

New Ds States: Experiment Confronts Theory

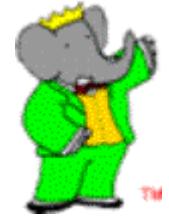
R. Cahn

LBNL

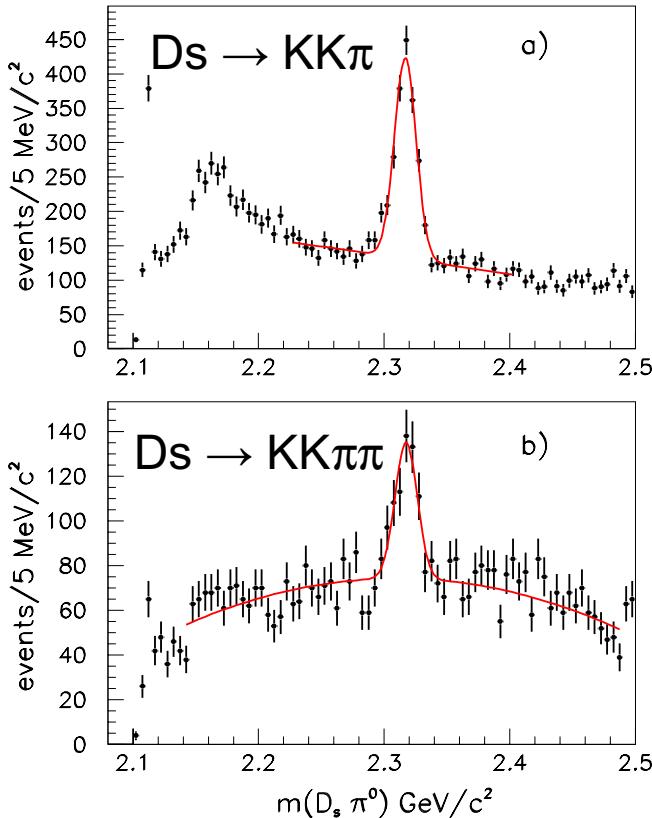
HEPAP – July 24, 2003



“I was looking for bumps.”



Antimo Palano



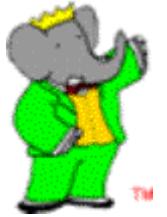
$D_s \pi^0$ shows narrow peak at 2.32 GeV

Too narrow for ordinary hadronic decay.

Impossible quantum numbers for q-qbar.

“Wrong” mass for c-sbar.

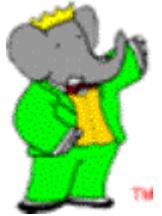
“But once I saw it, I understood.”



Deja Vu, All Over Again

Ds = hydrogen atom

- Charm quark = proton
- Strange quark = electron
- j = quark's spin + orbital angular momentum
 - Almost good quantum number
- $J=j+\text{heavy quark spin}$
 - Good quantum number



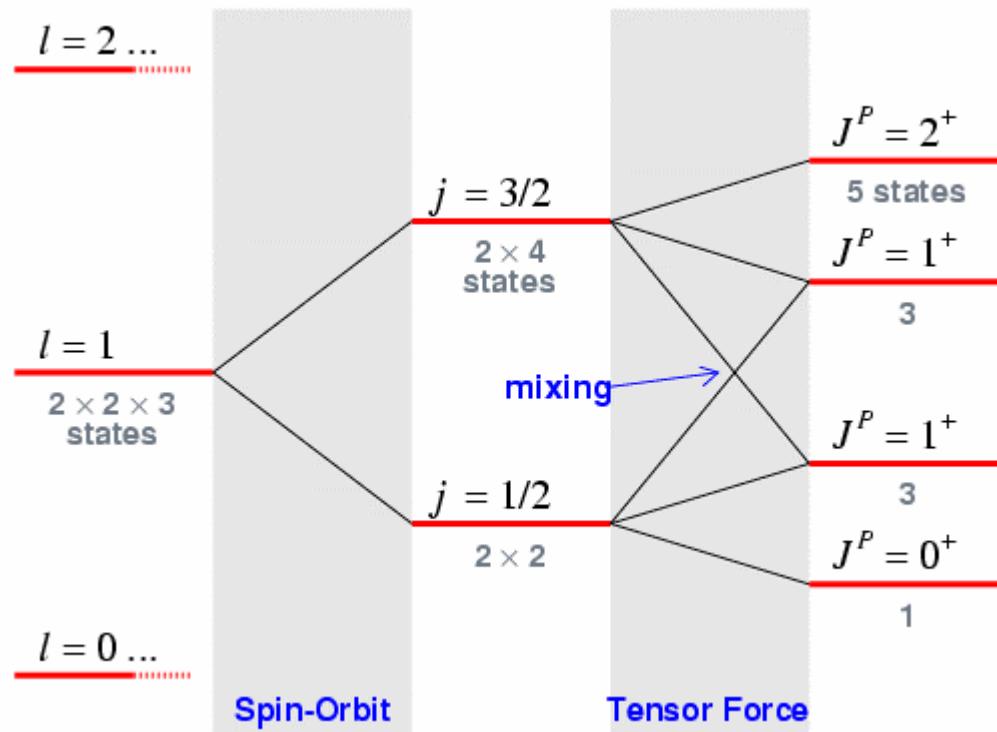
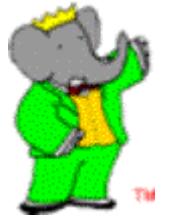
Selection Rules

- Decay strongly, if possible
- Decay violating isospin, if you must
- Decay electromagnetically, otherwise
- Decay weakly, as last resort
- Conserve J , absolutely
- Conserve j , if possible

Quantum mechanics: Everything not forbidden is compulsory.

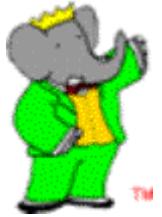


Forces Split Levels





Potential Models



- Try to explain D , D_s , B , B_s
- “Vector” potential: Coulombic
- Scalar potential: linear
- Spin-orbit interactions $\mathbf{L} \cdot \mathbf{S}$
- Spin-spin interactions $\mathbf{S}_1 \cdot \mathbf{S}_2$
- Tensor force



Before and After 2317



State	Theory	Exp
D		
2+	2.460	2.459
1+	2.490	2.400
1+	2.417	2.422
0+	2.377	2.290
Ds		
2+	2.581	2.572
1+	2.605	
1+	2.535	2.536
0+	2.487	2.317

DiPierro & Eichten,
PRD64,114004 (2001)

States not known to DP&E

Excellent agreement
on known states



Decay Widths



- $D_1(2422) \rightarrow D^*(2007)\pi$: $\Gamma = 20 \text{ MeV}$
- $D_{s1}(2535) \rightarrow D^*(2007)K$: $\Gamma < 2.3 \text{ MeV}$

Why so narrow?

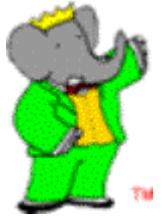
Nearly pure $j=3/2$ states.

Decay to $j=1/2$ by d wave, not s wave.



Can We Salvage the Potential Model ?

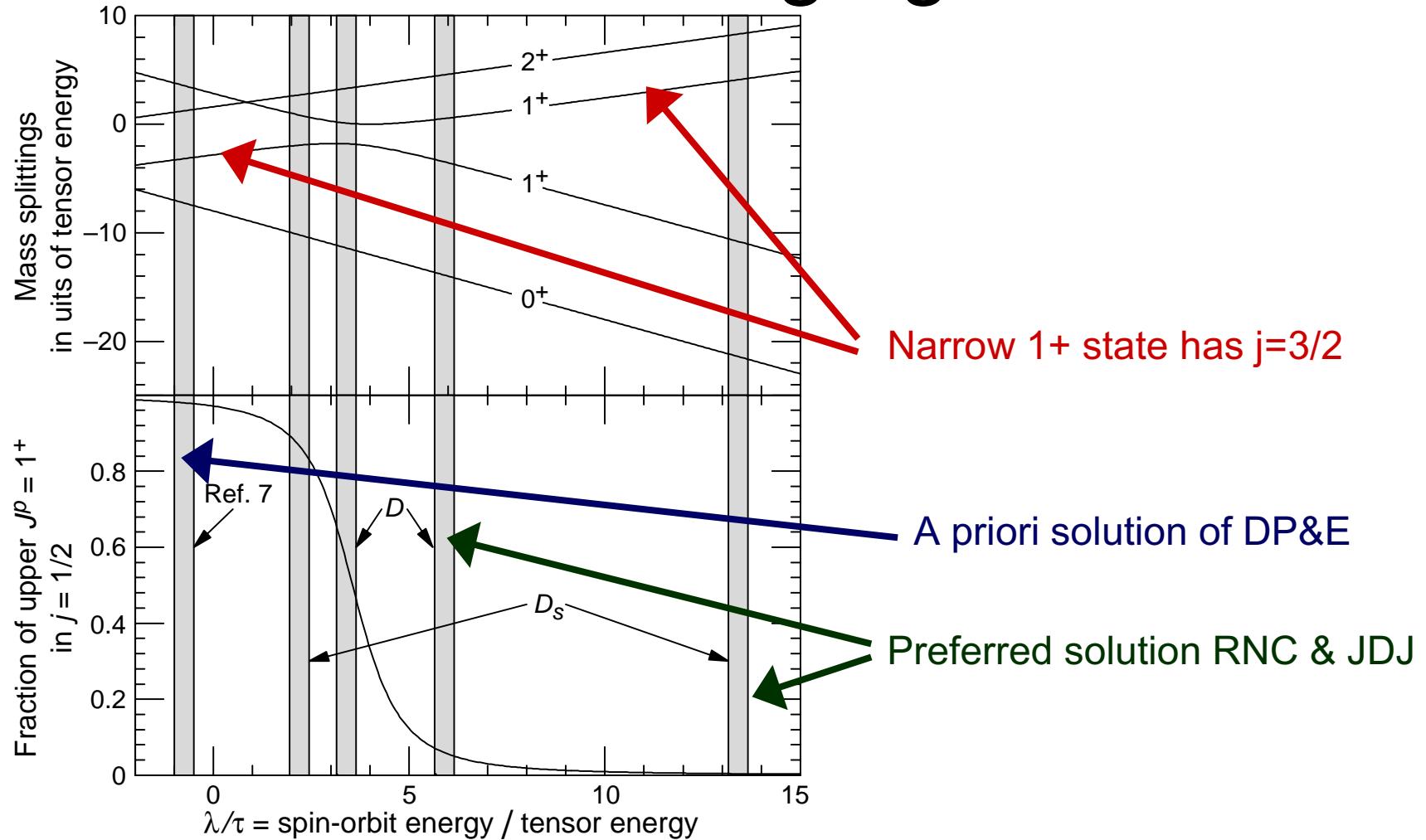
(RNC & JDJ)



- Vector potential: Coulomb
- Scalar potential: any
- Input 2+, 0+, one 1+
- Get out spin-orbit, tensor force couplings
- Get out masses, mixing of 1+ states



Must get masses and mixing right





Experiment vs Theory (Masses in GeV)



	Exp	RNC/JDJ:Sol. A	RNC/JDJ:Sol. B	DP & E
D				
2+	2.459	[2.459]	[2.459]	2.490
1+	2.400	2.400	2.385	2.460
1+	2.422	[2.422]	[2.422]	2.417
0+	2.290	[2.290]	[2.290]	2.377
Ds				
2+	2.572	[2.572]	[2.572]	2.581
1+	2.457	2.480	2.408	2.605
1+	2.536	[2.536]	[2.536]	2.535
0+	2.317	[2.317]	[2.317]	2.487

Narrow state

[] = input values

Chosen to make
narrow state narrow



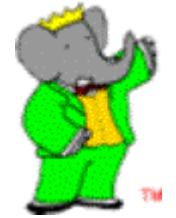
Potential Models: Not Yet Entirely Successful



- Must keep narrow states narrow.
- Balance of spin-orbit and tensor forces far from earlier studies.
- Broader class of scalar potentials allowed.
- Restriction to Coulombic vector potential could still be the problem.

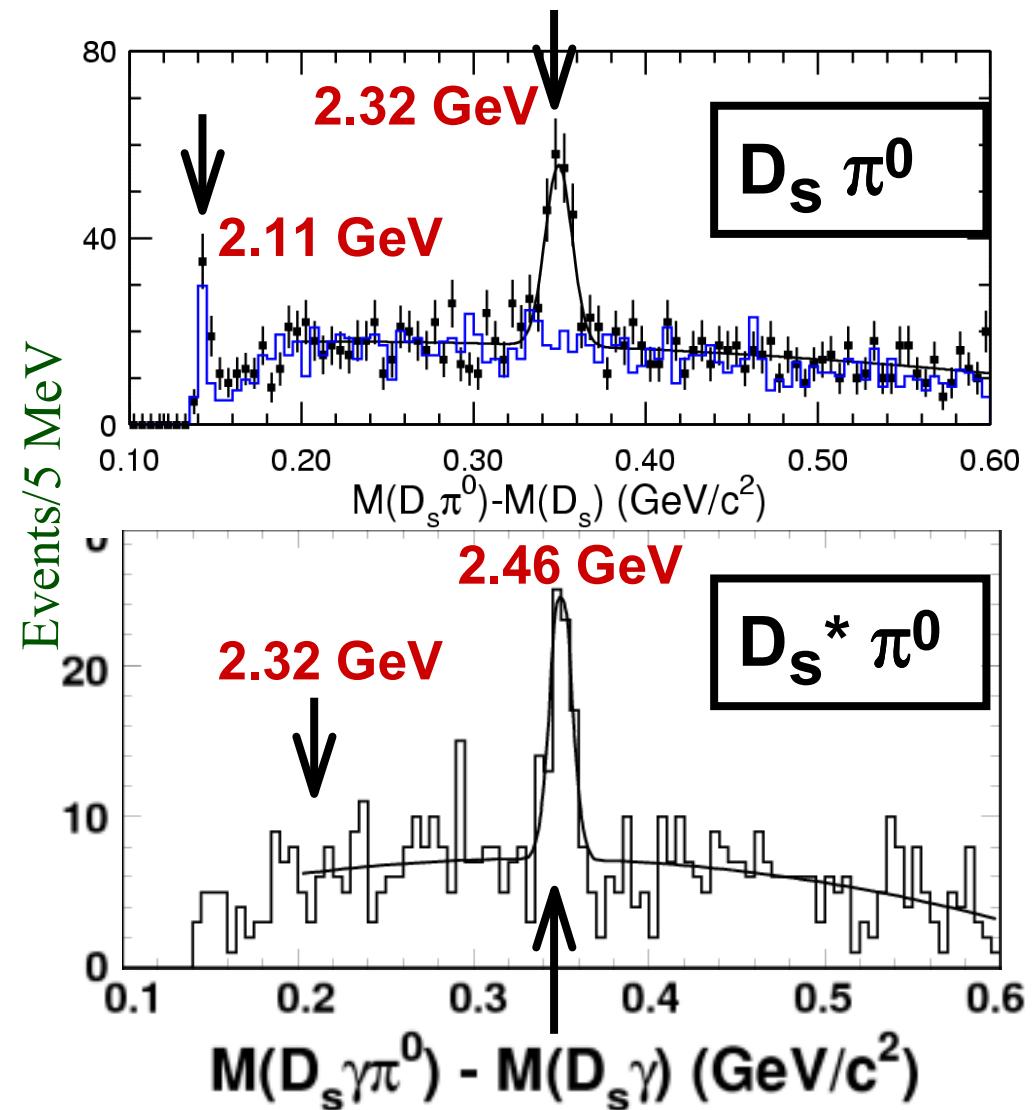


CLEO Confirms First State, Finds a Second



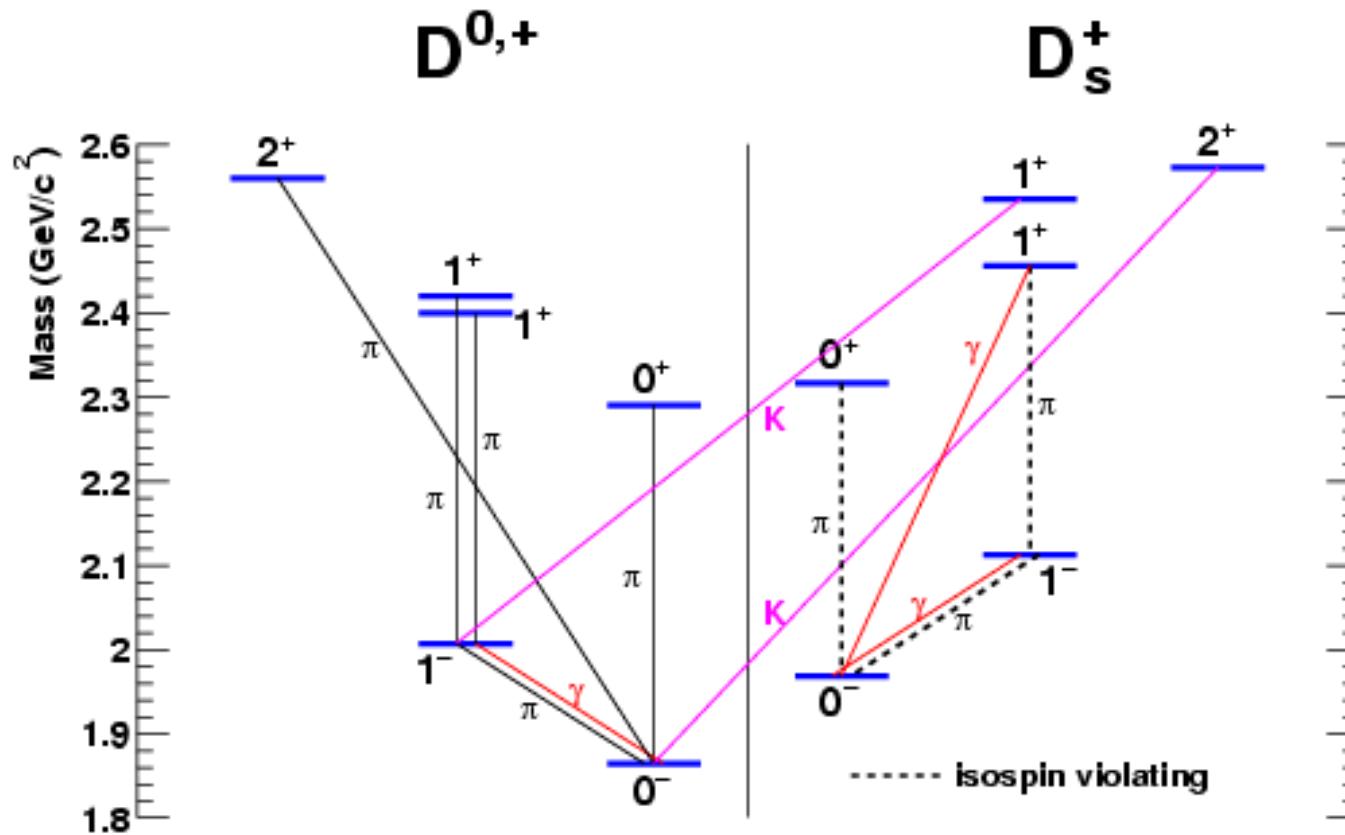
Second state fits
quark-antiquark picture

Splitting nearly the
same as $D_s^* - D_s$





D and D_s Systems

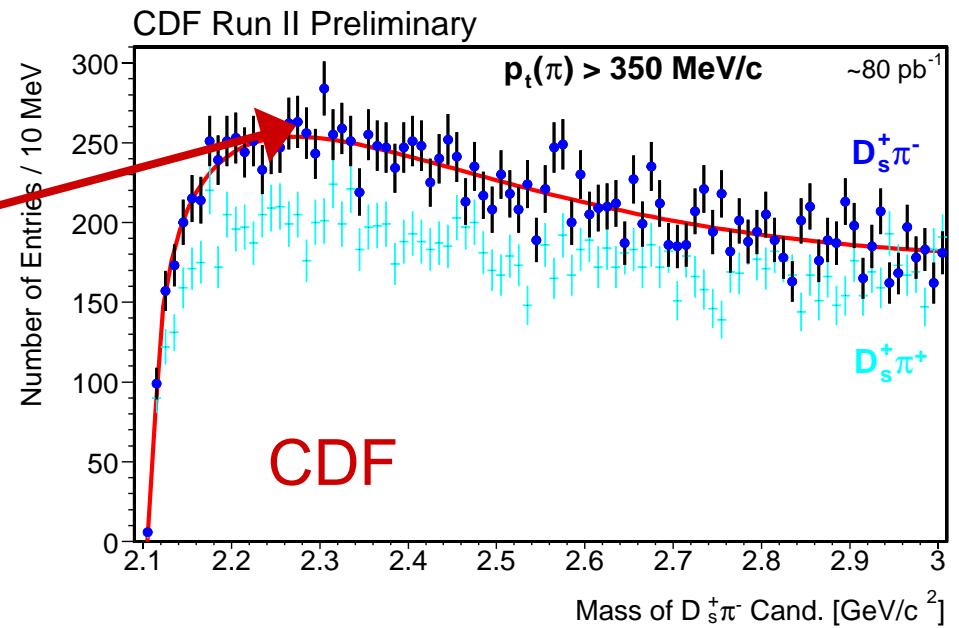




Quantum Numbers of $D_{sJ}^*(2371)$

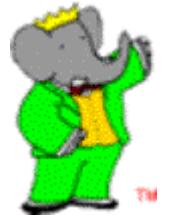


- Isospin: narrowness → isospin violation
 - $I=0$ confirmed by absence of $D_s \pi^+$
- Spin-parity: natural: $0+, 1-, \dots$
 - Radiative decay $\rightarrow D_s \gamma$ would exclude $0+:$ not seen
- Too light for $2+ ?$
- Quark-antiquark $\rightarrow J^P=0^+, I=0$





Quantum Numbers of D_{SJ}(2457)



Belle observes exclusive decays:

$$B^0 \rightarrow D^- D_{SJ}(2317)^+$$

$$B^0 \rightarrow D^- D_{SJ}(2457)^+$$

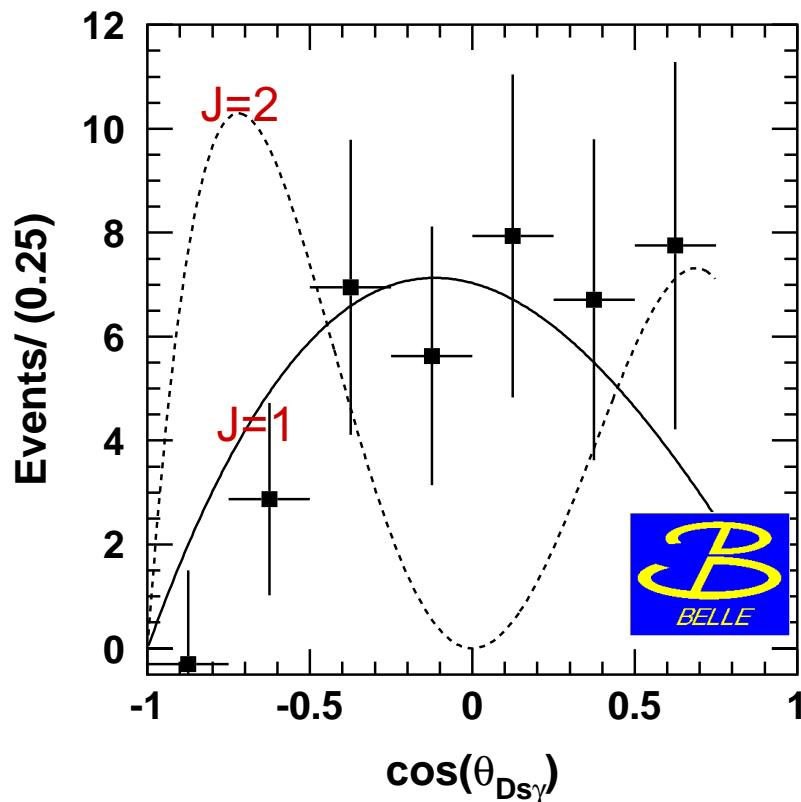
$$D_{SJ}(2457) \rightarrow D_s^*(2112) \pi^0$$

$$D_{SJ}(2457) \rightarrow D_s(1969) \gamma$$

No 0-to-0 radiative transitions.

Not spin-0.

Angular distribution: J=1





Chiral Theory of Heavy-Light Mesons



Bardeen and Hill, PRD 49, 409 (1994)
Bardeen, Eichten, and Hill

Heavy quarks → decoupling of spin interactions

0- (D_s) and 1- (D_s^*) degenerate

Light quarks → left-handed and right-handed independent of each other

(Chiral symmetry)

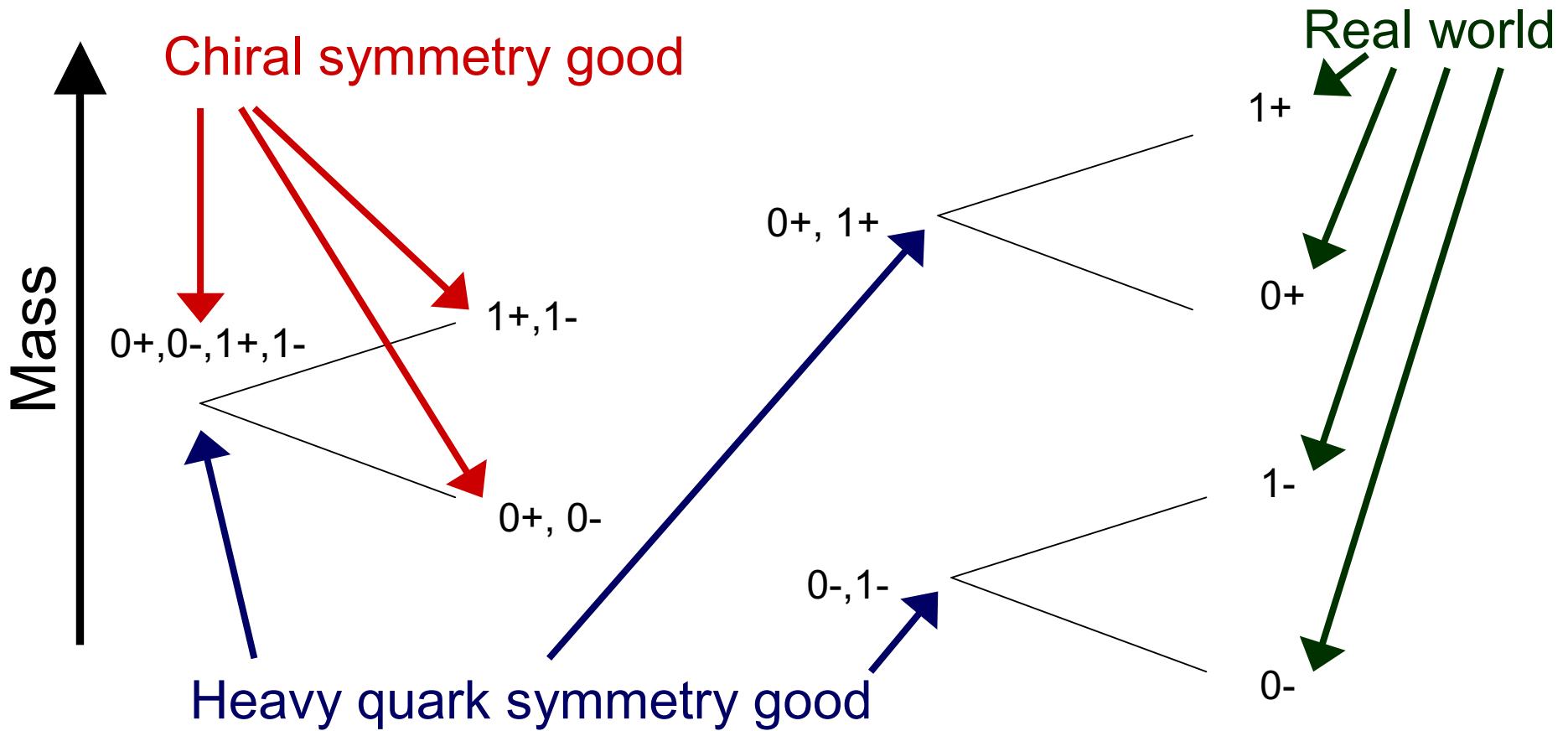
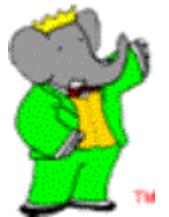
L, R degenerate → $L+R = V, S$; $L-R = A, P$ degenerate

0- and 0+ degenerate

1- and 1+ degenerate

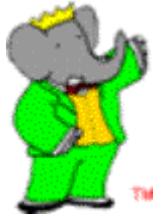


Symmetry Breaking Pattern





Predictions of Chiral Model



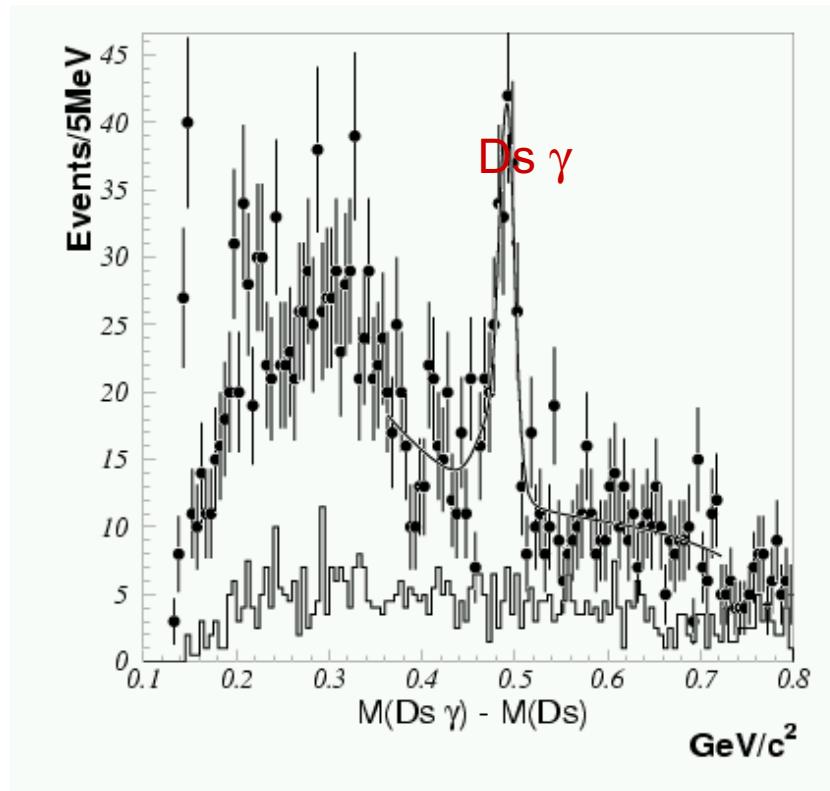
- $M(1+) - M(0+) = M(1-) - M(0-)$
 - $Ds: 2457 - 2317 = 2112 - 1969 \quad [140=141]$
 - $D: 2400 - 2290 = 2010 - 1865 \quad [110=145]$
- $M(Ds(0+)) - M(Ds(0-)) = M(D(0+)) - M(D(0-))$
 - $2317 - 1969 = 2290 - 1865 \quad [348=425]$
- $(Ds^* \rightarrow Ds \pi^0) / (Ds^* \rightarrow Ds \gamma) = 0.018 \quad [\text{exp. } 0.062 \pm 0.026]$
- $(Ds(0+) \rightarrow Ds(1-) \gamma) / (Ds(0+) \rightarrow Ds(0-) \pi^0) = 0.08$
- $(Ds(1+) \rightarrow Ds(1-) \gamma) / (Ds(1+) \rightarrow Ds(1-) \pi^0) = 0.22$
- $(Ds(1+) \rightarrow Ds(0-) \gamma) / (Ds(1+) \rightarrow Ds(1-) \pi^0) = 0.24$
 - Belle $[0.38 \pm 0.11 \pm 0.04] \text{ (excl.)}, [0.63 \pm 0.15 \pm 0.15] \text{ (ccbar)}$
- $(Ds(1+) \rightarrow Ds(0-) \pi \pi) / (Ds(1+) \rightarrow Ds(1-) \pi^0) = 0.20$



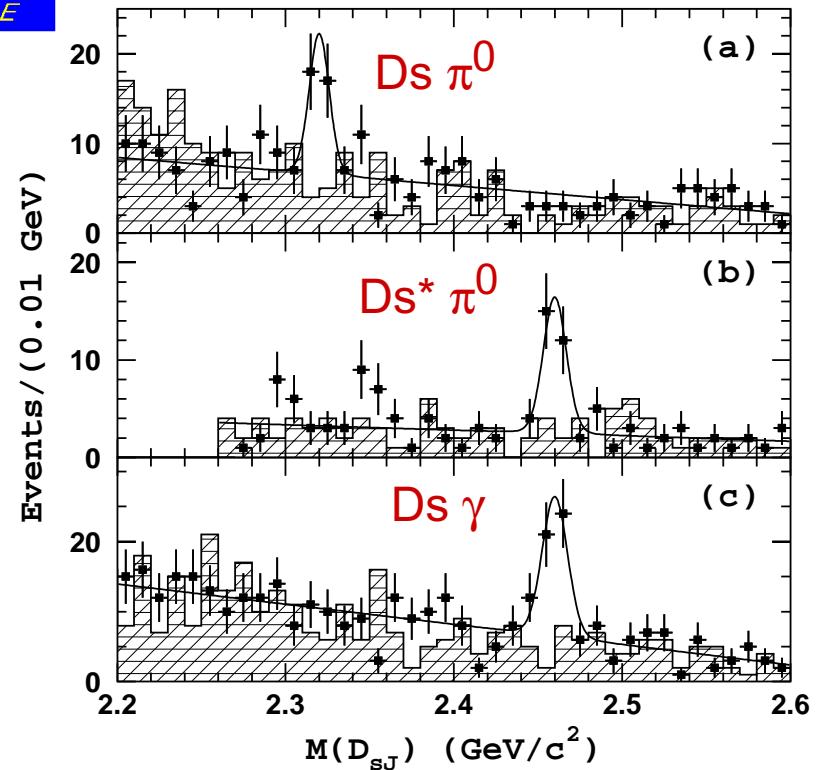
Belle's Results on Radiative Decay of ^{245}T



$\text{C cbar} \rightarrow \text{D}_{\text{sJ}} X$



$\text{B} \rightarrow \text{D D}_{\text{sJ}}$



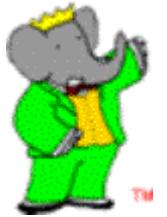


Belle's Exclusive Branching Ratios

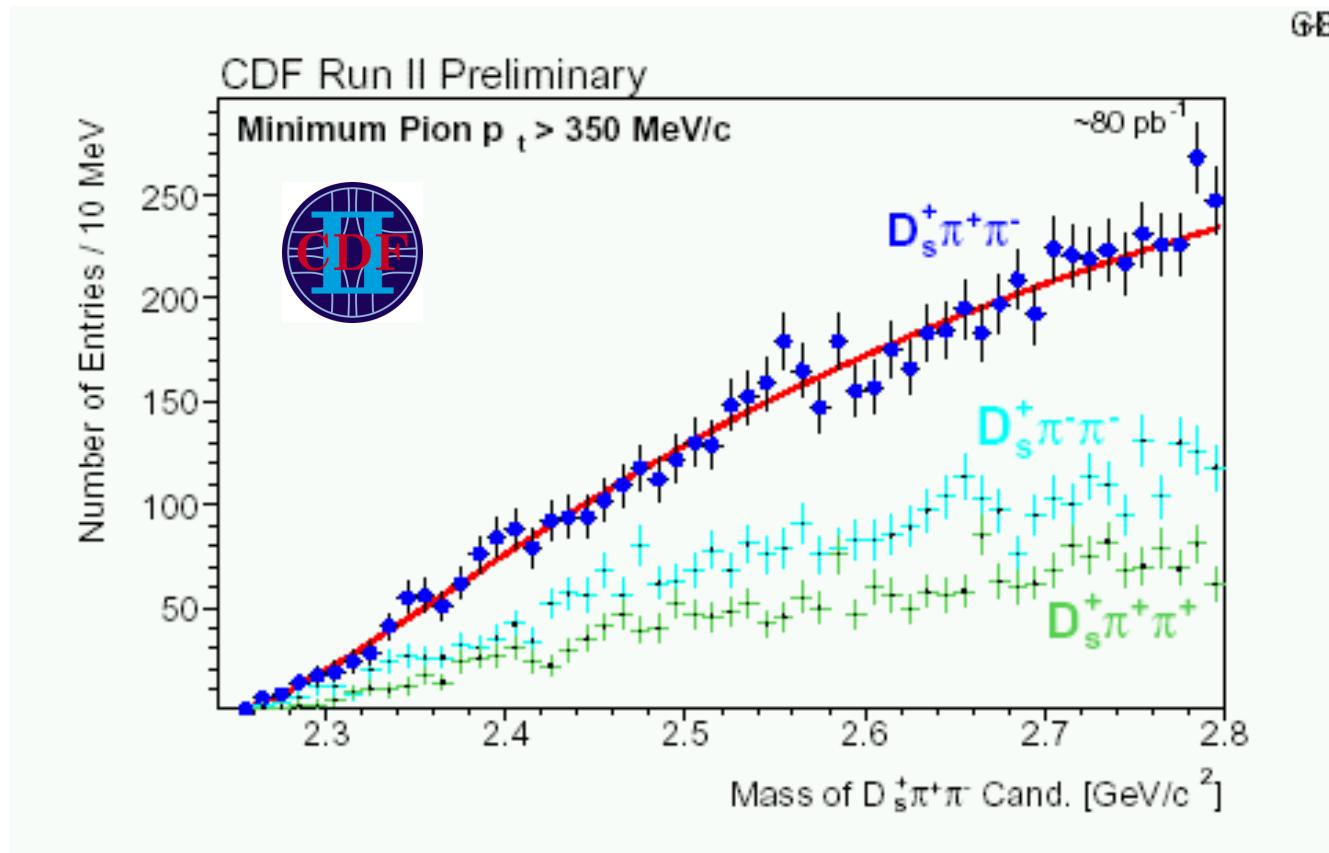


Decay Channel	B (10^{-4})	Significance(σ)
DDsJ*(2317) [Ds π^0]	8.5 (+2.1-1.9) +2.6	6.1
DDsJ*(2317) [Ds* γ]	2.5 (+2.0-1.8) (<5.8)	1.8
DDsJ*(2460) [Ds* π^0]	17.8 (+4.5-3.9)+-5.3	6.4
DDsJ*(2460) [Ds γ]	6.7 (+1.3-1.2)+-2.0	7.4
DDsJ*(2460) [Ds* γ]	2.7 (+1.8-2.5) (<5.6)	2.1
DDsJ*(2460) [Ds $\pi^+ \pi^-$]	<1.2	-
DDsJ*(2460) [Ds π^0]	<1.4	-

BELLE-CONF-0334



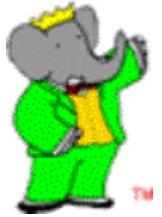
Dipion Emission



No signal from CDF, BaBar, CLEO, Belle



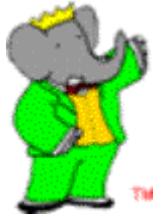
Molecular Physics?



- $D_s \pi$ cannot be $q - q\bar{q}$.
- Could be $D^0 K^+ / D^+ K^0$ $|l|=0$ bound state.
- What would convince skeptics that this is a “molecule?”
 - Observation of another $D_s \pi$ with $|l|=1$
 - Such a state wouldn’t be so narrow
 - Hard task!



Conclusions



- BaBar discovery has revitalized heavy-light spectroscopy.
- Failure of pre-existing potential models only partially resolved.
- Impressive success of chiral models but connection to potential models unclear.
- Molecular models will be hard to establish.
- Rich spectroscopy of narrow states to explore.
- BaBar, CLEO, Belle, CDF have all contributed.