Meson Spectroscopy Past, Present and Future

I apologize to the many workers in the field whose work I neglect to mention, but especially:

Ted Barnes, Kevin Dooley, Mariana Frank, Paul Geiger, Cameron Hayne, Gabriel Karl, Rick Kokoski, Roman Koniuk, Kim Maltman, Colin Morningstar, Pat O'Donnell, Cathy Reader, Daryl Scora, Eric Swanson, John Weinstein

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The New York Times ON THE WEB

August 15, 2000

10 Physics Questions to Ponder for a Millenium or Two

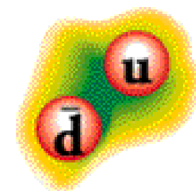
One of those questions:

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

Meson Spectroscopy is the ideal laboratory to accomplish this

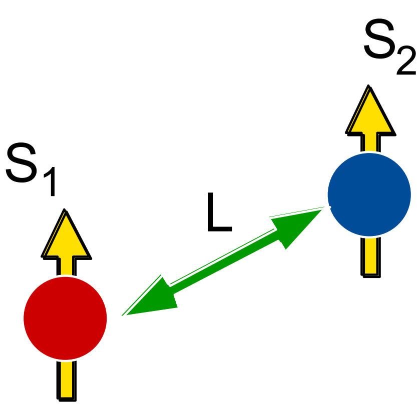
Mesons are composed of a quark-antiquark pair

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:

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

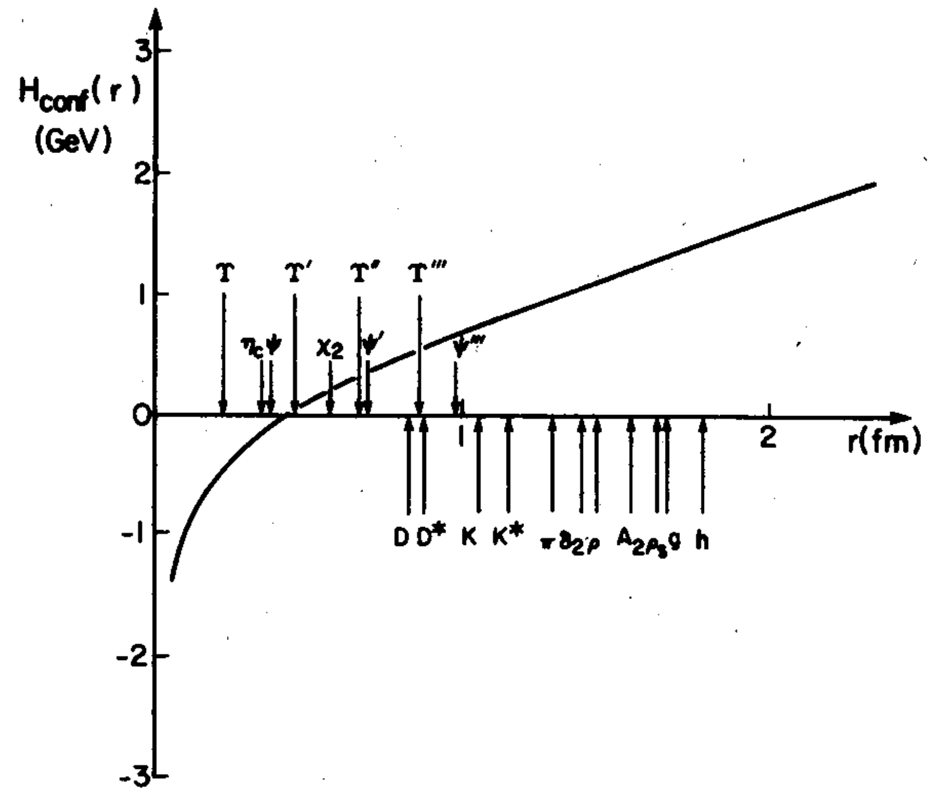
Not allowed: exotic combinations:

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

Quark-antiquark Potential

For given spin and orbital angular momentum configurations
& radial excitations generate our known spectrum of light quark mesons

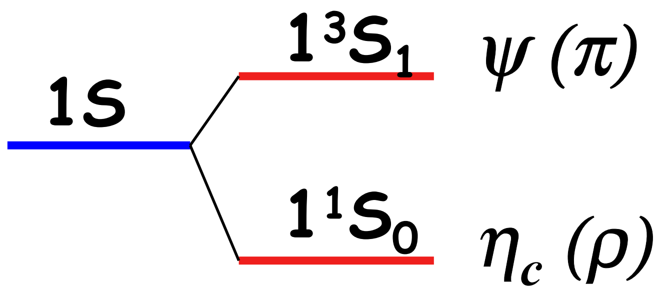
$$H_{ij}^{conf} = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$



Spin-dependent potentials:

Spin-spin interactions:

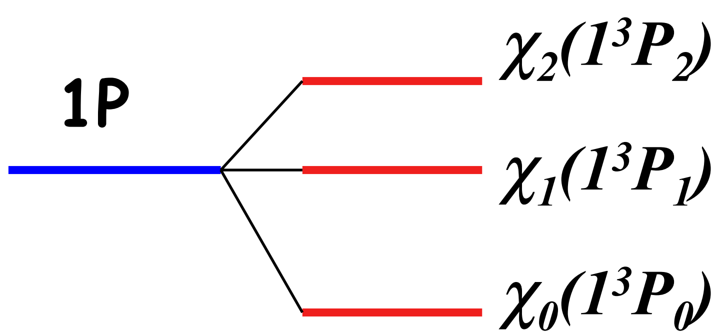
$$H_{ij}^{hyp} = \frac{4\alpha_s(r)}{3m_i m_j}\left\{\frac{8\pi}{3}\vec{S}_i\cdot\vec{S}_j\,\delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3}\left[\frac{3\vec{S}_i\cdot\vec{r}_{ij}\vec{S}_j\cdot\vec{r}_{ij}}{r_{ij}^2} - \vec{S}_i\cdot\vec{S}_j\right]\right\}$$

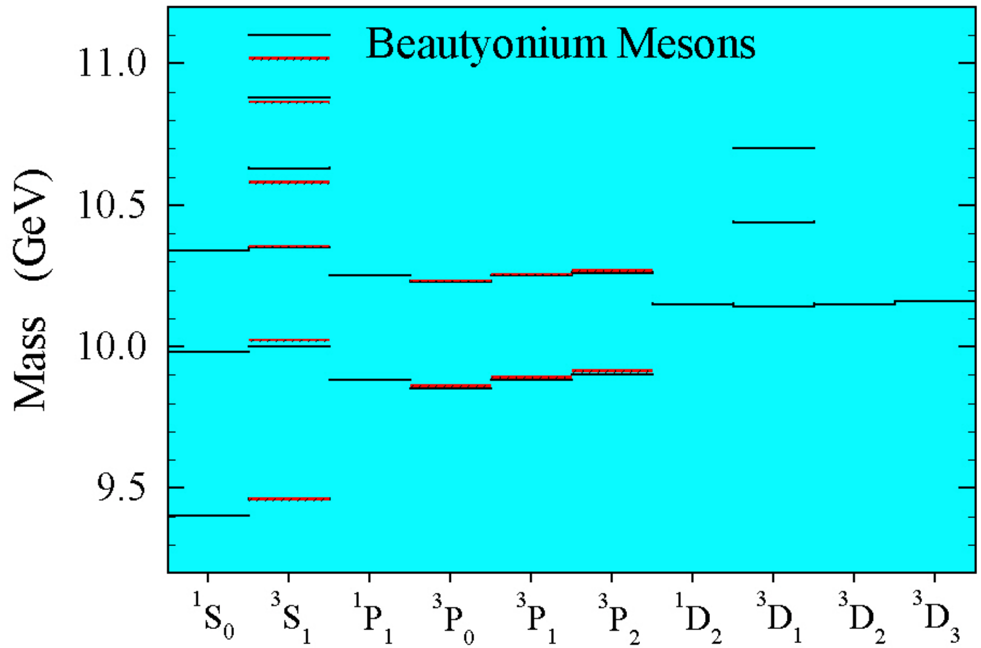


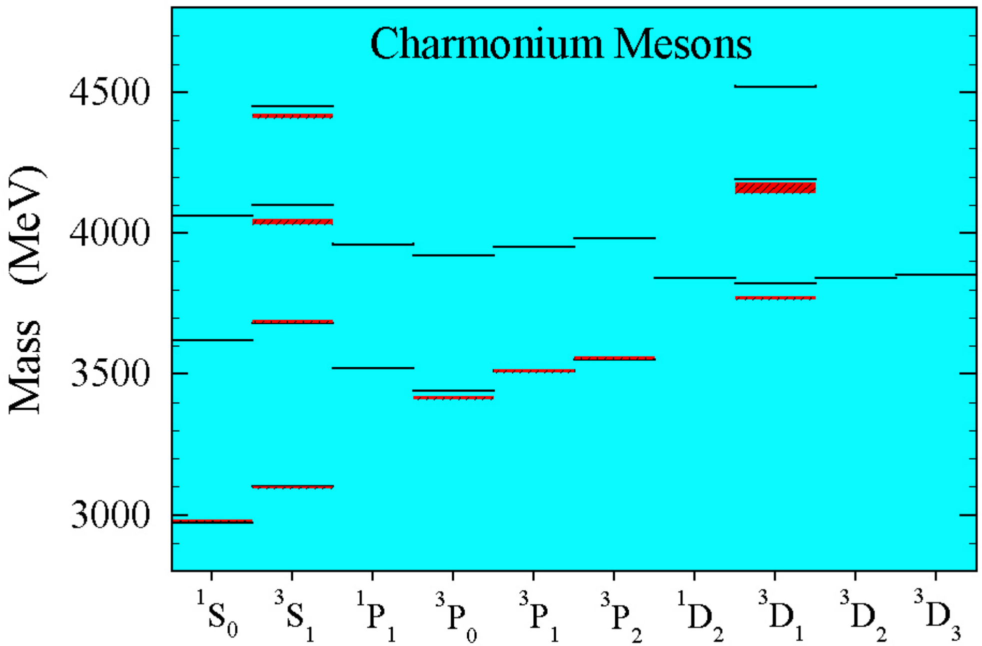
Spin-orbit interactions:

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

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



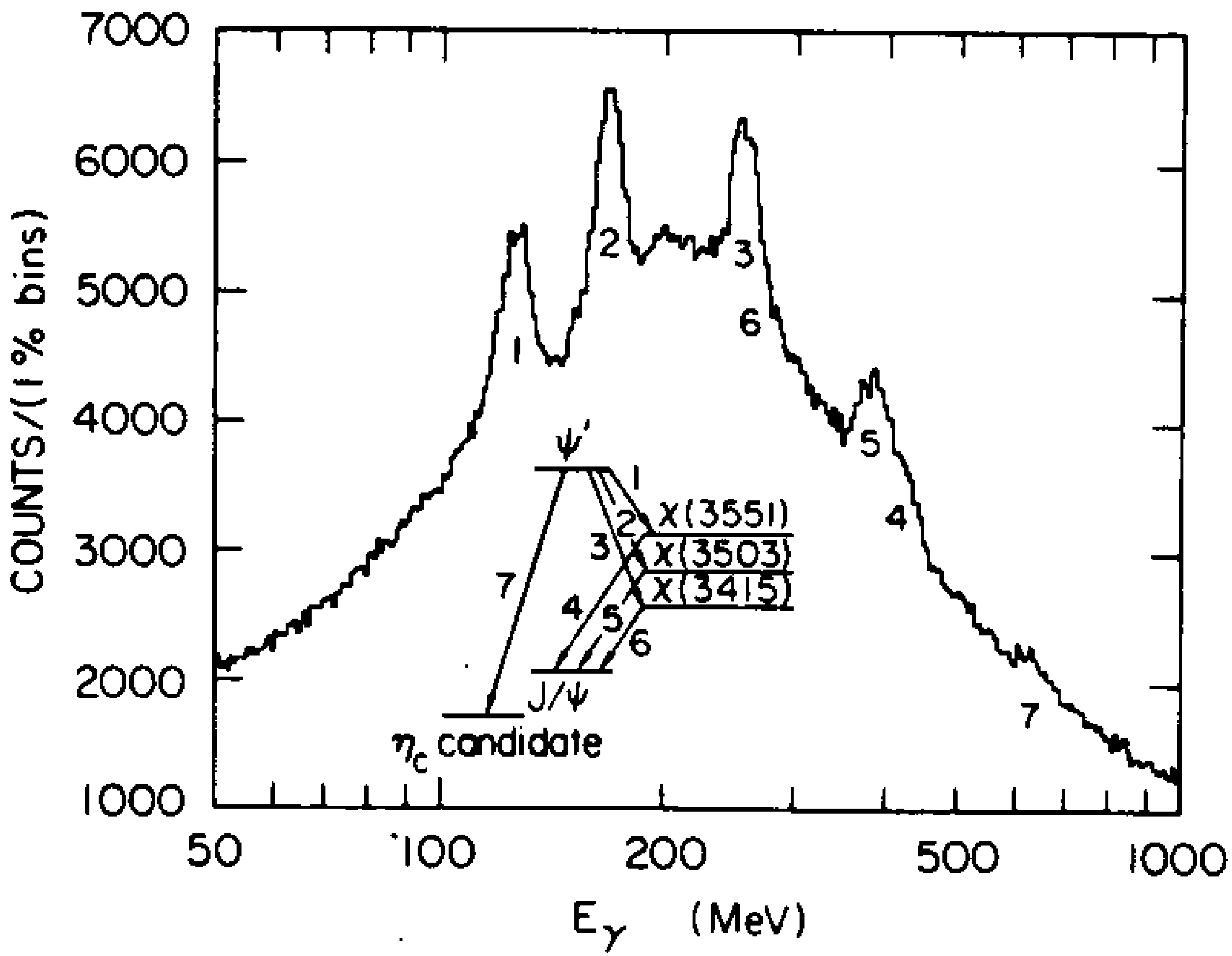

Beautyonium Mesons
Mass (GeV)
11.0
10.5
10.0
9.5
$^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$


Charmonium Mesons
Mass (MeV)
4500
4000
3500
3000
$^1S_0$ $^3S_1$ $^1P_1$ $^3P_0$ $^3P_1$ $^3P_2$ $^1D_2$ $^3D_1$ $^3D_2$ $^3D_3$

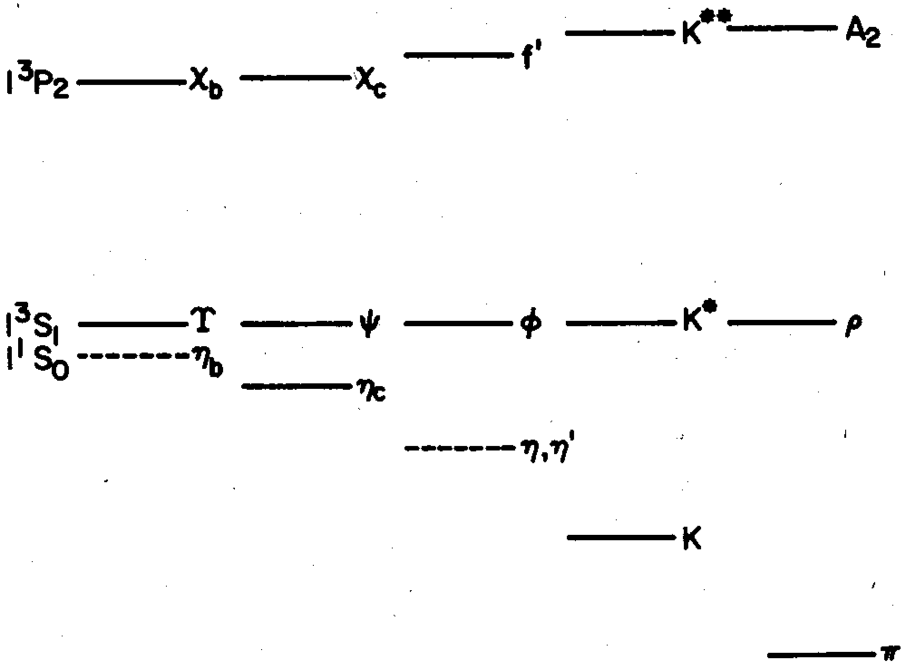
The Charmonium Spectrum

VOLUME 45, NUMBER 14 PHYSICAL REVIEW LETTERS 6 OCTOBER 1980

Observation of an η_c Candidate State with Mass 2978 ± 9 MeV



What about mesons with light quarks?

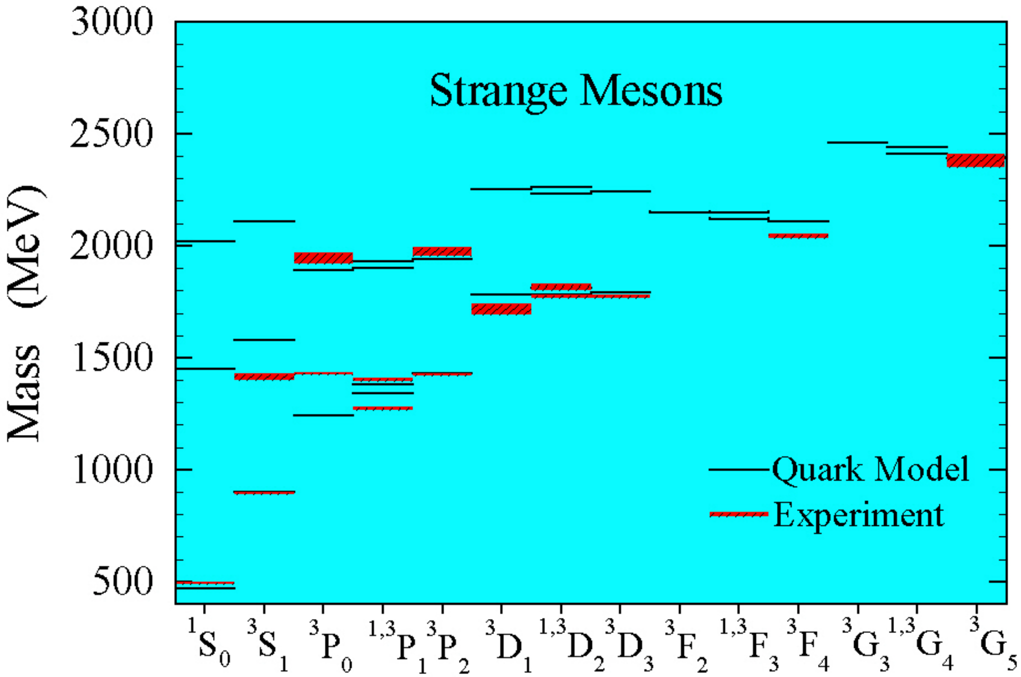


Essential features are the same, except:

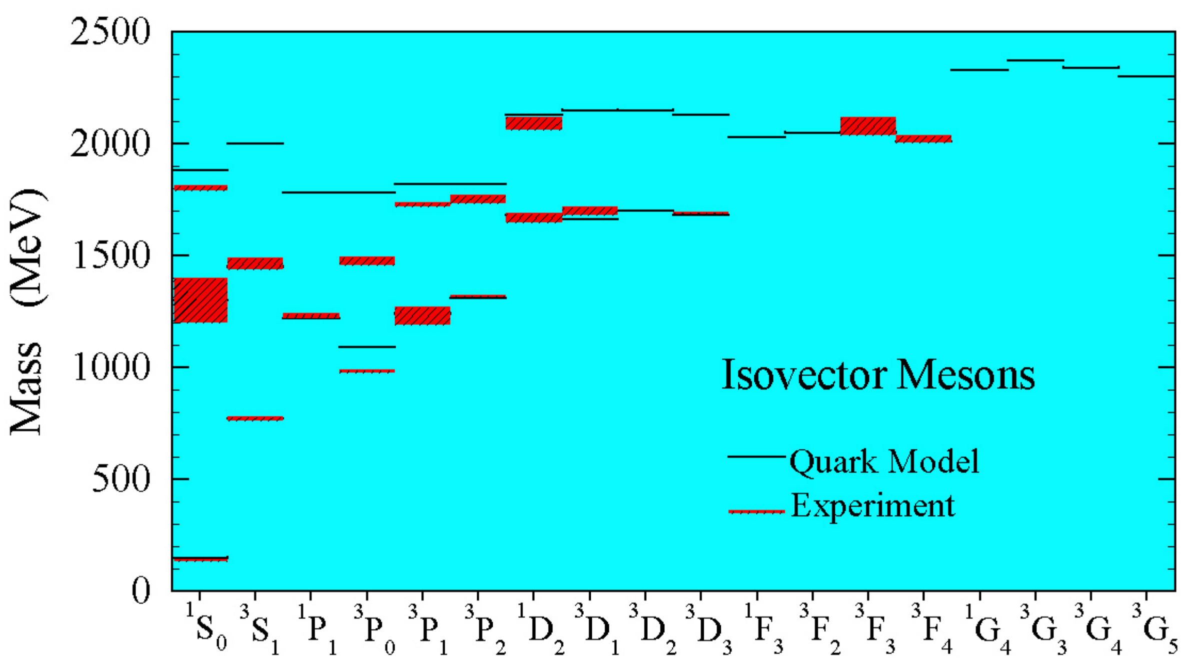
- Relative importance of relativistic effects
- Hyperfine splittings are comparable in size to orbital splittings

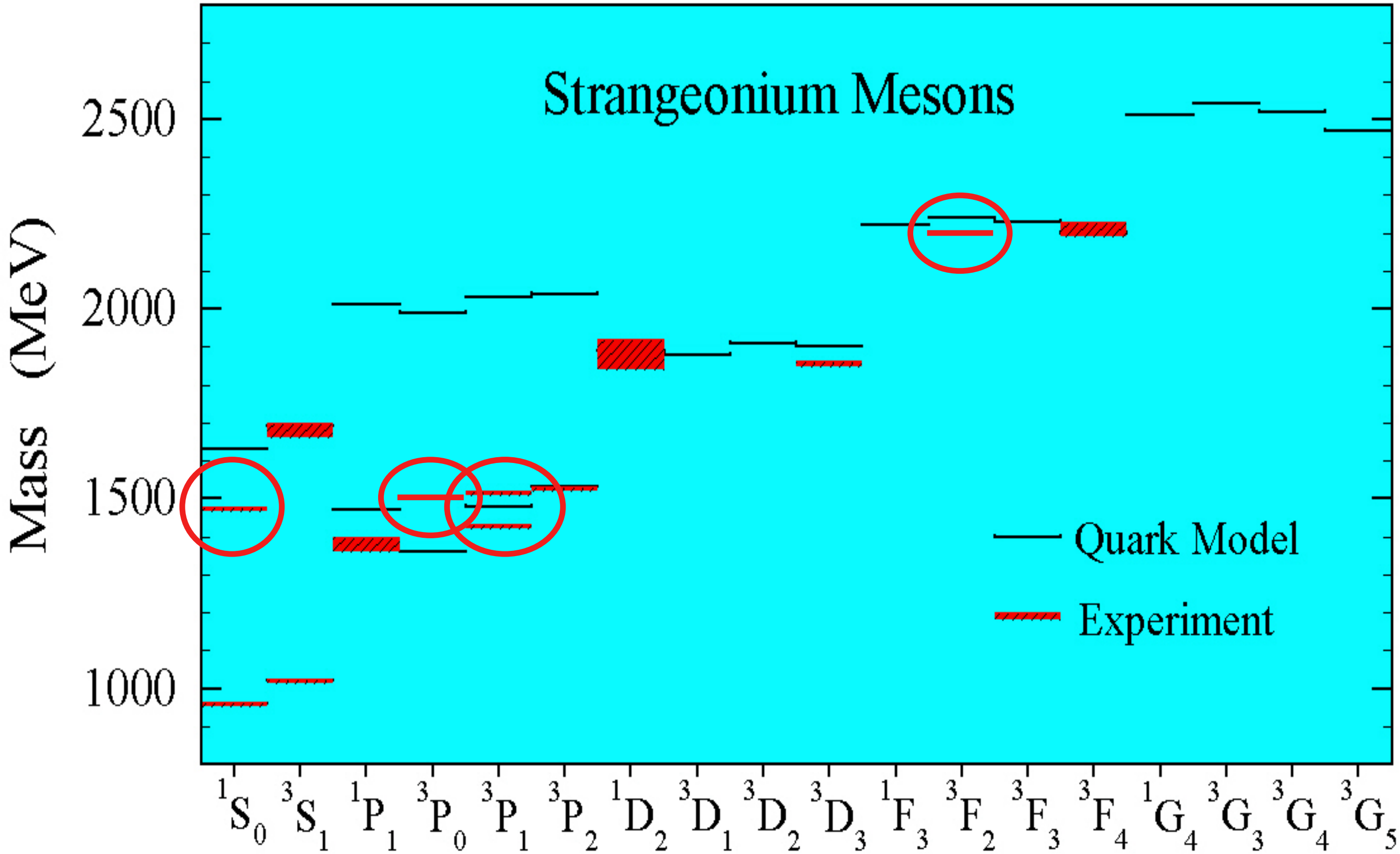
Conclude

- potential models approximately valid



Generally, good agreement for confirmed states





- Many unconfirmed states:

  $f_1(1530)$, $h_1(1380)$
- Many puzzles:

  $\eta(1440)$, $f_1(1420)$, $f_0(1500)$ $f_J(1710)$, $f_J(2200)$

- At this point there were many models that predicted new forms of hadronic matter:
    - Multiquark states (Baryonium)
    - Glueballs
    - Hybrids

- Also, **Lattice QCD;** numerical calculations of hadron properties starting from first principles in their infancy

Nathan developed **flux tube model** 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 and glueballs

PHYSICAL REVIEW D VOLUME 31, NUMBER 11 1 JUNE 1985

Flux-tube model for hadrons in QCD

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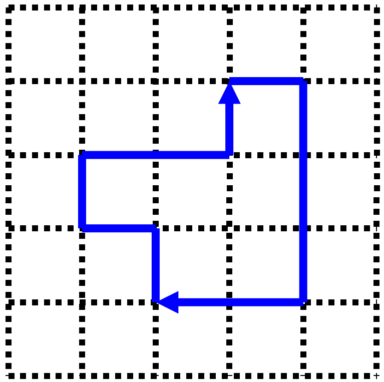
(Received 30 August 1984)

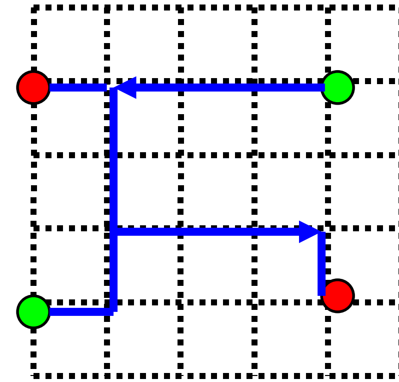
We extract from the strong-coupling Hamiltonian lattice formulation of QCD a model for hadrons based on the use of quark and flux-tube degrees of freedom. The ordinary quark model of mesons and baryons is recovered as an appropriate limit, but the properties of hybrids, pure glue, and multiquark hadrons are also predicted by the model. The basic tenets of the model can be tested by lattice Monte Carlo simulations.

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

Multiquarks



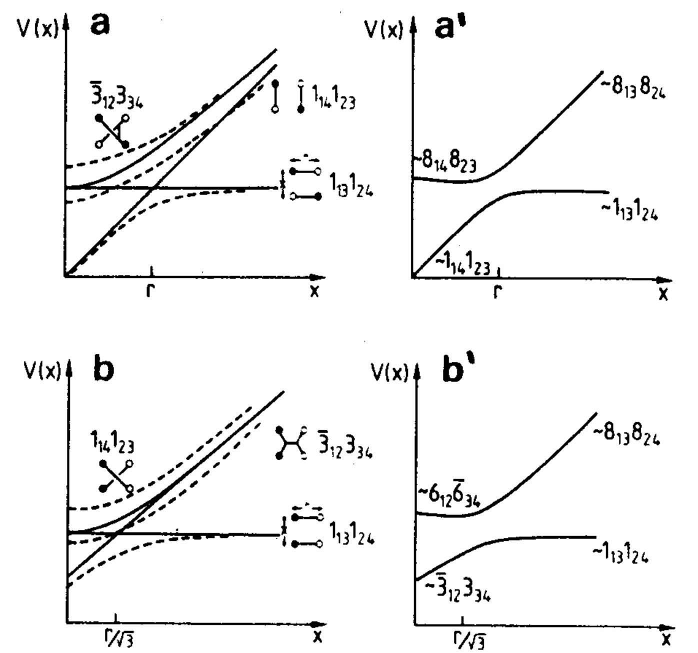
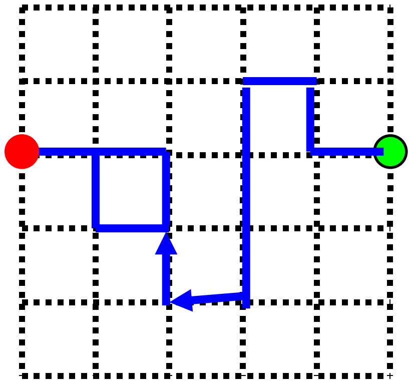


Fig. 1. The adiabatic potentials of the flux tube model and of the two body potential for two $qq\bar{q}\bar{q}$ arrangements: (a) and

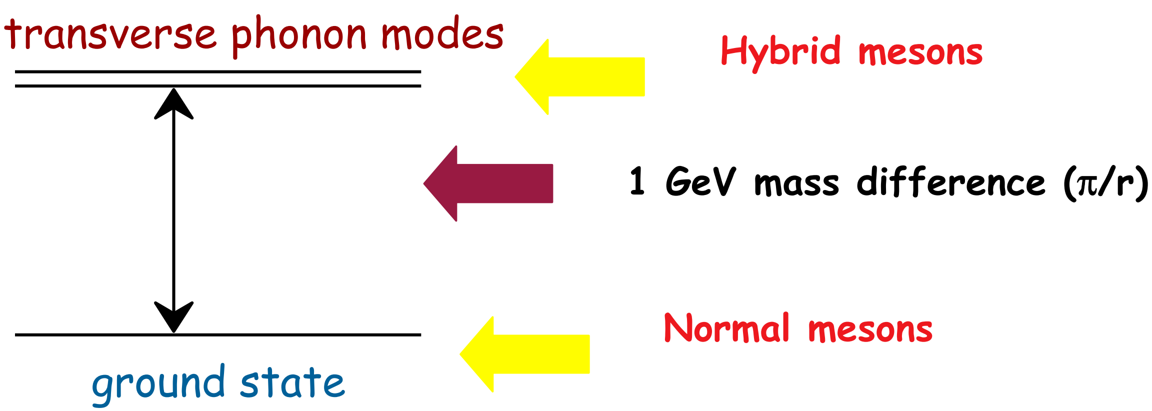
Hybrids



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
- Lowest excited adiabatic surface corresponds to transverse excitations



Lowest mass hybrids at 1.9 GeV

Doubly degenerate:

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

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

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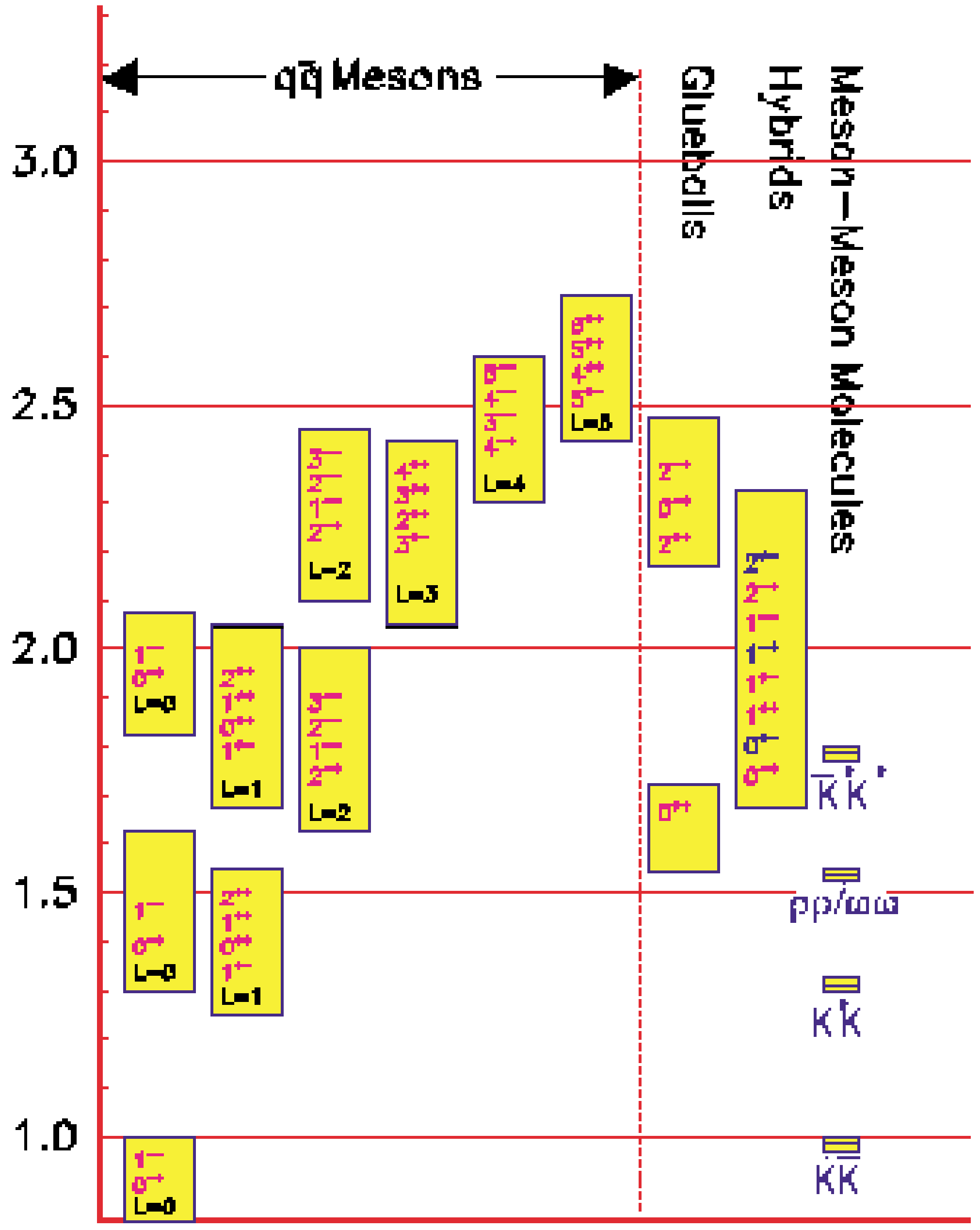
(Received 28 November 1984)

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., $B(1235)\pi$, $A_2(1320)\pi$, $K^*(1420)\bar{K}$, $\pi(1300)\pi, \ldots$] rather than to two ground-state mesons (e.g., $\pi\pi$, $\rho\pi$, $K^*\bar{K}, \ldots$). 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.

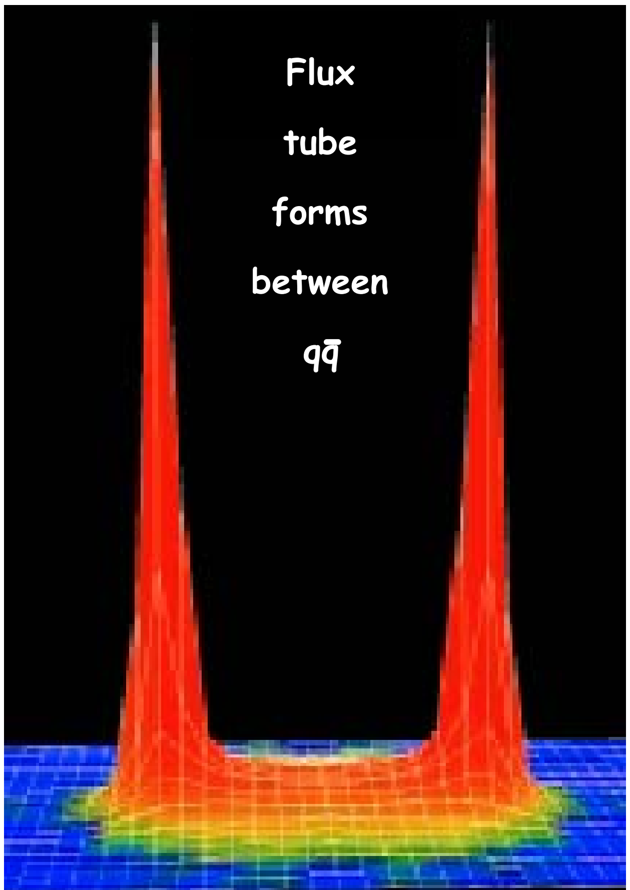

qq̄ Mesons
Glueballs
Hybrids
Meson−Meson Molecules
3.0
2.5
2.0
1.5
1.0
L=0
L=1
L=2
L=3
L=4
L=5
K̄K
K̄K*
ρρ/ωω

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

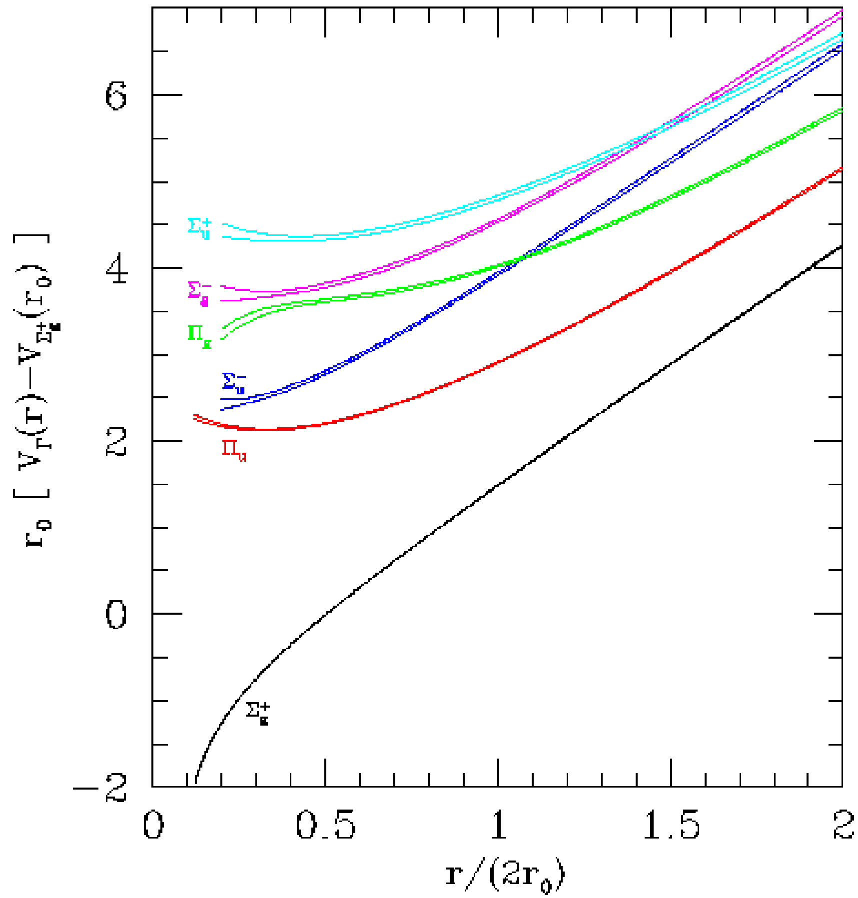
Predict that “diffractive photoproduction can produce plucked ρ, ω, and ϕ states so could be a good source for all four of the desirable exotics …”

Where are we now?

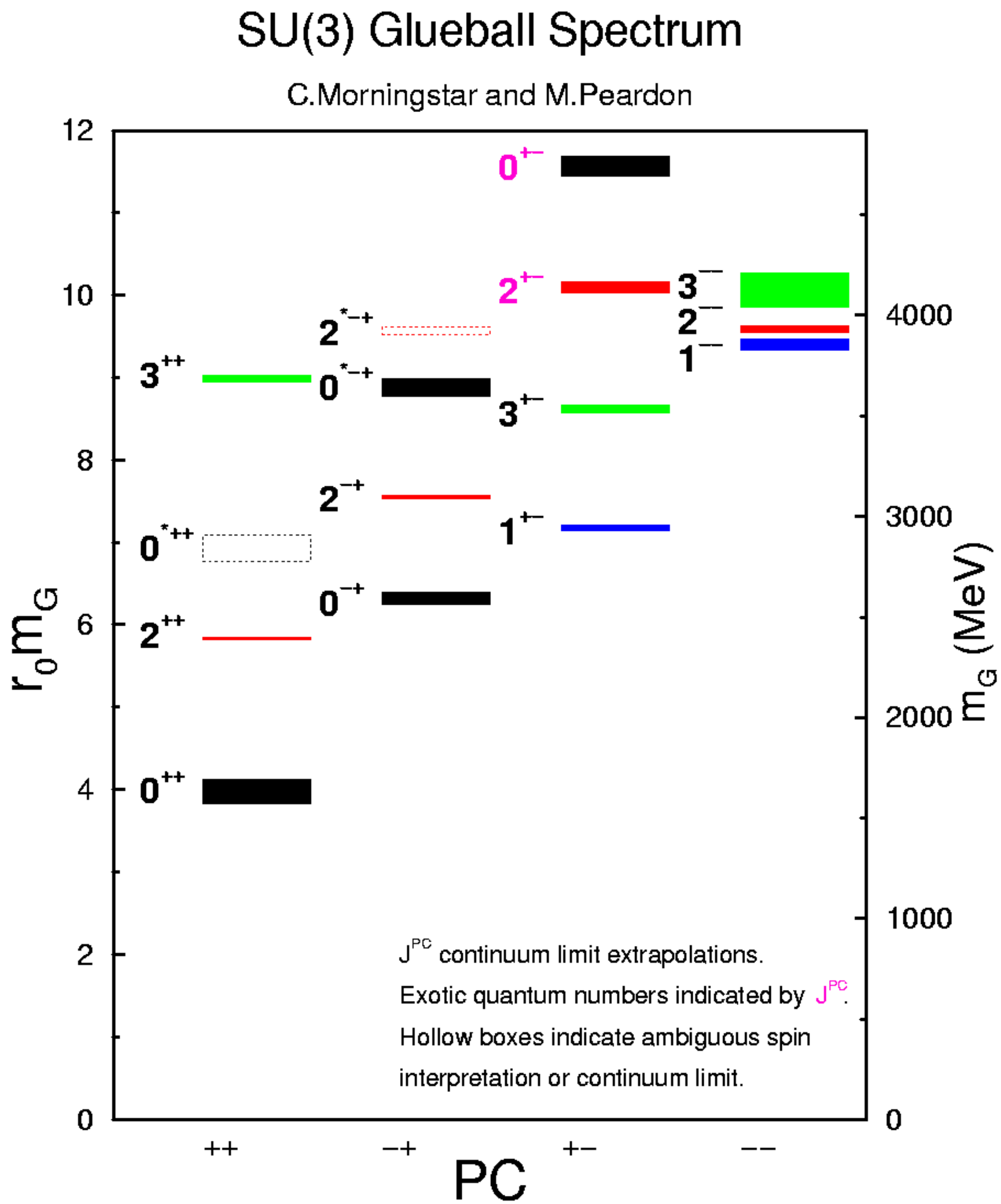
Lattice calculations have matured and supports the flux tube picture:



From G. Bali



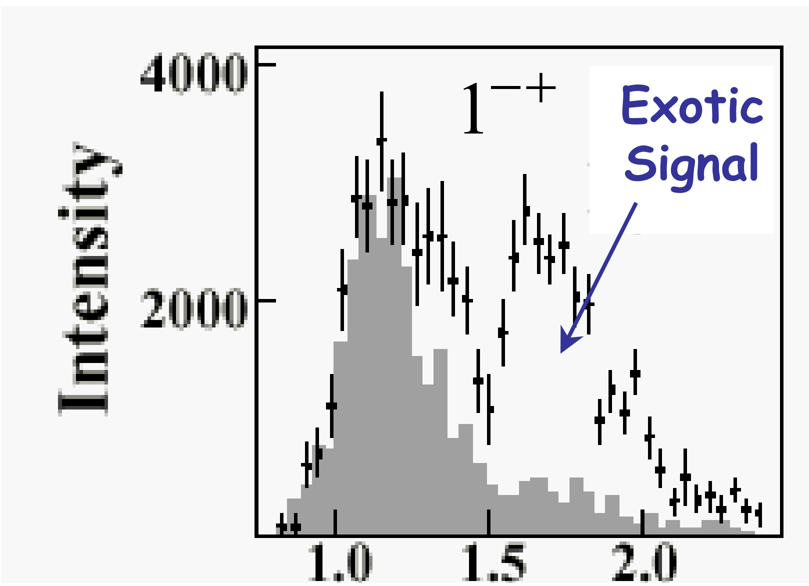
Juge, Kuti, and Morningstar,
Nucl. Phys. (Proc. Suppl.) **63A-C**, 326 (1998)


SU(3) Glueball Spectrum
C.Morningstar and M.Peardon
12
10
8
6
4
2
0
$r_0 m_G$
4000
3000
2000
1000
0
m_G (MeV)
0^{+-}
2^{+-}
3^{--}
2^{--}
1^{--}
2^{*-+}
3^{++}
0^{*-+}
3^{+-}
2^{-+}
1^{+-}
0^{*++}
0^{-+}
2^{++}
0^{++}
J^{PC} continuum limit extrapolations.
Exotic quantum numbers indicated by J^{PC}.
Hollow boxes indicate ambiguous spin
interpretation or continuum limit.
++
−+
+−
−−
PC

Where's the Glue?

An Exotic Signal in Brookhaven E852

$$\pi^- p \rightarrow \pi^+ \pi^- \pi^- p$$ **At 18 GeV/c**



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

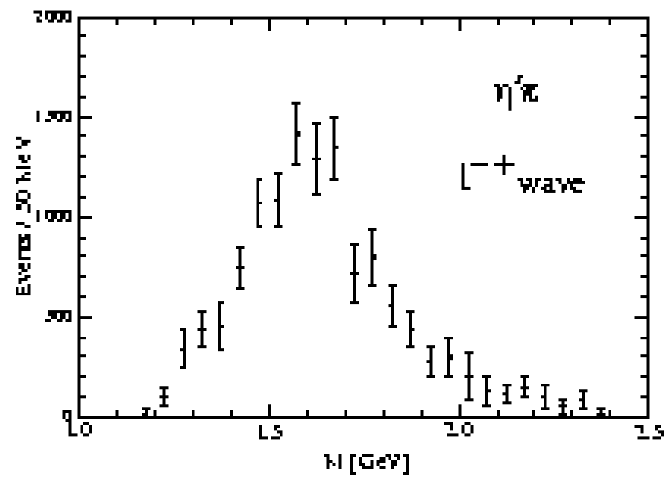


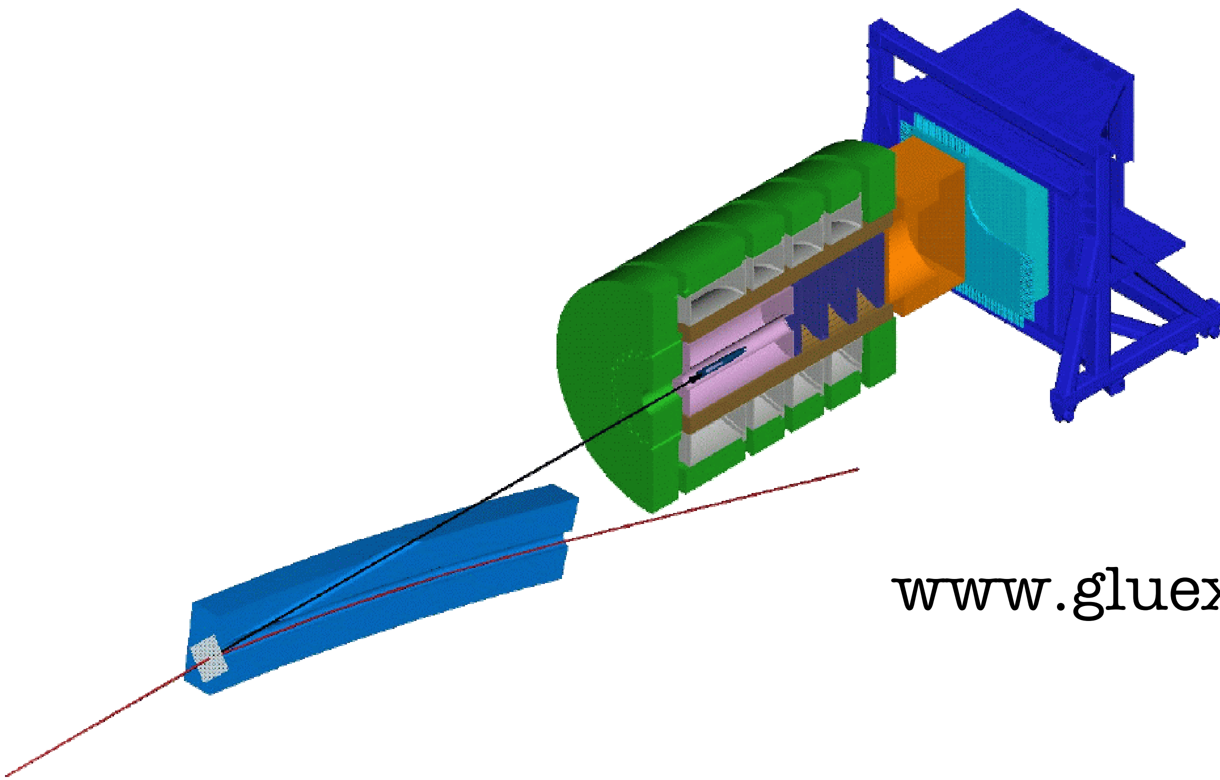
FIGURE 2. The E852 1^{-+} wave in $\eta'\pi^-$, showing a dominant $\pi_1(1600)$ exotic [11].

What about the future?

GLUE X CITATIONS PERIMENT

Hall D at Jefferson Lab

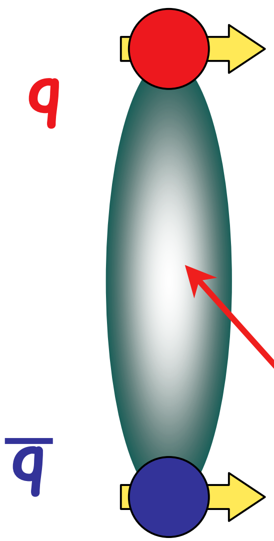
"Searching for Exotic Gluonic Excitations"



www.gluex.org

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

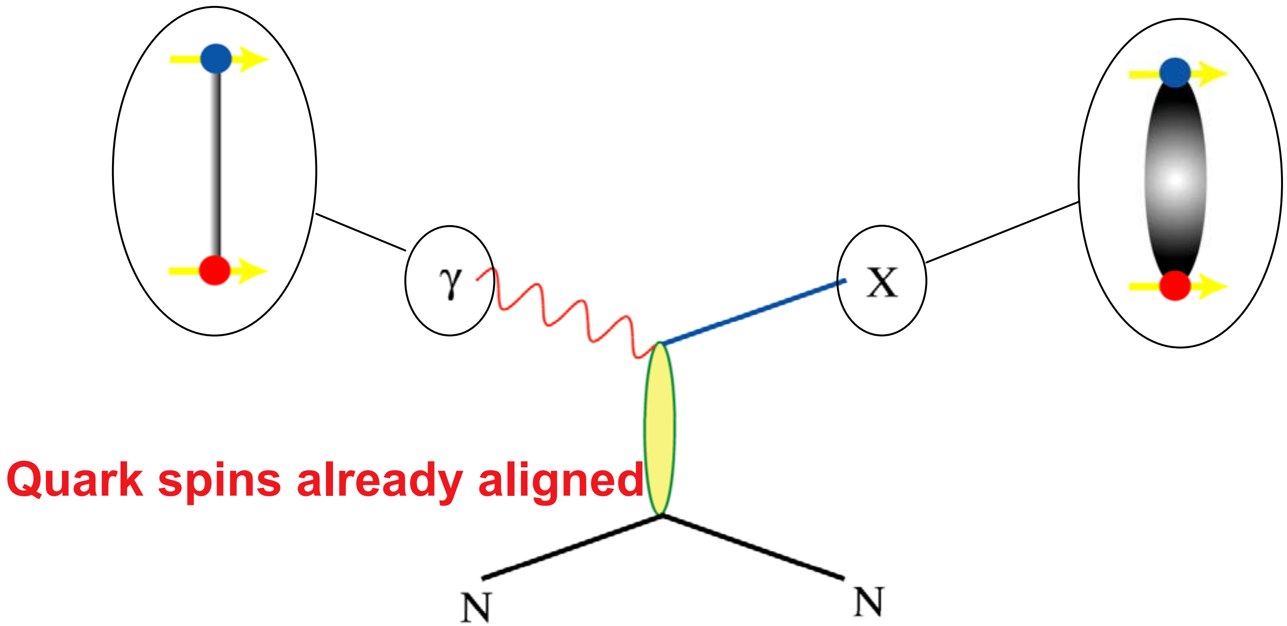
when combined with S=1 for quarks generate:

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

exotic

Like a vibrating string

Photoproduction:



Production of exotic hybrids favored.
Almost no data available

Optimum photon energy is about 9 GeV

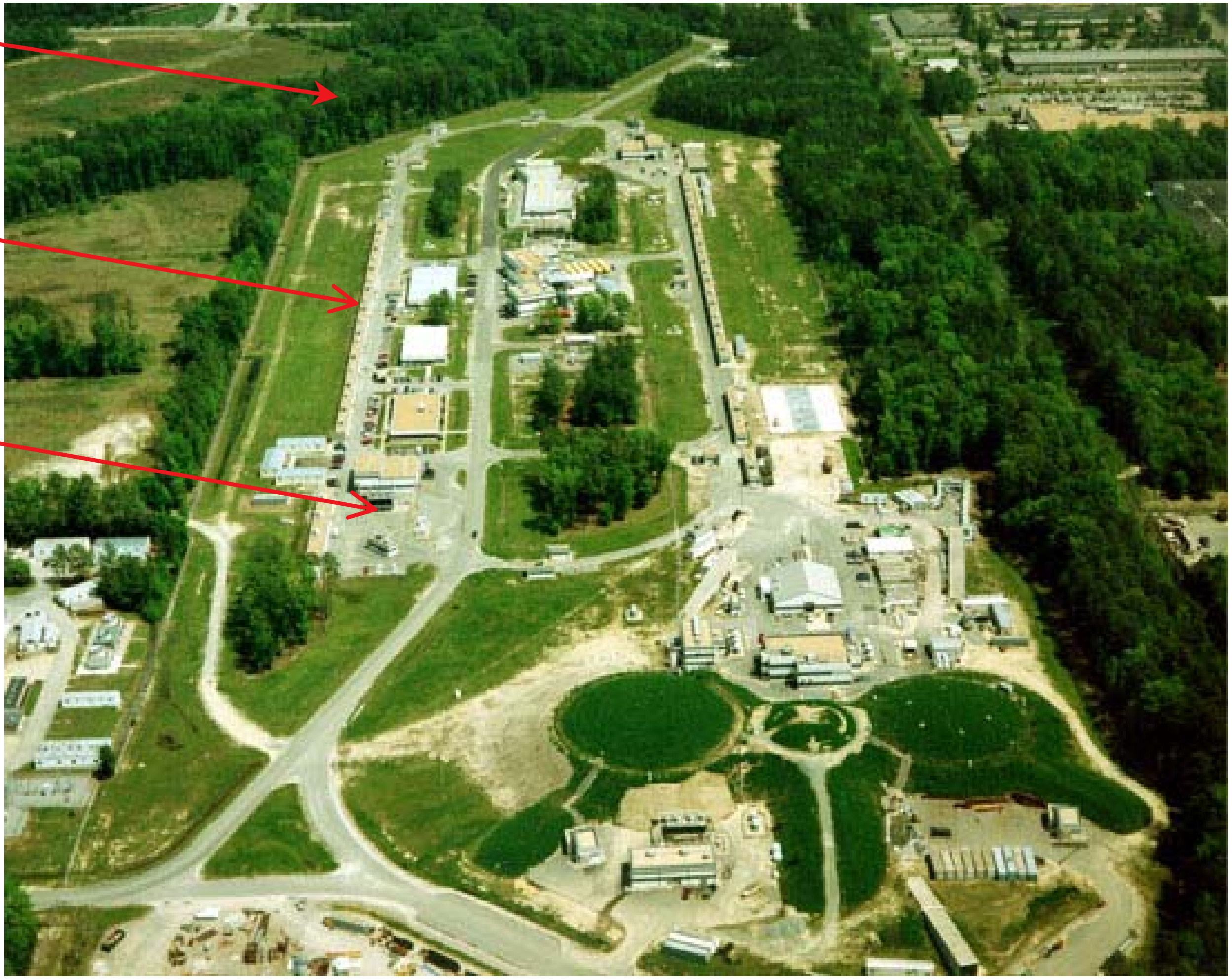
Proposal to upgrade CEBAF to 12 GeV
Produce photons through coherent bremsstrahlung

The JLab Accelerator Complex

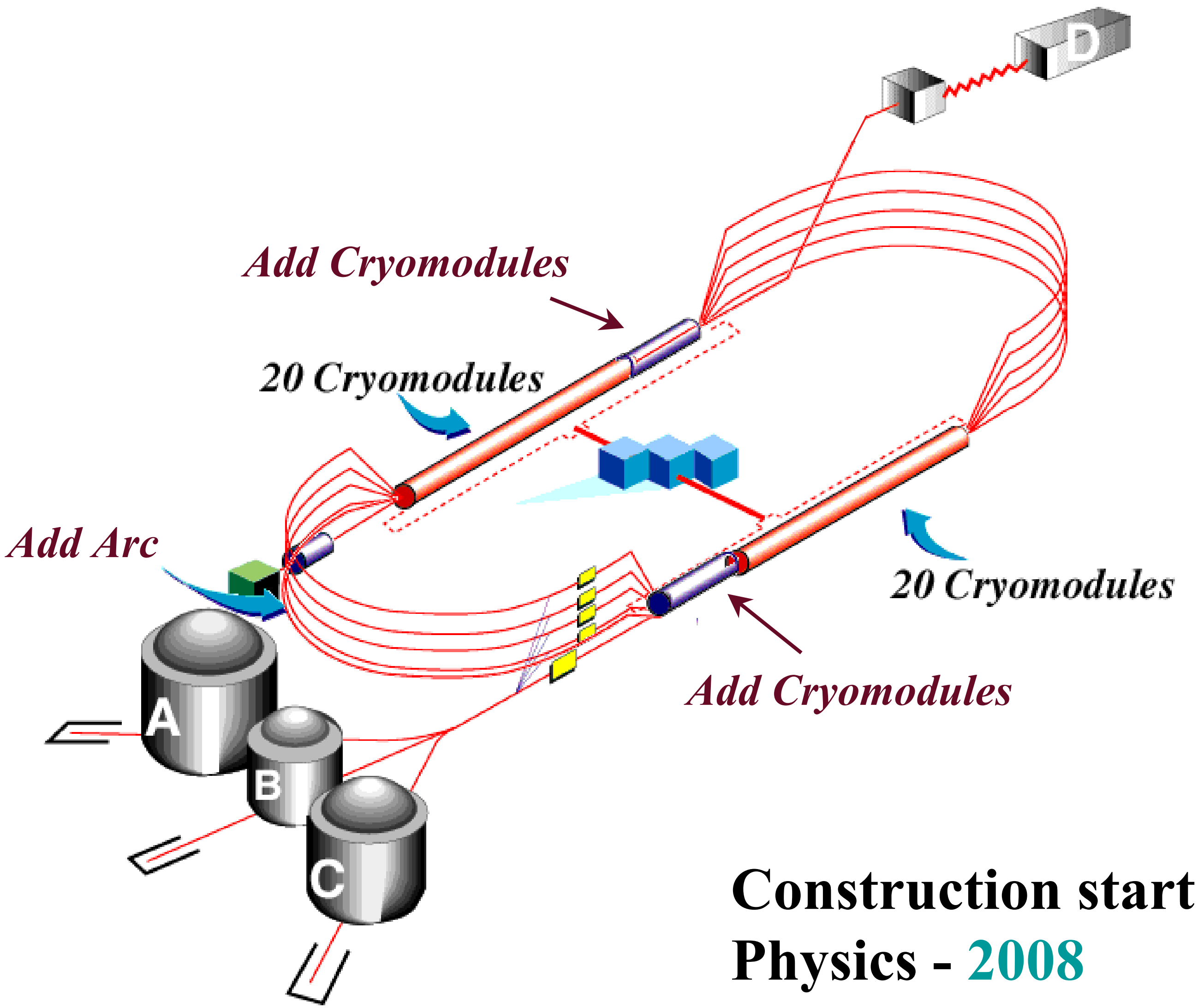
Hall D will be located here

Linac

Arc



Construction start – 2004 Physics - 2008



Construction start - 2004

Physics - 2008

Conclusion

- In the last decade there has been much theoretical progress especially in lattice QCD.
- Need comparable experimental results, especially on gluonic excitations, to understand the nature of confinement in QCD.
- Recent data provides hints of these excitations - but a detailed map of the hybrid spectrum is essential.
- Photoproduction promises to be rich in hybrids - starting with those possessing exotic quantum numbers and little or no data exist.
- The energy-upgraded JLab will provide photon beams along with a state-of-the-art detector to map out the hybrid spectrum

If exotic hybrids are there - we will find them.