CP asymmetries in SCS D decays

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Ref: BB, M. Gronau, J. L. Rosner, PRD **85** 054014.

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Motivation

Recent advances in measurement of direct CP Asymmetry in singly-Cabibbo-suppressed D decays:

- CDF 90% c.l. bounds on A_{CP} (PRD **85** 012009)

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

$$-0.21\% \leq A_{CP}(\pi^+\pi^-) \leq 0.65\%$$

- 3.5σ evidence for CPV from LHCb (PRL **108** 111602):

$$\begin{aligned} \Delta A_{CP} &= A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &= -0.82 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst}) \ \% \end{aligned}$$

- CDF + LHCb result (uncorrelated errors):

$$\Delta A_{CP} = (-0.67 \pm 0.16)\%$$

SM theory: $A_{CP} \sim 10^{-3}$ (Bigi+ JHEP 06 (2011) 089)
The LHCb & CDF results could well indicate new physics!
1111.4987, 1111.5196, 1111.6949, 1112.5268, etc.

Motivation

$c \to b \to u$ penguin (D decays): CKM suppressed ($\mathcal{O}(\lambda^5)$); can't benefit from m_B. Contrast: $b \to t \to s$ penguin in B decays gets enhanced due to the heavy top quark in the loop.

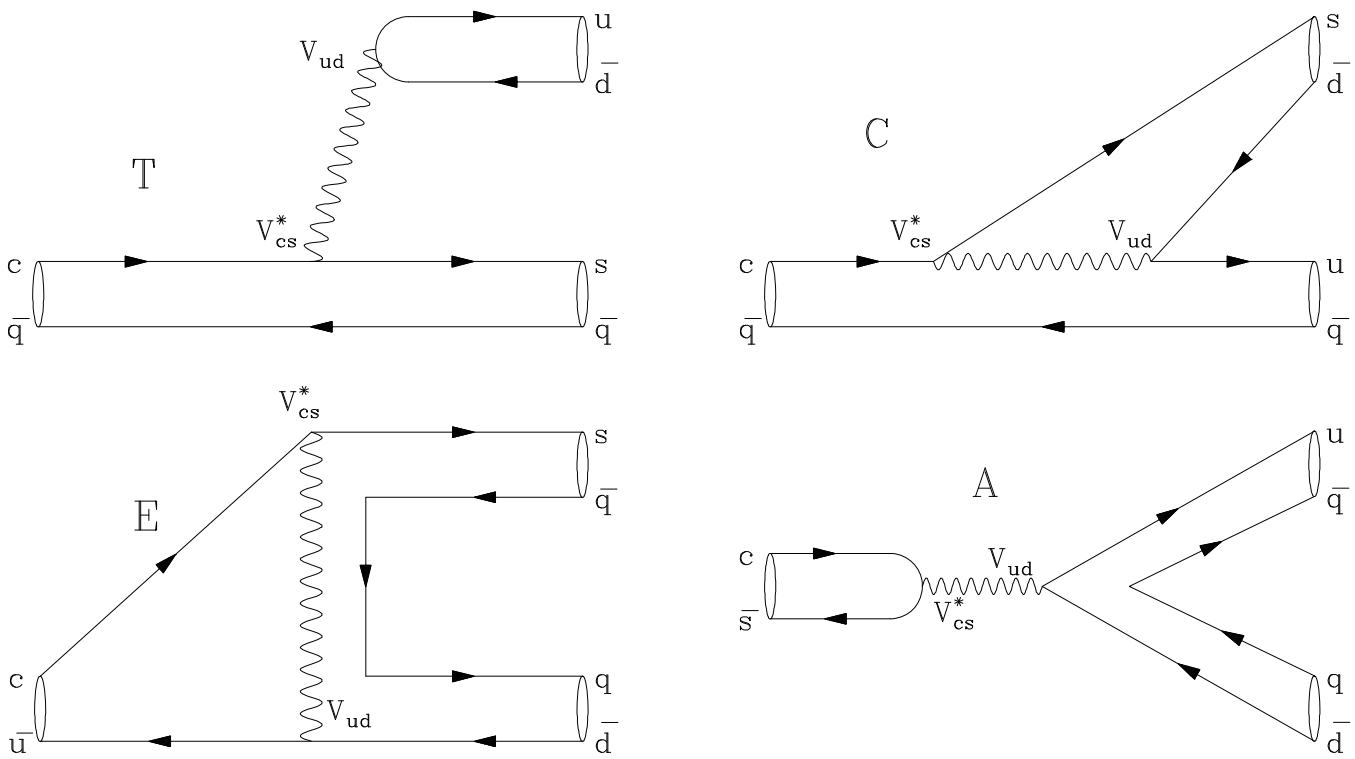
Golden and Grinstein (PLB 222, 501(1989)): Penguin enhancement due to non-perturbative effects.
Analogous to $s \to d$ penguin enhancement in $K \to \pi\pi$.

Recent works: Isidori+ PLB 711, 46(2012), Brod+ 1111.5000 suggest an order-of-magnitude enhancement of the $c \to u$ penguin is not unreasonable.

Using flavor SU(3) explore the possibility of an enhanced $c \to b \to u$ penguin: BB, M. Gronau, J. Rosner (PRD **85** 054014).
Among other recent works:
Cheng and Chiang (PRD **85** 034036, 1205.0580),
Brod+ (1203.6659), Pirtskhalava + Uttayarat (1112.5451).

Flavor-SU(3) Diagrammatics

- Flavor-SU(3) symmetry between "u", "d" and "s"
- Tree level in weak expansion: 4 topologies
- $|SCS| : |CF| = |V_{us} V_{cs}^*| : |V_{ud} V_{cs}^*| \sim \lambda \, (\simeq 0.23)$



Cabibbo-favored decays

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

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

Meson	Mode	$\mathcal{B}$ (%)	Rep.	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

Flavor SU(3) breaking

U-spin symmetry: $d \leftrightarrow s$

$$\Rightarrow \mathcal{A}(D^0 \to K^+K^-) \;=\; -\,\mathcal{A}(D^0 \to \pi^+\pi^-) \;=\; \lambda\,(T+E).$$

U-spin is broken in practice:

$$|\mathcal{A}(D^0 \to \pi^+\pi^-)| \;=\; 4.70 \pm 0.08\ ; \quad |\lambda\,(T+E)| \;=\; 5.82\ .$$
$$|\mathcal{A}(D^0 \to K^+K^-)| \;=\; 8.49 \pm 0.10\ . \quad \text{in units of } 10^{-7}\,GeV\ .$$

Factorizable SU(3) breaking in T helps but not enough:

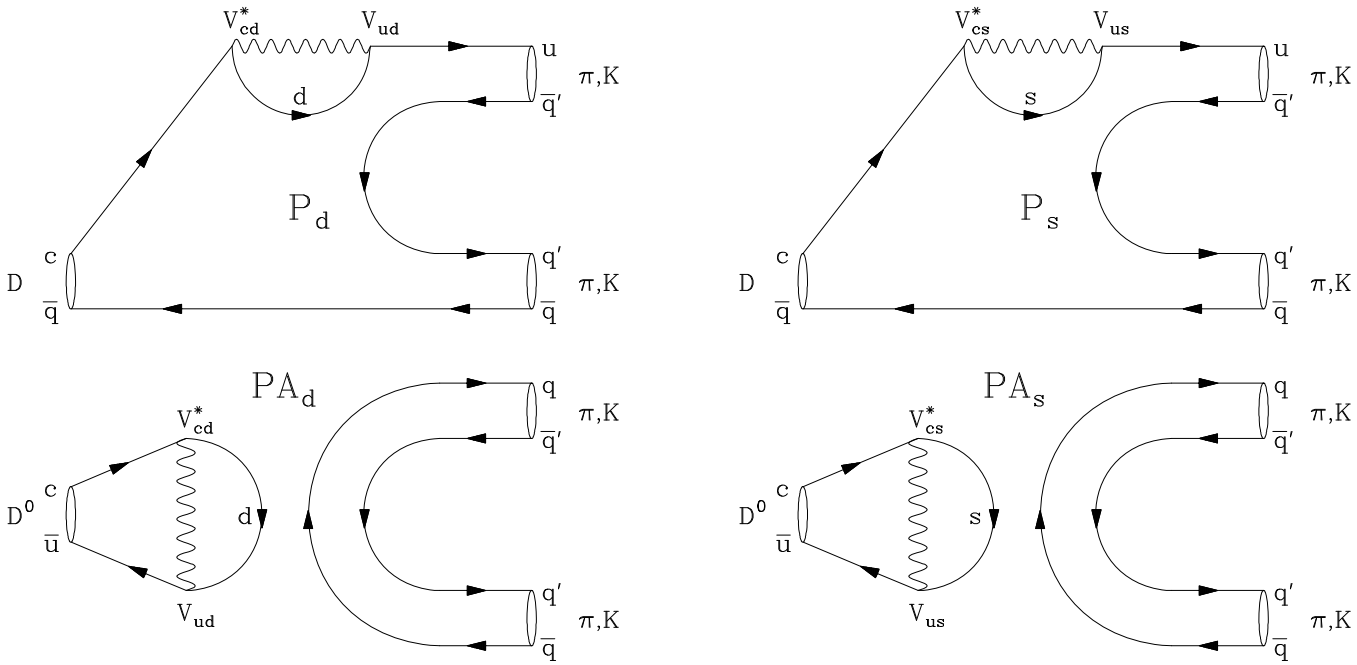
$$|\mathcal{A}(D^0 \to K^+K^-)| \;=\; |\;\lambda\,(T_K+E)| \;=\; 7.42\ ;$$
$$|\mathcal{A}(D^0 \to \pi^+\pi^-)| \;=\; |-\lambda\,(T_\pi+E)| \;=\; 5.74\ .$$

T_K and T_π include factorization corrections involving decay constants $f_{K,\pi}$, form factors $f_+(D \to K, \pi)$, etc.

Penguins with s, d quarks in the loop have same CKM factors as tree! Can contribute to SU(3) breaking without introducing direct CP violation.

Penguin Contributions

$P = P_d + P_s$ 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: theory amplitudes now closer to those measured!

Singly-Cabibbo-suppressed decays

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

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
$K^0\overline{K}^0$	$-(P + PA) + P$	2.39±0.14	2.37
$\pi^+\pi^0$	$-\lambda\,(T_\pi + C)/\sqrt{2}$	2.66±0.07	2.26
$K^+\overline{K}^0$	$\lambda\,(T_K - A_{D^+}) + P$	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

Acceptable fit to D^0 decays; Large errors in D_s^+.

Note that $D^0 \to K^0\overline{K}^0$ depends only on PA.

$\pi^+\pi^0$ gets no penguin contribution. (I = 2 final state).

All other amplitudes depend on P.

A_{CP}: Constraints from LHCb and CDF

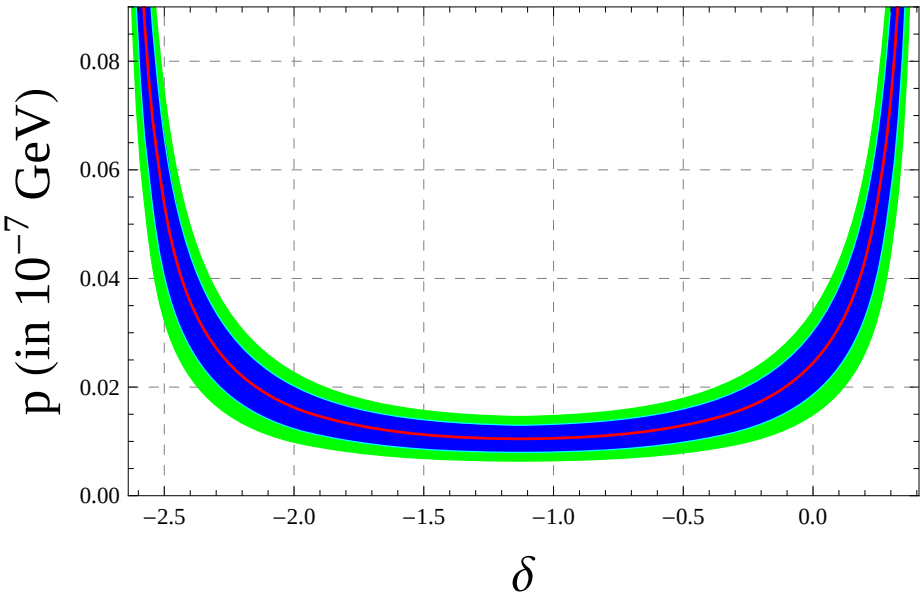
CP asymmetry introduced by adding $P_b = p\ e^{i(\delta-\gamma)}$.

To lowest order in $p/|T|$: $A_{CP} \simeq 2(p/|T|)\sin\gamma\sin(\delta-\phi^T)$.

ϕ^T = Strong phase of tree + P .

90% c.l. CDF bounds constrain δ: $-2.64 \leq \delta \leq 0.41$.

ΔA_{CP} from LHCb + CDF results constrain p vs. δ .



$\Delta A_{CP} = (0.67 \pm 0.16)\%$

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

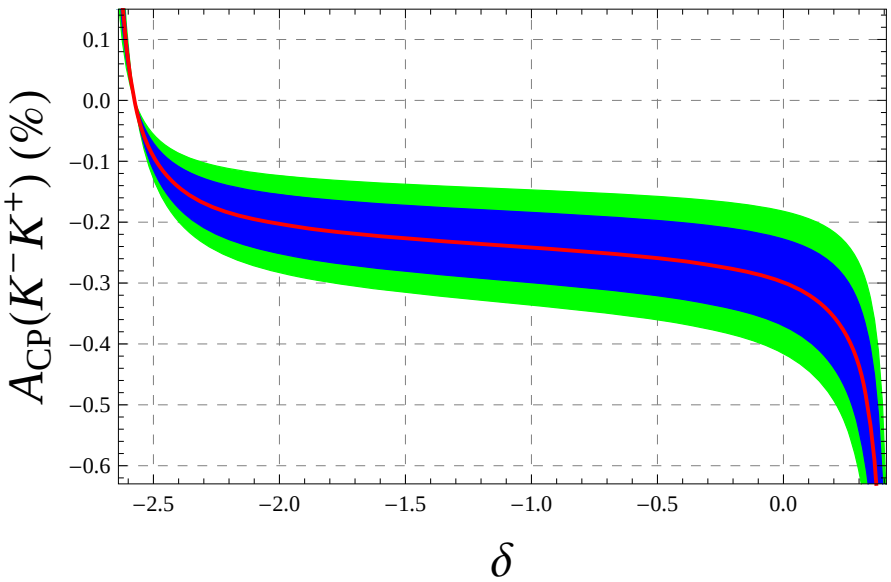
68% c.l. band in **blue** .

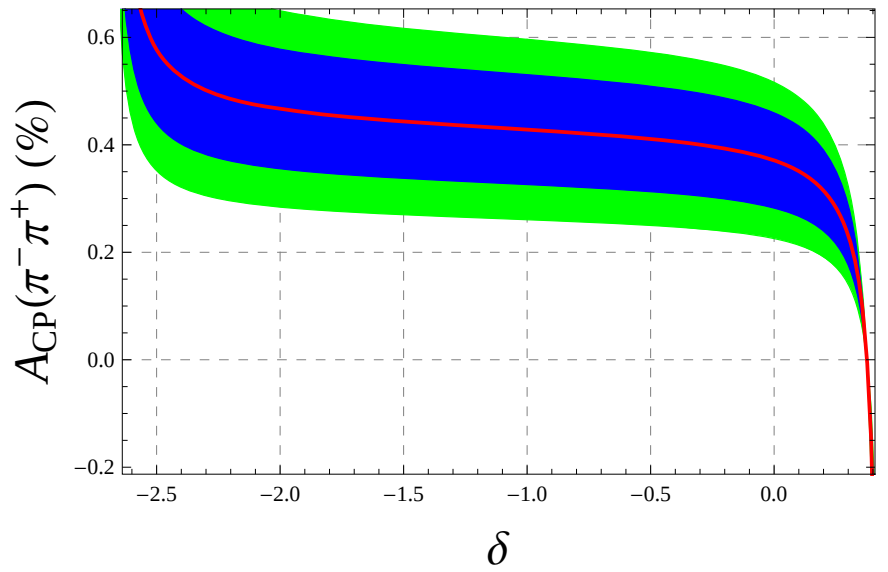
For a large range of δ:

$p < 2 \times 10^{-9}\,GeV$;

$p/|T_{K^+K^-}| \sim 2 \times 10^{-3}$.

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





A_{CP} (as a function of δ)

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

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

U-spin:

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

with broken U-spin:

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

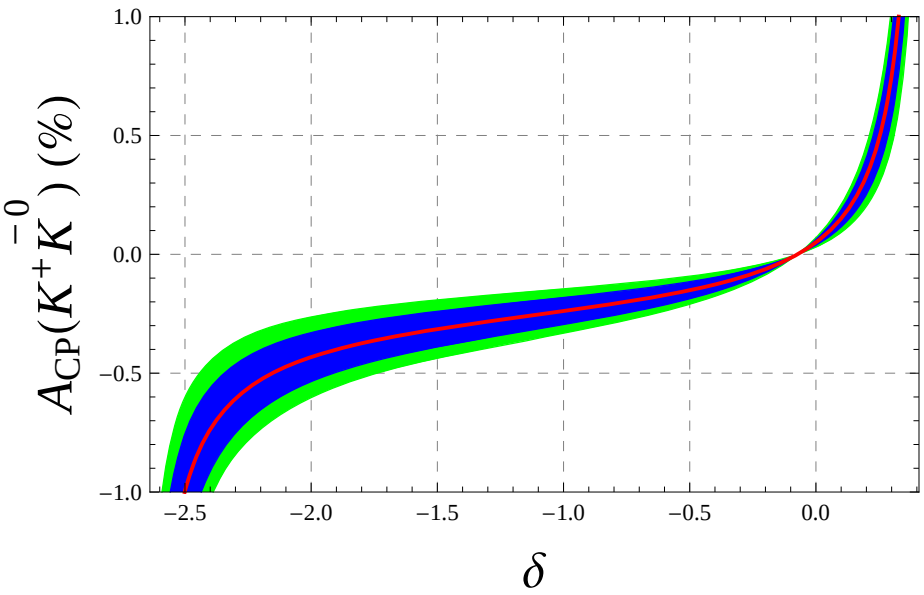
$A_{CP}(\pi^+\pi^-) > 0,$

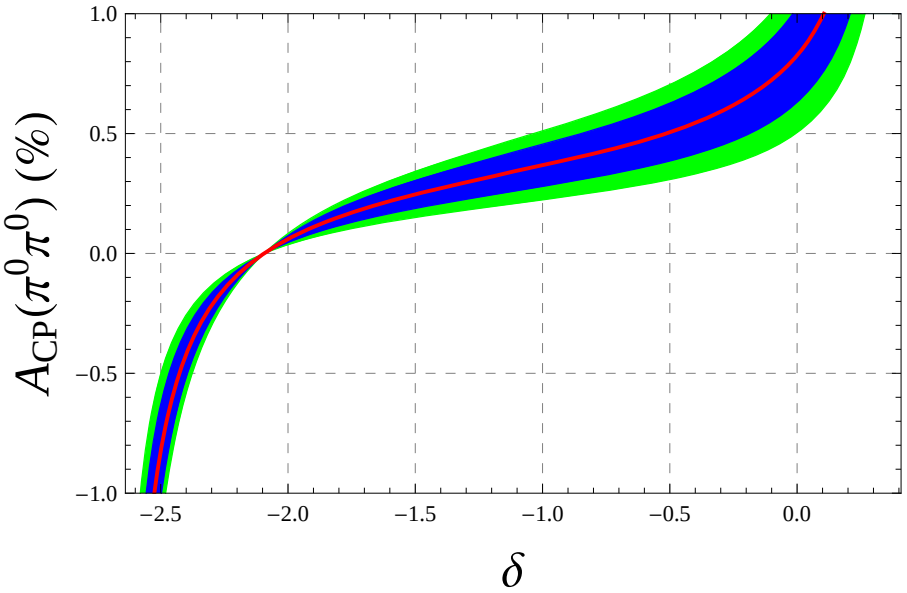
$|A_{CP}(K^+K^-)| < |A_{CP}(\pi^+\pi^-)|$

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} predictions (as a function of δ)

90% c.l. band in **green**; **68%** c.l. band in **blue** .

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

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

These are good targets for A_{CP} measurements ($\delta\mathcal{B}/\mathcal{B} \sim 4\%, 6\%$).

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

Summary and Conclusions

- LHCb and ΔA_{CP} measurements commensurate with SM with 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 strong phase 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

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

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:

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

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

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

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

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