Diquark-antidiquark Mesons : a new spectroscopy?

Report on work done with F. Piccinini, A. Polosa, V. Riquer

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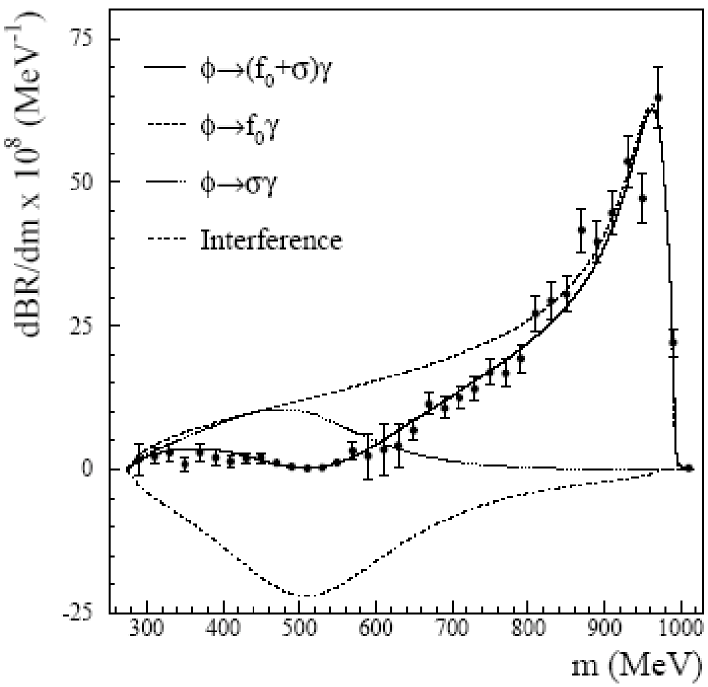
Tetraquark Mesons

- An idea which got momentum in the 70s (R. Jaffe, H. Lipkin...);
- QCD encourages the speculation that such states are indeed possible;
- As we shall see, the light scalar mesons a(980), f(980) really look like
- $$[qq]_{col=\bar{3}}[\bar{q}\bar{q}]_{col=3}$$
- In alternative: a(980), f(980) could be K-Kbar "molecules", bound by one-π exchange, i.e. in the configuration:
- $$(q\bar{q})_{col=1}(q\bar{q})_{col=1}$$
- the existence of lighter partners, σ and κ is crucial;
- Recent expts, at FNAL(E791), Frascati (KLOE) and BES, have seen again σ and κ : this would be against "molecules";
- …and there are states with hidden/open charm that do not look like charmonium states: X(3872), X(3940), (Belle, Babar in B decays), X(2632) (SELEX).



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

Study of the Decay ϕ(1020)→π0π0γ 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).

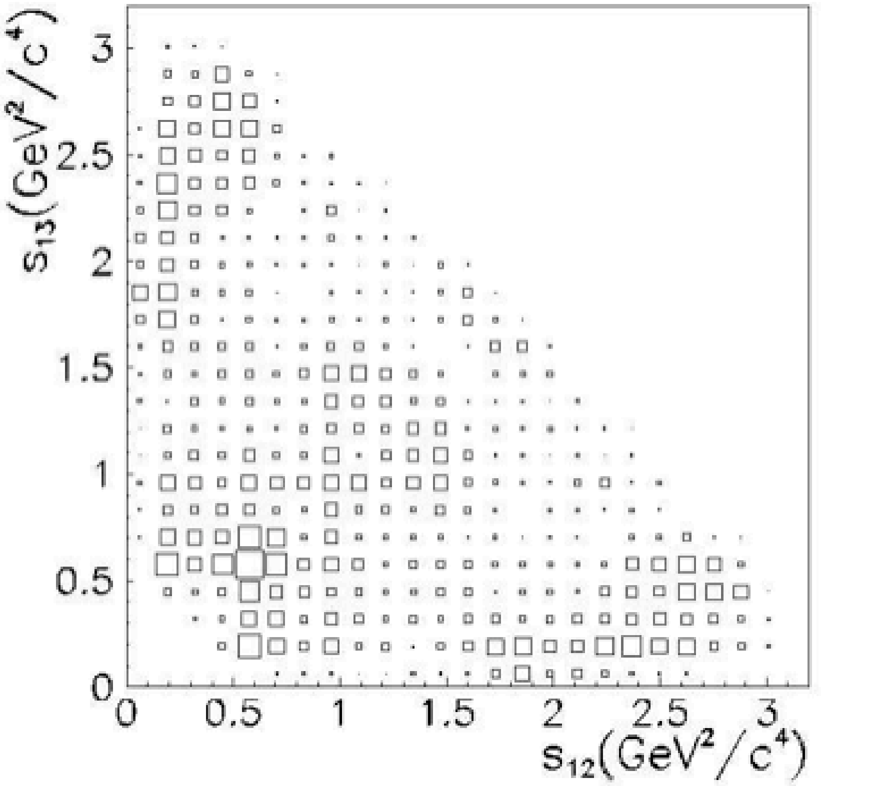
	Fit (A)	Fit (B)
χ^2/ndf	109.53/34	43.15/33
M_{f_0} (MeV)	962 ± 4	973 ± 1
$g^2_{f_0K^+K^-}/(4\pi)$ (GeV^2)	1.29 ± 0.14	2.79 ± 0.12
$g^2_{f_0K^+K^-}/g^2_{f_0\pi^+\pi^-}$	3.22 ± 0.29	4.00 ± 0.14
$g_{\phi\sigma\gamma}$	—	0.060 ± 0.008

Sigma parameters from E791

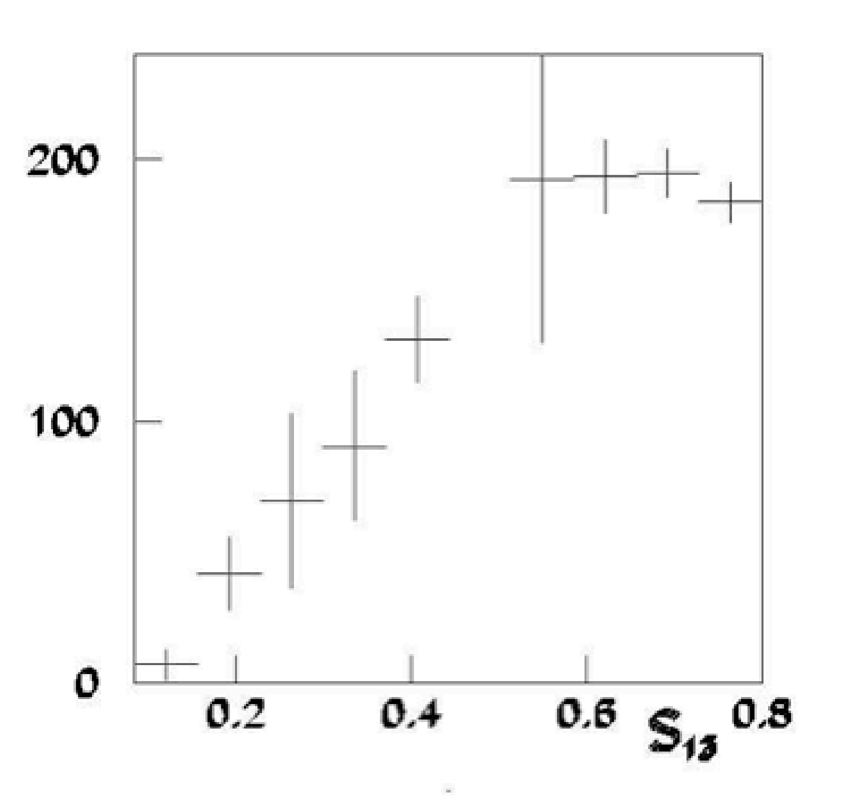
$M_\sigma = (478^{+24}_{-23} \pm 17)$ MeV

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

$\sigma(600)$ ad E791



PRL 86, 770 (2001)



hep-ex/0307008 (2003)

M = 478± 23± 17 MeV

Γ = 324 ±40± 21 MeV

$\sigma(600)$ @ BES II

- **BES II: σ in $J/\psi \to \omega\pi^+\pi^-$.**

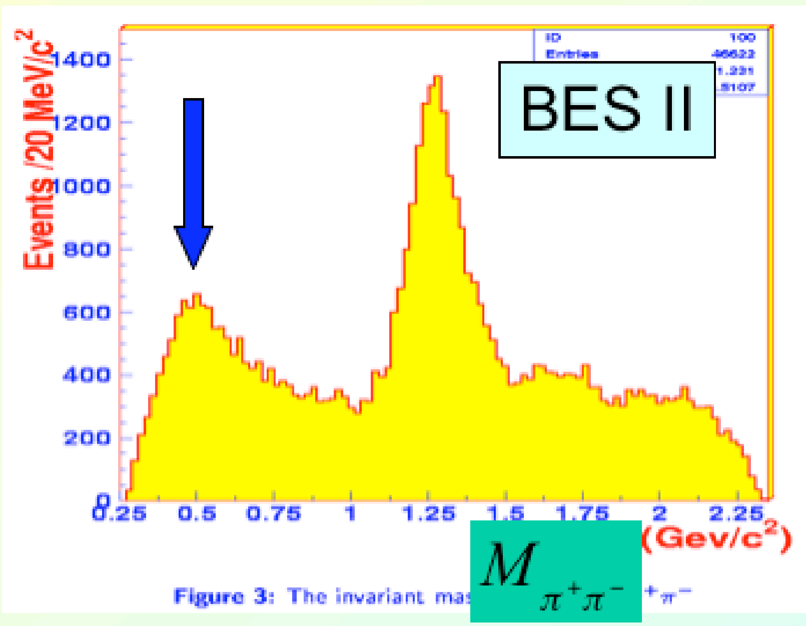
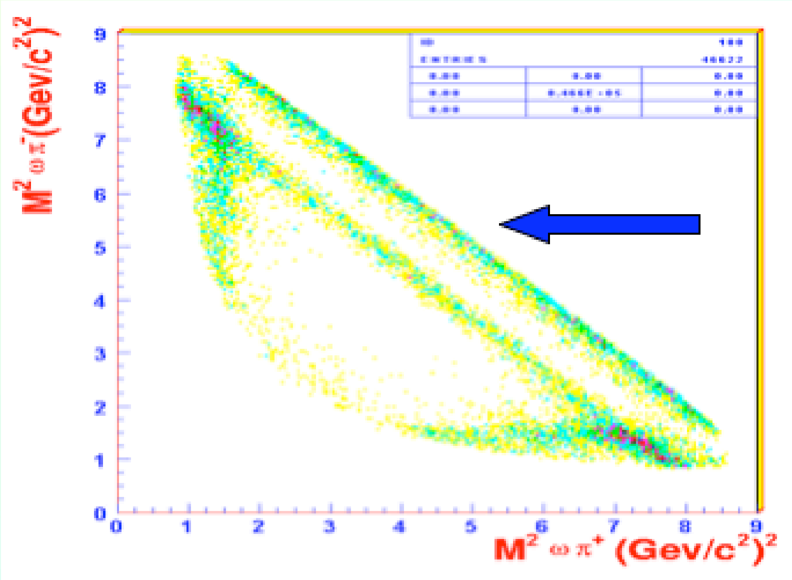


Figure 3: The invariant mas... $\pi^+\pi^-$

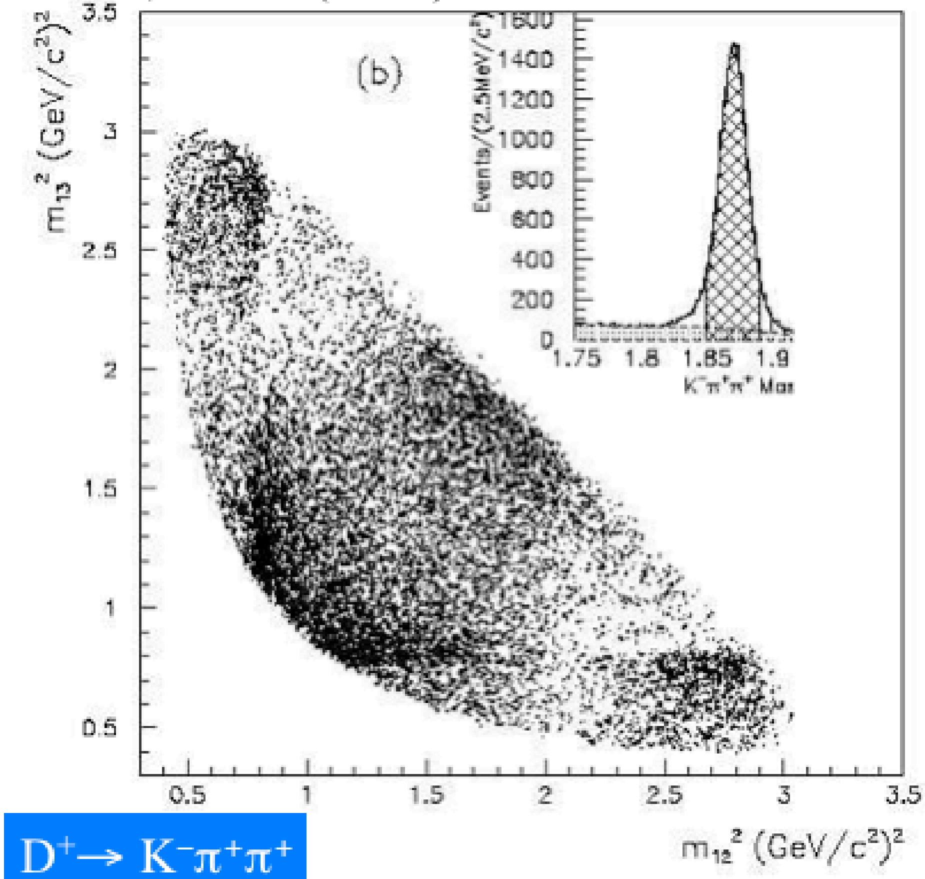


- **Partial wave analysis: pole position**

$$(541 \pm 39) - i(252 \pm 42) \quad MeV$$

$\kappa(800)$ @ E791

PRL 89, 12801 (2002)



$D^+ \rightarrow K^-\pi^+\pi^+$

No k needed in Dalitz plot fit of $D^0 \rightarrow K^-\pi^+\pi^0$ e $D^0 \rightarrow K_S\ \pi^+\pi^-$ (CLEO)

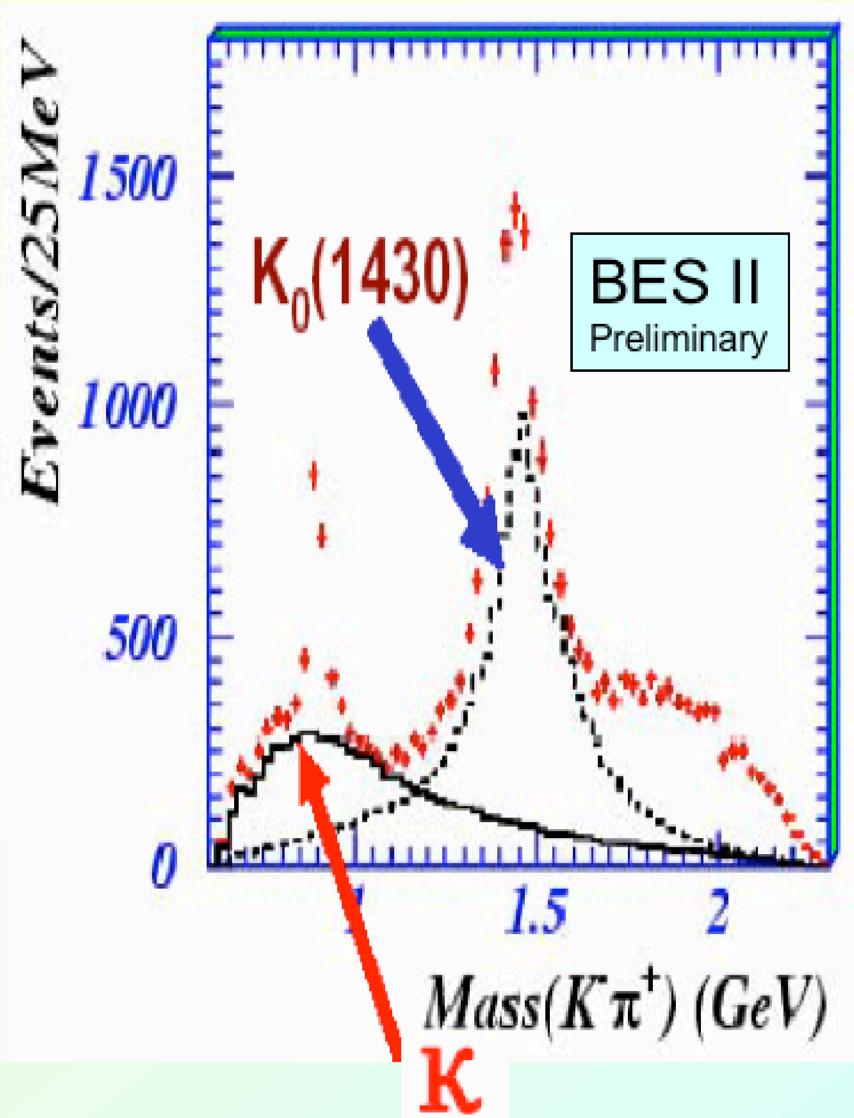
No k needed in Dalitz plot fit of $D^0 \rightarrow K^0\ K^-\pi^+$ e $D^0 \rightarrow K\ K^+\pi^-$ (BABAR)

M = 797± 19± 43 MeV

Γ = 410 ±43± 87 MeV

Non Res. Bkg. :90% (no k)→13% (k)

κ(800) @ BES II



- BES II: κ in J/ψ→K*Kπ→KπKπ.

$$(760 \sim 840) - i(310 \sim 420) MeV$$

The present work (1)

Recent evidence for σ at low energy led us to reconsider the case of sub-GeV scalar mesons. Many previous investigations (Joffe, Close&Tornqvist, Schecter and coll...).

We propose:

all scalars below 1 GeV are diquark-antidiquark bound states (1 nonet),
the q-qbar scalar nonet (L=1, S=1, J=0) has to be above.

Results:

- Low energy states show inverted mass spectrum, consistent with "perfect mixing";
- Strong decays are reasonably accounted for;
- Decays $\phi \to S\,\gamma$ still to be studied;
- Relations with ealier proposal by Rossi&Veneziano suggests connection to baryon-antibaryon, rather than meson-meson states (or molecule)

PRL **93**, 212002 (2004), hep-ph/0407017

The present work (2)

– Heavy quark interactions are spin independent: new spin states?

  – We propose that X(3872) observed by Belle and by Babar ***is a diquark-antidiquark bound state and estimate the spectrum of states of the spin multiplet with the same flavors:***

  – X(3872)=(J=1^{++})= $(cq)_{col=\bar{3},S=1}(\bar{c}\bar{q})_{col=3,S=1}$

  – with the same parameters, we can accommodate the X(2632) observed by SELEX:

  – X(2632)=(J=2^{++}) = $(cq)_{col=\bar{3},S=1}(\bar{s}\bar{q})_{col=3,S=1}$

– ***we predict X(3872) made by two states with Δm = (5-8) MeV ≈ 2 (m_d - m_u)***

– ***one state only in the decay: $B^+ \rightarrow K^+$X(3872), the other appears in $B^0 \rightarrow K_S$ X(3872)***

– ***bounds to the production of the charged partner X^+ are close but not in contradiction with BaBar.***

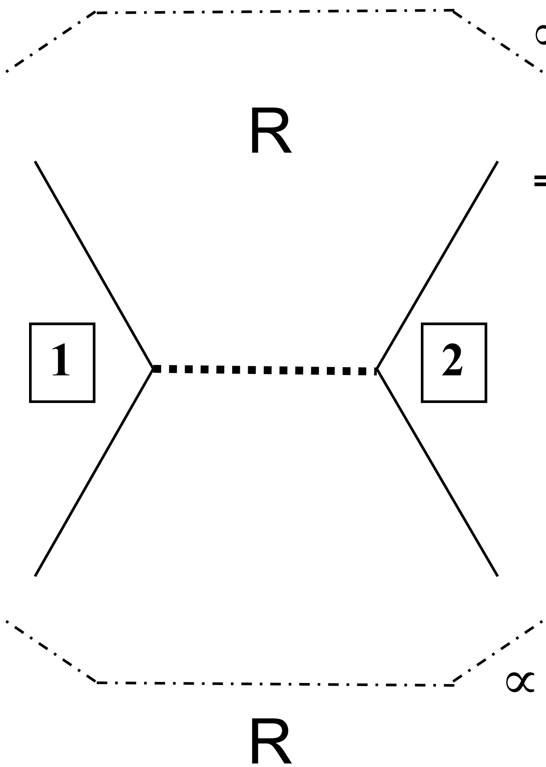
PR D70 054009 (2004), hep-ph/0407028;
PR D to appear, hep-ph/0412098

Summary

-
- Attractive and repulsive channels in QCD
- String structures: the “baryonium” model (Rossi & Veneziano, 1977)
- The light scalar mesons;
- Two-meson decays;
- Surprising charmonium states seen by Belle, Babar and Selex;
- S-wave Tetraquarks, the X(3872) and spectrum of related states;
- Selex particle, X(2632), and associated spectrum;
- Alignment to quark masses, isospin breaking;
- Conclusions

Attractive & repulsive channels in QCD

Interaction of two colored objects:



$$\propto g^2 < \vec{T}_1 \cdot \vec{T}_2 >_R = \frac{g^2}{2} [< (\vec{T}_1 + \vec{T}_2)^2 >_R - < \vec{T}^2 >_1 - < \vec{T}^2 >_2] =$$

$$= \frac{g^2}{2} [C^{(2)}(R) - C^{(2)}(1) - C^{(2)}(1)]$$

$q\bar{q} = \{$ octet = +1/3 repulsion; singlet = -8/3 attraction

$q\bar{q}$	octet = +1/3	repulsion
	singlet = -8/3	attraction
qq	"3bar" = -4/3	attraction
	"6 " = +2/3	repulsion

Spin-spin interaction

$$\propto -g^2 < \sigma_1 \vec{T}_1 \cdot \sigma_2 \vec{T}_2 >_R \propto -g^2 [C^{(2)}{}_{eff}(R)] [J(J+1) - 3/2]$$

$< q\bar{q} >_1$ *and* $< qq >_{\bar{3}} = \{$

spin 1= +1/2	repulsion
spin 0= -3/2	attraction

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 ⇒ $\bar{\mathbf{3}}_{\mathbf{f}}$

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

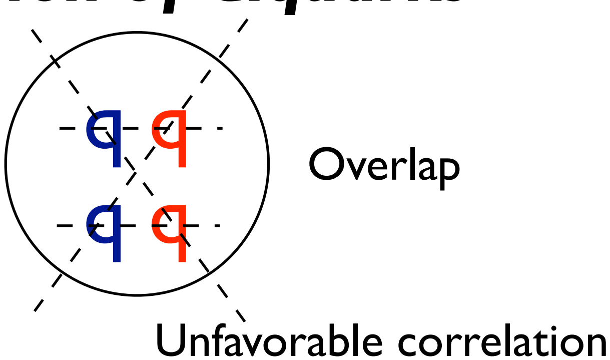
Bad diquarks: $(qq)_{\bar{\mathbf{3}}_{\mathbf{c}},\mathbf{3}_{\mathbf{s}},\mathbf{6}_{\mathbf{f}}}$

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

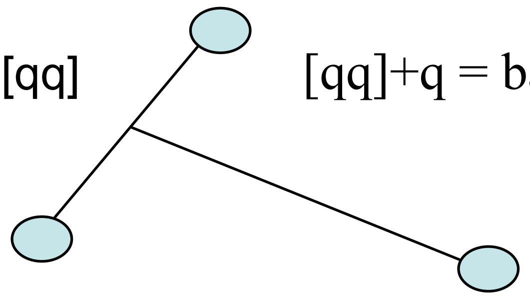
Repulsion of diquarks



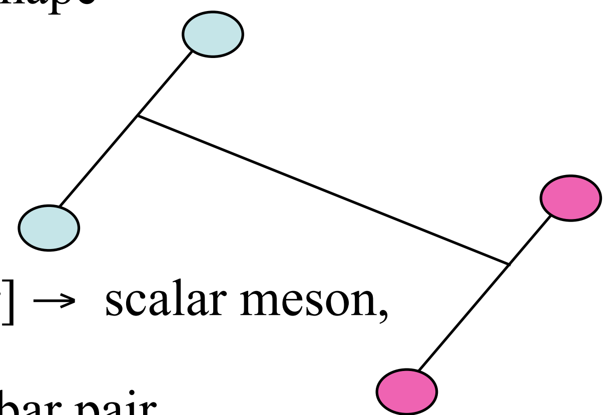
Diquark: [qq] in color = 3bar, spin=0, SU3 flavour = 3bar makes a simple unit to form color singlets (Jaffe..more recently Jaffe&Wilcezck, Karliner & Lipkin for penta-quark)

Diquark needs to combine with other colored objects

[qq]

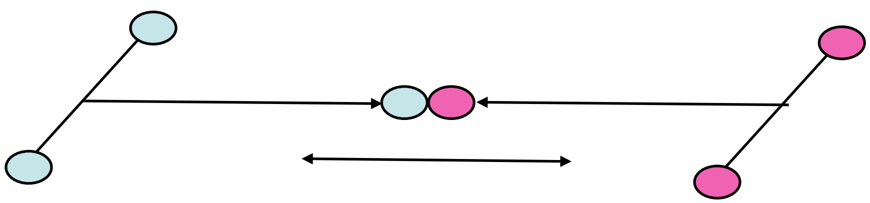


[qq]+q = baryon (e.g. Λ), Y-shape



[qq]+ [qbar qbar] $\rightarrow$ scalar meson,

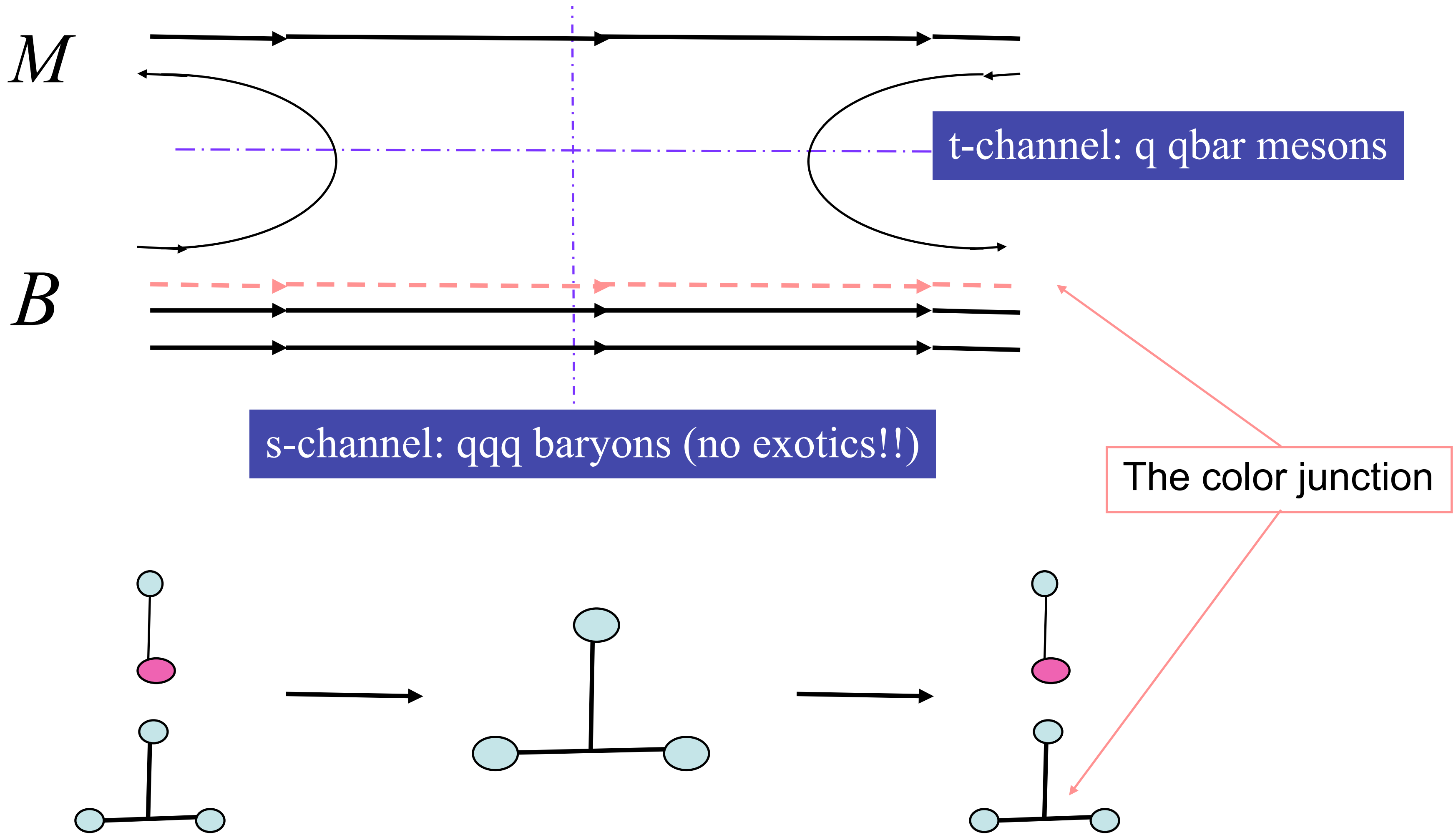
if you stretch the string, [qq][qbar qbar]$\rightarrow$ B Bbar pair
a new topology, related to B-B bar.



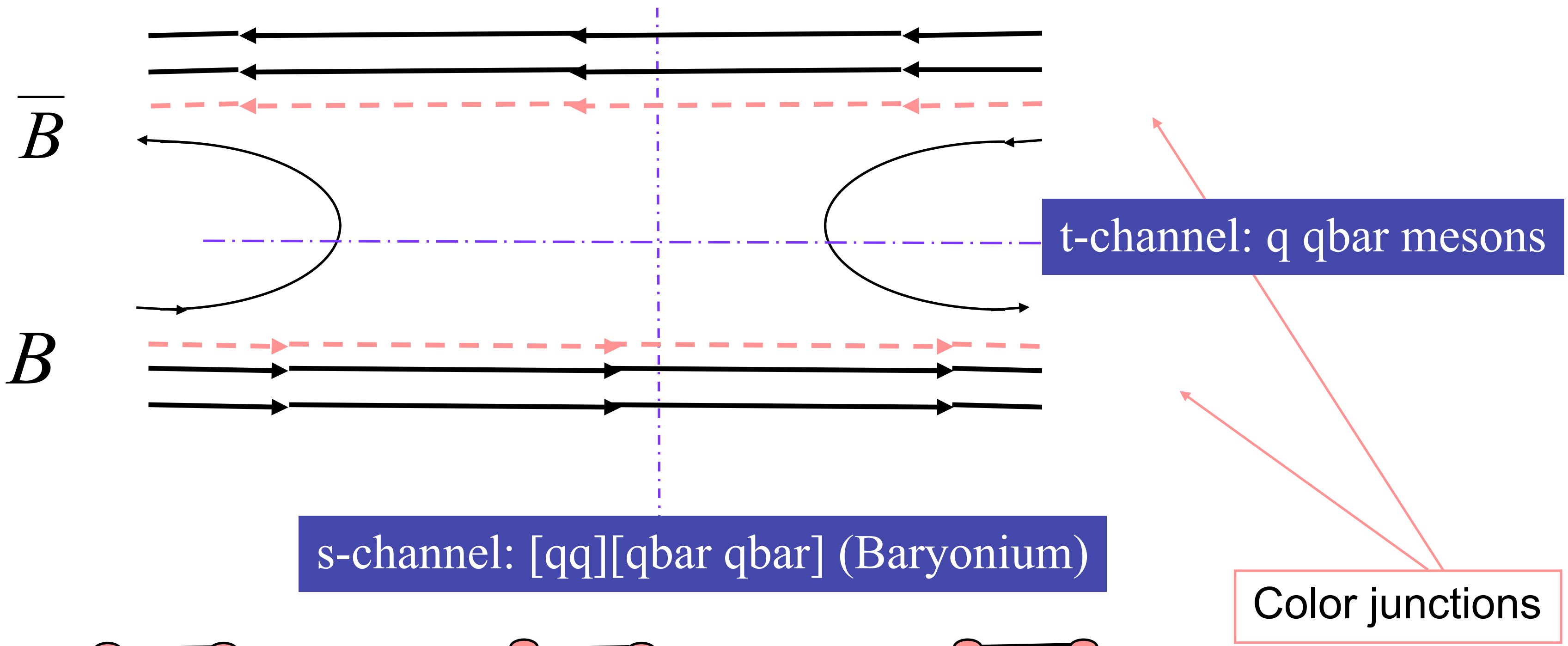
meson-meson molecules are in different color configuration.
But: do "residual" forces bind?

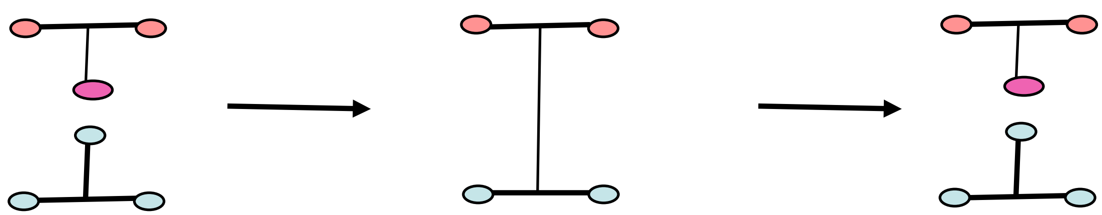
Duality in Meson-Baryon scattering

G.C. Rossi and G. Veneziano, Nucl. Phys. **B123** (1977) 507



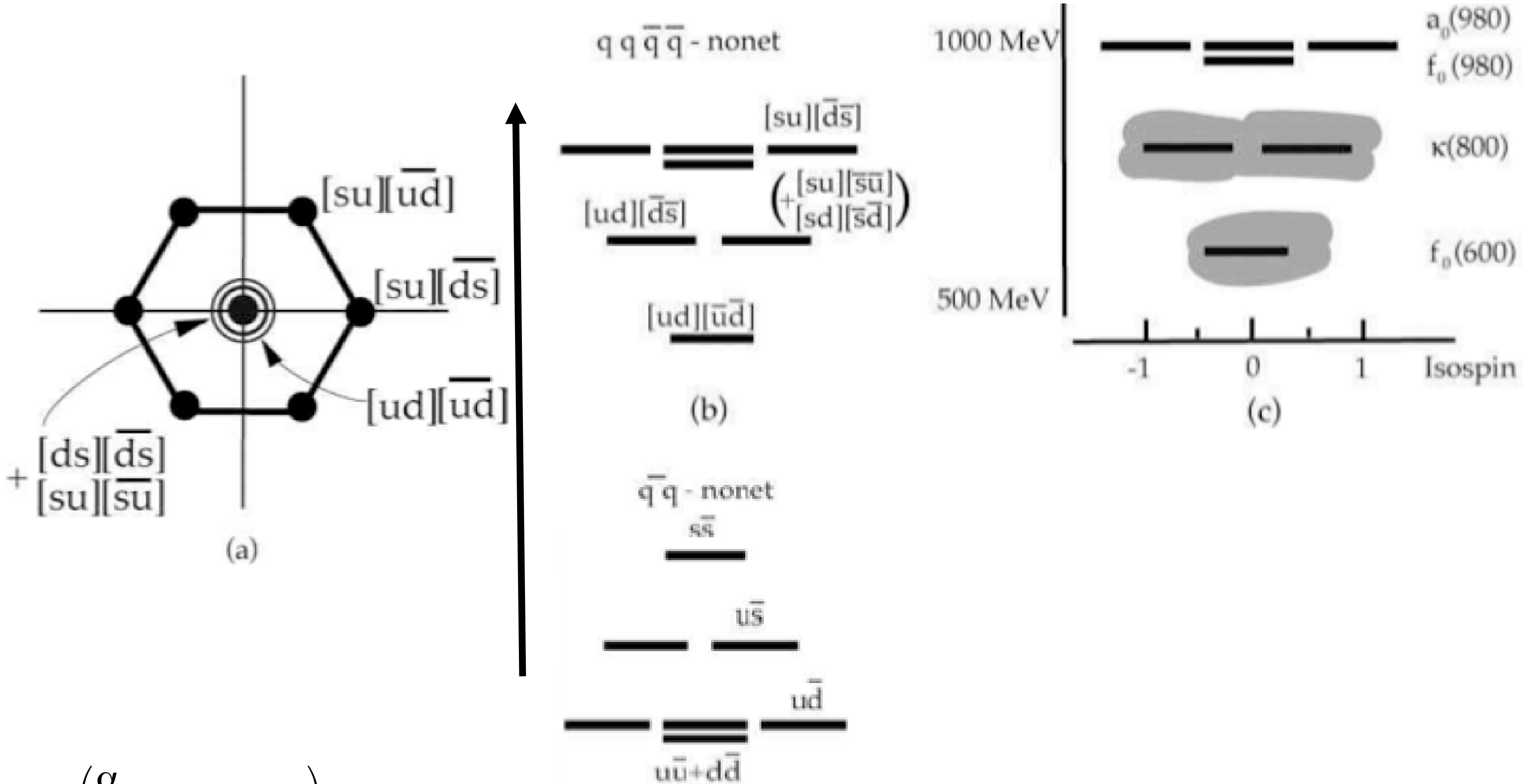
What about Baryon-Antibaryon scattering ?





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

Quantum numbers and mass formula



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

= diquark masses

4 parameters, 4 masses+1 mixing, one overall relation:

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

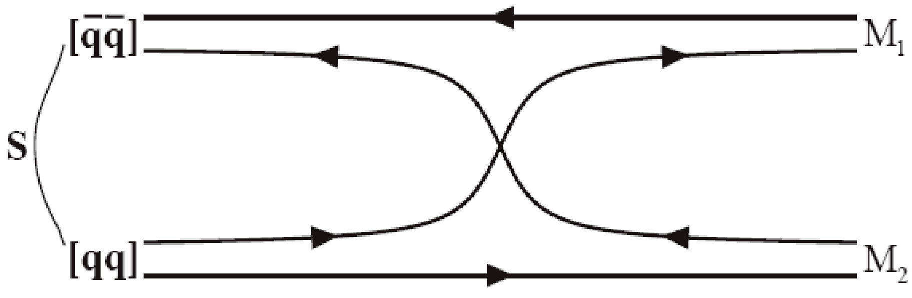
$$f_\circ(I=0) = \frac{1}{\sqrt{2}}\left([su][\bar{s}\bar{u}] + [sd][\bar{s}\bar{d}]\right)$$
$$\sigma_\circ(I=0) = [ud][\bar{u}\bar{d}]$$

$$|f\rangle = \cos\phi|f_\circ\rangle + \sin\phi|\sigma_\circ\rangle$$
$$|\sigma\rangle = -\sin\phi|f_\circ\rangle + \cos\phi|\sigma_\circ\rangle.$$

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

- Almost “ideal mixing”
- Linear mass formula gives very similar results
- With Linear m.f., parameters related to diquark masses: α=480 MeV, β = 250 MeV
- Note: α−β=230 MeV vs m_S=150 MeV.

Strong Decays



$$L_1 = A(S_i^j \varepsilon_{jlm} \varepsilon^{ikn}) M_k^l M_n^m$$

No derivative coupling!

FIG. 1: The decay of a scalar meson S made up of a diquark-antidiquark pair in two mesons $M_1 M_2$ made up of standard $(q\bar{q})$ pairs.

$$\Gamma(S \to i) = \frac{A^2}{8\pi} \frac{p}{M_s^2} x_{s \to i}, \qquad (13)$$

where p is the decay momentum, M the mass of the scalar meson and $x_{s \to i}$ a factor which includes numerical coefficients in the individual amplitudes and isospin multiplicities.

	Theory	Experiment	Theory	Experiment
	$\pi\pi$		KK	
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	-	

TABLE II: Fit with a single parameter $A = 2.6$ GeV. For g_π we have reported the upper limit to the decay rate obtained from the $f - \sigma$ mixing considered previously, see text.

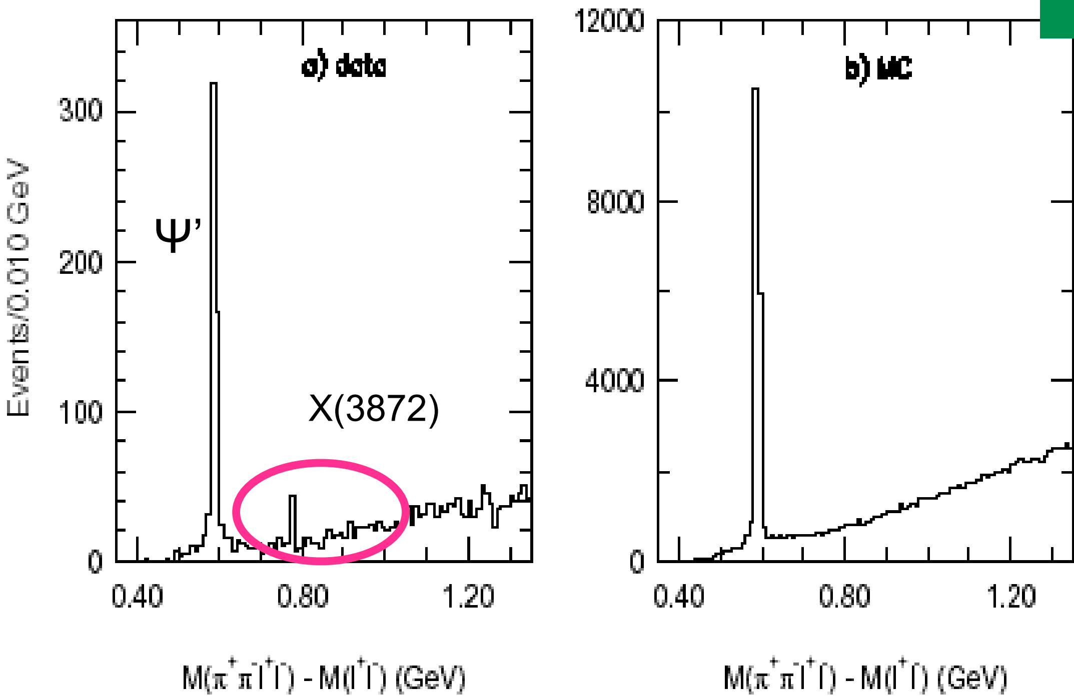
Maybe f ππ comes from "one-loop": $f \to K\bar{K} \to \pi\pi$,

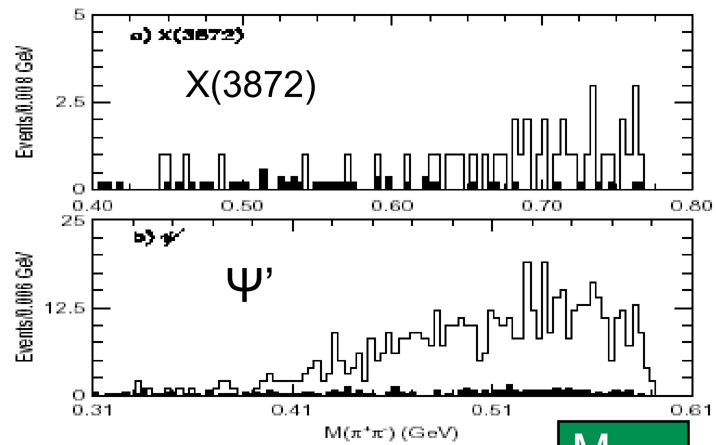
or perhaps (!!) $f \to B\bar{B} \to \pi\pi$ (Baryonium ?, see later)

All in all we get quite a consistent picture, reconciles the large σ width with narrow a and f widths and reinforces [qq][qbar qbar] assignement

Observation of a narrow charmonium-like state in exclusive $B^{\pm} \rightarrow K^{\pm}\pi^{+}\pi^{-}J/\psi$ decays

BELLE Collaboration

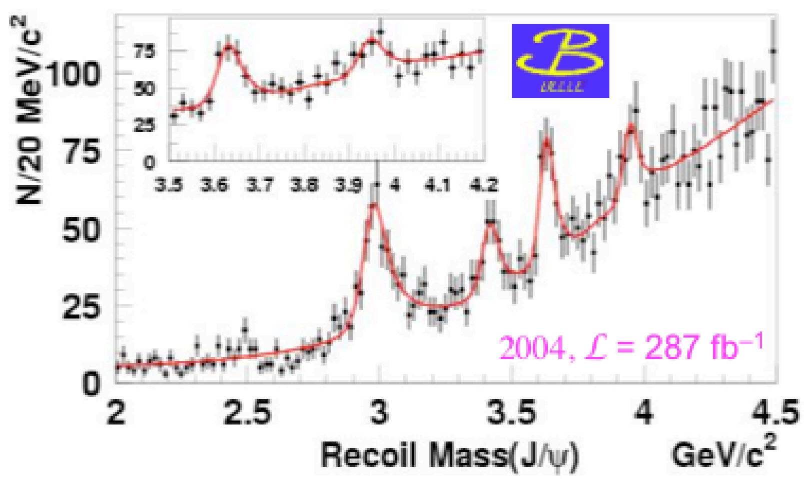




$M_{\pi\pi}$

A new peak in J/ψ recoil

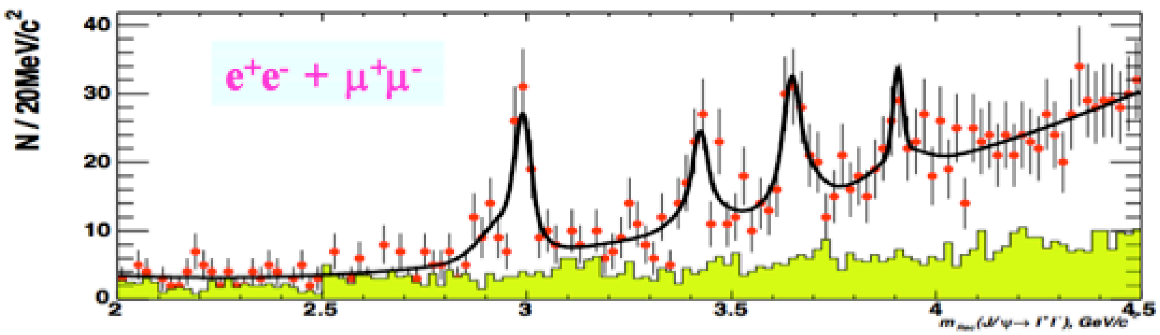
- At ICHEP '04 Belle presented an update with full statistics, extending the mass range again to the high part of the spectrum (3.8 - 4.5 GeV/c^2)
- No evidence for $X(3872)$ on the recoil
- New peak observed at higher mass:
  - $m_Y = (3940 \pm 11)$ MeV/c^2;
  - $N_Y = 148 \pm 33$ (4.5 σ);
  - width consistent with experimental resolution



BABAR double $c\bar{c}$ analysis

S. Ye, X. Lou, G. Williams
BAD 718

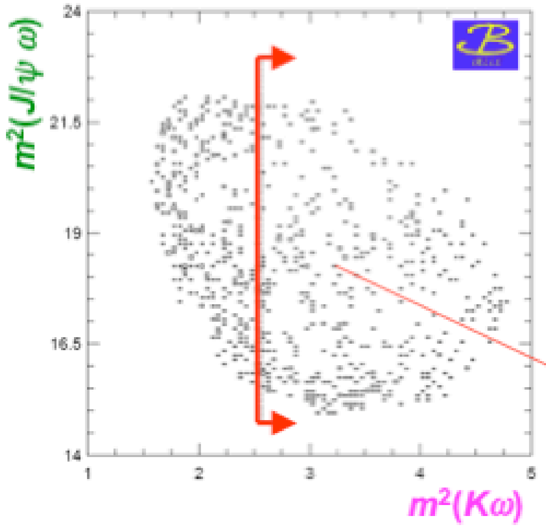
- Analysis similar to Belle's
  - Run 1-2-3, $\mathcal{L}$ = 124.4 fb^{-1}



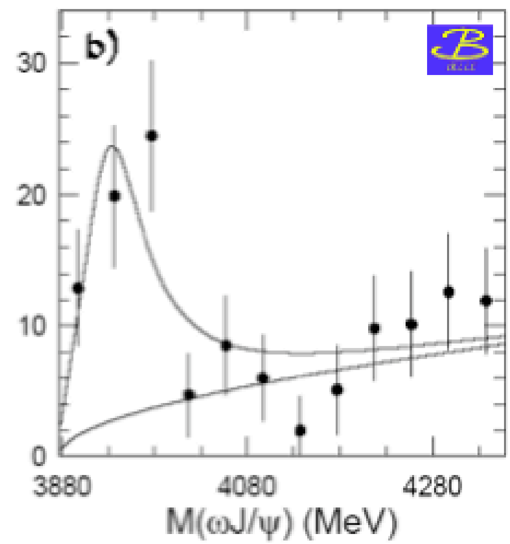
- Similar peak observed at high mass. Very preliminarily:
  - $m_Y \approx 3910$ MeV/c^2
  - $N_Y = 51 \pm 27$
- Missed ICHEP because of serious problem with lepton lists.
- Problem fixed. A few remaining issues before preliminary result ready.

E. Robutti Dresden, September 23, 2004 7

New status decaying to $J/\psi\ \omega$?



- Select events in $m(\pi^+\pi^-\pi^0) \sim m_\omega$ region
- Dalitz plot $m^2(J/\psi\ \omega)$ vs. $m^2(K\omega)$:
  - concentration at low $m^2(K\omega)$;
  - select events with $m^2(K\omega)$ to exclude B $\rightarrow J/\psi\ K^{**}$



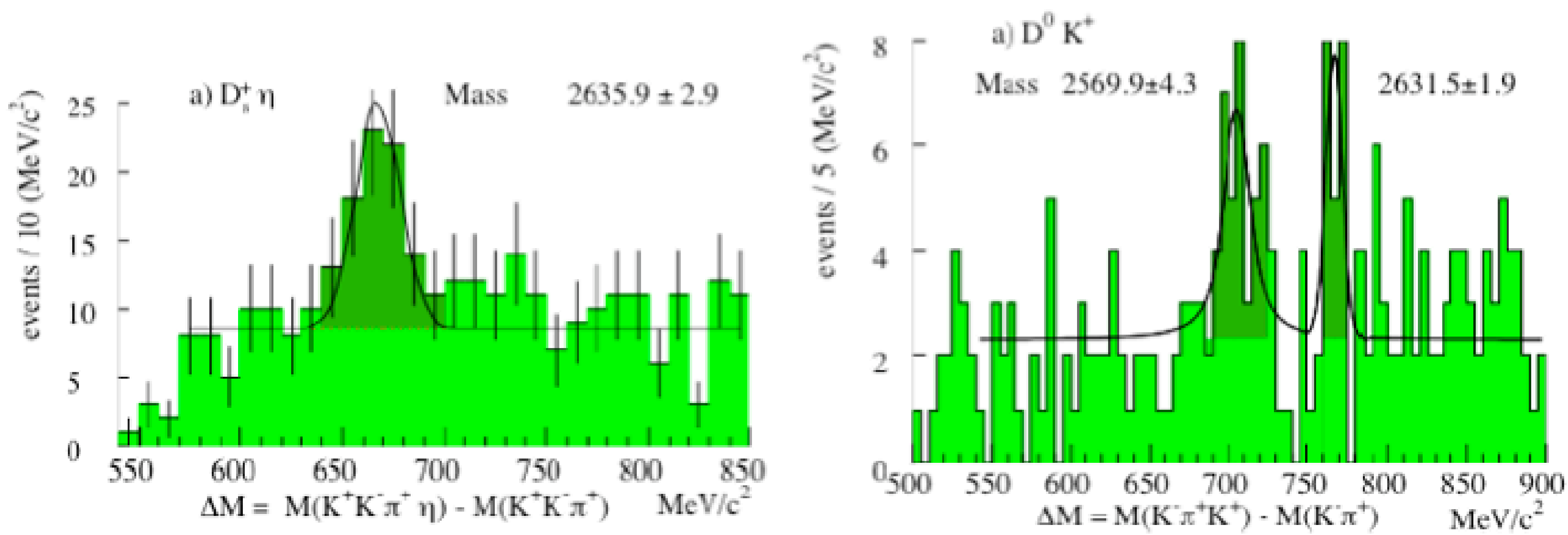
- Plot $m\,(J/\psi\ \omega)$ distribution after combinatorial bkg. subtraction:
  - enhancement just above threshold, not compatible with phase-space B $\rightarrow J/\psi\ \omega\ K$;
  - Fit to S-wave B-W yields: $N_Y = 61 \pm 11$ ($>8\sigma$); $m_Y = (3491 \pm 11)$ MeV/c^2; $\Gamma_Y = (92 \pm 24)$ MeV

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 Dsη decay rate dominates the D0K+ by a factor of ~6 despite having half the phase space.'

Dsj(2632) (?)

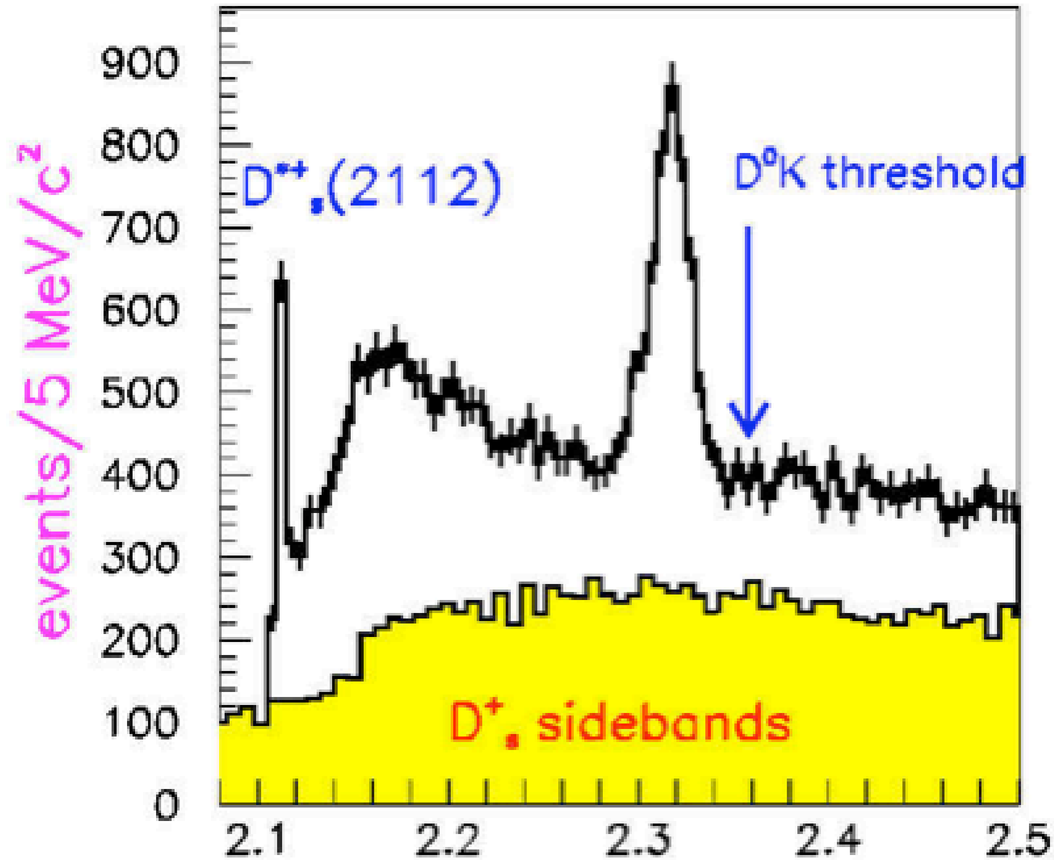


$D^*_s(2317)$ @ BABAR

Observed in 2003 in Ds π^0

Confirmed by BELLE e CLEO

Does not decay in photon



M=2317.4± 0.9 M

Γ < 4.6 MeV

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 mod were predicting these states higher in mass ⇒ 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/0

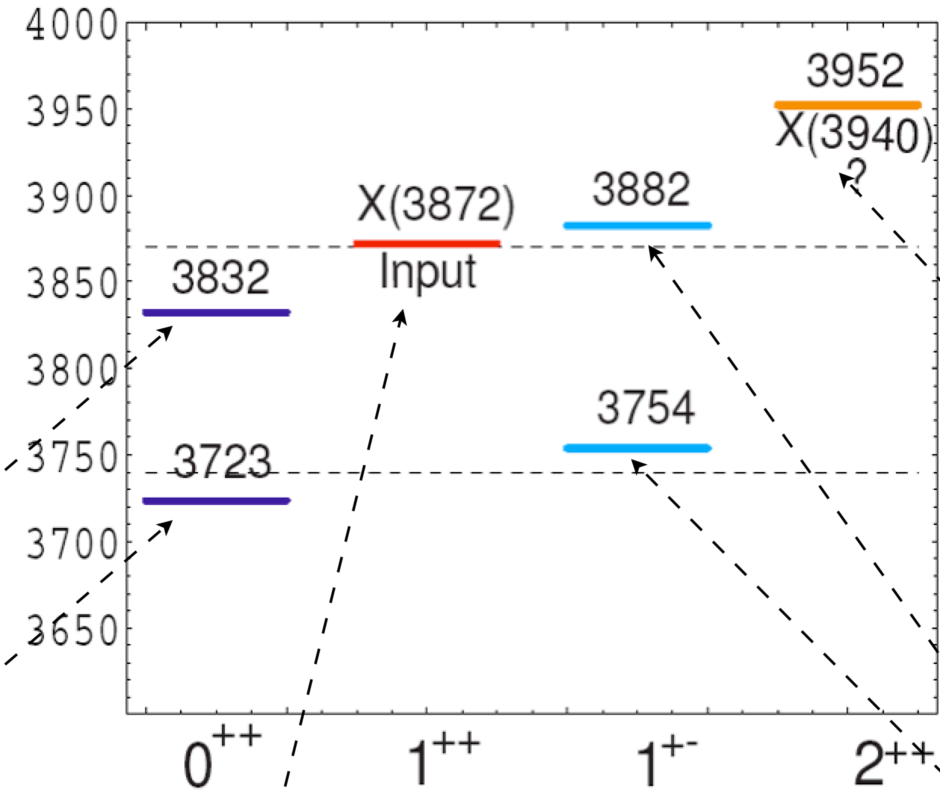
Tetraquarks with open and hidden charm
(Phys.Rev. **D70**, 054009 (2004); hep-ph/0412098)

- The spin-spin interaction between heavy quarks is O(1/M)
  - If S=0 diquarks are bound, S=1 diquarks do
  - All states in the composition $(S=0 \oplus S=1)\otimes(S=0 \oplus S=1)$ must exist
  - not natural spin-parity only!
  - a large multiplet with composition:

$$2\ (J^{PC}=0^{++})+(J=1^{++})+2\ (J=1^{+-})+(J=2^{++}).$$

- Mass spectrum determined by:
  - constituent diquark massess
  - spin-spin interactions
  - the latter: from meson and baryon spectrum or from one gluon exchange

X-states



Belle

-Could decay DDbar
(D-wave; searched)
-J/Ψ ω seen by BELLE.

DDbar

$\eta_c\eta$, $\eta_c\pi$, nH

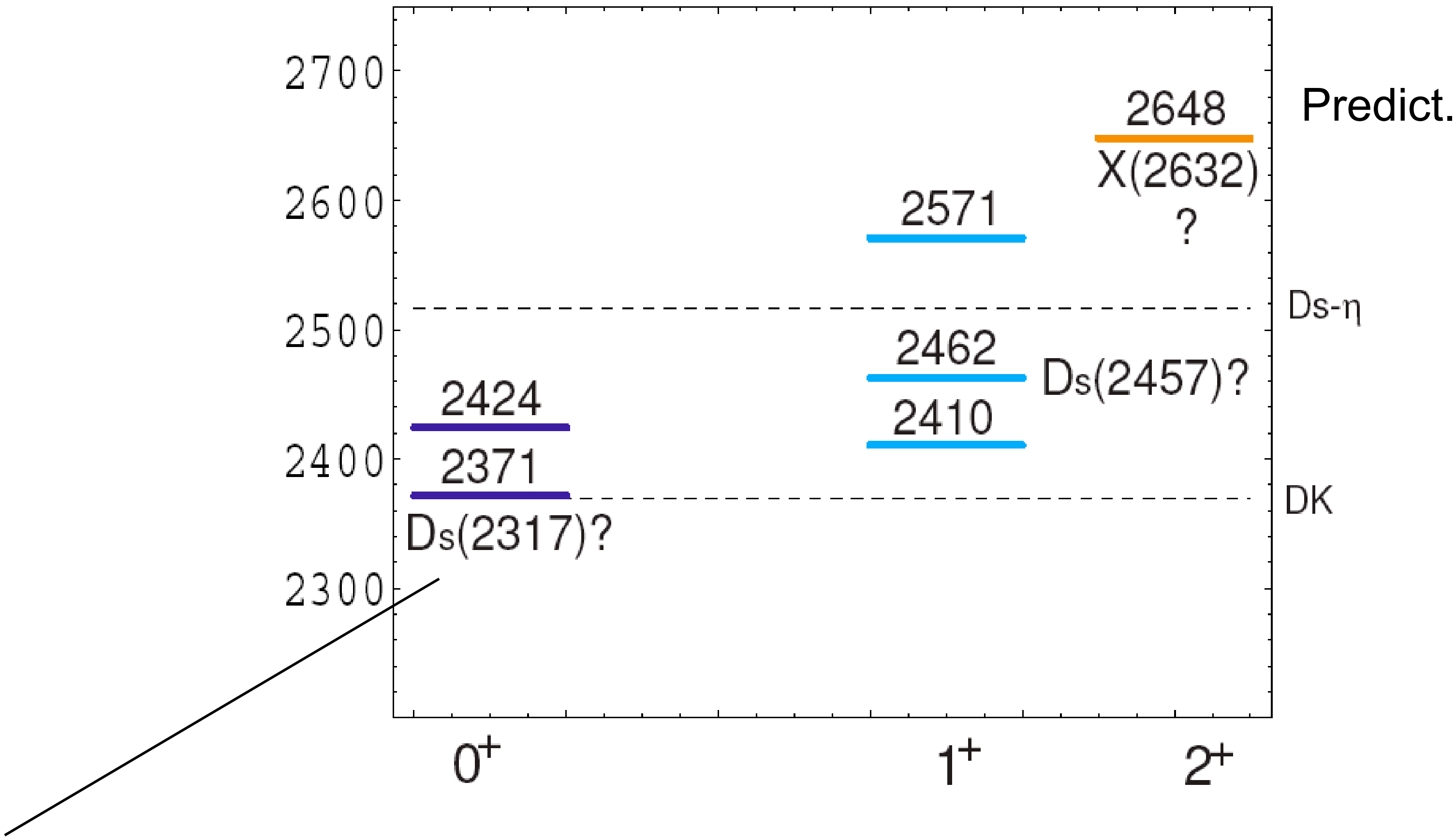
$$[cq]_{S=1}(\bar{c}\bar{q})_{S=0}+(cq)_{S=0}[\bar{c}\bar{q}]_{S=1}$$

-Unnatural spin-parity forbids decay in DDbar
Consistent with observed decays in J+V.
-It decays both to ρ and ω due to isospin breaking in its wave function.

J/Ψ π(η)
η_c ρ(ω)

The states:

$$[cu]_{S=0,1}[\bar{s}\bar{u}]_{S=0,1}$$



Masses

- Contributions to the mass of bound states: two conflicting mechanisms:
  - ***Annihilation***: $d\bar{d} \to u\bar{u}$
  - $u\bar{u} \to d\bar{d}$

  gives a matrix with all equal elements, which is diagonal in the isospin basis;
  - ***Quark Masses***: the eigenvectors are the states with quarks of definite flavor (e.g. ω/ϕ mixing)
  - TOTAL: $\begin{pmatrix} 2m_u + \delta & \delta \\ \delta & 2m_d + \delta \end{pmatrix}$
  -
  - At charmonium scale, quark mass should dominate (Rossi -Veneziano;Maiani-Piccinini-Polosa-Riquer)
  - therefore the approximate mass eigenstates are $X_u = [cu][\bar{c}\bar{u}]$
  - $X_d = [cd][\bar{c}\bar{d}]$

    rather then the I=1,0 states

- Belle sees both: X -> J+ρ, J+ ω with similar B.R.!!!! A new phenomenon !!!!

Isospin breaking

We consider in this section the finer structure of the $X(3872)$. In particular,we consider the neutral states with the composition:

$$X_u = [cu][\bar{u}\bar{c}]; X_d = [cd][\bar{d}\bar{c}] \tag{32}$$

Physical states could be expected to fall in isospin multiplets with $I = 1, 0$:

$$a_{c\bar{c}} = (X_u + X_d)/\sqrt{2}; \quad f_{c\bar{c}} = (X_u - X_d)/\sqrt{2} \tag{33}$$

$$X_{\rm low} = \cos\theta X_u + \sin\theta X_d; \quad X_{\rm high} = -\sin\theta X_u + \cos\theta X_d \tag{34}$$

we get:

$$M(X_d) - M(X_u) = \frac{2(m_{\rm down} - m_{\rm up})}{\cos(2\theta)} = \frac{(6-8)\ {\rm MeV}}{\cos(2\theta)} \tag{35}$$

$$\frac{\Gamma(3\pi)}{\Gamma(2\pi)})_{X_l} = \frac{(\cos\theta + \sin\theta)^2}{(\cos\theta - \sin\theta)^2} \cdot \frac{\langle p_\omega \rangle}{\langle p_\rho \rangle}; \quad \frac{\Gamma(3\pi)}{\Gamma(2\pi)})_{X_h} = \frac{(\cos\theta - \sin\theta)^2}{(\cos\theta + \sin\theta)^2} \cdot \frac{\langle p_\omega \rangle}{\langle p_\rho \rangle} \tag{44}$$

BELLE attributes all events with $\pi^+\pi^-\pi^0$ mass above 750 MeV to ω decay and divides by the total number of observed 2π events. They find:

$$(\frac{\Gamma(3\pi)}{\Gamma(2\pi)})_{BELLE} = 0.8 \pm 0.3_{stat} \pm 0.1_{syst} \tag{45}$$

The central value is compatible with eq.(44) for:

$$\theta \simeq \pm 20^0 \tag{46}$$

for X_l or X_h, respectively. Correspondingly, the mass difference of the two states is:

$$M(X_h) - M(X_l) \simeq 7 - 10\ MeV \tag{47}$$

Interference !

$$\frac{d\Gamma(X \to \psi + e^+e^-)}{ds} =$$

$$= \frac{|A|^2 B_{(\rho \to e^+e^-)}}{8\pi M_X^2} \frac{M_\rho \Gamma_V}{\pi} \cdot p(s) \cdot$$

$$\cdot \left| \frac{1}{(s - M_\rho^2) + i(M_\rho \Gamma_\rho)} \pm \frac{1/3}{(s - M_\omega^2) + i(M_\omega \Gamma_\omega)} \right|^2$$

we have assumed the quark-model ratio for the leptonic amplitudes of ρ and ω and used the narrow width approximation. The sign $\pm$ applies to X_u and X_d, respectively. Combining with eq.(43), with $\theta = 0$, we find:

$$B(X_u \to J/\Psi + e^+e^-) = 0.8 \cdot 10^{-4}$$
$$B(X_d \to J/\Psi + e^+e^-) = 0.3 \cdot 10^{-4} \qquad (49)$$

Decay widths

- The baryonium picture implies that the two-meson decays go via intermediate baryon-antibaryon states of high mass. This implies basically narrow widths.
- We describe the decay by a single switch amplitude, associated to the process (subscripts indicate color configuration): $[cu][\bar{c}\bar{u}] \rightarrow (c\bar{c})_{col=1}(u\bar{u})_{col=1}$

$$L_{X_u \Psi V} = g_V \epsilon^{\mu\nu\rho\sigma} P_\mu X_\nu \psi_\rho V_\sigma = \\ = g_V M_X (\mathbf{X} \wedge \psi) \cdot \mathbf{V}$$

$$g_V M_X = \frac{A}{\sqrt{2}}$$

- a bold guess: A=2.6 GeV

$$\Gamma(X_l \to J/\psi + \pi^+\pi^-) = \frac{2x_{l,\rho}|A|^2}{8\pi M_X^2}\langle p\rangle_\rho = \\ = 2x_{l,\rho} \cdot 2.3 \text{ MeV};$$

$$\Gamma(X_l \to J/\psi + \pi^+\pi^-\pi^0) = \frac{2x_{l,\omega}|A|^2}{8\pi M_X^2}\langle p\rangle_\omega = \\ = 2x_{l,\omega} \cdot 0.4 \text{ MeV}$$

- We anticipate small widths, comparable to the resolution of Belle and Babar

X particles in B decays

- Taking Belle data at face value, we conclude that only one of the two neutral states is produced appreciably in B^+ decay
- The the other has to appear in B^0 decay:
  - The X particles in B^+ and B^0 decays are not the same, and have a mass difference of 7±2 MeV
- Bounds to the production of X^+:

$$R^+ = \\ = \frac{\mathcal{B}(B^+ \to K_S X^+) \cdot \mathcal{B}(X^+ \to J/\Psi + \pi^+\pi^0)}{\mathcal{B}(B^+ \to K^+ X_{l/h}) \cdot \mathcal{B}(X_{l/h} \to J/\Psi + \pi^+\pi^-)} > 0.2$$

$$R^0 = \\ = \frac{\mathcal{B}(B^0 \to K^+ X^-) \cdot \mathcal{B}(X^- \to J/\Psi + \pi^-\pi^0)}{\mathcal{B}(B^0 \to K_S X_{h/l}) \cdot \mathcal{B}(X_{h/l} \to J/\Psi + \pi^+\pi^-)} > 0.53$$

to be compared with the upper limit given by BaBar [27]:

$$R^+ < 0.8$$

with large errors.

Conclusions

- A convincing picture of light scalars as $[qq][\bar{q}\bar{q}]$ states:
  - Masses
  - Ideal mixing
  - Decays reasonably described (exact SU3!) but for OZI violating (??)
  - Note: Δm(f-a)~10MeV, Δm(up-down) ~5MeV: are f(980) and a(980) pure I-spin eigenstates?
- New phenomena
  - States $[cq][\bar{c}\bar{q}]$ and $[cq][\bar{c}\bar{s}]$ should exist, with both natural and unnatural spin parity;
  - I-spin breaking expected maximal in certain decay: was the SELEX particle just the first case?
  - X(3872) a good candidate, X(3940) predicted

Study of Φ decays in KLOE very important

WERE ARE THE EXOTIC STATES??? !

APPENDIX

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

$$D \longrightarrow 3\pi$$

could resonate on a *scalar bump* with

$$m_\sigma = 478 \pm 24 \ \mathrm{M}eV$$
$$\Gamma_\sigma = 324 \pm 41 \ \mathrm{M}eV$$

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!*

The full SU(3) effective lagrangian...

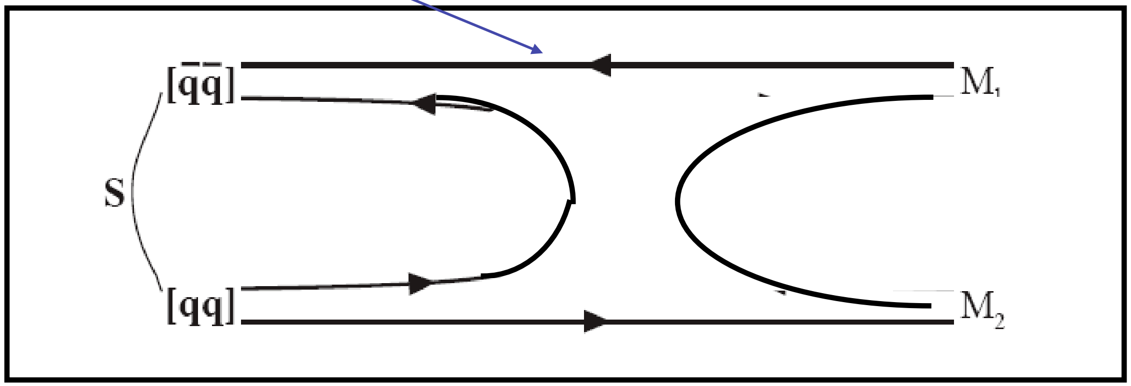
has three couplings:

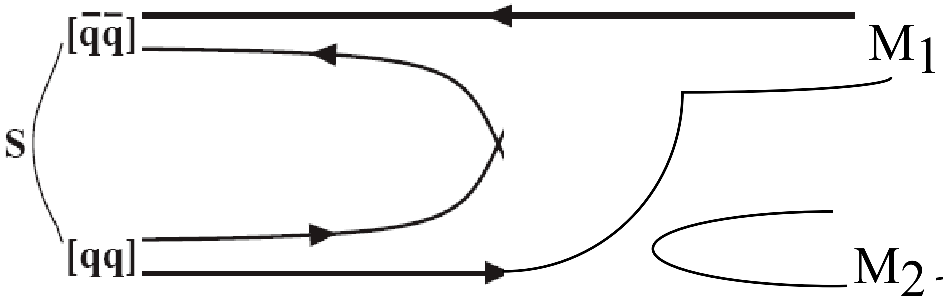
$$\mathcal{L} = (S_i^j)\epsilon_{jlm}\epsilon^{ikn}[aM_k^l M_n^m + b\delta_k^l (M^2)_n^m + \\ + c\delta_k^l (M)_n^m \mathrm{Tr}M],$$

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

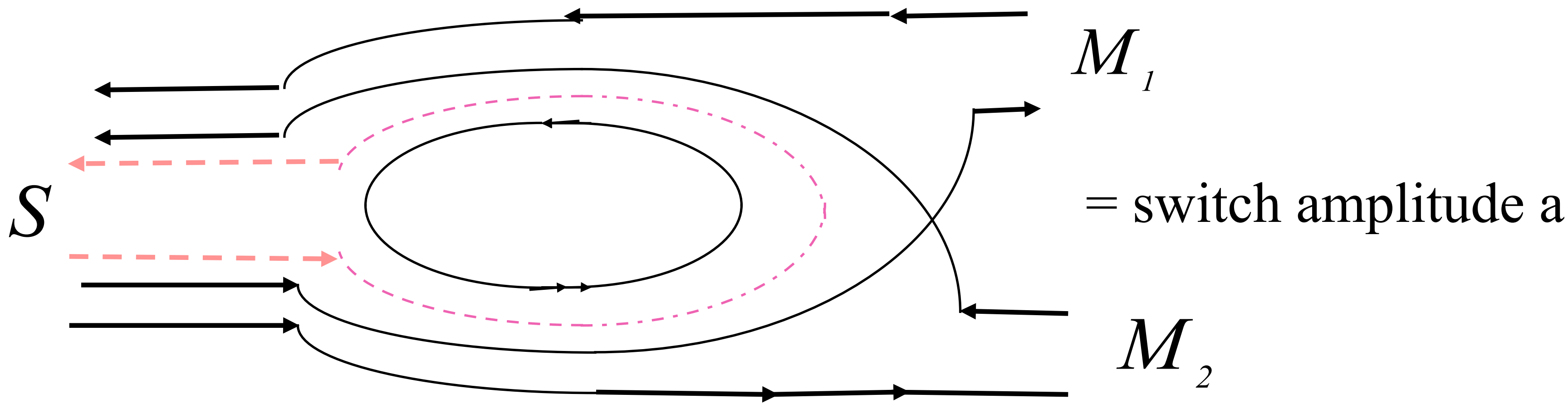
Quark rearrang.

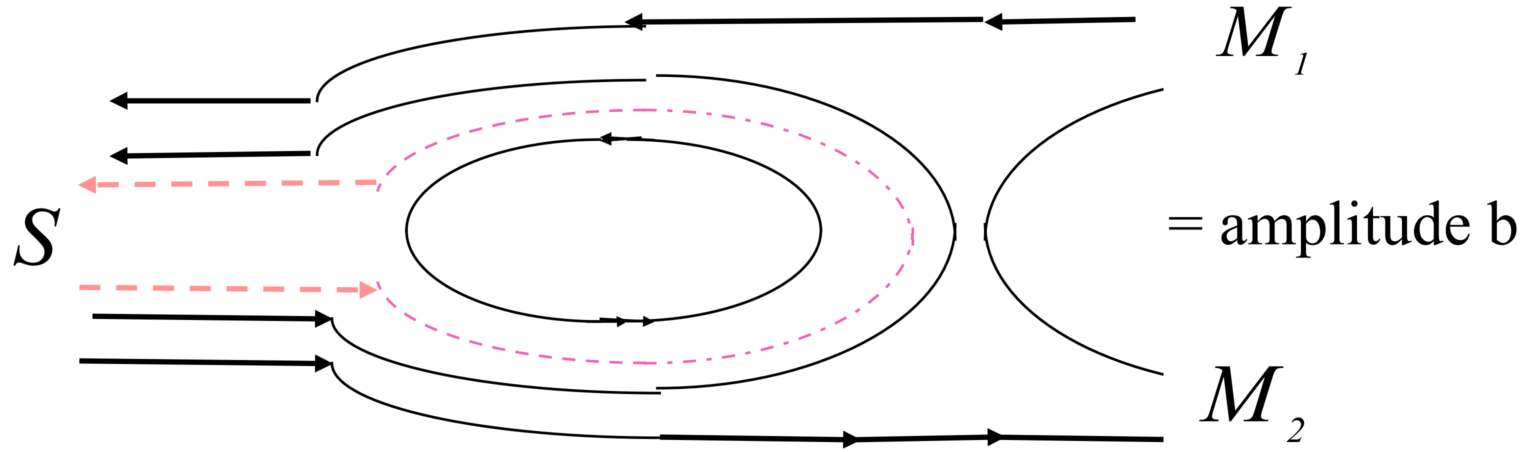
$$\mathcal{L} = (S_i^j)\epsilon_{jlm}\epsilon^{ikn}[aM_k^l M_n^m + b\delta_k^l (M^2)_n^m + \\ + c\delta_k^l (M)_n^m \mathrm{Tr} M],$$





Diquark-antidiquark decays





Decay proceed via B- Bbar virtual states! Should we try the same for $\phi \to S\gamma$?

$$|a-2b| = 2.6 \ \text{GeV} \ (= A) \ (\text{from} \ \sigma \to \pi\pi),$$
$$|a-3b| = 3.1 \ \text{GeV} \ (\text{from} \ f_0 \to K\bar{K}),$$
$$|a-b| = 1.8 \ \text{GeV} \ (\text{from} \ a_0 \to K\bar{K}), \qquad (19)$$

indeed equally spaced with: $b = -0.7$ GeV.

We find further: $\Gamma(\kappa) = 66$ MeV; $g_\pi = 0.06$.

c should be small: with c=0 we get $\Gamma(a \to \eta\pi)$=30 MeV vs 60±13MeV

Still too low.

Maybe f ππ comes from “one-loop”:

$$f \to K\bar{K} \to \pi\pi,$$

or perhaps (!!) $f \to B\overline{B} \to \pi\pi$ (Baryonium picture, see later)

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

1. 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:

$$\Gamma(a_0 \to \eta\pi) = 60 \pm 13 \text{ MeV}, \tag{14}$$
$$\Gamma(a_0 \to K\bar{K}) = 12 \pm 3 \text{ MeV}. \tag{15}$$

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:

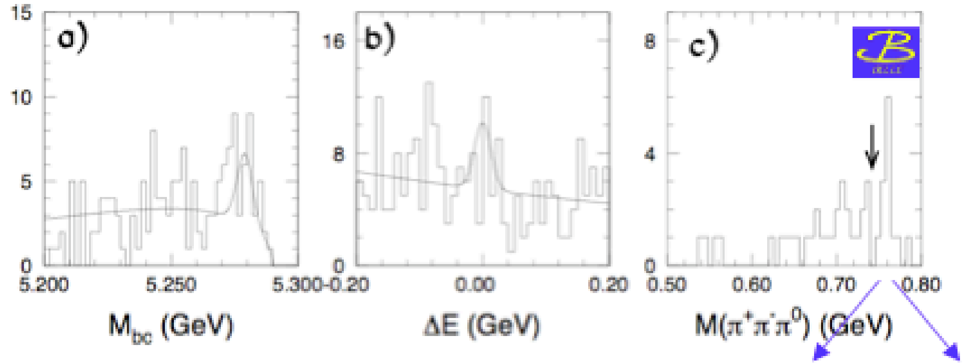
$$\Gamma(S \to i) = g_i p(M) \tag{16}$$

and fit the data to a Breit-Wigner formula with mass-dependent width, thus giving directly the values of g_i that we report in the Table II.

D. Barberis et al., Phys. Lett. **B453** (1999) 325.

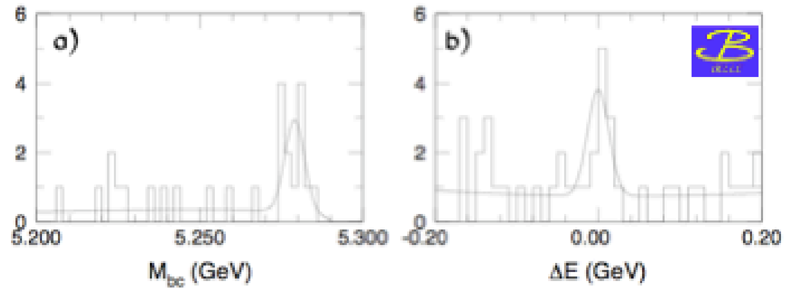
By the way…

- Events selected within 2σ (12 MeV/c^2) of 3872 MeV/c^2 show hints of a *B* signal.
  - After cutting at $m(\pi^+\pi^-\pi^0)$ > 750 MeV/c^2, a cleaner signal is present over a low background. Fit yields 10.0 ± 3.6 events (5.8 σ)



- Assuming all signal is ω (and *X*(3872)!):

$$\frac{\Gamma(X \to J/\psi\,\omega)}{\Gamma(X \to J/\psi\,\pi^+\pi^-)} = 0.8 \pm 0.3 \pm 0.1$$



E. Robutti Dresden, September 23, 2004 10

Diquark-Antidiquarks with Hidden or Open Charm and the Nature of $X(3872)$

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Heavy-light diquarks can be the building blocks of a rich spectrum of states which can accommodate some of the newly observed charmonium-like resonances not fitting a pure $c\bar{c}$ assignment. We examine this possibility for hidden and open charm diquark-antidiquark states deducing spectra from constituent quark masses and spin-spin interactions. Taking the $X(3872)$ as input we predict the existence of a 2^{++} state that can be associated to the $X(3940)$ observed by Belle and re-examine the state claimed by SELEX, $X(2632)$. The possible assignment of the previously discovered states $D_s(2317)$ and $D_s(2457)$ is discussed. We predict $X(3872)$ to be made of two components with a mass difference related to $m_u - m_d$ and discuss the production of $X(3872)$ and of its charged partner $X^{\pm}$ in the weak decays of $B^{+,0}$.

ROMA1-1396/2004, FNT/T-2004/20, BA-TH/502/04, CERN-PH-TH/2004-239

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iv:hep-ph/0412098 v2 21 Dec 2004

I. INTRODUCTION

It is an old idea that the light scalar mesons $a(980)$ and $f(980)$ may be 4-quark bound states [1]. The idea was more or less accepted in the mid-seventies but then it lost momentum, due to contradictory results that led the lowest-lying candidate members of a diquark-antidiquark nonet, σ and κ, to disappear from the Particle Data Tables.

From this point of view, the recent observations of $\sigma(480)$ and $\kappa(800)$ in D non-leptonic decays at Fermilab [3] and in the $\pi\pi$ spectrum in $\phi \to \pi^0\pi^0\gamma$ at Frascati [4], have considerably reinforced the case of a full nonet with inverted spectrum, as expected for $[qq][\bar{q}\bar{q}]$ states and fully antisymmetric diquark ($[qq]$: color $= \bar{3}$, flavor $= \bar{3}$, spin $= 0$). The isolated $I = 0$ state is the lightest and it likes to decay in $\pi\pi$; the heaviest particles have $I = 1, 0$ and like to decay in states containing strange quark pairs.