The New $D_s\pi^0$ State:

The Hydrogen Atom Revisited

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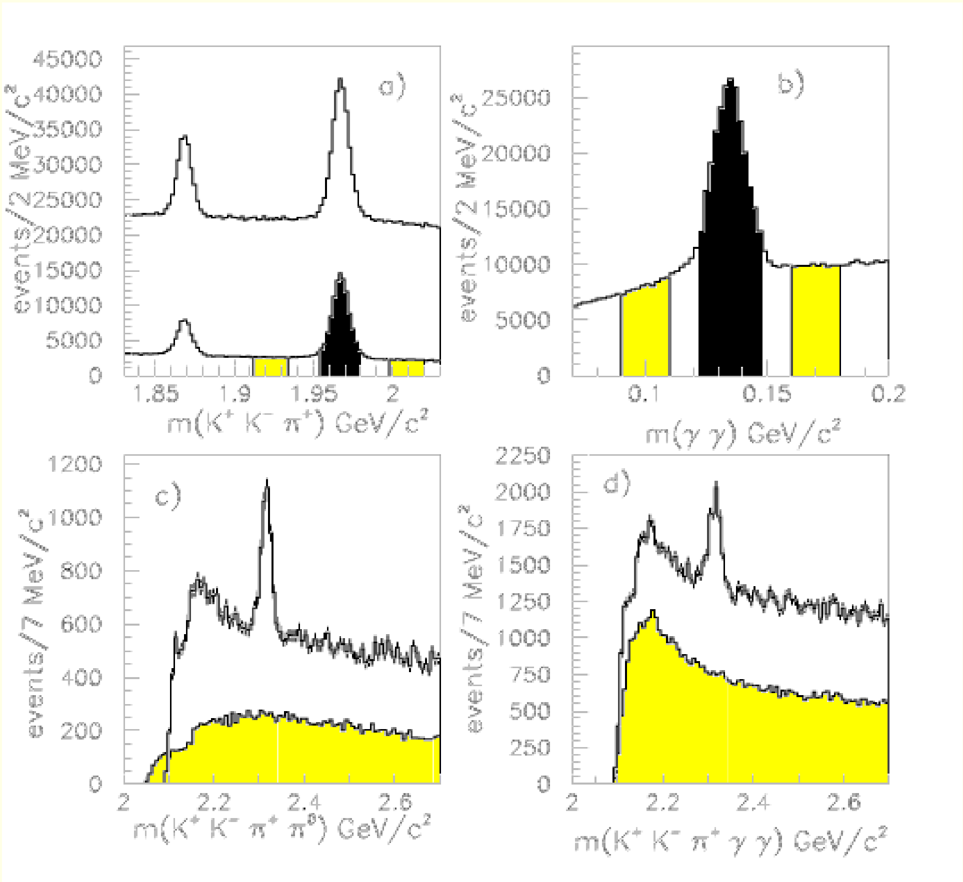
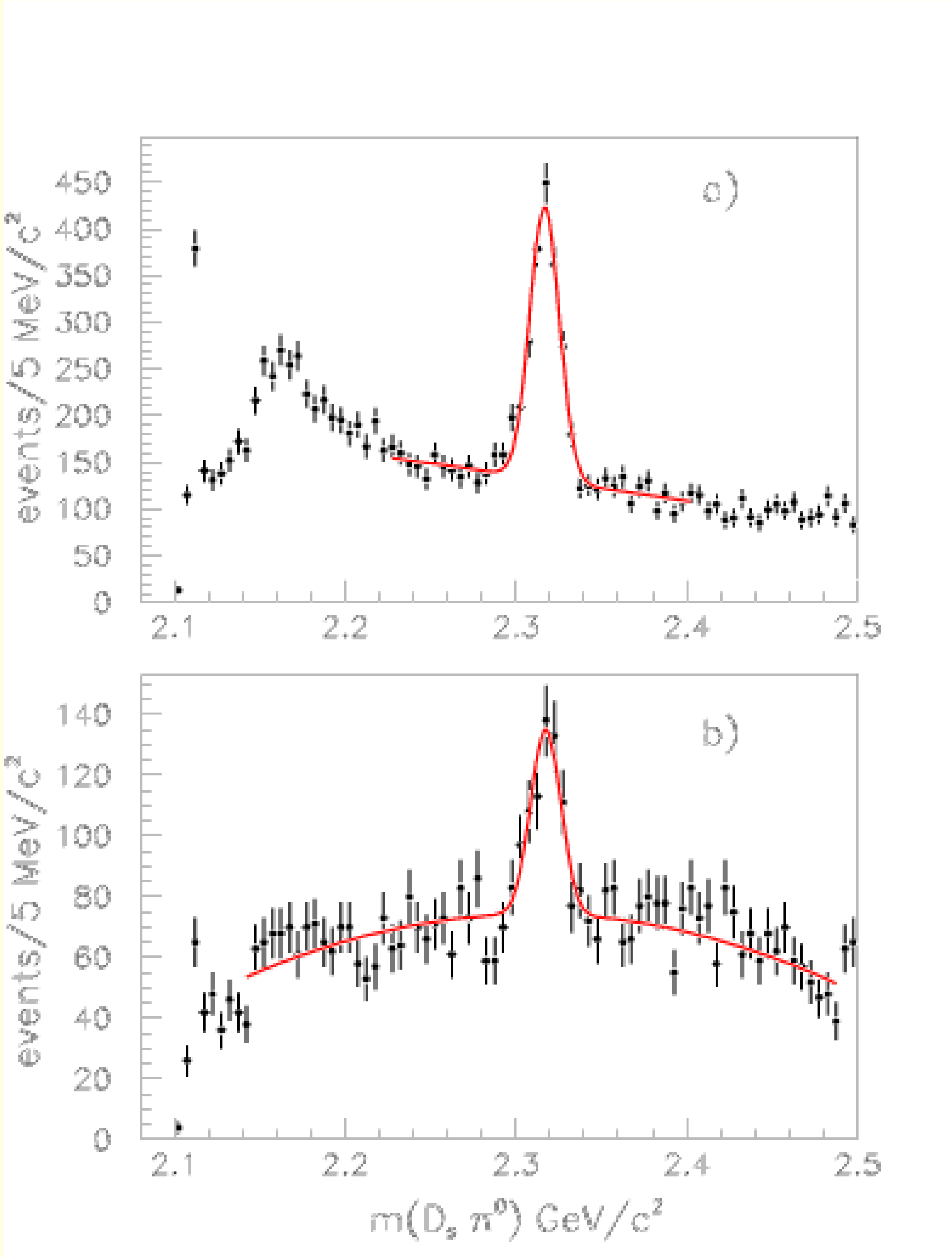
BaBar Discovery of Narrow State Decaying to $D_s\pi^0$



- π^0 signal + D_s signal gives peak
- π^0 signal + D_s sideband gives no peak
- π^0 sideband + D_s signal gives no peak



- $D_s\pi^0$ mass distribution for $D_s \to K^+K^-\pi^+$

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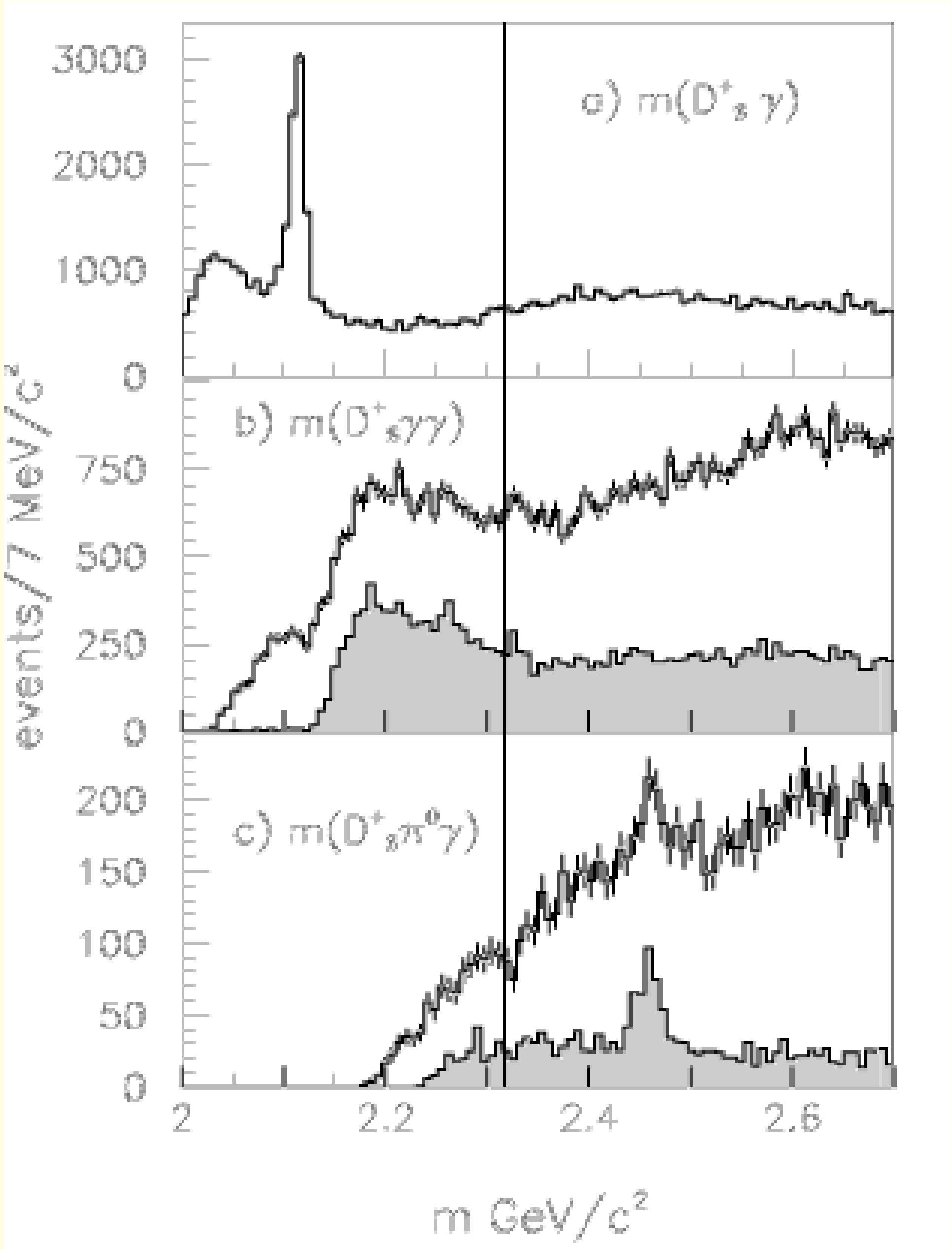


- No sign of $D^*_{sJ}(2317) \to D_s\gamma$

- No sign of $D^*_{sJ}(2317) \to D^*_s\gamma$

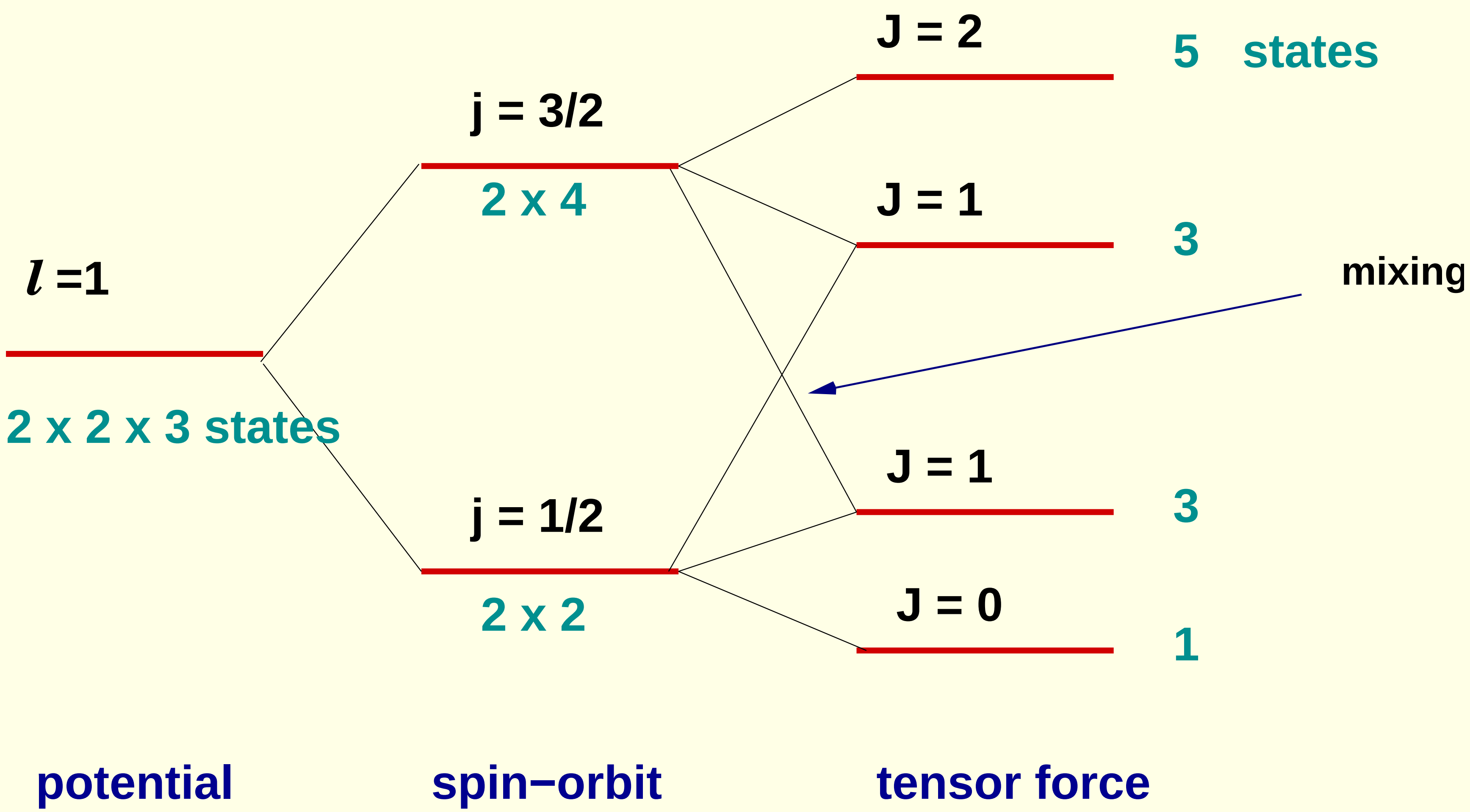
- Apparent structure in $D_s\pi^0\gamma$

Heavy Quark - Light Quark Spectroscopy

is the Hydrogen Atom

- First approximation: heavy quark is static source of potential
- Orbital angular momentum $\boldsymbol{\ell}$, light-quark spin $\boldsymbol{s}$, separately conserved
- Add spin-orbit interaction, $\boldsymbol{\ell} \cdot \boldsymbol{s}$
  - $\boldsymbol{j} = \boldsymbol{\ell} + \boldsymbol{s}$ conserved, not $\boldsymbol{\ell}, \boldsymbol{s}$
- Add heavy quark, with spin $\boldsymbol{S}$
  - Interactions suppressed by m/M
  - Spin-orbit interaction $\boldsymbol{\ell} \cdot \boldsymbol{S}$
  - Spin-spin contact interaction $\boldsymbol{s} \cdot \boldsymbol{S}\, \delta^3(\boldsymbol{r})$
  - Tensor force $3\boldsymbol{S} \cdot \hat{\boldsymbol{r}}\, \boldsymbol{s} \cdot \hat{\boldsymbol{r}} - \boldsymbol{S} \cdot \boldsymbol{s}$
  - $\boldsymbol{J} = \boldsymbol{j} + \boldsymbol{S}$ conserved, not $\boldsymbol{j} = \boldsymbol{\ell} + \boldsymbol{s}$

p−wave states



Canonical Approach

DiPierro and Eichten, PRD 64, 114004 (2001)

- Dirac equation with two potentials
  - Coulomb potential in fourth component of vector potential
  - Linear (confining) potential in scalar potential
- Solve Dirac equation with spin-orbit included
- Add tensor force (and small spin-orbit) perturbatively
- Fix coefficients of Coulomb and linear, masses of quarks to fit data from D, D_s, B, B_s systems

Predictions of DiPierro and Eichten

	D		D_s	
J^P	m(GeV) exp.	m(GeV) th	m(GeV) exp.	m(GeV) th
$S(J=0)$	1.865	1.868	1.969	1.965
$S(J=1)$	2.007	2.005	2.112	2.113
$P(J=0)$	$[2.290]$	2.377		2.487
$P(J=1)$	2.422	2.417	2.535	2.535
$P(J=2)$	2.459	2.460	2.573	2.581
$P(J=1)$	$[2.400]$	2.490		2.605

- The states $D_0(2290)$ and $D_1(2400)$ are from Belle at ICHEP and were not known at the time of the predictions.

- The same potentials are used for the D,D_s, B, and B_s systems.

Decays and Selection Rules

- Angular momentum conserved: no $0 \to 0\gamma$ decays
- Not weak decays: Parity conserved
  - $D^*_{sJ}(2317) \to D_s(0^-)\pi^0$ forces natural spin-parity for $D^*_{sJ}(2317)$ $[0^+, 1^-...$
  - $D^*_{sJ}(2317) \to D^*_s(1^-)\pi^0$ forbidden if $D^*_{sJ}(2317)$ is 0^+
- Isospin mostly conserved
  - $D^*_{sJ}(2317) \to D_s(0^-)\pi^0$ violates isospin
  - $D^*_s(2112) \to D_s(0^-)\pi^0$ violates isospin, 5% of $D_s(2112) \to D_s(0^-)\gamma$
  - $D_{s?}(2460?) \to D_s(0^-)(\pi\pi)_{L=0}$ allowed if 1^+, needs p-wave
  - $D_{s2}(2575) \to DK$ d-wave, $\to D^*K$ d-wave
  - $D_{s1}(2535) \to D^*K$ s-wave, d-wave

- Light-quark angular momentum ($\boldsymbol{j} = \boldsymbol{\ell} + \boldsymbol{s}$) nearly conserved
  - $D_{s1}(2535)$ mostly $j = 3/2$, $D(2007)$ all $j = 1/2$
  - $D_{s1}(2535) \rightarrow D(2007)K$ d-wave not s-wave ($\Gamma < 2.3$ MeV)
  - $D(J = 1, j = 1/2)$ should be broad

- Isospin violation
  - Violated by electromagnetism
  - Violated by $m_u \neq m_d$
  - Scale is $(m_u - m_d)/\Lambda_{QCD} << 1$

Chiral Symmetry and Isospin Violation

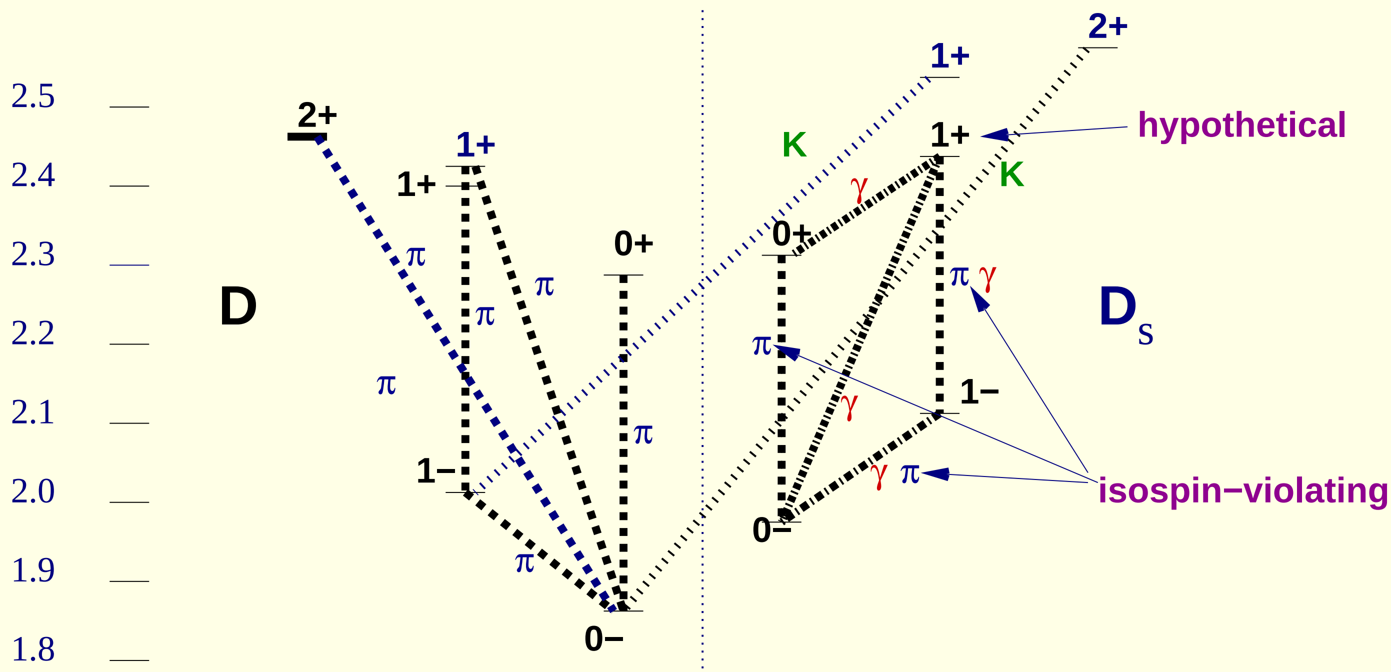
$$\Pi = \begin{pmatrix} \frac{\pi^0}{\sqrt{2}} + \frac{\eta}{\sqrt{6}} & \pi^+ & K^+ \\ \pi^- & \frac{\pi^0}{\sqrt{2}} - \frac{\eta}{\sqrt{6}} & K^0 \\ K^- & \overline{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix}; \qquad M = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_d & 0 \\ 0 & 0 & m_s \end{pmatrix}$$

Mass-squared term from Tr $\Pi\, M\, \Pi$ leads to $\pi^0 - \eta$ mixing, with mixing angle

$$\tan\theta = \frac{\sqrt{3}}{2}\frac{m_d - m_u}{m_s - (m_u + m_d)/2}$$

Use $\frac{m^2_{K^+} - m^2_{\pi^+}}{m^2_{K^0} - m^2_{\pi^0}} = \frac{m_s - m_d}{m_s - m_u}$; $\qquad \frac{m^2_\eta}{m^2_{\pi^0}} = \frac{(4m_s + m_u + m_d)/3}{m_u + m_d}$

to find $m_s/m_d = 20$, $m_u/m_d = 0.55$, $\tan\theta \approx 1/50$


2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
D
2+
1+
1+
0+
1−
0−
π
π
π
π
π
π
K
1+
2+
1+
0+
1−
0−
K
γ
γ
γ
π
π γ
π
D_s
hypothetical
isospin−violating

"Almost-Model-Independent' Spectroscopic Predictions (J. D. Jackson & RNC: hep-ph/0305012)

- Potential includes V and S
- V is Coulombic, as suggested by QCD
  - Fourth component of vector potential
- S is linear, confining
  - Scalar, not fourth component of vector potential
- Determine potentials from Feynman diagram, expand in v/c

Effective Interaction

$$\mathcal{V}_{quasi-static} = V + S + \left(\frac{V' - S'}{r}\right) \boldsymbol{\ell}\cdot\left(\frac{\boldsymbol{\sigma}_1}{4m_1^2} + \frac{\boldsymbol{\sigma}_2}{4m_2^2}\right) + \left(\frac{V'}{r}\right)\boldsymbol{\ell}\cdot\left(\frac{\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2}{2m_1 m_2}\right)$$
$$+\frac{1}{12m_1m_2}\left(\frac{V'}{r} - V''\right) S_{12} + \frac{1}{6m_1m_2}\nabla^2 V\, \boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2$$

- If V is Coulombic $-V'' + V'/r = 3V'/r$
- To order $1/m_2$: $M = \lambda\boldsymbol{\ell}\cdot\boldsymbol{s}_1 + 4\tau\boldsymbol{\ell}\cdot\boldsymbol{s}_2 + \tau S_{12}$

$$\lambda = \frac{1}{2m_1^2}\left[\frac{V'}{r}\left(1 + \frac{2m_1}{m_2}\right) - \frac{S'}{r}\right] \qquad \tau = \frac{1}{4m_1m_2}\frac{V'}{r}.$$

Quantum Mechanics in Action

- Can diagonalize commuting variables
- One choice: J^2, j^2, J_z
- Another: J^2, j'^2, J_z $\quad \boldsymbol{j}' = \boldsymbol{\ell} + \boldsymbol{s}_2$
- Yet another: J^2, S^2, J_z $\quad \boldsymbol{S} = \boldsymbol{s}_1 + \boldsymbol{s}_2$
- Must be possible to express one basis in terms of another
- Calculate $\boldsymbol{\ell} \cdot \boldsymbol{s}_1$ in first basis
- Calculate $\boldsymbol{\ell} \cdot \boldsymbol{s}_s$ in second basis
- Calculate S_{12} in third

Masses of the Four P states

$$M_2 = \frac{\lambda}{2} + \frac{5}{8}\tau$$
$$M_0 = -\lambda - 8\tau$$

Masses of the two $J = 1$ state from diagonalizing in the $|Jjm\rangle$ basis

$$\begin{pmatrix} \frac{\lambda}{2} - \frac{8}{3}\tau & -\frac{2\sqrt{2}}{3}\tau \\ -\frac{2\sqrt{2}}{3}\tau & -\lambda + \frac{8}{3}\tau \end{pmatrix} \tag{1}$$

The two eigenmasses for $J = 1$ are then

$$M_{1+} = -\frac{\lambda}{4} + \sqrt{\frac{\lambda^2}{16} + \frac{1}{2}(\lambda - 4\tau)^2}$$
$$M_{1-} = -\frac{\lambda}{4} - \sqrt{\frac{\lambda^2}{16} + \frac{1}{2}(\lambda - 4\tau)^2}$$

Use Three Measured States to Predict Fourth

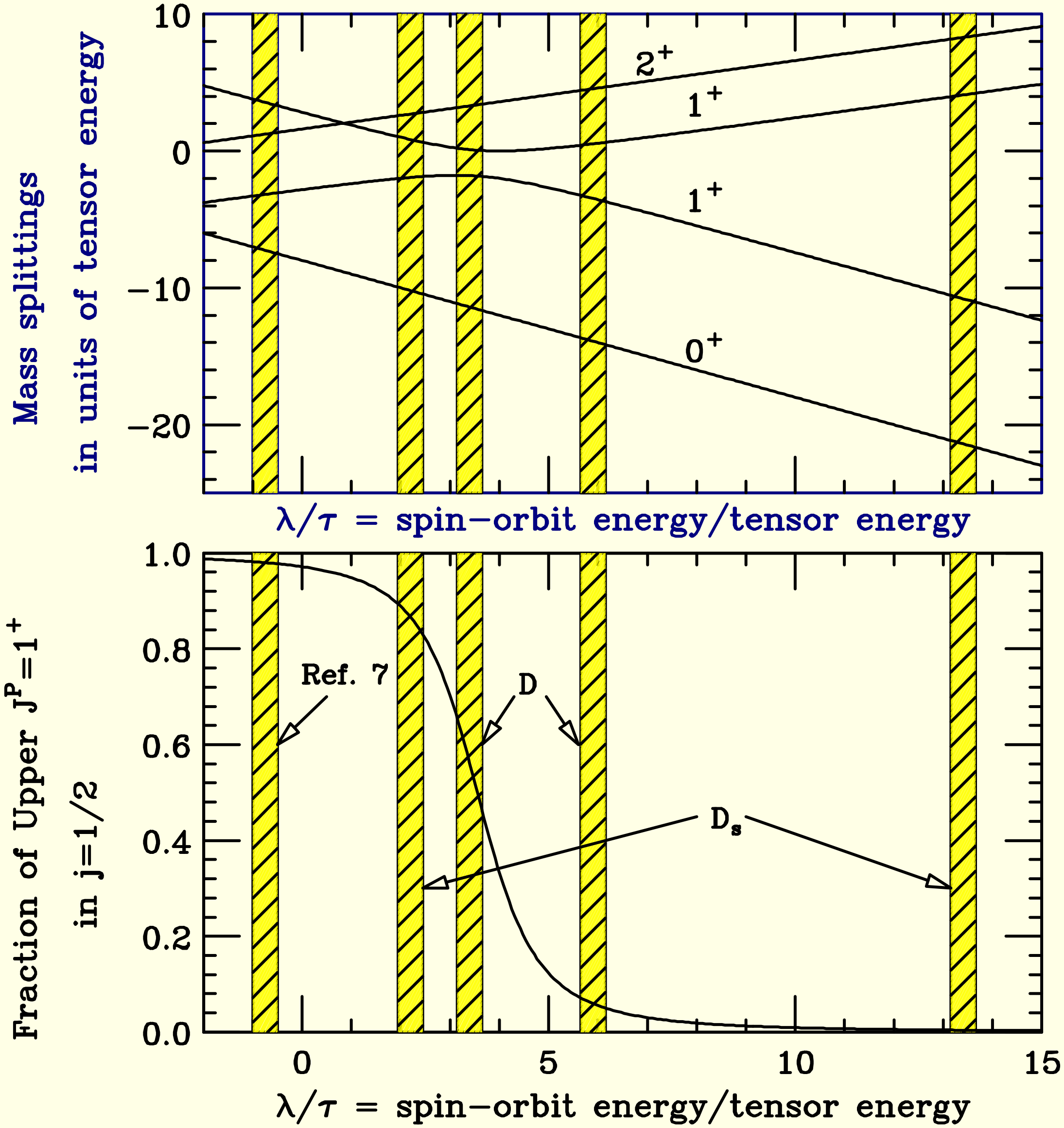
$$
\begin{aligned}
D_2 &= M_2 - M_0 \\
D_1 &= M_{1-} - M_0
\end{aligned}
$$

we find

$$
\tau = \frac{10}{87}D_2 - \frac{2}{29}D_1 \pm \sqrt{\left(\frac{10}{87}D_2 - \frac{2}{29}D_1\right)^2 + \frac{5}{232}(D_1^2 - D_1 D_2)}
$$

and

$$
\lambda = \frac{2}{3}D_2 - \frac{32}{5}\tau
$$


10
0
−10
−20
Mass splittings
in units of tensor energy
2^+
1^+
1^+
0^+
λ/τ = spin−orbit energy/tensor energy
1.0
0.8
0.6
0.4
0.2
0.0
Fraction of Upper $J^P=1^+$
in j=1/2
Ref. 7
D
D_s
0
5
10
15
λ/τ = spin−orbit energy/tensor energy

Masses in D and D_s P States

	Exp.	Theory		
		Sol. A	Sol. B	DiPierro-Eichten
D mesons				
$M(2^+)$(GeV)	2.459	[2.459]	[2.459]	2.460
$M(1^+)$(GeV)	2.400	2.400	2.385	2.490
$M(1^+)$(GeV)	2.422	[2.422]	[2.422]	2.417
$M(0^+)$(GeV)	2.290	[2.290]	[2.290]	2.377
λ (MeV)		39	54	-11
τ (MeV)		11	9	$+11$
D_s mesons				
$M(2^+)$(GeV)	2.572	[2.572]	[2.572]	2.581
$M(1^+)$(GeV)		2.480	2.408	2.605
$M(1^+)$(GeV)	2.536	[2.536]	[2.536]	2.535
$M(0^+)$(GeV)	2.317	[2.317]	[2.317]	2.487
λ (MeV)		43	115	-7
τ (MeV)		20	9	$+11$

Widths in D and D_s P States

	Exp.	DiPierro-Eichten	
		pure s-wave	pure d-wave
D mesons			
$D_2^*(2460) \to D(1865)\pi$	23 ± 5		16
$D_2^*(2460) \to D^*(2007)\pi$	23 ± 5		9
$D_1(2422) \to D^*(2007)\pi$	$18.9^{+4.6}_{-3.5}$	94	10
$D_1(2400) \to D^*(2007)\pi$	$380 \pm 100 \pm 100$	100	
$D_0^*(2290)$	$305 \pm 30 \pm 25$	100	
D_s mesons			
$D_2^*(2573) \to D(1865)K$	15^{+5}_{-4}		8.9
$D_2^*(2573) \to D^*(2007)K$	15^{+5}_{-4}		1.4
$D_1(2535) \to D^*(2007)K$	< 2.3	100	0.3

Choosing Solutions

- Need nearly pure $j = 3/2$ to suppress $D_1(2422)$, $D_s(2535)$ decays
- Forces solutions with large λ/τ
- Contrary to "traditional picture."

Alternative Views: Molecules not Atoms

- Barnes, Close, and Lipkin [hep-ph/0305025]
- Bound DK, near threshold
- Might be isovectors, too. Look for $D_s\pi^{\pm}$
- Expect to find regular $c\bar{s}$ states as well

Alternative Views
Chiral Symmetry + Heavy Quark Symmetry

- Bardeen, Eichten, and Hill [hep-ph/030549]
- If chiral symmetry good $(0^-, 1^-)$ degenerate with $(0^+, 1^+)$
- Predicted roughly 340 MeV splitting, new 1^+ at 2460!
- Predict
  - $\Gamma((D_s(0^+) \to D_s^*(1^-)\gamma) = 1.7 \text{ keV}$
  - $\Gamma((D_s(0^+) \to D_s^*(0^-)\pi^0) = 22 \text{ keV}$
  - $\Gamma((D_s(1^+) \to D_s(0^-)\gamma) = 5 \text{ keV}$
  - $\Gamma((D_s(1^+) \to D_s(1^-)\pi^0) = 22 \text{ keV}$
  - $\Gamma((D_s(1^+) \to D_s(0^-)\pi\pi) = 4 \text{ keV}$
  - $\Gamma((D_s(1^+) \to D_s(0^+)\gamma) = 3 \text{ keV}$

Summary

- BaBar results on $D_s\pi^0$ contradict theoretical predictions
- Belle results on D somewhat contradict theoretical predictions
- Can fit p-wave masses, but with bigger spin-orbit energy than expected
- To suppress decay rate of 1^+ states need to take extremely large spin-orbit energy
- BaBar results will profoundly affect heavy-quark light-quark spectroscopy