Non-leptonic charm decays and CP Violation

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Outline

- Why study charm?
- Part 1: D decays
    - Flavor-SU(3) symmetry
    - 2-body decays
    - 3-body decays
- Part 2: CP Asymmetries
    - Recent Developments
    - Direct asymmetries using flavor SU(3)
- Summary and Conclusions

Why study charm?

In the LHC era, experiments are expected to find evidence of new physics beyond the Standard Model (SM): may very well be observed in flavor physics.

Processes that are ordinarily suppressed in the SM: Good place to look for new physics. New-physics contributions may be same order as in the SM, hence easier to detect.

SM penguins in charm decays suffer from suppressions: Small CKM factors, down-type GIM mechanism. To identify new physics it's necessary to understand these in the SM.

Difficulties: The D meson is heavier than the QCD Scale, however not as heavy as the B meson. Hadronic uncertainties are difficult to ascertain.

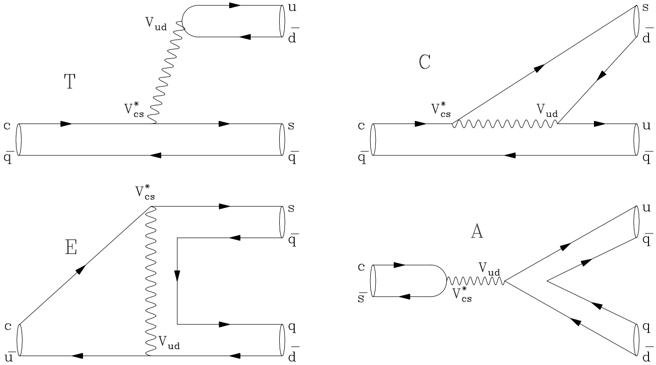
Questions: What can we learn using a phenomenological model? Is flavor SU(3) useful in studying charm decays?

Part 1: *D* decays

Flavor-SU(3) symmetry

$m_c \gg m_u, m_d, m_s$: Assume flavor-SU(3) symmetry.

Tree level, $D \to PP$ amplitudes: 4 distinct topologies:



CF($V^*_{cs} V_{ud} \sim 1$), SCS($V^*_{cs} V_{us} \sim \lambda$ or $V^*_{cd} V_{ud} \sim -\lambda$) and DCS($V^*_{cd} V_{us} \sim -\lambda^2$). $\lambda = \tan(\theta_{\mathrm{Cabibbo}}) = 0.2317$.

2-body D decays

CF $D \to PP$: 8 measured $\mathcal{B}$, 7 unknowns (Real T, C, E, A).

BB, J. Rosner, PRD **77**, 114020 (2008),
BB, J. Rosner, PRD **81**, 014026 (2010): Reasonable Fit.

Meson	Mode	$\mathcal{B}$ (%)	Rep.($\mathcal{A}$)	Th. $\mathcal{B}$ (%)
D^0	$K^-\pi^+$	3.89±0.08	$T+E$	3.91
	$\overline{K}^0\pi^0$	2.38±0.09	$(C-E)/\sqrt{2}$	2.35
	$\overline{K}^0\eta$	0.96±0.06	$C/\sqrt{3}$	1.00
	$\overline{K}^0\eta'$	1.90±0.11	$-(C+3E)/\sqrt{6}$	1.92
D^+	$\overline{K}^0\pi^+$	3.07±0.10	$C+T$	3.09
D_s^+	$\overline{K}^0K^+$	2.98±0.17	$C+A$	2.94
	$\pi^+\eta$	1.84±0.15	$(T-2A)/\sqrt{3}$	1.81
	$\pi^+\eta'$	3.95±0.34	$2(T+A)/\sqrt{6}$	3.60

$$T = 2.93,\ C = 2.34\, e^{-i\,152^\circ},\ E = 1.57\, e^{i\,121^\circ},\ A = 0.33\, e^{i\,70^\circ}$$

$$\chi^2 = 1.79\,(1\,\mathrm{d.o.f.}).\quad |\mathcal{A}| = M_D\sqrt{(8\pi\mathcal{B}\hbar)/(p^*\tau)}\ (\mathrm{in}\ 10^{-6}\,GeV)$$

2-body D decays

SCS $D \to PP$: $T' \sim \pm\lambda T$ $(+(-)$ if $V_{cs}(V_{cd}))$, C', E', A'.
Ignore small relative weak phase between V_{cd} and V_{us}.

U-spin symmetry: $d \leftrightarrow s \Rightarrow \mathcal{A}(D^0 \to K^0\overline{K}^0) \;=\; 0$, and
$\Rightarrow \mathcal{A}(D^0 \to \pi^+\pi^-) \;=\; -\mathcal{A}(D^0 \to K^+K^-) \;= (T' + E')$.

U-spin is broken in practice:

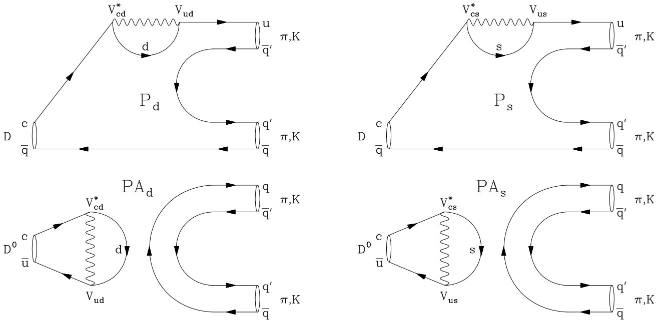
$$|\mathcal{A}(D^0 \to \pi^+\pi^-)| \;=\; 4.70 \pm 0.08 \;; \quad |\lambda\,(T+E)| \;=\; 5.82 \;.$$
$$|\mathcal{A}(D^0 \to K^+K^-)| \;=\; 8.49 \pm 0.10 \;; \quad \text{in units of } 10^{-7}\,GeV \;.$$
$$|\mathcal{A}(D^0 \to K^0\overline{K}^0)| \;=\; 2.39 \pm 0.14 \;. \qquad \sim (E'_s - E'_d)$$

Factorizable SU(3) breaking in T helps, but not enough:
$|\mathcal{A}(D^0 \to \pi^+\pi^-)| = |-\lambda\,(T_\pi + E)| \;=\; 5.74$.
$|\mathcal{A}(D^0 \to K^+K^-)| = |\;\lambda\,(T_K + E)| \;=\; 7.42$;

where, $\frac{T_\pi}{T} = \frac{f_{+(D\to\pi)}(m_\pi^2)}{f_{+(D\to K)}(m_\pi^2)} \cdot \frac{m_D^2 - m_\pi^2}{m_D^2 - m_K^2}$, $\frac{T_K}{T} = \frac{f_{+(D\to K)}(m_K^2)}{f_{+(D\to K)}(m_\pi^2)} \cdot \frac{f_K}{f_\pi}$

2-body D decays

Penguin contributions to SCS D decays: $P = P_d + P_s$ and $PA = PA_d + PA_s$ (zero under U-Spin)



Weak phases of P_d and P_s differ by $\sim 6 \times 10^{-4}$: No appreciable contribution to CP asymmetries.

$P + PA$ contributes to both $\mathcal{A}(K^+K^-)$ and $\mathcal{A}(\pi^+\pi^-)$ with same sign: can act as proxy for SU(3) violation!

2-body D decays

Extract P and $P+PA$ by fitting to SCS decay rates.

BB, M. Gronau, J. Rosner, PRD **85**, 054014.

$P+PA = 0.44 + 1.41\ i\ ;\ P = -1.52 + 0.08\ i\ (10^{-7}\ \mathrm{GeV})$.

Decay Mode	Amplitude representation	$\lvert\mathcal{A}\rvert$ $(10^{-7}$ GeV) Experiment	Theory
$\pi^+\pi^-$	$-\lambda\,(T_\pi + E) + (P + PA)$	4.70±0.08	4.70
K^+K^-	$\lambda\,(T_K + E) + (P + PA)$	8.49±0.10	8.48
$\pi^0\pi^0$	$-\lambda\,(C - E)/\sqrt{2} - (P + PA)/\sqrt{2}$	3.51±0.11	3.51
$\pi^+\pi^0$	$-\lambda\,(T_\pi + C)/\sqrt{2}$	2.66±0.07	2.26
$K^0\overline{K}^0$	$-(P + PA) + P$	2.39±0.14	2.37
$K^+\overline{K}^0$	$\lambda\,(T_K - A_{D^+}) + P$	6.55±0.12	6.87
π^+K^0	$-\lambda\,(T_\pi - A) + P$	5.94±0.32	7.96
π^0K^+	$-\lambda\,(C + A)/\sqrt{2} - P/\sqrt{2}$	2.94±0.55	4.44

$P+PA$ explains D^0 decay rates. Fit for P has large χ^2.
Measured D^+ and D_s^+ amplitudes have large errors.

2-body D decays

$D \to PV$: 10 unknowns: Real $T_{V,P}$, $C_{P,V}$, $E_{P,V}$.
BB, J. Rosner, PRD **79**, 034016 (2009).

CF decay rates used to extract parameters: 12 exact solutions ($\mathcal{B}(D^0 \to \overline{K}^{*0}\eta')$ may help resolve discrete ambiguities.)

Available SCS decay rates help choose lowest χ^2 solution:

$$T_V = 3.95 \ , \ C_P = 4.88\, e^{-i\, 162^\circ} \ , \ E_P = 2.94\, e^{-i\, 93^\circ} \ ,$$
$$T_P = 7.46 \ , \ C_V = 3.46\, e^{-i\, 172^\circ} \ , \ E_V = 2.37\, e^{-i\, 110^\circ} \ .$$

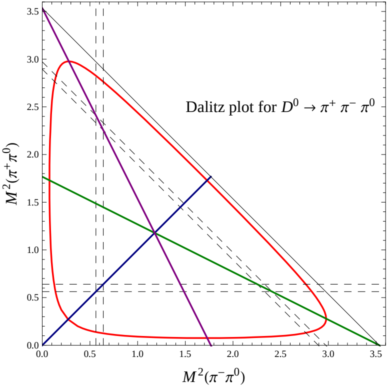
Tree amplitudes ($T_{P,V}$) assumed to be real (factorization.)

$D \to PV$ amplitudes may be used to study Dalitz plots in 3-body D decays involving intermediate vector resonances.

Large relative strong phases in 3-body D^0 decays involving intermediate vector resonances are useful for measuring γ, also good testing ground for flavor SU(3).

3-body *D* decays

$D^0 \to \pi^+\pi^-\pi^0$ Dalitz plot: $\rho^\pm$ and ρ^0 resonances.



BABAR: Gaspero et al. PRD **78**, 014015 (2008).

$I = 0$ dominance reported:

$\mathcal{A} = 0$ along symmetry axes.

Flavor SU(3) agrees with I = 0 dominance!

BB, C. -W. Chiang, J. Rosner, PRD **81**, 096008 (2010).

⇒ Flavor SU(3) finds correct relative strong phases.

Channel	Fraction(%)	vs BaBar(%)
I = 0	92.9±6.7	94.24±0.40
I = 1	4.8±0.3	2.17±0.17
I = 2	2.3±0.8	3.58±0.29

3-body *D* decays

List of other 3-body *D* decays studied in the context of relative phases on Dalitz plots:

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

BB, J. Rosner, PRD **82**, 074025 (2010)
BB, J. Rosner, PRD **82**, 114032 (2010)
BB, J. Rosner, arXiv:1203.6014 (2012)

Measured relative phases between amplitudes differ from flavor-SU(3) predictions.

Amplitudes and relative phases in cross-ratios agree better with flavor-SU(3).

Part 2: CP Asymmetries

$$A_{CP}(f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \bar{f})}$$

$f = f_{CP}$ (e.g. $\pi^+\pi^-$): $A_{CP}(f) \simeq A_{CP}^{\rm dir}(f) + \frac{\langle t \rangle}{\tau} A_{CP}^{\rm ind}$

(τ = true lifetime of D^0, $\langle t \rangle$ = average decay time)

$$A_{CP}^{\rm dir}(f) = \frac{|\mathcal{A}_f|^2 - |\overline{\mathcal{A}}_{\bar{f}}|^2}{|\mathcal{A}_f|^2 + |\overline{\mathcal{A}}_{\bar{f}}|^2} \text{, where } \begin{array}{l} \mathcal{A}_f \equiv \mathcal{A}(D^0 \to f) \\ \overline{\mathcal{A}}_{\bar{f}} \equiv \mathcal{A}(\overline{D}^0 \to \bar{f}) \end{array}$$

$$\begin{array}{l} \mathcal{A}_f = a_f(1 + r_f e^{i(\delta_f + \phi_f)}) \\ \mathcal{A}_{\bar{f}} = a_{\bar{f}}(1 + r_f e^{i(\delta_f - \phi_f)}) \end{array} \Rightarrow A_{CP}^{\rm dir} = -\frac{2\, r_f \, \sin\delta_f \sin\phi_f}{1 + r_f^2 + 2\, r_f \, \cos\delta_f \cos\phi_f}$$

$A_{CP}^{\rm ind}$ is universal to a good approximation:
Grossman, Kagan, Nir, PRD **75**, 036008 (2007)

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

$\simeq \Delta A_{CP}^{\rm dir} + \frac{\Delta\langle t \rangle}{\tau} A_{CP}^{\rm ind}$, where $\Delta\langle t \rangle = \langle t(K^+K^-) \rangle - \langle t(\pi^+\pi^-) \rangle$

Small $\Delta\langle t \rangle/\tau \Rightarrow \Delta A_{CP} \simeq \Delta A_{CP}^{dir}$, since in SM $A_{CP}^{\rm ind} < 1\%$.

Recent Results from CDF and LHCb

CDF (90% c.l.):

$-0.63\% \leq A_{CP}(D^0 \to K^+K^-) \leq 0.15\%$

$-0.21\% \leq A_{CP}(D^0 \to \pi^+\pi^-) \leq 0.65\%$ T. Aaltonen et al. PRD, **85**, 012009 (2012)

LHCb Result ($0.62 fb^{-1}$ of data collected in 2011):

$$\Delta A_{CP} = [-0.82 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})]\%$$

$$\Delta\langle t\rangle/\tau = [\ \ 9.83 \pm 0.22(\mathrm{stat}) \pm 0.19(\mathrm{syst})]\%$$

R. Aaij et al. PRL **108**, 111602 (2012)

CDF Update (Feb 2012):

$$\Delta A_{CP} = [-0.62 \pm 0.21(\mathrm{stat}) \pm 0.10(\mathrm{syst})]\%$$

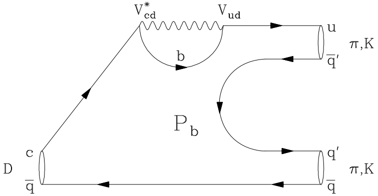
$$\Delta\langle t\rangle/\tau \sim (26 \pm 1)\%$$

CDF + LHCb (Assuming uncorrelated errors):

$$\Delta A_{CP}^{\mathrm{dir}} = (-0.67 \pm 0.16)\%, \qquad \text{CDF Note 10784}$$

$$\Delta A_{CP}^{\mathrm{ind}} = (-0.02 \pm 0.22)\%. \qquad (\text{CPV at} \sim 3.8\,\sigma)$$

Crude SM estimate of A_{CP}



CPV penguin in SM:
$P_b = p\, e^{i\delta}\, e^{-i\gamma}$;
$\gamma = \mathrm{Arg}[V_{ub}^*]$;
$|V_{cb}^* V_{ub}| \sim \mathcal{O}(\lambda^5)$;
(Large CKM suppression)

U-Spin symmetry: $A_{CP}(K^+K^-) \approx -A_{CP}(\pi^+\pi^-)$

$\Delta A_{CP} \sim 4\, \frac{p}{|T|} \sin\delta \sin\gamma \ , \quad p \ll |T|$

Perturbative QCD:

$\frac{p}{|T|} \sim \mathcal{O}(10^{-4})$ (CKM suppression: $\frac{|V_{cb}||V_{ub}|}{|V_{cs}||V_{us}|} \sim \mathcal{O}(\lambda^4)$)

$\Rightarrow \Delta A_{CP} \sim 10^{-4}$ ($\sin\gamma, \sin\delta \sim \mathcal{O}(1)$)

Observed ΔA_{CP} is at least an order of magnitude higher:
Good chance that it is new physics.

New physics?

P_b in $D \to PP$ has large CKM suppression. Also P_b can't benefit from mass of the b quark in the loop. In contrast, penguin in $B \to PP$ has the heavy top quark in the loop.

Long-distance effects and final state rescattering may provide valuable input. However, calculable-QCD effects using factorization fall short of explaining the observed value of ΔA_{CP}. Cheng and Chiang, PRD **85**, 034036 (2012)

New-physics enhancements are therefore natural to think of:

Isidori et al., PLB, **711**, 46 (2012): Large NP generically produces sizable CPV in $D - \overline{D}$ mixing: test at LHCb.

Wang and Zhu, PLB, **709**, 362 (2012): Up FCNCs or fourth generation quarks?: Additional bounds from top quark physics. See also Rozanov and Vysotsky, arXiv:1111.6949.

Hochberg and Nir, arXiv:1112.5268: Up-flavor non-universal coupling + extra scalar doublet as the source for both Large ΔA_{CP} and forward-backward asymmetry in $t\bar{t}$ production.

Penguin Enhancement

Numerous other new-physics ideas including supersymmetry, minimal flavor violation, etc. arXiv:1202.3300, 1202.5038, 1203.4218, 1204.1046, etc.

However, $s \to d$ penguin in $K \to 2\pi$ has been known to be a probable source of $\Delta I = 1/2$ enhancement: not calculable perturbatively. Golden and Grinstein, PLB, **222**, 501 (1989)

Since m_c is close to Λ_{QCD}, some amplitudes that are formally $1/m_c$ suppressed, may turn out to be large experimentally. Brod, Kagan and Zupan, arXiv:1111.5000

Non-perturbative calculations: difficult + often associated with sizeable uncertainties. Cannot rule out $P_b >$ crude SM expectation. Li, Lu and Yu, arXiv:1203.3120; See also Franco, Mishima and Silvestrini, arXiv:1203.3131

We adopt a phenomenological method, extract P_b from data, and predict CP asymmetries in other SCS channels. See also Pirtskhalava and Uttayarat, arXiv:1112.5451

ΔA_{CP} in flavor SU(3)

We introduce P_b as the source of CPV in the flavor-SU(3) model discussed earlier:

$$A_{CP}(f) = \frac{2\,p\,|T_f|\sin\gamma\sin(\delta-\phi_T^f)}{|T_f|^2+p^2+2\,p\,|T_f|\cos\gamma\cos(\delta-\phi_T^f)}\;;$$

In $D^0 \to \pi^+\pi^-$:

$$T_{\pi^+\pi^-} = |T_{\pi^+\pi^-}|\,e^{i\phi_T^{\pi^+\pi^-}} = -\lambda(T_\pi + E) + (P + PA)$$

Note: Tiny weak phase of tree can give $\mathcal{O}(\lambda^4)$ corrections.
PA_b (penguin annihilation, $c \to b \to u$) neglected.

CKM angle $\gamma = 76^\circ$. Unknowns: p and δ.

One may extract p as a function of δ using:

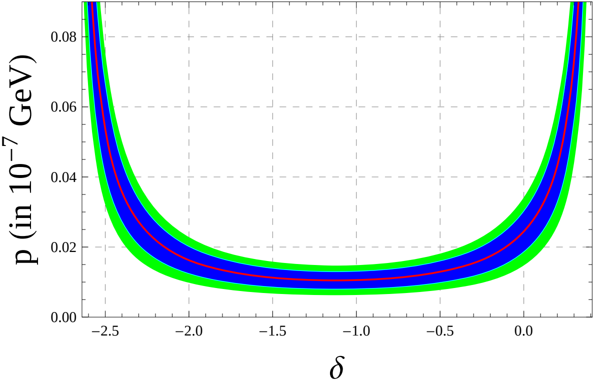
$$\Delta A_{CP}|_{\mathrm{CDF+LHCb}} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

BB, M. Gronau, J. Rosner, PRD **85**, 054014 (2012)
(Updated with CDF + LHCb combined results in this talk.)
(See also talk by M. Gronau at FPCP 2012, Hefei, China.)

Results:

90% c.l. CDF bounds on $A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$:

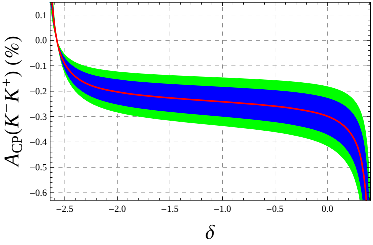
$$\Rightarrow -2.64 \le \delta \le 0.41$$

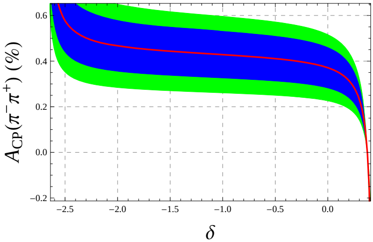


$\Delta A_{CP} = (0.67 \pm 0.16)\%$;
68% c.l. band in **blue** ,
90% c.l. band in **green** .

For a large range of δ:
$p < 2 \times 10^{-9} GeV$;
$p/|T_{K^+K^-}| \sim 2 \times 10^{-3}$.

$A_{CP}(K^+K^-)$ and $A_{CP}(\pi^+\pi^-)$





A_{CP} vs δ using $p - \delta$ constraint

68% c.l. band in **blue** .

90% c.l. band in **green** ,

U-spin is broken by $P + PA$!

For a large range of δ:

$A_{CP}(K^+K^-) < 0$,

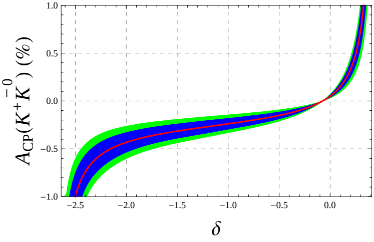
$A_{CP}(\pi^+\pi^-) > 0$,

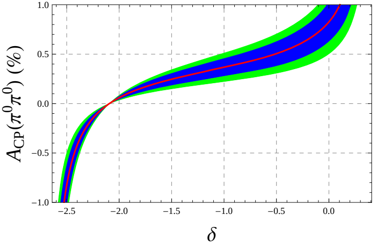
$|A_{CP}(K^+K^-)| < |A_{CP}(\pi^+\pi^-)|$

To pinpoint δ:

Need to improve individual A_{CP} error bars.

A_{CP} predictions: $K^+\overline{K}^0$ and $\pi^0\pi^0$





A_{CP} vs δ using $p - \delta$ constraint

68% c.l. band in **blue** ,

90% c.l. band in **green** .

A_{CP} in $K^+\overline{K}^0$ and $\pi^0\pi^0$ are correlated .

$|A_{CP}| < 1\%$ over a large range of δ .

Belle Result from 2010: $A_{CP}(K^+\overline{K}^0) = (-0.16 \pm 0.58 \pm 0.25)\%$.

A_{CP} in SCS decays

$D^+ \to K^+\overline{K}^0$ and $D^0 \to \pi^0\pi^0$ are good targets for A_{CP} measurements ($\delta\mathcal{B}/\mathcal{B} \sim 4\%, 6\%$).

A_{CP} in D_s^+ decays are harder to predict ($\delta\mathcal{B}/\mathcal{B} > 10\%$).

In our model $A_{CP} = 0$ in $D^0 \to K^0\overline{K}^0$ and $D^+ \to \pi^+\pi^0$.

If a non-zero $A_{CP}(K^0\overline{K}^0)$ is measured, then one has to add PA_b (annihilation penguin.)

Bose symmetry $\Rightarrow$ $\pi^+\pi^0$ final state is pure $I = 2$. $D^+ \to \pi^+\pi^0$ has to come from $\Delta I = 3/2$ operators.

SM penguins are $\Delta I = 1/2$! $A_{CP}(\pi^+\pi^0) \gtrsim 0.1\%$ is difficult to generate in SM. Thus, need new-physics amplitudes with both strong and weak phases different from SM tree.

Grossman, Kagan and Zupan, arXiv:1204.3557.

See also Feldmann, Nandi and Soni, arXiv:1202.3795 and Brod, Grossman, Kagan and Zupan, arXiv:1203.6659 for other approaches.

Summary and Conclusions

- CF $D \to PP$ decays fit well to a flavor-SU(3) framework.
- A model for SU(3) breaking in SCS $D^0 \to PP$ decays in the absence of GIM cancellation in penguins.
- $D \to PV$ decays are interesting, but more data needed.
- Flavor-SU(3) is successful in explaining $I = 0$ dominance in $D^0 \to \pi^0\pi^+\pi^-$ Dalitz plot.
- LHCb and CDF ΔA_{CP} measurements are commensurate with the SM: need penguin enhancement.
- A_{CP} in $D^+ \to K^+\overline{K}^0$ and $D^0 \to \pi^0\pi^0$ predicted
- Reducing error on individual A_{CP} can lead to better prediction of A_{CP} in other channels
- $A_{CP} \neq 0$ in $D^0 \to K^0\overline{K}^0$ needs PA_b (assumed absent in current framework)
- $A_{CP} \neq 0$ in $D^+ \to \pi^+\pi^0$ needs new dynamics with both weak and strong phases different from SM tree
- Study A_{CP} in $D \to PV$ channels such as $D^0 \to \rho\pi, K^*K$, $D^+ \to \phi\pi^+$, etc

A_{CP} from $P + PA$

Small relative weak phase between $V_{cd}^* V_{ud} = \lambda_d \simeq -\lambda$ and $V_{cs}^* V_{us} = \lambda_s \simeq \lambda$ doesn't change A_{CP} appreciably!

CKM Unitarity: $V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$

$\sin\phi = \sin[\mathrm{Arg}(\lambda_s \lambda_d^*)] \simeq \frac{|V_{cb}||V_{ub}|}{|V_{cs}||V_{us}|} \sin\gamma = -6.8 \times 10^{-4}$

In general:

$$A = a\,(1 + r\, e^{i\delta}\, e^{i\phi})\ , \qquad \overline{A} = a\,(1 + r\, e^{i\delta}\, e^{-i\phi})\ ,$$

$$A_{CP} = -\frac{2r\ \sin\delta \sin\phi}{1 + r^2 + 2r\ \cos\delta\cos\phi}\ .$$

$|A_{CP}(D \to \pi^+\pi^-, K^+K^-)| \sim (1-2) \times 10^{-4}$.

Exact answer depends on relative strong phase between $P_d + PA_d$ and $P_s + PA_s$.

Similarly small A_{CP} in D^+ and D_s^+ decays from interference between T, C and A.

ΔA_{CP} from LHCb measurement

$$A_{\mathrm{Raw}}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^*)$$

Detection asymmetry in D^0, zero for f self-conjugate.

Detection asymmetry of soft pions from the D^* decay chains.

D^* production asymmetry.

To first order, these cancel in the difference:

$$\begin{aligned}\Delta A_{CP} &= A_{\mathrm{Raw}}(K^+K^-) - A_{\mathrm{Raw}}(\pi^+\pi^-) \\ &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\end{aligned}$$

$$A_{CP} \simeq A_{CP}^{\mathrm{dir}} + \frac{\langle t\rangle}{\tau} A_{CP}^{\mathrm{ind}}$$

A_{CP}^{ind} is universal and small. $\langle t\rangle/\tau \sim 10\%$ for LHCb.

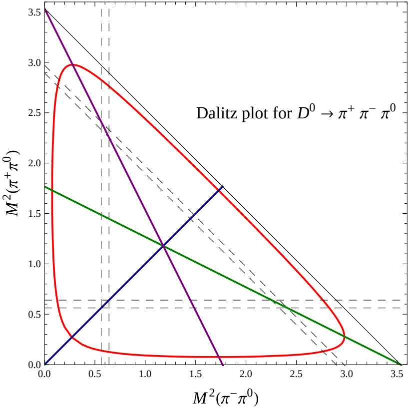
Thus: $\Delta A_{CP} \simeq A_{CP}^{\mathrm{dir}}(K^+K^-) - A_{CP}^{\mathrm{dir}}(\pi^+\pi^-)$.

LHCb + CDF: $\Delta A_{CP}^{\mathrm{dir}} = (-0.67 \pm 0.16)\%$;
$\Delta A_{CP}^{\mathrm{ind}} = (-0.02 \pm 0.22)\%$.

3-body D decays

$D^0 \to \pi^+\pi^-\pi^0$ Dalitz plot: $\rho^\pm$ and ρ^0 resonances.
BABAR: Gaspero+ PRD **78**, 014015 (2008).

$I = 0$ dominance reported: $\mathcal{A} = 0$ along symmetry axes.



$M^2(AB) = (p_A + p_B)^2$.

ρ Resonance bands between dashed lines .

Symmetry Axes:
Green : $p_\pi^- = p_\pi^0$,
Blue : $p_\pi^+ = p_\pi^-$,
Purple : $p_\pi^0 = p_\pi^+$.

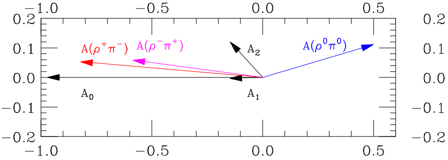
I = 0 part antisymmetric under $\pi_A \leftrightarrow \pi_B$: 0 along symmetry axes.

Flavor SU(3) agrees with this I = 0 dominance!
BB, C. -W. Chiang, J. Rosner, PRD **81**, 096008 (2010).

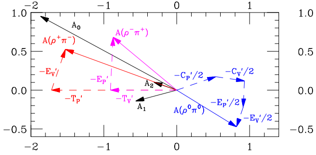
3-body D decays

$$\begin{aligned}
I_0 &= [\rho^+\pi^- - \rho^0\pi^0 + \rho^-\pi^+]/\sqrt{3} \\
I_1 &= [\rho^+\pi^- - \rho^-\pi^+]/\sqrt{2} \\
I_2 &= [\rho^+\pi^- + 2\,\rho^0\pi^0 + \rho^-\pi^+]/\sqrt{6}
\end{aligned}$$

$$\begin{aligned}
\mathcal{A}(\rho^+\pi^-) &= -T'_P - E'_V \\
\mathcal{A}(\rho^-\pi^+) &= -T'_V - E'_P \\
\mathcal{A}(\rho^0\pi^0) &= E'_P + E'_V \\
&\quad - C'_P - C'_V
\end{aligned}$$



BABAR Result



Flavor-SU(3) Result

Channel	Fraction(%)	vs BaBar(%)
I = 0	92.9±6.7	94.24±0.40
I = 1	4.8±0.3	2.17±0.17
I = 2	2.3±0.8	3.58±0.29

Flavor SU(3) leads to correct strong phases between interfering amplitudes thereby giving cancellations in appropriate places.