FLAVOR SYMMETRY AND CHARM DECAYS

J. Rosner – CHARM 2007 – Aug. 6, 2007
With B. Bhattacharya (student at Chicago);
earlier with C.-W. Chiang, M. Gronau, Y. Grossman, Z. Luo

Often useful to know strong phases of amplitudes in charmed particle decays

Example: relative strong phase in $D^0 \to K^- \pi^+$ and $\bar{D}^0 \to K^- \pi^+$ is important in interpreting $B \to (D^0, \overline{D}^0)X$ decays

Strong phases are non-negligible even in B decays to pairs of pseudoscalars (P) and appreciable in $D \to PP$ decays.

Today: an illustration of extraction of strong phases using SU(3) flavor symmetry; mainly the U-spin symmetry $d \leftrightarrow s$

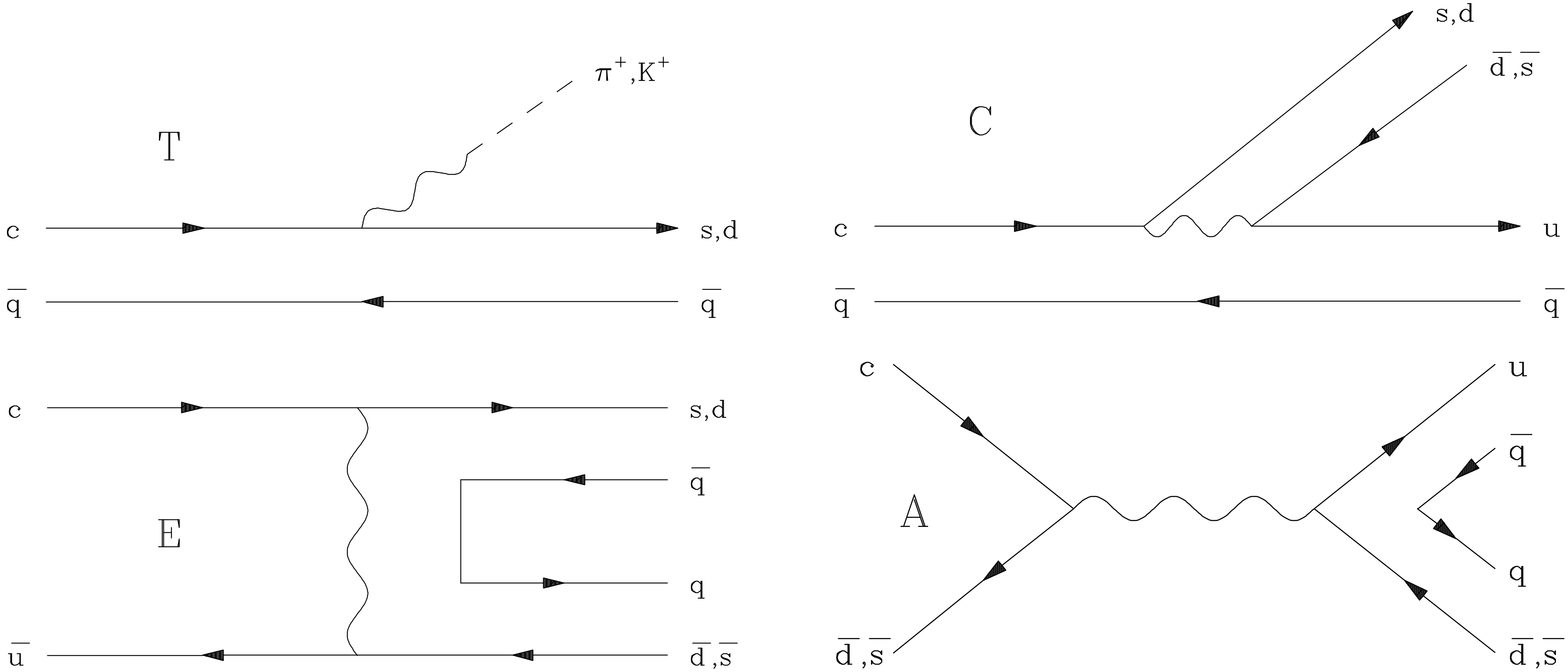
Wealth of new data allow testing of flavor symmetry and extraction of key amplitudes

Some references: L. L. Chau and H. Y. Cheng, PR D **36**, 137 (1987); PL B **222**, 285 (1989); JLR, PR D **60**, 114026 (1999); M. Gronau + JLR, PL B **500**, 247 (2001); M. Gronau, Y. Grossman, JLR, PL B **508**, 37 (2001); C.-W. Chiang + JLR, PR D **65**, 054007 (2002); H. Y. Cheng, EPJ C **26**, 551 (2003); C.-W. Chiang, Z. Luo, JLR, PR D **67**, 014001 (2003); JLR, PR D **74**, 057502 (2006).

DIAGRAMMATIC AMPLITUDE EXPANSION

L. L. Chau, Phys. Rep. **95**, 1 (1983); Chau and Cheng, PRL **56**, 1655 (1986)

Color-favored tree (T), color-suppressed tree (C), exchange (E), annihilation (A)



Cabibbo-favored (CF) amplitudes (unprimed) $\sim V_{ud}V^*_{cs}$; singly-Cabibbo-suppressed (SCS) amplitudes (primed) $\sim V_{us}V^*_{cs}$ or $V_{ud}V^*_{cd}$; doubly-Cabibbo-suppressed (DCS) amplitudes (tilde) $\sim V_{us}V^*_{cd}$. Relative hierarchy $1 : \lambda : -\lambda : -\lambda^2$ where $\lambda \simeq 0.23$

TODAY'S TOPICS (ALL $D_{(s)} \to PP$)

Cabibbo-favored decays

Updating/confirming PR D **60**: Large Arg(C/T), Arg(E/T); finding $A \simeq -E$

Singly-Cabibbo-suppressed decays

New data since PR D **67**: Consistent description of decays involving η, η' with large disconnected amplitude SA' (SE': S. Nisar, April 2007 APS meeting, unpubl.)

$\Gamma(D^0 \to \pi^+\pi^-)/\Gamma(D^0 \to K^+K^-) < 1$ indicates sources of SU(3) breaking

Doubly-Cabibbo-suppressed decays

Interference between $D^0 \to \overline{K}^0\pi^0$ (CF) and $D^0 \to K^0\pi^0$ (DCS) as expected

DCS $D^+ \to K^+(\pi^0, \eta, \eta')$ amplitudes have roughly expected magnitudes (Shabana Nisar, April 2007 APS meeting)

Relative strong phase in $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$ measurable through correlated $\psi(3770) \to D^0\overline{D}^0$ studies; as expected from SU(3) but error will decrease.

PDG 2007 for most averages; cf. A. Ryd for some new values

CABIBBO-FAVORED DECAYS

Extract amplitude $\mathcal{A} = M_D(8\pi\mathcal{B}\hbar/\tau)^{1/2}$ from branching ratio $\mathcal{B}$, lifetime τ (all from PDG unless noted). Amplitude triangles permit extraction of relative phases.

Meson	Decay mode	$\mathcal{B}$ (%)	p^* (MeV)	$\lvert\mathcal{A}\rvert$ (10^{-6} GeV)	Rep.
D^0	$K^-\pi^+$	3.82±0.07	861	2.49±0.03	$T+E$
	$\overline{K}^0\pi^0$	2.26±0.24	860	1.92±0.06	$(C-E)/\sqrt{2}$
	$\overline{K}^0\eta$	0.76±0.12	772	1.18±0.05	$C/\sqrt{3}$
	$\overline{K}^0\eta'$	1.82±0.28	565	2.13±0.09	$-(C+3E)/\sqrt{6}$
D^+	$\overline{K}^0\pi^+$	2.94±0.12	863	1.38±0.02	$C+T$
D_s^+	$\overline{K}^0K^+$	4.50±0.80	850	2.60±0.25	$C+A$
	$\pi^+\eta$	2.16±0.30	902	1.75±0.14	$(T-2A)/\sqrt{3}$
	$\pi^+\eta'$	4.80±0.60	743	2.88±0.20	$2(T+A)/\sqrt{6}$

$T = (2.71 + 0i) \times 10^{-6}$ GeV (defined to be real)

$C = (-1.77 - 1.01i) \times 10^{-6}$ GeV; $\delta(CT) = -150^\circ$

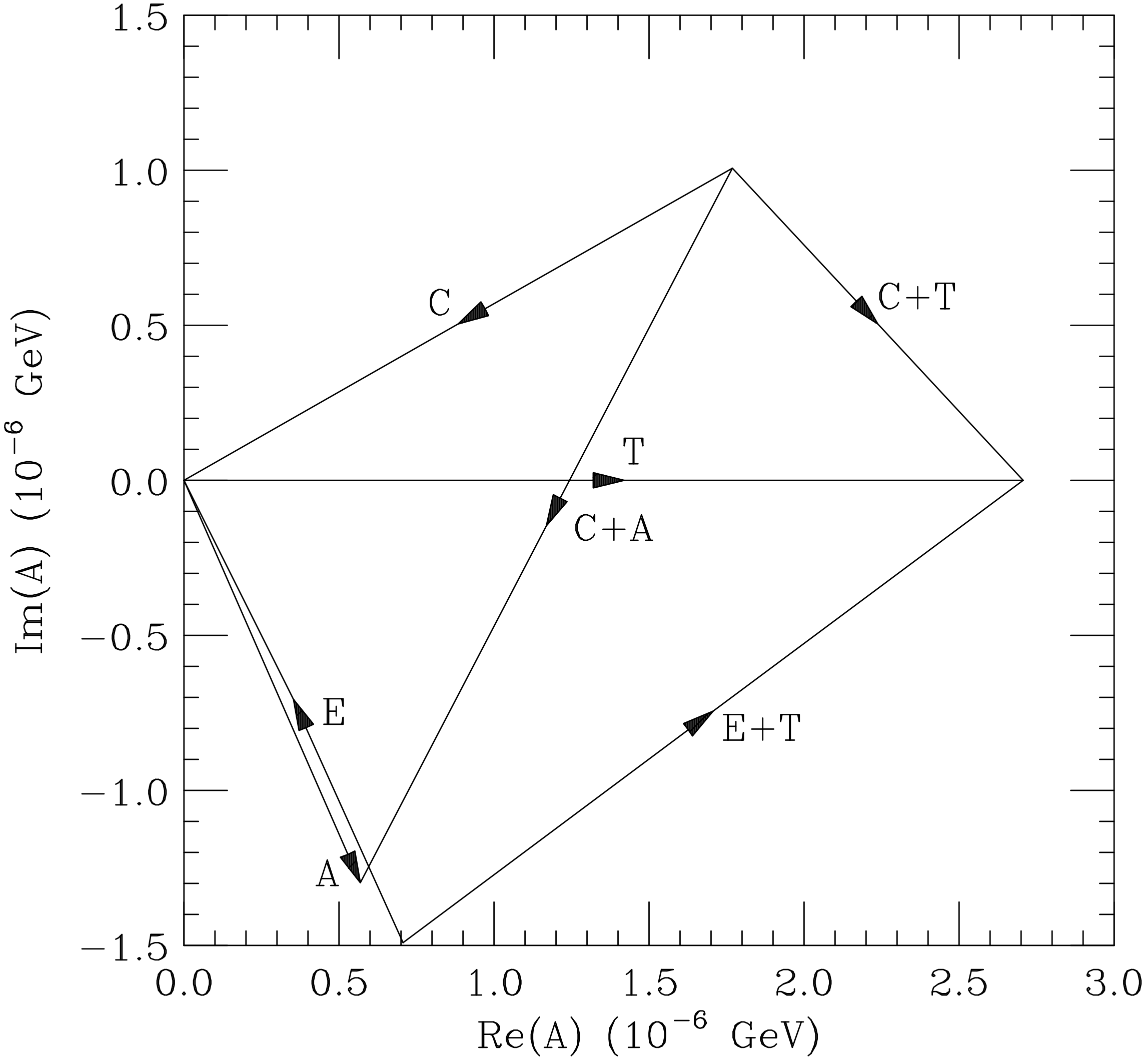
$E = (-0.71 + 1.49i) \times 10^{-6}$ GeV; $\delta(ET) = 115^\circ$

$A = (0.57 - 1.30i) \times 10^{-6}$ GeV; $\delta(AT) = -66^\circ$

These update (and are consistent with) values in PR D **60**, 114026

Ryd: All $\mathcal{B}(D_s^+)$ less

CONSTRUCTION OF CF AMPLITUDES



Here A was extracted from $D_s \to \pi^+\eta$ and $D_s \to \pi^+\eta'$; $\mathcal{A}(D_s \to \overline{K}^0 K^+)$ predicted to be 2.60×10^{-6} GeV vs. $(2.60 \pm 0.25) \times 10^{-6}$ GeV observed

Note importance of E and $A \simeq -E$ amplitudes

SCS DECAYS INVOLVING PIONS AND KAONS

Ratio of primed (SCS) to unprimed (CF) amplitudes expected to be $\tan\theta_C \simeq 0.23$

Meson	Decay mode	$\mathcal{B}$ (10^{-3})	p^* (MeV)	$\lvert\mathcal{A}\rvert$ $(10^{-7}$ GeV)	Rep.
D^0	$\pi^+\pi^-$	1.37±0.03	922	4.57±0.06	$-(T'+E')$
	$\pi^0\pi^0$	0.79±0.08	932	3.46±0.18	$-(C'-E')/\sqrt{2}$
	K^+K^-	3.85±0.09	791	8.26±0.11	$(T'+E')$
	$K^0\overline{K}^0$	0.72±0.14	789	3.58±0.35	0
D^+	$\pi^+\pi^0$	1.28±0.08	925	2.77±0.10	$-(T'+C')/\sqrt{2}$
	$K^+\overline{K}^0$	4.90±0.38	793	6.43±0.13	$T'-A'$
D_s^+	π^+K^0	2.46±0.40	916	5.87±0.28	$-(T'-A')$
	π^0K^+	0.75±0.28	917	3.24±0.63	$-(C'+A')/\sqrt{2}$

Predict $|\mathcal{A}(D^0 \to \pi^+\pi^-)| = |\mathcal{A}(D^0 \to K^+K^-)| = 5.73$; $|\mathcal{A}(D^0 \to \pi^0\pi^0)| = 4.41$; $|\mathcal{A}(D^+ \to \pi^+\pi^0)| = 2.24$. $\pi\pi$ isospin triangle $(I = 0, 2)$ has different shape from prediction. K^+K^- amplitude is $\sqrt{2}$ of predicted size (f_K, form factors)

Predict $|\mathcal{A}(D^+ \to K^+\overline{K}^0)| = |\mathcal{A}(D_s^+ \to \pi^+K^0)| = 6.78$; expt. low by (5%,13%)

$D^0 \to K^0\overline{K}^0$ forbidden by SU(3). CLEO: $\mathcal{B} = (3.04 \pm 0.66 \pm 0.28) \times 10^{-4}$

SCS DECAYS INVOLVING η, η'

Cabibbo-favored amplitudes C and E imply $C'/C = E'/E = \lambda$; write combinations with unit coefficient of SE' (disconnected "singlet" amplitude) for D^0 decays

Similarly: $D^+ \to (\pi^+\eta, \pi^+\eta')$ and $D_s^+ \to (K^+\eta, K^+\eta')$ (unit SA' coefficient).

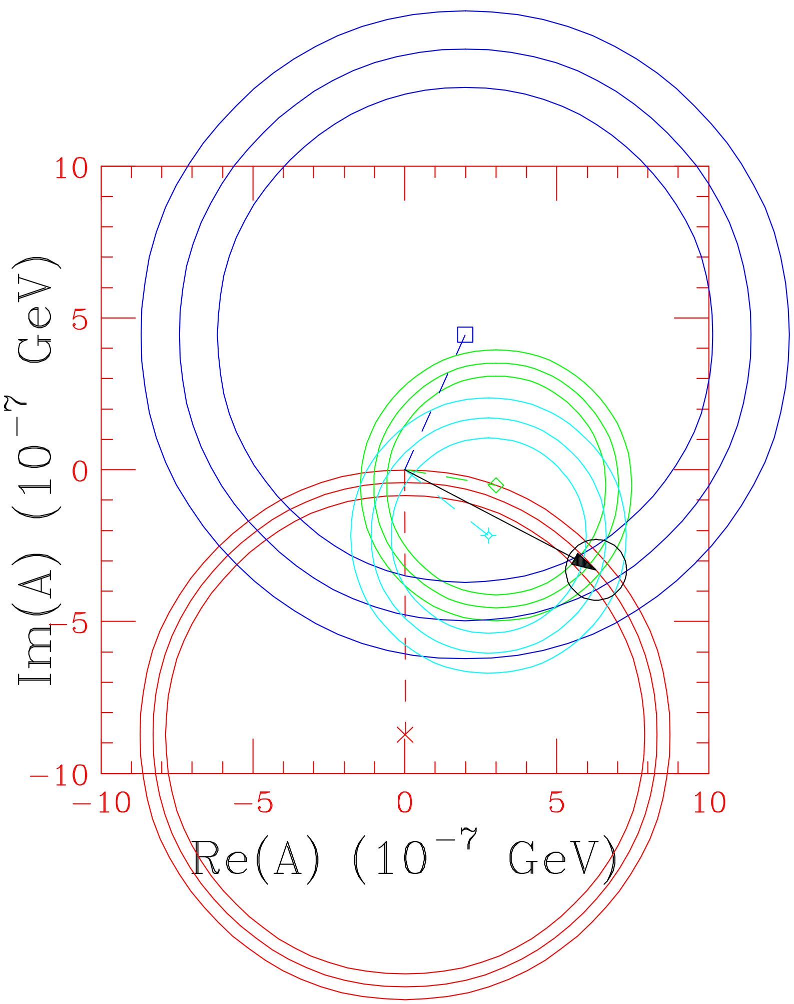
New CLEO D_s^+ measurements: arXiv:0708.0139 [hep-ex]

Amplitude	Expression	Re	Im	$\mathcal{A}_{\rm exp}$
$-\sqrt{6}\mathcal{A}(D^0 \to \pi^0\eta)$	$2E' - C' + SE'$	0.82	9.05	
$-\frac{\sqrt{3}}{2}\mathcal{A}(D^0 \to \pi^0\eta')$	$\frac{1}{2}(C' + E') + SE'$	-2.80	0.60	
$\frac{3}{2\sqrt{2}}\mathcal{A}(D^0 \to \eta\eta)$	$C' + SE'$	-4.01	-2.22	
$-\frac{3\sqrt{2}}{7}\mathcal{A}(D^0 \to \eta\eta')$	$\frac{1}{7}(C' + 6E') + SE'$	-1.94	2.61	
$\sqrt{3}\mathcal{A}(D^+ \to \pi^+\eta)$	$T' + 2C' + 2A' + SA'$	0.01	-8.73	8.03±0.38
$-\frac{\sqrt{6}}{4}\mathcal{A}(D^+ \to \pi^+\eta')$	$\frac{1}{4}(T' - C' + 2A') + SA'$	3.01	-0.52	4.03±0.42
$-\sqrt{3}\mathcal{A}(D_s^+ \to \eta K^+)$	$-(T' + 2C') + SA'$	1.99	4.44	9.41±1.06
$\frac{\sqrt{6}}{4}\mathcal{A}(D_s^+ \to \eta' K^+)$	$\frac{1}{4}(2T' + C' + 3A') + SA'$	2.76	-2.17	3.87±0.66

Amplitudes in units of 10^{-7} GeV (Re, Im as predicted in PR D**67**, 014001)

Use observed $|\mathcal{A}|$ values to search for solutions, find one with large $|SA'|$

AMPLITUDES FOR SCS DECAYS WITH η, η'



Red: $D^+ \to \eta\pi^+$

Green: $D^+ \to \eta'\pi^+$

Blue: $D_s^+ \to \eta K^+$

Cyan: $D_s^+ \to \eta' K^+$

Meson	Decay mode	$\mathcal{B}$ (10^{-3})	$\mathcal{A}$ $(10^{-7}$ GeV)
D^+	$\pi^+\eta$	3.50±0.32	4.79±0.22
	$\pi^+\eta'$	5.3±1.1	6.58±0.68
D_s^+	$K^+\eta$	1.92±0.43	5.42±0.61
	$K^+\eta'$	2.02±0.69	6.32±1.08

Black circle shows solution region

If $D_s \to K^+\eta$ rate were about half as large, would have had small-SA' solution

S. Nisar (D^0 decays): solutions with small, large SE'; in progress

DOUBLY-CABIBBO-SUPPRESSED DECAYS

Expansion in terms of doubly-Cabibbo-suppressed amplitudes $\tilde{T} \equiv -\tan^2\theta_C T$, $\tilde{C} \equiv -\tan^2\theta_C C$, $\tilde{E} \equiv -\tan^2\theta_C E$, $\tilde{A} \equiv -\tan^2\theta_C A$:

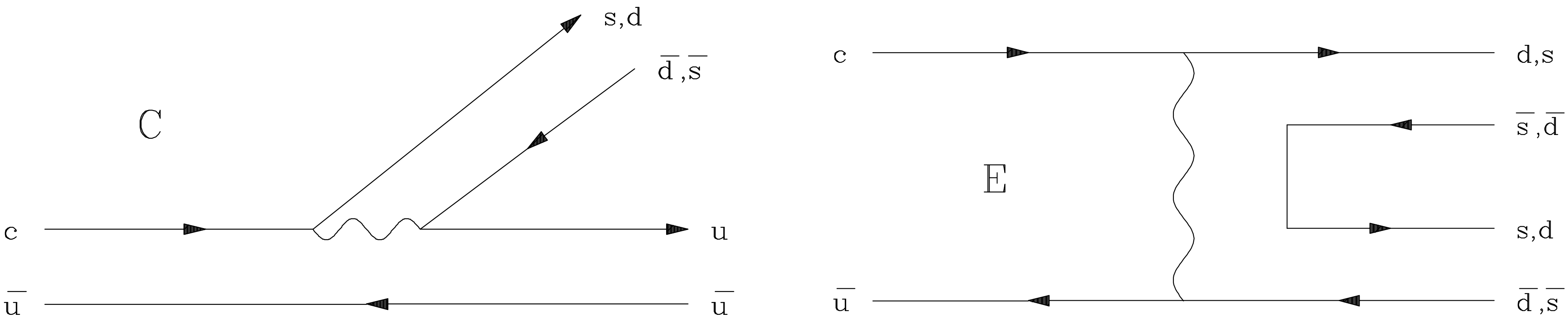
Meson	Decay mode	$\mathcal{B}$ (10^{-4})	p^* (MeV)	$\lvert\mathcal{A}\rvert$ $(10^{-7}$ GeV)	Rep.
D^0	$K^+\pi^-$	1.45±0.04	861	1.54±0.02	$\tilde{T}+\tilde{E}$
	$K^0\pi^0$	(a)	860	(a)	$(\tilde{C}-\tilde{E})/\sqrt{2}$
	$K^0\eta$	(a)	772	(a)	$\tilde{C}/\sqrt{3}$
	$K^0\eta'$	(a)	565	(a)	$-(\tilde{C}+3\tilde{E})/\sqrt{6}$
D^+	$K^0\pi^+$	(a)	863	(a)	$\tilde{C}+\tilde{A}$
	$K^+\pi^0$	2.28±0.39	864	1.21±0.10	$(\tilde{T}-\tilde{A})/\sqrt{2}$
	$K^+\eta$	1.01±0.37	776	0.85±0.15	$-\tilde{T}/\sqrt{3}$
	$K^+\eta'$	< 1.2	571	< 1.08	$(\tilde{T}+3\tilde{A})/\sqrt{6}$
D_s^+	K^0K^+	(a)	850	(a)	$\tilde{T}+\tilde{C}$

(a) Amplitude interferes with Cabibbo-favored decay to $\overline{K}^0 + X$

With $\tan\theta_C \simeq 0.23$ predict $|\mathcal{A}(D^0 \to K^+\pi^-)| = 1.32 \times 10^{-7}$ GeV and $|\mathcal{A}[D^+ \to K^+(\pi^0,\eta,\eta')]| = (0.93, 0.83, 1.27) \times 10^{-7}$ GeV. Qualitative agreement.

$D^0 \to (K^0\pi^0,\ \overline{K}^0\pi^0)$ INTERFERENCE

U-spin symmetry ($s \leftrightarrow d$) relates $D^0 \to K^0\pi^0$ to $D^0 \to \overline{K}^0\pi^0$



$$\text{CLEO}: \quad R(D^0) \equiv \frac{\Gamma(D^0 \to K_S\pi^0) - \Gamma(D^0 \to K_L\pi^0)}{\Gamma(D^0 \to K_S\pi^0) + \Gamma(D^0 \to K_L\pi^0)} = 0.122 \pm 0.024 \pm 0.030\ ;$$

$$R(D^+) \equiv \frac{\Gamma(D^+ \to K_S\pi^+) - \Gamma(D^+ \to K_L\pi^+)}{\Gamma(D^+ \to K_S\pi^+) + \Gamma(D^+ \to K_L\pi^+)} = 0.030 \pm 0.023 \pm 0.025\ .$$

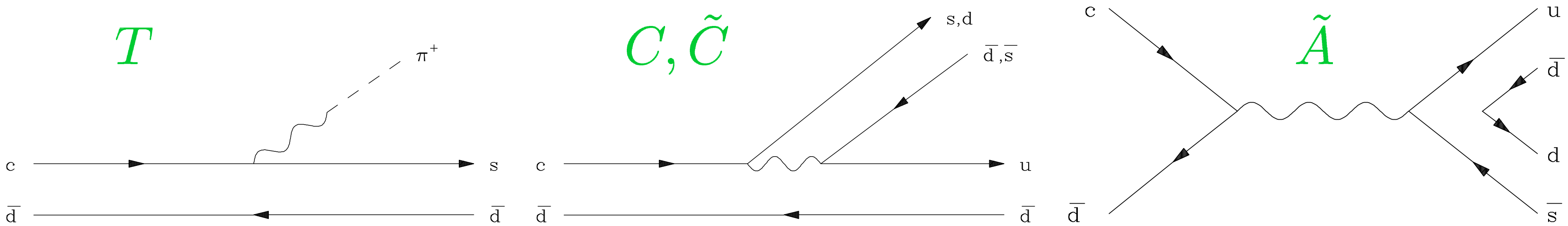
Expect $R(D^0) = 2\tan^2\theta_C \simeq 0.106$; prediction for $R(D^+)$ requires specific T, C, A

Same $R(D^0)$ predicted if π^0 is replaced by η or η': PR D **74**, 057502 (2006)

Also conclude $A[D^0 \to K^0(\rho^0, f_0, \ldots)]/A[D^0 \to \overline{K}^0(\rho^0, f_0, \ldots)] = -\tan^2\theta_C$

$D^+ \to (K^0\pi^+,\ \overline{K}^0\pi^+)$ INTERFERENCE

Contributing amplitudes:



Cabibbo-favored — Both — Doubly-Cabibbo-suppressed

$$R(D^+) = -2\ \mathrm{Re}\ \frac{\tilde{C}+\tilde{A}}{T+C} = 2\tan^2\theta_C\ \mathrm{Re}\ \frac{C+A}{T+C} = 0.067 \pm 0.007$$

Observed (CLEO): $R(D^+) = 0.030 \pm 0.023 \pm 0.023$ (Q. He *et al.*, hep-ex/0607068)

Relative phase of $C + A$ and $T + C$ is about 70°; real part of ratio hence is small

STRONG PHASES IN $(D^0, \overline{D}^0) \to K^-\pi^+$

M. Gronau *et al.*, PL B **508**, 37 (2001)

Produce a D^0_{CP} in a CP-eigenstate by opposite-side tagging [e.g., at $\psi(3770)$].

Define decay amplitudes as $\langle K^-\pi^+|D^0\rangle \equiv Ae^{i\delta_R}$, $\langle K^-\pi^+|\overline{D}^0\rangle \equiv \bar{A}e^{i\delta_W}$.

Difference $\delta = \delta_R - \delta_W$ of strong phases would vanish in the SU(3) limit.

At $\psi(3770)$ with $K^-\pi^+$ produced opposite a state S_ζ with CP eigenvalue ζ, $\Gamma(K^-\pi^+, S_\zeta) \approx A^2 A^2_{S_\zeta}(1 + 2\zeta r \cos\delta)$, so by choosing states with $\zeta = \pm 1$ can measure $(1 + 2r\cos\delta)/(1 - 2r\cos\delta)$, where $r = |\bar{A}/A| = 0.057 \simeq \tan^2\theta_C$.

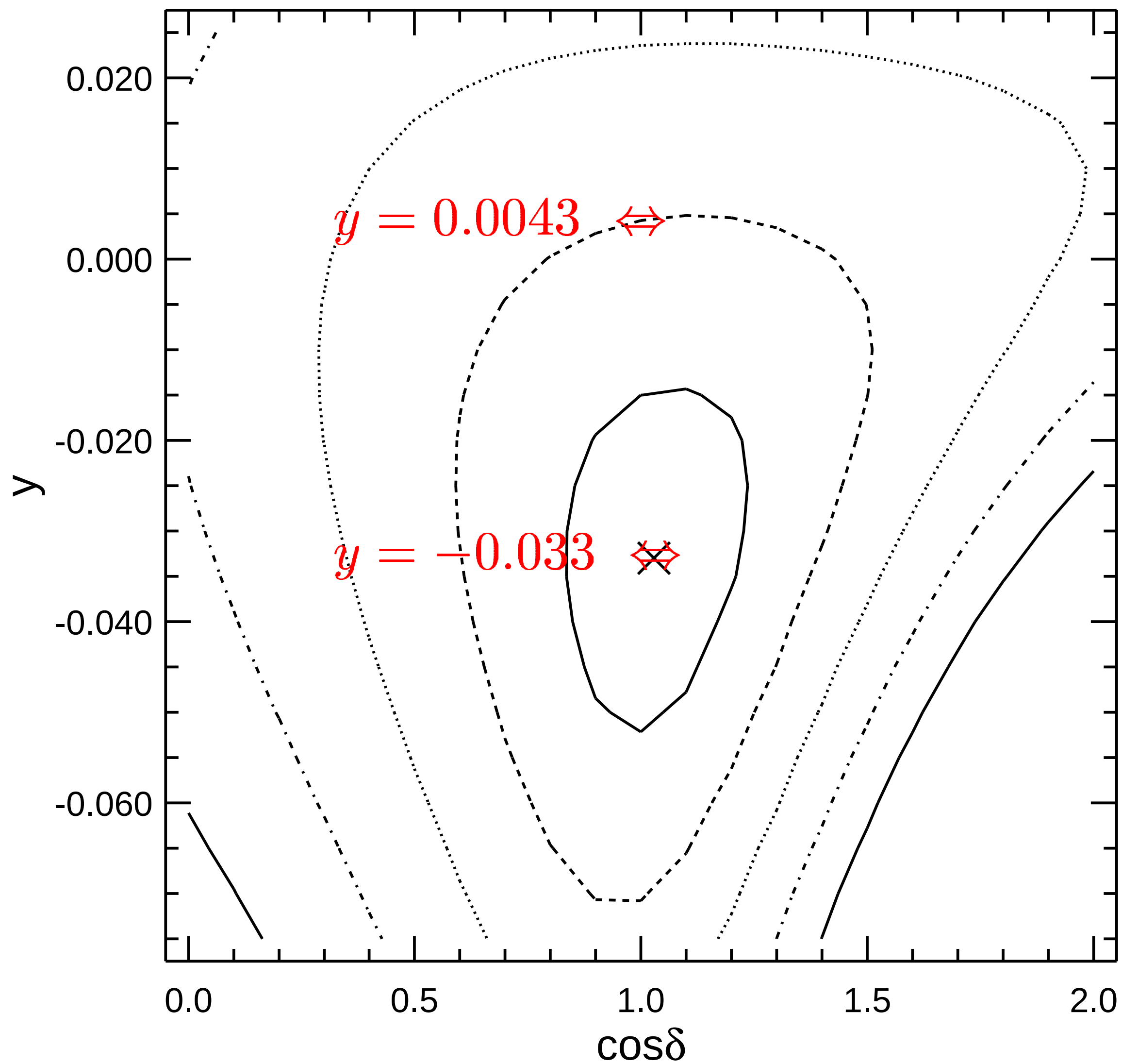
Present analysis based on 281 pb^{-1} [last error (prelim.) from $\Delta(x\sin\delta)$]:

External y, y' constraints	y (10^{-3})	$\cos\delta$
No	$-33 \pm 16 \pm 10 \pm 0$	$1.03 \pm 0.19 \pm 0.08 \pm 0.02$
Yes	$4.3 \pm 1.3 \pm 0.7 \pm ?$	$0.93 \pm 0.32 \pm 0.04 \pm ?$

For 750 pb^{-1} and $\sigma(D\bar{D}) = 6$ nb estimate an eventual error of $\Delta\cos\delta < \pm 0.2$

$\cos\delta$ ERROR VS. y

"Extended fit" with small y has smaller $r = |\bar{A}/A|$; $\cos\delta$ less well determined



OTHER THEORETICAL APPROACHES

F. Buccella +, hep-ph/9601343, PL B **379**, 246 (1996):

Final state interactions (resonant and nonresonant rescattering) violate flavor SU(3); can fit $\Gamma(D^0 \to K^+K^-)/\Gamma(D^0 \to \pi^+\pi^-) = 2.8 \pm 0.1$

Predicted $\mathcal{B}(D^0 \to K^0\overline{K}^0) = 9.8 \times 10^{-4}$

Many predictions for PV, PS final states of charm

D.-N. Gao, hep-ph/0610389, PL B **645**, 59 (2007):

Predicted $D^{0,+} \to K_{S,L}\pi^{0,+}$ asymmetry: $R(D^{0,+}) = (2\tan^2\theta_C,\ 0.040 \pm 0.005)$

A new ingredient: $A \simeq -0.4E$, essentially Fierz identity + QCD corrections

Tree amplitudes from factorization and semileptonic $D \to \pi$, $D \to K$ form factors

Main SU(3) breaking in $\tilde{T}/T$ from $f_K/f_\pi = 1.22$

Sum rule for $D^0 \to K^\mp\pi^\pm$, $D^+ \to K^+\pi^0$ predicts $|\delta| \simeq 7$–20° (0 in SU(3))

SUMMARY

Relative magnitudes and phases of amplitudes contributing to charm decays into two pseudoscalar mesons describable by flavor symmetry

Large relative strong phases between T and C, E; $A \simeq -E$

Largest symmetry breaking, in SCS $D^0 \to (\pi^+\pi^-/K^+K^-)$ ratio, partly understandable through form factor, decay constant effects

Decays involving η, η' mostly describable with small "disconnected" amplitudes; exception in SCS D^+ and D_s^+ decays. Would work out if $\mathcal{B}(D_s^+ \to K^+\eta)$ were lower by factor of ~ 2

Expected DCS–CF interference seen in $D^{0,+} \to K_{S,L}\pi^{0,+}$

On the trail of the relative strong phase in $(D^0, \overline{D}^0) \to K^-\pi^+$