Hadronic Charm Decays & D^o-$\bar{D}^o$ Mixing

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What We Hope to Learn

- Charm Mixing & CP Violation
  - Can we see new physics? SM mixing & CP violation is small, so new effects don't have large SM background as in the K or B systems
- Hadronic Charm Decays
  - Engineering numbers useful for other studies
    - B→Charm is dominant, so knowing lots about charm is useful, e.g. absolute $\mathcal{B}$'s, resonant substructure, phases on Dalitz plots, etc…
  - Learn about Strong Interactions, esp. final state interactions

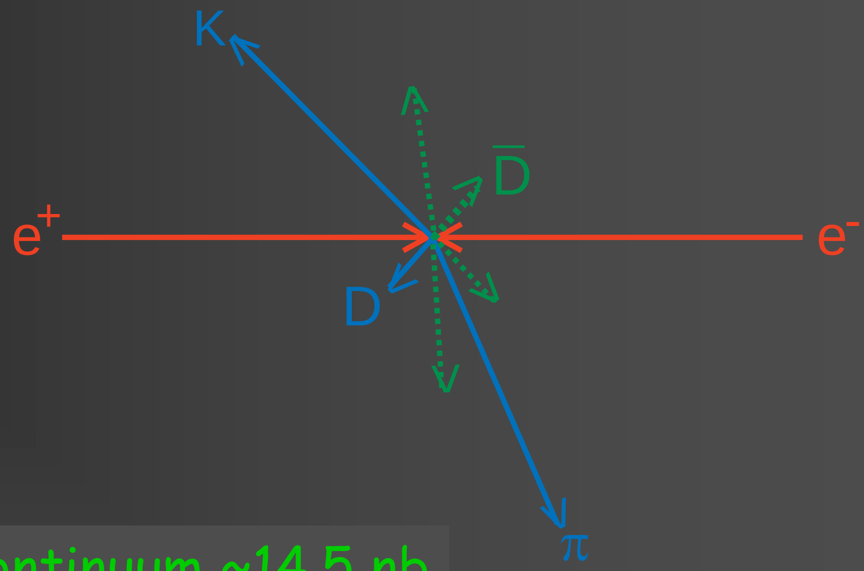
Absolute Charm Meson Branching Ratios & Other Hadronic Decays

D^o, D^+ & D_S

Experimental methods

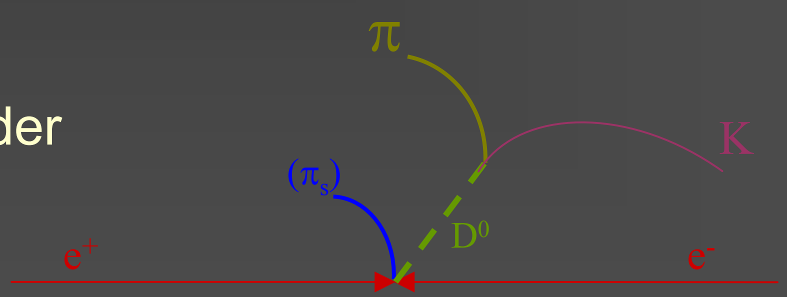
- $D\overline{D}$ production at threshold: used by Mark III, and more recently by CLEO-c and BES-II.
  - Unique event properties
    - Only $D\overline{D}$ not $D\overline{D}x$ produced
  - Large cross sections:

$\sigma(D^o\overline{D}^o)$ = 3.72±0.09 nb
$\sigma(D^+D^-)$ = 2.82±0.09 nb } World Ave
$\sigma(D_SD_S^*)$ = ~1 nb



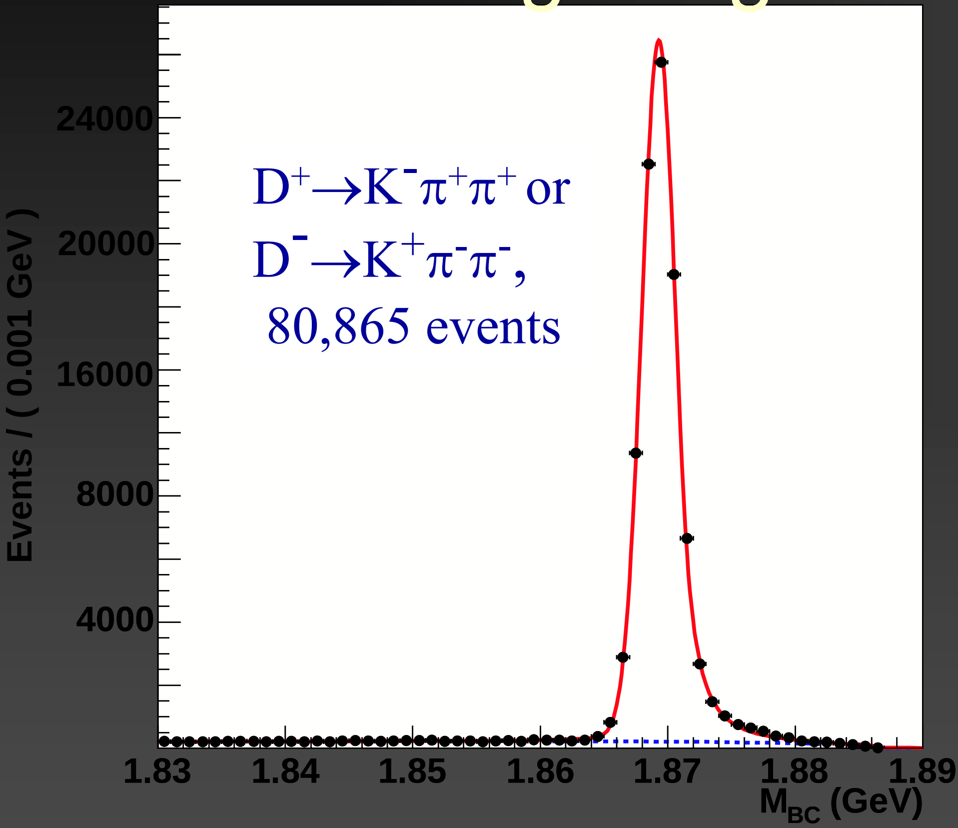
Continuum ~14.5 nb

  - Ease of B measurements using "double tags"
  - $\mathcal{B}_A$ = # of A/# of D's
- B-factories (e^+e^-) + fixed target & collider experiments at hadron machines
  - D displaced vertex
  - $D^{*+} \rightarrow \pi^+ D^0$ tag, or $D_S^* \rightarrow \gamma D_S$

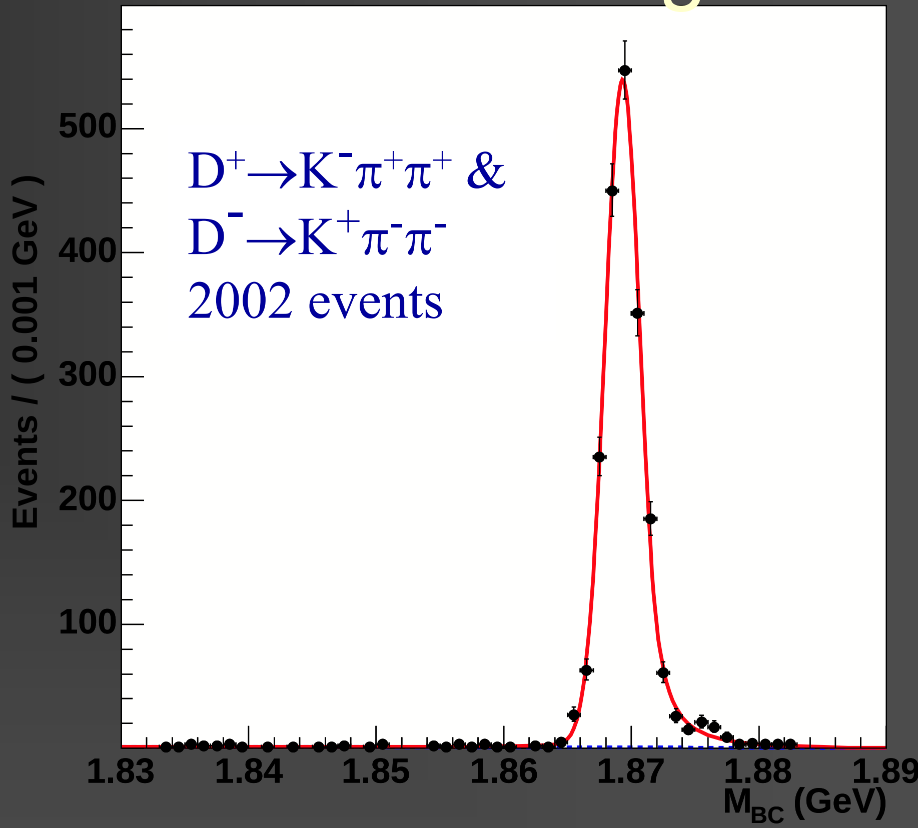


$D^+ \to K^- \pi^+ \pi^+$ at the ψ'' (CLEO-c)

Single tags



Double tags

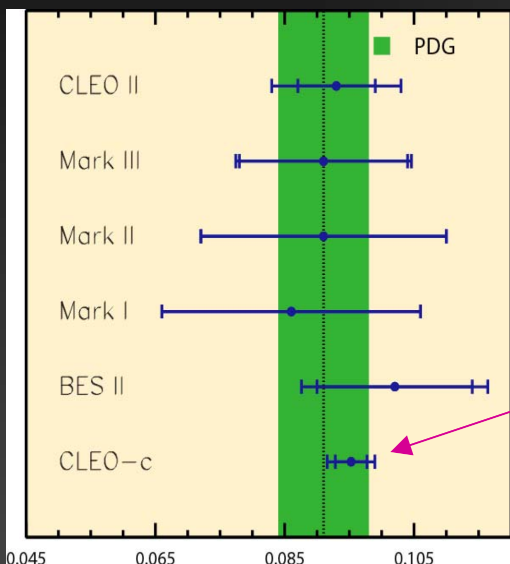


$$M_D^2 = \sum E_i^2 - \sum \vec{P}_i^2 = E_{beam}^2 - \sum \vec{P}_i^2$$

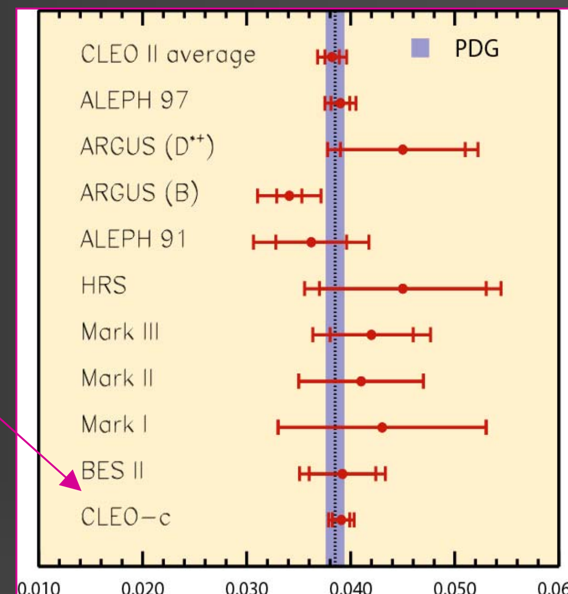
281 pb^{-1} of data at $\psi(3770)$

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

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



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



CLEO-c
(not in average)

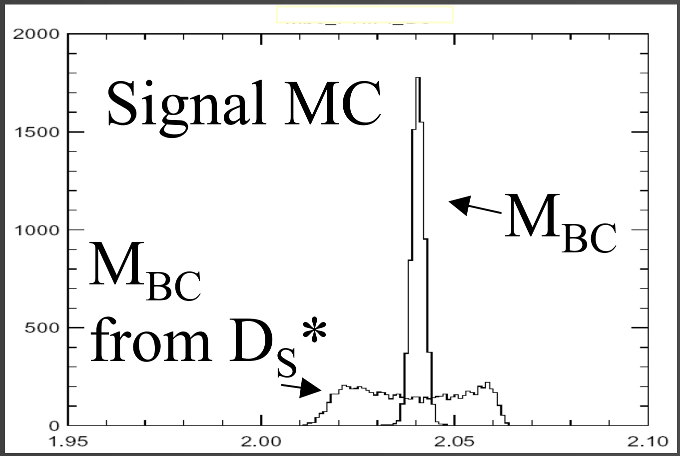
$\mathcal{B}$ (%)	Error(%)	Source
9.52 ±0.25±0.27	3.9	CLEO-c
9.2±0.6	6.5	PDG
9.43 ±0.31	3.3	World avg

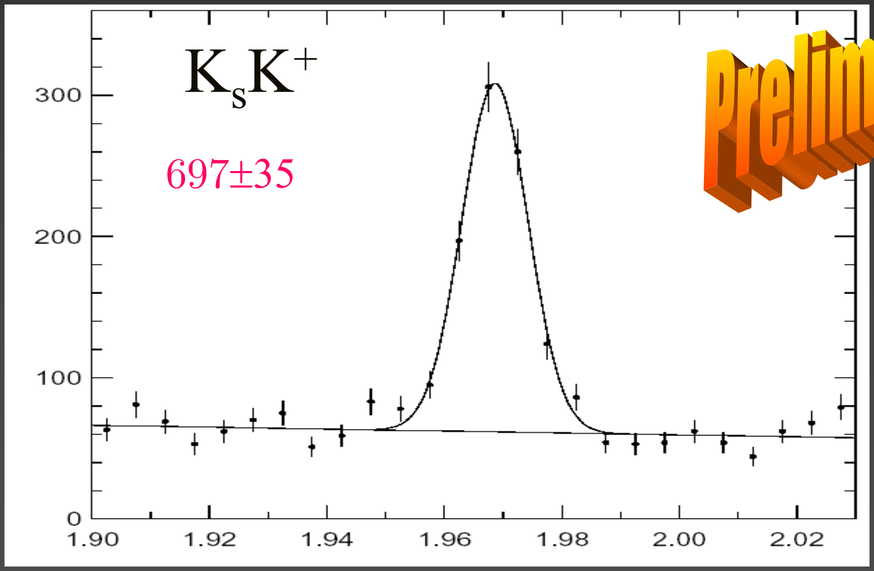
$\mathcal{B}$ (%)	Error(%)	Source
3.91±0.08 ±0.09	3.1	CLEO-c
3.81±0.09	2.4	PDG
3.85 ±0.07	1.9	World avg

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

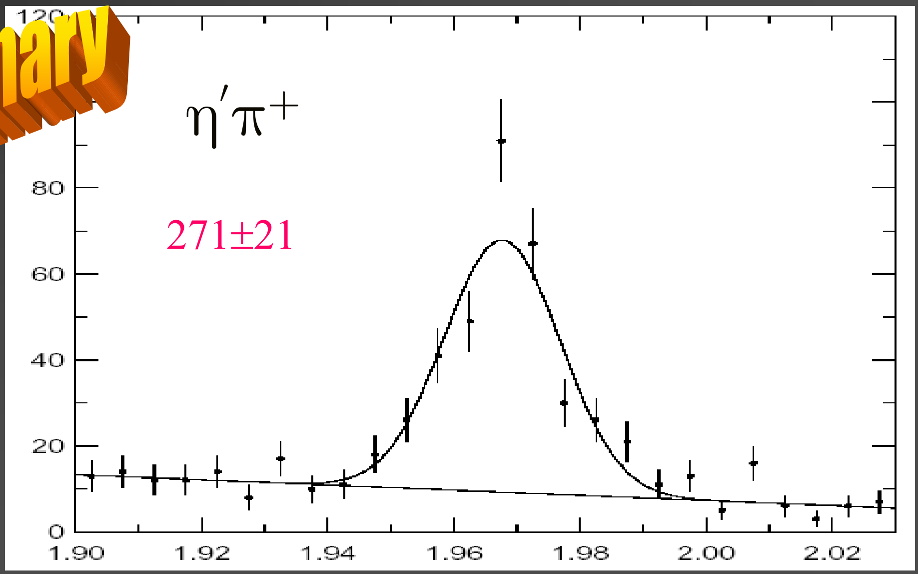
CLEO D_S^+ Results at 4170 MeV

- Since $e^+e^- \rightarrow D_S^* D_S$, the D_S from the D_S^* will be smeared in beam-constrained mass.
- $\therefore$ cut on M_{BC} & plot invariant mass (equivalent to a p cut)



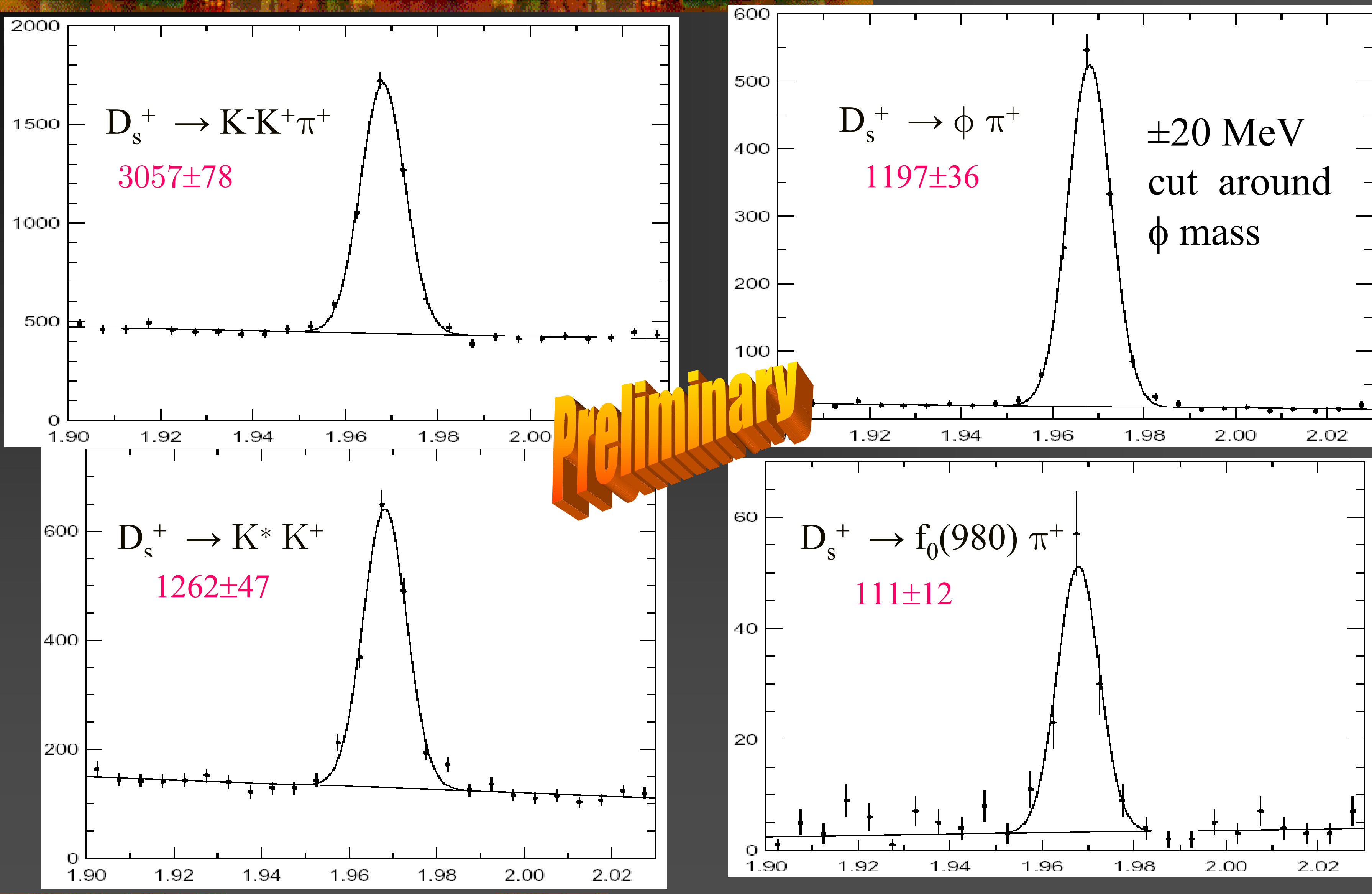


Inv Mass (GeV)



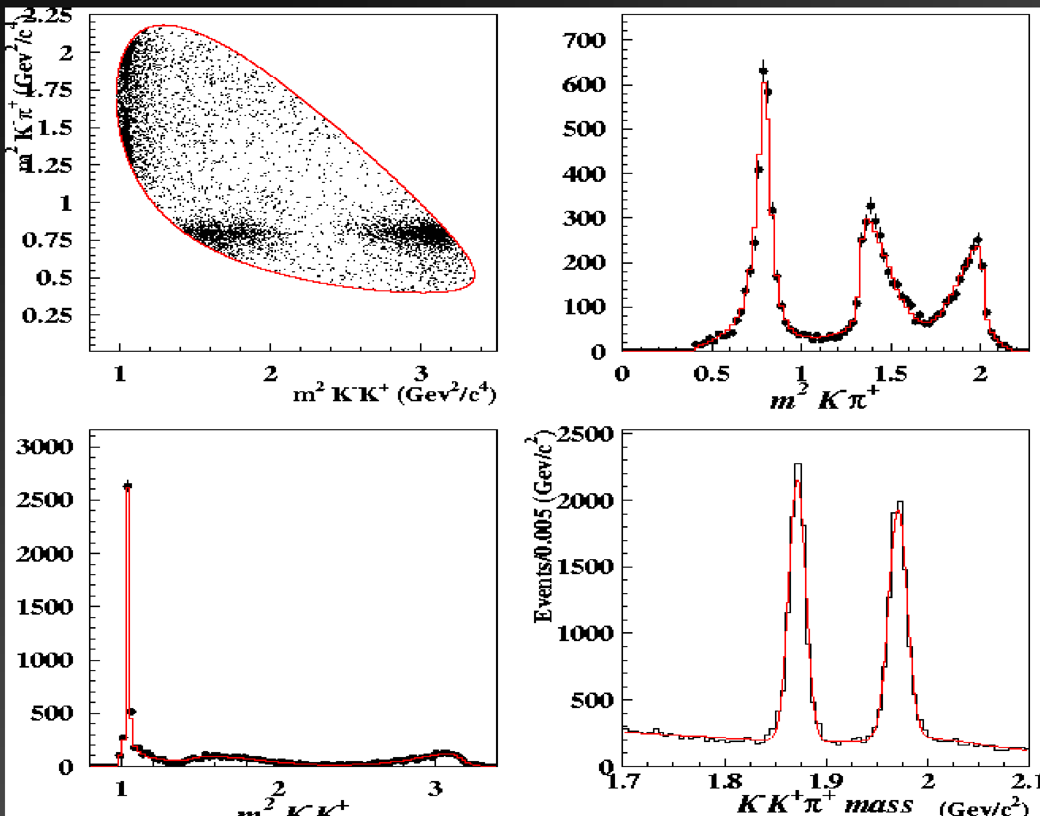
Inv Mass (GeV)

$D_s^+ \to K^-K^+\pi^+$ from CLEO-c (72 pb^{-1})



Inv Mass (GeV)   Inv Mass (GeV)

$D_s^+ \rightarrow K^-K^+\pi^+$ from FOCUS E831



From Sandra Malvezzi CIPANP 2000

AIP Conference Proceedings -- December 12, 2000 -- Volume 549, Issue 1, p. 569

Fit results

	Fit frac.	Phase (Deg)
K^{*0} (892)	0.44 ± 0.01	0.0 (fixed)
K^*_0 (1430)	0.06 ± 0.01	114 ± 5
ϕ (1020)	0.45 ± 0.01	148 ± 4
f_0 (980)	0.16 ± 0.01	135 ± 4
f_j (1710)	0.04 ± 0.01	106 ± 8

E687 published result

	Fit frac.	Phase (Deg)
K^{*0} (892)	0.48 ± 0.05	0.0 (fixed)
K^*_0 (1430)	0.09 ± 0.03	152 ± 40
ϕ (1020)	0.40 ± 0.03	178 ± 20
f_0 (980)	0.11 ± 0.04	159 ± 22
f_j (1710)	0.03 ± 0.02	110 ± 20

Single & Double D_S^+ Tags in 76 pb^{-1}

- Modes:
- Different selection criteria than other analyses
- Clean double tag signal

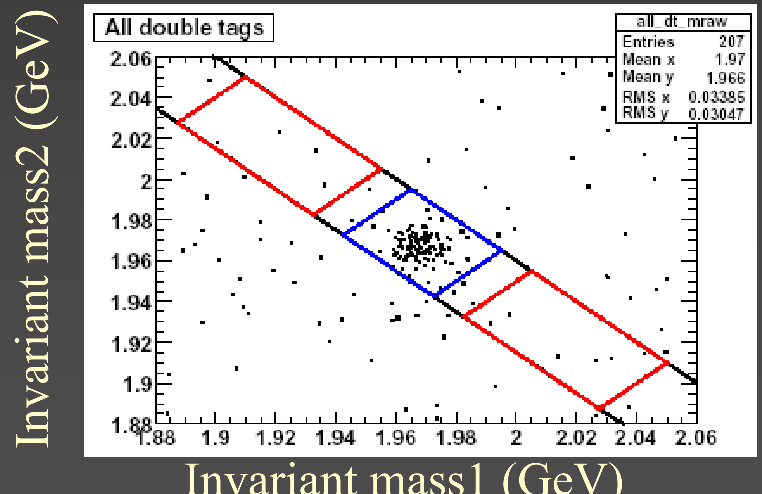
Single tags

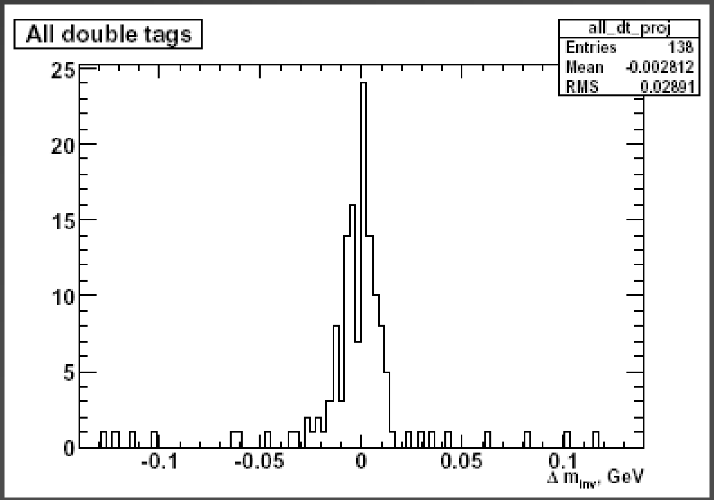
	$K_S K^+$	$K^- K^+ \pi^+$	$K^- K^+ \pi^+ \pi^0$	$\pi^+ \pi^+ \pi^-$
D_s^+	441.8 ± 25.3	1607.0 ± 53.6	332.6 ± 38.0	265.2 ± 29.0
D_s^-	346.3 ± 23.0	1736.8 ± 54.9	376.0 ± 37.8	274.1 ± 28.3

Double tags

	$K_S K^-$	$K^+ K^- \pi^-$	$K^+ K^- \pi^- \pi^0$	$\pi^- \pi^- \pi^+$
$K_S K^+$	4	5	7	3
$K^- K^+ \pi^+$	2	36	13.67	12.67
$K^- K^+ \pi^+ \pi^0$	3	12	5	4
$\pi^+ \pi^+ \pi^-$	2	8	0.33	Not used†

†Not used since continuum MC suggests possible structure





Δm=mass1-mass2

Absolute $\mathcal{B}$ Results for D_S^+ 76 pb^{-1}

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
- Results are *preliminary*: more modes are being added & more data is being taken
- What about $D_S \rightarrow \phi\pi^+$?

The Effective $\mathcal{B}(D_S \to \phi\pi^+)$

- **CLEO does not quote it.** Because of the presence of $f_0\pi^+$ & other interferences on the Dalitz plot, the $\mathcal{B}$ you get depends on your mass resolution & your mass cut
- I, however, will make an estimate based on CLEO's mass resolution since many experiments have similar resolution. (Note that the observed ϕ line shape is a convoluted BW & Gaussian)
- Using a ±10 MeV K^+K^- mass cut about the ϕ mass (91% efficient on the ϕ), I find from the observed ratio of $\phi\pi/KK\pi$ events: $\mathcal{B}^{eff}(D_S \to \phi\pi^+)=(3.49\pm0.39)\%$. For ±20 MeV cut (97% efficient) (3.73±0.42)%, which gives a scale of the mass cut sensitivity

Previous Measurements of $\mathcal{B}^{eff}(D_S \to \phi\pi^+)$

- Compare fully and partially reconstructed $B \to D^* D_{S(J)}^*$ decays
  - CLEO $\mathcal{B}^{eff}(D_S \to \phi\pi^+) = (3.6 \pm 0.8 \pm 0.5)\%$
  - BaBar $\mathcal{B}^{eff}(D_S \to \phi\pi^+) = (4.8 \pm 0.5 \pm 0.4)\%$
  - BaBar $\mathcal{B}^{eff}(D_S \to \phi\pi^+) = (4.8 \pm 0.4 \pm 0.5)\%$ (Marsiske's talk)
- BES $\mathcal{B}^{eff}(D_S \to \phi\pi^+) = (3.9^{+5.1+1.8}_{-1.9-1.1})\%$
- Compare with my estimate

  $\mathcal{B}^{eff}(D_S \to \phi\pi^+) = (3.5 \pm 0.4)\%$.
- Upper limit based on counting all known modes <4.8% @ 90% c.l $\to$ 5.2% based on current data (Muheim & Stone Phys. Rev. D 49, 3767 (1994)). They also predicted $\mathcal{B}(D_S \to \phi\pi^+) = (3.6 \pm 0.6)\%$

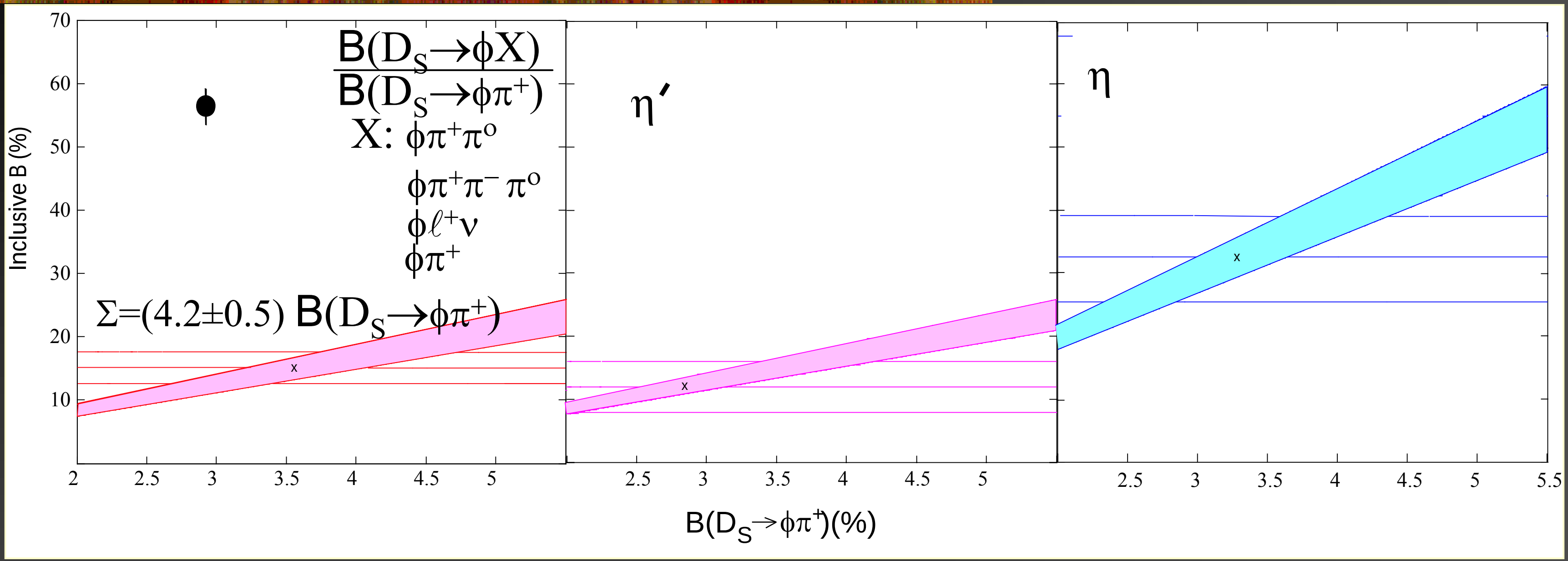
Inclusive $s\bar{s}$ Mesons from D decays

	η (%)	η' (%)	ϕ (%)
D^o	9.4 ± 0.4 ± 0.6	2.6 ± 0.2 ± 0.2	1.0 ± 0.1 ± 0.1
D^+	5.7 ± 0.5 ± 0.5	1.0 ± 0.2 ± 0.1	1.1 ± 0.1 ± 0.2
D_S	32.0 ± 5.6 ± 4.7	11.9 ± 3.3 ± 1.2	15.1 ± 2.1 ±1.5

- Done using double tag events
- ϕ & η' rates are much higher for D_S, useful for hadron collider b experiments

Preliminary

Can be used to check $\mathcal{B}^{eff}(D_S \to \phi\pi^+)$



- Procedure: take all modes containing ϕ, η' & η all measured wrt to $\phi\pi$ (bands are $\pm 1\sigma$). If new modes are found the slope of the bands would increase
- CLEOc measurements are horizontal lines, also at $\pm 1\sigma$)
- Consistent with a 3.5% $\phi\pi$ effective branching ratio
- If more modes are found slope would increase, implying a lower $\phi\pi$ branching ratio

The Real $\mathcal{B}(D_S \to \phi\pi^+)$

- You can use a Dalitz plot fit (i.e. FOCUS) to get the fraction of $\phi\pi$. This is not the same procedure that was done in the past of merely cutting on the K^+K^- invariant mass about the ϕ.
- The FOCUS Dalitz plot analysis has the $\phi\pi^+$ fraction of $K^+K^-\pi^+$ =0.45±0.01
- Dividing the CLEO number for $\mathcal{B}(D_S \to K^+K^-\pi^+)$ by $\mathcal{B}(\phi \to K^+K^-)$=.491, gives $\mathcal{B}(D_S \to \phi\pi^+)$=(4.16±0.41)%
- This is the branching ratio that is most appropriate to compare with theoretical calculations

Cabibbo Suppressed Decays

CLEO-c

Mode	Branching Ratio x 10^{-3}	PDG
$D^0 \to \pi^+\pi^-$	$1.39 \pm 0.04 \pm 0.04 \pm 0.03 \pm 0.01$	1.38±0.05
$D^0 \to \pi^0\pi^0$	$0.79 \pm 0.05 \pm 0.06 \pm 0.01 \pm 0.01$	0.84±0.22
$D^0 \to \pi^+\pi^-\pi^0$	$13.2 \pm 0.2 \pm 0.5 \pm 0.2 \pm 0.1$	11±4
$D^0 \to \pi^+\pi^+\pi^-\pi^-$	$7.3 \pm 0.1 \pm 0.3 \pm 0.1 \pm 0.1$	7.3±0.5
$D^0 \to \pi^+\pi^-\pi^0\pi^0$	$9.9 \pm 0.6 \pm 0.7 \pm 0.2 \pm 0.1$	
$D^0 \to \pi^+\pi^+\pi^-\pi^-\pi^0$	$4.1 \pm 0.5 \pm 0.2 \pm 0.1 \pm 0.0$	
$D^0 \to \omega\pi^+\pi^-$	$1.7 \pm 0.5 \pm 0.2 \pm 0.0 \pm 0.0$	
$D^0 \to \eta\pi^0$	$0.62 \pm 0.14 \pm 0.05 \pm 0.01 \pm 0.01$	
$D^0 \to \pi^0\pi^0\pi^0$	< 0.35 (90% CL)	
$D^0 \to \omega\pi^0$	< 0.26 (90% CL)	
$D^0 \to \eta\pi^+\pi^-$	< 1.9 (90% CL)	

BaBar

Mode	Branching Ratio x 10^{-3}	PDG
$D^+ \to K^+\pi^0$	0.246±0.046±0.024±0.016	
$D^+ \to \pi^+\pi^0$	1.22±0.10±0.08±0.08	1.33±0.22

CLEO-c

Mode	Branching Ratio x 10^{-3}	PDG
$D^+ \to \pi^+\pi^0$	1.25±0.06±0.07±0.04	1.33±0.22
$D^+ \to \pi^+\pi^+\pi^-$	3.35±0.10±0.16±0.12	3.1±0.4
$D^+ \to \pi^+\pi^0\pi^0$	4.8±0.3±0.3±0.2	
$D^+ \to \pi^+\pi^+\pi^-\pi^0$	11.6±0.4±0.6±0.4	
$D^+ \to \pi^+\pi^+\pi^+\pi^-\pi^-$	1.60±0.18±0.16±0.06	1.73±0.23
$D^+ \to \eta\pi^+$	3.61±0.25±0.23±0.12	3.0±0.6
$D^+ \to \omega\pi^+$	< 0.34 (90% CL)	

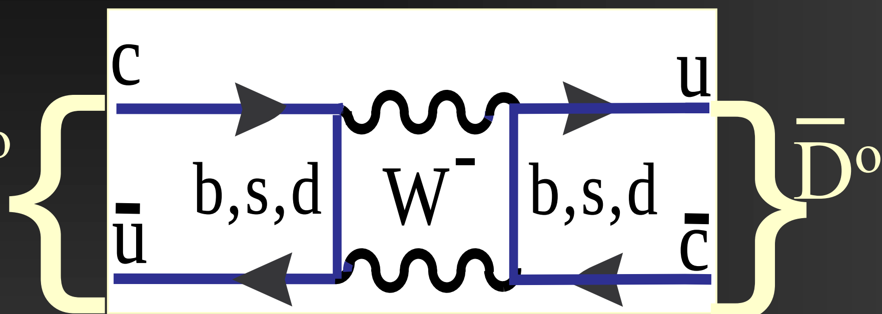
New value for phase shift in $D \to \pi\pi$ modes between $\Delta I=3/2$ & $\Delta I=1/2$ amplitudes of $(86.4 \pm 2.8 \pm 3.3)^\circ$

Searches for New Physics in Charm Decays

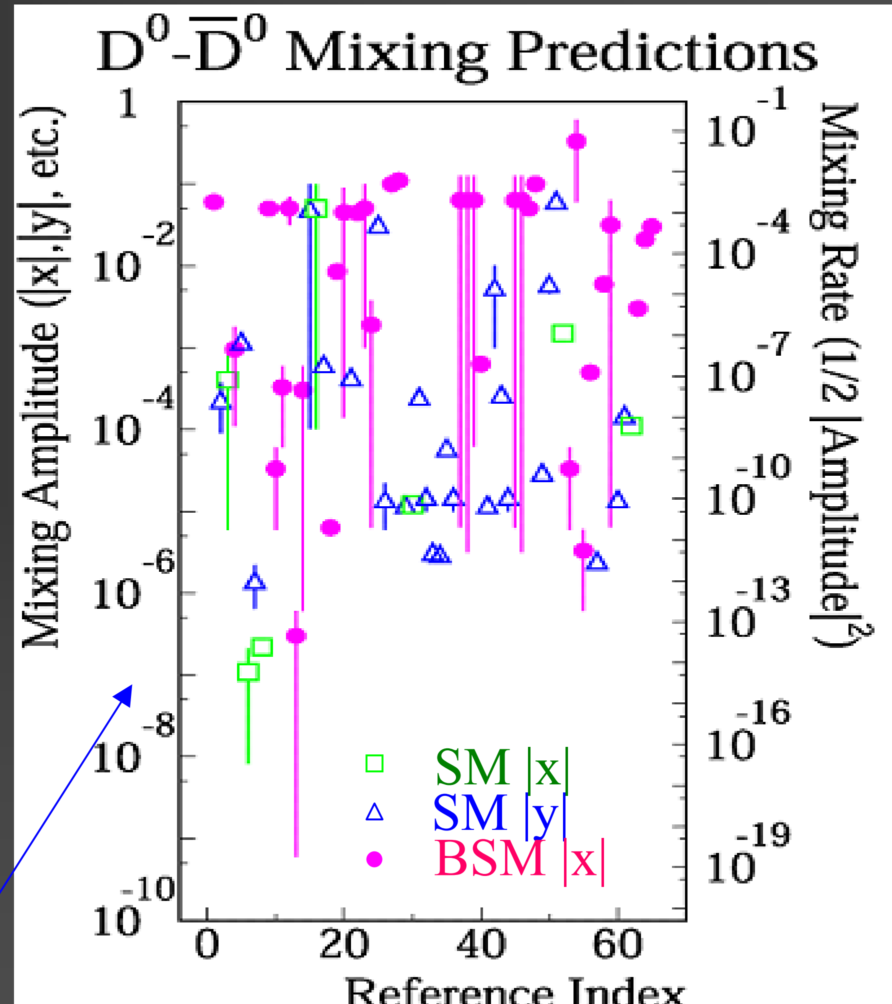
D^o-$\bar{D}^o$ Mixing

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

- Mixing could proceed via



- **the presence of d-type quarks in the loop makes the SM expectations for D^o- $\bar{D}^o$ mixing small** compared with systems involving u-type quarks in the box diagram because these loops include 1 dominant super-heavy quark (t): K^o (50%), B^o (20%) & B_s (50%)
- New physics in loops implies $x \equiv \Delta M/\Gamma >> y \equiv \Delta\Gamma/2\Gamma$; but long range effects —○— complicate predictions



From H. Nelson, updated by A.A. Petrov hep-ph/0311371

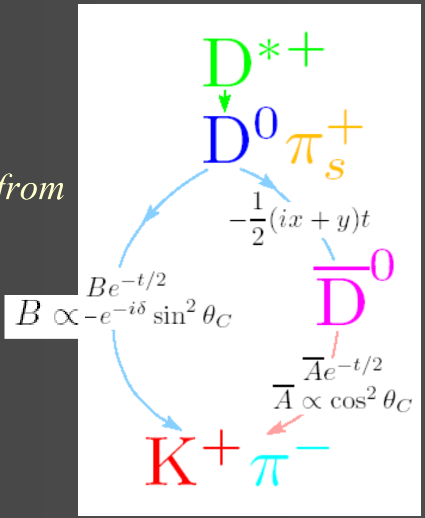
D^o- $\bar{D}^o$ mixing: Wrong-sign $K^-\pi^+$

- Complicated by interference between DCSD & mixing [strong phase δ – will be measured by CLEOc] $x' \equiv x\cos\delta + y\sin\delta$

$$R_{ws}(t) = e^{-\Gamma t}\left(R_D + \sqrt{R_D}\,y'\Gamma t + \tfrac{1}{4}(x'^2 + y'^2)(\Gamma t)^2\right)$$

- Complicated by CP violation

Stolen from Ligeti



Experiment	x'^2 (x10^{-3}) <@95 % CL		y'(95% C.L.) (x10^{-3})	
	CPV	No CPV	CPV	No CPV
BaBar (2003)	2.2	2.0	$-56<y'<39$	$-27<y'<22$
FOCUS (2004)	0.80	0.83	$-120<y'<67$	$-72<y'<41$
CLEO (2000)	0.82	0.78	$-58<y'<10$	$-52<y'<2$
Belle (2005)*	0.72	0.72	$-28<y'<21$	$-9.9<y'<6.8$

*consistent with no mixing at 3.9% cl

Other Studies

- CDF WS/RS in Kπ is $(4.05 \pm 0.21 \pm 0.12) \times 10^{-3}$ (350 pb^{-1})
- Direct measurements of C=+ and C=- D^0 lifetime differences (y_{CP})
- WS rate in semileptonic decays measures $(x^2+y^2)/2$ directly

Experiment	y_{CP}(%)
FOCUS[44]	$3.4 \pm 1.4 \pm 0.7$
CLEO[43]	$-1.2 \pm 2.5 \pm 1.4$
Belle, untagged[45]	$-0.5 \pm 1.0 \pm 0.8$
Belle, tagged[46]	$1.2 \pm 0.7 \pm 0.4$
BaBar[47]	$0.8 \pm 0.4^{+0.5}_{-0.4}$

Average 0.92 ± 0.43

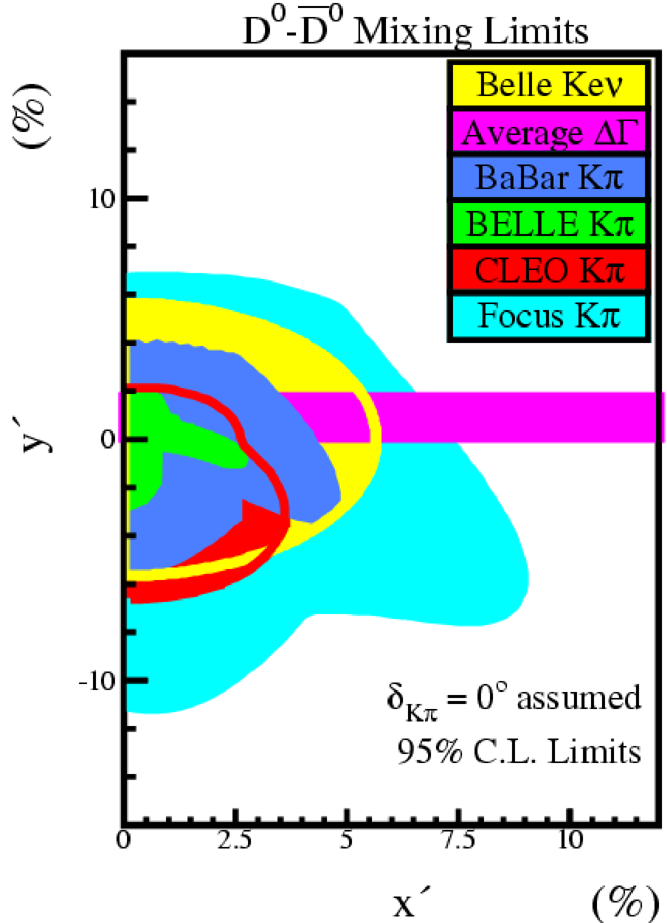


Table 7. Summary of mixing limits (95 % cl) from D^0 semileptonic decay studies.

Experiment	R_M	$\sqrt{x^2+y^2}$
CLEO[48]	0.0091	0.135
BaBar[49]	0.0046	0.1
Belle[50]	0.0016	0.056

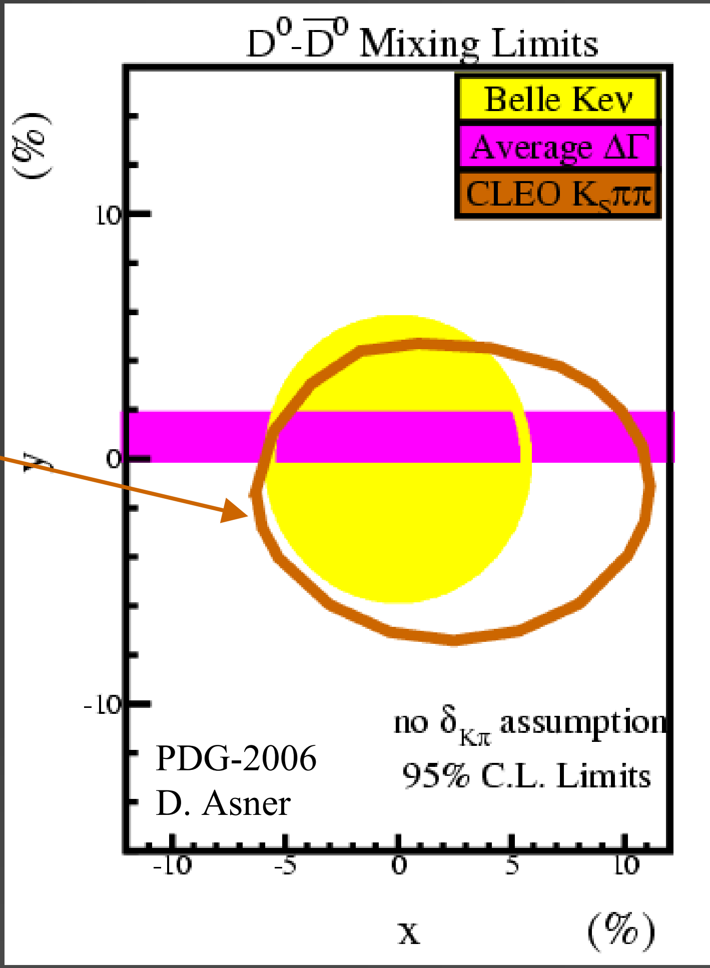
PDG 2006
D. Asner

Dalitz Plot Analyses: $D^0 \to K_S\pi^+\pi^-$

- CLEO: $D^0 \to K_S\pi^+\pi^-$ full time dependent analysis, compared with Belle semileptonic analysis
- Essential feature: distinct time-dependence of D_{CP+}, & D_{CP-} (CP+≡1, CP-≡1)

  $D_1(t) \sim \exp(-i(m_1 - i\Gamma_1/2)t)$

  $D_2(t) \sim \exp(-i(m_2 - i\Gamma_2/2)t)$



- Limits are (-4.5<x<9.3)% & (-6.4<y<3.6) %, @ 95% C.L., without assumptions regarding CP-violating parameters.

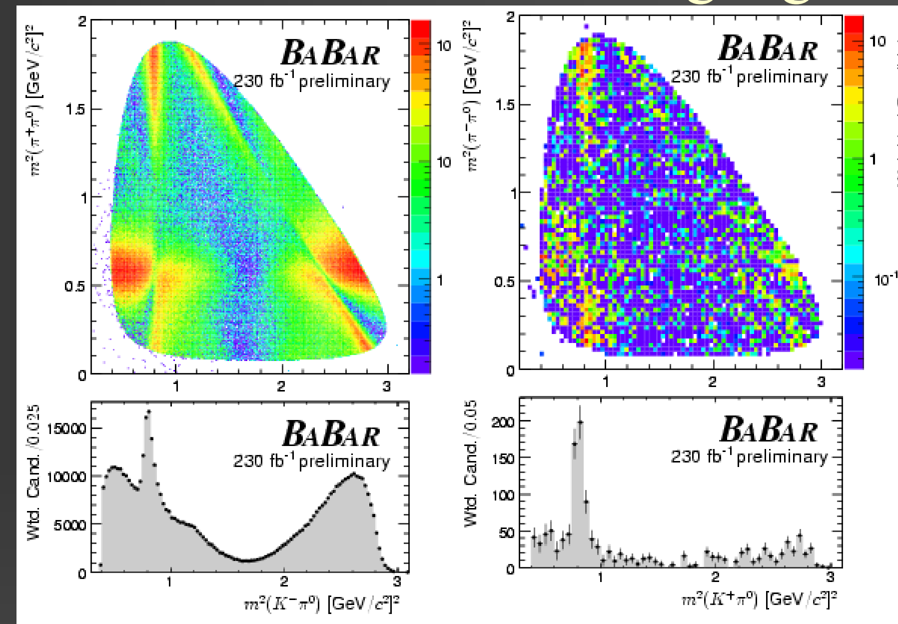
$D^0 \to K^+\pi^-\pi^o$

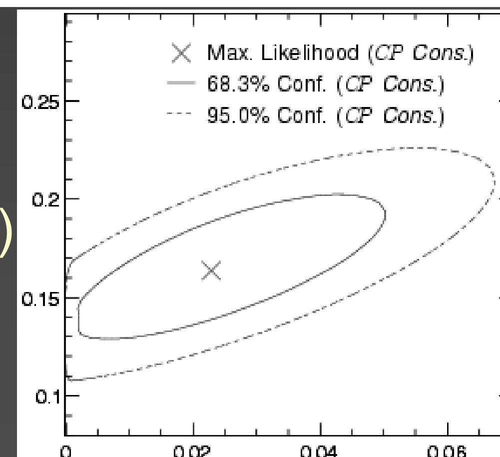
- BaBar: Uses Dalitz plot to enhance Cabibbo favored rate since it proceeds largely via $K^-\rho^+$, while wrong-sign rate goes to $K^{*+}\pi^-$ & $K^{*o}\pi^o$
- For CP conserving fit

$$R_M = \left(0.23^{+0.18}_{-0.14} \pm .04\right) x 10^{-3}$$

- $R_M < 0.54x10^{-3}$ @ 95% cl
- R_M is consistent with no mixing at 4.5% cl

Cabibbo favored Wrong-sign





R_D (%)

R_M (%)

CP/T Violation

- Unexpectedly large CP violation asymmetries may be a better signature for new physics (0.01-0.001)
- CP violation can be studied in a variety of ways:
  - Direct CP violation
  - CP violation in mixing
  - T violation in 4-body decays of D^0/D^+ (assuming CPT) and studying triple product correlations
  - Exploiting quantum coherence of $D\bar{D}$ produced in $\psi(3770)$ decays (Dave Cinabro's talk)

CP/T Violation: some recent data

Experiment	Decay mode	A_{CP} (%)	Notes
BaBar	$D^+ \to K^- K^+ \pi^+$	1.4±1.0 ±0.8	
BaBar	$D^+ \to \phi^+ \pi^+$	0.2±1.5±0.6	Res. Substr. Of $D^+ \to K^- K^+ \pi^+$
BaBar	$D^+ \to K^{*0} K^+$	0.9±1.7±0.7	
CLEO II.V	$D^0 \to \pi^+ \pi^- \pi^0$	$1^{+9}_{-7} \pm 8$	Dalitz plot analysis
CDF	$D^0 \to K^+ K^-$	2.0 ±1.2 ± 0.6	Direct CPV
CDF	$D^0 \to \pi^+ \pi^-$	1.0 ±1.3 ± 0.6	Direct CPV
FOCUS	$D^0 \to K^+ K^- \pi^+ \pi^-$	1.0 ±5.7±3.7	T violation through triple product correlations
FOCUS	$D^+ \to K^o K^+ \pi^+ \pi^-$	2.3 ±6.2±2.2	
FOCUS	$D_S \to K^o K^+ \pi^+$	-3.6 ±6.7±2.3	

Conclusions on Absolute B's

- D meson absolute B scale now becoming well known:
  - $B(D^+ \to K^- \pi^+ \pi^+)$ =(9.43±0.31)% [CLEOc+PDG]
    error 3.3% → 2.1% (in a few weeks)
  - $B(D^o \to K^- \pi^+)$ =(3.85±0.07)% [CLEOc+PDG]
    error 1.9% → 1.4% (in a few weeks)
  - $B(D_S \to K^- K^+ \pi^+) = 4.54^{+0.44}_{-0.42} \pm 0.25$ [CLEOc]
    error 11% → ~4-6% (this summer)
  - $\mathcal{B}^{eff}(D_S \to \phi \pi^+)$=(3.49±0.39)% [SS]
- Best to change base branching ratio for D_S from $\phi\pi$ to something else. Suggest $K^+K^-\pi^+$, or K_SK^+
- Already quite useful: # of charm particles/B decay: 1.09±0.04 (includes D^o, D^+, D_S, Λ_c, Ξ_c, 2x charmonium)

Conclusions II

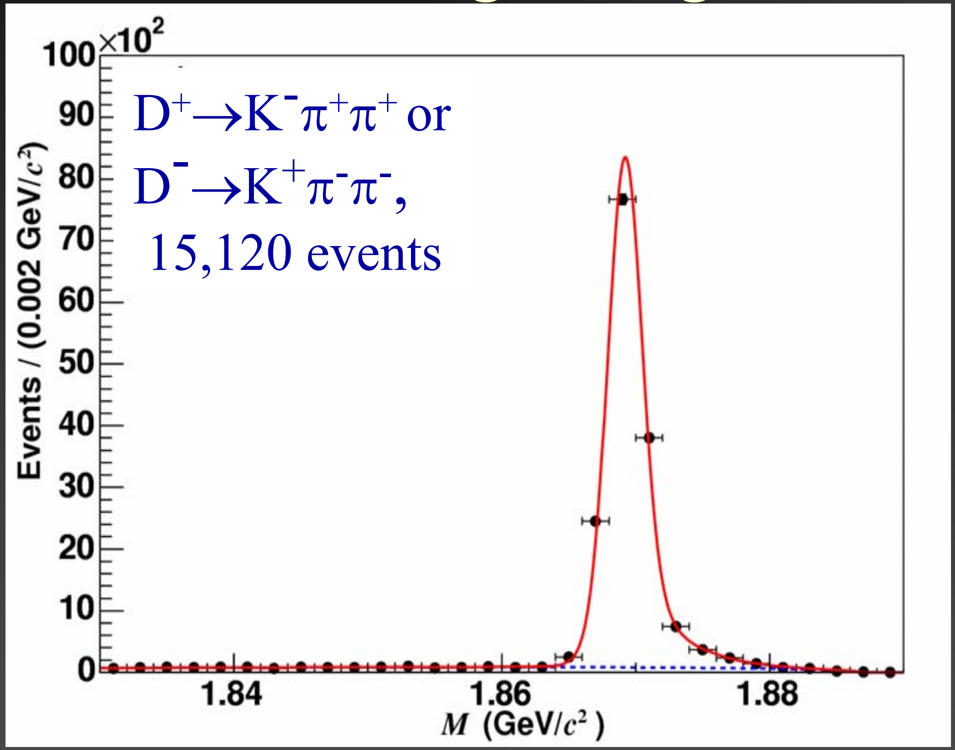
- Many more Cabibbo suppressed & DCS modes found. Large phase shifts in $D\to\pi\pi$
- No definitive evidence yet for charm mixing
  - Best limits are ~$|y'|<2.5\%$ & $|x'^2|<7.2\text{x}10^{-3}$ @ 95% cl
  - Hints from Belle in wrong sign $K^-\pi^+$ decays

    (only 3.9% cl for no mixing)
  - Hints from BaBar in wrong sign $K^+\pi^-\pi^o$ decays (only 4.5% cl for no mixing)
- No observations of CP Violation

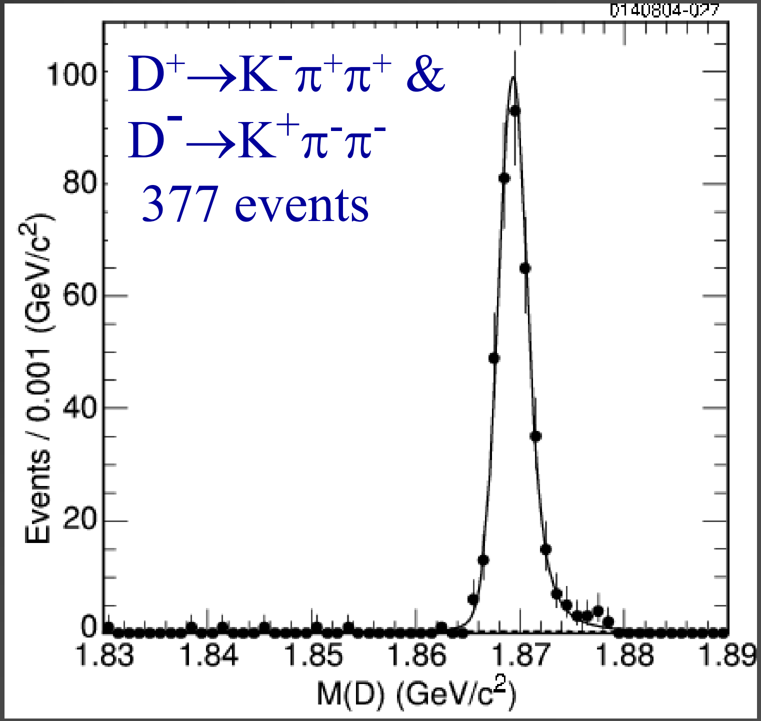
The End

$D^+ \to K^- \pi^+ \pi^+$ at the ψ'' (CLEO-c)

Single tags



Double



$$M_D^2 = \sum E_i^2 - \sum \vec{P}_i^2 = E_{beam}^2 - \sum \vec{P}_i^2$$

57 pb^{-1} of data at $\psi(3770)$, CLEO now has 281 pb^{-1}