Two Surprising New Charmed Strange Mesons

John Bartelt
SLAC & BaBar

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Two Surprising New Charmed Strange Mesons

I am reporting on work by **Antimo Palano** & other BaBarians.
Plus comparisons to other experiments' results.

Outline

- Historical and Theoretical Background
- *BABAR*'s discovery of the $D^*_{sJ}(2317)^+$
- The Second State
- Conclusions

Charmed Mesons: Some History

- 1974: Charm (J/ψ) discovered
- 1976: Open Charm observed: D^+, D^0
- 1976: De Rújula, Georgi, Glashow: light-degrees decouple
- 1989: “Heavy Quark Symmetry”

Systems with One Heavy Quark:

- Light Degrees of Freedom Decouple from Heavy
- $j_\ell = L \otimes s_\ell$ is conserved in limit $m_h \to \infty$

Charmed Mesons: Lab for Heavy Quark Studies

Mass of the Charm Quark $\sim 1500\ \mathrm{MeV}/c^2 \gg \Lambda_{QCD}$

Should make it a good testing ground for HQS, “Heavy Quark Effective Theory”, *etc.*

What is learned in Charm can be applied to the Bottom system

First, some background on Charm Spectroscopy

Heavy-Light Spectroscopy

It's like the hydrogen atom.

For $m_h \to \infty$, $s_h = j_h$ is fixed.

So $j_\ell = s_\ell \otimes L$ is separately conserved.

For $L = 1$ states this means:

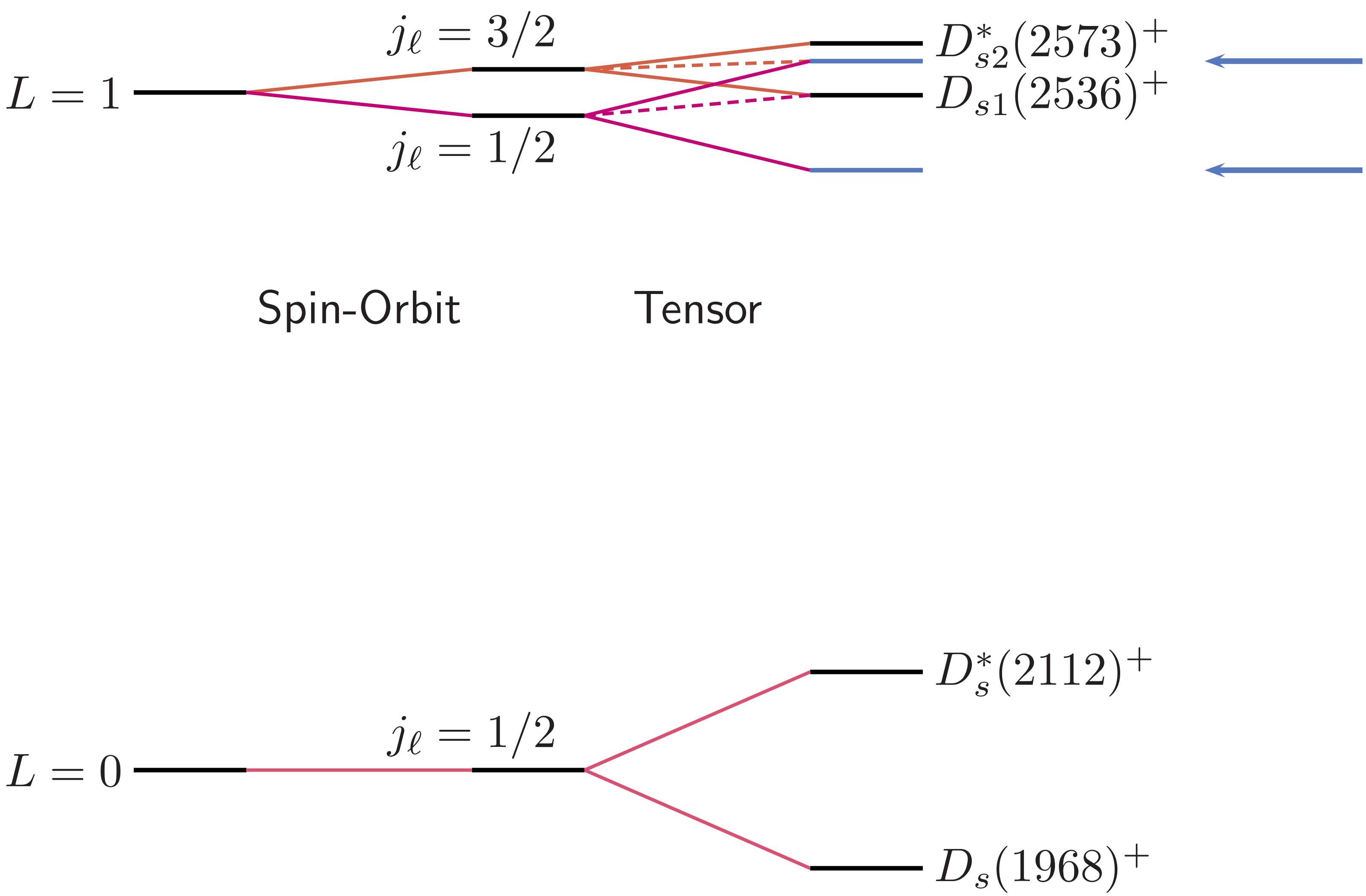
$\Rightarrow$ $j_\ell = 3/2$ states decay via D-wave

$\Rightarrow$ $j_\ell = 1/2$ states decay via S-wave.

$\Longrightarrow$ $j_\ell = 3/2$ states should be narrow

$\Longrightarrow$ $j_\ell = 1/2$ states should be broad.

HQ Potential Model Schematic



Heavy-Light Spectrscopy (2)

$L = 0$: one doublet:

${}^{1/2}S_0$: $D_s(1968)^+$	(0^-)	
${}^{1/2}S_1$: $D_s^*(2112)^+$	(1^-)	

$L = 1$: two doublets

${}^{1/2}P_0$: $D_{s0}^*(?)^+$	(0^+)	
${}^{1/2}P_1$: $D_{s1}(?)^+$	(1^+)	⎤
		—could be mixed
${}^{3/2}P_1$: $D_{s1}(2536)^+$	(1^+)	⎦
${}^{3/2}P_2$: $D_{sJ}^*(2573)^+$	(2^+)	[J=2 favored, not established]

Di Pierro & Eichten's notation: ${}^{j_\ell}L_J$

Heavy-Light Spectroscopy (3)

By c.1994, the six $j_\ell = 3/2$ narrow P-wave charmed mesons had been found.

J^P of the states are not rigorously established,
but not subject to serious doubt.

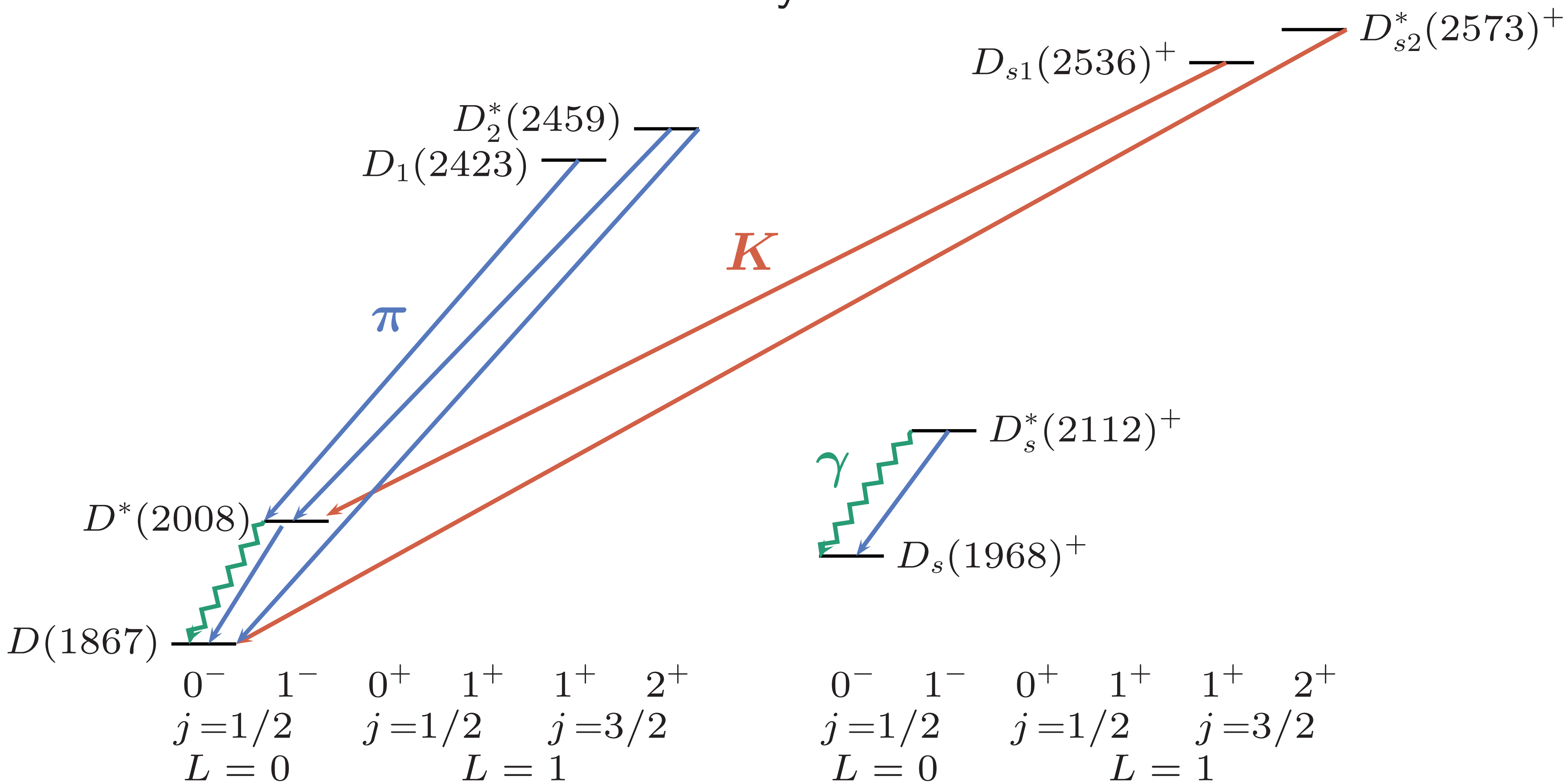
"Natural" (or "Normal") Spin-Parity:

True if $P = (-1)^J$ $[0^+, 1^-, 2^+ \ldots]$.

Flavored natural states get a *.

Charmed Meson Spectroscopy c.1995

Observed States and Decays



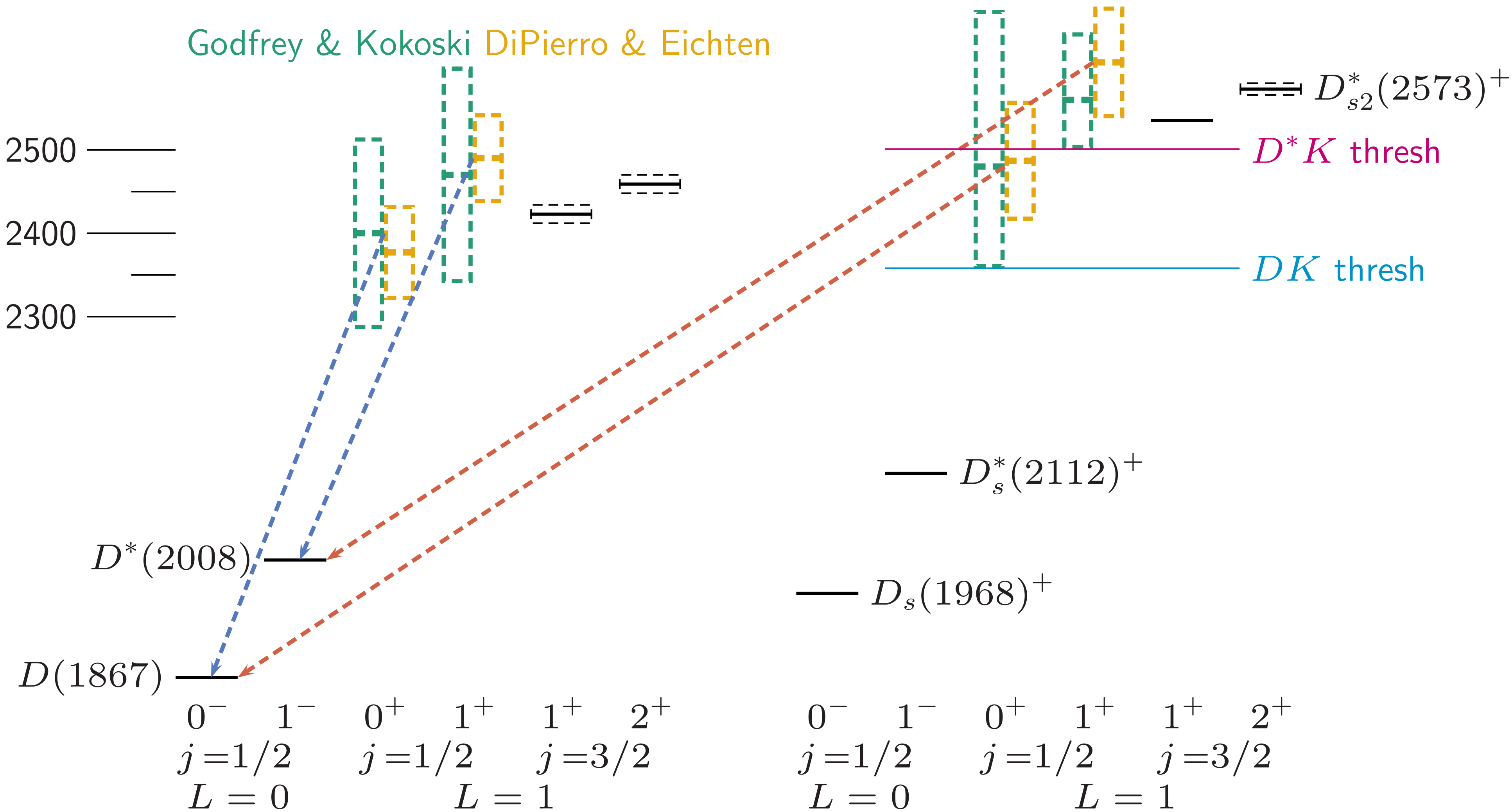
Predictions for $L = 1$ $j_\ell = 1/2$ Charmed Mesons

Many potential model calculations for masses and widths.

I mention only two examples here:
Godfrey & Kokoski PRD **43**, 1679 (1991)
Di Pierro & Eichten PRD **64**, 114004 (2001)

$L = 1$ $j_\ell = 1/2$ (MeV/c^2)								
	$^{1/2}D_0$		$^{1/2}D_1$		$^{1/2}D_{s0}$		$^{1/2}D_{s1}$	
	m	Γ	m	Γ	m	Γ	m	Γ
G&K	2400	290	2470	250	2480	310	2560	140
DP&E	2377	110	2490	110	2487	140	2605	130

Predictions for $L = 1$ $j_\ell = 1/2$ Charmed Mesons



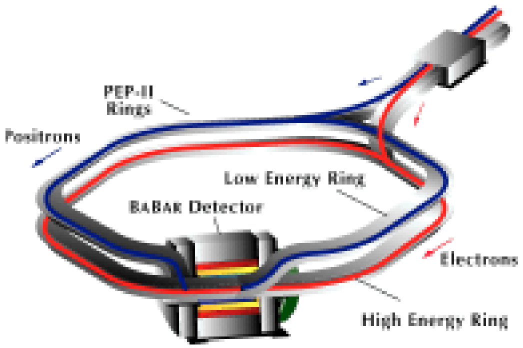
BaBar

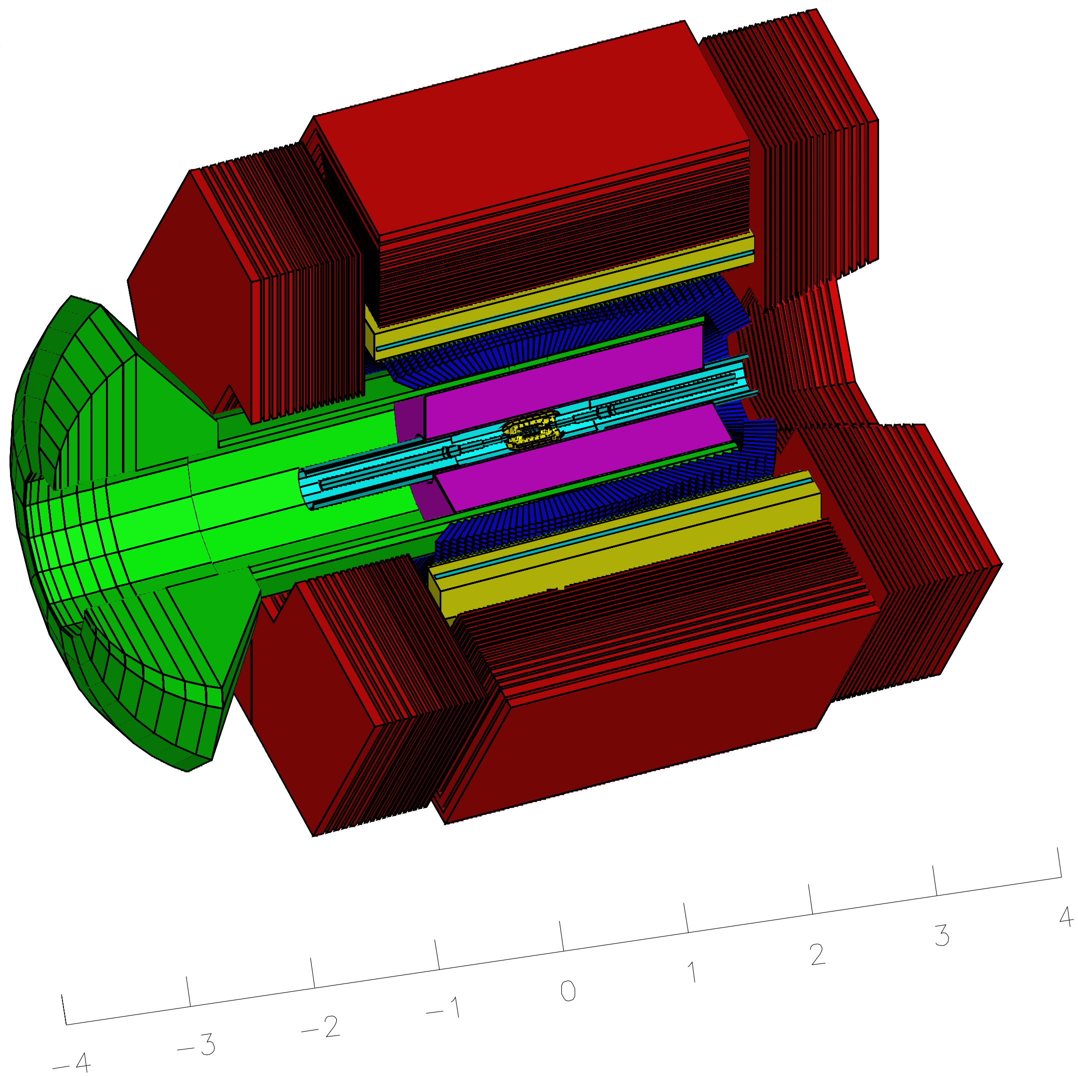
BaBar: General purpose solenoidal spectrometer with silicon vertex tracker, CsI calorimeter, DIRC particle ID, and instrumented flux return for muon and K_L detection.

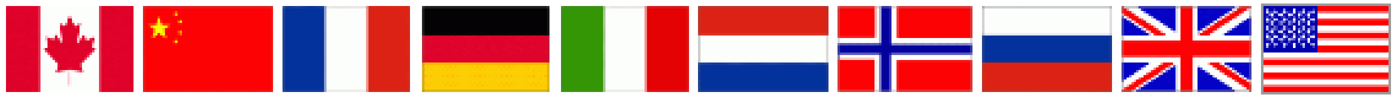
Operates at PEP-II asymmetric B-Factory:
E_{e^-}=9.0 GeV, E_{e^+}=3.1 GeV
$\sqrt{S} = m(\Upsilon(4\mathrm{S}))$ or just below
Best luminosity: 6.582×10^{33} cm^{-2} sec^{-1}

$\sigma(e^+e^- \rightarrow c\overline{c}) \approx 1.3$ nb
For 91 $\mathrm{fb}^{-1}$for this analysis; ∼120 million charm events
Or roughly 1.2 million $D^0 \rightarrow K^-\pi^+$

PEP-II and BABAR

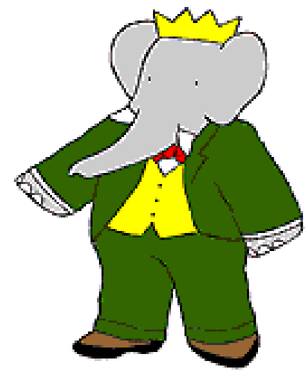






The BaBar Collaboration

10 countries
77 Institutions
~580 Physicists



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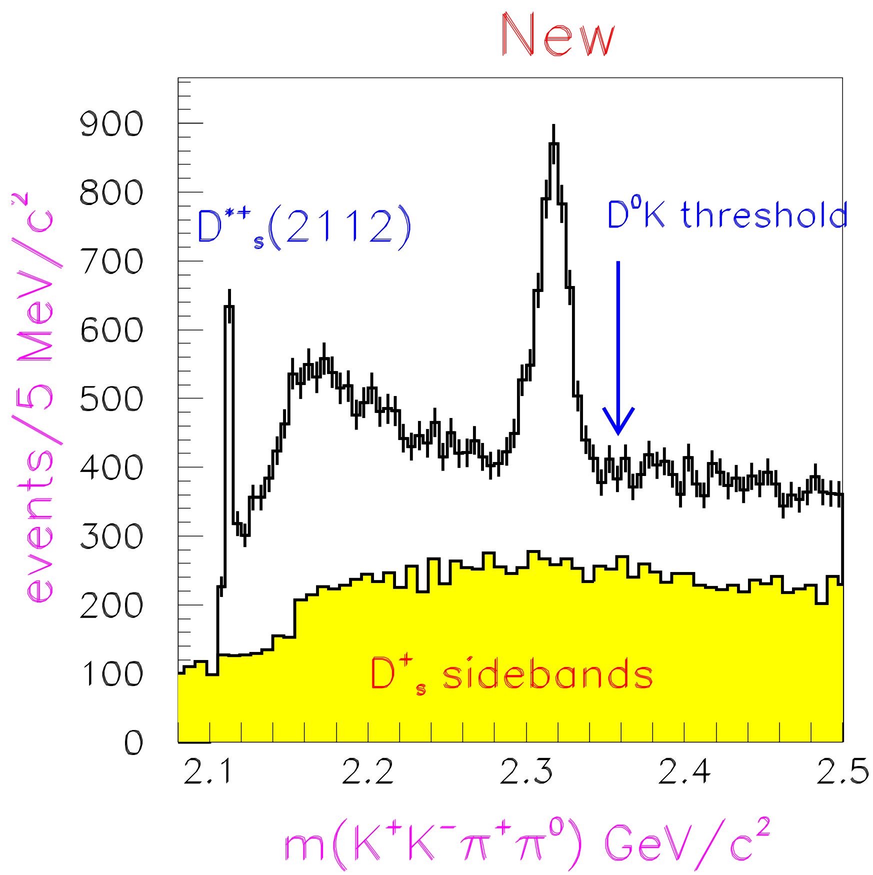
An Unexpected Signal

Early 2003: Antimo Palano was studying $D_s^+\pi^0$.
To everyone's surprise, he found a new, huge signal.



Analysis Details

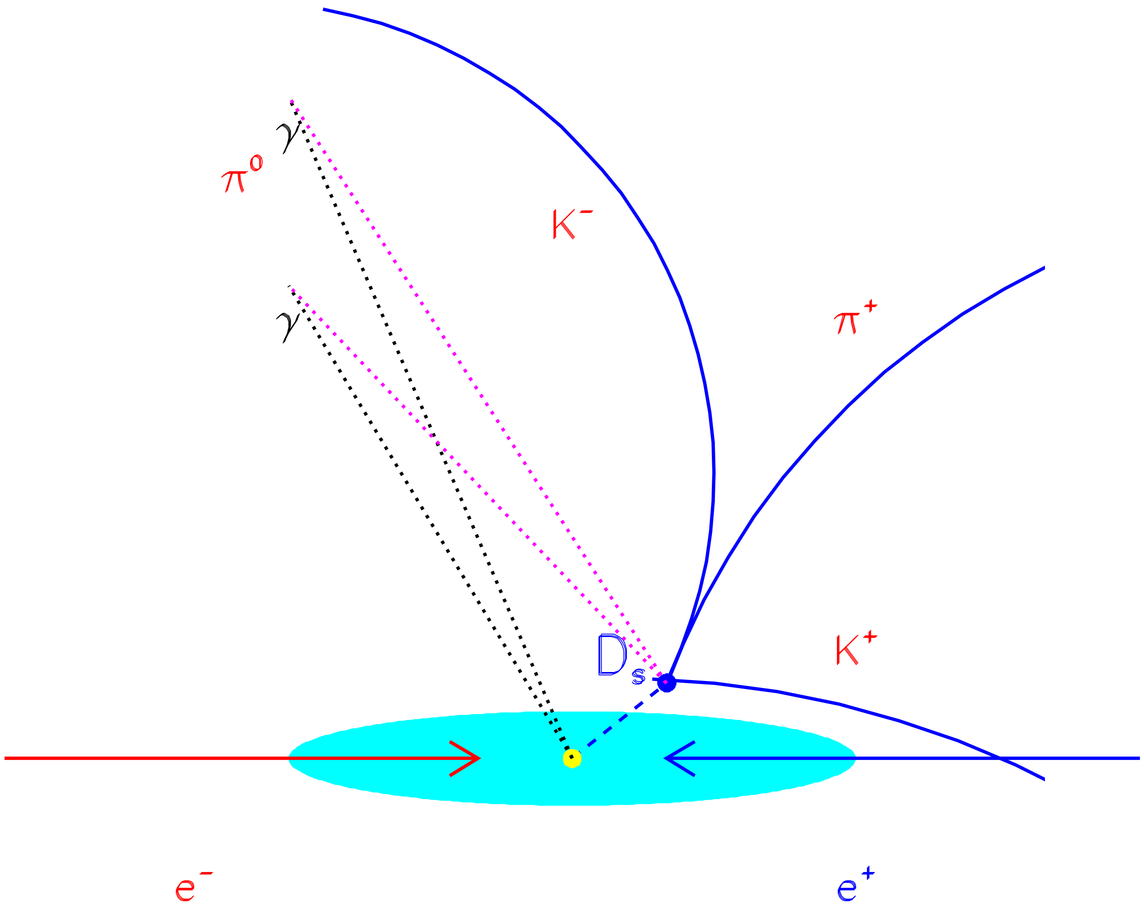
See also PRL, **90**, 242001 (2003)

Used 91 fb^{-1} collected on $\Upsilon(4\mathrm{S})$ and just below.
Studying $e^+e^- \to c\bar{c}$, not B decay (so far).

Reconstruct $D_s^+ \to K^+K^-\pi^+$.

- Kaons selected by Čerenkov (DIRC) & dE/dx
- Pion: any charged track that fails Kaon criteria
- $K^+K^-\pi^+$ fit to common vertex, $P > 0.1\%$.
- $\phi\pi^+$: $\pm 10\ \mathrm{MeV}/c^2$ around $m(\phi)$; $|\cos\theta_v| > 0.5$
- $\overline{K^{*0}}K^+$: $\pm 50\ \mathrm{MeV}/c^2$ around $m(\overline{K^{*0}})$; $|\cos\theta_v| > 0.5$

An Event



Analysis Details (2)

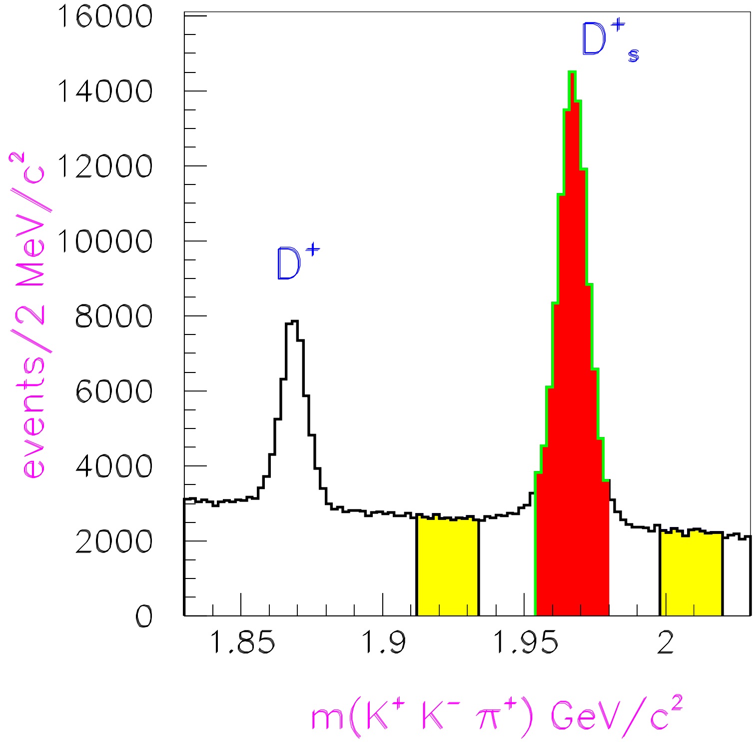
Reconstruct $\pi^0 \to \gamma\gamma$

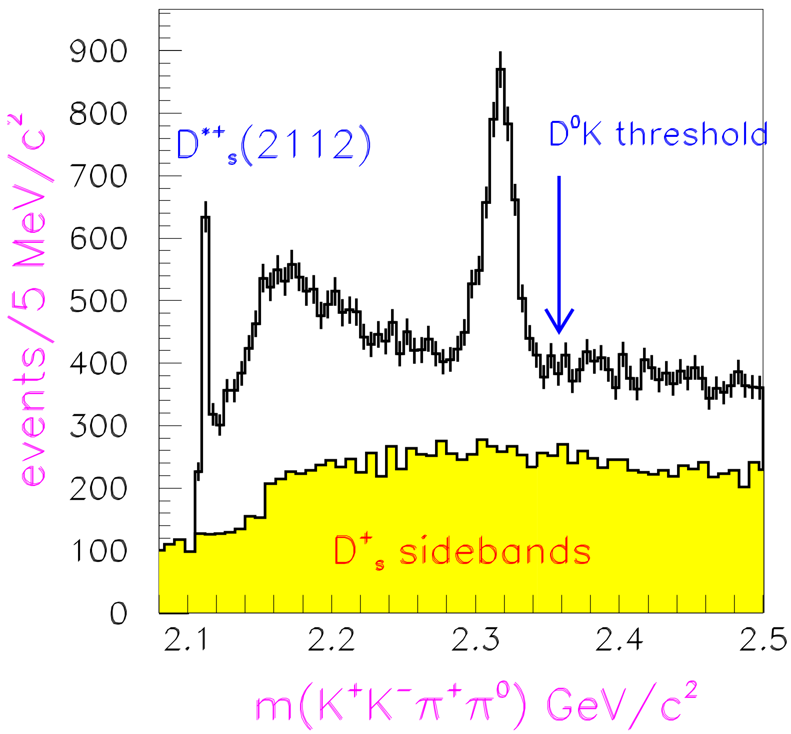
- $E(\gamma) > 100$ MeV
- One-constraint fit to π^0 mass ($P > 1\%$)
- Only use π^0 if no other π^0 candidate uses either γ
- $p^*(K^+K^-\pi^+\pi^0) > 2.5$ GeV/c.

π^0 signal region: 122 $\mathrm{MeV}/c^2 < m(\gamma\gamma) <$ 148 MeV/c^2
sidebands: 90—110 MeV and 160—180 MeV

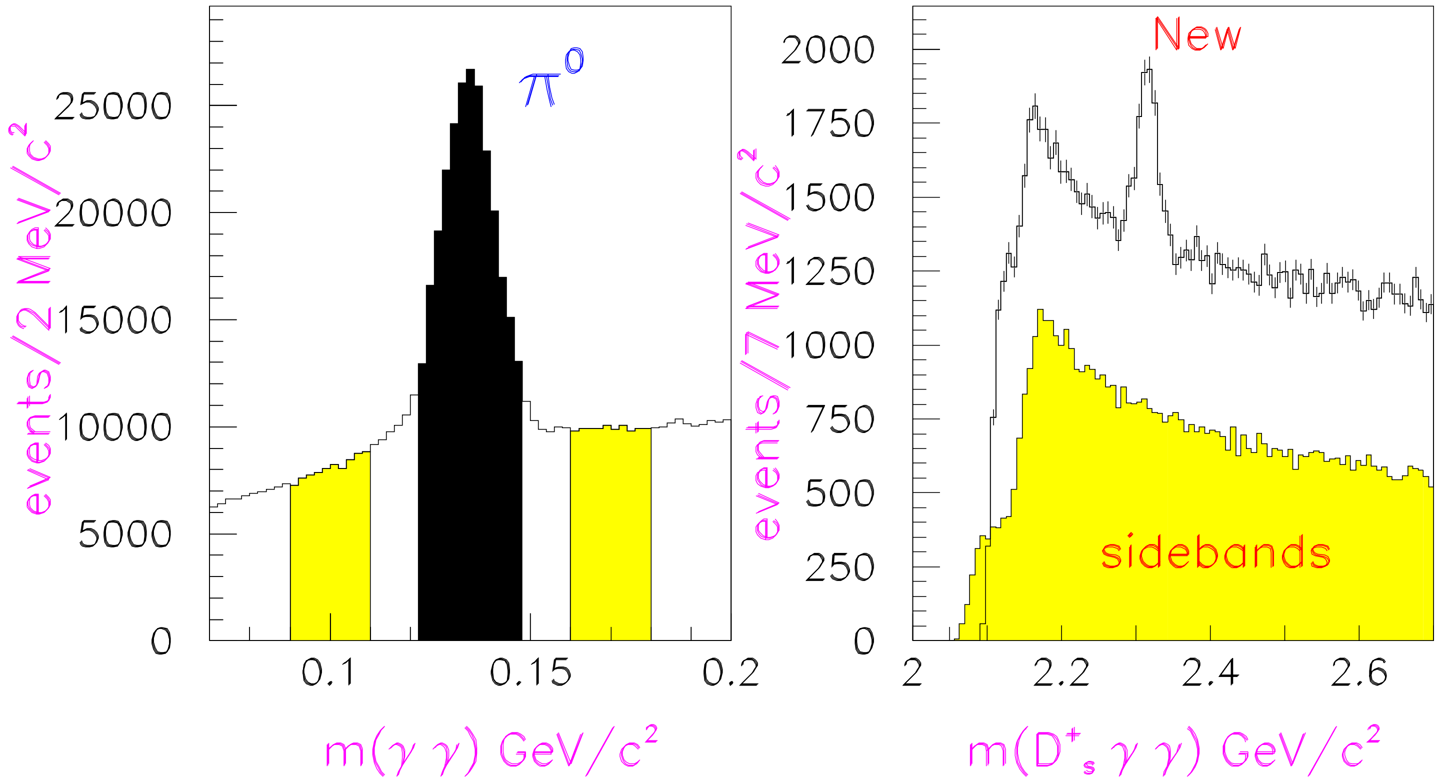
D_s^+ signal region: 1955 $\mathrm{MeV}/c^2 < m(K^+K^-\pi^+) <$ 1979 MeV/c^2
sidebands: 1912—1934 MeV/c^2 and 1998—2020 MeV/c^2

Combining D_s^+ and π^0 Candidates





Really π^0?

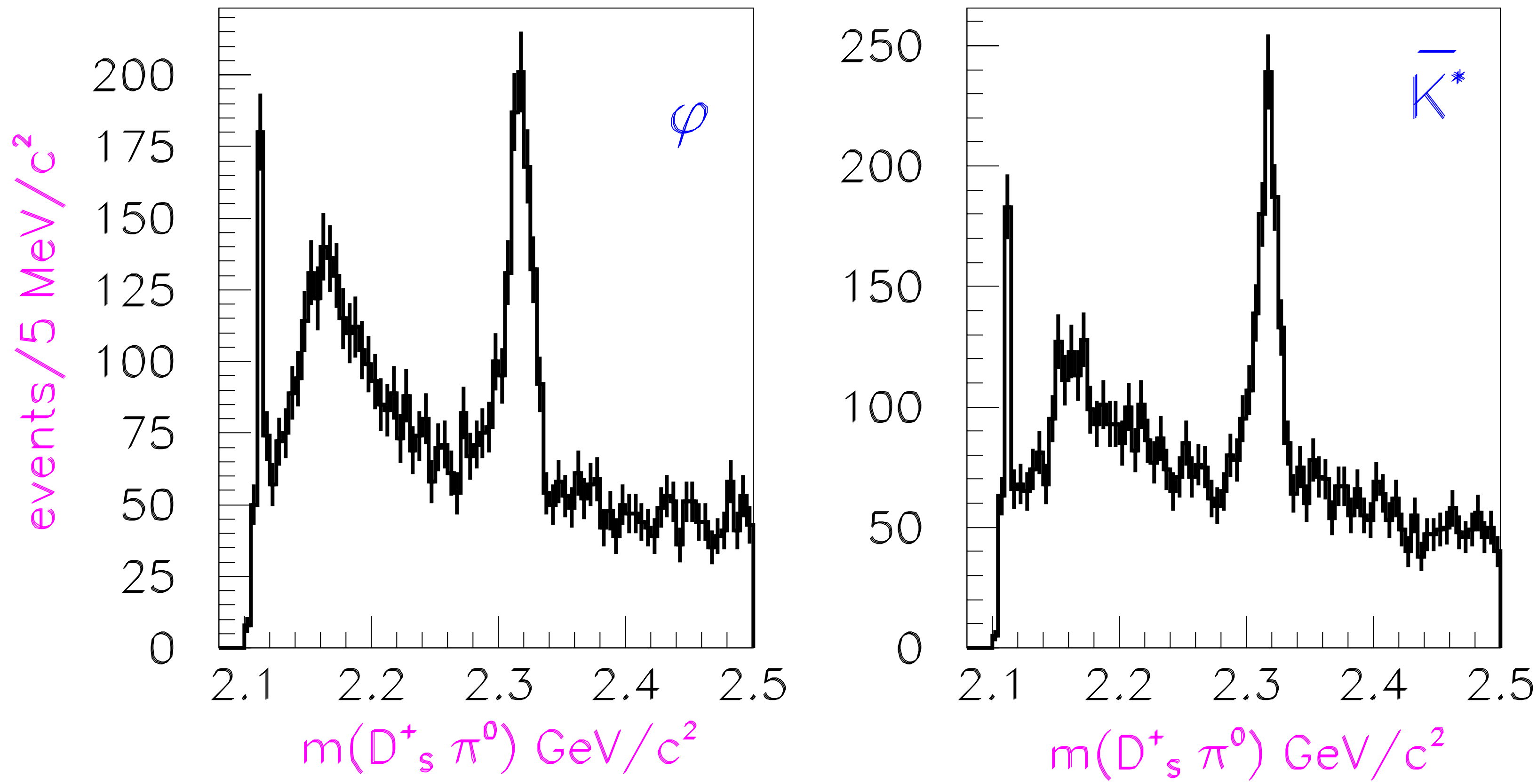


Note: these $\gamma\gamma$ pairs do not have same cuts as π^0 candidates.

Some More Checks

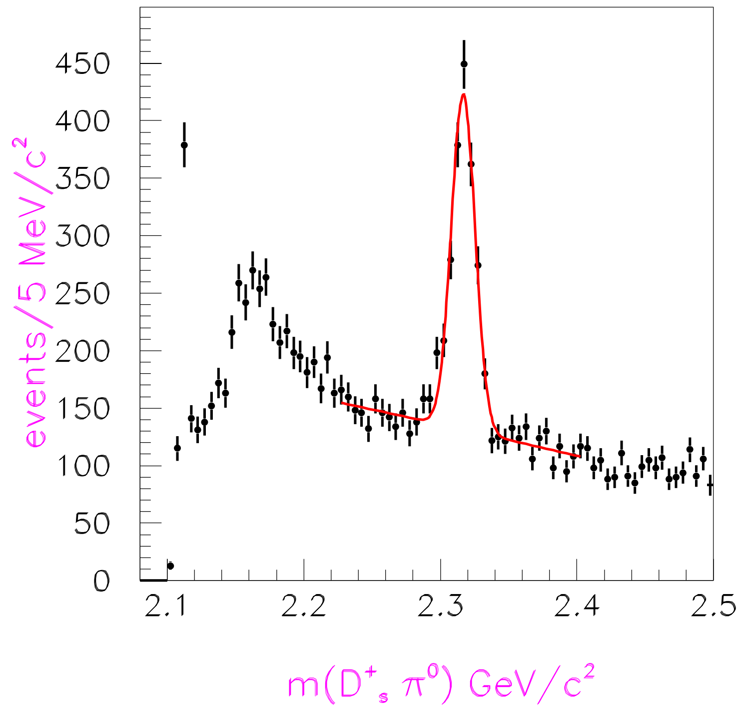
- Signal only appears in $D_s^+\pi^0$, not sidebands
- Signal in $D_s^+ \to \phi\pi^+$ and $D_s^+ \to \overline{K^{*0}}K^+$ as expected
- Try vetoing D_s^+ from $D_s^*(2112)^+ \to D_s^+\gamma$
- Nothing similar in $D^+\pi^0$
- Check for particle mis-ID (K/π)
- Nothing in Monte Carlo that makes a peak here
- p^* spectrum looks OK

$\phi\pi^+$ vs. $\overline{K^{*0}}K^+$



Fit the Combined Data

$p^* > 3.5\ \mathrm{GeV}/c$



1267 ± 53 events

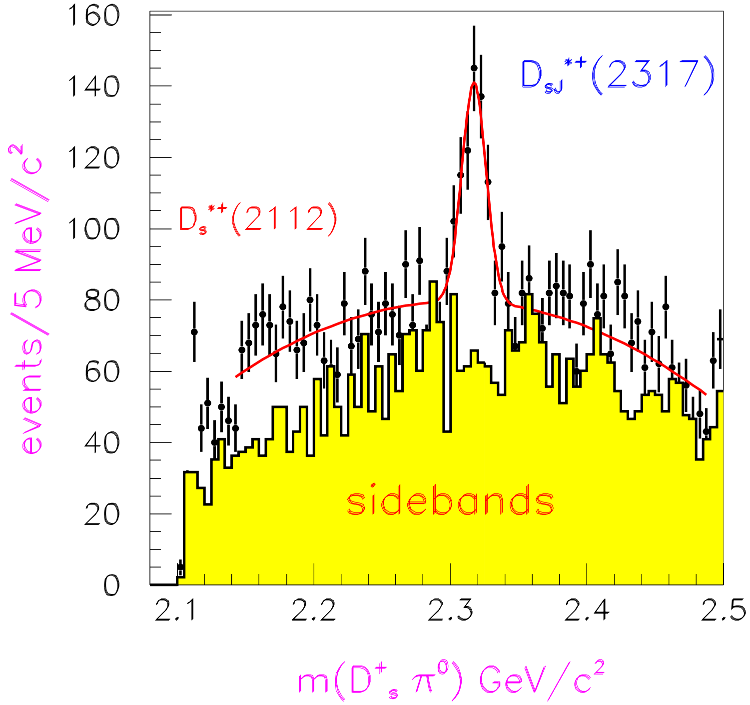
$M = 2316.8 \pm 0.4$ MeV/c^2

$\sigma = 8.6 \pm 0.4$ MeV/c^2
[Detector Resolution]

Statistical errors only!

Cross Check: use $D_s^+ \to K^+K^-\pi^+\pi^0$

$$p^* > 3.5\ \mathrm{GeV}/c$$



273 ± 33 events

$M = 2317.6 \pm 1.3$ MeV$/c^2$

$\sigma = 8.8 \pm 1.1$ MeV$/c^2$

[Detector Resolution]

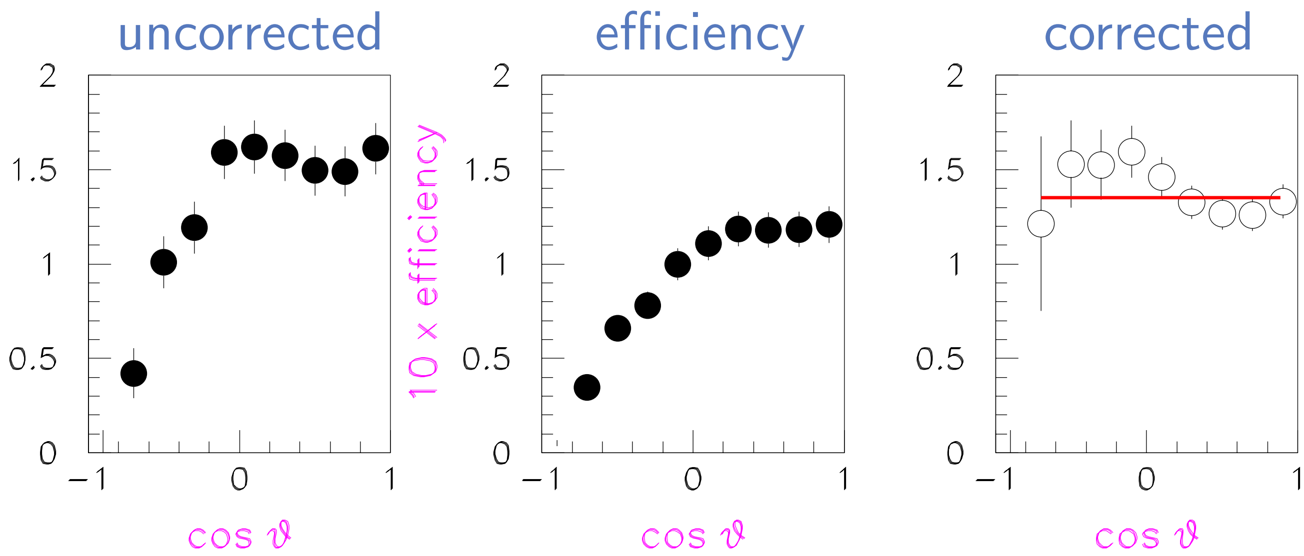
Statistical errors only!

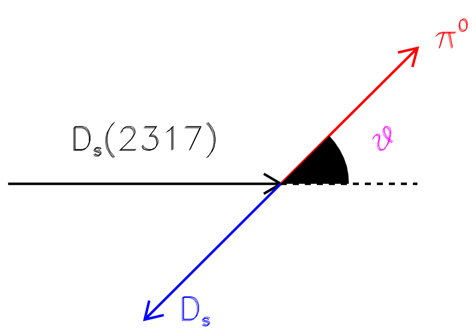
Initial Conclusions

- Signal width consistent with detector resolution, as estimated by Monte Carlo. $\Rightarrow \Gamma \lesssim 10\ \mathrm{MeV}/c^2$
- Decay to 2 pseudoscalars implies natural spin-parity
- If it is a $c\overline{s}$ state, decay violates isospin conserveration.
- If it is the missing 0^+, it is ∼170 MeV/c^2 lighter than expected
- Below D^0K^+ decay threshold forces this decay mode
- Isospin violating decay implies very narrow.

Call it $D^*_{sJ}(2317)^+$. What else can we learn about it?

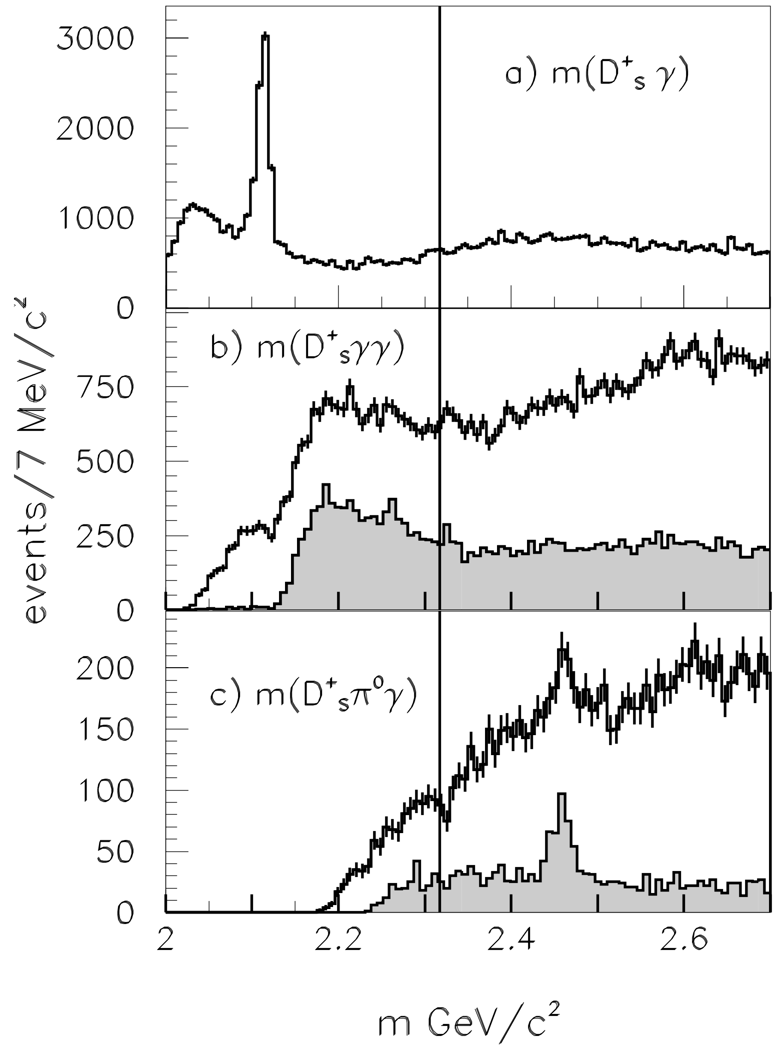
Decay Angle





Consistent with
$J = 0$ particle, or
unaligned $J > 0$ state.

Other Decay Modes?



Nothing seen at 2317 MeV/c^2 in

$D_s^+\gamma$

$D_s^+\gamma\gamma$

$D_s^{*+}\gamma$

$D_s^+\pi^0\gamma$

$D_s^{*+}\pi^0$

BABAR PRL **90**, 242001 (2003)

What is that at ∼2460 MeV/c^2?

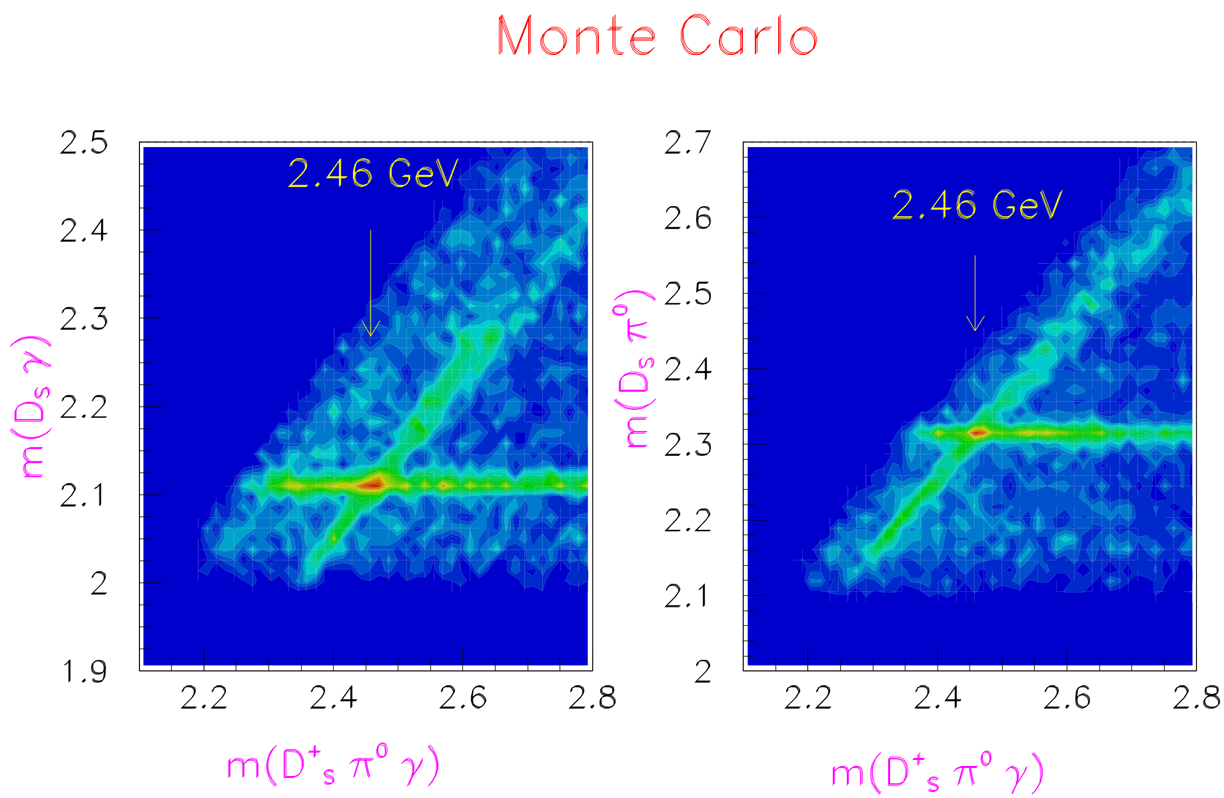
Could $X(2460) \to D_s^+\pi^0\gamma$ be the real source of the peak at 2317 MeV/c^2, if we have missed the γ?

No!

- Relative rate is too small.
- Would not produce a gaussian signal shape
- Mass is not quite right.

But, if real, can produce some background under the peak at 2317 MeV/c^2. [More on this later.]

Why the peak near 2460 MeV/c^2 is Tricky

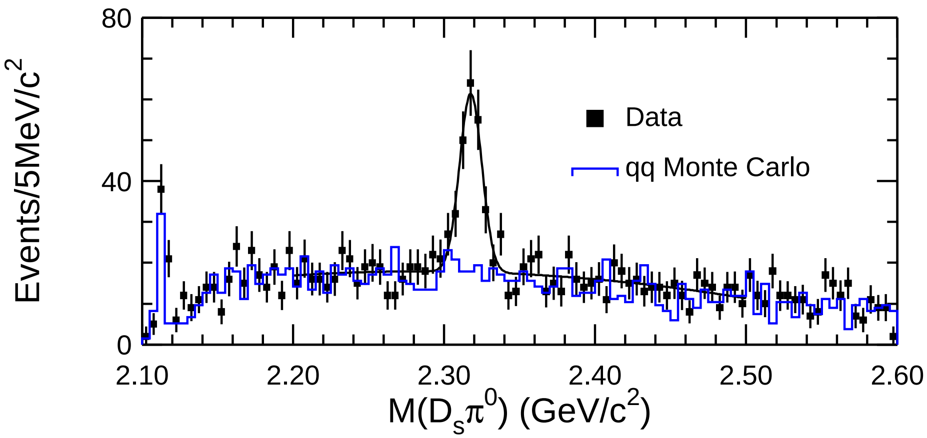


$D_s^*(2112)^+ + \pi^0_{random}$ crosses $D_{sJ}^*(2317)^+ + \gamma_{random}$ at $m(D_s^+\pi^0\gamma) \approx 2460\ \mathrm{MeV}/c^2$.

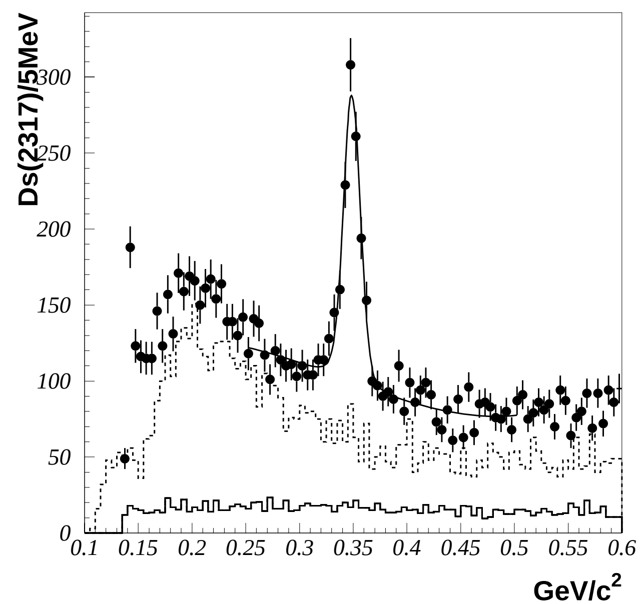
BABAR PRL 90, 242001 (2003)

"Although we rule out the decay of a state of mass 2.46 GeV/c^2 as the sole source of the $D_s^+\pi^0$ mass peak corresponding to the $D_{sJ}^*(2317)^+$, such a state may be produced in addition to the $D_{sJ}^*(2317)^+$. However, the complexity of the overlapping kinematics of the $D_s^*(2112)^+ \to D_s^+\gamma$ and $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ decays requires more detailed study, currently underway, in order to arrive at a definitive conclusion."

Other Experiments Confirm $D^*_{sJ}(2317)^+$



CLEO 13.5 fb^{-1}



Belle preliminary 78 fb^{-1}

CDF (preliminary): no signal for $D^*_{sJ}(2317)^+ \to D^+_s \pi^+ \pi^-$
$[0^+ \to 0^- 0^- 0^-$ is forbidden]

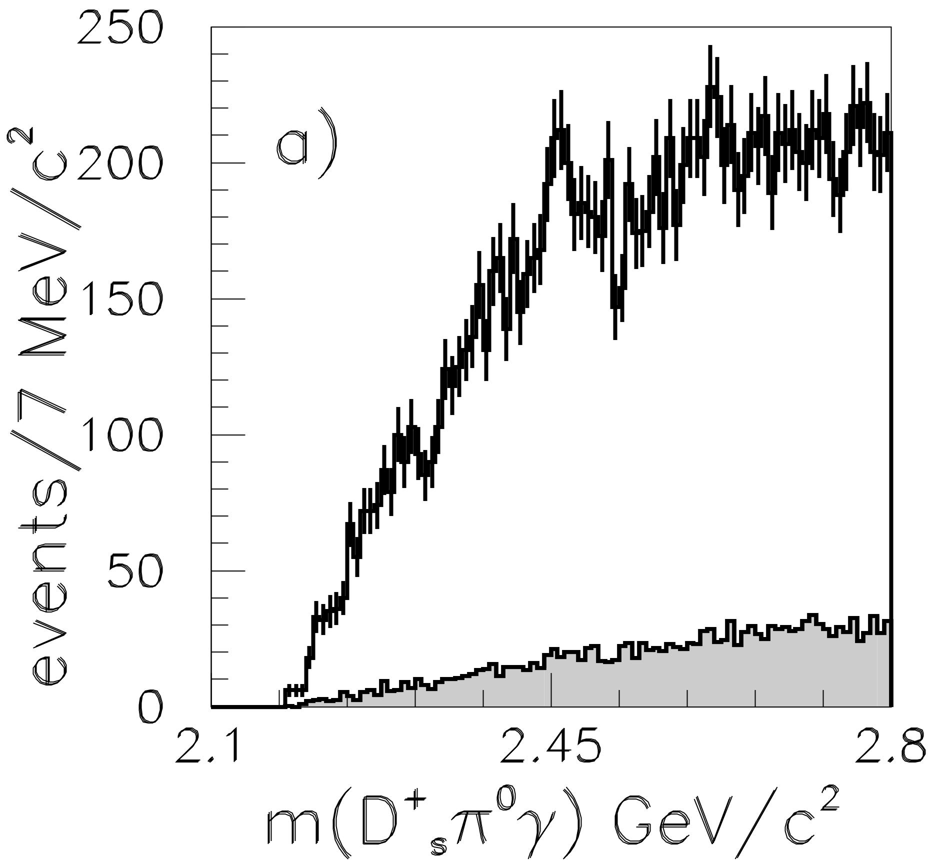
The $D_{sJ}(2463)^+$

CLEO's paper (submitted to PRD) is entitled:
Observation of a Narrow Resonance of Mass 2.46 GeV/c^2 *Decaying to* $D_s^{*+}\pi^0$ *and Confirmation of the* $D_{sJ}^*(2317)^+$ *State*

Belle has also seen two states.

What does *BaBar* *now* have to say about the second peak?

The Mass Peak

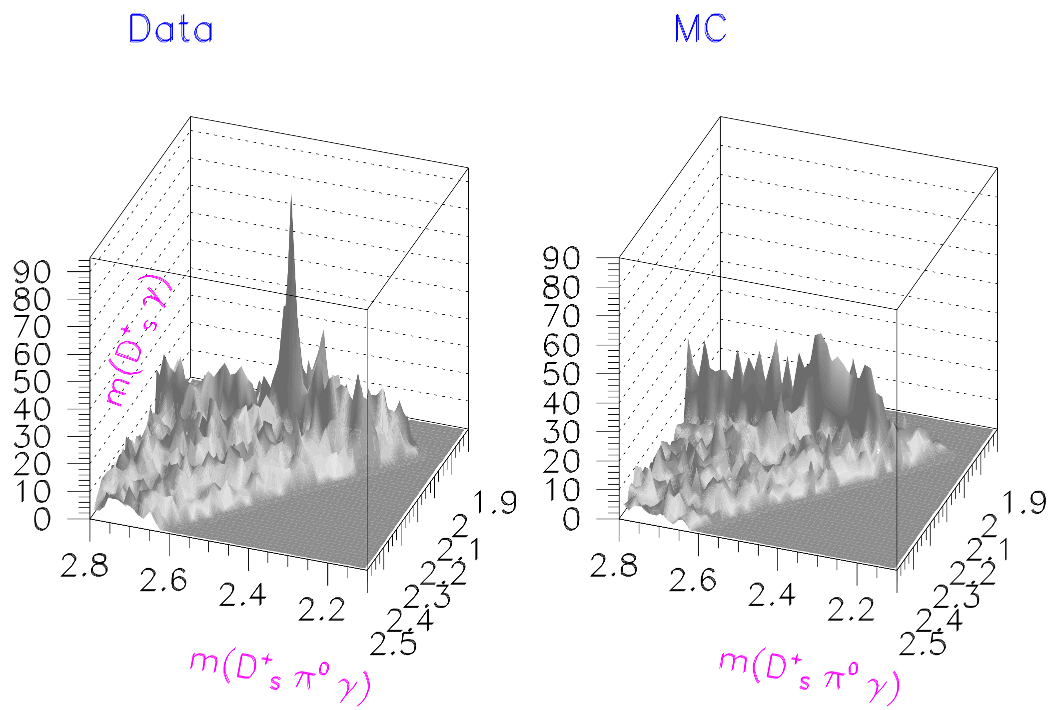


Inclusive $D_s^+\pi^0\gamma$ events

D_s^+ side band events

Preliminary

A 3-D View



A prominent peak appears in data, not in Monte Carlo, which includes the $D^*_{sJ}(2317)^+$.

Preliminary

$D_s^+\gamma\pi^0$: Sideband Subtraction

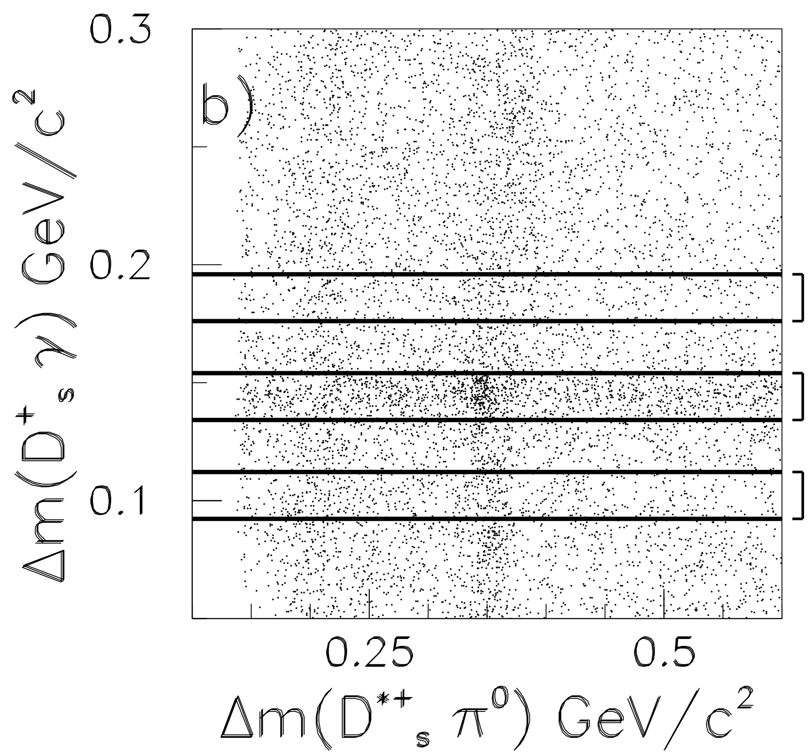
Change variables:

$$\Delta m(D_s^+\gamma) \equiv m(D_s^+\gamma) - m(D_s^+)$$

$D_{sJ}^*(2317)^+$ +random γ ⇓

D_s^{*+} + random π^0 ⟹

Preliminary

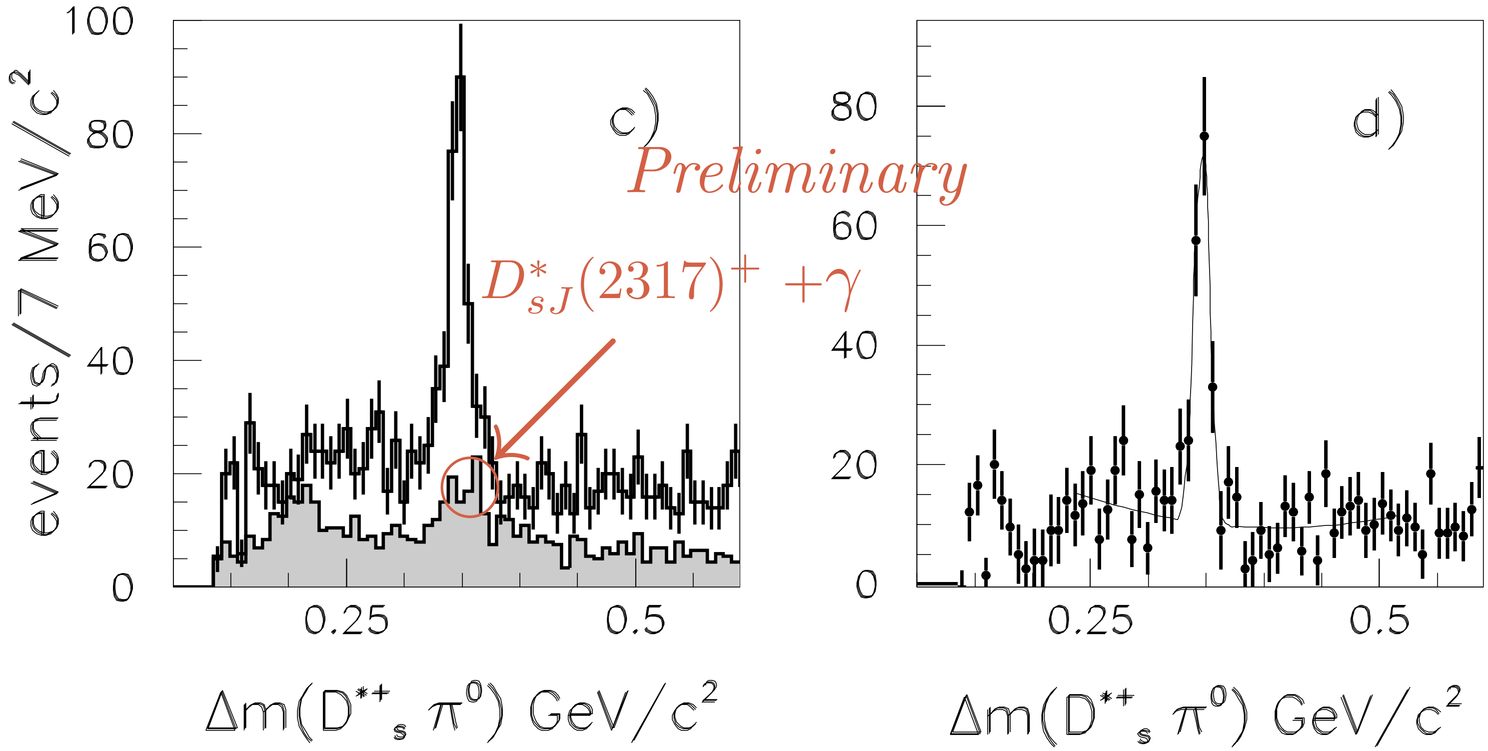


$$\Delta m(D_s^{*+}\pi^0) \equiv m(D_s^+\gamma\pi^0) - m(D_s^+\gamma)$$

$D_s^+\gamma\pi^0$: Sideband Subtraction (2)

Signal & Sideband

Difference, with Fit



peak: $\Delta m(D_s^{*+}\pi^0) = 346.2 \pm 0.9$ MeV$/c^2$

statistical error only

Channel Likelihood Method

Assign likelihoods to each event for:

1. $D_{sJ}(2458)^+ \rightarrow D^*_{sJ}(2317)^+\gamma$
2. $D_{sJ}(2458)^+ \rightarrow D^*_s(2112)^+\pi^0$
3. background $D^*_{sJ}(2317)^+$ plus random γ
4. background $D^*_s(2112)^+$ plus random π^0
5. combinatorial background

Assume the three-body decay $D_{sJ}(2458)^+ \rightarrow D_s^+\pi^0\gamma$ is absent.
Ignore any possible interference term (resolution would smear).

Channel Likelihood Fit Results

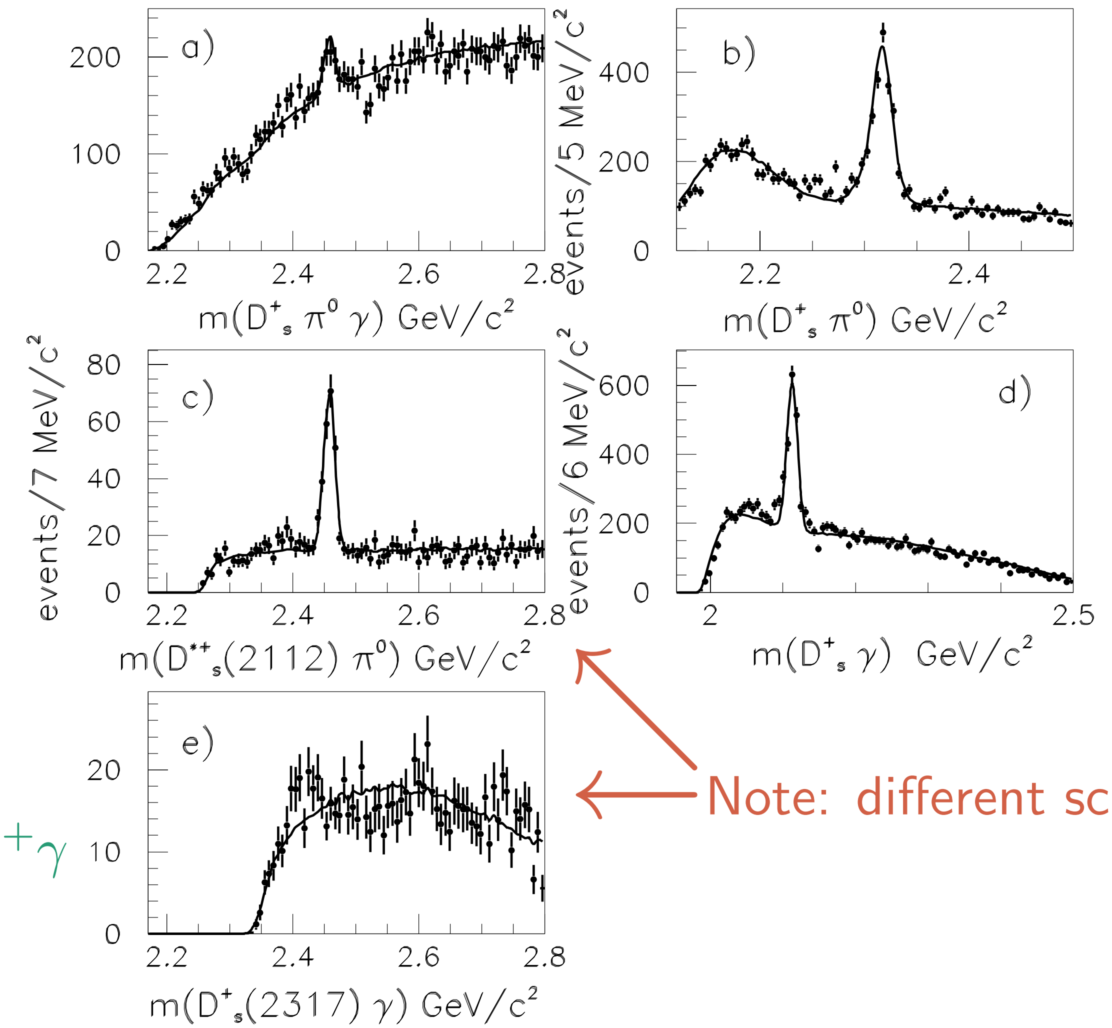
$D_s^+\gamma\pi^0$

$D_s^+\pi^0$ projection

weighted $D_s^{*+}\pi^0$

$D_s^+\gamma$ projection

weighted $D_{sJ}^*(2317)^+\gamma$



Note: different scales!

Preliminary

Preliminary Results

- 174 ± 22 events, $D_{sJ}(2458)^+ \rightarrow D_s^*(2112)^+\pi^0$
- 0 ± 19 events, $D_{sJ}(2458)^+ \rightarrow D_{sJ}^*(2317)^+\gamma$
- $m(D_{sJ}(2458)^+) = 2458.0 \pm 1.0 \pm 1.0 \text{ MeV}/c^2$
- Gaussian $\sigma = 8.5 \pm 1.0 \text{ MeV}/c^2$: Detector Resolution

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$$\frac{\mathcal{B}(D_{sJ}(2458)^+ \rightarrow D_{sJ}^*(2317)^+\gamma)}{\mathcal{B}(D_{sJ}(2458)^+ \rightarrow D_s^*(2112)^+\pi^0)} < 0.2 \ (95\%\text{C.L.})$$

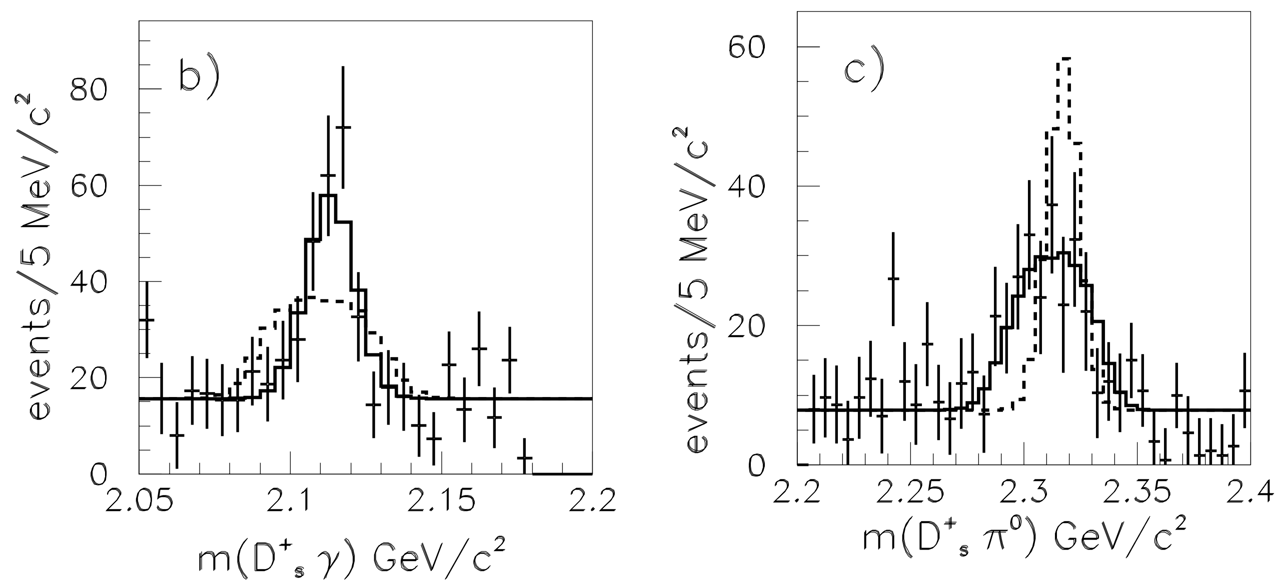
Refit $D_{sJ}^*(2317)^+ \rightarrow D_s^+\pi^0$ (account for $D_{sJ}(2458)^+$bkgd):

$$m(D_{sJ}^*(2317)^+) = 2317.3 \pm 0.4 \pm 0.8 \text{ MeV}/c^2$$

Decay Mode

Solid Hists: $D_{sJ}(2458)^+ \to D_s^*(2112)^+\pi^0$ Monte Carlo

Dashed Hists: $D_{sJ}(2458)^+ \to D_{sJ}^*(2317)^+\gamma$ Monte Carlo



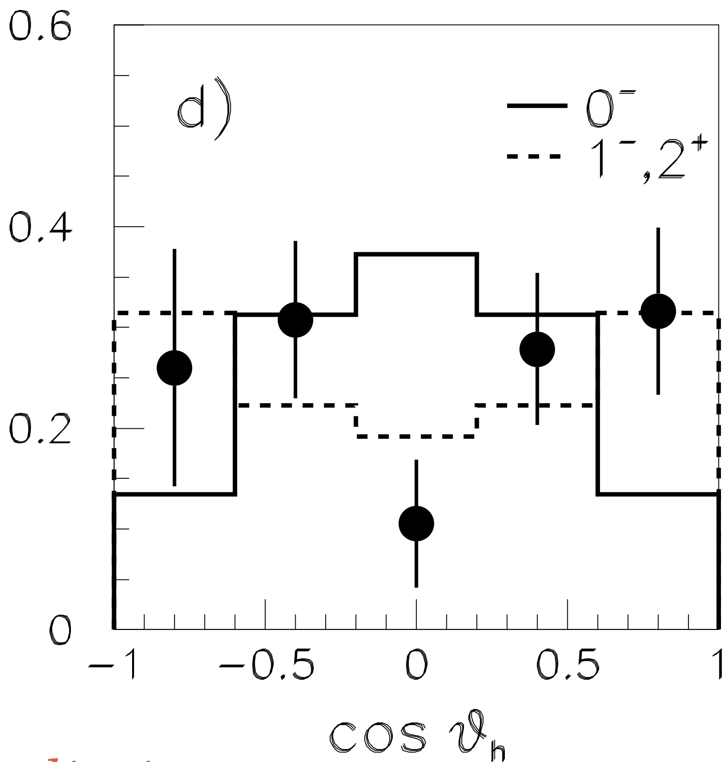
Data agree with Solid histograms. *Preliminary*

Spin-Parity of $D_{sJ}(2458)^+$?

- Decay to $D_s^{*+}\pi^0$ (1^-0^-) rules out 0^+
- Decay mode also makes other natural J^P $(1^-, 2^+, \ldots)$ highly unlikely (decay to D^0K^+, D^+K^0 available)
- That leaves unnatural: $0^-, 1^+, 2^-$

Helicity Angle

ϑ_h: angle between γ and $D_s^*(2112)^+$ in $D_s^*(2112)^+$ rest frame.



Preliminary

$J^P = 0^- \Rightarrow \sin^2\vartheta_h$

solid histogram

disfavored

$J^P = 1^-, 2^+ \ldots$

$\Rightarrow 1 + \cos^2\vartheta_h$

dashed histogram

OK (but unlikely)

$J^P = 1^+, 2^-, \ldots$: depends on alignment: no conclusion.

Relative Production Rate

Preliminary

$$\mathcal{P} \equiv \frac{\sigma(D_{sJ}(2458)^+)\mathcal{B}(D_{sJ}(2458)^+ \to D_s^*(2112)^+\pi^0)}{\sigma(D_{sJ}^*(2317)^+)\mathcal{B}(D_{sJ}^*(2317)^+ \to D_s^+\pi^0)}$$

$$= 0.23 \pm 0.03\ (\mathrm{stat.}) \pm 0.03\ (\mathrm{syst.})$$

for $p^* > 3.5\ \mathrm{GeV}/c$ for both states

Comparisons with CLEO and Belle

$D^*_{sJ}(2317)^+$mass:

BABAR	$2317.3 \pm 0.4 \pm 0.8\ \mathrm{MeV}/c^2$	[*preliminary*]
Belle	$2317.2 \pm 0.5 \pm 0.9\ \mathrm{MeV}/c^2$	continuum [prelim.]
Belle	$2319.8 \pm 2.1 \pm 2.0\ \mathrm{MeV}/c^2$	B decay
CLEO	$2318.5 \pm 1.2 \pm 1.2\ \mathrm{MeV}/c^2$	

my average: $2317.4 \pm 0.5 \pm 0.6\ \mathrm{MeV}/c^2\ [\chi^2 = 1.2]$
first error: stat&syst; second error from D_s^+ mass (common)

- Width is less than resolution. ($\Gamma < 7\ \mathrm{MeV}/c^2$: CLEO)
- No other decay modes seen.
- Everything consistent with $J^P = 0^+$.

Comparisons with CLEO and Belle (2)

$D_{sJ}(2458)^+$mass (from $D_s^*(2112)^+\pi^0$)

BaBar	$2458.0 \pm 1.0 \pm 1.0$ MeV/c^2	[*Preliminary*]
Belle	$2456.5 \pm 1.3 \pm 1.1$ MeV/c^2	continuum [prelim.]
Belle	$2459.2 \pm 1.6 \pm 2.0$ MeV/c^2	B decay
CLEO	$2463.1 \pm 1.7 \pm 1.2$ MeV/c^2	

my average: $2458.6 \pm 0.8 \pm 0.7$ MeV/c^2 [$\chi^2 = 6.4$]

first error: stat&syst; second error from D_s^{*+} mass (common)

Comparisons with CLEO and Belle (3)

$\mathcal{P}$, the $D_{sJ}(2458)^+/D^*_{sJ}(2317)^+$ production ratio

BABAR	$0.23 \pm 0.03 \pm 0.03$	$p^* > 3.5$ GeV/c [*prelim.*]
Belle	$0.26 \pm 0.05 \pm 0.06$	$p^* > 3.5$ GeV/c [prelim]
CLEO	$0.44 \pm 0.13 \pm 0.03(?)$	$p^* > 3.5$ GeV/c

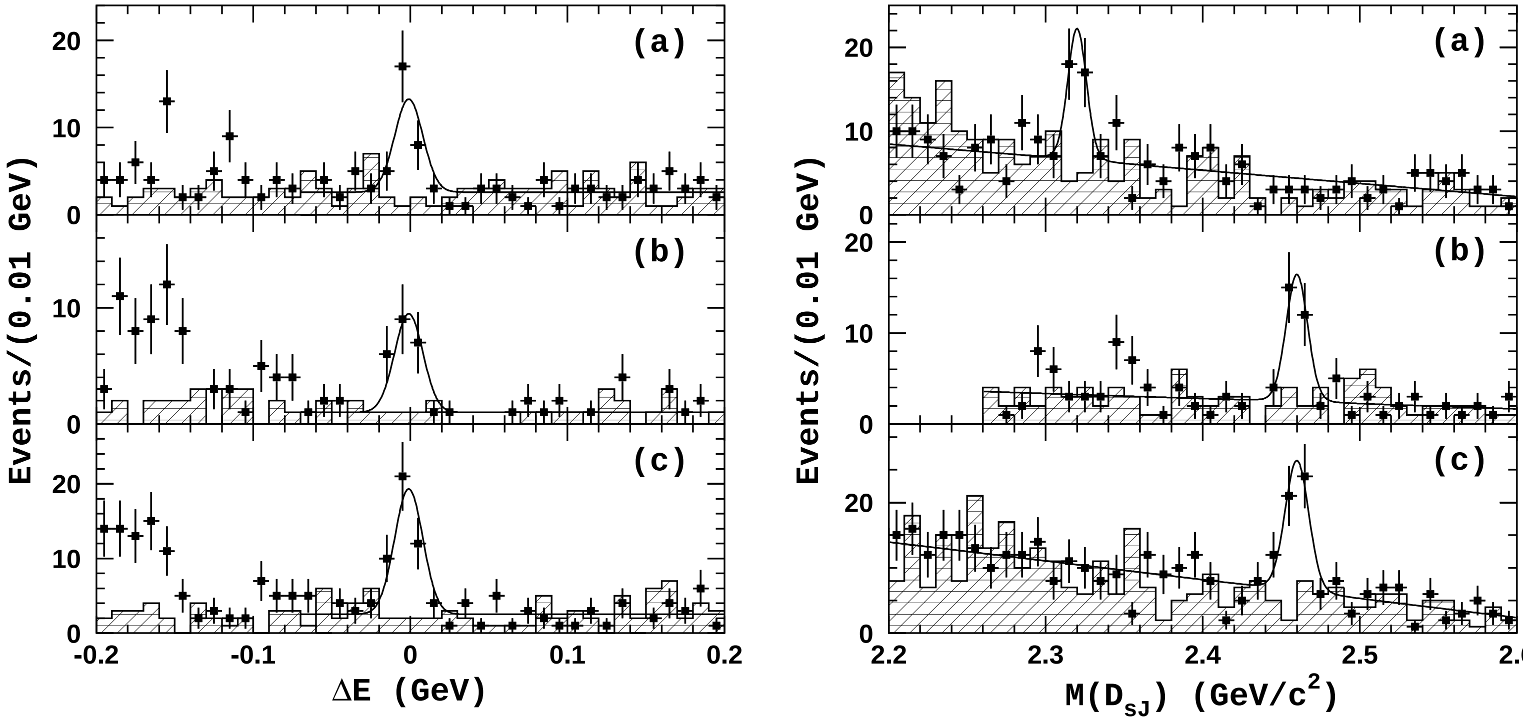
BABAR agrees with Belle, not so well with CLEO

Belle also sees the decay $D_{sJ}(2458)^+ \rightarrow D_s(1968)^+\gamma$ in both B decays and continuum events.

$$\frac{\mathcal{B}(D_{sJ}(2458)^+ \rightarrow D_s^+\gamma)}{\mathcal{B}(D_{sJ}(2458)^+ \rightarrow D_s^*(2112)^+\pi^0)} = 0.38 \pm 0.11 \pm 0.04\{B\}$$

$$= 0.63 \pm 0.15 \pm 0.15\{c\bar{c}\}[prelim]$$

Belle: Exclusive B Decay



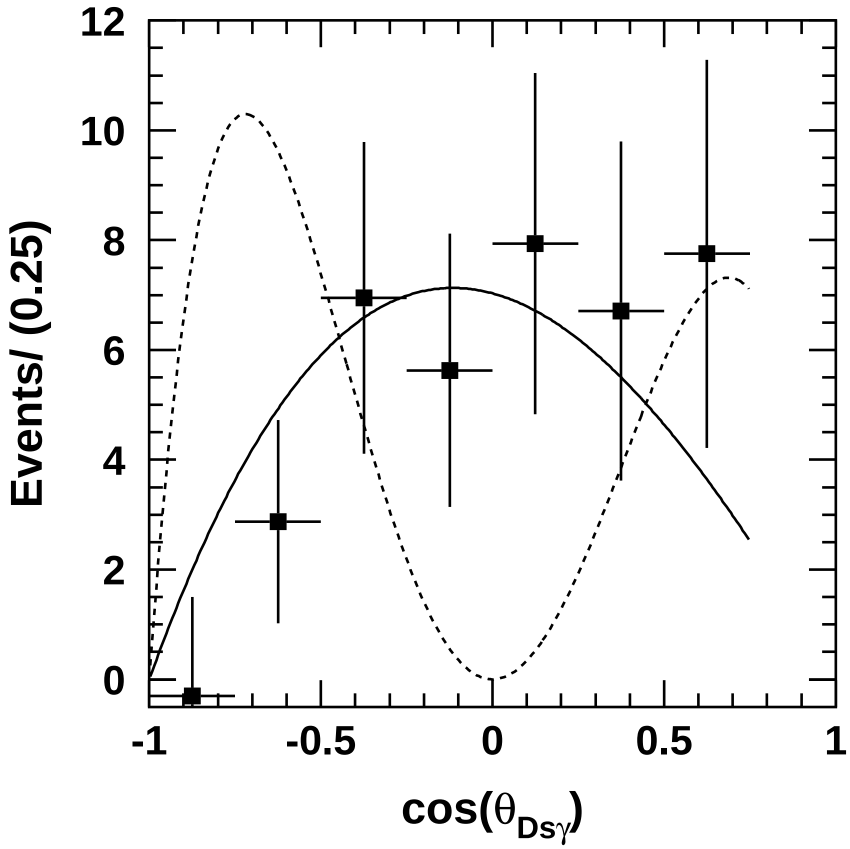
$B \to \overline{D} D_{sJ}$

(a) $D^*_{sJ}(2317)^+ \to D_s^+ \pi^0$

(b) $D_{sJ}(2458)^+ \to D_s^{*+} \pi^0$

(c) $D_{sJ}(2458)^+ \to D_s^+ \gamma$

Belle: Helicity Angle

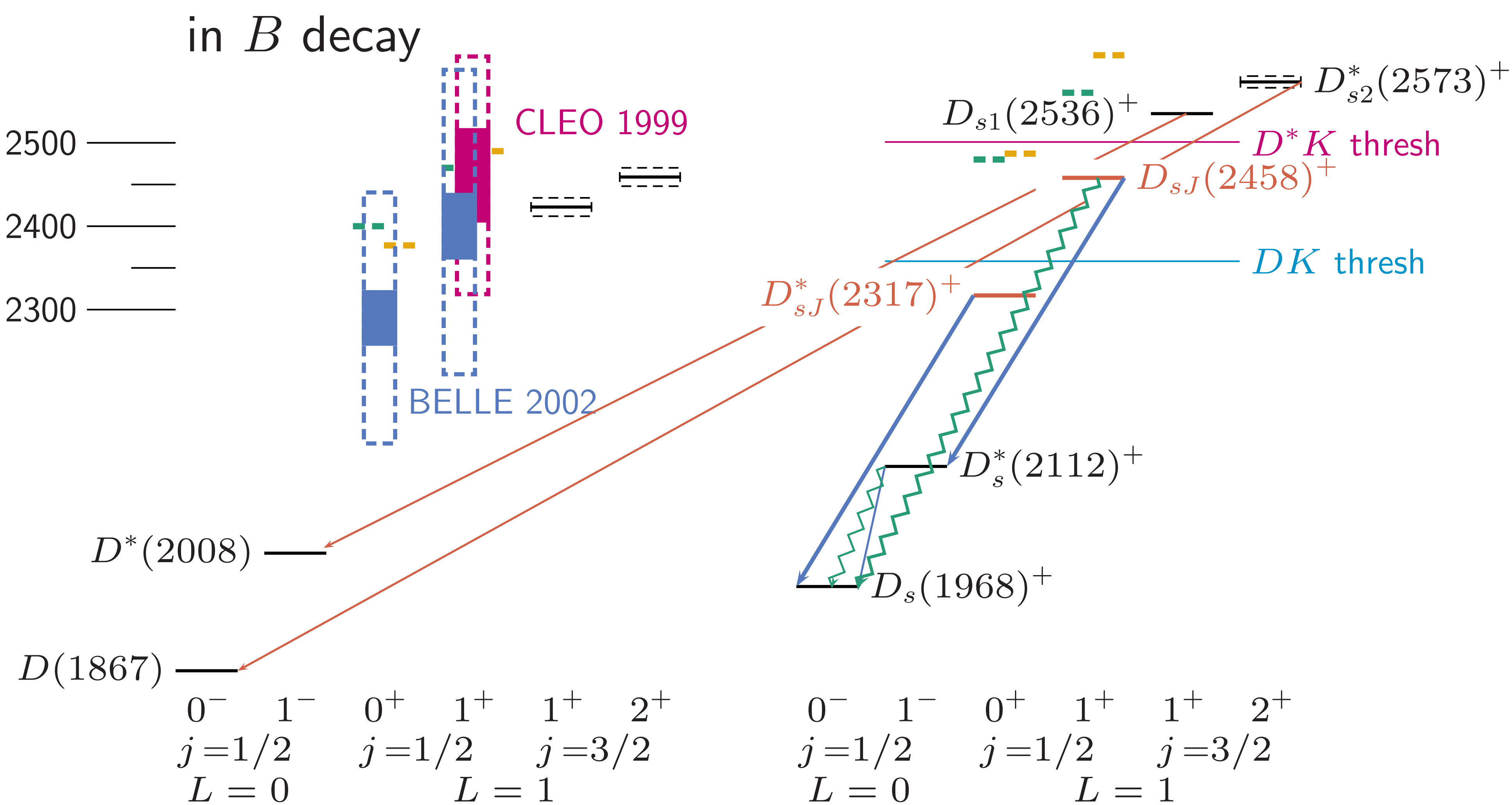


$B \to \overline{D} D_{sJ}(2458)^+$,
$D_{sJ}(2458)^+ \to D_s^+ \gamma$

Solid line: $J = 1$
Dotted line: $J = 2$

$J = 1$ clearly favored

Charm Spectroscopy Now



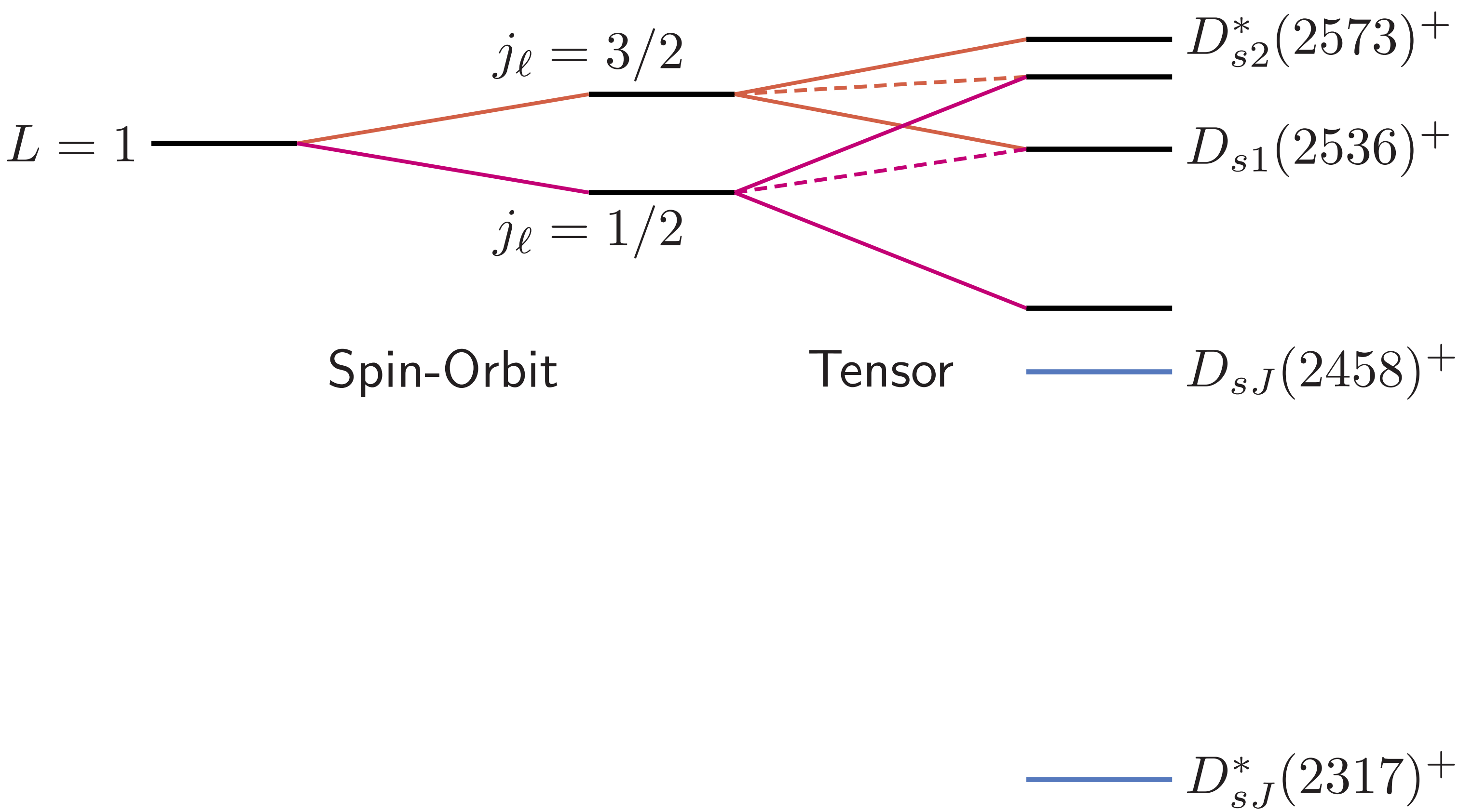
Observations of Non-Strange $j_\ell = 1/2$ States

To see broad $j_\ell = 1/2$ states, need to look in B decay.

CLEO CONF 99-6 (1999):
observe $B^- \to D_1^0\pi^-$, $D_1^0 \to D^{*+}\pi^-$:
$m = 2461^{+41}_{-34} \pm 10 \pm 32\ \mathrm{MeV}/c^2$ and $\Gamma = 290^{+101}_{-79} \pm 26 \pm 36\ \mathrm{MeV}/c^2$

BELLE CONF-0235 (2002):
observe $B^- \to D_1^0\pi^-$, $D_1^0 \to D^{*+}\pi^-$:
$m = 2400 \pm 30 \pm 20\ \mathrm{MeV}/c^2$ and $\Gamma = 380 \pm 100 \pm 100\ \mathrm{MeV}/c^2$
and observe $B^- \to D_0^{*0}\pi^-$, $D_0^{*0} \to D^+\pi^-$:
$m = 2290 \pm 22 \pm 20\ \mathrm{MeV}/c^2$ and $\Gamma = 305 \pm 30 \pm 25\ \mathrm{MeV}/c^2$

Potential Models Need Revision



Theoretical Discussion

- Cho & Wise (1994) Predicted rate for isopsin-violating decay $D_s^*(2112)^+ \to D_s^+\pi^0$. Described as occuring through η/π^0 mixing
- Cho & Trivedi (1994) predicted rate for $D_{s1}^+ \to D_s^*(2112)^+\pi^0$, if its mass were as low as 2480 MeV/c^2. (Dismiss the possibility of D_{s0}^{*+} being below DK threshold.) $\Gamma(D_{sJ}(2458)^+ \to D_s^{*+}\pi^0) \approx 20$ keV$/c^2$
- Cahn & Jackson can get potential model to give right masses: but the mixing comes out wrong
- If Belle/CLEO results for non-strange states are right, $m(c\overline{s}) - m(c\overline{d}) \sim 50\ \mathrm{MeV}/c^2$, not $\sim$100 MeV/c^2

Theoretical Discussion (2)

- Chiral models seem to do fairly well at predicting masses: $m(D_s^{*+}) - m(D_s^+) = m(D_{sJ}(2458)^+) - m(D_{sJ}^*(2317)^+)$
- Bardeen, Eichten & Hill (2003) also predicts rates
- Many other ideas floated when $D_{sJ}^*(2317)^+$ first reported
- Four-quark state?
- Di-meson moelcule? (Lipkin & Isgur, 1981)
- However, all data is consistent with the two states being $c\overline{s}$ mesons, with $J = 0, 1$ (in my opinion)

Summary and Conclusions

- BABAR discovered the surprising $D^*_{sJ}(2317)^+$
- BABAR has also observed the $D_{sJ}(2458)^+$
- CLEO and Belle have also provided import observations which help define the identity of these states
- BABAR is continuing its studies of these new states, in both $c\overline{c}$ events and in B decays, and hopes to publish more results soon.

Extra Foils

Compare: Charmonium Spectroscopy

$$S = s_1 \otimes s_2 = 0,\ 1$$
$$J = S \otimes L$$

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

notation: $^{2S+1}L_J$

Appropriate for two equal mass constituents.

Charmonium Spectroscopy (cont.)

$L = 0$: two singlets

${}^1S_0$:	η_c	(0^-)
${}^3S_1$:	J/ψ	(1^-)

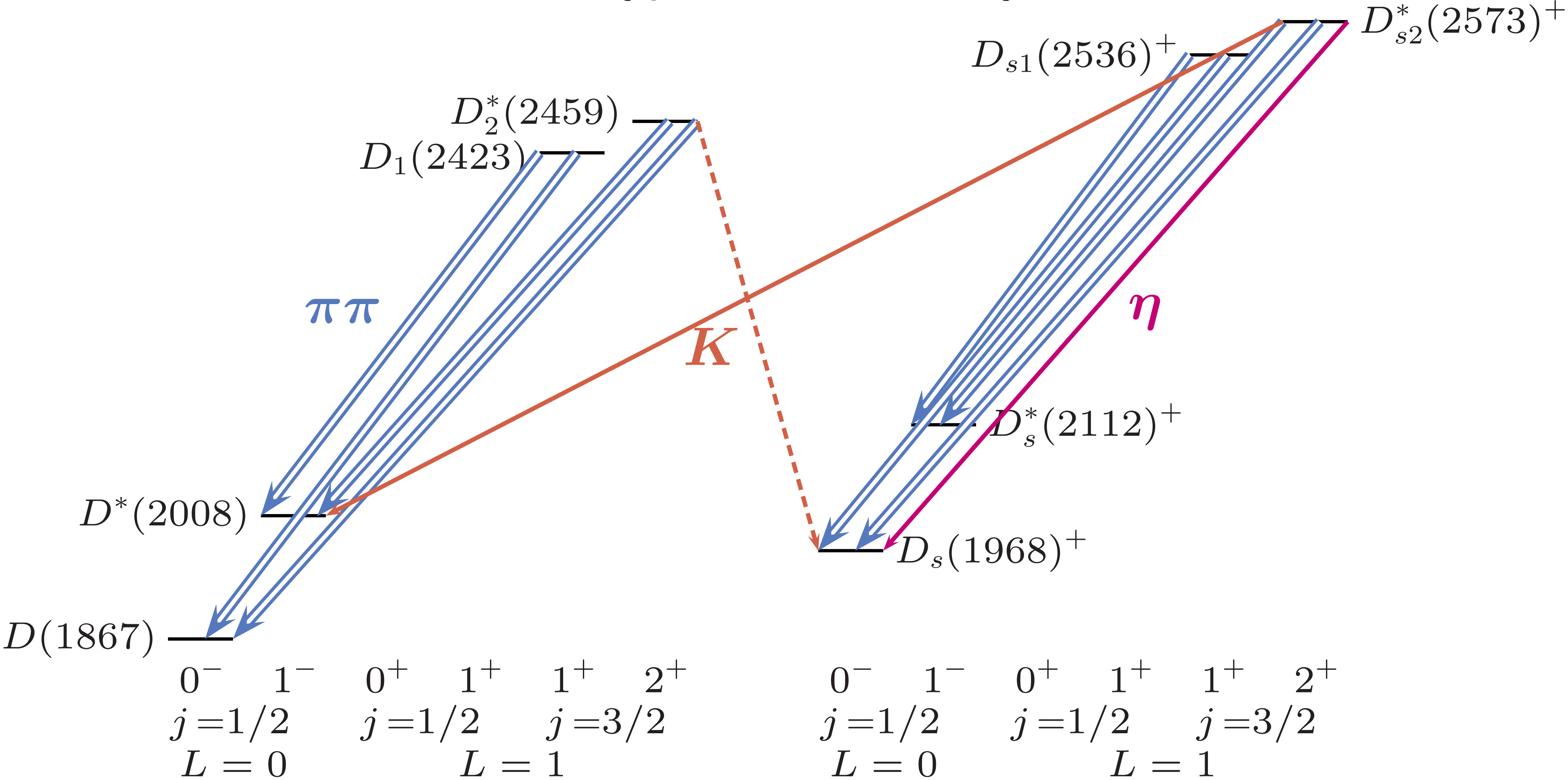
$L = 1$: singlet and triplet

${}^1P_1$:	h_c	(1^+)	$(C = -)$
${}^3P_0$:	χ_{c0}	(0^+)	
${}^3P_1$:	χ_{c1}	(1^+)	$(C = +)$
${}^3P_2$:	χ_{c2}	(2^+)	

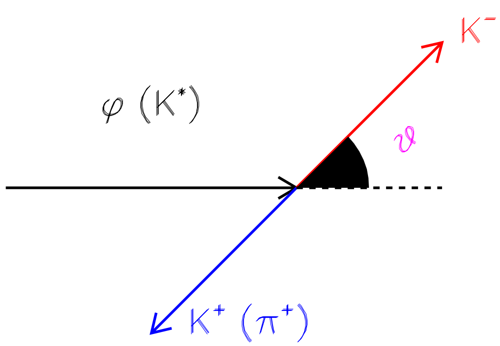
The two 1^+ states cannot mix.

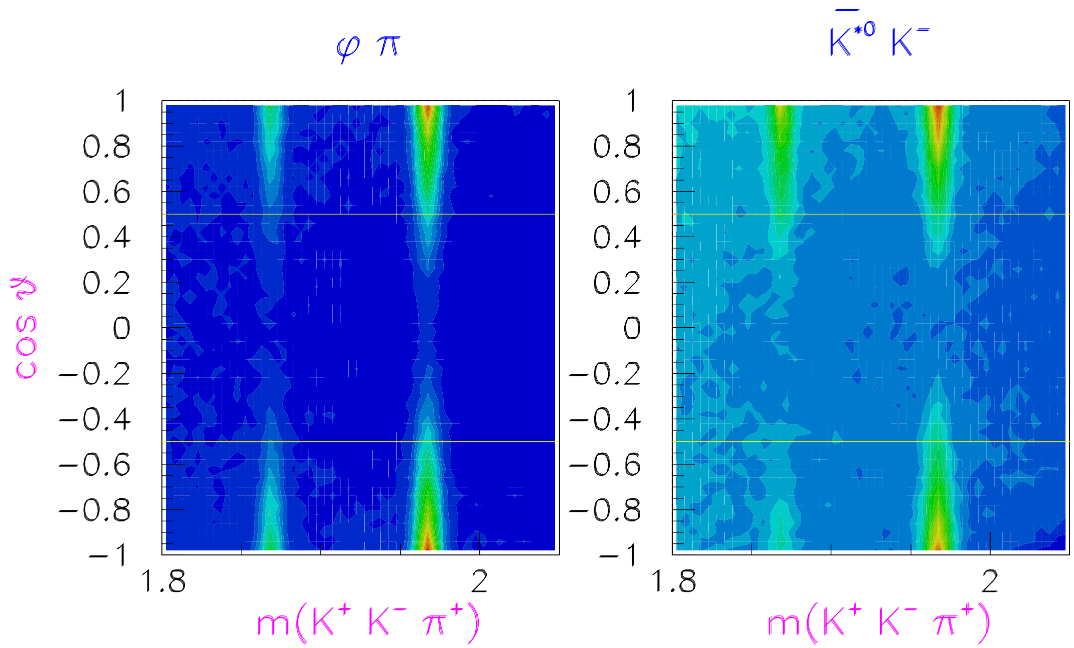
Charmed Meson Spectroscopy (2)

Observed States: Hypothetical Decays

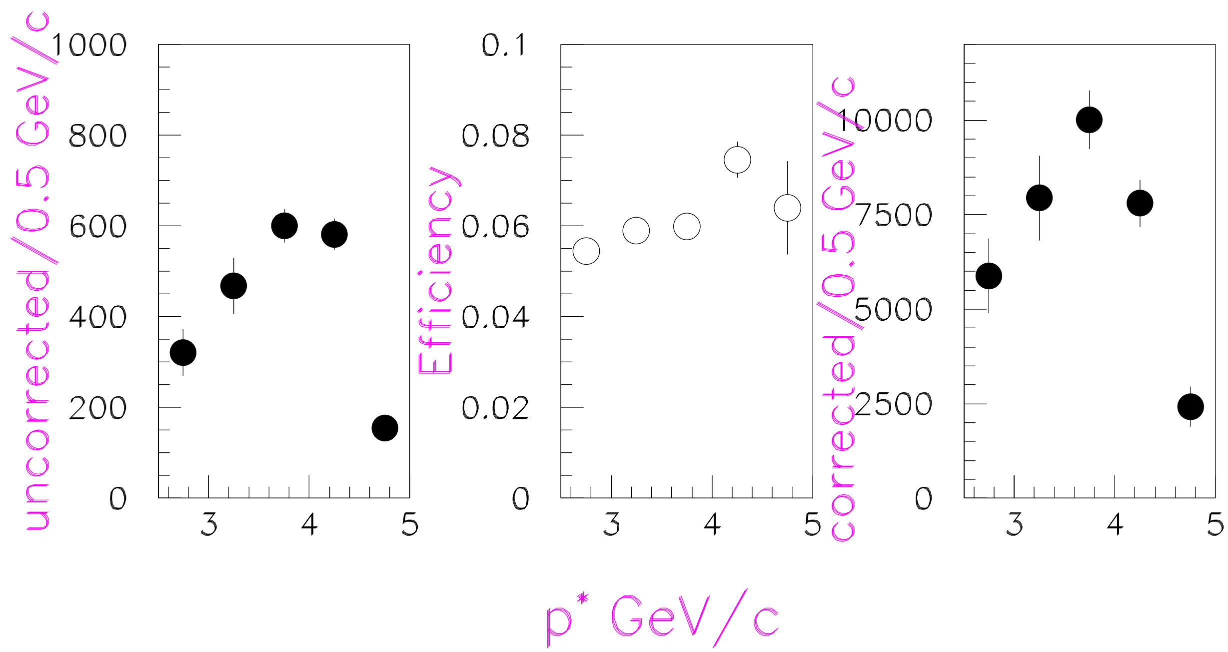


Helicity Angle Cut for ϕ or $\overline{K^{*0}}$

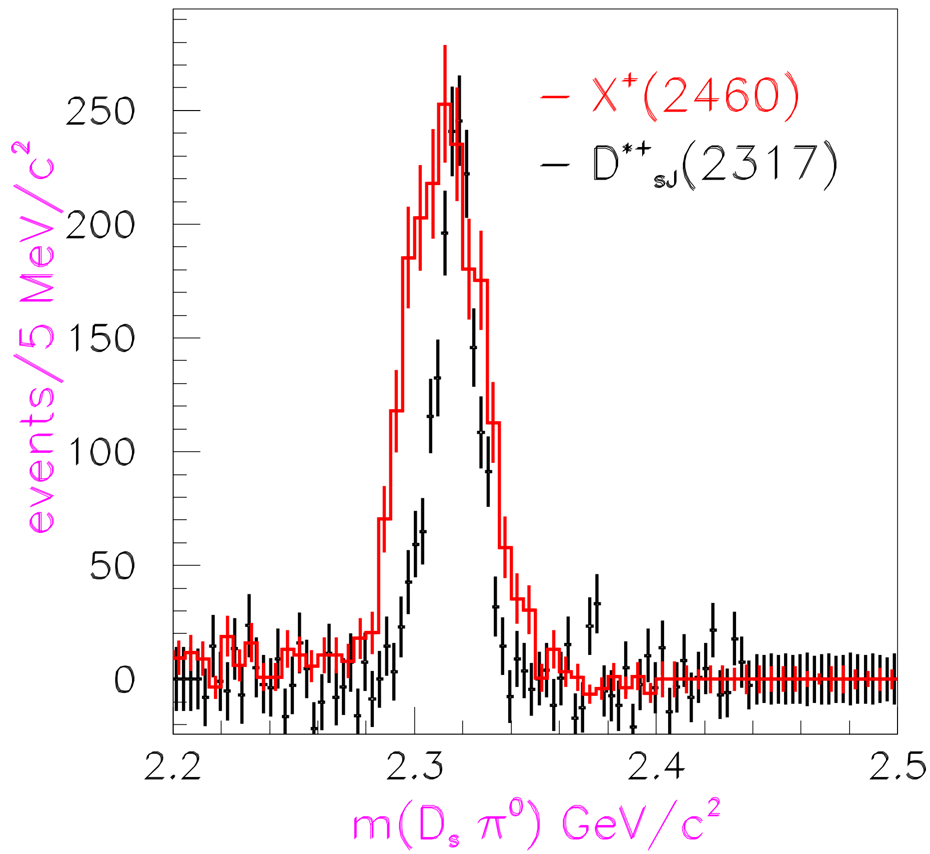




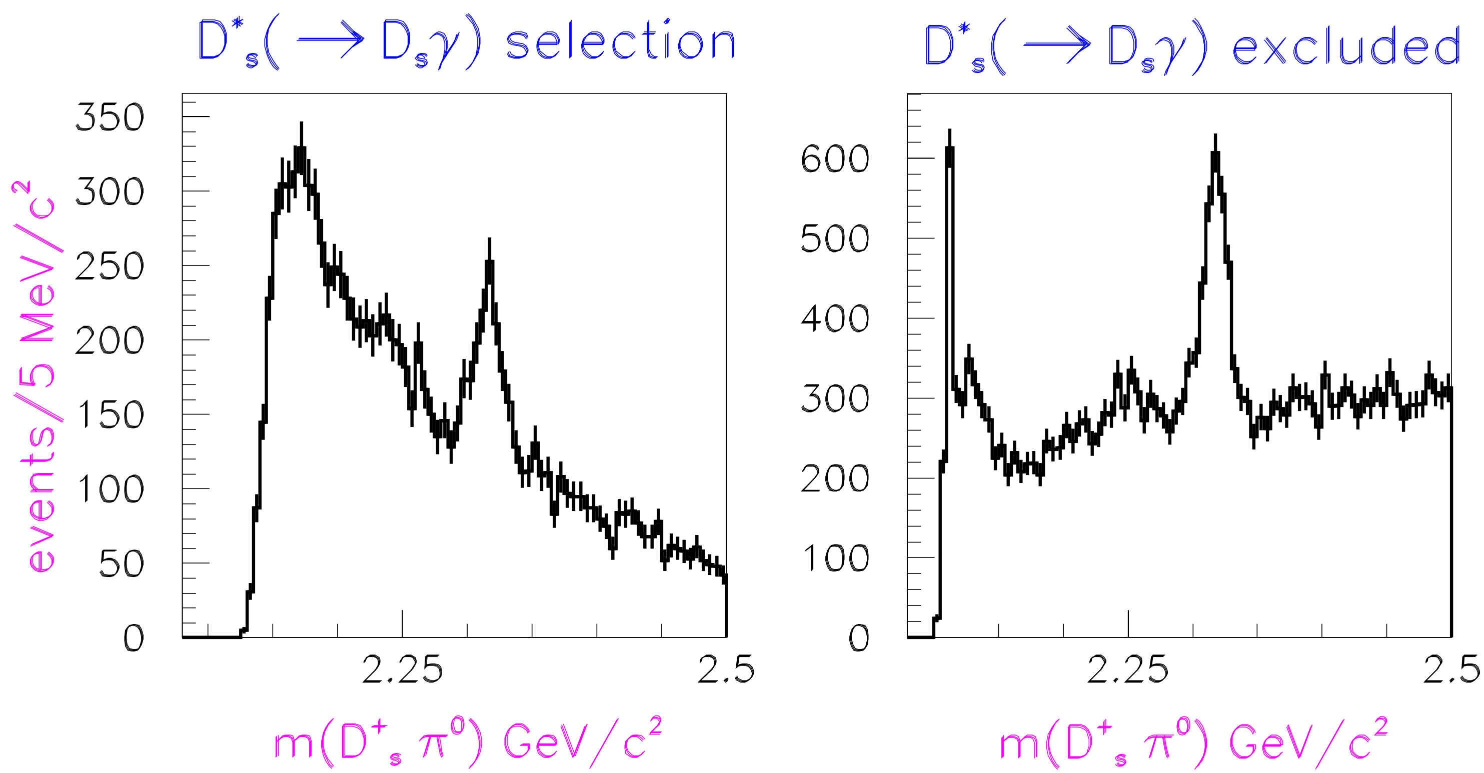
p^* Spectrum for $D_{sJ}^*(2317)^+$



2460 with missed γ



$D_s^*(2112)^+ \rightarrow D_s^+\gamma$ Background?



Search for $D^*_{sJ}(2317)^+ \rightarrow D_s^+\pi^0\pi^0$