An Experimental Overview of Gluonic Mesons

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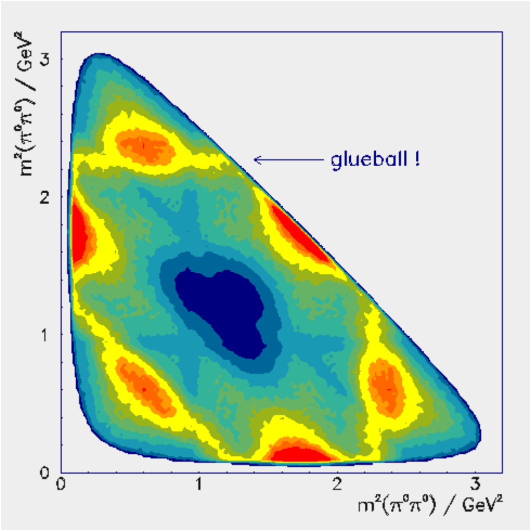
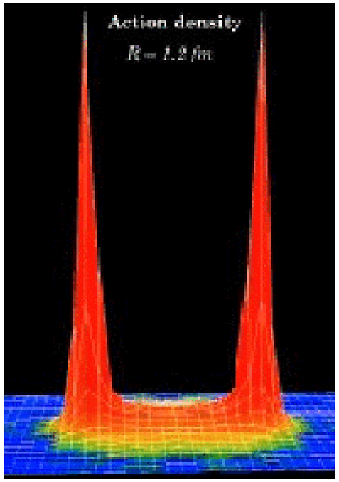
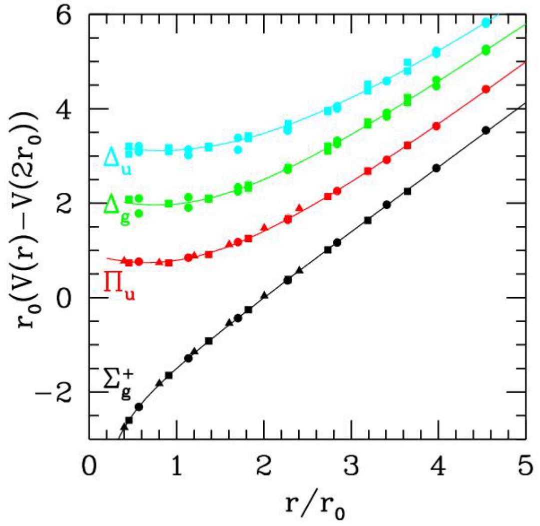






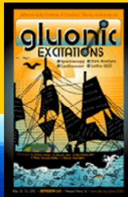
Talk Outline

What are gluonic excitations ?
Hybrids and Glueballs

Overview of evidence for exotic quantum number states.

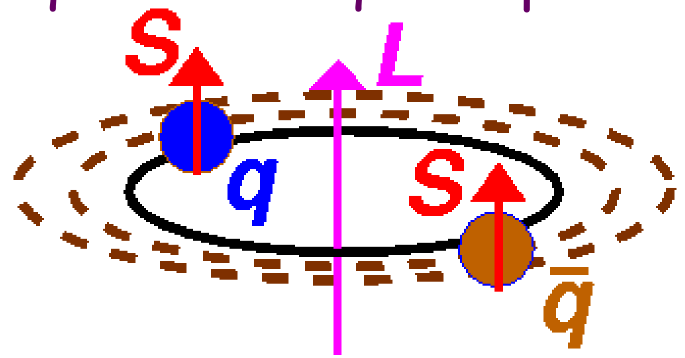
Non-exotic quantum number states.

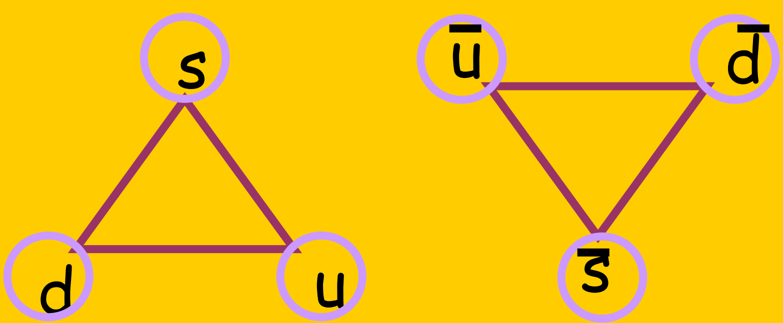
Overview of Glueballs.



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

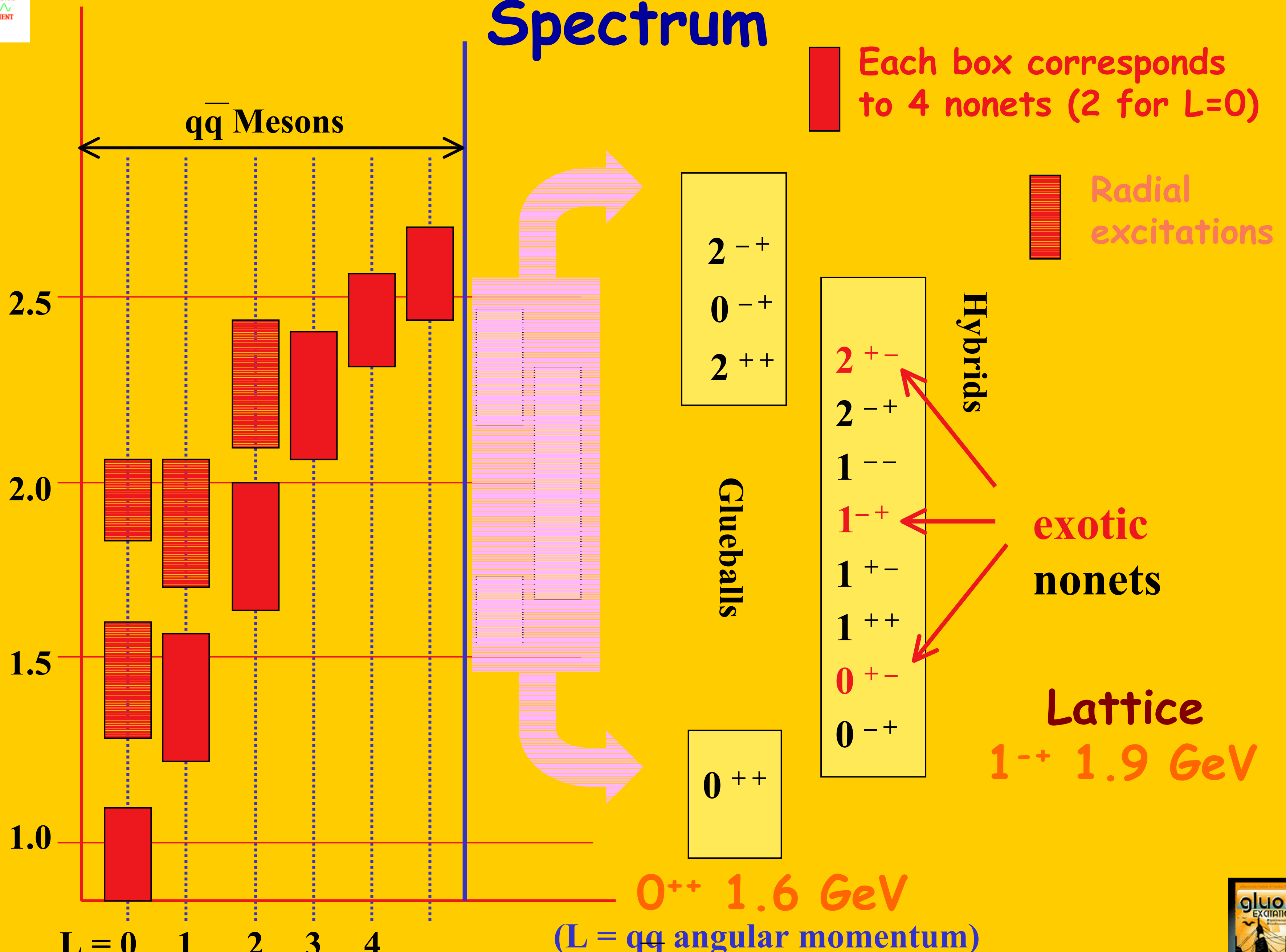
0^{--} 0^{+-} 1^{-+} 2^{+-} 3^{-+} …

orbital

radial

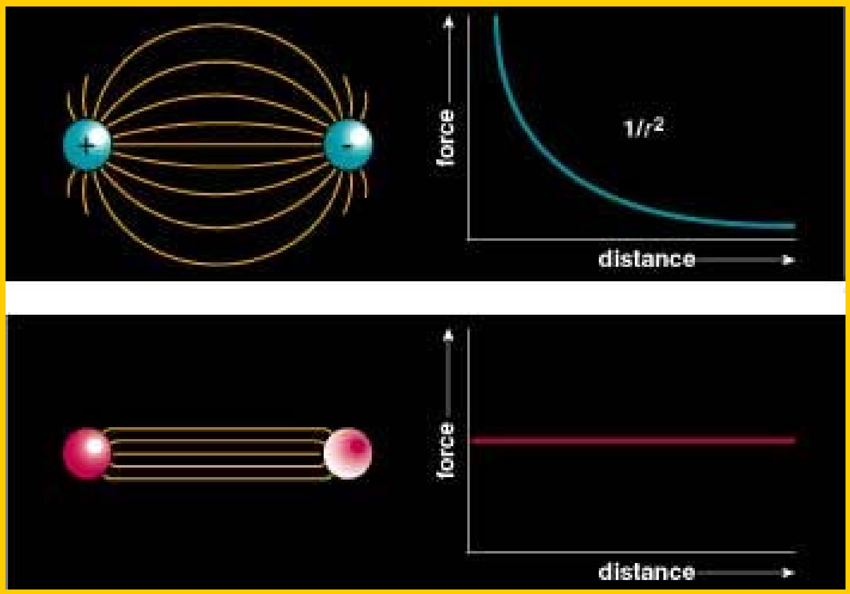
L=2	$\rho_3, \omega_3, \phi_3, K_3$	3^{--}
	$\rho_2, \omega_2, \phi_2, K_2$	2^{--}
	$\rho_1, \omega_1, \phi_1, K_1$	1^{--}
	$\pi_2, \eta_2, \eta'_2, K_2$	2^{-+}
L=1	a_2, f_2, f'_2, K_2	2^{++}
	a_1, f_1, f'_1, K_1	1^{++}
	a_0, f_0, f'_0, K_0	0^{++}
	b_1, h_1, h'_1, K_1	1^{+-}
L=0	ρ, ω, ϕ, K^*	1^{--}
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

Spectrum

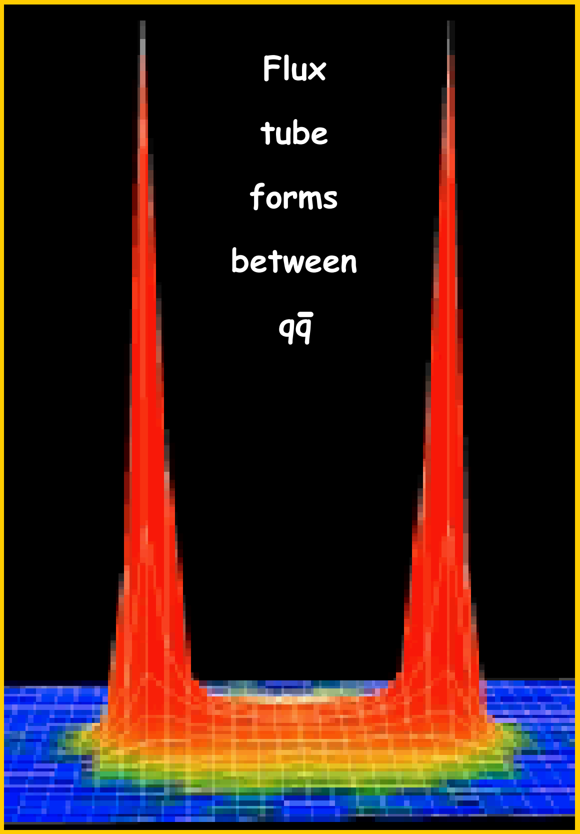


Each box corresponds to 4 nonets (2 for L=0)
Radial excitations
$q\bar{q}$ Mesons
2.5
2.0
1.5
1.0
L = 0
1
2
3
4
2^{-+}
0^{-+}
2^{++}
Glueballs
0^{++}
Hybrids
2^{+-}
2^{-+}
1^{--}
1^{-+}
1^{+-}
1^{++}
0^{+-}
0^{-+}
exotic nonets
Lattice
1^{-+} 1.9 GeV
0^{++} 1.6 GeV
(L = $q\bar{q}$ angular momentum)

Lattice QCD Flux Tubes Realized

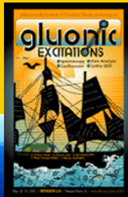


From G. Bali



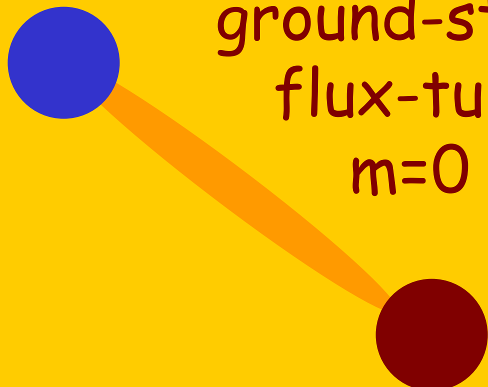
Color Field: Because of self interaction, confining flux tubes form between static color charges

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

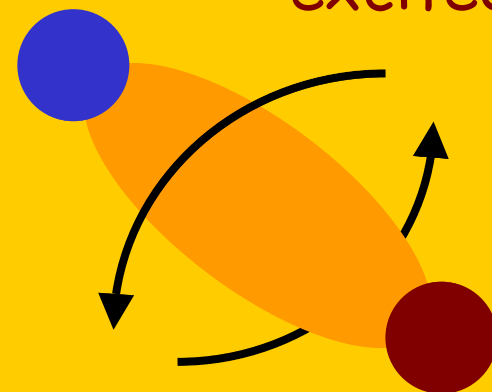


Hybrid Mesons

built on quark-model mesons



ground-state
flux-tube
m=0



excited flux-tube
m=1

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

ρ, ω, ϕ

normal mesons

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

Flux-tube Model

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

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)	$2^{-+}, 2^{+-}$

exotic

Hybrid Predictions

Flux-tube model: 8 degenerate nonets

$1^{++}, 1^{--}$ $0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}$ ~1.9 GeV/c²

$1^{++}, 1^{--}$: S=0

$0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, 2^{-+}, 2^{+-}$: S=1

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

~2.0 GeV/c²

1^{-+}, 0^{+-}: Splitting ≈ 0.20

1^{-+}, 0^{+-}, 2^{+-}: ≈ 0.50

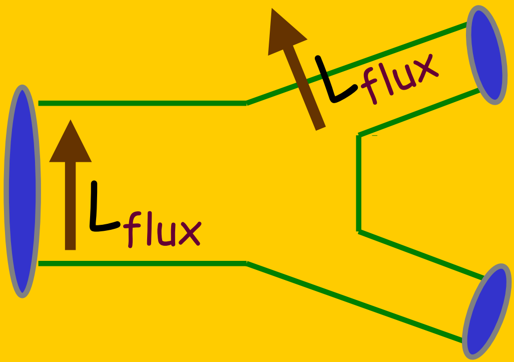
In the charmonium sector:

1^{-+}	4.39 ±0.08
0^{+-}	4.61 ±0.11

Splitting = 0.20

Decays of Hybrids

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



Exotic Quantum Number Hybrids

$\pi_1 \to \pi b_1 , \pi f_1 , \pi\rho , \eta a_1$	1:.25:.25:.20
$\eta 1 \to \pi(1300)\pi , a_1\pi$	1:1
$b_2 \to a_1\pi , h_1\pi , \omega\pi , a_2\pi$	1:1:0.5:0.25
$h_2 \to b_1\pi , \rho\pi , \omega\eta$	1:1:0.1
$b_0 \to \pi(1300)\pi , h_1\pi$	1:0.20
$h_0 \to b_1\pi , h_1\eta$	1:0.02

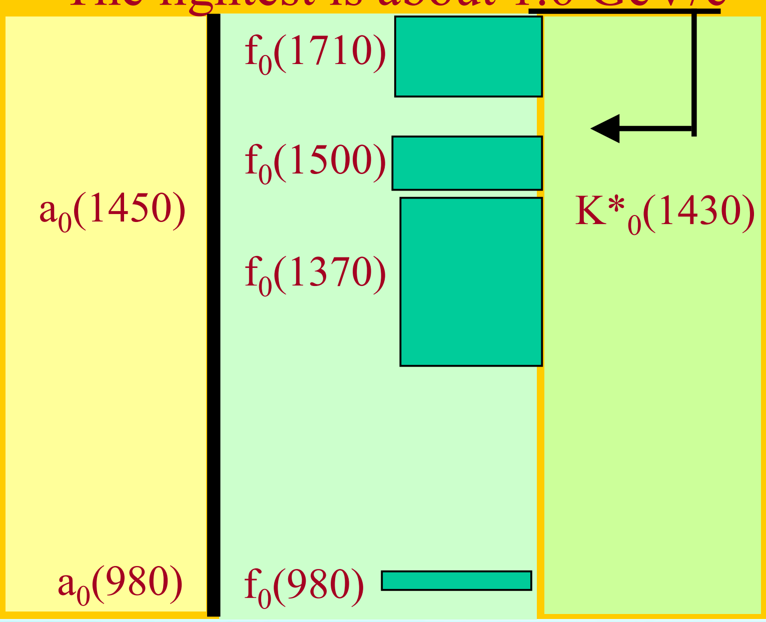
Mass and model dependent predictions

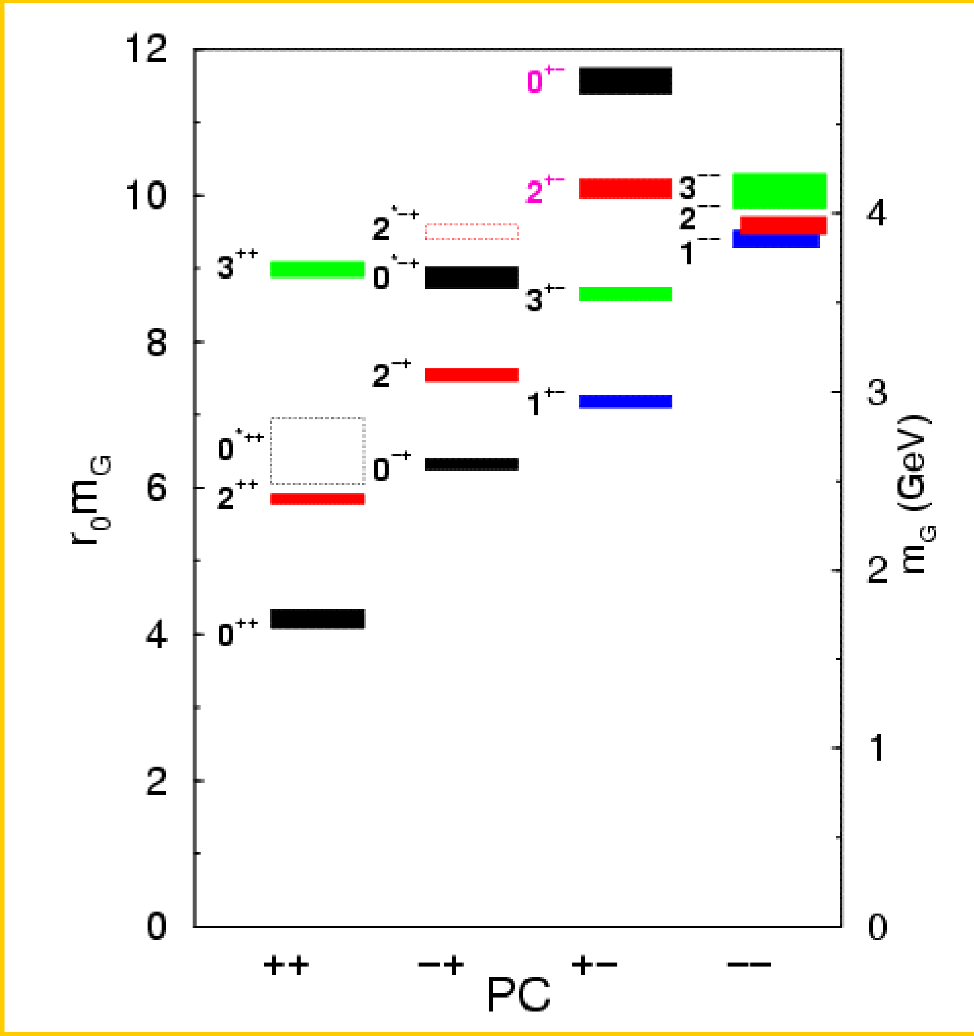
Glueball Mass Spectrum

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^{-+}.

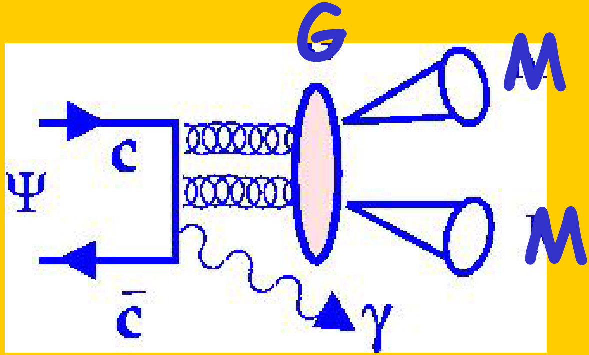
The lightest is about 1.6 GeV/c^2





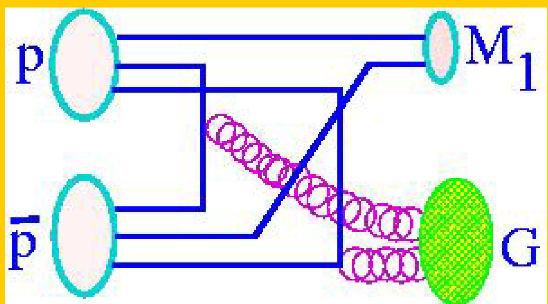
Morningstar et al.

Glue-rich channels



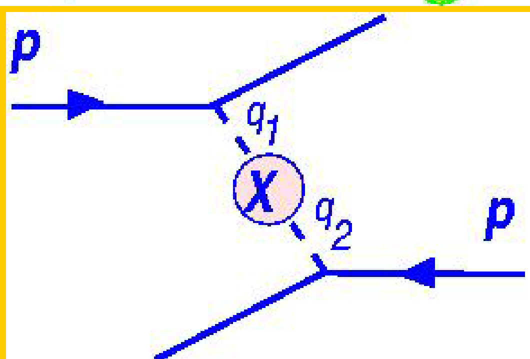
Radiative J/ψ Decays

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



Proton-Antiproton Annihilation

0^{++} $f_0(1370), f_0(1500)$



Central Production
(double-pomeron exchange)

0^{++} $f_0(1370), f_0(1500), f_0(1710)$

Glueballs should decay in a flavor-blind fashion.

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

Exotic Quantum Numbers 1^{-+} in $\eta\pi$

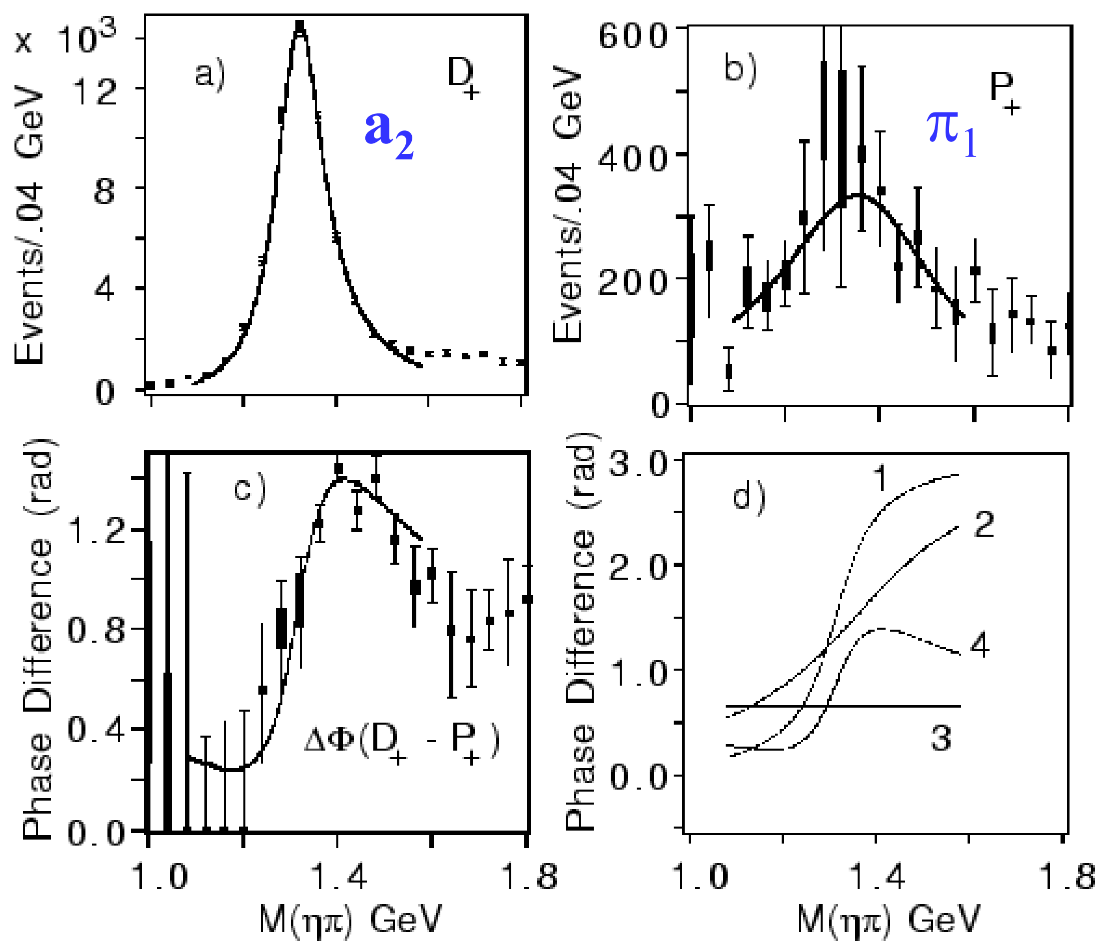
E852 Results

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

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

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.)



Exotic Quantum Numbers 1^{-+} in $\eta\pi$

Crystal Barrel

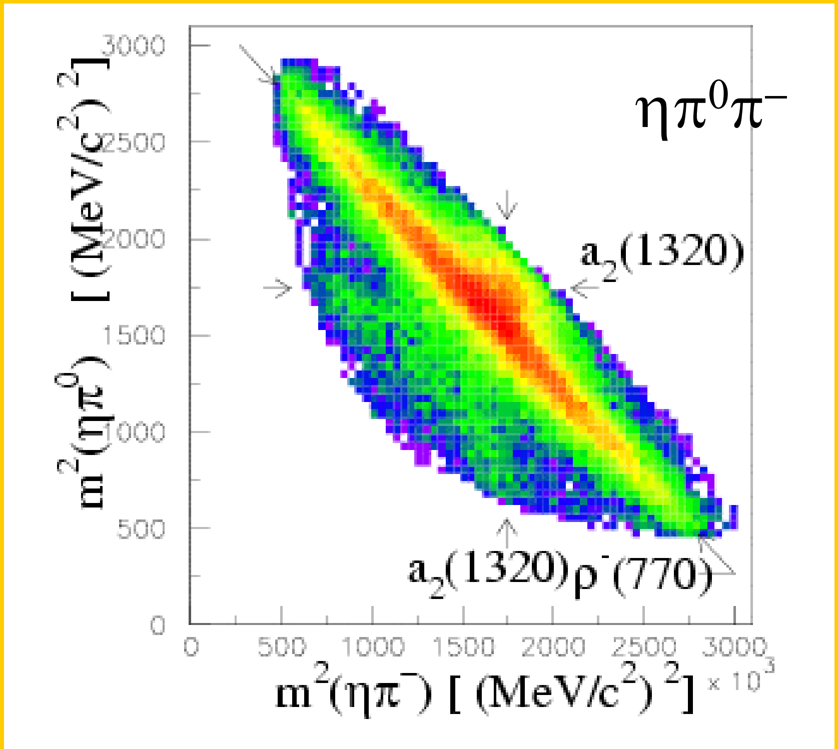
Same strength as the a_2.

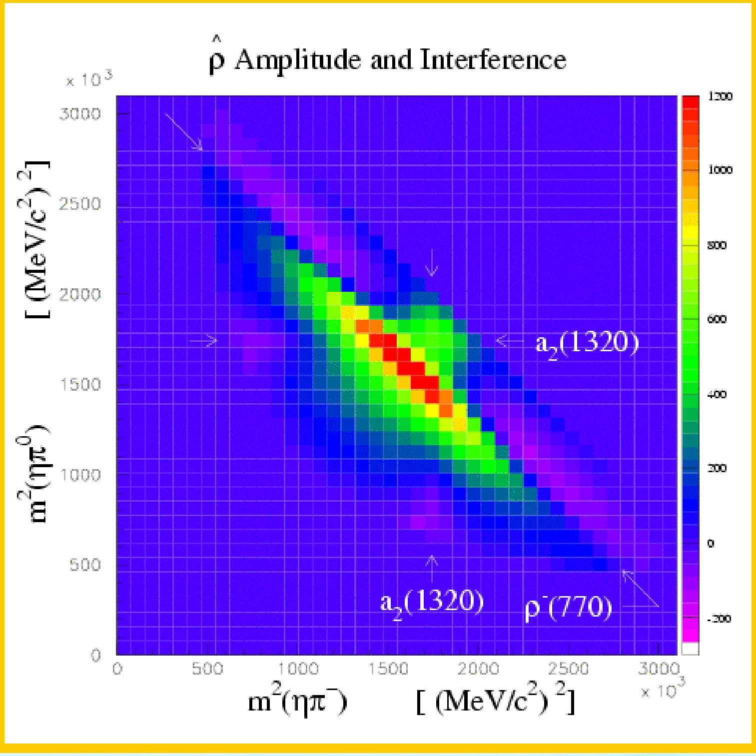
$\pi_1(1400)$ Mass = 1400 +- 20 +- 20 MeV/c^2

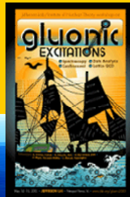
Width= 310+-50$^{+50}_{-30}$ MeV/c^2

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

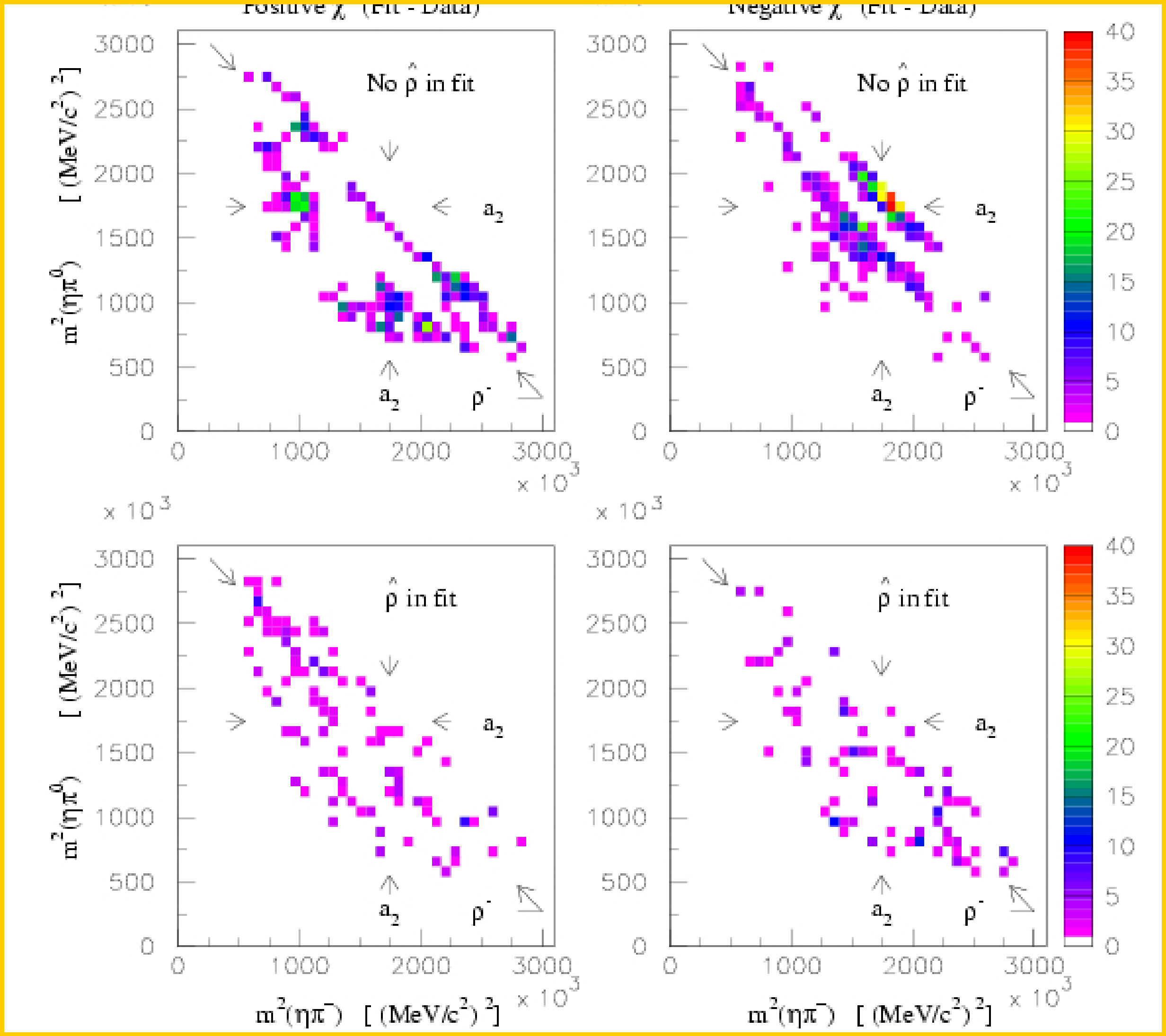
Without π_1 χ^2/ndf = 3, with = 1.29







Significance of signal.

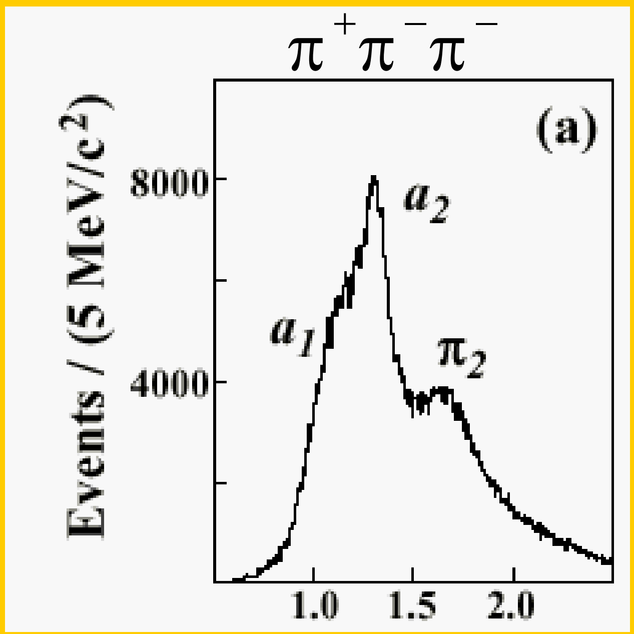


Exotic Quantum Numbers 1^{-+} in $\rho\pi$

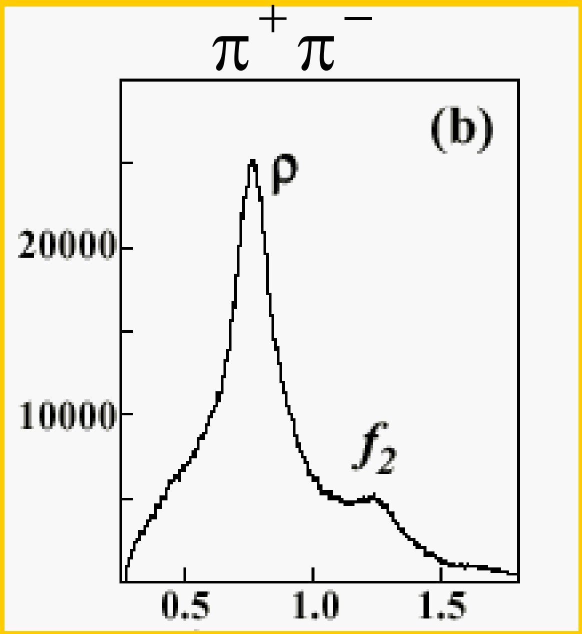
E852 Results

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

At 18 GeV/c



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

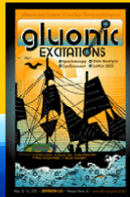


$M(\pi^+\pi^-)\ \left[\mathrm{GeV}/c^2\right]$

to partial wave analysis

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

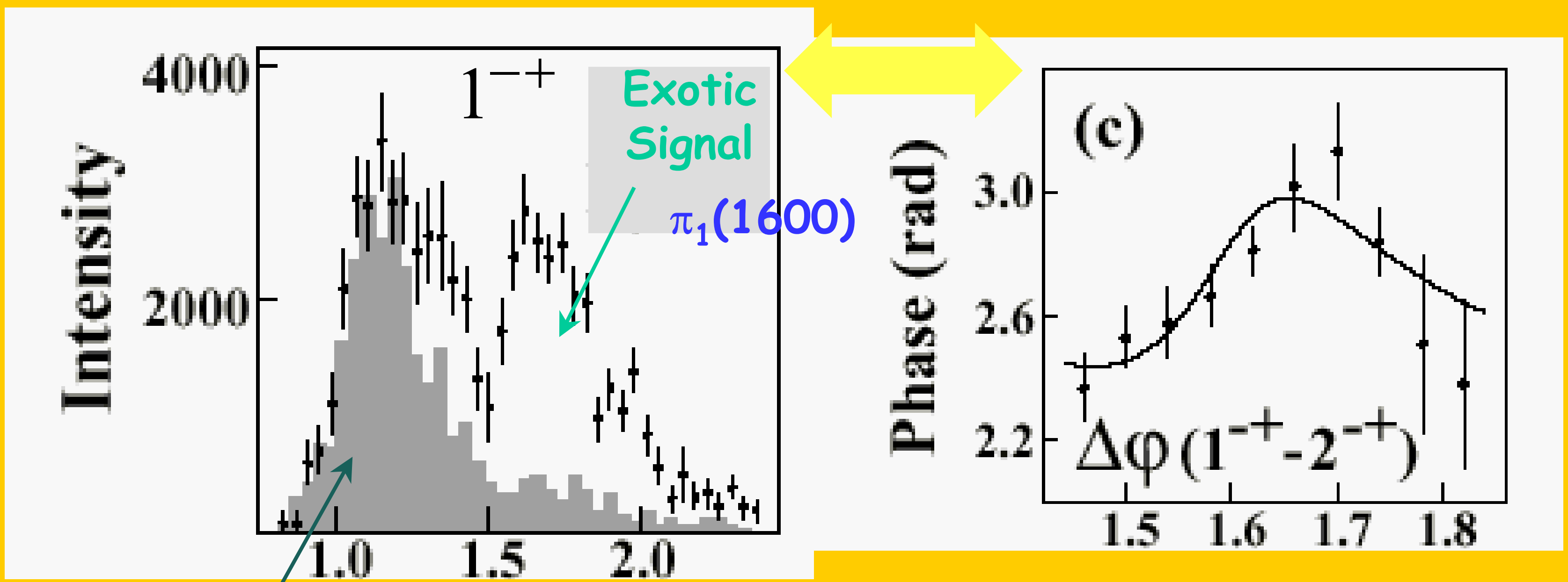
$\rightarrow \pi^+ \pi^- \pi^- p$



Exotic Quantum Numbers 1^{-+} in $\rho\pi$

E852 Results

Correlation of Phase & Intensity



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

Leakage From Non-exotic Wave due to imperfectly understood acceptance

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

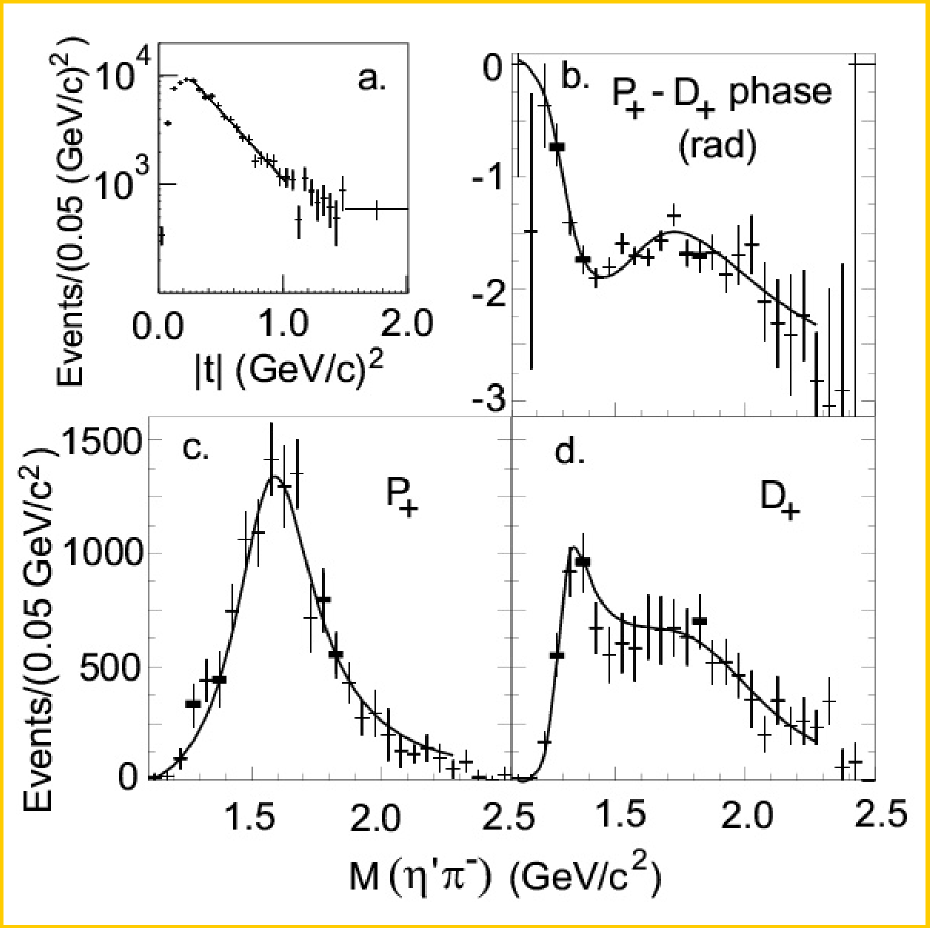
Exotic Quantum Numbers 1^{-+} in $\eta'\pi$

E852 Results

The $\pi_1(1600)$ is the Dominant signal in $\eta'\pi$.
Mass = 1.597±0.010 GeV
Width = 0.340±0.040 GeV

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

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



Other reports here:

$\pi_1(1600) \rightarrow b_1\pi$

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

$\rho\pi$, $b_1\pi$, $f_1\pi$, $\eta'\pi$

Exotic Quantum Numbers
1^{-+} in $\rho\pi$, $b_1\pi$ and $\eta'\pi$

VES Results

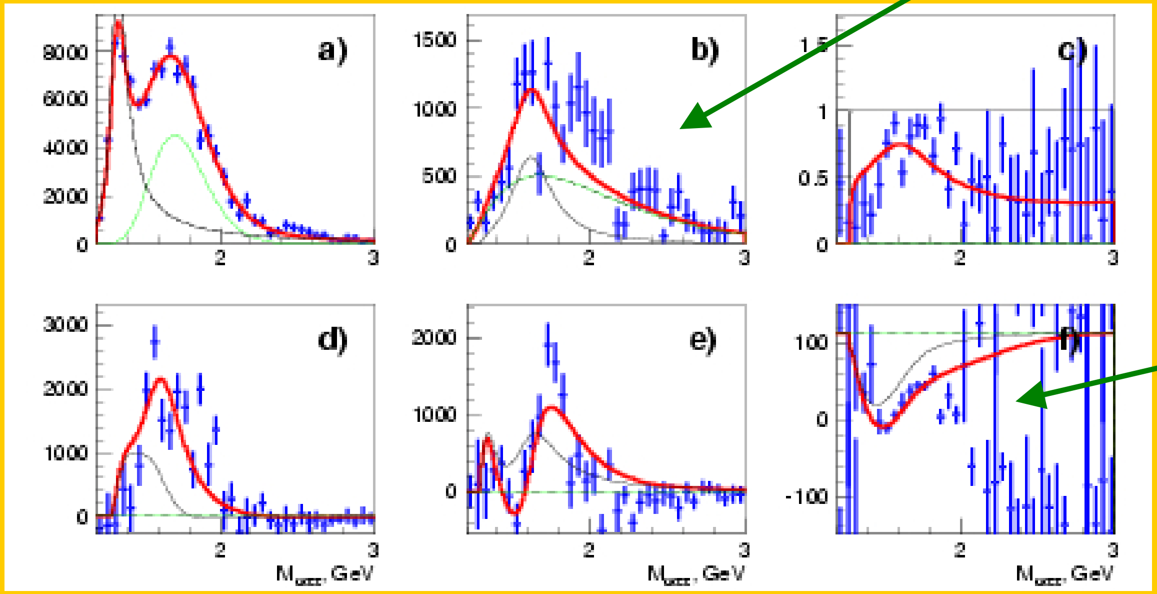
$\pi_1(1600)$ observed in πA reactions

$m = 1.6 \pm 0.02$ GeV/c^2
$\Gamma = 0.29 \pm 0.03$ GeV/c^2

$b_1\pi : \eta'\pi : \rho\pi = 1 : 1.0 \pm 0.3 : 1.6 \pm 0.4$

$\pi^- A \rightarrow \omega\pi\pi\ (A)$ (at 37 GeV/c)

$b_1\pi\ (1^{-+})$



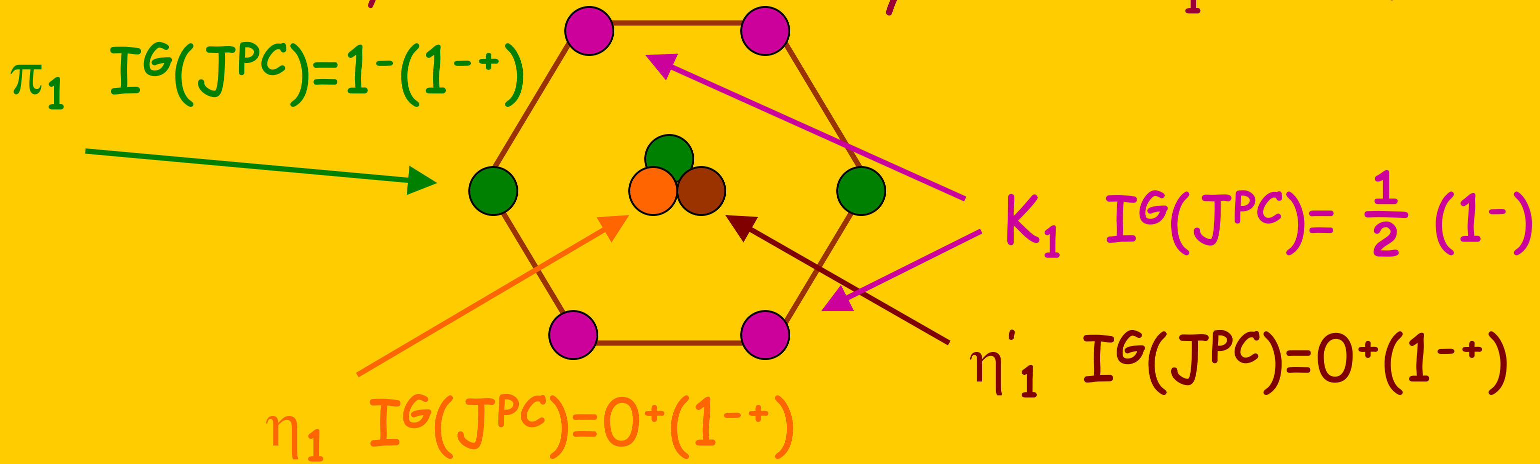
Phase wrt 2^+

Exotic Signals

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

π_1**(1600)** Width ~ 0.16 to 0.3 GeV, Decays $\rho\pi$, $\eta'\pi$, ($b_1\pi$)
Only seen in πp production, (E852 + VES)

In a nonet, there should only be one π_1 state.



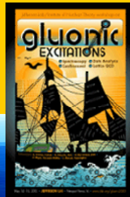
Both of these are lighter than expectations, and
The $\eta[\eta']\pi$ decay modes are not what are expected.

Hybrid Mesons with normal QN's

Assume that $\pi_1(1600)$ sets the mass scale

S=0 : $1^{++}, 1^{--}$	Non-exotic hybrid QN's
S=1 : $0^{-+}, 1^{+-}, 2^{-+}$	

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^{-+}



Hybrid Mesons with normal QN's

Assume that $\pi_1(1600)$ sets the mass scale

S=0 :	$1^{++}, 1^{--}$
S=1 :	$0^{-+}, 1^{+-}, 2^{-+}$

Non-exotic hybrid QN's

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^{-+}

1st radial excitation

a_1, f_1, f'_1, K_1

Hybrid Mesons with normal QN's

Assume that $\pi_1(1600)$ sets the mass scale

S=0 : 1^{++}, 1^{--}
S=1 : 0^{-+}, 1^{+-}, 2^{-+}

} Non-exotic hybrid QN's

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=2 orbital excitation

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^{+-}

1st/2nd radial excitation

L=0

ρ, ω, ϕ, K^* 1^{--}

π, η, η', K 0^{-+}

ρ, ω, ϕ, K^*

Hybrid Mesons with normal QN's

Assume that $\pi_1(1600)$ sets the mass scale

S=0 :	$1^{++}, 1^{--}$
S=1 :	$0^{-+}, 1^{+-}, 2^{-+}$

} Non-exotic hybrid QN's

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^{-+}

2^{nd} radial excitation

π, η, η', K

Hybrid Mesons with normal QN's

Assume that $\pi_1(1600)$ sets the mass scale

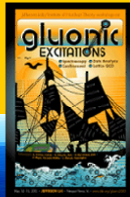
S=0 : $1^{++}, 1^{--}$
S=1 : $0^{-+}, 1^{+-}, 2^{-+}$

Non-exotic hybrid QN's

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^{-+}

1^{st} radial excitation

b_1, h_1, h'_1, K_1



Hybrid Mesons with normal QN's

Assume that $\pi_1(1600)$ sets the mass scale

S=0 :	$1^{++}, 1^{--}$
S=1 :	$0^{-+}, 1^{+-}, 2^{-+}$

Non-exotic hybrid QN's

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^{-+}

L=2 orbital excitation plus radial

$\pi_2, \eta_2, \eta'_2, K_2$

Hybrid Mesons with normal QN's

Assume that $\pi_1(1600)$ sets the mass scale

S=0 : 1^{++}, 1^{--}	Non-exotic hybrid QN's
S=1 : 0^{-+}, 1^{+-}, 2^{-+}	

L	Mesons	J^{PC}	Hybrids
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^{-+}	$\pi_2, \eta_2, \eta'_2, K_2$
L=1	a_2, f_2, f'_2, K_2	2^{++}	
	a_1, f_1, f'_1, K_1	1^{++}	a_1, f_1, f'_1, K_1
	a_0, f_0, f'_0, K_0	0^{++}	
	b_1, h_1, h'_1, K_1	1^{+-}	b_1, h_1, h'_1, K_1
L=0	ρ, ω, ϕ, K^*	1^{--}	ρ, ω, ϕ, K^*
	π, η, η', K	0^{-+}	π, η, η', K

The 1^{++} Mesons

1^{++} : 1^{st} Radial Excitation of $a_1(1260)/f_1(1285)$

$a_1(1640)$ } $m=1.64\pm0.05$ GeV/c^2
$\Gamma=0.30\pm0.1$ GeV/c^2

Decays to 3π via $f_2\pi$ and $(\pi\pi)_S\pi$

Consistent with a normal meson

The 1^{--} Mesons

1^{--} : 1^{st} Radial Excitation of ρ/ω.

2^{nd} Radial Excitation of ρ/ω.

L=2 D-wave (ρ_1, ρ_2, ρ_3)

$\rho(1450)$ $\omega(1420)$ $\phi(1680)$

$\rho(1700)$ $\omega(1650)$

$\rho(1900)$

$\rho(2150)$

L=2 Scale: $\rho_3(1690)$, $\omega_3(1670)$, $\phi_3(1850)$

Decay modes are significant here, but data is hard to interpret.

The 0^{-+} Mesons

$\pi(1800)$ — $m=1.801\pm0.013$ GeV/c^2, $\Gamma=0.210\pm0.015$ GeV/c^2

Decays: $f_0(980)\pi$, $f_0(1370)\pi$, $\rho\pi$, $\eta\eta\pi$, $a_0(980)\eta$, $f_0(1500)\pi$

Speculation that this may be a hybrid

$\eta(1760)$

Produced in J/ψ, decays to 4π

$\eta(2225)$ — $m=2.230\pm0.050$ GeV/c^2, $\Gamma=0.150\pm$large GeV/c^2

Produced in J/ψ, decays to $\phi\phi$

Glueball quantum numbers

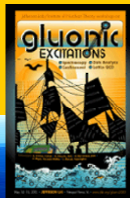
The 1^{+-} Mesons

1^{+-} : 1^{st} Radial Excitation of the $b_1(1235)/h_1(1170)$

$h_1(1595)$ } $m = 1.594 \pm 0.05$ GeV/c^2
$\Gamma = 0.384 \pm 0.15$ GeV/c^2

Produced in πp interactions
Decays to $\omega\eta$

Consistent with a normal meson ?



The 2^{-+} Mesons

$\pi_2(1670)$ $m=1.67\pm0.02\ GeV/c^2$
$\Gamma=0.259\pm0.001\ GeV/c^2$

Decays: $f_2\pi$, $\rho\pi$, $(\pi\pi)_S\pi$, $f_o(1370)\pi$, KK^* ($f_2\pi$ is 56%)

$\eta_2(1645)$ $m=1.617\pm0.005\ GeV/c^2$
$\Gamma=0.181\pm0.011\ GeV/c^2$

Decays: $a_2\pi$, $KK\pi$, $a_o\pi$ ($a_2\pi$ is largest)

$\eta_2(1870)$ $m=1.842\pm0.008\ GeV/c^2$
$\Gamma=0.225\pm0.014\ GeV/c^2$

Decays: $a_2\pi$, $f_2\eta$, $a_o\pi$ ($a_2\pi$ is largest)

} Hybrid Candidate?

$\pi_2(2100)$ $m=2.090\pm0.030\ GeV/c^2$
$\Gamma=0.625\pm0.100\ GeV/c^2$

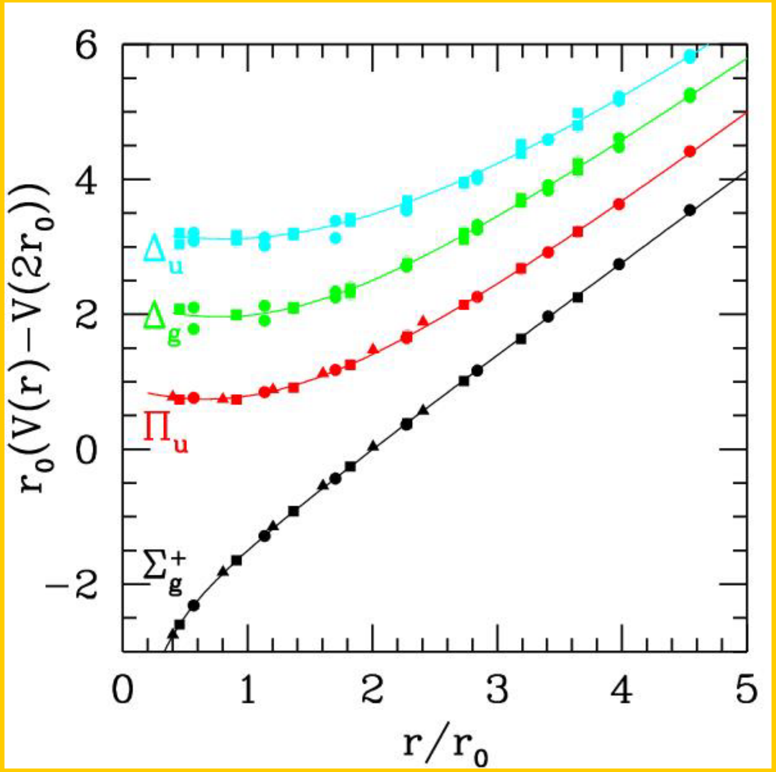
Decays: $f_2\pi$, $\rho\pi$, $(\pi\pi)_S\pi$

Exotics and QCD

In order to establish the existence of gluonic excitations, We need to establish the 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

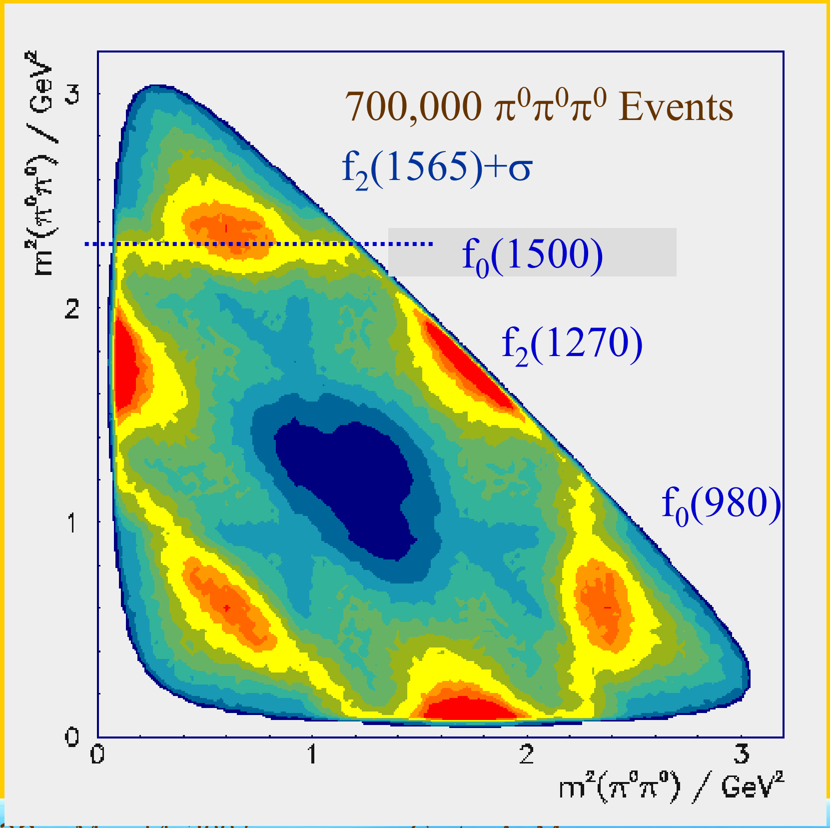
Results on Scalars

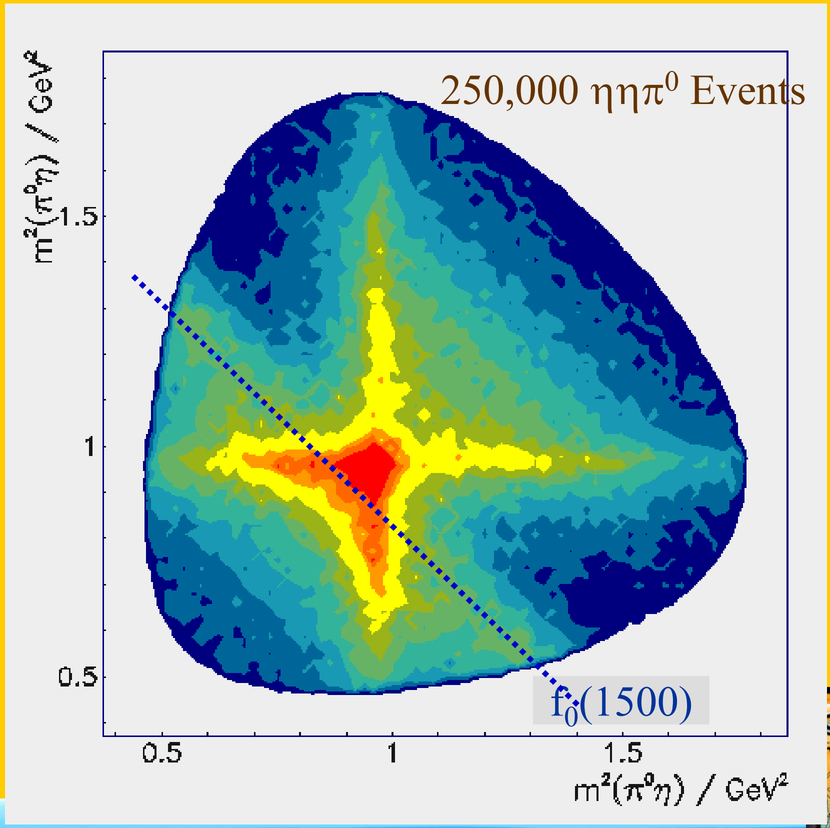
Crystal Barrel

Discovery of the $f_0(1500)$ — $f_0(1500) \Rightarrow \pi\pi, \eta\eta, \eta\eta', KK, 4\pi$

Solidified the $f_0(1370)$ — $f_0(1370) \Rightarrow 4\pi$

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





The $f_0(1500)$

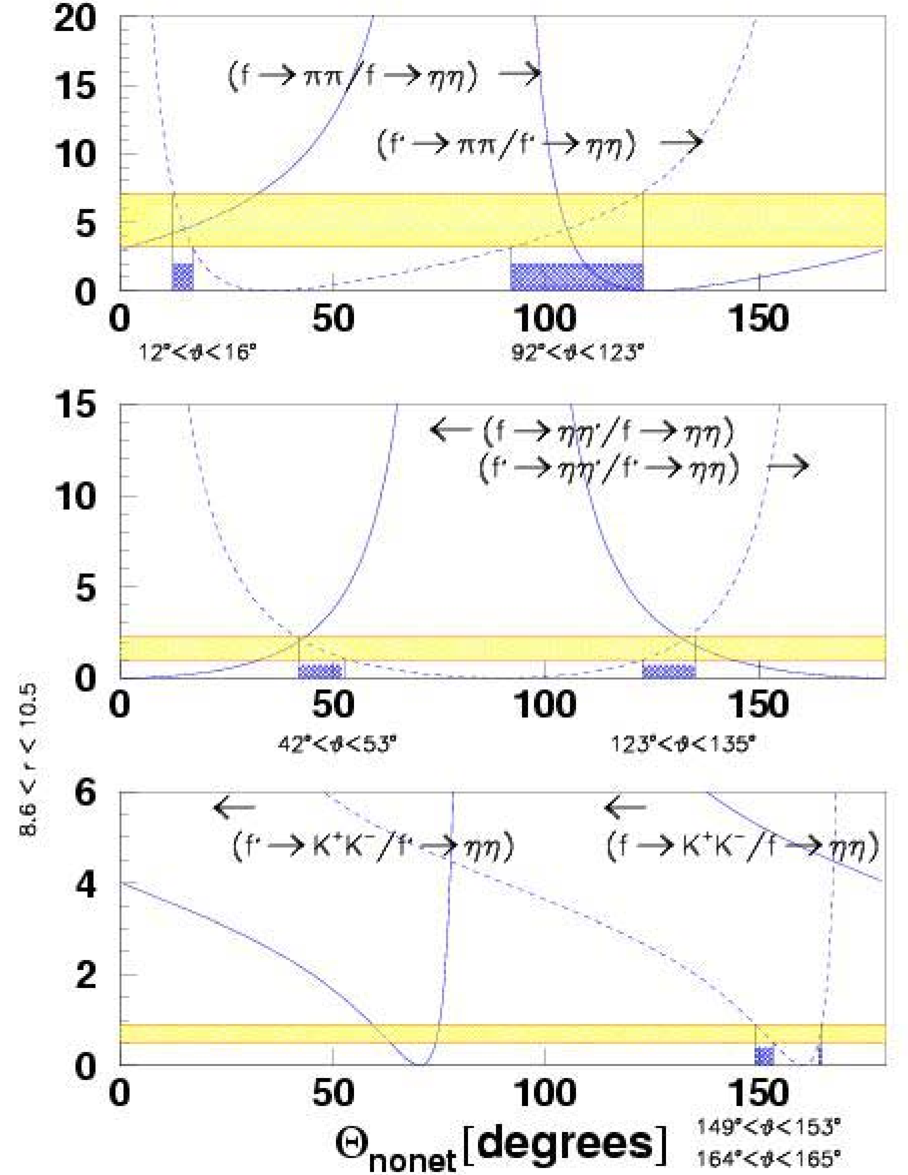
Is it possible to describe the $f_0(1500)$ as a member of a meson nonet?

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

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

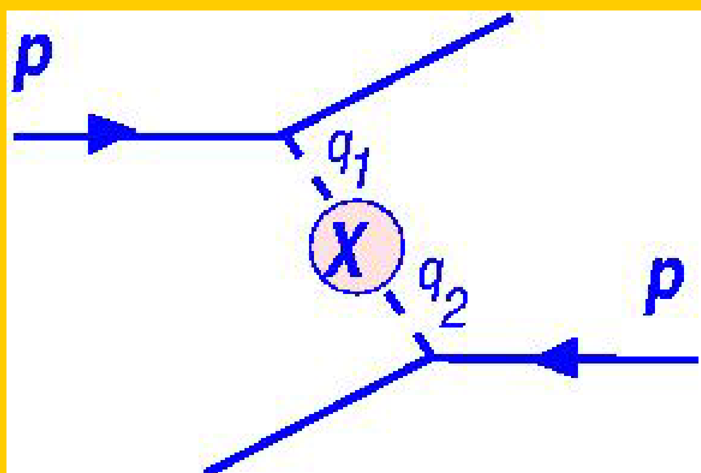


Both the $f_0(1370)$ and $f_0(1500)$ are $u\bar{u}$ & $d\bar{d}$

WA102 Results

CERN experiment colliding p on a hydrogen target.

Central Production Experiment



Recent comprehensive data set and a coupled channel analysis.

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

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

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

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

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

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

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

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

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	
$f_0(1500)$	-0.65±0.04	0.33±0.04	-0.70±0.07	octet piece
$f_0(1710)$	0.39±0.03	0.91±0.02	0.15±0.02	

m_1=1377±20 m_2=1674±10 m_G=1443±24

Lattice of about 1600

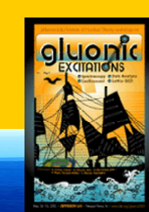
Glueball Expectations

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

Central Production: Couples to G and $\left(u\bar{u} + d\bar{d}\right)$ 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?

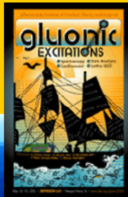
Part of the CLEO-c program will be to search for glueballs in radiative J/ψ decays.

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
f2(1950), f2(2010), f2(2300), f2(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.



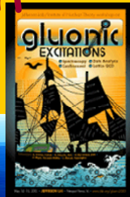
The Future

The CLAS experiment at Jefferson Lab is opening a small window to meson spectroscopy in photoproduction.

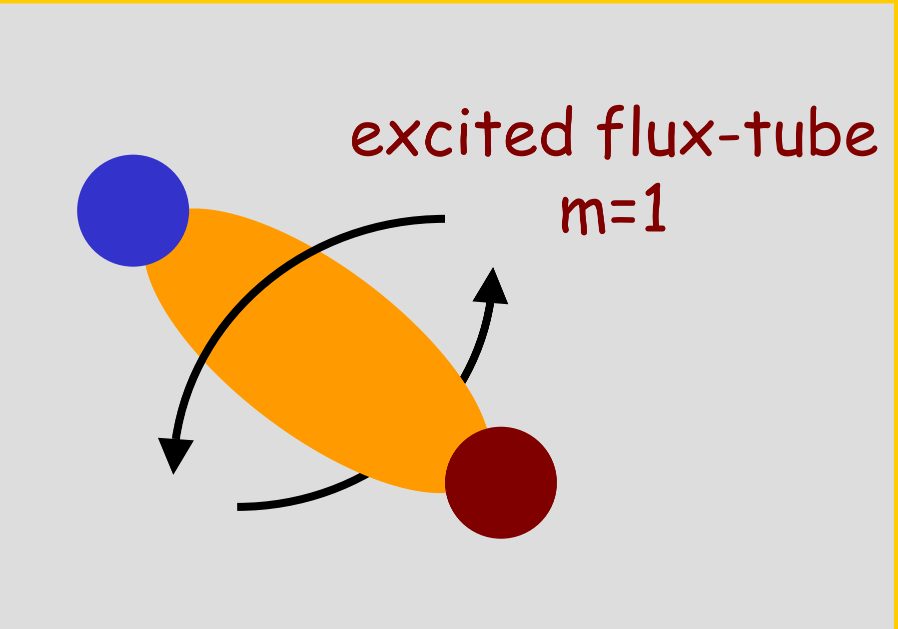
CLEO-c will reopen the J/ψ studies with 100 times Existing statistics. One goal is to find and study the Pseudoscalar (0^{-+}) and tensor glueball (2^{++})

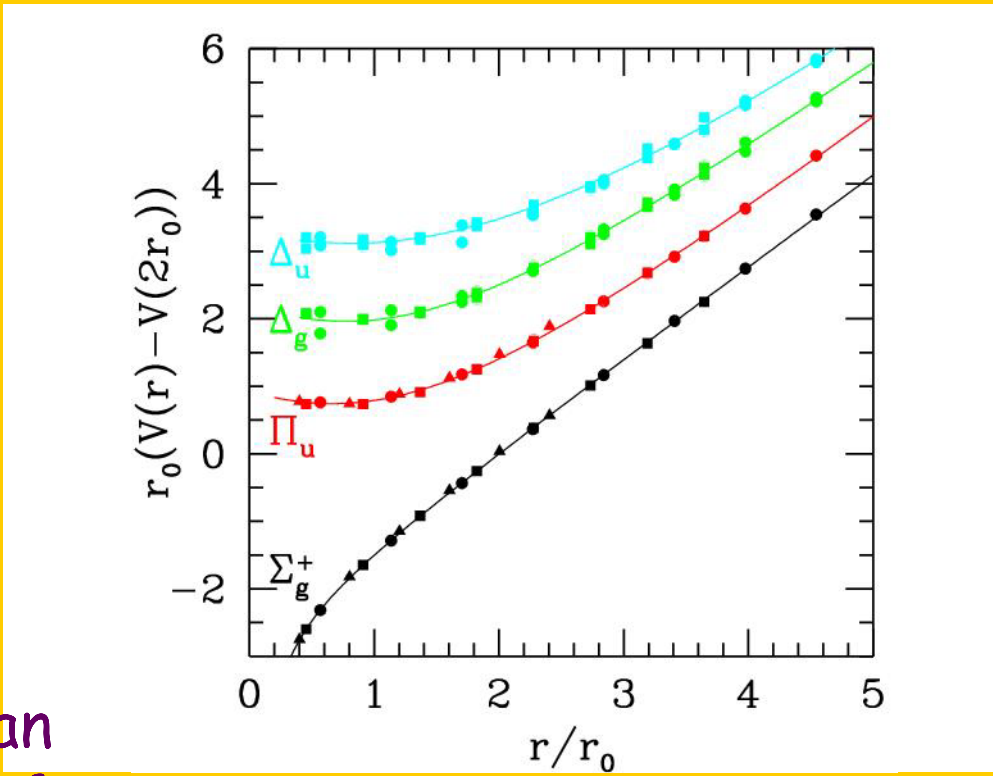
The GlueX experiment will be able to do for hybrids what Crystal Barrel and WA102 (together) did for glueballs. What are the properties of static glue in hadrons and how is this connected to confinement.

The antiproton facility at GSI (HESR) will look for hybrids in the charmonium system. (Just approved by the German government.)



QCD Potential





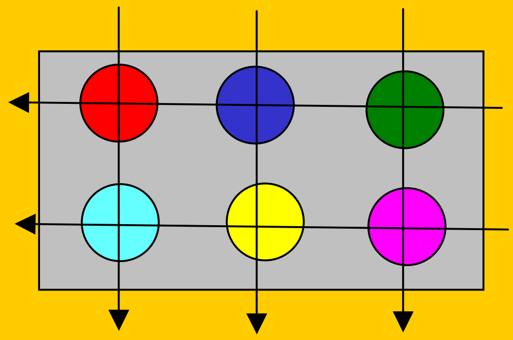
Gluonic Excitations provide an experimental measurement of the excited QCD potential.

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

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

Color singlet objects observed in nature:

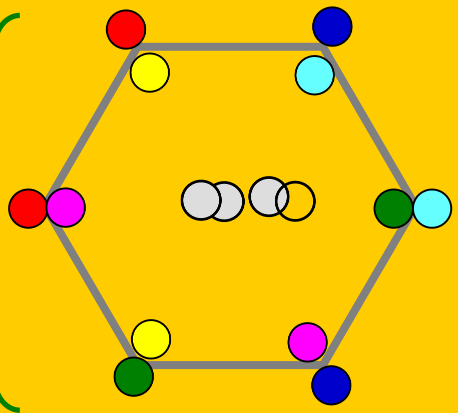
white



white

Quarks in 3 colors

8 Gluons carry color & anticolor



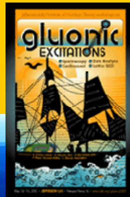
u $\bar{u}$

d $\bar{d}$ Focus on "light-quark mesons"

s $\bar{s}$

Glueballs Hybrids 4-quark

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



Nonet Mixing

The I=0 members of a nonet can mix:

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

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

$$\mathrm{SU(3)} \begin{vmatrix} f \\ f' \end{matrix}\Bigg\rangle = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{vmatrix} 1 \\ 8 \end{matrix}\Bigg\rangle$$

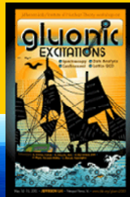
physical states

Ideal Mixing:

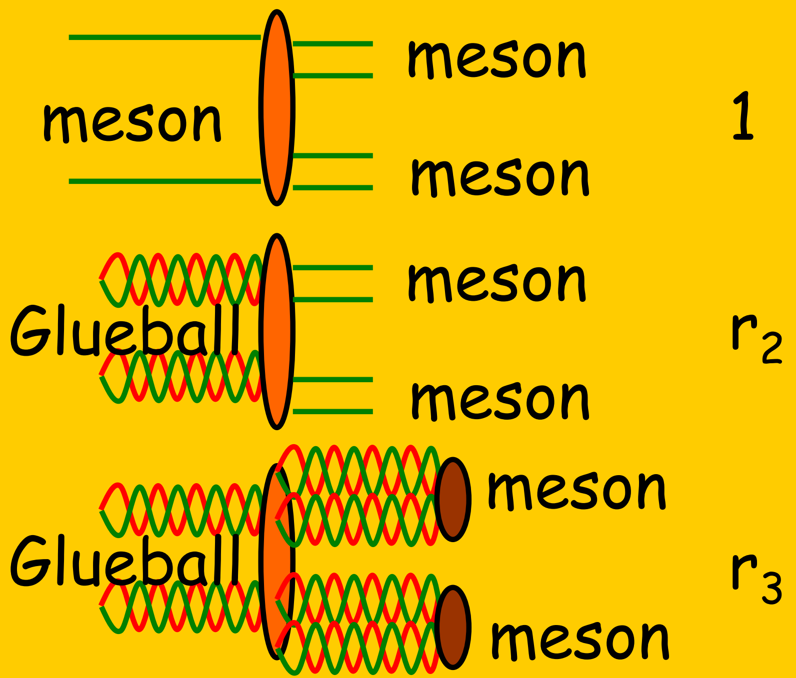
$$\cos\theta = \sqrt{\frac{2}{3}}$$

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

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



Model for Mixing

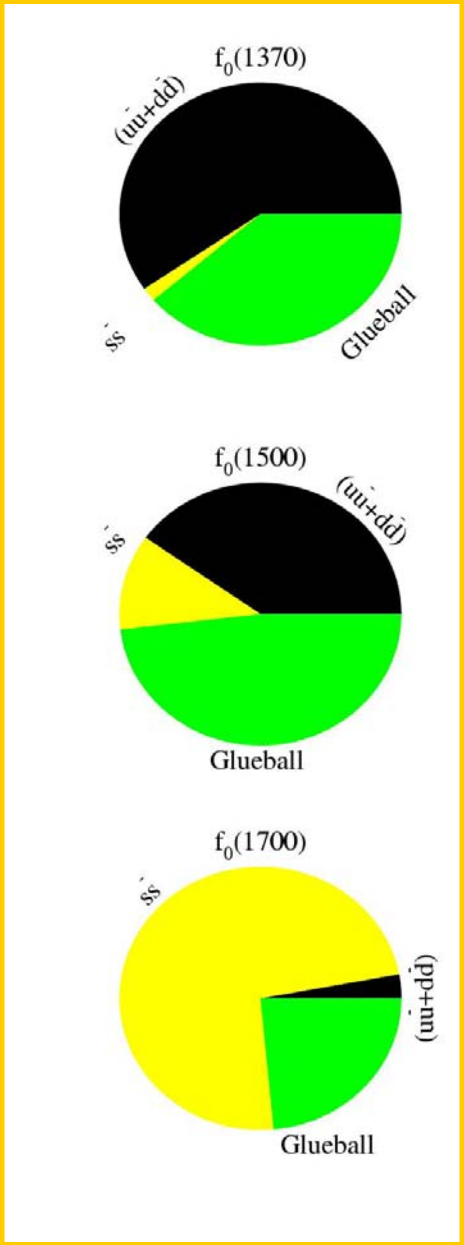


$G \rightarrow q\bar{q}$ flavor blind? r

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

Solve for mixing scheme

F.Close: hep-ph/0103173



Scalar Mesons

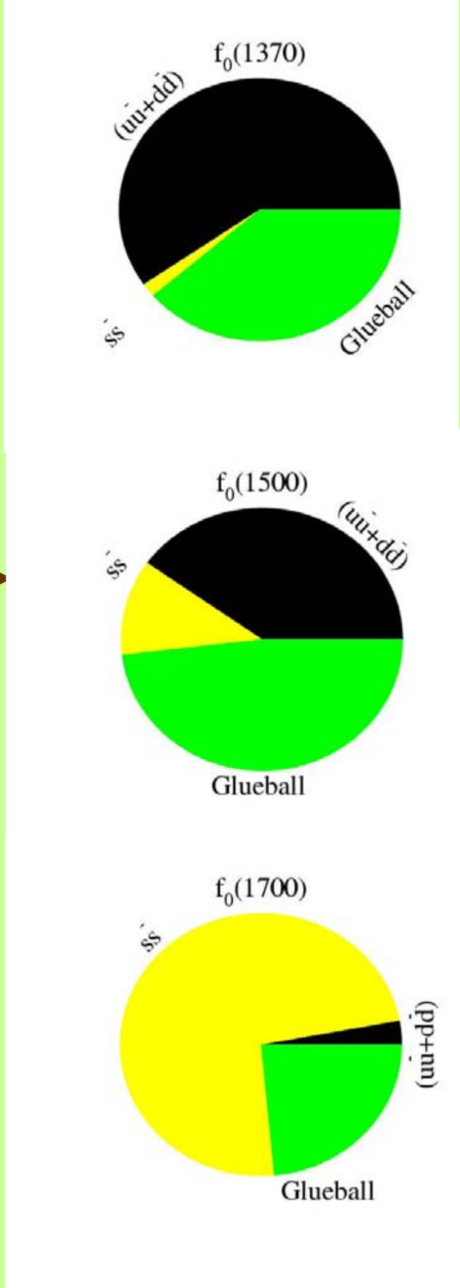
Overpopulation
Strange Decay Patterns
Seen in glue-rich reactions
Not in glue-poor

What about 2^{++} and 0^{-+} ?

J/Ψ Decays?

Awaiting CLEO-c

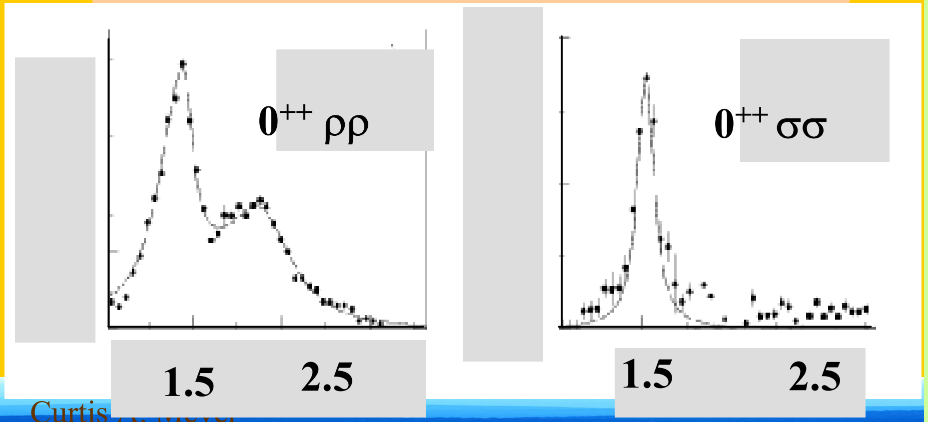
Glueball and Mesons are mixed. Scheme is model dependent.



Crystal Barrel proton-antiproton annihilation

Central Production WA102

Three States
$f_0(1370)$
$f_0(1500)$
$f_0(1710)$



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.