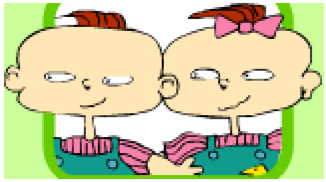
CP Violation in D Meson Decays

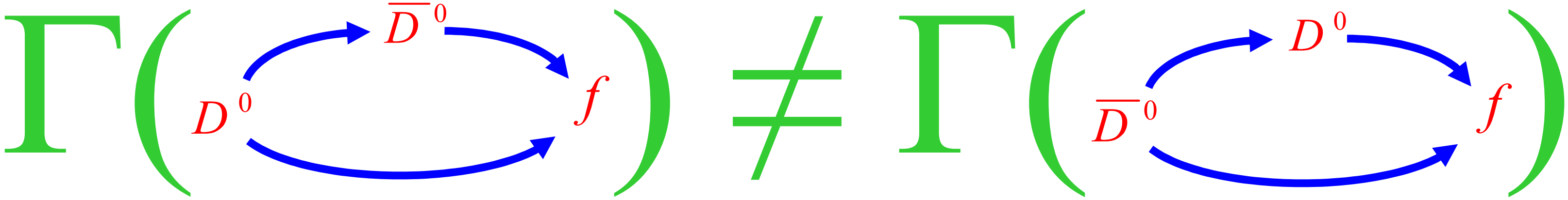


Mats Selen, University of Illinois

2002 FPCP Meeting, University of Pennsylvania

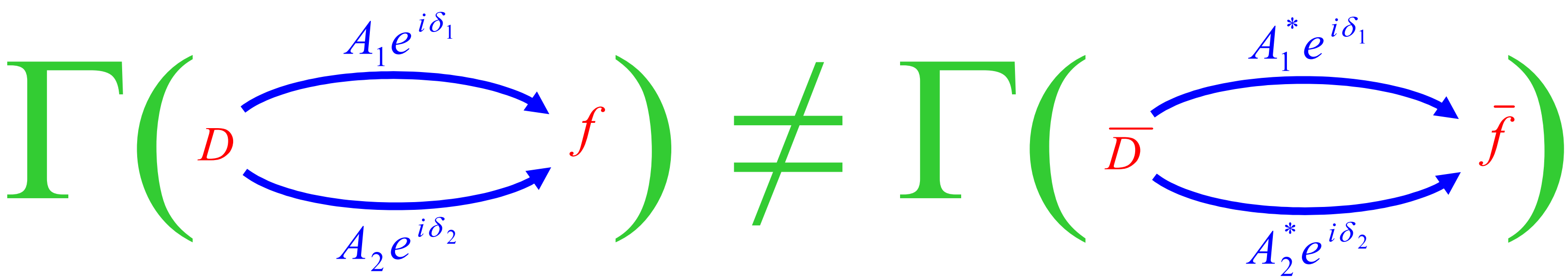
- Expectation
- Experiments
- Rate Asymmetries
- Other Approaches
- Outlook

Indirect CPV:



Very small in charm since mixing is suppressed
(i.e. good hunting ground for new physics)

Direct CPV:

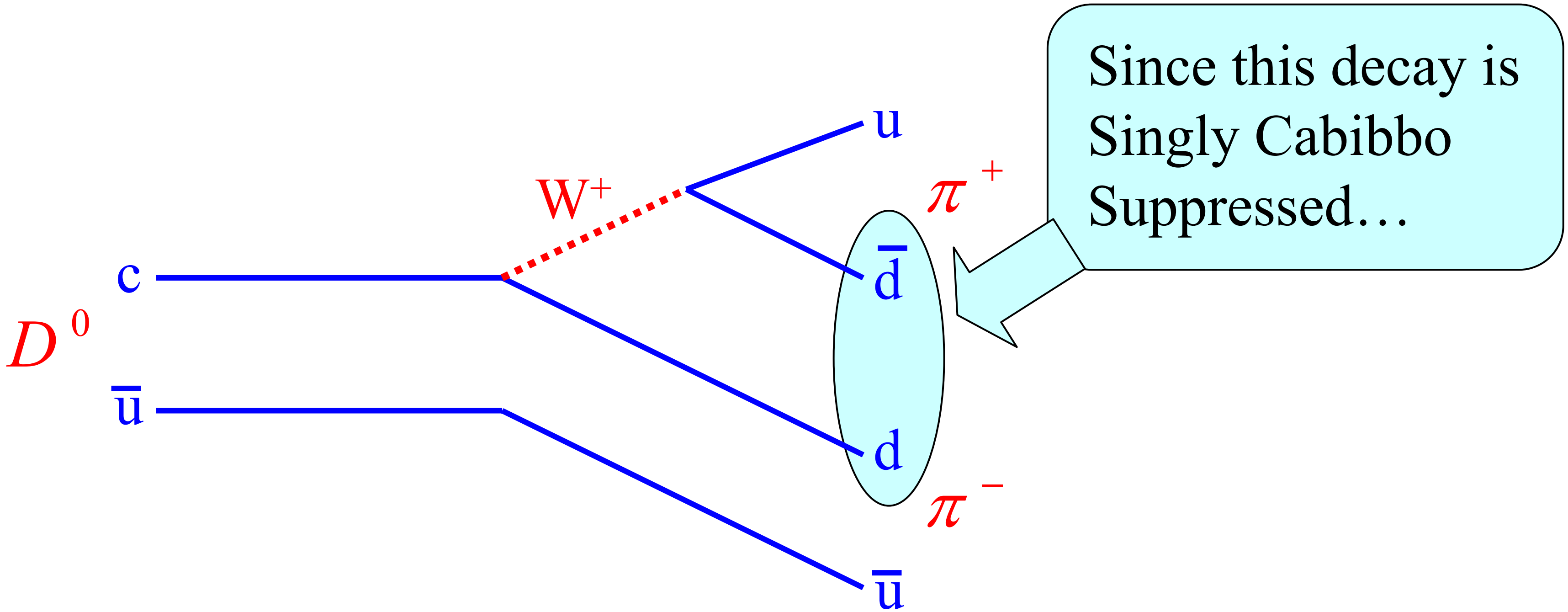


$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{2 Im A_1 A_2^* sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2 Re A_1 A_2^* cos(\delta_1 - \delta_2)} < 10^{-3}$$

Direct CPV:

1) Consider $D^0 \rightarrow \pi^+\pi^-$

(same for K^+K^-, $K^+K^-\pi^+$, $K^+K^-\pi^0$, $\phi\pi^+$, $\pi^+\pi^-\pi^+$, $\pi^+\pi^-\pi^0$, etc...)



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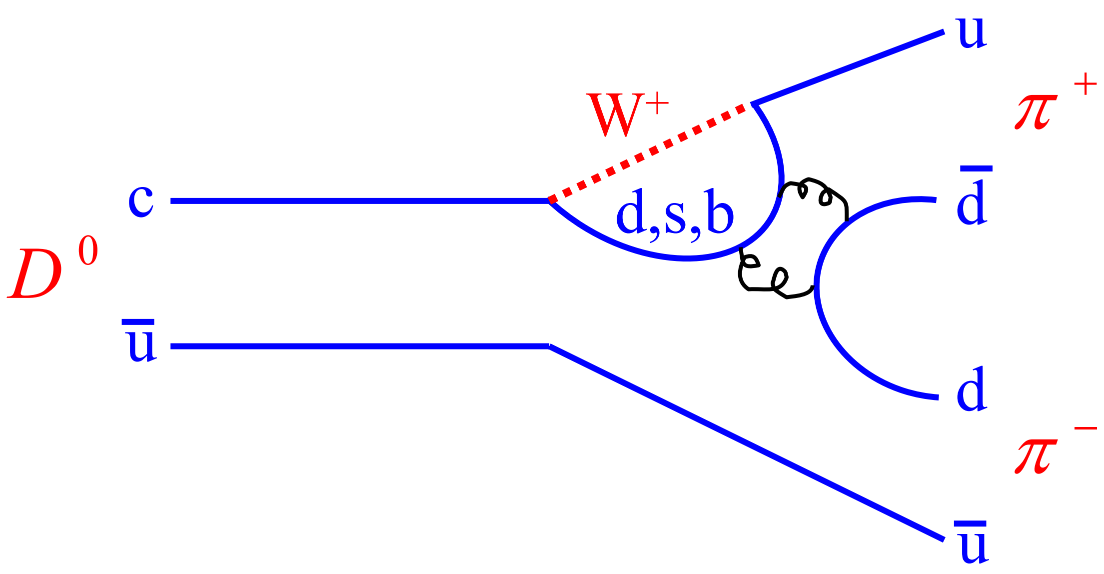
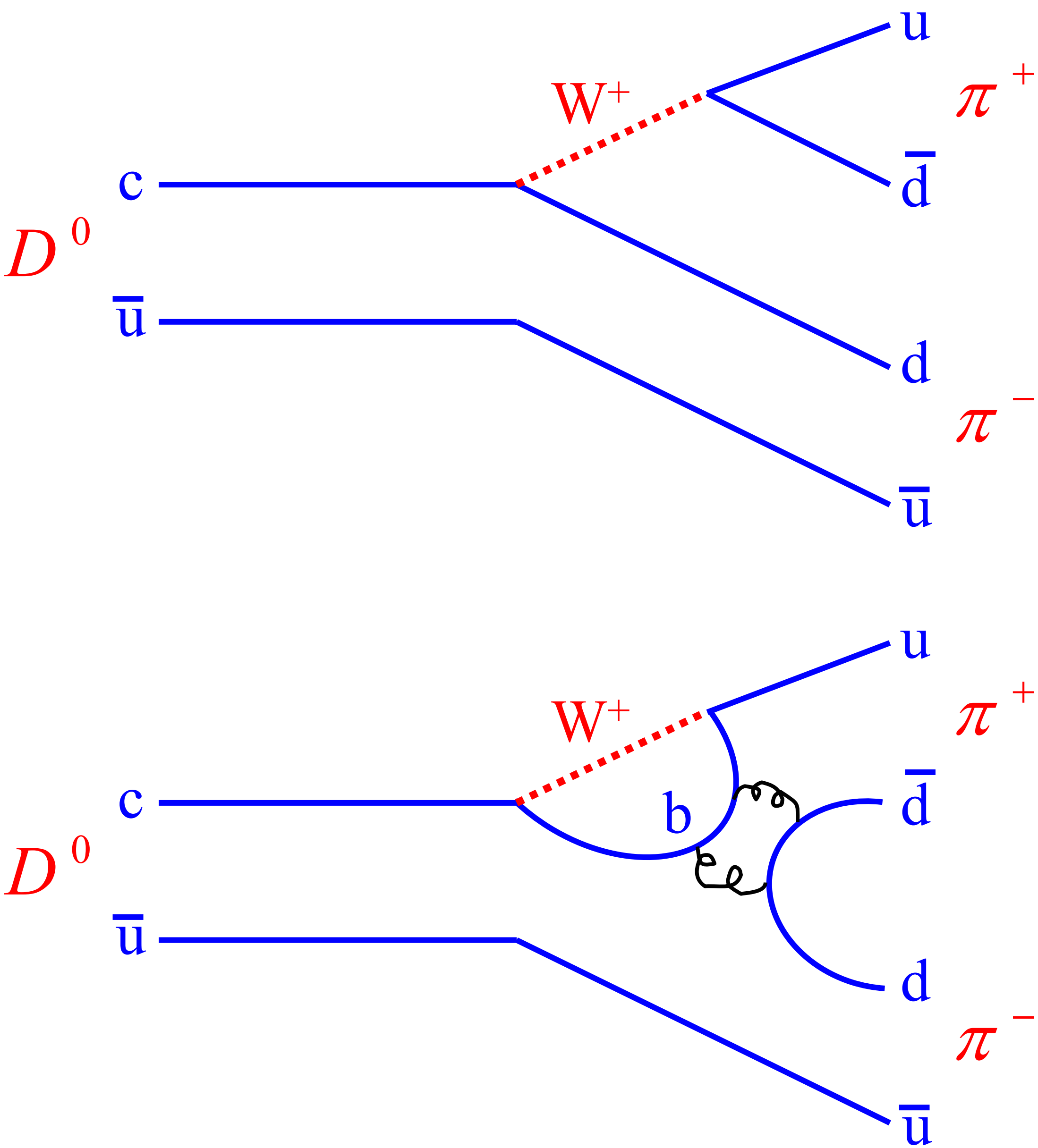


…we can modify it's topology in a simple way to get a penguin:



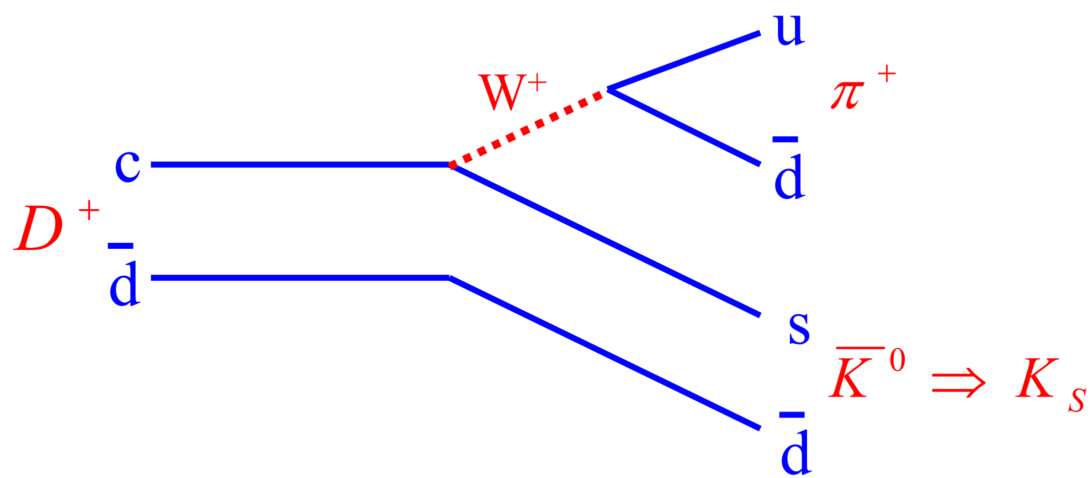
We have the ingredients:

$V_{cd}^{*}V_{ud}$	$\Delta I = \frac{1}{2}, \frac{3}{2}$
↑	↑
different weak phases	different strong phases are likely
↓	↓
$V_{cb}^{*}V_{ub}$	$\Delta I = \frac{1}{2}$

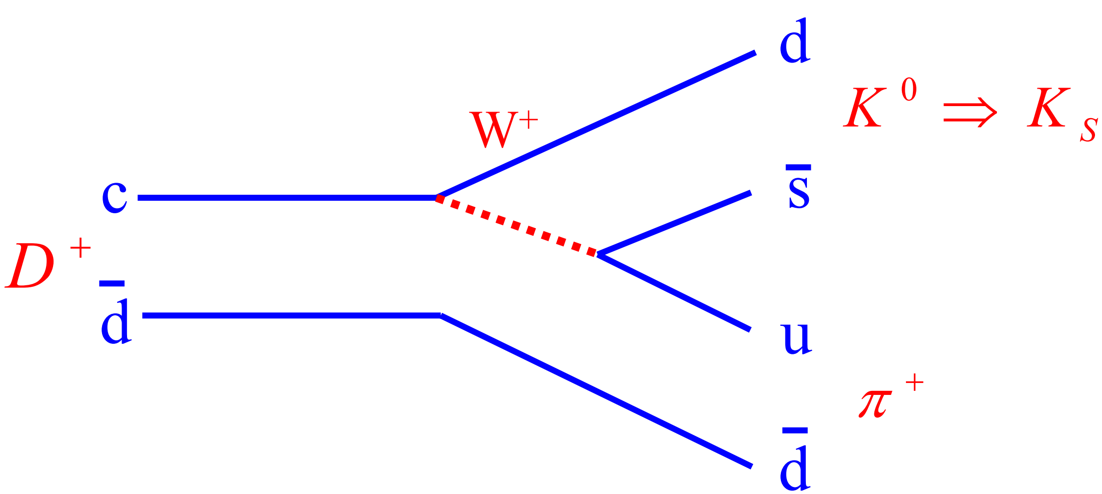
Expect $A_{CP} < 10^{-3}$ in most cases

2) Consider $D^+ \rightarrow K_S\pi^+$

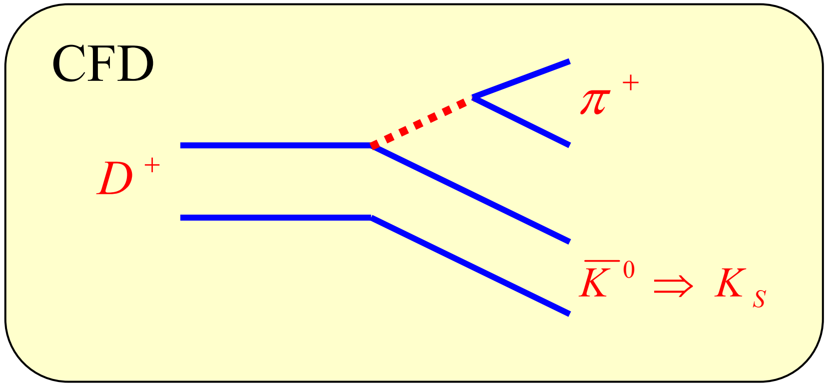
(also $K_S\rho$, K_Sa_1, $K^{*0}\pi^+$, $[K_S\pi^0]_{K*}\pi^+$, $K_S\pi^0$, $D_S \rightarrow K_SK^-$, $[K_S\pi^0]_{K*}K^-$, etc...)

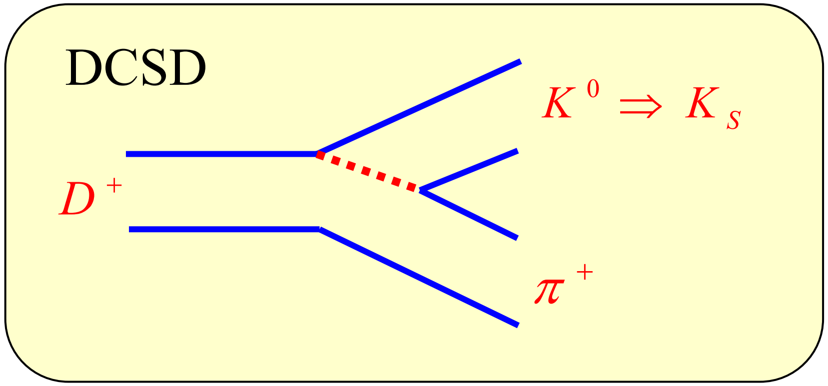


Cabibbo Favored Decay



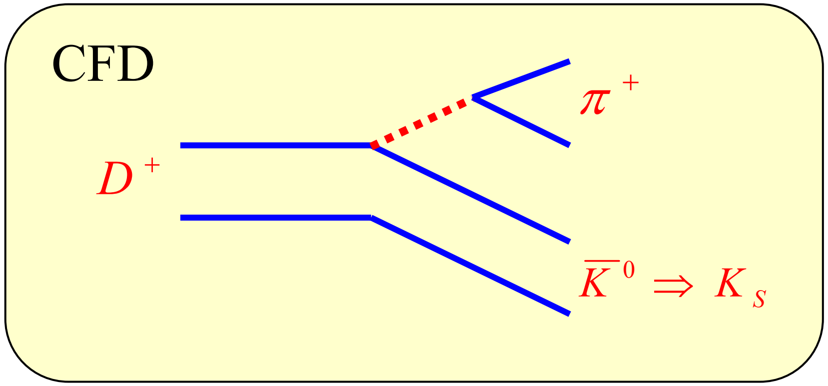
Doubly Cabibbo Suppressed Decay

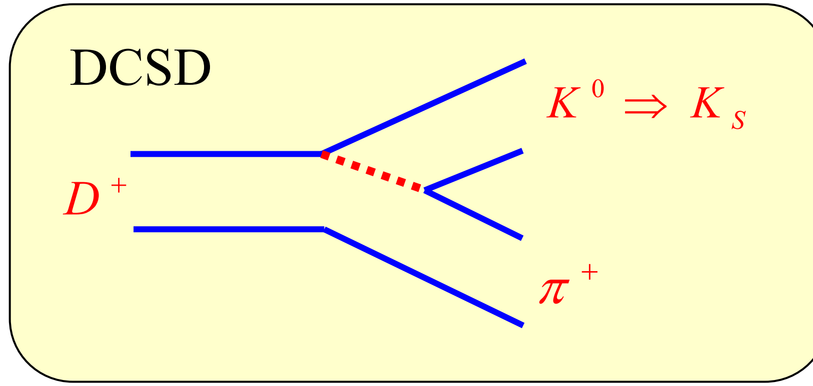




$$A_{CP} = \frac{\Gamma(D^- \to K_S\pi^-) - \Gamma(D^+ \to K_S\pi^+)}{\Gamma(D^- \to K_S\pi^-) + \Gamma(D^+ \to K_S\pi^+)} = \delta_K + 2R_d \tan^2\theta_C \sin\phi \sin\delta_d$$

Lipkin & Xing





$$A_{CP} = \frac{\Gamma(D^- \to K_S\pi^-) - \Gamma(D^+ \to K_S\pi^+)}{\Gamma(D^- \to K_S\pi^-) + \Gamma(D^+ \to K_S\pi^+)} = \delta_K + 2R_d \tan^2\theta_C \sin\phi \sin\delta_d$$

Lipkin & Xing

δ_K: From CPV in K^0 system $\sim 3\text{x}10^{-3}$

$2R_d$: ~1

$\tan^2\theta_C$: $\sim 5\text{x}10^{-2}$

$\sin\phi$: $\leq 10^{-3}$ in SM (from data)

New physics could make this much bigger

$\sin\delta_d$: hopefully big (measurable in principle)

$$A_{CP} = \frac{\Gamma(D^- \to K_S\pi^-) - \Gamma(D^+ \to K_S\pi^+)}{\Gamma(D^- \to K_S\pi^-) + \Gamma(D^+ \to K_S\pi^+)} = 3\text{x}10^{-3} + \text{new physics}$$

So what?

- $D^+ \to K_S\pi^+, K_S\rho^+, K_S a_1^+ \ldots$
- $D^0 \to K_S\pi^0, K_S\pi^+\pi^- \ \ldots$

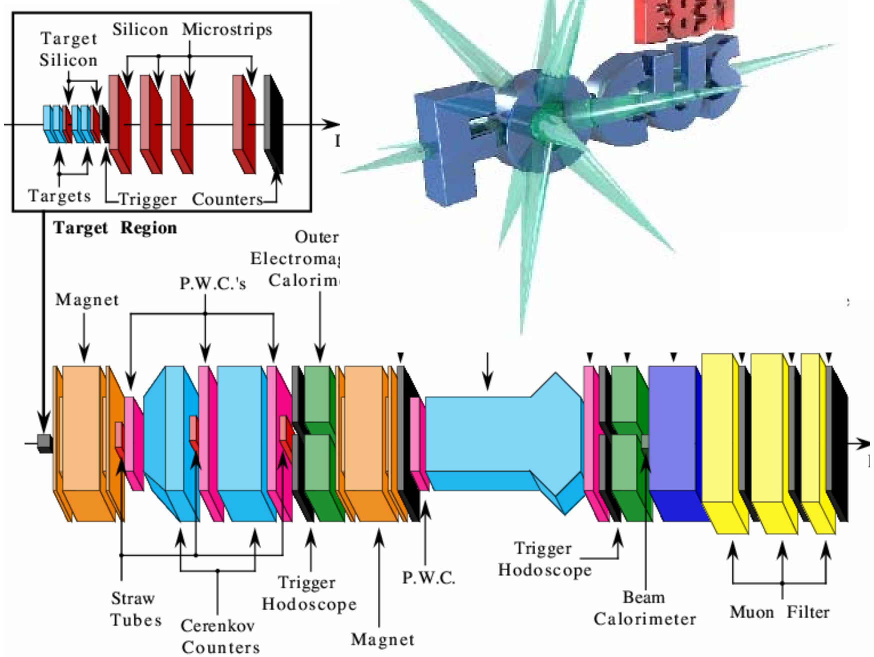
} not suppressed (big BR)

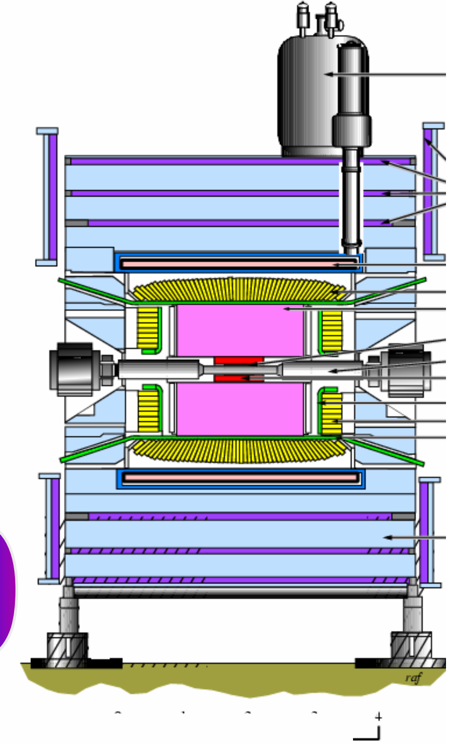
- Should be able to see δ_K induced CPV with 10^7-10^8 reconstructed D events.
  - This is in the ballpark for CLEO-c/Belle/BaBar

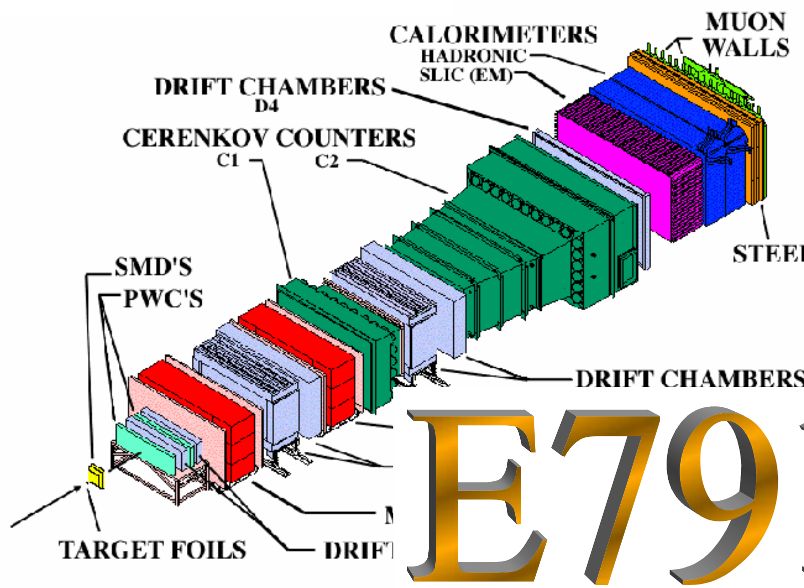
- New physics could make this asymmetry much bigger by increasing weak (and strong) phase differences.
  - If seen, this can be studied using a suite of decays involving K_L and K_S in final state.

See Lipkin & Xing, Phys. Lett B450 (1999)
Bigi & Yamamoto, Phys. Lett B349 (1995)

The usual suspects







Comments

- Since D^+ and D^- (and similarly D^0 and $\overline{D}^0$) are not produced in equal numbers in FOCUS and E791, these experiments normalize all asymmetries to some known Cabibbo favored mode.

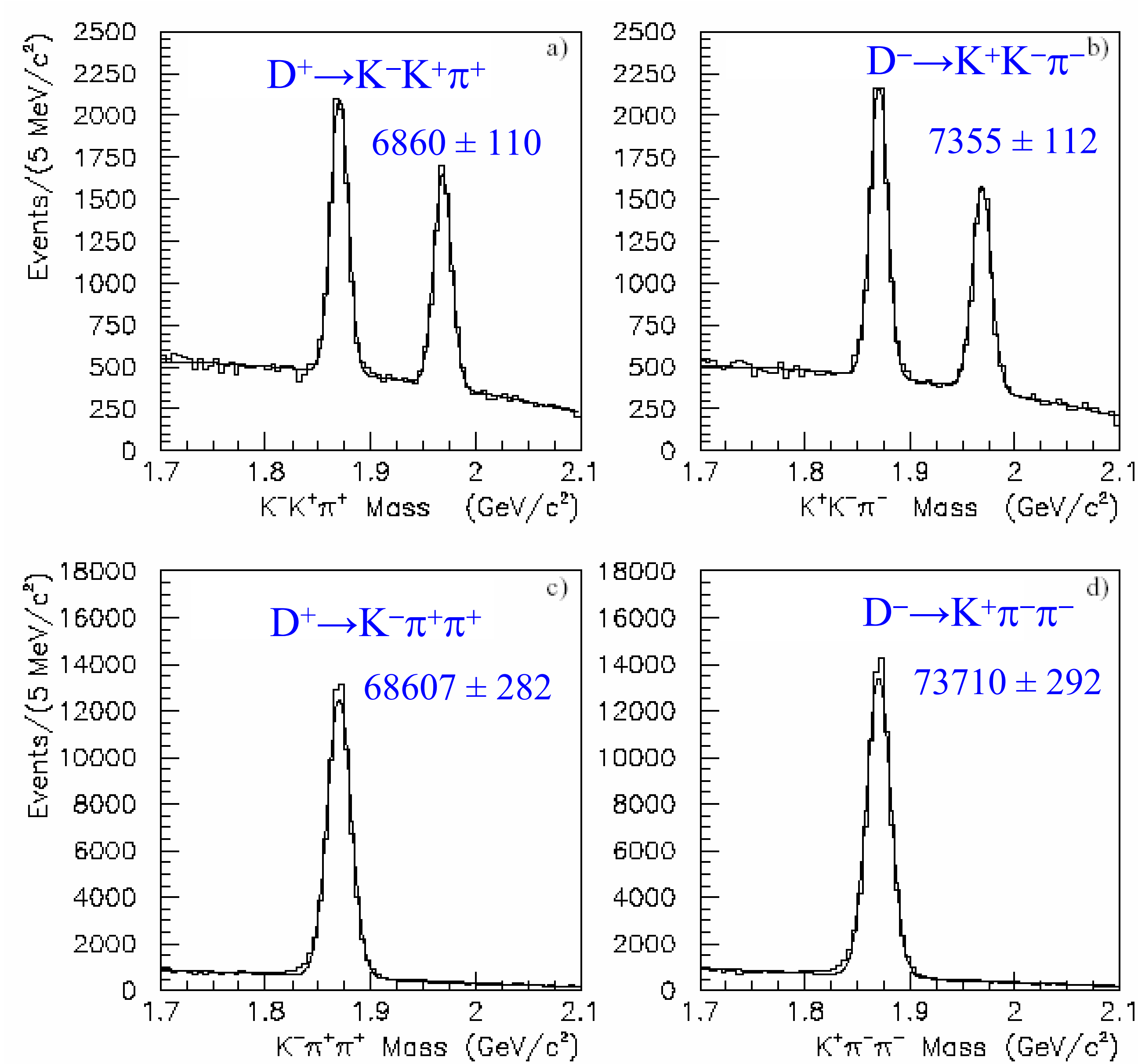
For example: $$A_{CP}(KK\pi) = \frac{\eta(D^+) - \eta(D^-)}{\eta(D^+) + \eta(D^-)}$$

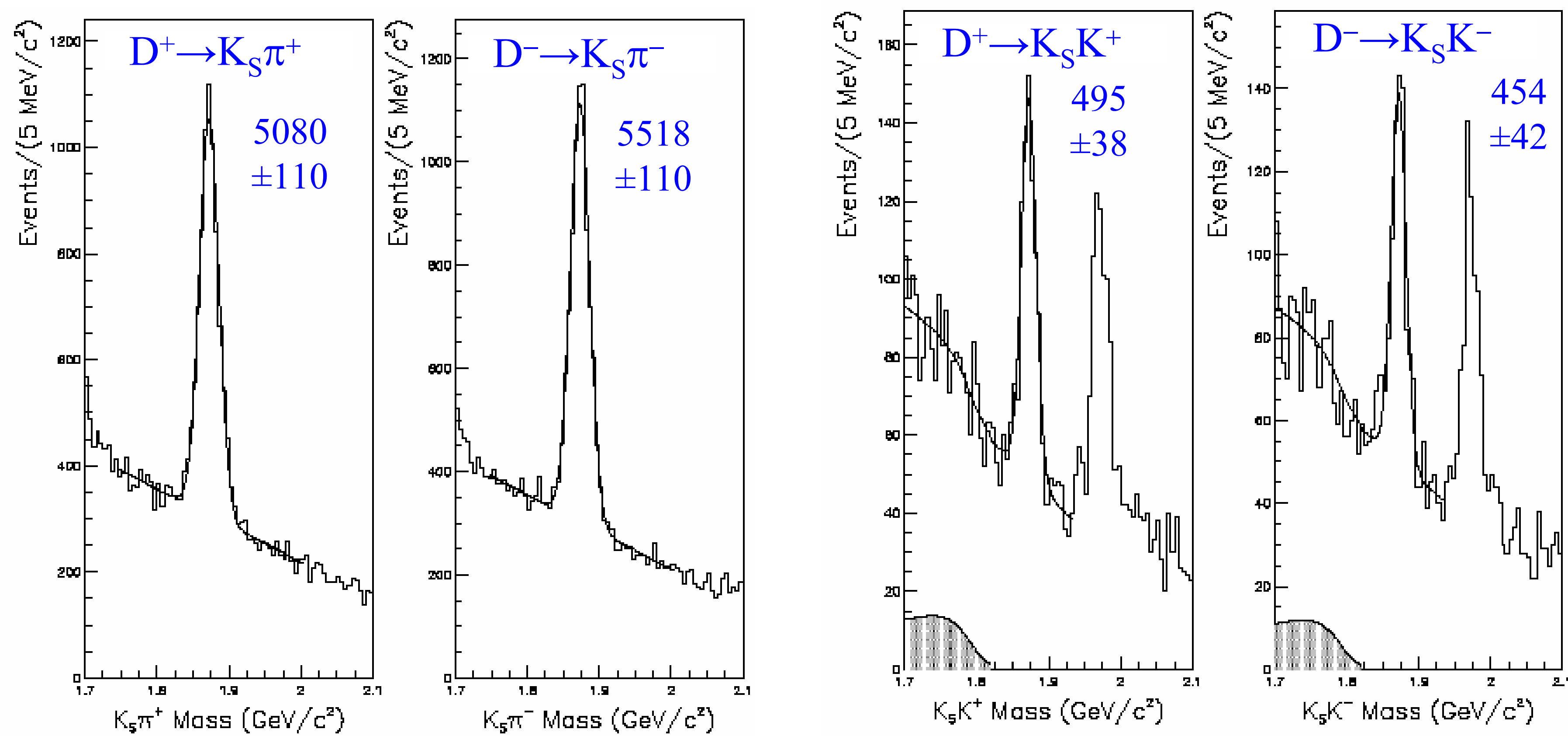
where $$\eta(D^\pm) = \frac{N(D^\pm \to K^\mp K^\pm \pi^\pm)}{N(D^\pm \to K^\mp \pi^\pm \pi^\pm)}$$

- e^+e^- experiments need to worry about, A_{+-}, A_{FB}

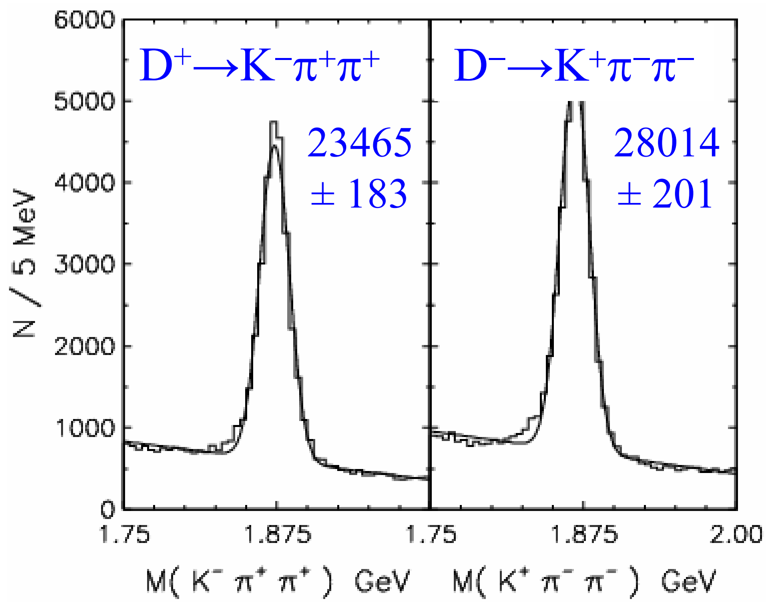
D^+ Decays

- These modes are "self-tagging" (no D* needed).
- E791
  - ➔ $D^+ \rightarrow K^+K^-\pi^+$, $\phi\pi^+$, $K^*(892)^0\pi^+$, $\pi^+\pi^-\pi^+$
- FOCUS
  - ➔ $D^+ \rightarrow K^+K^-\pi^+$, K_SK^+, $K_S\pi^+$

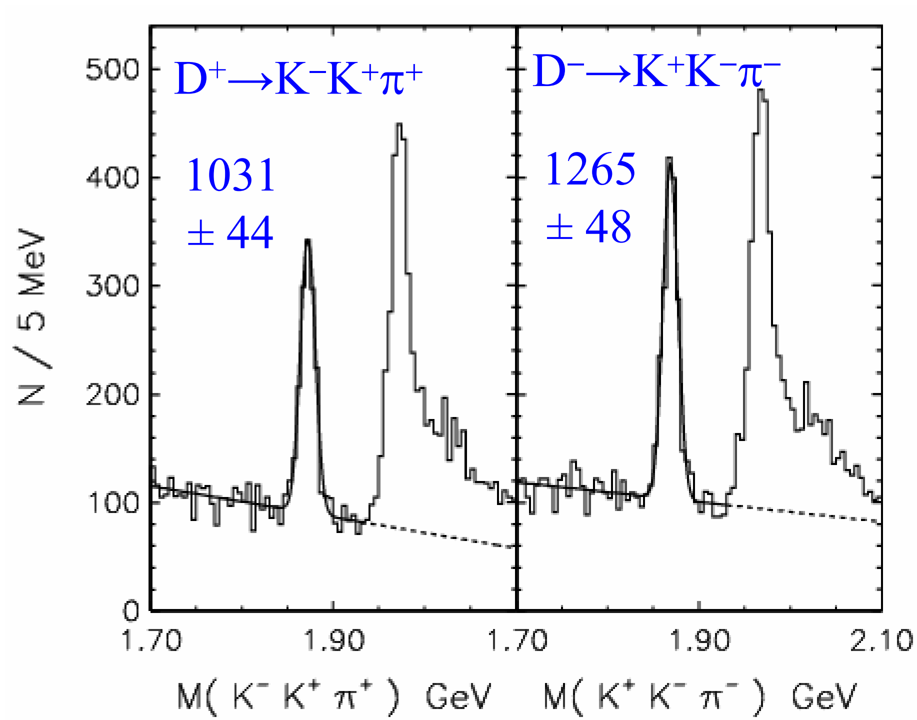

a)
D+→K−K+π+
6860 ± 110
Events/(5 MeV/c²)
K−K+π+ Mass (GeV/c²)
b)
D−→K+K−π−
7355 ± 112
K+K−π− Mass (GeV/c²)
c)
D+→K−π+π+
68607 ± 282
Events/(5 MeV/c²)
K−π+π+ Mass (GeV/c²)
d)
D−→K+π−π−
73710 ± 292
K+π−π− Mass (GeV/c²)


D⁺→K_Sπ⁺
5080
±110
Events/(5 MeV/c²)
K_Sπ⁺ Mass (GeV/c²)
D⁻→K_Sπ⁻
5518
±110
Events/(5 MeV/c²)
K_Sπ⁻ Mass (GeV/c²)
D⁺→K_SK⁺
495
±38
Events/(5 MeV/c²)
K_SK⁺ Mass (GeV/c²)
D⁻→K_SK⁻
454
±42
Events/(5 MeV/c²)
K_SK⁻ Mass (GeV/c²)

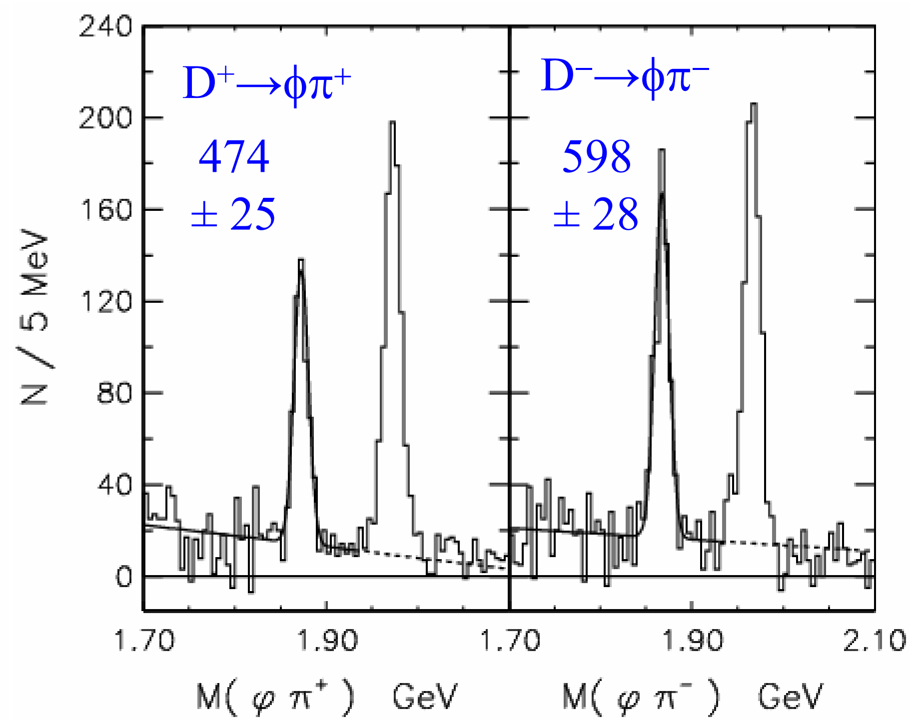
E791



$D^+ \to K^-\pi^+\pi^+$
23465 ± 183
$D^- \to K^+\pi^-\pi^-$
28014 ± 201
N / 5 MeV
6000
5000
4000
3000
2000
1000
0
1.75
1.875
1.75
1.875
2.00
M(K⁻ π⁺ π⁺) GeV
M(K⁺ π⁻ π⁻) GeV

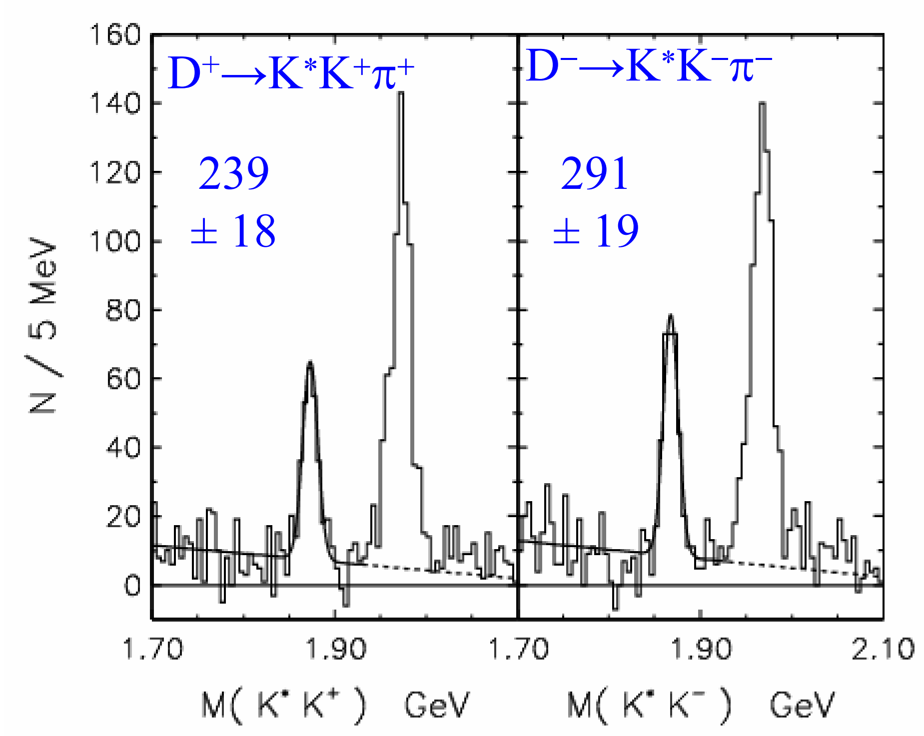


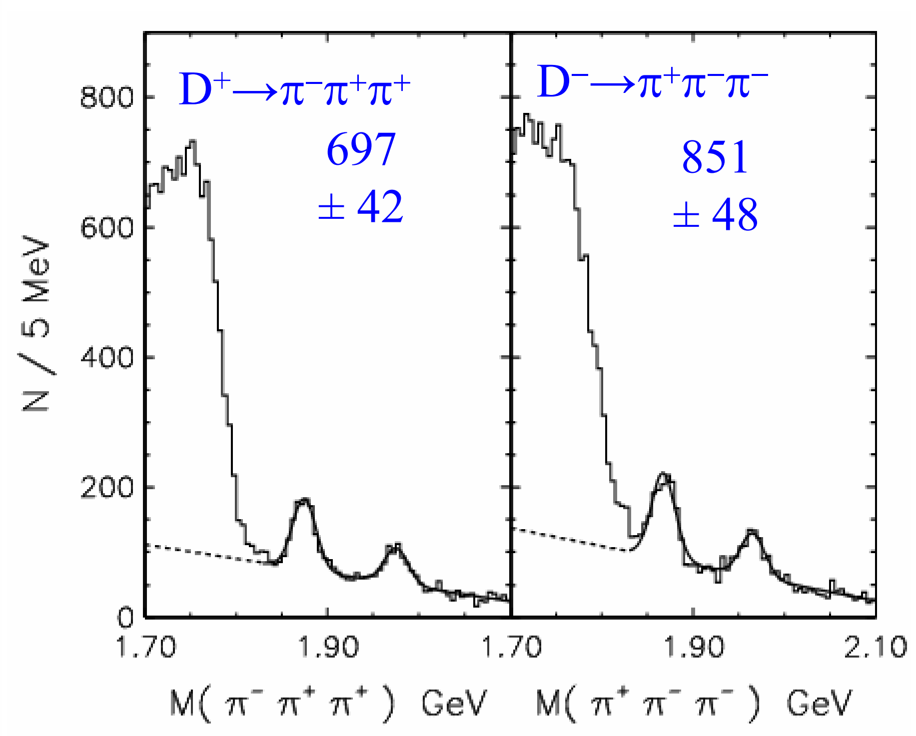
$D^+ \to K^-K^+\pi^+$
1031 ± 44
$D^- \to K^+K^-\pi^-$
1265 ± 48
N / 5 MeV
500
400
300
200
100
0
1.70
1.90
1.70
1.90
2.10
M(K⁻ K⁺ π⁺) GeV
M(K⁺ K⁻ π⁻) GeV



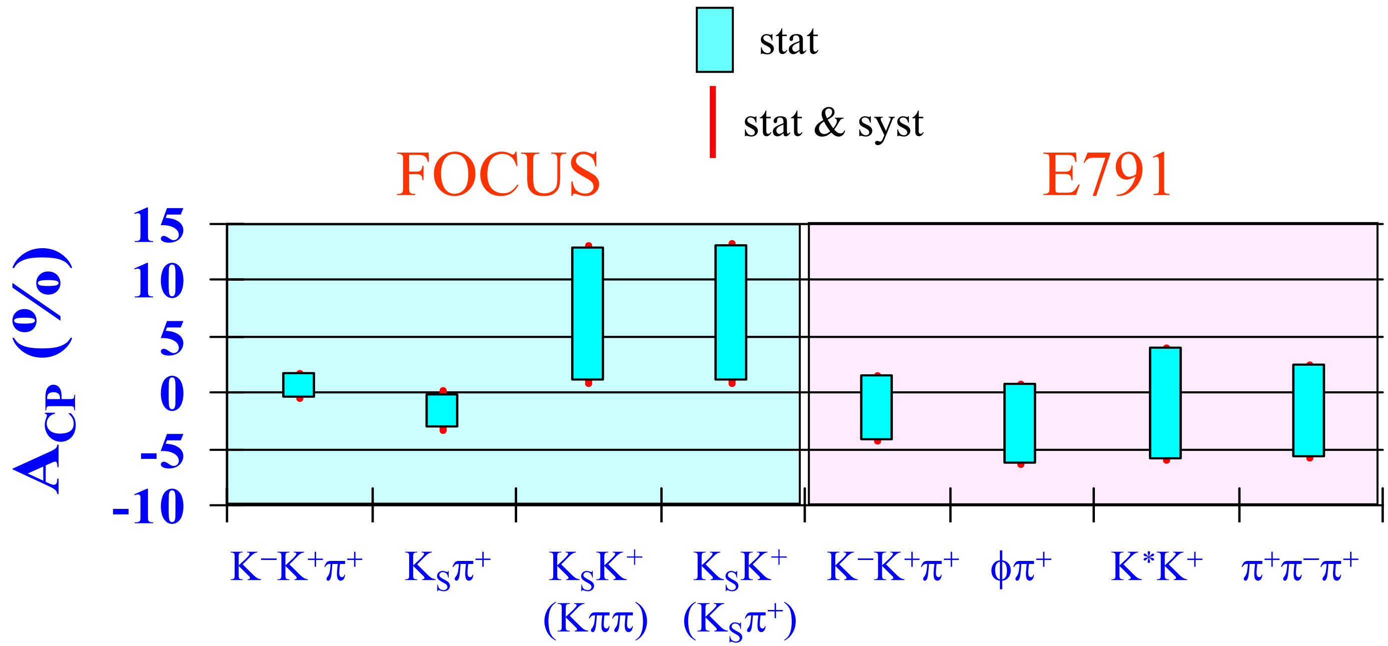
$D^+ \to \phi\pi^+$
474 ± 25
$D^- \to \phi\pi^-$
598 ± 28
N / 5 MeV
240
200
160
120
80
40
0
1.70
1.90
1.70
1.90
2.10
M(φ π⁺) GeV
M(φ π⁻) GeV

E791


D+→K*K+π+
239
± 18
D−→K*K−π−
291
± 19
N / 5 MeV
M(K* K+) GeV
M(K* K−) GeV


D+→π−π+π+
697
± 42
D−→π+π−π−
851
± 48
N / 5 MeV
M(π− π+ π+) GeV
M(π+ π− π−) GeV

$D^{\pm}$ A_{CP} Summary



$K^-K^+\pi^+$	$0.6 \pm 1.1 \pm 0.5$
$K_S\pi^+$	$-1.6 \pm 1.5 \pm 0.9$
K_SK^+ $(K^-\pi^+\pi^+)$	$6.9 \pm 6.0 \pm 1.5$
K_SK^+ $(K_S\pi^+)$	$7.1 \pm 6.1 \pm 1.2$
$K^-K^+\pi^+$	-1.4 ± 2.9
$\phi^+\pi^-$	-2.8 ± 3.6
$K^*(892)K^-$	-1.0 ± 5.0
$\pi^+\pi^-\pi^+$	-1.7 ± 4.2

* All analyses statistics limited.
* None are background free.

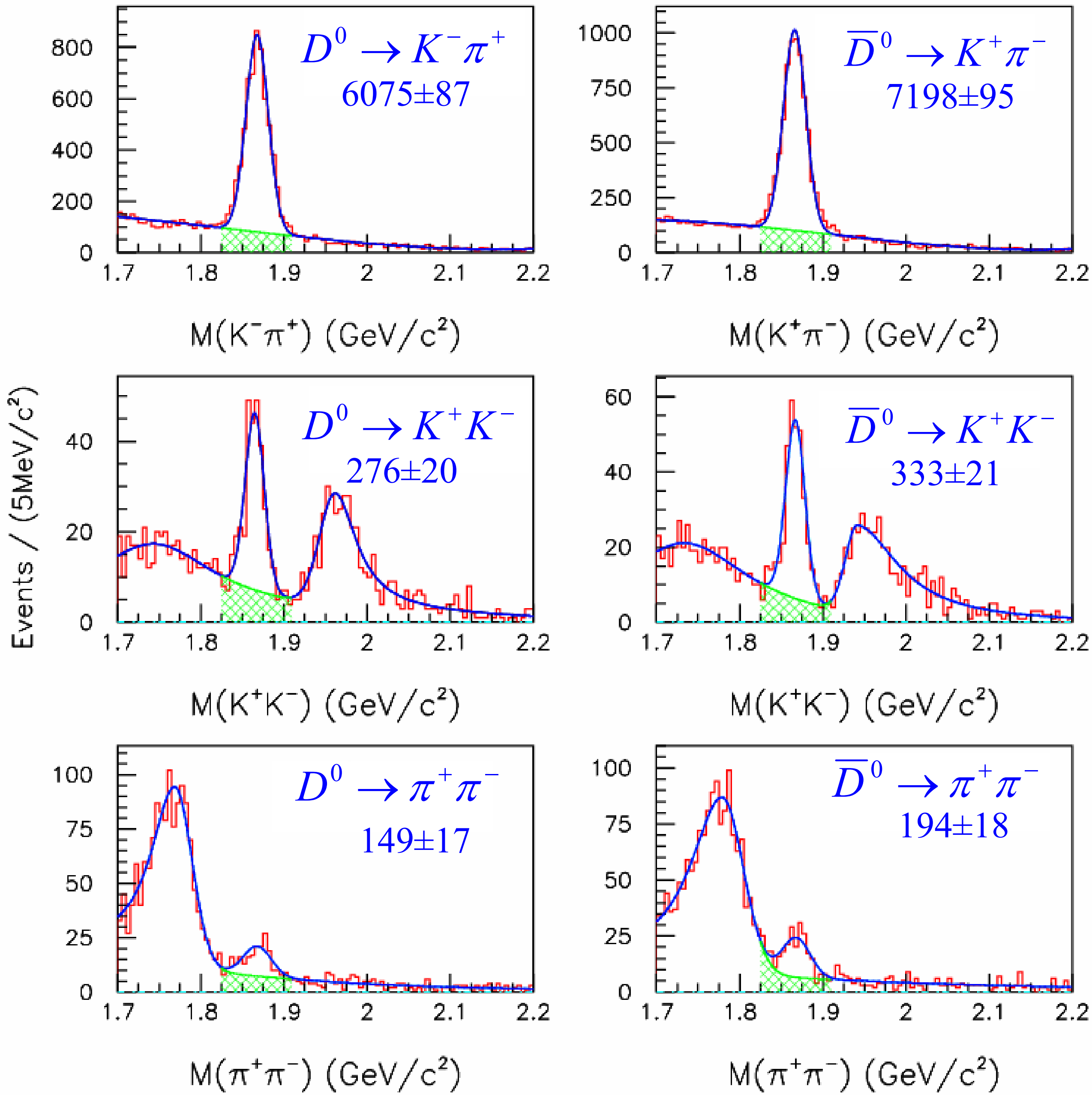
D^0 Decays

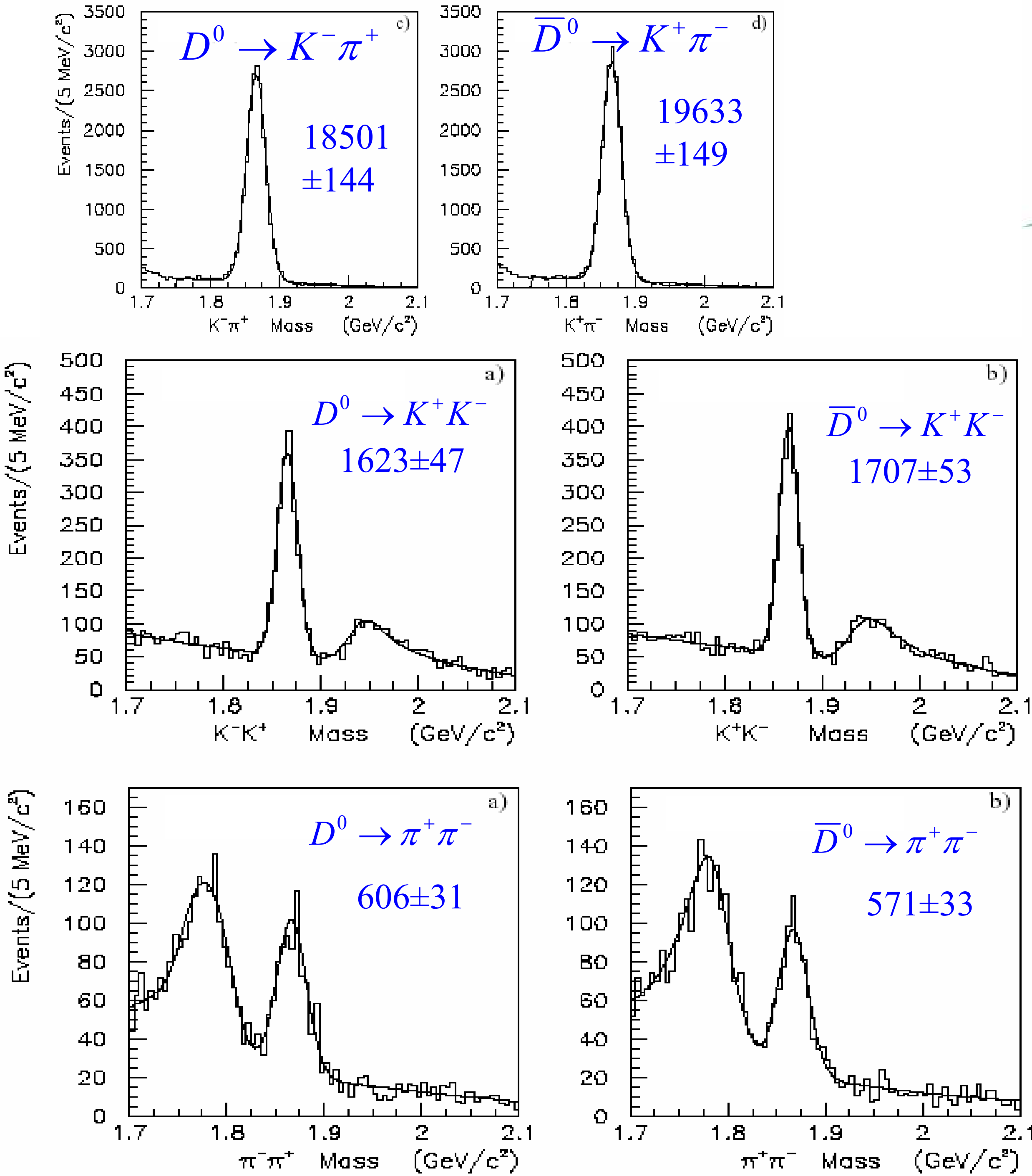
- Use D* decays to tag D^0 flavor:

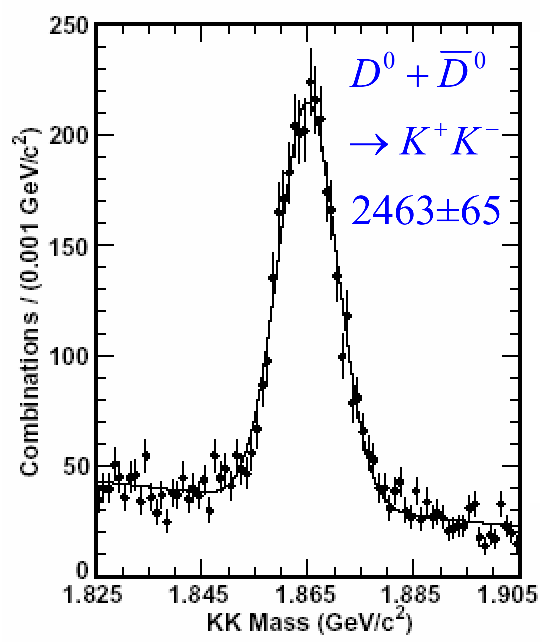
$$D^{*+} \to \pi^+ D^0, \quad D^0 \to f \qquad \begin{cases} \pi^+ \Rightarrow D^0 \\ \pi^- \Rightarrow \overline{D}^0 \end{cases}$$

- E791
  - $D^0 \to K^+K^-, \pi^+\pi^-, K^-\pi^+\pi^-\pi^+$
- FOCUS
  - $D^0 \to K^+K^-, \pi^+\pi^-$
- CLEO
  - $D^0 \to K^+K^-, \pi^+\pi^-, K_S\pi^0, K_SK_S, \pi^0\pi^0$

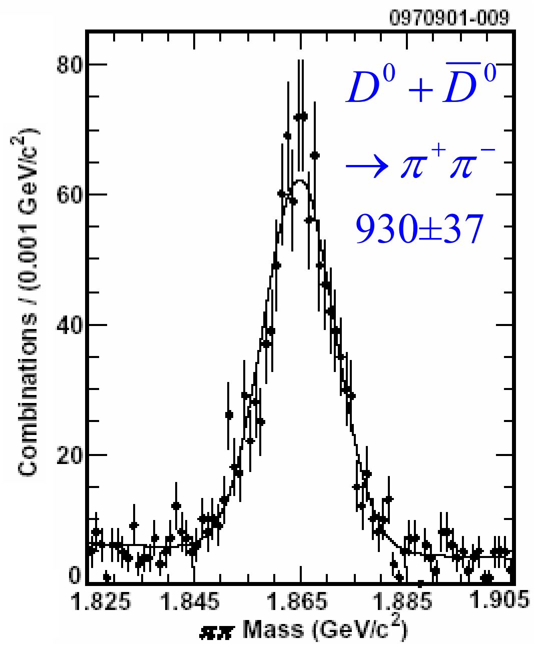
E791


$D^0 \to K^-\pi^+$
6075±87
$\overline{D}^0 \to K^+\pi^-$
7198±95
$D^0 \to K^+K^-$
276±20
$\overline{D}^0 \to K^+K^-$
333±21
$D^0 \to \pi^+\pi^-$
149±17
$\overline{D}^0 \to \pi^+\pi^-$
194±18
Events / (5MeV/c^2)
M(K$^-\pi^+$) (GeV/c^2)
M(K$^+\pi^-$) (GeV/c^2)
M(K$^+$K$^-$) (GeV/c^2)
M(K$^+$K$^-$) (GeV/c^2)
M($\pi^+\pi^-$) (GeV/c^2)
M($\pi^+\pi^-$) (GeV/c^2)

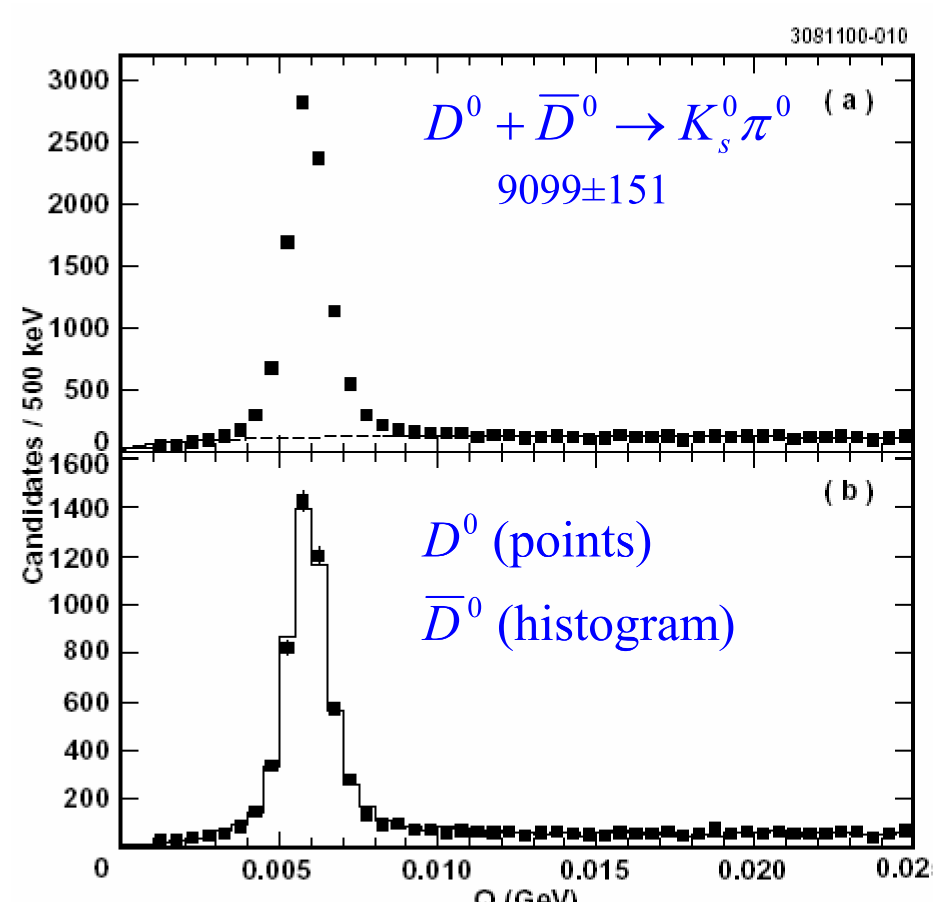

$D^0 \to K^-\pi^+$
18501 ±144
c)
$K^-\pi^+$ Mass (GeV/c²)
$\overline{D}^0 \to K^+\pi^-$
19633 ±149
d)
$K^+\pi^-$ Mass (GeV/c²)
$D^0 \to K^+K^-$
1623±47
a)
K^-K^+ Mass (GeV/c²)
$\overline{D}^0 \to K^+K^-$
1707±53
b)
K^+K^- Mass (GeV/c²)
$D^0 \to \pi^+\pi^-$
606±31
a)
$\pi^-\pi^+$ Mass (GeV/c²)
$\overline{D}^0 \to \pi^+\pi^-$
571±33
b)
$\pi^+\pi^-$ Mass (GeV/c²)
Events/(5 MeV/c²)



$D^0 + \overline{D}^0$
$\to K^+K^-$
2463±65
Combinations / (0.001 GeV/c^2)
KK Mass (GeV/c^2)
0 50 100 150 200 250
1.825 1.845 1.865 1.885 1.905

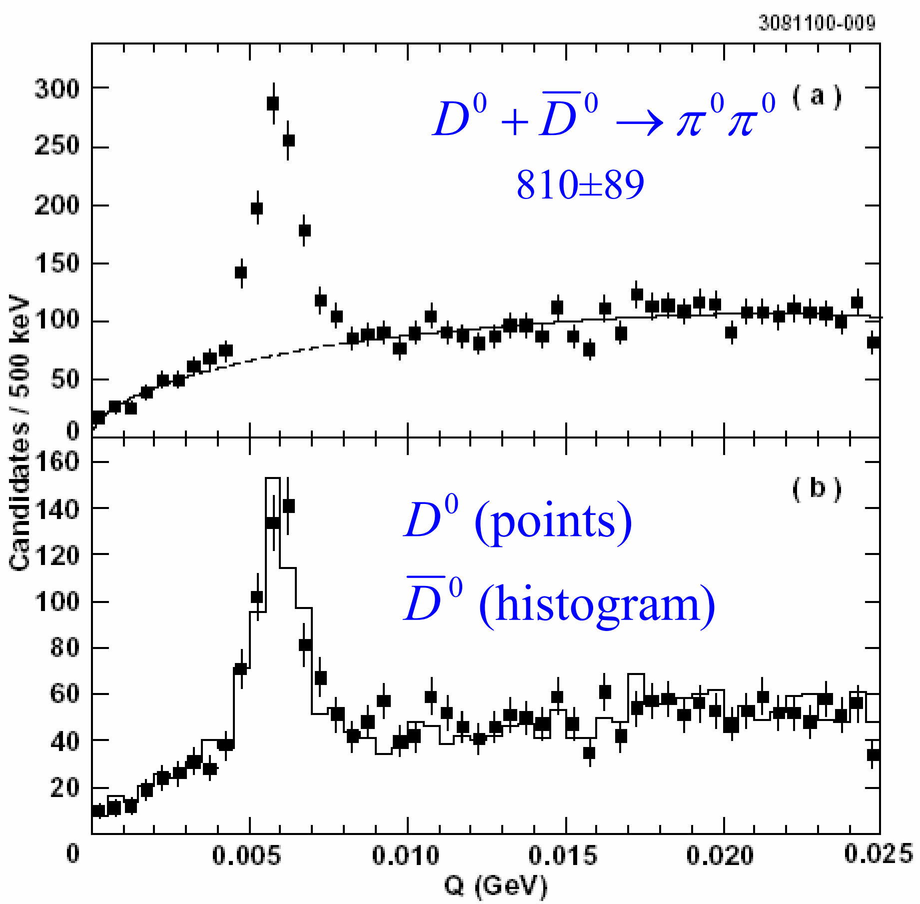


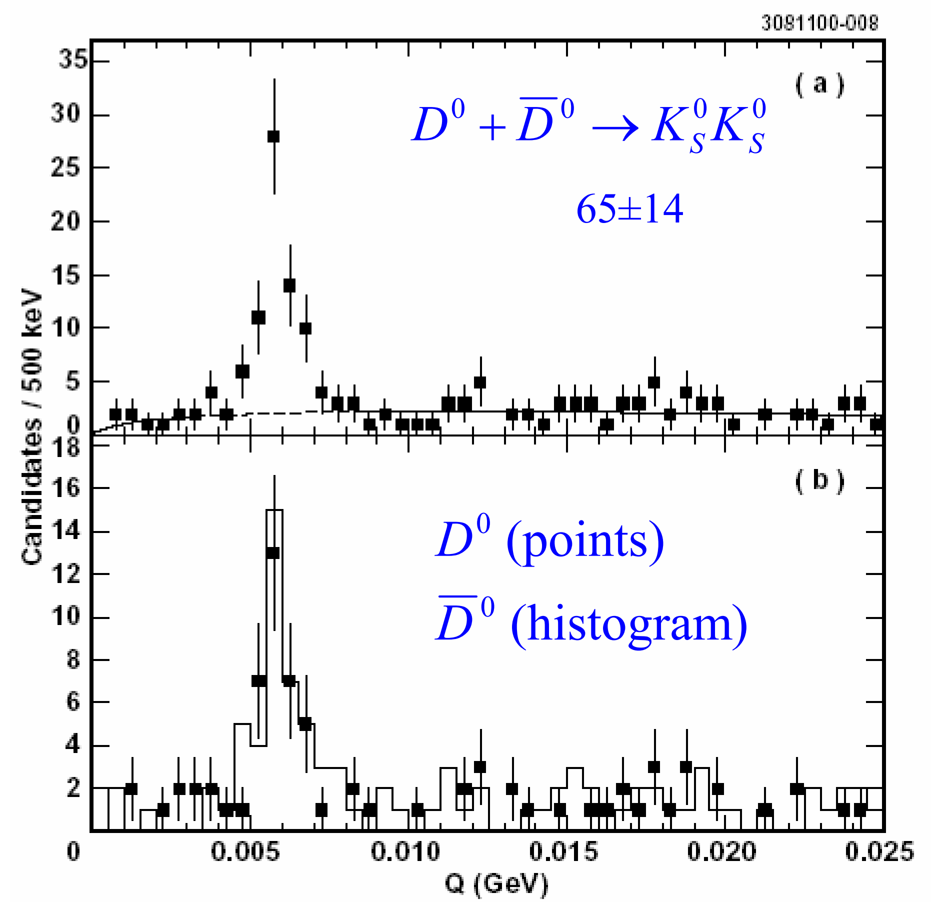
0970901-009
$D^0 + \overline{D}^0$
$\to \pi^+\pi^-$
930±37
Combinations / (0.001 GeV/c^2)
ππ Mass (GeV/c^2)
0 20 40 60 80
1.825 1.845 1.865 1.885 1.905



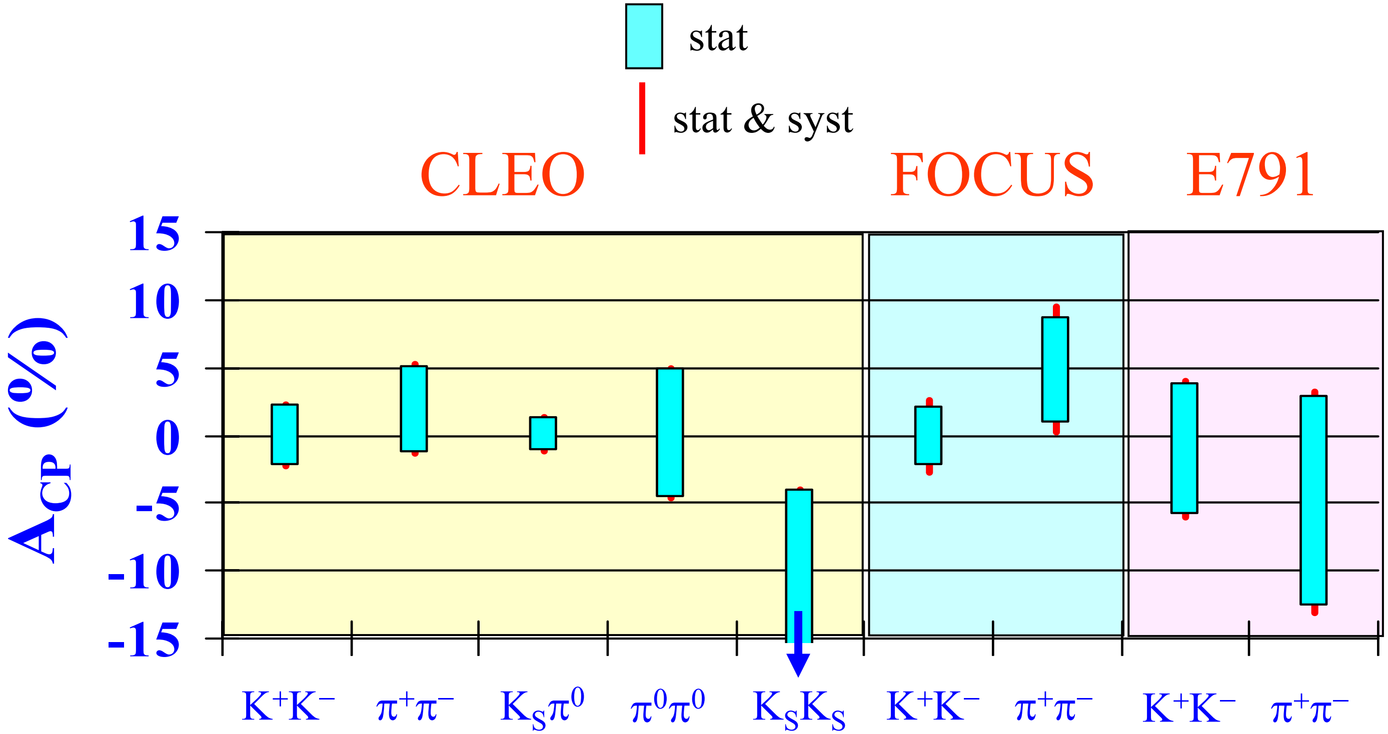
3081100-010
$D^0 + \overline{D}^0 \to K_s^0\pi^0$
9099±151
(a)
(b)
D^0 (points)
$\overline{D}^0$ (histogram)
Candidates / 500 keV
Q (GeV)
0 500 1000 1500 2000 2500 3000
200 400 600 800 1000 1200 1400 1600
0 0.005 0.010 0.015 0.020 0.025

CLEO


3081100-009
$D^0 + \overline{D}^0 \to \pi^0\pi^0$
810±89
(a)
(b)
D^0 (points)
$\overline{D}^0$ (histogram)
Candidates / 500 keV
Q (GeV)


3081100-008
$D^0 + \overline{D}^0 \to K_S^0 K_S^0$
65±14
(a)
(b)
D^0 (points)
$\overline{D}^0$ (histogram)
Candidates / 500 keV
Q (GeV)

D^0 A_{CP} Summary



K^+K^-	$0.0 \pm 2.2 \pm 0.8$
$\pi^+\pi^-$	$1.9 \pm 3.2 \pm 0.8$
$K_S\pi^0$	0.1 ± 1.3
$\pi^0\pi^0$	0.1 ± 4.8
$K_S K_S$	-23 ± 19
K^+K^-	$-0.1 \pm 2.2 \pm 1.5$
$\pi^+\pi^-$	$4.8 \pm 3.9 \pm 2.5$
K^+K^-	$-1.0 \pm 4.9 \pm 1.2$
$\pi^+\pi^-$	$-4.9 \pm 7.8 \pm 2.5$

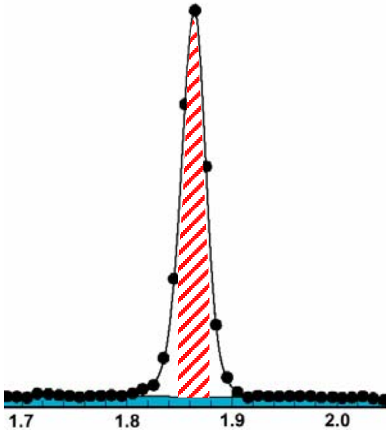
* All analyses statistics limited.
* None are background free.

Other Promising Approaches

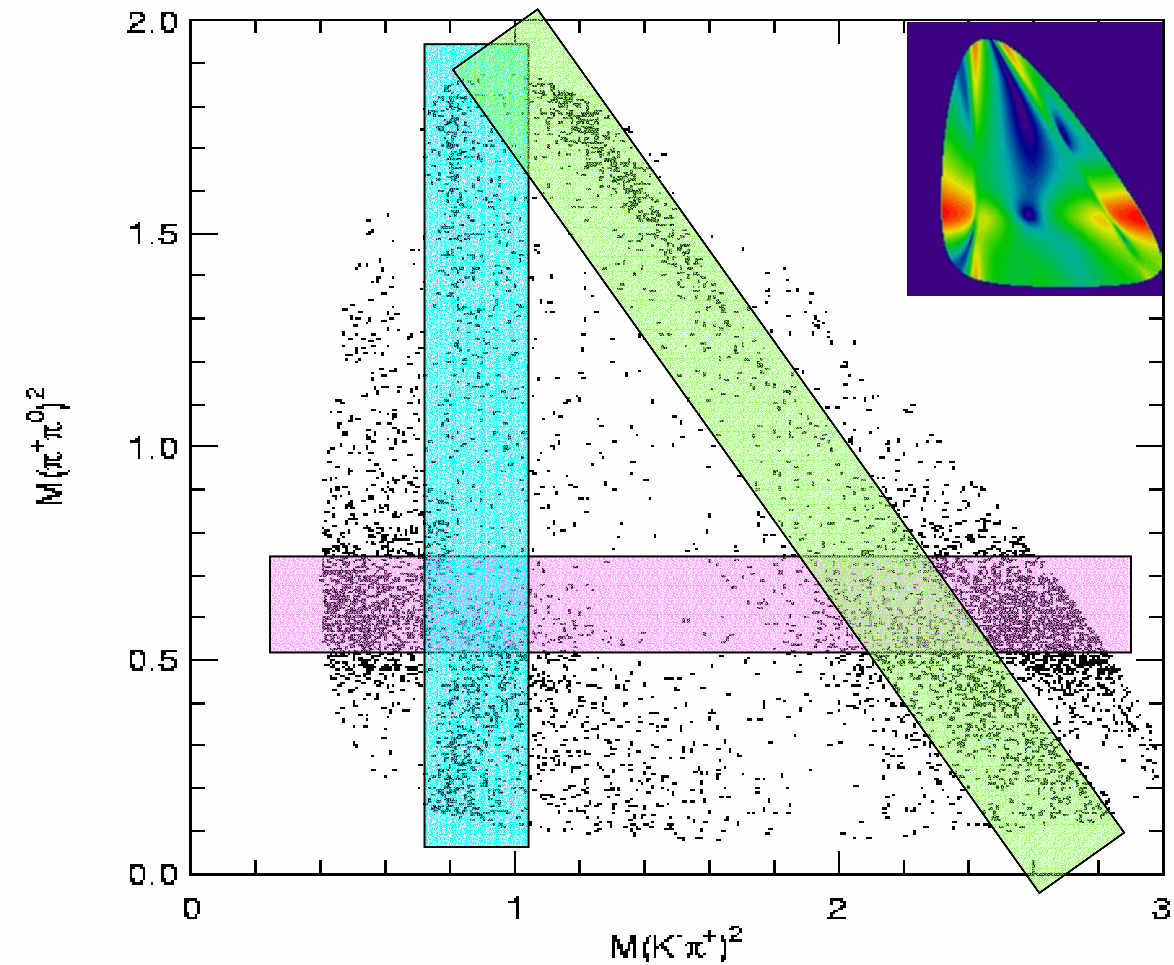
- Look for CPV in Dalitz Plots:
  - Analyze D and $\bar{D}$ samples separately
  - Any differences in amplitudes & phases is an indication of CPV.
  - Work under way by several groups.

- Examples from CLEO
  - $D^0 \rightarrow K^-\pi^+\pi^0$ (Published last year).
  - $D^0 \rightarrow K_S\,\pi^+\pi^-$ (Preliminary results).
  - $D^0 \rightarrow \pi^-\pi^+\pi^0$ (soon…)
  - $D^0 \rightarrow K_S\pi^0\pi^0$ (soon…).

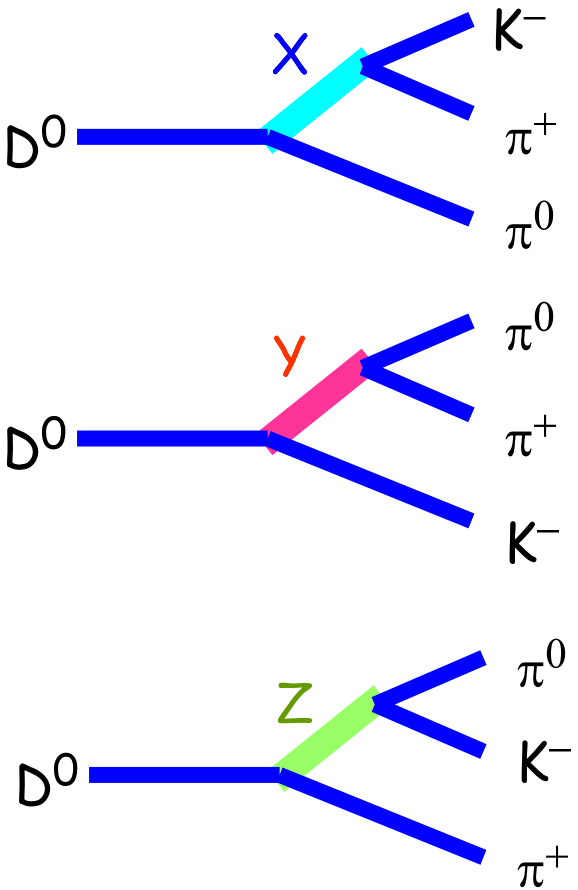
$D^0 \to K^- \pi^+ \pi^0$



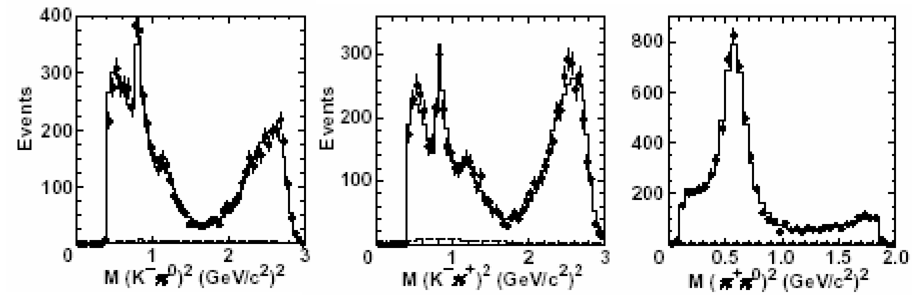
1.7
1.8
1.9
2.0



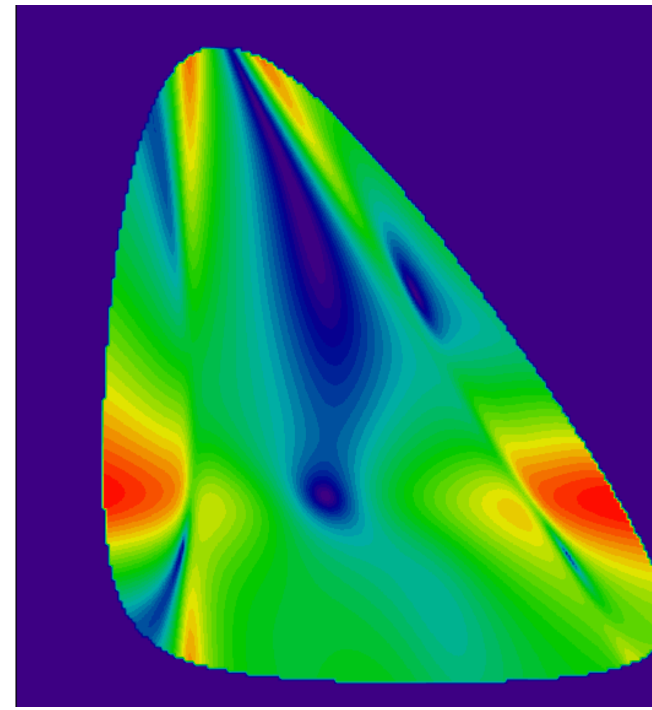
2.0
1.5
1.0
0.5
0.0
0
1
2
3
M(π⁺π⁰)²
M(K⁻π⁺)²



D0
x
K−
π+
π0
D0
y
π0
π+
K−
D0
z
π0
K−
π+



	Resonance	Fit Fraction	Phase
1	$\rho(770)^+$	0.788 ± 0.023	0 (fixed)
2	$K^*(892)^-$	0.161 ± 0.010	163 ± 4
3	$K^*(892)^0$	0.127 ± 0.010	0 ± 4
4	$\rho(1700)^+$	0.057 ± 0.011	171 ± 7
5	$K_0^*(1430)^0$	0.041 ± 0.009	166 ± 7
6	$K_0^*(1430)^-$	0.033 ± 0.009	56 ± 7
7	$K^*(1680)^-$	0.013 ± 0.004	103 ± 11
8	Non-res	0.075 ± 0.011	31 ± 7



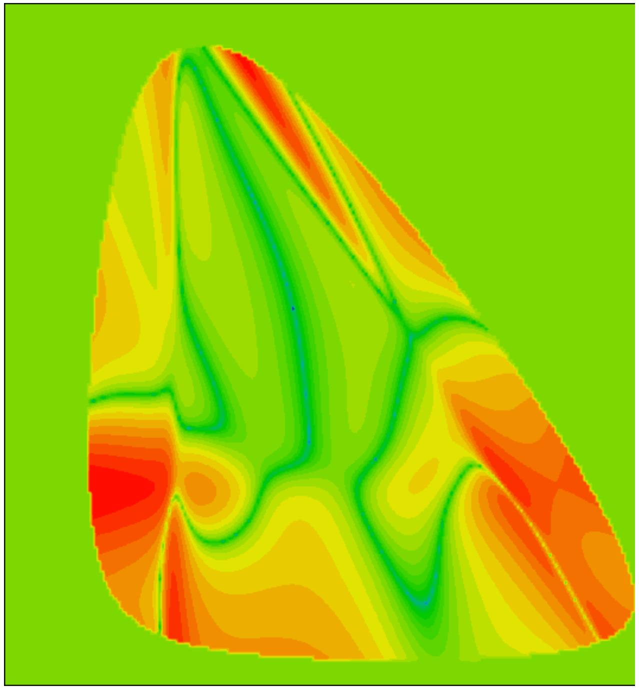
(Show Movie)

We are sensitive to the amplitude and phase of something with BR ~ 10^{-3}.

CLEO

Fit D^0 and $\overline{D^0}$ Dalitz Plots separately and look for asymmetries:

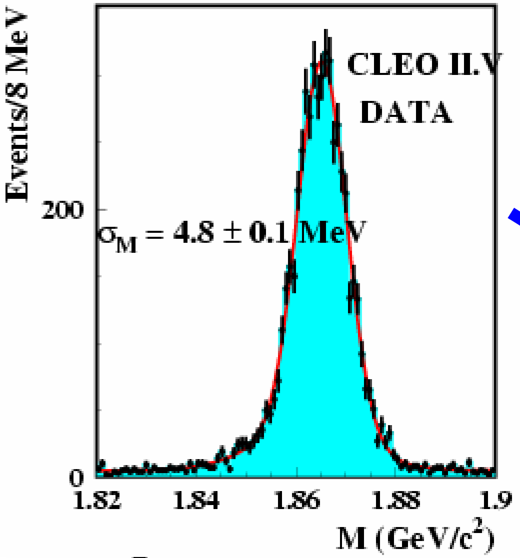
$$\mathcal{A}_{CP} = \int \frac{\left|\mathcal{M}_{D^0}\right|^2 - \left|\mathcal{M}_{\overline{D}^0}\right|^2}{\left|\mathcal{M}_{D^0}\right|^2 + \left|\mathcal{M}_{\overline{D}^0}\right|^2} d\mathcal{DP}$$



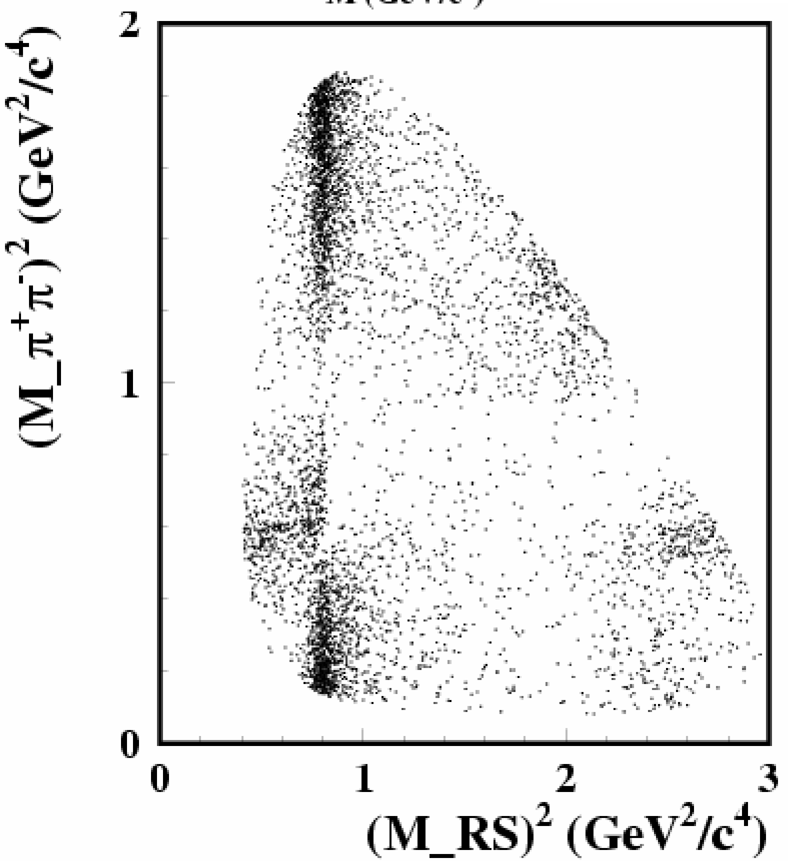
Find $\mathcal{A}_{CP} = 0.031 \pm 0.086$

(Not an optimized ACP analysis)

$D^0 \to K_S \pi^+ \pi^-$



Almost no background



Fit D^0 and $\overline{D}^0$ samples separately

writing

$$\left|D^0\right\rangle = \frac{1}{2p}\left(\left|D_1\right\rangle + \left|D_2\right\rangle\right)$$

$$\left|\overline{D}^0\right\rangle = \frac{1}{2q}\left(\left|D_1\right\rangle - \left|D_2\right\rangle\right)$$

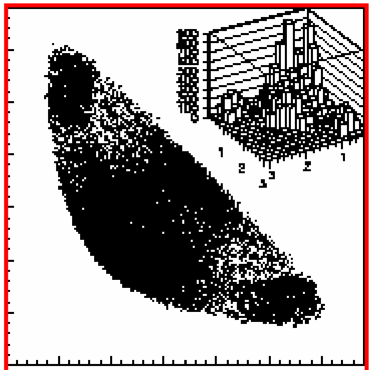
with $p^2 + q^2 = 1$

PRELIMINARY:

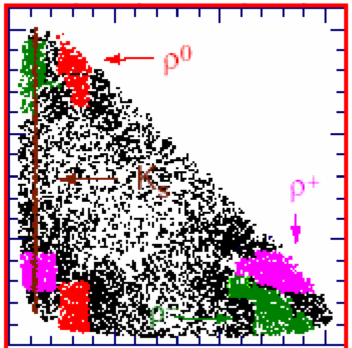
$$p = \left(\frac{1}{\sqrt{2}} - \left(-0.02 \pm 0.02\right)\right) e^{i(-0.03 \pm 0.04)}$$

Outlook (is interesting)

- E791 and FOCUS
  - Working on A_{CP} analyses (for example Dalitz plots).
- CLEO-c
  - Still working on analyses using CLEO-II, II.V and III data.
  - CLEO-c will turn on in about a year.
    - ~30 million DD events (and new A_{CP} search modes).
    - ~ 1.5 million D_sD_s events
- B Factories
  - In the next 5 (?) years Belle and BaBar will accumulate ~100 times the integrated luminosity that CLEO has at the Υ(4S).
    - Improve on present CLEO limits by at least a factor of 10.
- Hadron Machines
  - CDF & D0 are getting into the game.
  - BTeV (& LHC-b ?) could have 10^9 reconstructed charm events.
  - COMPASS ? Others ?
- BES



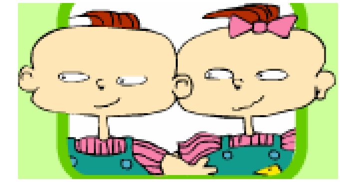
E791 $K^-\pi^+\pi^+$



CLEO $\pi^-\pi^+\pi^0$

Extra Slides…

CPV through quantum coherence at CLEO-c

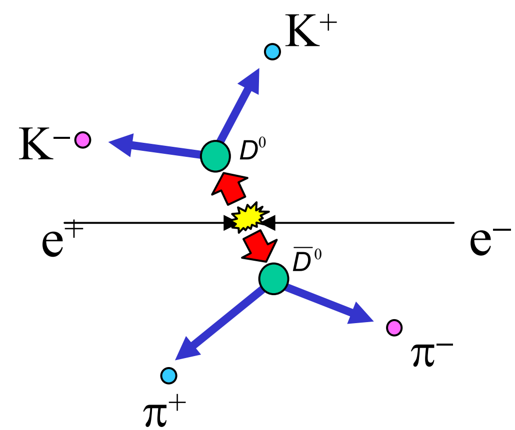


At the ψ”(3770)

$e^+e^- \rightarrow \psi'' \rightarrow D^0\bar{D}^0$

$J^{PC} = 1^{--}$

i.e. CP+



Suppose both D^0’s decay to CP eigestates f_1 and f_2:

These can **NOT** have the **same CP** :

$$CP(f_1 f_2) = \underbrace{CP(f_1)\, CP(f_2)}_{+}\ \underbrace{(-1)^l}_{-\ (\text{since } l = 1)} = CP-$$

Observing this is evidence of ~~CP~~

Sensitivity to this will be at the ~1% level

$D^0 \to K^- \pi^+ \pi^0$ A_{CP} Fits

	D^0 Sample		$\overline{D^0}$ Sample	
Component	Amplitude	Phase (degrees)	Amplitude	Phase (degrees)
$\rho(770)^+$	1.0 ± 0.0	0^o (fixed)	1.0 ± 0.0	0^o (fixed)
$K^*(892)^-$	0.433 ± 0.034	168.9 ± 3.3	0.442 ± 0.015	157.8 ± 3.4
$\overline{K}^*(892)^0$	0.391 ± 0.026	1.3 ± 3.7	0.410 ± 0.022	-4.9 ± 4.9
$\rho(1700)^+$	2.590 ± 0.538	175.0 ± 7.5	2.720 ± 0.272	163.9 ± 7.6
$\overline{K}_0(1430)^0$	0.989 ± 0.124	173.9 ± 8.2	0.774 ± 0.089	159.3 ± 8.1
$K_0(1430)^-$	0.701 ± 0.211	59.0 ± 10.0	0.917 ± 0.117	55.0 ± 7.1
$K^*(1680)^-$	2.567 ± 1.540	107.4 ± 69.2	2.060 ± 0.423	106.4 ± 13.5
Non Res.	1.840 ± 0.146	39.9 ± 7.9	1.780 ± 0.160	21.3 ± 6.0
χ^2	227		233	
$-2 \ln \mathcal{L}$	3237		3302	
C.L.(%)	93.1		80.7	

- E791 references:
  - ➔ Phys. Lett. B403 (1997) 377
  - ➔ Phys. Lett. B421 (1998) 405
- FOCUS references:
  - ➔ Phys. Lett. B491 (2000) 232
  - ➔ Phys. Rev. Lett. 88 (2002) 041602
- CLEO references:
  - ➔ Phys. Rev. D63 (2001) 071101
  - ➔ Phys. Rev. D65 (2002) 092001
  - ➔ T. J. Bergfeld (Ph.D. Thesis, UIUC)
- Theory references:
  - ➔ Buchella et. al., Phys. Rev. D51 (1995)
  - ➔ Burdman hep-ph/9407378
  - ➔ Bigi & Yamamoto, Phys. Lett B349 (1995)
  - ➔ Lipkin & Xing, Phys. Lett B450 (1999)