Charm spectroscopy, charm decays and new states at BaBar/Belle/Cleo

DIS 2006 , April 20-24

- Charm spectroscopy, etc.
  - D_{sJ} study
  - D_{sJ} Branching Fractions.
  - $D^+ \rightarrow K\pi^0$ Observation
  - D mixing in K π π (DCS)
  - Leptonic Decays $D \rightarrow \mu\upsilon$

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Representing the BaBar collaboration

Charm Production at BaBar, Belle and Cleo

- ✓ Continuum production at B factory:
  @ $\sqrt{s} \leq 10.58\,GeV$ **[the mass of Υ(4S)]**
  - ✓ Are Excellent facilities to study charm physics more precisely and to search for new particles.
- ✓ Production mechanism in $e^+ e^-$ enviornment:
  - ✓ $e^+ e^- \rightarrow c\bar{c}$ (continuum) [ISR and $\gamma^*\gamma^*$]
  - ✓ b→c transitions $\sqrt{s} \approx 10.58\,GeV$ (B decays)
- ✓ Cleo-c is running @ 3 < Ecm < 5 GeV, have > 480 pb^{-1} data. [a charm factory]
- ✓ Distinguish by center-of-mass (CM) momentum, p^* (B factories)
- ✓ Large data samples:
  - ✓ > 450 M $c\bar{c}$ events (from BaBar & Belle)
  - ✓ All these Detectors are with excellent tracking, vertexing, e.m. calorimetry, and particle ID

$D^*_{sJ}(2317)$ and $D_{sJ}(2460)$

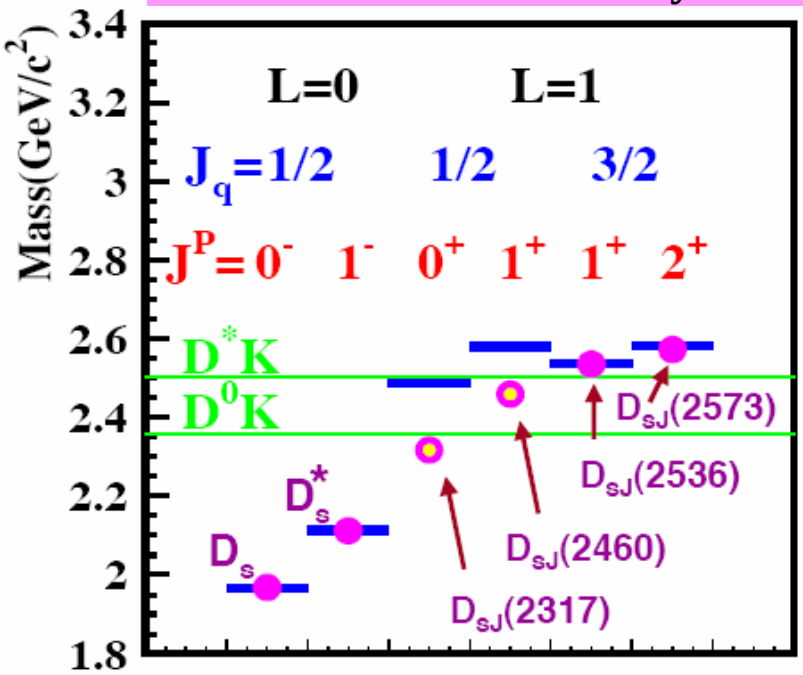
BABAR 91 fb^{-1}
PRL90,242001(2003)

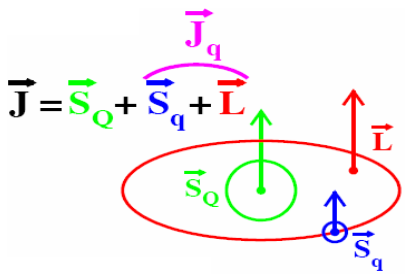
CLEO 13.5 fb^{-1}
PRD68,032002(2003)

BELLE 86.9 fb^{-1}
PRL 92, 012002(2003)

- ✓ $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ first observed by BABAR and CLEO in $c\bar{c}$ continuum events, and by Belle in B-decay
- ✓ Both masses unexpectedly low: below DK and D^*K threshold, respectively
- ✓ Only isospin-violating or electromagnetic decays kinematically allowed
  ➔ narrow widths
- ✓ Decay pattern and decay angular distributions consistent with interpretation as P-wave $c\bar{s}$ mesons with $J^P=0^+$ and $J^P=1^+$, respectively

Potential Model for CS system





$D^*_{sJ}(2317)$ and $D_{sJ}(2460)$

- ✓ Detailed study of these decays to D_s^+ plus one or two $\pi^\pm$, π^0, or γ's with 232 fb^{-1} data. (BaBar: Submitted to PRD; hep/ex-0604030)
  - ✓ Decay patterns follow the $J^P = 0^+$ and $J^P = 1^+$ expectations

only observed Mode For DsJ*(2317)+

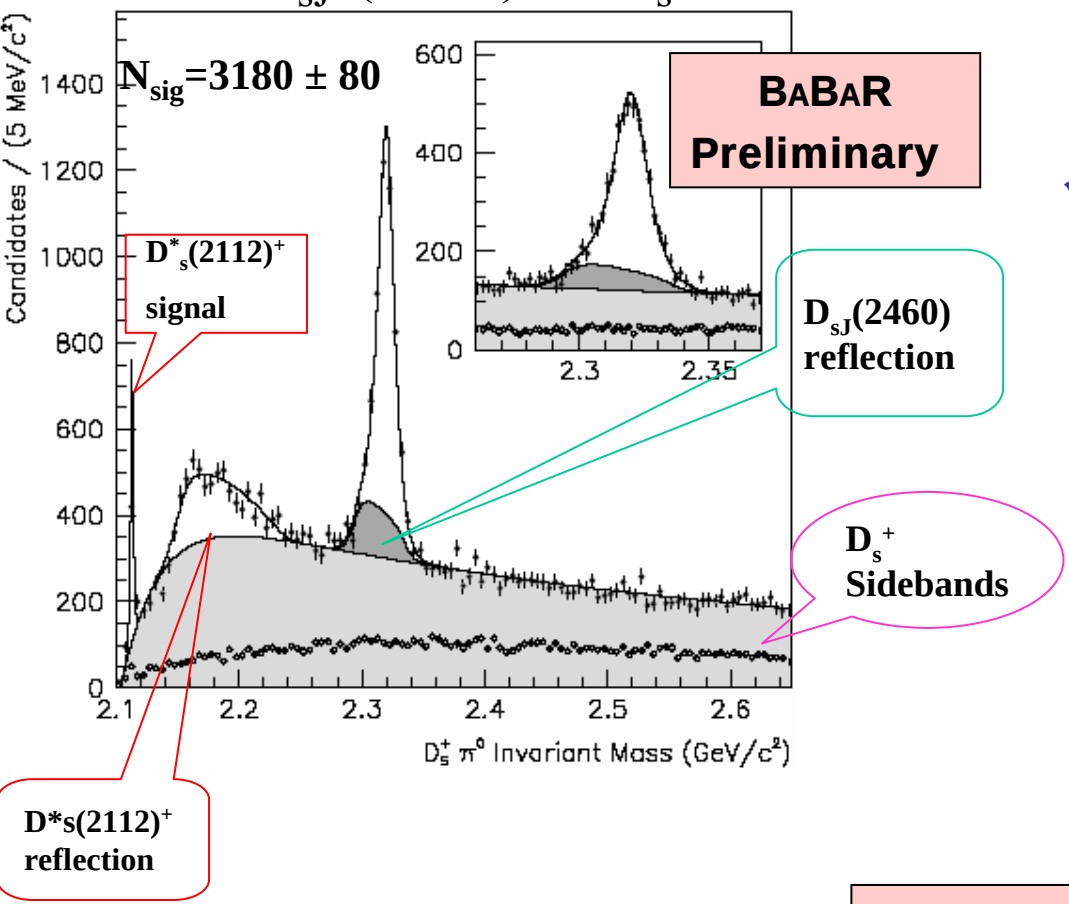
Decay Channel	$D^*_{sJ}(2317)^+$	$D_{sJ}(2460)^+$
$D_s^+\pi^0$	Seen	Forbidden
$D_s^+\gamma$	Forbidden	Seen
$D_s^+\pi^0\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\pi^0$	Forbidden	Seen
$D^*_{sJ}(2317)^+\gamma$	—	Allowed
$D_s^+\pi^0\pi^0$	Forbidden	Allowed
$D_s^+\gamma\gamma$ (a)	Allowed	Allowed
$D_s^*(2112)^+\gamma$	Allowed	Allowed
$D_s^+\pi^+\pi^-$	Forbidden	Seen

(a) Non-resonant only

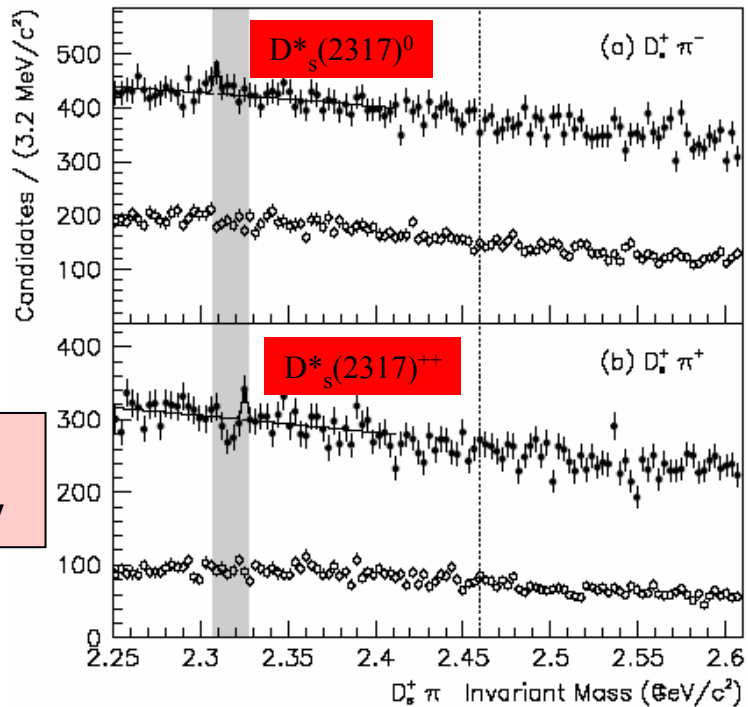
$D^*_{sJ}(2317) \longrightarrow D_s^+ \pi^0$

Submited to PRD
hep/ex-0604030

$D_{sJ}^*(2317)^+ \rightarrow D_s^+ \pi^0$



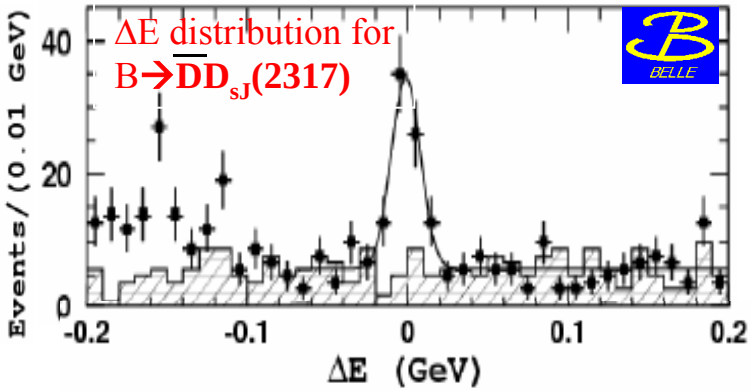
- ✓No indication of neutral or doubly-charged partner near 2317 MeV.
- ✓Casts doubt on the Four-quark explanation of low mass values of these states, as Explained by some authors e.g; **Phys.Lett. B580, 50(2004)**

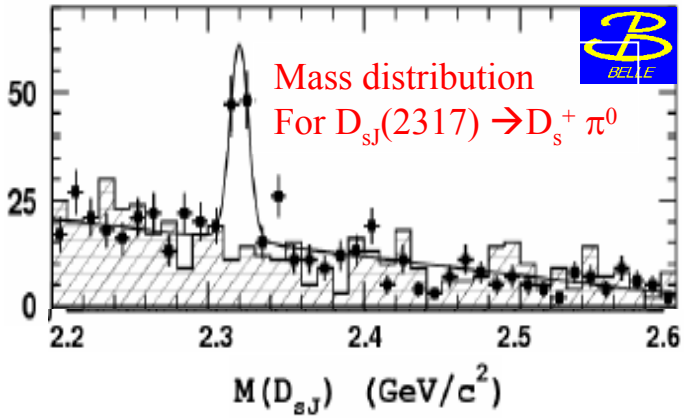


$$m = (2319.6 \pm 0.2 \pm 1.4)\ \mathrm{MeV/c^2}$$
$$\Gamma < 3.8\ \mathrm{MeV}\ @\ 95\%\ \mathrm{CL}$$

BABAR Preliminary

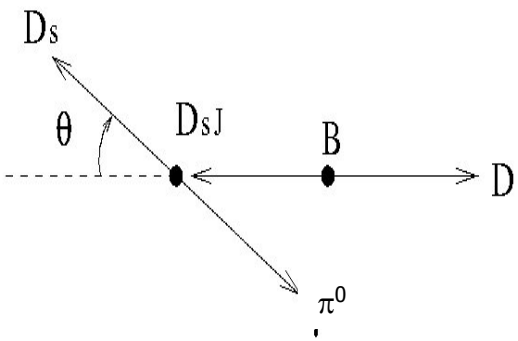
$B \to \bar{D} D_{sJ}^{*}(2317)^{+}$, $D_{sJ}^{*}(2317)^{+} \to D_s^{+}\pi^0$

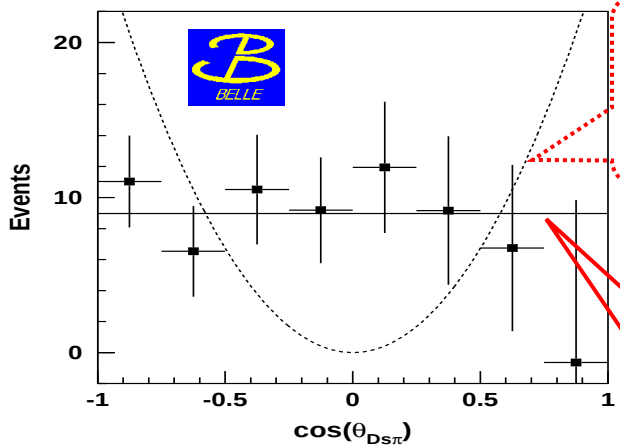




Belle: 274M $B\bar{B}$ BELLE-CONF-0461 (2004)

- ✓ $D_{sJ}^{*}(2317)$ decay mode ➔ natural spin-parity
- ✓ $D_{sJ}^{*}(2317)$ decay angular distribution ➔ spin 0





Dotted line:
J = 1
$\chi^2/_{d.o.f}$ = 38/8

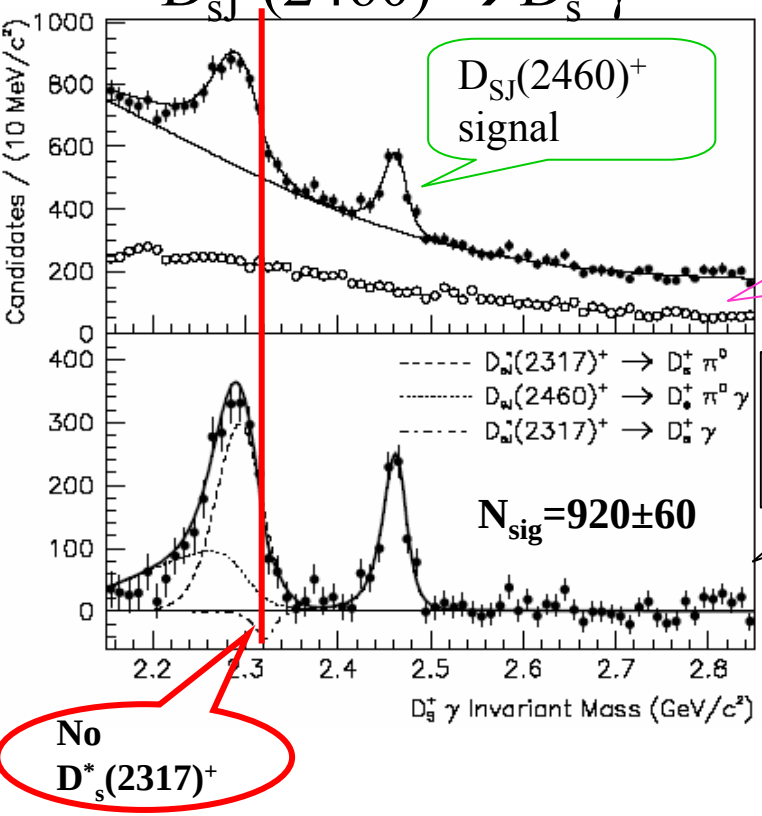
Solid line:
J = 0
$\chi^2/_{d.o.f}$ = 3/8

$J^P = 0^+$ established
$J^P = 1$ dis-favored

$D_{sJ}(2460)^+ \longrightarrow D_s^+\gamma$ / $D^*_s(2112)\,\pi^0$ → $D_s^+\gamma$

BABAR
Submited to PRD
hep/ex-0604030

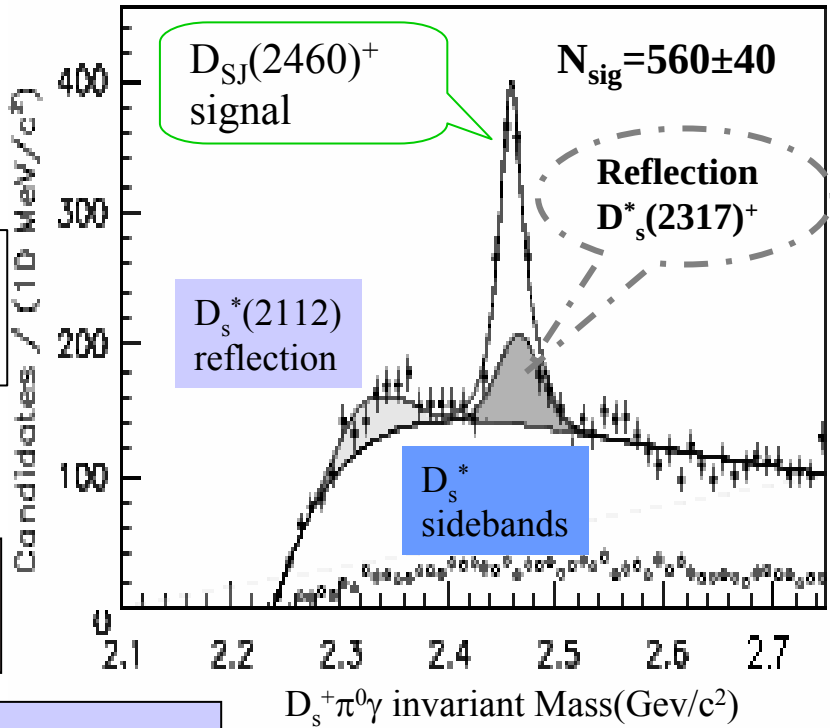
$D_{SJ}^*(2460)^+ \rightarrow D_s^+\gamma$



Same as above Fig. With D_s sidebands substracted

BABAR
Preliminary

$D_{SJ}^*(2460)^+ \rightarrow D_s^+\pi^0\gamma$

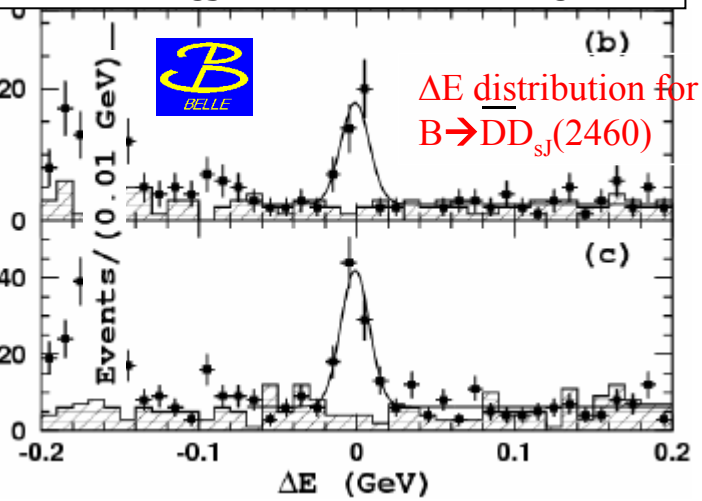


$$\frac{B(D_{sJ}(2460)^+ \to D_s^+\gamma)}{B(D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma)} = 0.337 \pm 0.036 \pm 0.038$$

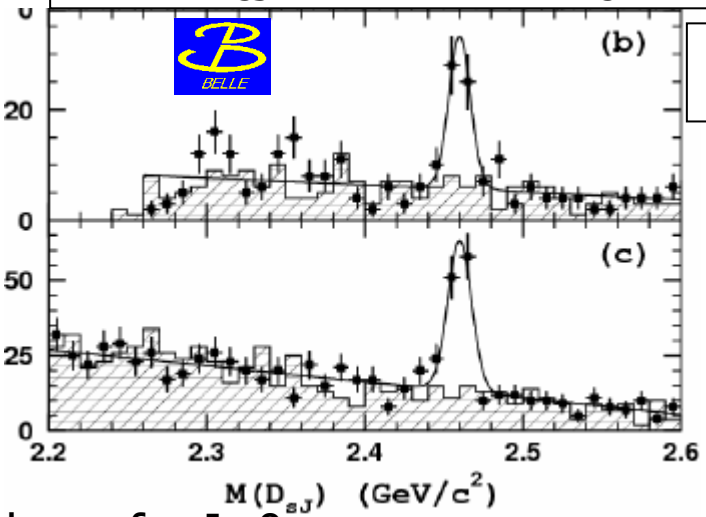
$B \rightarrow \bar{D} D_{sJ}(2460)^+$

Belle: 274M BB
BELLE-CONF-0461 (2004)

(b): $D_{sJ}(2460)^+ \rightarrow D_s^+ \gamma$

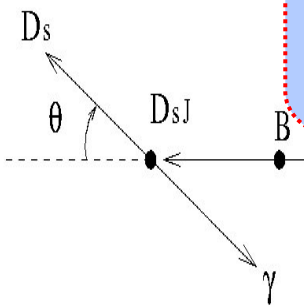


(c): $D_{sJ}(2460)^+ \rightarrow D_s^*(2112)^+ \pi^0$

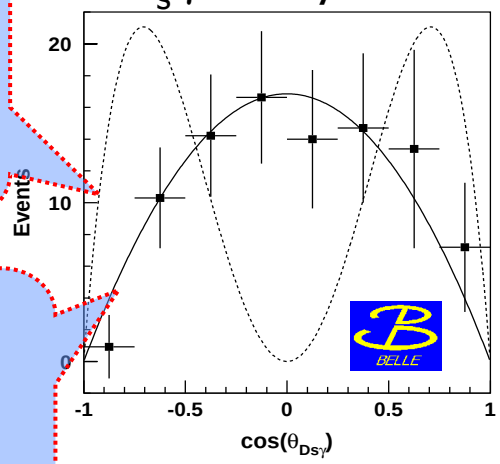


$D_s^{*+} \rightarrow D_s^+ \gamma$

No $D_s \gamma$ decay for J=0

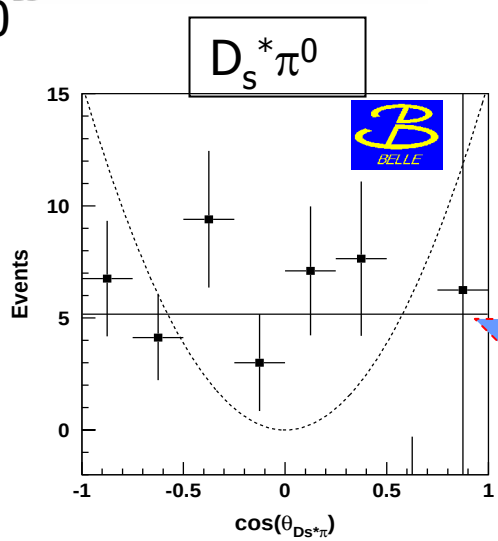


Dotted line:
J = 2 (dis-favored)
$\chi^2/_{d.o.f} = 89/8$



Solid line:
J = 1
$\chi^2/_{d.o.f} = 4/8$
Favored.

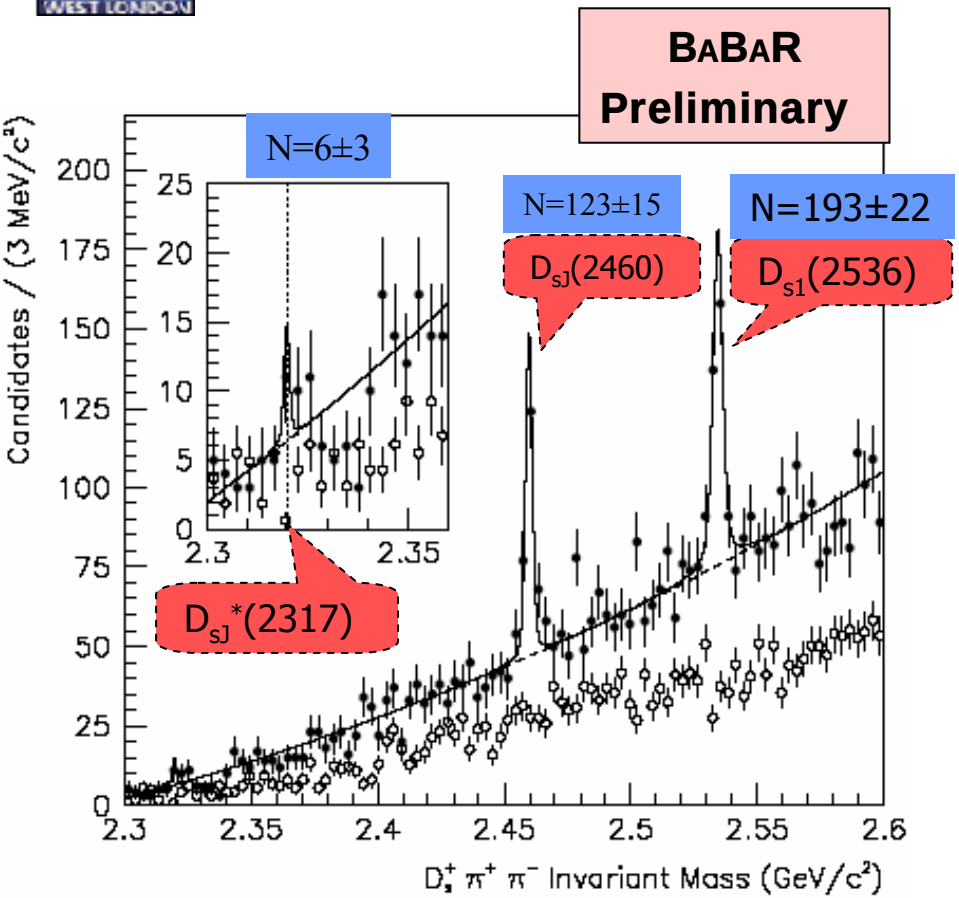
$D_s^* \pi^0$



Solid line:
S-wave
Favored;
$J^P = 1^+$

$D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-$

BABAR: 232 fb^{-1}
Submitted to PRD
hep/ex-0604030



- ✓ No significant signal for $D_{sJ}^*(2317)^+$
- ✓ Observed $D_{s1}(2536)^+$

$$m = (2460.2 \pm 0.2 \pm 0.8)\ \mathrm{MeV}/c^2$$
$$\Gamma < 3.5\ \mathrm{MeV}\ @\ 95\%\ \mathrm{CL}$$

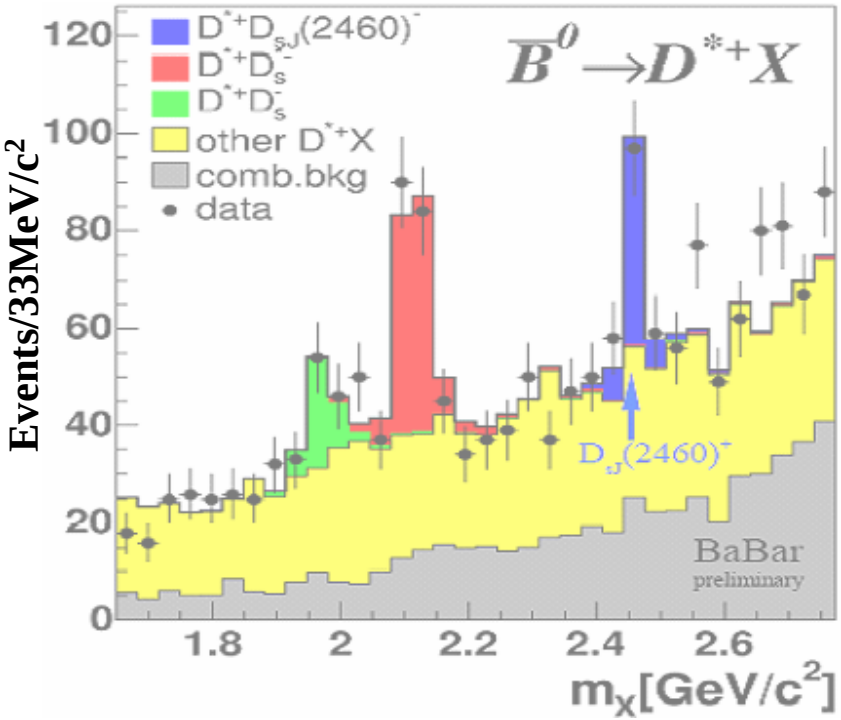
$$m = (2534.6 \pm 0.3 \pm 0.7)\ \mathrm{MeV}/c^2$$
$$\Gamma < 2.5\ \mathrm{MeV}\ @\ 95\%\ \mathrm{CL}$$

$$\frac{\mathrm{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^+ \pi^-)}{\mathrm{B}(D_{sJ}(2460)^+ \rightarrow D_s^+ \pi^0 \gamma)} = 0.077 \pm 0.013 \pm 0.008$$

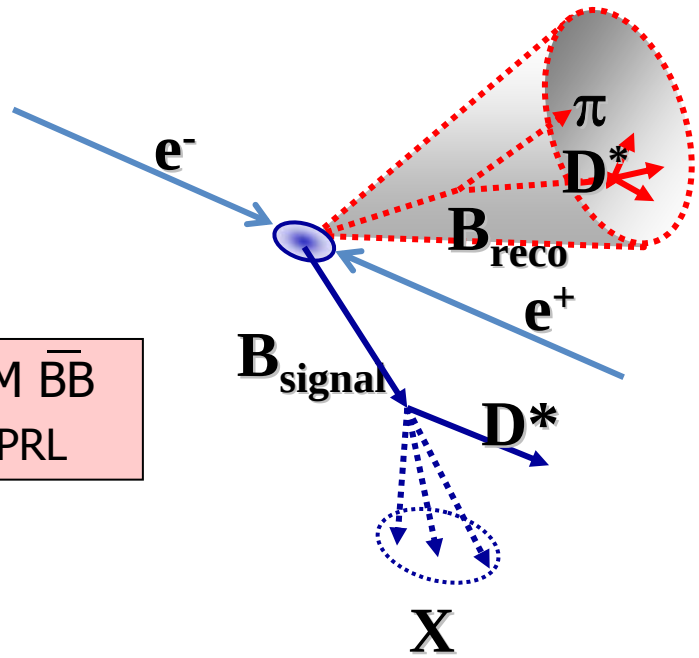
BABAR
Preliminary

$D_{sJ}(2460)^+$ Absolute Branching Fractions (BFs)

- ✓ $B\bar{B}$ sample with one B fully reconstructed
  - ✓ study decays of other $B \rightarrow D^{(*)+,0} X$
  - ✓ Observe $D_{sJ}(2460)$ signals in the recoil mass, m_X



BABAR: 230M $B\bar{B}$
To.b.subm.to PRL



$D_{sJ}(2460)^+$ Absolute BFs, cont.

- ✓ Combine with previously measured, exclusive product BFs $B \to \underline{D}^{(*)} D_{sJ}(2460)^+$, $D_{sJ}(2460)^+ \to D_s^+\gamma$ / $D_s^*(2112)^+\pi^0$ to obtain absolute BFs:

BABAR: 122M $B\bar{B}$ PRL 93, 181801 (2004)

$$B(D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0) = 0.51 \pm 0.11 \pm 0.09$$ ($D_s^{*+} \to D_s^+\gamma$)

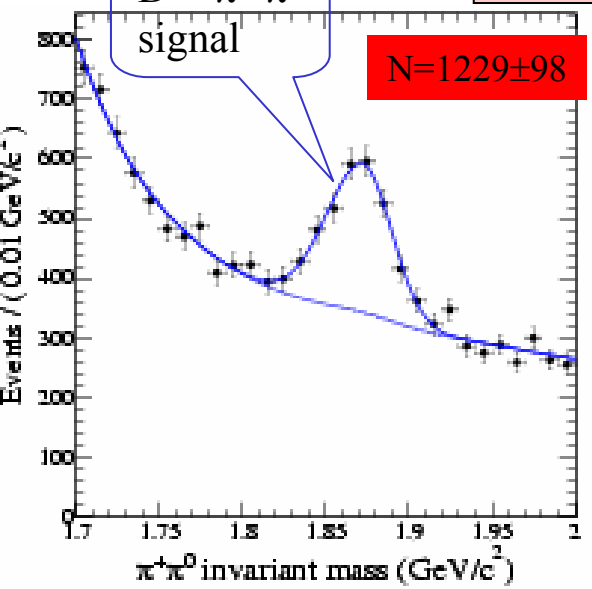
BABAR Preliminary

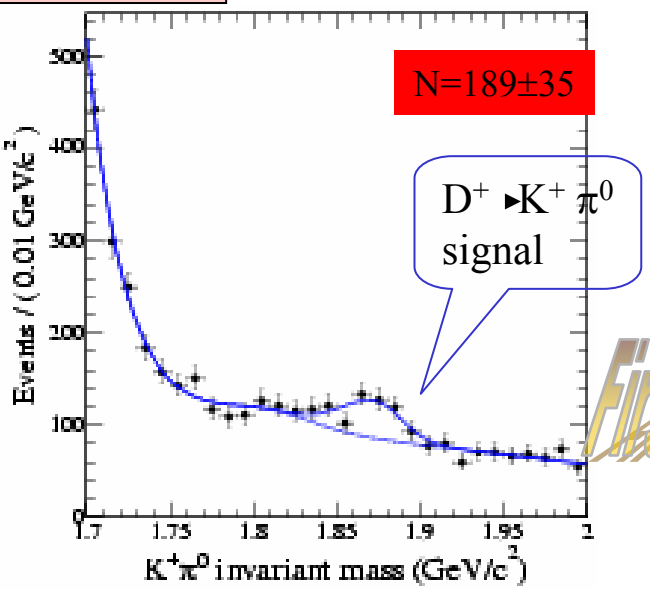
$$B(D_{sJ}(2460)^+ \to D_s^+\gamma) = 0.15 \pm 0.03 \pm 0.02$$

Using $B(D_s^+ \to \phi\pi^+) = (4.78 \pm 0.40 \pm 0.47)\%$ as determined in this analysis

$D^+ \longrightarrow K^+/\pi^+ \pi^0$ B.F.

BABAR Preliminary





First Observation

BABAR: 124 fb^{-1}
To Be submitted to PRL

BABAR Preliminary

$$B(D^+ \to K^+\pi^0) = (0.246 \pm 0.046_{\text{stat}} \pm 0.024_{\text{syst}} \pm 0.016_{[D^+ \to K^-\pi^+\pi^+]}) \times 10^{-3}$$

$$B(D^+ \to \pi^+\pi^0) = (1.22 \pm 0.10_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.08_{[D^+ \to K^-\pi^+\pi^+]}) \times 10^{-3}$$

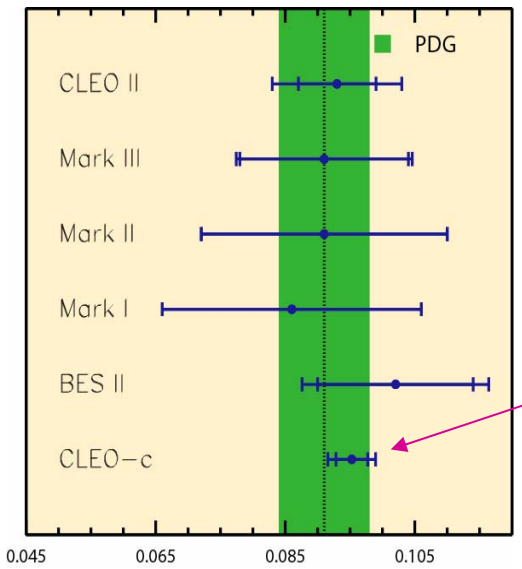
Using $D^+ \to K^-\pi^+\pi^+$
World avg.: 0.092±0.006

Significant improvement in $B(D^+ \to \pi^+\pi^0)$: $(2.6 \pm 0.7) \times 10^{-3}$ [PDG]

Absolute $\mathcal{B}$ Results for D^+ & D^0 (57 pb^{-1})

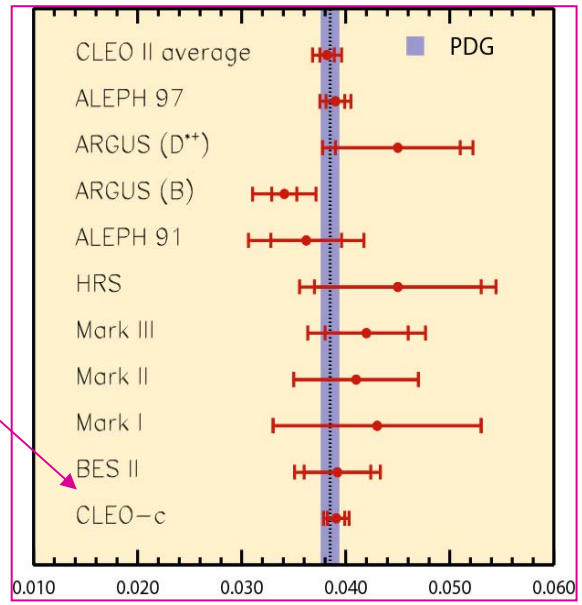
CLEO-c

$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$



CLEO-c
(not in average)

$\mathcal{B}(D^o \to K^-\pi^+)$



$\mathcal{B}$ (%)	Error(%)	Source
9.52 ±0.25±0.27	3.9	CLEO-c
9.2±0.6	6.5	PDG
9.43 ±0.31	3.3	World avg

$\mathcal{B}$ (%)	Error(%)	Source
3.91±0.08 ±0.09	3.1	CLEO-c
3.81±0.09	2.4	PDG
3.85 ±0.07	1.9	World avg

For 281pb^{-1}, ~few weeks:
2.2% projected error 1.8% projected error

Absolute $\mathcal{B}$ Results for D_s^+ (76 pb^{-1}) (Cleo-c)

Mode	$\mathcal{B}$ (%) (CLEO-c)	$\mathcal{B}$ (%) PDG
$K_S K^+$	$1.28^{+0.13}_{-0.12} \pm 0.07$	1.80±0.55
$K^+K^-\pi^+$	$4.54^{+0.44}_{-0.42} \pm 0.25$	4.3±1.2
$K^+K^-\pi^+\pi^o$	$4.83^{+0.49}_{-0.46} \pm 0.46$	-
$\pi^+\pi^+\pi^-$	$1.02^{+0.11}_{-0.10} \pm 0.05$	1.00±0.28

- ✓ About ±11% error
  - ✓ error 11% → ~4-6% (By this summer)
- ✓ Results are *preliminary*: more modes are being added & more data are being taken [CLEO-c]

Search for D^0 mixing in $K\pi\pi$

BABAR preliminary

Looking for New Physics:

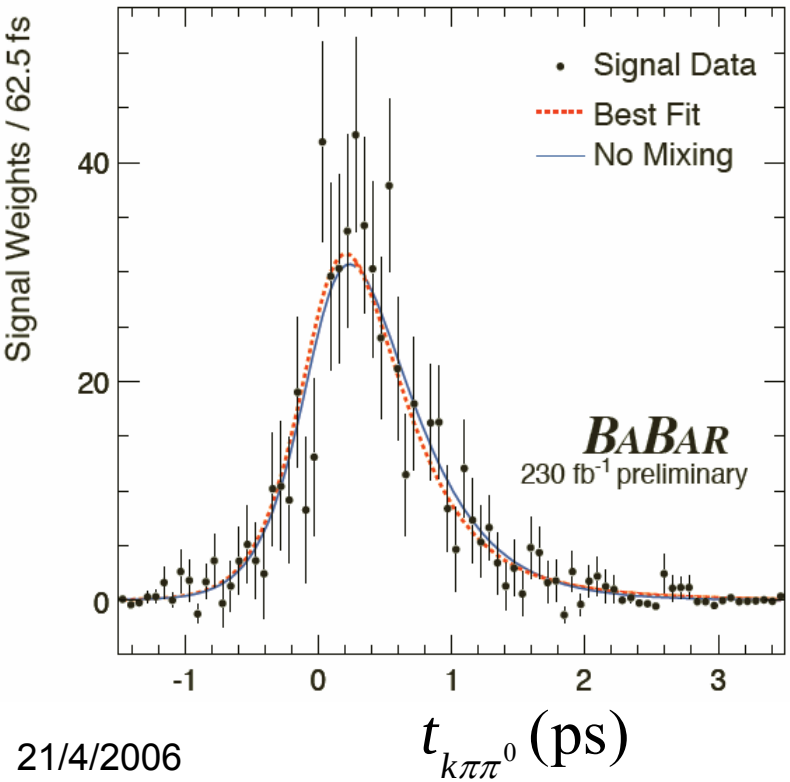
- CP violation in the D system
- x >> y

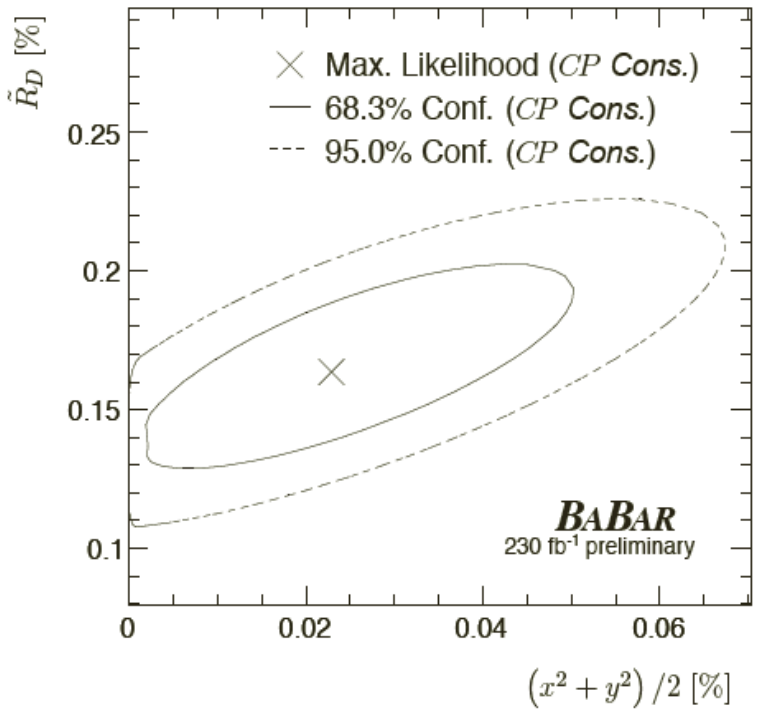
$$x \equiv 2\frac{m_2 - m_1}{\Gamma_2 + \Gamma_1},\ y \equiv \frac{\Gamma_2 - \Gamma_1}{\Gamma_2 + \Gamma_1}$$

Result consistent with no mixing

$$R = \frac{\Gamma(D^0 \to K^+\pi^-\pi^0)}{\Gamma(D^0 \to K^-\pi^+\pi^0)} = (0.214 \pm 0.008 \pm 0.008)\%$$

Smaller DCS relative to Kπ



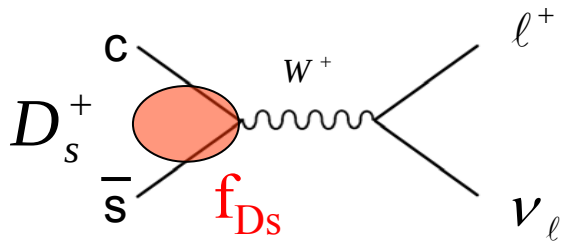


Leptonic decays: $D_s \to \mu\nu$ and f_{Ds}

Helicity-suppressed leptonic decay:

- directly related to decay constant f_{Ds}
- feeds interpretation of B, B_s mixing

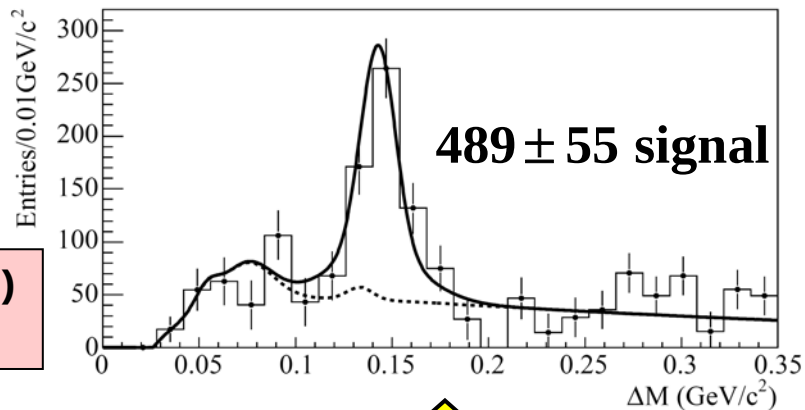
Analysis Method: "D reco" in $e^+e^- \to c\bar{c}$



$$\Gamma(D_s^+ \to l^+\nu_l) = \frac{G_F^2 |V_{cs}|^2}{8\pi} f_{D_s}^2 m_l^2 m_{D_s} \left(1 - \frac{m_l^2}{m_{D_s}^2}\right)^2$$

D reco side

$$\left.\begin{matrix} D^0 \\ D^+ \\ D_s^+ \\ D^{*+} \end{matrix}\right\} \Leftrightarrow D_s^{*+} \to D_s^+\gamma \to \mu^+\nu_\mu\gamma$$



BABAR (230fb^{-1})
Preliminary

$$B(D_s^+ \to \mu^+\nu_\mu) = (6.5 \pm 0.8_{stat} \pm 0.3_{sys} \pm 0.9_{[D_s \to \phi\pi]}) \times 10^{-3}$$

(normalize to $D_s \to \phi\pi$); $B(Ds \to \varphi\pi) = (4.81 \pm 0.64)$ %

Using BaBar measurement: Phys. Rev. D71, 091104 (2005)

Signal peak in $\Delta M = M_{D_s^*} - M_{D_s^+}$

Leptonic decays: $D_s \rightarrow \mu\nu$ and f_{Ds} (continued)

✓Decay constant:

$$f_{D_s} = (279 \pm 17_{\text{stat}} \pm 6_{\text{syst}} \pm 19_{D_s \rightarrow \phi\pi})\text{MeV}$$

BABAR (230fb^{-1}) Preliminary

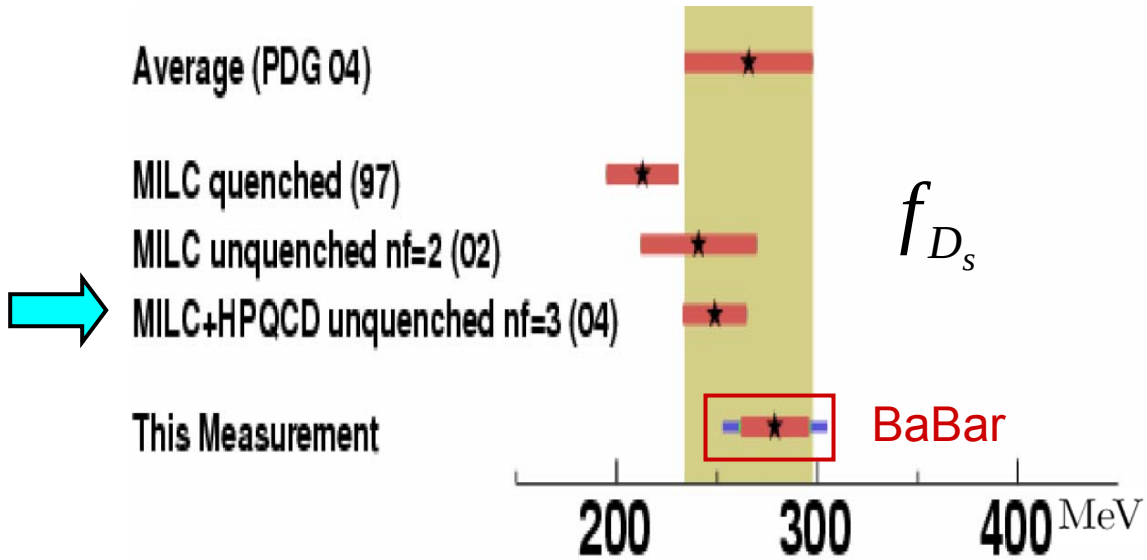
(normalize to $D_s \rightarrow \phi\pi$); B(Ds $\longrightarrow$ $\varphi\pi$)=(4.81 $\pm$ 0.64) %

Using BaBar measurement: Phys. Rev. D71, 091104 (2005)

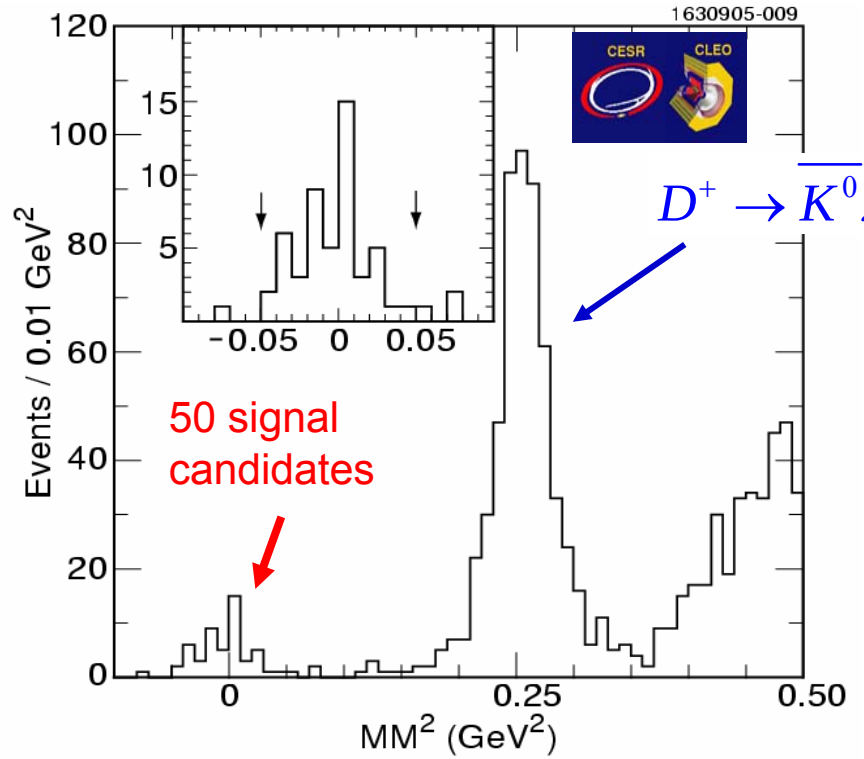
Lattice QCD:

$$f_{D_s} = (249 \pm 17)\text{MeV}$$

Single best measurement of decay constant!



Leptonic decays: $D^+ \to \mu^+\nu$ (CLEO)

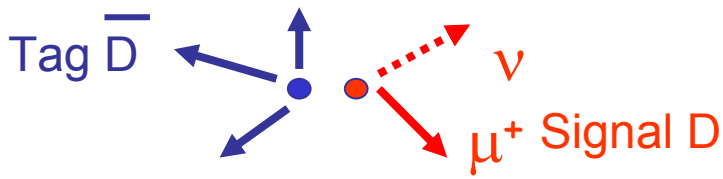


$$B\left(D^+ \to \mu^+\nu\right) = \left(4.40 \pm 0.66^{+0.09}_{-0.12}\right) \times 10^{-4}$$

$$f_{D^+} = \left(222.6 \pm 16.7^{+2.8}_{-3.4}\right) \text{ MeV}$$

$$f_{D+}^{\text{Fnal/Milc}} = (201 \pm 3 \pm 17)\text{MeV}$$

Phys. Rev. Lett. **95**, 251801 (2005)



$$f_{D_s}^{BaBar} / f_{D+}^{CLEO} = 1.25 \pm 0.14$$

(As expected from LQCD)

Summary & Conclusions

- ✓ Several Important results are presented here:
  - ✓ **the detailed study on the D_{sJ} meson.**
  - ✓ Absolute B.F. for D_{sJ} , D^+ and D^0 mesons.
  - ✓ Measurement of B.F. for $D^+ \rightarrow K^+\pi^0$
  - ✓ D^0 mixing for the DCS decays
  - ✓ Fully leptonic decays $D \rightarrow \mu\, \nu$ and f_D
- ✓ Many Charm Baryon studies also in progress at B-factories; new states being discovered [See talk by:Hiromichi (Belle)]
- ✓ ***B* factories:**
  - **Data is coming in fast & More new results are expected**
- ✓ **We can look forward to great advances in charm physics which will improve our understanding of the standard model and beyond**


The End

Back-up Slides

Charmed Meson Spectroscopy

- ✓ Untill 2003, this was believed that D_s ($C\bar{S}$) states were thought to be reasonably understood, but in April 2003….
- ✓ Unexpected observation of a narrow $D_s^+\pi^0$ resonance in BaBar, with a mass of 2317 MeV/c^2 ⇒ $D_{sJ}^*(2317)^+$ — 91 fb^{-1} PRL90,242001(2003)
- ✓ confirmed by Cleo.
- ✓ Later, CLEO observed a new $D_s^{*+}\pi^0$ resonance, at — 13.5 fb^{-1} PRD68,032002(2003)
- ✓ a mass of 2460 MeV/c^2 ⇒ $D_{sJ}(2460)^+$
- ✓ new resonance was confirmed by **BaBar** — 91 fb^{-1} PRD 69, 031101(2003)
- ✓ Belle confirmed both resonances, and found two additional decay modes for the second resonance. — 86.9 fb^{-1} PRL 92, 012002(2003)

$D^*_{sJ}(2317)$ and $D_{sJ}(2460)$

BABAR 91 fb^{-1}
PRL90,242001(2003)

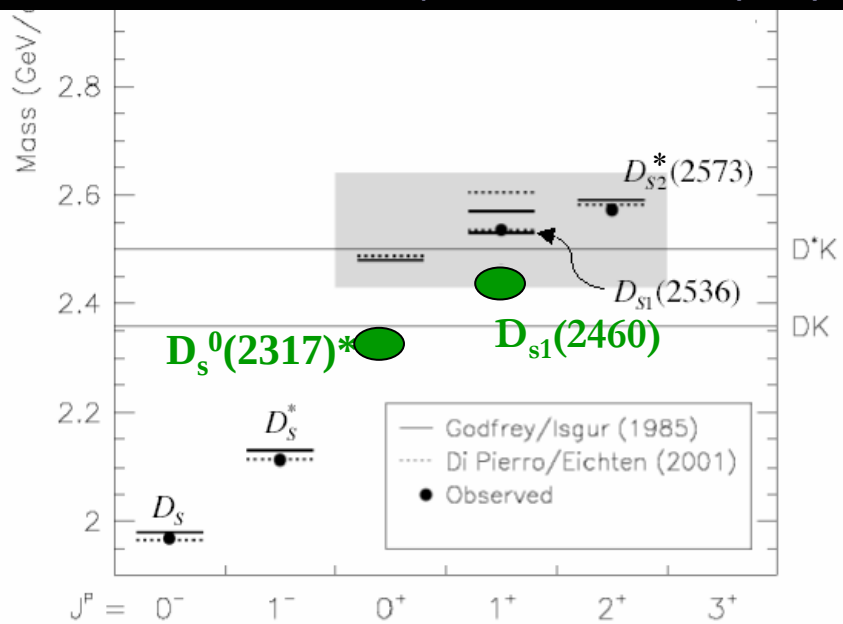
CLEO 13.5 fb^{-1}
PRD68,032002(2003)

BELLE 86.9 fb^{-1}
PRL 92, 012002(2003)

- ✓ $D_{sJ}^*(2317)$ and $D_{sJ}(2460)$ first observed by BABAR and CLEO in $c\bar{c}$ continuum events, and by Belle in B-decay
- ✓ Both masses unexpectedly low: below DK and D^*K threshold, respectively
- ✓ Only isospin-violating or electromagnetic decays kinematically allowed
  ➔ narrow widths
- ✓ Decay pattern and decay angular distributions consistent with interpretation as P-wave $c\bar{s}$ mesons with $J^P=0^+$ and $J^P=1^+$, respectively

Potential Model for CS system

* S. Godfrey and N. Isgur, Phys. Rev. **D32**, 189(1985)
* M. Di Pierro and E. Eitchen, Phys. Rev. **D64**, 114004(2001)



L = 0 L = 1

S-Wave | P-Wave

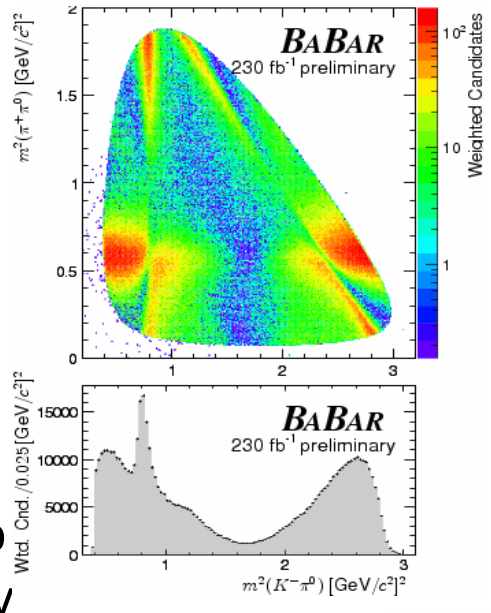
$C\bar{S}$

Search for D^0 mixing $K\pi\pi$

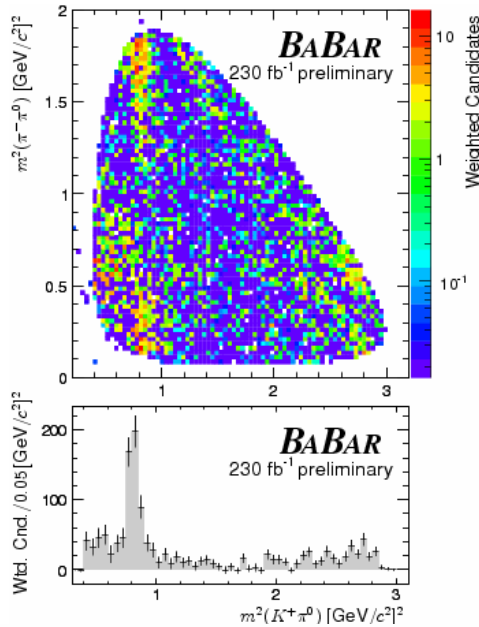
$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

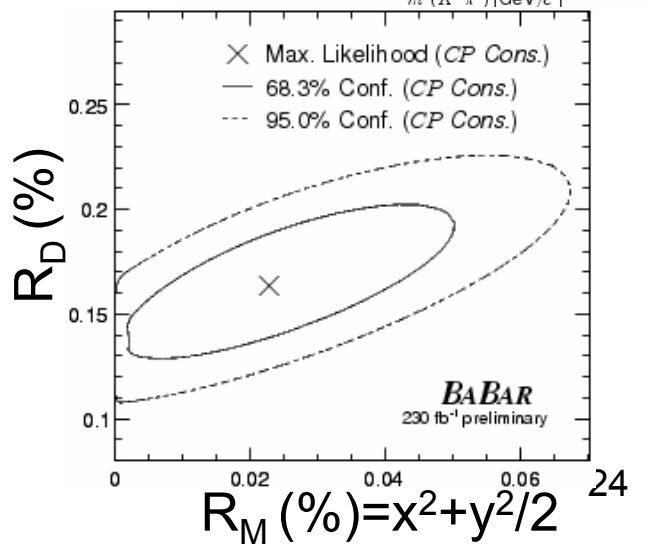
- ✓ Mixing is charecterized:
- ✓ $x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}$ $R_M(\%) = x^2 + y^2/2$
- ✓ Mixing occurs if x or y is non-zero
- ✓ Sign for New Physics:
  - ✓ Observation of CP violation
  - ✓ x >> y
- ✓ Uses Dalitz plot to enhance Cabibbo favored rate since it proceeds largely via $K^-\rho^+$, while wrong-sign rate goes to $K^{*+}\pi^-$ & $K^{*0}\pi^0$
- ✓ For CP conserving fit $R_M = \left(0.23^{+0.18}_{-0.14} \pm 0.04\right) \times 10^{-3}$
- ✓ $R_M < 0.54 \times 10^{-3}$ @ 95% C.L.
- ✓ R_M is consistent with no mixing at 4.5% C.L.

Cabibbo favored



Wrong-sign





New Charmed Baryon: $\Lambda_c(2940)^+$

$\Lambda_c^+ = c[du]$

BABAR: 287 fb^{-1}
Submitted to PRL
Preliminary

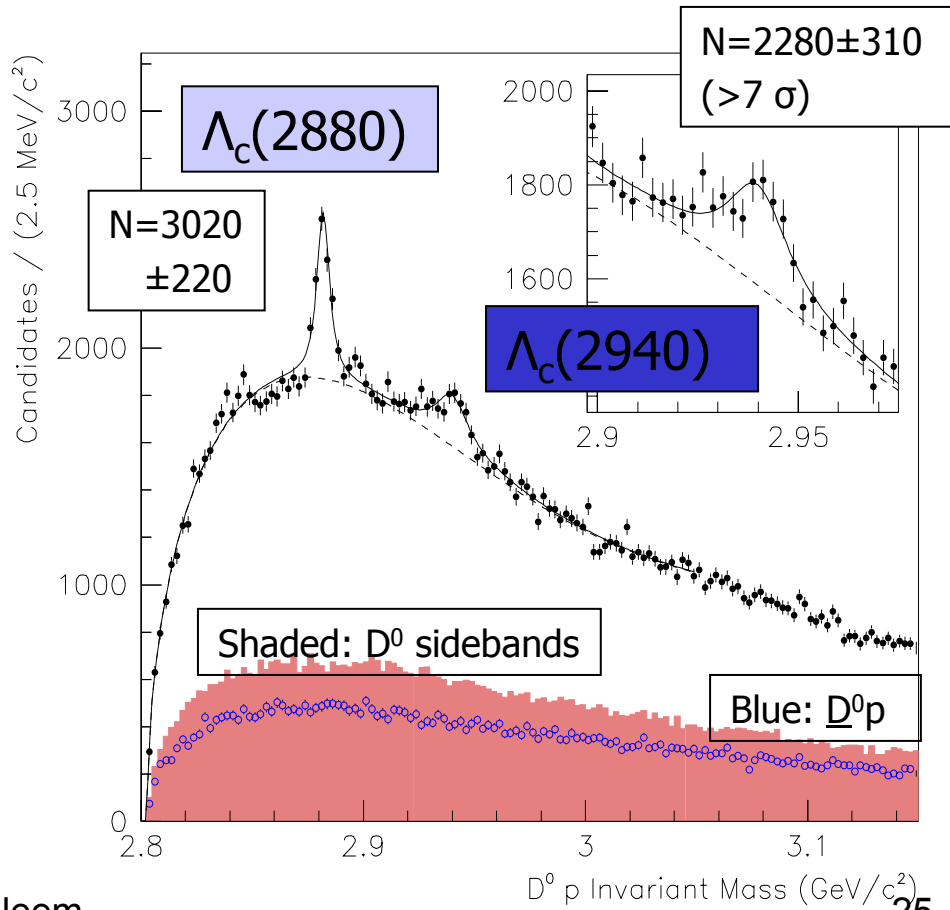
- ✓ Observed in $c\bar{c}$ continuum events in the decay mode D^0p ($D^0 \to K^-\pi^+$, $K^-\pi^+\pi^+\pi^-$)

$$m = (2939.8 \pm 1.3 \pm 1.0)\ \mathrm{MeV}/c^2$$
$$\Gamma = (17.5 \pm 5.2 \pm 5.9)\ \mathrm{MeV}$$

- ✓ First observation of $\Lambda_c(2880)^+ \to D^0p$

$$m = (2881.9 \pm 0.1 \pm 0.5)\ \mathrm{MeV}/c^2$$
$$\Gamma = (5.8 \pm 1.5 \pm 1.1)\ \mathrm{MeV}$$

- ✓ No structure in D^+p
  - – No doubly-charged partner for either state



Charm Mixing

- ✓ Time evolution is given by an effective Hamiltonian

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

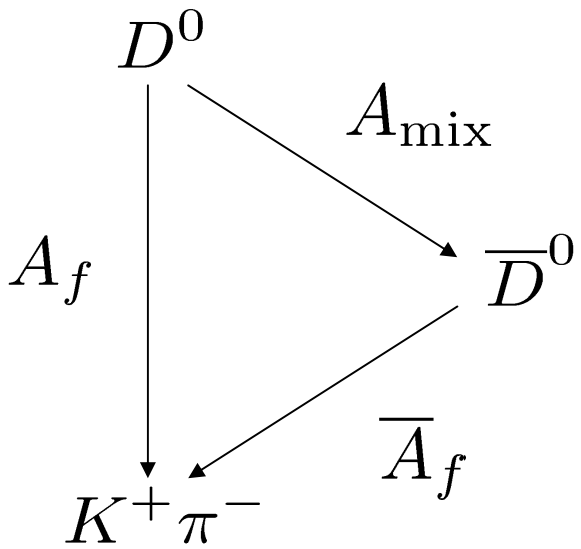
- ✓ The mass eigenstates D_1, D_2 are

$$|D_1\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\overline{D}^0\rangle$$

where $|q^2| + |p^2| = 1$

- ✓ Mixing can be characterized in terms of the masses m_1, m_2 and widths Γ_1, Γ_2 of the mass eigenstates: $x = \frac{\Delta m}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}$
- ✓ Mixing occurs if x or y is non-zero
- ✓ Sign for New Physics:
  - ✓ Observation of CP violation
  - ✓ x >> y

The *D*0 can decay to a final state *f* via direct decay or via mixing



$$\left|\frac{q}{p}\right|^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

Time Integrated Mixing Rate:

$R_M =$