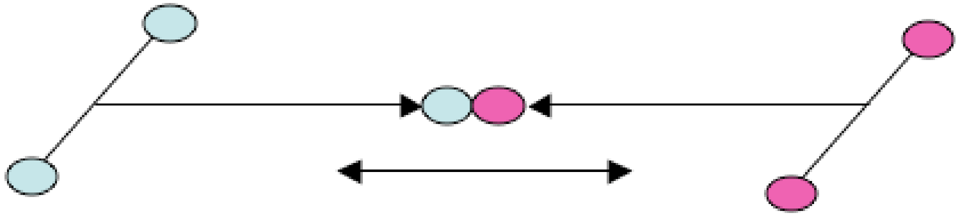
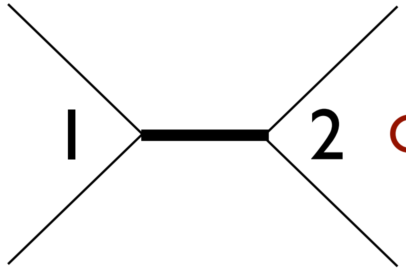


4-quark mesons

A.D. Polosa
Bari U.

in collaboration with L.Maiani, F. Piccinini, V. Riquer



Color interaction $\propto \sum_a T^a_{(1)} T^a_{(2)}$

$$T^a_{(1)} T^a_{(2)} = \frac{1}{2}\left(T^{a2} - T^{a\;2}_{(1)} - T^{a\;2}_{(2)}\right)$$

The Casimir gives the ‘size’ of the color representation.
The color force is most attractive in the least colorful states.

$$\langle T^a_{(1)} T^a_{(2)} \rangle = \begin{cases} -2/3 \text{ in } \bar{\mathbf{3}} & -4/3 \text{ in } \mathbf{1} \\ 1/3 \text{ in } \mathbf{6} & 1/6 \text{ in } \mathbf{8} \end{cases}$$

$$\langle\ \rangle = \frac{1}{\dim D_R}\mathrm{Sp}(\ )$$

qq $\qquad$ q$\bar{\text{q}}$

$$\langle \sigma_{(1)} T^a_{(1)} \cdot \sigma_{(2)} T^a_{(2)} \rangle \propto \left(J(J+1) - \frac{3}{2}\right) \quad \begin{matrix} \frac{1}{2} \otimes \frac{1}{2} \to 0 \\ \frac{1}{2} \otimes \frac{1}{2} \to 1 \end{matrix}$$

Baryons in the octet:

Λ=([ud] $_{J=0}$ s); Σ^0 =({ud}$_{J=1}$s)→ Λ is lighter than Σ

With antisymmetry in color and spin and a common spatial configuration, Fermi statistics $\Rightarrow\ \bar{\mathbf{3}}_{\mathbf{f}}$

Good diquarks: $[qq]_{\bar{\mathbf{3}}_{\mathbf{c}},\mathbf{1}_{\mathbf{s}},\bar{\mathbf{3}}_{\mathbf{f}}}$

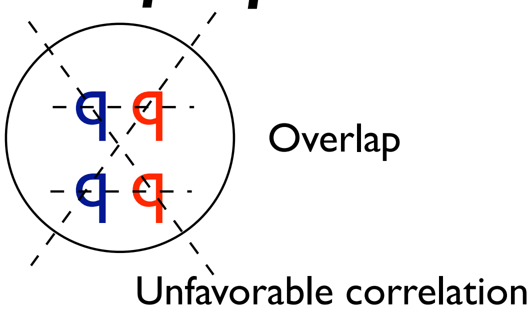
Bad diquarks: $(qq)_{\bar{\mathbf{3}}_{\mathbf{c}},\mathbf{3}_{\mathbf{s}},\mathbf{6}_{\mathbf{f}}}$

Since spin interaction is a relativistic effect we might expect it stronger for the lightest quarks....

$$\text{Splitting}:\ (ud)-[ud] > (us)-[us] > \underline{(uc)-[uc]\approx 0}$$

HQ Spin Symmetry

Repulsion of diquarks



Reluctant to fuse in baryon+quark

QCD: low energy qqbar pairs and gluons are omnipresent; hadrons contain an *indefinite number of soft particles*.

Quark Model: built upon *degrees of freedom* whose properties are modeled on the fundamental theory.

⇩

Working assumptions: Mesons (qqbar), Baryons (qqq)

Are there additional structures in the hadron spectrum?

Why not?
If yes, where?
If yes, why so few?

A way of creating **few** *exotica* is with *good diquarks pairs*: because of their antisymmetry they lock up flavor and color and because of their mutual repulsion they forbid mergers; **few** with respect to predictions from independent-particle models.

N.B. The diquark picture for constructing four-quark states is different from the original one:

$$O(x) = q_i\bar{q}^i q_j\bar{q}^j(x)$$

Gauge invariant four-quark operator

but

$$\langle O(x)O(y)\rangle \sim \langle q\bar{q}(x)q\bar{q}(y)\rangle^2$$

Two freely propagating mesons at leading 1/N

No interaction is required to dissociate to light mesons: 'fall apart decay'

⇩

Very broad or non-resonant states.

Cryptoexotics: [qq][qbqb] can explain for example the *non exotic structure of the light scalar meson nonet*.
Indeed for flavor one has:

$$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$$

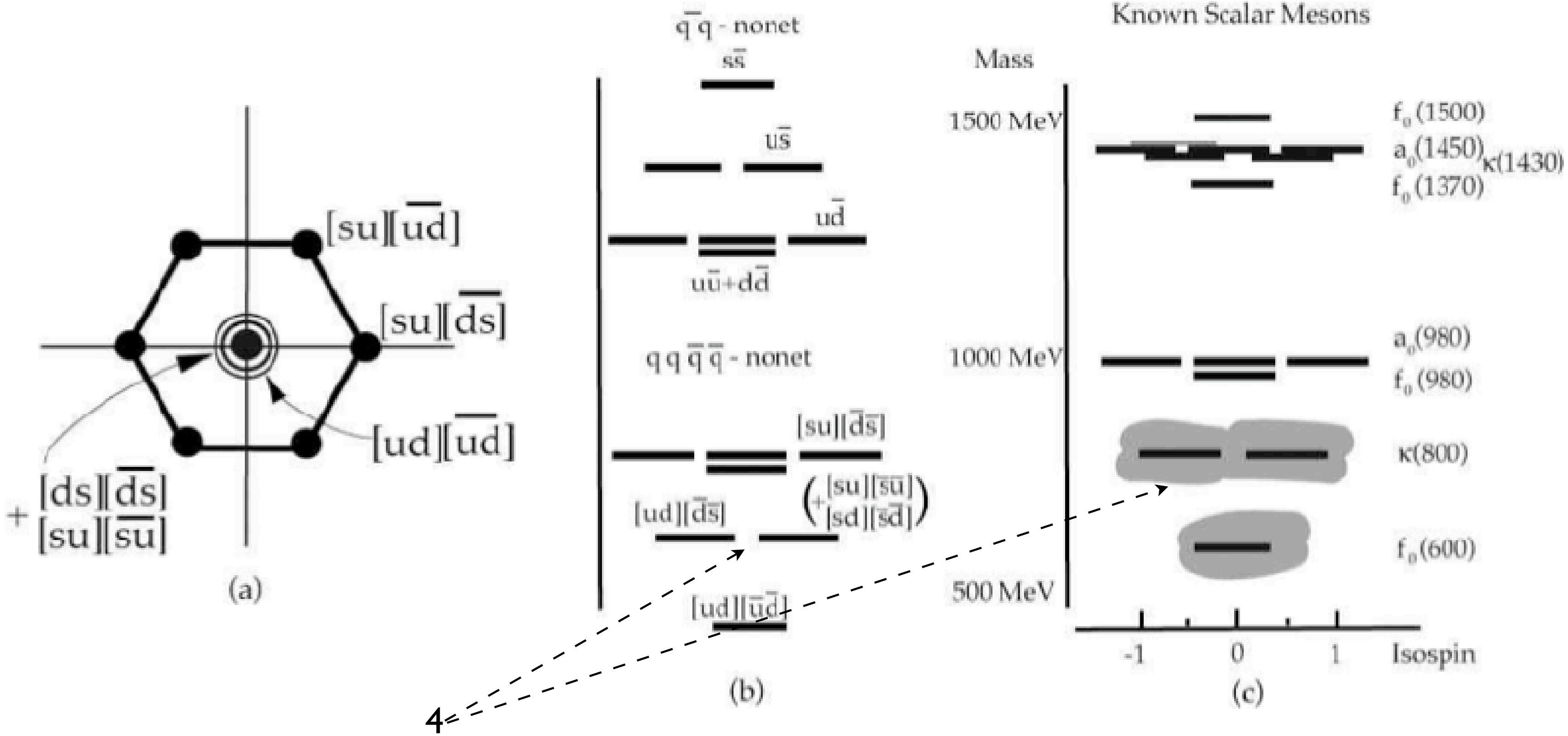
with the same charges as for qqb

A pure exotic particle, like uuddss (Jaffe's H), was predicted in the bag model to be possibly even below Λn threshold, i.e. stable even against lowest order weak interactions.

Good diquark correlations + diquark repulsion suggest a reason why the independent particle approach fails.

See recent papers by Jaffe & Wilczek

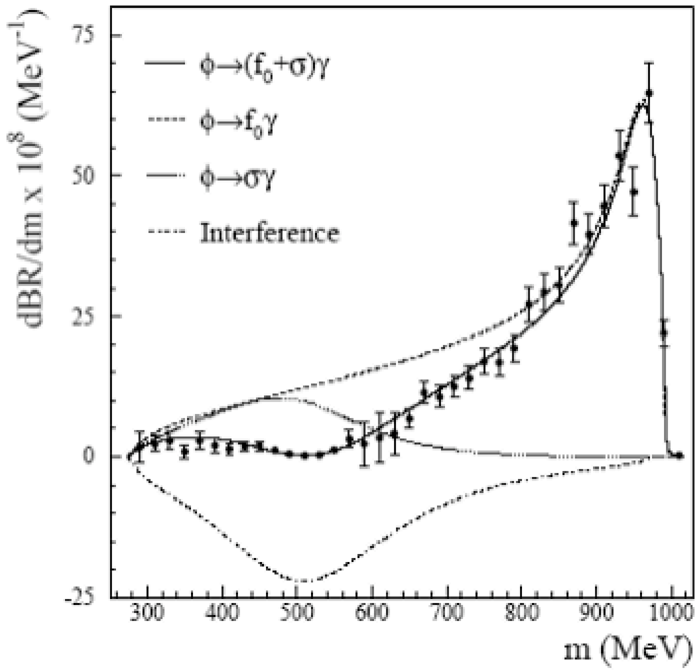
Light scalar mesons



$$I_3 = \frac{1}{2}(n_u - n_d)$$

$$Y = \frac{1}{3}(n_u + n_d - 2n_s)$$

see e.g. R. L. Jaffe hep-ph/0409065,
L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, hep-ph/0407017
To appear in Phys. Rev Lett.



$\phi(1020)\rightarrow\pi^0\pi^0\gamma$

Study of the Decay $\phi(1020)\rightarrow\pi^0\pi^0\gamma$ with the KLOE Detector
The KLOE Collaboration
arXiv:hep-ex/0204013 Apr 2002

Fit results using f_0 only, Fit (A), and including the σ, Fit (B).

	Fit (A)	Fit (B)
χ^2/ndf	109.53/34	43.15/33
M_{f_0} (MeV)	962 ± 4	973 ± 1
$g^2_{f_0 K^+K^-}/(4\pi)$ (GeV^2)	1.29 ± 0.14	2.79 ± 0.12
$g^2_{f_0 K^+K^-}/g^2_{f_0\pi^+\pi^-}$	3.22 ± 0.29	4.00 ± 0.14
$g_{\phi\sigma\gamma}$	—	0.060 ± 0.008

Sigma parameters from E791

$M_\sigma = (478^{+24}_{-23} \pm 17)$ MeV

$\Gamma_\sigma = (324^{+42}_{-40} \pm 21)$ MeV

E791-PRL86(2000) claims that almost the 46% of

$$D \to 3\pi$$

could resonate on a *scalar bump* with

$$m_\sigma = 478 \pm 24 \ MeV$$

$$\Gamma_\sigma = 324 \pm 41 \ MeV$$

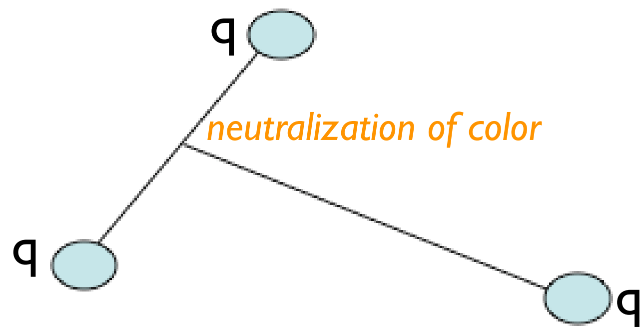
Has this something to do with the pole on the second sheet of the isoscalar S-wave in ππ scattering found, e.g., by Colangelo-Gasser-Leutwyler NPB603(2001) and many others?

$$\sqrt{s} = (479 \pm 30) - i(295 \pm 20)$$

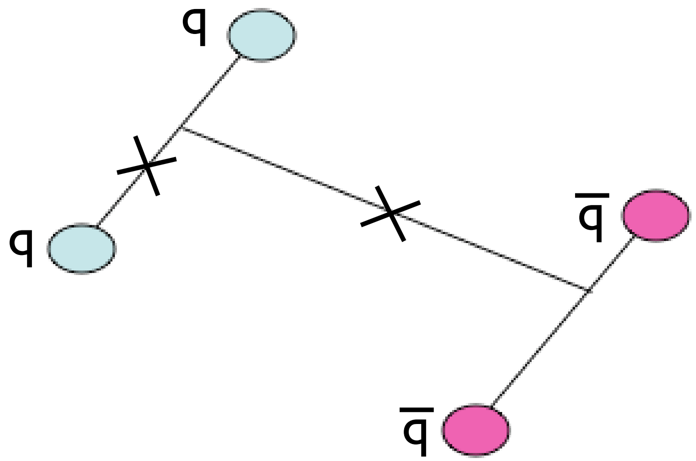
Their reply is '*there is no harm in calling this an unusually broad resonance...*'. Is it a broad enhancement whose dynamical origin is in the strong pionic FSI for these quantum numbers?

E791 made the data analysis describing this scalar bump as a *Breit-Wigner resonance!*

Diquark needs to combine with other color objects



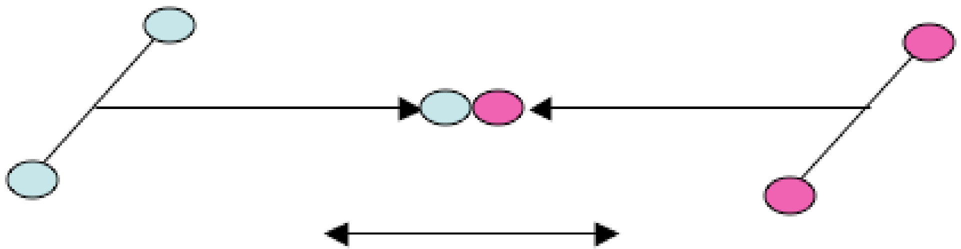
T-shape: baryon



Vacuum restricts to a *one-dimensional-string*
the color line of force from each quark

H-shape: scalar meson (?)

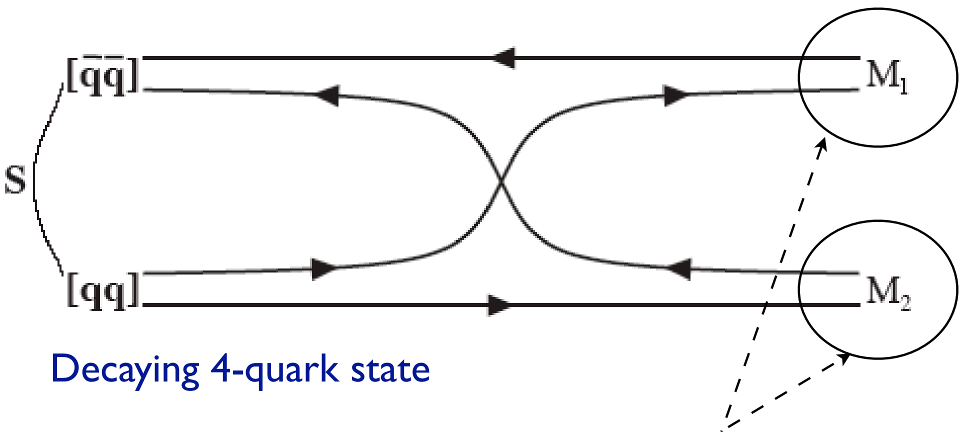
Stretching the string which keeps together the H shape
seems to excite a baryon-baryon pair...rather than a meson-meson pair



((Meson-Meson molecules: do residual forces bind?))

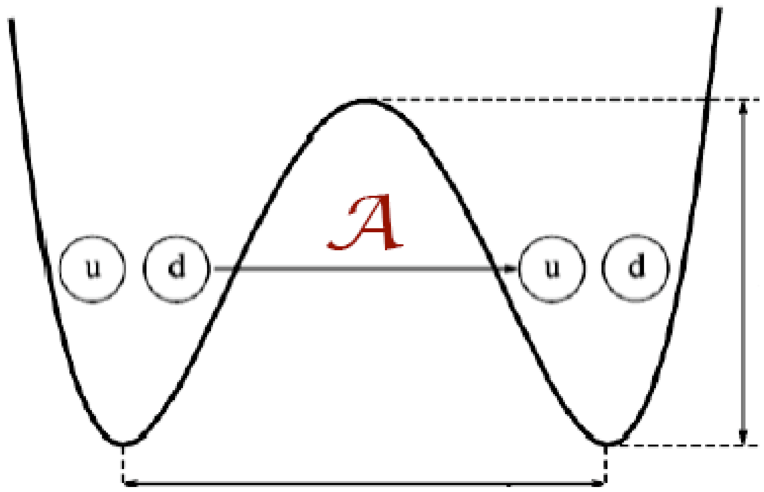
For the lightest scalar mesons the latter decay channels are forbidden

The rearrangement goes through a *barrier*, but at least is not so energetically expensive as producing a baryon-baryon pair!



Decaying 4-quark state

Color Singlet Mesons



$$\mathcal{L} = \mathcal{A} \cdot (S_i^j \varepsilon_{jlm} \varepsilon^{ikn} M_k^l M_n^m)$$ *No derivative coupling*

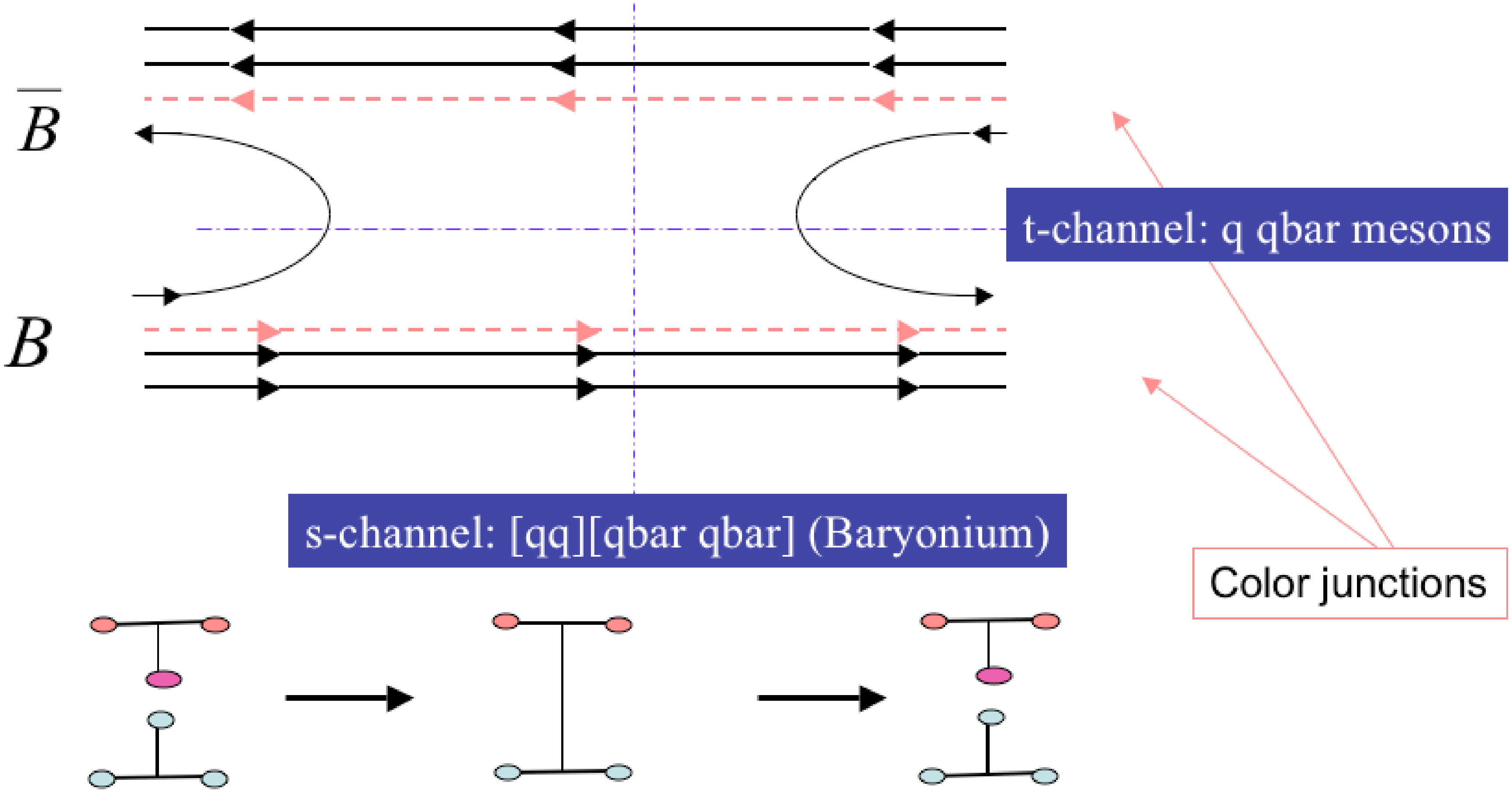
$$\Gamma(S \to i) = \frac{\mathcal{A}}{8\pi} \frac{p}{M_S^2} x_{S \to i}$$

p: the decaying momentum

M_S: the mass of the decaying scalar meson

x: numerical coefficients and Isospin amplitudes.

Baryon-Baryon scattering & Harari-Rosner duality

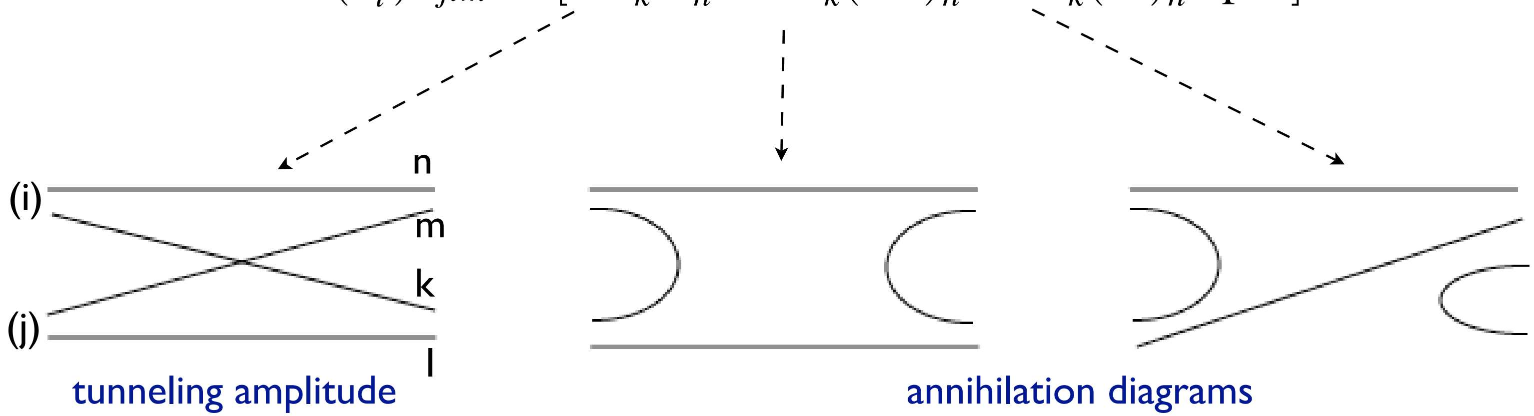


[qq][qbar qbar] mesons are dual to q qbar mesons in B-Bbar scattering. The relation to B-Bar persists in decays!!

Rossi&Veneziano, Nucl. Phys. **B127**, (1977) 507

The full SU_3 Lagrangian has three couplings

$$\mathcal{L}=(S_i^j)\varepsilon_{jlm}\varepsilon^{ikn}[aM_k^l M_n^m + b\delta_k^l (M^2)_n^m + c\delta_k^l (M)_n^m \mathrm{Sp}M]$$



The scalar mesons are defined by:

$$a^0(I=1,I_3=0)=\frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}]-[sd][\bar{s}\bar{d}]\right)$$
$$f_\circ(I=0)=\frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}]+[sd][\bar{s}\bar{d}]\right)$$
$$\sigma_\circ(I=0)=[ud][\bar{u}\bar{d}]$$
$$\kappa=[ud][\bar{s}\bar{d}],$$

where
$$\begin{cases} |f\rangle=\cos\phi|f_\circ\rangle+\sin\phi|\sigma_\circ\rangle \\ |\sigma\rangle=-\sin\phi|f_\circ\rangle+\cos\phi|\sigma_\circ\rangle. \end{cases}$$

Masses

Define S as the *nonet scalar meson* matrix:

$$S = \begin{pmatrix} \frac{f_\circ + a^0}{\sqrt{2}} & a^+ & \kappa^+ \\ a^- & \frac{f_\circ - a^0}{\sqrt{2}} & \kappa^0 \\ \kappa^- & \kappa^0 & \sigma_\circ \end{pmatrix}$$

Assuming octet symmetry breaking, masses depend on four parameters (we use squared masses):

$$M^2 = \frac{1}{2}\left\{ \mathrm{Sp}(S^2 m) + \sqrt{3} c\, \mathrm{Sp}(S\lambda_8)\mathrm{Sp}S + \frac{3}{2} d [\mathrm{Sp}(S\lambda_0)]^2 \right\}$$

$$m = \begin{pmatrix} \alpha & & \\ & \alpha & \\ & & \beta \end{pmatrix}$$

diquark masses
squared

α, β, c, d unknown coefficients

4 parameters, 4 masses(scalars), 1 mixing and an overall relation:

$$\cos 2\phi + 2\sqrt{2} \sin 2\phi = 1 + 4 \frac{a + \sigma - 2\kappa}{a - \sigma}.$$

squared

f_0 and a_0 degenerate

Meson	Mass (MeV)	Source
σ	$478 \pm 24 \pm 17$	[7]
κ	$797 \pm 19 \pm 43$	E791 [8]
f	980 ± 10	PDG [2]
a	984.7 ± 1.2	PDG [2]

Using the previous relation and exp. data:

$$\tan 2\phi = -0.07, \qquad \sigma = (570\text{MeV})^2,$$
$$\tan 2\phi = -0.19, \qquad \sigma = (470\text{MeV})^2,$$
$$\tan 2\phi = -0.31, \qquad \sigma = (370\text{MeV})^2.$$

-Almost ideal mixing

-$\alpha-\beta$ = 230 MeV vs m_s = 150 MeV

-Linear mass formula gives very similar results

Since we are holding *f* degenerate with *a*, the σ mass is pushed down as mixing becomes more negative being zero for tan(2ϕ)=-0.48. Mixing is small because OZI rule is respected in the physical mass spectrum.

Decays

The value of $\mathcal{A}$

$$\mathrm{Amp}(a^+ \to \bar{K}^0 K^+) = \mathcal{A};$$

$$\mathrm{Amp}(a^+ \to \pi^+\eta) = \mathcal{A}\left(-\sqrt{\frac{2}{3}}\cos\phi + \sqrt{\frac{1}{3}}\sin\phi\right) \simeq -0.69\mathcal{A}.$$

$\mathcal{A}$=2.6 GeV

$\Gamma_{tot}(a_0) = 72 \pm 16$ MeV and the KK branching ratio $\mathcal{B}(a_0 \to K\bar{K}) = 0.17 \pm 0.03$ thus obtaining:

$$\Gamma(a_0 \to \eta\pi) = 60 \pm 13 \ \ \mathrm{MeV}, \qquad (14)$$

$$\Gamma(a_0 \to K\bar{K}) = 12 \pm 3 \ \ \mathrm{MeV}. \qquad (15)$$

2. We compute the decay momentum with the central values of the parent mass, with the exception of the decay $a \to K\bar{K}$, which is below threshold at the central mass value. In this case we have averaged the decay momentum over a Breit-Wigner, using the $\Gamma_{tot}(a)$ given above, and find: $\langle p(a \to K\bar{K})\rangle \approx 84$ MeV, which gives the value of the partial width reported in Table II.

3. In the case of $f \to K\bar{K}$ or $\pi\pi$, the authors of ref. [11] define:

$$\Gamma(S \to i) = g_i p(M) \qquad (16)$$

and fit the data to a Breit-Wigner formula with mass-dependent width, thus giving directly the values of g_i

can we improve on these values?

Widths

	$\pi\pi$		$K\bar{K}$	
σ	345 MeV	324 ± 50 MeV		...
f	$g_\pi < 0.02$	$g_\pi = 0.19 \pm 0.05$	$g_K = 0.28$	$g_K = 0.40 \pm 0.6$
	$\eta\pi$			
a	43 MeV	60 ± 13 MeV	23 MeV	12 ± 3 MeV
	$K\pi$			
κ	138 MeV	410 ± 100 MeV		...

L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, PRL

Putting in the other 2 SU_3 couplings

$$
\begin{aligned}
\mathcal{L} = f_\circ & \left[b\sqrt{2}\frac{\pi\cdot\pi}{2} - (a-3b)\frac{\bar{K}K}{\sqrt{2}} + \ldots \right] \\
& + \sigma_\circ \left[-(a-2b)\frac{\pi\cdot\pi}{2} + b\bar{K}K + \ldots \right] \\
& + a^0 \left[(a-b)\frac{\bar{K}\tau_3 K}{\sqrt{2}} - (a-c)\eta_s\pi^0 \right. \\
& \left. - \sqrt{2}(b-c)\eta_q\pi^0 + \ldots \right] \\
& + (a-b)\left(\frac{\bar{K^+}\pi^0}{\sqrt{2}} + \bar{K}^0\pi^- \right)\kappa^+ + \ldots
\end{aligned}
$$

we get:

$$
\begin{aligned}
|a-2b| &= 2.6 \ \text{GeV} \ (\text{from} \ \sigma \to \pi\pi), \\
|a-3b| &= 3.1 \ \text{GeV} \ (\text{from} \ f_0 \to K\bar{K}), \\
|a-b| &= 1.8 \ \text{GeV} \ (\text{from} \ a_0 \to K\bar{K}),
\end{aligned}
$$

equally spaced allowing a *b*=-0.7 GeV!

We find further g_π=0.06; still too low

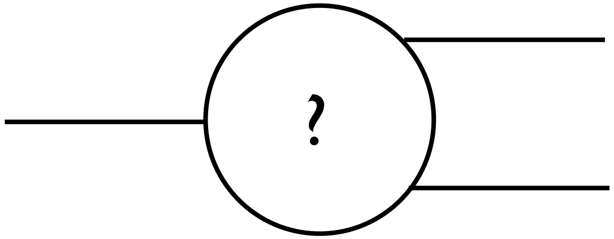
The annihilation contribution *c* should be small. With *c*=0 we get a rate for $a \to \eta\pi$ =30 MeV vs. 60±13

The weak point is fππ

Maybe it comes from 1-loop contributions

$$f \longrightarrow K\bar{K} \longrightarrow \pi\pi$$

$$f \longrightarrow B\bar{B} \longrightarrow \pi\pi \quad \textbf{new}$$



Overall we get quite a consistent picture, reconciles σ with a and f widths, reinforces [qq][qbar qbar] assignement

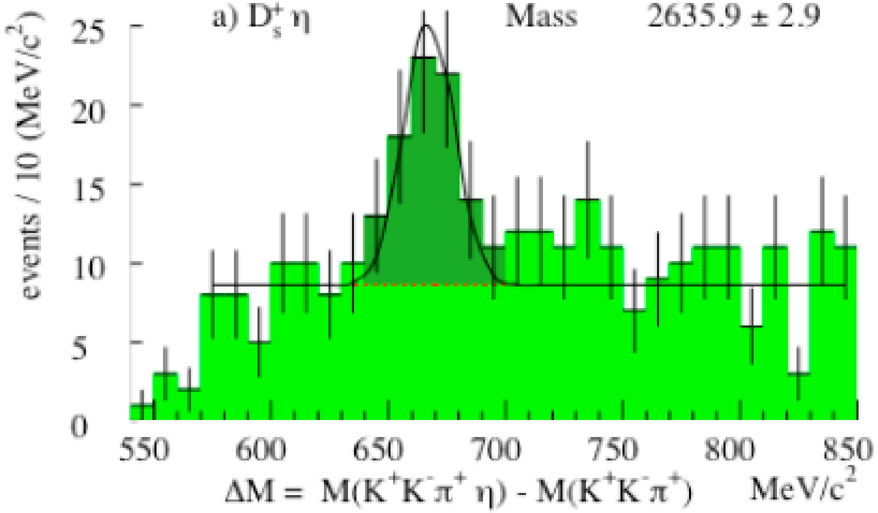
- Masses
- Ideal mixing
- Decays reasonably described (exact SU3!)
- Annihilation amplitudes are small
- Note: Δm(f-a)~10MeV, Δm(up-down) ~5MeV: are f/a I-spin eigenstates?

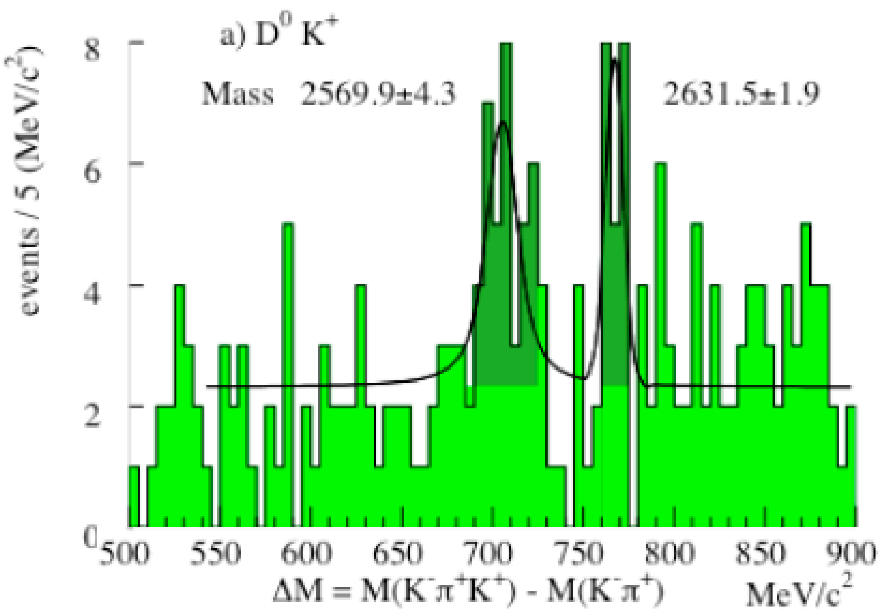
SELEX-Fermilab

hep-ex/0406045

'SELEX reports these peaks as the first observation of yet another high mass Ds state decaying strongly to a ground state charm plus a pseudoscalar meson. The mechanism which keeps this state narrow is unclear[...] The $D_s\eta$ decay rate dominates the D^0K^+ by a factor of ~6 despite having half the phase space.'

$D_{sj}(2632)$ (?)





HQET multiplets (Qqbar) / light dof	$(0^-,1^-)$	$(0^+,1^+)$	$(1^+,2^+)$
q=u,d	(D,D^*)	(D_0^*,D_1) broad	(D_1,D_2^*) narrow
q=s	(D_s,D_s^*)	$D_s^*(2317)$ $D_s(2460)$	(D_{s1},D_{s2}^*) narrow

BaBar `03

Likely the missing (csbar) states.
Very narrow.

The 0^+(csbar) state decays to $D_s\pi^0$ violating isospin because it is below (~40 MeV) threshold for DK decay. Relativistic potential models were predicting these states higher in mass $\Rightarrow$ broader.

Fayyazuddin and Riazuddin, Phys. Rev. D48, (2001) 2224; reminder in [hep-ph/0309283].
A. Deandrea, R.Gatto, G. Nardulli, A.D. Polosa, N. Tornqvist, Phys. Lett. B502, (2001) 79; reminder in [hep-ph/0307069].
W. A. Bardeen, E. J. Eichten, and C. T. Hill, [hep-ph/0305049],
based on W. A. Bardeen, and C. T. Hill, Phys. Rev. D49, (1994) 409.
for a review S. Stone, hep-ph/0310153

III. QUARK MODEL $c\bar{s}$ INTERPRETATION

As stated in the introduction, the only plausible $c\bar{s}$ assignment for the $D^+_{sJ}(2632)$ is $n^{(2S+1)}L_J = 2^3S_1$, which has a predicted mass in the Godfrey-Isgur model of 2730 MeV. Allowed open-flavor decay modes for this state, assuming the SELEX mass of 2632 MeV, are DK, $D_s\eta$ and D^*K. The first two modes have two 1S pseudoscalars in the final state, and hence are related by flavor matrix elements. This relation is $\mathcal{A}(D_s^+\eta) = \sin\theta\, \mathcal{A}(D^0K^+)$, where $\mathcal{A}$ is a strong decay amplitude and $\sin\theta \approx -1/\sqrt{2}$ is the amplitude of the $s\bar{s}$ component of the η. Assuming the $^3P_0$ decay model and identical D and D^* spatial wavefunctions, the decay amplitude to D^*K is also proportional to the same function, $\mathcal{A}(D^*K) = -\sqrt{2}\,\mathcal{A}(DK)$. Thus, one expects *reduced* relative strong decay widths (summed over charge modes, but divided by the momentum-dependent decay amplitude squared) of $D^*K : DK : D_s\eta = 4 : 2 : 1$.

As a simple initial estimate of physical branching fractions, since these are all P-wave decays we may assume a p_f^3 threshold dependence for all modes, which gives expected relative branching fractions (again summed over all charge modes) of

$$\text{B.F.}\ (D^*K : DK : D_s\eta) = 4.2 : 7.0 : 1\ . \qquad (4)$$

This is clearly in disagreement with the SELEX result (assuming equal D^0K^+ and D^+K^0 modes) of

$$\text{B.F.}\ (DK : D_s\eta) = 0.32 \pm 0.12 : 1\ . \qquad (5)$$

Options for the SELEX state $D^+_{sJ}(2632)$

T.Barnes*,[1] F.E. Close†,[2] J.J.Dudek‡,[2] S.Godfrey§,[3] and E.S.Swanson¶[4]

hep-ph/0407120

Open and hidden charm scalar mesons

L. Maiani, F. Piccinini, A.D. Polosa and V. Riquer, PRD, hep-ph/0407025

$$O = [cq][\bar{q}\bar{q}] \quad (3 \times 3 = 6 + \bar{3})$$
$$H = [cq][\bar{c}\bar{q}] \quad (3 \times \bar{3} = 8 + 1)$$

$$[\;]_{\bar{3}_f, \bar{3}_c, 0_s}$$

T^2_a=4/3 in $\bar{\mathbf{3}}$ vs. 10/3 in **6**

R.L. Jaffe and F. Wilczeck, Phys.Rev.Lett. 91 (2003) 232003

$\underline{S=1} \quad a_{c\bar{s}}(I=1);\ f_{c\bar{s}}(I=0) \quad [cq][\bar{q}\bar{s}]$

$$I = 0,1 \begin{cases} [cu][\bar{d}\bar{s}] & Q=2 \quad I_3=1 \\ [cu][\bar{u}\bar{s}] & Q=1 \quad I_3=0 \\ [cd][\bar{d}\bar{s}] & Q=1 \quad I_3=0 \\ [cd][\bar{u}\bar{s}] & Q=0 \quad I_3=-1 \end{cases}$$

$$a^+_{c\bar{s}} = \frac{[cu][\bar{u}\bar{s}] - [cd][\bar{d}\bar{s}]}{\sqrt{2}}$$
$$f^+_{c\bar{s}} = \frac{[cu][\bar{u}\bar{s}] + [cd][\bar{d}\bar{s}]}{\sqrt{2}}$$

$$a^+_{c\bar{s}} \longrightarrow D^+_s\pi^0, (DK)_{I=1,I_3=0}$$
$$f^+_{c\bar{s}} \longrightarrow D^+_s\eta, (DK)_{I=0}$$

Isospin conserving pattern:
Isospin eigenstates = Mass eigenstates

But DK looks suppressed with respect to $D_s\eta$

Mixing of a+ and f+ could lead to decays of the mass eigenstates that ***do not*** respect the ***isospin symmetric pattern***

Assume that ***mass eigenstates*** are superpositions of

OZI conserving

$$|S_u\rangle = [cu][\bar{u}\bar{s}]$$
$$|S_d\rangle = [cd][\bar{d}\bar{s}]$$

in such a way that

$$|D_h\rangle = \cos\theta|S_u\rangle + \sin\theta|S_d\rangle$$
$$|D_l\rangle = -\sin\theta|S_u\rangle + \cos\theta|S_d\rangle$$

and

$$a^+ \equiv |D_h\rangle^{\theta=-\pi/4}$$
$$f^+ \equiv |D_l\rangle^{\theta=-\pi/4}$$

Isospin eigenstates

Why I-mixing?

Mass eigenvalues are determined by the balance of two matrices:

(In the $u\bar{u}$,$d\bar{d}$ basis)

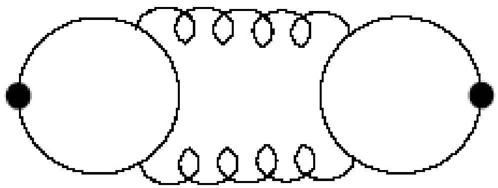
$$M_Q = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$$ (Quark Mass)

$$M_A = \delta \times \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}$$ (Annihilation)

If annihilation prevails,
eigenstates = (1,1) and (1,-1), i.e., I=0,1.
At large masses, annihilation disappears (asymptotic freedom) and
mass eigenstates align to quark mass even for u,d quarks!

For example, in the case of *pseudoscalar mesons* these terms are

$$\delta \sim g^4 \langle (F \cdot \tilde{F})^2 \rangle_{\rm YM}$$



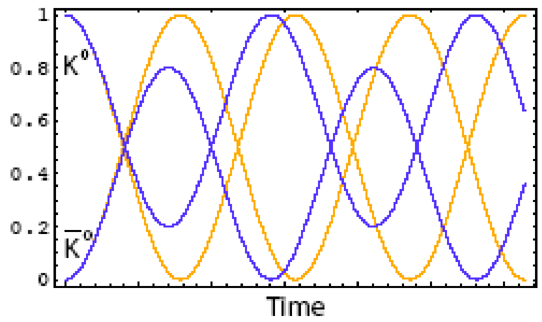
Because of the anomaly, δ is large and the mixing is

$$\phi \sim 11^\circ$$

The time development of the K0K0bar system is described by:

$$H = \begin{pmatrix} M - i\frac{\Gamma}{2} & M_{12} - i\frac{\Gamma_{12}}{2} \\ M_{12}^{*} - i\frac{\Gamma_{12}^{*}}{2} & M - i\frac{\Gamma}{2} \end{pmatrix}$$

operating on the amplitudes a(t)(b(t)) for finding K0(K0bar)



CPT

$M, \Gamma \in \mathbf{R}$

$\Gamma' s \sim G_F^2$

ΔS=2 effect$\Rightarrow \sim G_F^2$

because of GIM

A second order weak interaction is sufficient to *maximally* mix K0 and K0bar due to the *degeneracy* of the diagonal masses.

In a different context, (we think to a+ and f+), when the diagonal masses of the I=0 and I=1 states become degenerate within few MeV, comparable to the non-diagonal matrix element induced by (md-mu), one can expect large mixing of these states due to off-diagonal elements.

This mechanism has been investigated in the pentaquark context by G. Rossi and G. Veneziano, hep-ph/0404262 and PLB70, 255 (1977)

Strong decays

$$\eta_q = \underbrace{\frac{\cos\phi + \sqrt{2}\sin\phi}{\sqrt{3}}}_{X_q}\eta \quad ; \quad \eta_q = \frac{u\bar{u} + d\bar{d}}{\sqrt{2}}$$

where
$$\eta_8 = \cos\phi\,\eta - \sin\phi\,\eta'$$
$$\eta_0 = \sin\phi\,\eta + \cos\phi\,\eta'$$

We get the following decay table:

Decay mode / Decay state	$D_s^+\eta$	$D_s^+\pi^0$	D^0K^+	D^+K^0
D_h	$\mathcal{A}X_q\frac{c_\theta + s_\theta}{\sqrt{2}}$	$\mathcal{A}\frac{c_\theta - s_\theta}{\sqrt{2}}$	$-\mathcal{A}c_\theta$	$-\mathcal{A}s_\theta$
D_l	$\mathcal{A}X_q\frac{c_\theta - s_\theta}{\sqrt{2}}$	$-\mathcal{A}\frac{c_\theta + s_\theta}{\sqrt{2}}$	$\mathcal{A}s_\theta$	$-\mathcal{A}c_\theta$

$$\pi^0 = \frac{u\bar{u} - d\bar{d}}{\sqrt{2}}$$

$$[cu][\bar{u}\bar{s}] \longrightarrow (c\bar{s})(u\bar{u}) - (c\bar{u})(u\bar{s})$$
$$[cd][\bar{d}\bar{s}] \longrightarrow (c\bar{s})(d\bar{d}) - (c\bar{d})(d\bar{s})$$

Comparison with data

Define: P = probability of producing D_h
1-P = probability of producing D_l

where:

$$P = \left| A^{(I=0)} \frac{c_\theta + s_\theta}{\sqrt{2}} + A^{(I=1)} \frac{c_\theta - s_\theta}{\sqrt{2}} \right|^2$$

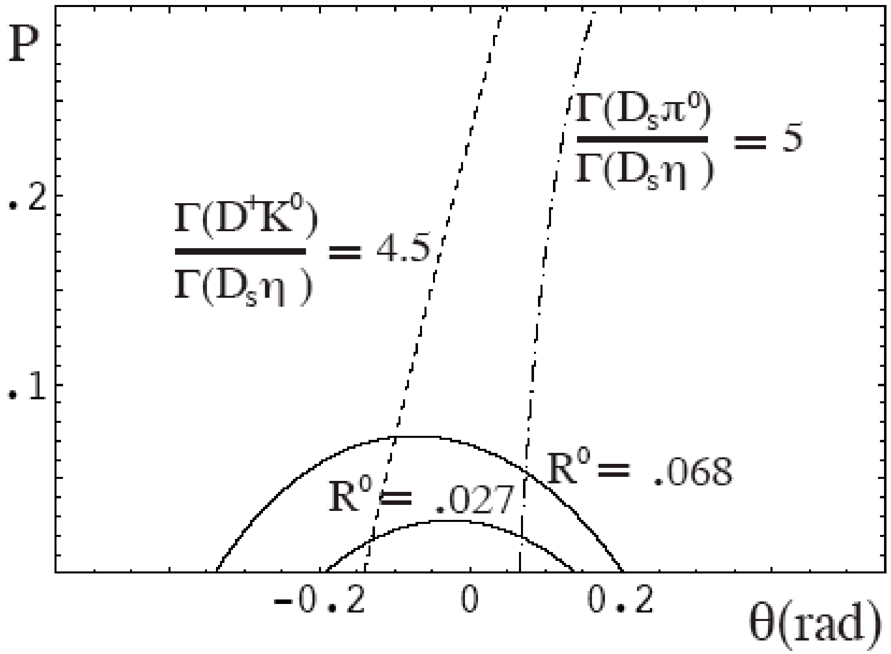
($A^{(I=0)}$ ↑ f+, $A^{(I=1)}$ ↑ a+)

$$\Gamma(X) = P\Gamma_h(X) + (1-P)\Gamma_l(X)$$

$$R^0 \equiv \left(\frac{\Gamma(D^0K^+)}{\Gamma(D_s^+\eta)}\right)_{\rm exp.} \left(\frac{X_q}{\sqrt{2}}\right)^2 \frac{p_{D_s\eta}}{p_{D^0K}} = \frac{Pc_\theta^2 + (1-P)s_\theta^2}{(1+s_{2\theta})P + (1-s_{2\theta})(1-P)}$$

~0.027

assuming S-wave decay



$$4 < \frac{\Gamma(D^+K^0)}{\Gamma(D_s^+\eta)} < 7.6 \quad 1.7 < \frac{\Gamma(D_s^+\pi^0)}{\Gamma(D_s^+\eta)} < 6.5$$

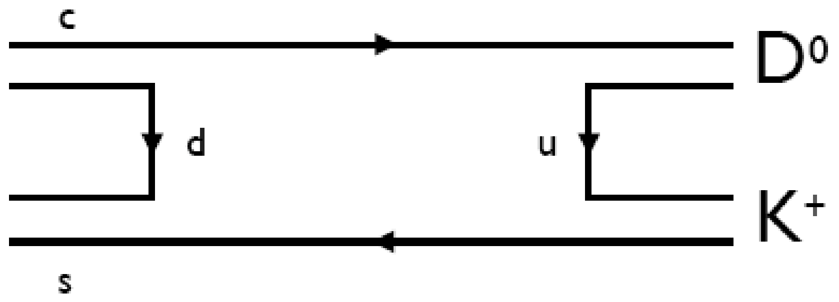
$$\left.\begin{array}{r} -0.19 < s_\theta < 0.14 \\ P < 0.03 \end{array}\right\} \xrightarrow{P} \text{almost all Dl} \xrightarrow{s_\theta} |D_l\rangle \approx |S_d\rangle = [cd][\bar{d}\bar{s}]$$

D^0K^+ OZI forbidden; only a small component along $|S_u>$ for which it is OZI allowed (OZI violations expected very small in heavy meson systems).

$$[cd][\bar{d}\bar{s}] \longrightarrow (c\bar{s})(d\bar{d}) - \underbrace{(c\bar{d})(d\bar{s})}$$

D^+K^0 OZI allowed

▲ ***Infact:***



▲ The smallness of P indicates almost complete cancellation between A(I=0) and A(I=1). However the a++ state should be produced only with A(I=1) therefore it should be produced as much as the $D_{sj}(2632)$.

$$a^{++}_{c\bar{s}} = [cu][\bar{d}\bar{s}] \longrightarrow D^+_s\pi^+,\ D^+K^+$$

Doubly charged charm mesons!

Heavy diquarks

For [cq][cbqb] the approximate spin independence of heavy quark interactions implies both good and bad diquarks.
A rich spectrum is implied with states having J=0,1,2 and both natural and unnatural J^{PC} .

We describe the *mass spectrum* in terms of *constituent diquark masses* and *spin-spin interactions*.

We derive the strenght of the latter interactions from known meson and baryon masses where possible or from educated guesses from one-gluon exchange otherwise.

X(3872)

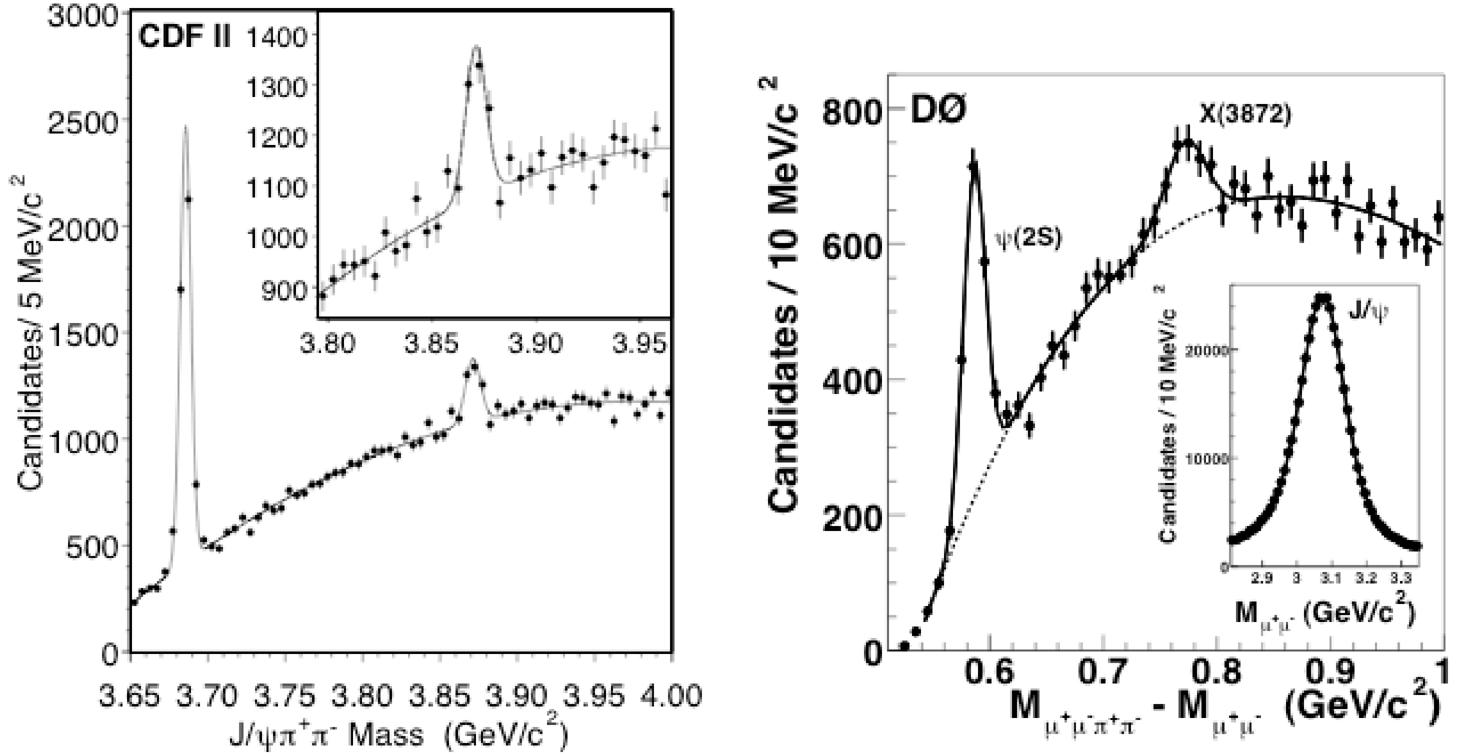


Figure 2. Evidence for $X(3872) \to \pi^+\pi^- J/\psi$, from Belle [19] (top left), BaBar [22] (top right), CDF [20] (bottom left), and DØ [21]. (bottom right). The prominent peak on the left of each panel is $\psi'(3686)$; the smaller peak near $\Delta M \equiv M(\pi^+\pi^-\ell^+\ell^-) - M(\ell^+\ell^-) \approx 775$ MeV, $M(J/\psi\,\pi^+\pi^-) \approx 3.87$ GeV is $X(3872)$. The CDF and DØ samples are restricted to dipion masses > 500 and 520 MeV, respectively.

C. Quigg, hep-ph/0407124

1.3. Discovery of $X(3872)$

Last summer, Belle [19] discovered $X(3872) \to \pi^+\pi^- J/\psi$, a candidate—by virtue of its decay mode—for a new charmonium state. The observation was confirmed in short order by CDF [20], DØ [21], and BaBar [22]. I summarize the observations in Figure 2 and Table 1.

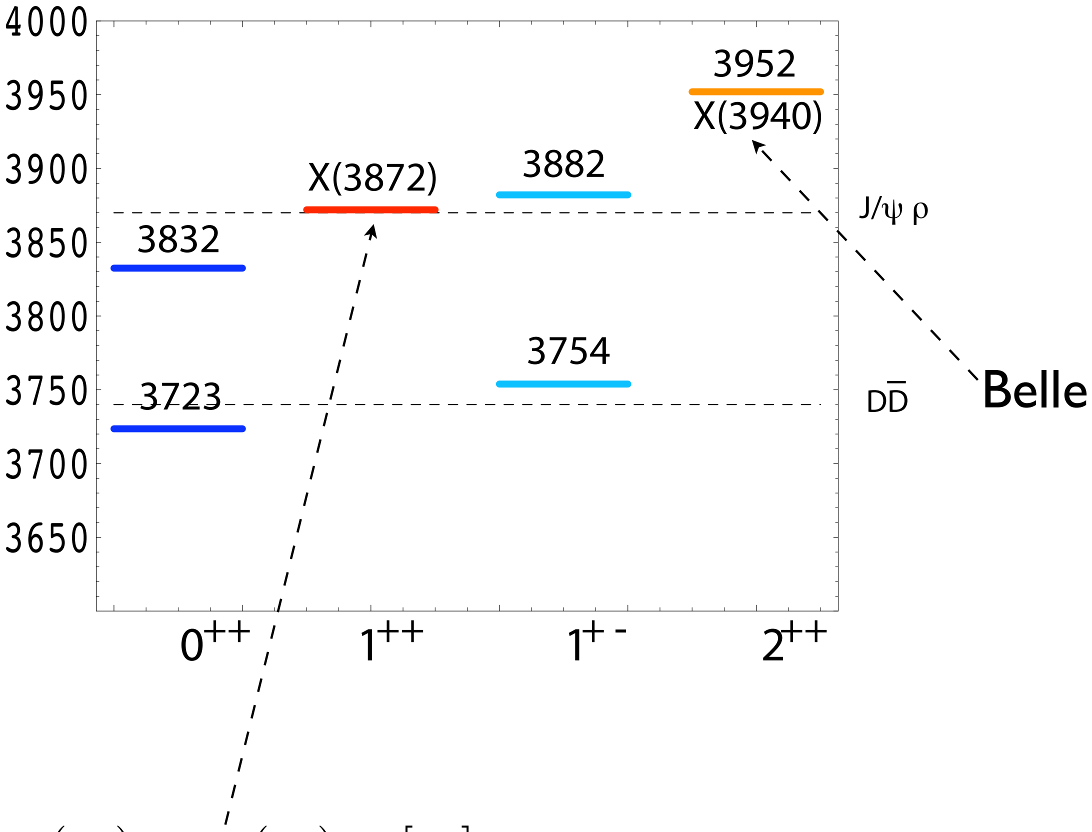
It is tantalizing that $X(3872)$ lies almost precisely at the $D^0\bar{D}^{*0}$ threshold, 3871.5 MeV. Belle places an upper limit of 2.3 MeV on the width of X. The production rates in 2-TeV $\bar{p}p$ collisions and the similar production characteristics of X and $\psi(2S)$ argue for appreciable prompt production at the Tevatron. A quantitative measure of prompt production *versus* B decay as the source of X should be forthcoming soon.

The natural prejudice is that $X(3872)$ should be identified as the $^3\mathrm{D}_2$ ψ_2 charmonium state, with $J^{PC} = 2^{--}$, but this expectation encounters challenges: The mass is somewhat higher than the 3815 MeV we expected in a single-channel potential model [10], but the mismatch is diminished once we take account of coupling to open-charm channels [11]. Perhaps more serious is the fact that the prominent—even dominant—radiative decays, $\psi_2 \to \gamma\chi_{c1,2}$ that we anticipated have not been seen. At 90% CL, Belle [19,23] limits

$$\mathcal{R}_{1,2} \equiv \frac{\Gamma(X(3872) \to \gamma\chi_{c1,2})}{\Gamma(X(3872) \to \pi^+\pi^- J/\psi)} < 0.89, 1.1\ . \quad (1)$$

The numerator is readily calculable in the framework of nonrelativistic quantum mechan-

X-states



$$[cq]_{S=1}(\bar{c}\bar{q})_{S=0} + (cq)_{S=0}[\bar{c}\bar{q}]_{S=1}$$

Consistent with observed decays in J+V

We consider neutral states with the composition:

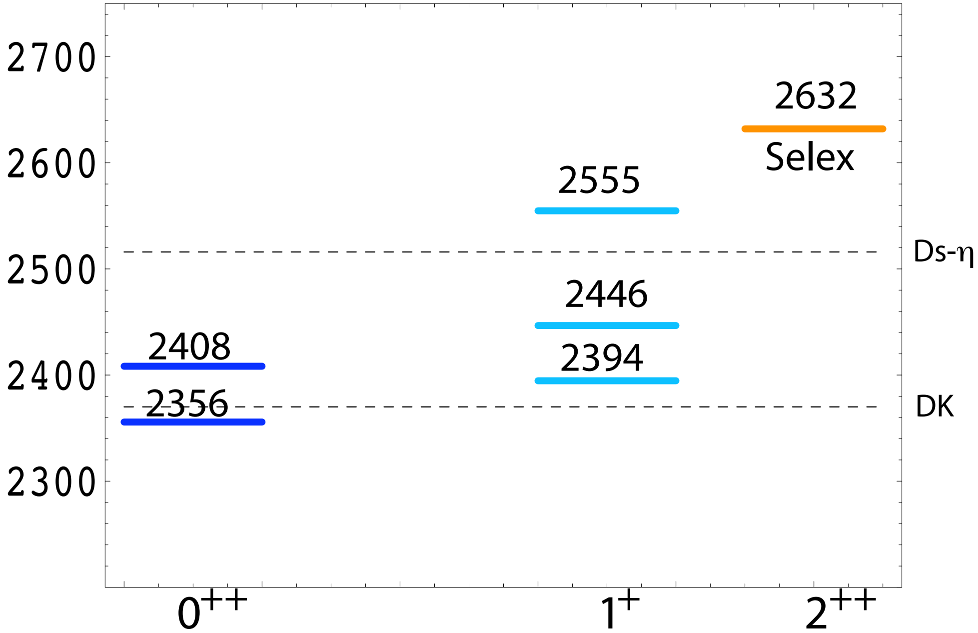
$$X_u = [cu][\bar{u}\bar{c}]$$
$$X_d = [cd][\bar{d}\bar{c}]$$

they can be arranged in two Isospin multiplets I=0,1

At the mass scale determined by the ccb pair we expect annihilation diagrams to be small (think to J width) thus mass eigenvectors should align on the quark mass basis.

At the X(3872) mass scale we expect annihilation diagrams to be dominated by the u-d quark mass difference.

We predict close to maximal Isospin breaking in the wave function and correspondingly in the hadronic decays of X(3872).



2700
2600
2500
2400
2300
2632
Selex
2555
Ds-η
2446
2408
2394
2356
DK
0++
1+
2++

Summary

- 4-quark light scalars < GeV
- 4-quark *open charm* and the Selex (?)
- 4-quark *hidden charm* and the X (!)
- other exotics [qq][cbqb]??