The XYZ's of $c\bar{c}$: Hints of Exotic New Mesons?

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FPCP 2006, Vancouver, April 10 2006

- Spectroscopy: Conventional and Hybrids

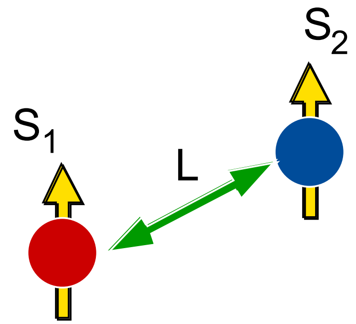
- New Charm States
  - $D_{sJ}^*(2317)$, $D_{sJ}(2460)$, $D_{sJ}(2630)$
  - $D_0^*(2308)$, $D_1'(2440)$,

- New Charmonium states
  - *X(3872), X(3943), Y(3943), Z(3931) and Y(4260)*

- Summary

General Remarks about Spectroscopy

Meson quantum numbers characterized by given J^{PC}:



$S = S_1 + S_2$

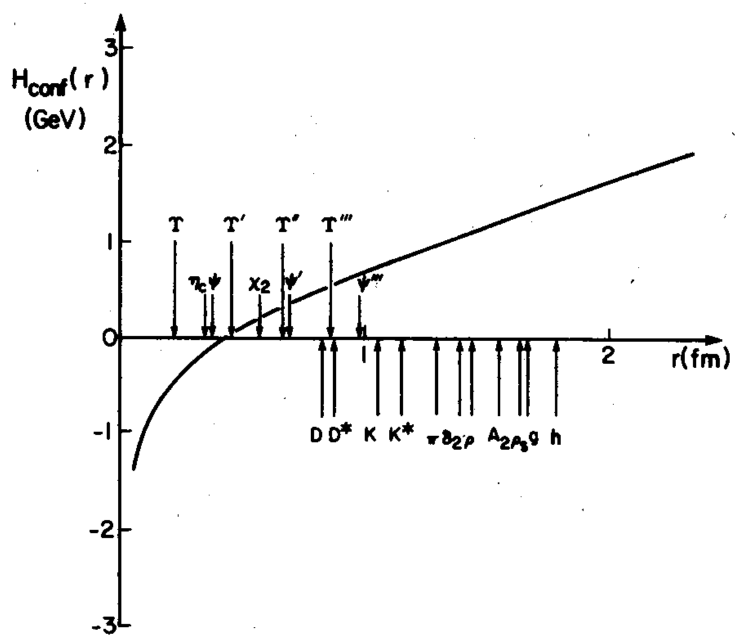
$J = L + S$

$P = (-1)^{L+1}$

$C = (-1)^{L+S}$

For given spin and orbital angular momentum configurations & radial excitations generate the meson spectrum

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$

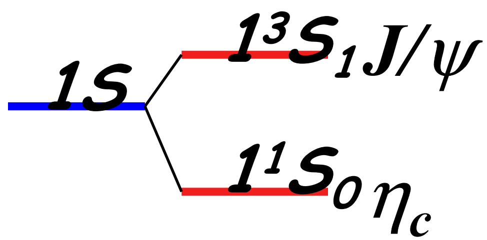


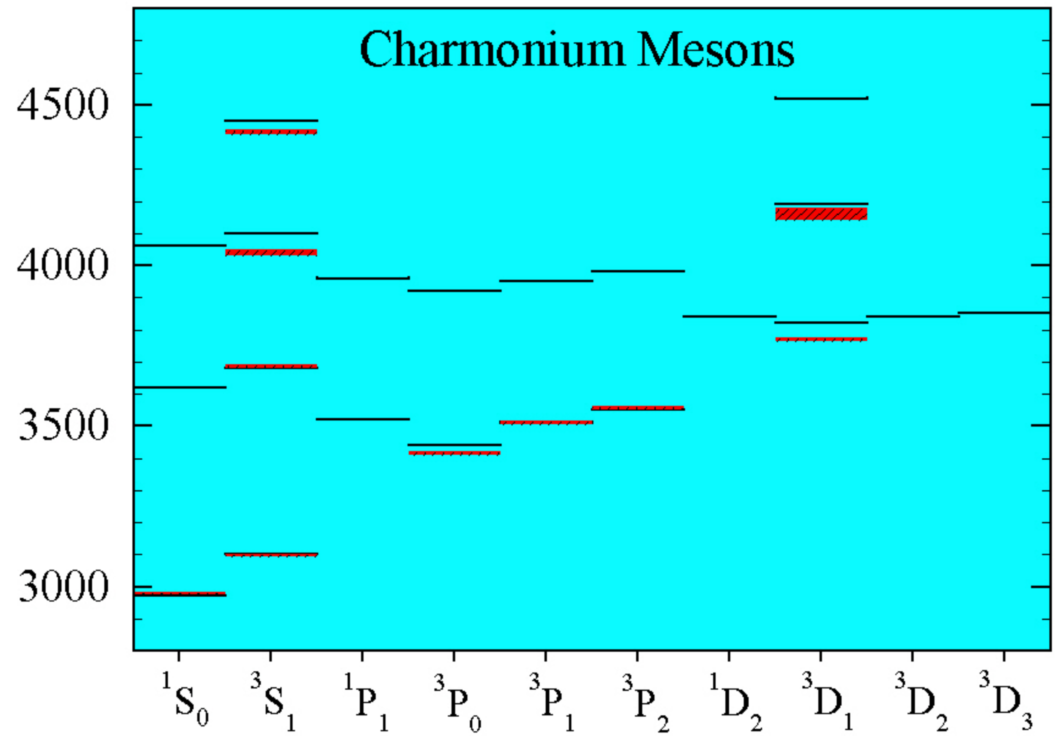
Spin-dependent potentials:

- Lorentz vector 1-gluon exchange + scalar confinement
- Spin-dependent interactions are $(v/c)^2$ corrections

Spin-spin interactions:

$$H_{ij}^{hyp} = \frac{4\alpha_s(r)}{3m_i m_j}\left\{\frac{8\pi}{3}\vec{S}_i\cdot\vec{S}_j\,\delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3}\left[\frac{3\vec{S}_i\cdot\vec{r}_{ij}\vec{S}_j\cdot\vec{r}_{ij}}{r_{ij}^2} - \vec{S}_i\cdot\vec{S}_j\right]\right\}$$

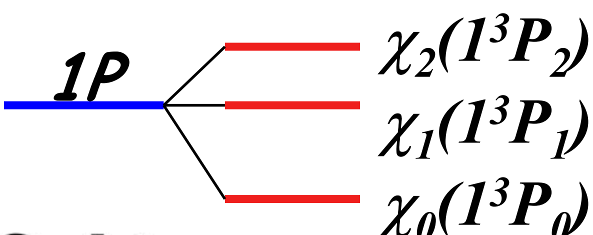




Spin-orbit interactions:

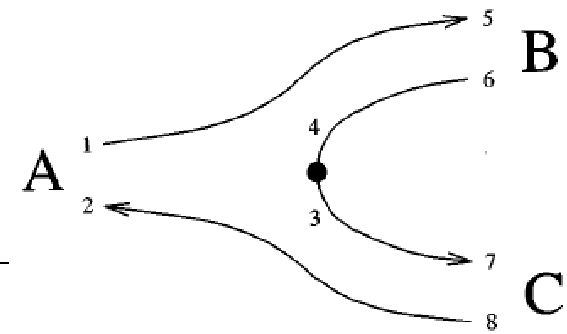
$$H_{ij}^{s.o.(cm)} = \frac{4\alpha_s(r)}{3r_{ij}^3}\left(\frac{1}{m_i}+\frac{1}{m_j}\right)\left(\frac{\vec{S}_i}{m_i}+\frac{\vec{S}_j}{m_j}\right)\cdot\vec{L}$$

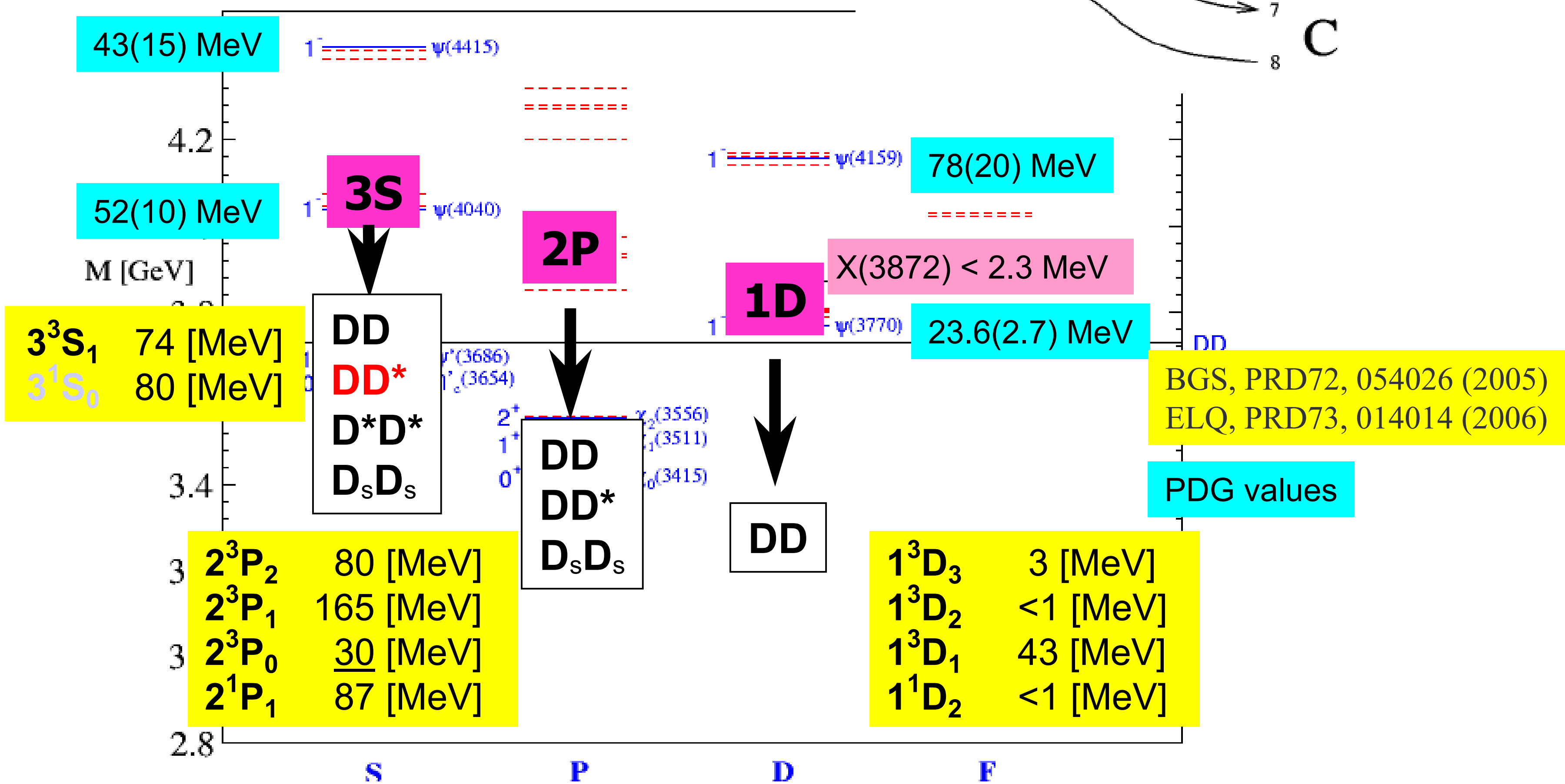
$$H_{ij}^{s.o.(tp)} = \frac{-1}{2r_{ij}}\frac{\partial V(r)}{\partial r_{ij}}\left(\frac{\vec{S}_i}{m_i^2}+\frac{\vec{S}_j}{m_j^2}\right)\cdot\vec{L}$$



Strong Decays

The $^3P_0$ decay model describes hadron decays reasonably well





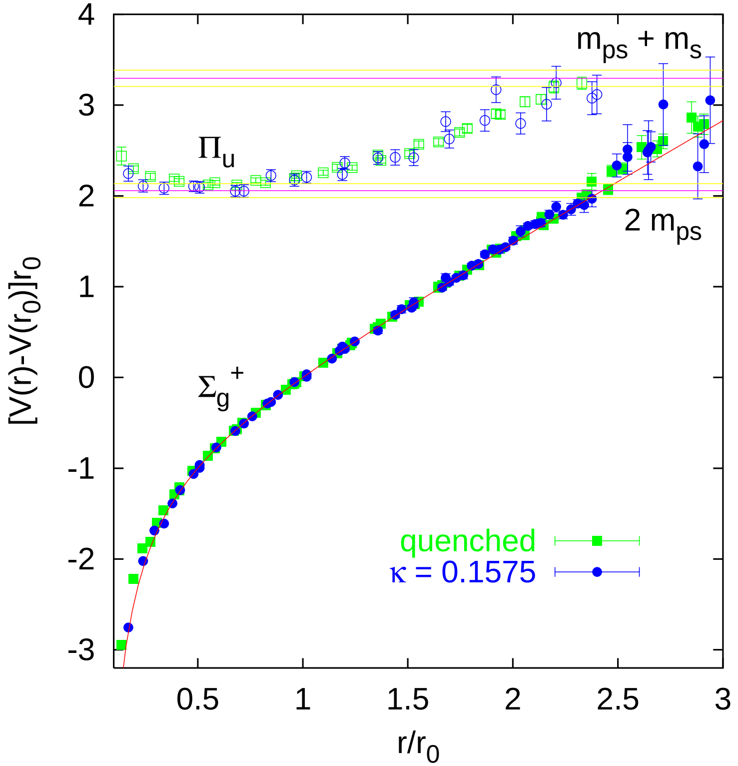
Important to understand charmonium states to identify states that don't fit and might represent new spectroscopies

Hybrids

Close and Godfrey PL B574, 210 (2003).

Bali: hep-ph/0010032

- Quarks move in adiabatic potentials
- Lowest excited adiabatic surface corresponds to transverse excitations
- Doubly degenerate lowest mass hybrids:
- J^{PC} = 0^{+-} 0^{-+} 1^{+-} 1^{-+} 2^{+-} 2^{-+} 1^{++} 1^{--}



T. BARNES, F. E. CLOSE, AND E. S. SWANSON PRD52, 5242 (1995).

TABLE I. Predicted 1^{-+} hybrid masses.

State	mass (GeV)	Model	Ref.
H_c	$\approx$ 3.9	Adiabatic bag model	[20]
	4.2–4.5	Flux tube model	[12–14]
	4.1–5.3	QCD sum rules (most after 1984)	[26–28]
	4.19(3) $\pm$ syst.	HQLGT	[23]

Hybrids Decays

Important decay modes:

1. $\psi_g \to D^{(*,**)} \overline{D}^{(*,**)}$

   hybrid decays to P-wave + S-wave mesons:
   - D(L=0)+D^{**}(L=1) should dominate
   - DD should not occur and DD^* have small widths

2. $\psi_g \to (c\bar{c})(gg) \to (c\bar{c}) + (\pi\pi, \eta, \ldots)$
   - Offers cleanest signature
   - IF total width small significant BR
     - $\psi_g(0^{+-}, 2^{+-}) \to J/\psi + (\pi\pi, \eta)$ and $\psi_g(1^{-+}) \to \eta_c + (\pi\pi, \eta)$
   - LGT (UKQCD) finds these decays to be large ~*O*(10's MeV)

     (shown for $\chi_b S$ where S is light scalar) [hep-lat/0201006]

Some other new states:

$\Upsilon(1D)$ CLEO: Phys. Rev. D70,032001 (2004) [hep-ex/0404021]

M=10161.1$\pm$ 0.6(stat) $\pm$ 1.6(syst) MeV
In agreement with potential models and Lattice QCD

B_c CDF: hep-ex/0505076

M=6287.0$\pm$ 4.8(stat) $\pm$ 1.1(syst) MeV/c^2
vs 6304 $\pm$ 12 (stat+syst) Lattice
6271 quark potential model

η_c' BELLE: Phys.Rev.Lett.89, 102001(2002) [hep-ex/0206002];142001(2002) [hep-ex/0205104]
CLEO: Phys.Rev.Lett. 92, 142001 (2004) [hep-ex/0312058]

M=3637.4$\pm$ 4.4 vs 3623 in quark potential model

h_c CLEO: Phys.Rev.Lett. 95, 102003 (2005) [hep-ex/0505073]

M=3524.4$\pm$ 0.6(stat) $\pm$ 0.4(syst) MeV/c^2
$M(^3P_J)-M(^1P_1)$=1.0 $\pm$ 0.6(stat) $\pm$ 0.4(syst)

$D_{sJ}(2317)$ & $D_{sJ}(2460)$

BABAR:

Phys.Rev.Lett. 90, 242001 (2003)

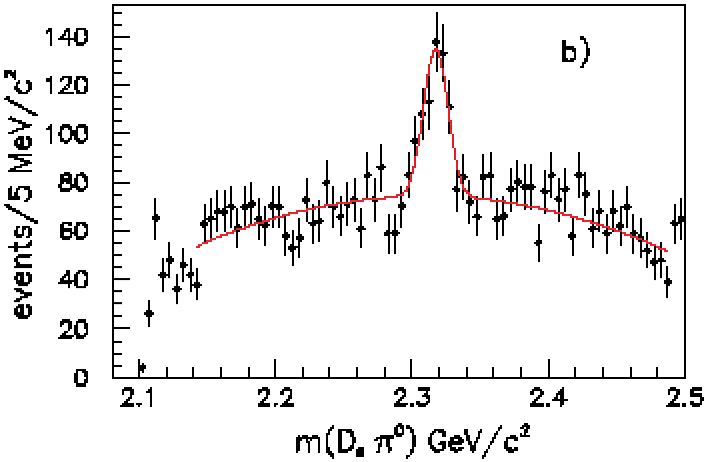


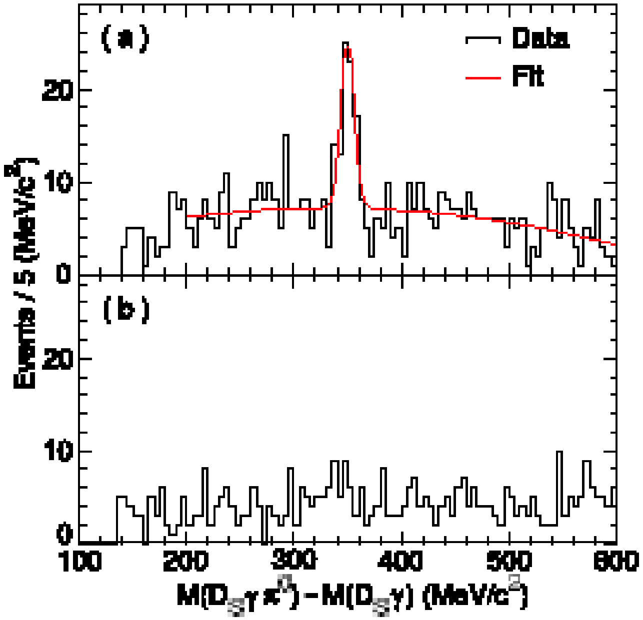
FIG. 2 (color online). The $D_s^+\pi^0$ mass distribution for (a) the decay $D_s^+ \to K^+K^-\pi^+$ and (b) the decay $D_s^+ \to K^+K^-\pi^+\pi^0$. The fits to the mass distributions as described in the text are indicated by the curves.

M=2316.8±0.4 MeV

$\Gamma \leq 3.8$ MeV

CLEO:

Phys.Rev. D68, 032002 (2003)

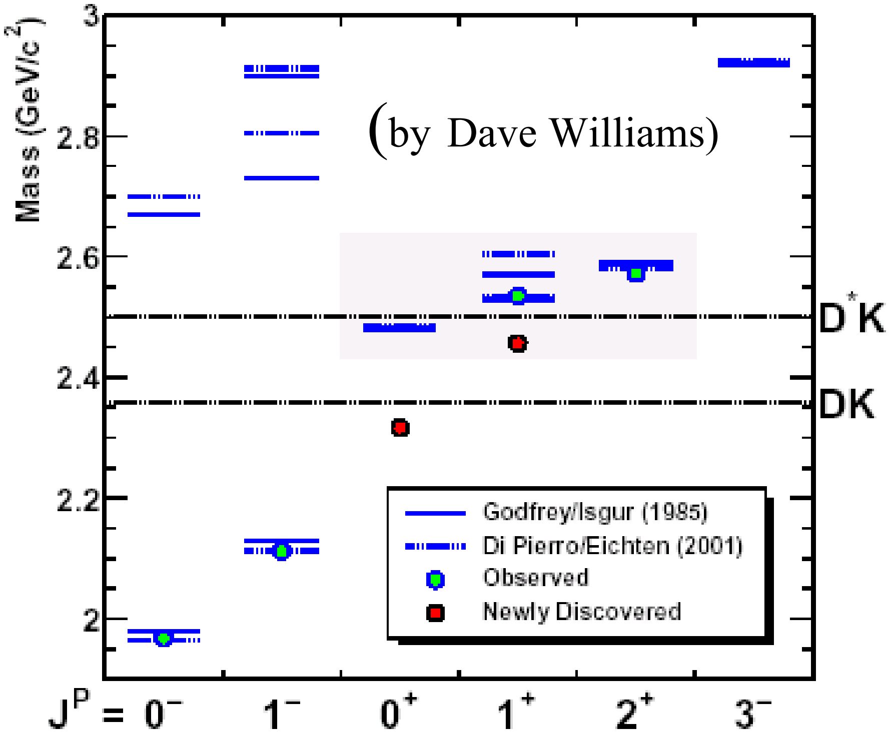


M=2463±0.4 MeV

$\Gamma \leq 3.5$ MeV

(Widths from Gowdy, Moriond talk)

- Also seen and studied by BELLE
- Properties consistent with $J^P=0^+$ and 1^+



j_q=1/2 predicted to be broad and decay to *DK* and *D*K*
not previously observed

But $D^*_{sJ}(2317)$ below *DK* threshold and very narrow!
$D_{sJ}(2460)$ below *D*K* threshold and very narrow!

Created major industry: (almost 300 citations!)

- Multiquark state
- Molecular state
- Dπ atom
- Conventional cs state but model needs improvement

The problem is the mass predictions

Once the masses are fixed the narrow widths follow

Radiative transitions are expected to have large BR's so their measurement is an important probe

$$\mathcal{B}(D_{sJ}(2460)^- \to D_s^{*-}\pi^0) = 0.51 \pm 0.11 \pm 0.09$$
$$\mathcal{B}(D_{sJ}(2460)^- \to D_s^-\gamma) = 0.15 \pm 0.03 \pm 0.02$$

Preliminary

Gowdy (Babar) Moriond talk

$$B(D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-) = 0.04 \pm 0.01 \text{ (stat. only)}$$

Where does the other (30 ± 15)% go?

Recall: $D_{s1}^{1/2} = -{}^1P_1 \sin\theta + {}^3P_1 \cos\theta$ PLB568, 254 (2003)

So $D_{s1}(2463) \to D_s^*\gamma$ is where it goes PRD72, 054029 (2005)

Can be used to determine mixing angle

$$\frac{\Gamma({}^3P_1 \to {}^3S_1 + \gamma)}{\Gamma({}^1P_1 \to {}^1S_0 + \gamma)} = \frac{\omega_t^3}{\omega_s^3} \frac{|\langle r \rangle_t|^2}{|\langle r \rangle_s|^2} \frac{\cos^2\theta}{\sin^2\theta}$$

Appears to be conventional cs L=1 states with masses shifted due to strong S-wave coupling to $DK^{(*)}$

Charmed mesons:

- Almost all the theoretical effort has concentrated on the D_{sJ} states
- But important to test the models on the D states which also contain important information

Decay	Expt*	Theory
$D_2^* \to D^*\pi + D\pi$	43.8 ± 2	55
$D_1 \to D^*\pi$	20.3	25
$D_1 \to D^*\pi$	339 ± 76	244
$D_0^* \to D\pi$	276 ± 66	277

* Average of PDG Belle PR D69 112002 (2004)
FOCUS PLB 586, 11 (2004)
CLEO NPA 663, 647 (2000)
CDF JP Conf Ser 9, 67 (2005)

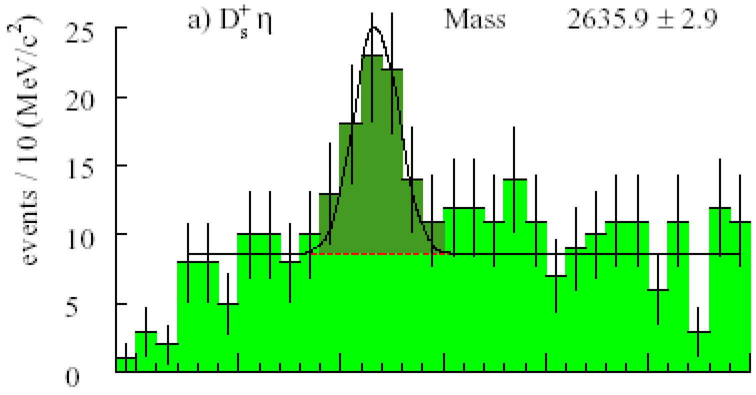
Theory: PR D43, 1679 (1991), (TRI-PP-86-51) PR D72, 054029 (2005)

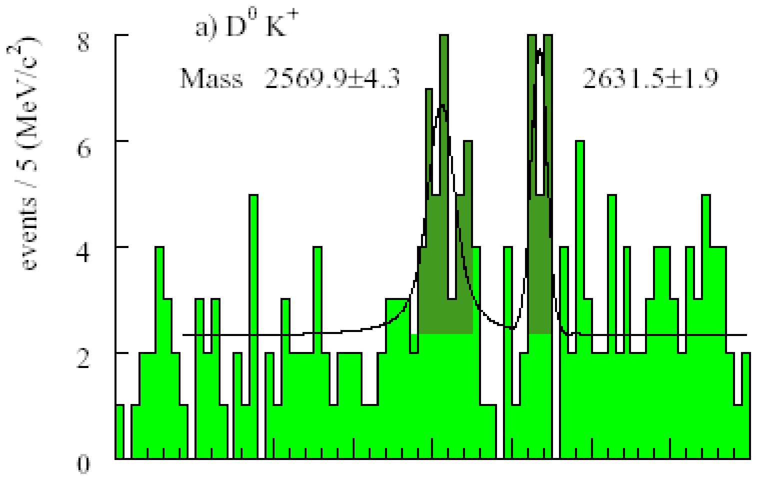
$D_{sJ}(2632)$

First Observation of a Narrow Charm-Strange Meson $D_{sJ}^{+}(2632) \to D_s^+\eta$ and D^0K^+

(The SELEX Collaboration)

Phys.Rev.Lett. 93, 242001 (2004) hep-ex/0406045





Seen in hadro-production in $D_s^+\eta$ and D^0K^+

M=2632.6±1.6 MeV/c^2 Γ<17 MeV/c^2 at 90% C.L.

$$\Gamma(D^0K^+)/\Gamma(D_s^+\eta) = 0.16 \pm 0.06$$

(Not seen by CLEO, Belle, Babar)

Possibilities:

- 2^3S_1(cs) State
- cs Hybrid
- 2-meson molecule

cs hybrid expected to be ~3170 MeV

Most plausible cs state is 2^3S_1 with $M(2^3S_1)$=2730 MeV
& $M(1^3D_1)$=2900 MeV

masses could be shifted by mixing with 2-meson continuum

Assuming the $D_{sJ}(2632)$ is $2^3S_1(c\bar{s})$ with M=2632

The allowed open-flavour decay modes are: $DK,\ D_s\eta,\ D^*K$

SELEX finds:

$BR(DK/D_s\eta) = 0.32 \pm 0.12$ (assuming $BR(D^0K^+)=BR(D^+K^0)$)

In $^3P_0$ model for preferred expect:

$$\Gamma(D^*K) > \Gamma(DK) >> \Gamma(D_s\eta)$$

$$\Gamma(D_{sJ}(2632)) = 36 \text{ MeV}$$

$$\Gamma(DK)/\Gamma(D_s\eta) \approx 9$$

Not consistent with experiment

It is possible to tune model to achieve agreement with experiment

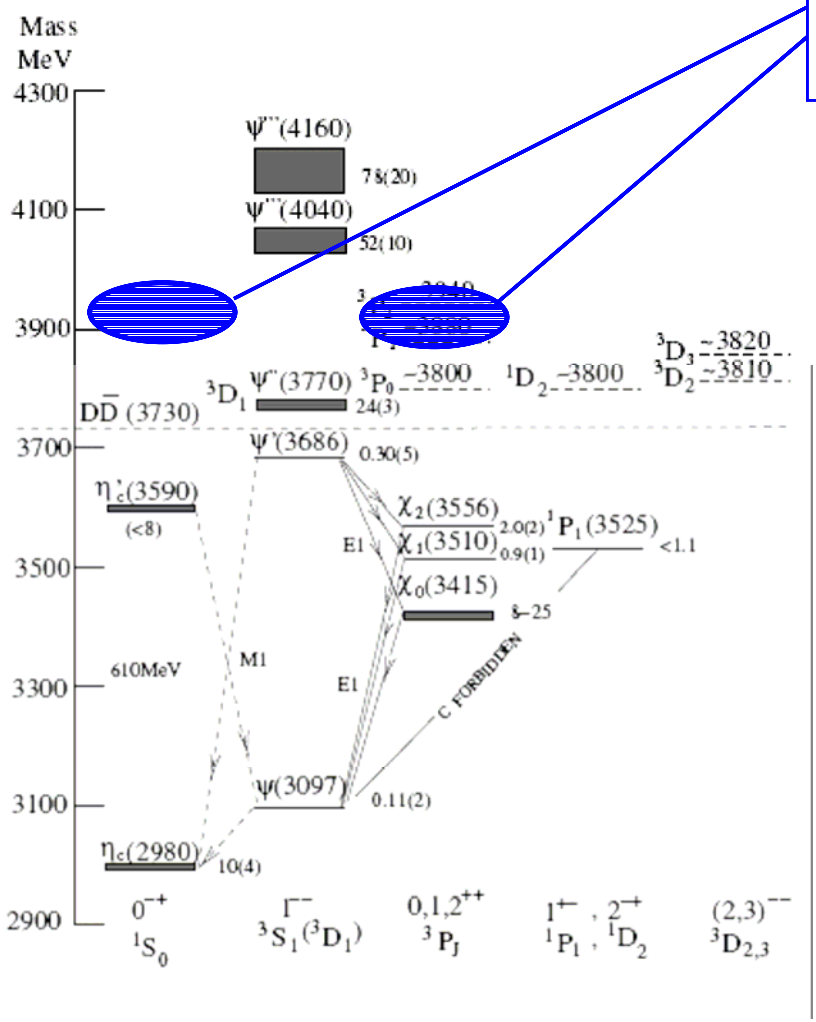
But this tuning seems unlikely

SELEX $D_{sj}(2632)$ state:

1. **Needs confirmation**
2. If 2^3S_1 state expect to see D^*K decay mode
3. **Should see the 2^3S_1 in B decays**
4. The 1^3D_1 state should be ~200 MeV higher in mass

X(3943), Y(3943), and Z(3931)

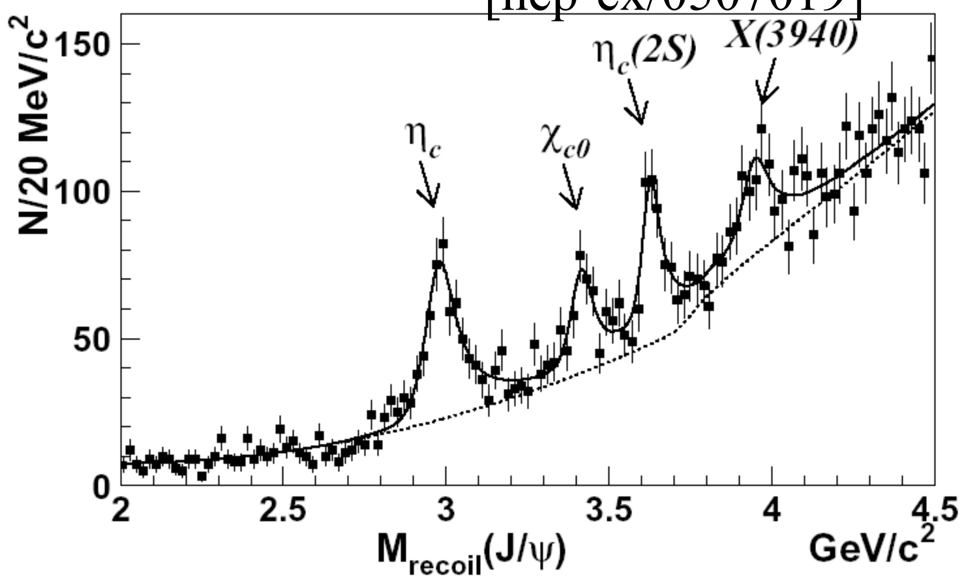
Possible new C=(+) cc states at these masses!



2P or not 2P that is the question!

X(3940)

Seen by Belle recoiling against J/ψ in e^+e^- collisions



M=3943 ± 6 ± 6 MeV

Γ < 52 MeV

$BR(X \rightarrow DD^*)=96^{+45}_{-32} \pm 22\%$

$BR(X \rightarrow DD) < 41\%$ (90% CL)

Suggests unnatural parity state

$BR(X \rightarrow \omega J/\psi) < 26\%$ (90% CL)

- Decay to DD^* but not DD suggests unnatural parity state

- Belle speculates that X is 3^1S_0 given the 3^3S_1 $\psi(4040)$
  - Mass is roughly correct
  - . η_c and η_c' are also produced in double charm production

See also Eichten Lane Quigg PRD73 014014(2006)

- Predicted width for 3^1S_0 with M=3943 ~ 50 MeV close to $\Gamma(X(3943))$ upper bound

- Identification of $\psi(4040)$ as 3^3S_1 state implies hyperfine splitting 88 MeV with X(3943)

- Larger than the 2S splitting and larger than predicted in potential models
- Discrepancy could be due to:
  - Difficulty in fitting true pole position of 3^3S_1 state
  - Nearby thresholds with s-wave + p-wave charm mesons so possibly stronger threshold effects

- Another possibility due to dominant DD^* mode is the 2^3P_1 χ_1'

- Natural to try 2P cc assignment since

  $M(2^3P_J)$ =3920-3980 MeV

  $\Gamma(2^3P_J)$ =30-165 MeV

- If DD^* mode is dominant suggests X(3940) is 2^3P_1

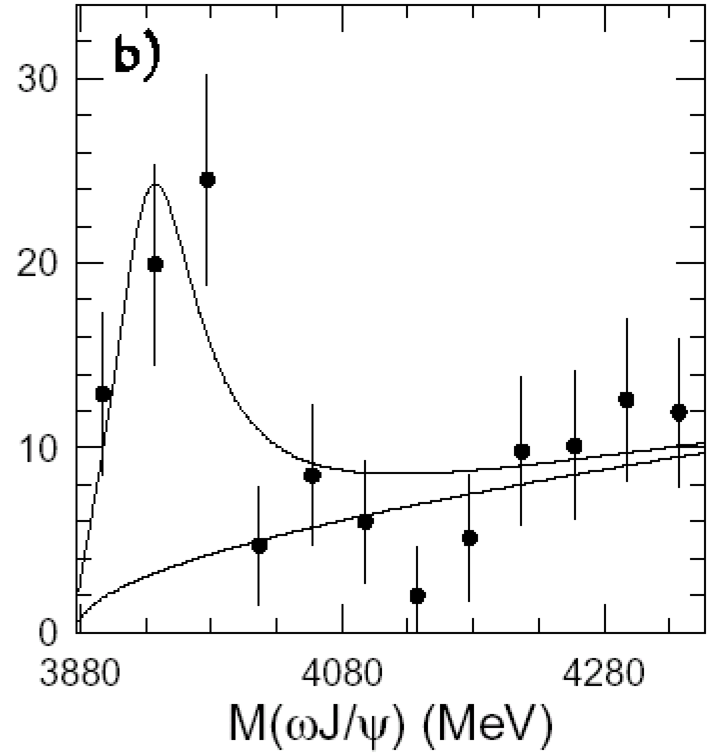
- Problems:
  - No evidence for 1^3P_1 in the same data
  - $\Gamma(2^3P_J)$ =135 MeV (for M=3943 MeV)
  - Y(3943) also a candidate for 2^3P_1 χ_1'

Test of 3^1S_0 η_c assignment is search for this state in $\gamma\gamma \rightarrow DD^*$

Y(3940)

See in $\omega J/\psi$ subsystem of the decay $B \to K\,\pi\pi\pi\,J/\psi$

Belle: Phys. Rev. Lett. 94, 182002 (2005)



$M = 3943 \pm 11 \pm 13$ MeV

$\Gamma = 87 \pm 22 \pm 26$ MeV

Not seen in $Y \to DD$ or DD^*

Mass and width suggest radially excited P-wave charmonium

But $\omega J/\psi$ decay mode is peculiar:

$BR(B \to KY)\, BR(Y \to \omega J/\psi) = 7.1 \pm 1.3 \pm 3.1 \bullet 10^{-5}$

where one expects $BR(B \to K\chi'_{cJ}) < BR(B \to K\chi_{cJ}) = 4 \bullet 10^{-4}$

Implies $BR(Y \to \omega J/\psi) > 12\%$ which is unusual for state above open charm threshold

- Large width to $\omega J/\psi$ led Belle to suggest Y(3943) might be hybrid

- But mass is 500 MeV below LGT estimates making hybrid assignment unlikely

- Possibility is 2^3P_1 cc state: identifyies Y(3943) as 2P χ'_{c1}
  - DD^* is the dominant decay mode
  - Width consistent with Y(3943): Γ=135 MeV
  - . χ_{c1} is seen in B decays

- $1^{++} \to \omega J/\psi$ is unusual
  - but corresponding $\chi'_{b1,2} \to \omega Y(1S)$ also seen
  - Maybe rescattering: $1^{++} \to DD^* \to \omega J/\psi$
  - Maybe due to mixing with 1^{++} molecular state X(3872)?
- Important to - look for DD and DD*
  - study angular distributions to DD and DD*

Z(3930)

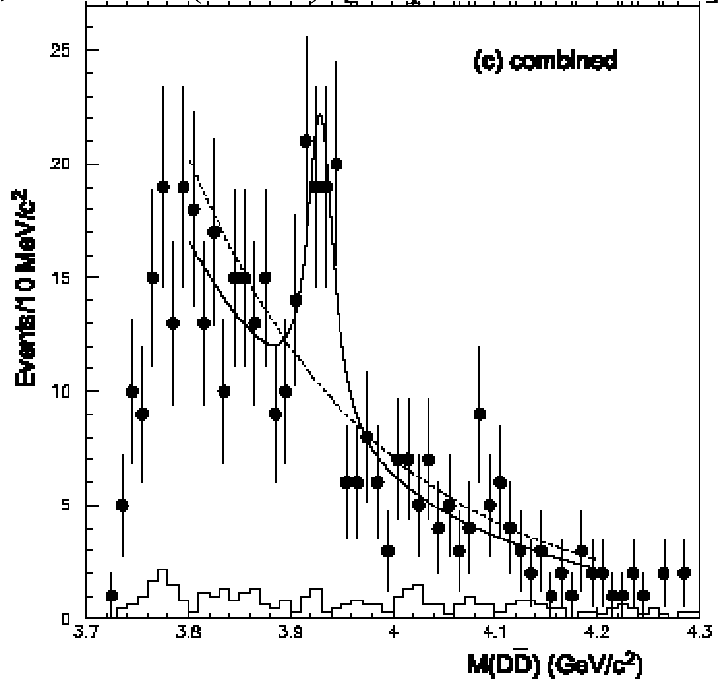
Belle: Phys Rev Lett 96, 082003(2006) [hep-ex/0512035]

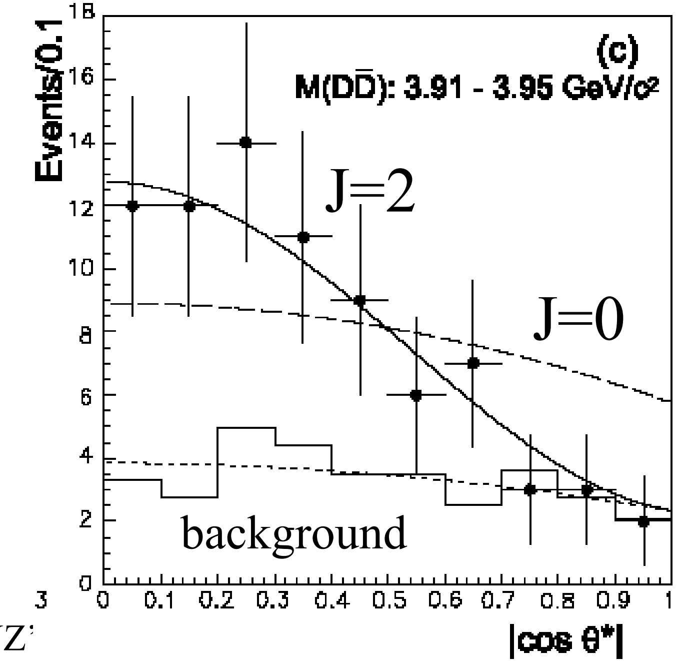
- Observed by Belle in $\gamma\gamma \to DD$
  $M=3929 \pm 5 \pm 2$ MeV
  $\Gamma = 29 \pm 10 \pm 2$ MeV

- Two photon width:
  $\Gamma_{\gamma\gamma} \bullet B_{DD} = 0.18 \pm 0.05 \pm 0.03$ keV

- DD angular distribution consistent with J=2

- Below $D^* D^*$ threshold





- Obvious candidate for χ'_{c2} (the χ'_{c1} cannot decay to DD)

  - Predicted χ'_{c2} mass is 3972

    $\Gamma(\chi'_{c2} \to DD)$= 21.5 MeV

    $\Gamma(\chi'_{c2} \to DD^*)$= 7.1 MeV

    Γ =47 MeV assuming $M(\chi'_{c2})$=3931
- In reasonable agreement with experiment

- Predicted $BR(\chi'_{c2} \to \mathbf{DD})$=70% $\Rightarrow \Gamma_{\gamma\gamma} * B_{DD} = 0.47$ keV

  ($\Gamma_{\gamma\gamma}$ from T.Barnes, IX[th] Intl. Conf. on $\gamma\gamma$ Collisions, La Jolla, 1992.)
- Observed two-photon width about 1/2 predicted value for χ'_{c2}

- No reason not to believe that Z(3930) is not the χ'_{c2}

- Another possibility is χ'_{c0} (unlikely due to angular distributions)

- Can confirm χ'_{c2} by searching for DD^*

  χ'_{c0} only decays to DD

  χ'_{c2} decays to DD and DD^* in ratio of $DD^*/DD \sim 1/3$

- Largest radiative transition is

  BGS, PRD72, 054026 (2005)

  $\Gamma(\chi'_{c2} \to \gamma \psi') \sim 200$ keV vs $\Gamma(\chi'_{c0} \to \gamma \psi') \sim 130$ keV

  (ELQ find decays are suppressed due to coupled channel effects PRD73 014014(2006))

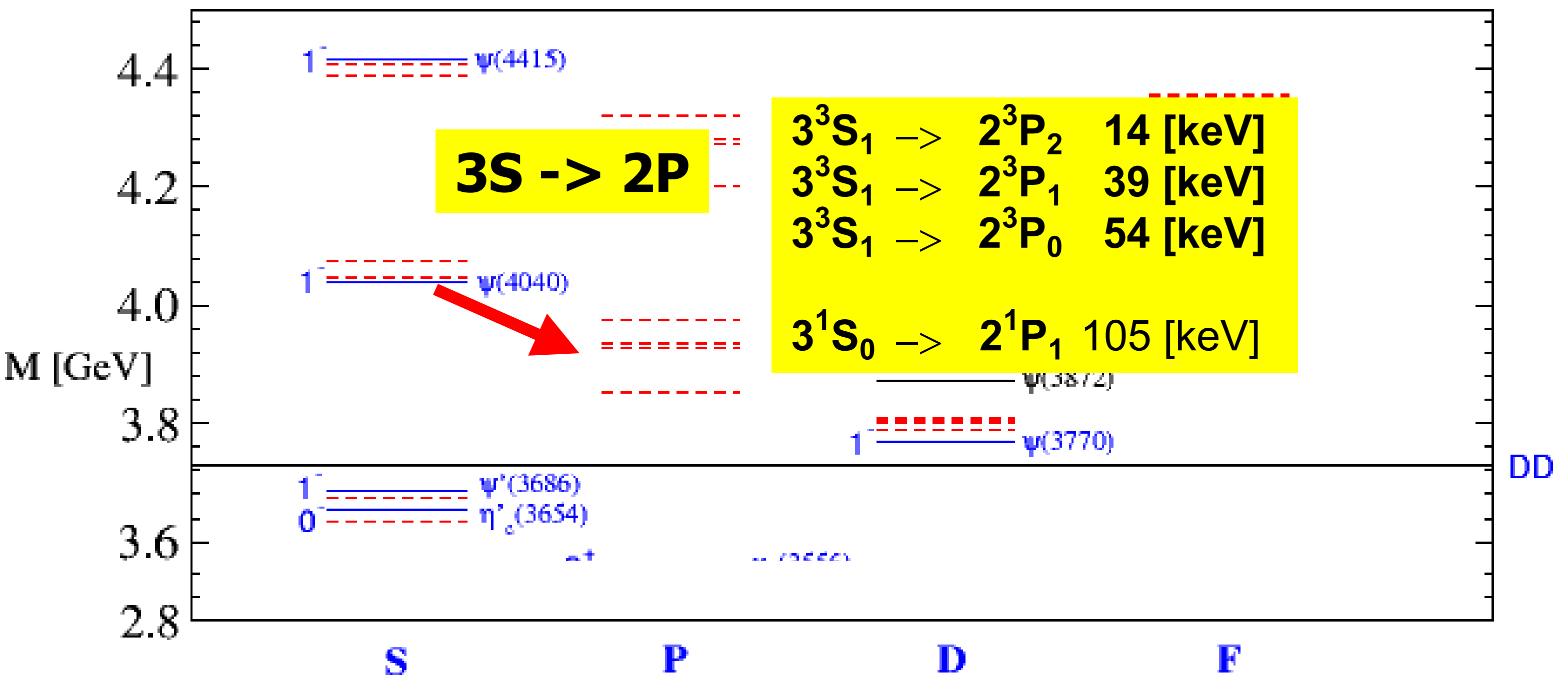
Could further study 2^3P_J states via radiative transitions:

Can *find* all three $^3 2P_J$ $c\underline{c}$ states using

$\psi(4040)$ and $\psi(4160) \to \gamma DD, \gamma DD^*$

All three E1 rad BFs of the $\psi(4040)$ are ~$0.5 * 10^{-3}$.

These would further test whether the *Z,X,Y (3.9)* are 2P cc



X(3872)

New state 1st observed by Belle: X(3871)

Phys Rev. Lett. 91, 2622001 (2003) [hep-ex/0309032]

Confirmed by: CDF Phys Rev. Lett. 93, 072001 (2004)
D0 Phys Rev. Lett. 93, 162002 (2004)
BABAR Phys Rev. D71, 071103 (2005)

M=3872.0 $\pm$ 0.6 $\pm$ 0.5 MeV $\Gamma < 2.3$ MeV at 90% C.L.
width consistent with detector resolution.

1. $D^0 D^{*0}$ molecule
2. A charmonium hybrid
3. 2^3P_J 1^3D_2 state?
4. Glueball?

Consider the charmonium possibilities:

T.Barnes,S.Godfrey, PR D69, 050400 (2004)
Eichten, Lane, Quigg, PR D69, 094019 (2004)
Barnes, Godfrey, Swanson, PR D 054026 (2005)

1D and 2P multiplets only states nearby in mass

1^3D_2 1^3D_3 2^1P_1 have C=-
1^1D_2 2^3P_0 2^3P_1 2^3P_2 have C=+

But $X(3872) \rightarrow \gamma J/\psi$ implies C=+ Belle [hep-ex/0505037]
Babar Gowdy Moriond talk

Angular distributions favour $J^{PC}=1^{++}$ Belle [hep-ex/0505038]

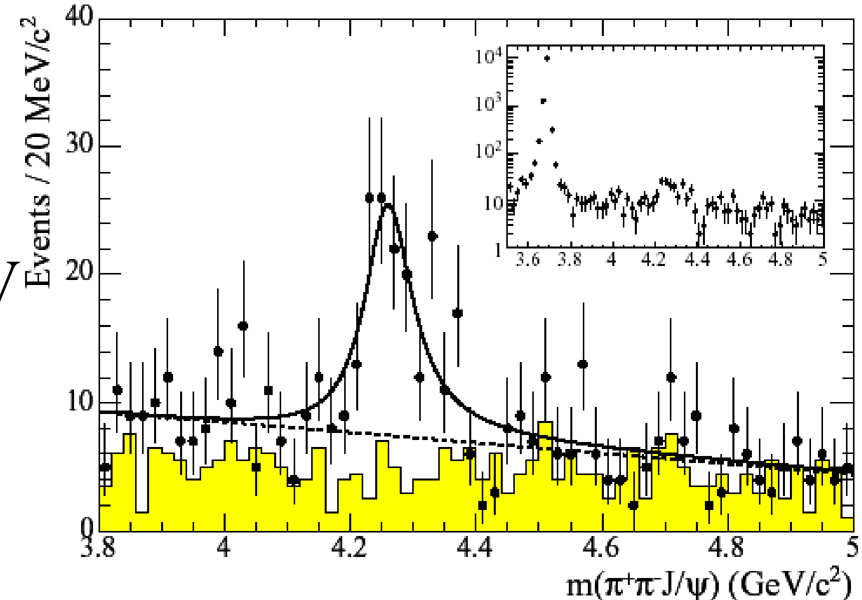
The unique surviving charmonium candidate is 2^3P_1

BUT identification of Z(3931) with 2^3P_2
implies 2P mass ~ 3940 MeV

D^0D^{*0} molecule or "tetraquark"
is a popular/likely explanation: see Voloshin

Y(4260)

Discovered by Babar as enhancement in $\pi\pi\ J/\psi$ subsystem in $e^+e^- \to \gamma_{ISR}\ \psi\pi\pi$ PRL 95, 142001(2005) [hep-ex/0506081]



M=4259 $\pm$ 8 $\pm$ 4 MeV

Γ =88 $\pm$ 23 $\pm$ 5 MeV

$\Gamma_{ee}\times BR(Y \to \pi^+\pi^- J/\psi)=5.5 \pm 1.0 \pm 0.8$ eV

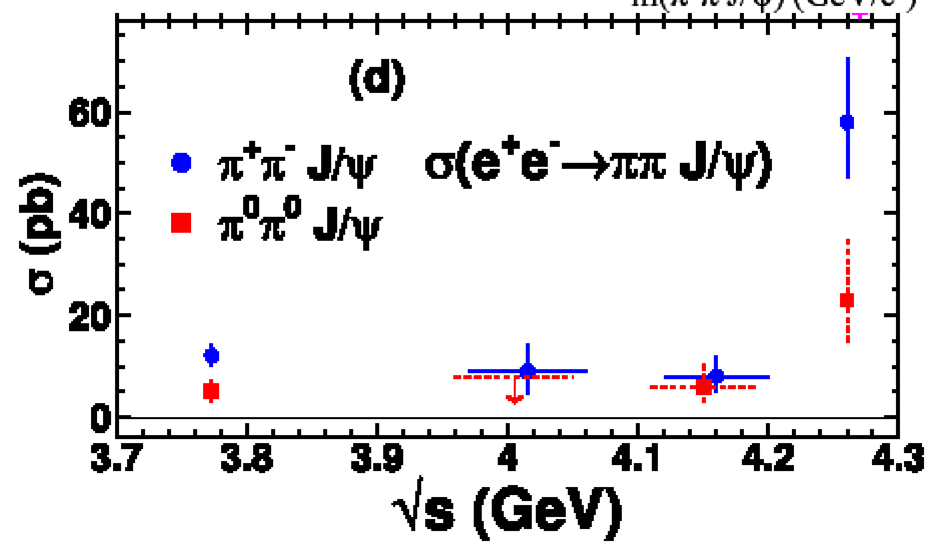
ISR production tells us $J^{PC}=1^{--}$

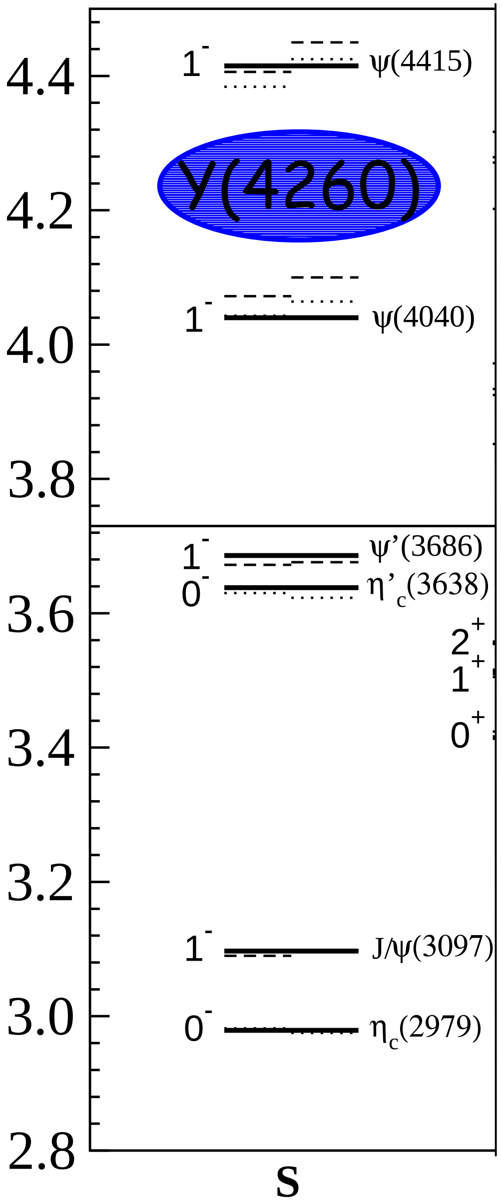
Further evidence in

$B\to K(\pi^+\pi^- J/\psi)$ PR D73, 011101(2006)

Confirmed by CLEO

hep-ex/0602034





- The first unaccounted 1^{--} state is the ψ(3D)
- Quark models estimate M(ψ(3D))~4500 MeV much too heavy for the Y(4260)

Y(4260) represents an overpopulation of expected 1^{--} states

Absence of open charm production also against conventional cc state

Other explanations are:

- . ψ(4S) Phys Rev D72, 031503 (2005)
- Tetraquark Phys Rev D72, 031502 (2005)
- cc hybrid Phys Lett B625, 212 (2005); Phys Lett B628, 215 (2005) Phys Lett B631, 164 (2005)

Y(4260): Hybrid?

- Flux tube model predicts lowest cc hybrid at 4200 MeV

- LGT expects lowest cc hybrid at 4200 MeV [Phys Lett B401, 308 (1997)]

- Models of hybrids say $\Psi(0)=0$ so would have small e^+e^- width

- LGT found bb hybrids have large couplings to closed flavour modes
  - Similar to BaBar observation of $Y \to \pi^+\pi^- J/\psi$:

$$BR(Y \to \pi^+\pi^- J/\psi) > 8.8\%$$
$$\Gamma(Y \to \pi^+\pi^- J/\psi) > 7.7 \pm 2.1 \text{ MeV}$$

- Much larger than typical charmonium transitions:

$$\Gamma(\psi(3770) \to \pi^+\pi^- J/\psi) \sim 80 \text{ keV}$$

- Y is seen while $\psi(4040)$, $\psi(4160)$ $\psi(4415)$ are not

How to test Y(4260) hybrid assignment:

Decays:

- LGT study suggest searching for other closed charm modes with $J^{PC}=1^{--}$ $J/\psi\eta,\ J/\psi\eta',\ \chi_J\omega\ldots$
- Models predict the dominant hybrid charmonium open-charm decay modes will be a meson pair with
  S-wave (D, D^*, D_s, D_s^*) + P-wave (D_J, D_{sJ})
- The dominant decay mode expected to be $D+D_1(2430)$
  $D_1(2420)$ has width ~300 MeV and decays to $D^*\pi$
- **Suggests search for Y(4260) in $DD^*\pi$**
- Evidence of large $DD_1(2430)$ signal would be strong evidence for hybrid
- But models of hybrids are untested so to be cautious
- If seen in other modes like DD^*, $D_sD_s^*$ comparable to $\pi^+\pi^-J/\psi$ maybe still hybrid but decay model not accurate

Search for Partner States: (fill in the multiplet)

- Mass *ca.* 4.0 – 4.5 GeV, with LGT preferring the higher range.
  (e.g.: X.Liao and T.Manke, hep-lat/0210030)
- Confirm that no $c\underline{c}$ states with the same J^{PC} are expected at this mass.
- Identify J^{PC} partners of the hybrid candidate nearby in mass.
- The most convincing evidence:
  - partners, especially J^{PC} exotics.
- The f-t model expects:

$$0^{+-},\ 1^{-+},\ 2^{+-},\ 0^{-+},\ 1^{+-},\ 2^{-+},\ 1^{++},\ 1^{--}$$

Summary

Many new results, considerable progress!

$D_{sJ}(2317)$	Most likely $0^+(c\bar{s})$
$D_{sJ}(2460)$	Most likely $1^+(c\bar{s})$
$D_{sJ}(2632)$	Needs confirmation
X(3872)	Molecule? - see Voloshin
X(3943)	η''_c (3^1S_0) -look for $\gamma\gamma \rightarrow DD^*$
Y(3943)	χ'_{c1} (2^3P_1) -look for DD & DD*
Z(3930)	χ'_{c2} (2^3P_2) -confirm by DD*
Y(4260)	Hybrid?

- Much more to learn; ie search for 1^3D_3 1^3D_2 1^1D_2 1^3F_2 1^3F_4

Thank experimentalists for all the wonderful results they're providing