Direct CP Violation in Nonleptonic Charm Decays

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Talk based on:
BB, Michael Gronau, Jon Rosner, Phys. Rev. D **85**, 054014

What is interesting?

Direct CP asymmetry in $D^0 \to f$, where $f = K^+K^-, \pi^+\pi^-$:

$$\mathcal{A}_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \bar{f})}$$

Experiments measure : CP violation in Charm $(2.5 - 3.5\sigma)$!

$$\begin{aligned} \Delta\mathcal{A}_{CP} &= \mathcal{A}_{CP}(K^+K^-) - \mathcal{A}_{CP}(\pi^+\pi^-) \\ &= [-0.82 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})] \quad (\mathrm{LHCb}) \\ &= [-0.62 \pm 0.21(\mathrm{stat}) \pm 0.10(\mathrm{syst})] \quad (\mathrm{CDF}) \end{aligned}$$

Questions:

- Is this SM or New physics? We don't know yet!
- U-spin $(d \leftrightarrow s)$: $|A(K^+K^-)| = |A(\pi^+\pi^-)|$;
  In practice $|A(K^+K^-)| < |A(\pi^+\pi^-)|$. Is there a resolution?
- What can we say about other nonleptonic D decays?

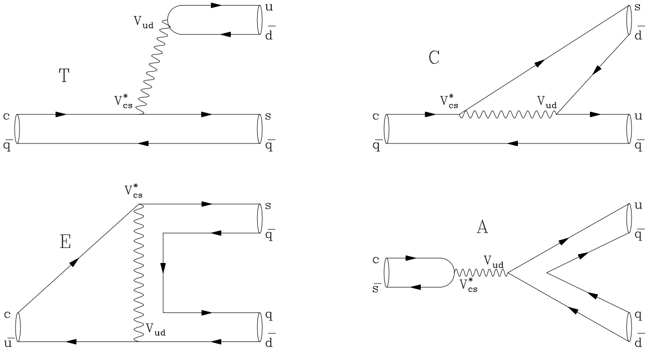
Outline

- Part 1 : Decay amplitudes
- Part 2 : Direct CP Asymmetry
- Summary and Conclusions

Discussion in the context of flavor-SU(3) symmetry

Topologies in Flavor SU(3)

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



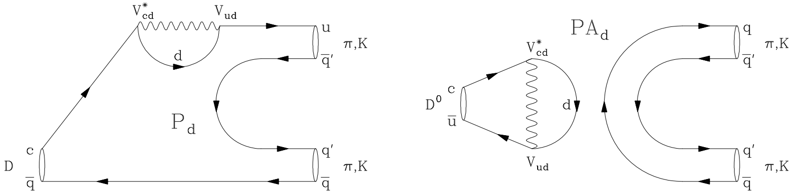
Cabibbo favored$(V^*_{cs}V_{ud} \sim 1)$ *Doubly Cabibbo suppressed*$(V^*_{cd}V_{us} \sim -\lambda^2)$

Singly Cabibbo suppressed$(V^*_{cs}V_{us} \sim \lambda$ or $V^*_{cd}V_{ud} \sim -\lambda)$

$$\lambda = \tan(\theta_{\rm Cabibbo}) = 0.2317$$

Penguins in SCS D decays

Penguin topology (d, s, b quarks in the loop) : Only appear in SCS decays



CKM Unitarity $\Rightarrow$ only 2 relevant parameters : P and P_b

$$\sum_q V^*_{cq} V_{uq} \mathcal{P}_q = V^*_{cs} V_{us} (\mathcal{P}_s - \mathcal{P}_d) + V^*_{cb} V_{ub} (\mathcal{P}_b - \mathcal{P}_d) = P + P_b$$

Similarly penguin-annihilation topology: PA and PA_b

CKM suppression $(|V^*_{cb} V_{ub}| \ll |V^*_{cs} V_{us}|) \Rightarrow |P_b| \ll |P|$

Ignore P_b for the discussion of decay rates

Cabibbo-favored decays

8 measured $\mathcal{B}$, 7 unknowns (Real T, C, E, A).

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

Singly-Cabibbo-suppressed D decays

$T' \sim \pm\lambda T$ $(+(-)$ if $V_{cs}(V_{cd}))$, C', E', A'.

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:

$$\begin{aligned} |\mathcal{A}(D^0 \to \pi^+\pi^-)| &= 4.70 \pm 0.08 \; ; \\ |\mathcal{A}(D^0 \to K^+K^-)| &= 8.49 \pm 0.10 \; ; \\ |\mathcal{A}(D^0 \to K^0\overline{K}^0)| &= 2.39 \pm 0.14 \; . \end{aligned}$$

$|\lambda\,(T + E)| \; = \; 5.82$.
in units of $10^{-7}\,GeV$.
$\sim (E'_s - E'_d)$

Factorizable SU(3) breaking in T :
$|\mathcal{A}(D^0 \to \pi^+\pi^-)| = |-\lambda\,(T_\pi + E)| \; = \; 5.74$.
$|\mathcal{A}(D^0 \to K^+K^-)| = |\;\lambda\,(T_K + E)| \; = \; 7.42$;

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

Fit to extract penguins

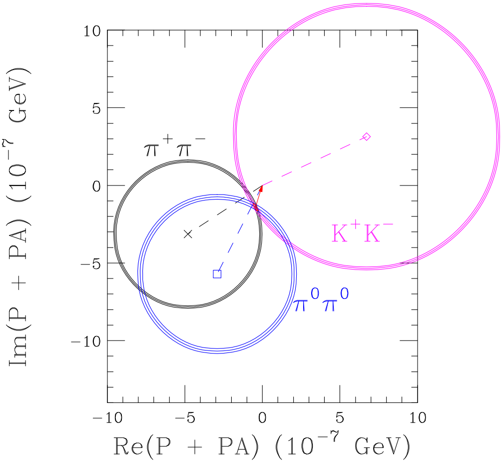
Extract P and $P + PA$ by fitting to SCS decay rates.

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

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.

Construction technique



- Amplitudes normalized so that coefficient of $P + PA$ is unity
- Radius of circle represents measured amplitude
- Center of circle represents known parameters
- Intersection of circles represents $P + PA$

$\chi^2 \sim 0.012$: solution in line with clear intersection of circles.

$$|P + PA|/|A_{K^+K^-}| \sim 0.2$$

Direct CP Asymmetry

$$\mathcal{A}_{CP}(f) \equiv \frac{\Gamma(D^0\to f)-\Gamma(\overline{D}^0\to \bar{f})}{\Gamma(D^0\to f)+\Gamma(\overline{D}^0\to \bar{f})} \quad \text{with} \quad f = \pi^+\pi^-, K^+K^-$$

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

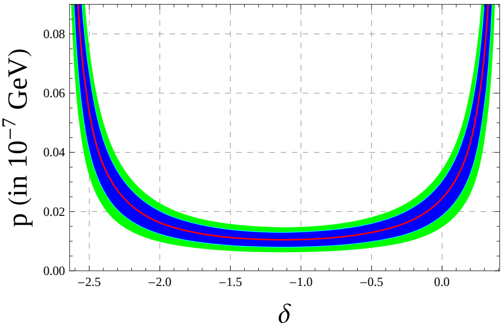
- Direct CP asymmetry : 2 terms with different strong and weak phases
- Add CPV penguin : $P_b = p\, e^{i\delta}\, e^{-i\gamma}$;

$$A_f = T_f + P_b = T_f \left(1 + \frac{|P_b|}{|T_f|} e^{i(\delta_f-\gamma)}\right) \qquad \overline{A}_{\bar{f}} \equiv A_f|_{\gamma\to-\gamma}$$

$$\Rightarrow \boxed{\mathcal{A}_{CP} \approx 2\,\frac{|P_b|}{|T_f|}\ \sin\delta_f \sin\gamma}\ , \text{ where } \delta_f = \delta - \phi_T^f$$

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(K^+K^-) - \mathcal{A}_{CP}(\pi^+\pi^-) : \text{ Constrain } \delta \text{ vs } |P_b|$$

Results:



$\Delta\mathcal{A}_{CP} = (-0.67 \pm 0.16)\%$;
(Combined LHCb + CDF)
68% c.l. band in **blue** ,
90% c.l. band in **green**

90% c.l. CDF bounds :
$-0.63\% \leq \mathcal{A}_{CP}(K^+K^-) \leq 0.15\%$
$-0.21\% \leq \mathcal{A}_{CP}(\pi^+\pi^-) \leq 0.65\%$
$-2.64 \leq \delta \leq 0.41$

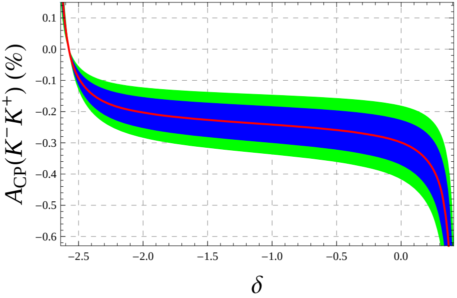
For a large range of δ :
$p = |P_b| < 2 \times 10^{-9}\,GeV$;
$|P_b|/|T_{K^+K^-}| \sim 2 \times 10^{-3}$

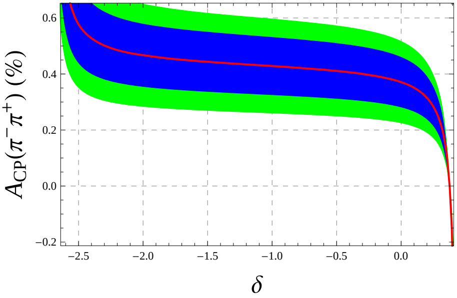
Compare with SM-theory prediction :

$$\frac{|P_b|}{|T_f|} = \frac{|V^*_{cb}V_{ub}|}{|V^*_{cd}V_{ud}|} \cdot \frac{|\mathcal{P}_b|}{|\mathcal{T}_f|} \sim 2 \times 10^{-4}$$

An order of magnitude enhancement of the CPV penguin
– Not surprising : Nonperturbative effects!

$\mathcal{A}_{CP}(K^+K^-)$ and $\mathcal{A}_{CP}(\pi^+\pi^-)$





$\mathcal{A}_{CP}$ vs δ using $p - \delta$ constraint

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

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

U-spin :

$\mathcal{A}_{CP}(K^+K^-) \approx -\mathcal{A}_{CP}(\pi^+\pi^-)$

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

For a large range of δ:

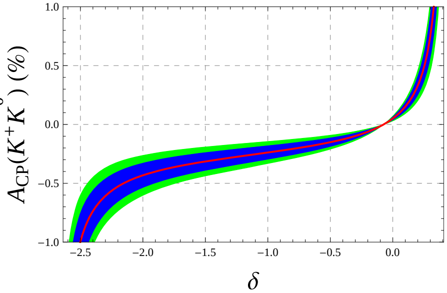
$$\mathcal{A}_{CP}(K^+K^-) < 0,$$
$$\mathcal{A}_{CP}(\pi^+\pi^-) > 0,$$

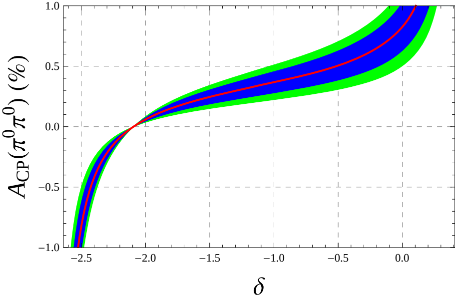
$$|\mathcal{A}_{CP}(K^+K^-)| < |\mathcal{A}_{CP}(\pi^+\pi^-)|$$

To pinpoint δ:

Need to significantly reduce individual $\mathcal{A}_{CP}$ error bars.

Predictions: $\mathcal{A}_{CP}(K^+\overline{K}^0)$ and $\mathcal{A}_{CP}(\pi^0\pi^0)$





$\mathcal{A}_{CP}$ vs δ using $p - \delta$ constraint

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

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

$\mathcal{A}_{CP}$ in $K^+\overline{K}^0$ and $\pi^0\pi^0$ are correlated

Over a large range of δ :

$$|\mathcal{A}_{CP}| < 1\%$$

Belle Result from 2010 :

$\mathcal{A}_{CP}(K^+\overline{K}^0) = (-0.16 \pm 0.58 \pm 0.25)\%$

If CPV in K^+K^- and $\pi^+\pi^-$ is confirmed, look for CPV in $D^+ \to K^+\overline{K}^0, D^0 \to \pi^0\pi^0$

$\mathcal{A}_{CP}$ in other SCS decays

$D^+ \to K^+\overline{K}^0$ and $D^0 \to \pi^0\pi^0$ are good targets for $\mathcal{A}_{CP}$ measurements : rate measurements are under control ($\delta\mathcal{B}/\mathcal{B} \sim 4\%, 6\%$)

$\mathcal{A}_{CP}$ in SCS D_s^+ decays are harder to predict at the moment ($\delta\mathcal{B}/\mathcal{B} > 10\%$)

$\mathcal{A}_{CP}$ in SCS D decays involving a final state η/η' also complicated : Rates may involve large singlet amplitudes (disconnected diagrams)

In our model $\mathcal{A}_{CP} = 0$ in $D^0 \to K^0\overline{K}^0$ and $D^+ \to \pi^+\pi^0$

$\mathcal{A}_{CP}(K^0\overline{K}^0) \neq 0$ can be explained by adding PA_b (annihilation penguin)

$\mathcal{A}_{CP}(\pi^+\pi^0) \gtrsim 0.1\%$ cannot be explained by a SM penguin
Need new-physics amplitudes with both strong and weak phases different from SM tree

Interesting to study $D \to PV$ decays using a similar framework

Summary and Conclusions

- LHCb and CDF $\Delta\mathcal{A}_{CP}$ measurements call for an enhanced CPV penguin (compared to a typical SM-theory penguin)
- A wide range of values allowed for the relative strong phase between tree and CPV penguin
- $\mathcal{A}_{CP}$ in $D^+ \to K^+\overline{K}^0$ and $D^0 \to \pi^0\pi^0$ predicted to be correlated and close to a percent level!
- Reducing error on individual $\mathcal{A}_{CP}$ can lead to better prediction of $\mathcal{A}_{CP}$ in other channels
- $\mathcal{A}_{CP} \neq 0$ 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
- If CPV in $D \to K^+K^-, \pi^+\pi^-$ is confirmed : A plethora of D decay channels need to be studied both theoretically and experimentally!

$\mathcal{A}_{CP}$ 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 $\mathcal{A}_{CP}$ appreciably!

CKM Unitarity: $\lambda_d + \lambda_s + \lambda_b = 0; \quad (\lambda_b = V_{cb}^* V_{ub})$

$\sin\phi = \sin[\mathrm{Arg}(\lambda_s \lambda_d^*)] = \frac{\lambda_b}{\lambda_s} \sin\gamma \approx 6.8 \times 10^{-4}$

$\mathcal{A}_{CP} \approx -2\frac{|P+PA|}{|T_f|} \sin\phi = -2\frac{|\mathcal{P}+\mathcal{PA}|}{|\mathcal{T}_f|} \cdot \frac{|V_{cb}^* V_{ub}|}{|V_{cs}^* V_{us}|} \sin\gamma$

$\mathcal{A}_{CP}(K^+K^-)$ and $\mathcal{A}_{CP}(\pi^+\pi^-) \sim (1-2) \times 10^{-3}$

Order of magnitude smaller than $\mathcal{A}_{CP}$ from P_b!

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

$\Delta\mathcal{A}_{CP}$ from LHCb measurement

$$\mathcal{A}_{\mathrm{Raw}}(f) = \mathcal{A}_{CP}(f) + \mathcal{A}_D(f) + \mathcal{A}_D(\pi_s) + \mathcal{A}_P(D^*)$$

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:

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

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

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

Thus: $\Delta\mathcal{A}_{CP} \simeq \mathcal{A}_{CP}^{\mathrm{dir}}(K^+K^-) - \mathcal{A}_{CP}^{\mathrm{dir}}(\pi^+\pi^-)$

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