How to Make Sense of the XYZ Mesons from QCD

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arXiv:1401.7351, arXiv:1402.0438
(with C. Langmack and D. H. Smith)

How to Make Sense of the *XYZ* Mesons from QCD (using the Born-Oppenheimer Approximation)

- constituent models for *XYZ* mesons
- Born-Oppenheimer approximation
  for $Q\bar{Q}$ hybrid mesons
  for $Q\bar{Q}$ tetraquark mesons
- hadronic transitions of *XYZ* mesons

XYZ Mesons

- more than 2 dozen new $c\bar{c}$ and $b\bar{b}$ mesons discovered since 2003

- some of them are tetraquark mesons

- many of them are surprisingly narrow

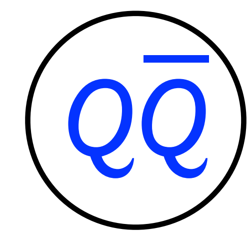
- most were observed through hadronic transitions

- a major challenge to our understanding of the QCD spectrum!

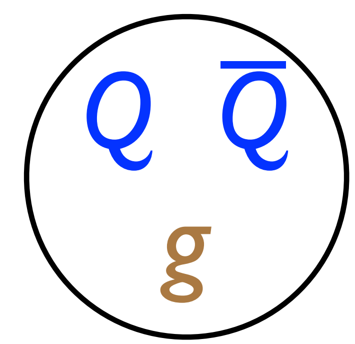
Models for XYZ Mesons

three basic categories

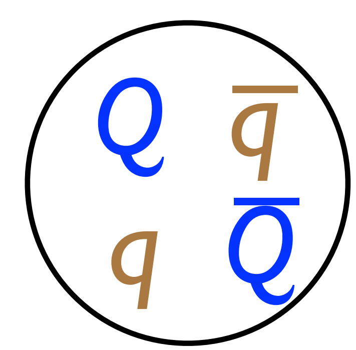
- conventional quarkonium



- quarkonium hybrid



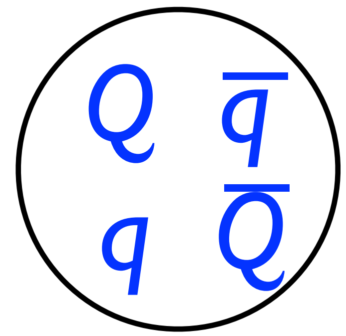
- quarkonium tetraquark



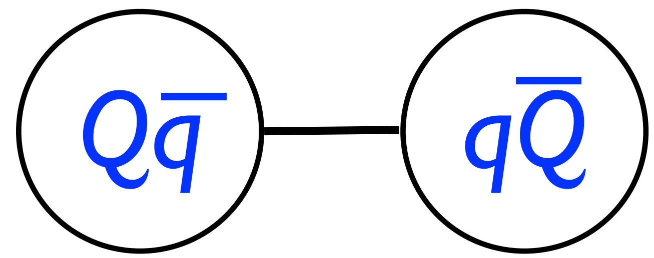
Models for *XYZ* Mesons

Quarkonium Tetraquarks

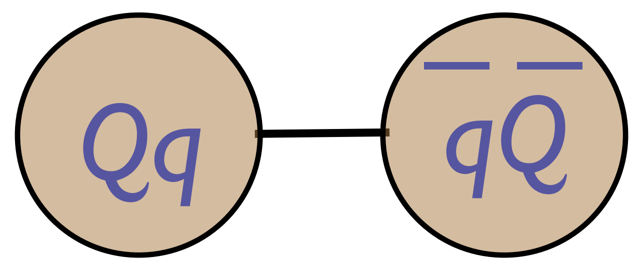
- compact tetraquark



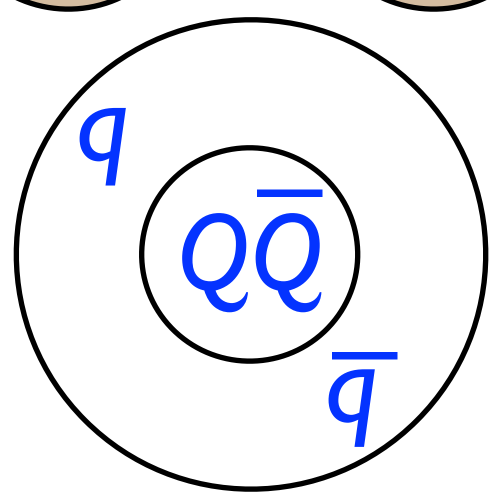
- meson molecule



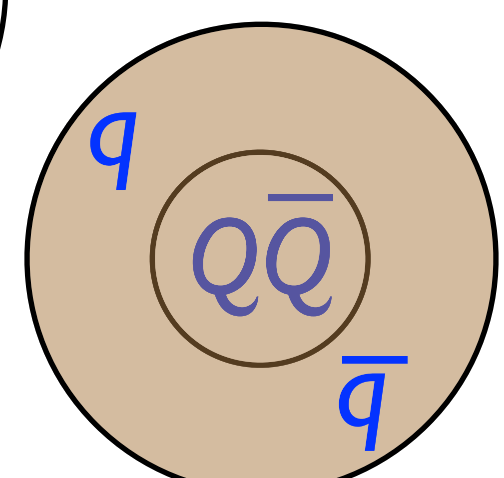
- diquark-onium



- hadro-quarkonium



- quarkonium adjoint meson



Models for XYZ Mesons

- little connection with fundamental theory QCD

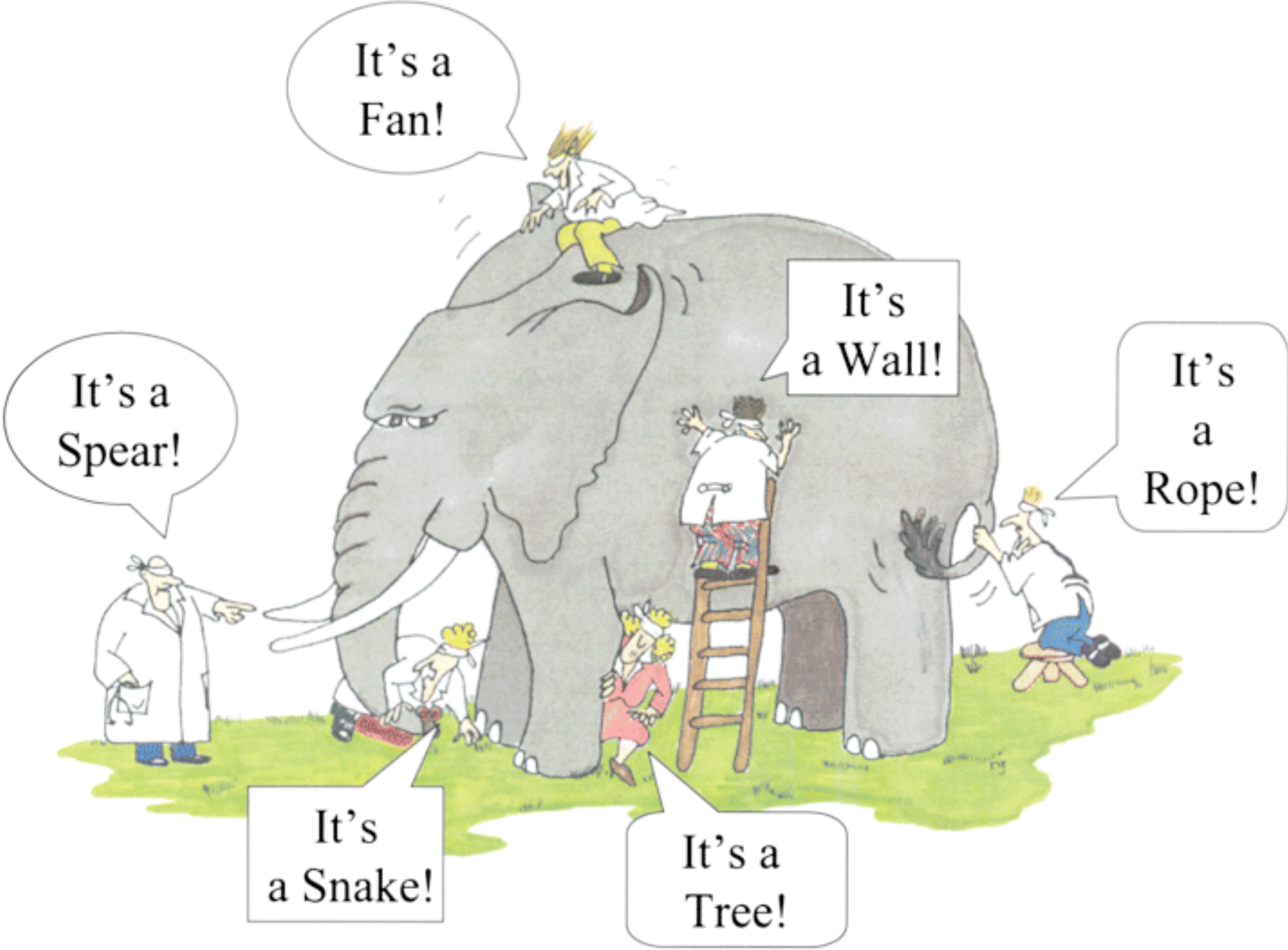
  constituents: degrees of freedom from QCD

  interactions: purely phenomenological

- some success in describing individual XYZ mesons

- no success in describing pattern of XYZ mesons

Models for XYZ Mesons



Approaches within QCD

fundamental fields: quarks and gluons

parameters: α_s, quark masses

- Lattice QCD
- QCD Sum Rules?
- Born-Oppenheimer approximation

Born-Oppenheimer Approximation for Quarkonium Hybrids

- pioneered by Juge, Kuti, Morningstar 1999
- heavy quark mass ≫ Λ_{QCD}
- Q and $\bar{Q}$ move nonrelativisticly
- gluons respond almost instantaneously to the motion of the Q and $\bar{Q}$

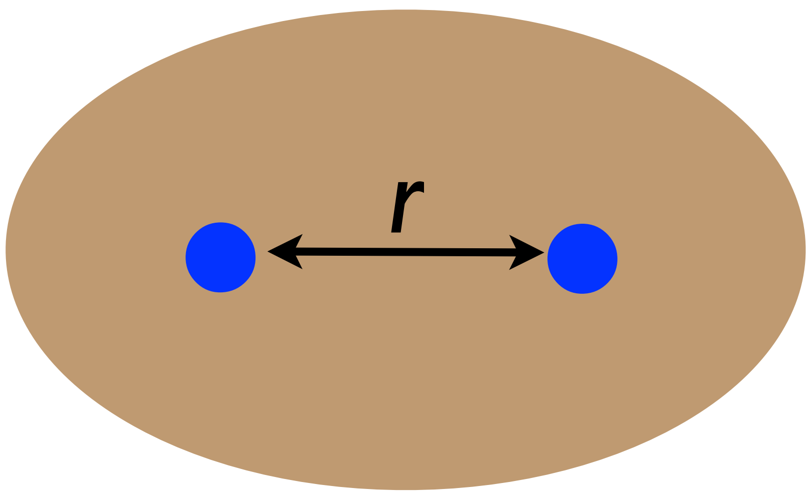
B-O approximation: hybrids

- given the positions of the Q and $\bar{Q}$,
  the gluon fields are in a stationary state
  in the presence of static Q and $\bar{Q}$ sources

- as the positions of the Q and $\bar{Q}$ change,
  the gluon fields remain adiabatically
  in that stationary state

B-O approximation: hybrids

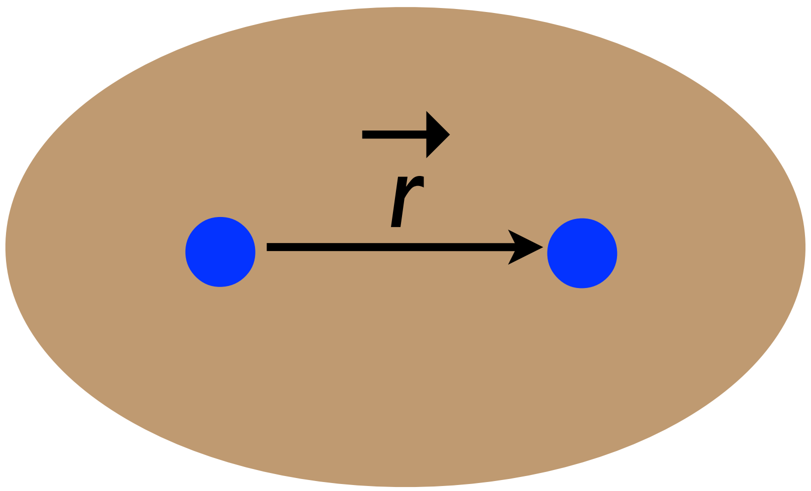
- energy of stationary state of gluon fields in presence of static Q and $\bar{Q}$ sources separated by distance r defines Born-Oppenheimer potential $V(r)$



- Born-Oppenheimer approximation: motion of Q and $\bar{Q}$ is described by Schroedinger equation in potential $V(r)$

B-O approximation: hybrids

stationary states for gluon fields
in presence of static Q and $\bar{Q}$ sources
separated by vector $\vec{r}$



conserved quantum numbers: Λ_η^ϵ

- absolute value of component of angular momentum
  $|\hat{r} \cdot \vec{J}_{light}| \equiv \Lambda = 0, 1, 2, \ldots$ (or $\Sigma, \Pi, \Delta, \ldots$)
- product of charge conjugation and parity
  $(CP)_{light} \equiv \eta = +1, -1$ (or g, u)
- reflection through plane containing sources
  $R_{light} \equiv \epsilon = +1, -1$ (or $+, -$)

B-O approximation: hybrids

Born-Oppenheimer potentials

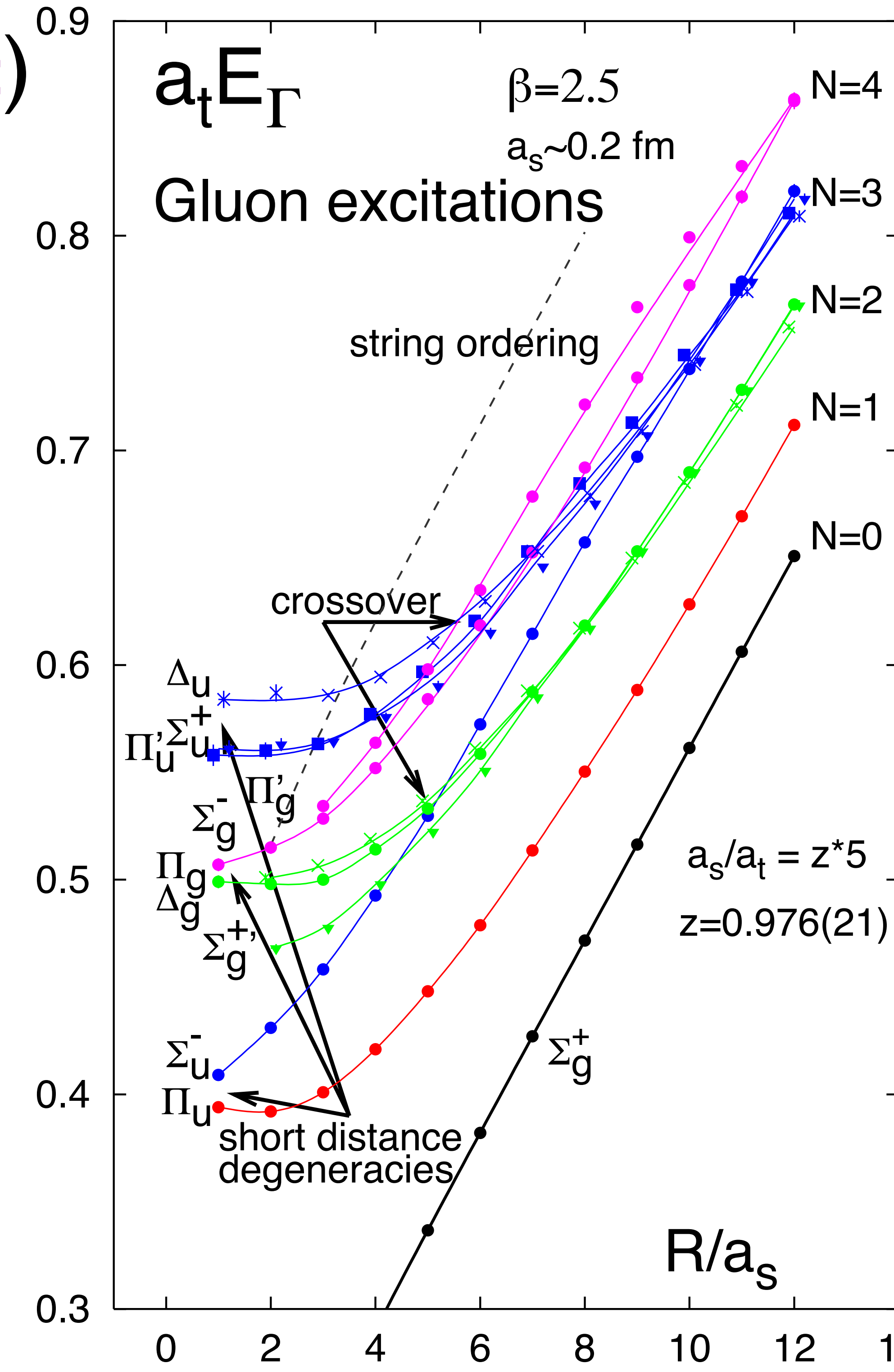
labelled by $|\hat{r}\cdot\vec{J}_{light}| \equiv \Lambda$, $(CP)_{light} \equiv \eta$, $R_{light} \equiv \varepsilon$

or by Λ_η^ε ($\Lambda=\Sigma,\Pi,\ldots$, $\eta=g,u$, $\varepsilon=\pm$)

calculate using lattice QCD

Juge, Kuti, Morningstar 1999

- anisotropic lattice: $10^3 \times 30$
- lattice spacing: $a = 0.2$ fm
- quenched: no virtual quark-antiquark pairs!



lowest Born-Oppenheimer potentials:

Σ_g^+, $\Pi_u^\pm$, Σ_u^-, ...

B-O approximation: hybrids

solve Schroedinger equation in Born-Oppenheimer potentials

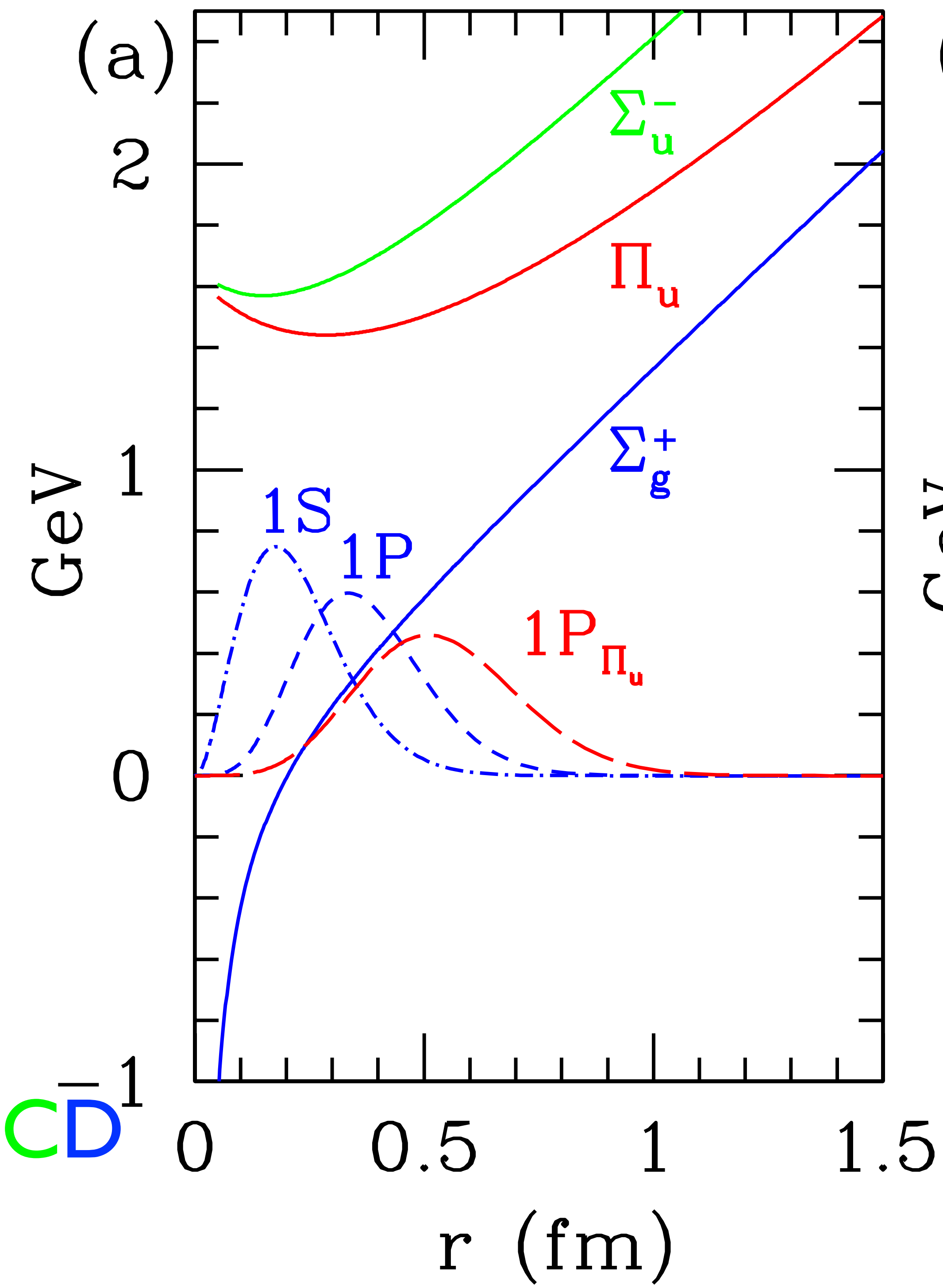
Juge, Kuti, Morningstar 1999

energy levels labelled by nL

radial quantum number: $n = 1,2,3,...$

orbital angular momentum: $L \geq \Lambda$

$L = 0, 1, 2, ...$ or $S, P, D, ...$



energy levels in Σ_g^+ potential:

quarkonium

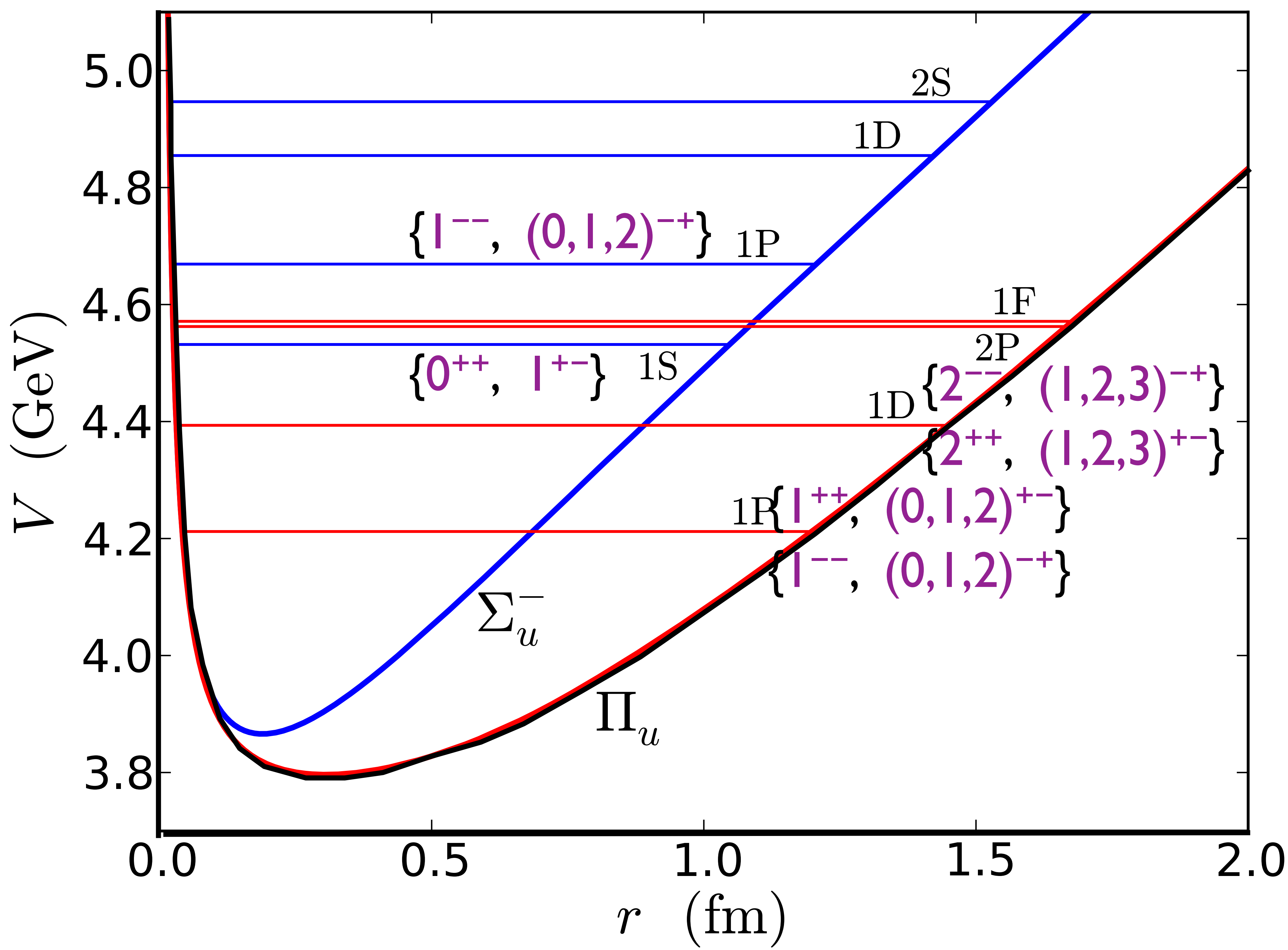
energy levels in $\Pi_u^\pm$, Σ_u^-, ... potentials:

quarkonium hybrids

qualitative agreement with lattice NRQCD

B-O approximation: hybrids

J^{PC} states for lowest hybrid energy levels nL



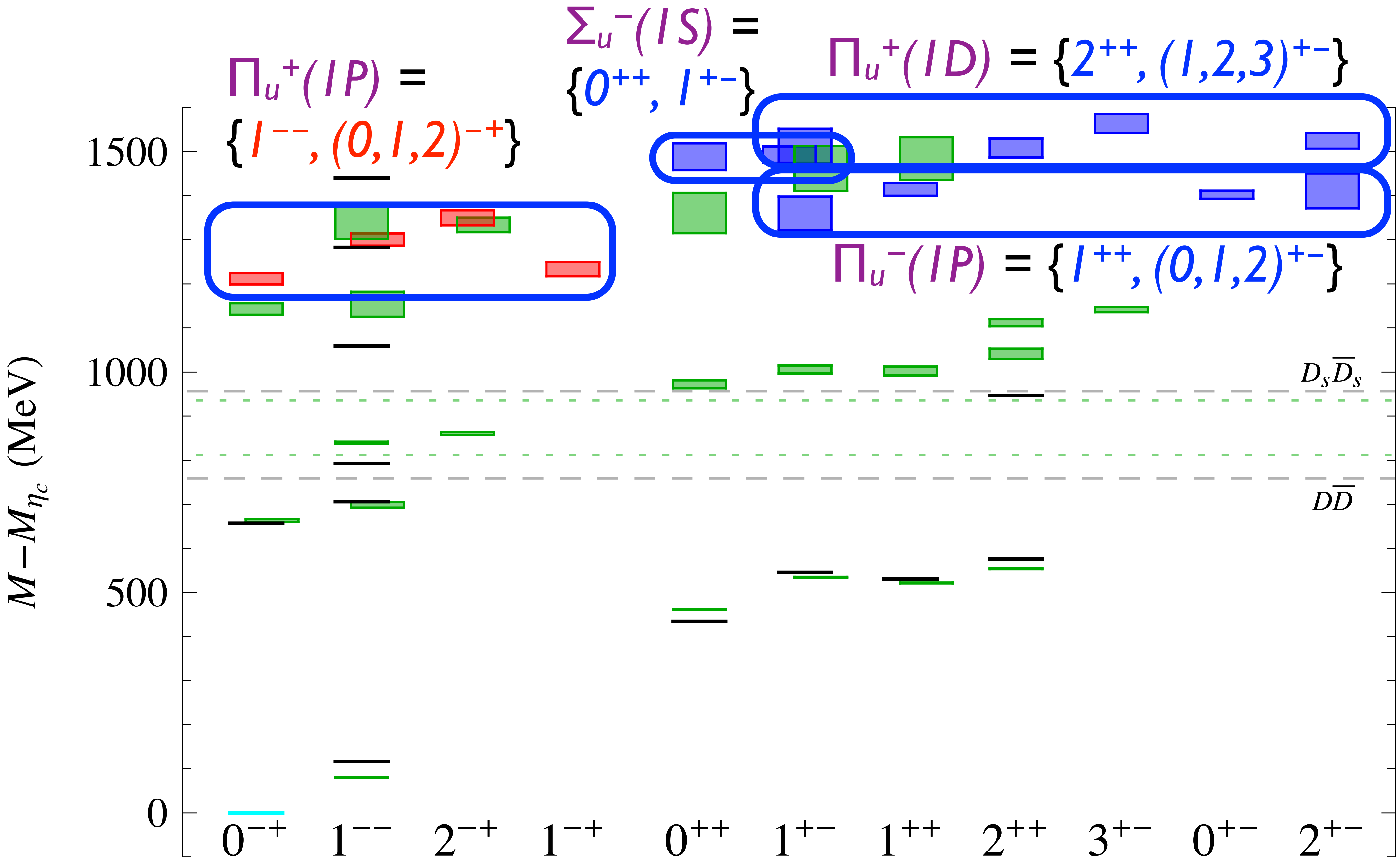
B-O approximation: hybrids

Lattice QCD Hadron Spectrum Coll 2012

14 charmonium hybrid candidates

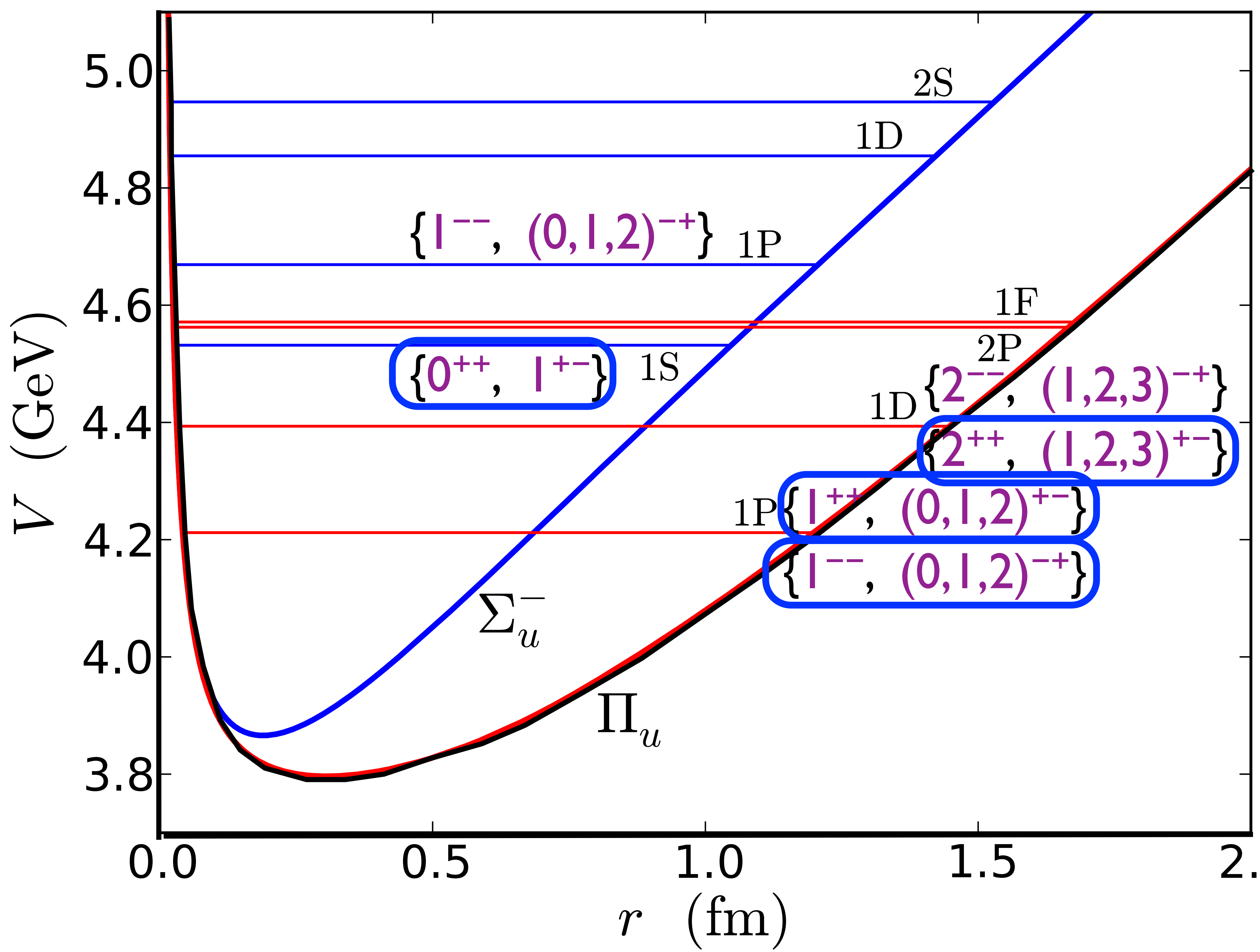
fill out 4 heavy-quark spin multiplets

in lowest Born-Oppenheimer energy levels



B-O approximation: hybrids

J^{PC} states for lowest hybrid energy levels nL



B-O approximation: hybrids

Born-Oppenheimer potentials at small R

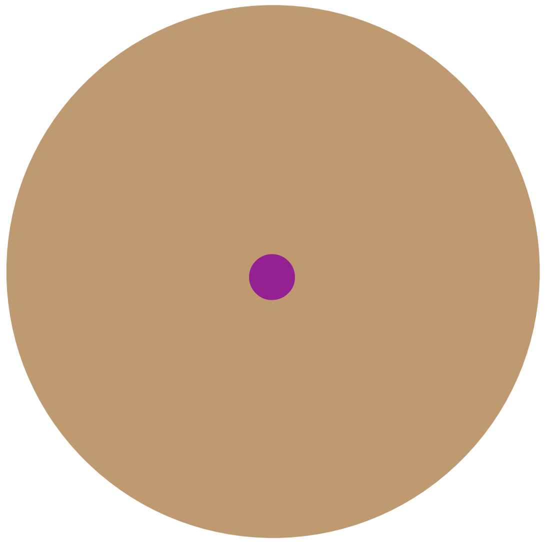
Hybrid potentials: $\Pi_u^{\pm}$, Σ_u^{-}, ...

Q and $\bar{Q}$ sources $\rightarrow$ local color-octet source (gluino)

stationary state $\rightarrow$ gluelump ≡ gluon fields bound to color-octet source

potential: $V(r) \longrightarrow \frac{\alpha_s}{6R} + \text{constant}$

constant = energy of gluelump



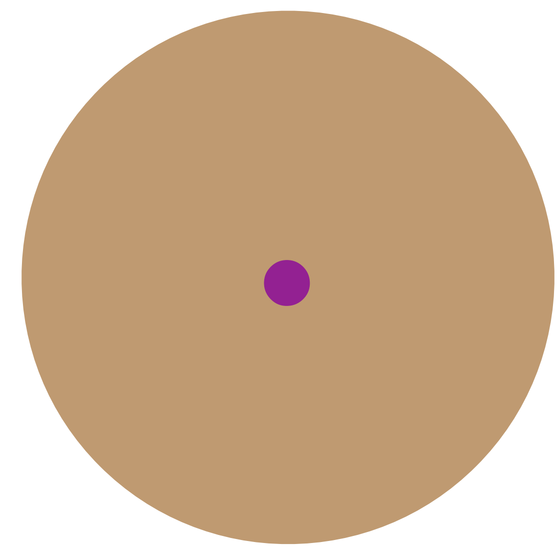
B-O approximation: hybrids

gluelump spectrum from Lattice QCD

Marsh and Lewis arXiv:1309.1627

Lattice QCD

- anisotropic lattice: $28^3 \times 56$
- lattice spacing: a = 0.07 fm
- light quark masses: m_π = 480 MeV



lowest energy: 1^{+-}

2nd lowest: 1^{--} (300 MeV higher)

3rd lowest: 2^{--} (700 MeV higher)

lowest energy gluelump

$\Longrightarrow$ deepest Born-Oppenheimer potentials

$$1^{+-} \Longrightarrow \Pi_u, \Sigma_u^-$$

B-O approximation: hybrids

Born-Oppenheimer potentials at large *R*

Quarkonium and hybrid potentials: Σ_g^+, Π_u, Σ_u^-, ...

stationary state $\rightarrow$ flux tube between Q and $\bar{Q}$ sources

potential: $V(r) \longrightarrow \sigma R + \text{constant}$

B-O approximation: hybrids

Born-Oppenheimer potentials at large *R*

Quarkonium and hybrid potentials: $\Sigma_g^+, \Pi_u, \Sigma_u^-, \ldots$

if there are light quarks,
lowest energy stationary state $\rightarrow$ 2 static mesons

potential: $V(r) \longrightarrow \text{constant}$

constant = 2 x (energy of static meson)

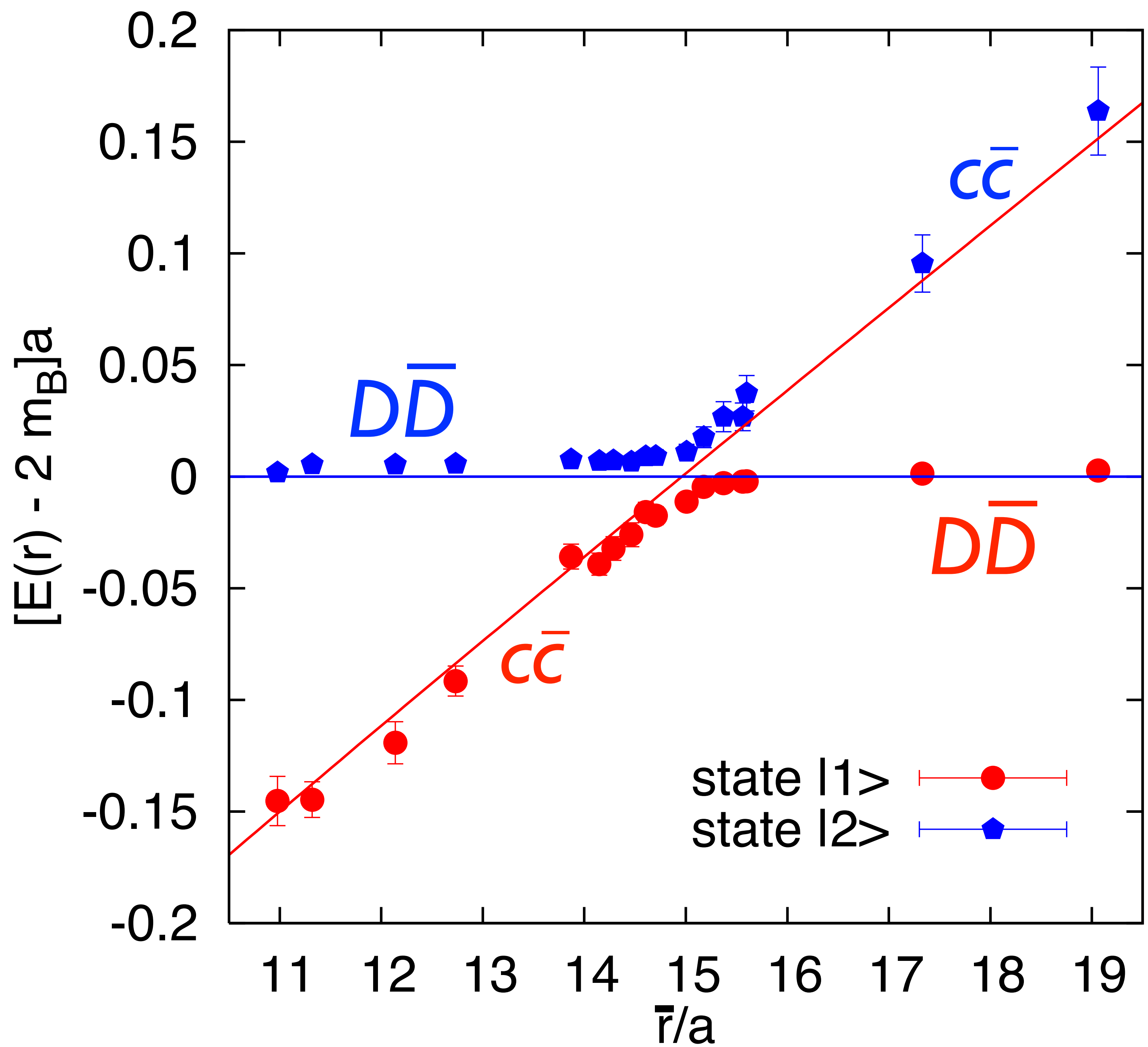
B-O approximation: hybrids

Σ_g^+ (quarkonium) and static meson pair potential

SESAM hep-lat/0505012

Lattice QCD

- anisotropic lattice: $24^3 \times 40$
- lattice spacing: $a = 0.08$ fm
- light quark masses:
  $m_\pi = 540$ MeV



avoided crossing
can be calculated!

B-O approximation: hybrids

- quarkonium hybrids definitely exist
  as states in the QCD spectrum

- whether they can be observed in experiments
  depends on how narrow they are and
  whether they have favorable decay modes

- some of the *XYZ* mesons may be hybrids,
  some are definitely tetraquarks

Born-Oppenheimer Approximation for Quarkonium Tetraquarks

- Charged *XYZ* mesons: constituents include $Q\bar{Q}$ and $u\bar{d}$

  $b\bar{b}$ tetraquarks: $Z_b^+(10610)$, $Z_b^+(10650)$

  $c\bar{c}$ tetraquarks: $Z^+(4430)$, $Z_c^+(3900)$, ...

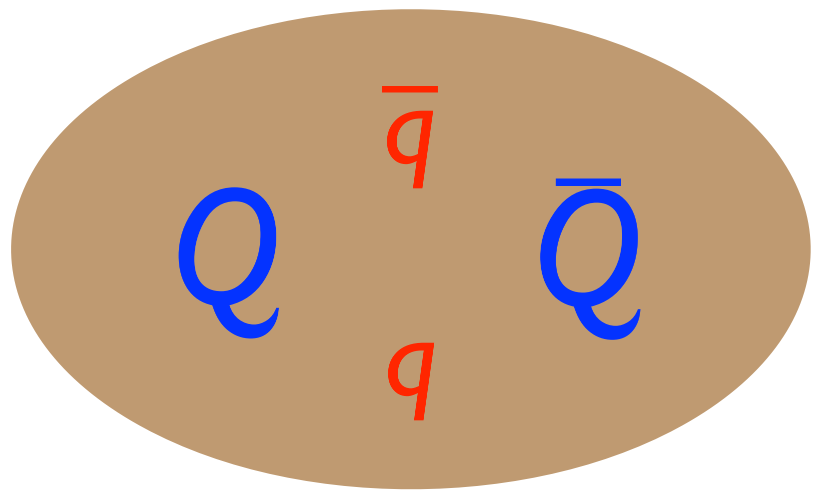
- Neutral *XYZ* mesons

  some may also be tetraquark mesons

Quarkonium Tetraquarks
can be treated using the Born-Oppenheimer approximation

B-O approximation: tetraquarks

Light quarks can respond almost instantaneously
to the motion of the heavy quarks,
just like gluon fields

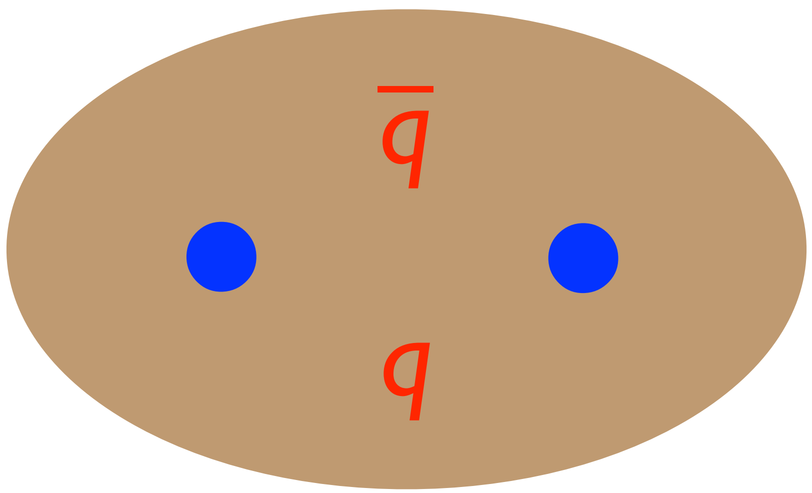


Quarkonium Tetraquarks
can be treated using the Born-Oppenheimer approximation
just like Quarkonium Hybrids
except that the stationary state of gluons and light quarks
has B-O quantum numbers Λ_η^ϵ
and also light-quark+antiquark flavors

Braaten arXiv:1305.6905

B-O Approximation: tetraquarks

- What are the Born-Oppenheimer potentials
  for light-quark and gluon fields
  with light-quark+antiquark flavor?



There are no Lattice QCD calculations
of tetraquark Born-Oppenheimer potentials

but there is one hint from Lattice QCD

B-O approximation: tetraquarks

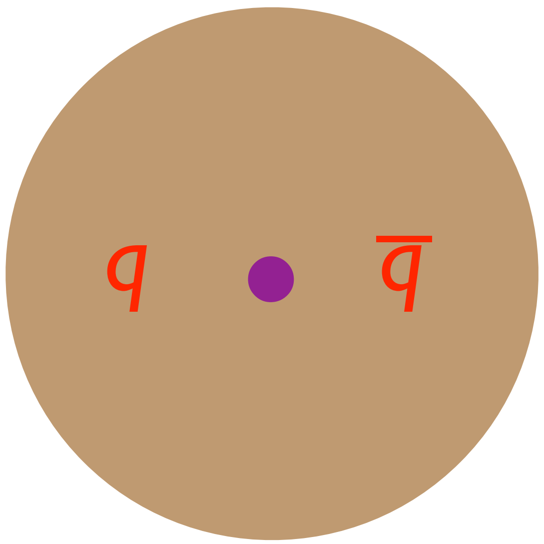
adjoint meson ≡ light-quark and gluon fields
with light-quark+antiquark flavor
bound to color-octet source (gluino)

adjoint meson spectrum from Lattice QCD

Foster, Michael hep-lat/9811010

Lattice QCD

- anisotropic lattice: $24^3 \times 48$
- lattice spacing: a = ?
- quenched: no virtual light-quark-antiquark pairs



lowest energy: 1^{--} or 0^{-+}

lowest-energy adjoint mesons

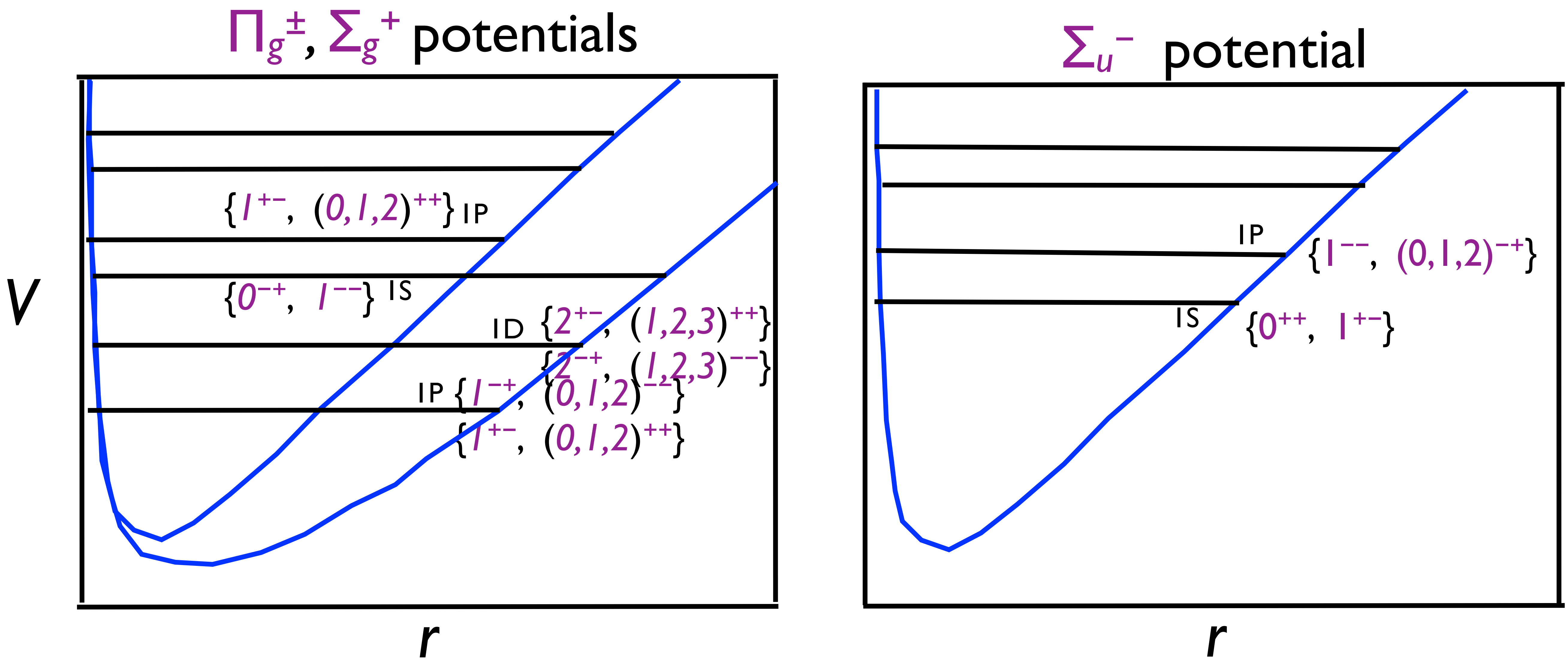
$\Longrightarrow$ deepest tetraquark Born-Oppenheimer potentials

$$1^{--} \Longrightarrow \Pi_g, \Sigma_g^+ \qquad 0^{-+} \Longrightarrow \Sigma_u^-$$

B-O Approximation: tetraquarks

J^{PC} states for lowest tetraquark energy levels nL

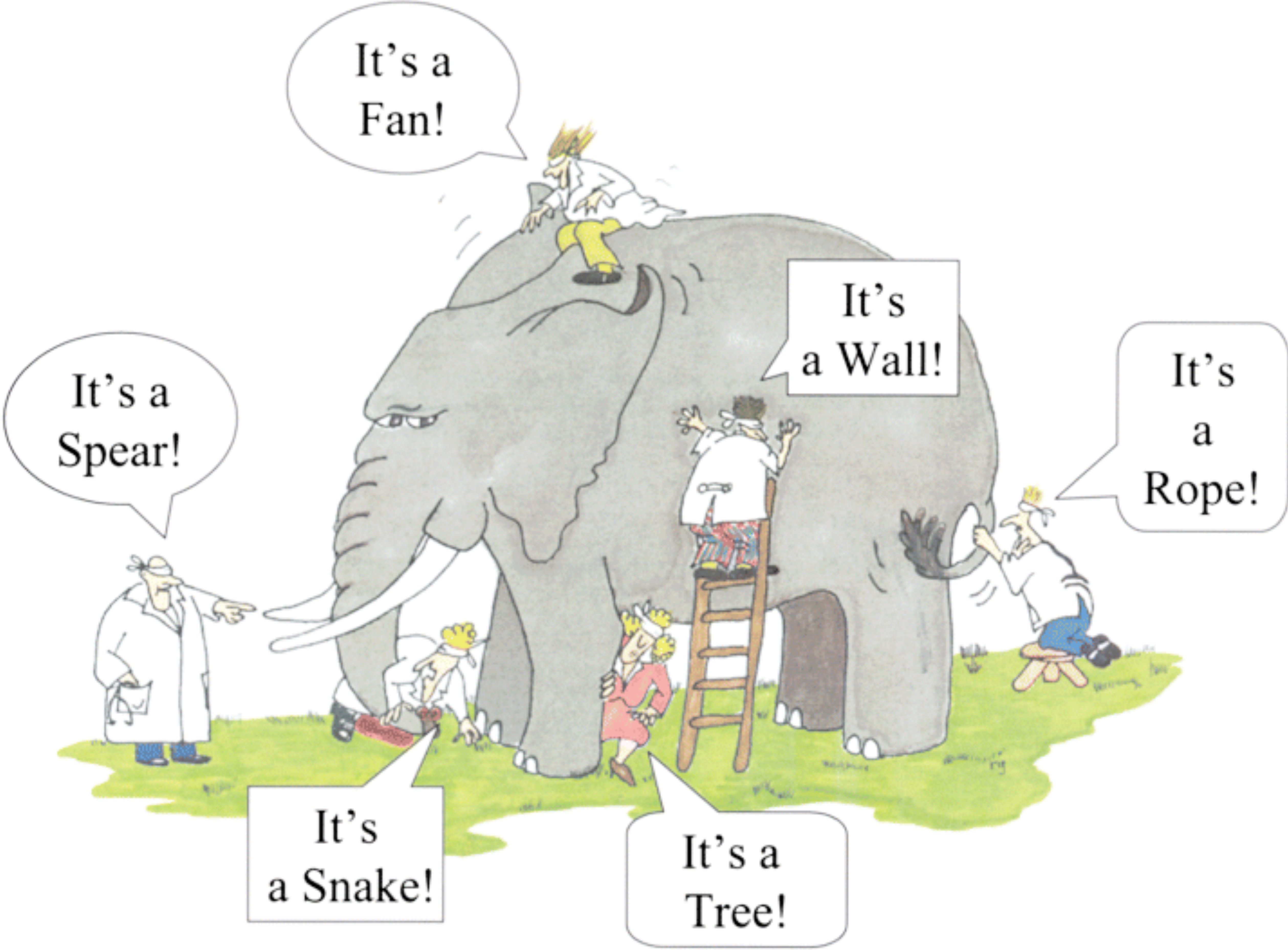
(IF quenched lattice QCD correctly identifies lightest adjoint mesons)



separate tetraquark B-O potentials

for each of three light flavors: isospin 1, isospin 0, $s\bar{s}$

What is an XYZ Meson?



What is an XYZ Meson?

What are the XYZ mesons
from the Born-Oppenheimer perspective?

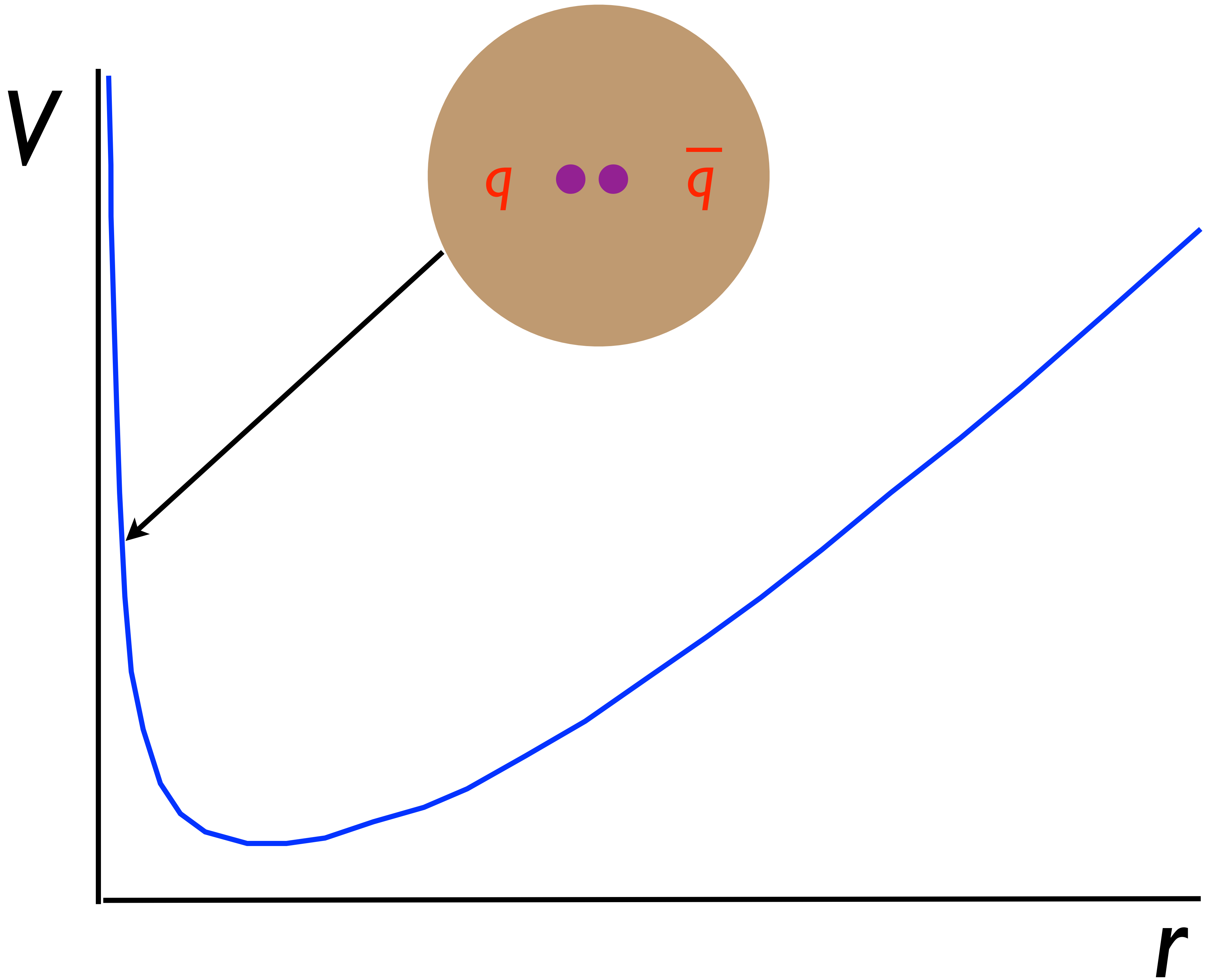
compact tetraquarks?
diquark-onium?
adjoint mesons?
meson molecules?

All of the above!

Each of these possibilities describes some region
of the Born-Oppenheimer wavefunction

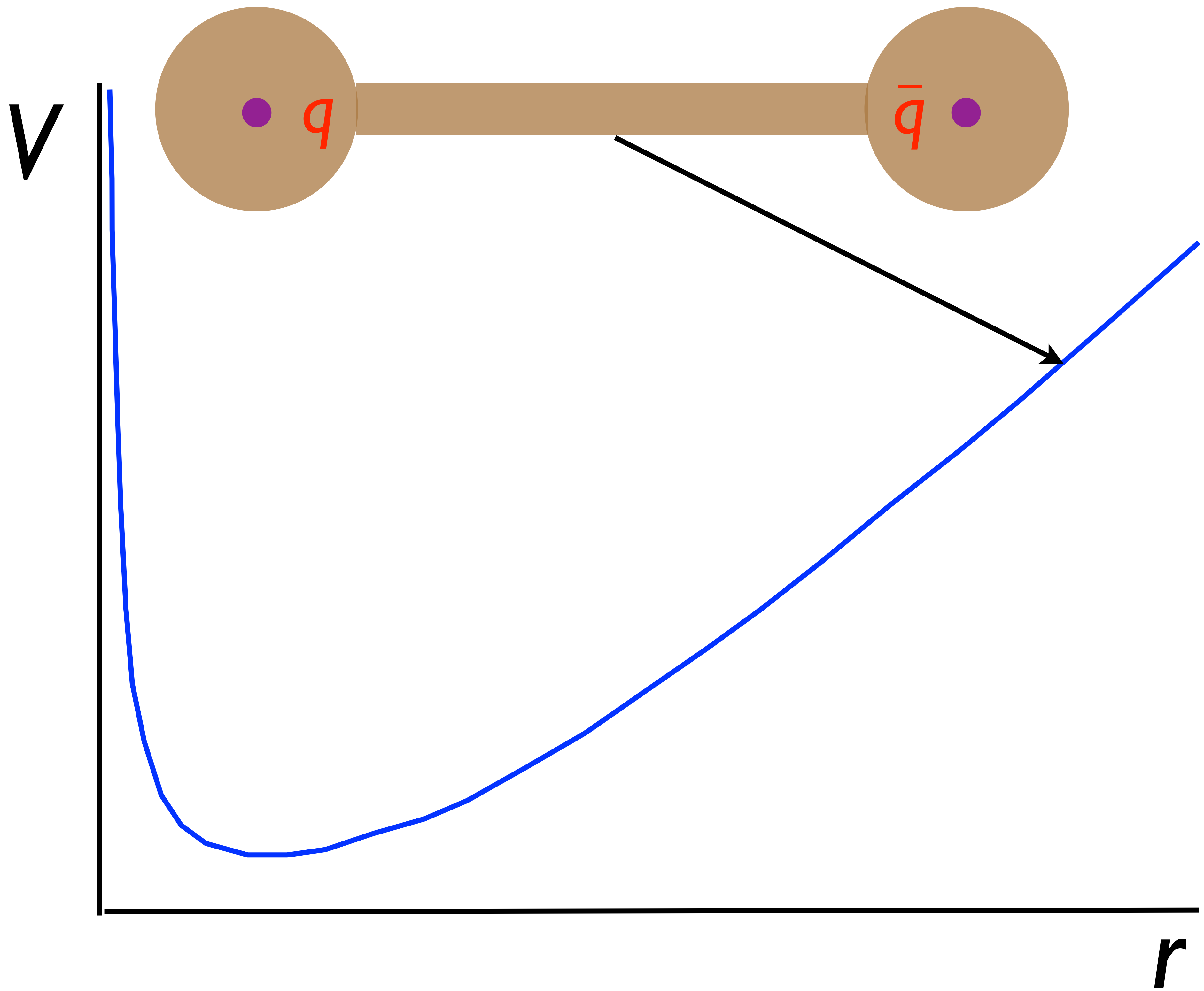
What is an *XYZ* meson?

It's an adjoint meson!



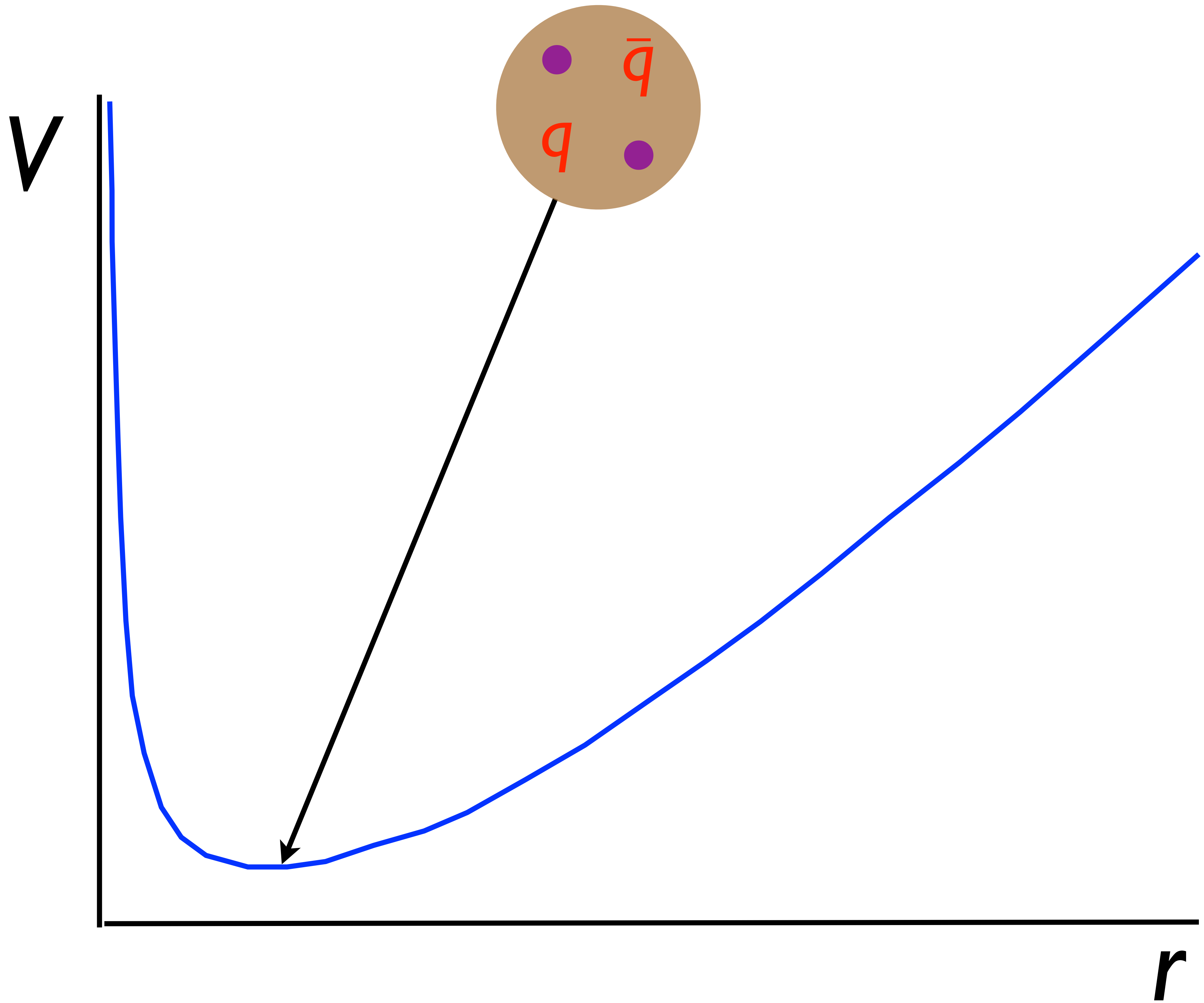
What is an *XYZ* meson?

It's a diquark-onium!



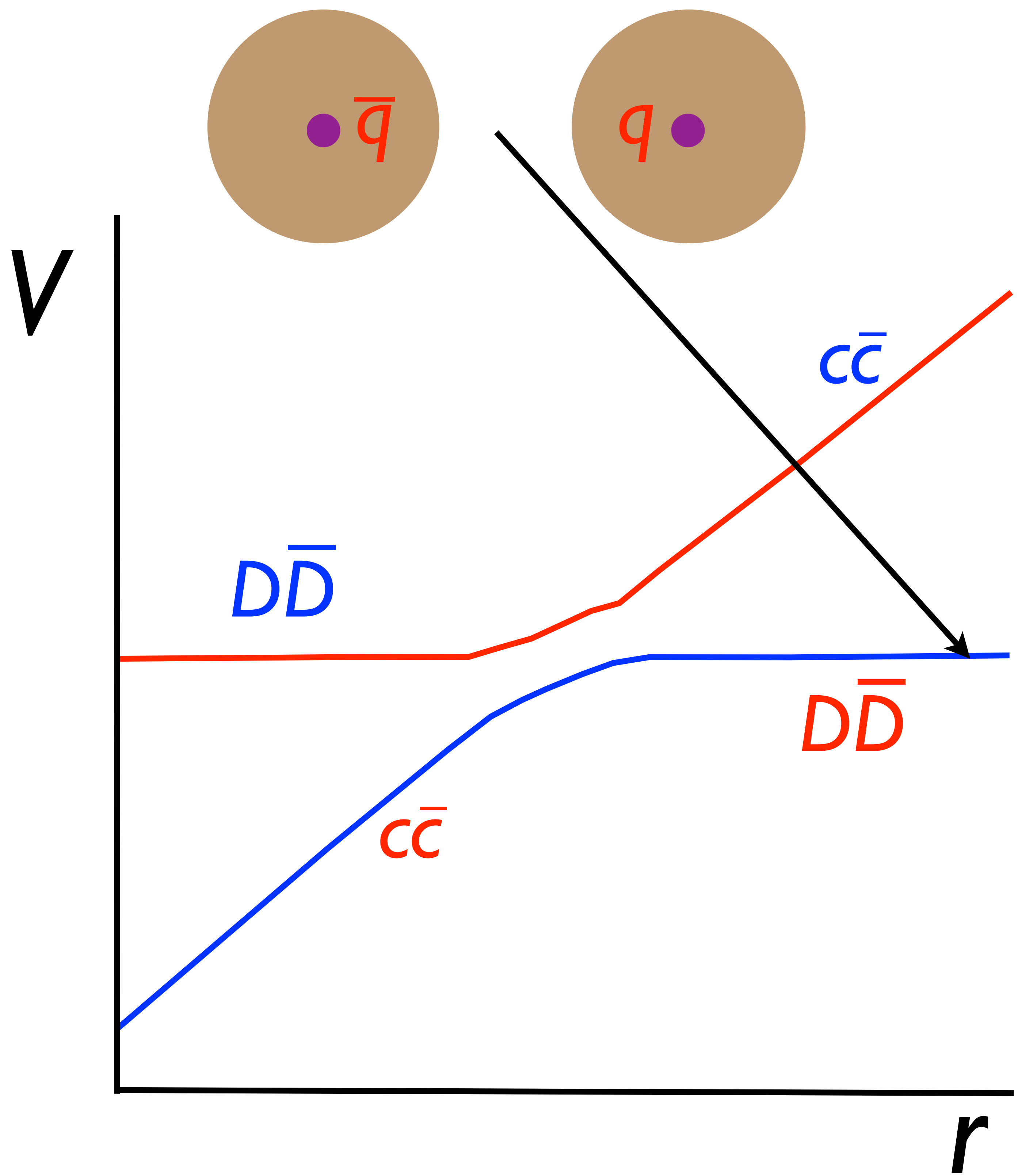
What is an XYZ meson?

It's a compact tetraquark!



What is an *XYZ* meson?

It's a meson molecule!



What is an *XYZ* meson?

Born-Oppenheimer approximation

has not yet revealed a compelling pattern

for the *XYZ* mesons

- too many unknown B-O potentials
- too few *XYZ* mesons with known J^{PC}

Selection rules for hadronic transitions

between Born-Oppenheimer configurations

may provide useful constraints

Braaten, Langmack, Smith arXiv:1401.7351

arXiv:1402.0438

Hadronic Transitions of XYZ Mesons

Braaten, Langmack, Smith arXiv:1401.7351
arXiv:1402.0438

most of the XYZ mesons
have been observed through hadronic transitions:

$X(3872) \to J/\psi + \pi^+\pi^-$
$Y(4260) \to J/\psi + \pi^+\pi^-$
$Z^+(4430) \to J/\psi + \pi^+$
$Y(4140) \to J/\psi + \varphi$
$Z_b^+(10610) \to \Upsilon(nS) + \pi^+$
$Z_c^+(3900) \to J/\psi + \pi^+$

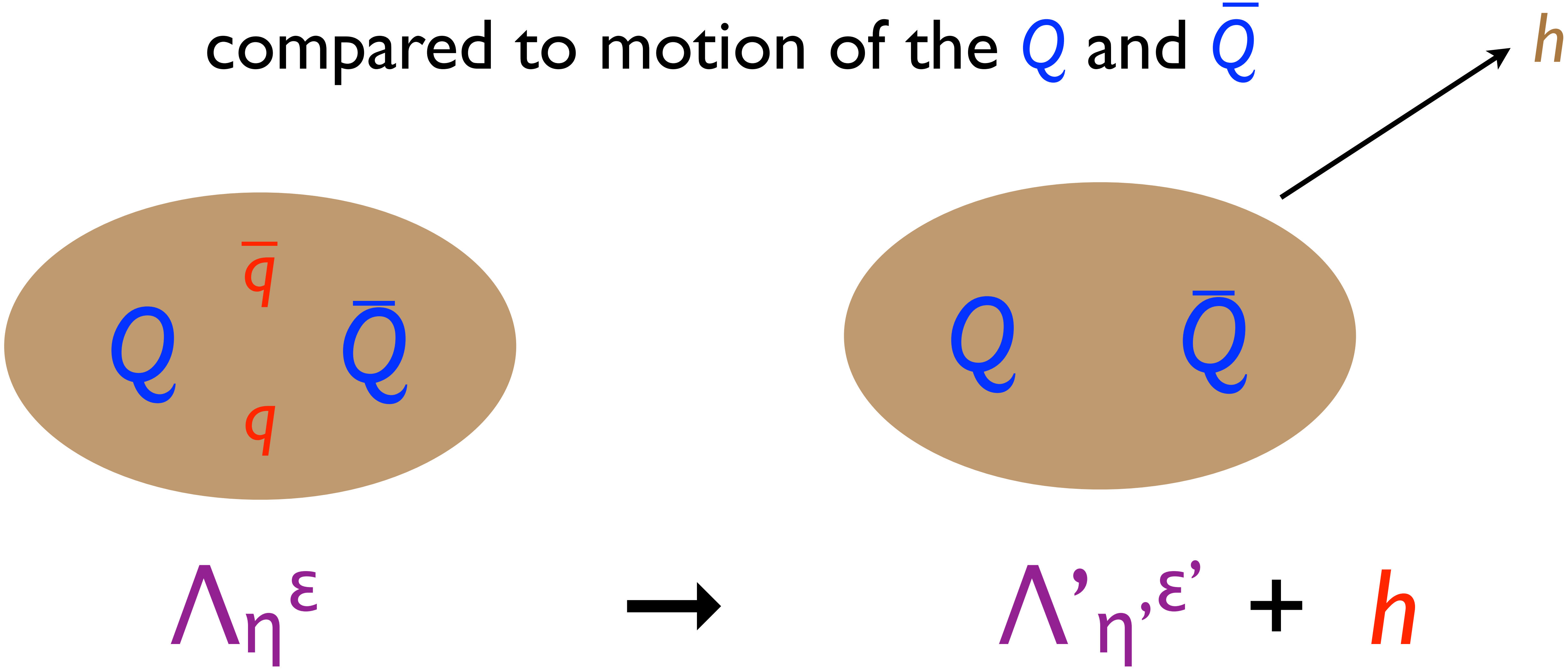
hadronic transitions

- difficult to calculate using lattice QCD
- can be treated using Born-Oppenheimer approximation

Hadronic transitions of XYZ mesons

Born-Oppenheimer approximation

emission of light hadron h
is almost instantaneous
compared to motion of the Q and $\bar{Q}$



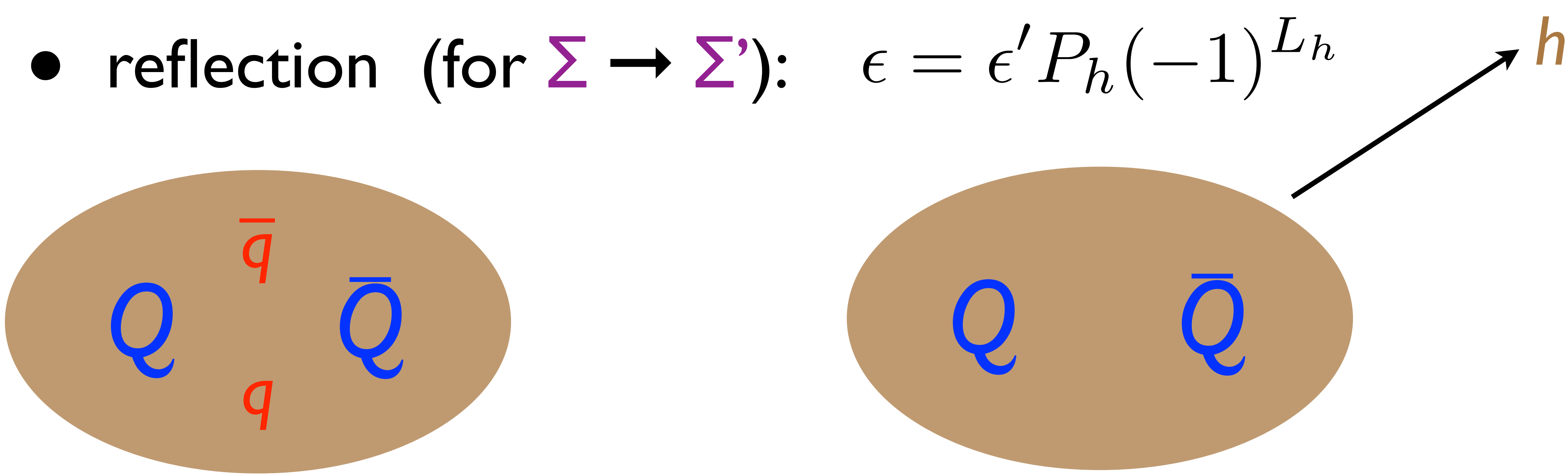
Hadronic transitions of *XYZ* mesons

Selection Rules

emission of light hadron *h*

with quantum numbers J_h, P_h, C_h
and orbital angular momentum L_h

- heavy quark spin: $S = S'$
- conservation of $(CP)_{light}$: $\eta = \eta' C_h P_h (-1)^{L_h}$
- reflection (for $\Sigma \rightarrow \Sigma'$): $\epsilon = \epsilon' P_h (-1)^{L_h}$



selection rules for hadronic transitions of XYZ mesons to quarkonium

$\Longrightarrow$ constraints on Born-Oppenheimer potentials

XYZ $\rightarrow$ quarkonium + S-wave vector meson (ω or φ)

$\Longrightarrow$ hybrid: NO

tetraquark: Π_g^+ or Π_g^-

XYZ $\rightarrow$ quarkonium + P-wave pion

$\Longrightarrow$ hybrid: NO

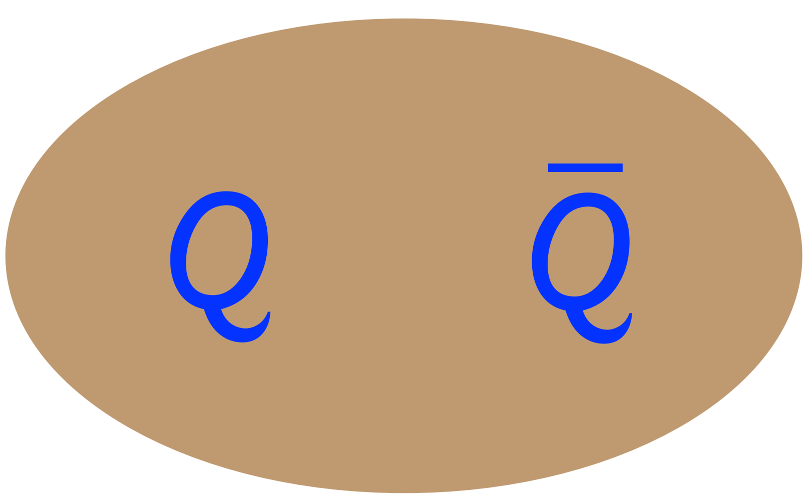
tetraquark: Π_g^- or Π_g^+ or Σ_g^+

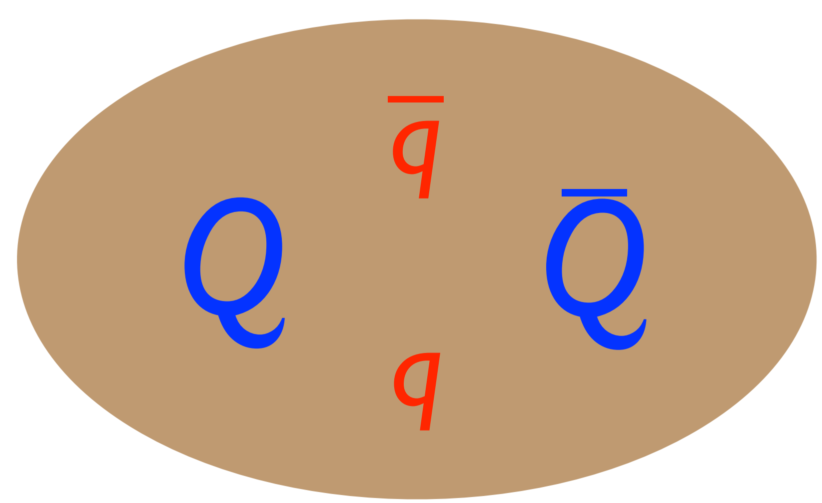
Conclusions

The discoveries of the *XYZ* mesons
have revealed a serious gap in our understanding
of the QCD spectrum

Constituent models for the *XYZ* mesons
have not presented a compelling pattern
and make little contact with QCD

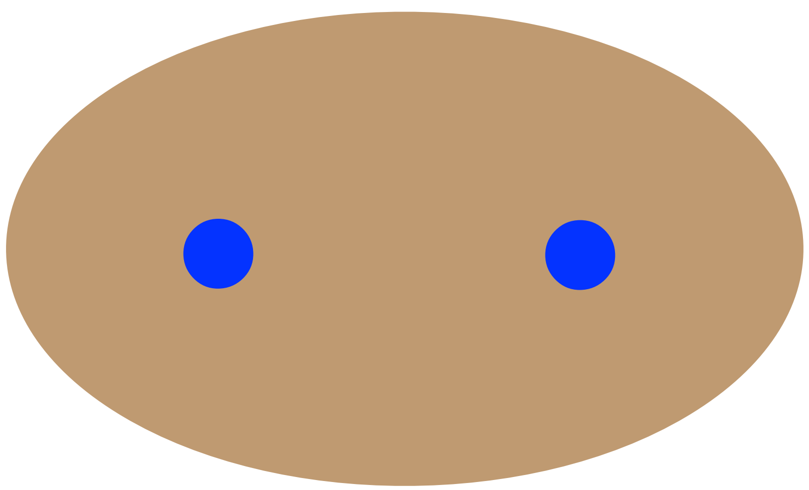
Born-Oppenheimer approximation
has not yet provided a compelling pattern for the *XYZ* mesons
but it is based firmly on QCD

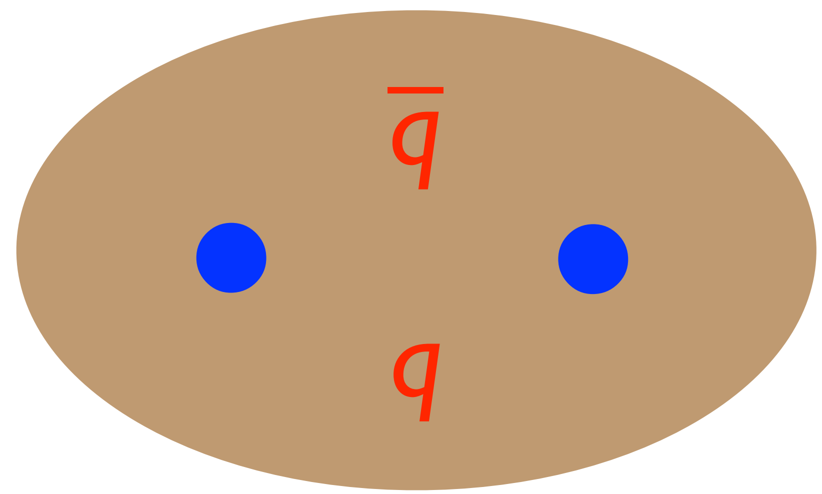




What is needed from Lattice QCD

- Born-Oppenheimer potentials
  for hybrids and for tetraquarks
- avoided crossings with meson-pair thresholds





What is needed from experiment

- more J^{PC}'s
- more transitions (hadronic and radiative)
- more XYZ mesons