Non $q\bar{q}$ Light Meson Spectroscopy

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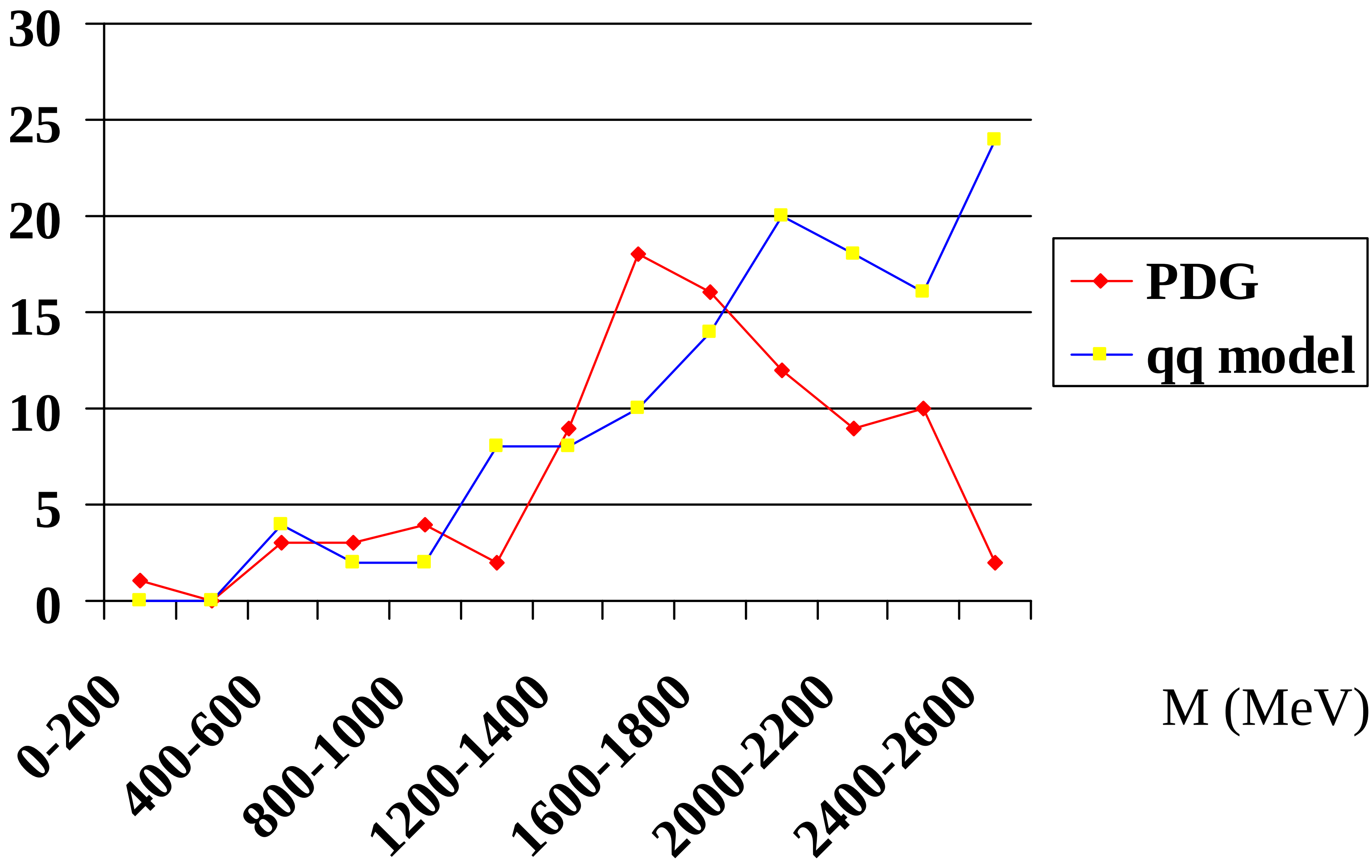
Non qq Light Meson Spectroscopy

- Matters of Principle
- Fast look at the spectrum
- Explicit Gluonic Degrees of Freedom
- Multiquark States

What is Spectroscopy?
How many mesons are there?



Fock Space Expansion:

$| q\bar{q} > + | q\bar{q}q\bar{q} > + | gg > + | q\bar{q}g > + | q\bar{q}q\bar{q}q\bar{q} > \ldots$

Whatever is not forbidden,
is compulsory:
"This state is an (X) state"
misleading when strong mixing.

Discrete part of the spectrum

→ MASS GAP

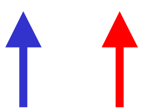
Quarks	u/d	300 MeV
Quark	s	500 MeV
Gluon	g	800 MeV

L unit 400 MeV

n (radial) unit 700 MeV

Standard quark-antiquark states

$q\bar{q}$ quantum numbers 

 1/2 x 1/2 $S = 0, 1$ $J = L+S$

1 -1

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

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

L	S	J^{PC}
0	0	0^{-+}
0	1	1^{--}
1	0	1^{+-}
1	1	$0\ 1\ 2^{++}$
2	0	2^{-+}
2	1	$1\ 2\ 3^{--}$
3	0	3^{+-}
3	1	$2\ 3\ 4^{++}$

L	S	J^{PC}
0	0	0^{-+}
0	1	1^{--}
1	0	1^{+-}
1	1	$0\ 1\ 2^{++}$
2	0	2^{-+}
2	1	$1\ 2\ 3^{--}$
3	0	3^{+-}
3	1	$2\ 3\ 4^{++}$

J^{PC} EXOTICA

$1^{-+} \quad 3^{-+} \ldots$

$0^{+-} \quad 2^{+-} \ldots$

0^{--}

~~$|qq>$~~ $+\ |qqqq> \ +\ |gg>$

$+\ |qqg> +\ |qqqqqq> \ \ldots$

$I\ q = 0, 1/2$ $\qquad$ $I\ q\bar{q} = 0, 1/2, 1$

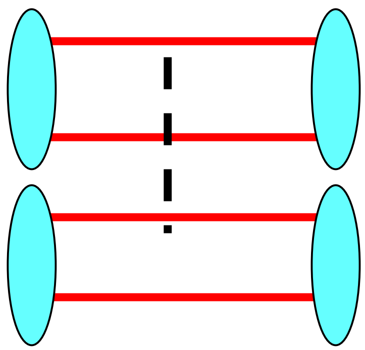
$S q = 0, 1$ $\qquad$ $S\ q\bar{q} = 0, 1$

SU(3) Exotica

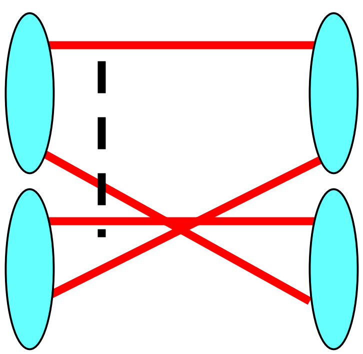
Any meson with I=3/2 and higher
or strangeness S=2 and higher

Exotic SU(3) channels are repulsive

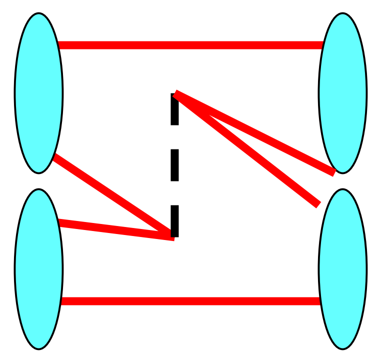
(Explanation by E. Ribeiro 1980)



= 0 (color factor)



repulsive



attractive

In exotic scattering the second diagram can't contribute

for example $\pi+\pi+$ (I=2) $u\bar{d}\ u\bar{d}$ no annihilation

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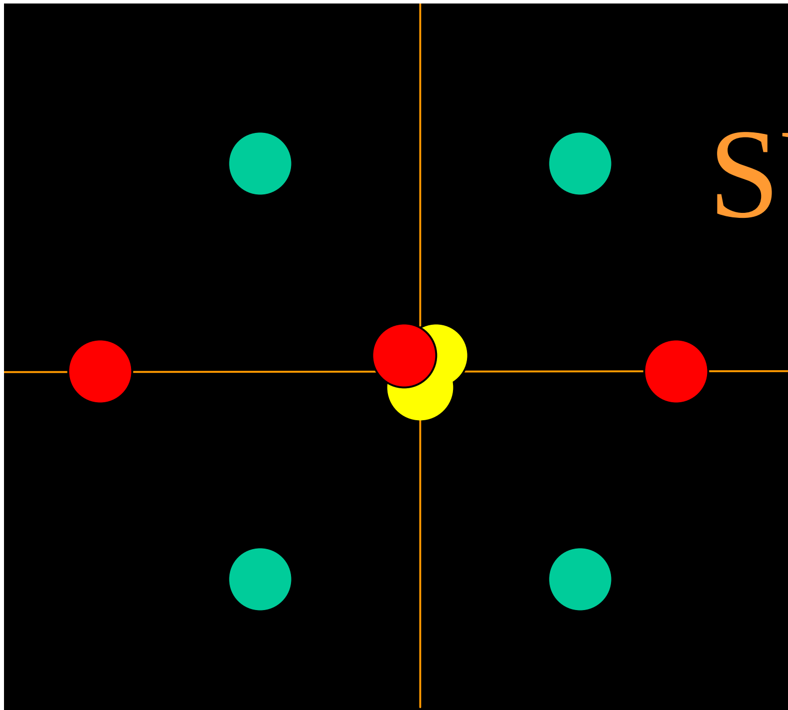

SU (3) Flavor Nonets

L = 0 , S = 0,1

0^{-+} π K η η'

1^{--} ρ K^* ω ϕ

L = 1, S = 0

1^{+-} $b_1(1235)$ K_{1B} $h_1(1170,1380)$

$L = 1$, $S = 1$

0^{++}	$a_0(1450)$	$K_0^*(1400)$	$f_0(1370,1710)$
0^{++}	$a_0(980)$	$\kappa(900)$	$f_0(600,980)$
1^{++}	$a_1(1260)$	K_1A	$f_1(1285,1420)$
2^{++}	$a_2(1320)$	$K_2^*(1430)$	$f_2(1430,1525)$
	$a_2(1700)$	$K_2^*(1980)$	$f_2(\text{various})$

0^{-+}	$\pi(1300)$	$K(1460)$	$\eta(1295, 1440_H)$	
	$\pi(1800)$	$K(1830)$	$\eta(1760, 2225\ ?)$	
1^{--}	$\rho(1450)$	$K^*(1410)$	$\omega(1420)$	$\phi(1680)$
	$\rho(1700)$	$K^*(1680)$	$\omega(1650)$	
	$\rho(1900)$	$\rho(2150)$ ...		
2^{-+}	$\pi_2(1670)$	$K_2(1770)$	$\eta_2(1645, 1870)$	
3^{--}	$\rho_3(1690)$	$K_3^*(1780)$	$\omega_3(1670)$	$\phi_3(1850)$
4^{++}	$a_4(1260)$	$K_4(1400)$	$f_4(1285,1420)$	

And an assortment of other resonances...
Some in excess: Cryptoexotic?

1) $f_2(1270)$ $\eta_L(1440)$ (4quark states?)
2) $f_0(1500)$ (some glueball component)
3) $K_2(1580)$ (dubious)
4) $K_2(1770)$ $K_2(1820)$ (complete D-wave 2^{-+}nonet; the orthogonal state could be a hybrid/4q state)

Some missing:

b_1 around 1600 to complete a 1^{+-} nonet

a_0 around 1800 to complete a 0^{++} nonet

K_1 around 1800 to complete a 1^{++} nonet

ϕ around 1800 to complete 1^{--} nonet

AND SOME EXOTICS ...

π_1 (1400) M = 1380 (20) MeV

Γ = 300 (40) MeV

decay to $\eta\pi$

π_1 (1600) M = 1600 (25) MeV

Γ = 310 (60) MeV

decay to $\eta' \pi$

X (1600) I=2 state!! If confirmed, 4q

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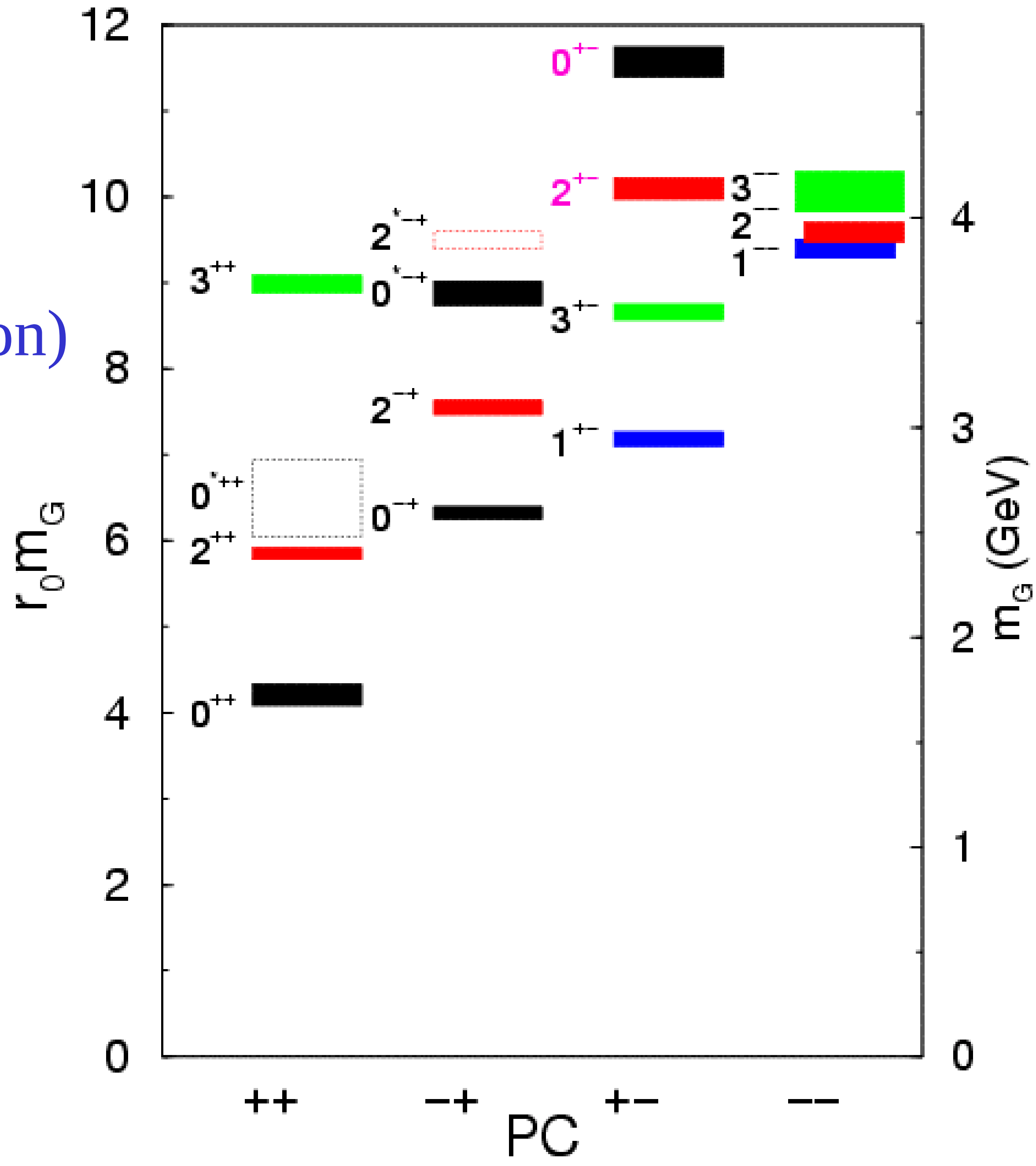
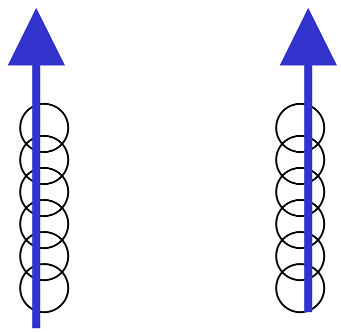
GLUEBALLS

(Lattice spectrum from Morningstar and Peardon)



Coulomb gauge BCS-TDA glueballs

(A. Szczepaniak et al. PRL 76, 2011 (1996),
F. Llanes-Estrada et al. NPA (2002).)



$$\langle s_1\, m_1\, s_2\, m_2 \,|\, S\, m_S \rangle \quad Y_L^m$$

$L=0$: 0^{++}, ~~1^{++}~~, 2^{++}

$L=1$: 0^{-+}, 2^{-+}, 3^{-+}

J = 1 is absent (Yang's theorem)

P = -1 requires a p-wave
(therefore pushed up 500-600 MeV)

C = - 1 requires three quasi-gluons
(therefore pushed up 800 MeV)

I = 0, S = 0 (always flavor singlets)

LOWEST GLUEBALL STATES:

0^{++} (1600) 2^{++} (2000 and up)

Glueballs fall on Regge Trajectories

* Interaction between color densities as suggested by QCD in the Coulomb gauge (non abelian gluon-gluon interaction)
* Slope of Regge trajectories much smaller than for quark mesons because color factor 3 instead of 4/3
* In (L,S) notation: model (0,0) 0^{++}, (2,0) 2^{++}, (4,0) 4^{++} fall on Regge trajectory parallel to pomeron.
* The 2^{++} (0,2) falls on Pomeron Regge trajectory, within lattice error bands.
* These are little sensitive to spin-orbit coupling which is the model's largest weakness.

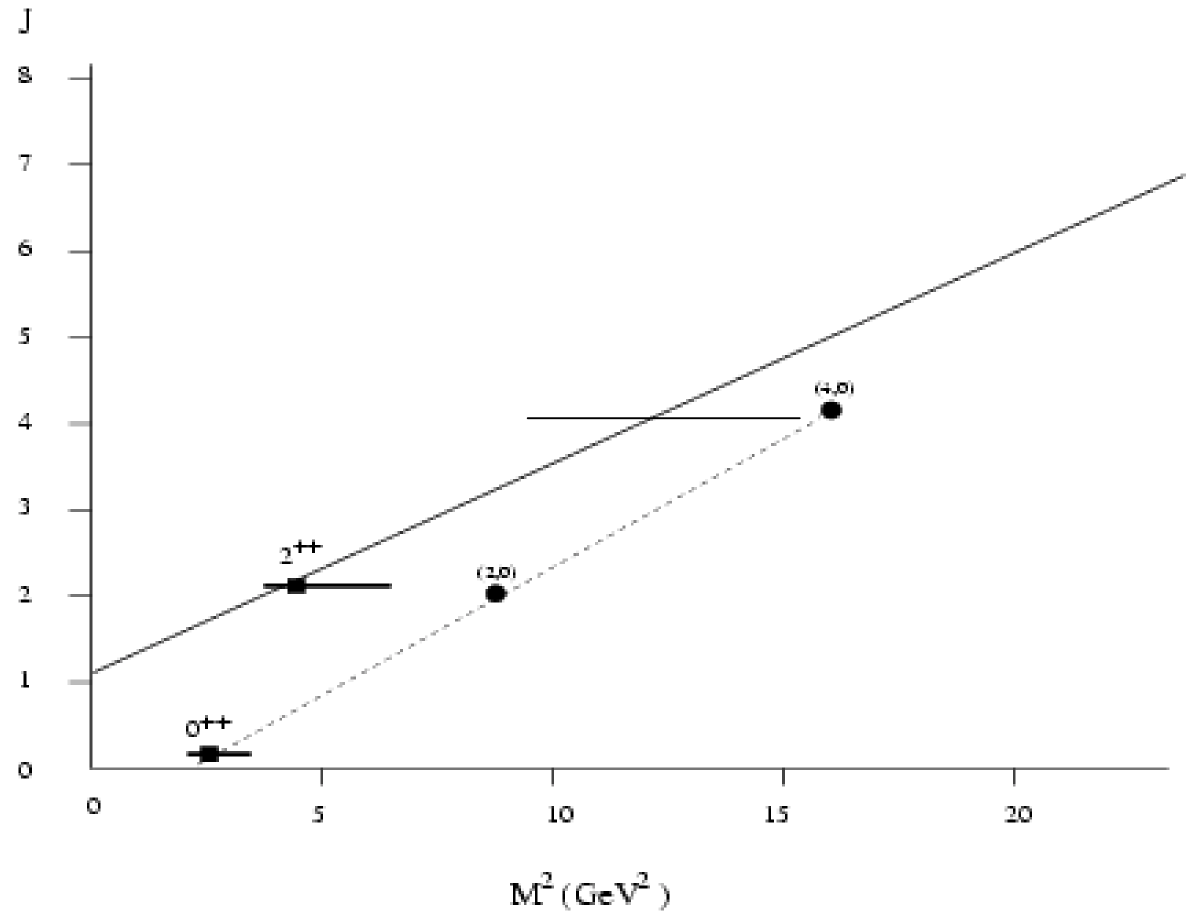
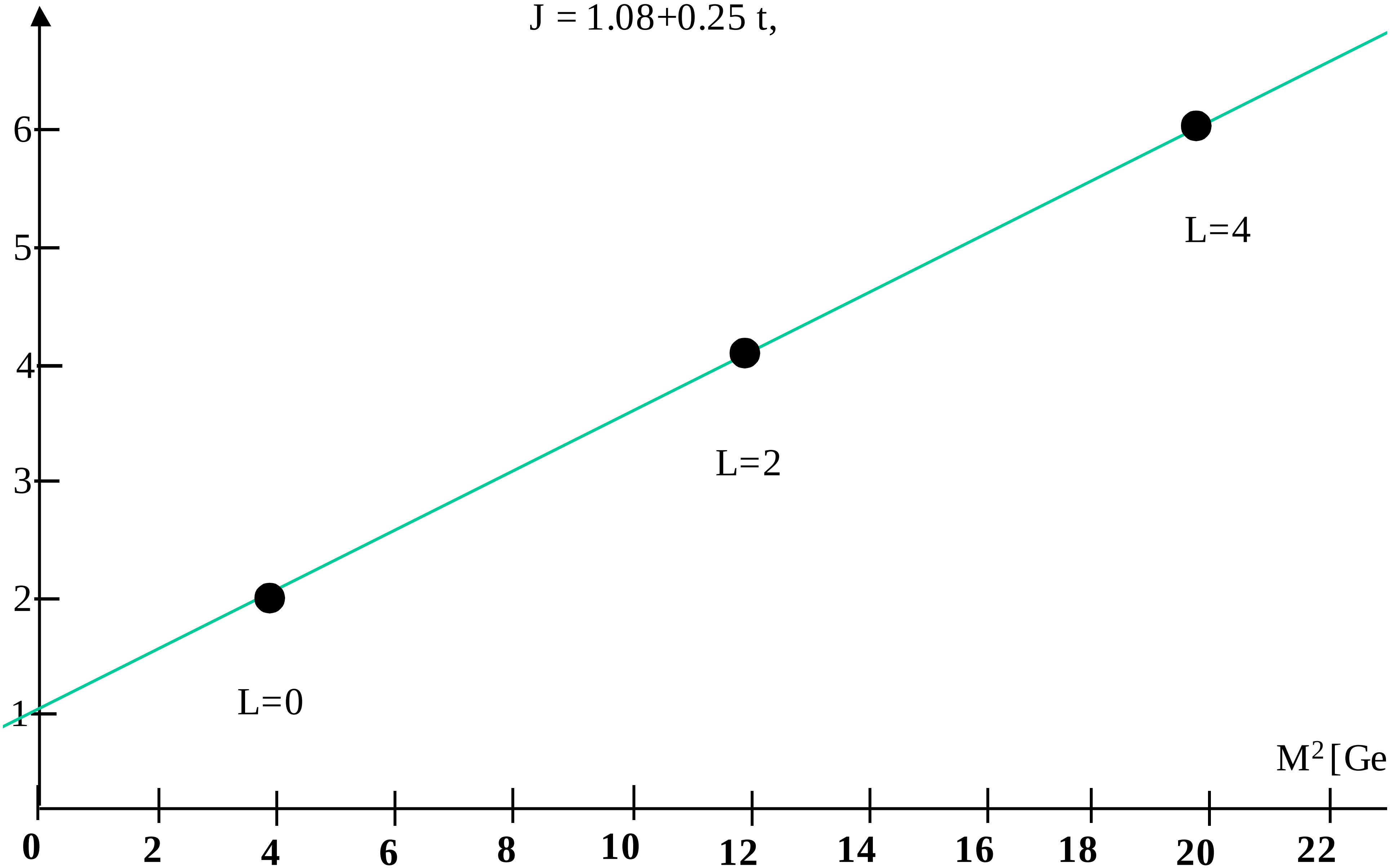


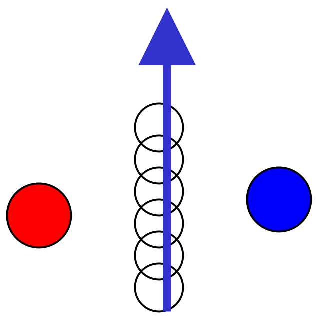
FIG. 3. Comparison of TDA (boxes) and lattice (horizontal bars) 2^{++} and 0^{++} glueballs with the Pomeron (solid line) and daughter (dashed line) Regge trajectories, respectively. The slope of the daughter trajectory is .28 GeV^{-2} and was determined by the higher $(L = 2, S = 0)$ and $(L = 4, S = 0)$ orbital excitations (solid circles).



J = 1.08+0.25 t,
6
5
4
3
2
1
L=0
L=2
L=4
M2 [Ge
0
2
4
6
8
10
12
14
16
18
20
22

HYBRID MESONS

From few-body point of view
(Llanes-Estrada & Cotanch, PLB 2001).



$$\overbrace{s_q + s_{\bar{q}}}^{S} + s_g + L_+ + L_- = J$$

$q_+ = (q + \bar{q})/2$
$q_- = q - \bar{q}$

$P = (-1)^{L_+ + L_-}$ $\qquad$ $C = (-1)^{1 + S + L_-}$

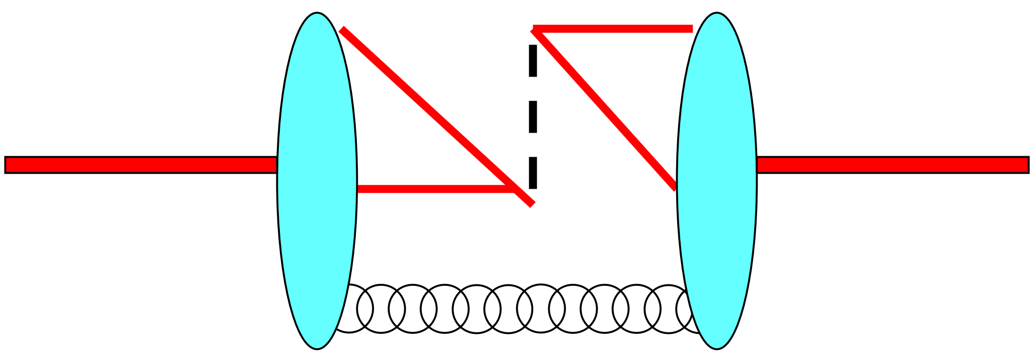
$$L_+ = L_- = 0 \quad \begin{cases} 1^{+-} \\ 0^{++} \\ 1^{++} \\ 2^{++} \end{cases}$$

$$L_- = 1 \quad \begin{cases} 0^{-+} \\ 1^{-+} \\ 2^{-+} \\ 0^{--} \\ 1^{--} \\ 2^{--} \\ 3^{--} \end{cases}$$

$$L_+ = 1 \quad \begin{cases} 0^{-+} \\ 1^{-+} \\ 2^{-+} \\ 3^{-+} \\ 1^{--} \\ 2^{--} \end{cases}$$

Flavor: Hybrids come in isospin nonets

Isospin 1 is lighter than isospin zero
if the quark-antiquark spins are aligned.



FLUX TUBE M ODEL

Isgur and Paton 1983

Predicts I=1 hybrids with J^{PC}=

$(012)^{+-}$ $(012)^{-+}$ 1^{++} 1^{--}

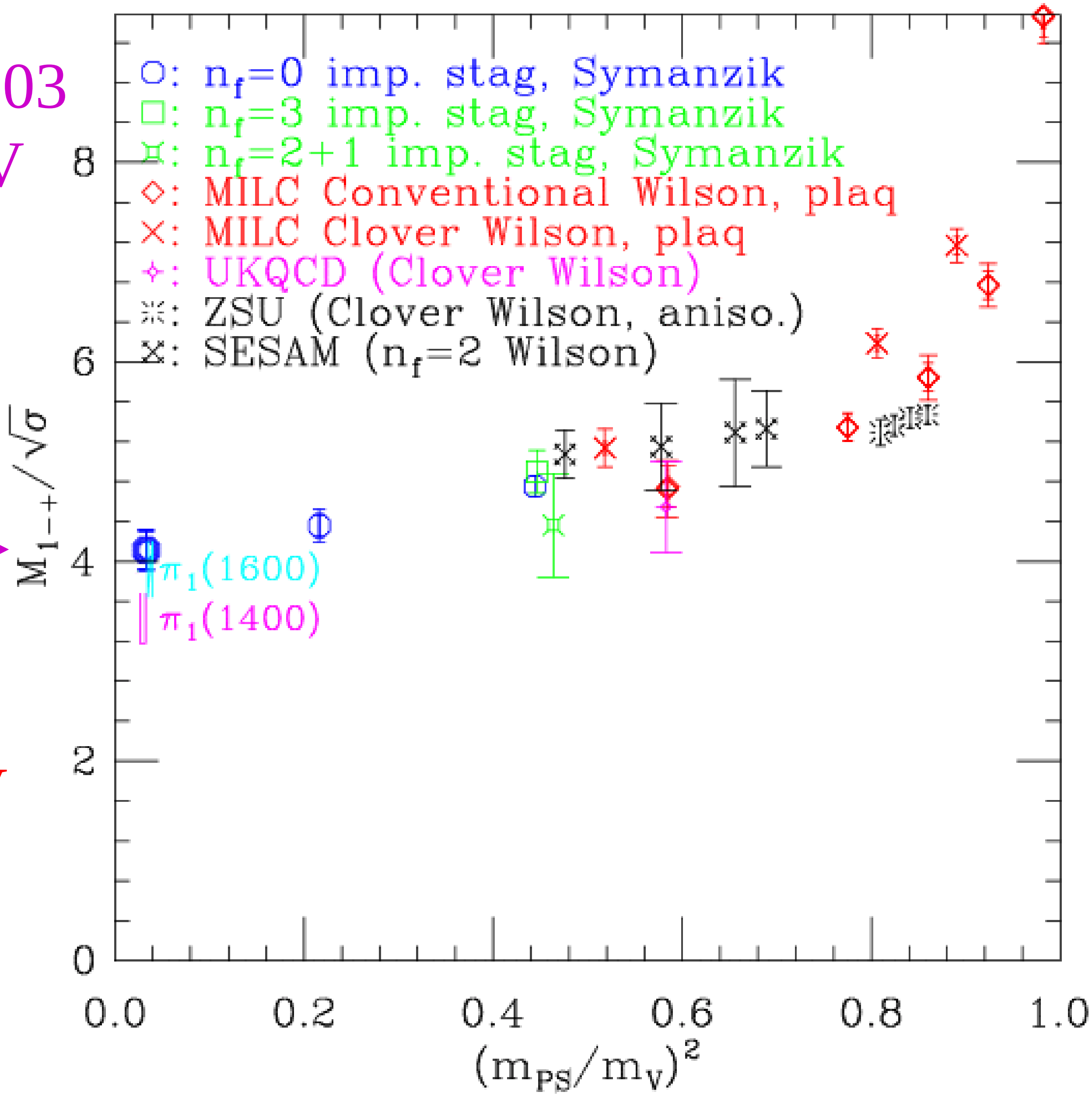
at about 1.9 GeV

Stringy glue configuration in a color singlet state makes the potential between q and $\bar{q}$ attractive.

Recent lattice calculations

C. Bernard et al 2003

1^{-+} hybrid 1.7 GeV



Mei & Luo 2002

1^{-+} hybrid 2.1 GeV

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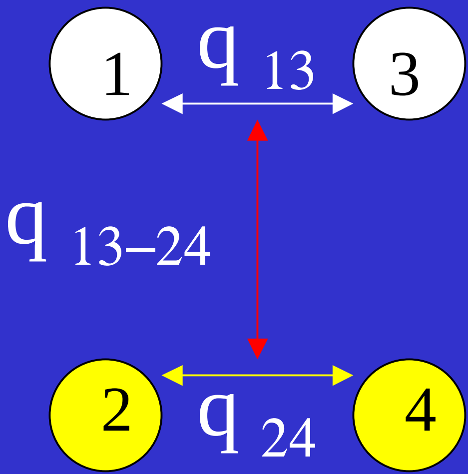
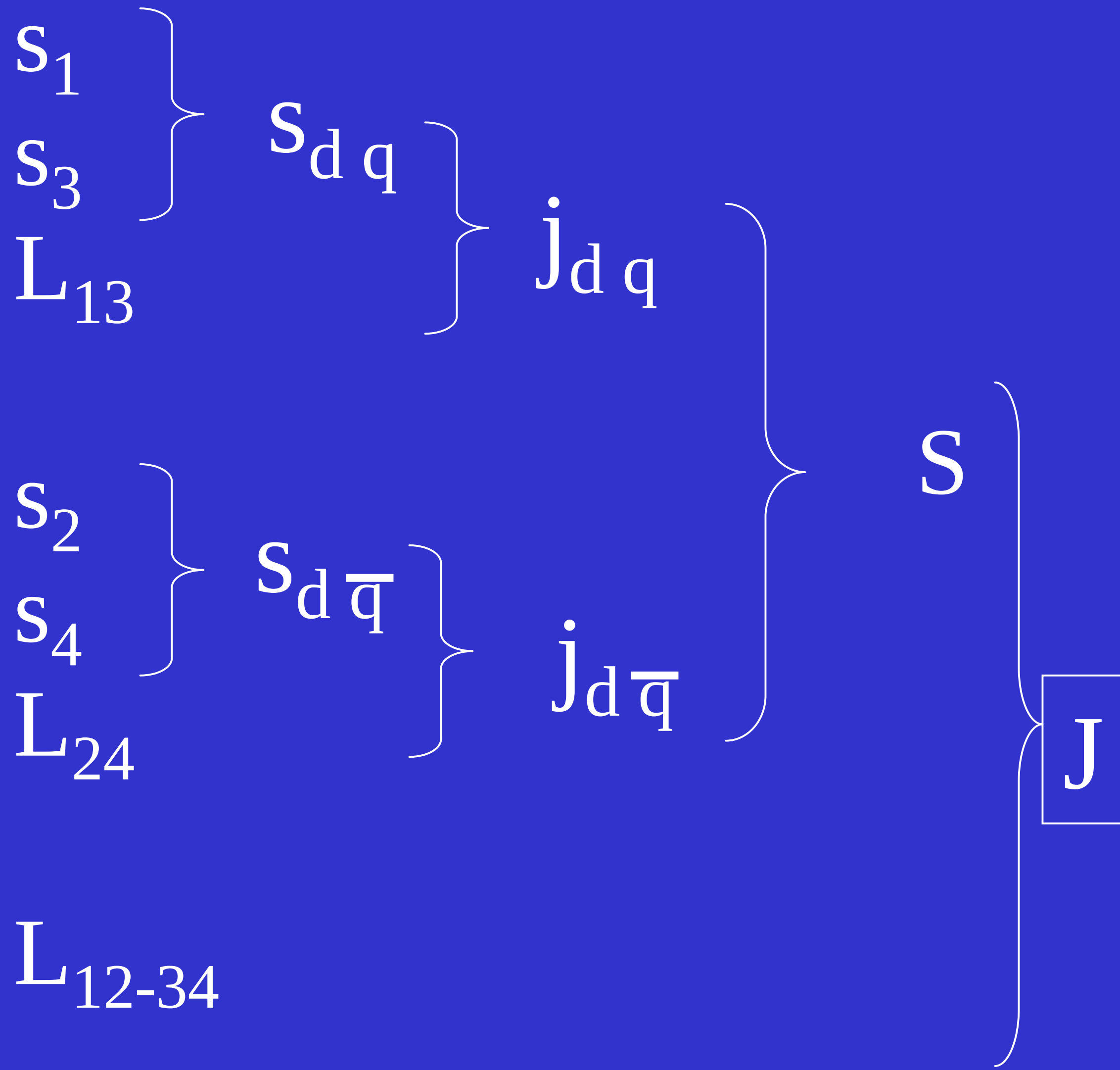




$$P = (-1)^{L_{13}+L_{24}+L_{12-34}} \qquad C = (-1)^{S+L_{12-34}}$$

GROUND STATE

S-waves only : 0^{++} 1^{+} 1^{+-} 2^{++}

P-wave: 1^{--} $(0\ 1\ 2\ 3)^{-}$ $(0\ 1\ 2)^{-+}$

(with various multiplicities)

Rich spectrum "state inflation"
hopefully most are too broad.

Badalyan (1987; Dafne 1991
LNF-91/017 (R)) Jaffe (1977)

M (4 light q´s) =	1565	1450 MeV
M (2 light 2 s) =	1950	1800 MeV
M (4 s q´s) =	2260	2150 MeV

$J^{PC} = 1^{--}$ states (Mulders, Aerts, de Swart)

1500,1660,1830,1860,1940,2000,2070,2140, 2210... P-wave exotica 1^{-+} from 1700

Four quark states are broad
(this is indeed how the π_1s are)
unless just below natural threshold
like f0(980) is.

Isgur and Weinstein 1983; variational qqqq calculation with free mesons in the basis.
NO MULTIQUARK HADRONS EXIST other than nuclei and the scalar nonet.

BUT

CONFIRMED PENTAQUARK Θ^+ (1540)

Nakano et al., Spring 8 $p K^0$, $n K^+$ threshold 1435 MeV

Leading wavefunction $| uudd\bar{s} >$

Molecular state such as $f_0(980)$ or deuterium?

KN repulsive in S-wave

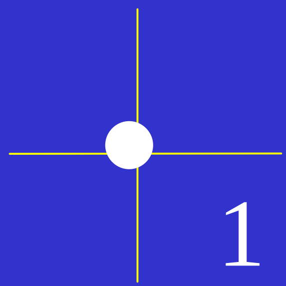
attractive but weak in P-wave

$K\pi N$ too weak to bind

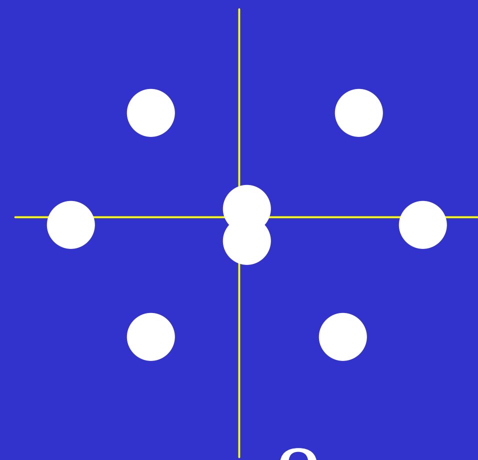
Bicudo & Marques; Oset & Llanes-Estrada

COMPACT PENTAQUARK

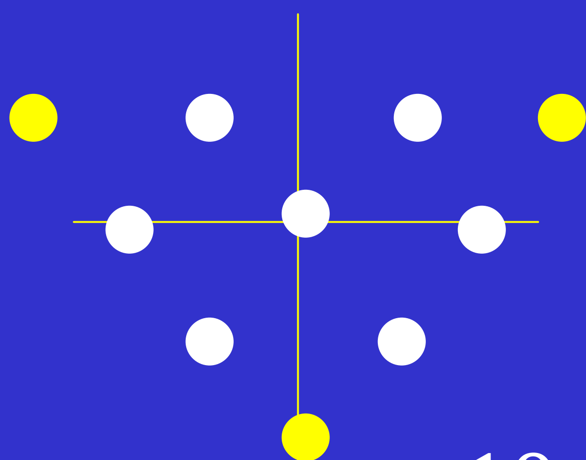
Look for states with S=2 or I_3=3/2, 2



1



8



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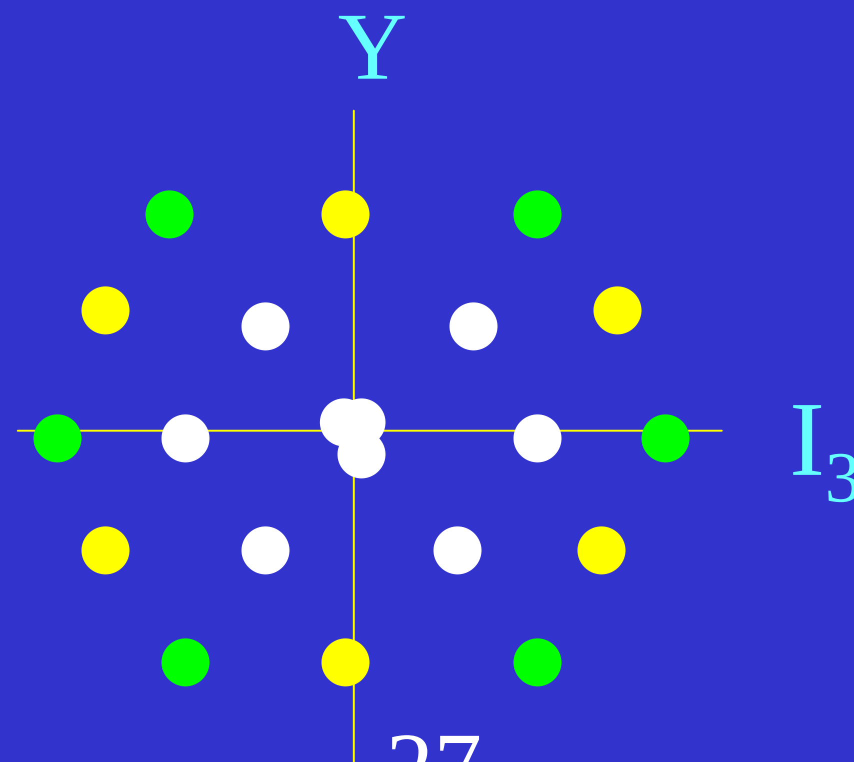
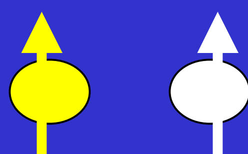


27

How about 6 q states ?

Obvious place to look is $N\bar{N}$ system

HOT ! BES results suggest parabaryonium has been found.



0^{-+} parabaryonium

1^{--} orthobaryonium

(almost degenerate, relatively narrow resonances below NN threshold, suppressed KK decay)

CONCLUSIONS

Below 1.6 GeV state saturation.
Identification of 4 q states (THEORY)

Above 1.6 GeV many states missing
(go bump hunting)

Glueballs: Scalar (1600) and tensor (2000)
stirred in through the f_0 f_2 families.

CONCLUSIONS

Hybrids : Employ exotic quantum numbers to separate from conventional mesons.
Difficult to distinguish from 4q composites.
Waves 0^{--} even $^{+-}$ odd $^{-+}$

To correctly identify glue, first illuminate multiquark spectroscopy. (Flavor Exotics).

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