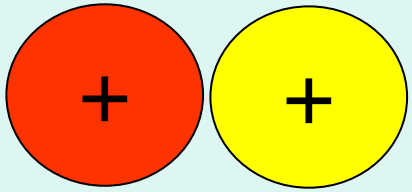
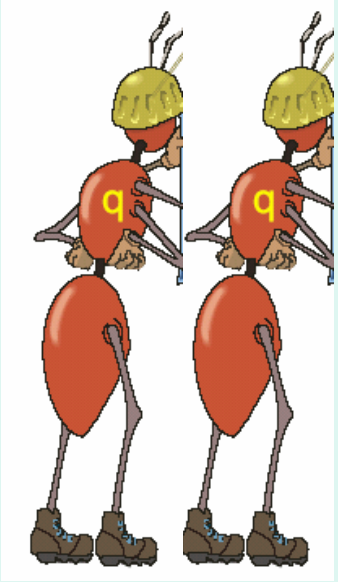
States outside the quark model:

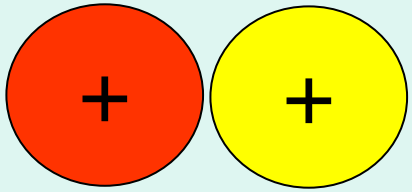
2.Tetraquarks

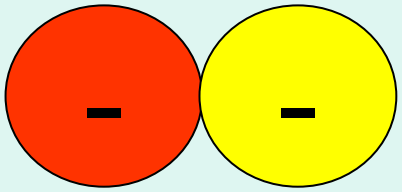
New combinations of quarks



Attraction of two quarks to make a "diquark"

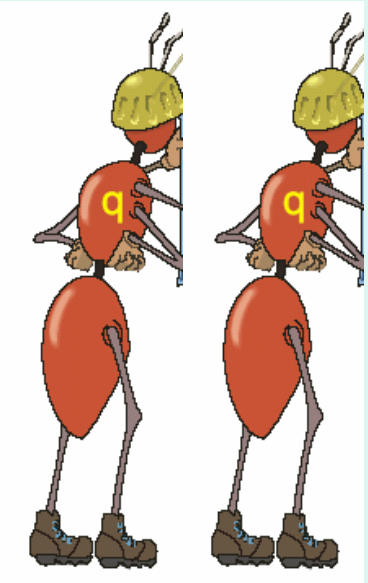


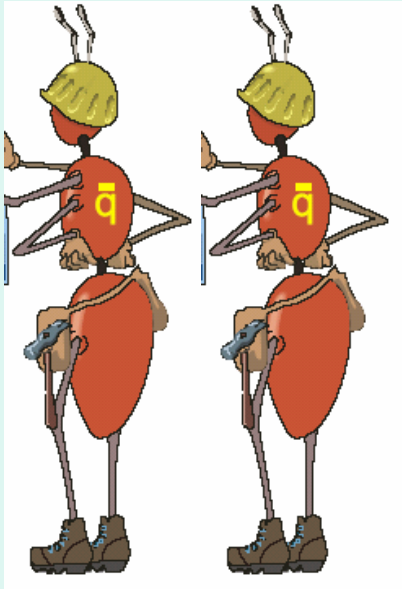


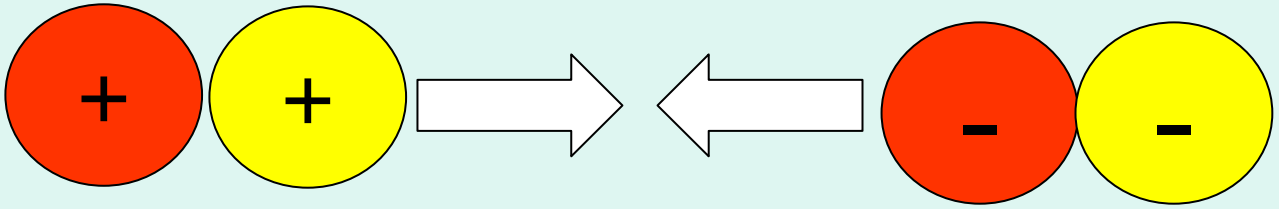


Attraction of two quarks to make a "diquark"

And two antiquarks Making an "anti-diquark"

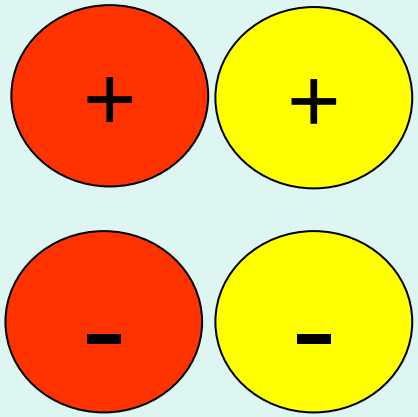




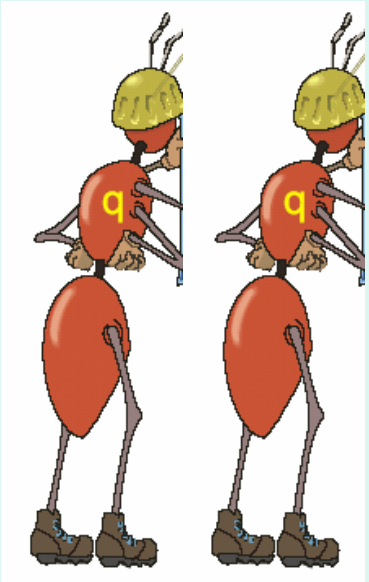


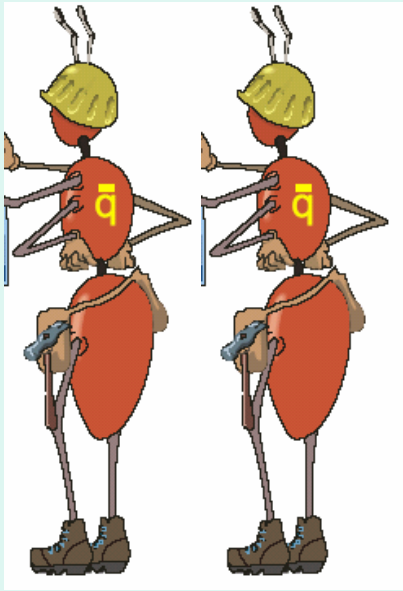
They can mutually attract one another……

……Making a hadron from diquarks
= 2 quarks and 2 antiquarks



Tetraquark





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

1D: 1- 1700

2S: 1- 1460

2+ 1270/1525

? qq* + Glueball

1+ 1285/1530

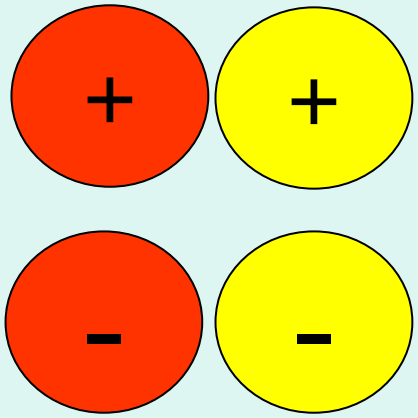
[qq][q*q*]

0+ 1370/1500/1710

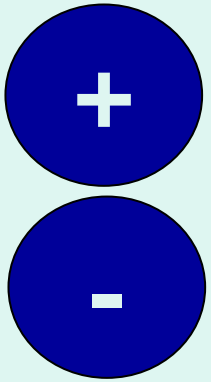
980/600

1S: 1- 770

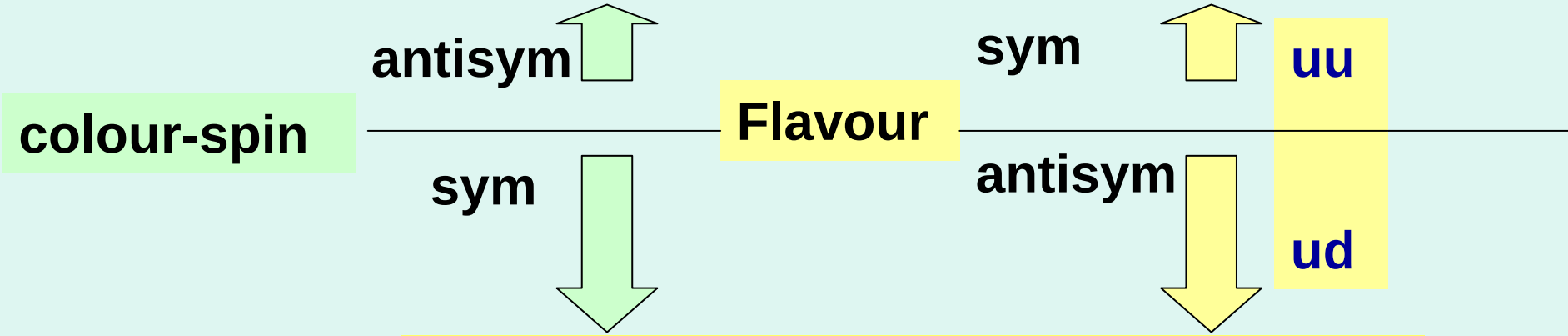
How can we tell if its this



Or this?



Beyond qq*: diquarks and tetraquarks



e.g. 3*,S=0……flavour 3*

Attraction for unlike flavours
Repulsion for like flavours

Jaffe model of light scalar mesons

Strong QCD attraction of 3^*_c 3^*_f qq into 0^+ diquark

$$f_0(980)/a_0(980)([us][\bar{u}\bar{s}] \pm [ds][\bar{d}\bar{s}]$$

$$\kappa(800)[ud][\bar{u}\bar{s}]$$

$$\sigma(500)([ud][\bar{u}\bar{d}]$$

Later: Basis of Jaffe Wilczek pentaquark model

Inverted flavour multiplets

1-

1020 ss*

890 su* sd*

780 uu*+dd*
770 uu*- dd*

0+

980 (uu*+dd*)ss*
980 (uu*- dd*)ss*

800 (su*)uu* (sd*)dd*

500 uu*dd*

Inverted flavour multiplets

1- + hybrid

H ss*

K su* sd*

L uu*+dd*
L uu*- dd*

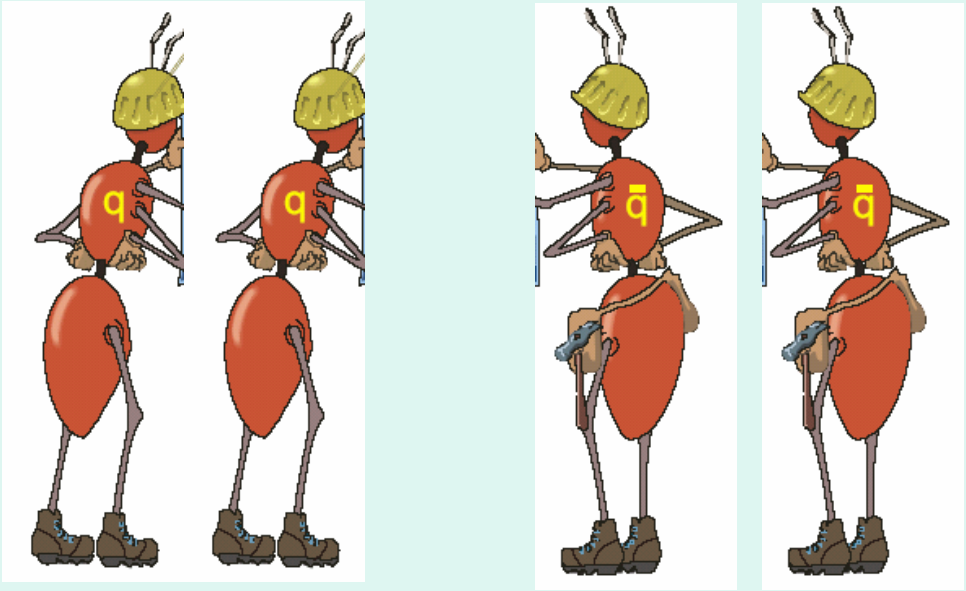
1- + tetraquark/mol

H (uu*+dd*)ss*
H (uu*- dd*)ss*

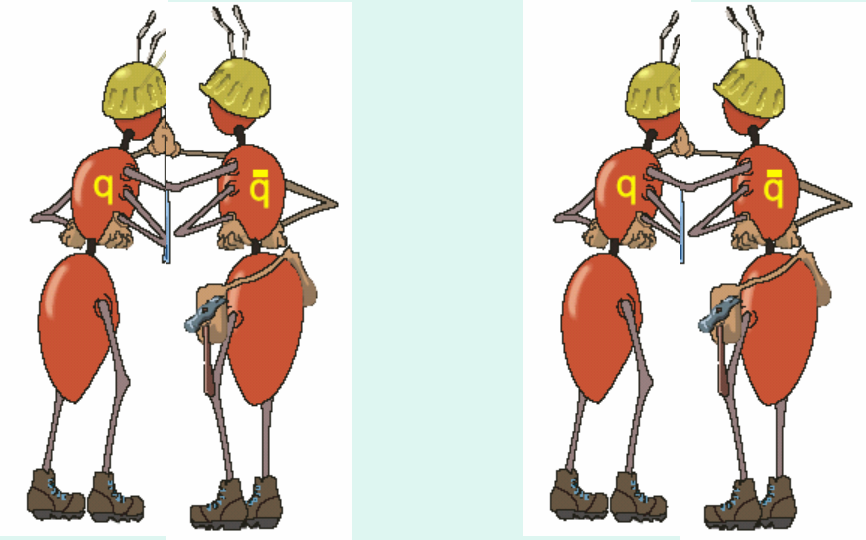
K (su*)uu* (sd*)dd*

L uu*dd*

Tetraquark



Molecule…or two mesons



New states outside the quark model:

D_s(cs*) states

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

1D: 1- 2900

2S: 1- 2730

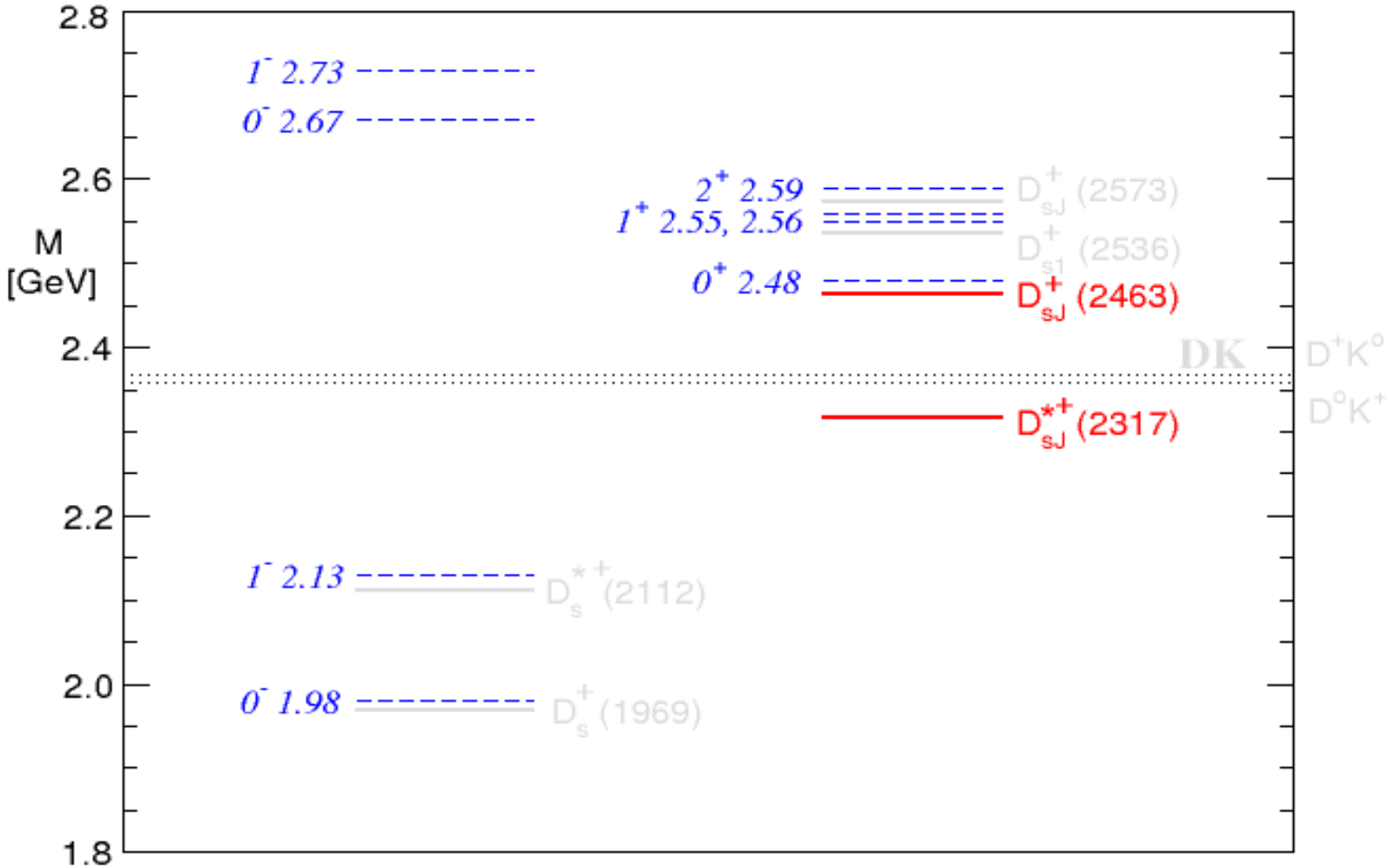
2+ 2590

1+ 2550/2560

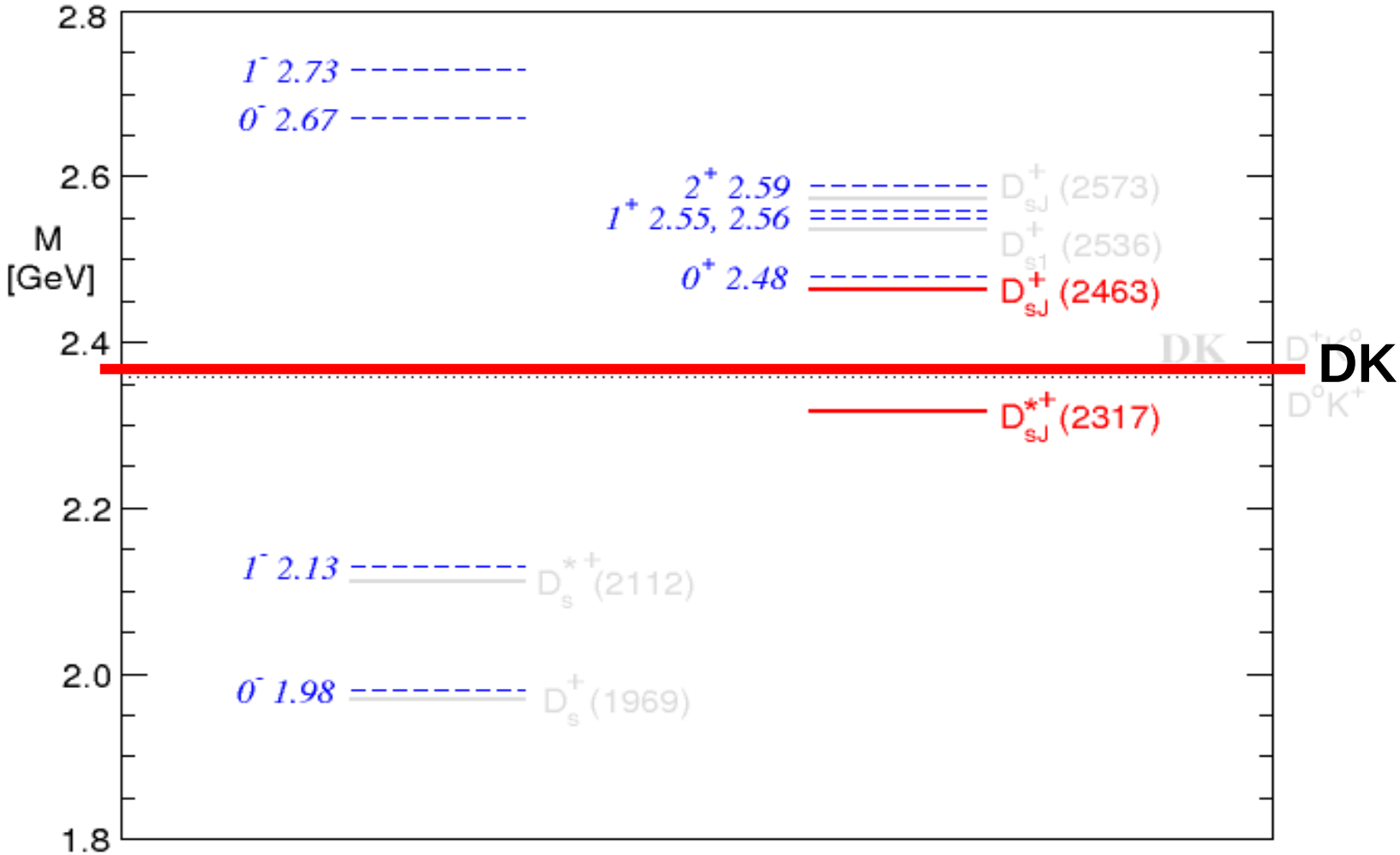
0+ 2480

1S: 1- 2130

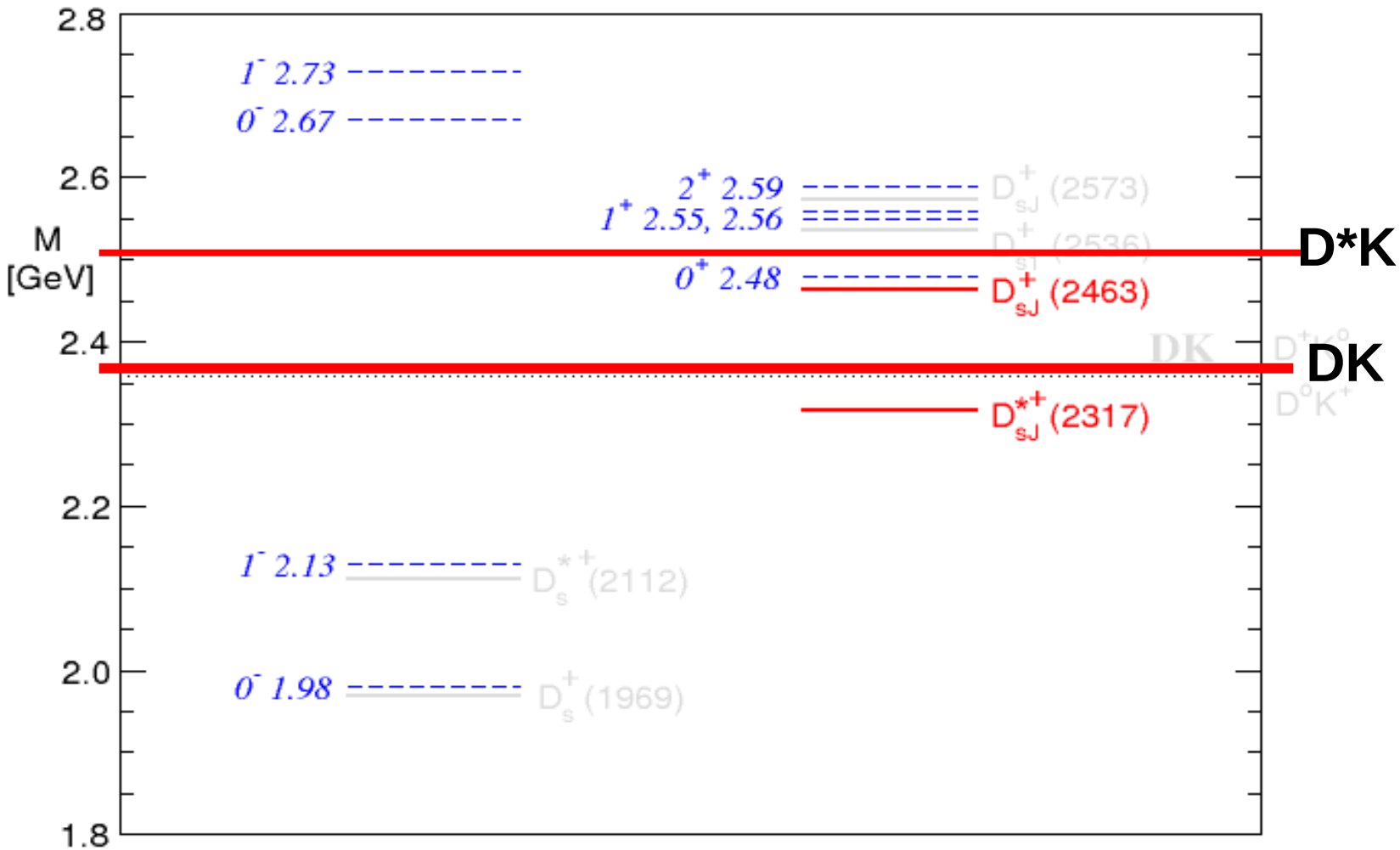
Theory, Ds mesons (blue) and the new BaBar states (red)



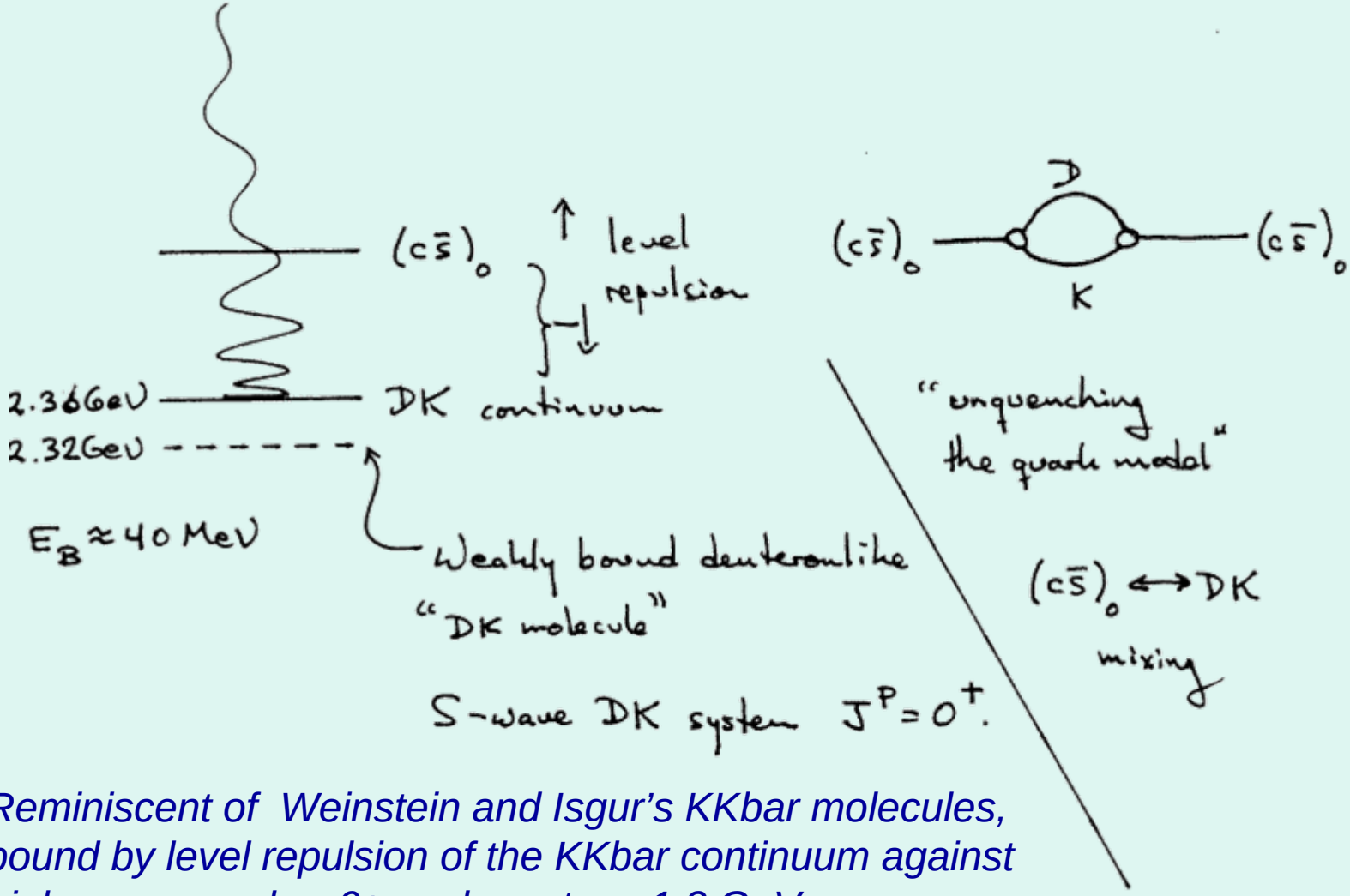
Theory, Ds mesons (blue) and the new BaBar states (red)



Theory, Ds mesons (blue) and the new BaBar states (red)



A conjecture: T.Barnes, F.E.Close, H.J.Lipkin, hep-ph/0305025, PRD.



Reminiscent of Weinstein and Isgur's KKbar molecules, bound by level repulsion of the KKbar continuum against higher mass qqbar 0+ scalars at ca. 1.3 GeV.

S-wave meson-meson beats P-wave qq* (continued)

Whatever makes scalar f_0(980) light (= just below KK)
(compared to qq* p-wave)

Probably makes scalar 2317 light (= just below DK)
(compared to qq* p-wave)

…and 2460 axial light (just below D*K)

New states outside the quark model:

cc* X(3872) anomalous charmonium

A narrow charmonium state

$$X(3872) \to \psi\pi\pi$$

Seen in B \to K X(3872)

ψ (cc*)

1D: 1- 3772

2S: 1- 3686

2S: 0- 3625

2+ 3556

1+ 3510

0+ 3415

1S: 1- 3097

1S: 0- 2980

ψ (cc*)

1D: 1- 3770

2S: 1- 3686

2+ 3556

1+ 3510

0+ 3415

1S: 1- 3097

ψ (cc*)

3-

DD*

2-

1D: 1- 3770

DD

2S: 1- 3686

2+ 3556

1+ 3510

0+ 3415

1S: 1- 3097

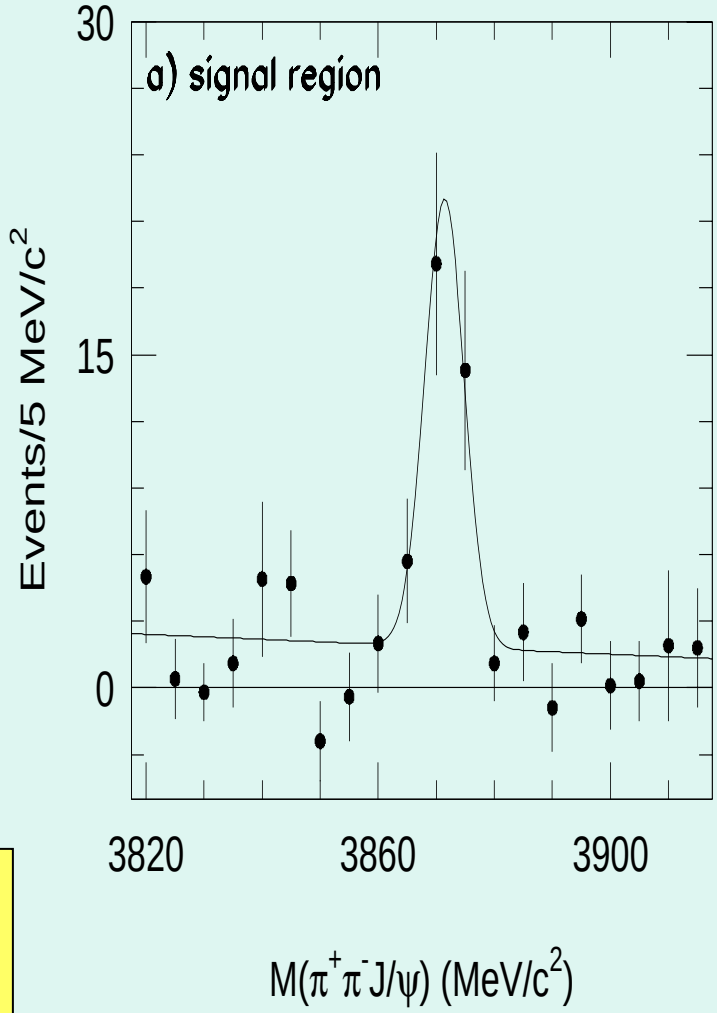
B decay = a new source of charmonium

A **narrow** charmonium state

$$X(3872) \to \psi\pi\pi$$

Charmonium candidates
2- 3- radial **1+**
are narrow below DD*

Mass, width, angular dist etc
all inconsistent with cc*



Standard cc* theory wrong?
Or is X(3872) not simple cc*?

ψ (cc*)

2- ? 3871.8

DD*

1D: 1- 3770

DD

2S: 1- 3686

2+ 3556

1+ 3510

0+ 3415

1S: 1- 3097

ψ (cc*)

3871.8

DD* 3871.3

coincidence?

1D: 1- 3770

DD

2S: 1- 3686

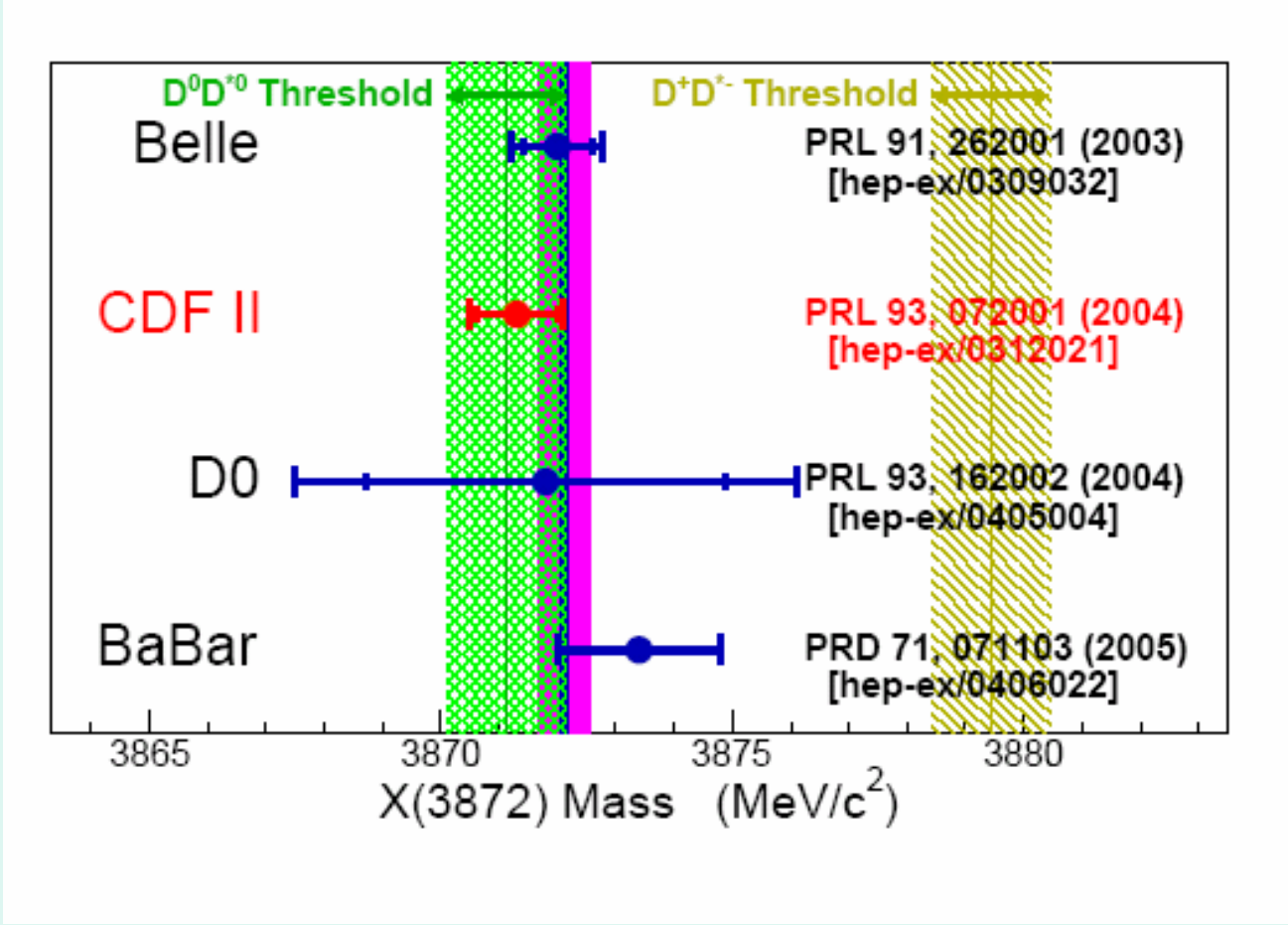
2+ 3556

1+ 3510

0+ 3415

1S: 1- 3097

X(3872) mass compared with DD* thresholds



DD* molecule "tetraquark"

Mass same as neutral threshold
to better than 1 in 10,000

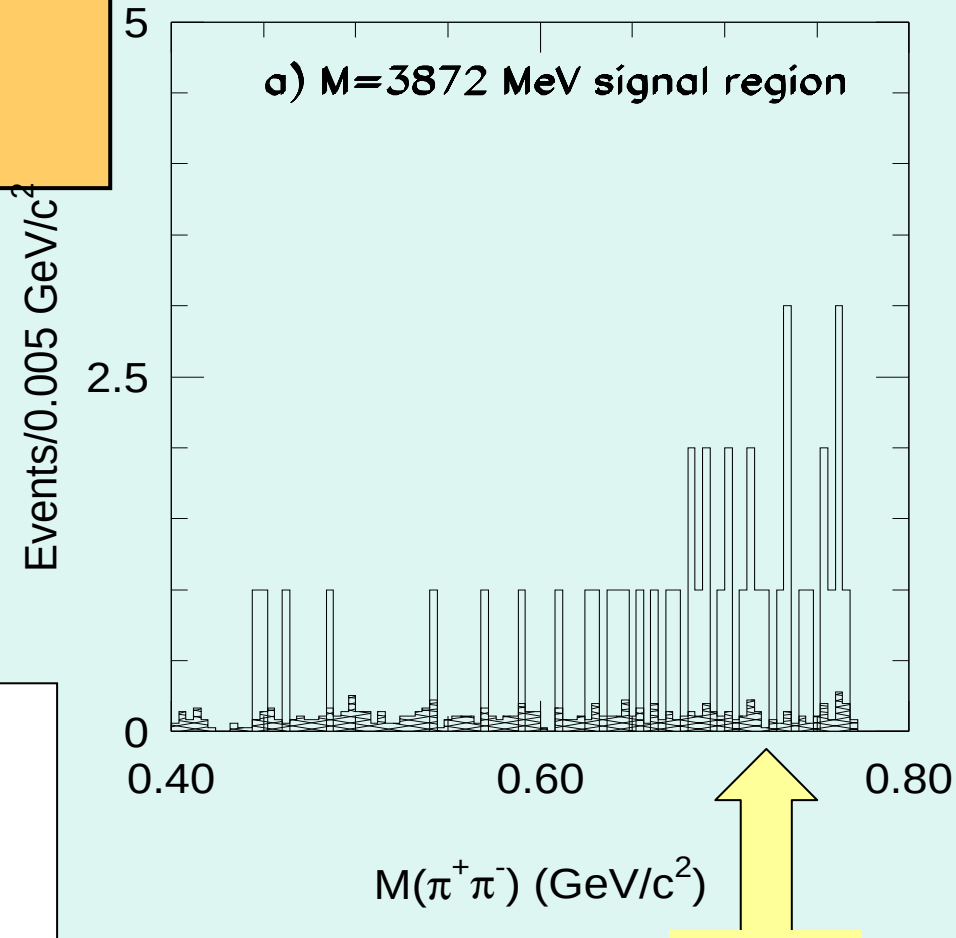
cuc*u* S-wave $J^{PC} = 1^{++}$
= isospin maximally broken

Close+Page
Tornqvist
Swanson

$X \to \psi\pi\pi$ is really

$X \to \psi\rho$!!!

Also psi omega: Belle

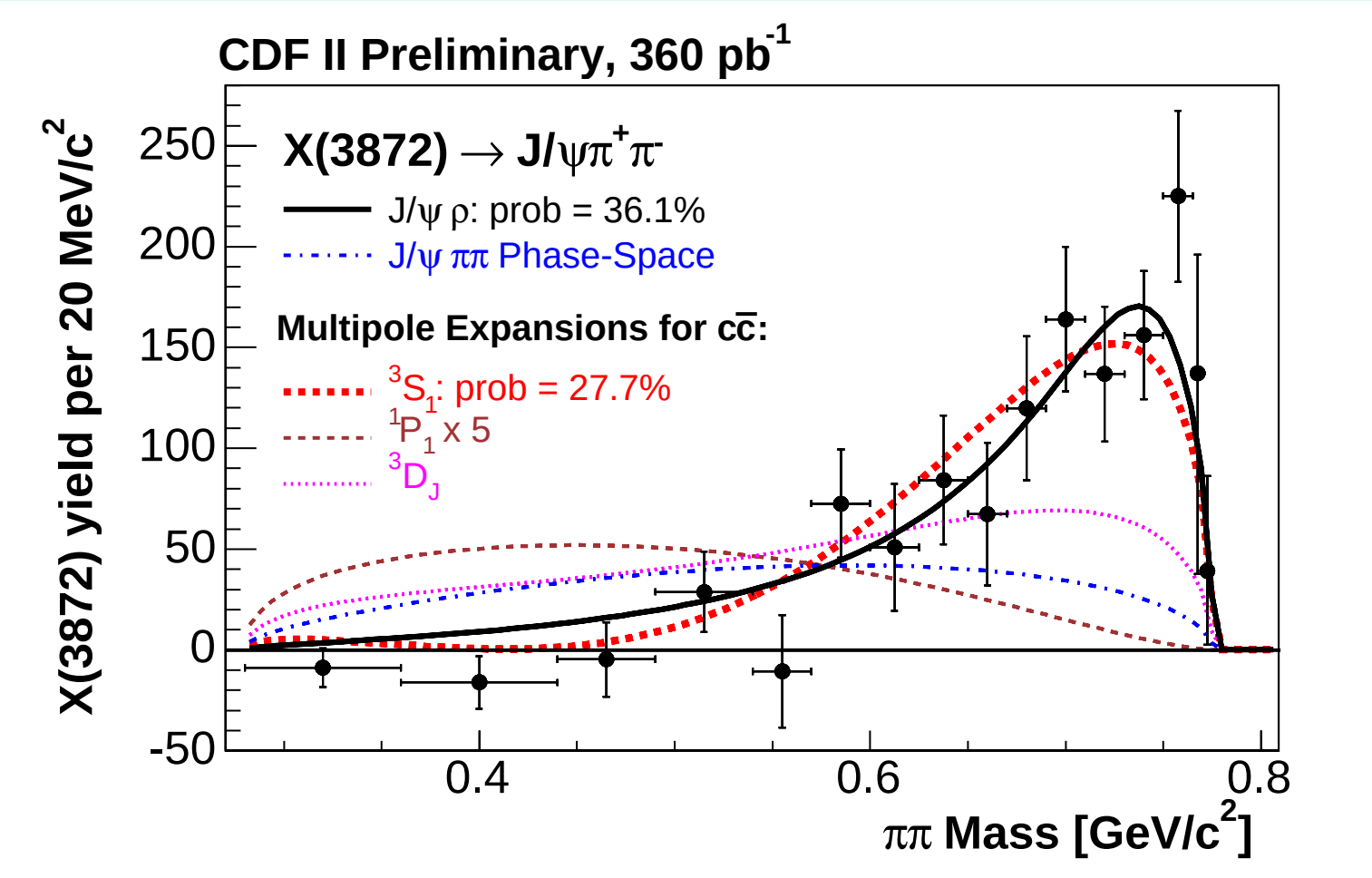


Rho?

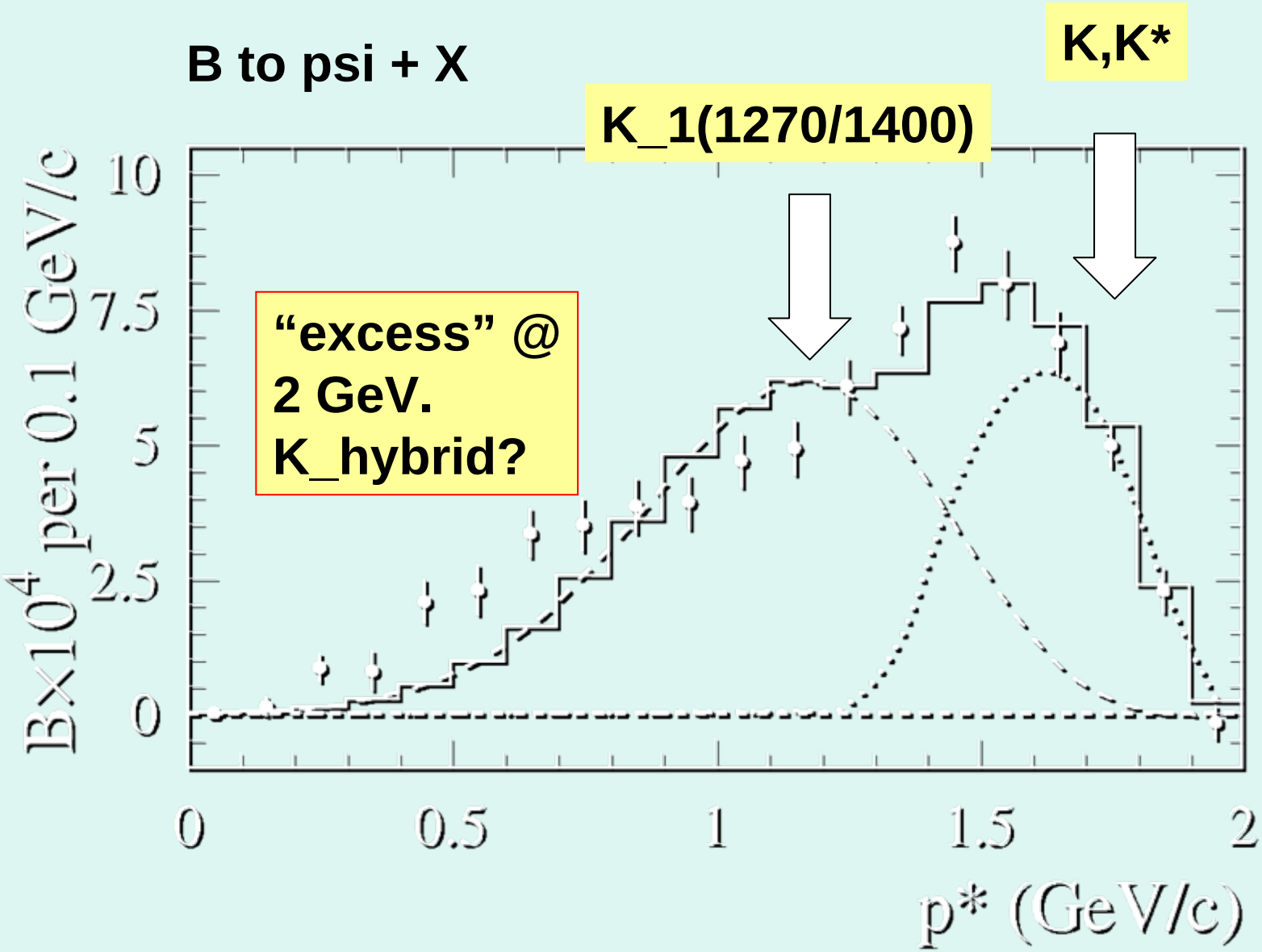
Test: no pi0pi0

X \to K+K-\pi>> K0K0\pi

CLEOc/BES test for 1++ 3550 also


CDF II Preliminary, 360 pb^{-1}
X(3872) → J/ψπ$^+$π$^-$
J/ψ ρ: prob = 36.1%
J/ψ ππ Phase-Space
Multipole Expansions for cc̄:
$^3S_1$: prob = 27.7%
$^1P_1$ x 5
^3D_J
X(3872) yield per 20 MeV/c^2
250
200
150
100
50
0
-50
0.4
0.6
0.8
ππ Mass [GeV/c^2]

B as new source of charmonium continued



States outside the quark model:

3.Hybrids and 4…….

4. Weird + unusual charm

$\Upsilon(b\bar{b})$ ψ (cc*)

1D: 1- 3772

2S: 1- 10023 3686

Empirically =
Linear potential
V(r) = kr

Flux tube model

2+ 9913 3556

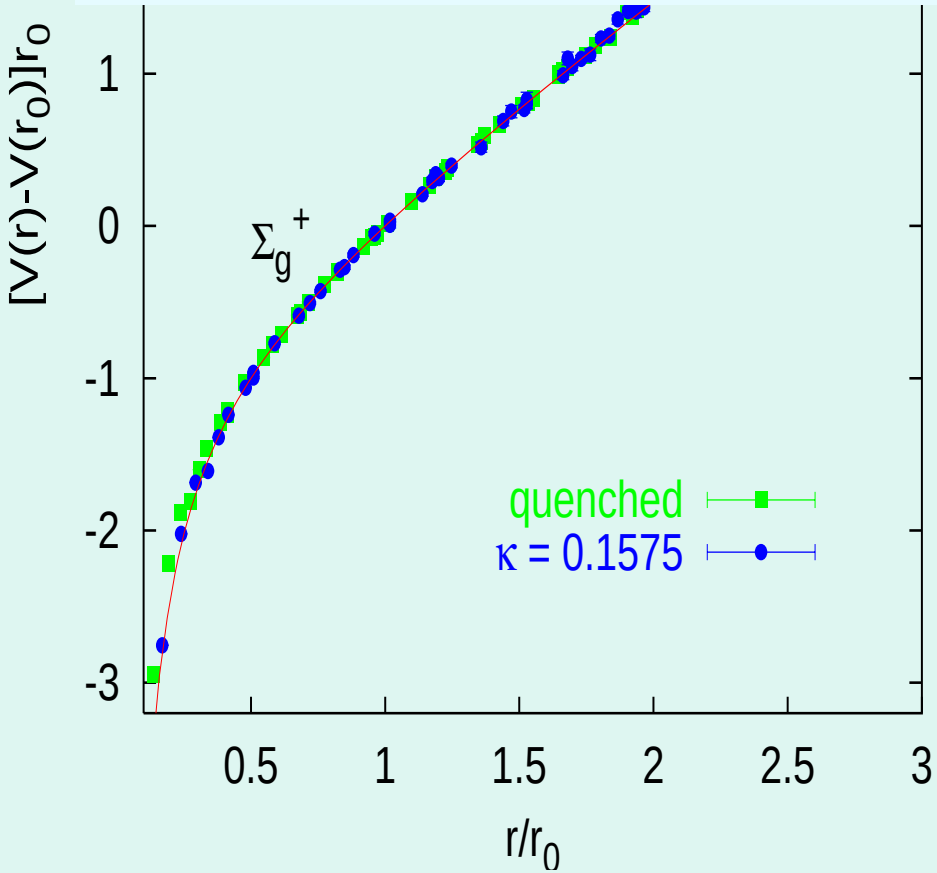
1+ 9893 3510

0+ 9860 3415

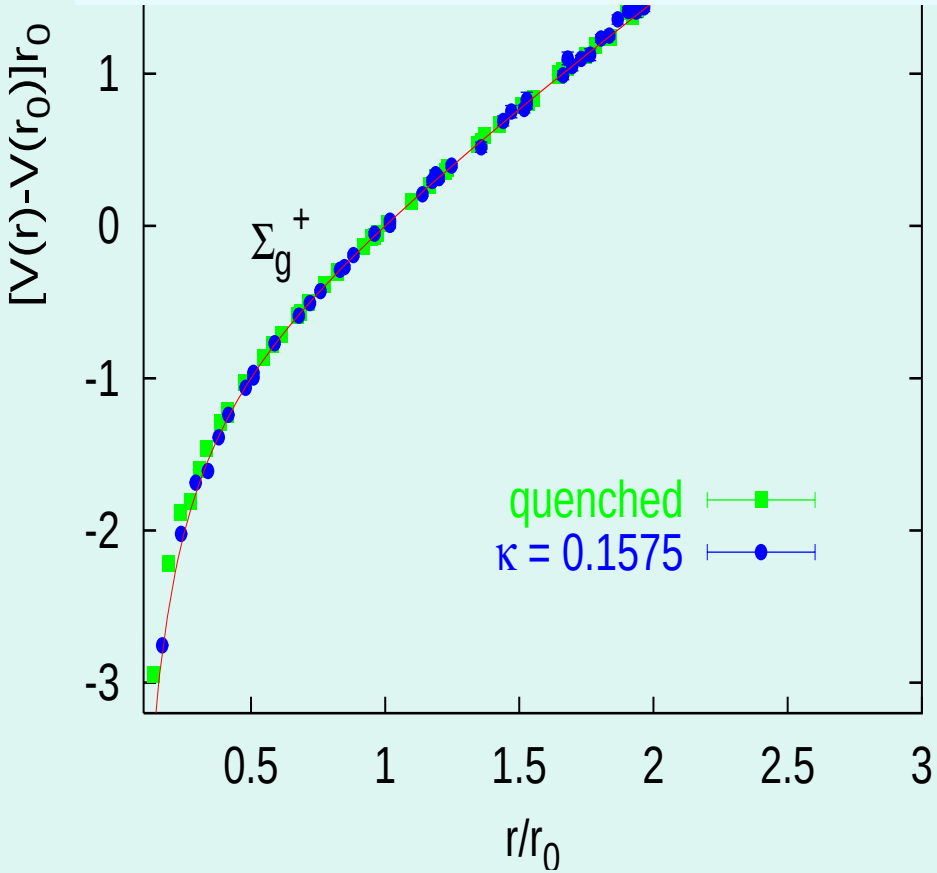
1S: 1- 9460 3097

Narrow below MM threshold

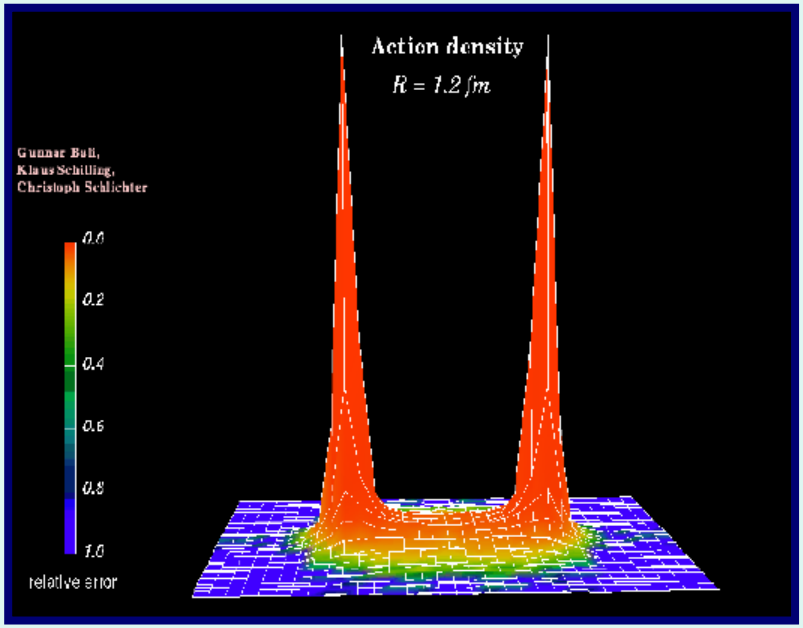
Lattice Linear Potential



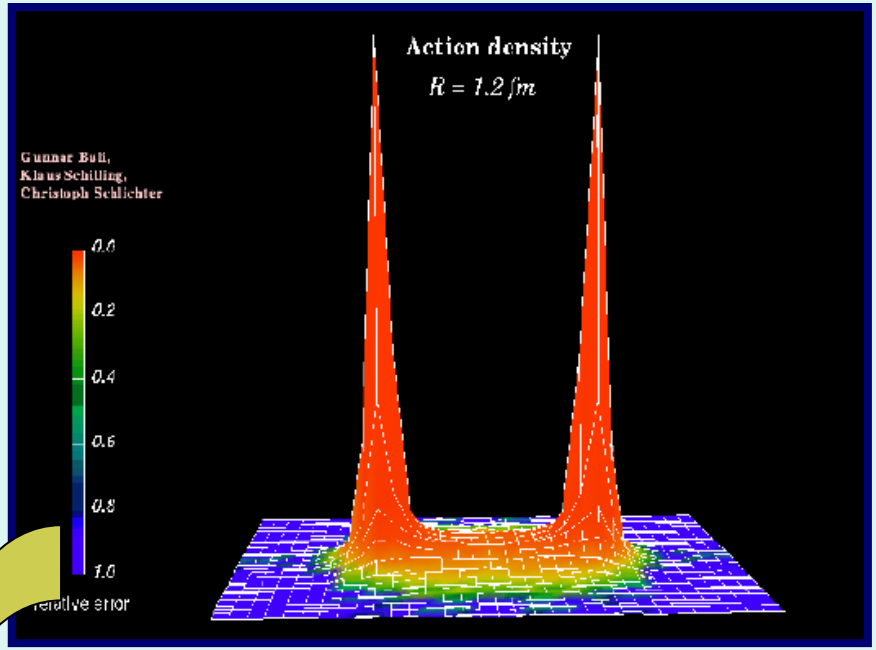
Lattice Linear Potential

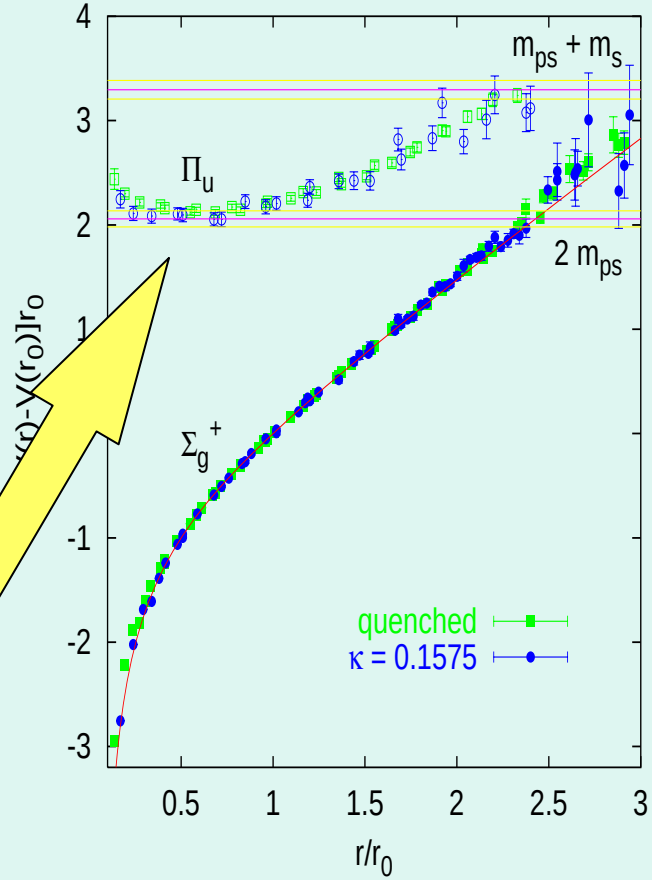


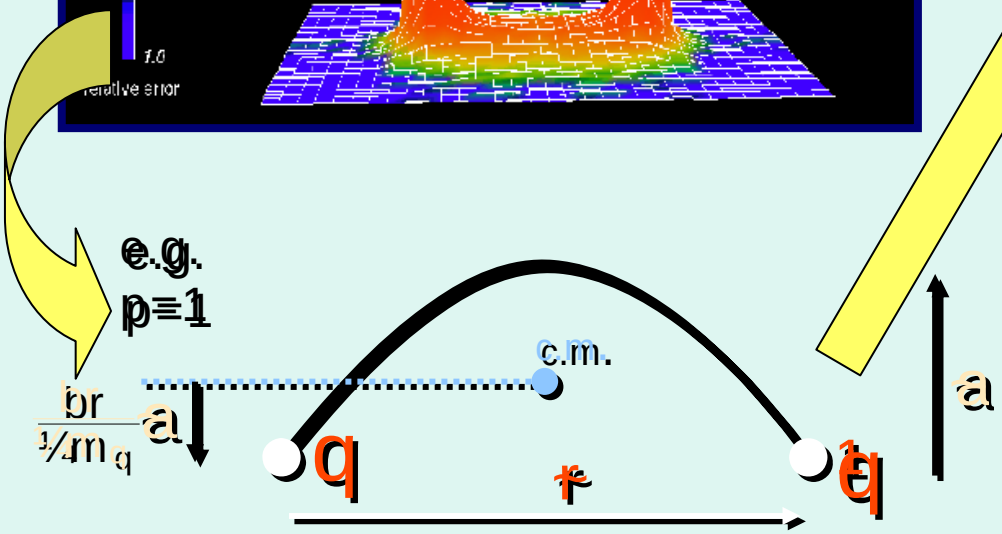
Linear flux tube



Gluonic hybrid mesons



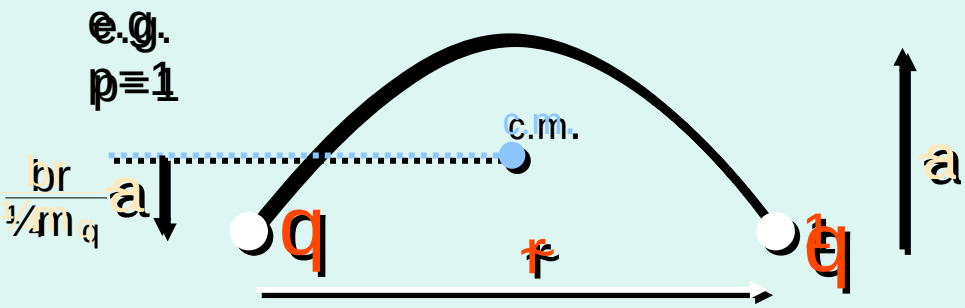




Exciting the flux tube

Lattice and model agree spectrum; decays in FT not yet lattice

flux-tube degrees-of-freedom



Costs about 1 to 1.5GeV energy to excite phonon "pi/R"
Hybrid nn* @ 2GeV; Hybrid cc* @ 4-4.5GeV

TABLE I. Predicted 1^{-+} Hybrid Masses.

state	mass (GeV)	model	Ref.
$H_{u,d}$	1.3-1.8	bag model	[19]
	1.8-2.0	flux tube model	[11–14]
	2.1-2.5	QCD sum rules (most after 1984)	[26–28]

1-+ signals: [20]

resonant? (Pennington); hybrid or molecule? (Klempt) [12–14]

E1 photoproduction of hybrids gamma p to n H^+ \sim 50% relative to conventional mesons (Isgur; FC Dudek) [26–28]

[23]

2+- also expected. Diffractive Photoproduction!! Should exceed 1-+ strength. JeffersonLab@12GeV; HERA [20]

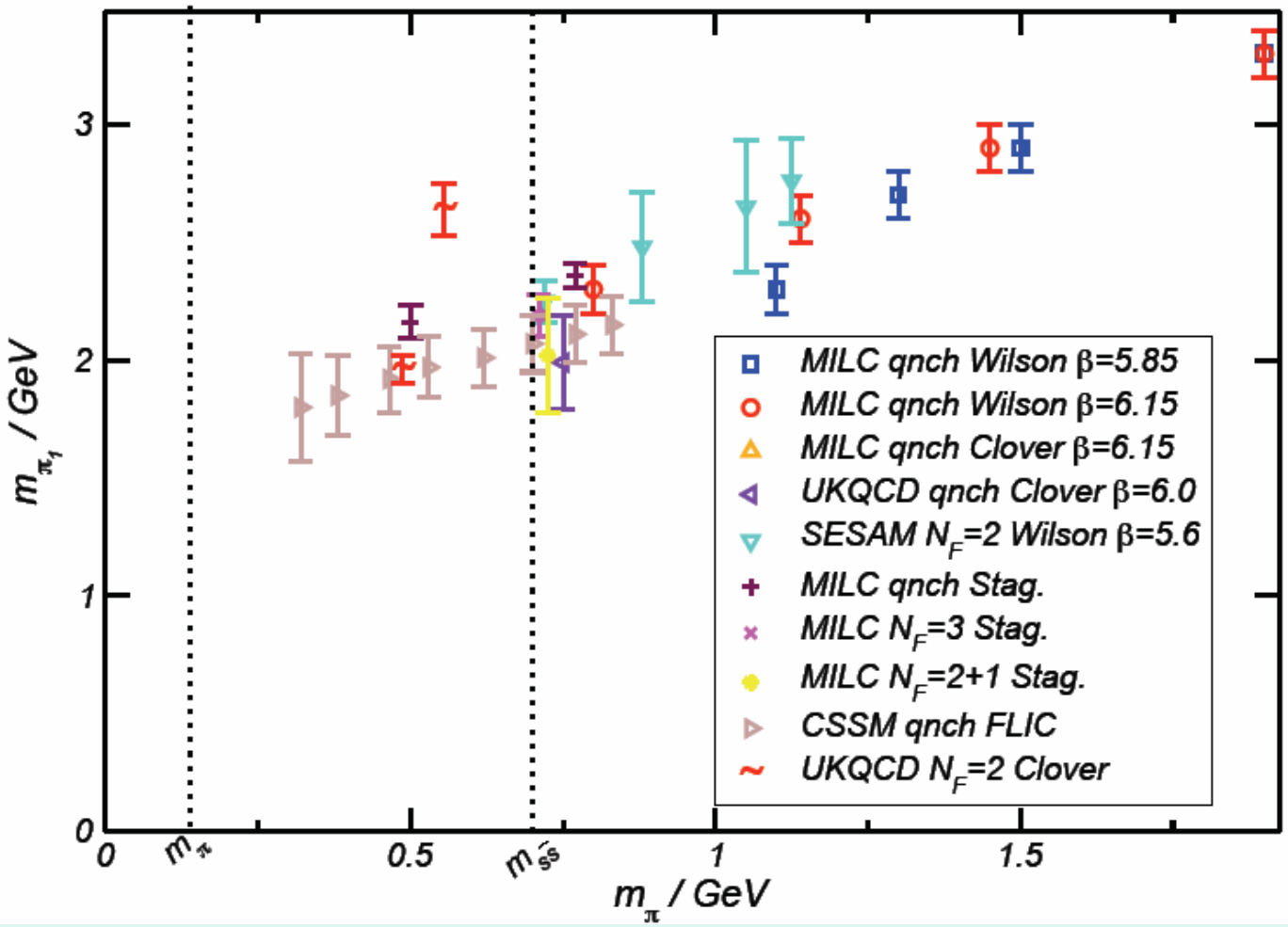
[12–14]

[26–28]

[23]

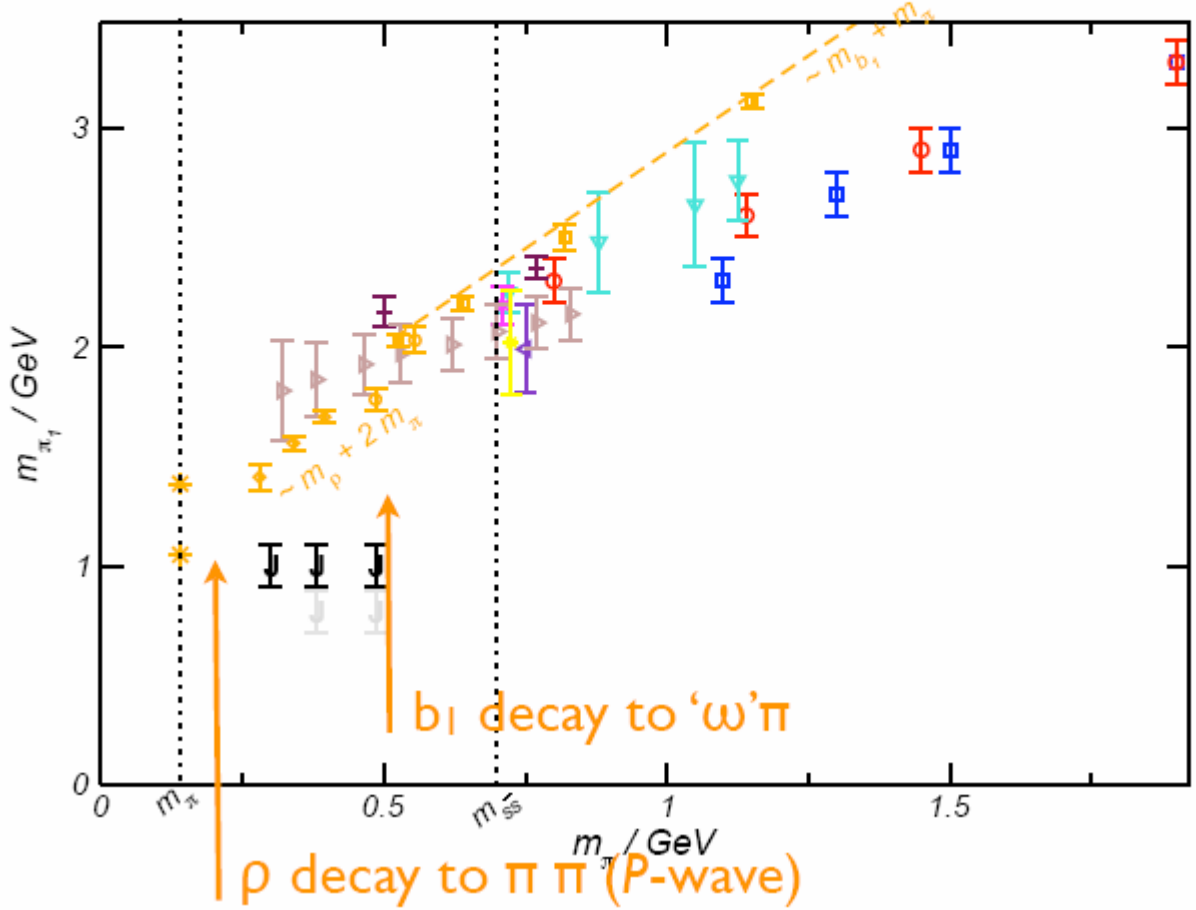
CSSM '05

Hedditch et al.



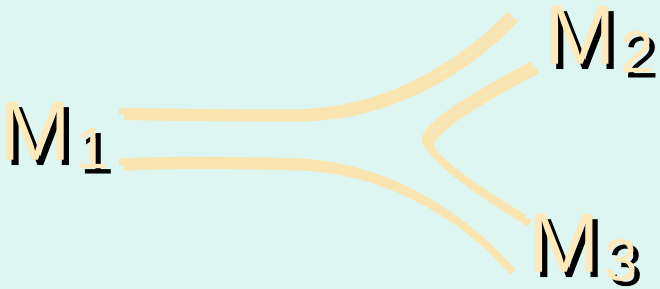
lightest 1^{-+} ?

★ multi-hadron states lightest at low pion mass

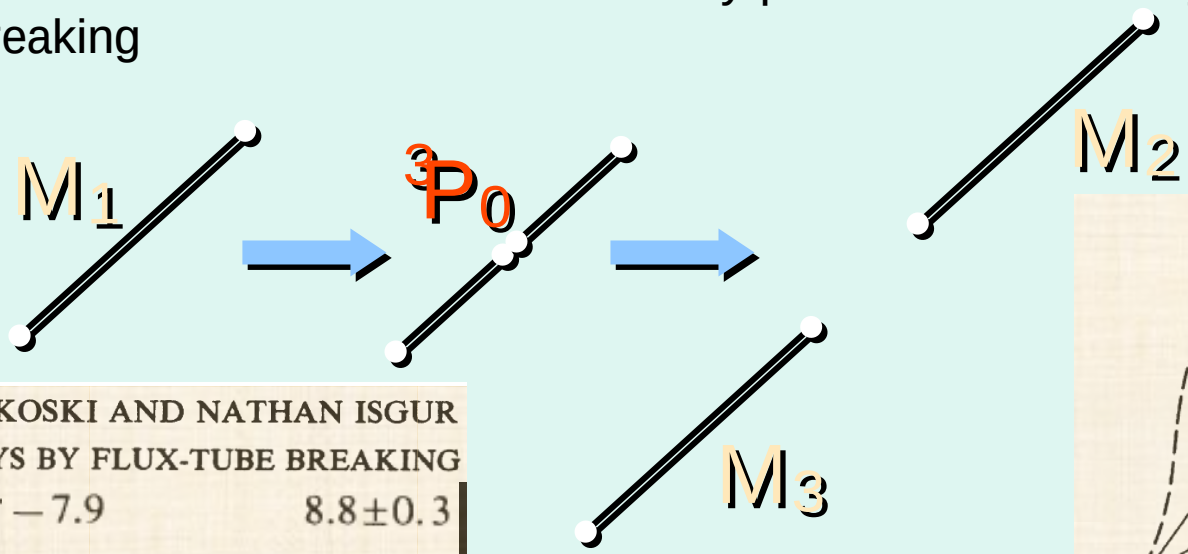


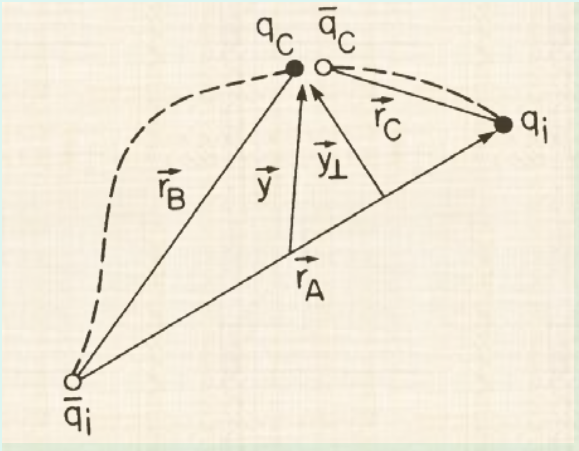
Decays in the Flux-Tube model

- there is a reasonably successful model of conventional meson decays called $^3P_0$ - because a $q\bar{q}$ pair is produced with these quantum numbers



- within the flux-tube model this decay process is realised by flux-tube breaking





RICHARD KOKOSKI AND NATHAN ISGUR
MESON DECAYS BY FLUX-TUBE BREAKING

$A_2 \to (\pi\pi)_\rho \pi$	-7.9	8.8 ± 0.3
$A_2 \to \eta\pi$	$+4.1$	4.0 ± 0.1
$A_2 \to K\bar{K}$	-2.8	2.3 ± 0.1

Hybrid Decays

- the same model can be applied to hybrids – the only difference is that the initial state has a tube phonon excited
- the angular momentum carried by the phonon has to go into the two-meson end state
  - leads to a selection rule that hybrids will not decay to a pair of *S* - wave mesons

    e.g. $\mathcal{H} \not\to 1/2\, 1/2$ $\mathcal{H} \not\to 1/2\, 1/2$ $\mathcal{H} \not\to 1/2\, 1/2$
  - the dominant decays are found to be to *S* + *P* e.g. $\mathcal{H} \to 1/2\, 1$
- this hierarchy of decays has become the "folklore" of the hybrid hunters

F.E. Close, P.R. Page/Nuclear Physics B 443 (1995) 233–254

$$\pi f_1 : \pi b_1 : \pi\rho : \eta\pi : \eta'\pi = 60 : 170 : 5 - 20 : 0 - 10 : 0 - 10$$

hybrid decay?

	FTM Ref [?] 1.9GeV	FTM Ref[?] 2.0 GeV	Lattice Ref [?] 2.0 GeV
$\Gamma(\pi_1 \to b_1\pi)_S$	100	70	400 ± 120
$\Gamma(\pi_1 \to b_1\pi)_D$	30	30	
$\Gamma(\pi_1 \to f_1\pi)_S$	30	20	90 ± 60
$\Gamma(\pi_1 \to f_1\pi)_D$	20	25	

TABLE I: Comparison of flux tube and lattice predictions for π_1 decays.

hybrid decay?

	FTM Ref [?] 1.9GeV	FTM Ref[?] 2.0 GeV	Lattice Ref [?] 2.0 GeV
$\Gamma(\pi_1 \to b_1\pi)_S$	100	70	400 ± 120
$\Gamma(\pi_1 \to b_1\pi)_D$	30	30	
$\Gamma(\pi_1 \to f_1\pi)_S$	30	20	90 ± 60
$\Gamma(\pi_1 \to f_1\pi)_D$	20	25	

TABLE I: Comparison of flux tube and lattice predictions for π_1 decays.

$$\begin{aligned}
\langle \omega\pi|\sigma\cdot\nabla|b_1\rangle &= S(k) \\
\langle b_1\pi|\sigma\cdot\nabla|\pi_1\rangle &= \sqrt{2}\frac{\kappa\sqrt{b}}{\beta}S(k) \\
\langle f_1\pi|\sigma\cdot\nabla|\pi_1\rangle &= \frac{1}{\sqrt{2}}\frac{\kappa\sqrt{b}}{\beta}S(k)
\end{aligned}$$

$$\frac{\Gamma(\pi_1 \to b_1\pi)}{\Gamma(\pi_1 \to f_1\pi)} = 4$$

	$b_1 \to \omega\pi$	$\pi_1 \to b_1\pi$	$\pi_1 \to f_1\pi$
Lattice (C410)	2.3 ± 0.1	2.9 ± 0.4	1.5 ± 0.4
Lattice (U355)	3.4 ± 0.2	2.9 ± 0.3	1.1 ± 0.4
Flux tube (A)	2.7	2.9	1.4
Flux tube (B)	3.3	3.9	1.9

Transition amplitudes $\langle BC|\sigma \cdot \nabla|A\rangle$ and $\langle BC|\text{latt}|A\rangle$ in units of $\text{GeV}^{-1/2}$.

(A) $\gamma_0 = 0.39, \beta = 0.40, \kappa = 0.7$
(B) $\gamma_0 = 0.45, \beta = 0.36, \kappa = 0.7$

photoproduction of hybrids

- photoproduction has a limited history as a means of obtaining spectroscopic information – so GlueX will be rather novel

- there's a handwaving argument that photo-production is preferrable to pion hadro-production

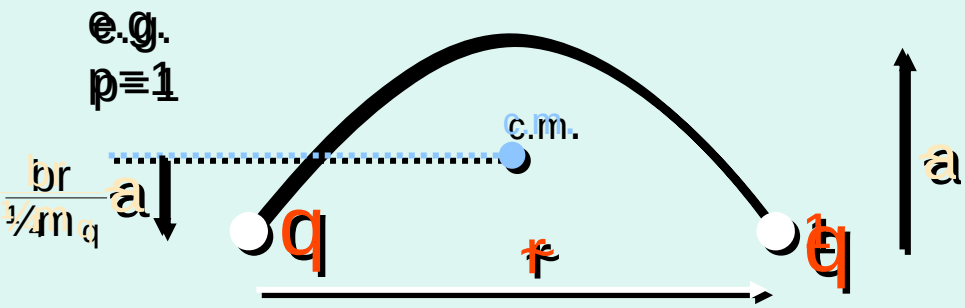
  - in most sensible models the exotic $1^{i\ +}$ hybrid has its quarks in a spin-triplet state

  - an incident pion can be viewed as having a spin-singlet quark pair

  - the 'glancing blow' dealt to the pion in a diffractive process isn't able to both 'pluck' the flux-tube and flip the spin and hence a hybrid is not excited

  - a photon can act like a virtual rho meson with has a spin-triplet quark pair and hence only tube excitation is required – should be easier to excite a hybrid in photoproduction

flux-tube degrees-of-freedom



★ a_p are new degrees-of-freedom, *not present in the quark model*.

Isgur showed that they have measurable effects on conventional states

Close Dudek: E1 excitation of hybrids = r^2 meson: Cabibbo Radicatti

(Lattice only now beginning to look at this)

Costs about 1 to 1.5GeV energy to excite phonon "pi/R"
Hybrid nn* @ 2GeV; Hybrid cc* @ 4-4.5GeV

“Leading” expt. candidates for hybrid mesons (exotic and nonexotic)

state	reported in
$\square_1(1400)$	$\sim$ $\square$
$\square_1(1600)$	$\square$ $\square$ $\sim'$ $\square$ $f_{\square}$ $\square$ $b_{\square}$ $\square$
$\square_1(2000)$	$f_{\square}$ $\square$ $b_{\square}$ $\square$

$\square_2$ and $\sim_2$ overpopulation (nonexotic)

others discussed include higher-mass $\square$ and $\square$ overpopulation

If you can decode this slide, you can find hybrids

….hybrid charmonium sighting?