The Constituent Quark Model and beyond

Diquarks, Tetraquarks, Pentaquarks

and no quarks

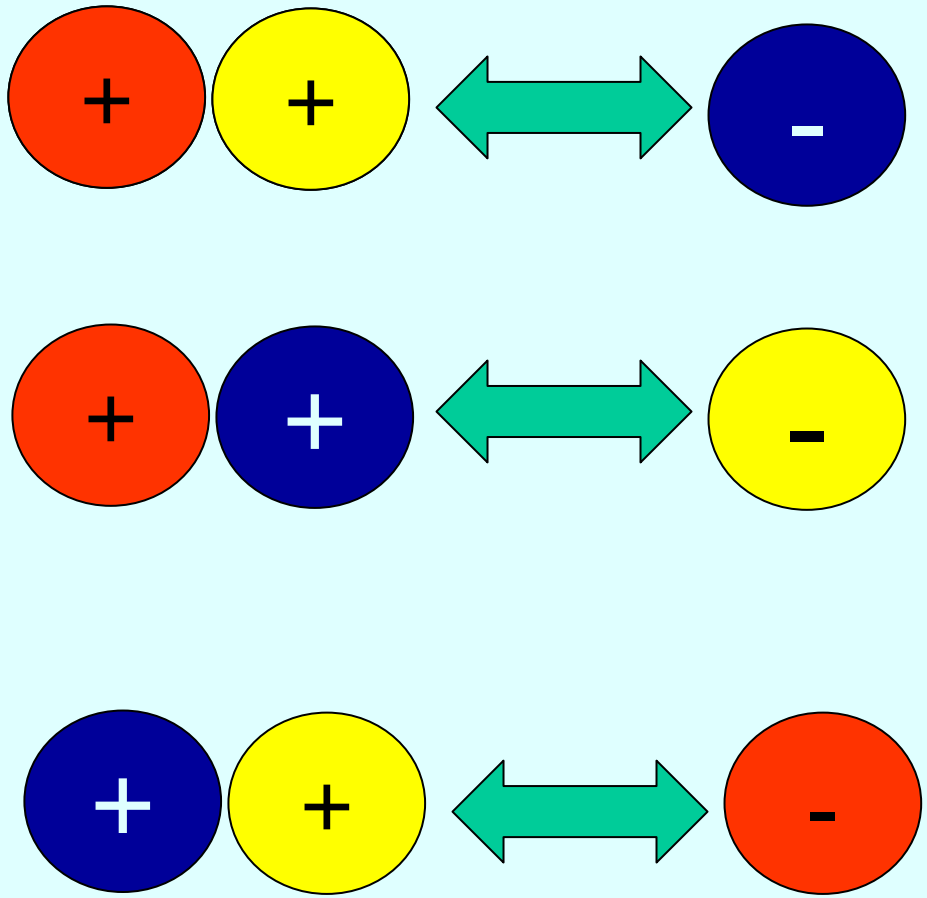
Frank Close

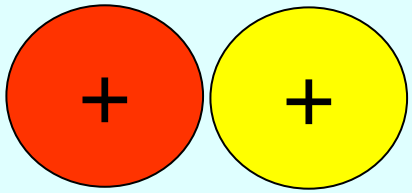
New states outside the quark model:

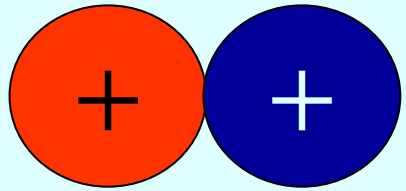
Pentaquark baryons

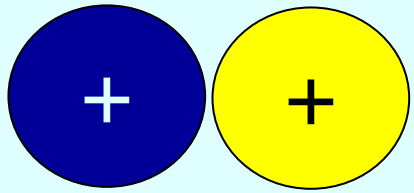
Attraction of two quarks to make a “diquark”

Recap how colour attractions work: two attracted quarks act like the “missing colour”

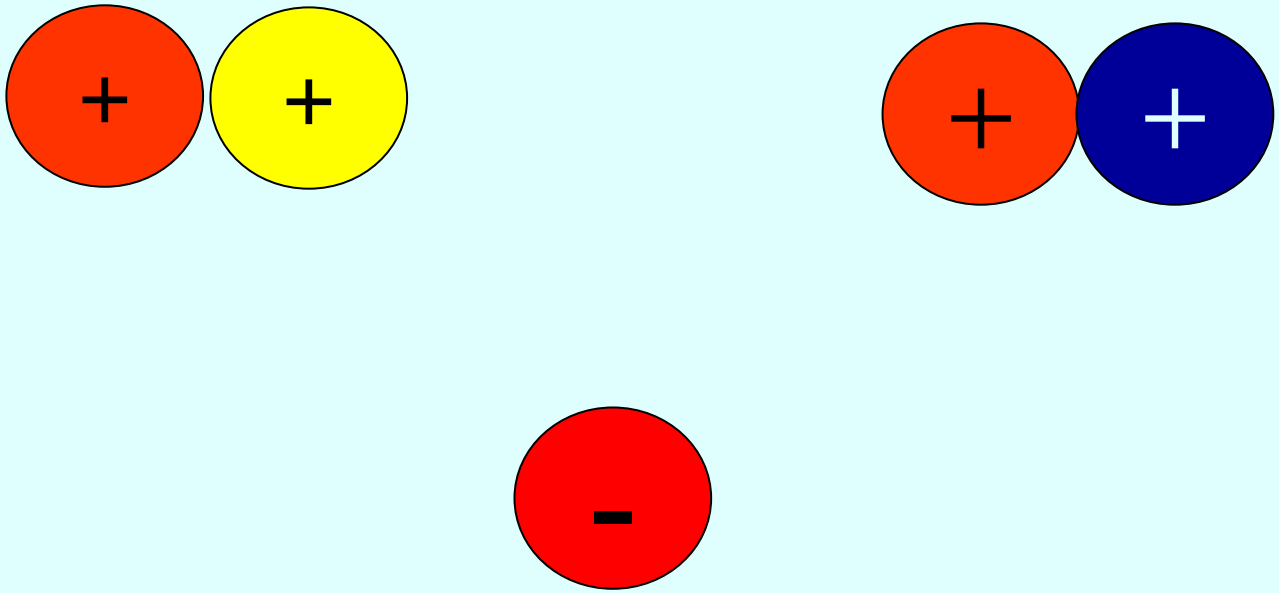








Lets try another way: replace the BLUE YELLOW Diquark by a RED antiquark



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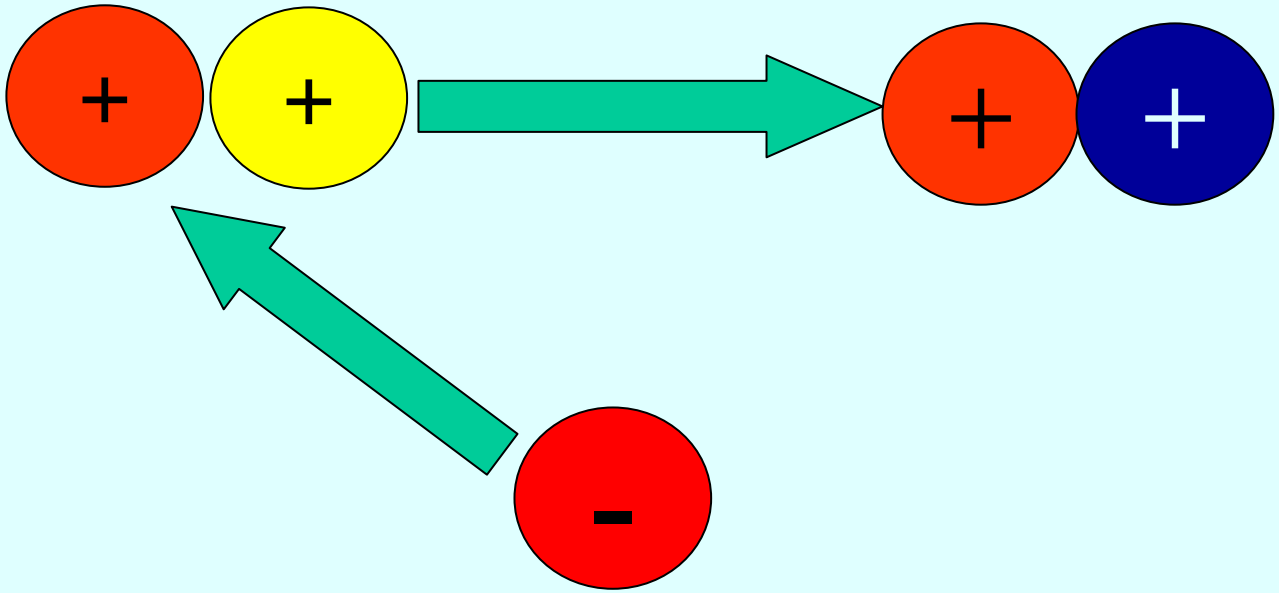
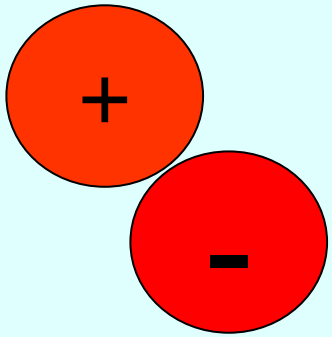
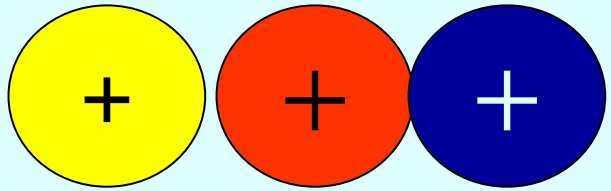




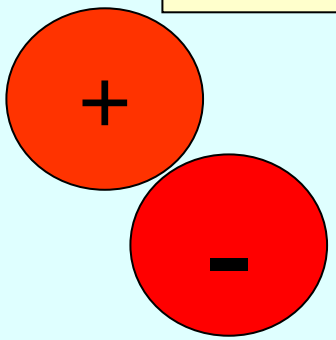
meson



nucleon

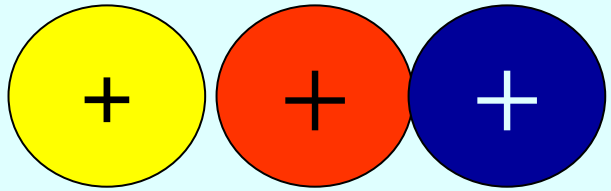
The forces rearrange them to make e.g. a neutron and a meson (kaon)

us*



K

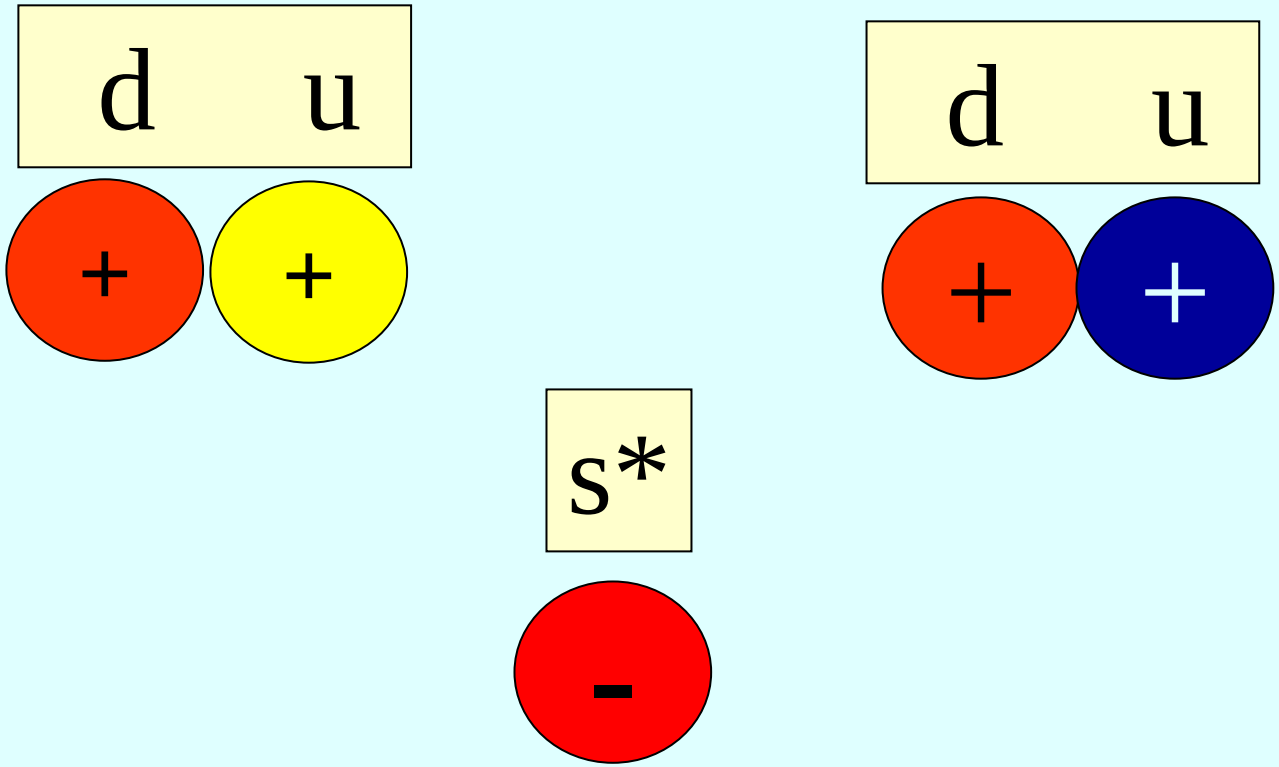
d d u



neutron

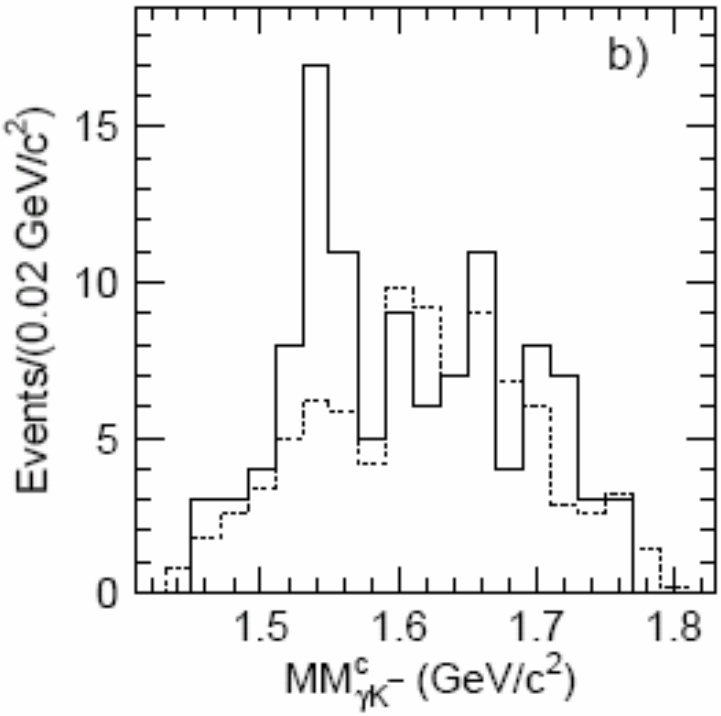
The forces rearrange them to make e.g. a neutron and a meson (kaon)…
Or so we thought!!!
2002 discovered a pentaquark!

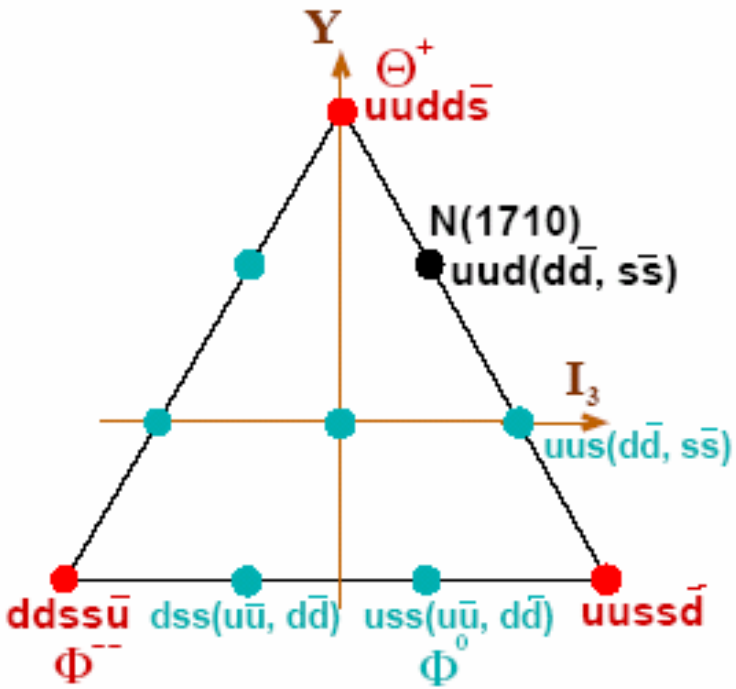
maybe



The diquarks seemed to maintain their identities 100 times more stable than anticipated (expt)

The plot that launched a thousand preprints





FEC slide from 2004

Pentaquarks

- Why is this thing so stable?
- Is it real?

- Is this the first hint of something profound in QCD?
- Or will higher statistics show it to be an artefact

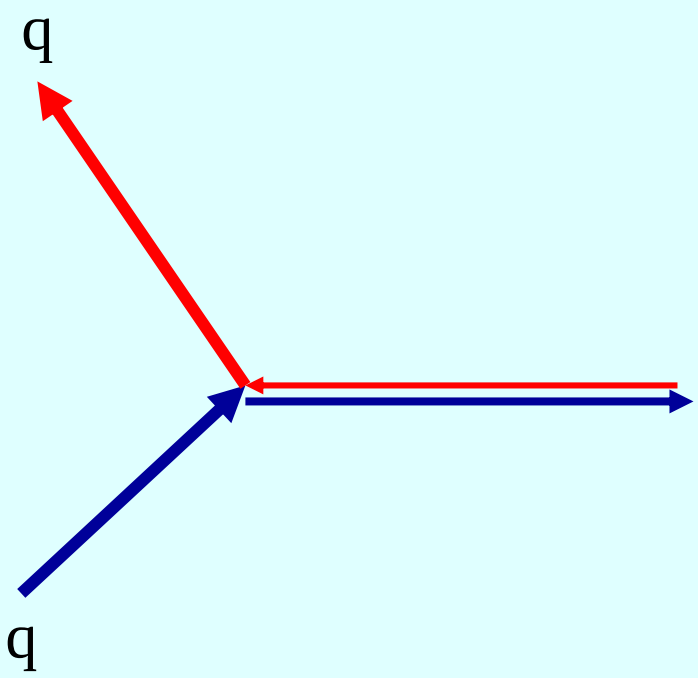
FEC slide from 2004

Arndt
Buccella
Carlson
Dyakanov
Ellis
Faber
Giannini
Huang
Inoue
Jaffe
Karliner
Lipkin
Maltman
Nussinov
Oh
Polyakov
Qiang
Rosner
Stech
Trilling
U
Veneziano
Wilczek
Xiang
Yang
Zhu

If Theta doesn't exist,
then these (and many other theorists)
should be congratulated on their creativity

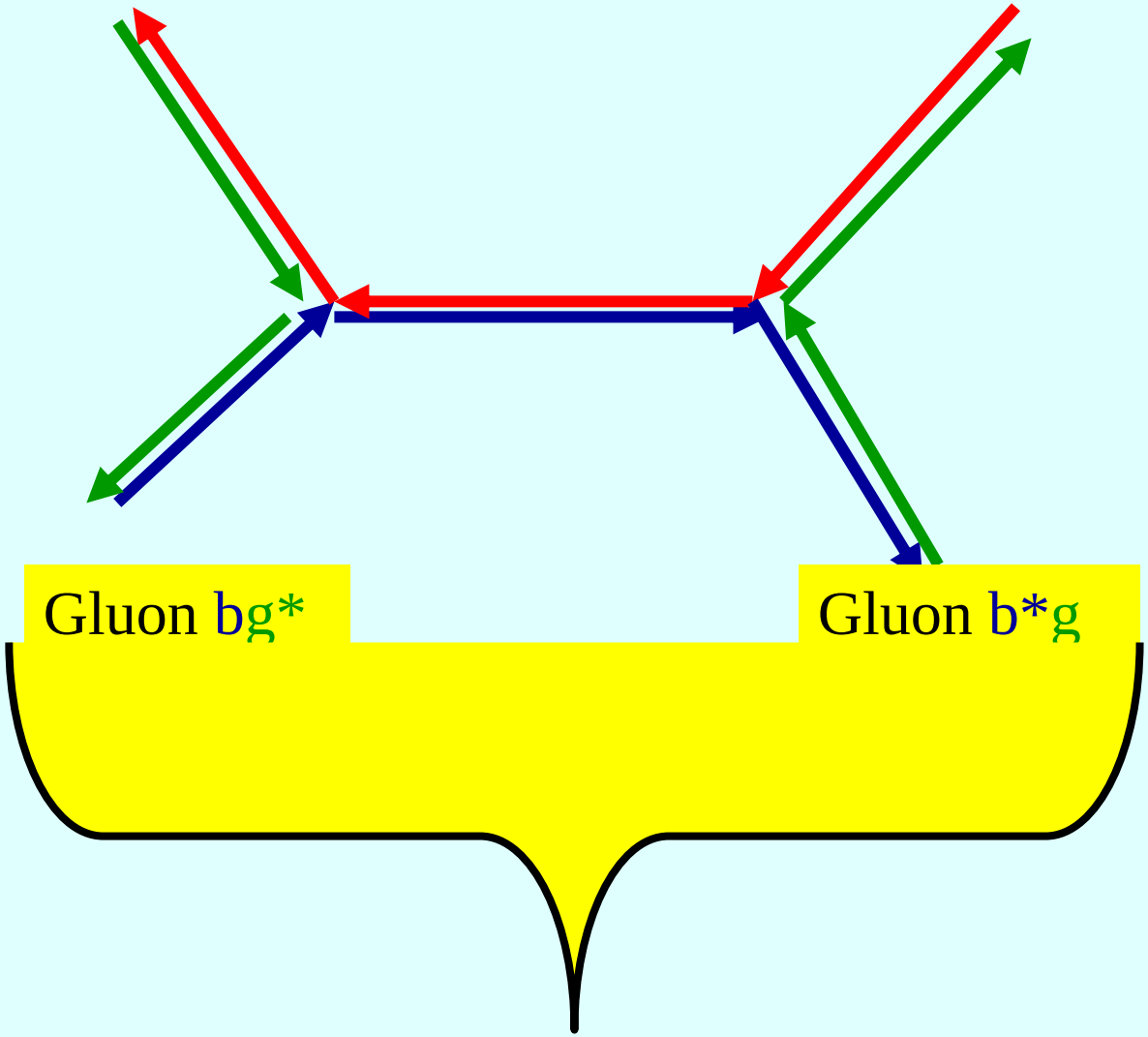
States outside the quark model:

1. Glueballs

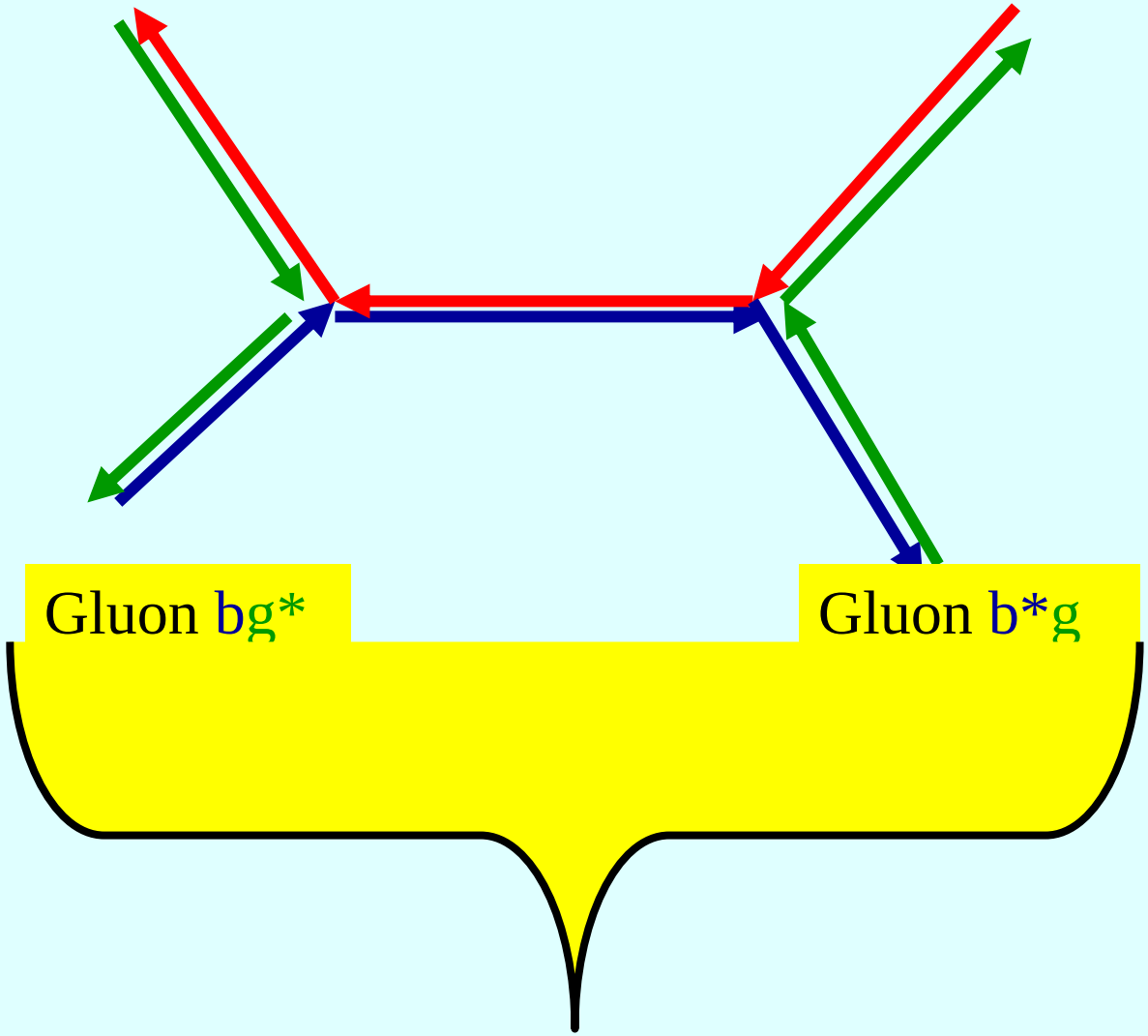


Gluon is coloured
Carries the “charge”

Like QED as far as pert theory concerned
Strong at long range/low energy
Need lattice QCD and models based on this



Colour singlet glueball



Colour singlet glueball

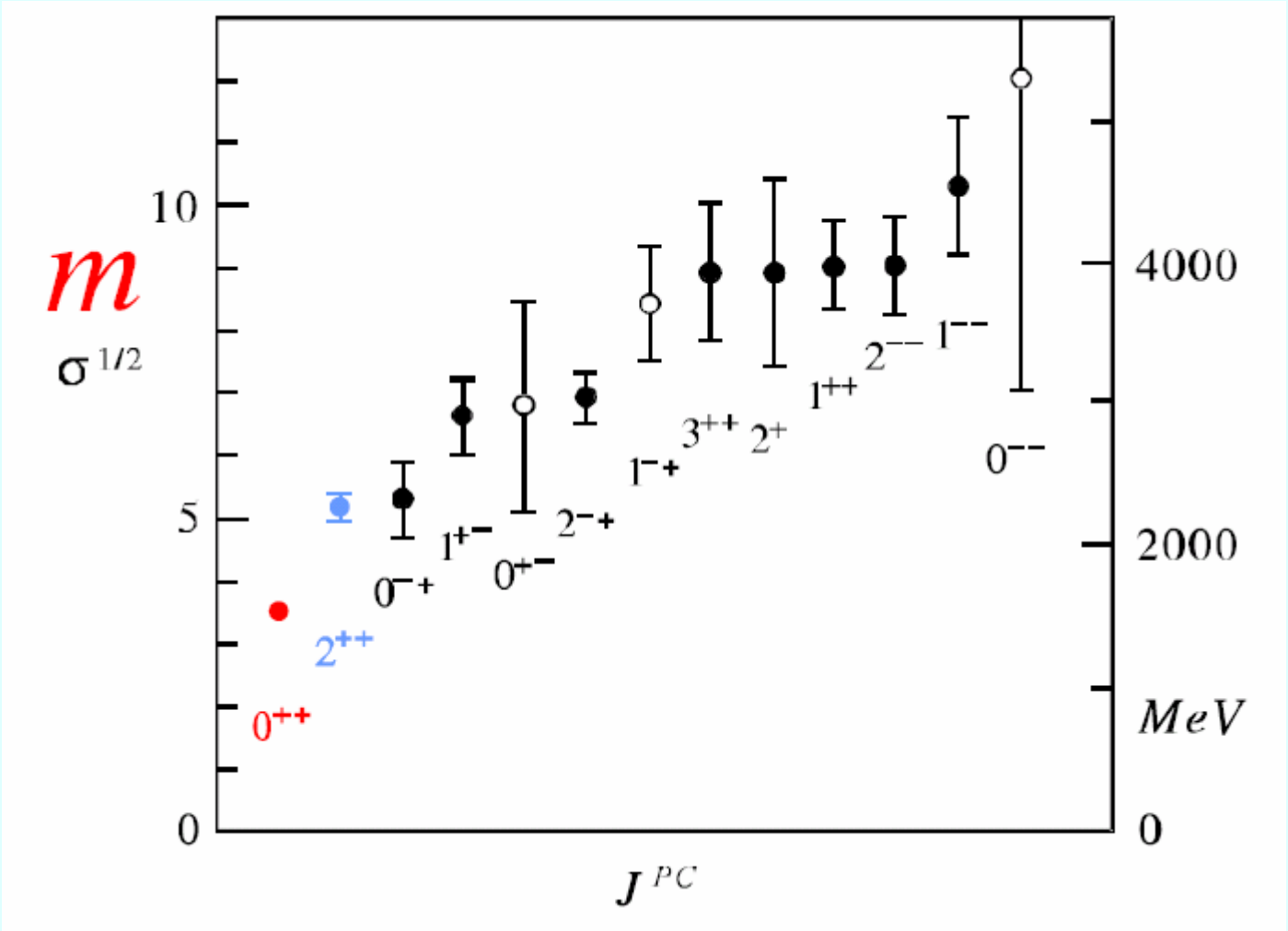
Lattice QCD

2++ 2.2GeV
0-+ 2.2GeV

0++ 1.5GeV

All \pm 0.2GeV

Glueballs spectrum from Lattice

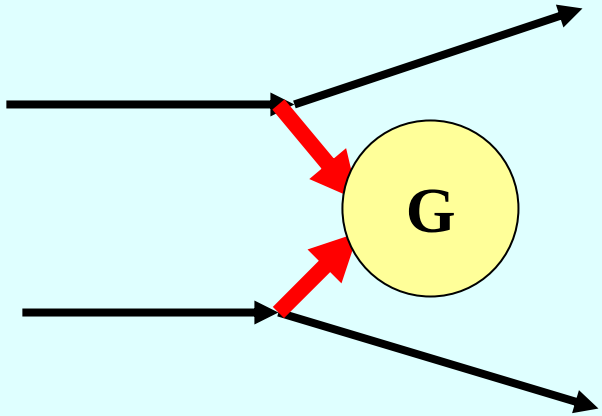


Far away from qq* lowest multiplets… **except for 0++**

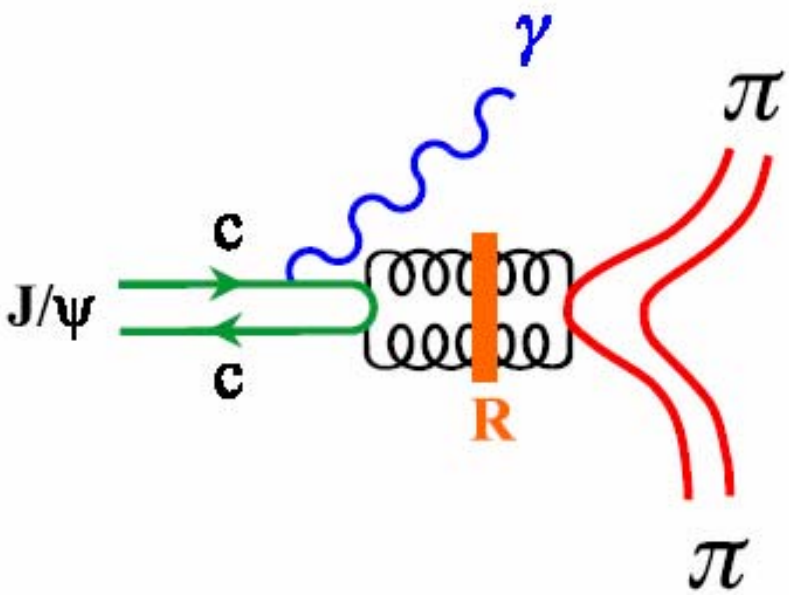
Folklore: where to look for glueballs

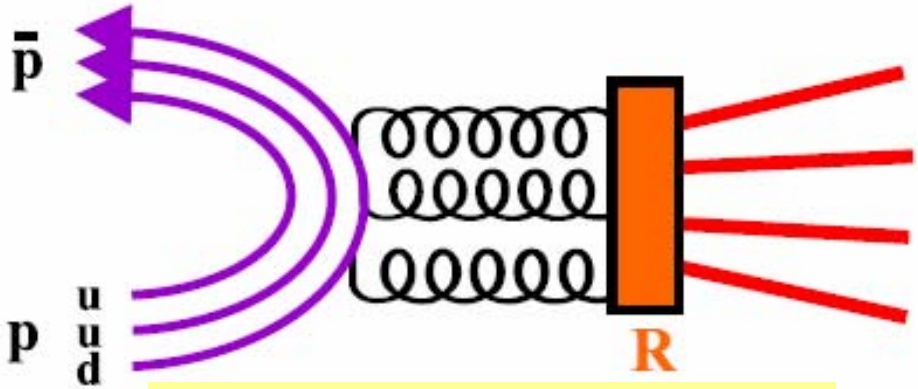
- **Get rid of the quarks**
- psi to (gamma gg) = (gamma G)>(gamma qq*)
- High energy production in central PP to P G P
- Low energy P- Pbar annihilation (LEAR)

Glueballs and central production



Idea: Robson, FC 77





Partial annihilation better

As well as looking for where glueballs might be…

Remember Sherlock Holmes dog that didn’t bark….

Check for evidence of where they are NOT!

$\Upsilon(b\bar{b})$ ψ (cc*)

1D: 1- ☐ 3772

2S: 1- 10023 3686

2+ 9913 3556

1+ 9893 3510

0+ 9860 3415

1S: 1- 9460 3097

Narrow below MM threshold

$\Upsilon(b\bar{b})$ ψ (cc*)

1D: 1- [ ] 3772

2S: 1- 10023 3686

Either no G with these JPC in this region **(0-+ 2.5<eta_c)** **(1– 3.8Gev ~ psiprime?)** or don't couple strongly to G

2+ 9913 3556

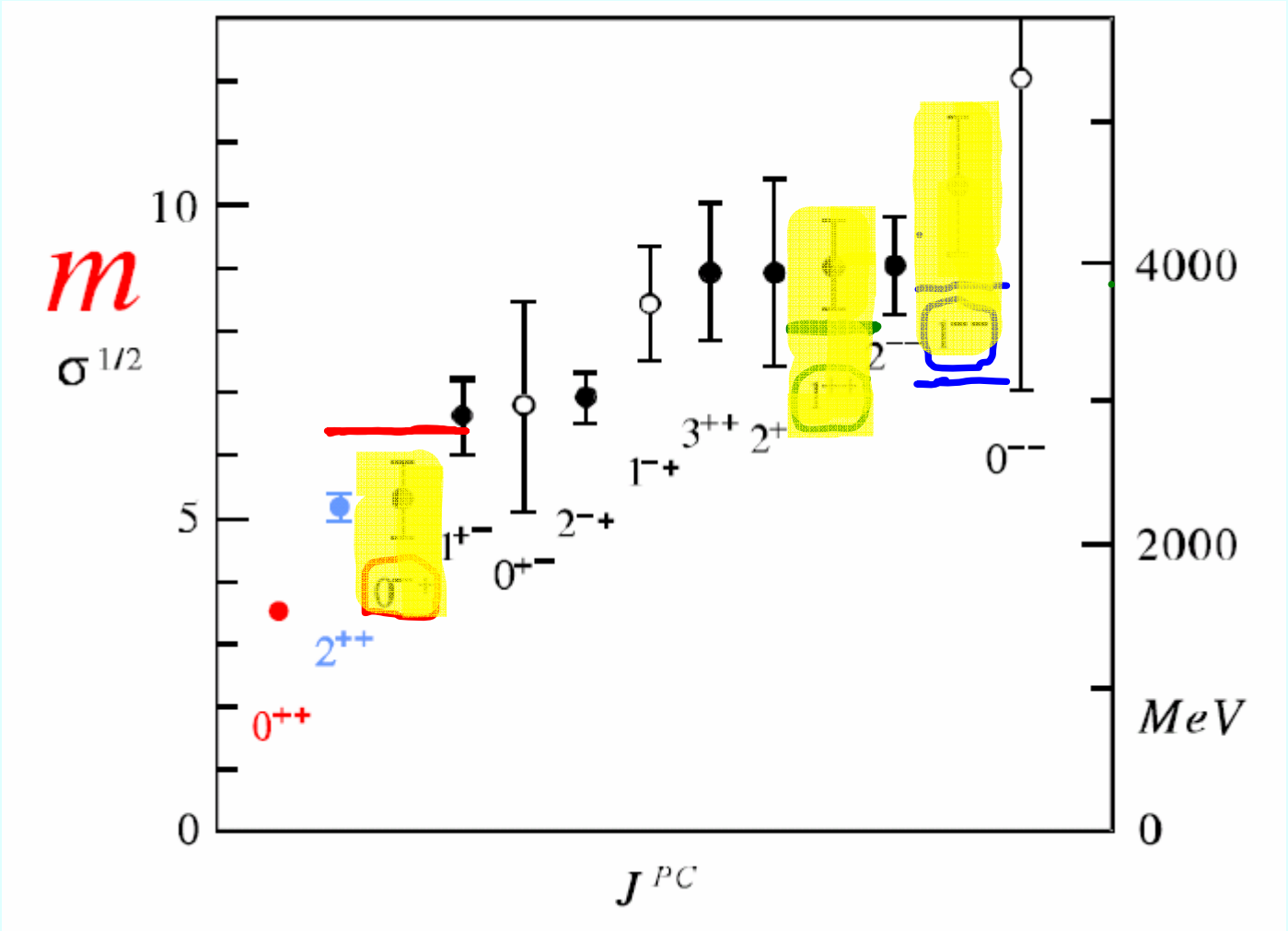
1+ 9893 3510

0+ 9860 3415

1S: 1- 9460 3097

Narrow below MM threshold

Glueballs spectrum from Lattice



As well as looking for where glueballs might be…

Remember Sherlock Holmes dog that didn't bark….

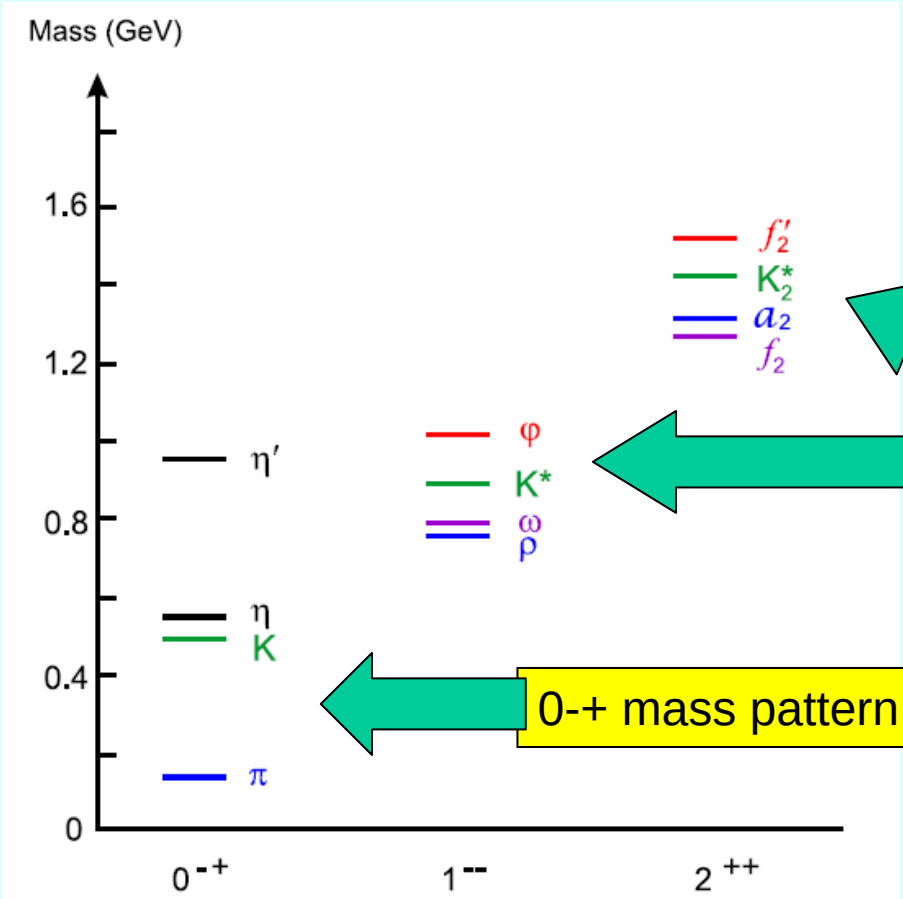
Check for evidence of where they are NOT!

Light flavors: All canonical for 2++ 1++ but not 0++
And for 1– but not 0-+

What do we know about flavours for light qq* nonets

Vector 1^{--} and tensor 2^{++} are flavour pure nonets

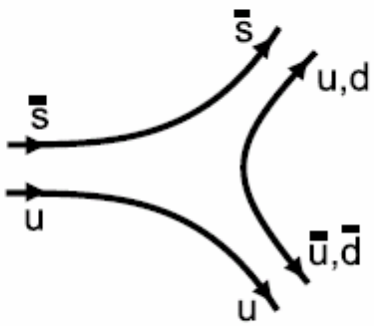
Evidence: 1. masses of nn*, K and ss* states
2. strong decays
3. Electromagnetic transitions “weigh” the flavours



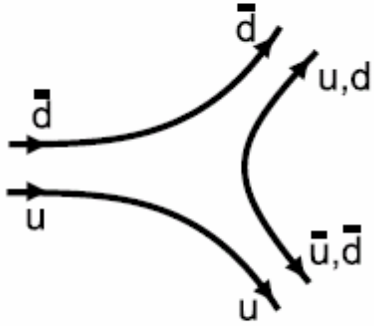
1- - and 2++ masses follow the flavours uniformly

0-+ mass pattern all mixed up

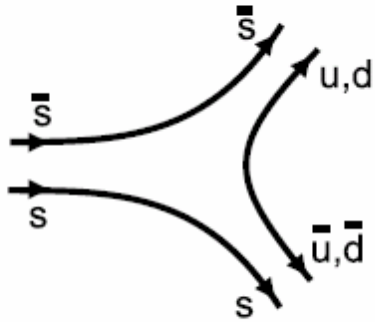
Strong decays “OZI rule” also fits



$K^{*+} \rightarrow K^{+}\pi^{0}, K^{0}\pi^{+}$



$\rho^{+} \rightarrow \pi^{+}\pi^{0}$



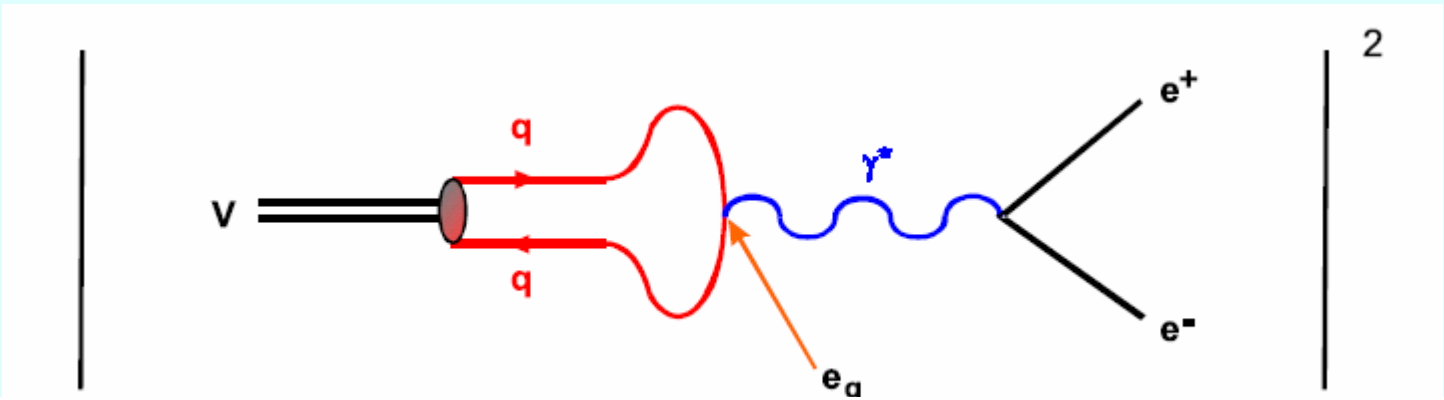
$\varphi \rightarrow K^{+}K^{-}, K^{0}\bar{K}_{0}$

Mass: middle…… light…… …heavy

Vector 1^{--} and tensor 2^{++} are flavour pure nonets

Evidence: 1. masses of nn*, K and ss* states
2. strong decays
3. Electromagnetic transitions “weigh” the flavours

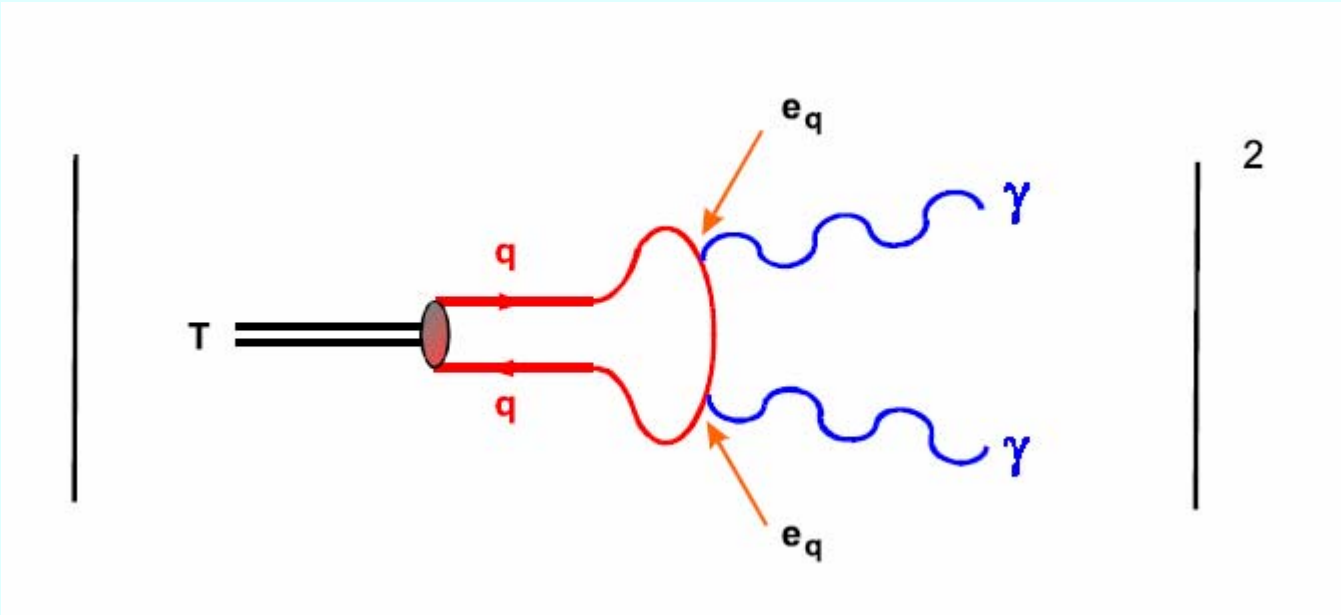
e.g. of electromagnetic: vector mesons



$$\Gamma(\rho^0 \rightarrow e^+e^-) : \Gamma(\phi \rightarrow e^+e^-) : \Gamma(\omega \rightarrow e^+e^-) =$$

$$\left[\frac{1}{\sqrt{2}}\left(\left(\frac{2}{3}\right) - \left(-\frac{1}{3}\right)\right)\right]^2 : \left(-\frac{1}{3}\right)^2 : \left[\frac{1}{\sqrt{2}}\left(\left(\frac{2}{3}\right) + \left(-\frac{1}{3}\right)\right)\right]^2 = 9 : 2 : 1$$

e.g of electromagnetic: tensor mesons



$$\Gamma(T \to \gamma\gamma) \sim \alpha^2 \langle e_q^2 \rangle^2$$

$$\Gamma(f_2(1270) \to \gamma\gamma) : \Gamma(a_2(1320) \to \gamma\gamma) : \Gamma(f_2'(1525) \to \gamma\gamma) = 25 : 9 : 2$$

$$25 : (10 \pm 1) : (1 \pm 1)$$

I=1 vector :

I=0 nn*; ss*

+ Problem of nn* ss* flavour mixing

1D: 1- 1700

2S: 1- 1460

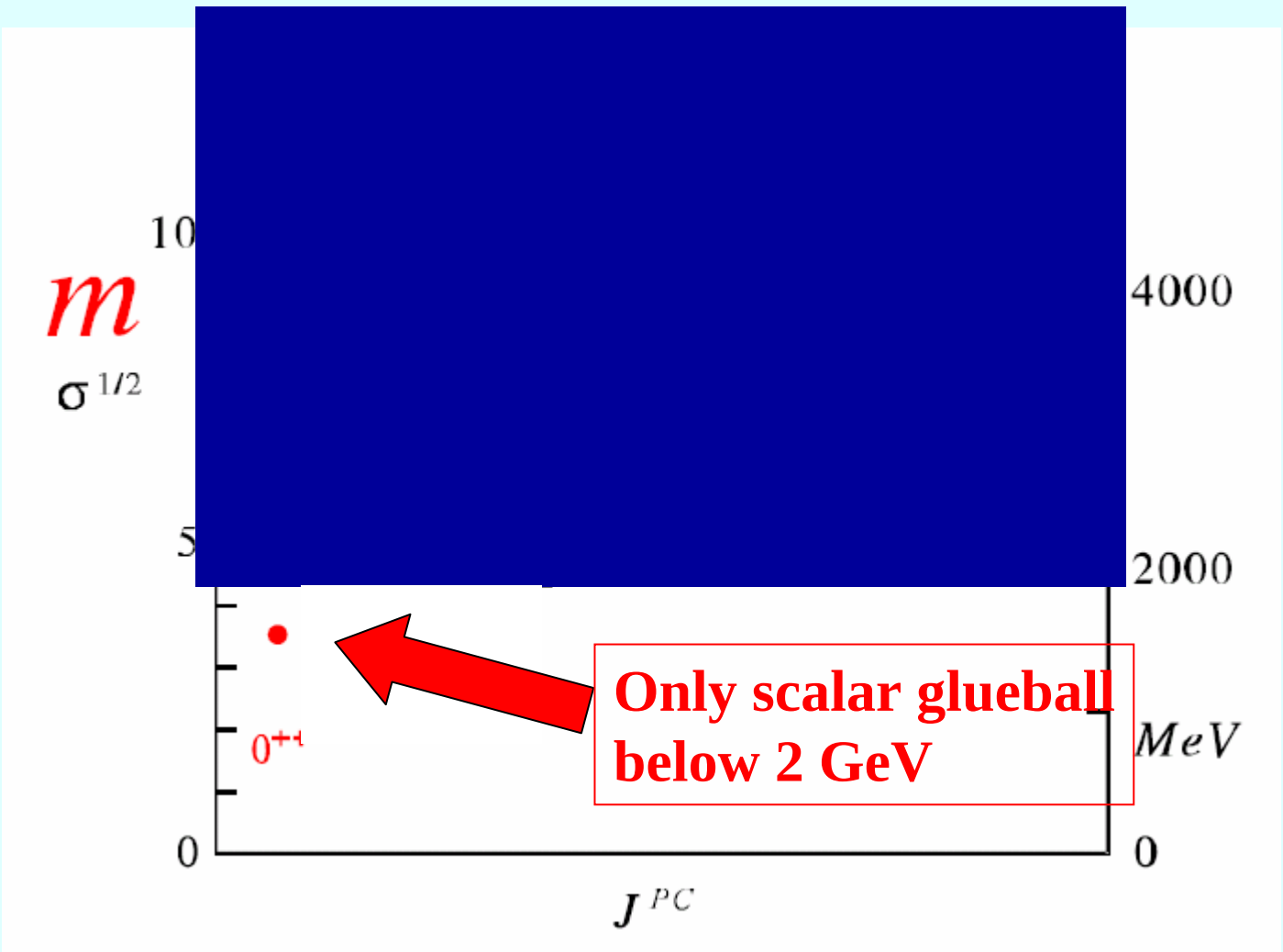
2+ 1320 1270/1525

1+ 1300 1285/1530

0+ 1420

1S: 1- 770 780/1020

Glueballs also predicted: Strong QCD spectrum from Lattice



Far away from qq* lowest multiplets… **except for 0++**

I=1 vector : I=0 $J^P = 2^+ 1^+ 0^+$

1D: 1- 1700

2S: 1- 1460

2+ 1270/1525

? qq* + Glueball

Lattice G =1.6 \pm

1+ 1285/1530

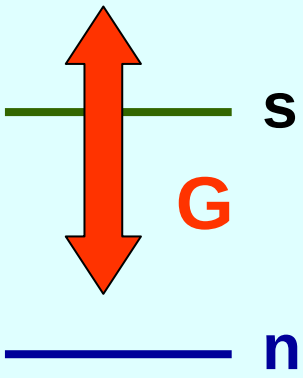
Data do not imply G
But given lattice and qq*
Does consistent pic emerge?

0+ 1370/1500/1710

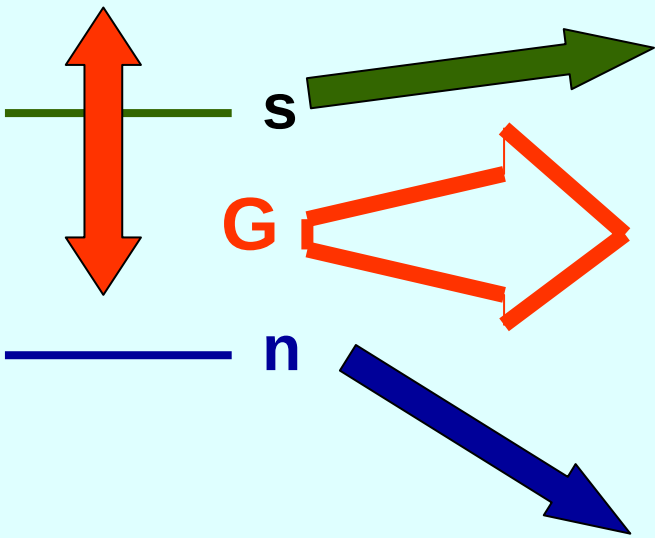
980/600

Can data eliminate it; or even make it robust?

Scalar Glueball and Mixing



Scalar Glueball and Mixing



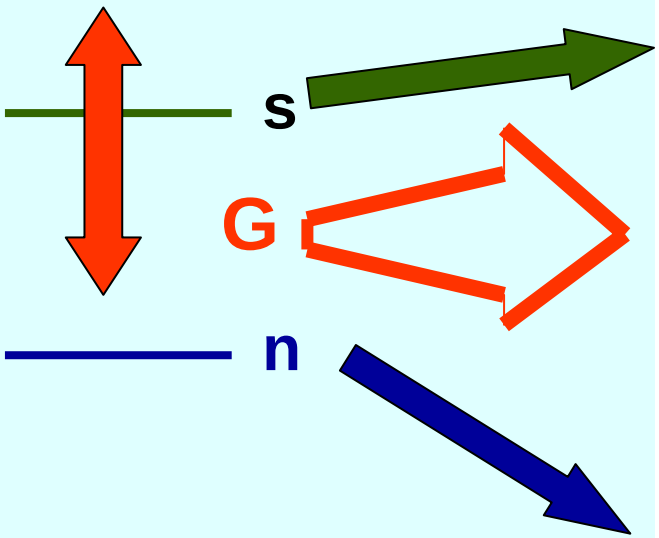
Meson

1710

1500

1370

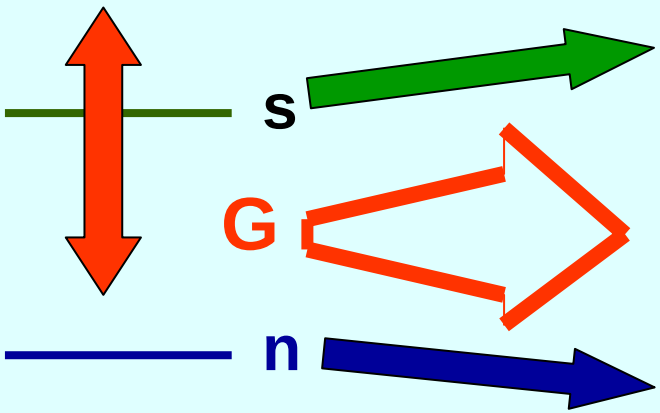
Scalar Glueball and Mixing



Meson	G	ss*	nn*
1710	+	+	+
1500	-	+	-
1370	-	+	+

3 state mixing
Relative phases

Scalar Glueball and Mixing

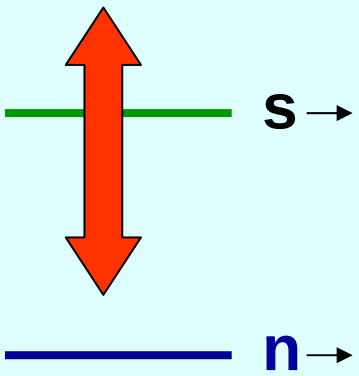


Meson	G	ss*	nn*
1710	0.39	0.91	0.15
1500	- 0.65	0.33	- 0.70
1370	- 0.69	0.15	0.70

LEAR/WA102
Meson pair decays

Scalar Glueball and Mixing

a simple example for expt to rule out



Meson	G	ss*	nn*
1710	0.39	0.91	0.15
1500	- 0.6	0.33	- 0.70
1370	- .69	0.15	0.70

0- 0- meson decays LEAR/ WA102

FC Kirk

+BES FC- QiangZhao

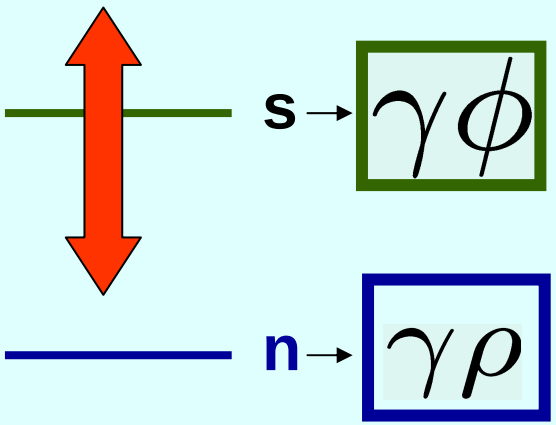
heavy

middle

light

Nontrivial correlation with relative masses

Scalar Glueball and Mixing: how to measure flavour state



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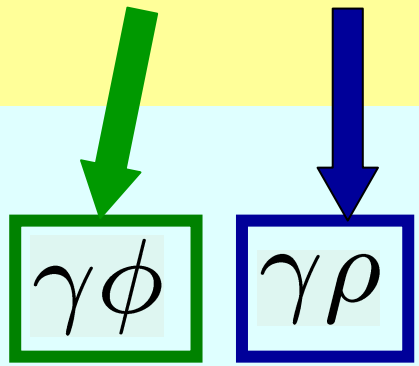
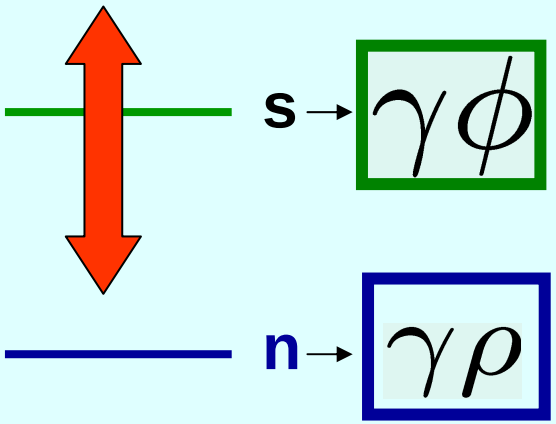


Scalar Glueball and Mixing



Meson	G	ss*	nn*
1710	0.39	0.91	0.15
1500	- 0.65	0.33	- 0.70
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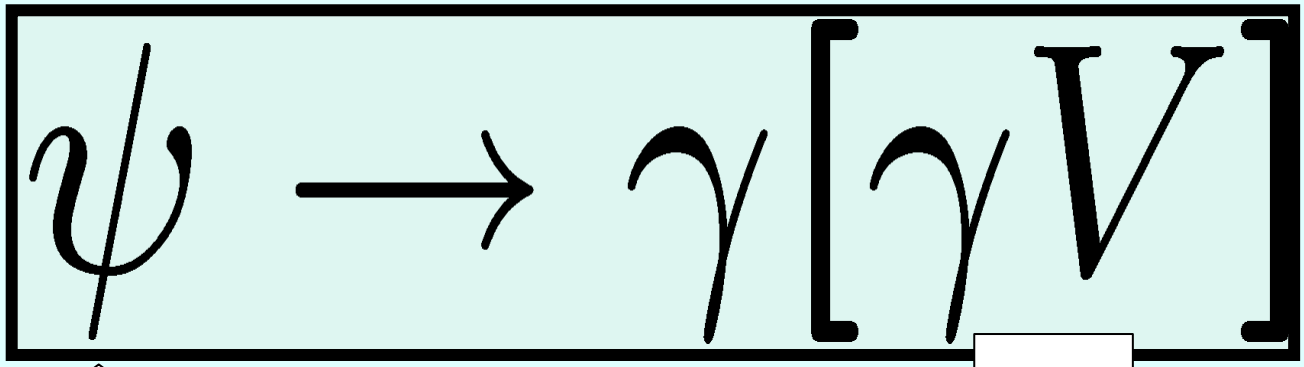
$$\psi \longrightarrow \gamma\,[\gamma V]$$

$\gamma\phi$ $\gamma\rho$



>1 billion

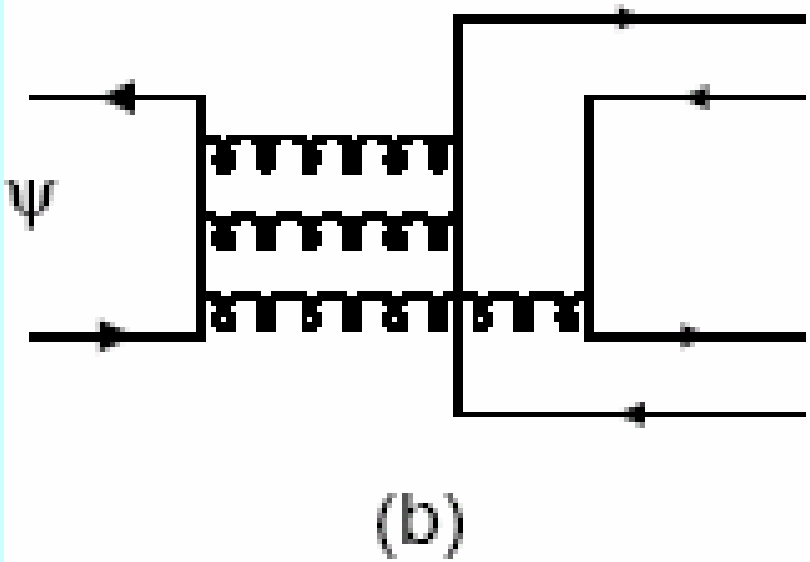
Coming soon from BES and CLEO-c

1000 per meson

A flavour filter for 0++ 0-+ 2++ mesons and glueballs

Challenge:
Turn Lattice QCD Glueball spectrum into physics

OZI rule and flavor tagging in J/ψ hadronic decays



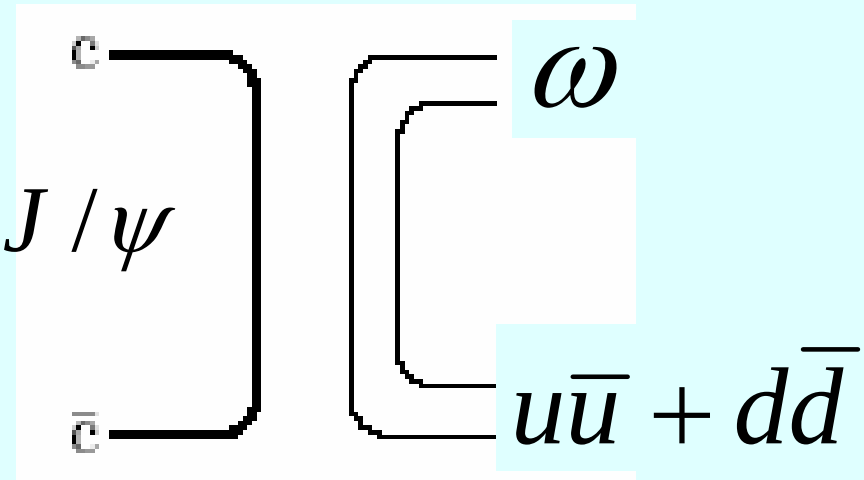
Known ss*/nn*

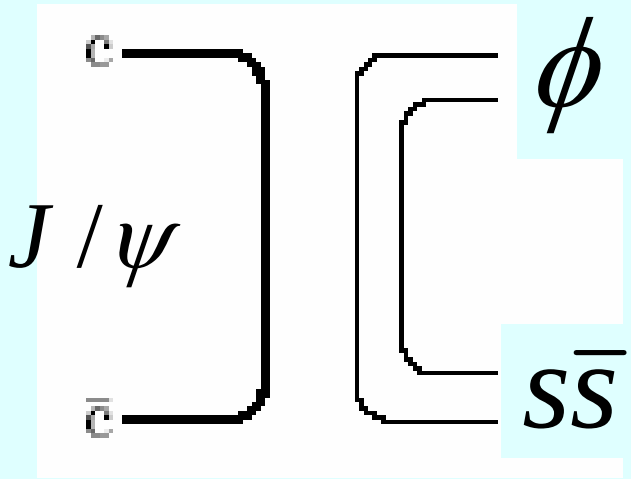
measure ss*/nn*

Example of “known” ss*/nn* = 1– or 2+ “ideal” flavour states

OZI rule and flavor tagging in J/ψ hadronic decays

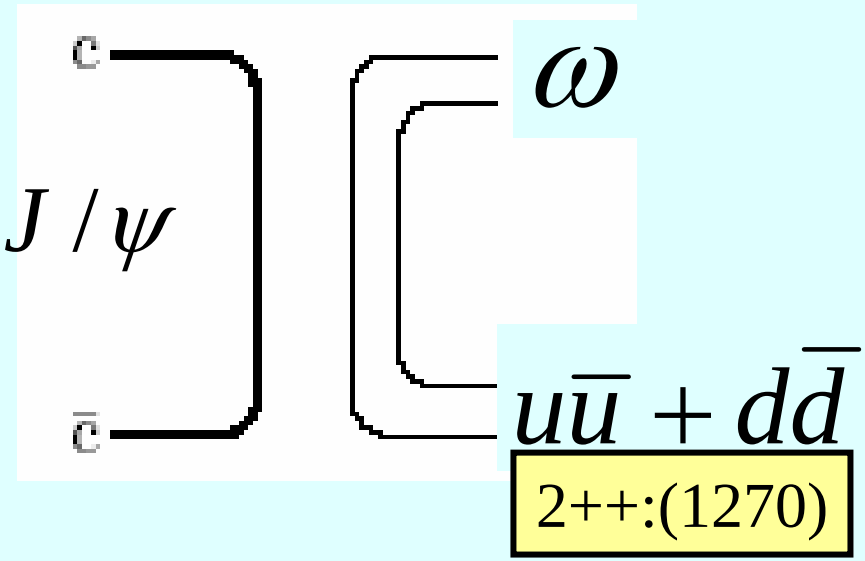
- **In J/ψ hadronic decays, an ω or Φ signal determines the $u\bar{u}+d\bar{d}$ or $s\bar{s}$ component, respectively. ← OZI rule**

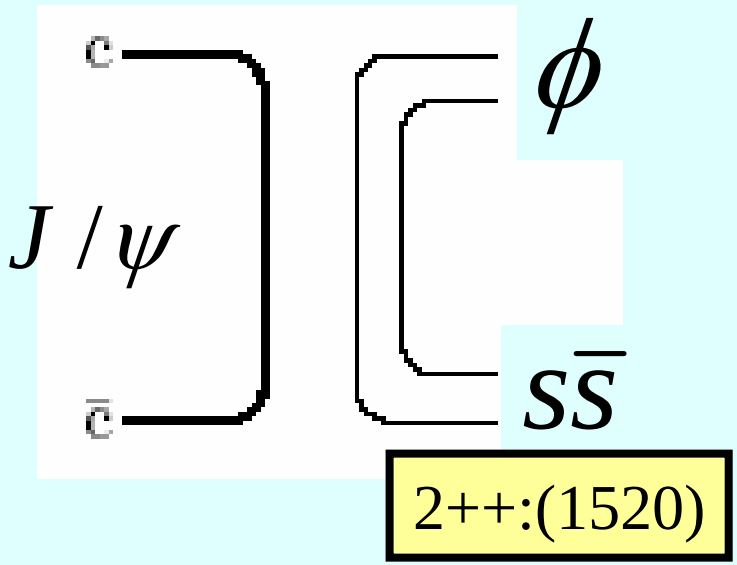




OZI rule and flavor tagging in J/ψ hadronic decays

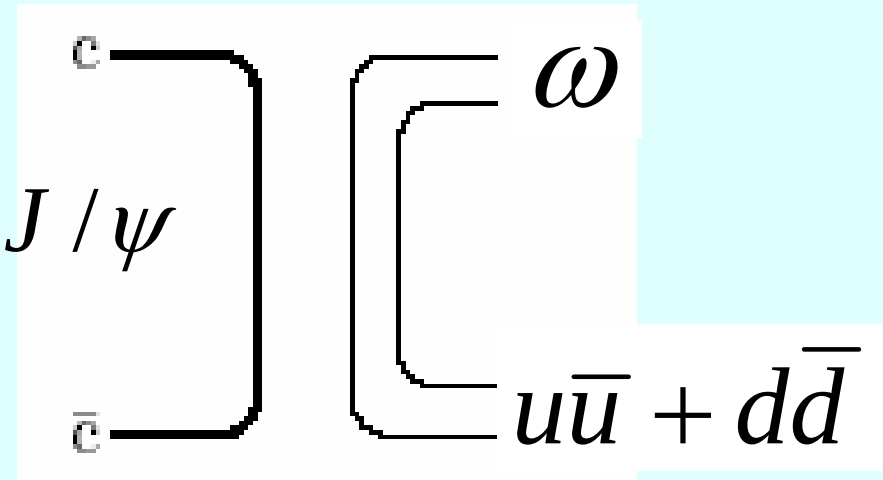
Works nicely for 2++ where BOTH are ideal

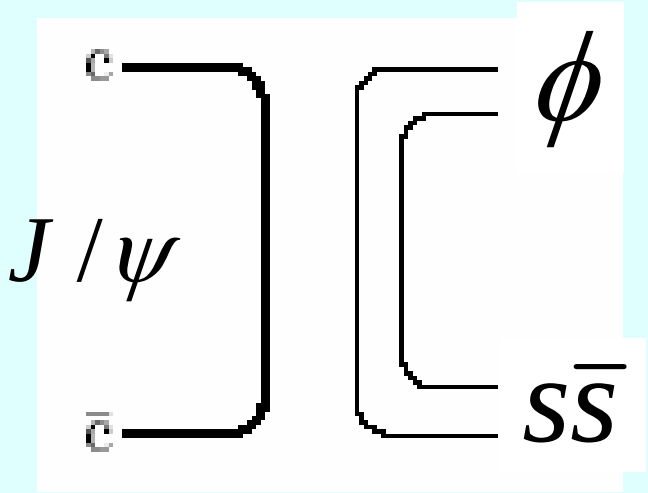




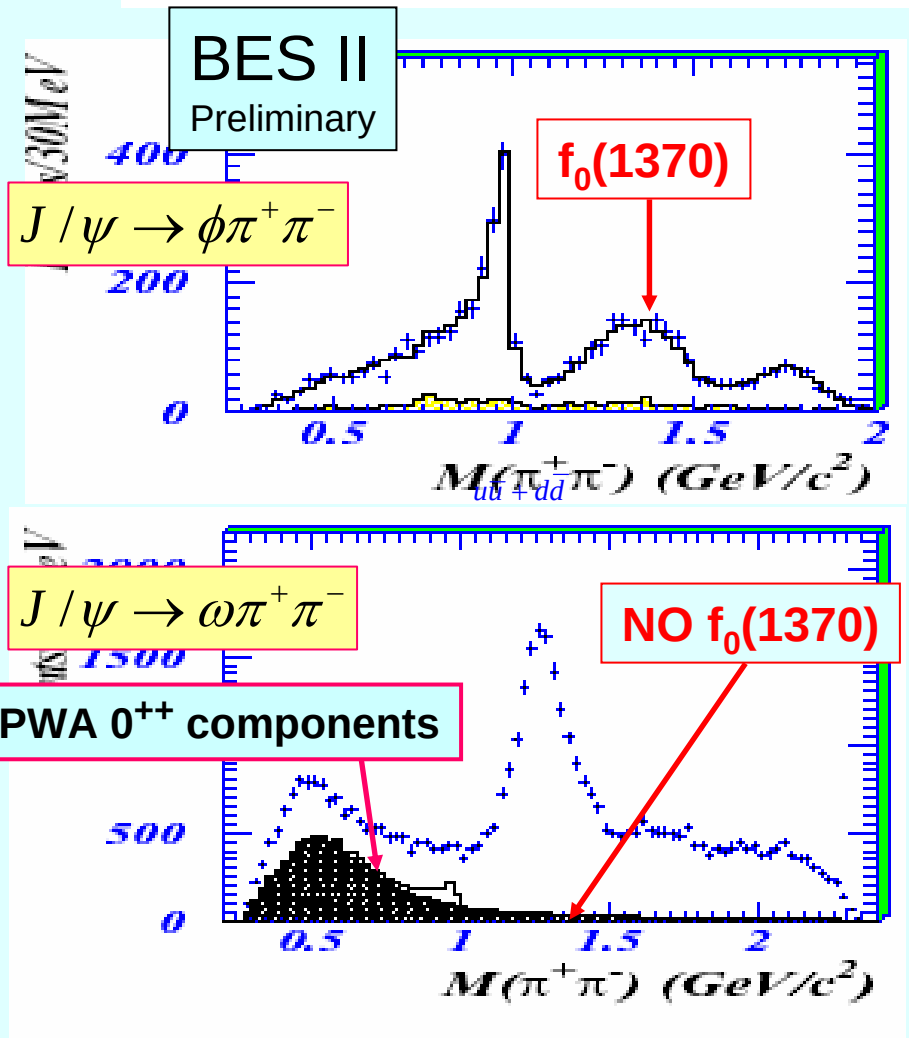
OZI rule and flavor tagging in J/ψ hadronic decays

Fails completely for 0^{++} !!!





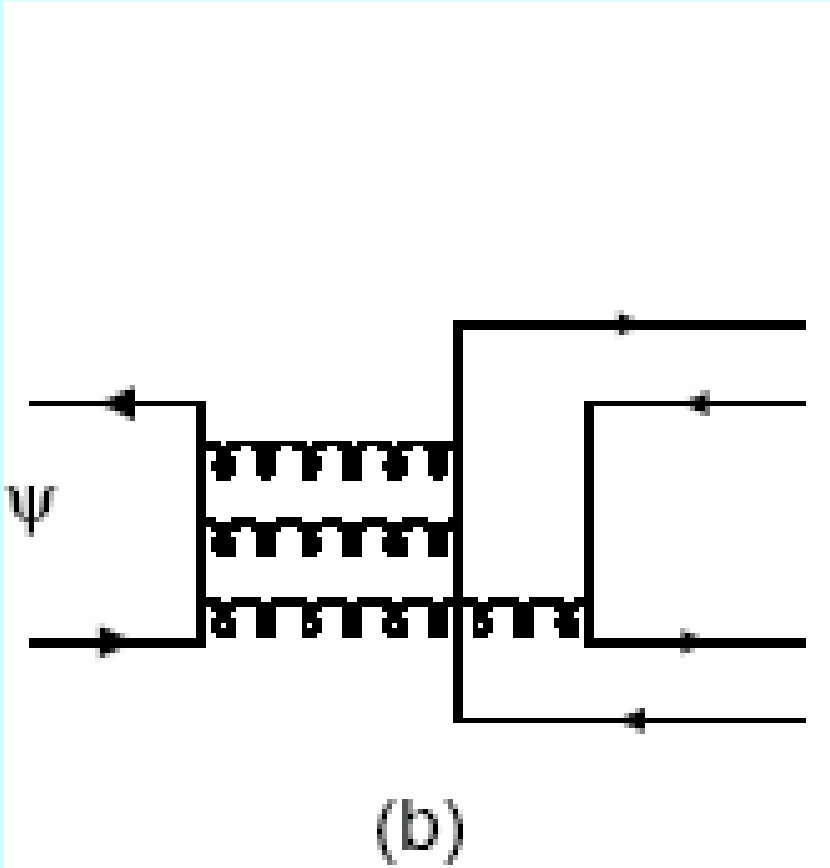
$f_0(1370)$ at BES



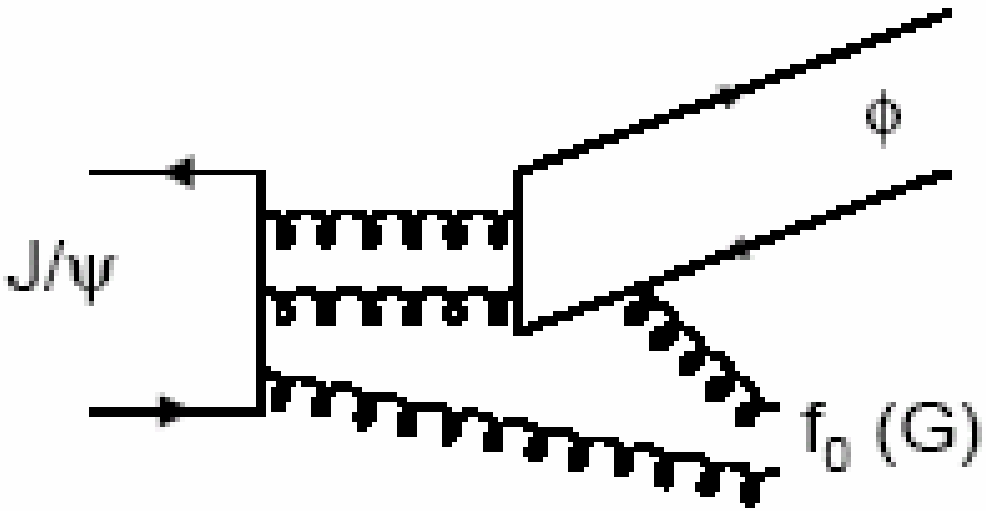
- **$f_0(1370)$** (uu*+dd*) **clearly seen** in $J/\psi \to \phi\pi\pi$, but **not** seen in $J/\psi \to \omega\pi\pi$.

$$M = 1350 \pm 50 \ MeV$$
$$\Gamma = 265 \pm 40 \ MeV$$

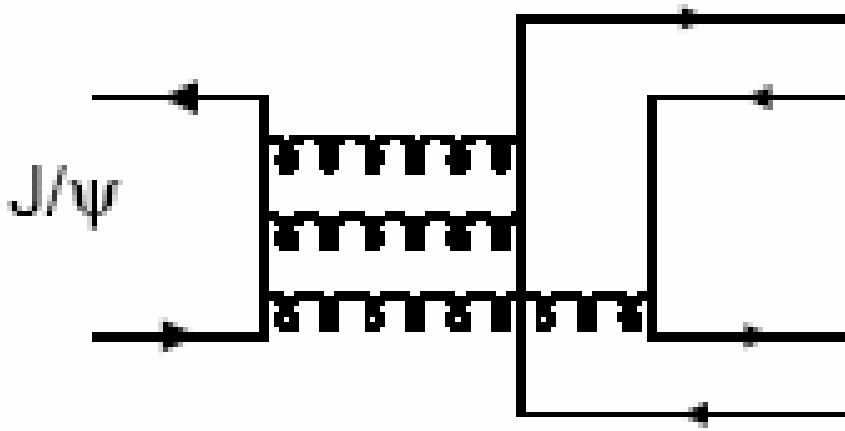
Leading diagram
if 0+ meson
contains qq* only



Extra diagram if 0++ has glueball in its wavefunction



(a)



(b)

FC+Qiang Zhao

Rates agree with data!

Unusual properties of $f_0(1370)$, $f_0(1500)$ $f_0(1710)$

Scalar Puzzle

$$\psi \longrightarrow \gamma\,[\gamma V$$

\psi \to 0^{++} V

A consistent pattern in these two experiments can establish role of **Scalar Glueball**

Challenge: quantify the predictions