The heavy-quark hybrid meson spectrum in lattice QCD

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Workshop on Gluonic Excitations, JLab

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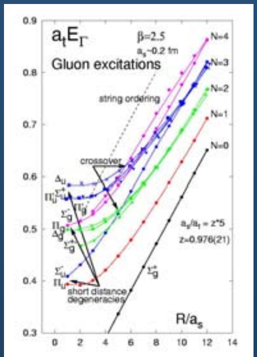
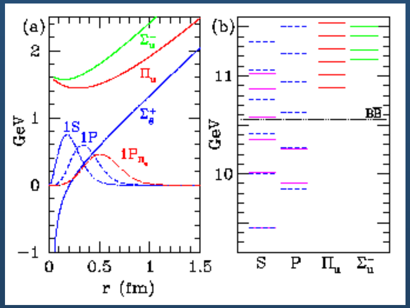
Outline

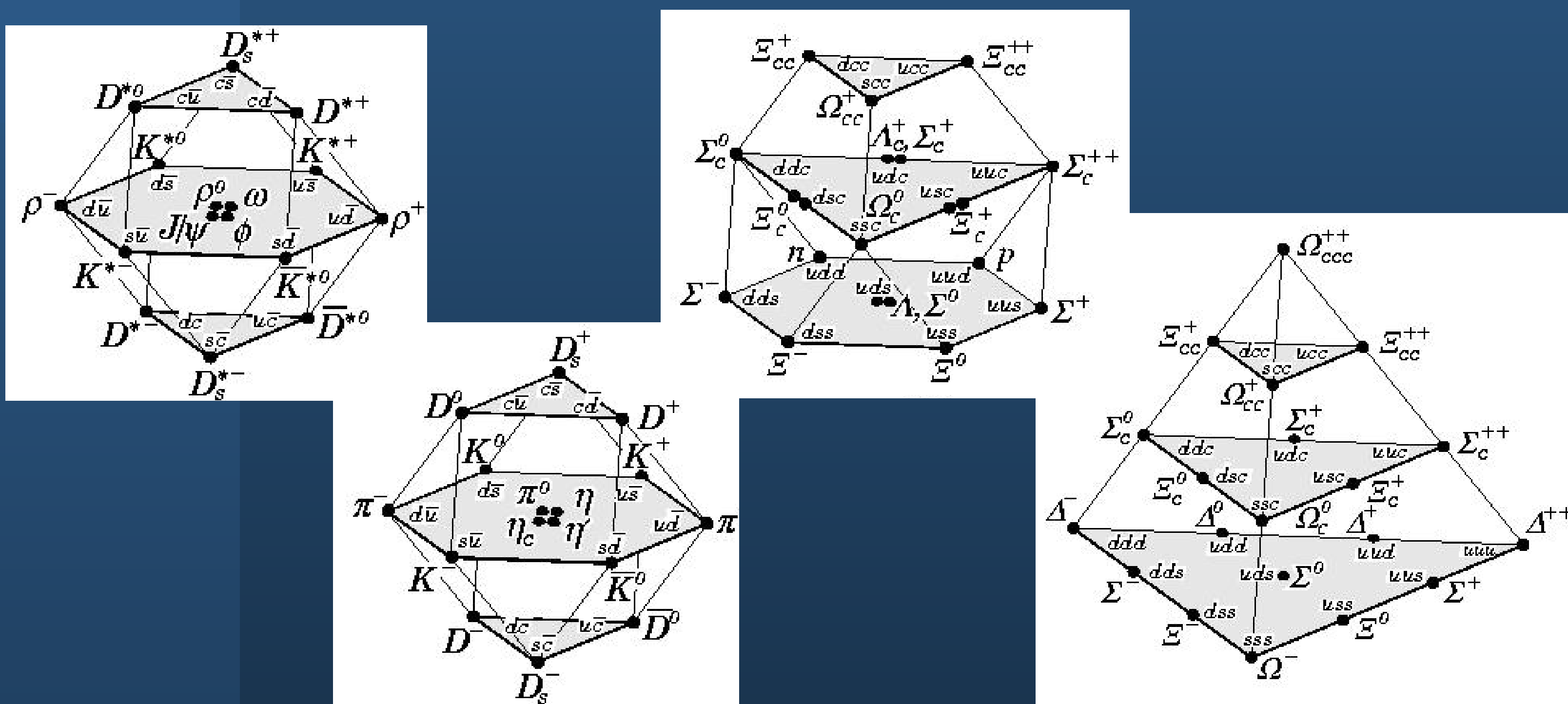
- Introduction
- Heavy-quark mesons: leading Born-Oppenheimer approximation
  - Stationary states of gluons in presence of static $q\bar{q}$-pair
  - Leading order spectrum (no light quark pairs)
  - Testing the leading Born-Oppenheimer approximation
- Quark spin effects
- Incorporation of light quark loops
- Other tidbits
- Conclusion





Constituent quark model

- much of our understanding of hadron formation comes from the *constituent quark model*
  - motivated by QCD
  - valence quarks interacting via Coulomb + linear potential
  - gluons: source of the potential, *dynamics ignored*



Quark model (continued)

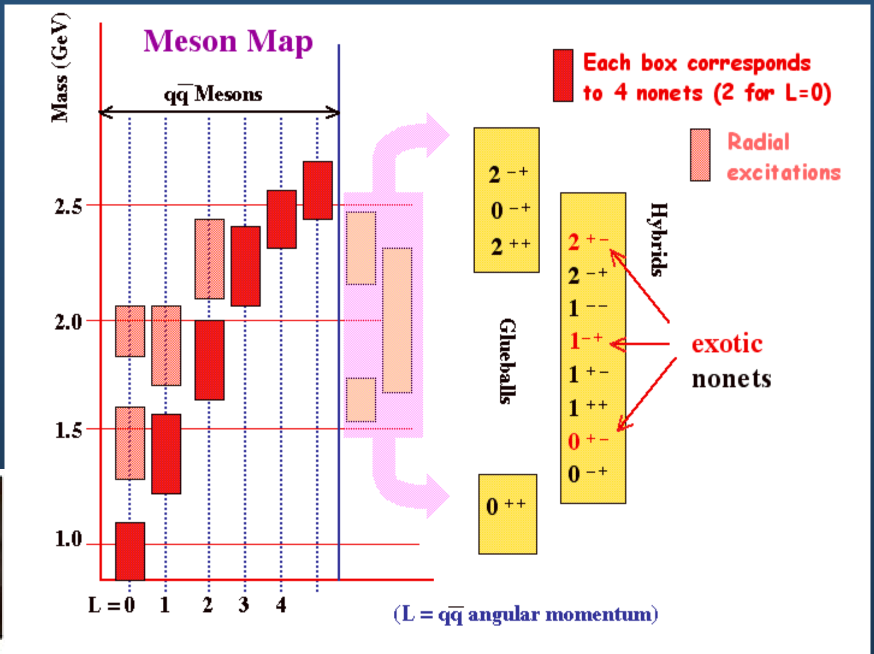
- *most* of observed low-lying hadron spectrum described reasonably well by quark model
  - agreement is amazing given the crudeness of the model
- mesons: only certain J^{PC} allowed:
  - $0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, 3^{-+}, 4^{+-}, \ldots$ forbidden

$$P = (-1)^{L+1} \qquad L = 0,1,2,\ldots$$
$$C = (-1)^{L+S} \qquad S = 0,1$$

- experimental results now need input beyond the quark model
  - over-abundance of states
  - forbidden 1^{-+} states

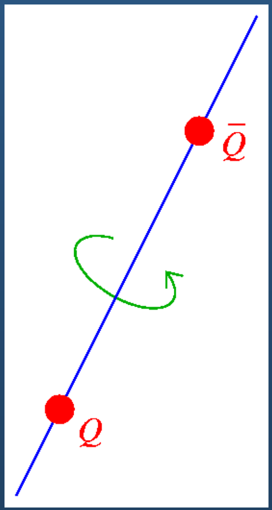
Gluonic excitations (new form of matter)

- QCD suggests existence of states in which *gluon* field is excited
  - glueballs (*excited glue*)
  - hybrid mesons ($q\bar{q}$ + *excited glue*)
  - hybrid baryons (qqq + *excited glue*)
- such states not well understood
  - quark model fails
  - perturbative methods fail
- lack of understanding makes identification difficult!
- confront gluon field behavior
  - bags, strings, …
- clues to confinement



Heavy-quark hybrid mesons

- more amenable to theoretical treatment than light-quark hybrids
- early work: Hasenfratz, Horgan, Kuti, Richards (1983), Perantonis, Michael (1990)
- possible treatment like diatomic molecule (Born-Oppenheimer)
  - slow heavy quarks ←→ nuclei
  - fast gluon field ←→ electrons
    (and light quarks)



- gluons provide adiabatic potentials $V_{Q\bar{Q}}(r)$
  - gluons fully relativistic, interacting
  - potentials computed in lattice simulations
- nonrelativistic quark motion described in *leading order* by solving Schrodinger equation for each $V_{Q\bar{Q}}(r)$

$$\left\{\frac{p^2}{2\mu}+V_{Q\bar{Q}}(r)\right\}\psi_{Q\bar{Q}}(r)=E\,\psi_{Q\bar{Q}}(r)$$

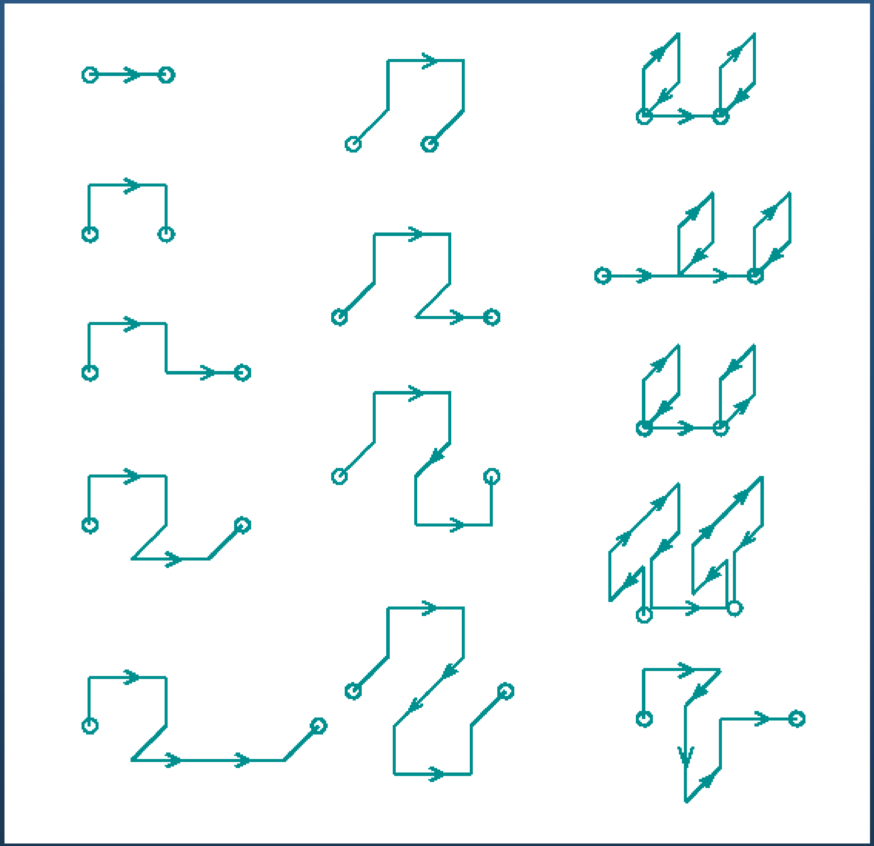
- conventional mesons from Σ_g^+ ; hybrids from $\Pi_u, \Sigma_u^-, \ldots$

First step in Born-Oppenheimer

- first step in Born-Oppenheimer approximation
  - determine the “gluonic terms”
- calculational approach → resort to Monte Carlo methods
  - familiar perturbative Feynman diagram techniques fail
  - Schwinger-Dyson equations intractable
- estimate path integrals: very high dimensionality
  - Markov chain methods
- lattice regularization permits formulation of field theory suitable for computer simulations

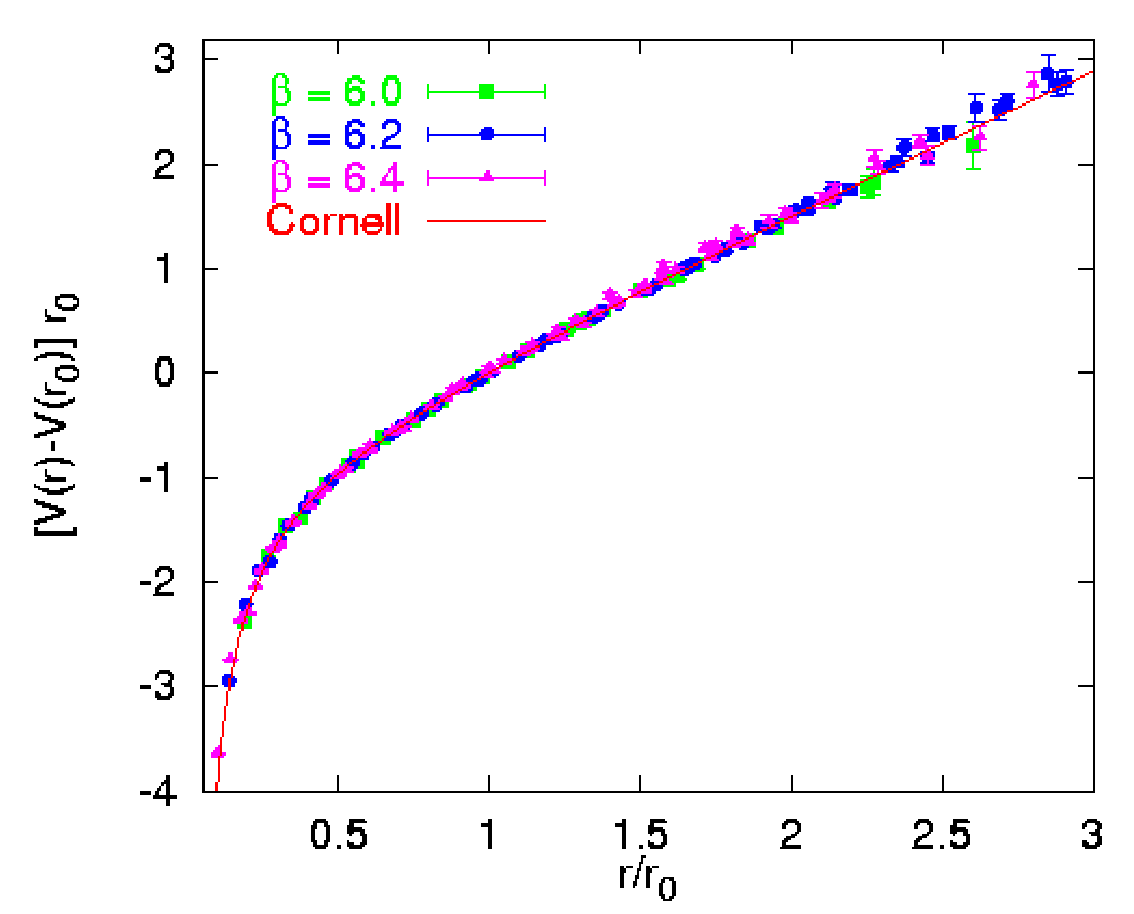
Generalized Wilson loops

- gluonic terms extracted from generalized Wilson loops
- large set of gluonic operators → correlation matrix



Static quark-antiquark potential

- lattice simulations confirm linearly rising potential from gluon exchange

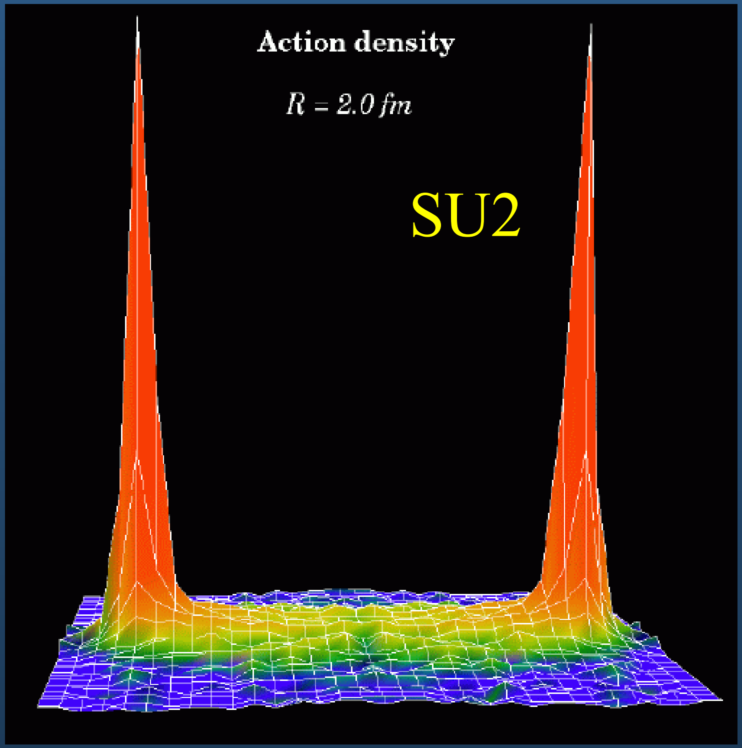


Bali *et al.*

$r_0 = 0.5$ fm

Gluonic flux profile

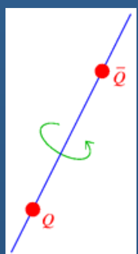
- computation of gluonic flux profile suggests that gluon field forms a *string*-like object between quark-antiquark

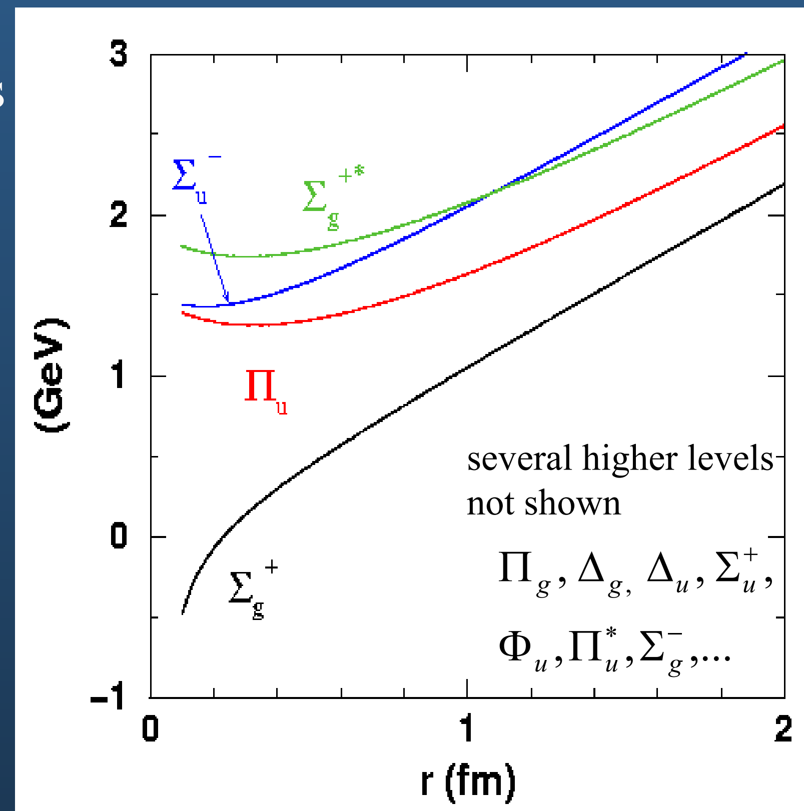


Bali *et al.*

Excitations of static quark potential

- gluon field in presence of static quark-antiquark pair can be *excited*
- classification of states: (notation from molecular physics)
  - magnitude of glue spin projected onto molecular axis
    $\Lambda = 0, 1, 2, \ldots$
    $= \Sigma, \Pi, \Delta, \ldots$
  - charge conjugation + parity about midpoint
    $\eta = g$ (even)
    $= u$ (odd)
  - chirality (reflections in plane containing axis) Σ^+, Σ^-
    $\Pi, \Delta, \ldots$ doubly degenerate
    (Λ doubling)

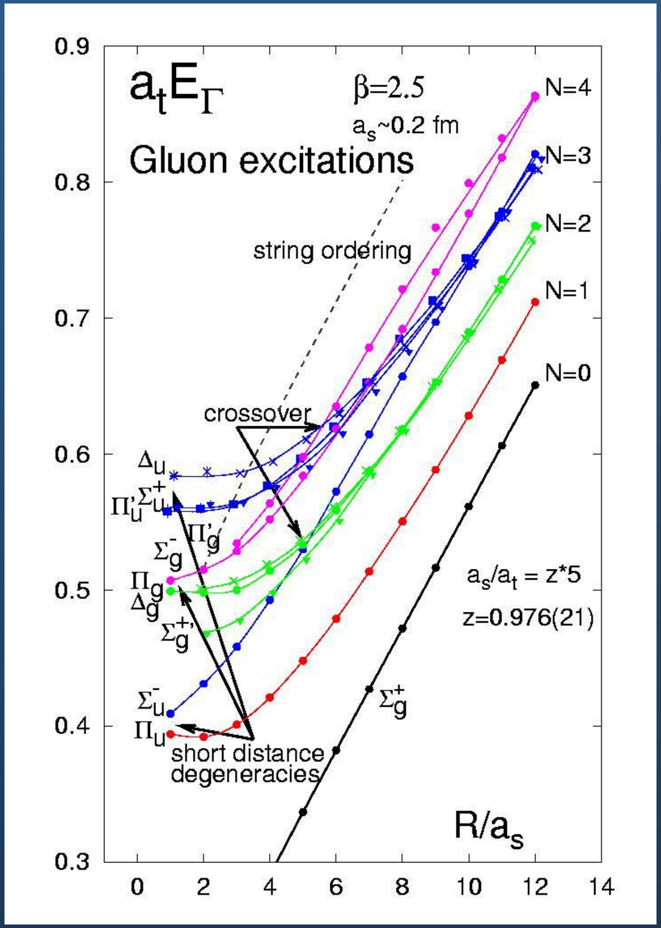




Juge, Kuti, Morningstar, PRL 90, 161601 (2003)

Three scales

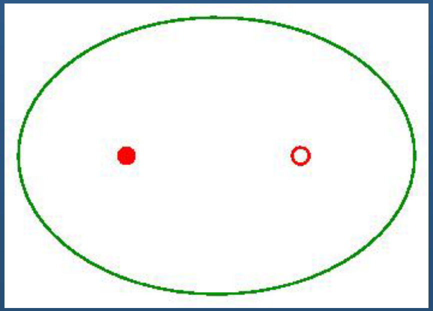
- small quark-antiquark separations r
  - excitations consistent with states from multipole OPE
- crossover region $0.5\text{fm} < r < 2\text{fm}$
  - dramatic level rearrangement
- large separations $r > 2\text{fm}$
  - excitations consistent with expectations from string models

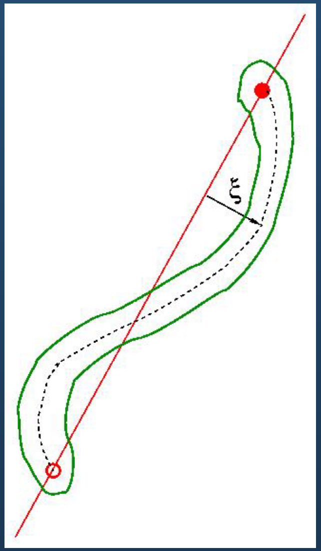


Juge, Kuti, Morningstar, PRL 90, 161601 (2003)

Possible interpretation

- small r
  - strong E field of $q\bar{q}$-pair repels physical vacuum (dual Meissner effect) creating a *bubble*
  - separation of degrees of freedom
    - gluonic modes inside bubble (low lying)
    - bubble surface modes (higher lying)
- large r
  - bubble stretches into thin tube of flux
  - separation of degrees of freedom
    - collective motion of tube (low lying)
    - internal gluonic modes (higher lying)
  - low-lying modes described by an effective string theory ($N\pi/r$ gaps – Goldstone modes)





Leading Born-Oppenheimer

- replace covariant derivative $\vec{D}^2$ by $\vec{\nabla}^2$ → neglects retardation
- neglect quark spin effects
- solve radial Schrodinger equation

$$\frac{-1}{2\mu}\frac{d^2u(r)}{dr^2}+\left\{\frac{\langle L_{q\bar{q}}^2\rangle}{2\mu r^2}+V_{q\bar{q}}(r)\right\}u(r)=Eu(r)$$

- angular momentum

$$\vec{J}=\vec{L}+\vec{S} \qquad \vec{S}=\vec{s}_q+\vec{s}_{\bar{q}} \qquad \vec{L}=\vec{L}_{q\bar{q}}+\vec{J}_g$$

- in LBO, L and S are good quantum numbers
- centrifugal term

$$\langle \vec{L}_{q\bar{q}}^2\rangle = L(L+1)-2\Lambda^2+\langle \vec{J}_g^2\rangle$$

$$\langle \vec{J}_g^2\rangle = 0 \quad (\Sigma_g^+)$$
$$= 2 \quad (\Pi_u, \Sigma_u^-)$$

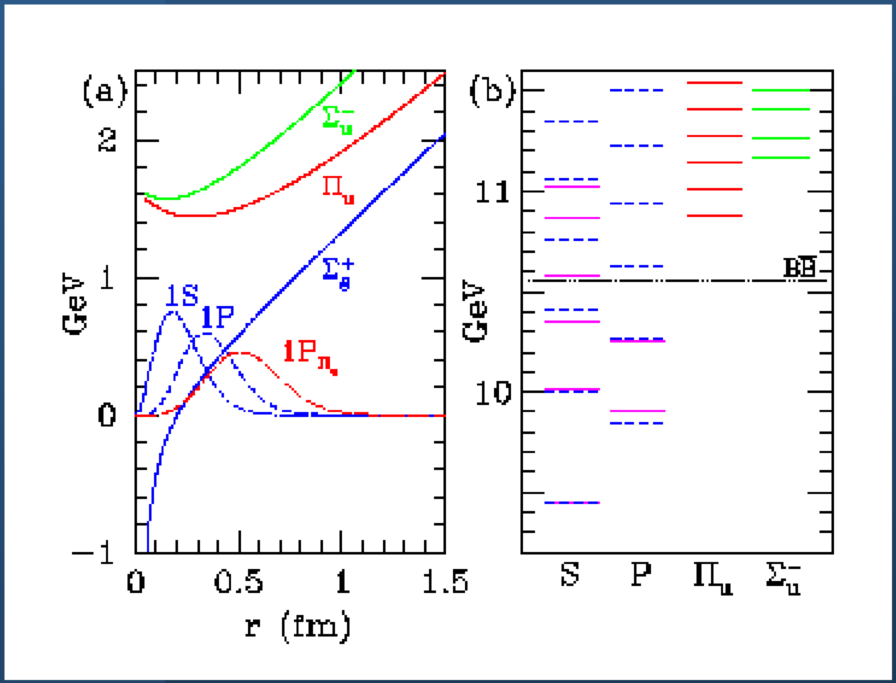
- J^{PC} eigenstates → Wigner rotations

$$|LSJM;\Lambda\eta\rangle+\varepsilon|LSJM;-\Lambda\eta\rangle$$

  - η is CP, $\varepsilon=\pm1$ for $\Lambda\geq1$, $\varepsilon=\pm1$ for $\Sigma^\pm$
- LBO allowed J^{PC} → $P=\varepsilon(-1)^{L+\Lambda+1}$, $C=\eta\varepsilon(-1)^{L+S+\Lambda}$

Leading Born-Oppenheimer spectrum

- results obtained (in absence of light quark loops)
- good agreement with experiment below $B\bar{B}$ threshold
- plethora of hybrid states predicted (caution! quark loops)
- but is a Born-Oppenheimer treatment valid?



LBO degeneracies:

$\Sigma_g^+(S)$: $0^{-+}, 1^{--}$

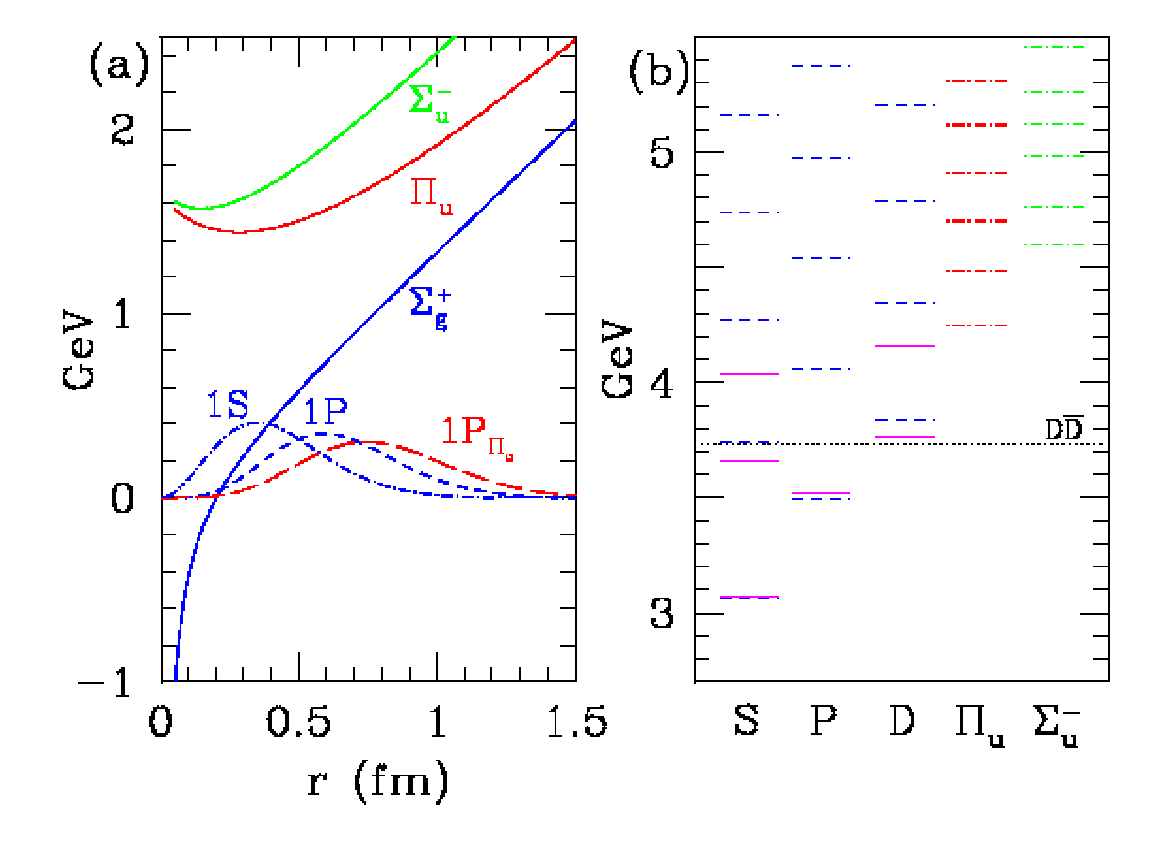
$\Sigma_g^+(P)$: $0^{++}, 1^{++}, 2^{++}, 1^{+-}$

$\Pi_u(P)$: $0^{-+}, 0^{+-}, 1^{++}, 1^{--}, 1^{+-}, 1^{-+}, 2^{+-}, 2^{-+}$

Juge, Kuti, Morningstar, Phys Rev Lett **82**, 4400 (1999)

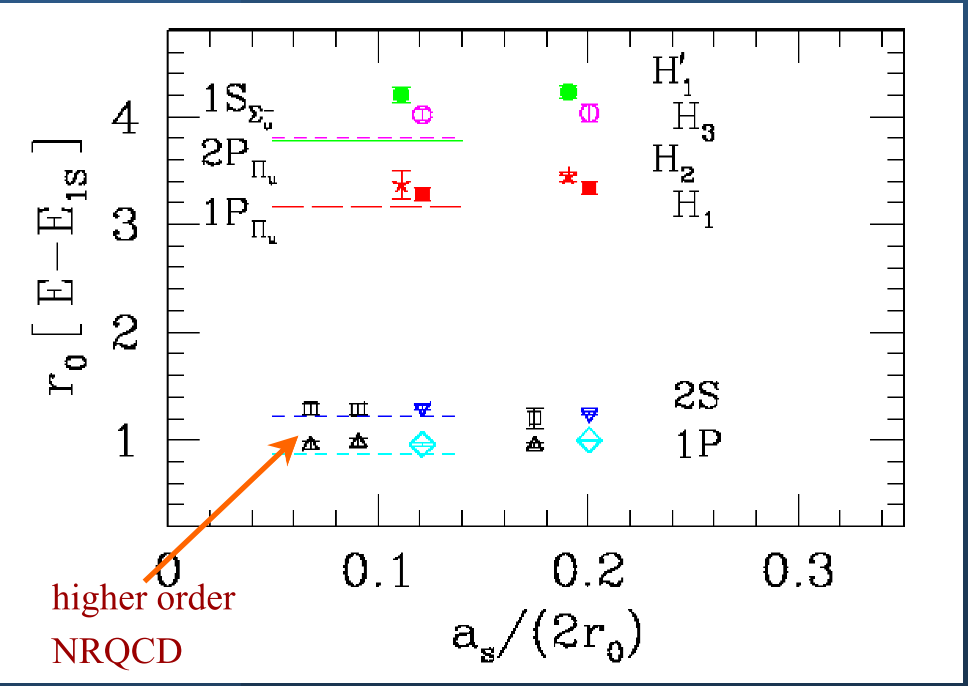
Charmonium LBO

- same calculation, but for charmonium



Testing LBO

- test LBO by comparison of spectrum with NRQCD simulations
  - include retardation effects, but no quark spin, no $\vec{p}^4$, no light quarks
  - allow possible mixings between adiabatic potentials
- dramatic evidence of validity of LBO
  - level splittings agree to 10% for 2 conventional mesons, 4 hybrids



$$H_1, H_1' = 1^{--}, 0^{-+}, 1^{-+}, 2^{-+}$$

$$H_2 = 1^{++}, 0^{+-}, 1^{+-}, 2^{+-}$$

$$H_3 = 0^{++}, 1^{+-}$$

J^{PC}		Degeneracies	Operator
0^{-+}	S wave	1^{--}	$\tilde\chi^\dagger\,[\hat\Delta^{(2)}]^p\,\tilde\psi$
1^{+-}	P wave	$0^{++}, 1^{++}, 2^{++}$	$\tilde\chi^\dagger\,\hat{\mathbf{\Delta}}\,\tilde\psi$
1^{--}	H_1 hybrid	$0^{-+}, 1^{-+}, 2^{-+}$	$\tilde\chi^\dagger\,\hat{\mathbf{B}}\,[\hat\Delta^{(2)}]^p\,\tilde\psi$
1^{++}	H_2 hybrid	$0^{+-}, 1^{+-}, 2^{+-}$	$\tilde\chi^\dagger\,\hat{\mathbf{B}}\times\hat{\mathbf{\Delta}}\,\tilde\psi$
0^{++}	H_3 hybrid	1^{+-}	$\tilde\chi^\dagger\,\hat{\mathbf{B}}\cdot\hat{\mathbf{\Delta}}\,\tilde\psi$

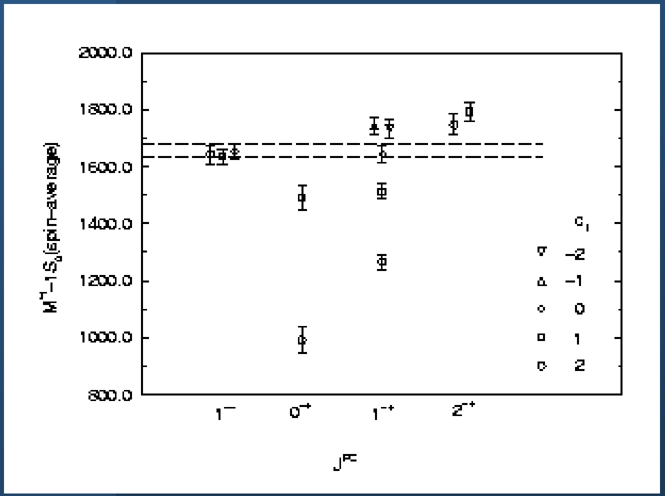
lowest hybrid 1.49(2)(5) GeV above 1S

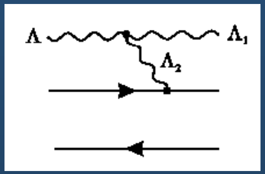
Compelling physical picture

- Born-Oppenheimer provides simple physical picture for heavy-quark conventional and hybrid meson states
  - partial explanation of quark model success
  - insight into light quarks?
  - allows incorporation of gluon dynamics (beyond quark model)
- does this BO picture survive inclusion of
  - quark spin?
  - light-quark effects?

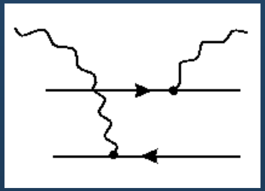
Quark spin effects

- quark spin: recent studies *suggest* BO picture survives
  - Drummond *et al.* Phys.Lett.B478, 151 (2000)
    - looked at 4 hybrids degenerate in LBO using NRQCD
    - found significant shifts from $c_1\,\sigma\cdot B/M$ but used bag model to interpret results as not arising from surface mixing effects
  - suggestive, but not definitive





dominant (but does not spoil BO)



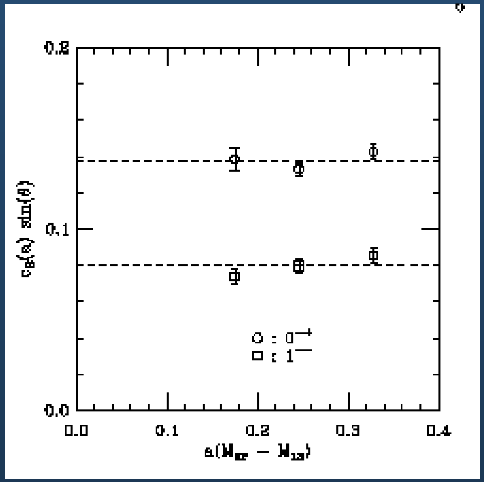
mixes adiabatic surfaces, but very small (10^{-4})

Quark spin effects (continued)

- Burch and Toussaint, hep-lat/0305008
  - NRQCD simulations, measured mixing via $c_1\,\sigma\cdot B/M$
  - mixing in bottomonium seems not to spoil BO picture
  - larger effect in charmonium

$$\langle 1H \,|\, \Upsilon \rangle \approx 0.076 - 0.11 \qquad \langle 1H \,|\, J/\Psi \rangle \approx 0.18 - 0.25$$

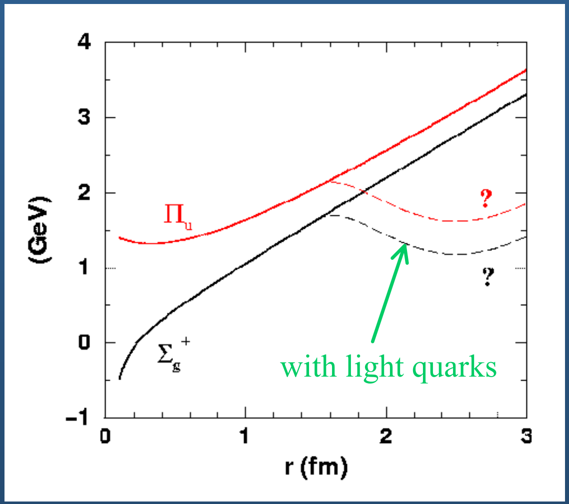
$$\langle 1H \,|\, \eta_b \rangle \approx 0.13 - 0.19 \qquad \langle 1H \,|\, \eta_c \rangle \approx 0.29 - 0.4$$

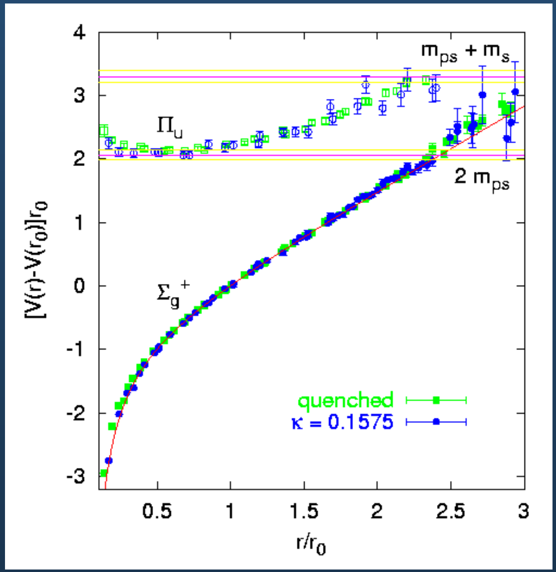


Light quark spoiler?

- spoil B.O.? → unknown
- light quarks change $V_{Q\overline{Q}}(r)$
  - small corrections at small r
    - fixes low-lying spectrum
  - large changes for $r>1$ fm

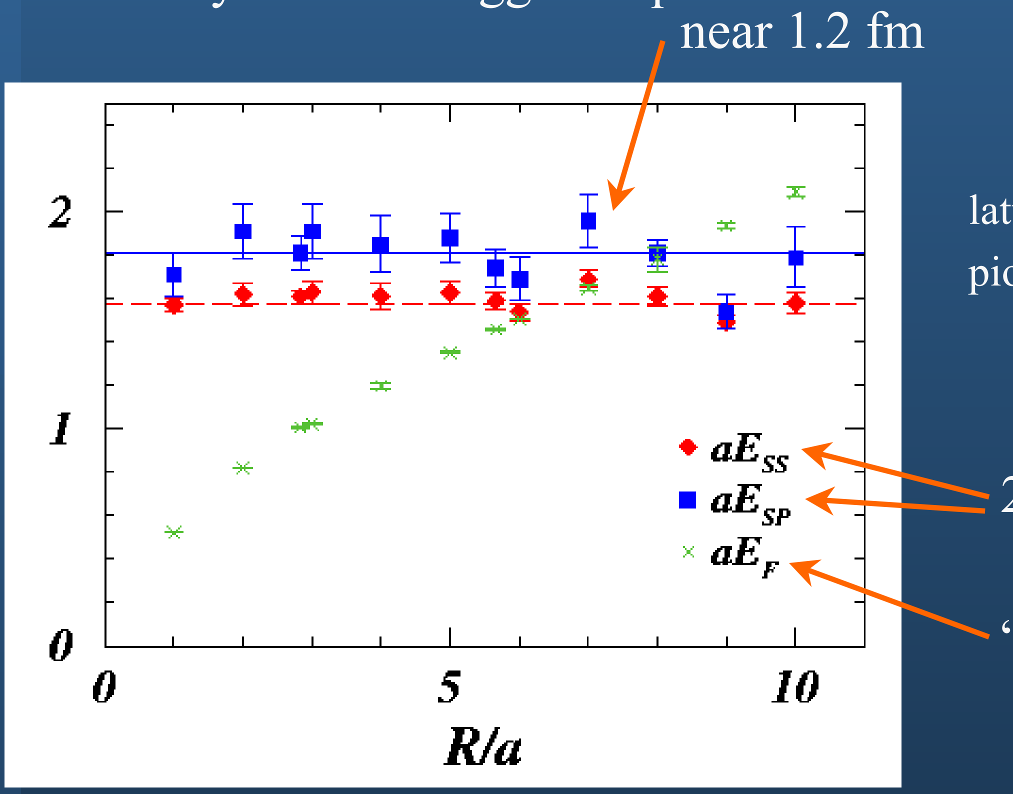
    → fission into $(Q\overline{q})(\overline{Q}q)$
- states with diameters over 1 fm
  - most likely *cannot exist* as observable resonances
- dense spectrum of states from pure glue potentials will not be realized
  - survival of a few states conceivable given results from Bali *et al.*
- discrepancy with experiment above $B\overline{B}$
  - most likely due to light quark effects





String breaking

- string "breaking" using 2 body operators
- two flavors of dynamical staggered quarks



lattice spacing 0.16 fm

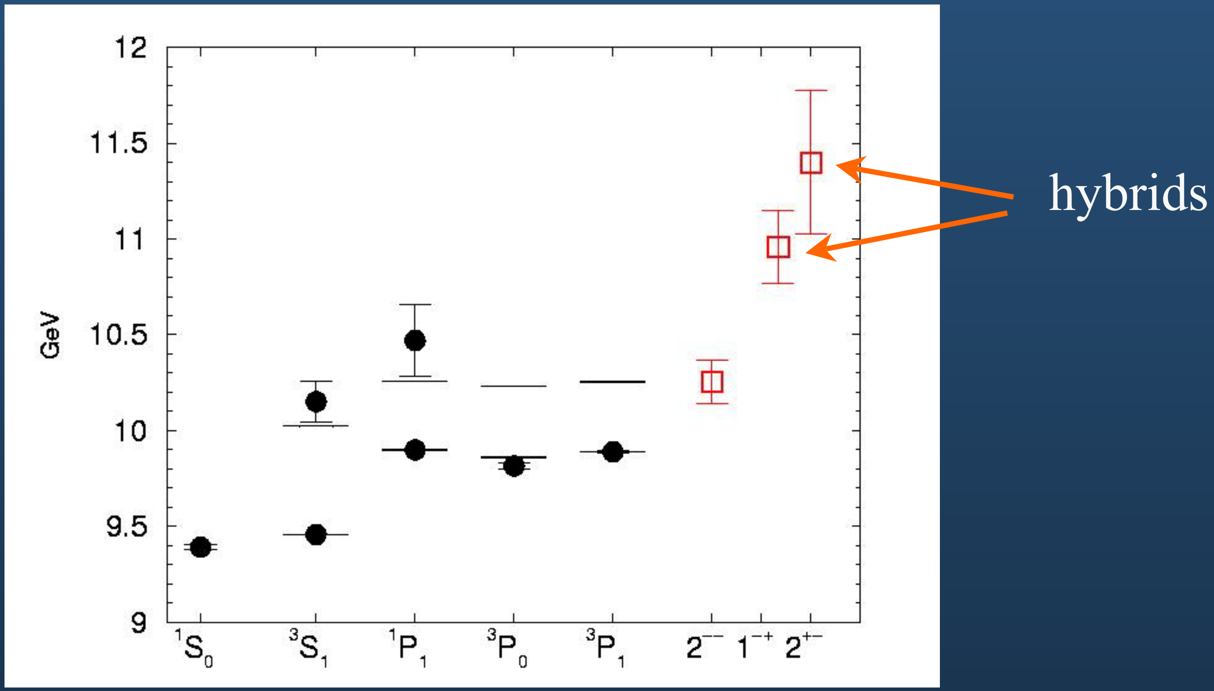
pion/rho mass 0.36

Bernard et al., PRD64, 074509 (2001)

Bottomonium hybrids

- recent calculation of bottomonium hybrids confirms earlier results
  - quenched, several lattice spacings so $a \to 0$ limit taken
  - improved anisotropic gluon and fermion (clover) actions
  - good agreement with Born-Oppenheimer (but errors large)

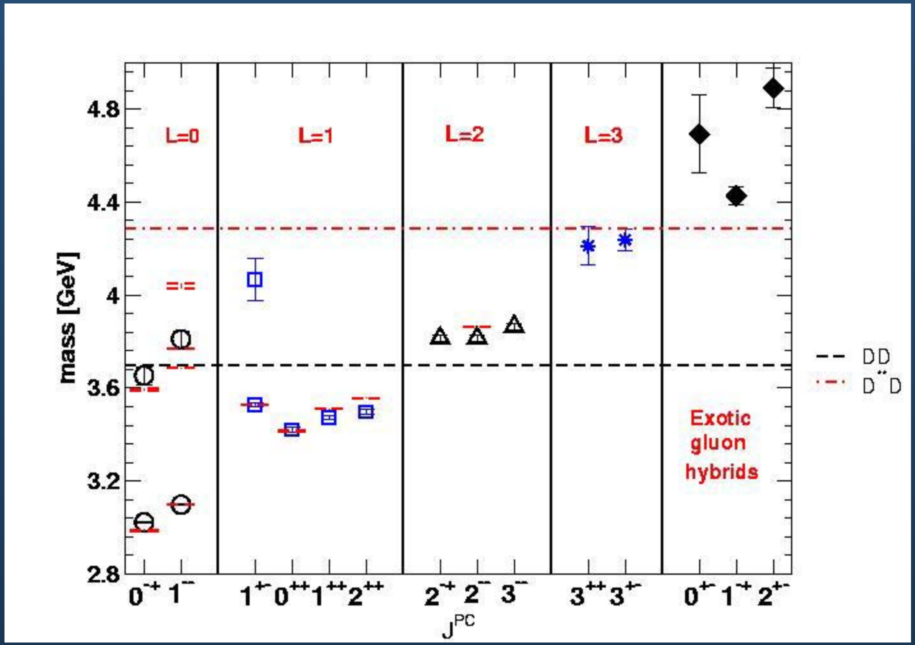
Liao, Manke, PRD**65**, 074508 (2002)



Charmonium hybrids

- recent determination of some charmonium hybrids
  - quenched, several lattice spacings for continuum limit
  - improved, anisotropic gluon and fermion (clover) actions
  - results suggest significant (but not large) corrections from LBO

Liao, Manke, hep-lat/0210030



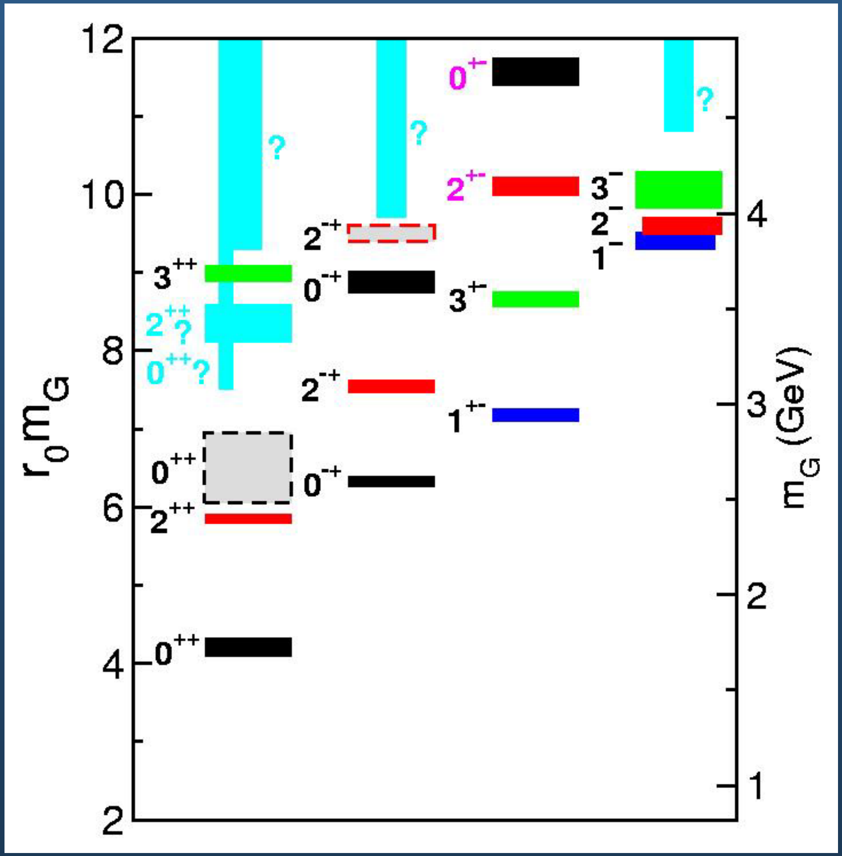
Tidbits

- glueballs
- light quark hybrids
- static three quark potential

Yang-Mills SU(3) Glueball Spectrum

- gluons can bind to form glueballs
- first glimpse of rich spectrum
- probe of confinement
- "experimental" results in simpler world (no quarks) to help build models of gluons
- add quarks for QCD glueballs
- future work: glueball structure
  - bag model, flux loops?

C. Morningstar and M. Peardon, Phys. Rev. D 60, 034509 (1999)



$r_0^{-1} = 410(20)$ MeV, states labeled by J^{PC}

Glueballs (qualitative features)

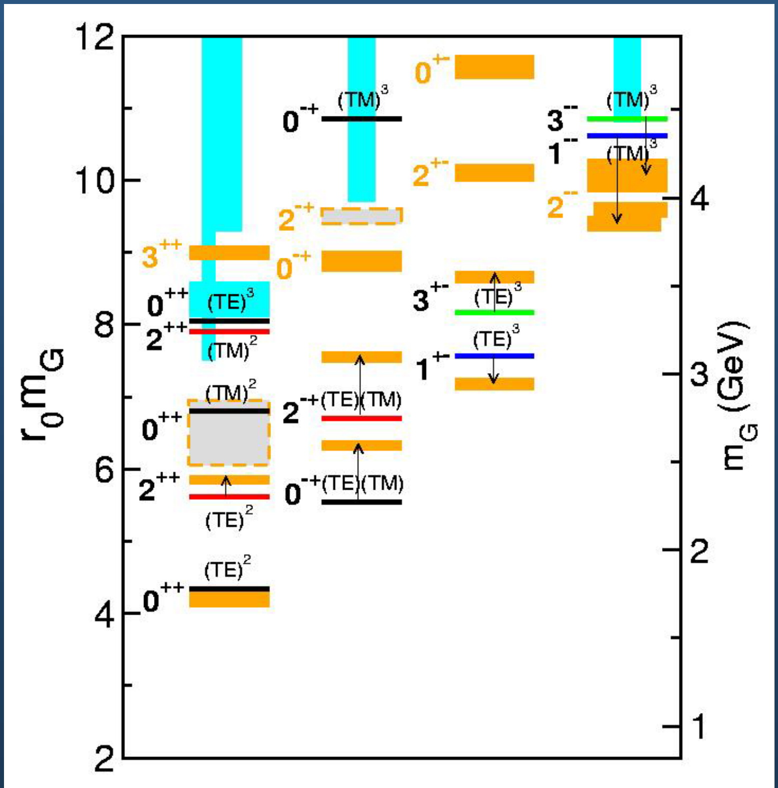
- spectrum can be qualitatively understood in terms of interpolating operators of minimal dimension (Jaffe,Johnson,Ryzak, Ann. Phys. **168**, 344 (1986))
  - dimension 4: $\mathrm{Tr}\, F_{\mu\nu} F_{\alpha\beta} \Rightarrow 0^{++}, 0^{-+}, 2^{++}, 2^{-+}$
  - dimension 5: $\mathrm{Tr}\, F_{\mu\nu} D_{\rho} F_{\alpha\beta} \Rightarrow 1^{++}, 3^{++}$
  - dimension 6: $\mathrm{Tr}\, F_{\mu\nu} F_{\delta\sigma} F_{\alpha\beta} \Rightarrow 0^{\pm+}, 1^{\pm\pm}, 2^{\pm\pm}, 3^{\pm-}$
    $\mathrm{Tr}\, F_{\mu\nu} \{D_{\rho}, D_{\sigma}\} F_{\alpha\beta} \Rightarrow 1^{-+}, 3^{-+}, 4^{\pm+}$
- of lightest 6 states, 4 have the J^{PC} of the dimension 4 operators
- absence of low-lying $0^{\pm-}, 1^{-+}$ glueballs explained

Glueballs (bag model)

- qualitative agreement with bag model
  - constituent gluons are TE or TM modes in spherical cavity
  - Hartree modes with residual perturbative interactions
  - center-of-mass correction

Carlson, Hansson, Peterson, PRD27, 1556 (1983);
J. Kuti (private communication)

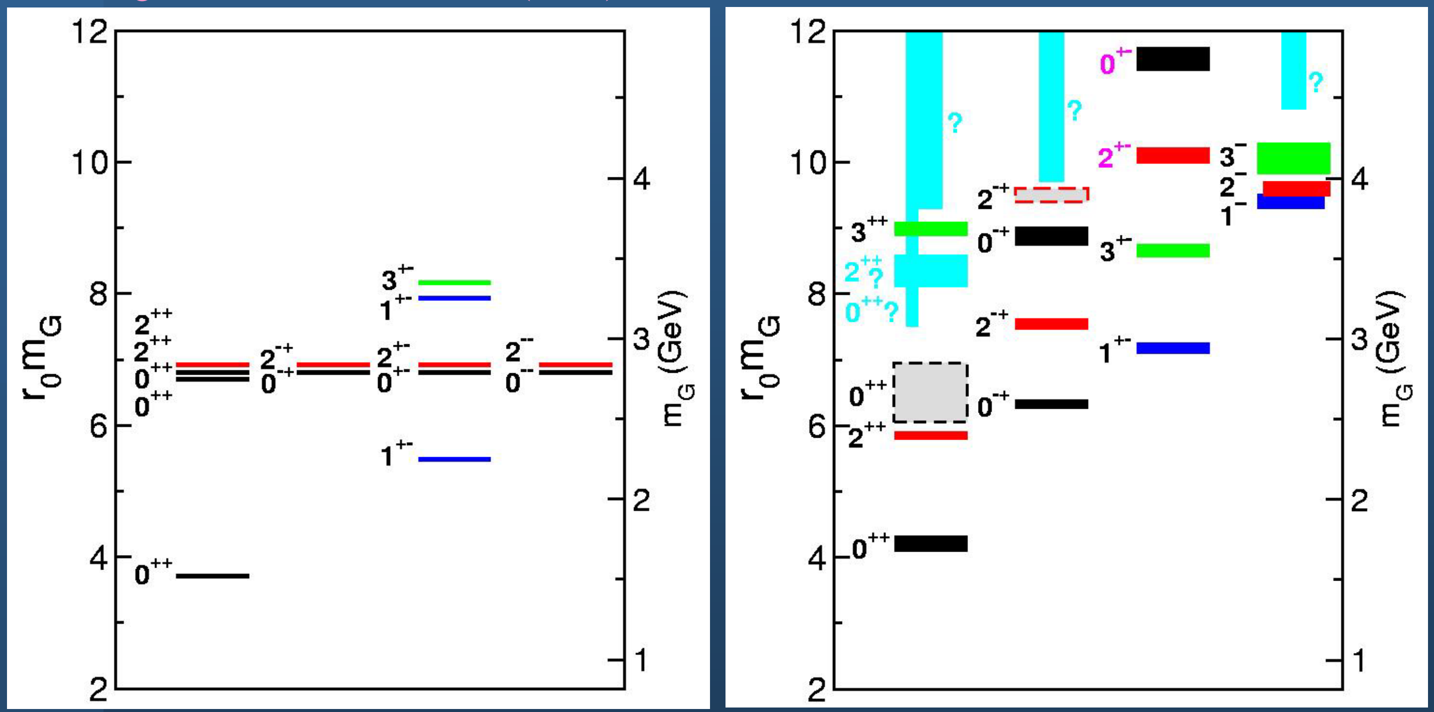
	1983	1993
	light baryon spectroscopy	static-quark potential
α_s	1.0	0.5
$B^{1/4}$	230 MeV	280 MeV



Glueballs (flux tube model)

- disagreement with one particular string model

Isgur, Paton, PRD**31**, 2910 (1985)

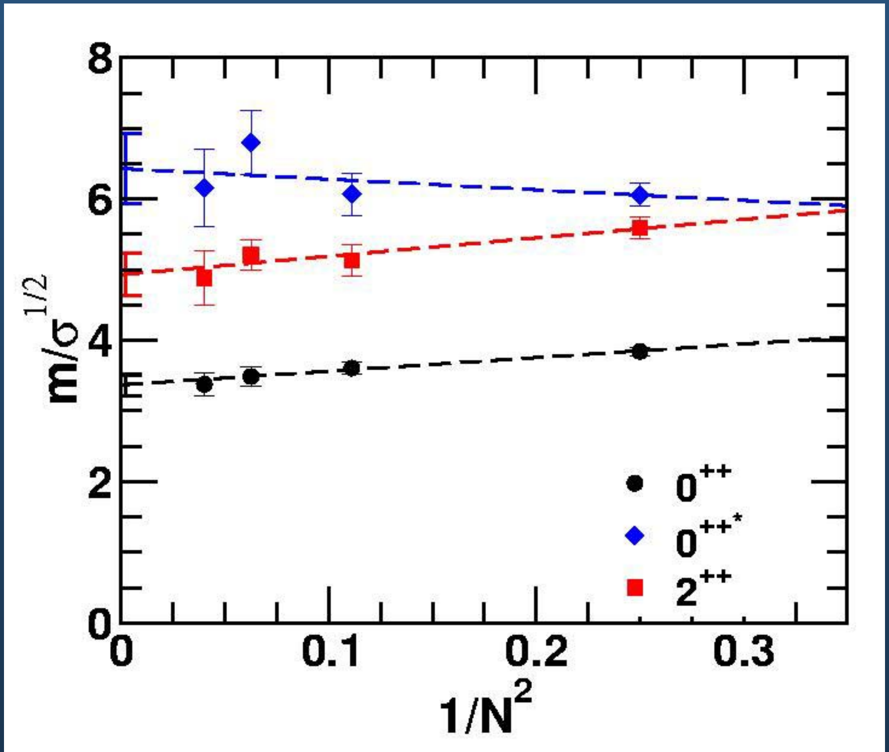


- future comparisons:
  - with more sophisticated string models (soliton knots)
  - AdS theories, duality

SU(N) Glueballs

- recent study of $0^{++}, 2^{++}, 0^{++*}$ glueballs in SU(N), N=2,3,4,5
- masses depend linearly on $1/N^2$
- large $N \to \infty$ limits differ little from $N = 3$

Lucini, Teper, JHEP **06**, 050 (2001).



Light-quark hybrids

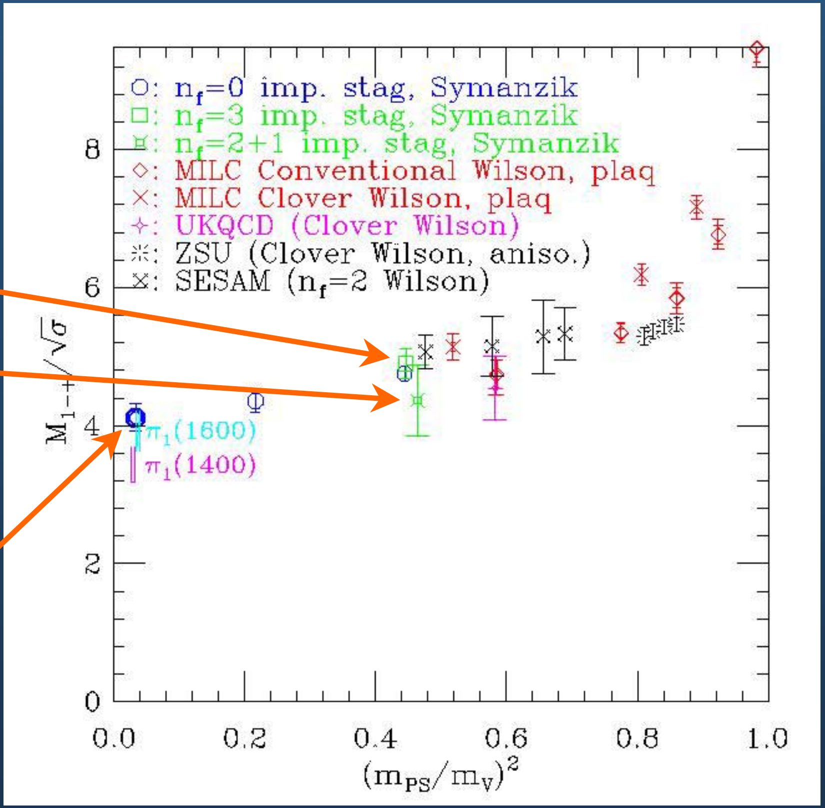
- recent new determination of exotic 1^{+-} hybrid meson
  - improved staggered fermions (lighter quark masses)
  - quenched and unquenched, Wilson gluon action
  - $a \approx 0.09$ fm
  - lightest mass still above experiment

MILC, hep-lat/0301024

$N_f = 3, \quad m_u = m_d = m_s$
(around strange quark mass)

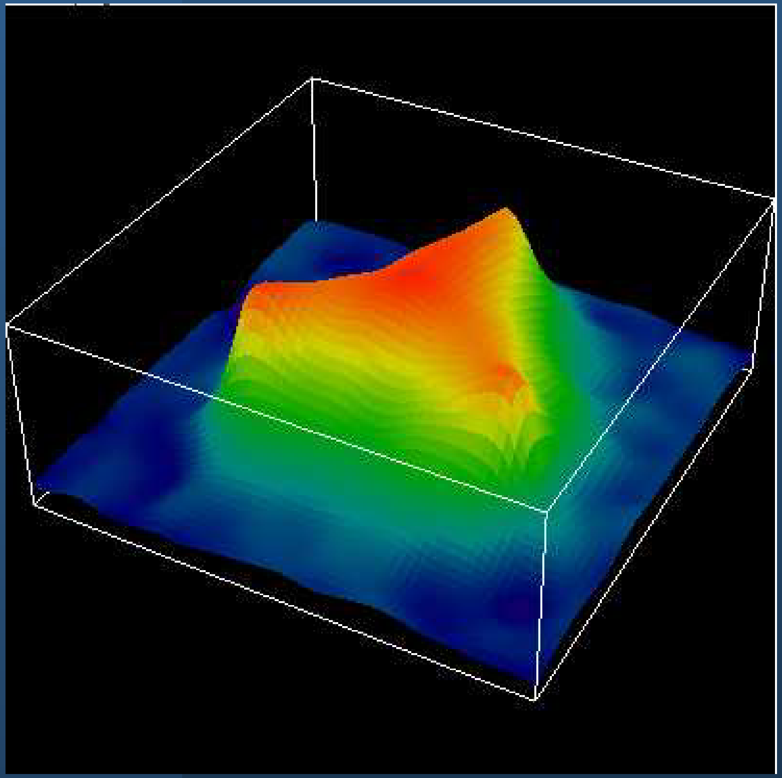
$m_u = m_d = 0.4 m_s$

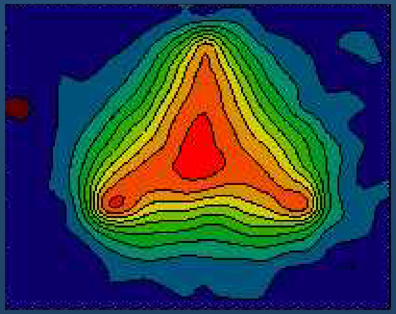
quenched continuum limit



Static three-quark system

- recent determination of the abelian action distribution of gluons and light quarks in the presence of three static quarks
  - supports a Y-type flux configuration



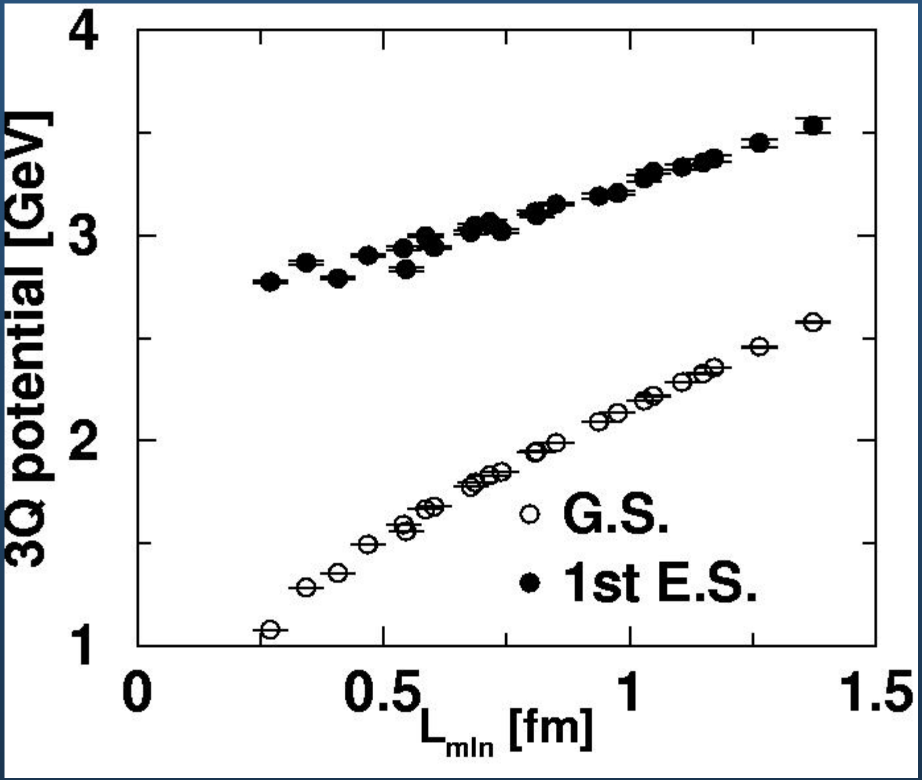


Ichie, Bornyakov, Struer, Schierholz, hep-lat/0212024

Excitation of the static 3q system

- first excitation of the static 3q system recently determined
  - excitation energy about 1 GeV
  - finite spacing, finite volume errors still to be studied

Takahashi, Suganuma, hep-lat/0210024



Conclusion

- hadronic states bound by an *excited* gluon field
  - interesting new form of matter
  - shed new light on confinement in QCD
- heavy-quark hybrid mesons
  - validity of a Born-Oppenheimer treatment
  - relationship to excitations of the static quark potential
  - compelling physical picture
  - quark spin effects do not spoil BO
  - light quark loops → survival issue