Towards a Theoretical Understanding of the XYZ Mesons (and Baryons) from QCD

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Simons Foundation

Towards a Theoretical Understanding of the *XYZ* Hadrons from QCD

- constituent models for *XYZ* hadrons
- Lattice QCD
- Born-Oppenheimer approximation

  for quarkonium hybrid mesons

  Juge, Kuti, Morningstar 1999

  for quarkonium tetraquark mesons

  for quarkonium pentaquark baryons

XYZ Mesons

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

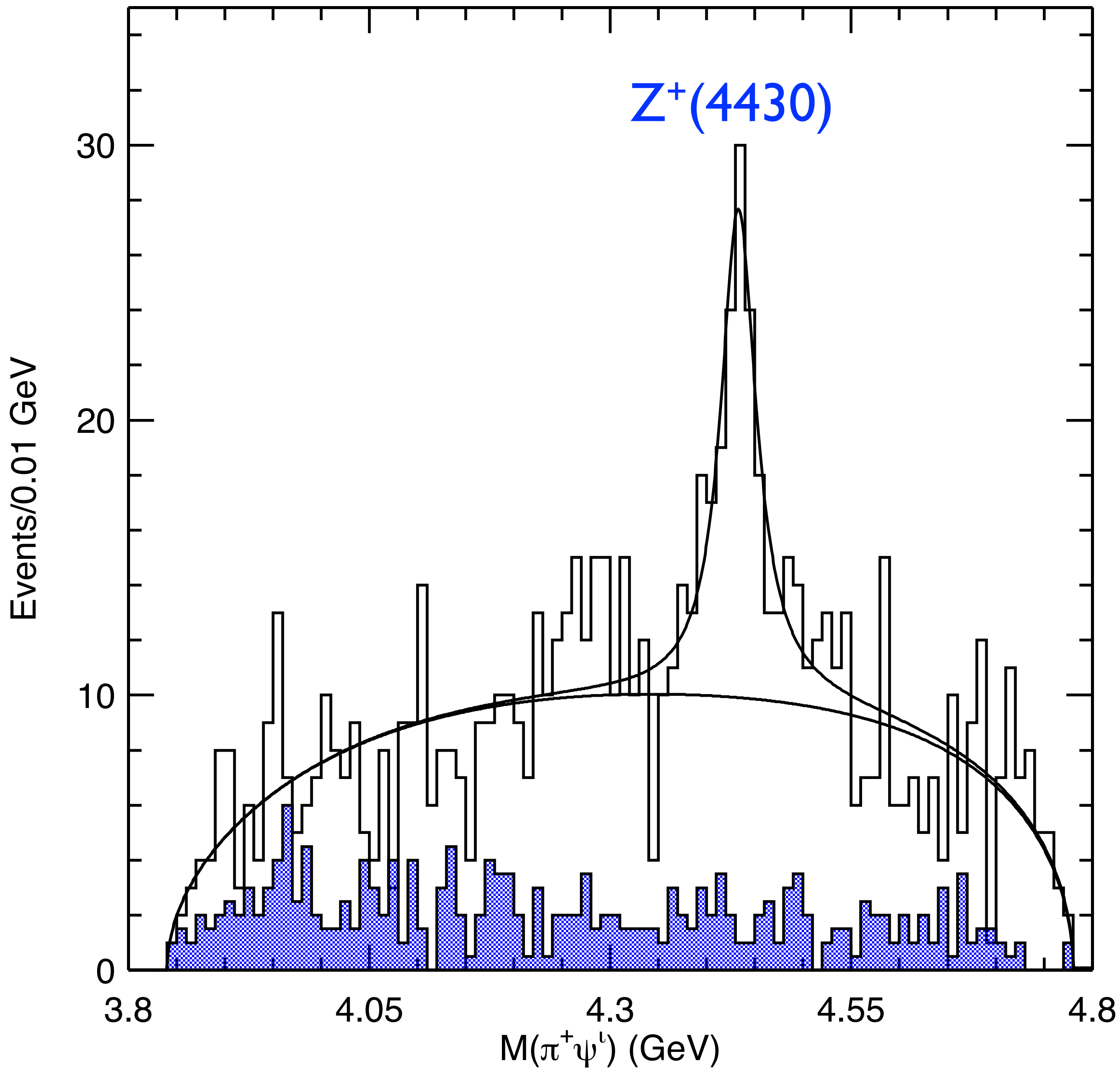
- contain heavy quark and antiquark, but seem to require additional constituents
- some of them are tetraquark mesons that contain two quarks and two antiquarks
- many of them are surprisingly narrow
- a major challenge to our understanding of the QCD spectrum!

First Charmonium Tetraquark

$Z^+(4430)$ Belle 2007

decays into $\psi(2S)\ \pi^+$

- constituents must include $c\ \bar{c}$ and $u\ \bar{d}$
- not confirmed by Babar 2009
  but confirmed by LHCb 2014
- quantum numbers $1^{+(-)}$
- not seen in $J/\psi\ \pi^+$

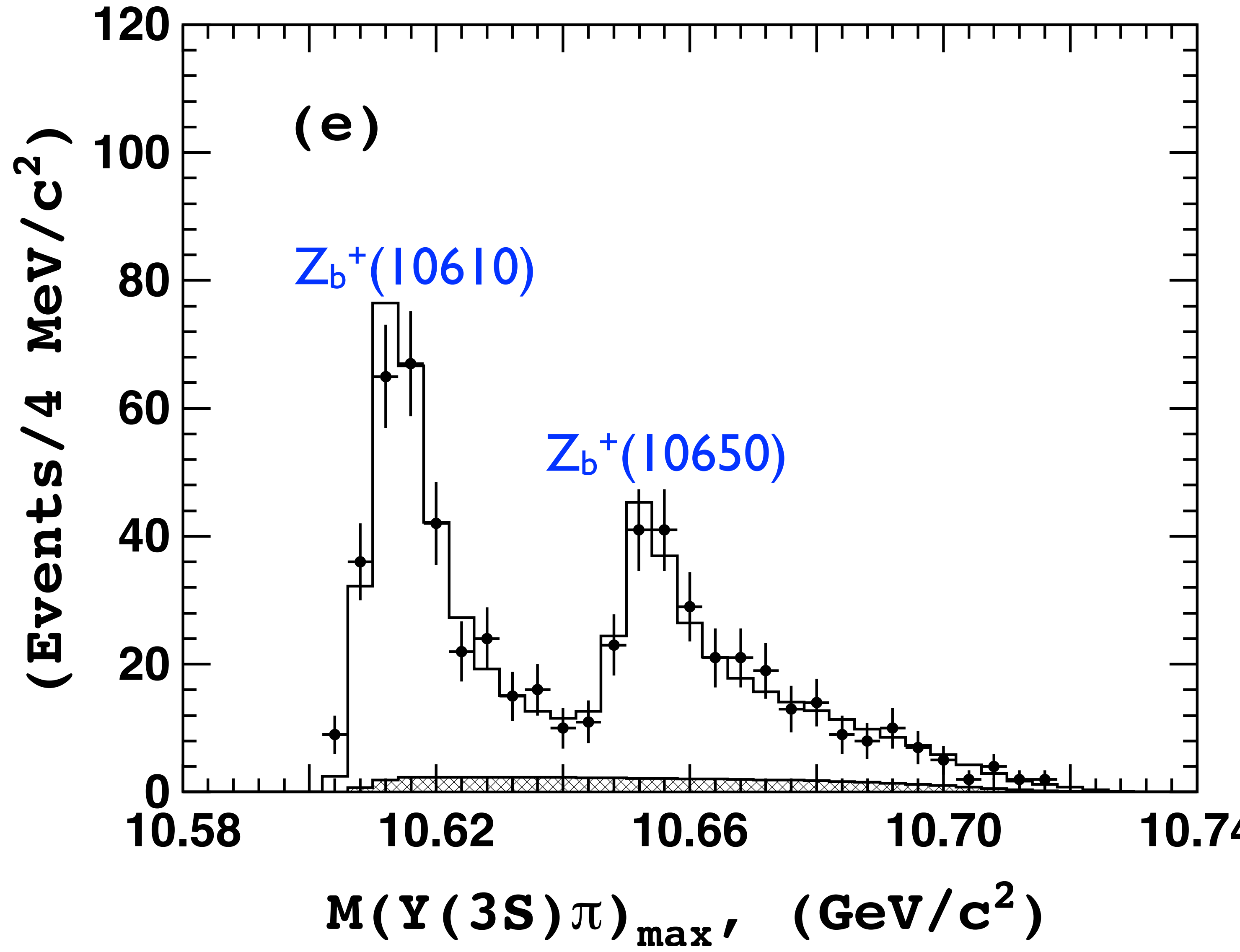


Bottomonium Tetraquarks

$Z_b^+(10610)$, $Z_b^+(10650)$ Belle 2011

decay into $\Upsilon(nS)$ π^+ and into $h_b(nP)$ π^+

- constituents must include $b\ \bar{b}$ and $u\ \bar{d}$
- decays into both Υ and h_b violate heavy-quark spin symmetry
- quantum numbers $1^{+(-)}$
- just above thresholds for $B^*\bar{B}$ and $B^*\bar{B}^*$



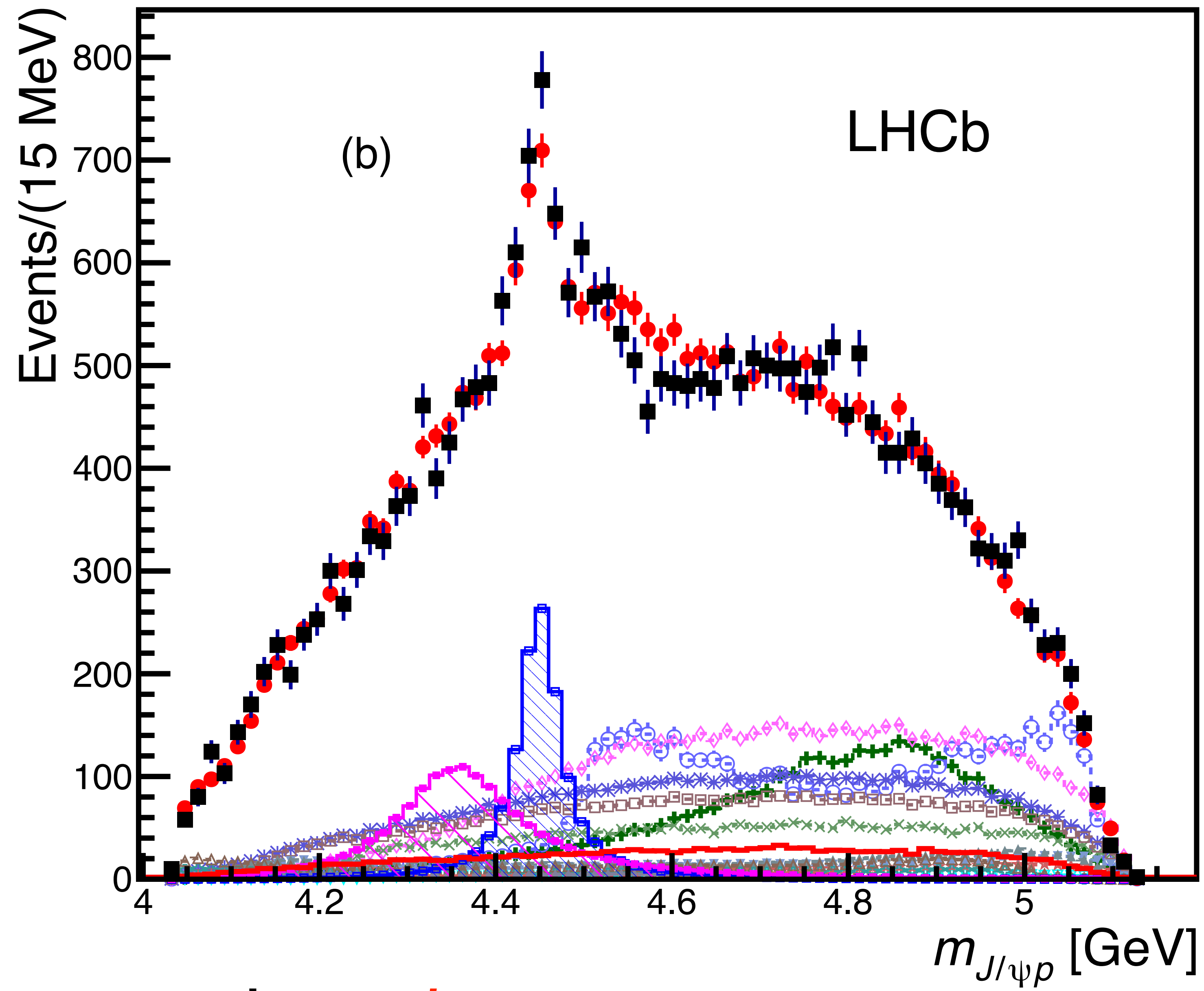
Charmonium Pentaquarks

$P_c(4380), P_c(4450)$

decay into J/ψ p

LHCb Collaboration

arXiv:1507.03414

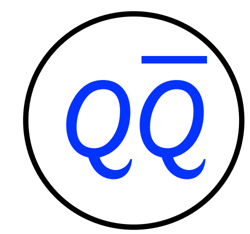


- constituents must include $c\ \bar{c}$ and $u\ u\ d$
- one of the pentaquarks is surprisingly narrow
- another major challenge to our understanding of the QCD spectrum!

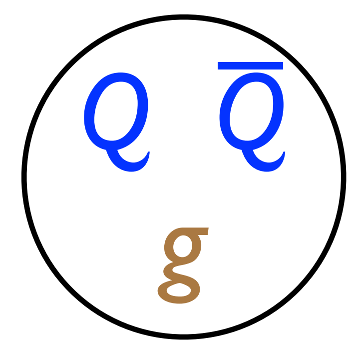
Models for XYZ Mesons

three basic categories

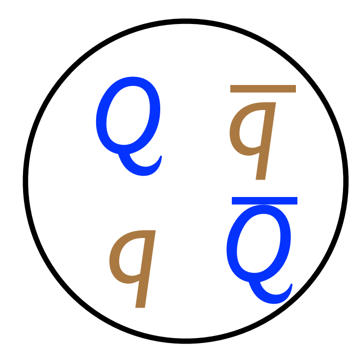
- conventional quarkonium



- quarkonium hybrid



- quarkonium tetraquark



Conventional Quarkonium

$Q\bar{Q}$

- well-developed phenomenology
  based on quark potential models

- accurate below open-heavy-flavor threshold
  well-defined predictions above threshold

- energy levels
  orbital angular momentum $L = 0, 1, 2, \ldots$ $(S, P, D, \ldots)$
  radial excitations $n = 1, 2, 3, \ldots$

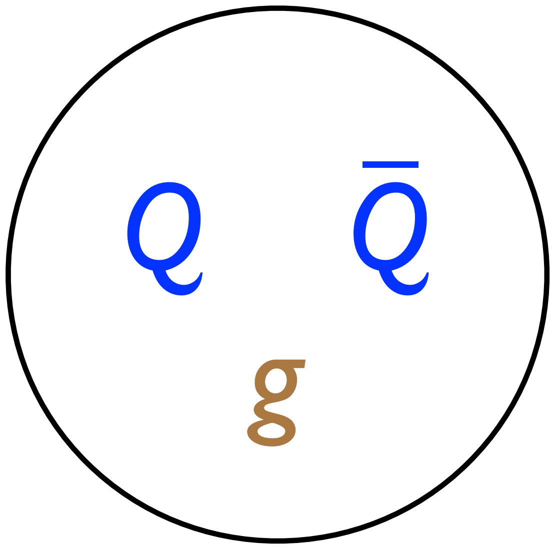
- heavy-quark spin multiplets: {spin-singlet, spin-triplets}
  S-wave: $\{0^{-+}, 1^{--}\}$
  P-wave: $\{1^{+-}, (0,1,2)^{++}\}$
  D-wave: $\{2^{-+}, (1,2,3)^{--}\}$

- forbidden quantum numbers (exotic):
  $0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, 3^{-+}, \ldots$

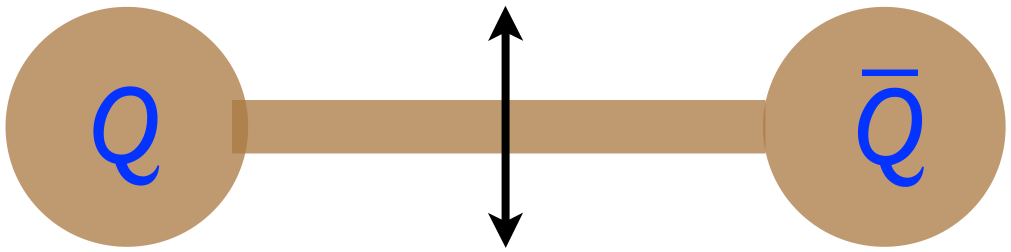
Models for XYZ Mesons

Quarkonium Hybrid

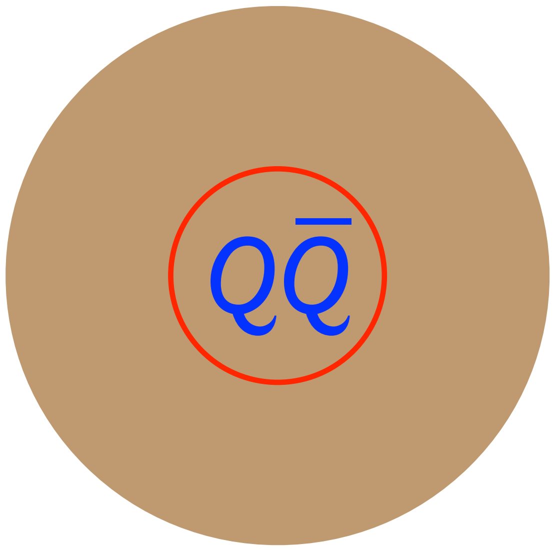
- constituent gluon model



- flux tube model



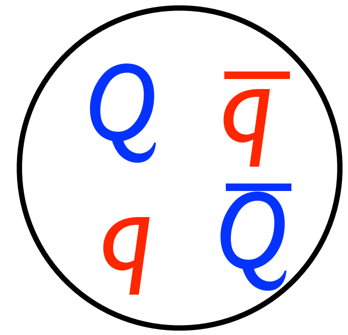
- gluelump model



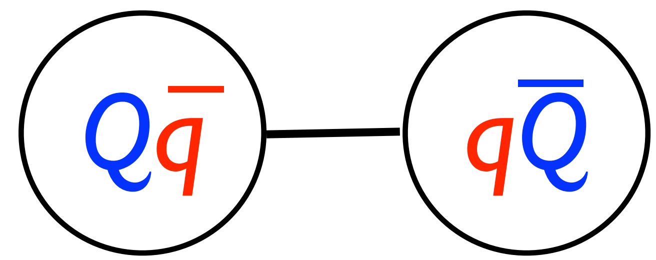
Models for XYZ Mesons

Quarkonium Tetraquarks

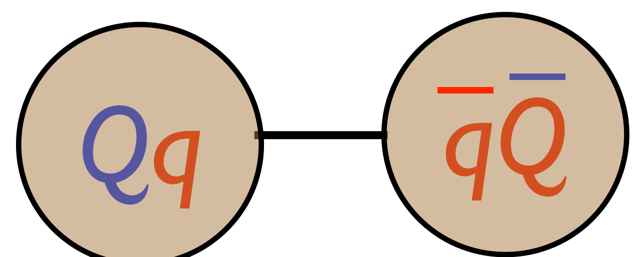
- compact tetraquark



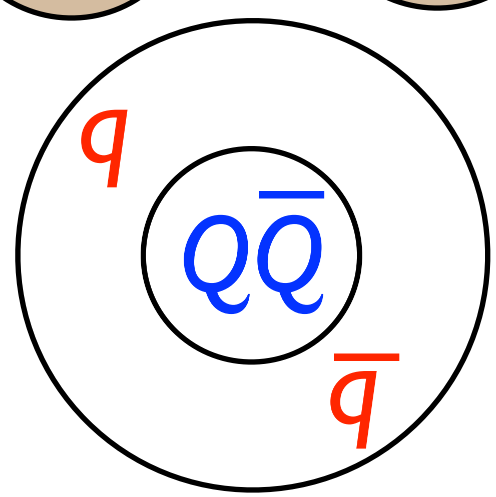
- meson molecule



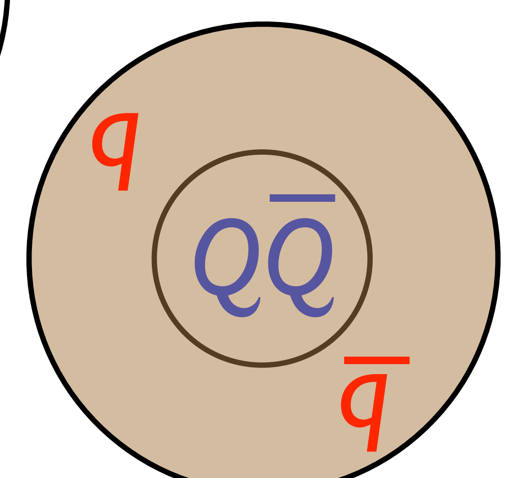
- diquark-onium



- hadro-quarkonium



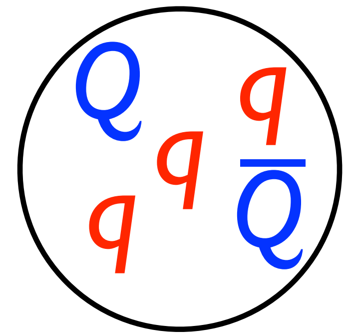
- quarkonium adjoint meson



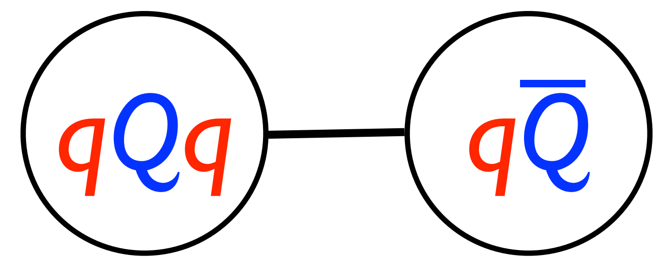
Models for *XYZ* Mesons

Quarkonium Pentaquarks

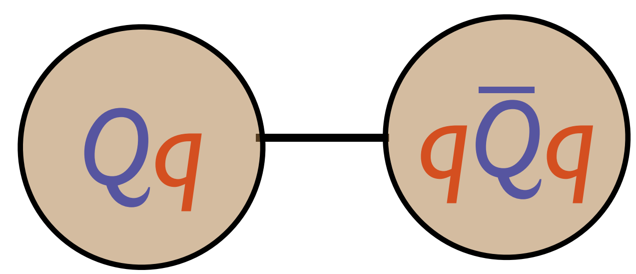
- compact pentaquark



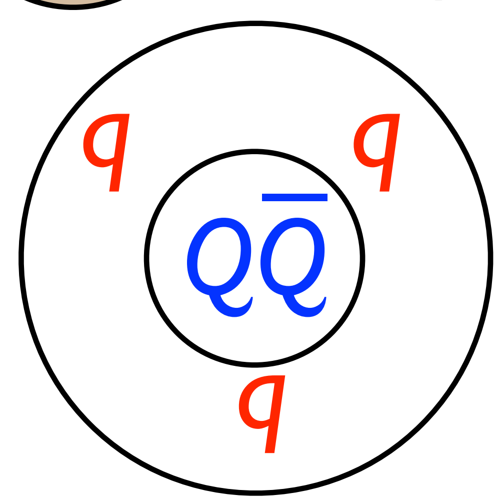
- baryon-meson molecule



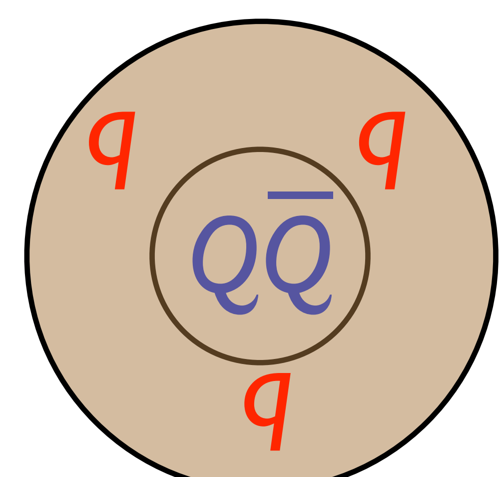
- diquark+triquark



- hadro-quarkonium



- quarkonium adjoint baryon



Models for *XYZ* Hadrons

- little connection with fundamental theory QCD

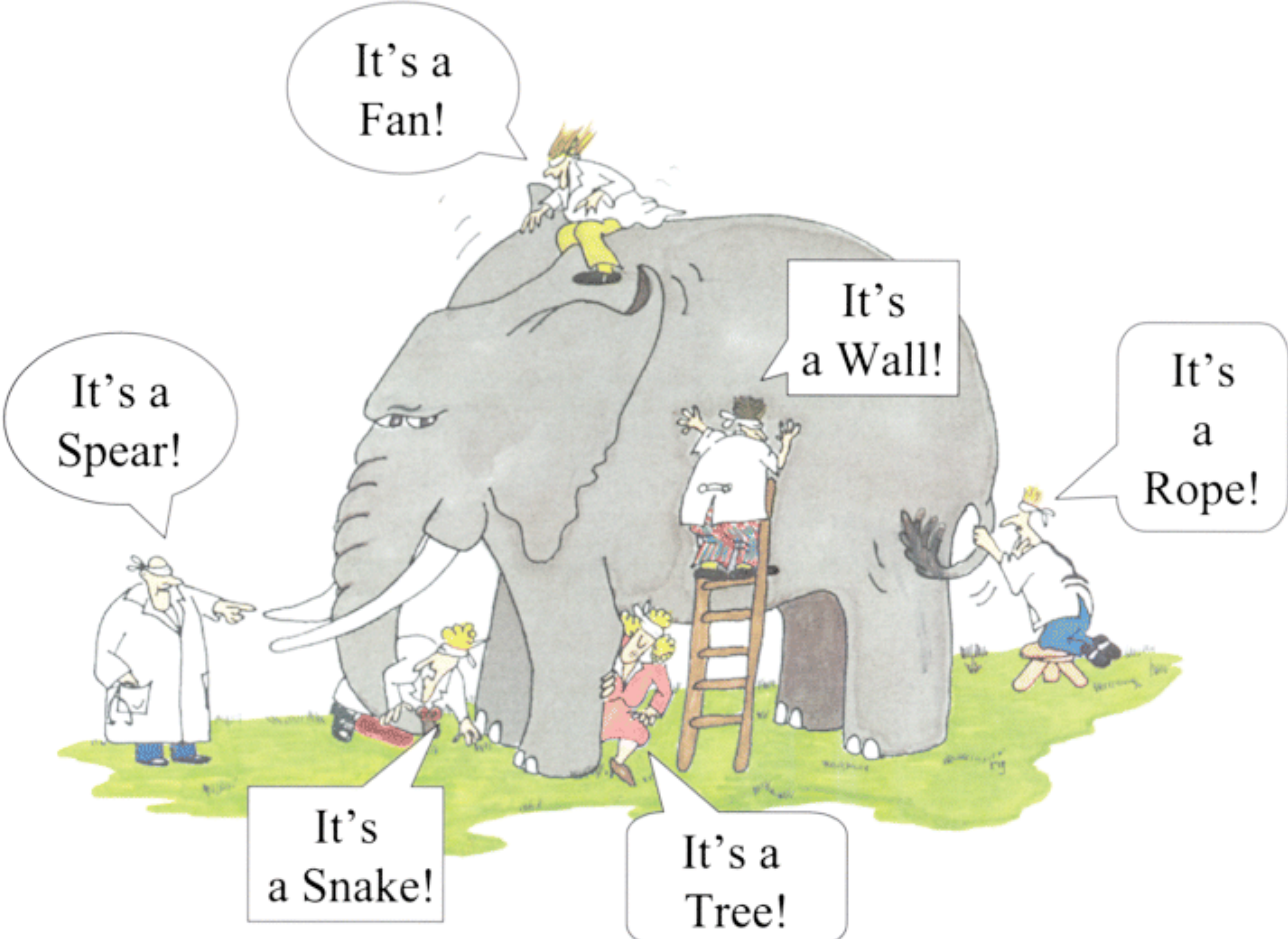
  constituents: plausible degrees of freedom from QCD

  interactions: purely phenomenological

- some success in describing individual *XYZ* mesons

- no success in revealing pattern of *XYZ* mesons

Models for XYZ Hadrons



Approaches within QCD

fundamental fields: quarks and gluons
parameters: α_s, quark masses

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

$c\bar{c}$ Mesons from Lattice QCD

Dudek, Edwards, Mathur, Richards 2007
Hadron Spectrum Collaboration 2012

Lattice QCD
- anisotropic lattice: $24^3 \times 128$
- lattice spacing: a = 0.12 fm
- unphysical light quark masses: m_π = 400 MeV

caveats: no extrapolation to physical *u,d* quark masses
no extrapolation to $a = 0$

- determine masses of charmonium and charmonium hybrids from cross-correlators of many operators

- identified 46 states with various J^{PC}:
  J up to 4, mass up to 4.6 GeV

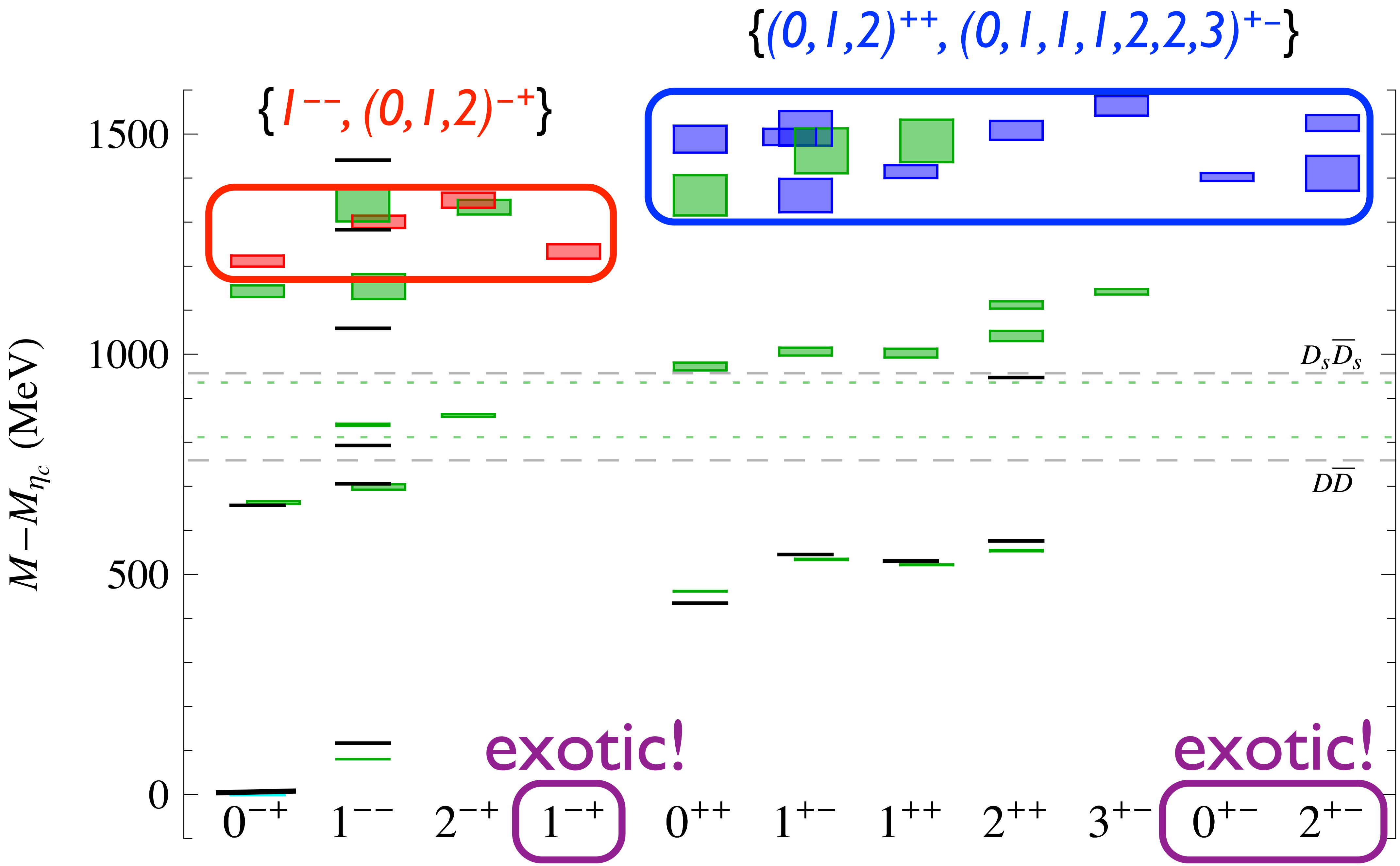
- discriminate between charmonium and charmonium hybrids

$c\bar{c}$ Mesons from Lattice QCD

Hadron Spectrum Collaboration 2012

14 charmonium hybrid candidates

lowest 4 form a spin-symmetry multiplet



$b\bar{b}$ Mesons from Lattice NRQCD

m_b large $\Longrightarrow$ use nonrelativistic effective field theory:
lattice NRQCD

Lattice NRQCD   Juge, Kuti, Morningstar 1999

- anisotropic lattice: $15^3 \times 45$
- lattice spacing: $a = 0.11$ fm
- quenched: no virtual quark-antiquark pairs!

caveat: no dynamical light quarks

- identified 4 bottomonium hybrid states

  spin-singlet 1^{--} state   (from $\{1^{--}, (0,1,2)^{-+}\}$ multiplet?)

  1^{++}

  0^{++}

  2nd spin-singlet 1^{--} state (radial excitation?)

Quarkonium Tetraquark Mesons from Lattice QCD

tetraquark $c\bar{c}$ mesons

with light quark+antiquark flavors

Prelovsek, Leskovec, Moehler

Lattice QCD

- anisotropic lattice: $16^3 \times 32$
- lattice spacing: $a = 0.12$ fm
- light quarks: 2 flavors, $m_\pi = 270$ MeV

interpolating operators: $c+\bar{c}$, $D^*+\bar{D}$, $J/\psi+\pi$, diquark+antidiquark, …

- $J^{PC} = 1^{++}$: candidate for $X(3872)$ but probably $\chi_{c1}(2P)$
- $J^{PC} = 1^{+-}$: no signal for Z_c^+ tetraquark

tetraquark $b\bar{b}$ mesons ???

Quarkonium Pentaquark Baryons
from Lattice QCD

Born-Oppenheimer Approximation for Quarkonium Hybrids

pioneered by Juge, Kuti, Morningstar 1999

- heavy quark mass $\gg \Lambda_{QCD}$
- Q and $\bar{Q}$ move nonrelativisticly
- gluons respond almost instantaneously to the motion of the Q and $\bar{Q}$

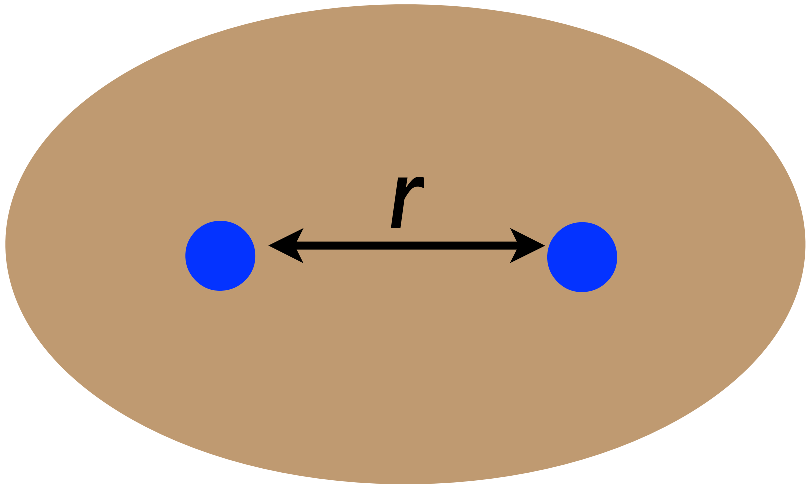
B-O approximation: hybrids

- 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

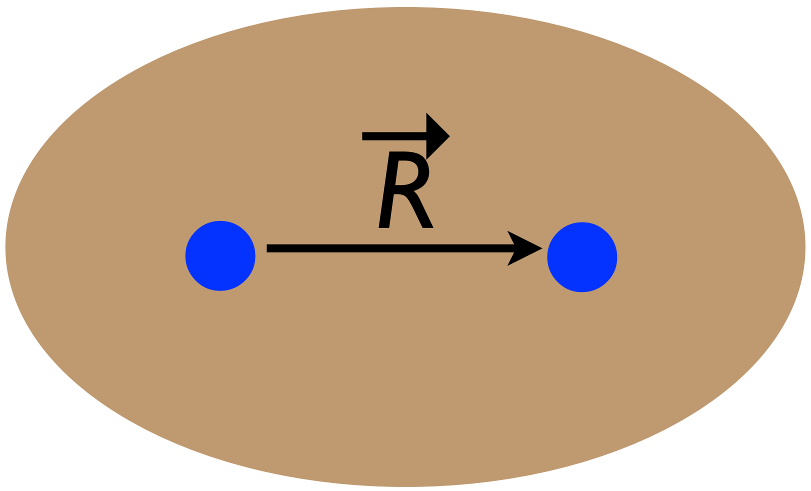
- energy of stationary state of gluon fields
  in presence of static Q and $\bar{Q}$ sources
  separated by distance R
  defines Born-Oppenheimer potential $V(R)$



- 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: $|\Omega|_\eta^\varepsilon$

- component of angular momentum along symmetry axis
  $\hat{R} \cdot \vec{J}_{light} \equiv \Omega$, $|\Omega| = 0, 1, 2, \ldots$ (or $\Sigma, \Pi, \Delta, \ldots$)

- product of charge conjugation and parity
  $(CP)_{light} \equiv \eta = +1, -1$ (or g, u)

- for $\Omega = 0$ (Σ), reflection through plane containing sources
  $R_{light} \equiv \varepsilon = +1, -1$ (or $+, -$)

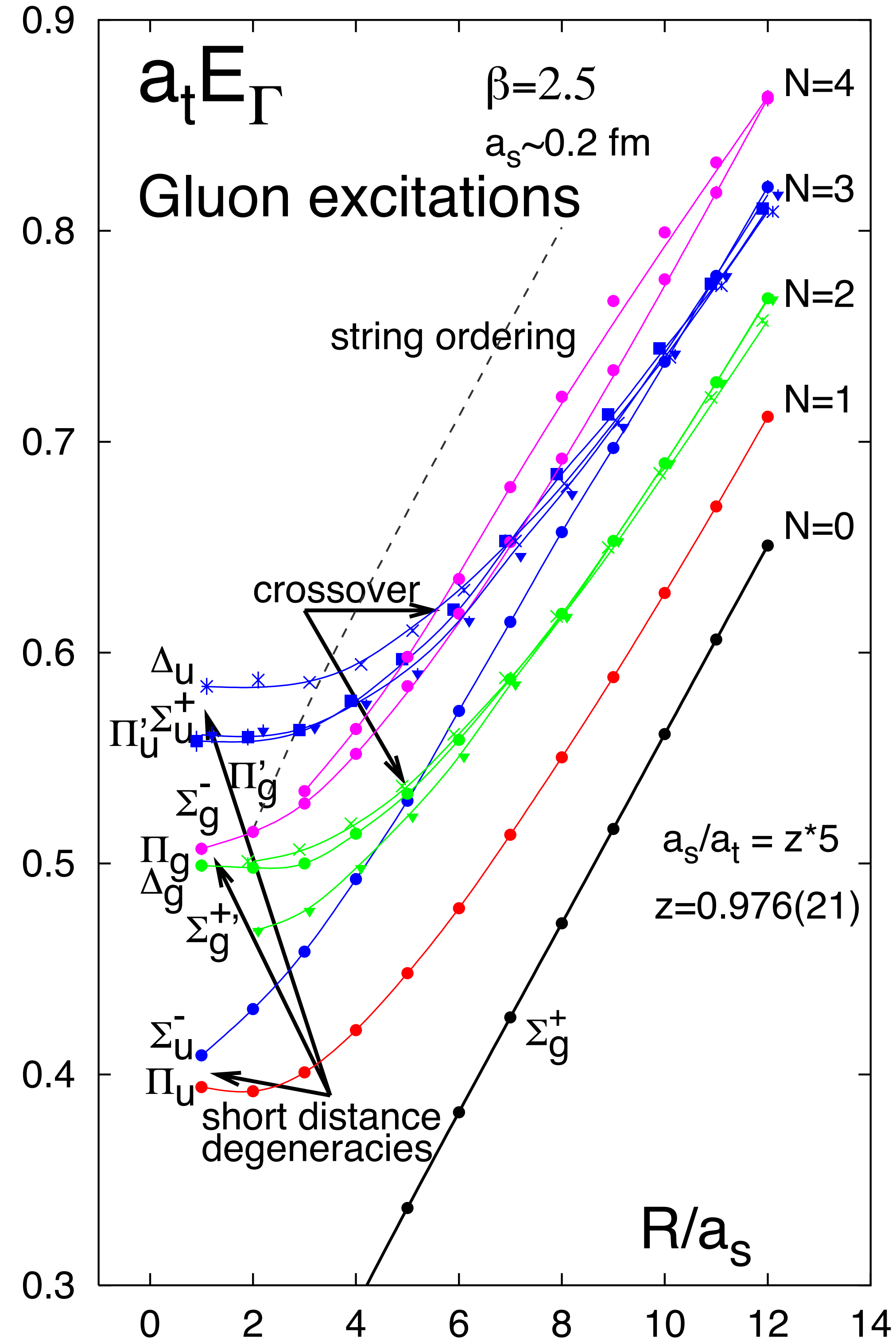
B-O approximation: hybrids

Born-Oppenheimer potentials

labelled by $|\Omega|_\eta$

$|\Omega| = \Sigma, \Pi, \ldots$

$\eta = g, u$



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!

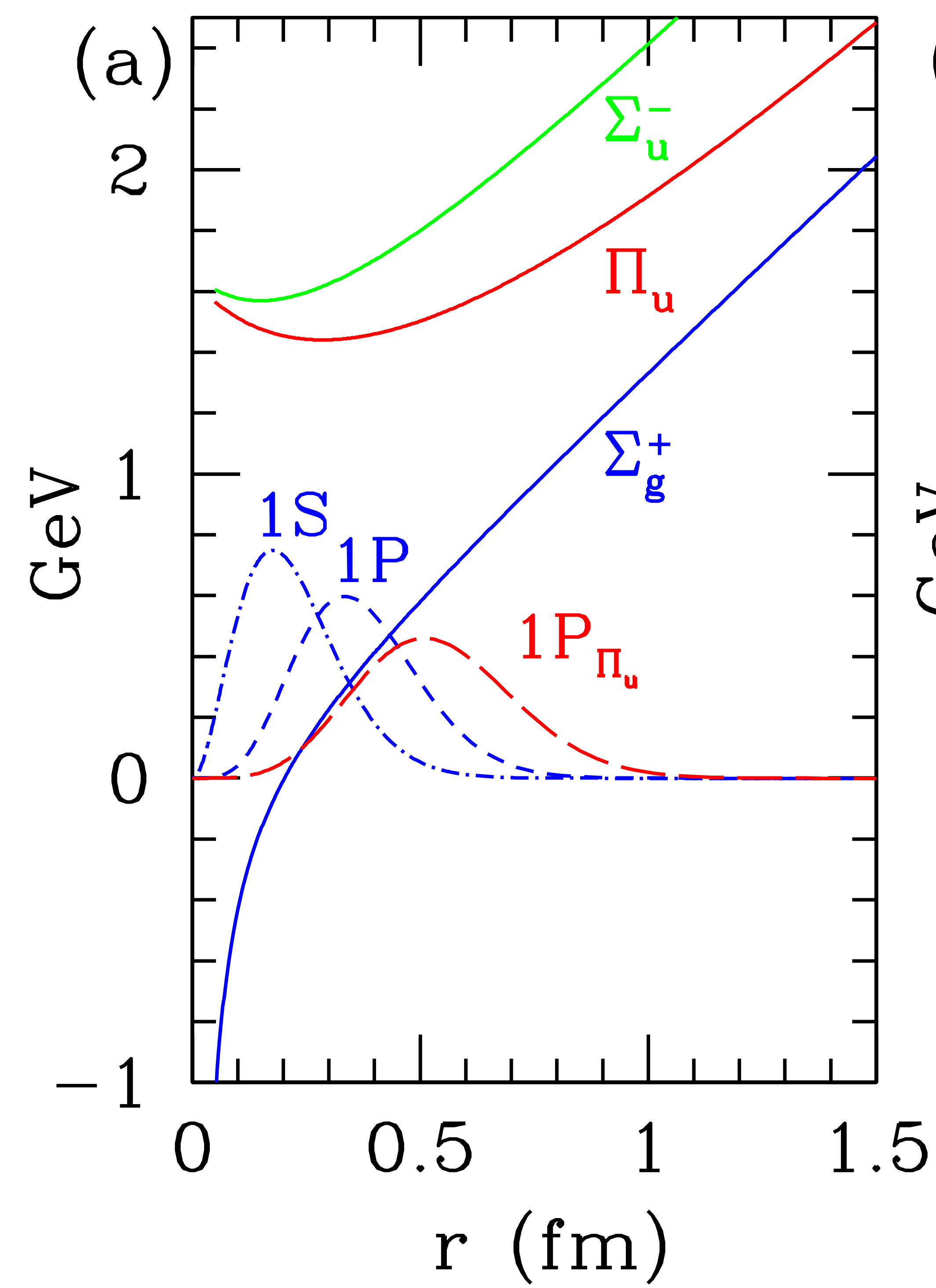
deepest Born-Oppenheimer potentials:

$\Sigma_g^+, \Pi_u, \Sigma_u^-, \ldots$

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 $S,P,D,...$



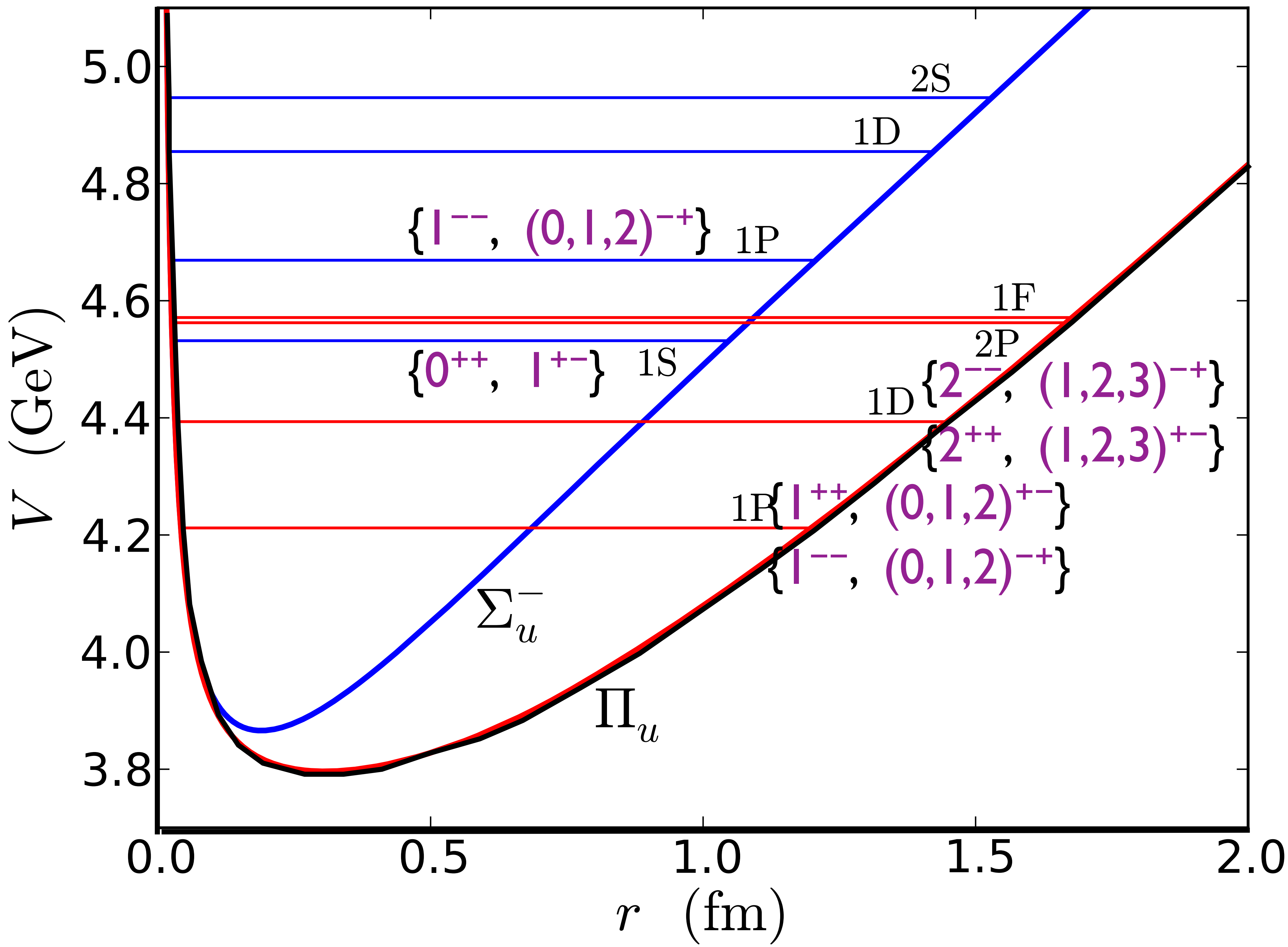
energy levels in Σ_g^+ potential:
quarkonium

energy levels in Π_u, Σ_u^-, ... potentials:
quarkonium hybrids

energy splittings: semiquantitative agreement with lattice NRQCD

B-O approximation: hybrids

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



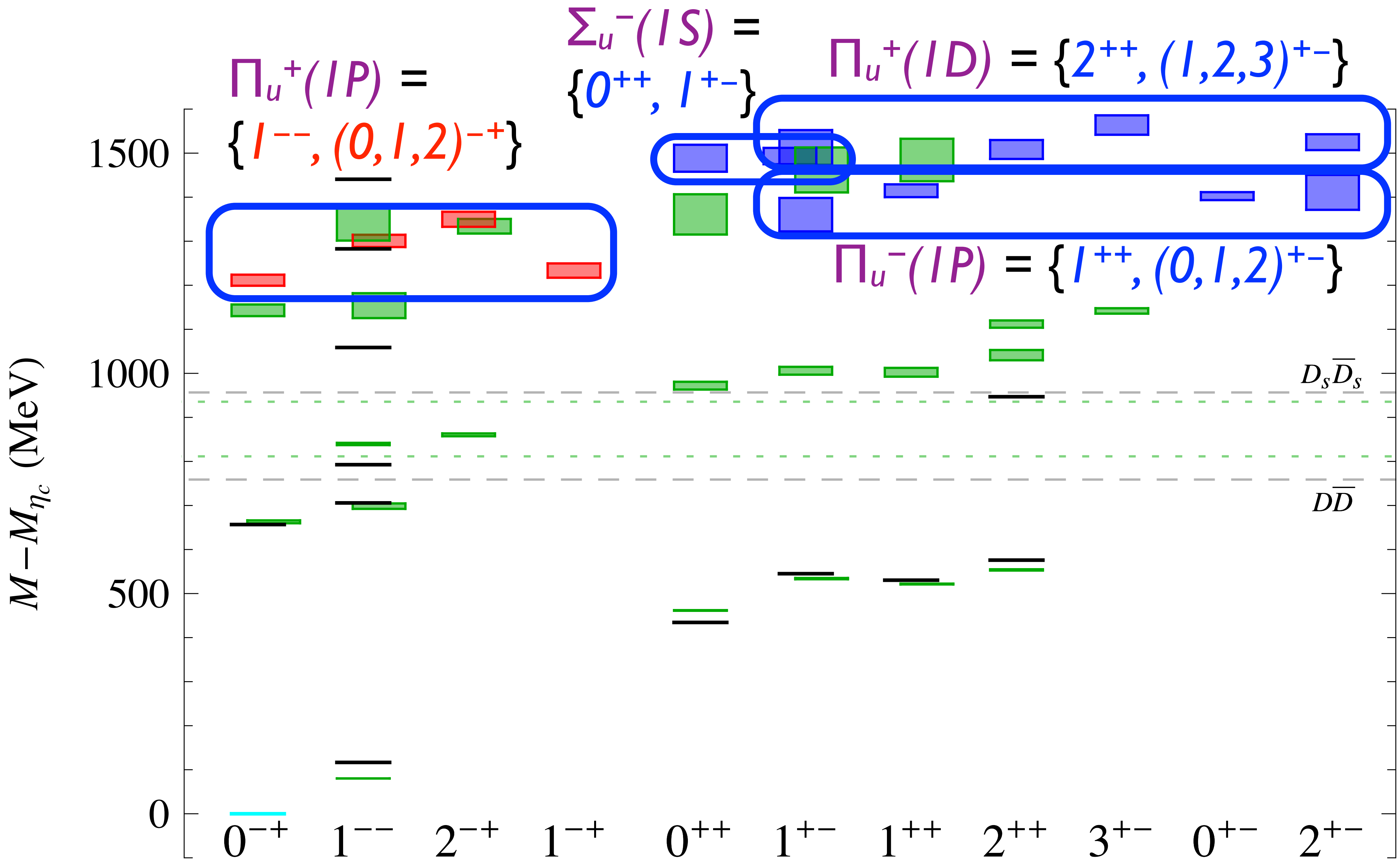
B-O approximation: hybrids

Lattice QCD Hadron Spectrum Coll 2012

14 charmonium hybrid candidates

4 complete heavy-quark spin multiplets

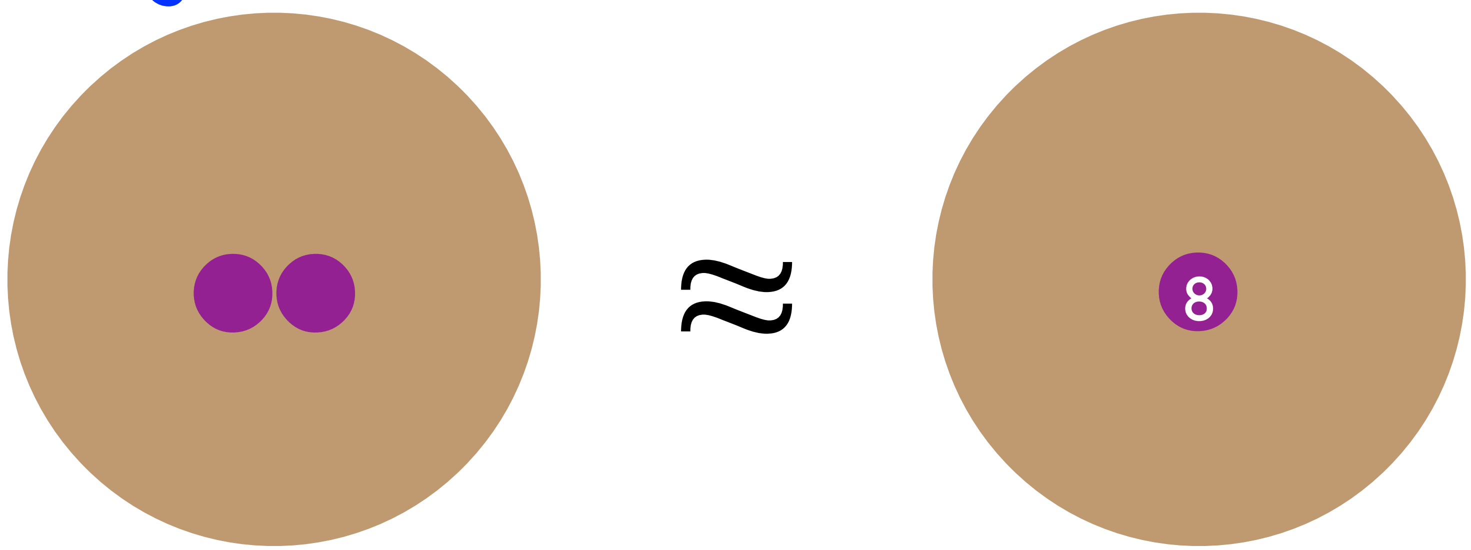
4 of the lowest Born-Oppenheimer energy levels



B-O approximation: hybrids

Hybrid Born-Oppenheimer potentials (Π_u, Σ_u^-, . . .) at small R

Q and $\bar{Q}$ sources $\longrightarrow$ local color-octet source



stationary state $\longrightarrow$ gluelump

gluon fields bound to color-octet source (gluino)

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

constant = energy of gluelump

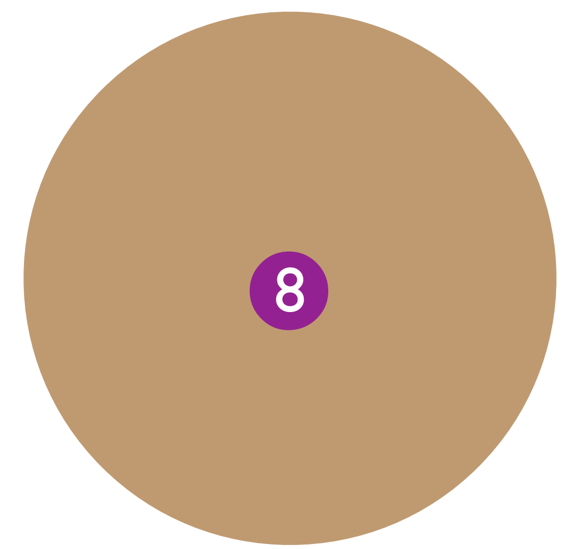
B-O approximation: hybrids

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
- unphysical light quark masses: m_π = 480 MeV



lowest energy: 1^{+-}

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

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

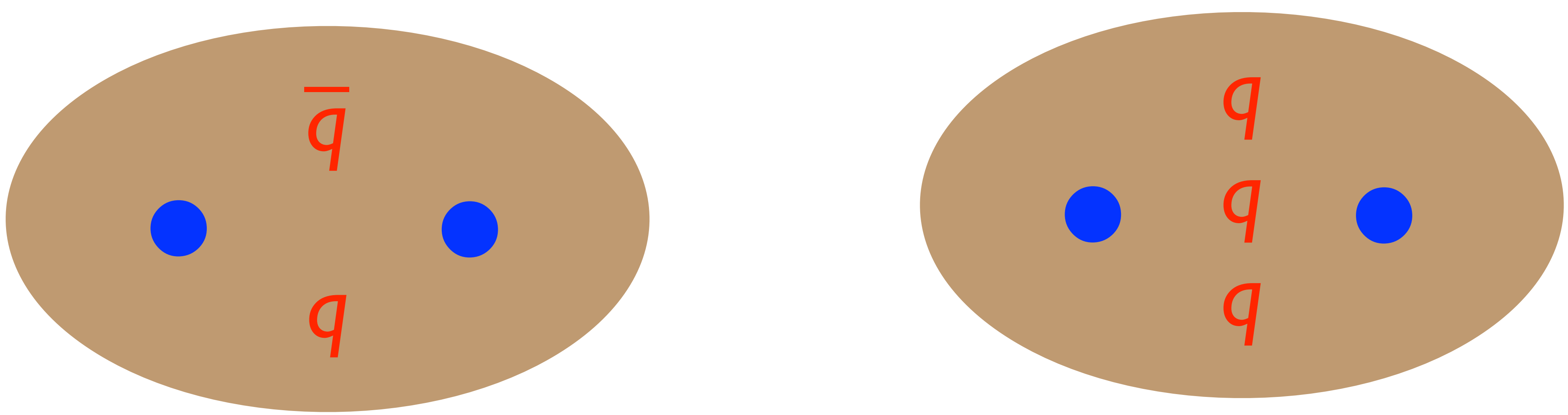
lowest energy gluelump

$\Longrightarrow$ deepest hybrid Born-Oppenheimer potentials

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

Born-Oppenheimer Approximation
for Quarkonium Tetraquarks and Pentaquarks

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

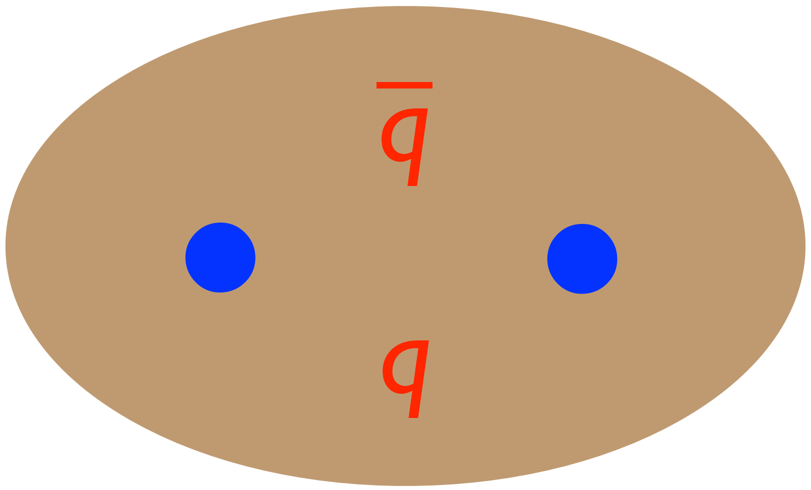


Quarkonium Tetraquarks (and Pentaquarks)
can be treated using the Born-Oppenheimer approximation
just like Quarkonium Hybrids
except that the stationary state of gluons and light quarks
has Born-Oppenheimer quantum numbers
and also light-quark flavors

Braaten arXiv:1305.6905

B-O Approximation: tetraquarks

Tetraquark Born-Oppenheimer potentials?



No Lattice QCD calculations
of tetraquark Born-Oppenheimer potentials

but there is one hint from Lattice QCD

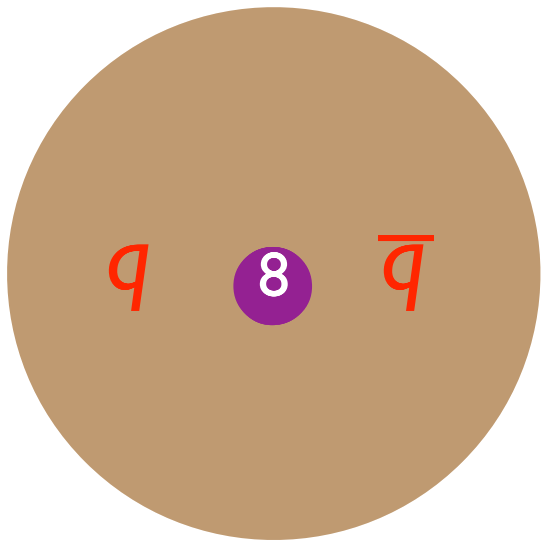
B-O approximation: tetraquarks

adjoint meson spectrum

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

quenched Lattice QCD

Foster, Michael hep-lat/9811010



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

lowest-energy adjoint mesons

$\Longrightarrow$ deepest tetraquark Born-Oppenheimer potentials

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

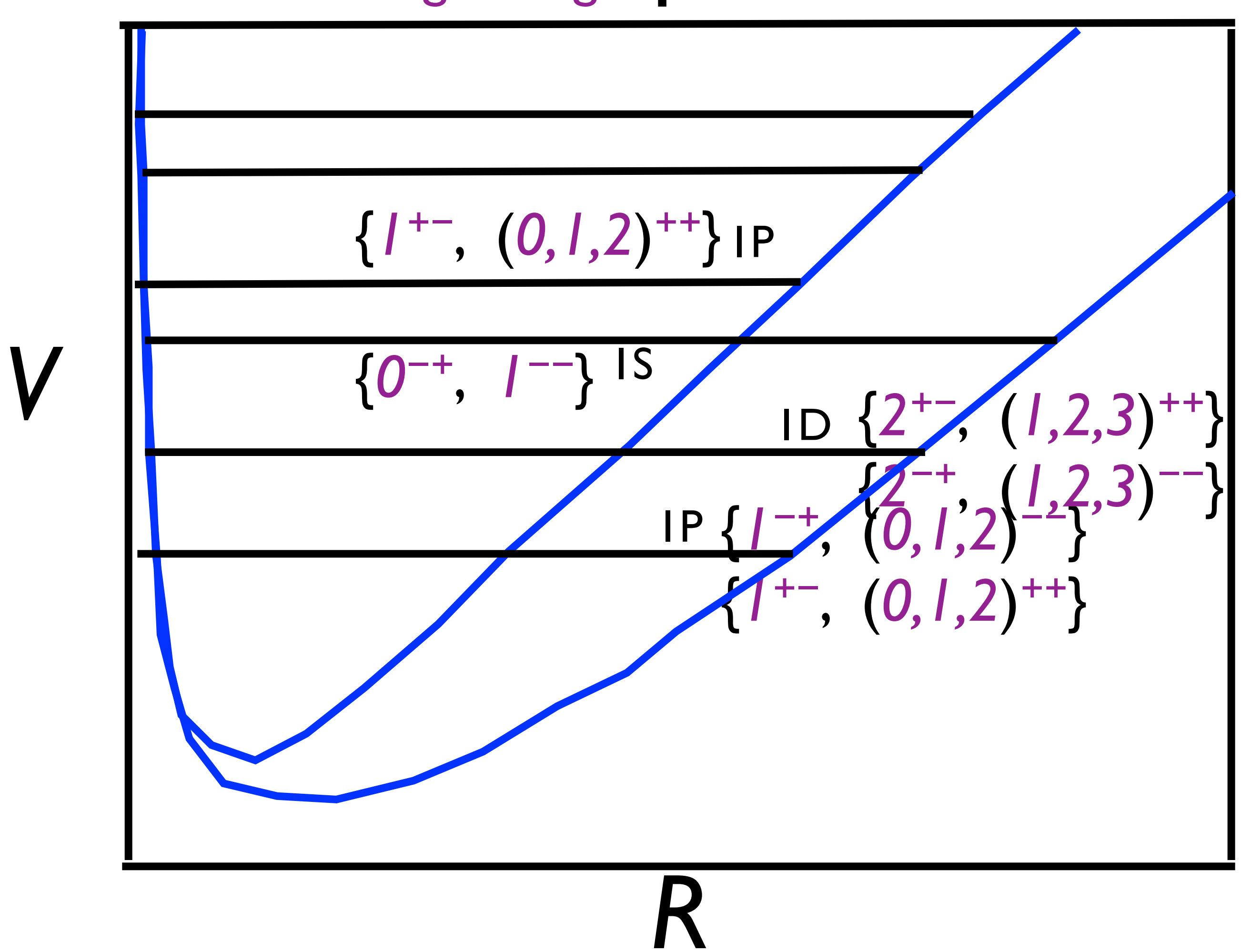
B-O Approximation: tetraquarks

separate tetraquark Born-Oppenheimer potentials
for each of three light flavors: isospin 1, isospin 0, $s\bar{s}$

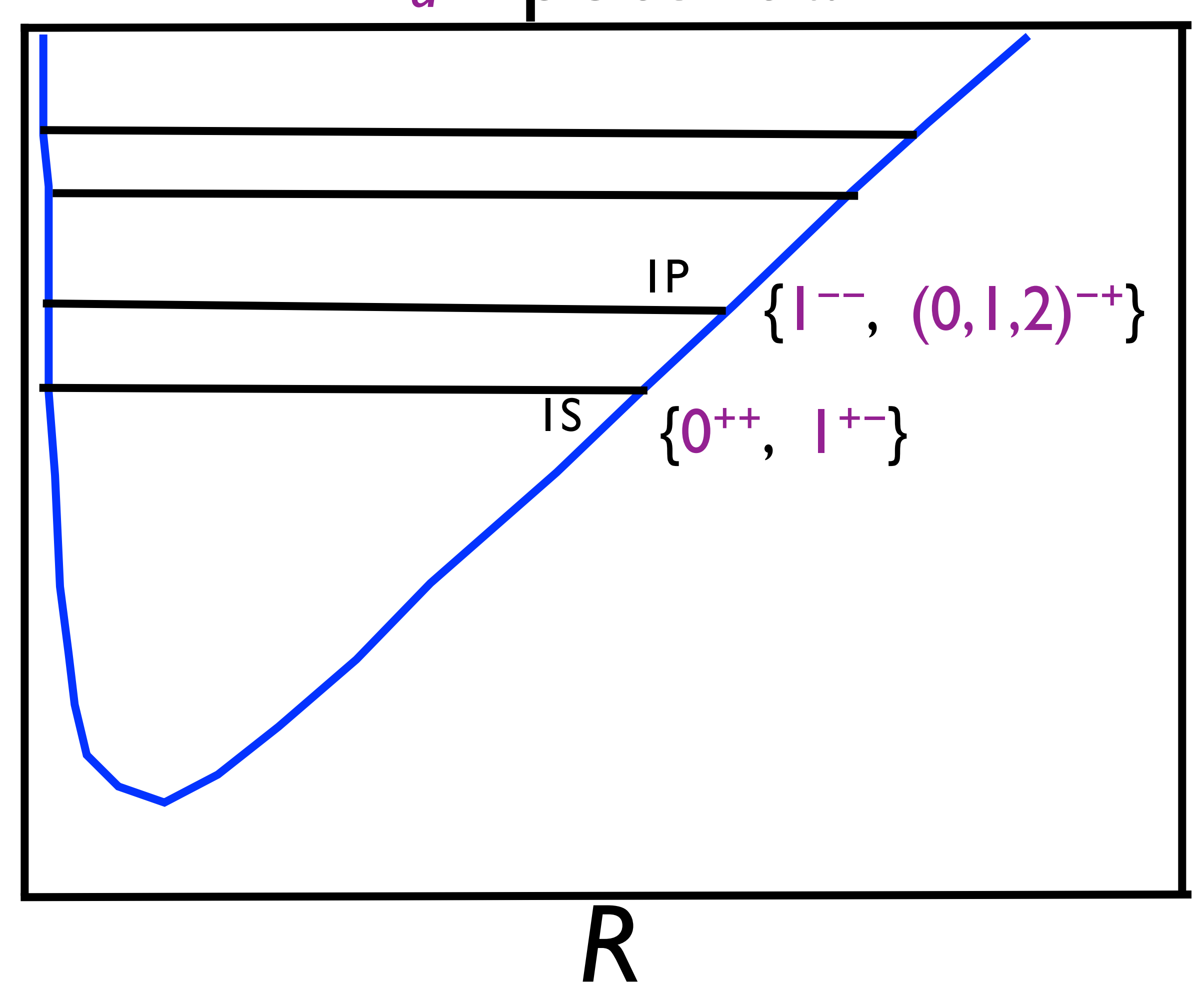
J^{PC} states for lowest tetraquark energy levels nL

(IF quenched lattice QCD correctly identifies lightest adjoint mesons)

$\Pi_g^{\pm}, \Sigma_g^{+}$ potentials

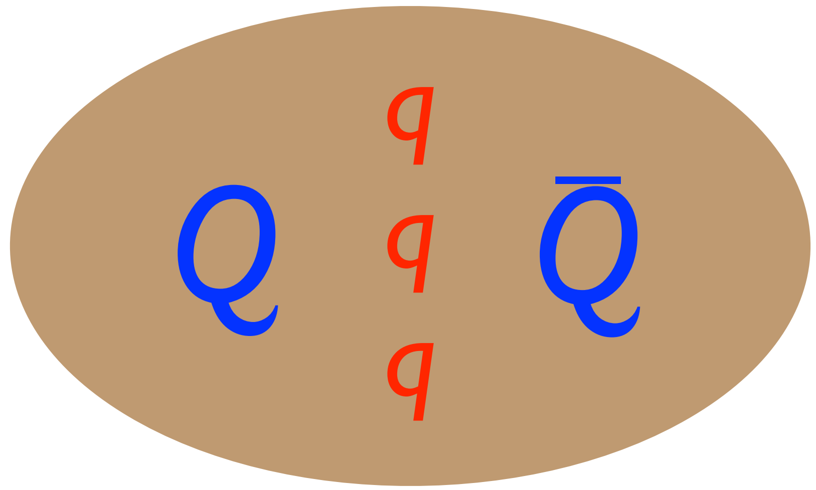


Σ_u^{-} potential



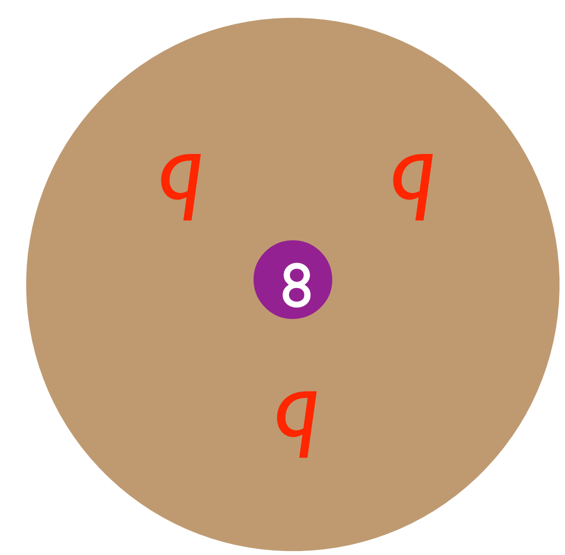
B-O Approximation: pentaquarks

Pentaquark Born-Oppenheimer potentials?



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

There are not even Lattice QCD calculations
of the adjoint baryon spectrum



Born-Oppenheimer approximation

implies that quarkonium hybrids, tetraquarks, pentaquarks should all exist as states in the QCD spectrum

whether they can be observed in experiments depends on

- how narrow they are
- how easily they can be produced
- whether they have favorable decay modes

Born-Oppenheimer approximation
has not yet revealed a compelling pattern for the *XYZ* hadrons

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

Selection rules for hadronic transitions
between B-O configurations may provide useful constraints

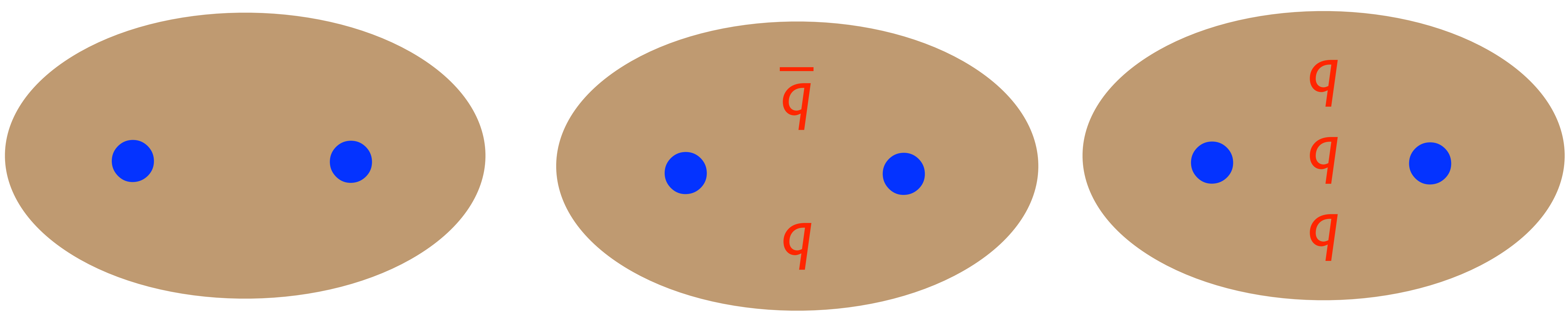
Braaten, Langmack, Smith arXiv:1401.735, arXiv:1402.0438

Conclusions

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

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

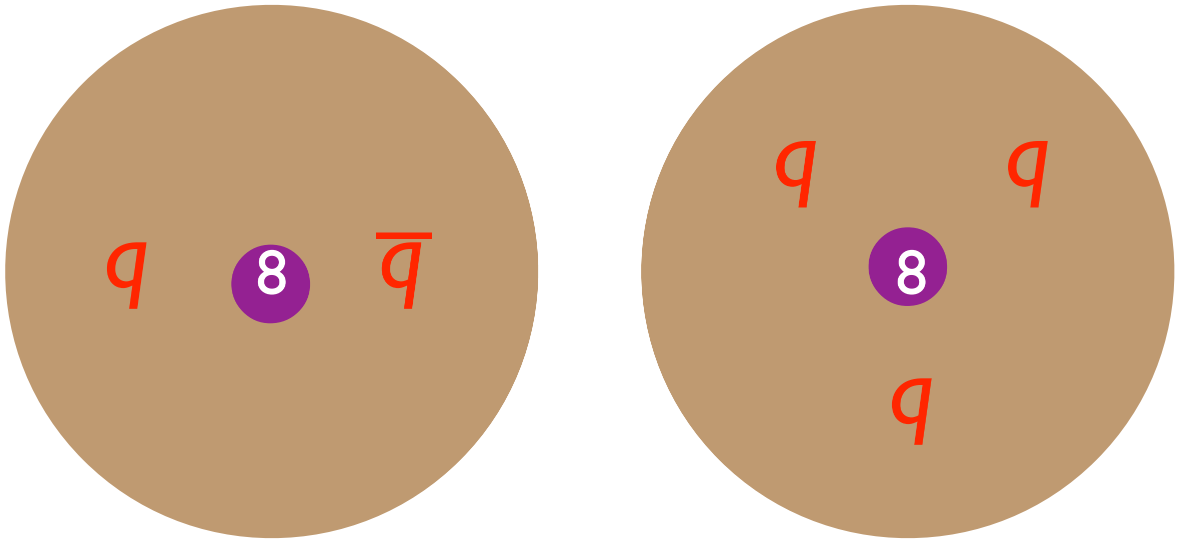
Born-Oppenheimer approximation
has not yet provided a compelling pattern for the *XYZ* hadrons
but it is based firmly on QCD



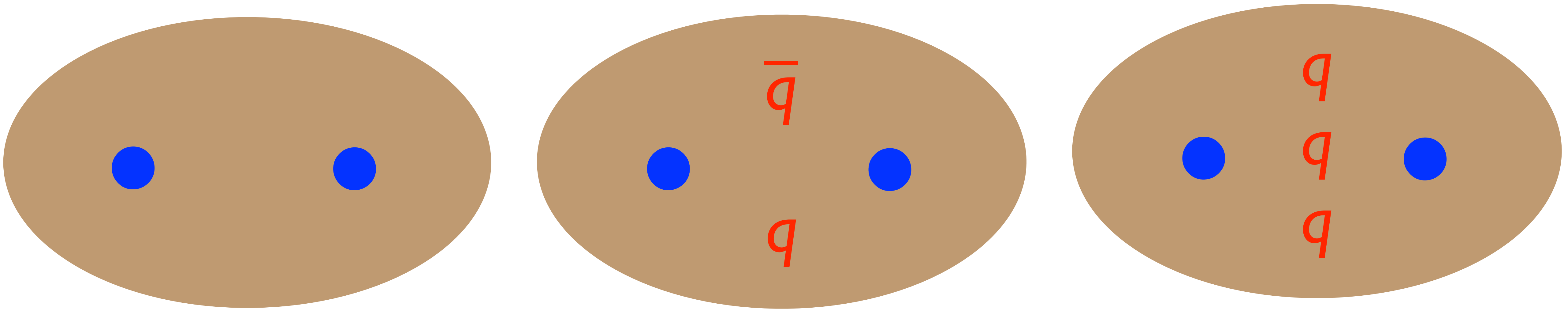
Conclusions

What is needed from Lattice QCD

- spectrum of adjoint mesons
  and adjoint baryons



- $b\bar{b}$ hybrid meson spectrum
- Born-Oppenheimer potentials for tetraquarks
  and for pentaquarks
- avoided crossings between
  B-O potentials and hadron-pair thresholds



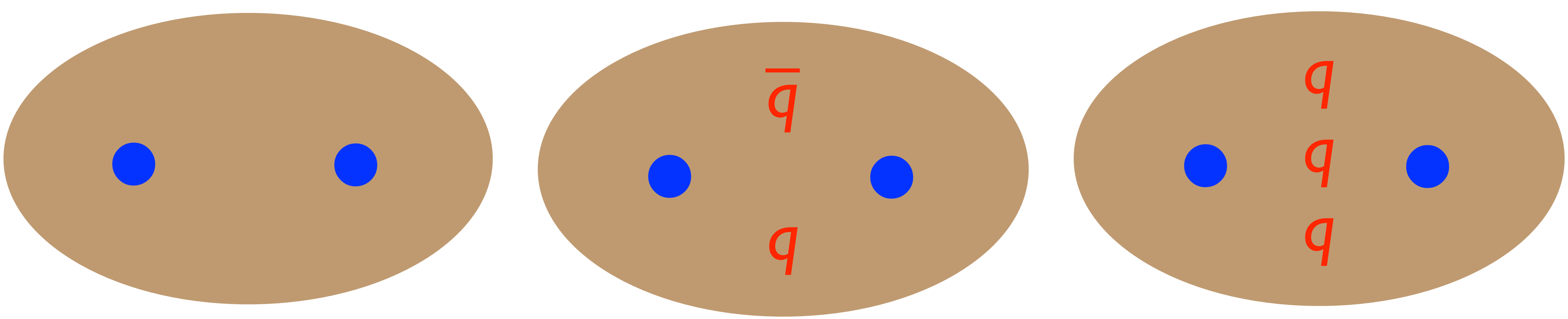
Conclusions

What is needed from non-lattice theory

- infer Born-Oppenheimer potentials
  from data on XYZ hadrons?

- phenomenological models for hadronic transitions
  between quarkonium, hybrids, tetraquarks, pentaquarks

- develop effective field theory (BOEFT?)
  based on the Born-Oppenheimer approximation



Future experiments on the *XYZ* hadrons

- e^+e^- experiments
  charm factory BEPCII
  bottom factory Super KEK-B

- LHC experiments
  ATLAS and CMS
  LHCb

- PANDA: $p\bar{p}$ annihilation at resonance
  into charmonium (and hybrids and tetraquarks)

What is needed from experiment

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