The Constituent Quark Model and beyond

Diquarks, Tetraquarks, Pentaquarks

and no quarks

Frank Close

How Quarks Behave

The meson landscape

Scalars and Glueballs

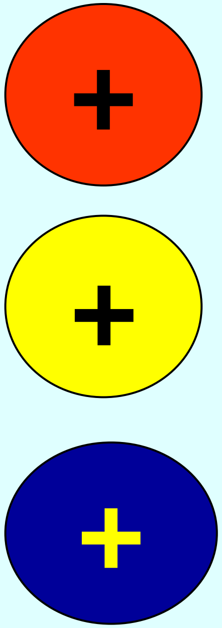
Beyond $q\bar{q}$

Weird charmonium and other things

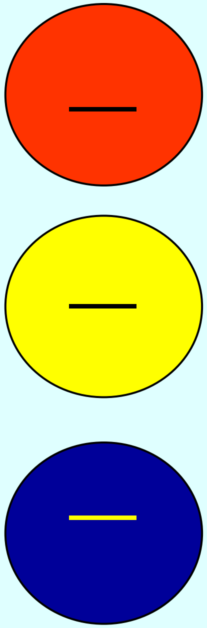
HOW QUARKS BEHAVE

CHROMOSTATICS

Quarks carry any of three "colour" charges



Antiquarks carry any of three “colour” charges but negative



Now use familiar rules

“Like charges (colours) repel; opposite (colours) attract”

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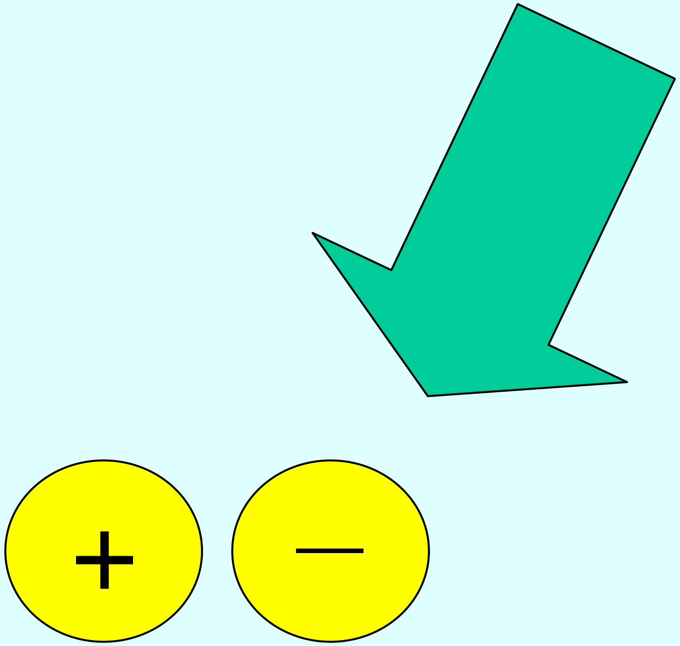
“Like charges (colours) repel; opposite (colours) attract”



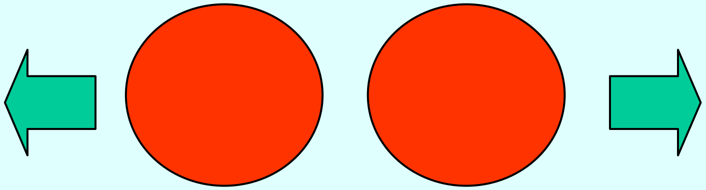
Makes a “meson”.

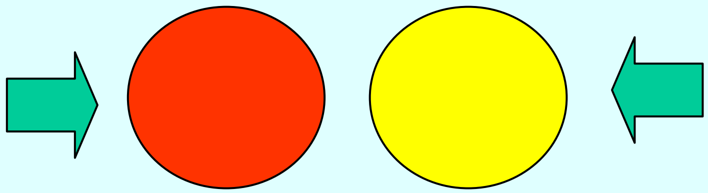
Simplest “chromostatic” analogue of electrostatic positronium

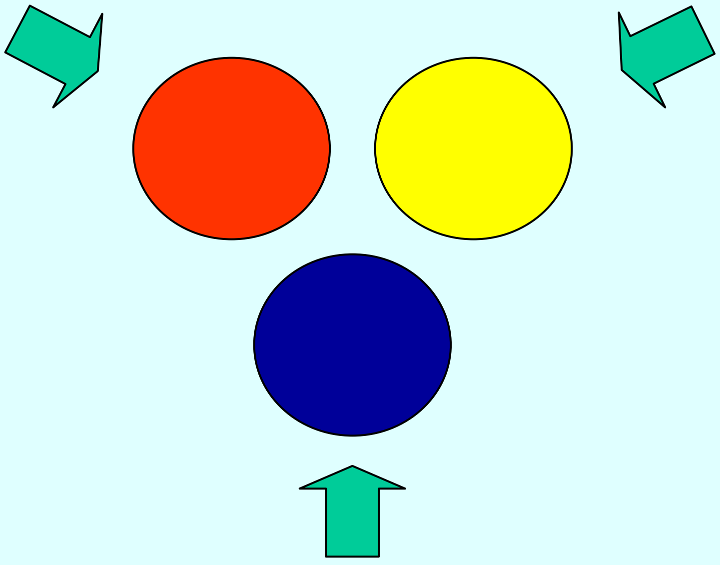
The THREE colours

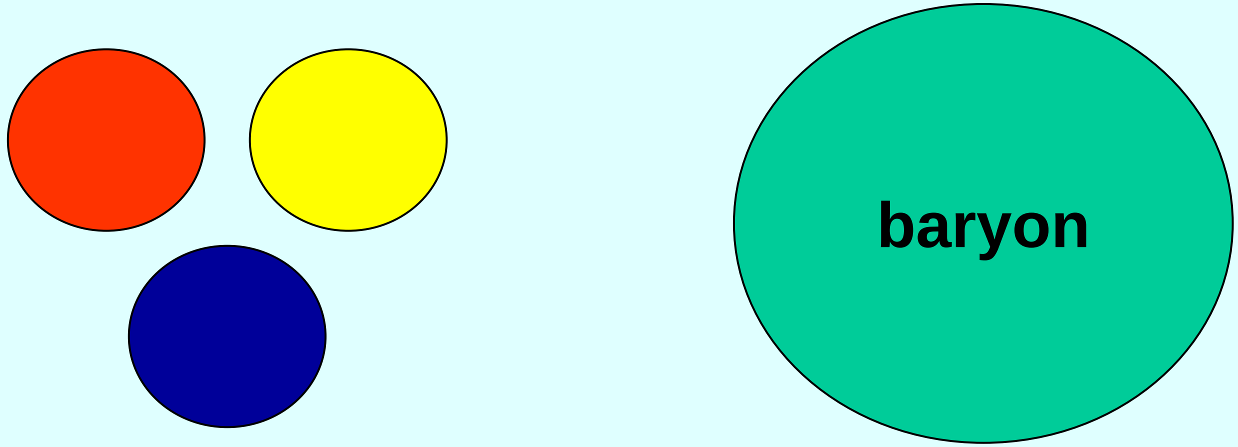
enable quarks to attract one another

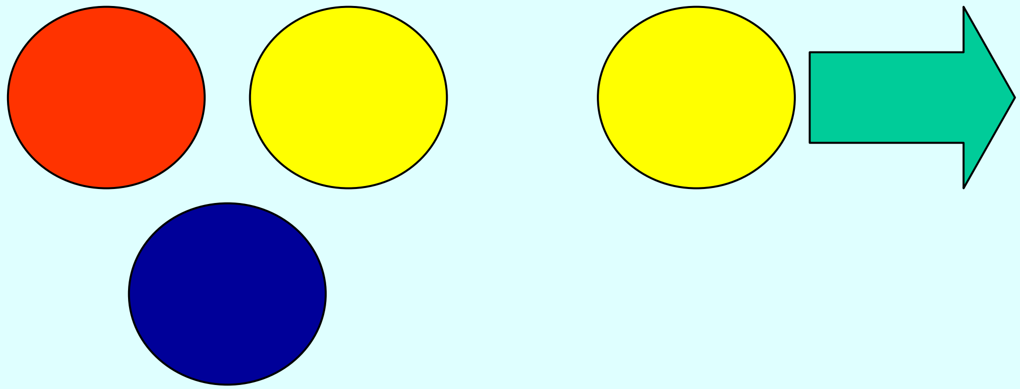
making BARYONS (e.g. the proton)

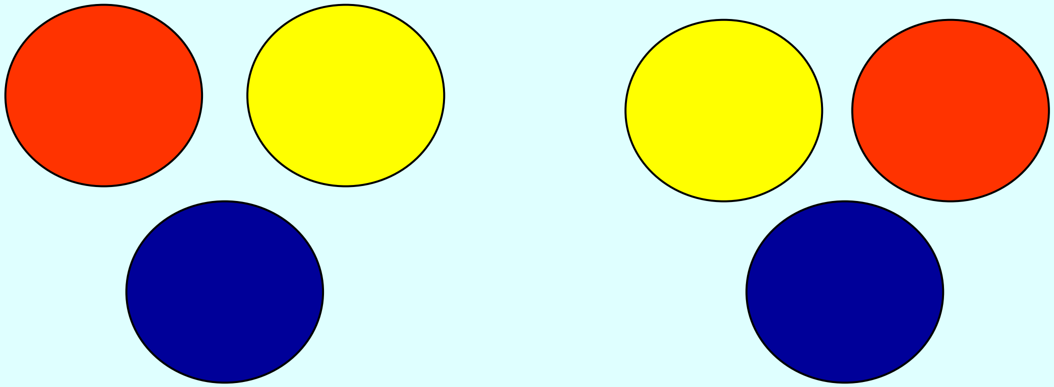




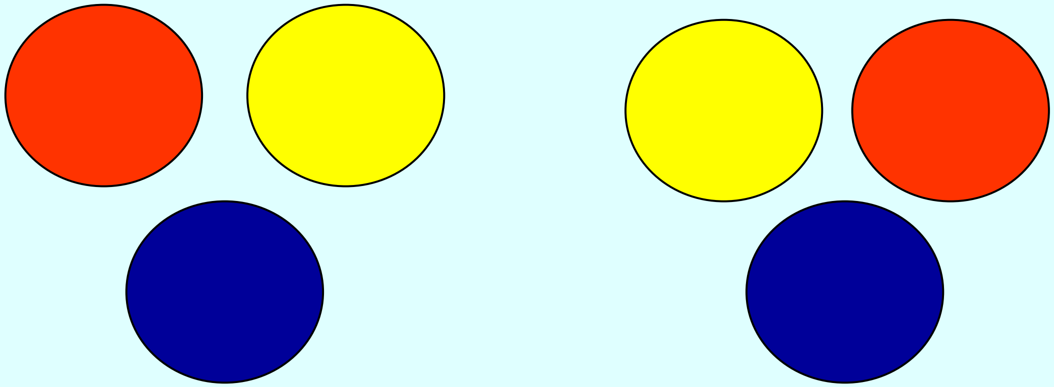



baryon





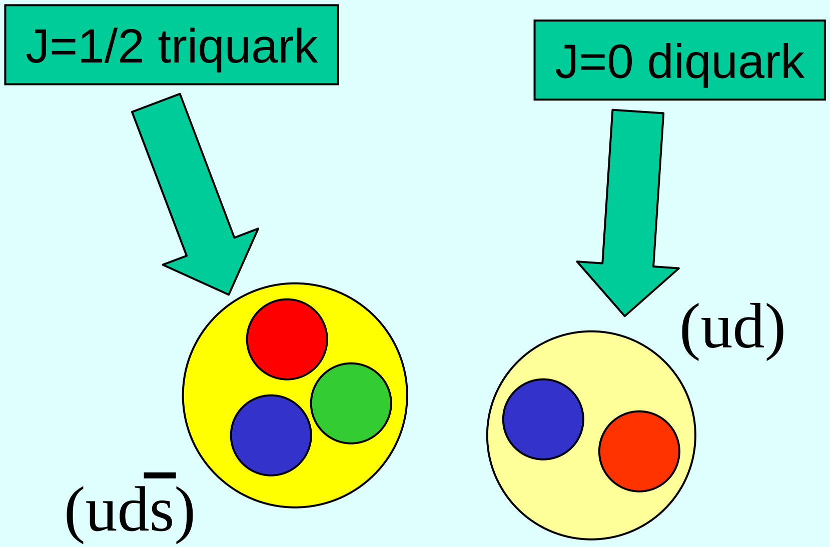
Simple nucleus (deuteron)

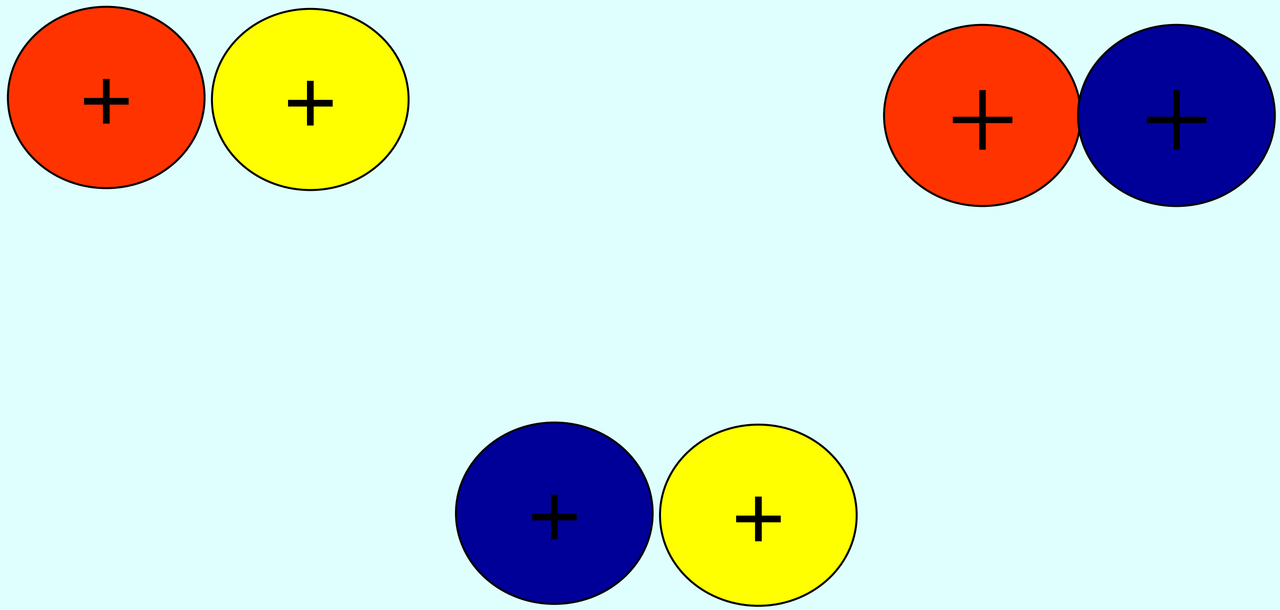


Colour charge → Baryons → Nucleus

Electric charge → Atoms → Molecules

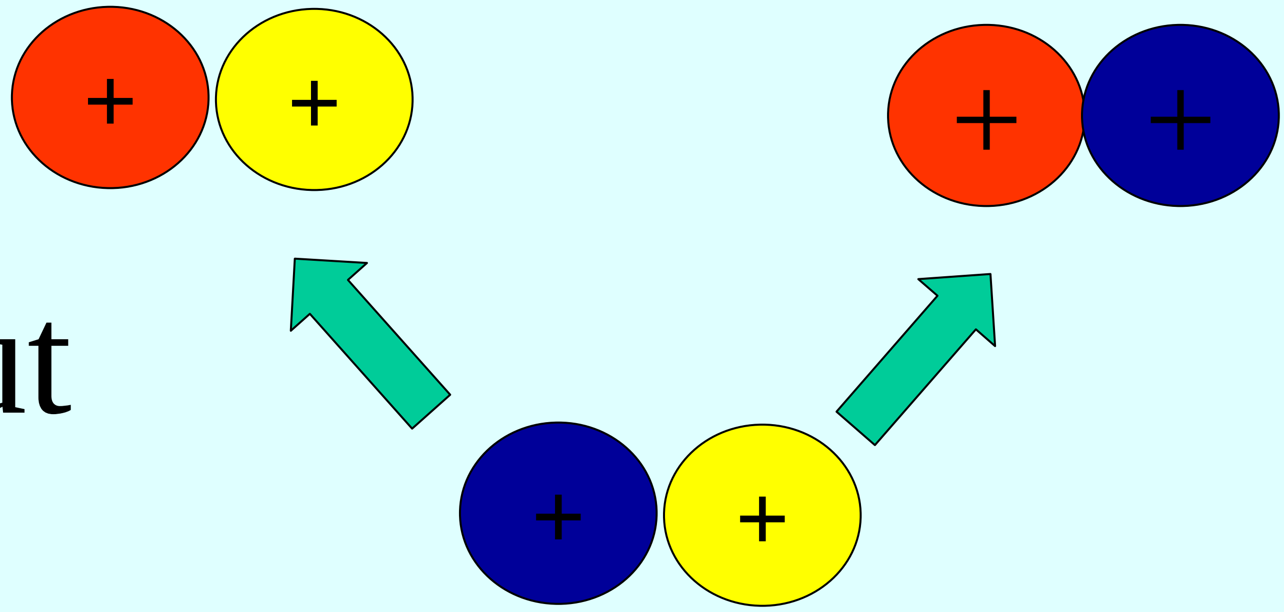
Two other ways that coloured q/q* can attract

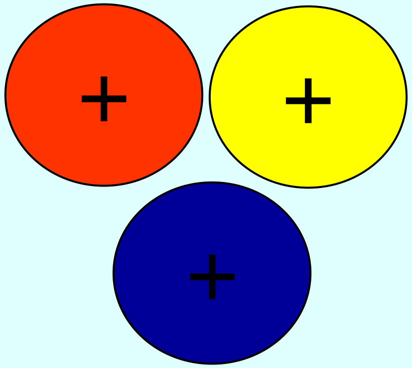


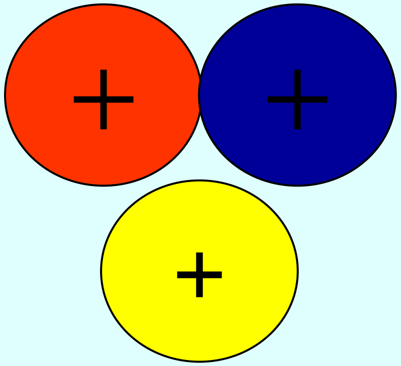


Three different coloured diquarks can mutually attract one another………

but





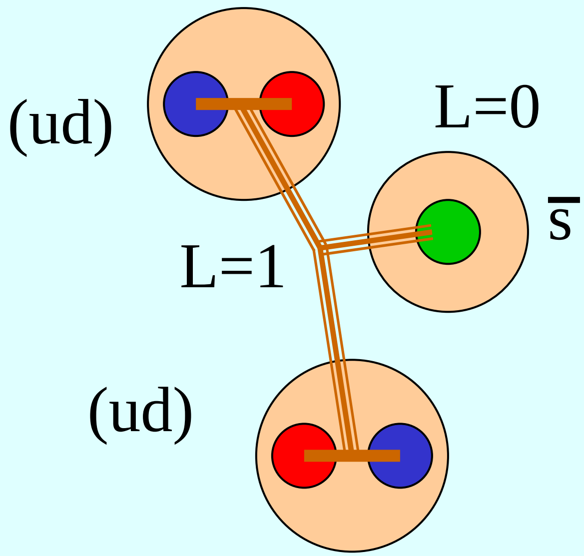


But rearrange to make…
e.g. a neutron and proton

Or even a deuteron

Can mutually attract forming a Pentaquark (….later)

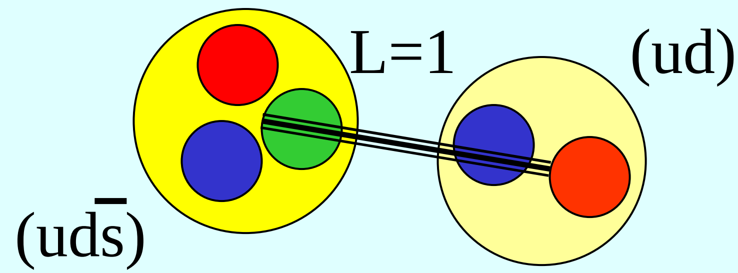
(Jaffe, Wilczek)



$J^P = ½^+$

–

Karliner, Lipkin)



$J^P = ½^+$

Quantum Electrodynamics: QED

Electric charge ➡ Atoms ➡ Molecules

Quantum Chromodynamics: QCD

Colour charge ➡ Baryons ➡ Nucleus

Quantum Electrodynamics: QED

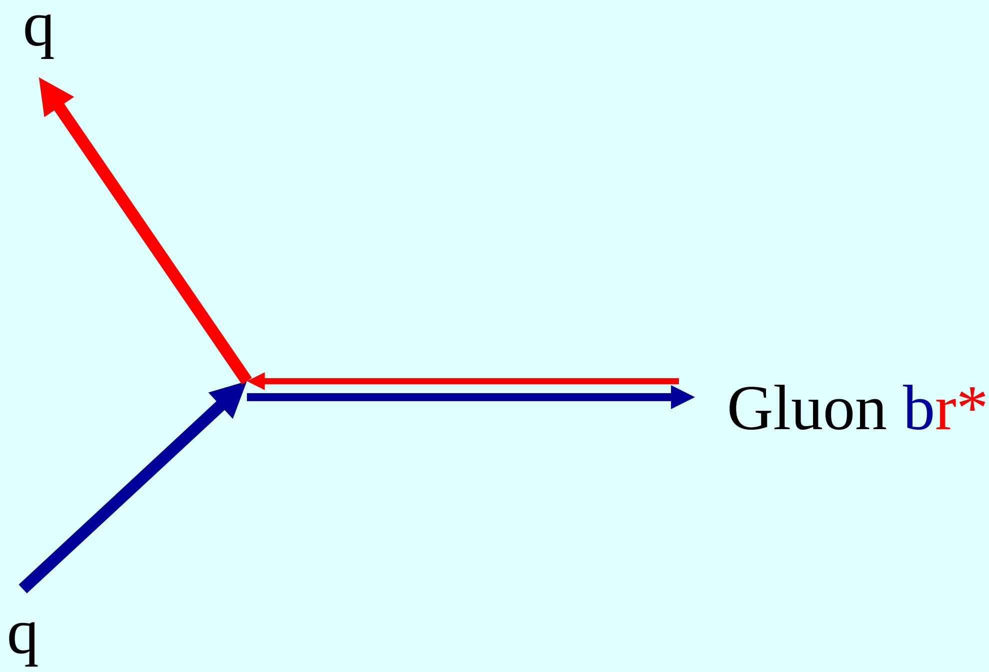
Electric charge → Atoms → Molecules

Interaction of electric charges and photons

Quantum Chromodynamics: QCD

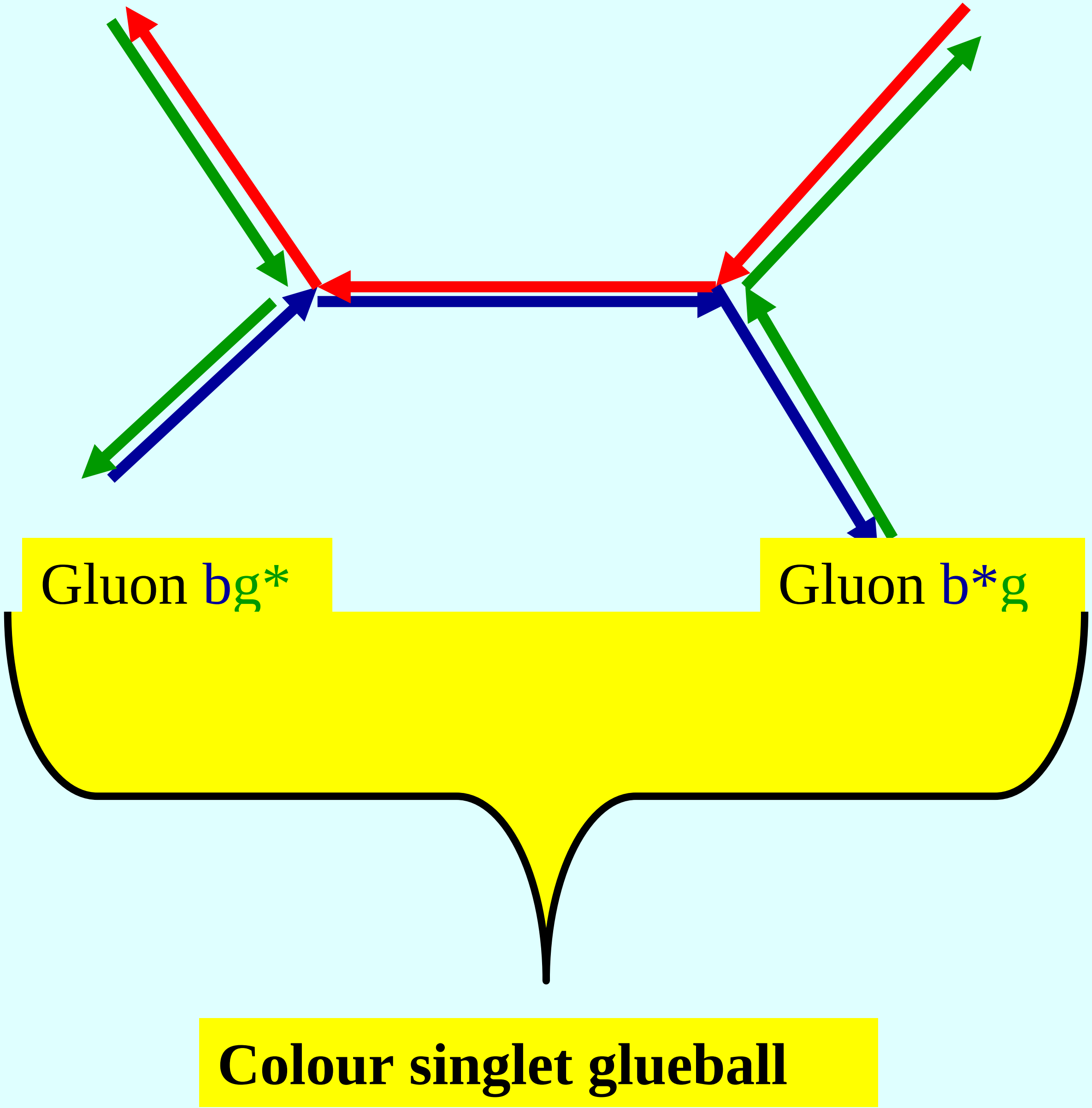
Colour charge → Baryons → Nucleus

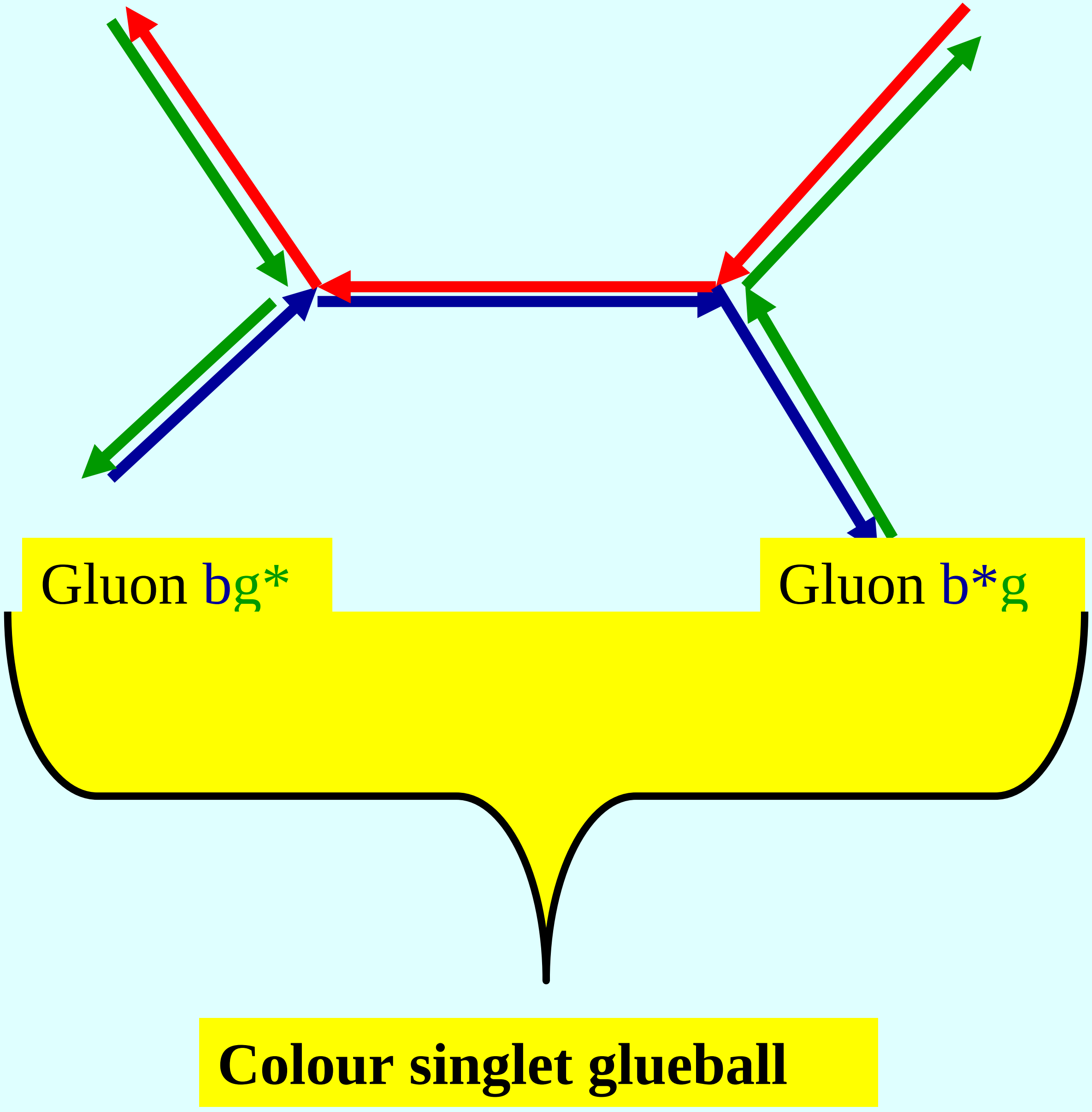
Interaction of colour charges and gluons



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


Gluon bg*
Gluon b*g
Colour singlet glueball



Lattice QCD

2++ 2.2GeV
0-+ 2.2GeV

0++ 1.5GeV

All \pm 0.2GeV

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)

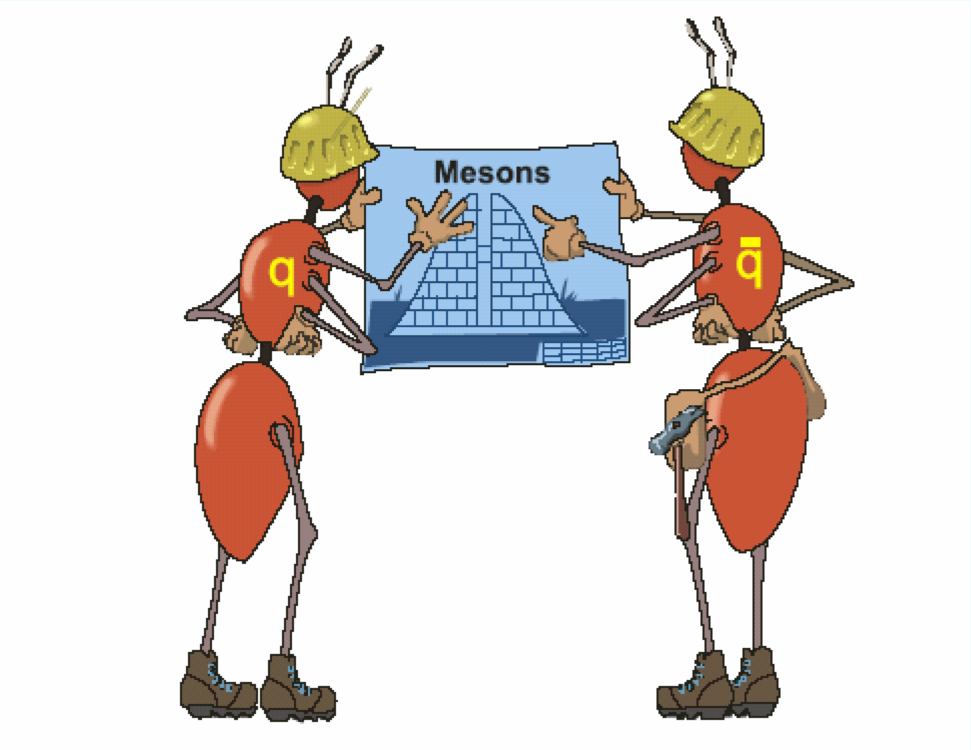
Look at these phenomena later.

Chromostatics explains qq* and baryons; but we expect also….

States outside the quark model

The reasons why

Mesons as quark antiquark: Heavy to Light Flavours



What do we know; what goes weird; what suggests glue?

Quarkonium template: qq*   L + S (= 0,1) =J

1D: 1- 2- 3-

2-

2S: 1- 0-

1P: 0+ 1+ 2+

1+

1S: 1- 0-

L=0

L=1

L=2

Allowed $q\bar{q}$ quantum numbers:

Spatial parity $P_{q\bar{q}} = (-1)^{(L+1)}$ C-parity $C_{q\bar{q}} = (-1)^{(L+S)}$

The complete list of allowed $q\bar{q}$ J^{PC} quantum numbers has gaps!

The J^{PC} forbidden to $q\bar{q}$ are called “J^{PC}-exotic quantum numbers”.

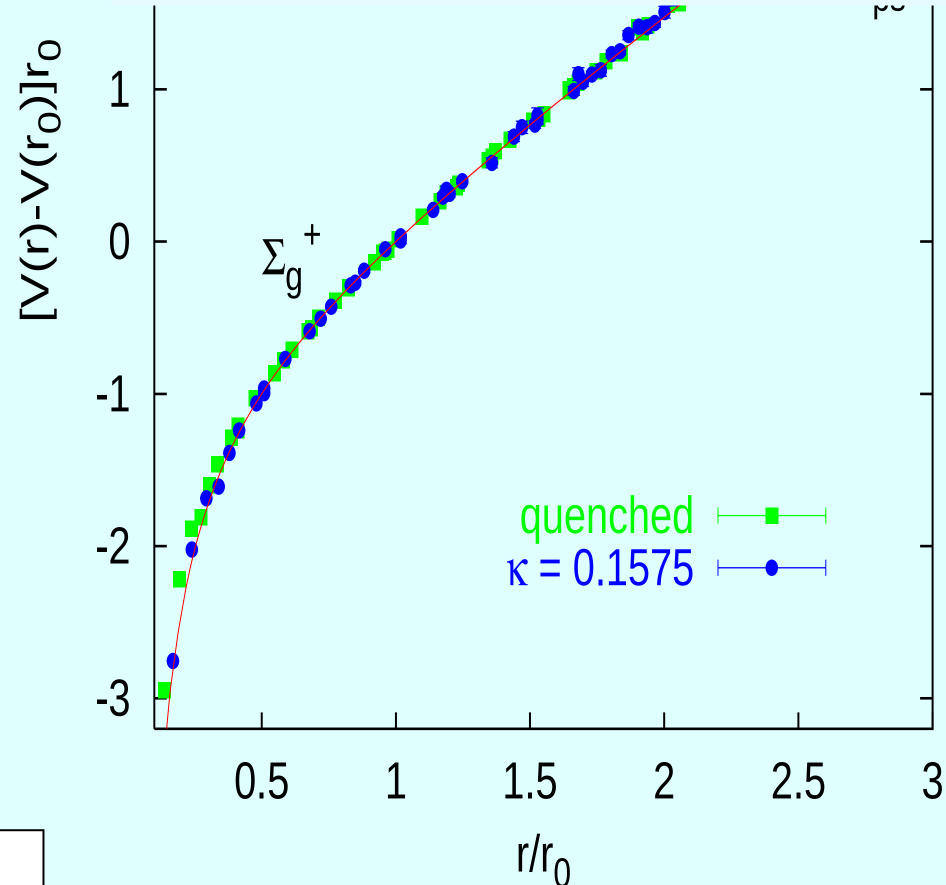
Exotic $J^{PC} = 0^{--};\ 0^{+-},\ 1^{-+},\ 2^{+-},\ 3^{-+}\ \ldots$

PDG is (almost) full of conventional “non exotic” J^{PC}

Lattice Linear Potential

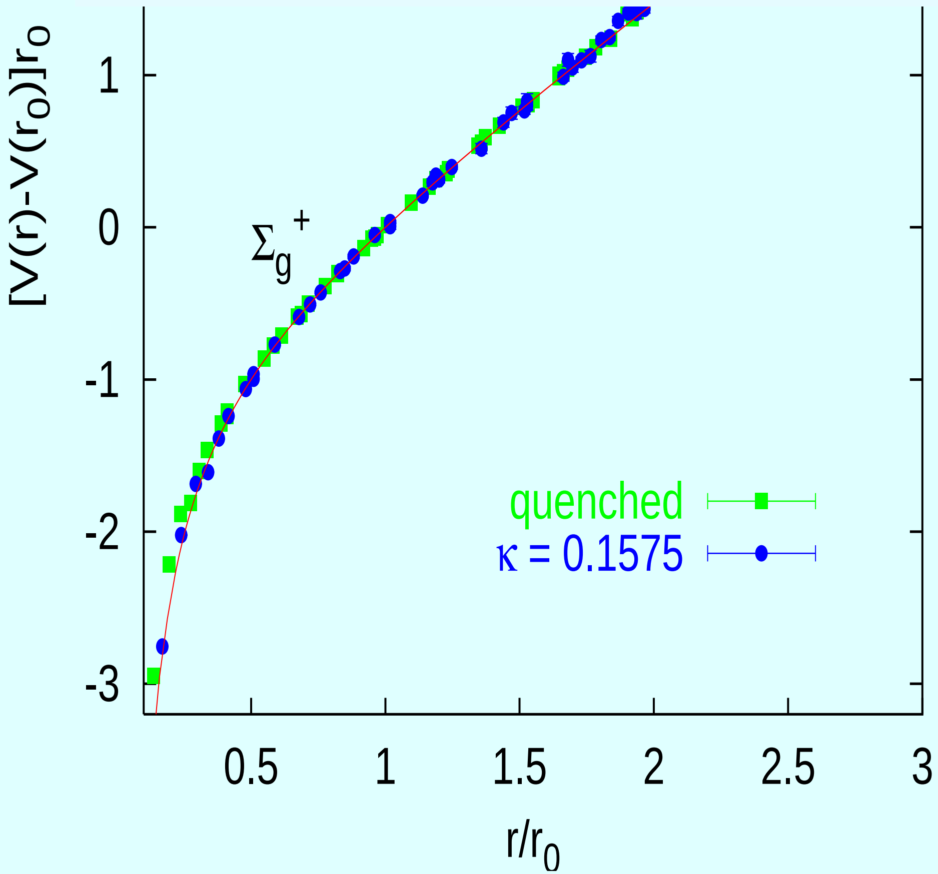
qq* spectrum
Empirically =
Linear potential
V(r) = kr

Lattice QCD
predicts this too

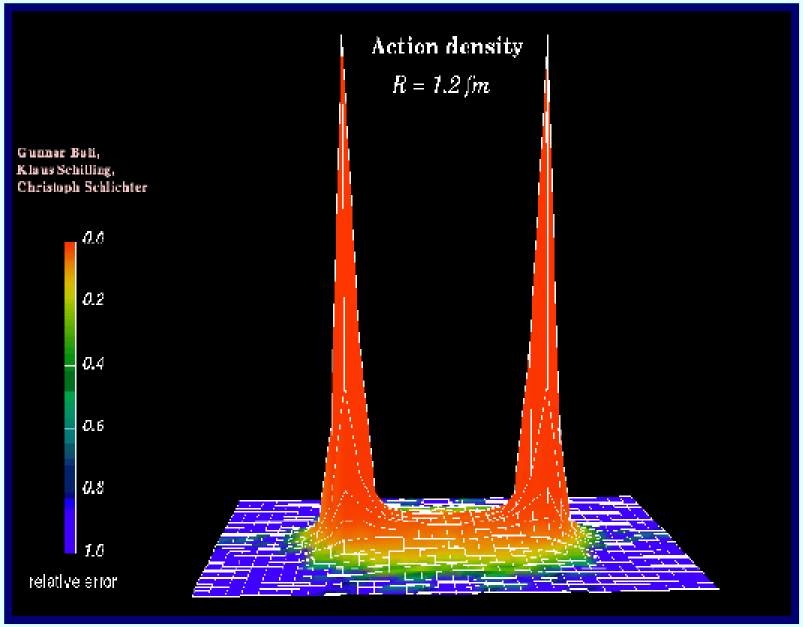


What does this imply for force fields? Contrast 1/r Coulomb and 3D space…..

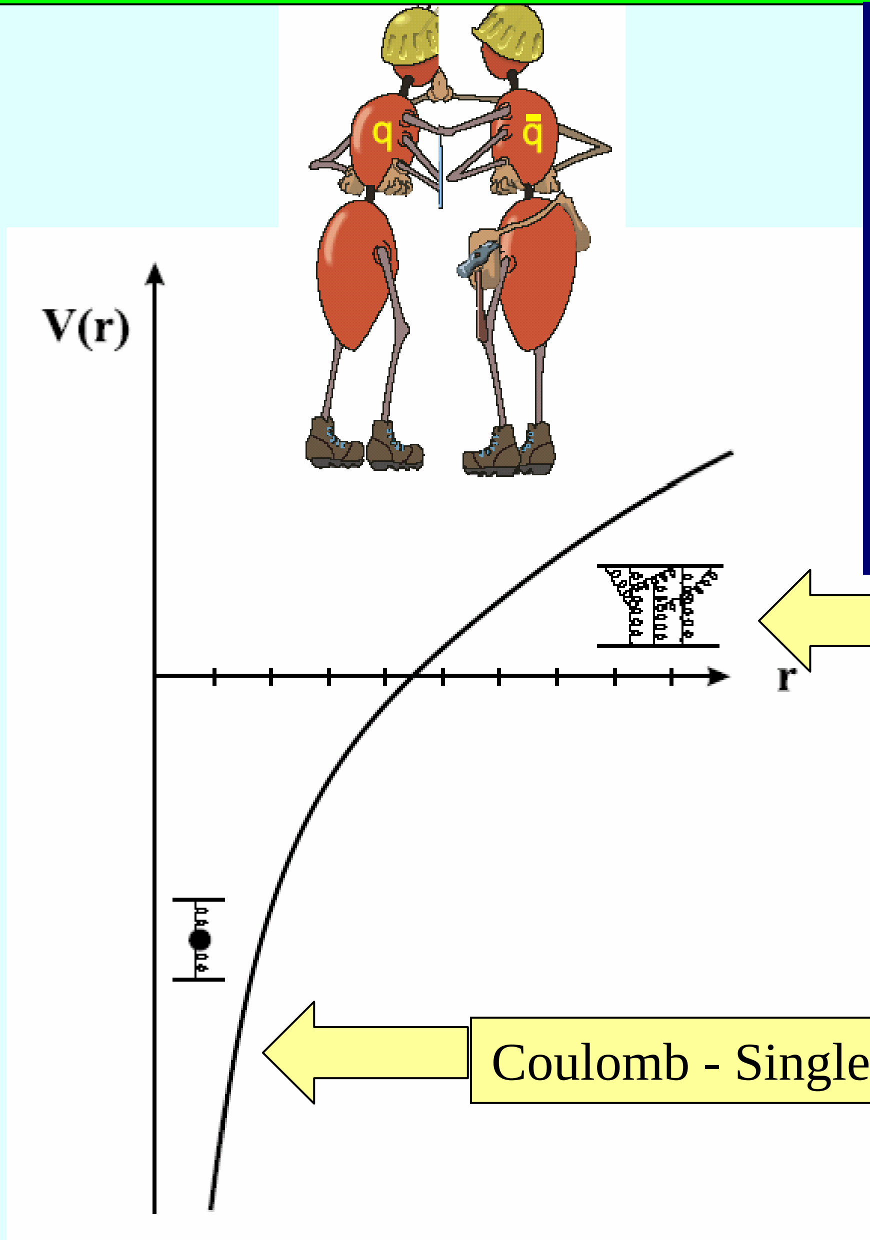
Lattice Linear Potential

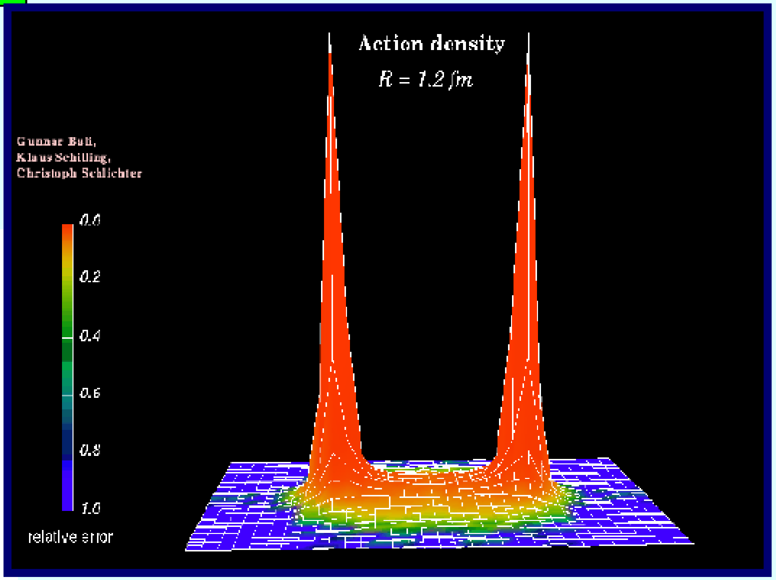


Linear flux tube



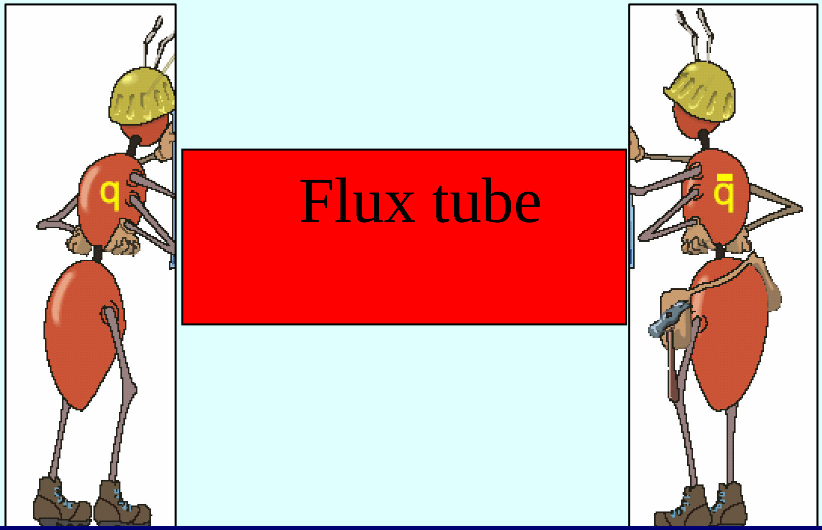
QCD inspired potential for heavy QQ*

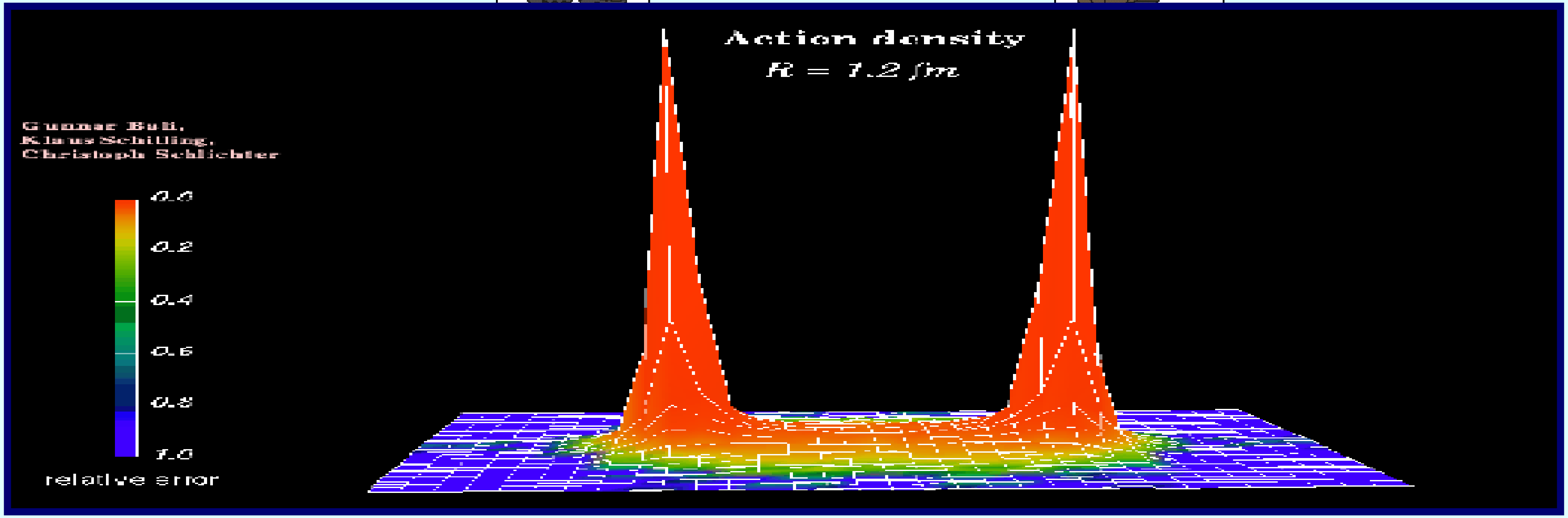




Lattice flux tube; V(r) = br

Coulomb - Single gluon exchange





Excite the gluonic flux tube = hybrid mesons (includes exotic JPC)

Allowed $q\bar{q}$ quantum numbers:

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The complete list of allowed $q\bar{q}$ J^{PC} quantum numbers has gaps!

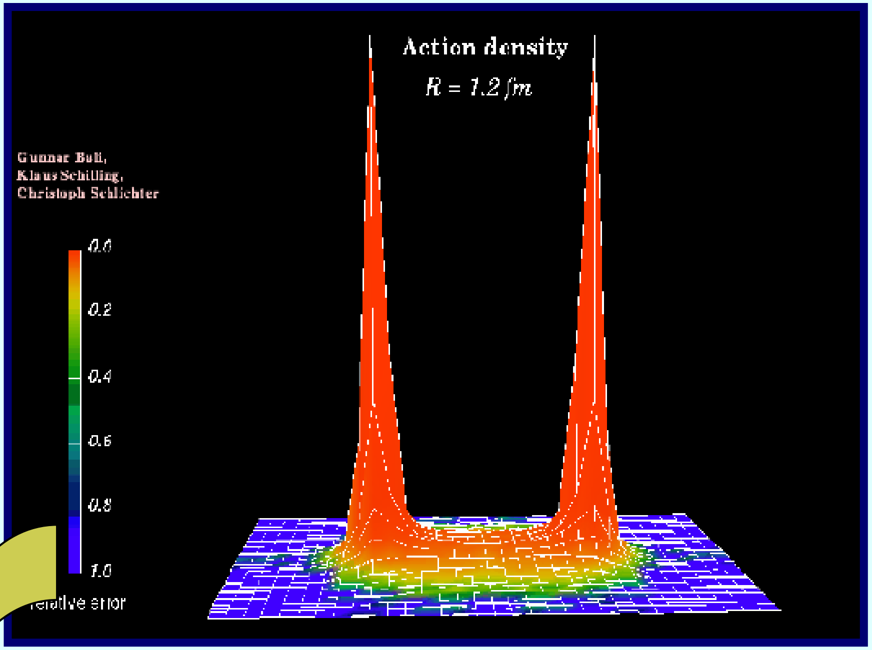
The J^{PC} forbidden to $q\bar{q}$ are called “J^{PC}-exotic quantum numbers”.

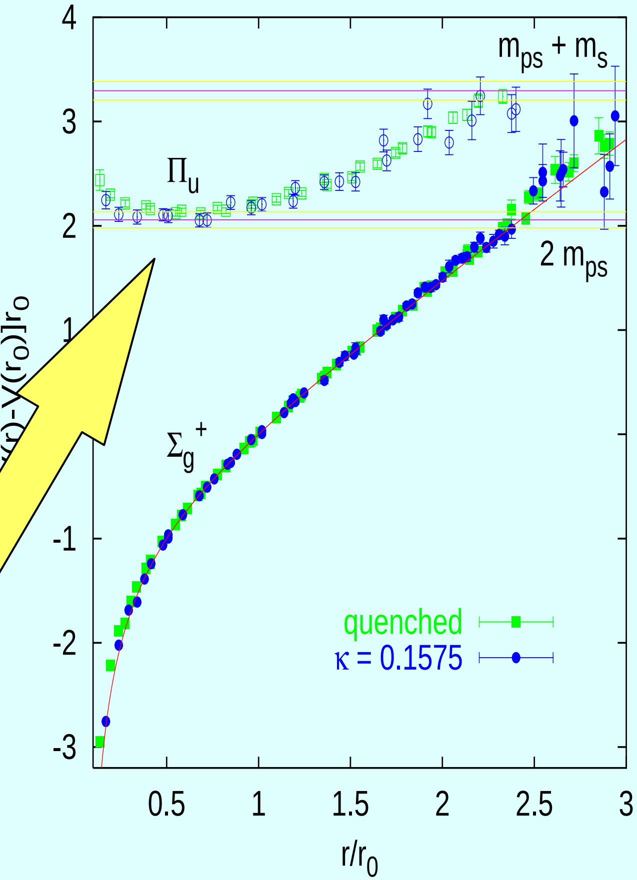
$$\text{Exotic } J^{PC} = 0^{--};\ 0^{+-},\ 1^{-+},\ 2^{+-},\ 3^{-+} \ldots$$

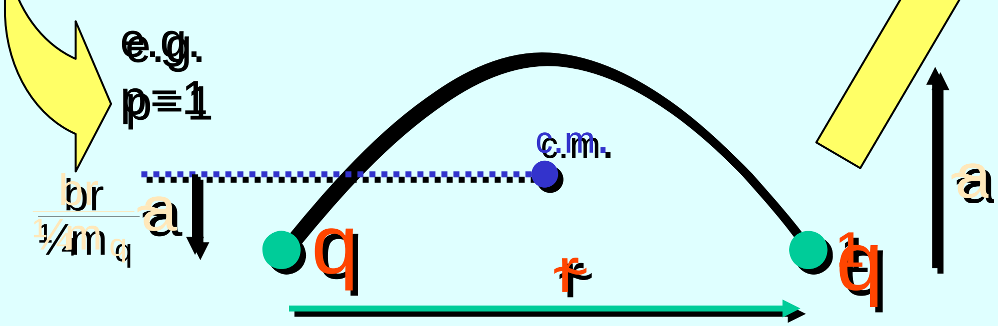
If you find a resonance with exotic J^{PC},
you are certainly beyond the naive $q\bar{q}$ quark model.

Plausible J^{PC}-exotic candidates =
hybrids, glueballs (high mass), maybe multiquarks (fall-apart decays).

Gluonic hybrid mesons







Exciting the flux tube

Lattice and model agree spectrum; and 2006 decays! (later)

1.Quarkonium for all flavors

…….and hints of glue

Quarkonium template: qq*   L + S (= 0,1) =J

1D: 1- 2- 3-

2-

2S: 1- 0-

1P: 0+ 1+ 2+

1+

1S: 1- 0-

L=0

L=1

L=2

Quarkonium template: Scalar qq* is canonical

1D: 1-

2S: 1-

2+

1+

0+

1S: 1-

$\Upsilon(b\bar{b})$

1D: 1-

2S: 1- 10023

2+ 9913

1+ 9893

0+ 9860

1S: 1- 9460

ψ (cc*)

1D: 1- 3770

2S: 1- 3686

2+ 3556

1+ 3510

0+ 3415

1S: 1- 3097

$\Upsilon(b\bar{b})$ 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

2+ | 9913 | 3556

1+ | 9893 | 3510

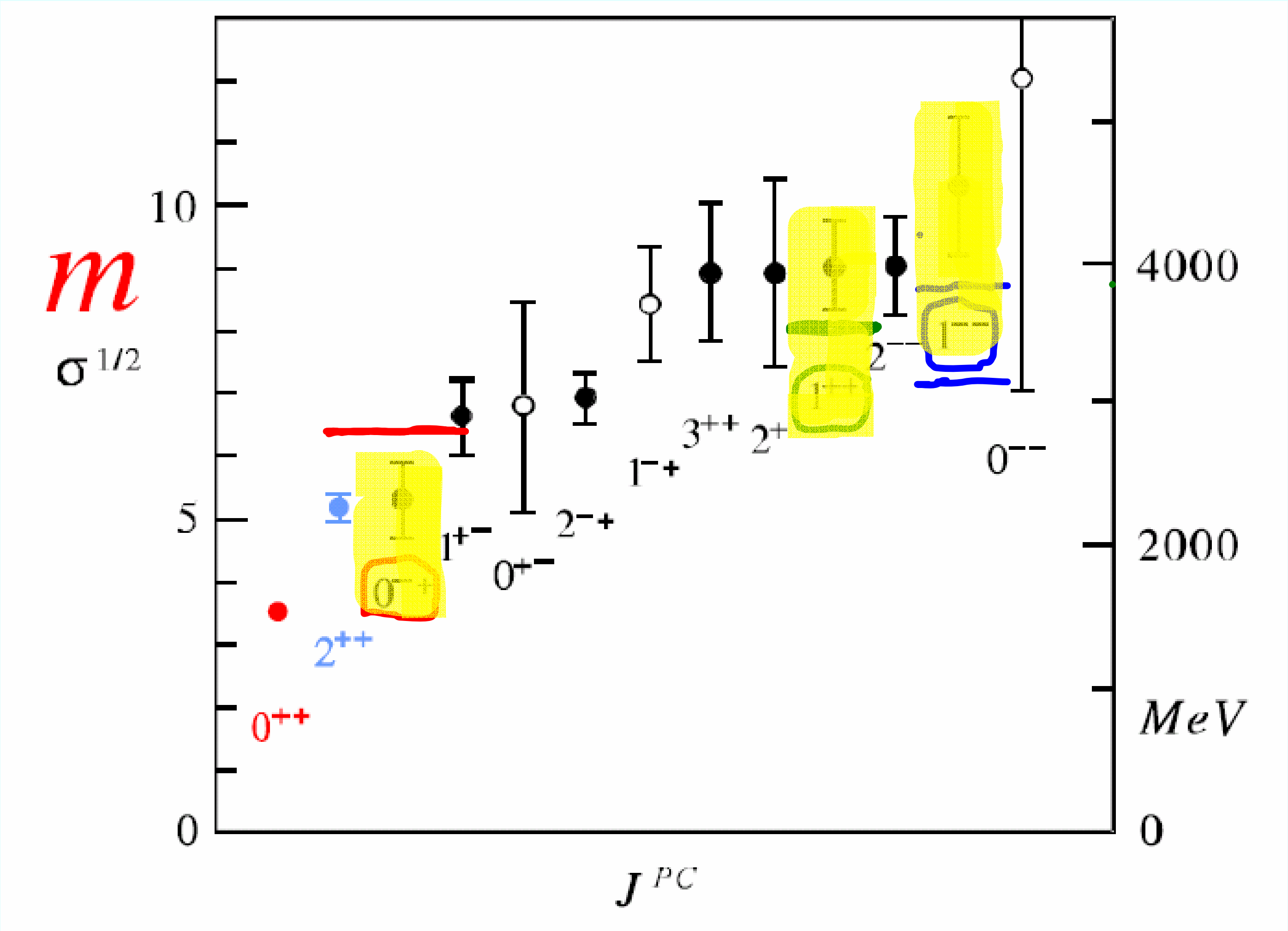
0+ | 9860 | 3415

1S: 1- | 9460 | 3097

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

Narrow below MM threshold

Glueballs spectrum from Lattice



$D_s(c\bar{s})$ **(Potential model prediction)**

1D: 1- **2900**

2S: 1- **2730**

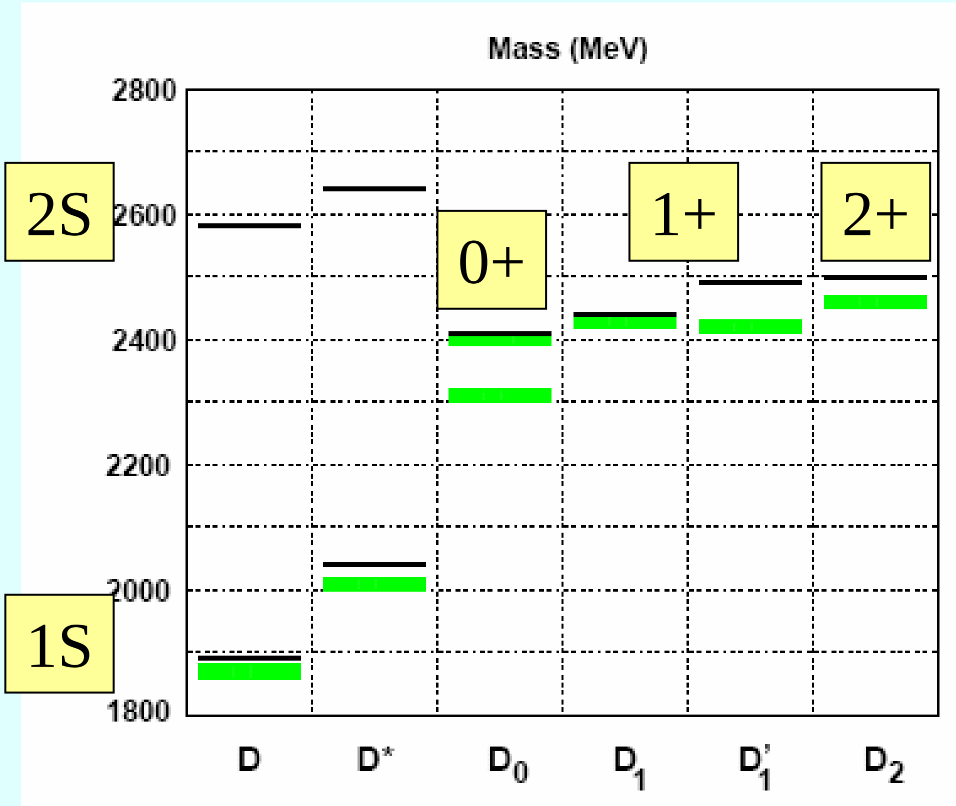
2+ **2590**

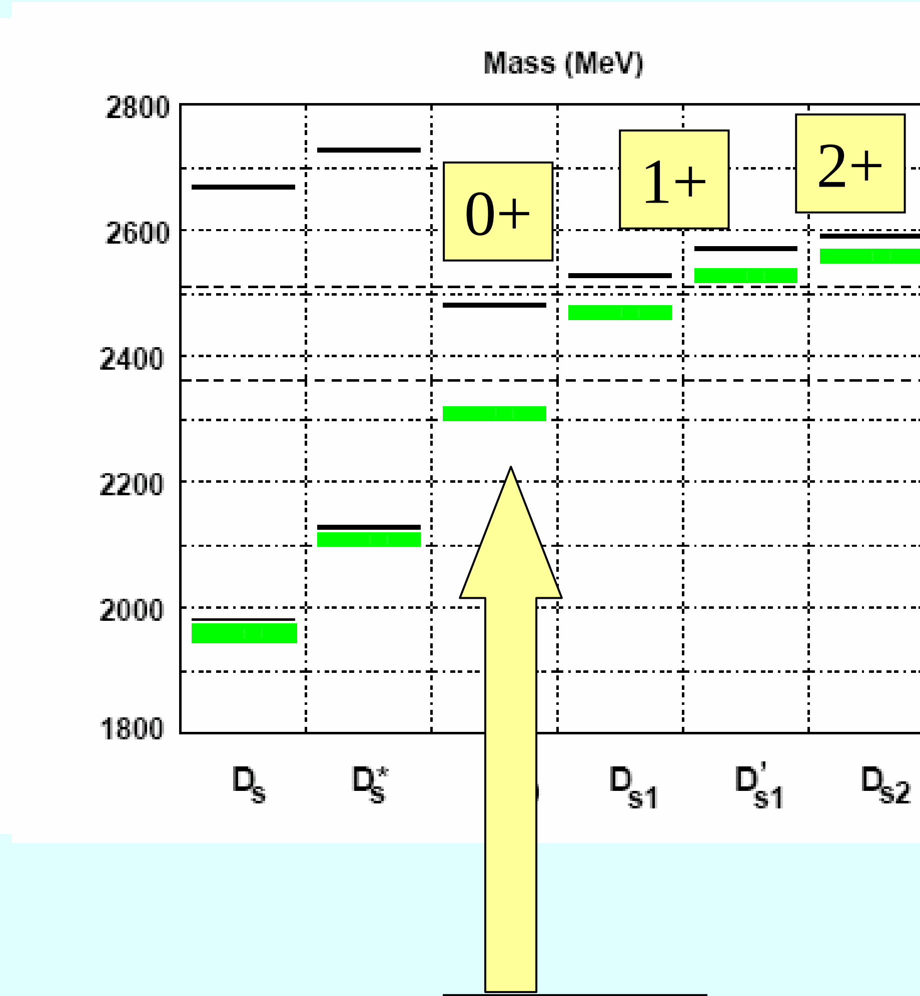
1+ **2550/2560**

0+ **2480**

1S: 1- **2130**

Charm……...............and…….   Charm-Strange Mesons





0+ low
See later

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

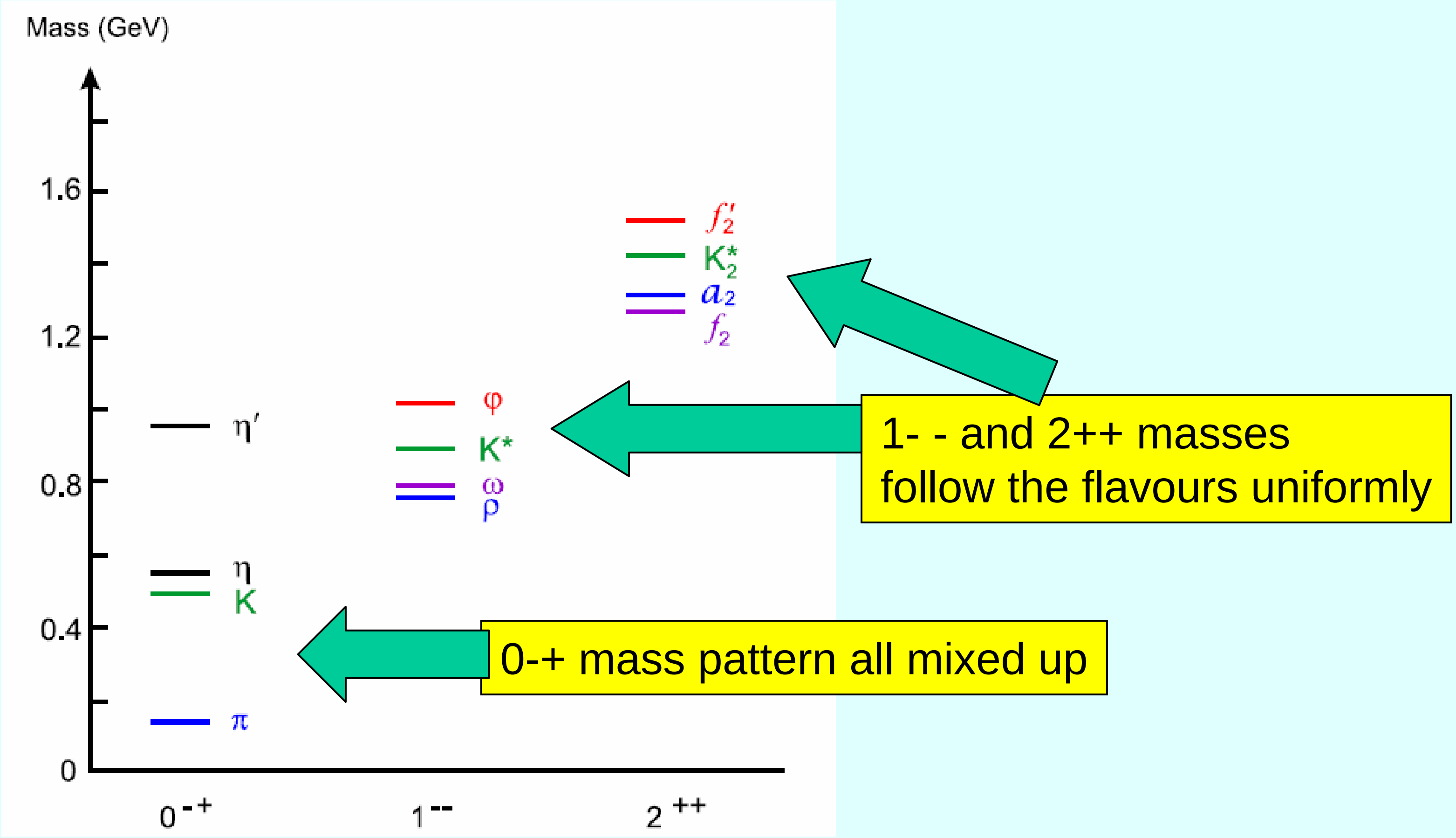
0+ 1420

1S: 1- 770 780/1020

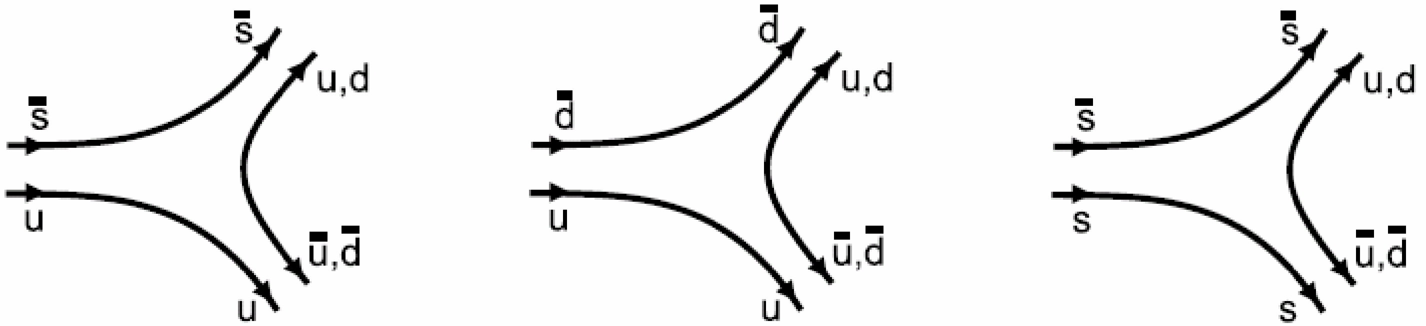
What do we know about flavours for light qq* nonets

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



Strong decays “OZI rule” also fits



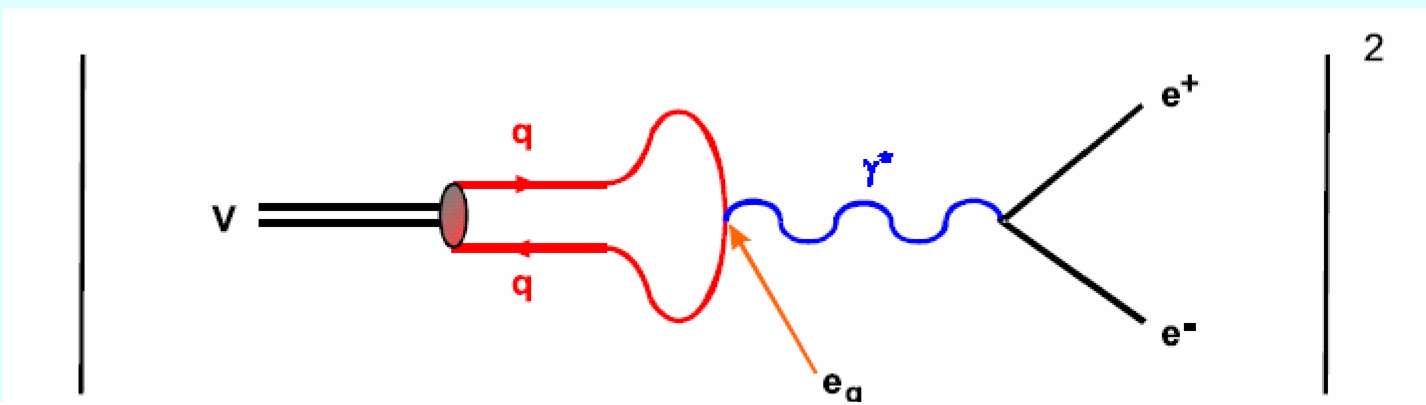
$K^{*+} \to K^{+}\pi^{0}, K^{0}\pi^{+}$ $\rho^{+} \to \pi^{+}\pi^{0}$ $\varphi \to K^{+}K^{-}, K^{0}\bar{K}_{0}$

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

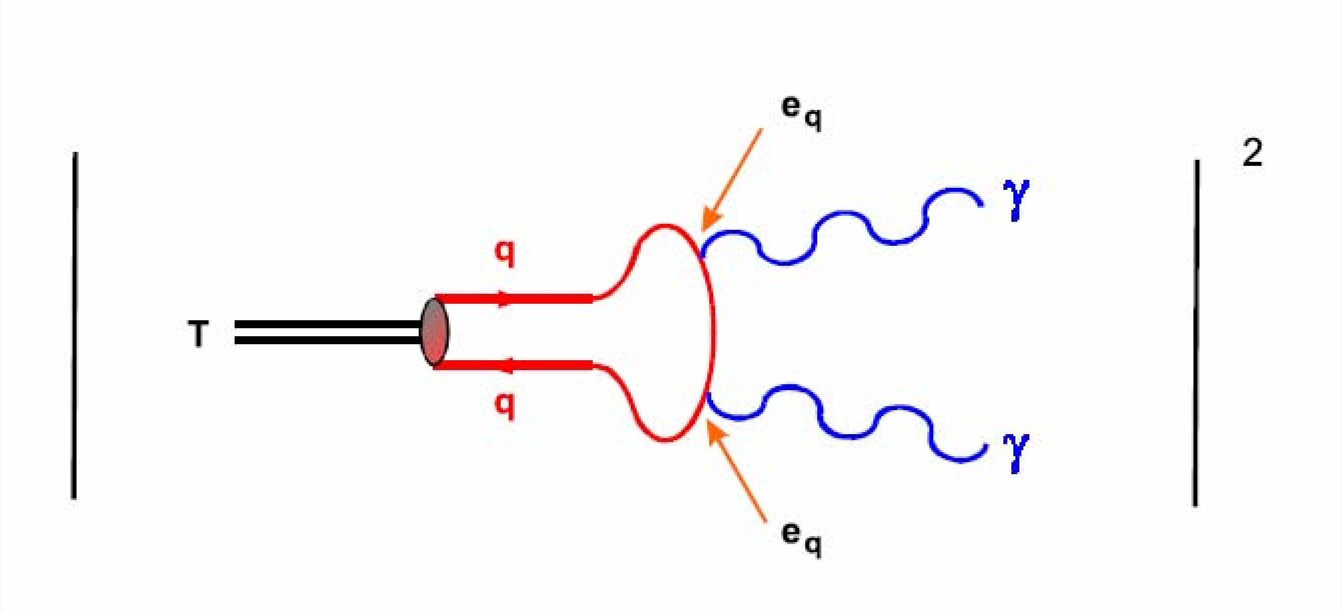
e.g. of electromagnetic: vector mesons



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

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

e.g of electromagnetic: tensor mesons

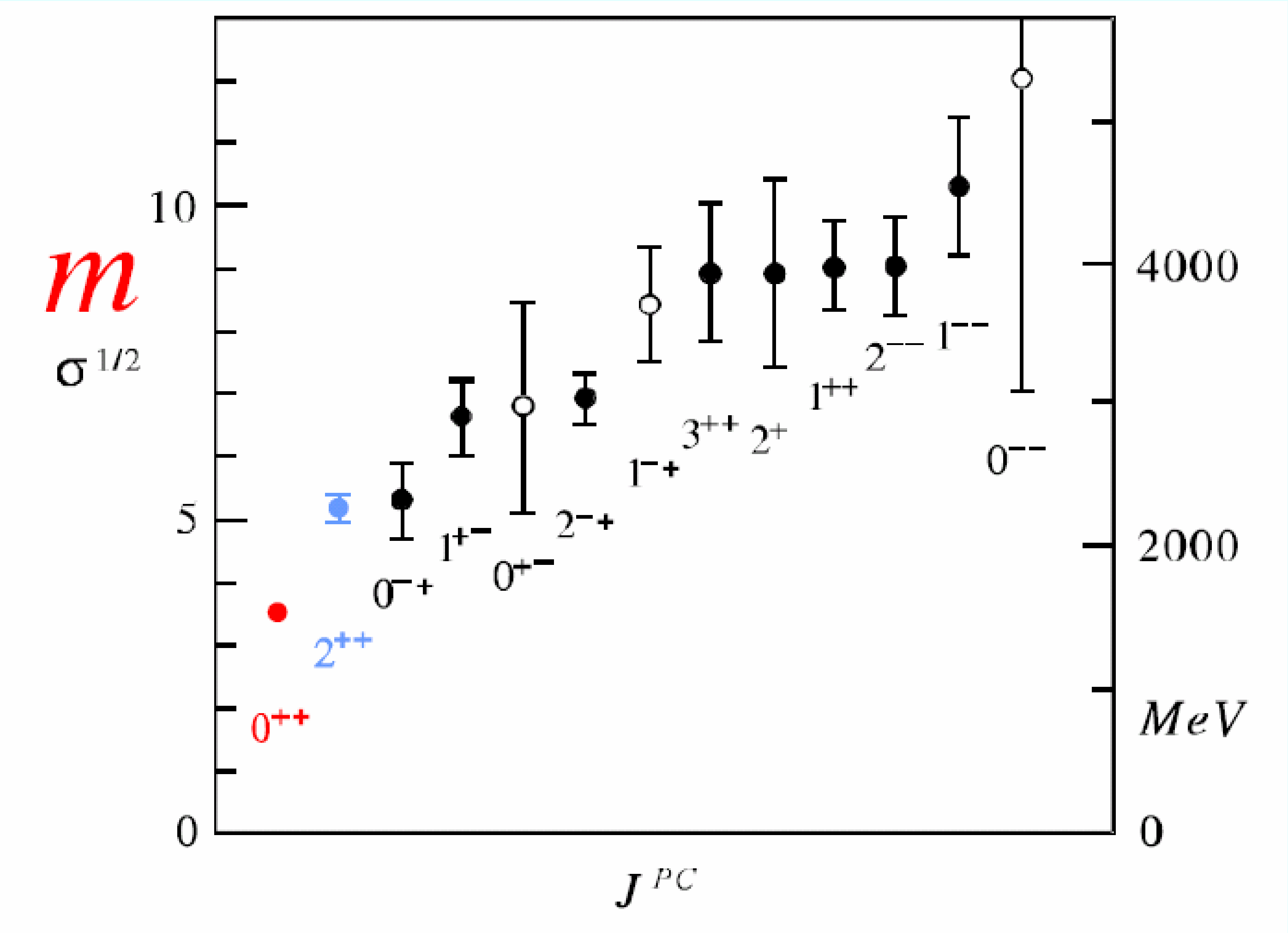


$$\Gamma(T \to \gamma\gamma) \ \sim \ \alpha^2 \ \langle \ e_q^2 \ \rangle^2$$

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

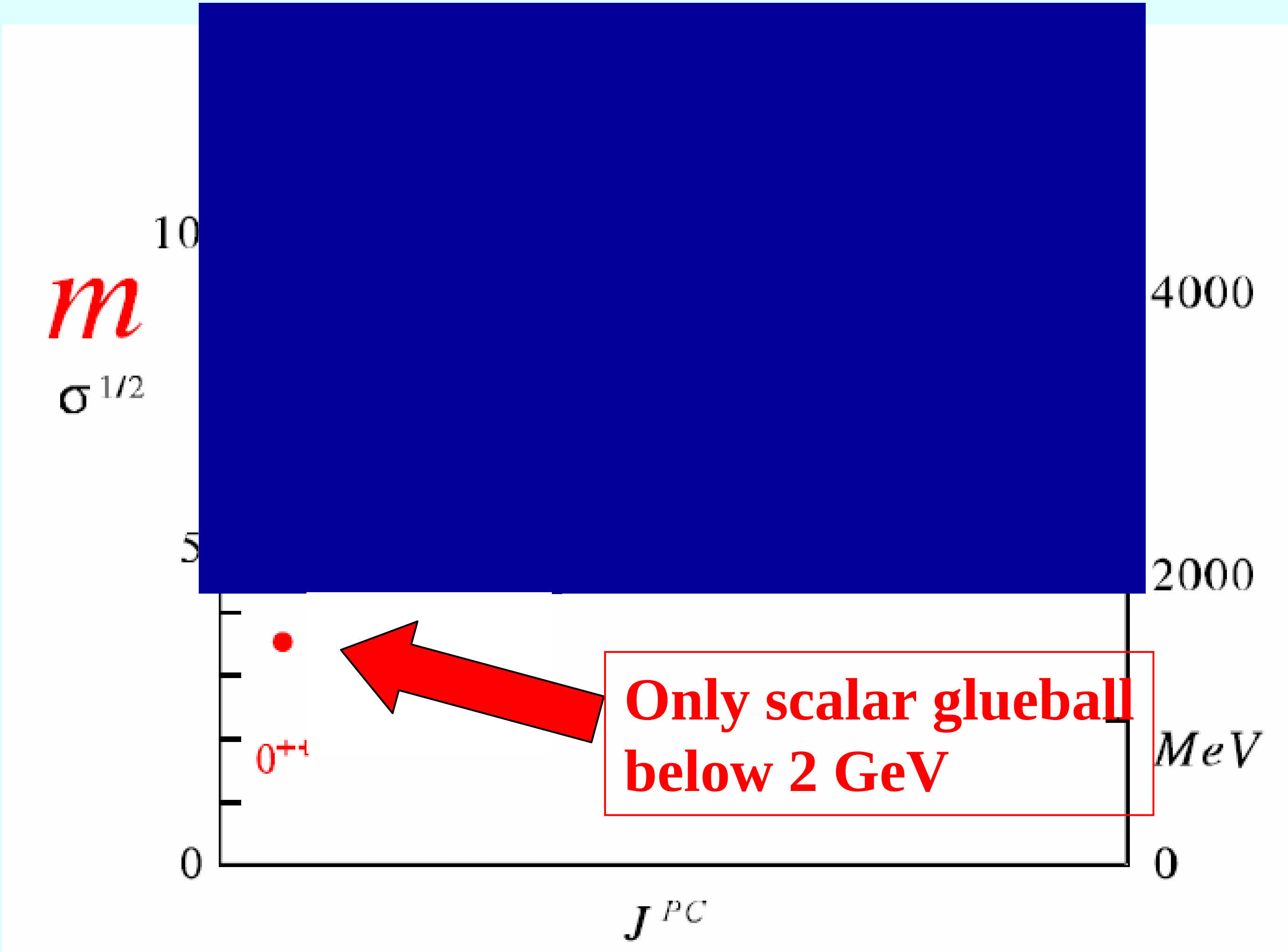
$$25 \ : \ (10 \pm 1) \ : \ (1 \pm 1)$$

Glueballs spectrum from Lattice



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

Glueballs also predicted: Strong QCD spectrum from Lattice



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

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

Clean below S-wave MM thresholds
And no prominent G expected

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 1370/1500/1710

1S: 1- 770 780/1020

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

1D: 1- 1700

2S: 1- 1460

2+ 1320 1270/1525

1+ 1300 1285/1530

0+ 1420 1370/1500/1710

980 980/600

1S: 1- 770

I=1 vector : I=0 $J^P = 2^+ \; 1^+ \; 0^+$ (nn* ss*)

1D: 1- 1700

2S: 1- 1460

2+ 1270/1525

1+ 1285/1530

qq* seed dominates
If no S-wave meson
channels are open.

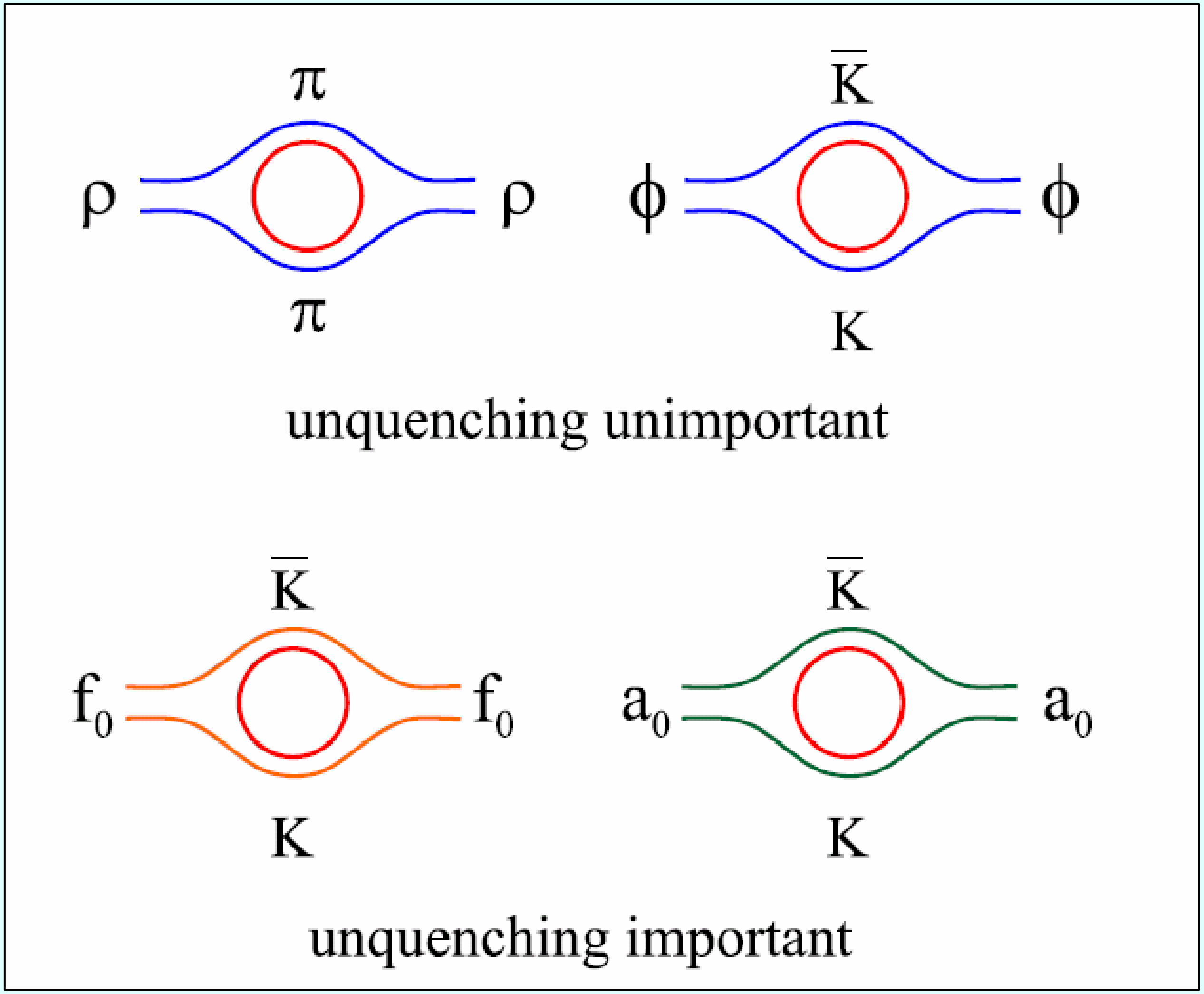
S-wave hadrons hide qq*

Production channels
give different impressions
of Fock state

Big problem for scalars
which couple to pi pi etc
in s-wave even though qq*
is in p-wave

1S: 1- 770

Comment 1. Role of S-waves: multiquarks; especially scalars



This produces the scalars below 1 GeV (tetraquarks or molecules later)

Comment 2: Scalar glueball @ 1.6 GeV will affect scalars above 1 GeV

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

0+ 1370/1500/1710

980/600

1S: 1- 770

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**

0+ **1370/1500/1710**

980/600

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

Can data eliminate it; or even make it robust?