Forefront Issues in Meson Spectroscopy

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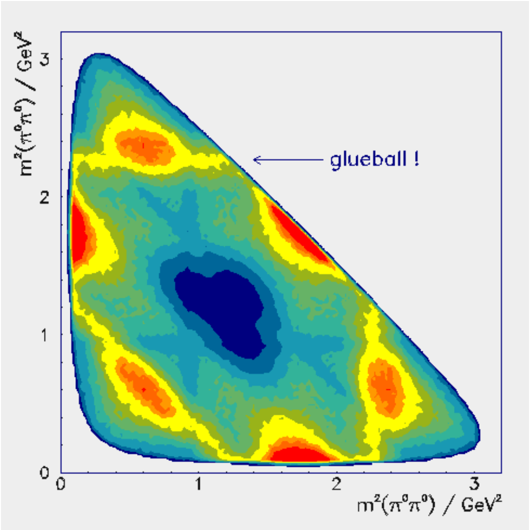
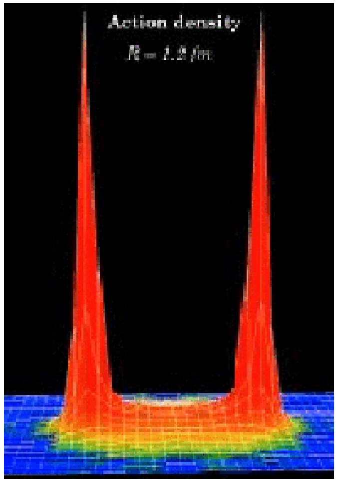
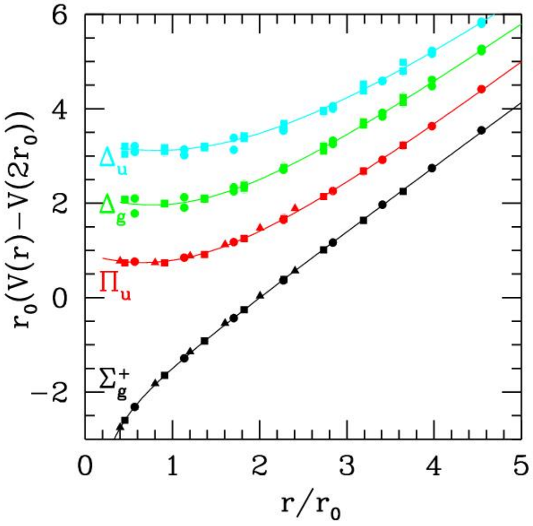
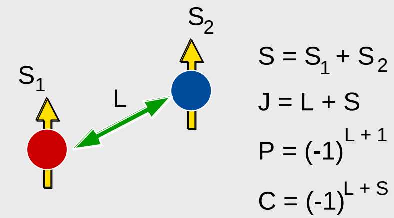


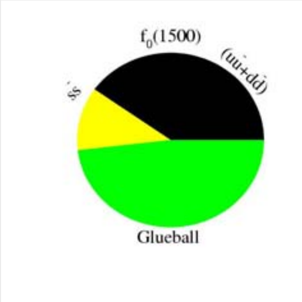


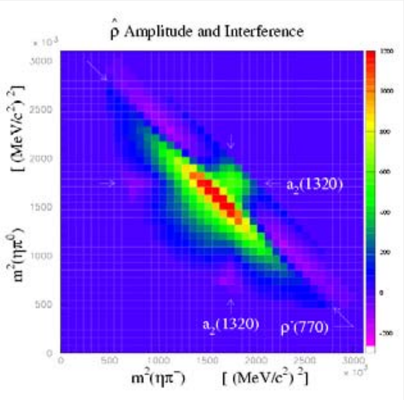


Outline of Talk

- Introduction
- Meson Spectroscopy
- Glueballs
  - Expectations
  - Experimental Data
  - Interpretation
- Hybrid Mesons
  - Expectations
  - Experimental Data
- Summary and Future



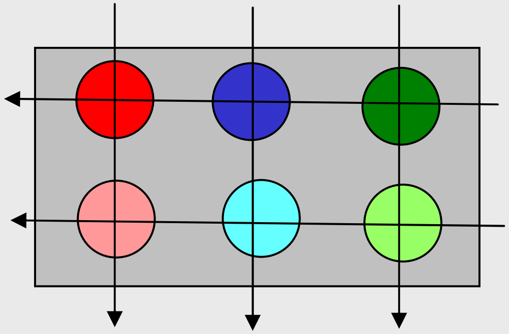




QCD is the theory of quarks and gluons

$$L_{QCD} = \overline{\psi}(i\gamma^{\mu}D_{\mu} - m)\psi - 1/2\, tr(G^{\mu\nu}G_{\mu\nu})$$

white



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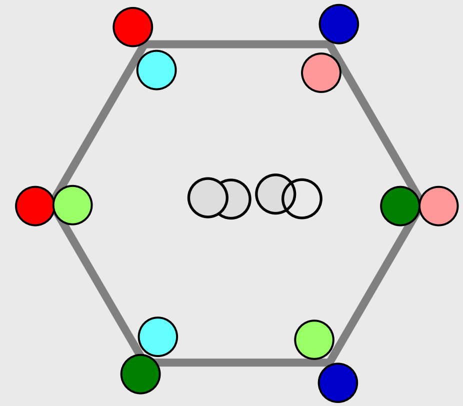
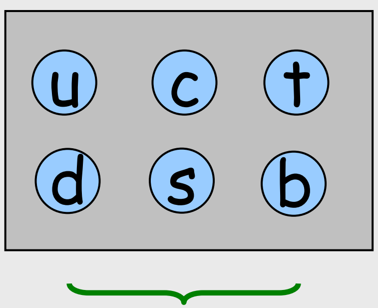
3 Colors
3 Anti-colors



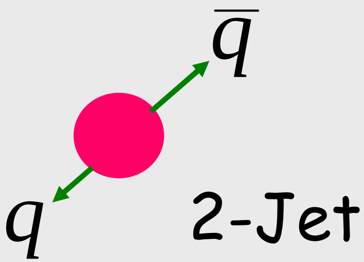
8 Gluons, each of which has a color an an anti-color Charge.

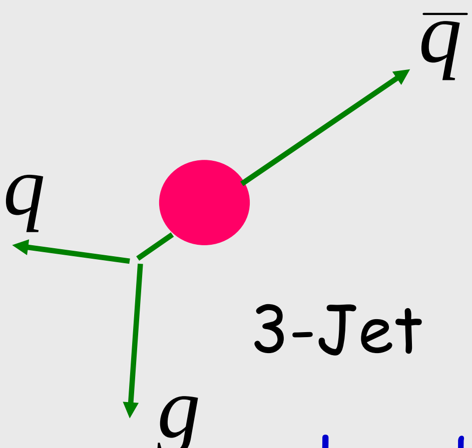


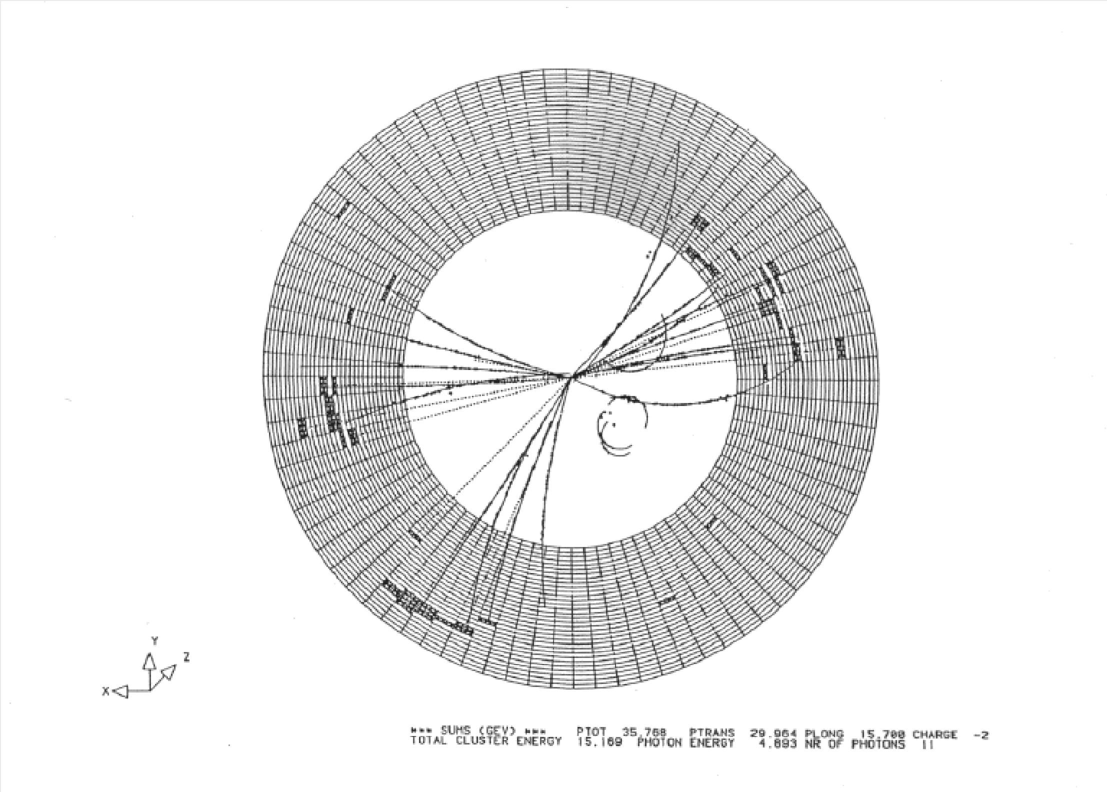
Six Flavors of quarks

Jets at High Energy

Direct evidence for gluons come from high energy jets. But this doesn't tell us anything about the "static" properties of glue. We learn something about α_s



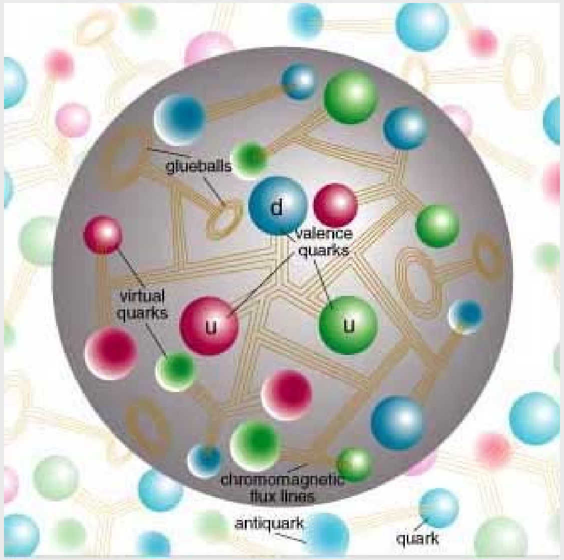


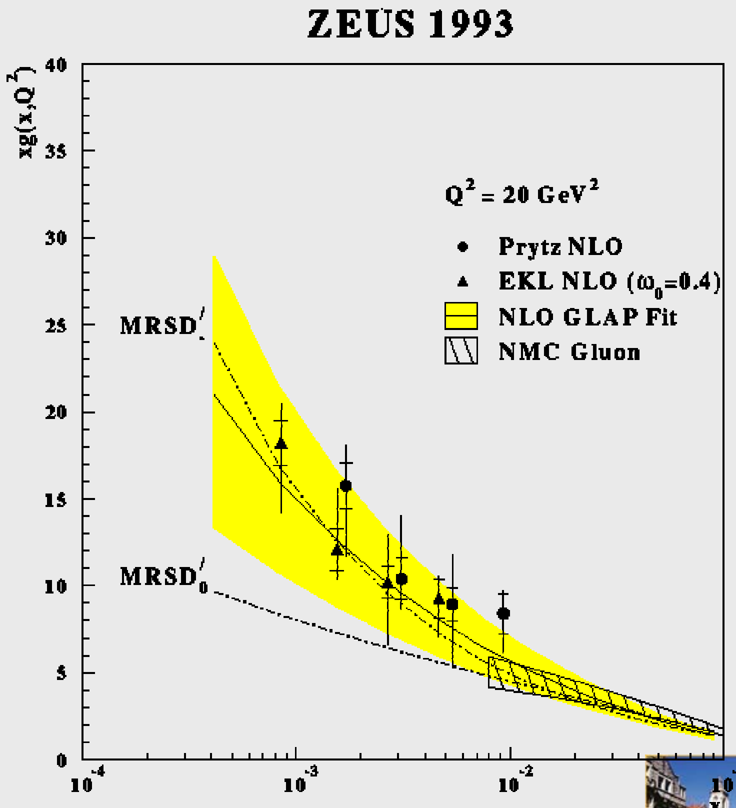


gluon bremsstrahlung $q(\bar{q}) \rightarrow q(\bar{q})g$

Deep Inelastic Scattering

As the nucleon is probed to smaller and smaller x, the gluons become more and more important. Much of the nucleon momentum and most of its spin is carried by gluons!



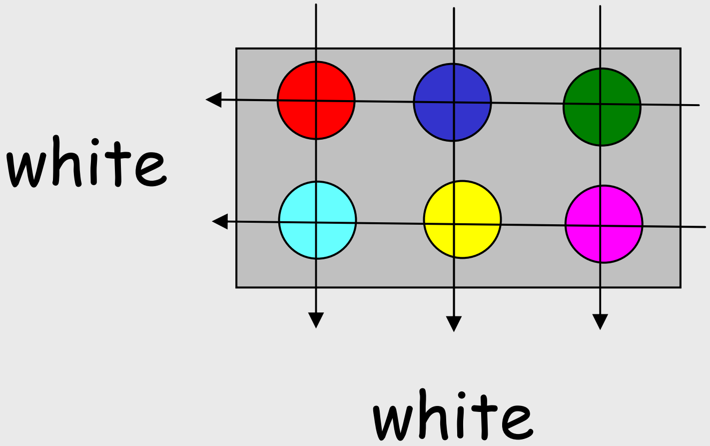


Glue is important to hadronic structure.

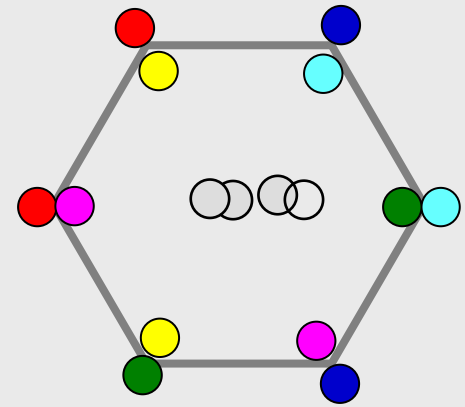
Strong QCD

See $q\bar{q}$ and qqq systems.

Color singlet objects observed in nature:



Nominally, glue is not needed to describe hadrons.



$u \quad \bar{u}$

$d \quad \bar{d}$

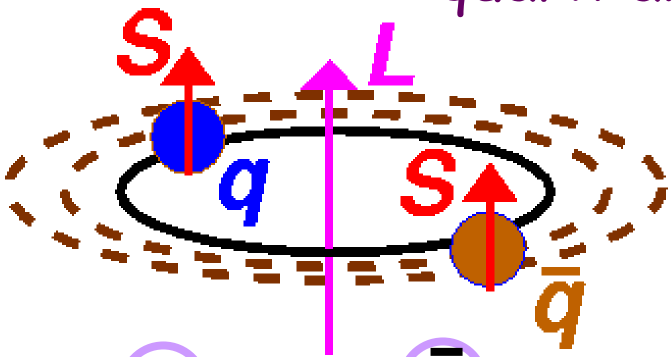
$s \quad \bar{s}$

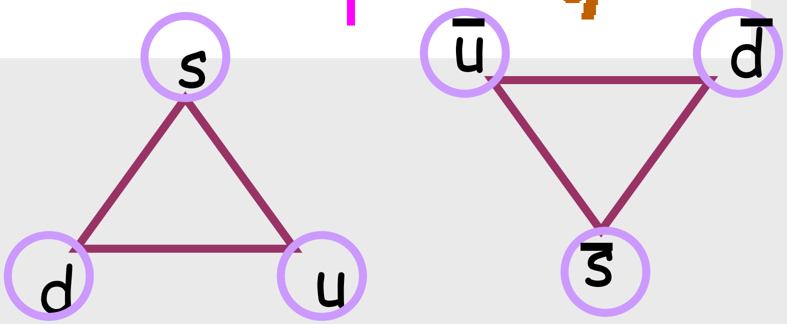
Focus on "light-quark mesons"

Allowed systems: gg, ggg, $q\bar{q}g$, $q\bar{q}q\bar{q}$

Normal Mesons

quark-antiquark pairs





$J = L + S$

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

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

$G = C\,(-1)^{I}$

$^{(2S+1)}L_J$

$^1S_0 = 0^{-+}$

$^3S_1 = 1^{--}$

Non-quark-antiquark

0^{--} 0^{+-} 1^{-+} 2^{+-} 3^{-+} ...

orbital ↑

radial →

L=2	$\rho_3, \omega_3, \phi_3, K_3$	3^{--}
	$\rho_2, \omega_2, \phi_2, K_2$	2^{--}
	$\rho_1, \omega_1, \phi_1, K_1$	1^{--}
	$\pi_2, \eta_2, \eta'_2, K_2$	2^{-+}
L=1	a_2, f_2, f'_2, K_2	2^{++}
	a_1, f_1, f'_1, K_1	1^{++}
	a_0, f_0, f'_0, K_0	0^{++}
	b_1, h_1, h'_1, K_1	1^{+-}
L=0	ρ, ω, ϕ, K^*	1^{--}
	π, η, η', K	0^{-+}

Nonet Mixing

The I=0 members of a nonet can mix:

$$|1\rangle = \frac{1}{\sqrt{3}}\left(u\bar{u} + d\bar{d} + s\bar{s}\right)$$

$$|8\rangle = \frac{1}{\sqrt{6}}\left(u\bar{u} + d\bar{d} - 2s\bar{s}\right)$$

SU(3)

$$\begin{vmatrix} f \\ f' \end{matrix}\rangle = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{vmatrix} 1 \\ 8 \end{matrix}\rangle$$

physical states

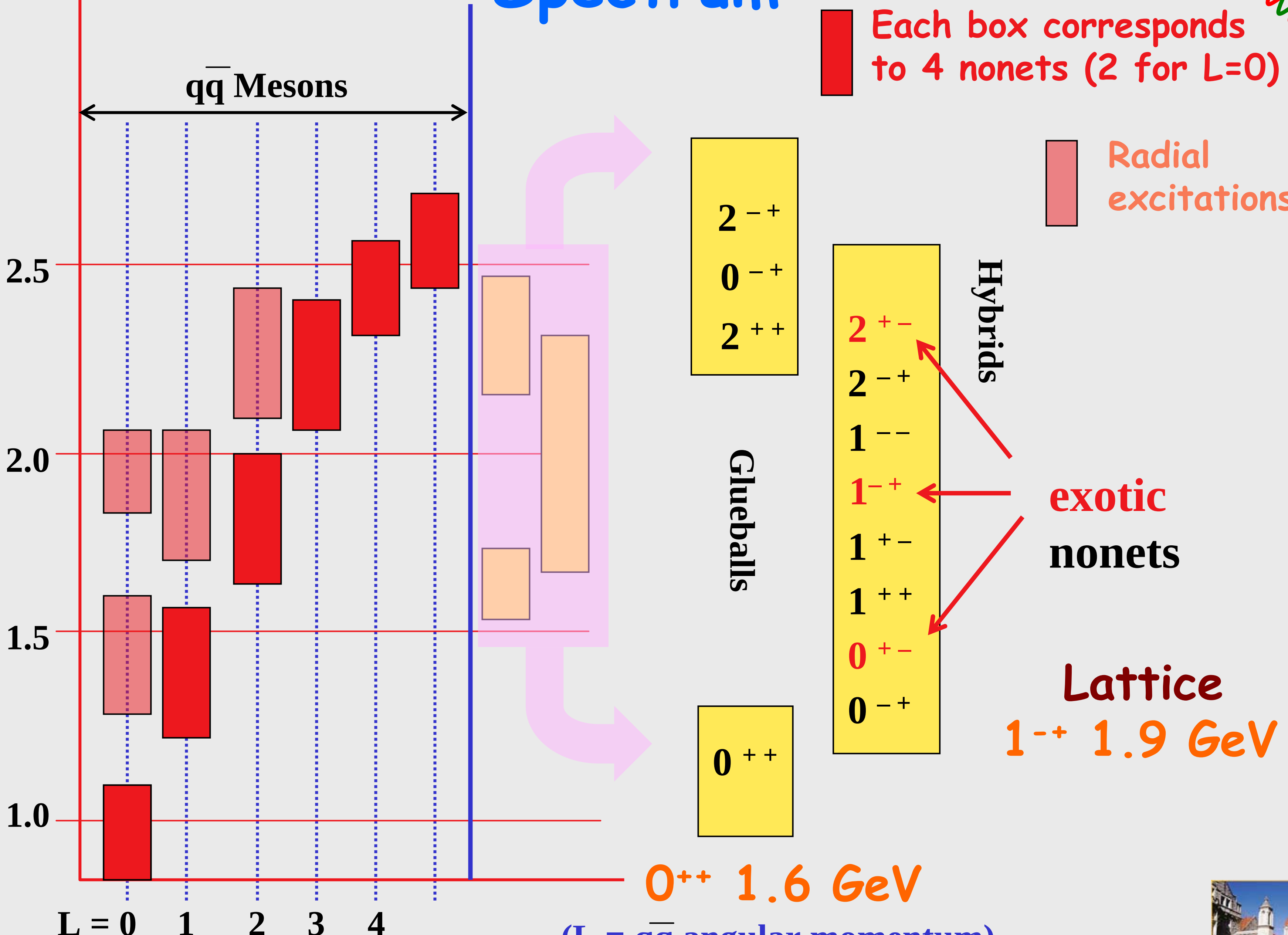
Ideal Mixing:

$$\cos\theta = \sqrt{\frac{2}{3}}$$

$$\sin\theta = \sqrt{\frac{1}{3}}$$

$$\begin{vmatrix} f \\ f' \end{matrix}\rangle = \begin{vmatrix} \frac{1}{\sqrt{2}}\left(u\bar{u} + d\bar{d}\right) \\ s\bar{s} \end{matrix}\rangle$$

Spectrum



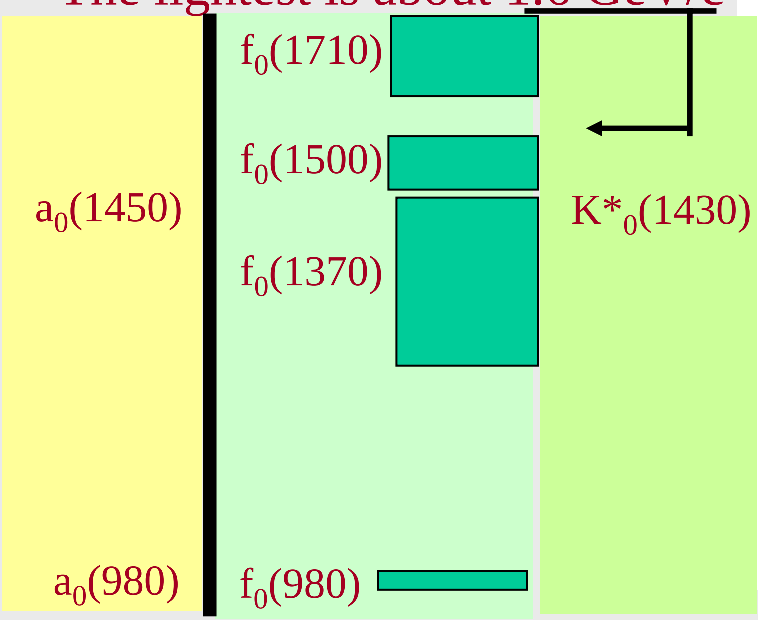
(L = $q\bar{q}$ angular momentum)

QCD is a theory of quarks and gluons

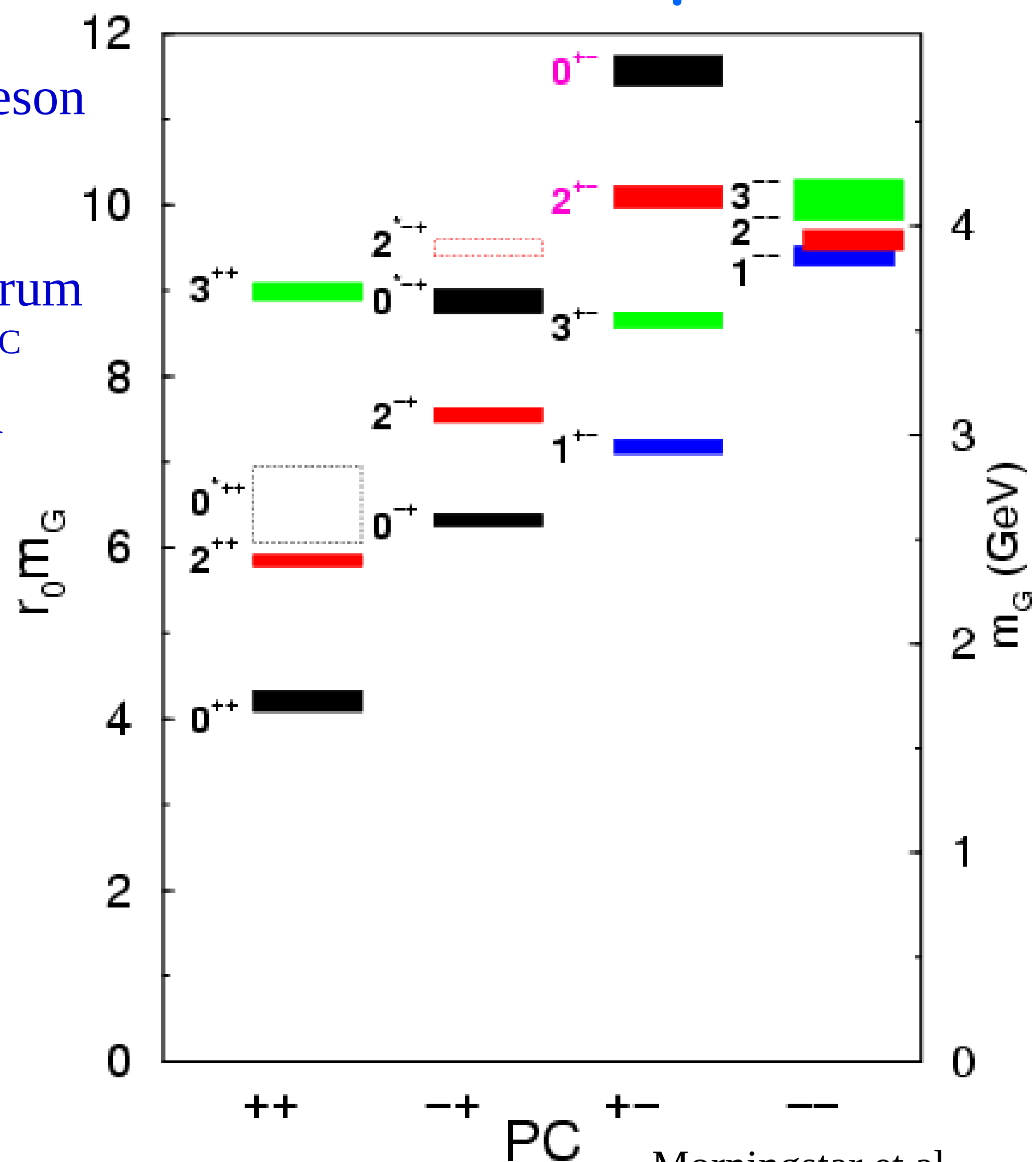
What role do gluons play in the meson spectrum?

Lattice calculations predict a spectrum of glueballs. The lightest 3 have J^{PC} Quantum numbers of 0^{++} , 2^{++} and 0^{-+}.

The lightest is about 1.6 GeV/c^2



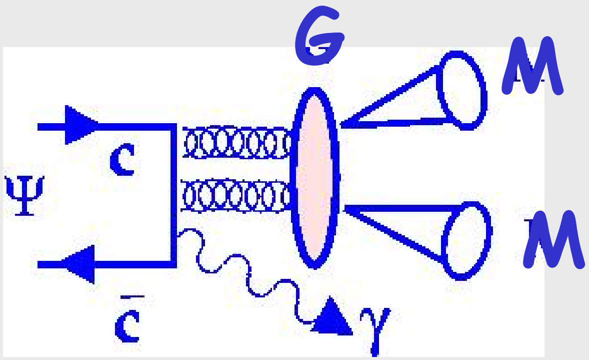
Glueball Mass Spectrum



Morningstar et al.

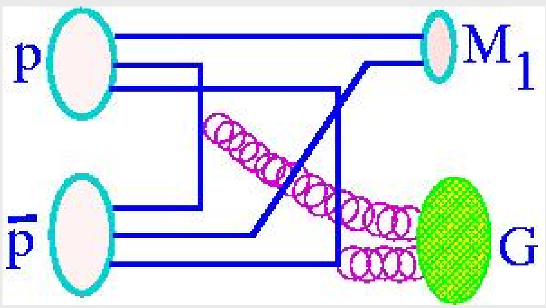
Glue-rich channels

Where should you look experimentally for Glueballs?

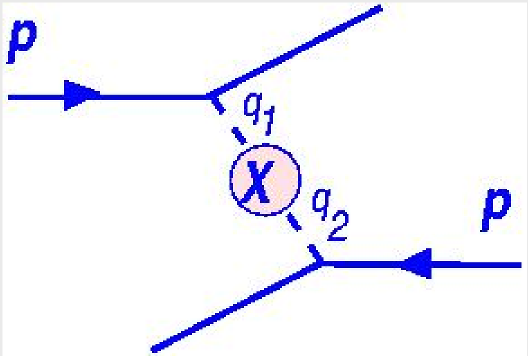


Radiative J/ψ Decays

0^{-+} $\eta(1440)$
0^{++} $f_0(1710)$ } Large signals



Proton-Antiproton Annihilation



Central Production
(double-pomeron exchange)

Decays of Glueballs?

Glueballs should decay in a flavor-blind fashion.

$$\pi\pi : K\overline{K} : \eta\eta : \eta'\eta' : \eta\eta' = 3 : 4 : 1 : 1 : 0$$

$\eta\eta'$=0 is true for any SU(3) singlet and for any pseudoscalar mixing angle. Only an SU(3) "8" can couple to $\eta\eta'$.

Flavor-blind decays have always been cited as glueball signals. Not necessarily true – coupling proportional to daughter mass can distort this.

Crystal Barrel Results: antiproton-proton annihilation at rest

$$p\bar{p} \rightarrow X\pi$$

Study decays of X

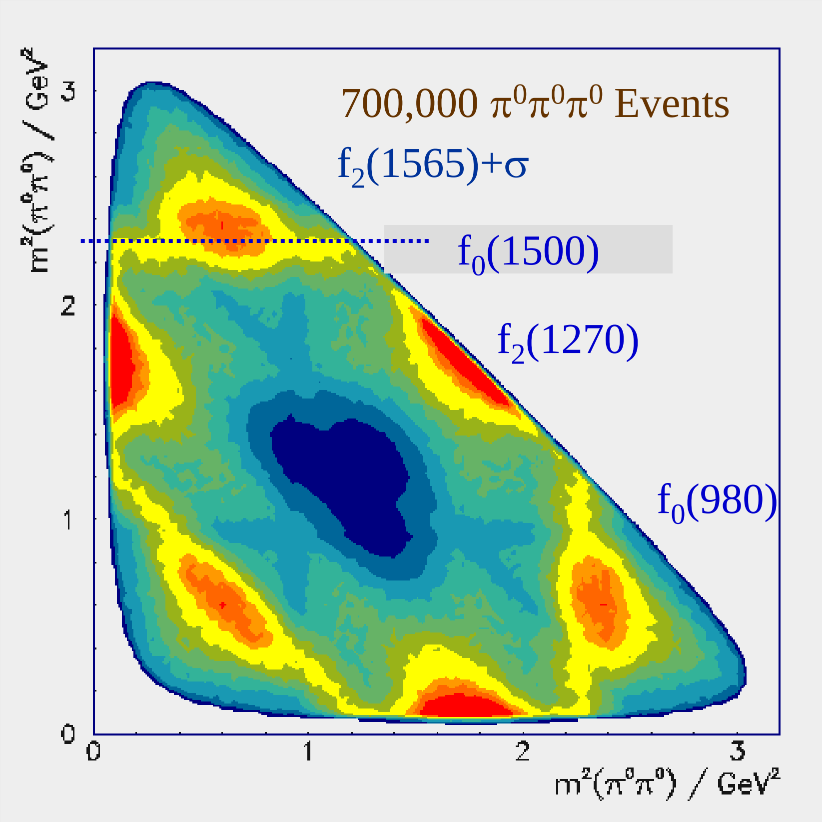
Discovery of the $f_0(1500)$

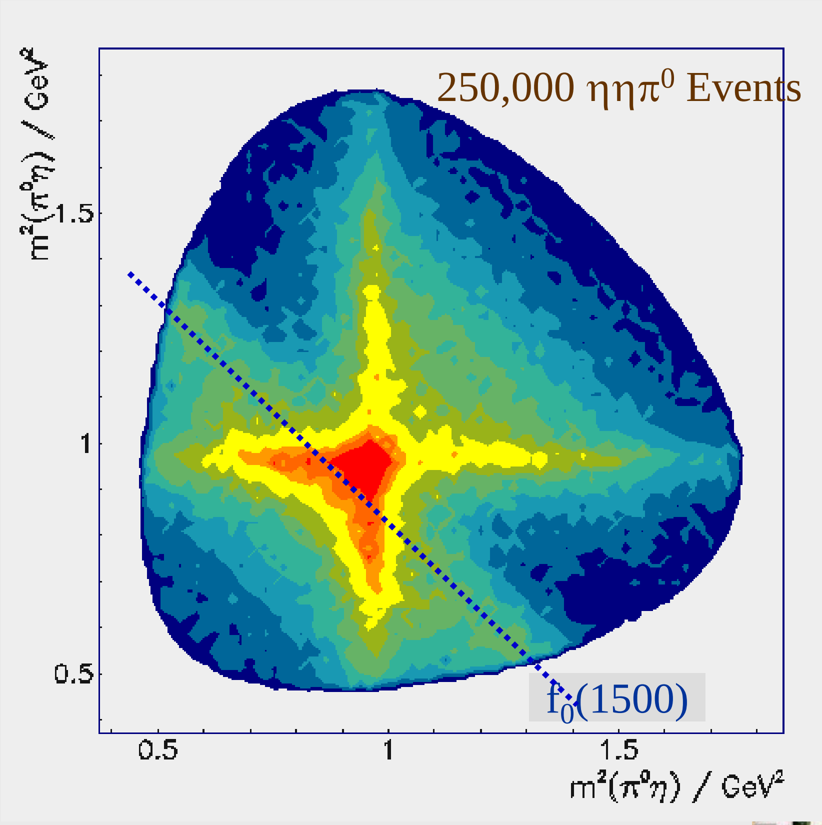
Solidified the $f_0(1370)$

Discovery of the $a_0(1450)$ → Establishes the scalar nonet

$f_0(1500)$ ⇨ ππ, ηη, ηη', KK, 4π

$f_0(1370)$ ⇨ 4π





The $f_0(1500)$

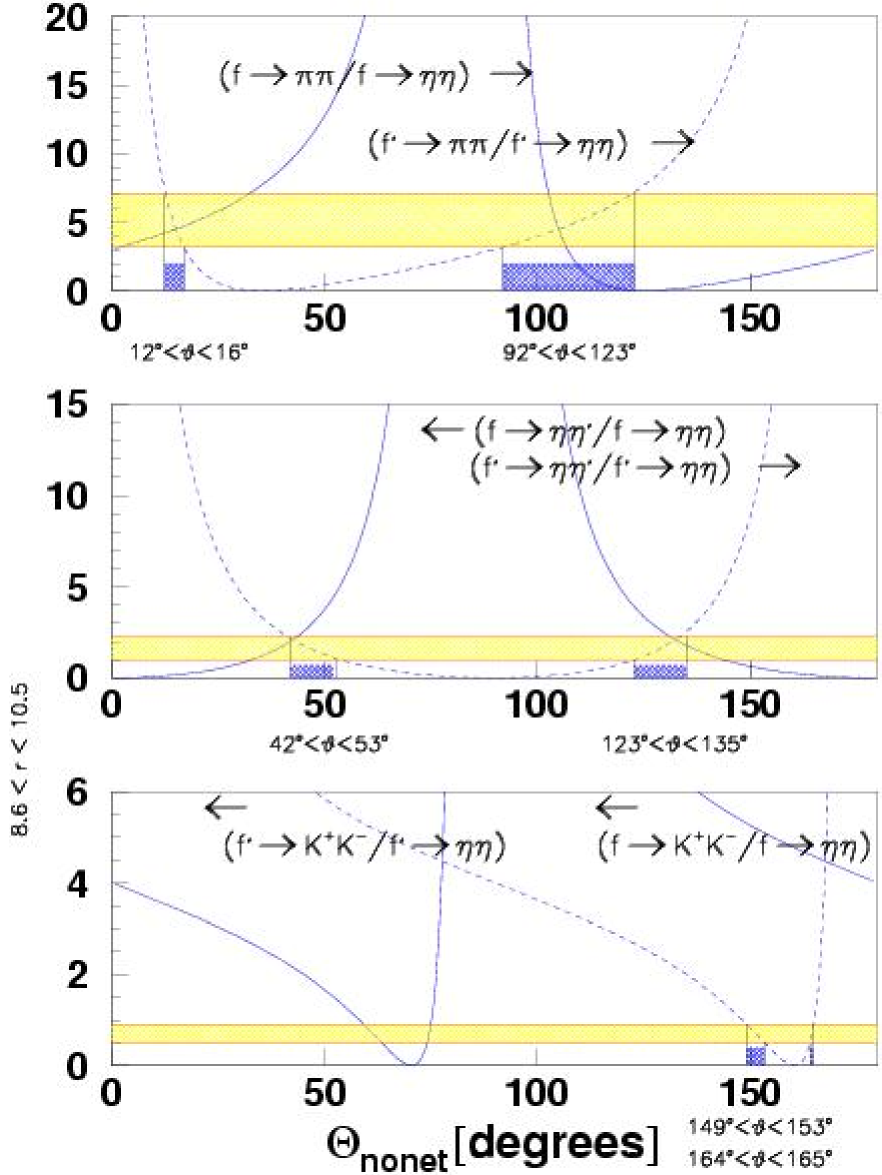
Is it possible to describe the $f_0(1500)$ as a member of a meson nonet?

$$\left|\begin{matrix} f_0(1370) \\ f_0(1500) \end{matrix}\right\rangle = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \left|\begin{matrix} 1 \\ 8 \end{matrix}\right\rangle$$

Use SU(3) and OZI suppression to compute relative decays to pairs of pseudoscalar mesons

Get an angle of about 143°

90% light-quark
10% strange-quark

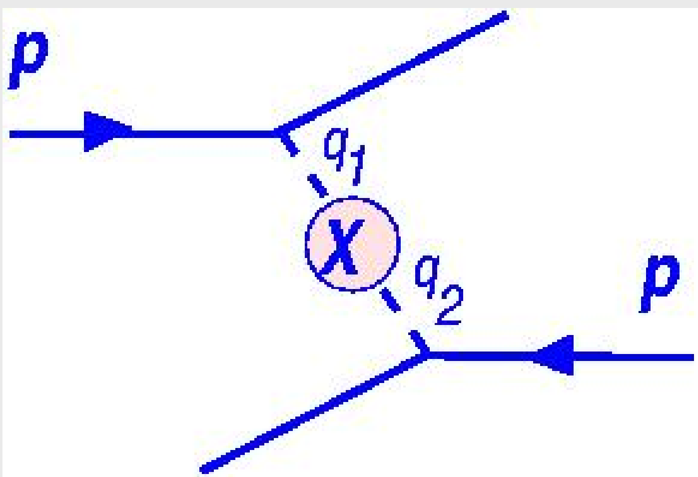


Both the $f_0(1370)$ and $f_0(1500)$ are $u\bar{u}$ & $d\bar{d}$

WA102 Results

CERN experiment colliding p on a hydrogen target.

Central Production Experiment



Recent comprehensive data set and a coupled channel analysis.

$$\frac{f_0(1370)\to\pi\pi}{f_0(1370)\to K\bar{K}} = 2.17 \pm 0.90$$

$$\frac{f_0(1370)\to\eta\eta}{f_0(1370)\to K\bar{K}} = 0.35 \pm 0.21$$

$$\frac{f_0(1500)\to\pi\pi}{f_0(1500)\to \eta\eta} = 5.5 \pm 0.84$$

$$\frac{f_0(1500)\to K\bar{K}}{f_0(1500)\to \pi\pi} = 0.32 \pm 0.07$$

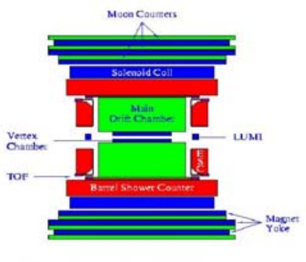
$$\frac{f_0(1500)\to\eta\eta'}{f_0(1500)\to \eta\eta} = 0.52 \pm 0.16$$

$$\frac{f_0(1710)\to\pi\pi}{f_0(1710)\to K\bar{K}} = 0.20 \pm 0.03$$

$$\frac{f_0(1710)\to\eta\eta}{f_0(1710)\to K\bar{K}} = 0.48 \pm 0.14$$

$$\frac{f_0(1710)\to\eta\eta'}{f_0(1710)\to \eta\eta} < 0.05 (90\% cl)$$

BES Results $J/\psi \to \gamma X$



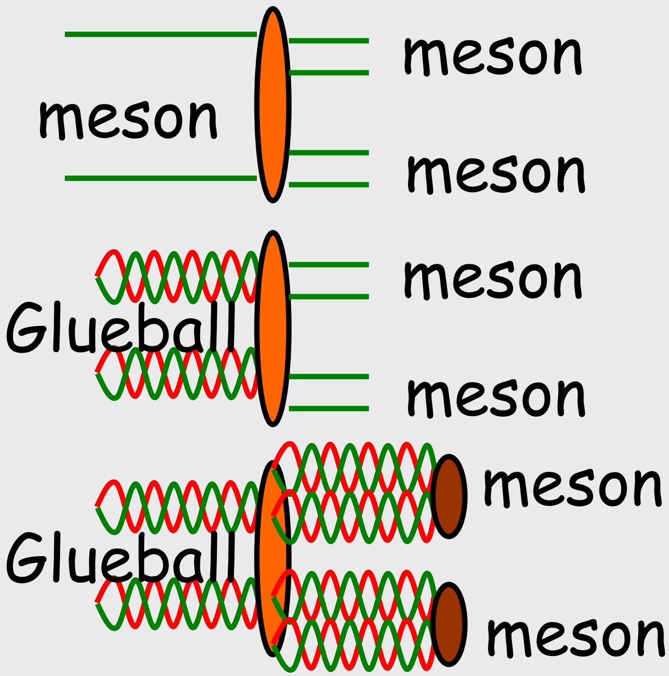
Side view of the BES detector

$J/\psi \to \gamma f_0(1500) \Rightarrow f_0(1500) \to \pi^+\pi^-$	0.665 10^{-4}
$J/\psi \to \gamma f_0(1500) \Rightarrow f_0(1500) \to \pi^0\pi^0$	0.34 10^{-4}
$J/\psi \to \gamma f_0(1500) \Rightarrow f_0(1500) \to \pi^+\pi^-\pi^+\pi^-$	3.1 10^{-4}

$J/\psi \to \gamma f_0(1710) \Rightarrow f_0(1710) \to \pi^+\pi^-$	2.64 10^{-4}
$J/\psi \to \gamma f_0(1710) \Rightarrow f_0(1710) \to \pi^0\pi^0$	1.33 10^{-4}
$J/\psi \to \gamma f_0(1710) \Rightarrow f_0(1710) \to K\bar{K}$	9.62 10^{-4}
$J/\psi \to \gamma f_0(1710) \Rightarrow f_0(1710) \to \pi^+\pi^-\pi^+\pi^-$	3.1 10^{-4}

Clear Production of $f_0(1500)$ and $f_0(1710)$, no report of the $f_0(1370)$. $f_0(1710)$ has strongest production.

Model for Mixing



1

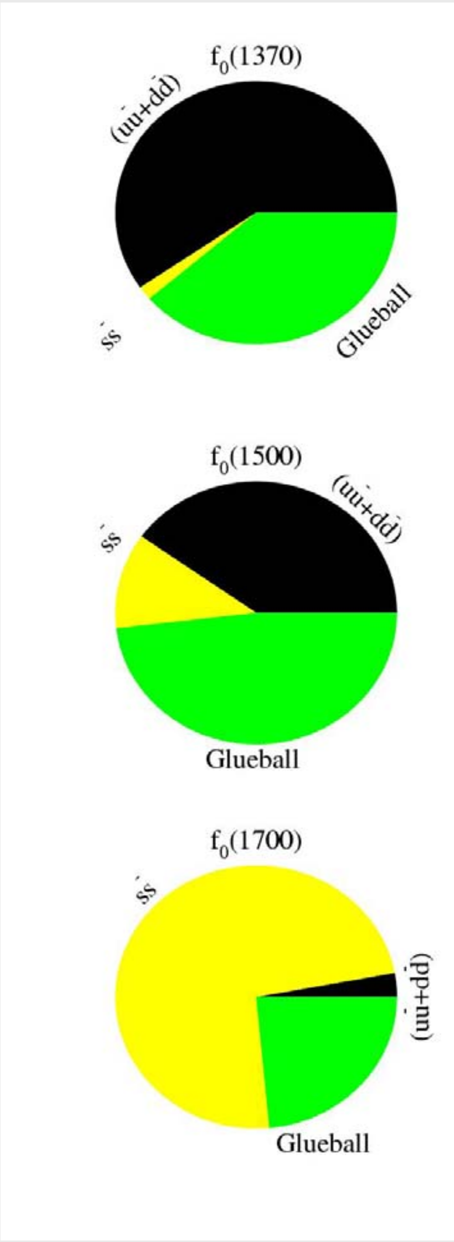
r_2

r_3

$G \rightarrow q\bar{q}$ flavor blind? r

$u\bar{u}, d\bar{d}, s\bar{s}$

Solve for mixing scheme



F.Close: hep-ph/0103173

Meson Glueball Mixing

Physical Masses

$f_0(1370), f_0(1500), f_0(1710)$

Bare Masses:

m_1, m_2, m_G

$$\frac{(u\bar{u} + d\bar{d})}{\sqrt{2}}$$

$$s\bar{s}$$

	(G)	(S)	(N)	
$f_0(1370)$	-0.69 ± 0.07	0.15 ± 0.01	0.70 ± 0.07	$\sim(\|1\rangle - \|G\rangle)$
$f_0(1500)$	-0.65 ± 0.04	0.33 ± 0.04	-0.70 ± 0.07	$\sim(\|8\rangle - \|G\rangle)$
$f_0(1710)$	0.39 ± 0.03	0.91 ± 0.02	0.15 ± 0.02	$\sim(\|1\rangle + \|G\rangle)$

$m_1 = 1377 \pm 20$ $m_2 = 1674 \pm 10$ $m_G = 1443 \pm 24$

Lattice of about 1600

Glueball Expectations

Antiproton-proton: Couples to $(u\bar{u} + d\bar{d})$
Observe: $f_0(1370)$, $f_0(1500)$

Central Production: Couples to G and $(u\bar{u} + d\bar{d})$ in phase.
Observe: $f_0(1370)$, $f_0(1500)$, weaker $f_0(1710)$.

Radiative J/ψ: Couples to G, |1>, suppressed |8>
Observe strong $f_0(1710)$ from constructive |1>+G
Observe $f_0(1500)$ from G
Observe weak $f_0(1370)$ from destructive |1>+G

Two photon: Couples to the quark content of states, not to the glueball. Not clear to me that $\gamma\gamma \rightarrow f_0$ has been seen.

Higher mass glueballs?

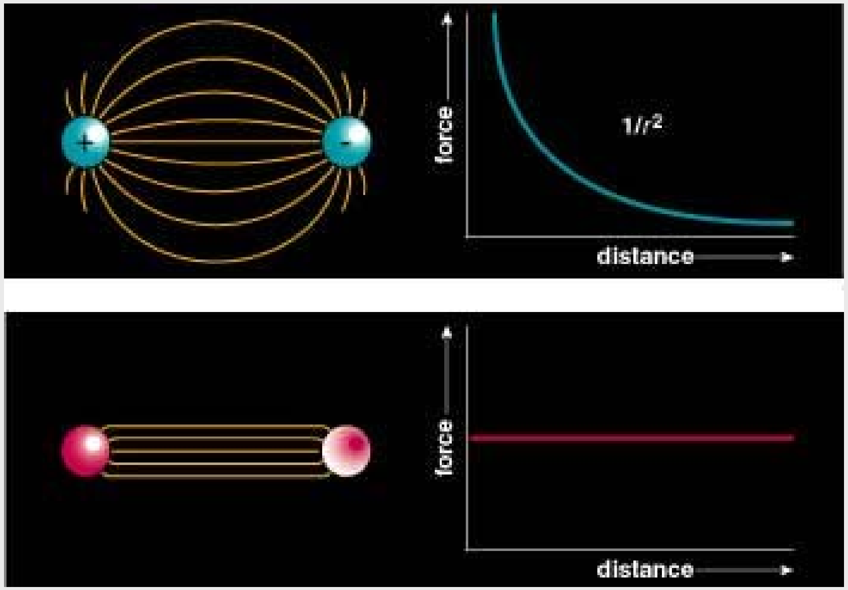
Lattice predicts that the 2^{++} and the 0^{-+} are the next two, with masses just above $2 GeV/c^2$.

Radial Excitations of the 2^{++} ground state
L=3 2^{++} States + Radial excitations
$f_2(1950)$, $f_2(2010)$, $f_2(2300)$, $f_2(2340)$…

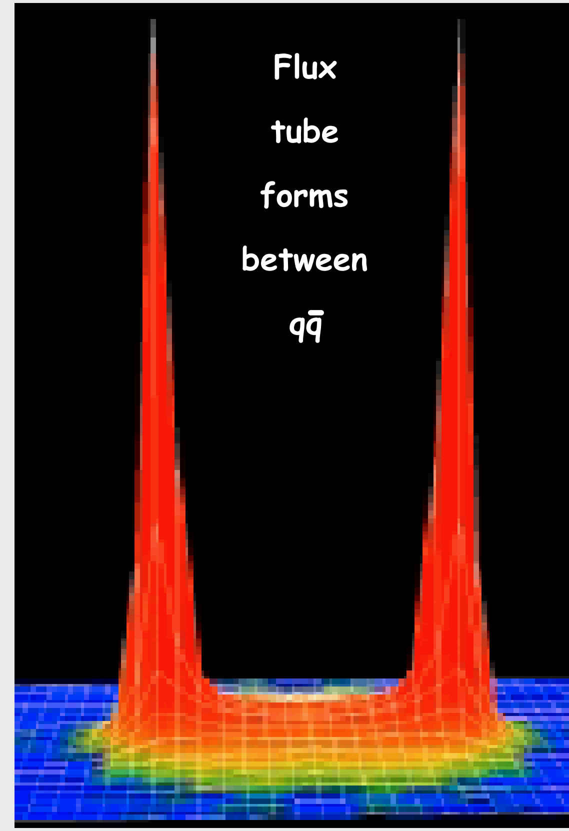
2'nd Radial Excitations of the η and η', perhaps a bit cleaner environment! (I would Not count on it though….)

I expect this to be very challenging. Evidence from BES for an $\eta(1760) \rightarrow \omega\omega$.

Lattice QCD Flux Tubes Realized



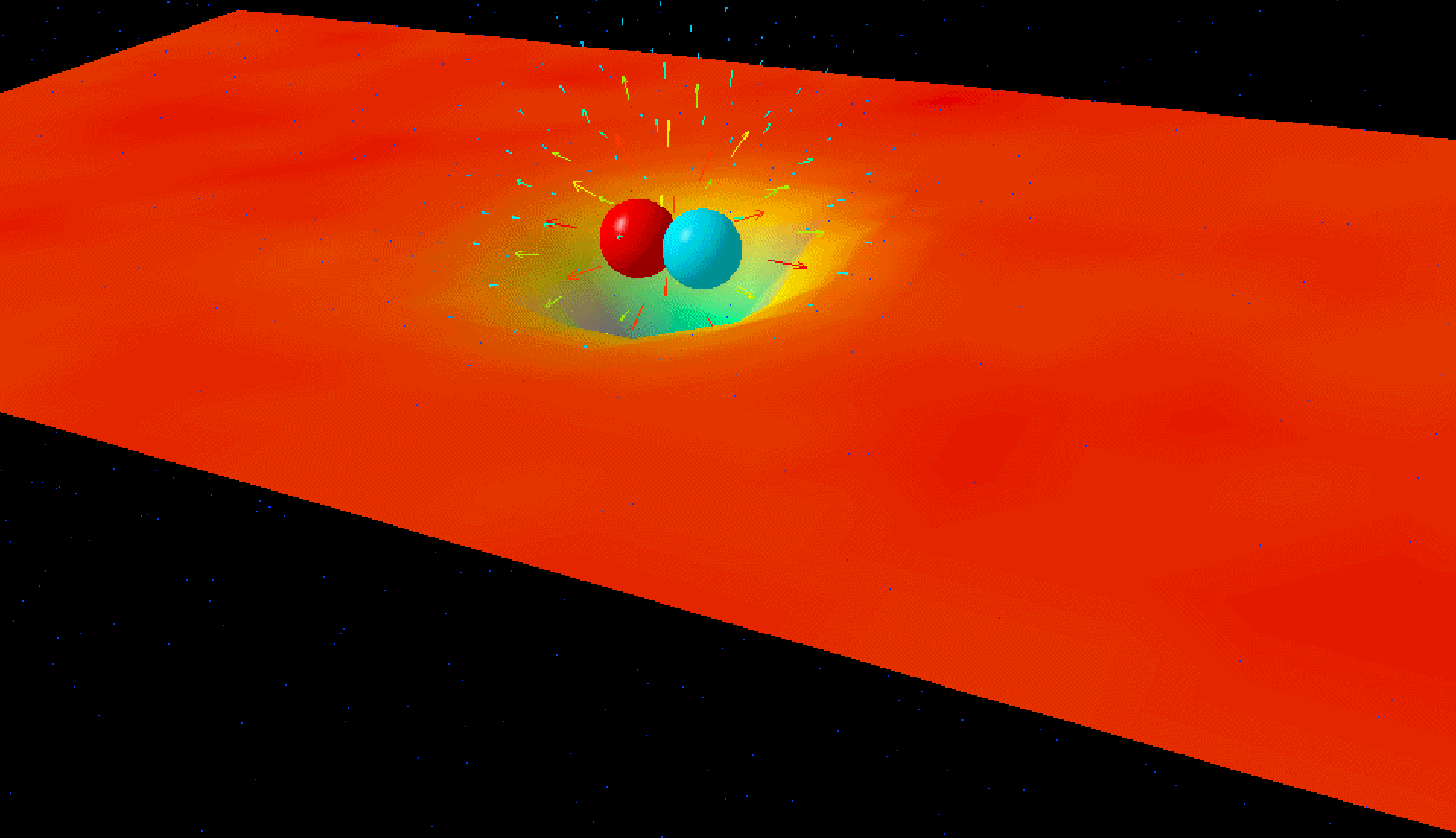
From G. Bali



Color Field: Because of self interaction, confining flux tubes form between static color charges

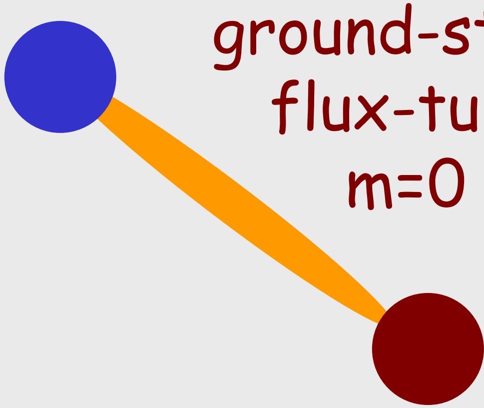
Confinement arises from flux tubes and their excitation leads to a new spectrum of mesons

Flux Tubes

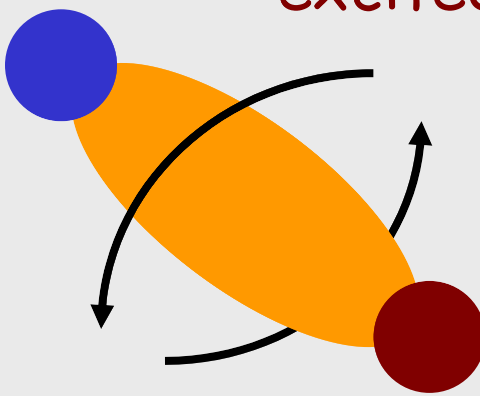


Hybrid Mesons

built on quark-model mesons



ground-state
flux-tube
m=0



excited flux-tube
m=1

1^{-+} or 1^{+-}

normal mesons

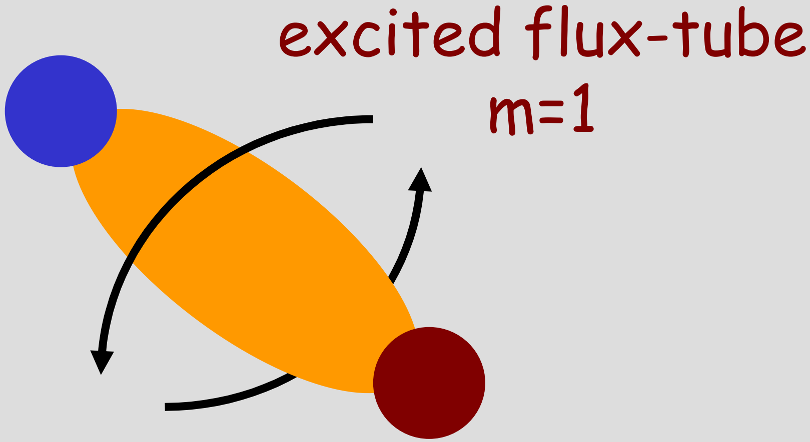
$CP=\{(-1)^{L+S}\}\{(-1)^{L+1}\}$
$=\{(-1)^{S+1}\}$

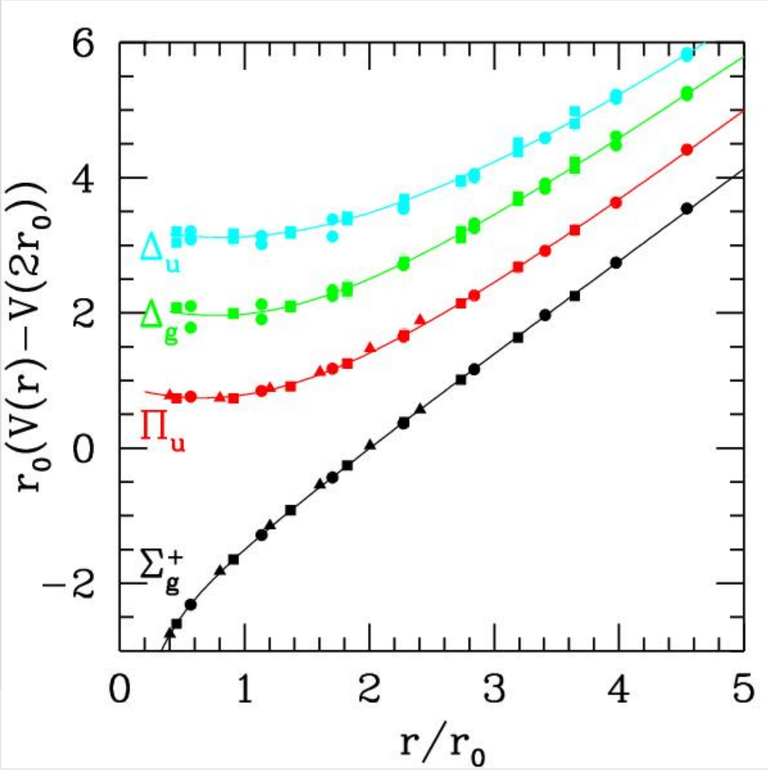
Flux-tube Model

m=0 $CP=(-1)^{S+1}$
m=1 $CP=(-1)^{S}$

	ρ, ω, ϕ
S=0,L=0,m=1	S=1,L=0,m=1
J=1 CP=+	J=1 CP=-
$J^{PC}=1^{++},1^{--}$	$J^{PC}=0^{-+},0^{+-}$
	$1^{-+},1^{+-}$
(not exotic)	
exotic	$2^{-+},2^{+-}$

QCD Potential





Gluonic Excitations provide an experimental measurement of the excited QCD potential.

Observations of exotic quantum number nonets are the best experimental signal of gluonic excitations.

Hybrid Predictions

Flux-tube model: 8 degenerate nonets

$1^{++}, 1^{--}$ (S=0) $0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}$ (S=1) ~1.9 GeV/c²

Lattice calculations --- 1^{-+} nonet is the lightest

UKQCD (97)	1.87 ±0.20
MILC (97)	1.97 ±0.30
MILC (99)	2.11 ±0.10
Lacock(99)	1.90 ±0.20
Mei(02)	2.01 ±0.10
Bernard(04)	1.792±0.139

1^{-+}	1.9± 0.2
2^{+-}	2.0± 0.11
0^{+-}	2.3± 0.6

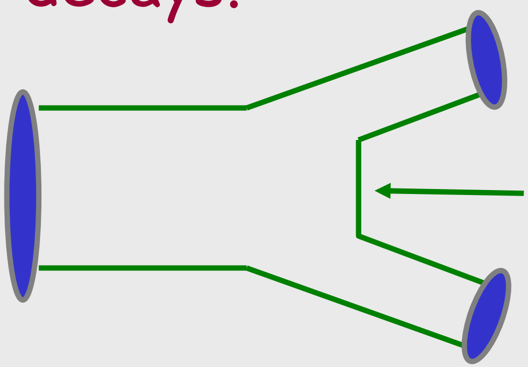
In the charmonium sector:

1^{-+}	4.39 ±0.08
0^{+-}	4.61 ±0.11

Splitting = 0.20

Decays of Hybrids

Decay calculations are model dependent, but the $^3P_0$ model does a good job of describing normal meson decays.



0^{++} quantum numbers ($^3P_0$)

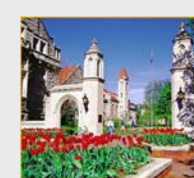
The angular momentum in the flux tube stays in one of the daughter mesons (L=1) and (L=0) meson.

L=0: $\pi,\rho,\eta,\omega,\ldots$
L=1: a,b,h,f,…

} $\eta\pi,\rho\pi$, … not preferred.

$\pi_1 \to \pi b_1, \pi f_1, \pi\rho, \eta a_1$ 87,21,11,9 MeV (partial widths)

first lattice prediction ~400MeV



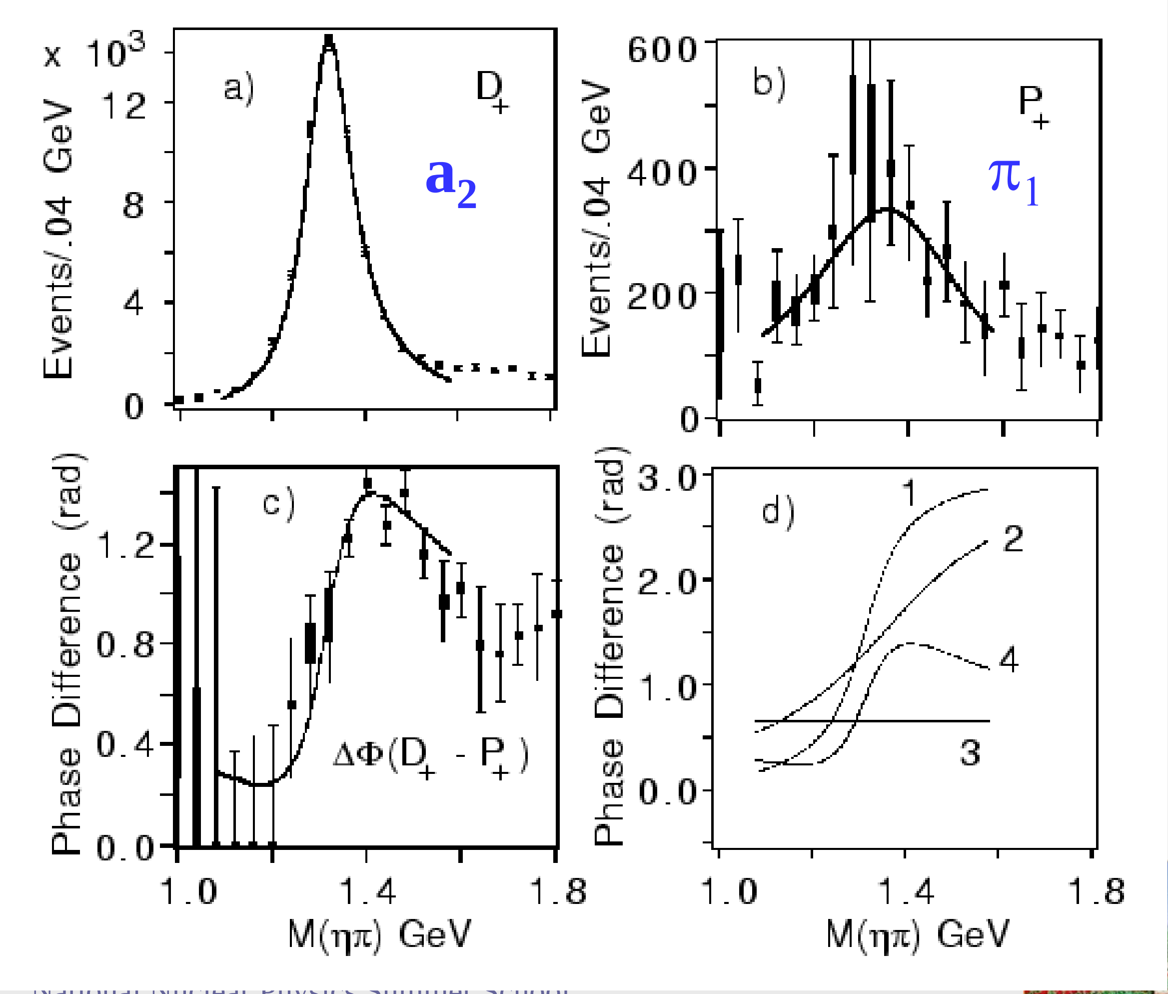
E852 Results

$\pi^- p \to \eta\pi^- p$ (18 GeV)

$\pi_1(1400)$ Mass = 1370 +-16$^{+50}_{-30}$ MeV/c^2
Width= 385 +- 40$^{+65}_{-105}$ MeV/c^2

The $a_2(1320)$ is the dominant signal. There is a small (few %) exotic wave.

Interference effects show a resonant structure in 1^{-+}. (Assumption of flat background phase as shown as 3.)



Crystal Barrel Results: antiproton-neutron annihilation

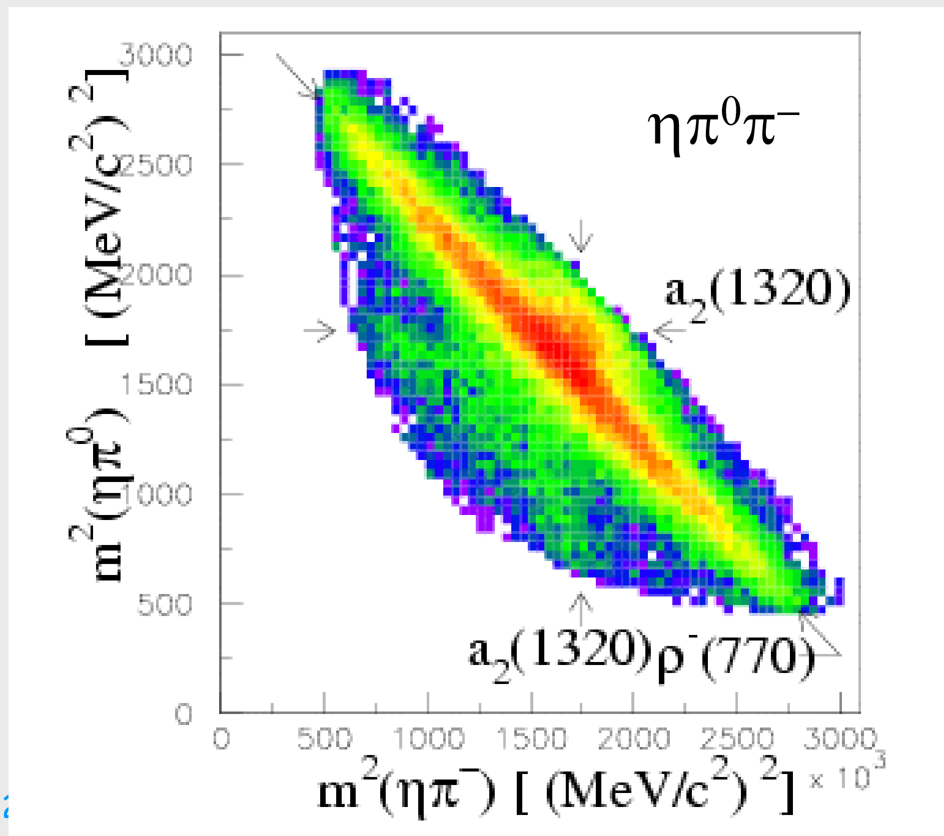
$\pi_1(1400)$ Mass = 1400 +- 20 +- 20 MeV/c^2

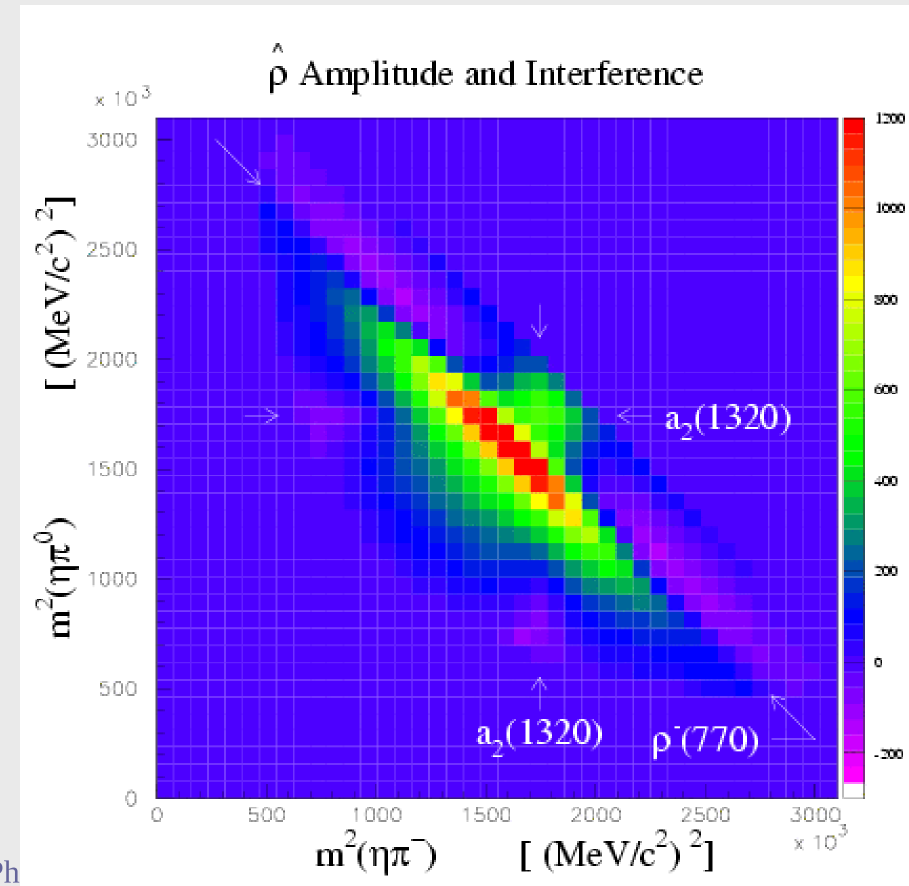
Width= 310+-50$^{+50}_{-30}$ MeV/c^2

Without π_1 χ^2/ndf = 3, with = 1.29

Same strength as the a_2.

Produced from states with **one unit** of angular momentum.





Controversy

In analysis of E852 $\eta\pi^\circ$ data, so evidence of the $\pi_1(1400)$

In CBAR data, the $\eta\pi^0$ channel is not conclusive.

Analysis by Szczepaniak shows that the exotic wave is not resonant – a rescattering effect.

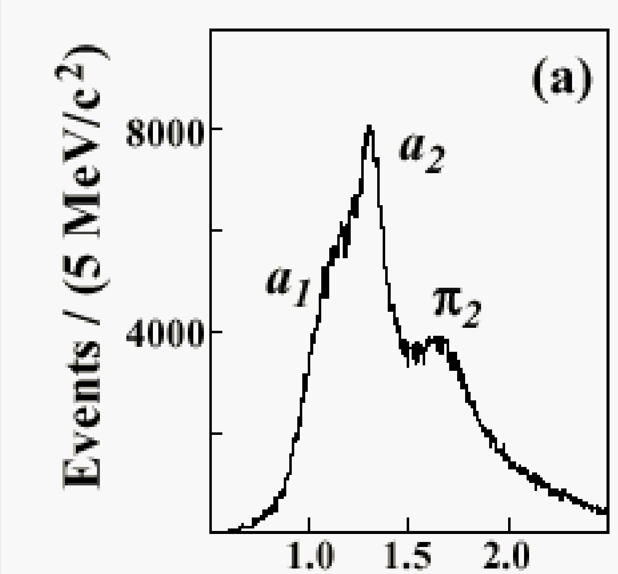
The signal is far too light to be a hybrid by any model.

This is not a hybrid and may well not be a state.

E852 Results $\pi^- p \rightarrow \pi^+\pi^-\pi^- p$

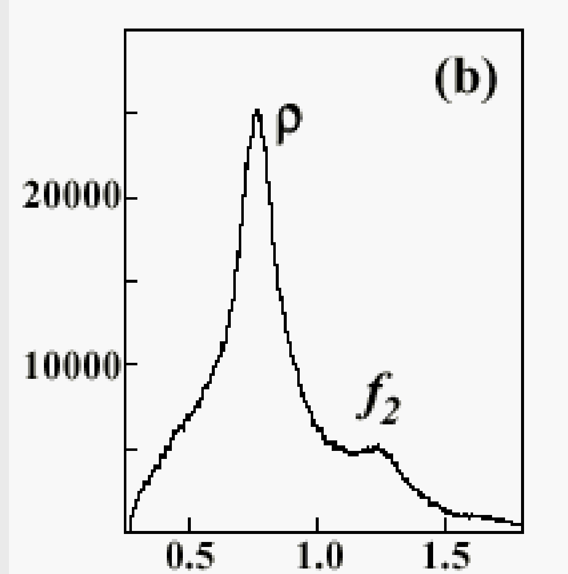
At 18 GeV/c

$\pi^+\pi^-\pi^-$



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

$\pi^+\pi^-$



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

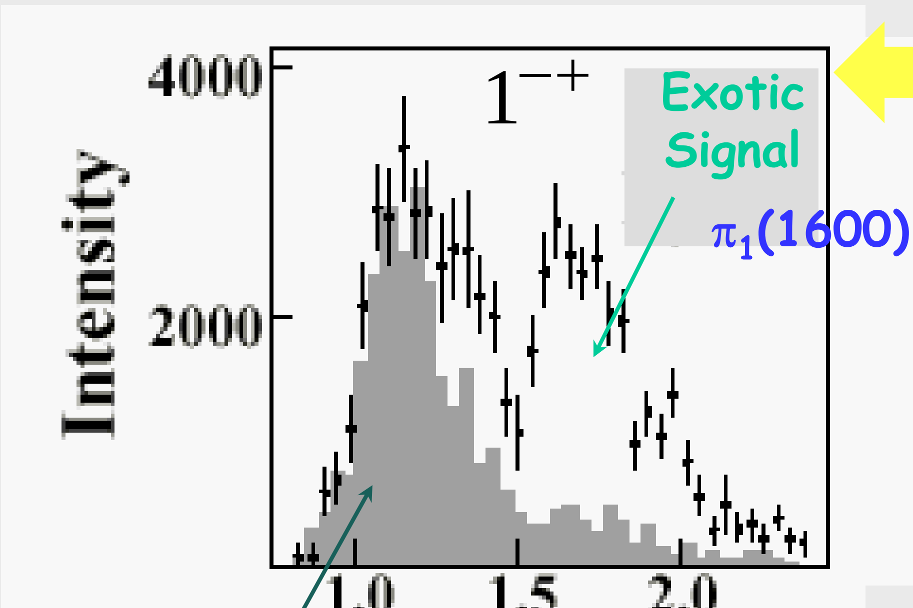
to partial wave analysis

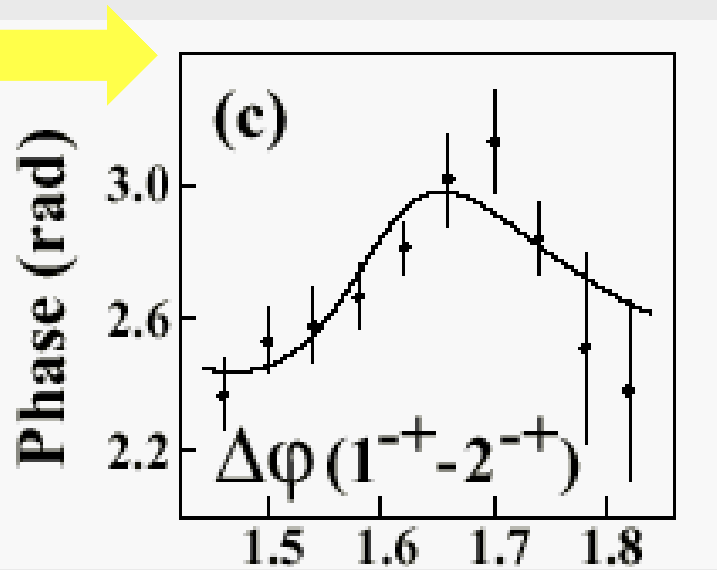
suggests $\pi^- p \rightarrow \rho^0 \pi^- p$

$\rightarrow \pi^+\pi^-\pi^- p$

An Exotic Signal

Correlation of
Phase
&
Intensity





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

Leakage
From
Non-exotic Wave
due to imperfectly
understood acceptance

3π m=1593+-8$^{+28}_{-47}$ Γ=168+-20$^{+150}_{-12}$

$\pi\eta'$ m=1597+-10$^{+45}_{-10}$ Γ=340+-40+-50

In Other Channels

E852 Results

1-+ in η′π

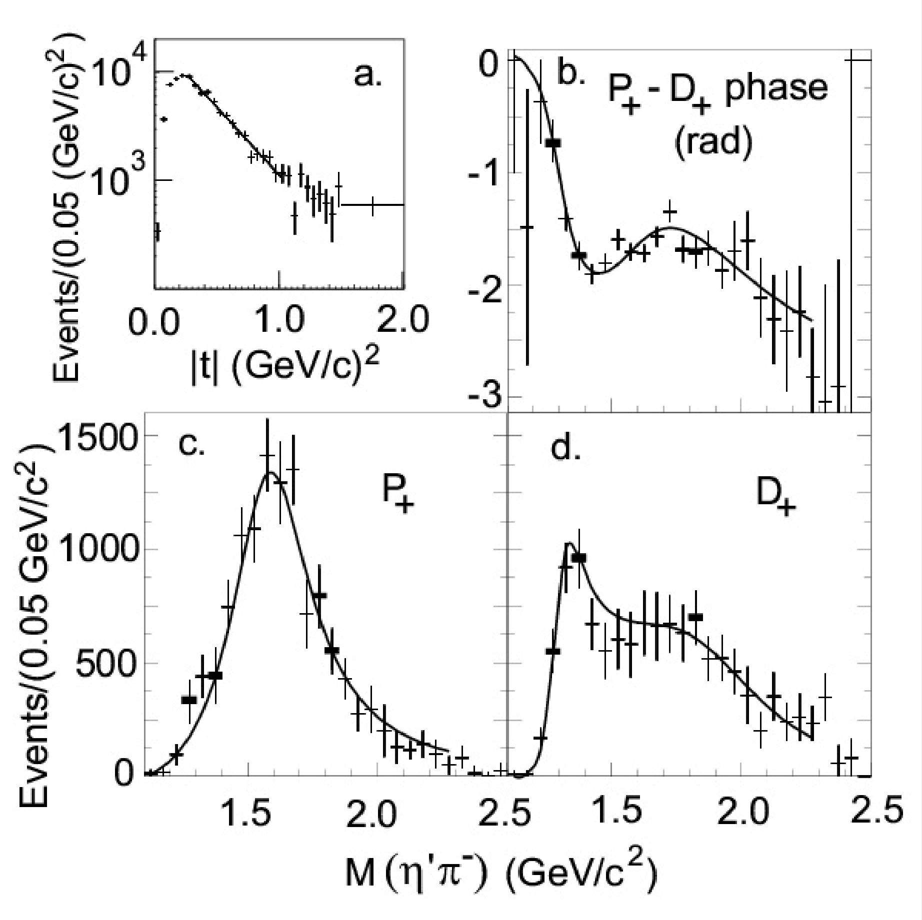
$\pi^- p \rightarrow \eta' \pi^- p$ at 18 GeV/c

The $\pi_1(1600)$ is the Dominant signal in $\eta'\pi$.

Mass = 1.597±0.010 GeV

Width = 0.340±0.040 GeV

$\pi_1(1600) \rightarrow \eta'\pi$



In Other Channels

E852 Results

1-+ in $f_1\pi$ and $b_1\pi$

$\pi^- p \rightarrow \eta\pi^+\pi^-\pi^- p$

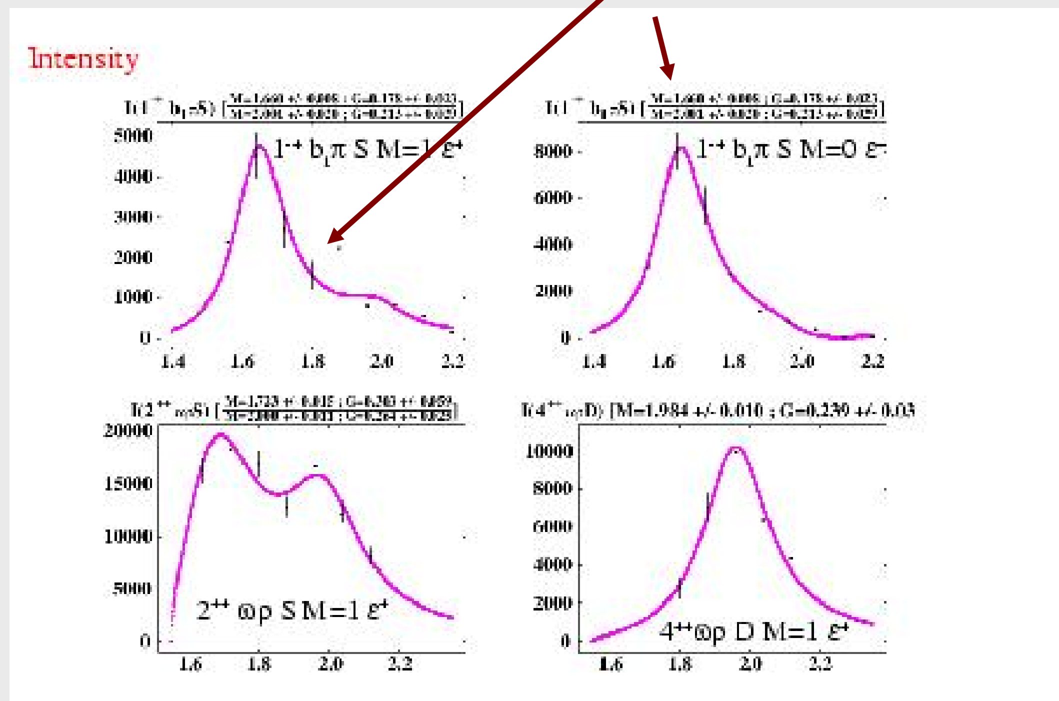
$\pi_1(1600) \rightarrow f_1\pi$

Mass=1.709±0.024 GeV

Width=0.403±0.08 GeV

In both $b_1\pi$ and $f_1\pi$, observe Excess intensity at about $2 GeV/c^2$.
Mass ~ 2.00 GeV,
Width ~ 0.2 to 0.3 GeV

$\pi^- p \rightarrow \omega\pi^0\pi^- p$ $\pi_1(1600) \rightarrow b_1\pi$



Mass = 1.687±0.011 GeV

Width = 0.206±0.03 GeV

$\pi_1(1600)$ Consistency

3π	m=1593	Γ=168
$\eta'\pi$	m=1597	Γ=340
$f_1\pi$	m=1709	Γ=403
$b_1\pi$	m=1687	Γ=206

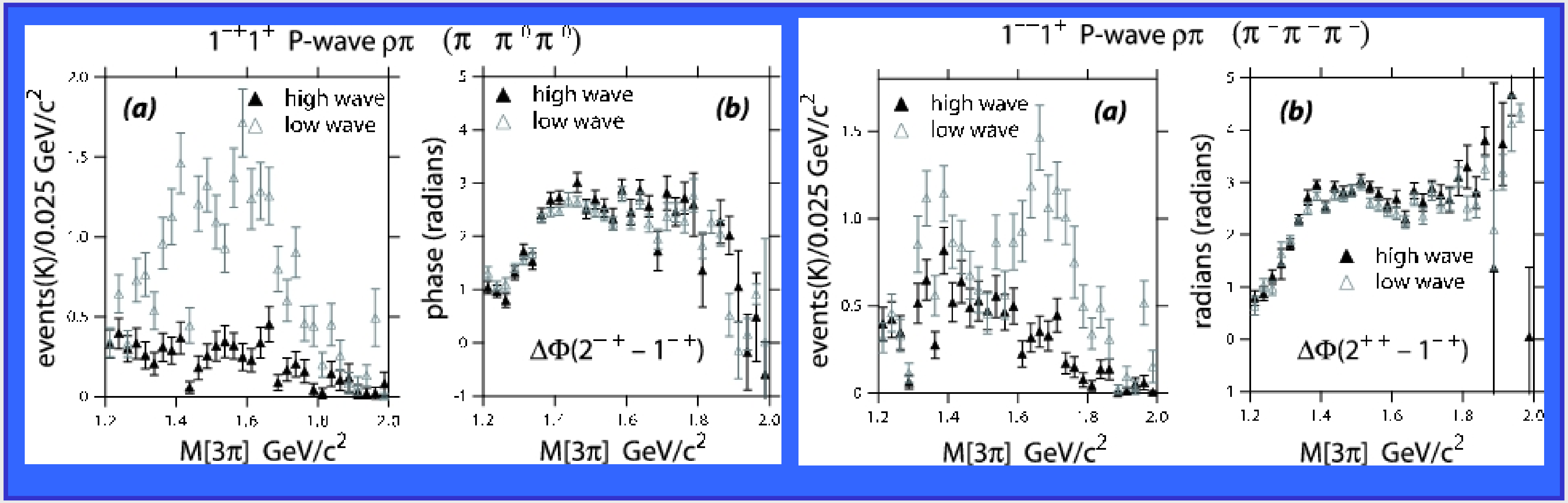
Not Outrageous, but not great agreement.
Mass is slightly low, but not crazy.

Szczepaniak: Explains much of the η' signal as a background rescattering similar to the $\eta\pi$.

Still room for a narrower exotic state.

New Analysis

Dzierba et. al. PRD 73 (2006)



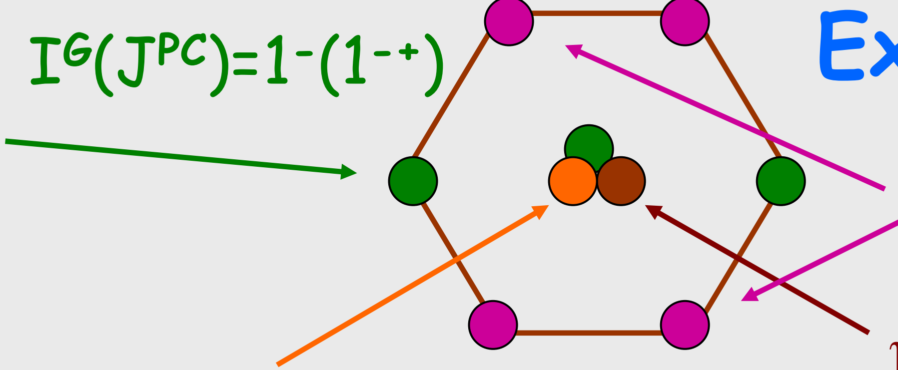
Add $\pi_2(1670) \to \rho\pi$ (L=3)
Add $\pi_2(1670) \to \rho_3\pi$
Add $\pi_2(1670) \to (\pi\pi)_S\pi$
Add a_3 decays
Add $a_4(2040)$

No Evidence for the $\pi_1(1670)$

10 times statistics in each of two channels.

Get a better description of the data via moments comparison

Exotic Signals



π_1 $I^G(J^{PC})=1^-(1^{-+})$

K_1 $I^G(J^{PC})=\frac{1}{2}(1^-)$

η'_1 $I^G(J^{PC})=0^+(1^{-+})$

η_1 $I^G(J^{PC})=0^+(1^{-+})$

π_1(1400) Width ~ 0.3 GeV, Decays: only $\eta\pi$
weak signal in πp production (scattering??)
strong signal in antiproton-deuterium.

NOT A HYBRID

π_1(1600) Width ~ 0.16 GeV, Decays $\rho\pi, \eta'\pi, (b_1\pi)$
Only seen in πp production, (E852 + VES)

Does this exist?

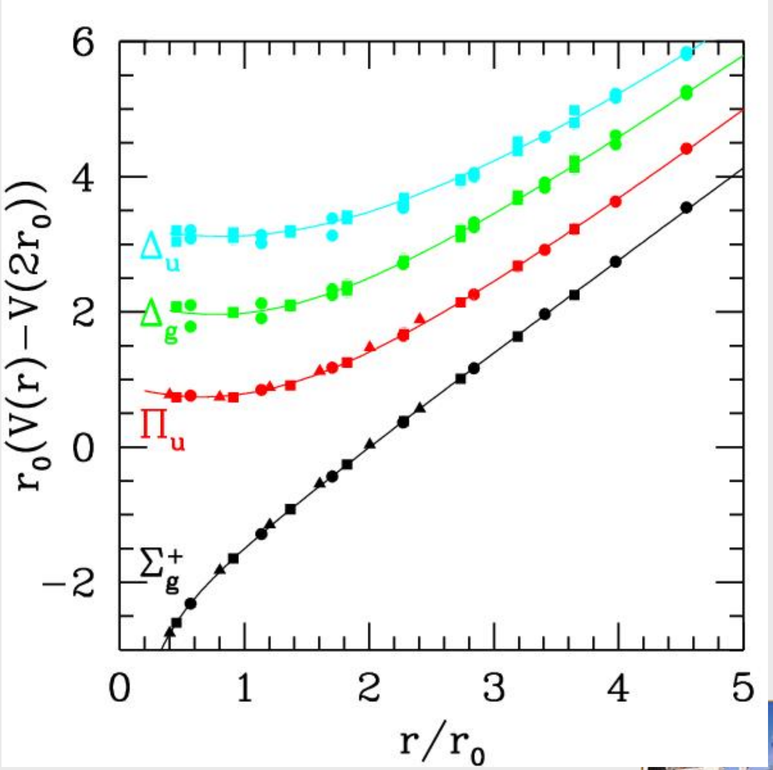
π_1(2000) Weak evidence in preferred hybrid modes $f_1\pi$ and $b_1\pi$

The right place. Needs confirmation.

Exotics and QCD

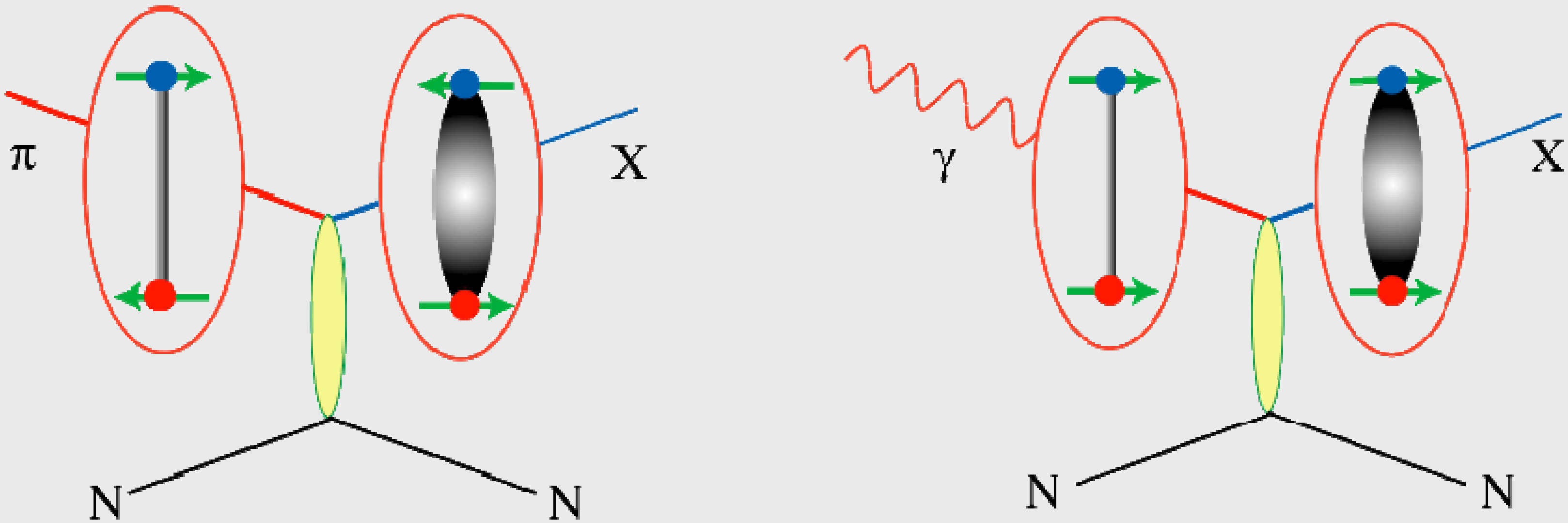
In order to establish the existence of gluonic excitations, We need to establish the existence and nonet nature of the 1^{-+} state.
We need to establish at other exotic QN nonets – the 0^{+-} and 2^{+-}.

In the scalar glueball sector, the decay patterns have provided the most sensitive information. I expect the same will be true in the hybrid sector as well.



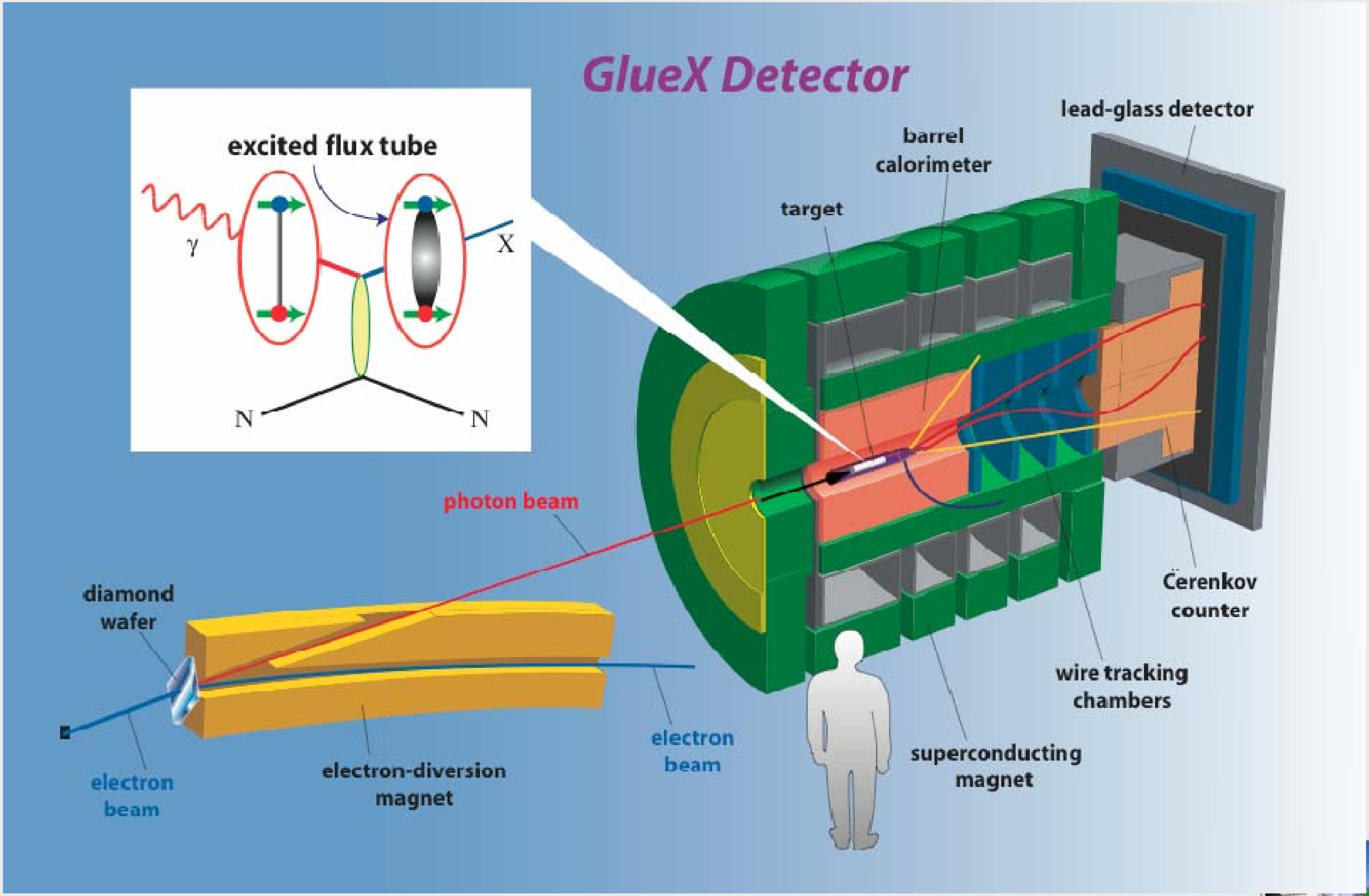
DECAY PATTERS ARE CRUCIAL

Photoproduction



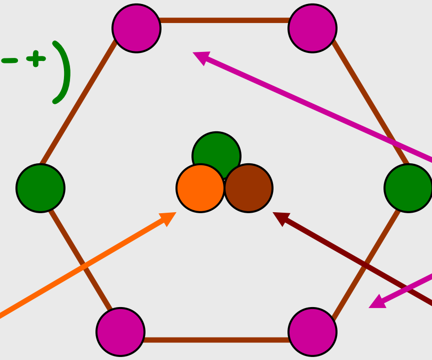
More likely to find exotic hybrid mesons using beams of photons

The GlueX Experiment



Exotics in Photoproduction

1^{-+} nonet

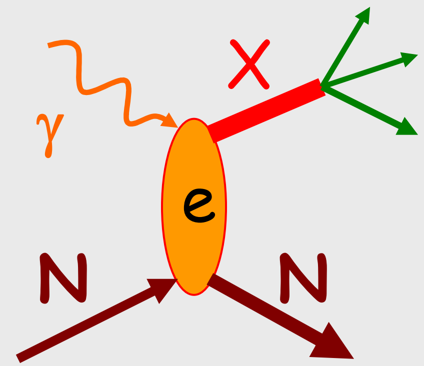


$\pi_1 \quad I^G(J^{PC})=1^-(1^{-+})$

$K_1 \quad I^G(J^{PC})=\frac{1}{2}(1^-)$

$\eta'_1 \quad I^G(J^{PC})=0^+(1^{-+})$

$\eta_1 \quad I^G(J^{PC})=0^+(1^{-+})$



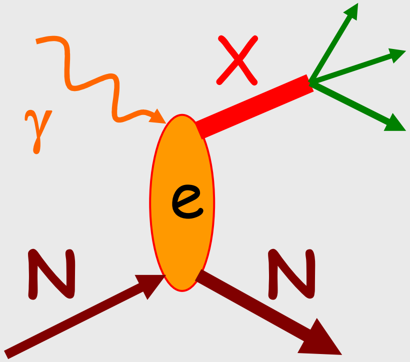
Need to establish nonet nature of exotics: π η η'

$\gamma \Leftrightarrow \rho,\omega,\phi$

Need to establish more than one nonet: 0^{+-} 1^{-+} 2^{+-}

0^{+-} and 2^{+-} Exotics

In photoproduction, couple to ρ, ω or ϕ?



b_0 $I^G(J^{PC})=1^+(0^{+-})$ $\omega a_1, \rho f_0, \rho f_1$

h_0 $I^G(J^{PC})=0^-(0^{+-})$ $\omega f_0, \omega f_1, \rho a_1$

h'_0 $I^G(J^{PC})=0^-(0^{+-})$ $\phi f_0, \phi f_1, \rho a_1$

K_0 $I(J^P)=\frac{1}{2}(0^+)$

$\omega\pi$, $\omega a_1, \rho f_0, \rho f_1$ b_2 $I^G(J^{PC})=1^+(2^{+-})$

"Similar to π_1" $\omega\eta, \rho\pi, \omega f_0, \omega f_1, \rho a_1$ h_2 $I^G(J^{PC})=0^-(2^{+-})$

$\phi\eta, \rho\pi, \phi f_0, \phi f_1, \rho a_1$ h'_2 $I^G(J^{PC})=0^-(2^{+-})$

K_2 $I(J^P)=\frac{1}{2}(2^+)$

Kaons do not have exotic QN's

Summary

The first round of J/ψ experiments opened the door to exotic spectroscopy, but the results were confused.

LEAR at CERN opened the door to precision, high-statistics spectroscopy experiments and significantly improved both our understanding of the scalar mesons and the scalar glueball.

Pion production experiments at BNL (E852) and VES opened the door to states with non-quark-anti-quark quantum numbers. Recent analysis adds to controversy.

CERN central production (WA102) provided solid new data on the scalar sector, and a deeper insight into the scalar glueball.

BES is collecting new J/ψ data. CLEO-c can hopefully add with the ψ' program.

The Future

The GlueX experiment at JLab will be able to do for hybrids what Crystal Barrel and WA102 (together) did for glueballs. What are the properties of static glue in light-quark hadrons and how is this connected to confinement.

The antiproton facility at GSI (HESR) will look for hybrids in the charmonium system – PANDA. May also be able to shed more light on the Glueball spectrum.