Four Quark Interpretation of Y(4260)

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Observation of a Broad Structure in the $\pi^+\pi^-$ J/ Mass Spectrum around 4.26GeV/c2, B. Aubert et al. BaBar Collaboration

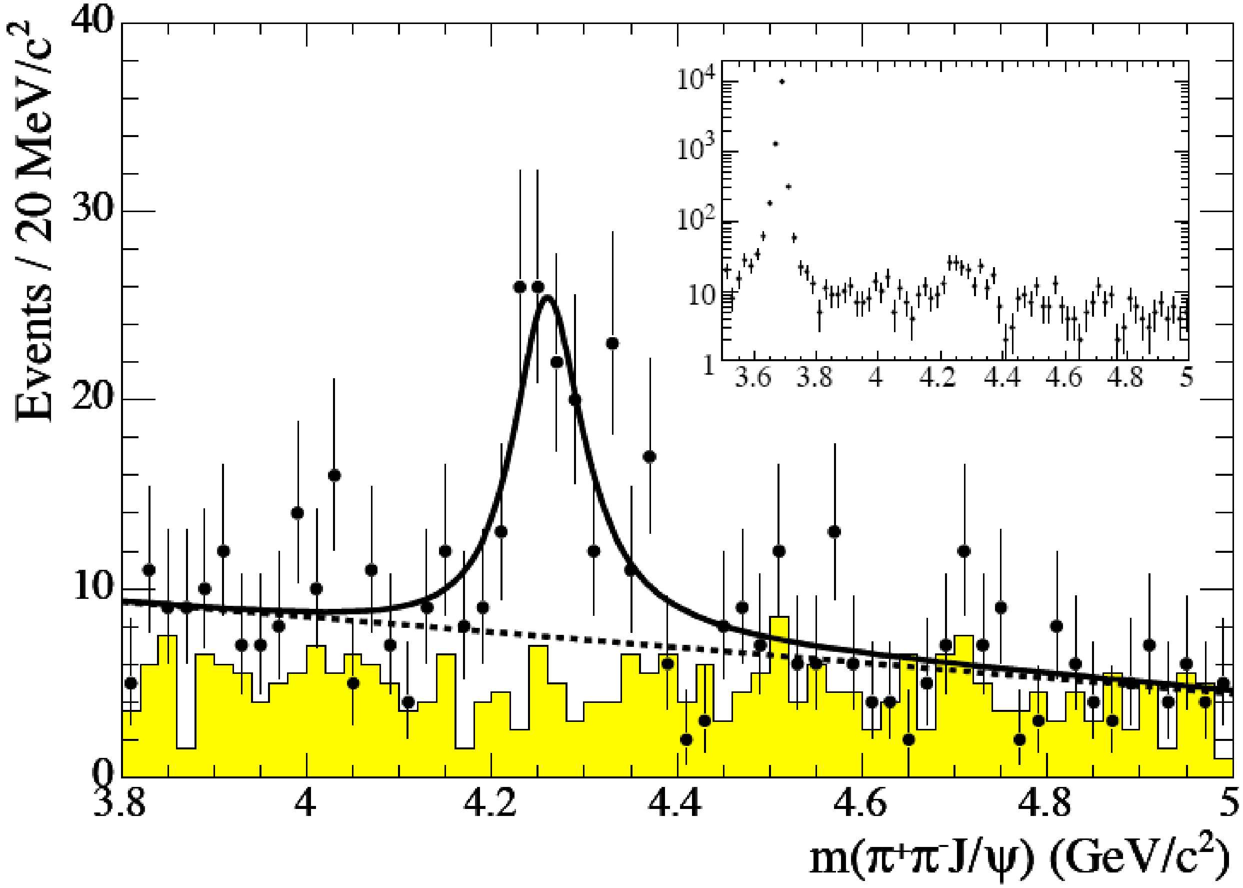


FIG. 1: The $\pi^+\pi^- J/\psi$ invariant mass spectrum in the range 3.8$-$5.0 GeV/c^2 and (inset) over a wider range

Presumably in coincidence with one energetic photon from Initial State Radiation.

Thus: $J^{PC}=1^{--}$

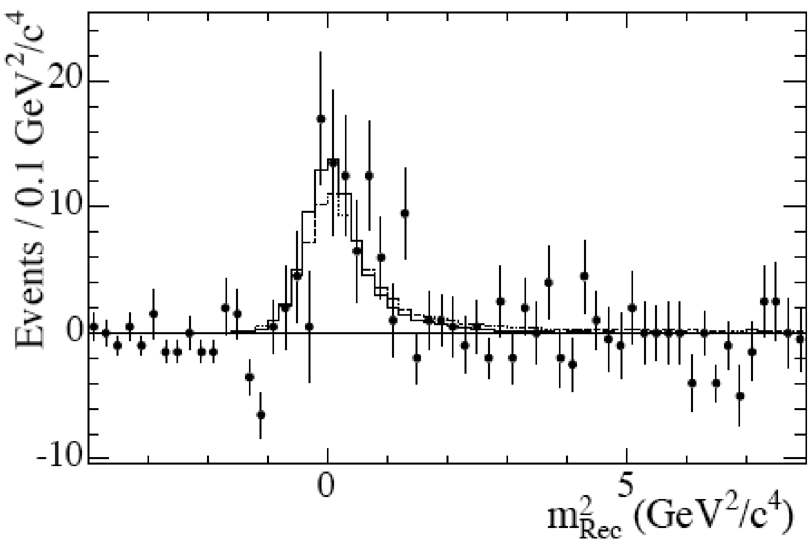


FIG. 2: The distribution of m^2_{Rec}. The points represent the data events passing all selection criteria except that on m^2_{Rec} and having a $\pi^+\pi^- J/\psi$ mass near 4260 MeV/c^2, minus the scaled distribution from neighboring $\pi^+\pi^- J/\psi$ mass regions (see text). The solid histogram represents ISR Y Monte Carlo events, and the dotted histogram represents the ISR $\psi(2S)$ data events.

$J/\Psi\ \pi^+\pi^-$ decays of X(4260)

$f_0(980)$??

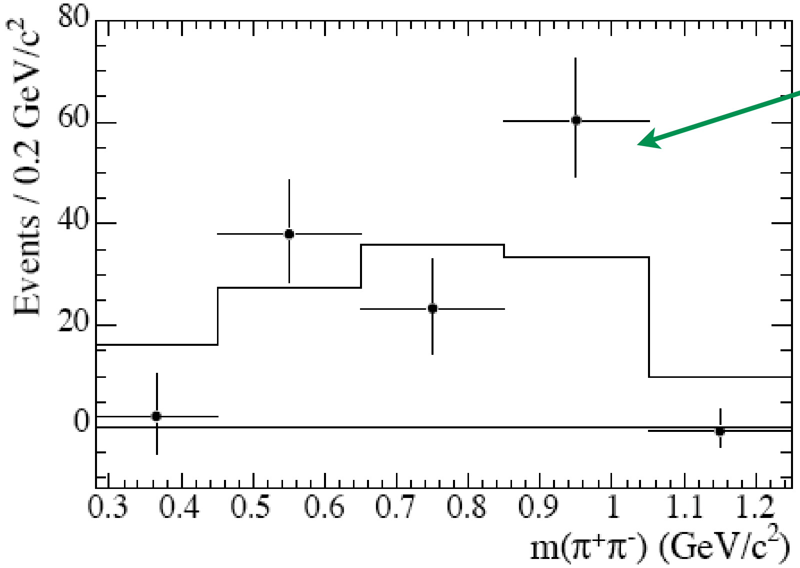
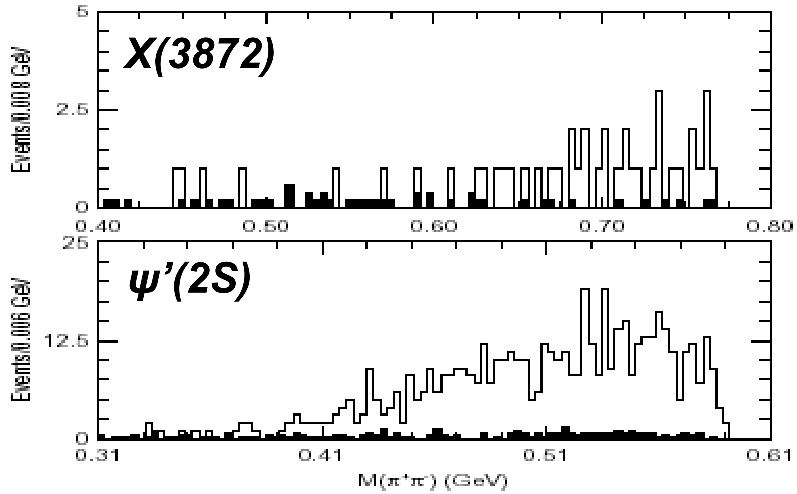


FIG. 3: The dipion mass distribution for $Y(4260) \to \pi^+\pi^- J/\psi$ data is shown as points with error bars. The histogram shows the distribution for Monte Carlo events where $Y(4260) \to \pi^+\pi^- J/\psi$ is generated according to an S-wave phase space model.

For comparison:



S-wave 4quark hidden charm states

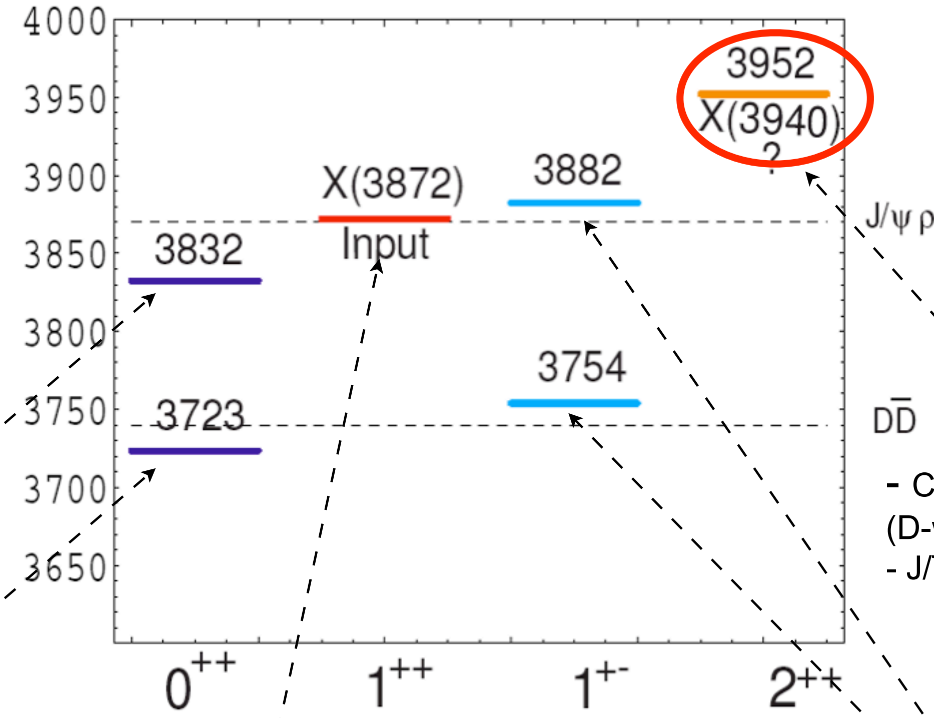
Tetraquarks with open and hidden charm (Phys.Rev. **D70**, 054009 (2004); hep-ph/0412098)

- 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 ⊕ S=1)⊗(S=0 ⊕ 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

$$M = \sum_i m_i + \sum_{i<j} 2\kappa_{ij}(S_i \cdot S_j)$$

X-states



Belle

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

DDbar

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

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

J/Ψ π(η), η_c ρ(ω)

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

D-D* molecule

- one state only: D^0-D^{*0}
- ... and very extended:
- $$R = \frac{1}{\sqrt{2M_D E_{bind}}} \sim 4\, fm$$
- most of the time (70-80%), D and D* are too far to exchange a c-quark and form a J/Ψ;
- for a tight state: BR(Ψ'→ Ψ$\pi^+\pi^-$) ≈ 0.3, maybe: BR(X→ Ψ $\pi^+\pi^-$)≈ 0.03
- the measure of inclusive B(B^+→ XK^+) determines the X BR from the overall ratio:
- $$R = \frac{B(B^+ \to XK^+)B(X \to J/\Psi\, \pi^+\pi^-)}{B(B \to \Psi' K^+)B(\Psi' \to J/\Psi\, \pi^+\pi^-)} = 0.063 \pm 0.014$$
-
- and it would give an important clue.

Confining vs short range forces

- Colored objects such as diquarks in a rising confining potential should exhibit a series of orbital angular momentum excitations.
- Molecular picture: two colorless objects bound by a short range potential should have a very limited spectrum, possibly restricted to S-wave states only.
- we propose that the first orbital excitation of a diquark-antidiquark state may have indeed been found in the state Y (4260).
- The most revealing property is that the dominant decay mode of Y (4260) should be in D_s-bar D_s pairs.
- We comment on the possibility of an additional narrow state.
- We shall briefly discuss other states implied by the scheme and their properties.

- The diquark-antidiquark assumption and negative parity call for at least one unit of orbital angular momentum.
- The decay into f0(980), which fits the ([sq][¯s¯q])S–wave hypothesis, suggests a [cs][cbar sbar] composition.
- All considered, we are led to the following assumption for the Y (4260):
  Y (4260) = $([cs]_{S=0}[\bar{\ }\text{cbar sbar}]_{S=0})_{\text{P-wave}}$
- both diquarks are in a 3-bar color state.

- We expect diquarks involving charmed quarks to be bound also in states with non- vanishing spin (bad diquarks, with S = 1).
- Several other states with $J^{PC} = 1^{--}$ are possible and one would expect the physical Y (4260) to be a linear superposition of all such states.
- Restrict to the simplest, unmixed, state in the first analysis
- Comment later on the other states.

Spin-spin interactions: what do we know?

	q	s	c
constituent	305	490	1670
mass (MeV)	362	546	1721

TABLE I: Constituent quark masses derived from the $L = 0$ mesons (first row) or from the $L = 0$ baryons (second row).

q-qbar Mesons

	$q\bar{q}$	$s\bar{q}$	$s\bar{s}$	$c\bar{q}$	$c\bar{s}$	$c\bar{c}$
$(\kappa_{ij})_0$ (MeV)	315	195	121*	70	72	59
$(\kappa_{ij})_0 m_i m_j (\text{GeV})^3$	0.029	0.029		0.036	0.059	0.16

TABLE II: Spin-spin couplings for quark-antiquark pairs in color singlet from the hyperfine splittings of $L = 0$ mes (first row). The values in the second row show the app imate scaling of the couplings with inverse masses (ma from meson spectrum). *The $s\bar{s}$ coupling which is not ex imentally accessible, is obtained by rescaling the $s\bar{q}$ one the factor m_q/m_s.

diquarks in Baryons

	qq	sq	cq	cs
$(\kappa_{ij})_{\bar{3}}$ (MeV)	103	64	22	25
$(\kappa_{ij})_{\bar{3}} m_i m_j (\text{GeV})^3$	0.014	0.013	0.014	0.024

TABLE III: Spin-spin couplings for quark-quark pairs in color $\bar{\mathbf{3}}$ state from $L = 0$ baryons. One gluon exchange implies $(\kappa_{ij})_{\bar{3}} = 1/2(\kappa_{ij})_0$. The values in the second row, show the approximate scaling of the couplings with inverse masses (masses from the baryon spectrum).

What is the mass?

$$M_Y = 2m_{[cq]} + 2(m_s - m_q) - 3\kappa_{cs} + B_c \left(\frac{L(L+1)}{2} \right). \quad (3)$$

$m_{[cq]}$ is the mass of the heavy-light diquark as computed in Ref. [1], i.e., $m_{[cq]} = 1933$ MeV, m_q and m_s are the constituent up and strange quark masses, respectively. A fit to the lowest lying meson and baryon masses, as reported in Table I of [1], gives $m_s - m_q = 185$ MeV.

we are neglecting $H_{\text{spin-spin}} = 2\kappa_{cs}(\vec{S}_c \cdot \vec{S}_s + \vec{S}_{\bar{c}} \cdot \vec{S}_{\bar{s}})$

- spin-spin interactions between quarks and antiquarks (because of the angular momentum barrier which separates the diquark from the antidiquark)
- spin-orbit interaction (because of S = 0).

Spin-orbit interaction can mix the good diquark, S = 0, with the bad diquark, S = 1, giving however only a second order correction to the mass that we neglect.

The orbital angular momentum term in (3) is the only new ingredient with respect to Ref. [1] and it can be estimated from the mass spectrum of the $q\bar{q}$ mesons with $L = 0$ and $L = 1$. We describe the masses of the $S = 1$ states $\rho(770), a_1(1230), a_2(1320)$ with the equation:

$$M(S = 1, L, J) =| K + 2A_q \vec{S} \cdot \vec{L} + B_q \frac{L(L+1)}{2}. \quad (5)$$

One finds at once (symbols indicate particle masses):

$$B_q = \frac{a_1 + a_2 - 2\rho}{2} = 0.495 \text{ GeV}. \quad (6)$$

To estimate the analogous coefficient in Eq. (3) we observe that for the quantum rotator $B \propto (mR^2)^{-1}$, with R the radius of the bound state. We take for m the diquark mass and $R \sim (\alpha_s m)^{-1}$. In conclusion we find:

$$B = \left[\frac{\alpha_s(m_{[cs]})}{\alpha_s(m_q)}\right]^2 \frac{m_{[cs]}}{m_q} B_q \sim 0.24 \times B_q \sim 120 \text{ MeV} \quad (7)$$

where we have used $\alpha_s(m_{[cs]}) \simeq 0.2$, $\alpha_s(m_q) \simeq 1$, $m_q = 0.350$ GeV [1] and $m_{[cs]} = 2.1$ GeV as given above.

Putting everything together we arrive to the estimate:

$$M_Y = 4.28 \text{ GeV}, \quad (8)$$

DECAYS

Given the quantum numbers $J^{PC} = 1^{--}$, the state in Eq. (2) should decay strongly into a pair of mesons with open charm. The quark composition in (2) implies a definite preference for charm-strange states:

$$\Gamma_Y(D_s\bar{D}_s) >> \Gamma_Y(D\bar{D}) \qquad (9)$$

Dominant $D_s\bar{D}_s$ decay is quite a distinctive signature of the validity of the present model.

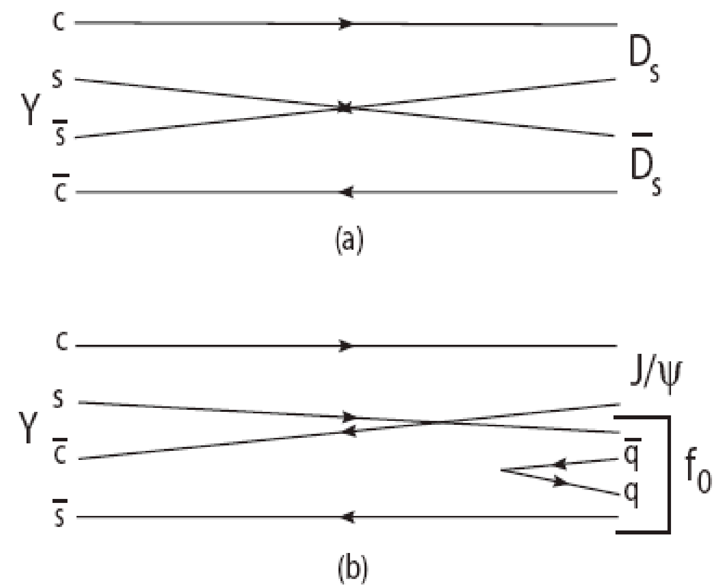
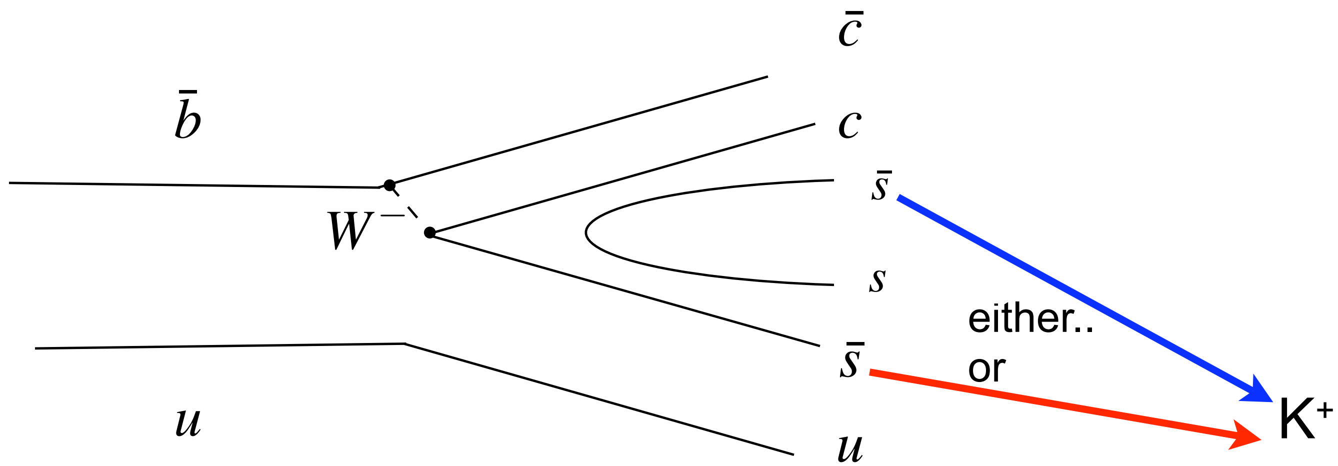


FIG. 1: (a) Quark diagram for the dominant decay channel to $D_s\bar{D}_s$ see Ref. [3]. (b) Decay amplitude for $Y \to J/\psi f_0(980)$ under the assumption that both Y and f_0 are four-quark states.

X particles in B decays

There are two amplitudes for $B^+ \Rightarrow K^+ X$



A narrow satellite line?

- The BaBar data suggest, although inconclusively, that there may be a considerably more narrow satellite line at M ~ 4330 MeV.
- Such a mass difference is of the order of the spin-spin interaction.
- If one calls into play bad diquark states with S = 1 there are several additional 1^{--} states with the same quark composition, $(cs)(\bar{c}\bar{s})$.
- Among them, the state with both diquark and antidiquark with S=1, combined to $S_{tot} = 2$.
- This state projects only on spin one cbar s and sbar c states.
- In the limit where the spin of the s quark is a good quantum number, such state could decay only into $D^*_s(D^*_s)$bar, wth substantial reduction of its decay width.

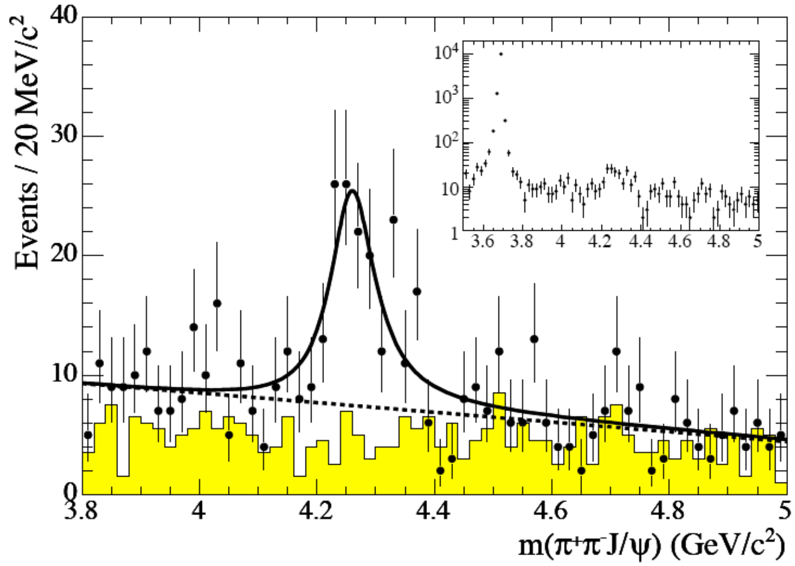
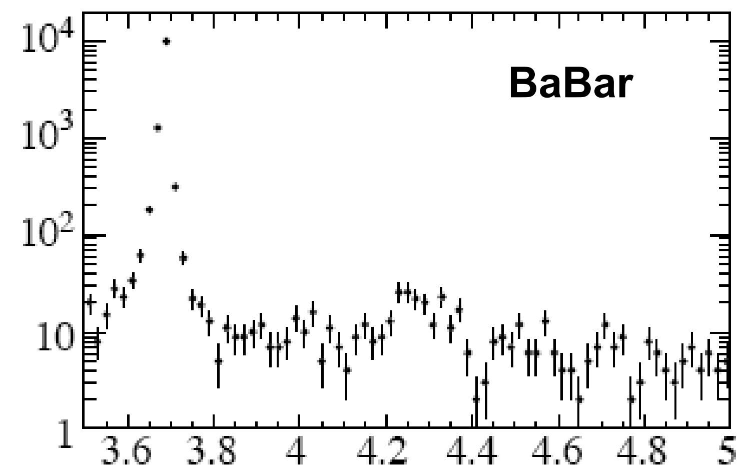


FIG. 1: The $\pi^+\pi^- J/\psi$ invariant mass spectrum in the range 3.8–5.0 GeV/c^2 and (inset) over a wider range that includes

Related states: a full SU3 nonet

- Y_{qqbar} = ([cq]$_{S=0}$[¯cbar qbar']$_{S=0}$)$_{P\text{-wave}}$ (q, q' = u, d, s)
- From the charm baryon spectrum one finds:
  $(\kappa_{cs})_{3bar} \simeq (\kappa_{cq})_{3bar}$, so that the levels in the nonet are equispaced by ≃ 185 MeV
- (s=strangeness):
  M (I=0,1;s=0) = 3.91 GeV; M (I=1/2;s=±1) = 4.10 GeV.
- They fall in very busy region !



- Neutral members of the non-strange complex should be seen in e+e– annihilation and in B non-leptonic decays
- Dominant decay modes: D Dbar .
- Similar to the X(3872) case, significant isospin breaking in the wave function of the non-strange states is expected, i.e. unequal branching ratios of each mass eigenstate in D^+D^- versus D^0 D^0bar
- ([cu][cbar ubar])$_{P-wave}$ → D^0 D^0bar only, ([cd][cbar dbar])$_{P-wav}$ → D^+D^-.
- Decays into J/ψ π+π– expected, with π+π– peaking at the σ(480) mass

Conclusions

- BELLE and BaBar are finding a wealth of new states
- variety of JPC quantum numbers, several of them decay in J/Ψ +pions, many do not fit the c-cbar scheme.
- The observation of $J^{PC}=1^{--}$ state X(4260) is very interesting: orbital excitations are typical of colored objects in confining potential
- hybrid (constituent gluon) interpretation of X(4260) also attempted, but: why does it not decay in D-Dbar?
- The observation of D_s $D_s$bar decay will be the turning point, validating or disproving 4q
- but still many puzzle and mysteries

stay tuned on hadron spectroscopy: it is alive and well!!