Direct CP violation in SCS D decays: Standard Model versus Current Bounds

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Introduction

CPV in charm provides a unique probe of New Physics (NP)

- sensitive to NP in the up sector
- SM charm physics is CP conserving to first approximation (2 generation dominance)

Nevertheless, the statement "any signal for CPV would be NP" needs sharpening due to continuing improvement in experimental bounds:

- In the SM, CPV in mixing enters at $O(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$
  - how large can SM indirect CPV really be?
- In the SM, direct CPV enters at $O([V_{cb}V_{ub}/V_{cs}V_{us}]\ \alpha_s/\pi) \sim 10^{-4}$ in singly Cabibbo suppressed decays (SCS)
  - how large can SM direct CPV really be?

Three types of D decays

- Cabibbo Favored (CF)

$$c \to s\bar{d}u \quad (D \to K^- \pi^+)$$

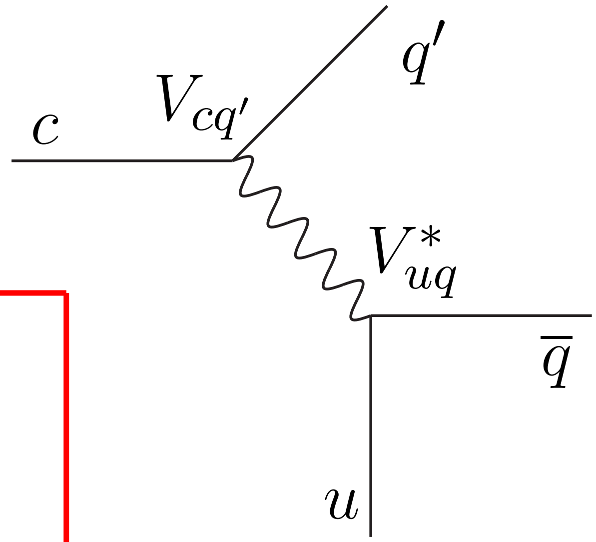
- Singly Cabibbo Suppressed (SCS)

$$c \to s\bar{s}u \quad (D \to K^- K^+)$$

$$c \to d\bar{d}u \quad (D \to \pi^- \pi^+)$$

- Doubly Cabibbo Suppressed (DCS)

$$c \to d\bar{s}u \quad (D \to \pi^- K^+)$$



$$q, q' = s, d$$

Direct CP Violation

Consider CP conjugate decay amplitudes of mesons $M \to f$ and $\bar{M} \to \bar{f}$:

$$A_f(M \to f) = A_f^T e^{-i\phi_f^T} [1 + r_f e^{i(\delta_f + \phi_f)}]$$

$$\overline{A}_{\overline{f}}(\bar{M} \to \bar{f}) = A_f^T e^{-i\phi_f^T} [1 + r_f e^{i(\delta_f - \phi_f)}]$$

- A_f^T is a dominant tree-level amplitude with weak (CP violating) phase ϕ_f^T; r_f is relative magnitude of subleading amplitude containing new weak phase ϕ_f , relative strong phase δ_f;

- In SM SCS D decays the subleading amplitudes are the penguins

- Direct CP asymmetry:

$$a^{\rm dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 - |\bar{A}_{\bar{f}}|^2} = 2 r_f \sin\phi_f \sin\delta_f$$

- in charged $D_{(s)}$ decays, straightforward to measure - just the rate difference:

$$a^{\rm dir} = \frac{\Gamma(D^+ \to f) - \Gamma(D^- \to \bar{f})}{\Gamma(D^+ \to f) + \Gamma(D^- \to \bar{f})}$$

e.g., $a^{\rm dir}(K_s K^+) = (0.09 \pm 0.63)\%$ HFAG, (at Belle: $0.16 \pm 0.6\%$)

- D^0's more complicated: must subtract indirect CPV contribution from time integrated CP asymmetries:

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

- The indirect CP asymmetry $a^{\rm ind} = a^m + a^i$
  - a^m: CP violation in mixing CPVMIX
  - a^i: CP violation in the interference of decays with and without mixing CPVINT
  - $a^{\rm ind}$ is universal - independent of final state. Note $a^{\rm ind} = \Delta Y$ (the time-dependent CP asymmetry)

- at the B-factories

$$a_f = a_f^{\mathrm{dir}} + a^{\mathrm{ind}}, \quad a^{\mathrm{ind}} = a^m + a^i$$

- at CDF (due to cuts on proper decay times):

$$a_{\pi^+\pi^-} = a^{\mathrm{dir}}_{\pi^+\pi^-} + 2.40\, a^{\mathrm{ind}}, \qquad a_{K^+K^-} = a^{\mathrm{dir}}_{K^+K^-} + 2.65\, a^{\mathrm{ind}}$$

- at LHCb (due to cuts on proper decay times):

$$a_{K^+K^-} - a_{\pi^+\pi^-} = a^{\mathrm{dir}}_{K^+K^-} - a^{\mathrm{dir}}_{\pi^+\pi^-} + (0.1 \pm 0.01)\, a^{\mathrm{ind}}$$

$D \to K^+K^-$ and $D \to \pi^+\pi^-$ in the SM

Obtain the effective weak $\Delta C = 1$ Hamiltonian $H_{\rm eff}$ at scales $\mu \sim m_c$ to NLO:

- W is integrated out at $\mu \approx m_W$
- b-quark is integrated out at scale $\mu \approx m_b$ with NLO matching, yielding

$$H_{\rm eff}^{\Delta C=1} = \frac{G_F}{\sqrt{2}} \left[\sum_{p=d,s} V_{cp}^* V_{up} \left(C_1 Q_1^p + C_2 Q_2^p \right) - V_{cb}^* V_{ub} \sum_{i=3}^{6} C_i(\mu) Q_i(\mu) + C_{8g} Q_{8g} \right] + \text{H.c.}$$

  - "Tree" operators (α, β are color indices)

$$Q_1^p = (\bar{p}c)_{V-A}(\bar{u}p)_{V-A} \qquad Q_2^p = (\bar{p}_\alpha c_\beta)_{V-A}(\bar{u}_\beta p_\alpha)_{V-A}$$

  - Penguin operators ($q = u, d, s$)

$$Q_3 = (\bar{u}c)_{V-A} \sum_q (\bar{q}q)_{V-A} \qquad Q_4 = (\bar{u}_\alpha c_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V-A}$$

$$Q_5 = (\bar{u}c)_{V-A} \sum_q (\bar{q}q)_{V+A} \qquad Q_6 = (\bar{u}_\alpha c_\beta)_{V-A} \sum_q (\bar{q}_\beta q_\alpha)_{V+A}$$

$$Q_{8g} = -\frac{g_s}{8\pi^2} m_c \bar{u}\, \sigma_{\mu\nu}(1+\gamma_5) G^{\mu\nu} c$$

- Renormalization group running of Wilson coefficients $C_i(\mu)$ from $\mu \approx m_b$ to $\mu \sim m_c$

The tree amplitudes

- the tree amplitudes (in $SU(3)_F$ diagrammatic notation) are

$$A^T(K^+K^-) = V_{cs}^* V_{us}(T_{KK} + E_{KK}), \quad A^T(\pi^+\pi^-) = V_{cd}^* V_{ud}(T_{\pi\pi} + E_{\pi\pi})$$

T is the usual tree-level amplitude, E is the "W-exchange " annihilation topology power correction amplitude

- T_{PP} at leading power and in naive factorization is the familiar $T \propto f_\pi F_{D\to\pi}$
- The PP data implies

$$E_{KK} \sim T_{KK}, \quad E_{\pi\pi} \sim T_{\pi\pi}$$

with large relative strong phases, large $SU(3)$ breaking

- Set magnitudes of tree amplitudes equal to the measured ones

$$10^6 A^T(K^+K^-) \approx 0.8 \text{ GeV}, \quad 10^6 A^T(\pi^+\pi^-) \approx 0.5 \text{ GeV}$$

The QCD penguin amplitudes at leading power

- the penguin amplitudes are

$$A^P(K^+K^-) = -V_{cb}^* V_{ub} P_{KK}, \quad A^P(\pi^+\pi^-) = -V_{cb}^* V_{ub} P_{\pi\pi}$$

weak phases (relative to trees): $-\gamma$ $(\pi\pi)$ and $\pi - \gamma$ (KK), and $\sin\gamma \approx 0.9$

- Evaluate leading power penguin amplitudes at NLO in QCD factorization: naive factorization + $O(\alpha_s)$ corrections (down and strange quark loop penguin contractions, vertex corrections, hard spectator interactions)

- Study penguin/tree amplitude ratios for K^+K^-, $\pi^+\pi^-$:

$$r^{\mathrm{LP}} \equiv \left| \frac{A^P(\text{leading power})}{A^T(\exp)} \right|$$

$$r^{\mathrm{LP}}(K^+K^-) \approx (0.01 - 0.02)\,\%, \quad r^{\mathrm{LP}}(\pi^+\pi^-) \approx (0.015 - 0.025)\%$$

(ren. scales $\mu \in [1, m_D]$ GeV; $m_d, m_s \sim 0.1 - 0.4$ GeV in the penguin contraction loops,....)

- Leading power would yield the naive expectation $a^{\mathrm{dir}} = O(0.01\%)$, assuming $O(1)$ strong phases δ_f

QCD penguin power corrections

- Consider "annihilation" topology: two examples

$$\mathrm{Amp}_1(PP) = -\frac{G_F}{\sqrt{2}} V_{cb} V_{ub}^* \, C_6^{\mathrm{eff}} \times \langle P^+ P^- | -2\,(\bar{u}u)_{S+P} \otimes^A (\bar{u}c)_{S-P} | D^0 \rangle$$

$$\mathrm{Amp}_2(PP) = -\frac{G_F}{\sqrt{2}} V_{cb} V_{ub}^* \, 2\,(C_4^{\mathrm{eff}} + C_6^{\mathrm{eff}}) \times \langle P^+ P^- | \,(\bar{u}_\alpha u_\beta)_{V\pm A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A} | D^0 \rangle$$

- the effective Wilson coefficients correspond to combinations of the annihilation and "penguin contraction" annihilation transition operators. They eliminate the leading $\log(\mu)$ dependence, and scheme dependence in the amplitudes

$$C_6^{\mathrm{eff}}\left(\mu, \frac{q^2}{m_c^2}\right) = C_6(\mu) + C_1(\mu)\frac{\alpha_s(\mu)}{2\pi}\left(\frac{1}{6} + \frac{1}{3}\log\left(\frac{m_c}{\mu}\right) - \frac{1}{8} G\left[\frac{m_s^2}{m_c^2}, \frac{m_d^2}{m_c^2}, \frac{q^2}{m_c^2}\right]\right)$$

We can obtain the order of magnitudes of these matrix elements by appealing to the tree-level "W-exchange annihilation amplitudes

- can write the latter as

$$E_{PP} = \frac{G_F}{\sqrt{2}} C_1 \sin\theta_c \langle P^+P^-|(\bar{p}_\alpha p_\beta)_{V-A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A}|D\rangle, \;\; p = d, s$$

- expect that

$$\frac{\langle P^+P^-|(\bar{u}u)_{S+P} \otimes^A (\bar{u}c)_{S-P}|D^0\rangle}{\langle P^+P^-|(\bar{p}_\alpha p_\beta)_{V-A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A}|D\rangle} = O(N_c)$$

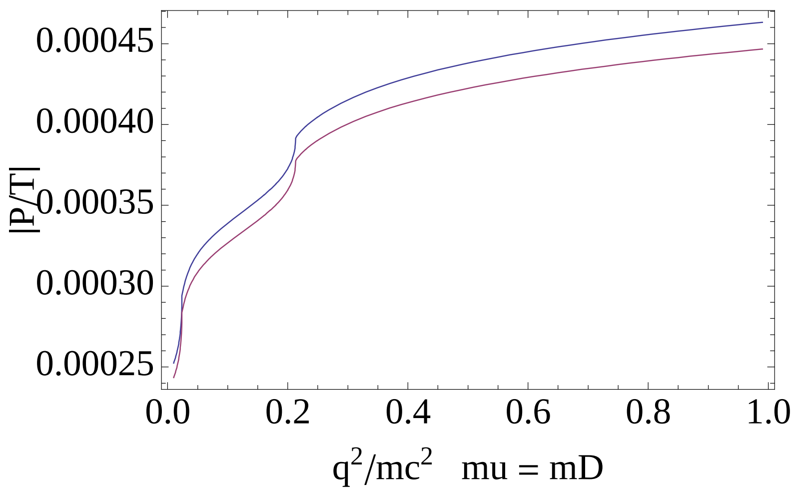
$$\frac{\langle P^+P^-|\,(\bar{u}_\alpha u_\beta)_{V\pm A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A}|D^0\rangle}{\langle P^+P^-|(\bar{p}_\alpha p_\beta)_{V-A} \otimes^A (\bar{u}_\beta c_\alpha)_{V-A}|D\rangle} = O(1)$$

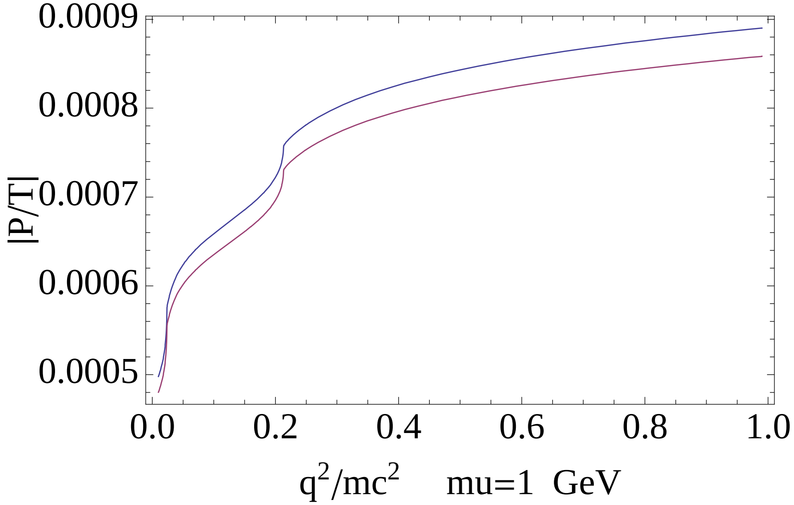
  - know that $E_{KK} \sim T_{KK}$ and $E_{\pi\pi} \sim T_{\pi\pi}$ from experiment
  - setting E_{KK}, $E_{\pi\pi}$ equal to the measured amplitudes yields estimates for the non-perturbative annihilation amplitudes
  - the resulting estimates for $|P/T|$ depend on the momentum transfer (q^2/m_c^2) in the "annihilation penguin contractions"

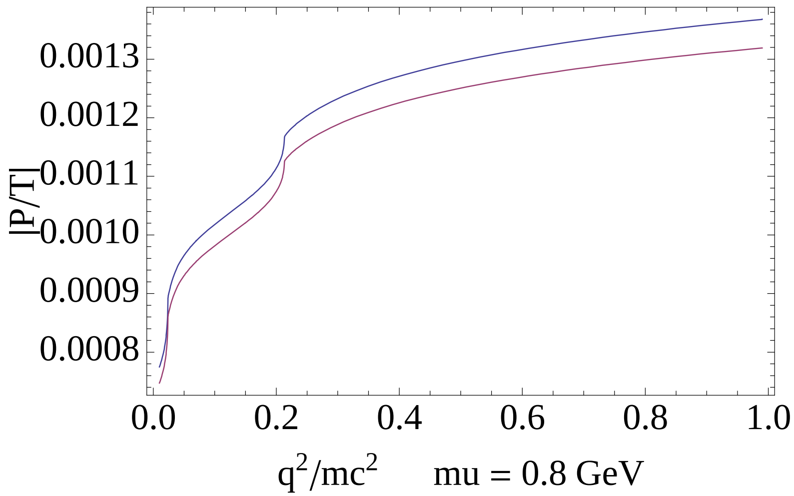
Order of magnitude estimates of $|P/T|$

Plots of $|P/T|$ vs. q^2/m_c^2 for annihilation example Amp_1, for three renormalization scales: $\mu = m_D$, 1 GeV, 0.8 GeV ($m_s = 0.3$, $m_d = 0.1$ in the penguin contractions)

K^+K^- (purple), and $\pi^+\pi^-$ (blue)



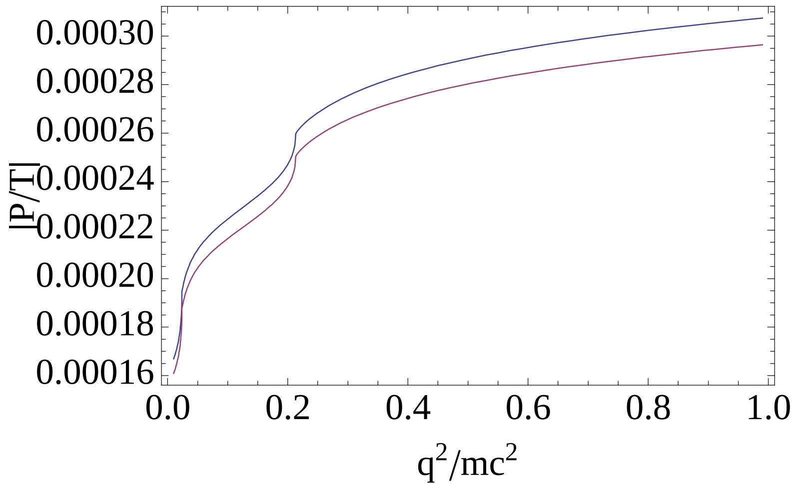


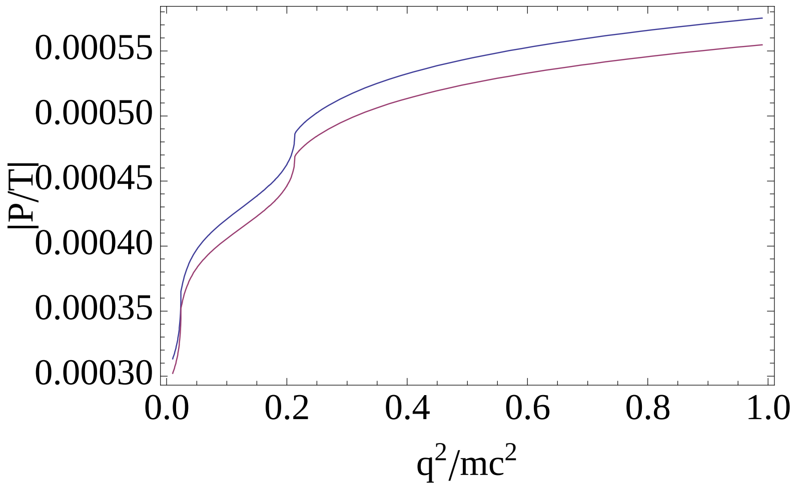


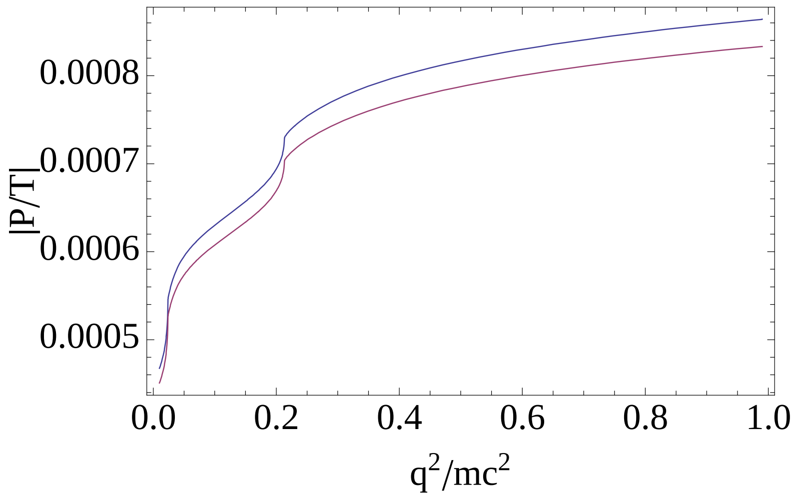
Order of magnitude estimates of $|P/T|$

Plots of $|P/T|$ vs. q^2/m_c^2 for Amp_2, for three renormalization scales: $\mu = m_D$, 1 GeV, 0.8 GeV ($m_s = 0.3$, $m_d = 0.1$ in the penguin contractions)

K^+K^- (purple), and $\pi^+\pi^-$ (blue)







Conclusion

- find that its plausible that QCD penguin power corrections can yield $|P/T| \lesssim 0.1\%$ for $\pi^+\pi^-$ and K^+K^-
- given that $\sin\gamma \approx 0.9$, and that large strong phases are expected in power corrections, particularly at the D mass scale, it is therefore also plausible that $a^{\rm dir} \lesssim 0.1\%$ for K^+K^- and $\pi^+\pi^-$.
- the generic expectation from U-spin symmetry is that $a^{\rm dir}(\pi^+\pi^-) = -a^{\rm dir}(K^+K^-)$ Grossman, AK, Nir
  - U-spin predicts that the "Tree" amplitudes have opposite sign,while the penguin ampltiudes have same sign
  - this is also true for New Physics in the penguins that could enhance the asymmetries
  - large U-spin violation in power corrections could soften this conclusion, and lead to different magnitudes for the two asymmetries
- An example of New Physics in penguins that could enhance the direct CP asymmetries by $O(10)$ without violating the $D^0 - \overline{D^0}$ mixing bound is supersymmetic gluino - squark loops with large charm-top squark mass insertions Grossman, AK, Nir
- Other examples with enhancement exist, e.g., little Higgs models Bigi et al