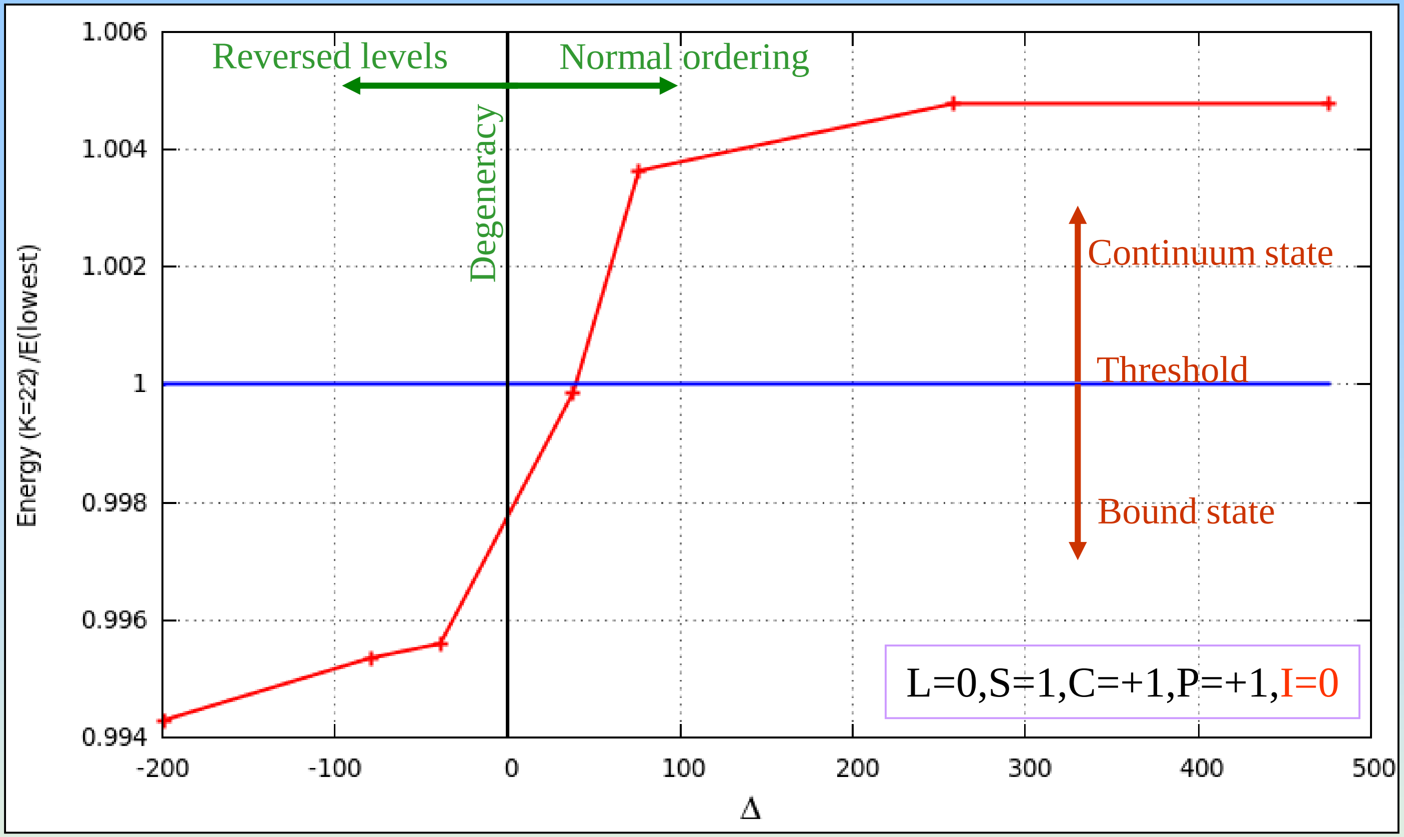
$$M_{QQ} + M_{\underline{n}\underline{n}} \le M_{Q\underline{n}} + M_{n\underline{Q}}$$





Conclusions

- In multiquark studies, both CE and CM effects have to be included, color may generate conflicts between the preferred configurations.
- All-heavy tetraquarks are unstable in naive CE models.
- (QqQq) might have some opportunities of metastability below the M$\underline{M}$ threshold, which is extremely important for the existence of the X(3872) in the charm sector.
- (QQqq) are definitively the best candidates for stable multiquark states due to the striking M/m dependence in the CE limit. Besides, for non-identical quarks and antiquarks, string potentials offer good opportunities.
- Hidden heavy flavor pentaquarks are predicted in the chromomagnetic limit due to hidden-color components dynamics.
- Hidden flavor components (unquenching the quark model) offer a possible explanation of new experimental data and old problems in the meson and baryon spectra. There is not a proliferation of multiquarks, they are very rare.
- We have presented a plausible mechanism explaining the origin of the XYZ mesons: based on coupled-channel effects.
- We do not find evidence for charged and bottom partners of the X(3872). To answer this question is a keypoint to advance in the study of hadron spectroscopy.



X axis

$\Delta = E[(Q\underline{n})(n\underline{Q})] - E[(Q\underline{Q})(n\underline{n})]$

- $\Delta = 0 \Rightarrow E[(Q\underline{n})(n\underline{Q})] = E[(Q\underline{Q})(n\underline{n})]$: Degeneracy
- $\Delta > 0 \Rightarrow E[(Q\underline{n})(n\underline{Q})] > E[(Q\underline{Q})(n\underline{n})]$: Normal ordering
- $\Delta < 0 \Rightarrow E[(Q\underline{n})(n\underline{Q})] < E[(Q\underline{Q})(n\underline{n})]$: Reversed levels

Y axis

$E_{K=22}[(Qn\underline{Q}\underline{n})]/[E(M_1)+E(M_2)]$

- $=1 \Rightarrow E[(Qn\underline{Q}\underline{n})] = [E(M_1)+E(M_2)]$: Threshold
- $>1 \Rightarrow E[(Qn\underline{Q}\underline{n})] > [E(M_1)+E(M_2)]$: Continuum state
- $<1 \Rightarrow E[(Qn\underline{Q}\underline{n})] < [E(M_1)+E(M_2)]$: Bound state

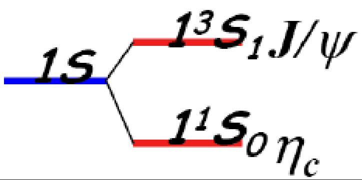
Theory: Predictions

Chromoelectric central potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$

Chromomagnetic spin-spin correction:

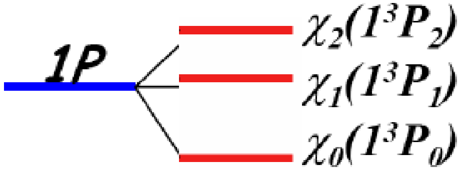
$$\frac{4\alpha_s(r)}{3m_i m_j}\left\{\frac{8\pi}{3}\vec{S}_i\cdot\vec{S}_j\,\delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3}\left[\frac{3\vec{S}_i\cdot\vec{r}_{ij}\vec{S}_j\cdot\vec{r}_{ij}}{r_{ij}^2} - \vec{S}_i\cdot\vec{S}_j\right]\right\}$$



Chromomagnetic spin-orbit term:

$$H_{ij}^{s.o.(cm)} = \frac{4\alpha_s(r)}{3r_{ij}^3}\left(\frac{1}{m_i}+\frac{1}{m_j}\right)\left(\frac{\vec{S}_i}{m_i}+\frac{\vec{S}_j}{m_j}\right)\cdot\vec{L}$$

$$H_{ij}^{s.o.(tp)} = \frac{-1}{2r_{ij}}\frac{\partial V(r)}{\partial r_{ij}}\left(\frac{\vec{S}_i}{m_i^2}+\frac{\vec{S}_j}{m_j^2}\right)\cdot\vec{L}$$



T. Barnes et al., Phys. Rev. D72, 054026 (2005)

Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
1S	$J/\psi(1^3S_1)$	3096.87 ± 0.04	3097	3090	3098
	$\eta_c(1^1S_0)$	2979.2 ± 1.3	2979	2982	2975
2S	$\psi'(2^3S_1)$	3685.96 ± 0.09	3686	3672	3676
	$\eta_c'(2^1S_0)$	3637.7 ± 4.4	3638	3630	3623
3S	$\psi(3^3S_1)$	4040 ± 10	4040	4072	4100
	$\eta_c(3^1S_0)$			4043	4064
4S	$\psi(4^3S_1)$	4415 ± 6	4415	4406	4450
	$\eta_c(4^1S_0)$			4384	4425
1P	$\chi_2(1^3P_2)$	3556.18 ± 0.13	3556	3556	3550
	$\chi_1(1^3P_1)$	3510.51 ± 0.12	3511	3505	3510
	$\chi_0(1^3P_0)$	3415.3 ± 0.4	3415	3424	3445
	$h_c(1^1P_1)$	see text		3516	3517
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$			3852	3916
	$h_c(2^1P_1)$			3934	3956
3P	$\chi_2(3^3P_2)$			4317	4337
	$\chi_1(3^3P_1)$			4271	4317
	$\chi_0(3^3P_0)$			4202	4292
	$h_c(3^1P_1)$			4279	4318
1D	$\psi_3(1^3D_3)$			3806	3849
	$\psi_2(1^3D_2)$			3800	3838
	$\psi(1^3D_1)$	3769.9 ± 2.5	3770	3785	3819
	$\eta_{c2}(1^1D_2)$			3799	3837
2D	$\psi_3(2^3D_3)$			4167	4217
	$\psi_2(2^3D_2)$			4158	4208
	$\psi(2^3D_1)$	4159 ± 20	4159	4142	4194
	$\eta_{c2}(2^1D_2)$			4158	4208

Symmetry breaking

- ✓ QM ⇒ Min $(p^2 + x^2 + \lambda x) <$ Min $(p^2 + x^2)$ ⇒ Min $(H_{even} + H_{odd}) <$ Min (H_{even})
- ✓ Min $(M^+ M^+ m^- m^-) <$ Min $(\mu^+ \mu^+ \mu^- \mu^-)$,, $2\mu^{-1} = M^{-1} + m^{-1}$
  - ❑ They have the same threshold

$$\frac{\vec{p}_1^{\,2}}{2\,M} + \frac{\vec{p}_2^{\,2}}{2\,M} + \frac{\vec{p}_3^{\,2}}{2\,m} + \frac{\vec{p}_4^{\,2}}{2\,m} + V = \left[\sum_i \frac{\vec{p}_i^{\,2}}{2\,\mu} + V\right] + \left(\frac{1}{4\,M} - \frac{1}{4\,m}\right)\left[\vec{p}_1^{\,2} + \vec{p}_2^{\,2} - \vec{p}_3^{\,2} - \vec{p}_4^{\,2}\right]$$

⇒ Min $(H_{C\text{-}even} + H_{C\text{-}odd}) <$ Min $(H_{C\text{-}even})$

⇒ H_2 is more stable tan Ps_2

Breaking particle symmetry

- ❑ Thus $(M^+ m^+ M^- m^-)$ more stable than $(\mu^+ \mu^+ \mu^- \mu^-)$????

$$\frac{\vec{p}_1^{\,2}}{2\,M} + \frac{\vec{p}_2^{\,2}}{2\,m} + \frac{\vec{p}_3^{\,2}}{2\,M} + \frac{\vec{p}_4^{\,2}}{2\,m} + V = \left[\sum_i \frac{\vec{p}_i^{\,2}}{2\,\mu} + V\right] + \left(\frac{1}{4\,M} - \frac{1}{4\,m}\right)\left[\vec{p}_1^{\,2} + \vec{p}_3^{\,2} - \vec{p}_2^{\,2} - \vec{p}_4^{\,2}\right]$$

No!!

⇒ Symmetry breaking benefits more to $(M^+M^-)+(m^+m^-)$

⇒ One may expect some kind of metastability below $(M^+m^-)+(m^+M^-)$

In short: (Un)favorable symmetry breaking can (spoil)generate stability

Symmetry breaking

✓ Equal-mass case: Asymmetry in the potential energy

$$H = \sum_i \frac{\vec{p}_i^{\,2}}{2\,m} + \sum_{i<j} g_{ij}\, V(r_{ij})\,, \qquad \sum_{i<j} g_{ij} = 2$$

⇒ Equal g_{ij} gives the highest energy
⇒ The broader the distribution of g_{ij} gives the lower energy

(abcd)	$V(r_{ij})$	g_{ij}	$\underline{g}$	Δg
Threshold (1,3)+(2,4)	$-1/r_{ij}$, r_{ij}	{0,0,1,0,1,0}	1/3	0.52
Ps_2	$-1/r_{ij}$	{-1,1,1,1,1,-1}	1/3	1.03
$\lvert T\rangle \equiv [(qq)_{\underline{3}}(\underline{qq})_3]$	$-1/r_{ij}$, r_{ij}	{1/2,1/2,1/4,1/41/4,1/4}	1/3	0.13
$\lvert M\rangle \equiv [(qq)_6(\underline{qq})_{\underline{6}}]$	$-1/r_{ij}$, r_{ij}	{-1/4,-1/4,5/8,5/8,5/8,5/8}	1/3	0.45

⇒ Ps_2 favored compared to quark models
⇒ Mixing effects do not help much