6. Exotic Hadrons:
Multiquarks, Glueball and Hybrids

1. Why?
2. Multiquarks
3. Glueballs
4. Hybrids
5. Summary

*For a recent review see Godfrey and Napolitano, Rev Mod Phys 71, 1411(1999)

The New York Times ON THE WEB

August 15, 2000

10 Physics Questions to Ponder for a Millenium or Two

One of those questions:

How can we understand quark and gluon confinement in Quantum Chromodynamics?

Meson Spectroscopy is the ideal laboratory to accomplish this

A fundamental question to this is end is

"How does glue manifest itself in the soft QCD regime?"

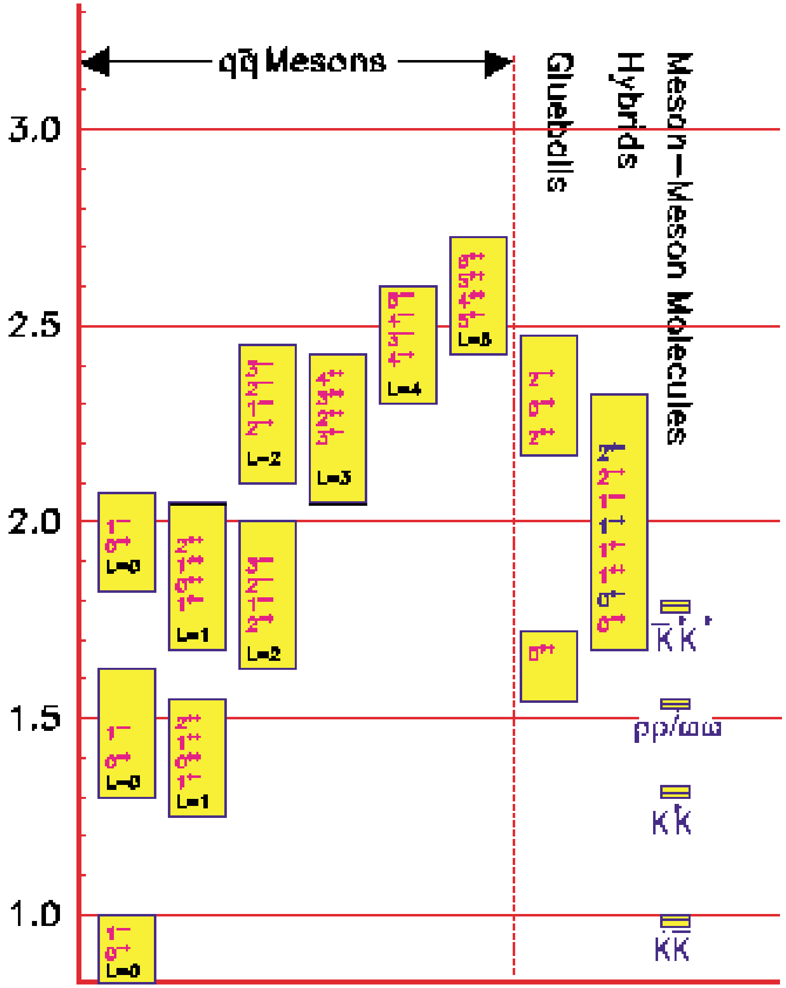
Models of hadron structure

- Lattice QCD (C. McNeille)
- Bag Model
- Flux tube model
- Sum rules approach

predict new forms of hadronic matter with the glue degree of freedom manifest explicitly:

- Glueballs
- Hybrids

and in addition: Multiquark States



Lattice calculations not yet enough.

Also need phenomenological models to help to find these states:

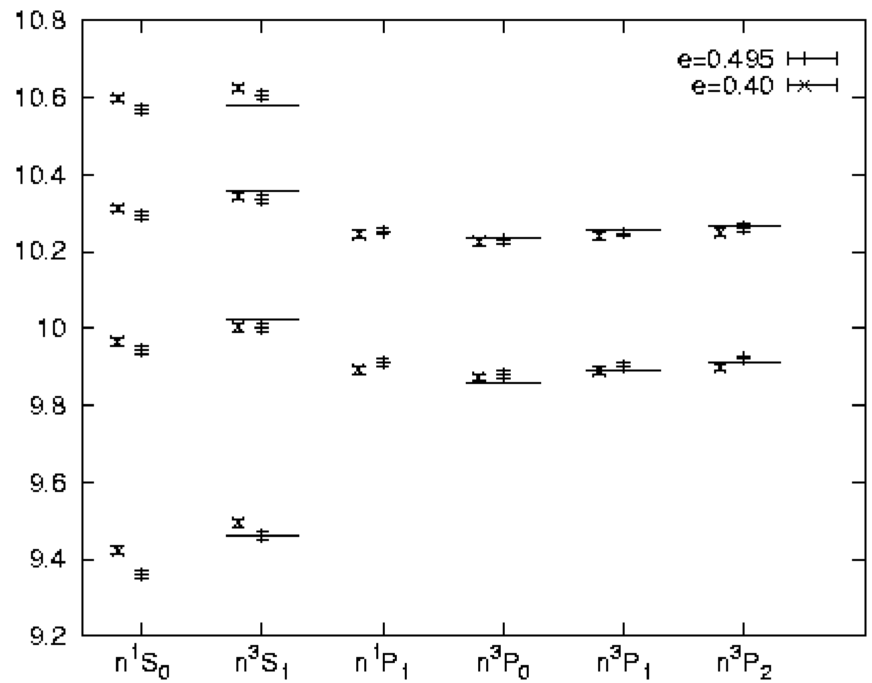
- Disentangle their properties
- Build up a physical picture

Much theoretical progress:

- Lattice QCD is a first principles calculation starting from the QCD lagrangian (C. McNeille)

- Gives a good description of the observed spectrum or heavy quarkonium

- Potential description works well

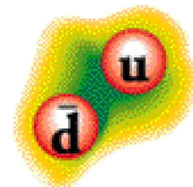


Bali, Schilling and Wachter
hep-ph/9611226

Conventional Mesons:

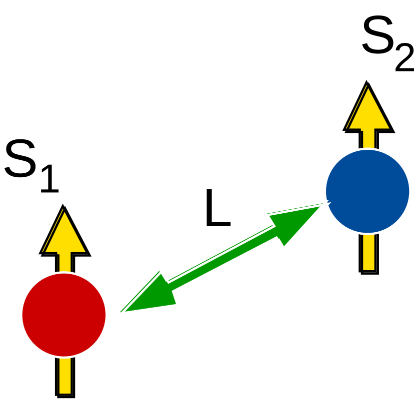
Mesons are composed of a quark-antiquark pair

Combine u,d,s,c,b quark and antiquark to form various mesons:



π meson

Meson quantum numbers characterized by given J^{PC}



$S = S_1 + S_2$

$J = L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

Allowed:

$J^{PC} = 0^{-+}\ \ 1^{--}\ \ 1^{+-}\ \ 0^{++}\ \ 1^{++}\ \ 2^{++}$ …

Not allowed: exotic combinations:

$J^{PC} = 0^{--}\ \ 0^{+-}\ \ 1^{-+}\ \ 2^{+-}$ …

Multiquark Mesons: $qq\bar{q}\bar{q}$

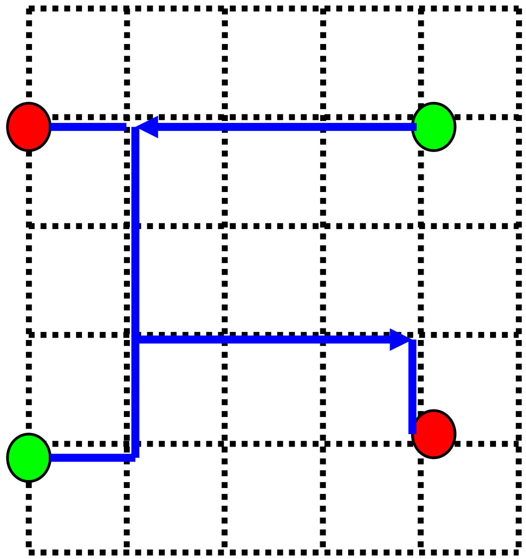
Multiquarks manifests themselves in many ways and important in many places:

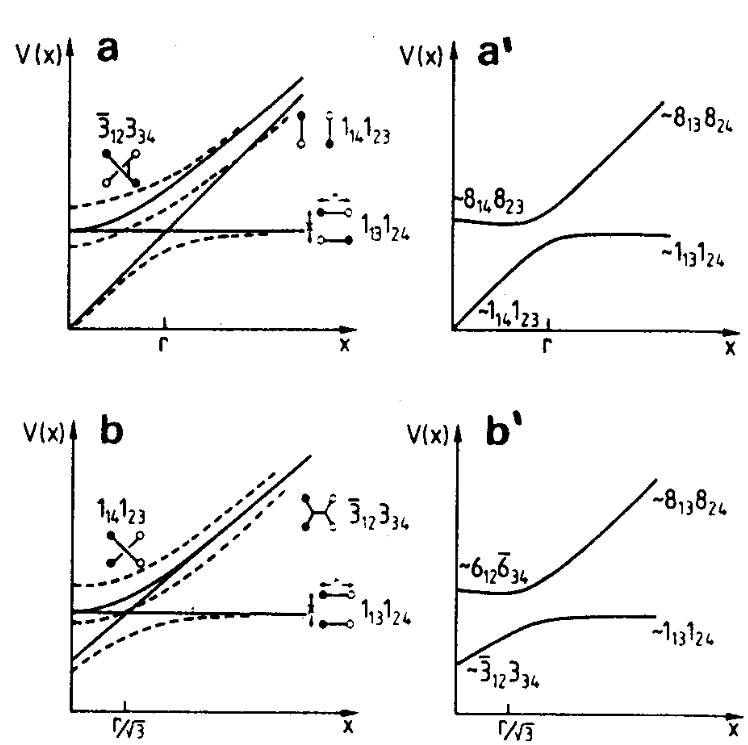
- More complicated than $q\bar{q}$ states
- Meson-meson potentials in scattering
- Leads to final state interactions in weak decays resulting in strong phases
  Need to understand strong phases to extract weak phases and hence extract CP violating phases
- Higher Fock space components which shift $q\bar{q}$ masses

Next simplist hadron multiquark hadron:

- Neither forbidden by colour confinement like q, qq, $qq\bar{q}$
- Nor required like $q\bar{q}$, qqq
- Next complication beyond qqq
- Less complicated than $6q$

Multiquark Mesons:

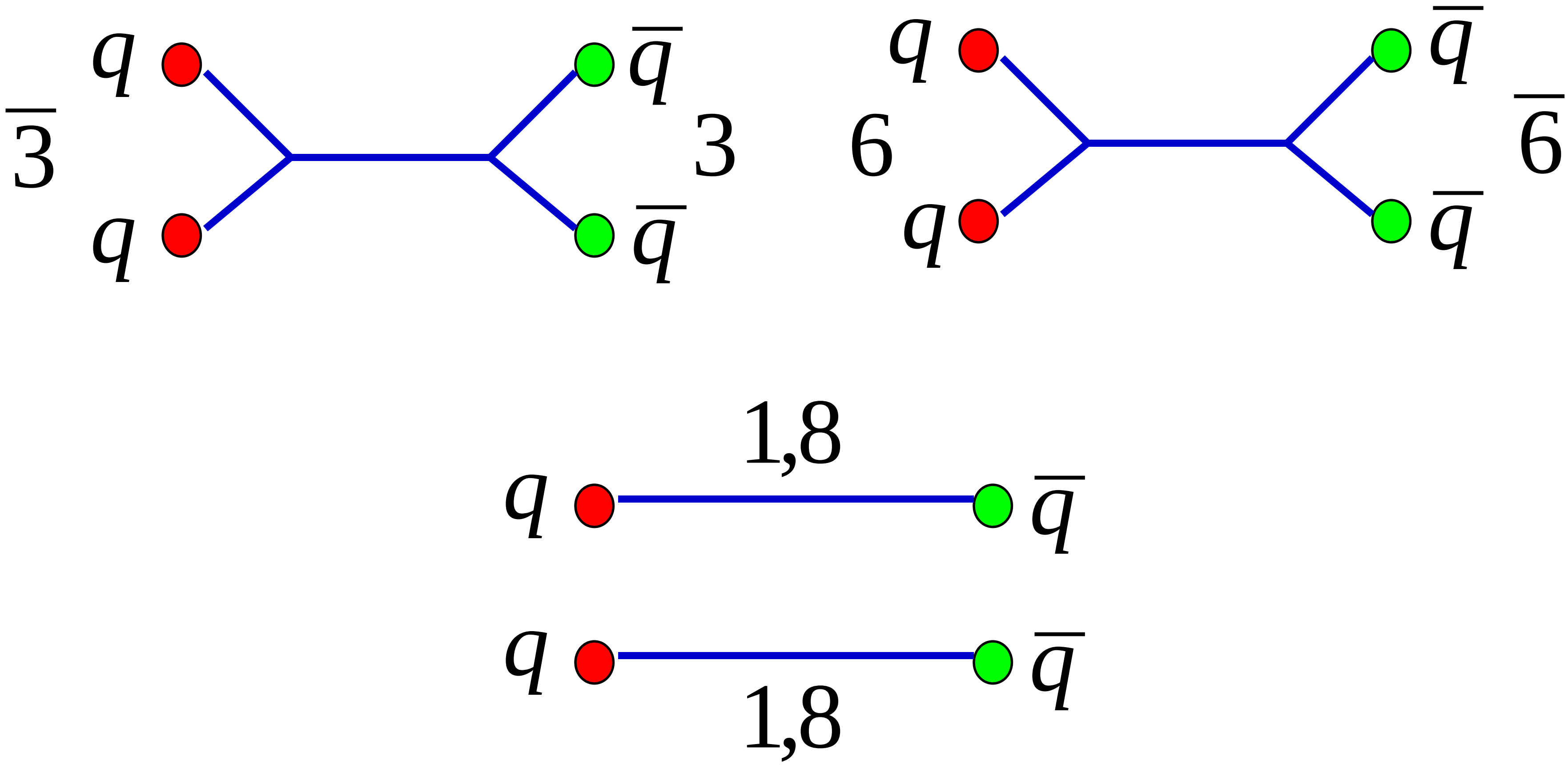




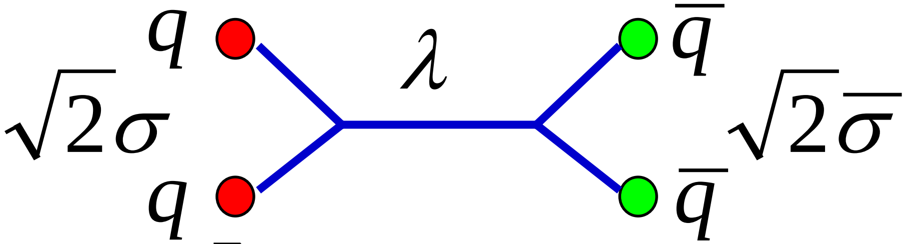
- No time to discuss but mention as another ingredient
  - $f_0(980)$, $a_0(980)$ believed to be multiquark states
  - $f_1(1430)$ long standing puzzle (E/ι puzzle)
  - $f_J(1710)$ also open to interpretation
- Could also have multiquarks with exotic quantum #'s
- Best bets are fractional or doubly charged mesons

Additional Complications:

- Colour configurations no longer unique
- 3 relative coordinates



Take $H = \sum_{i=1}^{4} (m_i + \frac{p_i^2}{2m_i}) + \sum_{i<j} [-\frac{1}{2} k r_{ij}^2 \vec{F}_i \cdot \vec{F}_j + H_{hyp}^{ij}]$



In $|\bar{3}_{12} 3_{34}\rangle - |6_{12} \bar{6}_{34}\rangle$ basis

$$H = \frac{1}{2m}(p_\sigma^2 + p_{\bar{\sigma}}^2 + p_\lambda^2) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \frac{1}{2} k \begin{pmatrix} 2\sigma^2 + 2\bar{\sigma}^2 + \frac{1}{3}\lambda^2 & -2\sqrt{2}\vec{\sigma} \cdot \vec{\bar{\sigma}} \\ -2\sqrt{2}\vec{\sigma} \cdot \vec{\bar{\sigma}} & \sigma^2 + \bar{\sigma}^2 + \frac{10}{3}\lambda^2 \end{pmatrix}$$

The solution <u>must</u> include free mesons

Solve variationally and find:

- No weakly bound states or resonances
- Best viewed as 2 weakly bound mesons analogous to Nucleon-nucleon structure of deuteron with residual interactions

It is widely believed that the $f_0(980)$ and $a_0(980)$ with $J^{PC}=0^{++}$ resonances are $K\bar{K}$ molecules

Explains why they are relatively narrow:

- The $K\bar{K}$ are weakly bound
  - Far apart
  - Not likely to annihilate to $\pi\pi$

Much interesting physics:

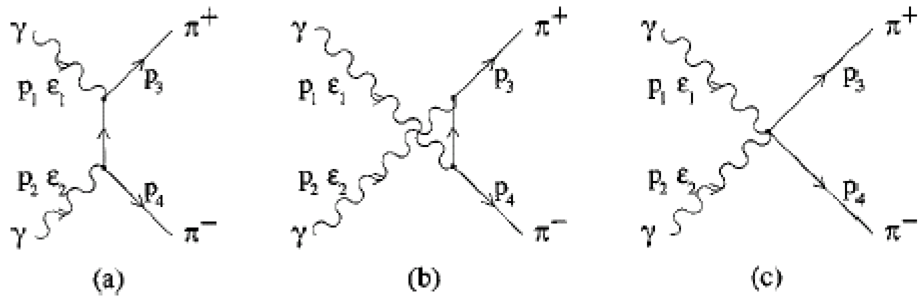
- Can calculate potentials between mesons

⇒ • final state interactions

Very important for B-decays looking for asymmetries

⇒ CP violation

1st Example: $\gamma\gamma \rightarrow \pi\pi$



$$f_{LM_L}^{\lambda_1\lambda_2} = \int d\Omega \, Y_{LM_L}^{*}(\theta,\phi)\mathcal{M}_{\lambda_1\lambda_2}.$$

$$u_l(k,r) \overset{r\rightarrow\infty}{\rightarrow} \frac{1}{kr}\sin(kr - l\pi/2 + \delta_l).$$

$$f_{LM_L}^{\rm FSI}(s(k_f)) = \frac{2}{\pi}\sqrt{s(k_f)}e^{i\delta_L}\int_0^\infty dk \int_0^\infty dr r^2 k^2 \frac{f_{LM_L}(s(k))}{\sqrt{s(k)}} \times j_L(kr)u_L(k_f,r). \qquad (11)$$

$$
\begin{aligned}
\psi^{-\pi^+\pi^-*}(k) &= \langle \psi^{-\pi^+\pi^-}_{\vec{k}_f} | \phi^{\pi^+\pi^-}_{\vec{k}} \rangle \\
&= \left[\sqrt{\frac{2}{3}} \langle \psi^{-0}_{\vec{k}_f} | + \sqrt{\frac{1}{3}} \langle \psi^{-2}_{\vec{k}_f} | \right] \\
&\quad \times \left[\sqrt{\frac{2}{3}} | \phi^{0}_{\vec{k}} \rangle + \sqrt{\frac{1}{3}} | \phi^{2}_{\vec{k}} \rangle \right] \\
&= (2\pi)^{3/2} \left[\frac{2}{3} \psi^{-0*}_{\vec{k}_f}(\vec{k}) + \frac{1}{3} \psi^{-2*}_{\vec{k}_f}(\vec{k}) \right],
\end{aligned}
$$

$$
\begin{aligned}
f^{\mathrm{FSI}}_{LM_L\pi^+\pi^-}(s(k_f)) &= \frac{2}{\pi} \sqrt{s(k_f)} \\
&\quad \times \int_0^\infty dk \int_0^\infty dr\, r^2 k^2 \frac{f_{LM_L}(s(k))}{\sqrt{s(k)}} j_L(kr) \\
&\quad \times \left[\frac{2}{3} e^{i\delta_L^0} u_L^0(k_f, r) + \frac{1}{3} e^{i\delta_L^2} u_L^2(k_f, r) \right]
\end{aligned}
$$

$$
\begin{aligned}
|f^{\mathrm{FSI}}_{LM_L\pi^0\pi^0}|^2 &= \frac{2}{9}(g^0_{LM_L})^2 + \frac{2}{9}(g^2_{LM_L})^2 \\
&\quad - \frac{4}{9} g^0_{LM_L} g^2_{LM_L} \cos(\delta_L^0 - \delta_L^2).
\end{aligned}
$$

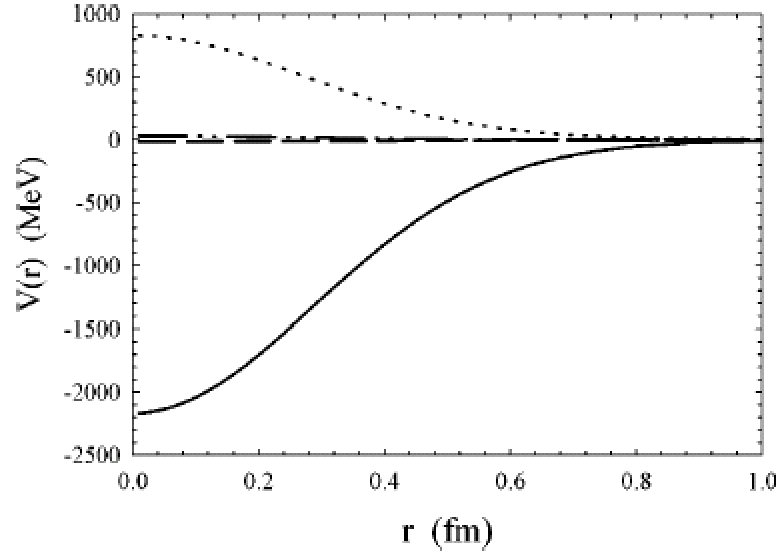
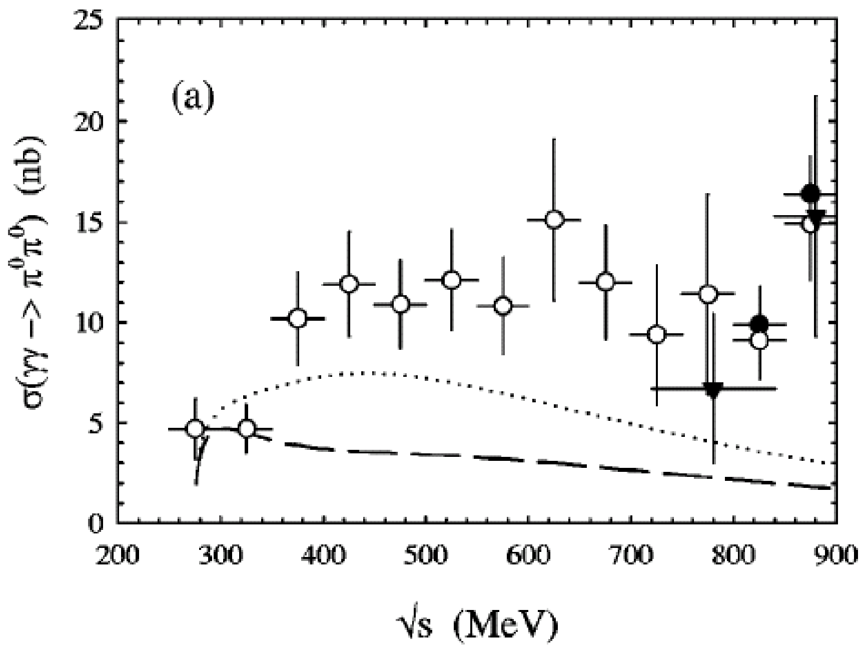


FIG. 2. The $\pi\pi$ potentials vs r for $I=0$, $L=0$ (solid line), $I=0$, $L=2$ (dashed line), $I=2$, $L=0$ (dotted line), and $I=2$, $L=2$ (dot-dot-dashed line). The potentials are given by Eq. (8) with the



2^{nd} Example: 6 quarks or nuclear physics from the quark model

Even more complicated than $qq\bar{q}\bar{q}$

Numerous spin, colour, flavour configurations

5 relative coordinates

Solved variationally with 3-quark clusters wavefunction and intercluster configuration

Found:

1. Strong clustering into 2 3-quark systems with quantum numbers of the neutron and proton
2. Nucleon physics is appropriate for nuclear physics
   - Strong repulsive core
   - Intermediate range binding
   - $^3S_1$ less repulsive than $^1S_0$

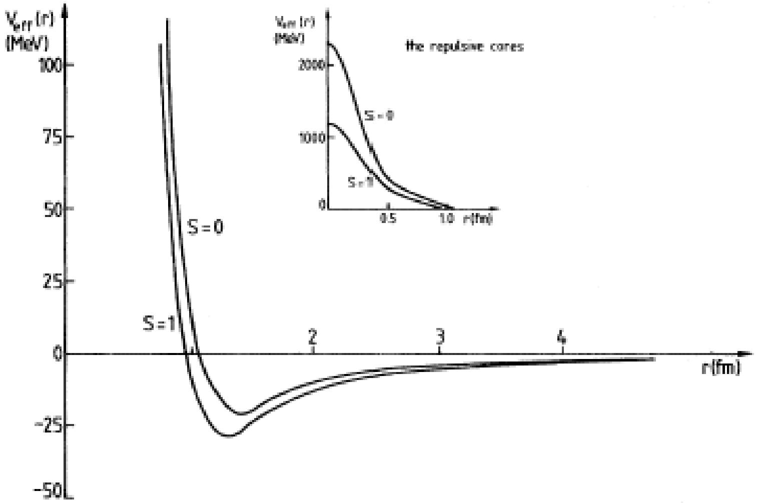
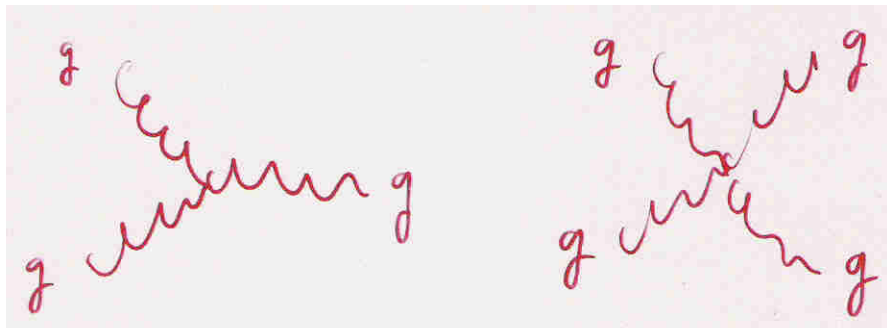


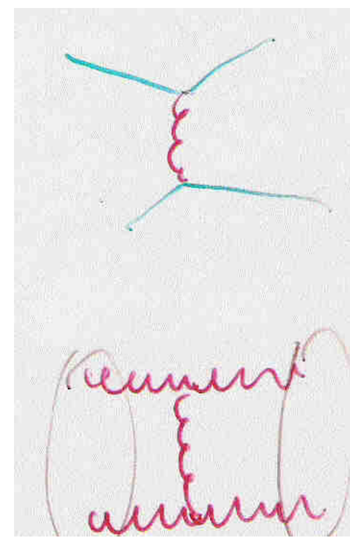
FIG. 1. The effective nucleon–nucleon potential from residual quark forces in the $^3S_1$ and $^1S_0$ channels.

Glueballs and Hybrids; Back to QCD

$$\mathcal{L}_{QCD} = \sum_{f}^{n_f} \bar{q}_f [i\gamma_\mu(\partial^\mu + igA^\mu) - m_f] q_f - \frac{1}{2}\mathrm{Tr}(F_{\mu\nu}F^{\mu\nu})$$



Believed that gluons act as both mediators of strong force and constituent of new types of hadrons



Now know it is far more complicated

To distinguish glueballs and hybrids from conventional states look for quantum numbers that don't follow from quark model

To enumerate J^{PC} quantum numbers consider gauge invariant interpolating fields (this is model independent)

$$\mathcal{O} = \left(\bar{\psi}\, \Gamma \frac{\lambda_a}{2} \psi\right) \otimes \left(\vec{E}^a \text{ or } \vec{B}^a\right)$$

colour octets

$$\vec{E}^a \sim F^a_{0i} \qquad \vec{B}^a \sim F^a_{ij}$$

for example:

1^{-+} $\quad (\bar{\psi}\, \vec{\gamma}\, \psi) \times \vec{B}$

2^{+-} $\quad (\bar{\psi}\, \vec{\gamma} \gamma_5 \psi) \otimes \vec{B}$

There are numerous models of hybrids and glueballs:

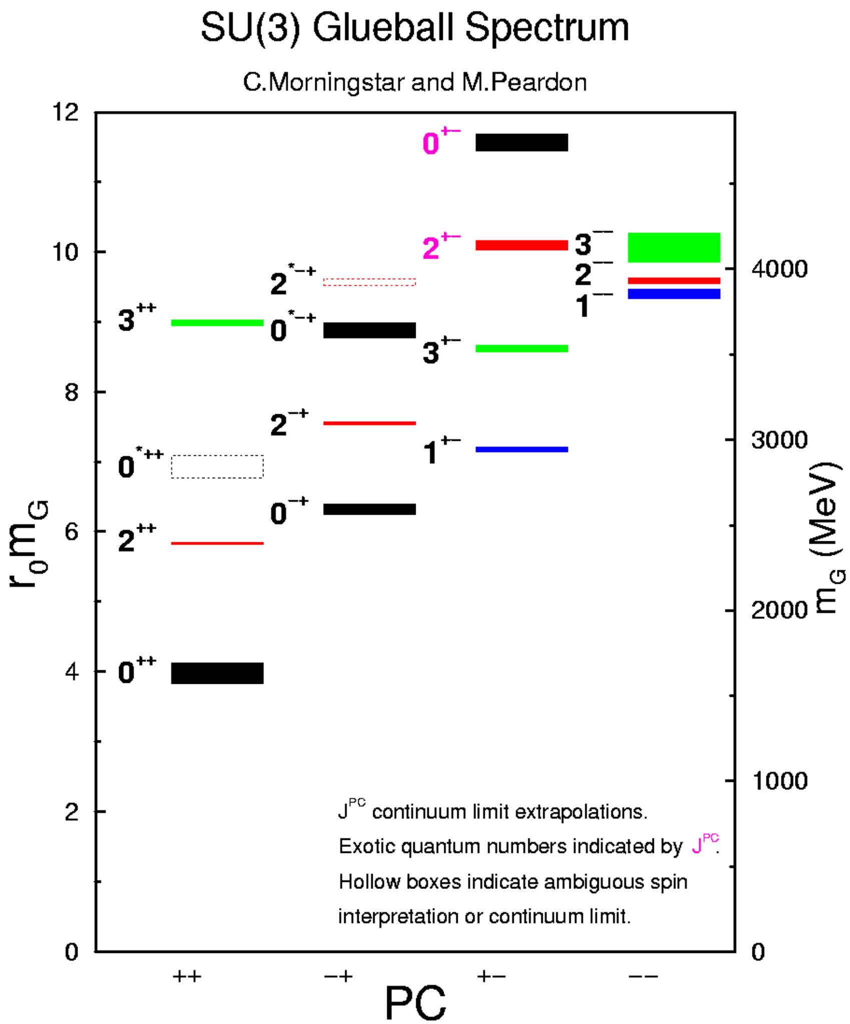
- The Bag Model
- Constituent Glue Models
- QCD Sum Rules
- The Flux tube model
- Lattice QCD (not a model – a real calculation)

Glueballs:

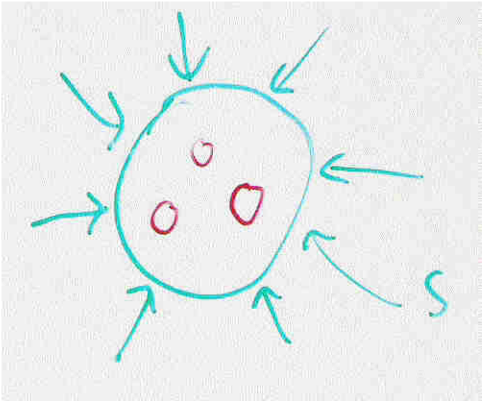
- Need to unambiguously observe glueballs and measure their properties

- This will test QCD

- But deeper than this it builds up confidence that we really can do nonperturbative field theory calculations



The Bag Model



Quarks obey free Dirac equation:

$$(\bar{p} - m)\psi = 0 \text{ inside S}$$

$$\psi = 0 \text{ outside S}$$

+ no colour current through the bag surface

Quarks in $1S_{1/2}$, $1P_{1/2}$, $1P_{3/2}$ eigenmodes:

Lowest state: $(1S_{1/2})^2 \Longrightarrow J^P = 0^-, 1^-$

Excited state $(1S_{1/2})\,(1P_{1/2}) \Longrightarrow J^P = 0^+, 1^+$

Gluons obey the free Helmholtz equation:

$$(\nabla^2 + \omega^2)\vec{A}^a = 0 \text{ inside S}$$
$$\vec{A}^a = 0 \text{ outside S}$$
$$\text{and } \eta_\mu F^a_{\mu\nu}|_s = 0$$

T solutions are the TE and TM cavity resonator modes:

$$\text{TE } J^{PC} = 1^{+-}$$
$$\text{TM } J^{PC} = 1^{--}$$

In addition there are contributions from gluon exchange

Uncertainties: Bag pressure ±30%
Quark and Gluon self energies ±30%
Value of α_s

Hybrids:

$$(q\bar{q})_8 \times g_8 = (q\bar{q}g)_1 + \ldots$$

Lowest hybrid meson multiplet constructed:

$$q(J^P = \tfrac{1}{2}^+) \times \bar{q}(J^P = \tfrac{1}{2}^+) \times g(1^{+-}) = (q\bar{q}g)$$
$$(0^-,\ 1^-) \times 1^+(TE) = 2^{-+},\ 1^{-+},\ 1^{--},\ 0^{-+}$$

- Spurious CofM degree of freedom
- What about decays?

Lattice QCD

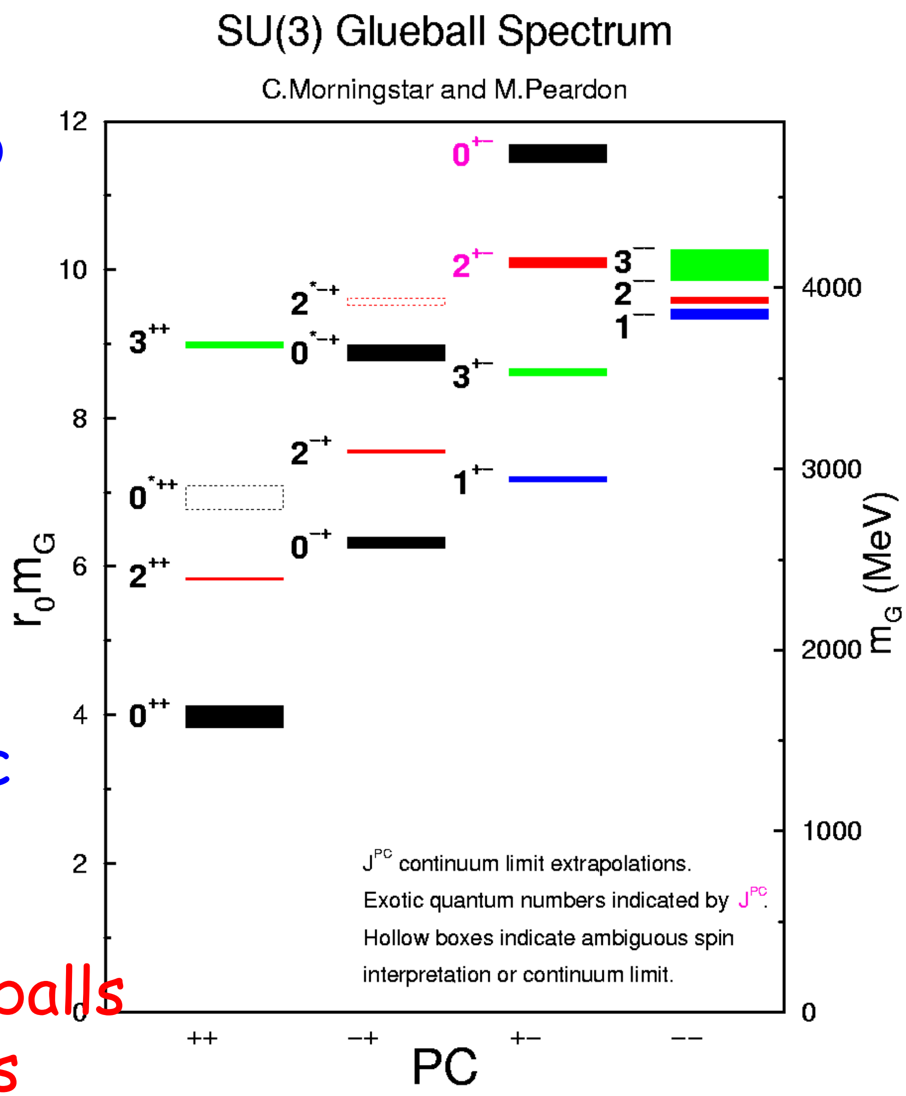
Mass predictions by Lattice QCD are fairly robust.

Lowest mass glueballs have conventional quantum numbers:

$M_{0}^{++} \sim 1.6$ GeV
$M_{2}^{++} \sim 2.3$ GeV
$M_{0}^{-+} \sim 2.5$ GeV

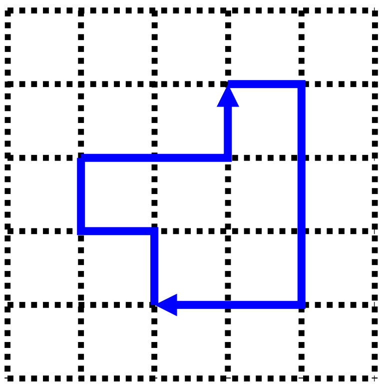
Lowest lying glueballs with exotic quantum numbers 0^{+-}, 2^{+-}, 1^{-+} are much higher in mass

- Difficult to produce exotic glueballs
- Difficult to disentangle glueballs with conventional Q#'s from dense background of conventional states



Flux Tube Model

Glueballs



$M(0^{++})=1.52$ GeV
$M(1^{+-})=2.25$ GeV
$M(0^{++})=2.75$ GeV
$M(0^{+-})=2.79$ GeV
$M(0^{--})=2.79$ GeV
$M(2^{++})=2.84$ GeV
$M(2^{+-})=2.84$ GeV

Model	0^{++}	$(0^{++})'$	0^{-+}	2^{++}	$(2^{++})'$	2^{-+}
lattice (anisotropic)	1.63(6)(8)			2.40(1)(12)	3.32(2)(16)	
lattice (UKQCD)	1.55(5)			2.27(10)		
lattice (GF11)	1.74(7)			2.36(13)		
lattice (Teper)	1.57(9)	2.87(34)	2.16(27)	2.22(12)		3.06(26)
lattice (SESAM)	1.66(5)			2.32(25)		
QCDSR (SVZ)	∼1.2		2-2.5	∼1.2		
QCDSR (Narison)	1.5(2)		2.05(20)	2.0(1)		
bag (MIT)	∼1		∼1.2	∼1		∼1.2
bag (BCM)	∼1		∼1.5	∼1.5		∼2.1
flux tube	1.52	2.75	2.79	2.84		2.84
const glue (Barnes)	∼1.5	∼2.1	∼1.5	∼1.8	∼2.1	∼2.1
const glue (Cornwall+Soni)[a]	1.5		1.76	2.08		
const glue (NCSU)	1.60	2.64	2.03	2.05	2.83	2.82

Glueball Properties:

Expect glueball decays to have flavour symmetric couplings to final state hadrons:

$$\frac{\Gamma(G \to \pi\pi : K\bar{K} : \eta\eta : \eta\eta' : \eta'\eta')}{\text{Phase Space}} = 3:4:1:0:1$$

But situation complicated by mixing with

$$q\bar{q} \text{ and } q\bar{q}q\bar{q}$$

Physical states are linear combinations:

$$|f_0\rangle = \alpha|n\bar{n}\rangle + \beta|s\bar{s}\rangle + \gamma|G\rangle + \delta|q\bar{q}q\bar{q}\rangle$$

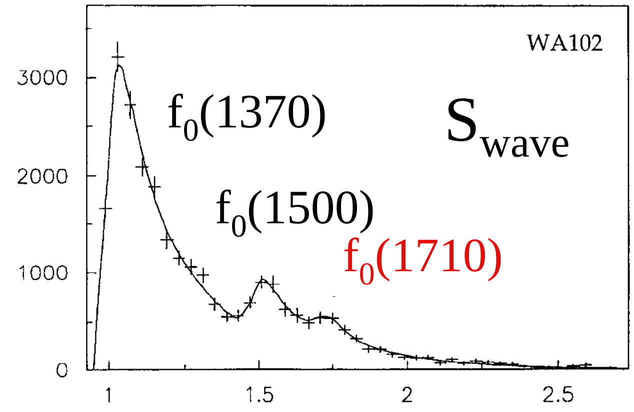
Will shift unquenched glueball mass and distort naïve couplings

Close & Kirk, PL B483, 345 (2000); Eur. Phys. J. C21, 531 (2001)

Meson properties can be used to extract the mixings and understand the underlying dynamics

pp -> p_s [KK, ππ] p_f @ 450 GeV

$$\left.\begin{matrix} f_0(1370) \\ f_0(1500) \\ f_0(1710) \end{matrix}\right\} \frac{K\bar{K}}{\pi\pi} \left\{\begin{matrix} <1 & (0.5 \pm 0.2) \\ <<1 & (0.3 \pm 0.1) \\ >>1 & (5.5 \pm 0.8) \end{matrix}\right.$$



Using decay information Close and Kirk get:

$$|f_0(1370)\rangle = -0.79|n\bar{n}\rangle - 0.13|s\bar{s}\rangle + 0.60|G\rangle$$

$$|f_0(1500)\rangle = -0.62|n\bar{n}\rangle + 0.37|s\bar{s}\rangle - 0.69|G\rangle$$

$$|f_0(1710)\rangle = +0.14|n\bar{n}\rangle + 0.91|s\bar{s}\rangle + 0.39|G\rangle$$

The point is not the details of the mixing but that mixing is an important consideration in the phenomenology

C. Amsler PL B541 (2002) 22

$$|\, f\,\rangle = \cos\alpha\,|\, n\bar{n}\,\rangle - \sin\alpha\,|\, s\bar{s}\,\rangle$$

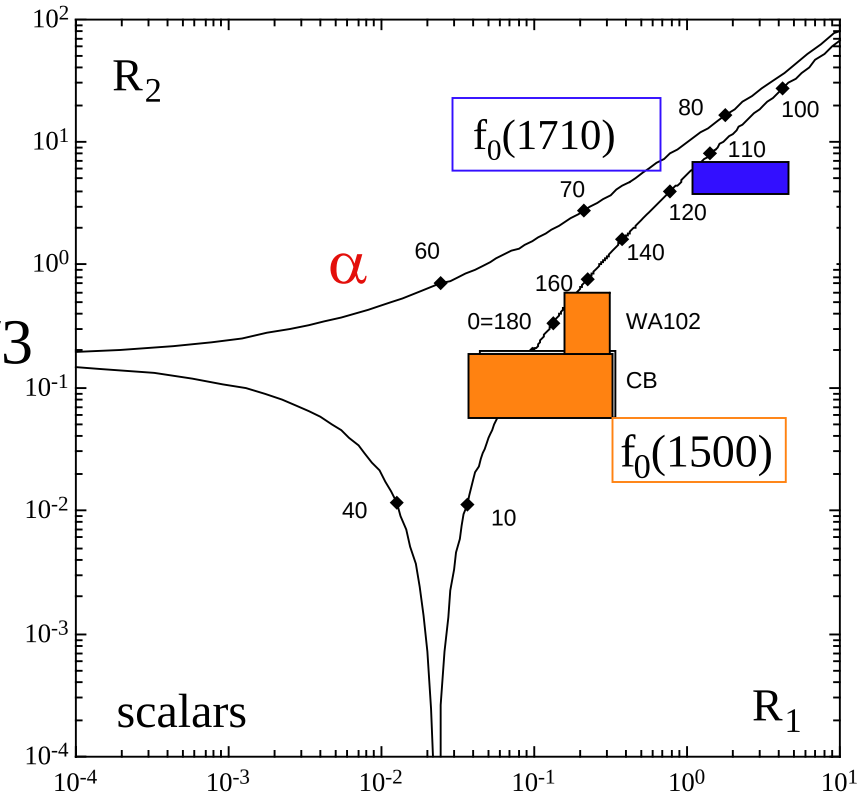
$$R_1 = \frac{\gamma^2(\eta\eta)}{\gamma^2(\pi\pi)}$$

$$R_2 = \frac{\gamma^2(K\bar{K})}{\gamma^2(\pi\pi)}$$

as a function of α

works perfectly for 2^{++} mesons:
$\alpha = 82^{o}$, as from mass formula

1/3



Assuming $q\bar{q}$:

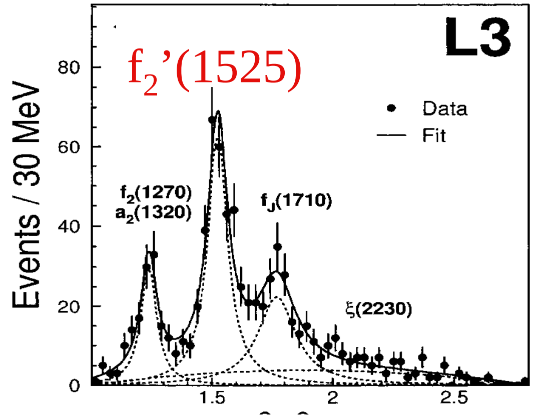
$f_0(1500)$ is $|\, n\bar{n}\,\rangle$ $\quad -10^{o} < \alpha < 5^{o}$

$f_0(1700)$ is dominantly $|\, s\bar{s}\,\rangle$

$\gamma\gamma$ couplings is a very sensitive probe of $q\bar{q}$ content

$\gamma\gamma \to K_S K_S$

(Acciarri 01,Braccini 01)



m($K_S K_S$)
[GeV]

no $f_0(1500)$: -/-> KK (?)

An important test of glue content is comparing the gluon rich channel $J/\Psi \to \gamma X$ to $\gamma\gamma$ couplings

$$S = \frac{\Gamma(J/\psi \to \gamma X)}{PS(J/\psi \to \gamma X)} \times \frac{PS(\gamma\gamma \to X)}{PS(\gamma\gamma \to X)}$$

large Stickiness reflects enhanced glue content

Production of Glueballs:

1. $J/\psi \to \gamma X$
2. $p\bar{p}$ annihilation
3. $pp \to p_f (G) p_s$ central production (Donskov)

•In central production diffractive process via "*gluonic pomeron exchange*"

•Expect competition with $q\bar{q}$ production

•But kinematic filter discovered which appears to suppress established $q\bar{q}$ states when in P-wave or higher wave

Central Production:

$$pp \rightarrow p_f\,(G)\,p_s$$

- p_S and p_f represent the slowest and fastest particles
- believe to be dominated by double *Pomeron* exchange
- *Pomeron* believed to have large gluonic content
- Folklore assumed that Pomeron is 0^{++} with flat distribution
- But distributions not flat
- Modelled with J=1 exchange particle:
  - Pomeron transforms as a non-conserved vector current
- Data from WA102 appears to support this hypothesis

Kinematic filter seems to suppress established $q\bar{q}$ when they are in P and higher waves Close & Kirk PL B397, 333 (1997)

The pattern of resonances depends on the vector difference of the transverse momentum recoil of the final state protons

$$dP_T = \left| \vec{k}_{T_1} - \vec{k}_{T_2} \right|$$

for

- dP_T large well established $q\bar{q}$ states are prominent
- dP_T small, established $q\bar{q}$ states are suppressed while $f_0(1500)$, $f_0(1710)$, $f_0(980)$ survive

ϕ, the angle between k_T vectors

Close Kirk & Schuler give a good account of the data modeling Pomeron as Vector exchange particle:

0^{-+} - parity requires the vector pomeron
to be transversely polarized; peaks at 90^o
1^{++} - one transverse the other longitudinal; peaks at 180^o
2^{-+} - similar to 0^{-+} case; peaks at 0^o
(helicity 2 suppressed by Bose statistics)
2^{++} - established states peak at 180^o while $f_2(1950)$ at 0^o
0^{++} - peaks at 0^o for some states while others are spread out:

- $f_0(1500)$, $f_0(1710)$, $f_0(980)$ peak at small ϕ
- $f_0(1370)$ peaks at large ϕ

Fact that $f_0(1370)$ and $f_0(1500)$ have different ϕ dependence Indicates not just J dependent phenomena

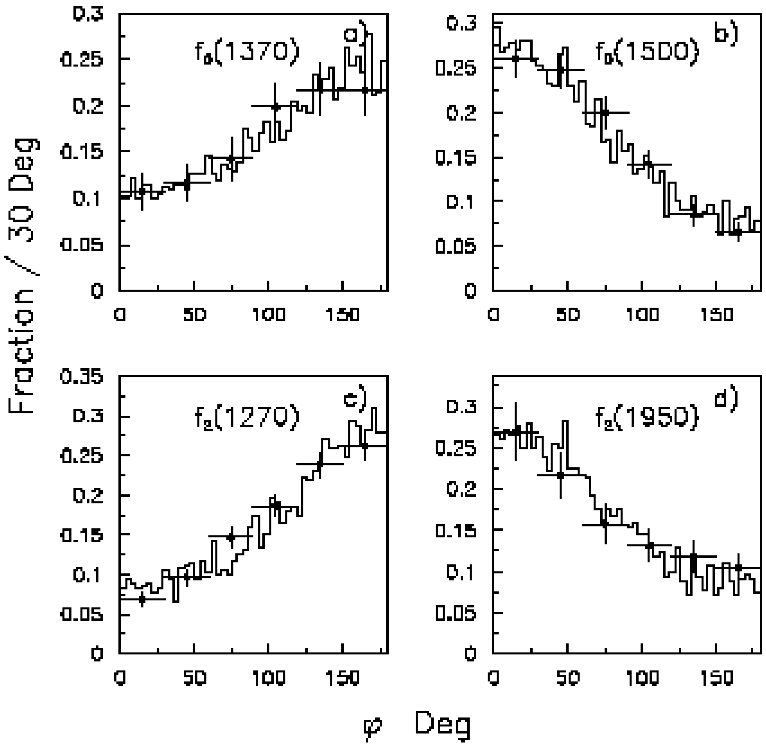
Close, Kirk, & Schuler PL B477, 13 (2000); Close & Schuler PLB 458, 127 (1999); PLB 464, 279 (1999)

0^{++}, 2^{++} expect both TT & LL contributions

$$\frac{d\sigma}{d\phi} \sim \left[1 + \frac{\sqrt{t_1 t_2}}{\mu^2} \frac{a_T}{a_L} \cos\phi \right]^2$$

described by varying $\mu^2 a_L / a_T$

= -0.5 GeV^2 for $f_0(1370)$
= +0.7 GeV^2 for $f_0(1500)$
= -0.4 GeV^2 for $f_2(1270)$
= +0.7 GeV^2 for $f_0(1950)$



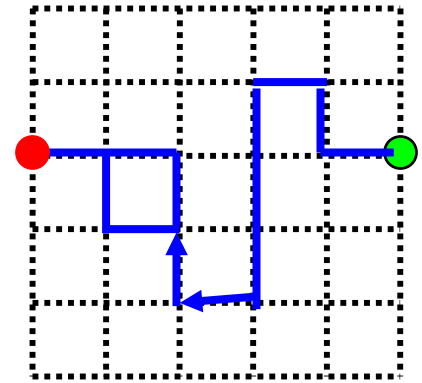
Close, Kirk, & Schuler PL B477, 13 (2000)

ϕ distributions fitted with only 1 parameter

Hybrid Mesons:

Hybrid mesons are defined as those in which the gluonic component is non-trivial

Hybrids



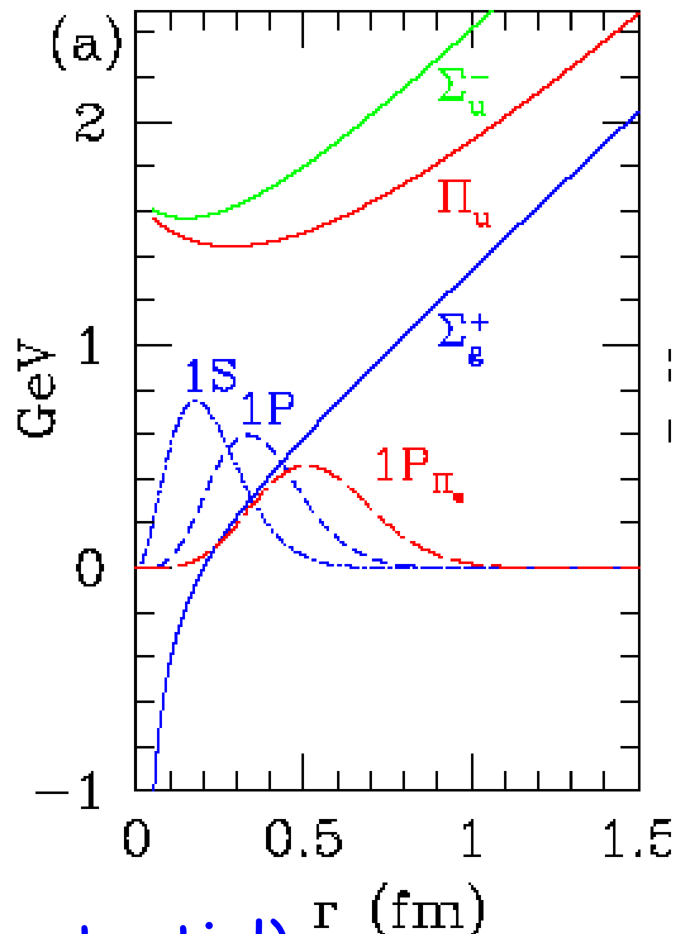
Two types of hybrids:

- **Vibrational hybrids**
- **Topological hybrids**

- Quarks move in effective potentials of adiabatically varying state of flux tubes
- A given *adiabatic surface* corresponds to various string topologies and excitations
- In Flux-Tube model the lowest excited adiabatic surface corresponds to transverse excitations

Hybrids: Lattice QCD

- Expect that can treat heavy quark mesons like a diatomic molecule
  - Slow moving heavy quarks
  - Fast moving gluons and sea quarks
- Excited states have non-trivial representation of the flux tube symmetry
- Calculate energy levels of fast degrees of freedom as a function of QQ separation
- Levels define an adiabatic surface (or potential)
- Describe heavy quarks in leading Born-Oppenheimer approximation by Schrodinger eqn using each of these potentials



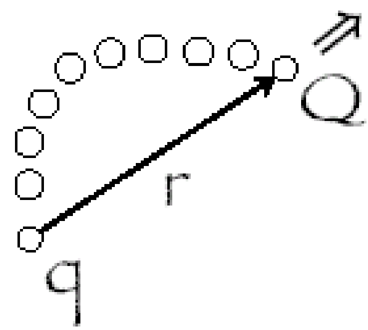
Label by:

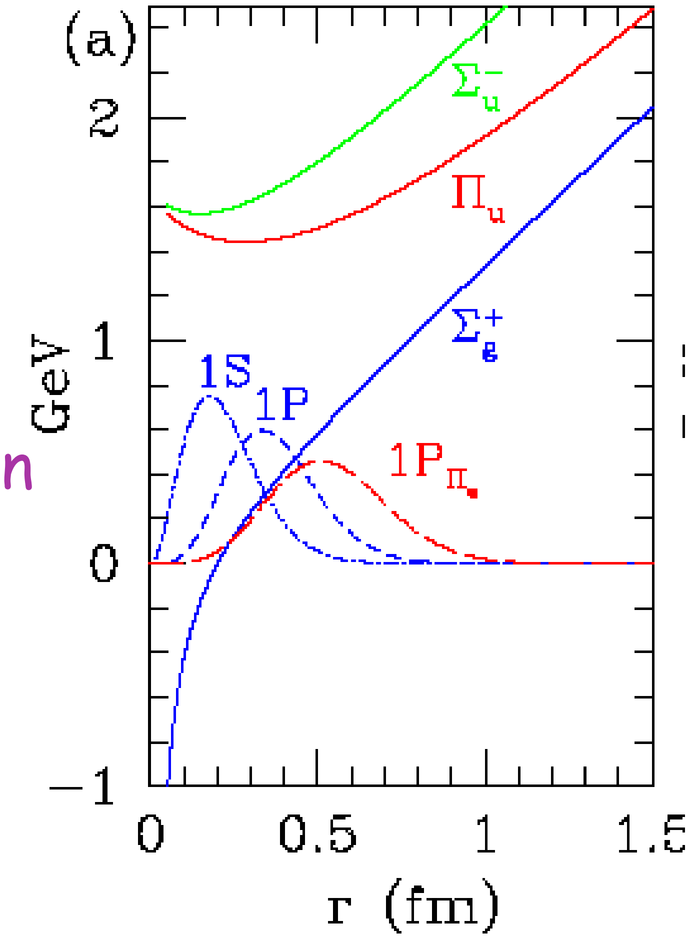
- Magnitude of Λ of the projection of the total angular mometum of the gluon field onto the molecular axis
- $\eta=\pm 1$ the symmetry under charge conjugation combined with spatial inversion about the midpoint between Q and Q

$\Lambda=0, 1, 2$ .. Σ, Π, Δ

g even

o odd

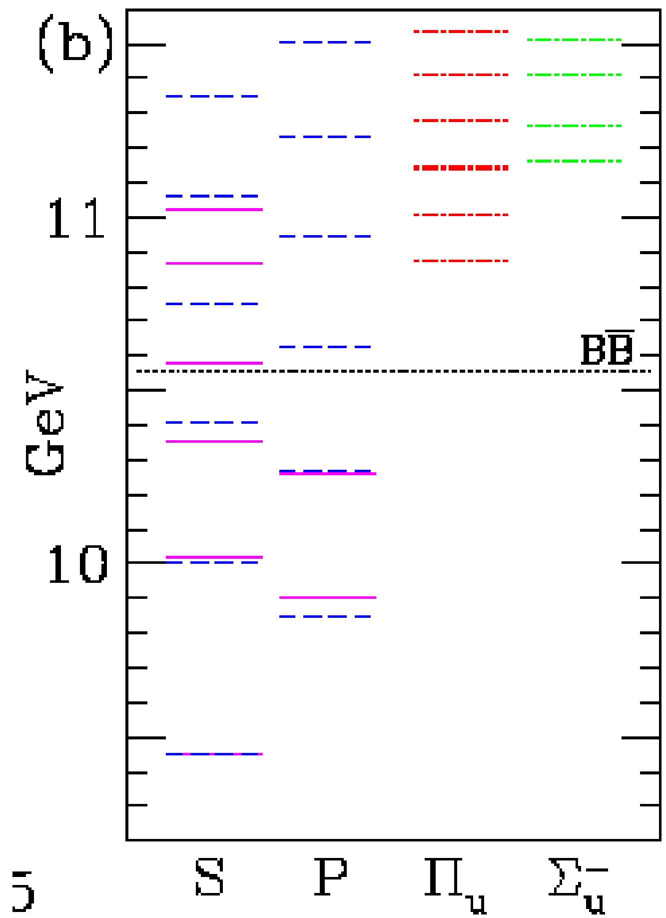




$\pm$ superscript for Σ states for odd or even symmetry under a reflection in a plane containing the molecular axis

- Calculate energies using the adiabatic potentials

- For light quark hybrids also calculate masses directly



•For light quark sector calculate masses directly
•Limited to masses of lightest exotic states

$I = 1$

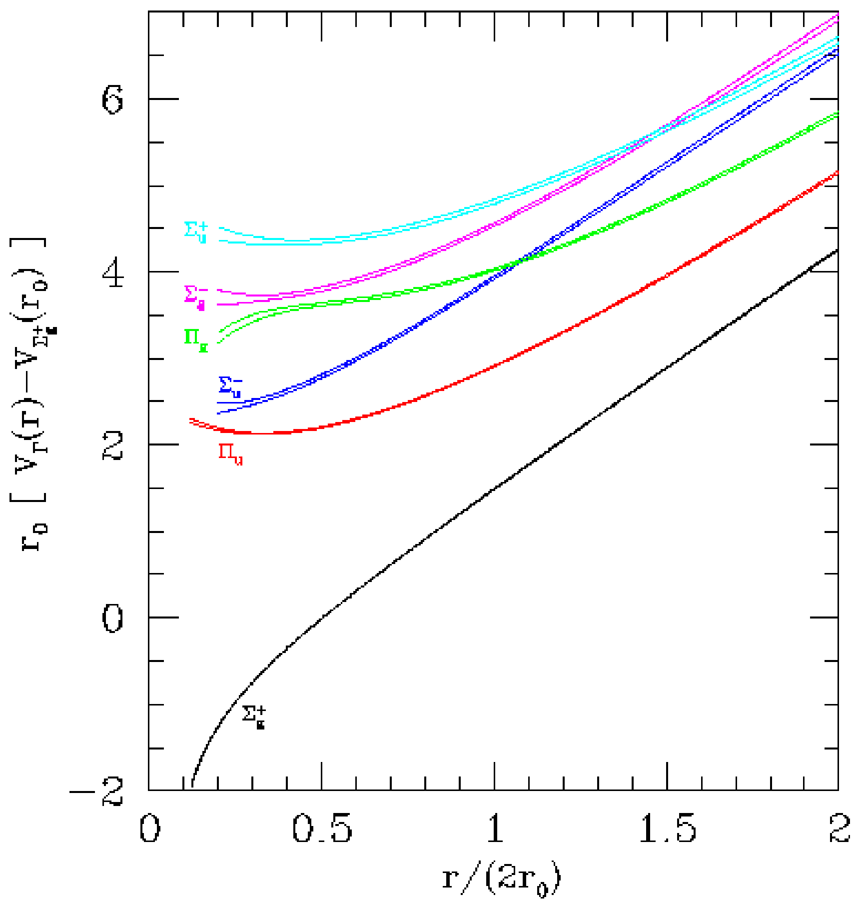
1^{-+}

date	ref.	mass/MeV
1996	Lacock:1996vy	1880(200)
1996	Bernard:1997ib	1970(90)(300)
1998	Lacock:1998be	1900(200)
1998	McNeile:1998cp	2110(100)
2002	Luo:2002rz	2013(26)(71)
2002	Bernard:2002rz	2033(70)
2002	Bernard:2002rz	1854(65)

- Need to map out the higher adiabatic surfaces to test our understanding of "Soft QCD"

- Not enough to discover one meson with exotic quantum numbers

- Need to find enough excited states to map out the excited surfaces



Juge, Kuti, and Morningstar,
Nucl. Phys. (Proc. Suppl.) **63A-C**, 326 (1998)

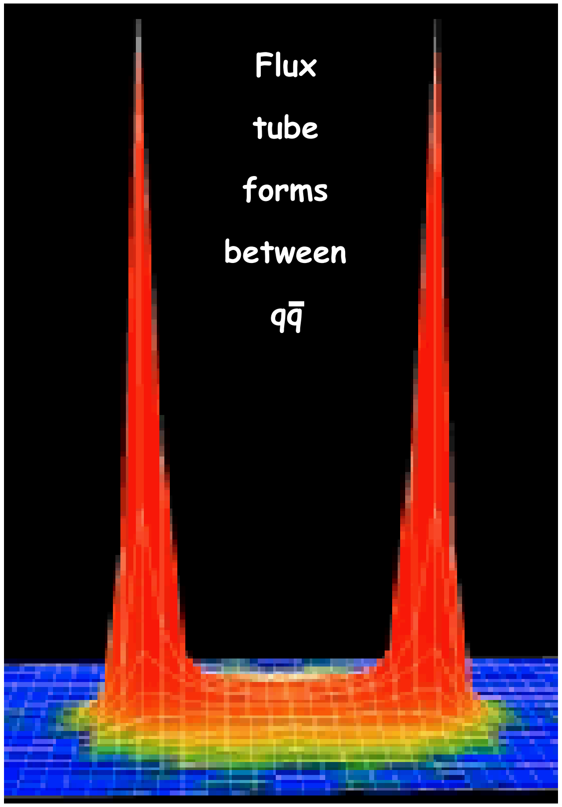
Flux Tube Model

Need model to calculate hybrid properties:

Flux tube model is based on the strong coupling Hamiltonian lattice QCD

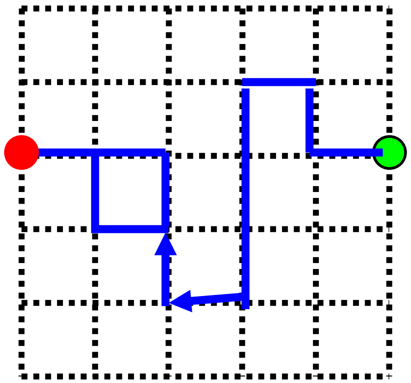
- Based on quark and flux-tube degrees of freedom
- Provides a unified framework of:
  - ***conventional hadrons,***
  - ***multiquark states,***
  - ***hybrids***
  - ***glueballs***

Expect strong mixing between non-spin exotic hybrids and conventional mesons



Lattice calculations supports the flux tube picture:

Hybrids

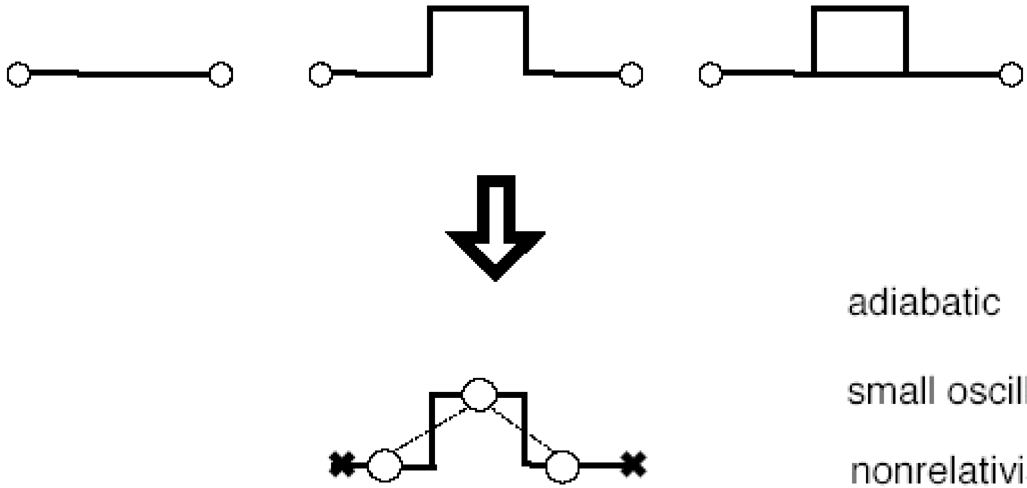


- Flux tube model based on the strong coupling limit of QCD
- Eigenstates consist of quarks on lattice sites connected by paths of flux links

Two types of hybrids:

- **Vibrational hybrids**
- **Topological hybrids**

- Quarks move in effective potentials of adiabatically varying state of flux tubes
- A given *adiabatic surface* corresponds to various string topologies and excitations
- Conventional hadrons correspond to gluon fields in ground states
- Hybrids correspond to excitations of quantum strings
- Lowest excited adiabatic surface corresponds to transverse excitations

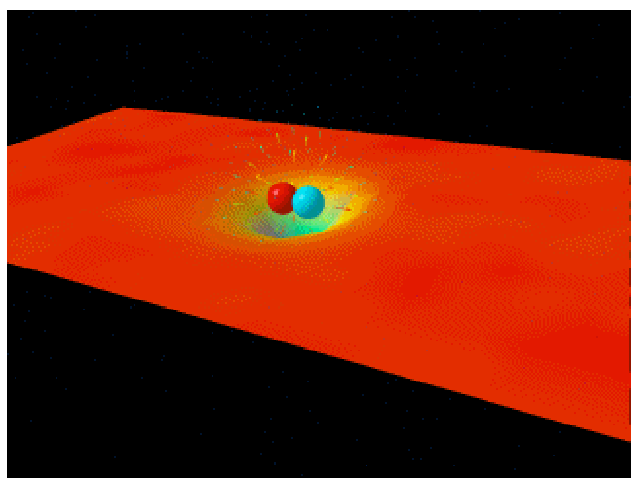


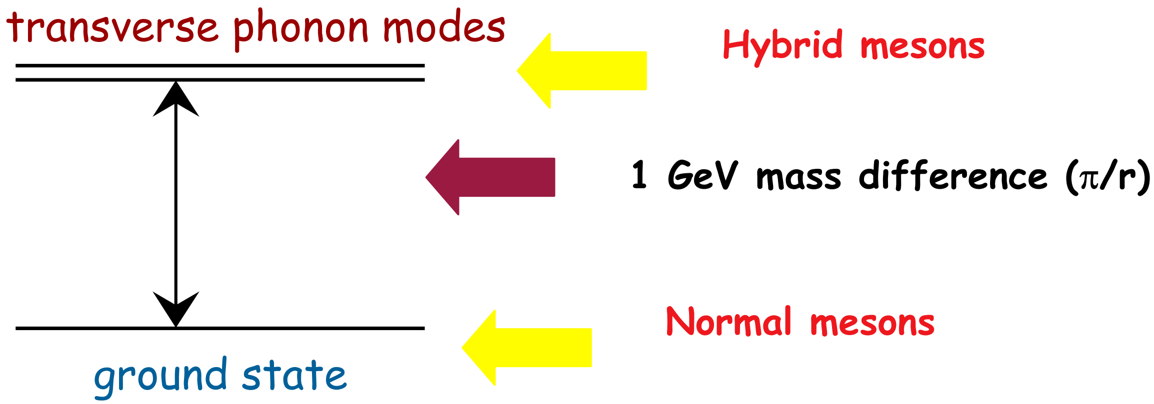
adiabatic

small oscillation

nonrelativistic beads

$m_b = b\ a$





Lowest mass hybrids at 1.9 GeV

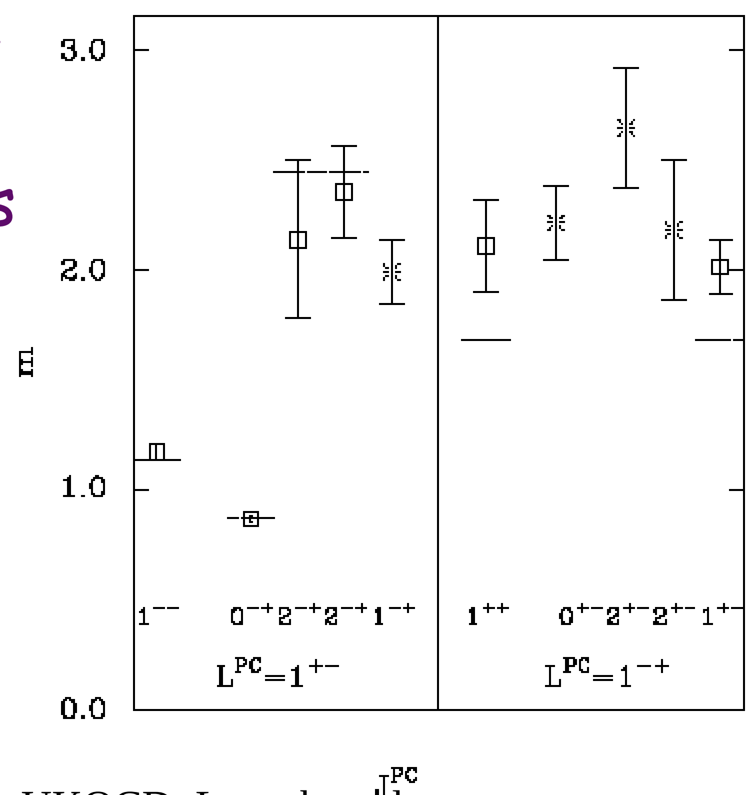
Doubly degenerate:

J^{PC} = 0^{+-} 0^{-+} 1^{+-} 1^{-+}
2^{+-} 2^{-+} 1^{++} 1^{--}

Expect degeneracies to be broken by different excitation energies of flux tube modes, spin dependence, mixings with $q\bar{q}$

Lattice results generally consistent with these predictions

$M(1^{-+}) \sim 1.9$ GeV
$M(0^{+-}) \sim 2.1$ GeV
$M(2^{+-}) \sim 2.1$ GeV



UKQCD; Lacock et al,
PR D54, 6997 (1996); PL B401, 308 (1997)

Model	$u\bar{u}$	$s\bar{s}$	$c\bar{c}$	$b\bar{b}$
MIT Bag	1.3-1.8		$\sim$ 3.9	10.5
HHKR adiabatic bag			3.9	10.49(20)
QCD Sum Rules	2.1-2.5		4.1-5.3	10.6-11.2
Flux Tube	1.8-2.0		4.2-4.5	10.8-11.1
BCS	1.8-1.9	2.1-2.2	4.1-4.2	
lattice (UKQCD)		2.00(20)		
lattice (MILC)	$1.97(9)(30)^a$	2.17(8)(20)	4.39(8)(20)	
lattice (adiabatic)			4.2	10.8
lattice (adiabatic)				10.8
lattice (NRQCD)				11.10(16)

Decay Properties:

Restrict Discussion to J^{PC} Exotics:

$$\hat{\rho}_g \to [\pi\eta,\ \pi\eta',\ \pi\rho,\ K^*K,\ \eta\rho,\ldots]$$

$$\to [\pi b_1,\ \pi f_1,\ \eta a_1,\ KK_1,\ldots]$$

$$\hat{\omega}_g \to [K^*K,\ \pi\pi(1300),\ \eta\eta',\ldots]_P$$

$$\to [a_1\pi,\ \bar{K}K_1,\ \ldots]_S$$

$$\hat{K}_g \to [\pi K,\ \eta K,\ \phi K,\ \eta' K,\ldots]_P$$

$$\to [\pi K_1,\ Ka_1,\ \mathrm{Kb}_1,\ldots]_S$$

$$\hat{\phi}_g \to [K\bar{K}(1400),\ KK^*,\ \eta\eta',\ldots]_P$$

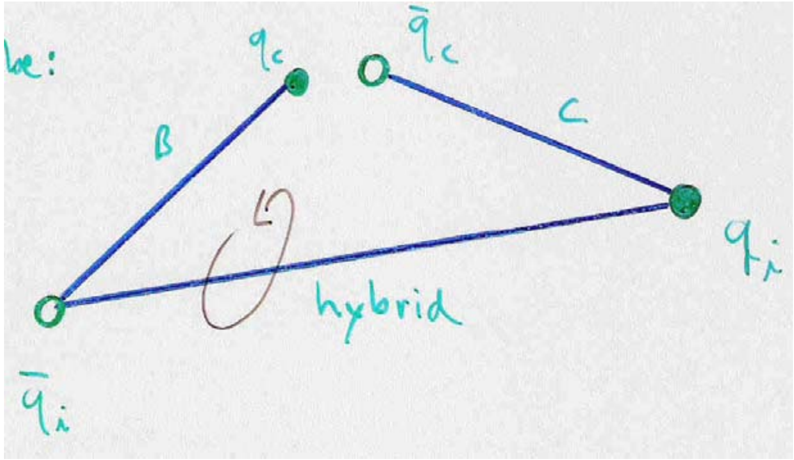
$$\to [\bar{K}K_1]_S$$

$$\to [\bar{K}K_1]_D$$

The highlighted decays uniquely signal 1^{-+} state

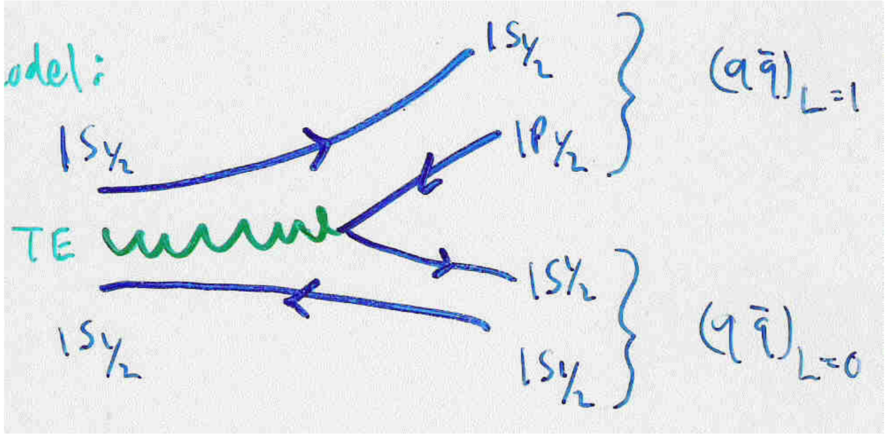
Decay Properties:

Flux Tube Model:



Expect stronger coupling to one s-wave and one p-wave final state meson

Bag Model:



Expect one excited meson and one ground state meson

<u>But</u> also possible that excited quark loses its angular Momentum to orbital ang. mom.

Decay Properties:

Decays need to preserve symmetries

A General Selection Rule:

To preserve symmetries of quark and colour fields about the quarks the Π_u hybrid must decay to Meson in a P-wave

e.g. cannot transfer angular momentum as relative angular momentum but appears as internal angular momentum

This appears to be a universal selection rule

For 1^{-+} exotic expect $\hat{\rho} \to b_1\pi,\ f_1\pi$ modes to dominate

- S-wave decays have large phase space so may be too broad to be seen
- Favoured final state contains broad P-wave meson
  - Eg $\omega_{g_1}^{-+} \rightarrow [a_1\pi]_S \quad (\Gamma \approx 100 \text{ MeV})$

    $\rightarrow [\pi(1300)\pi]_P \quad (\Gamma \approx 100 \text{ MeV})$

- Best bets (according to flux tube model)

$$\hat{\rho}_{g_1}^{-+} \rightarrow [\pi b_1]_S \qquad (\Gamma \approx 100 \text{ MeV})$$

$$\hat{\omega}_{g_2}^{+-} \rightarrow [\pi b_1]_P \qquad (\Gamma \approx 500 \text{ MeV})$$

$$\hat{\phi}_{g_2}^{+-} \rightarrow [KK^*]_P \qquad (\Gamma \approx 250 \text{ MeV})$$

For exotic hybrids:

Isgur, Kokoski and Paton, PRL, 54, 907
Close & Page, NP B443, 233 (1995)

A	B, C	L	Γ_1	Γ_2
$\pi 1^{-+}$	$b_1(1235)\pi$	S	100	100
		D	20	30
	$f_1(1285)\pi$	S	30	30
		D	20	20
$\omega 1^{-+}$	$a_1(1260)\pi$	S	90	100
		D	60	70
	$K_1(1400)K$	S	100	100
$\pi 2^{+-}$	$a_2(1320)\pi$	P	350	450
	$a_1(1260)\pi$	P	100	100
	$h_1(1170)\pi$	P	125	150

A	B, C	L	Γ_1	Γ_2
$\phi 1^{-+}$	$K_1(1270)K$	D	90	80
	$K_1(1400)K$	S	200	250
$\pi 0^{+-}$	$a_1(1260)\pi$	P	600	800
	$h_1(1170)\pi$	P	100	100
$\omega 0^{+-}$	$b_1(1235)\pi$	P	250	250
$\phi 0^{+-}$	$K_1(1270)K$	P	500	800
	$K_1(1400)K$	P	70	50
$\omega 2^{+-}$	$b_1(1235)\pi$	P	350	500
$\phi 2^{+-}$	$K_2^*(1430)K$	P	300	250
	$K_1(1400)K$	P	250	200

$\hat{a}_0, \hat{f}'_0$ too broad

$\hat{\omega}_1$ decays to $[a_1\pi]_S$

with $\Gamma \approx 100$ MeV

similarly for $\hat{\phi}_1$

Best bets:

$\hat{\rho}_1 \rightarrow [b_1\pi]_S, \; [f_1\pi]_S$

$\hat{f}_2 \rightarrow [b_1\pi]_P \quad (\Gamma \approx 350 \text{ MeV})$

$\hat{f}_2' \rightarrow [K_2^*\overline{K}]_P \quad (\Gamma \approx 300 \text{ MeV})$

$\rightarrow [K_1\overline{K}]_P \quad (\Gamma \approx 250 \text{ MeV})$

But there is variation in model predictions

For non exotic hybrids:

Close & Page, NP B443, 233 (1995); PR D56, 1584 (1997)

To distinguish non-exotic hybrids from conventional states need detailed predictions of properties:

$\pi(1800)$

TABLE III. Decay of quark model and hybrid $\pi(1800)$.

	Partial widths to final states					
State	$\pi\rho$	$\omega\rho$	$\rho(1465)\pi$	$f_0(1300)\pi$	$f_2\pi$	K^*K
$\pi_{3S}(1800)$	30	74	56	6	29	36
$\pi_H(1800)$	30	—	30	170	6	5

$\rho\omega$ can be used as discriminator between possibilities observed in $\pi f_0(1300)$

(but recent paper by Swanson and Szczepaniak [PR D56, 5692] predicts small $\rho\omega$ partial width)

ρ' and ω'

Close & Page, PR D56, 1584 (1997)
Barnes et al, PR D55, 4157 (1997)

Expect mixing: $|V\rangle = \alpha|2^3S_1\rangle + \beta|1^3D_1\rangle + \gamma|V_H\rangle$

	$\pi\pi$	$\omega\pi$	$\rho\eta$	$\rho\rho$	KK	K^*K	$h_1\pi$	$a_1\pi$	Total
$\rho_{2S}(1465)$	74	122	25	-	35	19	1	3	279
$\rho_{1D}(1700)$	48	35	16	14	36	26	124	134	435
$\rho_H(1500)$	0	5	1	0	0	0	0	140	$\approx$150

the πh_1 and πa_1 can discriminate between ρ_{2S}, ρ_{1D} and ρ_H or to disentangle the mixings

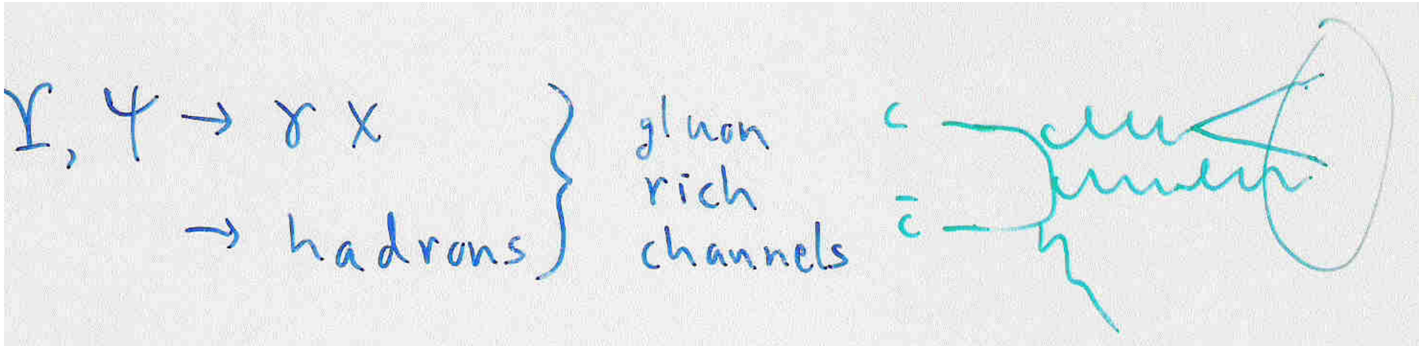
	$\rho\pi$	$\omega\eta$	KK	K^*K	$b_1\pi$	Total
$\omega_{2S}(1419)$	328	12	31	5	1	378
$\omega_{1D}(1649)$	101	13	35	21	371	542
$\omega_H(1500)$	20	1	0	0	0	$\approx$20

$\omega(1420) \to \pi b_1$ and $\omega(1600) \to \pi b_1$ are observed to be small so both unlikely to be pure 1^3D_1 state implying ω_H admixture

Production of Hybrids:

1. $J/\psi \rightarrow \gamma X$
2. $p\bar{p}$ annihilation
3. peripheral production (Dorofeev)
4. photoproduction (Moinester)

Radiative J/ψ Decay (CLEO-c/ BESIII)



$$J/\psi \to [\rho\rho_{g_1}^{-+}]$$

$$\to [\pi b_1,\ \pi f_1]_S$$

$$\to [\pi\eta,\ \pi\eta',\ \pi\rho,\ K^* K]_P$$

(suppressed in flux tube)

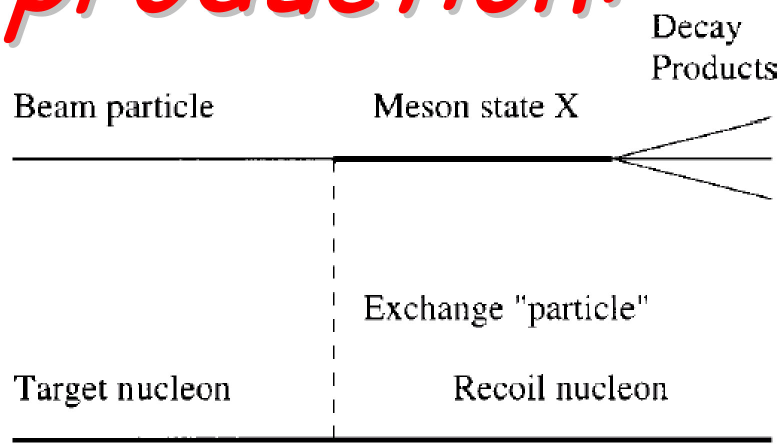
$$\to [\rho\phi_{g_1}^{-+}]$$

$$\to [\eta\eta',\ K^* K]_P$$

$$\to [\eta\omega_{g_2}^{+-}]$$

$$\to [\pi b_1]_P$$

Peripheral production:



Beam particle is excited and continuous to move forward exchanging momenta and quantum #'s with recoiling nucleus

eg: LASS, E852, BENKEI, VES, GAMS

Evidence for $\hat{\rho}(1600)$ (Dunnweber, Dorofeev)

Serpukhov: $\pi^- N \to (\pi^+\pi^-\pi^-)N$ 40 GeV / c π beam

in $\rho^0\pi^-$, $\pi\eta$ and πb_1

BNL E852: $\pi^- p \to \pi^-\pi^+\pi^- p$ at 18 GeV / c π beam

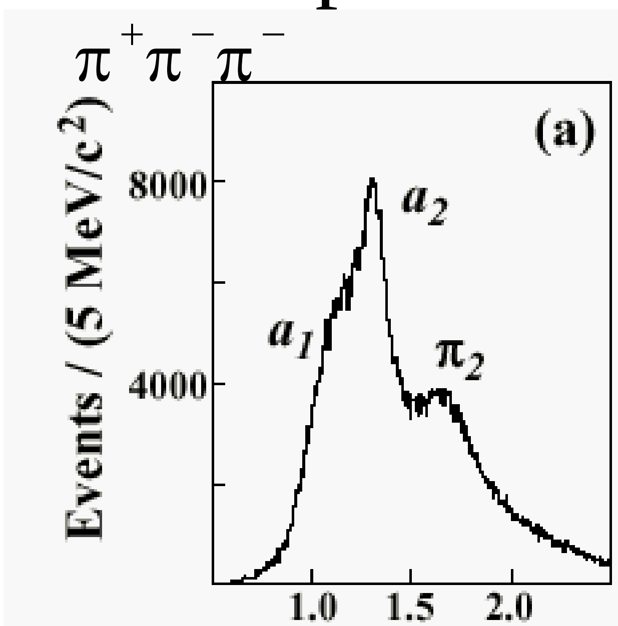
signal in $\pi f_1(1285)$

- No reason a priori to expect that any type of hadron is preferred over any other in this mechanism

- π exchange only provides access to natural parity states

- Advantage is high statistics

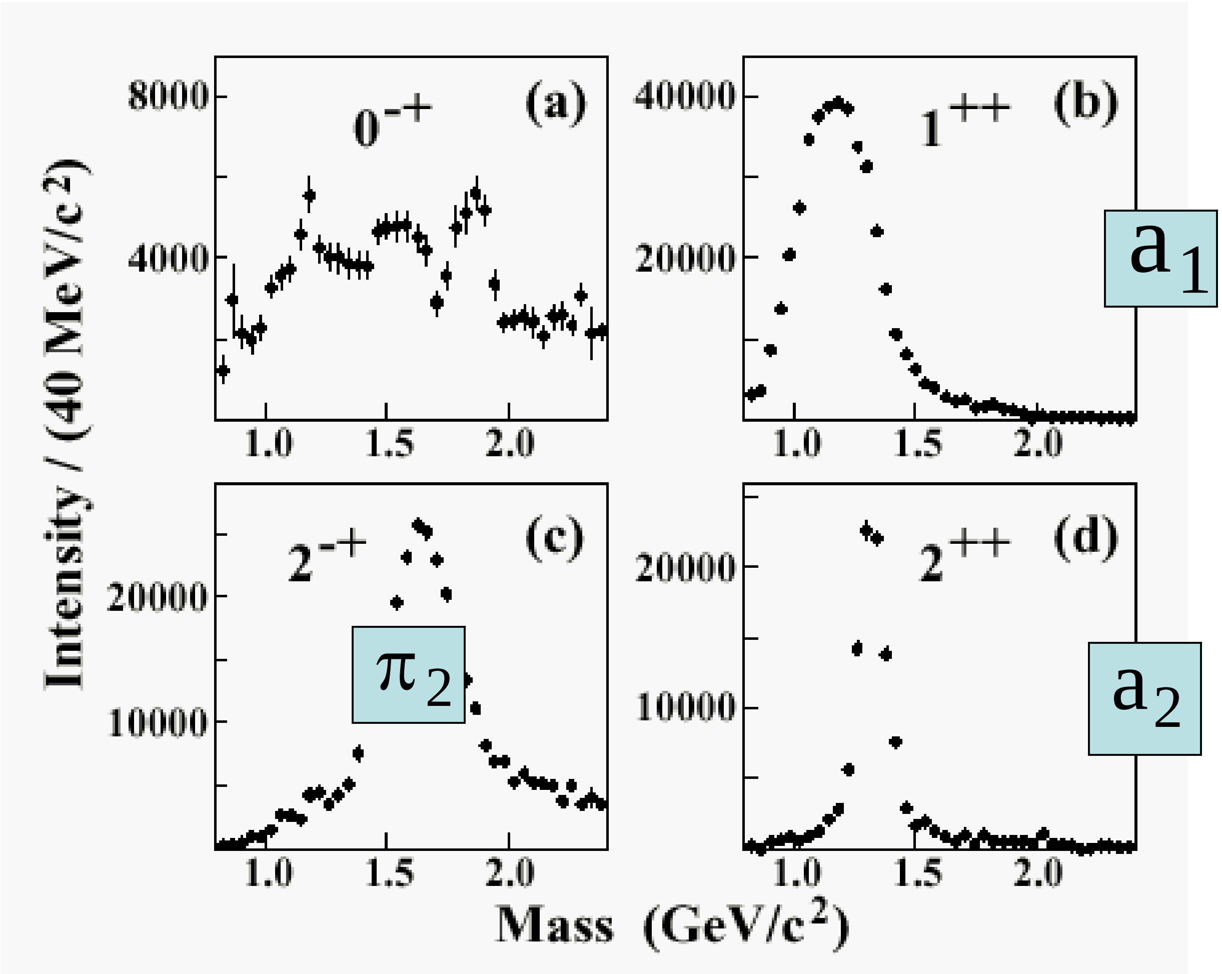
E852 Results: $\pi^- p \to \pi^+ \pi^- \pi^- p$ **At 18 GeV/c**



$M(\pi^+\pi^-\pi^-)$ $[GeV/c^2]$

to partial wave analysis

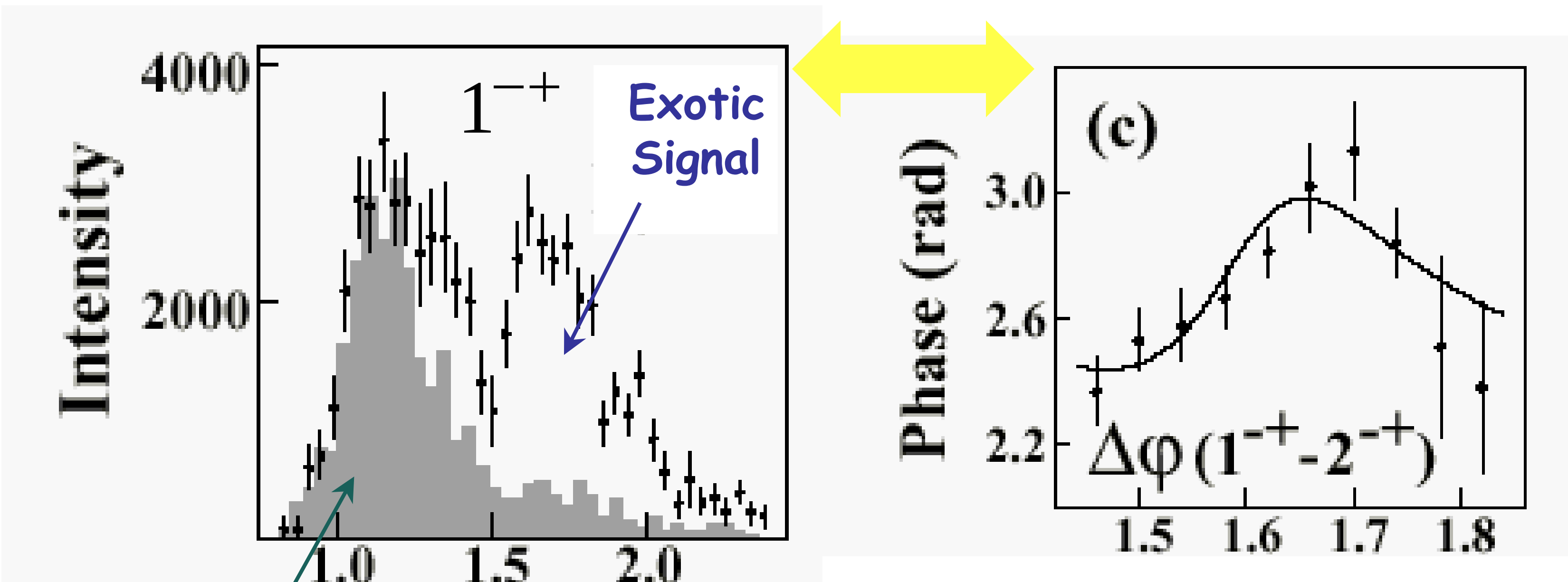
Results of Partial Wave Analysis



Benchmark resonances

An Exotic Signal in E852

Correlation of Phase & Intensity



$M(\pi^+\pi^-\pi^-)\ \left[\mathrm{GeV}/c^2\right]$

Leakage From Non-exotic Wave

due to imperfectly understood acceptance

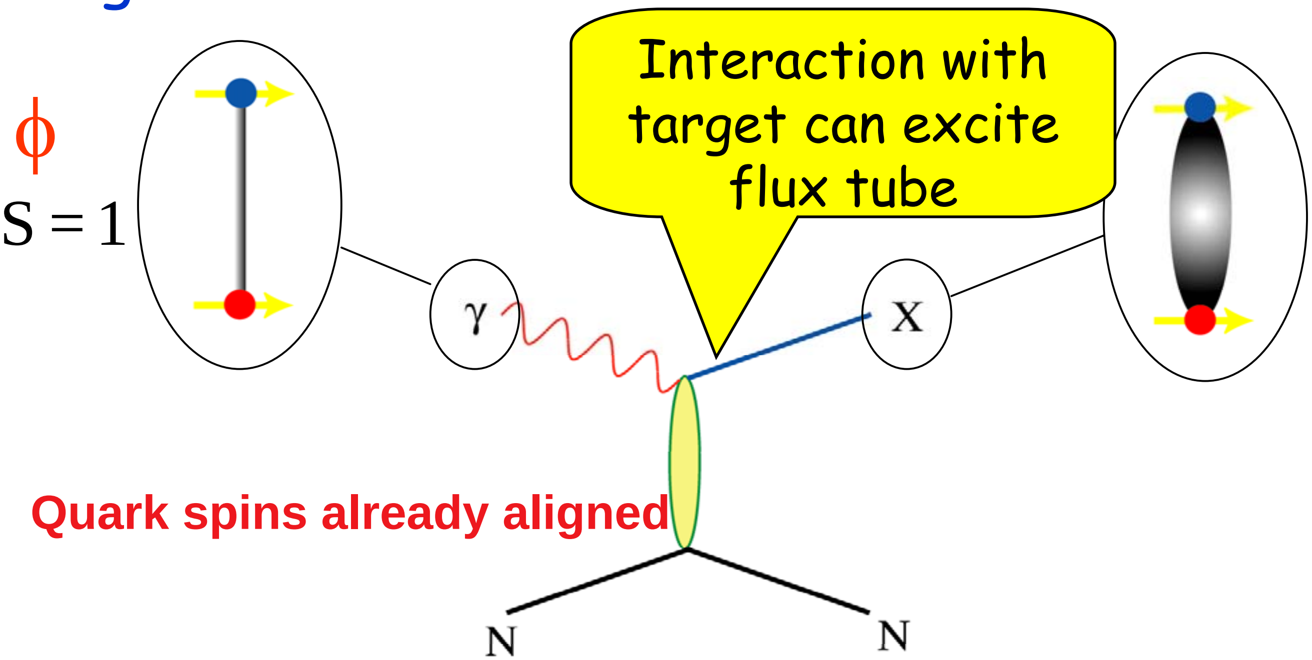
Photoproduction:

Qualitative alternative to hadronic peripheral production

- series of preferred excitations is likely to be different
- strong source of ss states

ρ, ω, φ

$q\bar{q}$ with S = 1



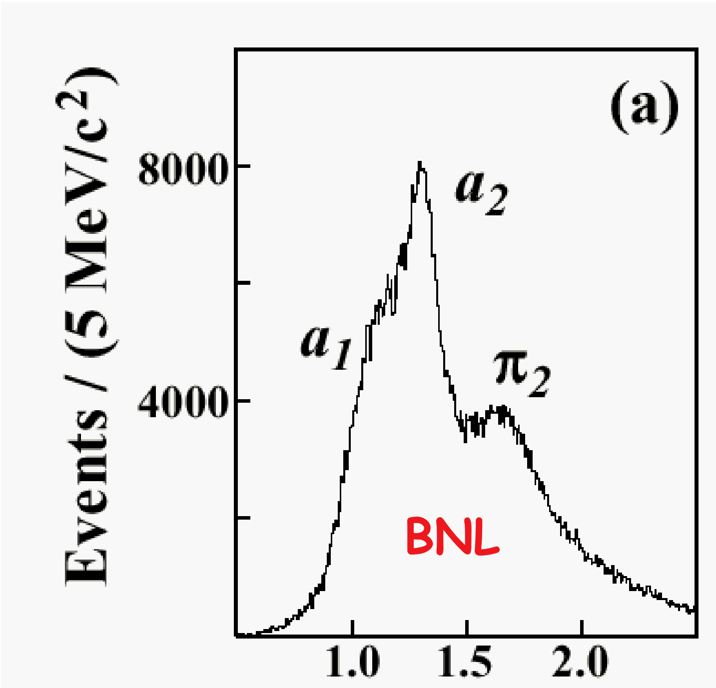
- Production of exotic hybrids is favoured: $J^{PC}=0^{+-}, 1^{-+}, 2^{+-}$
- *Almost no data is available*

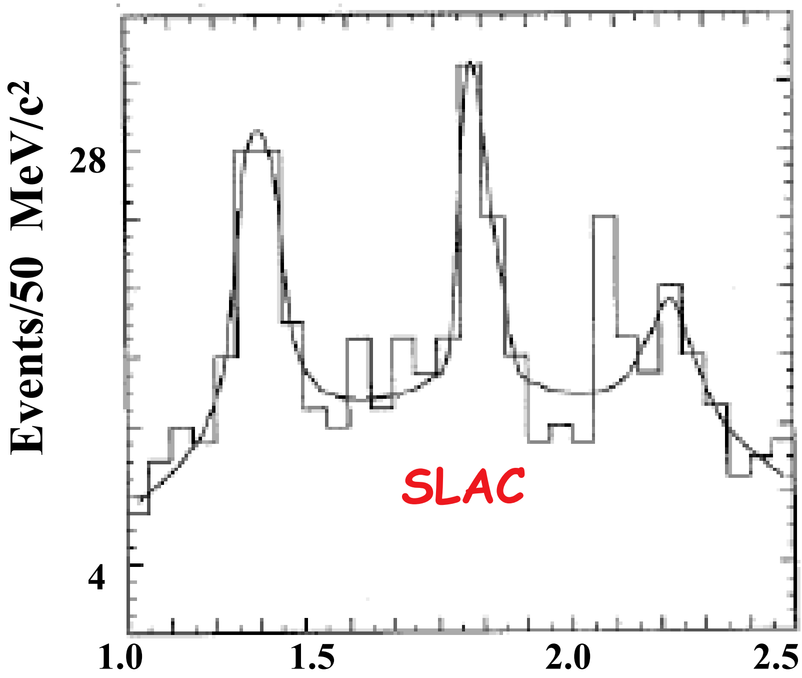
Compare πp and γp Data

Compare statistics and shapes

$\pi^- p \to \pi^+ \pi^- \pi^- p$ $\gamma p \to \pi^+ \pi^+ \pi^- n$

ca. 1998 **@ 18 GeV** **ca. 1993** **@ 19 GeV**





$M(3\pi)\ \left[\mathrm{GeV}/c^2\right]$

Summary

- The discovery and mapping out of the glueball and hybrid meson spectrum is a crucial test of QCD
- It will help validate Lattice QCD as an important computational tool for non-perturbative field theory
- It will take detailed studies to distinguish Glueball and Hybrid candidates from conventional $q\bar{q}$ states
- This will require extremely high statistics experiments
  - To measure meson properties
    - Partial widths
    - Production mechanisms
      - t-channel exchange
      - central production distributions

The XYZ's of cc:
Hints of Exotic New Mesons?

An exercise in hadron phenomenology

- Spectroscopy: Conventional and Hybrids

- New Charm States
  - D_{sJ}*(2317), D_{sJ}(2460), D_{sJ}(2630)
  - D_0*(2308), D_1'(2440),

- New Charmonium states
  - *X(3872), X(3943), Y(3943), Z(3931) and Y(4260)*

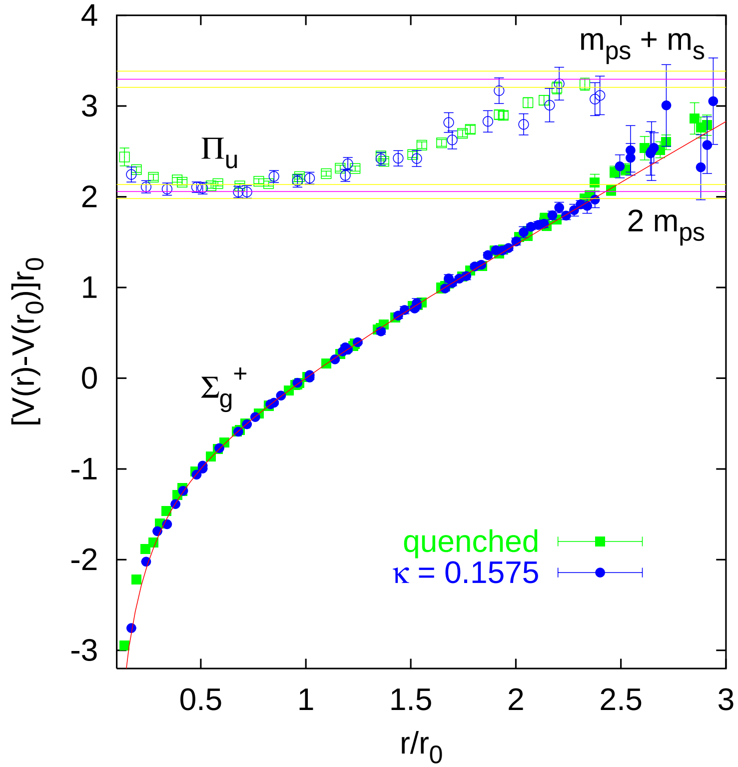
- Summary

Hybrids

Close and Godfrey PL B574, 210 (2003).

Bali: hep-ph/0010032

- Quarks move in adiabatic potentials
- Lowest excited adiabatic surface corresponds to transverse excitations
- Doubly degenerate lowest mass hybrids:
- J^{PC} = 0^{+-} 0^{-+} 1^{+-} 1^{-+} 2^{+-} 2^{-+} 1^{++} 1^{--}



T. BARNES, F. E. CLOSE, AND E. S. SWANSON PRD52, 5242 (1995).

TABLE I. Predicted 1^{-+} hybrid masses.

State	mass (GeV)	Model	Ref.
H_c	$\approx$ 3.9	Adiabatic bag model	[20]
	4.2–4.5	Flux tube model	[12–14]
	4.1–5.3	QCD sum rules (most after 1984)	[26–28]
	4.19(3) $\pm$ syst.	HQLGT	[23]

Hybrids Decays

Important decay modes:

1. $\psi_g \to D^{(*,**)}\overline{D}^{(*,**)}$

   hybrid decays to P-wave + S-wave mesons:
   - D(L=0)+D^{**}(L=1) should dominate
   - DD should not occur and DD^* have small widths

2. $\psi_g \to (c\bar{c})(gg) \to (c\bar{c}) + (\pi\pi, \eta, \ldots)$
   - Offers cleanest signature
   - IF total width small significant BR
     - $\psi_g(0^{+-}, 2^{+-}) \to J/\psi + (\pi\pi, \eta)$ and $\psi_g(1^{-+}) \to \eta_c + (\pi\pi, \eta)$
   - LGT (UKQCD) finds these decays to be large ~*O*(10's MeV)

   (shown for $\chi_b S$ where S is light scalar) [hep-lat/0201006]

$D_{sJ}(2317)$ & $D_{sJ}(2460)$

BABAR:

Phys.Rev.Lett. 90, 242001 (2003)

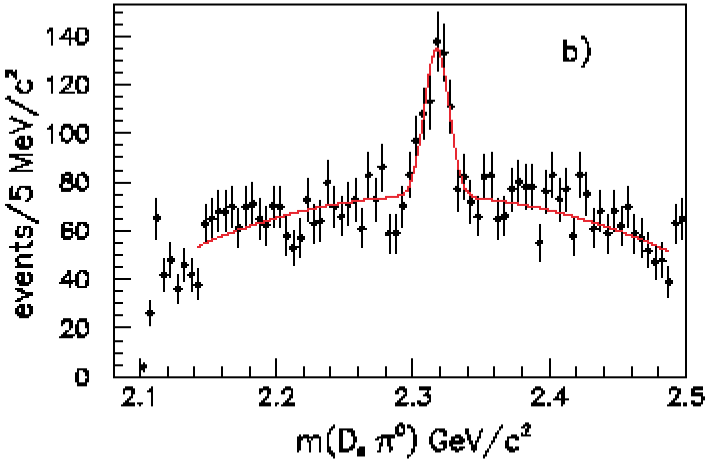


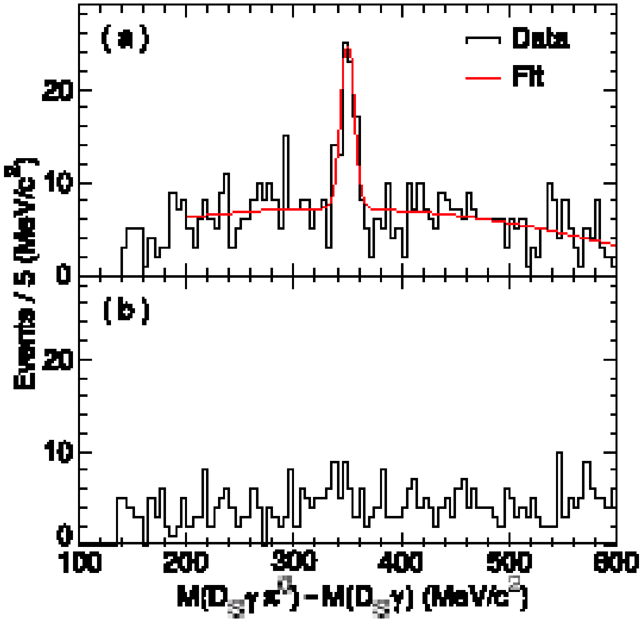
FIG. 2 (color online). The $D_s^+\pi^0$ mass distribution for (a) the decay $D_s^+ \to K^+K^-\pi^+$ and (b) the decay $D_s^+ \to K^+K^-\pi^+\pi^0$. The fits to the mass distributions as described in the text are indicated by the curves.

M=2316.8±0.4 MeV

Γ≤3.8 MeV

CLEO:

Phys.Rev. D68, 032002 (2003)

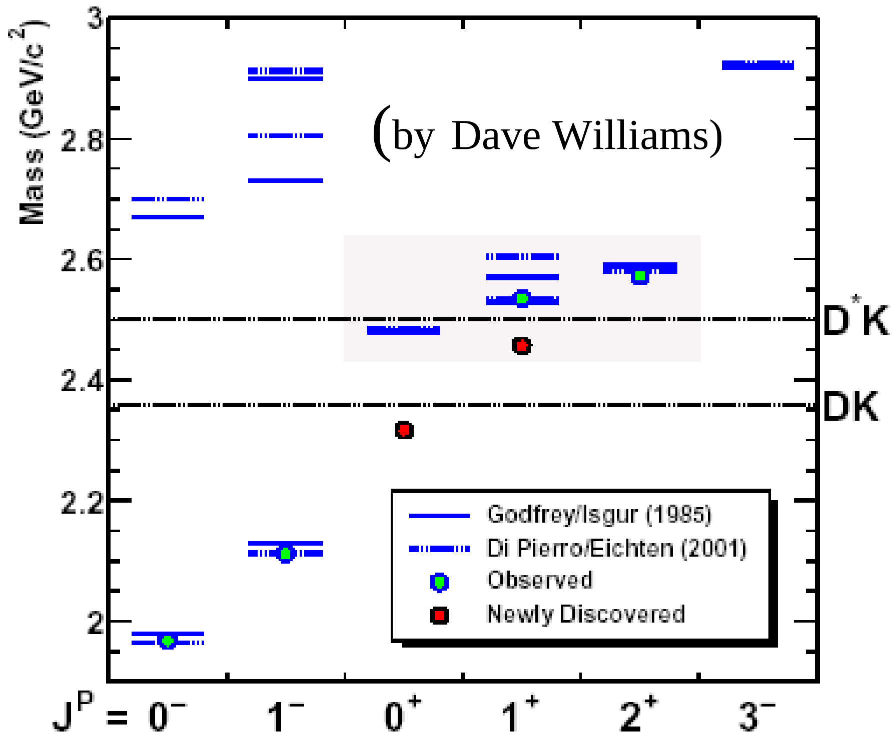


M=2463±0.4 MeV

Γ≤3.5 MeV

(Widths from Gowdy, Moriond talk)

- Also seen and studied by BELLE
- Properties consistent with $J^P=0^+$ and 1^+



j_q=1/2 predicted to be broad and decay to *DK* and *D**K*
not previously observed

But D^*_{sJ}(2317) below *DK* threshold and very narrow!
D_{sJ}(2460) below *D**K* threshold and very narrow!

Created major industry: (almost 300 citations!)

- Multiquark state
- Molecular state
- Dπ atom
- Conventional cs state but model needs improvement

The problem is the mass predictions

Once the masses are fixed the narrow widths follow

Start with non-strange charm mesons

Masses: Good agreement with predicted splittings.

Strong Decays:

Decay		Theory	Expt
$D_2^* \to D^*\pi + D\pi$	$\frac{3}{10} D^2 q^5 + \frac{1}{5} D^2 q'^5$	63	23
$D_1 \to D^*\pi$	$\frac{1}{2}[\sin^2(\theta+\theta_0) S^2 q + \cos(\theta+\theta_0) D^2 q^5]$	26	18.9
$D_1 \to D^*\pi$	$\frac{1}{2}[\cos^2(\theta+\theta_0) S^2 q + \sin(\theta+\theta_0) D^2 q^5]$	250	329
$D_0^* \to D\pi$	$\frac{1}{2} S^2 q$	290	262

$\theta_0 = 35.3^o$ (arises from Clebschs)

In HQL one D_1 becomes pure S-wave the other pure D-wave

Good agreement between theory and experiment

Charmed mesons:

- Almost all the theoretical effort has concentrated on the D_{sJ} states
- But important to test the models on the D states which also contain important information

Decay	Expt*	Theory
$D_2^* \to D^*\pi + D\pi$	43.8 ± 2	55
$D_1 \to D^*\pi$	20.3	25
$D_1 \to D^*\pi$	339 ± 76	244
$D_0^* \to D\pi$	276 ± 66	277

* Average of PDG Belle PR D69 112002 (2004)
FOCUS PLB 586, 11 (2004)
CLEO NPA 663, 647 (2000)
CDF JP Conf Ser 9, 67 (2005)

Theory: PR D43, 1679 (1991), (TRI-PP-86-51) PR D72, 054029 (2005)

Radiative Transitions

- Transitions probe the internal structure
- Radiative E1 transitions given by:

$$\Gamma(i \to f + \gamma) = \tfrac{4}{27}\alpha\left\langle e_Q\right\rangle^2 \omega^3 (2J_f + 1)\left|\left\langle {}^{2s+1}S_{J'}\left|r\right|{}^{2s+1}P_J\right\rangle\right| S_{if}$$

$$\left\langle e_Q\right\rangle = \frac{m_q e_c + m_c e_{\bar{q}}}{m_c + m_q}$$

$$D_{s1}^{3/2} = {}^1P_1 \cos\theta + {}^3P_1 \sin\theta$$

$$D_{s1}^{1/2} = -{}^1P_1 \sin\theta + {}^3P_1 \cos\theta$$

θ_{uc}=-26°

Initial state	Final State	Width	BR
$D^{*+}_2(2502)$	$D^{*+}\gamma$	590 keV	2.5%
$D_1(2456)$	$D^*\gamma$	87 keV	0.44%
	$D\gamma$	635 keV	3.2%
$D^*_1(2467)$	$D^*\gamma$	381 keV	$\sim 10^{-3}$
	$D\gamma$	163 keV	$\sim 10^{-3}$
$D^{*+}_0(2308)$	$D^{*+}\gamma$	288 keV	10^{-3}

- Should be observable
- Can be used to determine mixing angle!

$$\frac{\Gamma({}^3P_1 \to {}^3S_1 + \gamma)}{\Gamma({}^1P_1 \to {}^1S_0 + \gamma)} = \frac{\omega_t^3}{\omega_s^3}\frac{\left|\left\langle r\right\rangle_t\right|^2}{\left|\left\langle r\right\rangle_s\right|^2}\frac{\cos^2\theta}{\sin^2\theta}$$

Good agreement between quark model Predictions and experiment for charmed P-wave mesons

Models explaining the $D_s(2317)$ must also describe the D L=1 states

Strong Decays

In heavy quark limit 4 L=1 states grouped into 2 doublets
Characterized by angular momentum of light quark:

j=3/2
j=1/2

j=3/2 are predicted to be relatively narrow
identified with $D_{s1}(2536)$ and $D_{sJ}(2573)$

		Theory	Expt
$D_{s2}^* \to D^* K + DK$	$\frac{2}{5} D^2 q^5 + \frac{4}{15} D^2 q'^5$	21	15^{+5}_{-4}
$D_{s1} \to D^* K$	$\frac{2}{3}[\sin^2(\theta+\theta_0) S^2 q + \cos(\theta+\theta_0) D^2 q^5]$	0.3	<2.3

Reasonable agreement with model predictions

j=1/2 predicted to be broad and decay to *DK* and D^*K
not previously observed

But $D^*_{sJ}(2317)$ below *DK* threshold
$D_{sJ}(2460)$ below D^*K threshold

Only $D_s \to D_s^* \pi^0$ allowed but violates I-spin so small

Estimate: $\Gamma(D^*_{s0} \to D_s \pi^0) = \Gamma(D_{s1} \to D_s^* \pi^0) \approx 10 \text{ keV}$

Radiative Transitions: expected to have large BR's

Initial state)	Final State	Width	BR	$/D_s\pi^0$	$/D_s\pi^0$
$D^{*+}_{s0}(2317)$	$D^{*+}_s\gamma$	1.9 keV	16%	0.19	<0.059 (CLEO)
					<0.18 (Belle)
	$D^+_s\gamma$	0		0	<0.052 (CLEO)
					<0.05 (Belle)
	$D_s\pi^0$	~10 keV	84%		
$D_{s1}(2463)$	$D^*_s\gamma$	5.5 keV	24%	0.56	<0.16 (CLEO)
					<0.31 (Belle)
					0.274±0.049 (Babar)
	$D_s\gamma$	6.2 keV	27%	0.63	0.44 ± 0.17 (Babar)
					0.55±0.15 (Belle)
					<0.49 (CLEO)
	$D_s\pi^0$	~10 keV	43%		
	$D_s\pi\pi$	~1.6 keV	7%	0.16	0.14 ±0.04 (Belle)

Radiative transitions are expected to have large BR's so their measurement is an important probe

$$\mathcal{B}(D_{sJ}(2460)^- \to D_s^{*-}\pi^0) = 0.51 \pm 0.11 \pm 0.09$$
$$\mathcal{B}(D_{sJ}(2460)^- \to D_s^-\gamma) = 0.15 \pm 0.03 \pm 0.02$$

Preliminary

Gowdy (Babar) Moriond talk

$$\mathcal{B}(D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-) = 0.04 \pm 0.01 \text{ (stat. only)}$$

Where does the other (30 ± 15)% go?

Recall: $D_{s1}^{1/2} = -{}^1P_1 \sin\theta + {}^3P_1 \cos\theta$ PLB568, 254 (2003)

So $D_{s1}(2463) \to D_s^*\gamma$ is where it goes PRD72, 054029 (2005)

Can be used to determine mixing angle

$$\frac{\Gamma({}^3P_1 \to {}^3S_1 + \gamma)}{\Gamma({}^1P_1 \to {}^1S_0 + \gamma)} = \frac{\omega_t^3}{\omega_s^3} \frac{|\langle r \rangle_t|^2}{|\langle r \rangle_s|^2} \frac{\cos^2\theta}{\sin^2\theta}$$

Appears to be conventional cs L=1 states with masses shifted due to strong S-wave coupling to DK$^{(*)}$

Multiquark States

Barnes Close & Lipkin hep-ph/0305025
van Beveren and Rupp hep-ph/0305035

Either DK molecule or cqqs object?

- A likely possibility with much in common with description of $f_0(980)$ and $a_0(980)$
- $D_{sj}(2317)$ lies just below DK threshold
  $f_0(980)$ and $a_0(980)$ lie below KK
- Both couple strongly to nearby channels
  $D_{sj}(2463)$ could be D^*K molecule lie E/I puzzle
- No fall apart mode since DK threshold is 2.36 GeV

Predictions:

<u>If 4q states</u>

- Expect I=1 baryonium
- would have fall apart to $D_s\pi$ so would be broad
- Small admixture of I=1 explains narrow width to $D_s\pi^0$
- Search for $D_s\pi^{\pm}$ events
- Expect exotic partners

<u>If molecule:</u>

- Due to coupling to S-wave DK threshold
- KK attraction in I=0,1 channels
- Repulsion between KK continuum and scalar qq state
- If DK molecule I=1 partner less likely
- Expect anomalous em couplings relative to qq state
- Search for $D_s^+\gamma$ which is forbidden for $^3P_0$ state

van Beveren & Rupp (but not Barnes Close & Lipkin)

Predict:

- D_0^* state with mass 2100-2300 MeV
- Above $D\pi$ threshold so width several hundred MeV

$^3P_0$ (cs) with mass 2.79 GeV
$^3P_0$ (cu) with mass 2.64 GeV Γ~200 MeV

Analogous to $a_0(980)$ and $a_0(1450)$ states

Further Tests

Chen & Li hep-ph/0307075
Datta & O'Donnell hep-ph/0307106
Suzuki hep-ph/0307118
Cheng hep-ph/0307168

- **B decays**

$$\frac{B(B \to D_{sJ}^{*} + M)}{B(B \to D_{s}^{*} + M)} \approx 1 \qquad \text{if } q\bar{q}$$

$$\frac{B(B \to D_{sJ}^{*} + M)}{B(B \to D_{s}^{*} + M)} \approx 0.1 \qquad \text{if molecule / multiquark}$$

$$(\mathrm{M} = \mathrm{D}, \pi, \mathrm{K})$$

- Claim is that the BR favours multiquarks
- Based on $f_{D_{sJ}} \approx f_{D_s^*}$

Summary

- The D L=1 states are described well by the quark model
- Two new narrow states have been observed with cs content

  $D^*_{sJ}(2317)$ and $D_{sJ}(2460)$
- Their masses are lower than expected for the missing

  0^+ and 1^+ states in cs spectroscopy
- If cs states then expect very small total widths with

  Large branching ratios to $D^{*+}_s\gamma$ and $D^+_s\gamma$
- Measuring radiative transitions is crucial test
  - Absence supports molecule designation
  - Then need to find cs states
- B and B_s P-wave states could shed some light on the problem
- No model of the D_{sJ} states gives a good description of

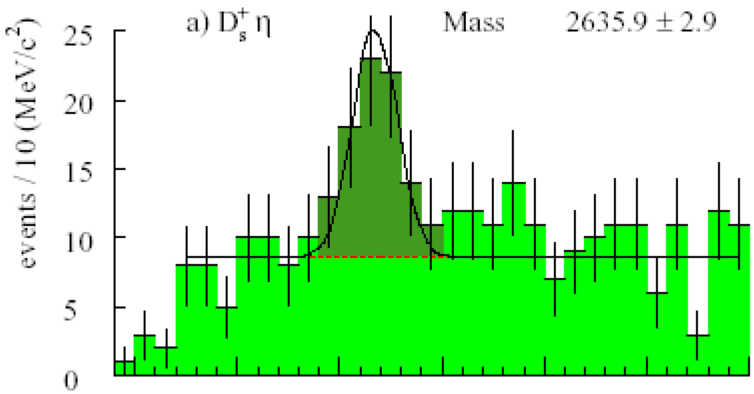
  both the both the D_{sJ} and D_s states simultaneously

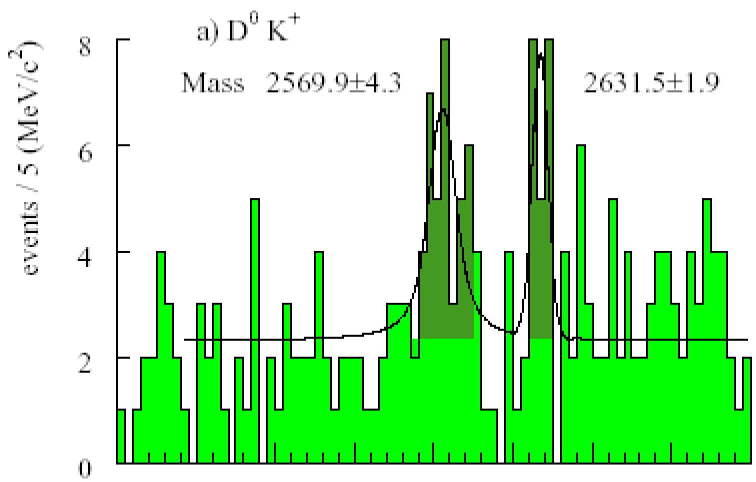
$D_{sJ}(2632)$

First Observation of a Narrow Charm-Strange Meson $D_{sJ}^{+}(2632) \rightarrow D_s^{+}\eta$ and D^0K^+

(The SELEX Collaboration)

Phys.Rev.Lett. 93, 242001 (2004)   hep-ex/0406045





Seen in hadro-production in $D_s^+\eta$ and D^0K^+

M=2632.6±1.6 MeV/c² Γ<17 MeV/c² at 90% C.L.

$$\Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.16 \pm 0.06$$

(Not seen by CLEO, Belle, Babar)

Possibilities:

- 2^3S_1(cs) State
- cs Hybrid
- 2-meson molecule

cs hybrid expected to be ~3170 MeV

Most plausible cs state is 2^3S_1 with $M(2^3S_1)$=2730 MeV
& $M(1^3D_1)$=2900 MeV

masses could be shifted by mixing with 2-meson continuum

Assuming the D_{sJ}(2632) is $2^3S_1(c\bar{s})$ with M=2632

The allowed open-flavour decay modes are: $DK,\ D_s\eta,\ D^*K$

SELEX finds:

$BR(DK/D_s\eta) = 0.32 \pm 0.12$ (assuming BR(D^0K^+)=BR(D^+K^0))

In $^3P_0$ model for preferred expect:

$$\Gamma(D^*K) > \Gamma(DK) >> \Gamma(D_s\eta)$$

$$\Gamma(D_{sJ}(2632)) = 36 \text{ MeV}$$

$$\Gamma(DK)/\Gamma(D_s\eta) \approx 9$$

Not consistent with experiment

It is possible to tune model to achieve agreement with experiment

But this tuning seems unlikely

SELEX $D_{sj}(2632)$ state:

1. **Needs confirmation**

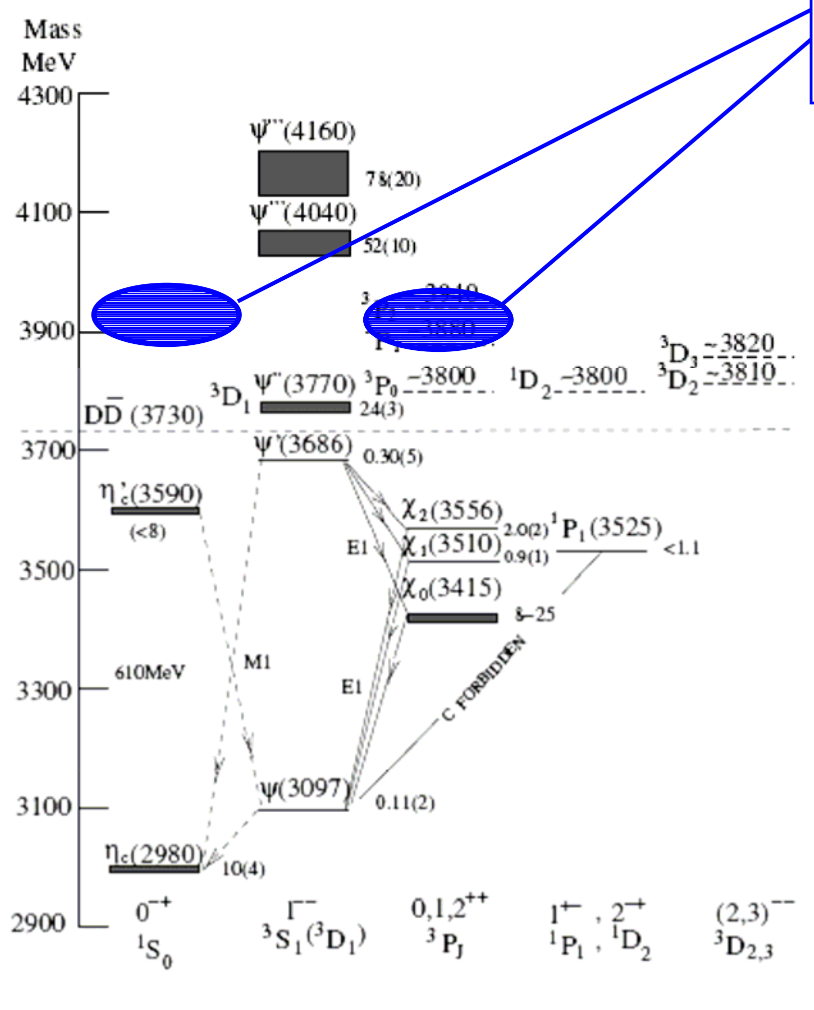
2. If 2^3S_1 state expect to see D^*K decay mode

3. **Should see the 2^3S_1 in B decays**

4. The 1^3D_1 state should be ~200 MeV higher in mass

X(3943), Y(3943), and Z(3931)

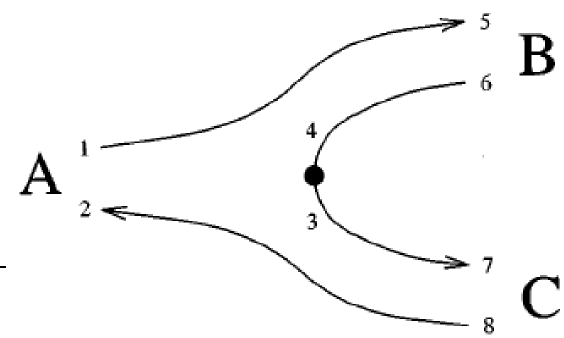
Possible new C=(+) cc̲ states at these masses!

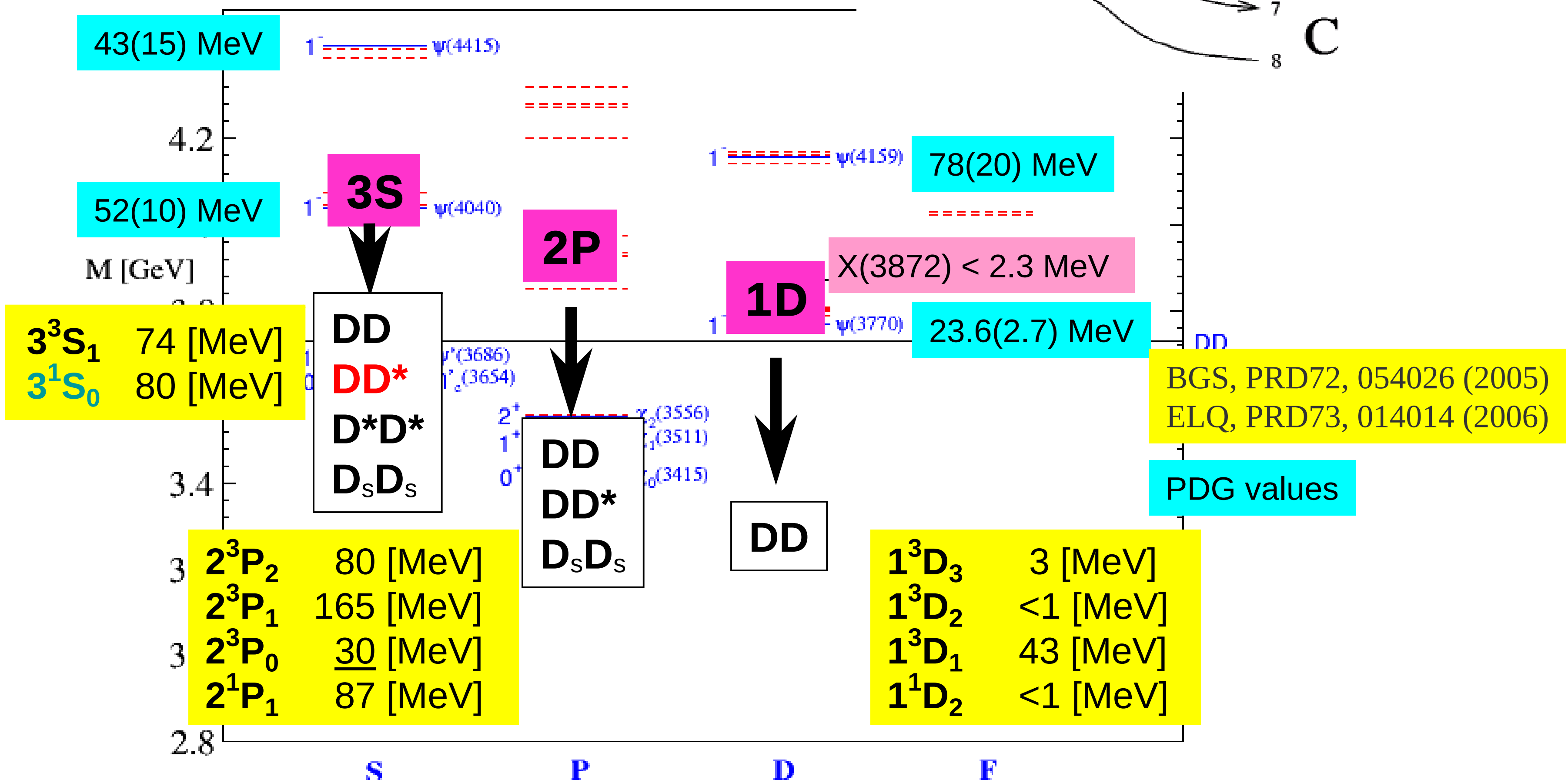


2P or not 2P that is the question!

Strong Decays

The $^3P_0$ decay model describes hadron decays reasonably well

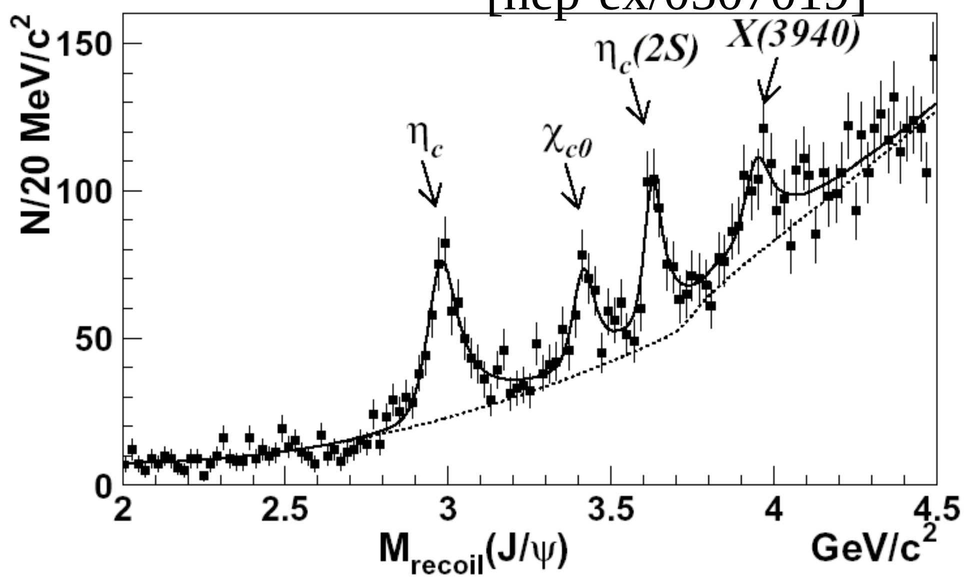




Important to understand charmonium states to identify states that don't fit and might represent new spectroscopies

X(3940)

Seen by Belle recoiling against J/ψ in e^+e^- collisions



$M=3943 \pm 6 \pm 6$ MeV

$\Gamma < 52$ MeV

$BR(X \to DD^*) = 96^{+45}_{-32} \pm 22\%$

$BR(X \to DD) < 41\%$ (90% CL)

Suggests unnatural parity state

$BR(X \to \omega J/\psi) < 26\%$ (90% CL)

- Decay to DD^* but not DD suggests unnatural parity state

- Belle speculates that X is 3^1S_0 given the 3^3S_1 $\psi(4040)$
  - Mass is roughly correct
  - . η_c and η_c' are also produced in double charm production

See also Eichten Lane Quigg PRD73 014014(2006)

- Predicted width for 3^1S_0 with M=3943 ~ 50 MeV close to Γ(X(3943)) upper bound

- Identification of ψ(4040) as 3^3S_1 state implies hyperfine splitting 88 MeV with X(3943)

- Larger than the 2S splitting and larger than predicted in potential models
- Discrepancy could be due to:
  - Difficulty in fitting true pole position of 3^3S_1 state
  - Nearby thresholds with s-wave + p-wave charm mesons so possibly stronger threshold effects

- Another possibility due to dominant DD^* mode is the 2^3P_1 χ_1'

- Natural to try 2P cc assignment since

$$M(2^3P_J) = 3920\text{-}3980 \text{ MeV}$$
$$\Gamma(2^3P_J) = 30\text{-}165 \text{ MeV}$$

- If DD^* mode is dominant suggests X(3940) is 2^3P_1

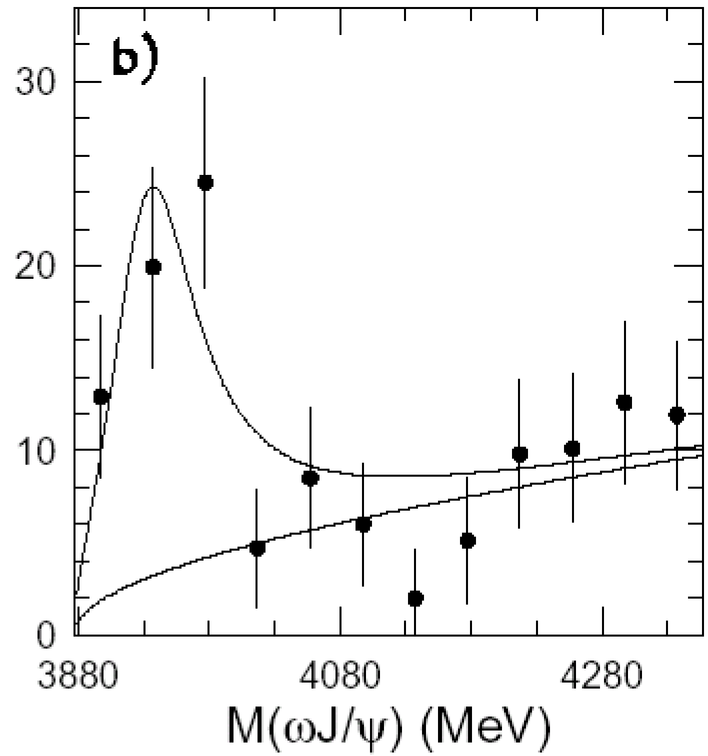
- Problems:
  - No evidence for 1^3P_1 in the same data
  - $\Gamma(2^3P_J) = 135$ MeV (for M=3943 MeV)
  - Y(3943) also a candidate for 2^3P_1 χ_1'

Test of 3^1S_0 η_c assignment is search for this state in $\gamma\gamma \to DD^*$

Y(3940)

See in $\omega J/\psi$ subsystem of the decay $B \to K \pi\pi\pi J/\psi$

Belle: Phys. Rev. Lett. 94, 182002 (2005)



$M = 3943 \pm 11 \pm 13$ MeV

$\Gamma = 87 \pm 22 \pm 26$ MeV

Not seen in $Y \to DD$ or DD^*

Mass and width suggest radially excited P-wave charmonium

But $\omega J/\psi$ decay mode is peculiar:

$BR(B \to KY)\ BR(Y \to \omega J/\psi) = 7.1 \pm 1.3 \pm 3.1 \bullet 10^{-5}$

where one expects $BR(B \to K\chi'_{cJ}) < BR(B \to K\chi_{cJ}) = 4 \bullet 10^{-4}$

Implies $BR(Y \to \omega J/\psi) > 12\%$ which is unusual for state above open charm threshold

- Large width to $\omega J/\psi$ led Belle to suggest Y(3943) might be hybrid

- But mass is 500 MeV below LGT estimates making hybrid assignment unlikely

- Possibility is 2^3P_1 cc state: identifyies Y(3943) as 2P χ'_{c1}
  - DD^* is the dominant decay mode
  - Width consistent with Y(3943): Γ=135 MeV
  - . χ_{c1} is seen in B decays

- $1^{++} \rightarrow \omega J/\psi$ is unusual
  - but corresponding $\chi'_{b1,2} \rightarrow \omega Y(1S)$ also seen
  - Maybe rescattering: $1^{++} \rightarrow DD^* \rightarrow \omega J/\psi$
  - Maybe due to mixing with 1^{++} molecular state X(3872)?
- Important to - look for DD and DD*
  - study angular distributions to DD and DD*

Z(3930)

Belle: Phys Rev Lett 96, 082003(2006) [hep-ex/0512035]

- Observed by Belle in $\gamma\gamma \rightarrow DD$

  $M=3929 \pm 5 \pm 2$ MeV

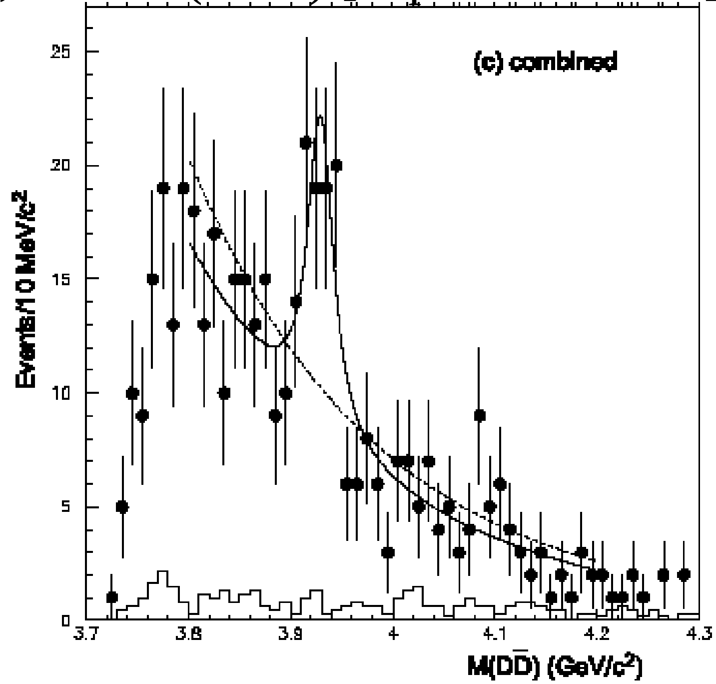
  $\Gamma = 29 \pm 10 \pm 2$ MeV

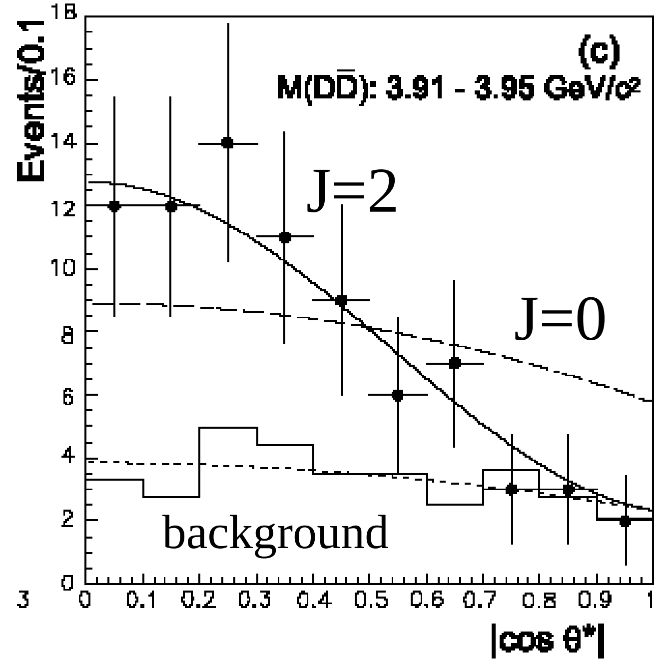
- Two photon width:

  $\Gamma_{\gamma\gamma} \bullet B_{DD} = 0.18 \pm 0.05 \pm 0.03$ keV

- DD angular distribution consistent with J=2

- Below D* D* threshold





- Obvious candidate for χ'_{c2} (the χ'_{c1} cannot decay to DD)

  - Predicted χ'_{c2} mass is 3972

    $\Gamma(\chi'_{c2} \to DD)$= 21.5 MeV

    $\Gamma(\chi'_{c2} \to DD^*)$= 7.1 MeV

    Γ =47 MeV assuming M(χ'_{c2})=3931

- In reasonable agreement with experiment

- Predicted BR($\chi'_{c2} \to \mathbf{DD}$)=70% $\Rightarrow \ \Gamma_{\gamma\gamma} * B_{DD} = 0.47$ keV

  ($\Gamma_{\gamma\gamma}$ from T.Barnes, IX[th] Intl. Conf. on $\gamma\gamma$ Collisions, La Jolla, 1992.)

- Observed two-photon width about 1/2 predicted value for χ'_{c2}

- No reason not to believe that Z(3930) is not the χ'_{c2}

- Another possibility is χ'_{c0} (unlikely due to angular distributions)

- Can confirm χ'_{c2} by searching for DD^*

  χ'_{c0} only decays to DD

  χ'_{c2} decays to DD and DD^* in ratio of $DD^*/DD \sim 1/3$

- Largest radiative transition is

  BGS, PRD72, 054026 (2005)

  $\Gamma(\chi'_{c2} \to \gamma\, \psi') \sim 200$ keV vs $\Gamma(\chi'_{c0} \to \gamma\, \psi') \sim 130$ keV

  (ELQ find decays are suppressed due to coupled channel effects PRD73 014014(2006))

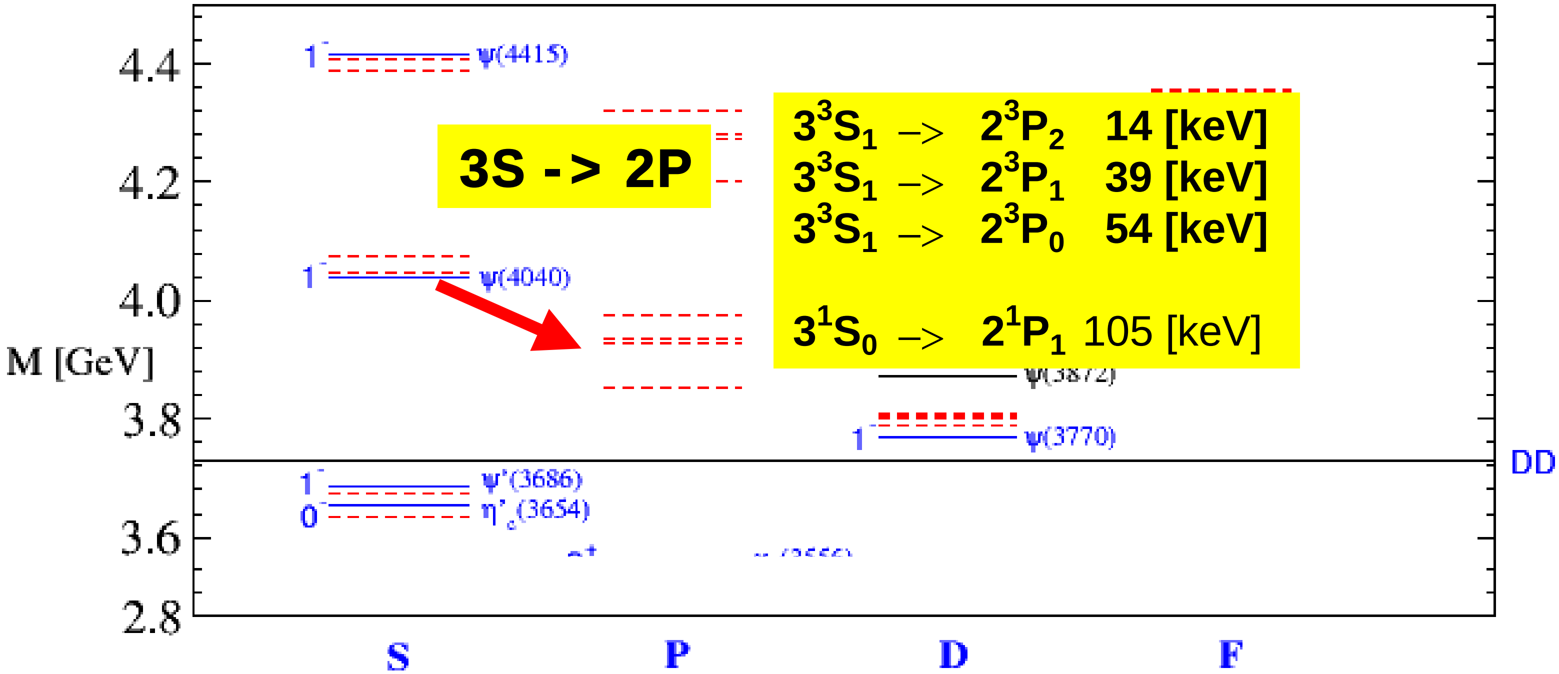
Could further study 2^3P_J states via radiative transitions:

Can *find* all three $^3 2P_J$ $c\underline{c}$ states using

$\psi(4040)$ and $\psi(4160) \to \gamma DD, \gamma DD^*$

All three E1 rad BFs of the $\psi(4040)$ are ~$0.5 * 10^{-3}$.

These would further test whether the *Z,X,Y (3.9)* are 2P cc



X(3872)

New state 1st observed by Belle: X(3871)

Phys Rev. Lett. 91, 2622001 (2003) [hep-ex/0309032]

Confirmed by: CDF Phys Rev. Lett. 93, 072001 (2004)
D0 Phys Rev. Lett. 93, 162002 (2004)
BABAR Phys Rev. D71, 071103 (2005)

M=3872.0 ± 0.6 ± 0.5 MeV $\Gamma < 2.3$ MeV at 90% C.L.
width consistent with detector resolution.

1. $D^0 D^{*0}$ molecule
2. A charmonium hybrid
3. 2^3P_J 1^3D_2 state?
4. Glueball?

News Front Page
Africa
Americas
Asia-Pacific
Europe
Middle East
South Asia
UK
Business
Health
Science/Nature
Technology
Entertainment
Have Your Say
Country Profiles
In Depth
Programmes
RELATED SITES
BBC SPORT
BBC WEATHER
BBC ON THIS DAY

Last Updated: Wednesday, 30 April, 2003, 21:22 GMT 22:22 UK

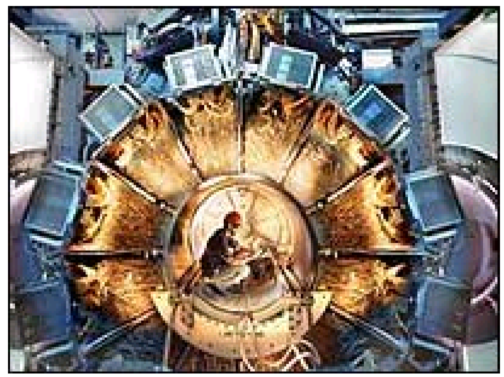
Email this to a friend Printable version

Physicists find 'rebel' particle

By Dr David Whitehouse
BBC News Online science editor

Physicists have found a new subatomic particle, named Ds (2317). It will help them better understand the building blocks of matter.

The particle consists of an unusual combination of more fundamental particles - quarks.



Inside the BaBar detector

Two quarks form Ds (2317) and, curiously, its properties are not what theory predicted.

The announcement was made by physicist Antimo Palano to a packed auditorium at the Stanford Linear Accelerator Center (Slac) in the US.

The discovery was made by the BaBar international consortium, which operates a detector at Slac that analyses debris from subatomic particle collisions.

'Back to the drawing boards'

"Congratulations to BaBar," said Slac's director, Jonathan Dorfan.

"The existence of the particle is not a surprise, but its mass is lower than expected. This result will send theorists back to their drawing boards."

SEE ALSO:
- Did quark matter strike Earth? 22 Nov 02 | Science/Nature
- Physicists make 'strange' matter 22 Aug 01 | Science/Nature
- 'Little Bang' creates cosmic soup 10 Feb 00 | Science/Nature

RELATED INTERNET LINKS:
- Quarks
- Antiparticles
- Slac
- BaBar

TOP SCIENCE/NATURE STORIES NOW
- Oblivion threat to 12,000 species
- Scientists find mystery particle
- Centre opens for X-rated science
- Huge rock-ice body circles Sun

Consider the charmonium possibilities:

T.Barnes,S.Godfrey, PR D69, 050400 (2004)
Eichten, Lane, Quigg, PR D69, 094019 (2004)
Barnes, Godfrey, Swanson, PR D 054026 (2005)

1D and 2P multiplets only states nearby in mass

1^3D_2 1^3D_3 2^1P_1 have C=-
1^1D_2 2^3P_0 2^3P_1 2^3P_2 have C=+

But $X(3872) \to \gamma J/\psi$ implies C=+ Belle [hep-ex/0505037]
Babar Gowdy Moriond talk

Angular distributions favour $J^{PC}=1^{++}$ Belle [hep-ex/0505038]

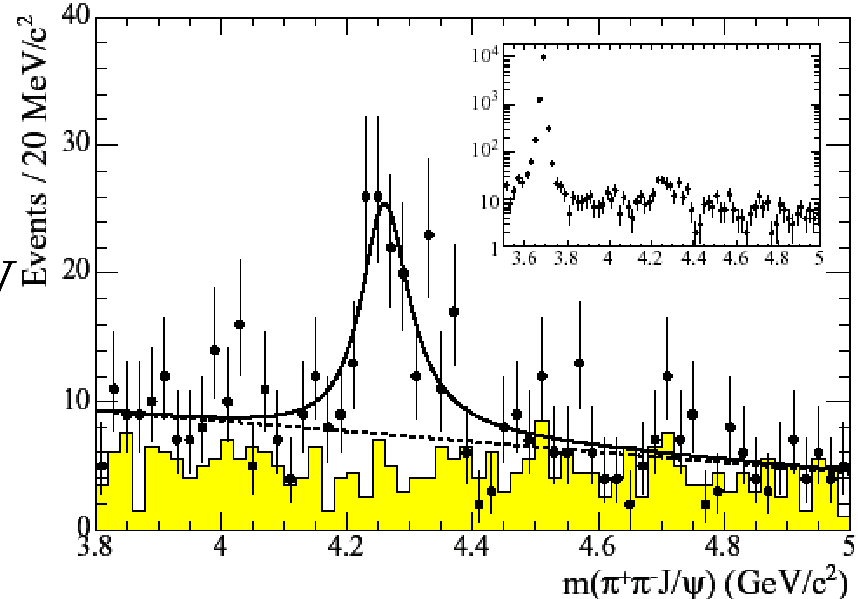
The unique surviving charmonium candidate is 2^3P_1

BUT identification of Z(3931) with 2^3P_2
implies 2P mass ~ 3940 MeV

D^0D^{*0} molecule or "tetraquark" is a popular/likely explanation

Y(4260)

Discovered by Babar as enhancement in $\pi\pi$ J/ψ subsystem in $e^+e^- \to \gamma_{ISR}\, \psi\pi\pi$ PRL 95, 142001(2005) [hep-ex/0506081]



M=4259 ± 8 ± 4 MeV

Γ =88 ± 23 ± 5 MeV

$\Gamma_{ee} \times BR(Y \to \pi^+\pi^- J/\psi) = 5.5 \pm 1.0 \pm 0.8$ eV

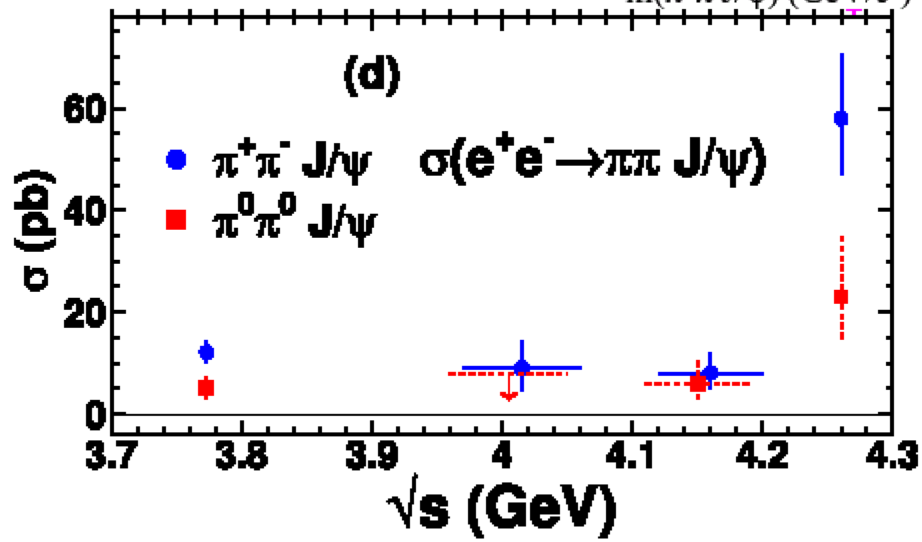
ISR production tells us $J^{PC}=1^{--}$

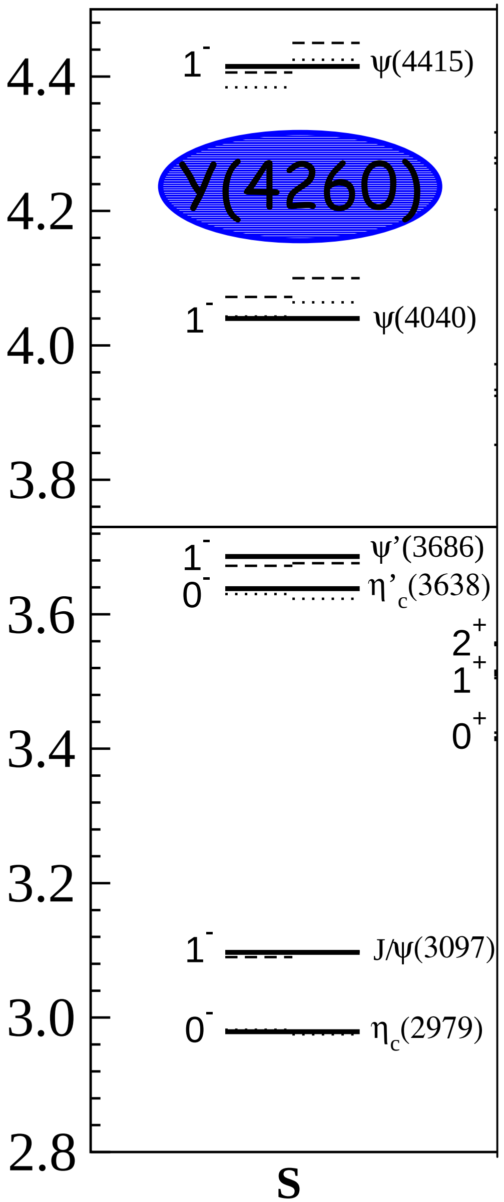
Further evidence in

$B \to K(\pi^+\pi^- J/\psi)$ PR D73, 011101(2006)

Confirmed by CLEO

hep-ex/0602034





- The first unaccounted 1^{--} state is the $\psi(3D)$
- Quark models estimate $M(\psi(3D))$~4500 MeV much too heavy for the Y(4260)

Y(4260) represents an overpopulation of expected 1^{--} states

Absence of open charm production also against conventional cc state

Other explanations are:

- . $\psi(4S)$ Phys Rev D72, 031503 (2005)
- Tetraquark Phys Rev D72, 031502 (2005)
- cc hybrid Phys Lett B625, 212 (2005); Phys Lett B628, 215 (2005) Phys Lett B631, 164 (2005)

Y(4260): Hybrid?

- Flux tube model predicts lowest cc hybrid at 4200 MeV
- LGT expects lowest cc hybrid at 4200 MeV [Phys Lett B401, 308 (1997)]
- Models of hybrids say $\Psi(0)=0$ so would have small e^+e^- width
- LGT found bb hybrids have large couplings to closed flavour modes
  - Similar to BaBar observation of $Y\to\pi^+\pi^- J/\psi$:

$$BR(Y \to \pi^+\pi^- J/\psi) > 8.8\%$$
$$\Gamma(Y \to \pi^+\pi^- J/\psi) > 7.7 \pm 2.1 \text{ MeV}$$

- Much larger than typical charmonium transitions:

$$\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) \sim 80 \text{ keV}$$

- Y is seen while $\psi(4040)$, $\psi(4160)$ $\psi(4415)$ are not

How to test Y(4260) hybrid assignment:

Decays:

- LGT study suggest searching for other closed charm modes with $J^{PC}=1^{--}$ $J/\psi\eta,\ J/\psi\eta',\ \chi_J\omega\ldots$
- Models predict the dominant hybrid charmonium open-charm decay modes will be a meson pair with S-wave (D, D^*, D_s, D_s^*) + P-wave (D_J, D_{sJ})
- The dominant decay mode expected to be $D+D_1(2430)$ $D_1(2420)$ has width ~300 MeV and decays to $D^*\pi$
- **Suggests search for Y(4260) in $DD^*\pi$**
- Evidence of large $DD_1(2430)$ signal would be strong evidence for hybrid
- But models of hybrids are untested so to be cautious
- If seen in other modes like DD^*, $D_sD_s^*$ comparable to $\pi^+\pi^-J/\psi$ maybe still hybrid but decay model not accurate

Search for Partner States: (fill in the multiplet)

- Mass *ca.* 4.0 – 4.5 GeV, with LGT preferring the higher range.
  (e.g.: X.Liao and T.Manke, hep-lat/0210030)
- Confirm that no $c\underline{c}$ states with the same J^{PC} are expected at this mass.

- Identify J^{PC} partners of the hybrid candidate nearby in mass.

- The most convincing evidence:
  - partners, especially J^{PC} exotics.

- The f-t model expects:

$$\mathbf{0^{+-}, 1^{-+}, 2^{+-}, 0^{-+}, 1^{+-}, 2^{-+}, 1^{++}, 1^{--}}$$

Summary

Many new results, considerable progress!

$D_{sJ}(2317)$	Most likely $0^+(c\bar{s})$
$D_{sJ}(2460)$	Most likely $1^+(c\bar{s})$
$D_{sJ}(2632)$	Needs confirmation
X(3872)	Molecule? - see Voloshin
X(3943)	$\eta''_c\,(3^1S_0)$ -look for $\gamma\gamma \to DD^*$
Y(3943)	$\chi'_{c1}\,(2^3P_1)$ -look for DD & DD*
Z(3930)	$\chi'_{c2}\,(2^3P_2)$ -confirm by DD*
Y(4260)	Hybrid?

- Much more to learn; ie search for 1^3D_3 1^3D_2 1^1D_2 1^3F_2 1^3F_4

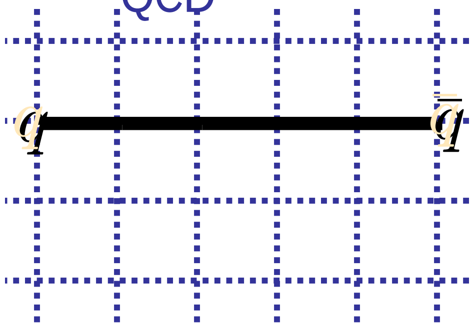
Thank experimentalists for all the wonderful results they're providing

Final Summary

Still much interesting physics:

- Final state interactions
- Effect of decay channel coupling
- Where are the hybrids?
- Where are the glueballs?

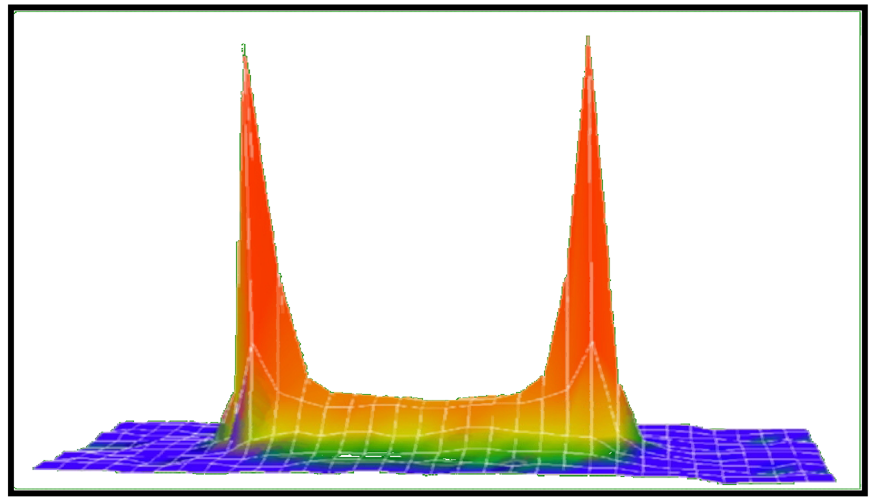
★ has a justification in the strong coupling limit of Hamiltonian lattice QCD



$$E_g \sim L$$

string $$V = bL$$

★ support from numerical lattice studies



"Discovering experimental evidence for gluonic degrees of freedom in hadron spectroscopy is, in our estimation, the most important outstanding qualitative test for QCD."

Predict that "diffractive photoproduction can produce plucked ρ, ω, and ϕ states so could be a good source for all four of the desirable exotics …"

Gluonic Excitations of Mesons: Why They Are Missing and Where to Find Them

Nathan Isgur and Richard Kokoski
Department of Physics, University of Toronto, Toronto, Ontario M5S 1A7, Canada

and

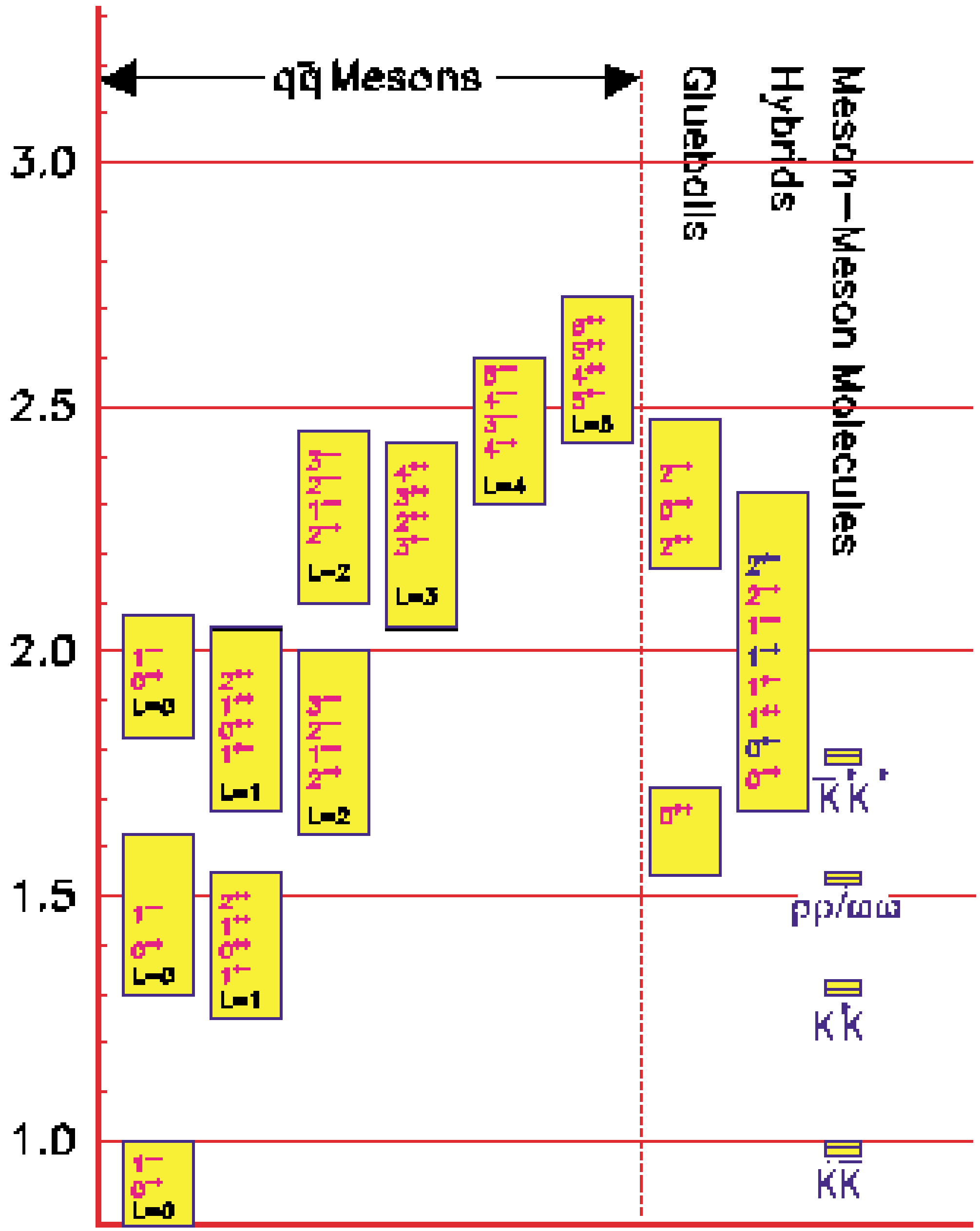
Jack Paton
Department of Theoretical Physics, University of Oxford, Oxford OX1 3NP, England
(Received 28 November 1984)

We have studied the decays of the low-lying gluonic excitations of mesons (hybrids) predicted by a flux-tube model for chromodynamics. The probable reason for the absence to date of signals for such states is immediately explained: The lowest-lying hybrids decay preferentially to final states with one excited meson [e.g., $B(1235)\pi$, $A_2(1320)\pi$, $K^*(1420)\bar{K}$, $\pi(1300)\pi$, . . .] rather than to two ground-state mesons (e.g., $\pi\pi$, $\rho\pi$, $K^*\bar{K}$, . . .). We make specific predictions of decay channels which will contain J^{PC} exotic hybrid resonance signals and suggest some possibly fruitful production mechanisms.

TABLE I. The dominant decays of the low-lying exotic meson hybrids.

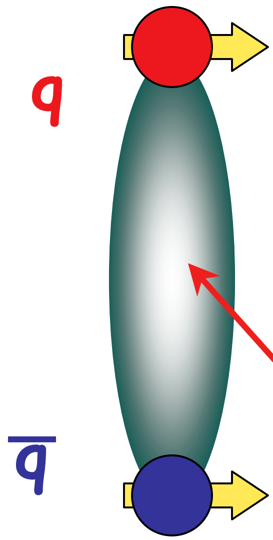
Hybrid state[a]	J^{PG}	(Decay mode)$_{L \text{ of decay}}$	Partial width (MeV)
x_2^{+-} (1900)	2^{++}	$(\pi A_2)_P$	450
		$(\pi A_1)_P$	100
		$(\pi H)_P$	150
{ y_2^{+-} (1900)	2^{+-}	$(\pi B)_P$	500 }
{ z_2^{+-} (2100)	2^{+-}	$[\bar{K}K^*(1420)+\text{c.c.}]_P$	250 }
		$(\bar{K}Q_2+\text{c.c.})_P$	200
{ x_1^{-+} (1900)	1^{--}	$(\pi B)_{S,D}$	100,30 }
		$(\pi D)_{S,D}$	30,20
y_1^{-+} (1900)	1^{-+}	$(\pi A_1)_{S,D}$	100,70
		$[\pi\pi(1300)]_P$	100
		$(\bar{K}Q_2+\text{c.c.})_S$	~100
z_1^{-+} (2100)		$(\bar{K}Q_1+\text{c.c.})_D$	80
		$(\bar{K}Q_2+\text{c.c.})_S$	250
		$[\bar{K}K(1400)+\text{c.c.}]_P$	30
x_0^{+-} (1900)	0^{++}	$(\pi A_1)_P$	800
		$(\pi H)_P$	100
		$[\pi\pi(1300)]_S$	900
{ y_0^{+-} (1900)	0^{+-}	$(\pi B)_P$	250 }
z_0^{+-} (2100)	0^{+-}	$(\bar{K}Q_1+\text{c.c.})_P$	800
		$(\bar{K}Q_2+\text{c.c.})_P$	50
		$[\bar{K}K(1400)+\text{c.c.}]_S$	800

[a] x, y, and z denote the flavor states $(1/\sqrt{2})(u\bar{u}-d\bar{d})$, $(1/\sqrt{2})(u\bar{u}+d\bar{d})$, and $s\bar{s}$. The subscript on a state is J; the superscripts are P and C_n.


qq̄ Mesons
Glueballs
Hybrids
Meson—Meson Molecules
3.0
2.5
2.0
1.5
1.0
L=0
L=1
L=2
L=3
L=4
L=5
KK̄*
ρρ/ωω
KK̄
KK̄

How do we see flux tubes in spectroscopy?

Quantum-mechanically a photon sometimes behaves like a quark-antiquark pair with spins aligned



First excited state of flux tube has J=1

when combined with S=1 for quarks generate:

$J^{PC} = 0^{-+}\ 0^{+-}\ 1^{+-}\ 1^{-+}\ 2^{-+}\ 2^{+-}$

exotic

Like a vibrating string