New Physics Models of Direct CP Violation in Charm Decays

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Evidences of CP Violation

LHCb observed a difference between the time integrated CP asymmetries in $D \to K^+K^-$ and $D \to \pi^+\pi^-$ (LHCb, 1112.0938)

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

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

Confirmed by CDF (CDF Note 10784)

$$\Delta A_{\text{CP, CDF}} = (-0.62 \pm 0.21 \pm 0.10)\%$$

$$\Delta A_{\text{CP, world average}} = (-0.67 \pm 0.16)\%$$

3.8σ away from zero.

CP Violation in the SM

- Naively $\Delta A_{\text{CP}} = \mathcal{O}((\alpha_s/\pi)(V_{ub}V_{cb}^*)/(V_{us}V_{cs}^*)) \sim 0.01\%$.
- Precise SM calculation is difficult as m_c is close to Λ_{QCD}.

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- Precise SM calculation is difficult as m_c is close to Λ_{QCD}.
- Some works have suggested that the SM contributions can be big. (Golden & Grinstein, Phys.Lett.B222, 501; Brod,et.al: 1111.5000; Cheng & Chiang: 1201.0785; Brod,et.al.: 1203.6659)

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- Precise SM calculation is difficult as m_c is close to Λ_{QCD}.
- Some works have suggested that the SM contributions should be small. (Franco,et.al.:1203.3131; Li,et.al: 1203.3120)

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- Precise SM calculation is difficult as m_c is close to Λ_{QCD}.
- The SM contributions can be either big or small.
- But this could be a sign of new physics!

Our Approach

- We consider new physics models with minimal additional field contents.
- We use naive factorization and allow $1\times$ and $3\times$ enhancement.
- We impose relevant constraints from flavor physics measurements and collider experiments.

$\Delta F = 1$ Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = \Big(\sum_p \lambda_p \sum_{i=1}^{2} \Big(C_i^{(1)p} O_i^{(1)p} + \tilde{C}_i^{(1)p} \tilde{O}_i^{(1)p} \Big) + \sum_i \Big(C_i^{(1)} O_i^{(1)} + \tilde{C}_i^{(1)} \tilde{O}_i^{(1)} \Big) \Big) + \text{ h.c. },$$

where $\lambda_p = V_{cp} V_{up}^*$.

$\Delta F = 1$ Effective Hamiltonian

$$
\begin{aligned}
O_1^{(1)p} &= (\bar{u}p)_{V-A}(\bar{p}c)_{V-A} \,, \\
O_2^{(1)p} &= (\bar{u}_\alpha p_\beta)_{V-A}(\bar{p}_\beta c_\alpha)_{V-A} \,, \\
O_3^{(1)} &= (\bar{u}c)_{V-A}\sum_q(\bar{q}q)_{V-A} \,, \\
O_4^{(1)} &= (\bar{u}_\alpha c_\beta)_{V-A}\sum_q(\bar{q}_\beta q_\alpha)_{V-A} \,, \\
O_5^{(1)} &= (\bar{u}c)_{V-A}\sum_q(\bar{q}q)_{V+A} \,, \\
O_6^{(1)} &= (\bar{u}_\alpha c_\beta)_{V-A}\sum_q(\bar{q}_\beta q_\alpha)_{V+A} \,,
\end{aligned}
$$

$$
\begin{aligned}
O_7^{(1)} &= \frac{3}{2}(\bar{u}c)_{V-A}\sum_q e_q(\bar{q}q)_{V+A} \,, \\
O_8^{(1)} &= \frac{3}{2}(\bar{u}_\alpha c_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V+A} \,, \\
O_9^{(1)} &= \frac{3}{2}(\bar{u}c)_{V-A}\sum_q e_q(\bar{q}q)_{V-A} \,, \\
O_{10}^{(1)} &= \frac{3}{2}(\bar{u}_\alpha c_\beta)_{V-A}\sum_q e_q(\bar{q}_\beta q_\alpha)_{V-A} \,, \\
O_{8g}^{(1)} &= \frac{g_s}{8\pi^2} m_c \bar{u}\sigma^{\mu\nu}(1+\gamma_5)c_\beta t^a_{\alpha\beta}G^a_{\mu\nu} \,, \\
O_{S1}^{(1)} &= (\bar{u}P_L s)(\bar{s}P_L c) \,, \\
O_{S2}^{(1)} &= (\bar{u}_\alpha P_L s_\beta)(\bar{s}_\beta P_L c_\alpha) \,, \\
O_{T1}^{(1)} &= (\bar{u}\sigma_{\mu\nu}P_L s)(\bar{s}\sigma^{\mu\nu}P_L c) \,, \\
O_{T2}^{(1)} &= (\bar{u}_\alpha\sigma_{\mu\nu}P_L s_\beta)(\bar{s}_\beta\sigma^{\mu\nu}P_L c_\alpha) \,.
\end{aligned}
$$

$\Delta F = 2$ Effective Hamiltonian

$$\mathcal{H}_{\rm eff} = \sum_{i=1}^{5} C_i^{(2)} O_i^{(2)} + \sum_{i=1}^{3} \tilde{C}_i^{(2)} \tilde{O}_i^{(2)} \; + \; \text{h.c.} \; .$$

$$\begin{aligned}
O_1^{(2)D} &= (\bar{u}_\alpha \gamma_\mu P_L c_\alpha)(\bar{u}_\beta \gamma^\mu P_L c_\beta) \; , \\
\tilde{O}_1^{(2)D} &= (\bar{u}_\alpha \gamma_\mu P_R c_\alpha)(\bar{u}_\beta \gamma^\mu P_R c_\beta) \; , \\
\tilde{O}_2^{(2)D} &= (\bar{u}_\alpha P_R c_\alpha)(\bar{u}_\beta P_R c_\beta) \; .
\end{aligned}$$

New Physics

Tree level

- Flavor changing Z'.
- Flavor changing heavy gluon.
- Charged vector boson.
- Two Higgs doublet model.
- Scalar octet.
- Scalar diquarks.

Loop level

- Fermion + scalar loop without GIM mechanism.
- Fermion + scalar loop with GIM mechanism.
- Chirally enhanced magnetic penguin.

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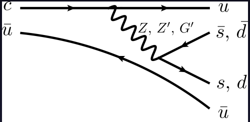
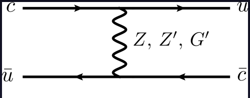
Flavor Changing Z'

$$
\begin{aligned}
\mathcal{L}_{\text{int}} &= g_L \bar{Q}_L^i \gamma^\mu Q_L^i Z'_\mu + g_u \bar{u}_R^i \gamma^\mu u_R^i Z'_\mu \\
&\quad + g_d \bar{d}_R^i \gamma^\mu d_R^i Z'_\mu + X_{cu} \bar{c}_R \gamma^\mu u_R Z'_\mu \ + \ \text{h.c.}\ .
\end{aligned}
$$



(a)



(b)

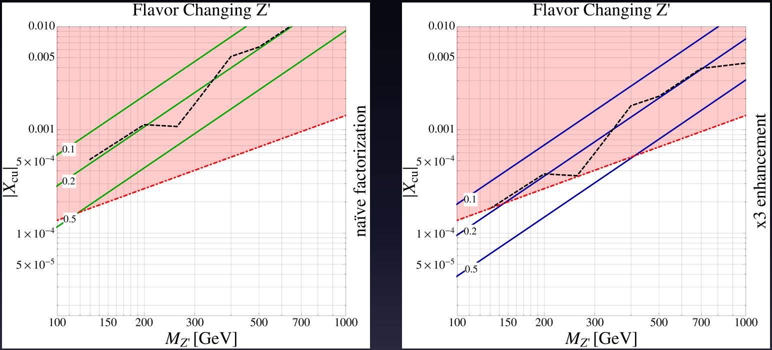
Contributions to CP asymmetry:

$$
\tilde{C}_3^{(1)} = \frac{(g_u + 2g_d)}{3} \frac{X_{cu}^*}{4M_{Z'}^2}, \tilde{C}_9^{(1)} = \frac{2(g_u - g_d)}{3} \frac{X_{cu}^*}{4M_{Z'}^2}, \tilde{C}_5^{(1)} = \frac{g_L X_{cu}^*}{4M_{Z'}^2}.
$$

Contribution to $D^0 - \bar{D}^0$ mixing:

$$
\tilde{C}_1^{(2)D} = \frac{(X_{cu}^*)^2}{2M_{Z'}^2}\ .
$$

Flavor Changing Z'



Bounds considered:

- $D^0 - \bar{D}^0$ mixing.
- Bounds on Z' productions from UA1, CDF and CMS.

Flavor Changing Heavy Gluon

$$\mathcal{L}_{\text{int}} = g_L \bar{Q}^i_L \gamma^\mu T^a Q^i_L (G')^a_\mu + g_u \bar{u}^i_R \gamma^\mu T^a u^i_R (G')^a_\mu + g_d \bar{d}^i_R \gamma^\mu T^a d^i_R (G')^a_\mu + X_{cu} \bar{c}_R \gamma^\mu T^a u_R (G')^a_\mu + \text{h.c.}\,.$$

Contributions to CP asymmetry:

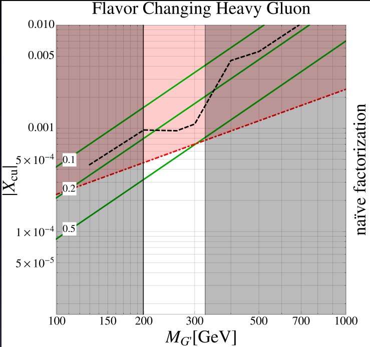
$$\tilde{C}^{(1)}_4 = \frac{(g_u + 2g_d)}{3}\frac{X^*_{cu}}{8M^2_{G'}}\,, \quad \tilde{C}^{(1)}_3 = \frac{-1}{N_c}\tilde{C}^{(1)}_4\,, \tilde{C}^{(1)}_{10} = \frac{2(g_u - g_d)}{g_u + 2g_d}\tilde{C}^{(1)}_4\,,$$

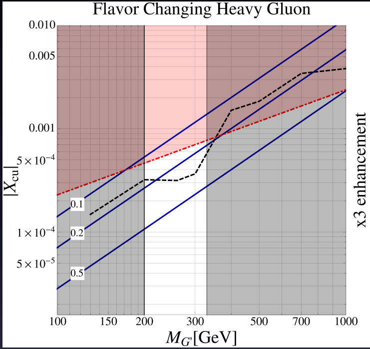
$$\tilde{C}^{(1)}_9 = \frac{-1}{N_c}\tilde{C}^{(1)}_{10}\,, \tilde{C}^{(1)}_6 = \frac{g_L X^*_{cu}}{8M^2_{G'}}\,, \quad \tilde{C}^{(1)}_5 = \frac{-1}{N_c}\tilde{C}^{(1)}_6\,.$$

Contribution to $D^0 - \bar{D}^0$ mixing:

$$\tilde{C}^{(2)D}_1 = \frac{1 - N_c}{2N_c}\frac{(X^*_{cu})^2}{2M^2_{G'}}\,.$$

Flavor Changing Heavy Gluon





Bounds considered:

- $D^0 - \bar{D}^0$ mixing.
- Bounds on Z' productions from UA1, CDF and CMS.
- Dijet pair searches at ATLAS and CMS.

Two Higgs Doublet Model

The most general couplings of the two Higgs bosons to SM fermions read

$$\begin{aligned}\mathcal{L}_{\text{int}} &= Y_u\bar{Q}UH_u + Y_d\bar{Q}DH_d + Y_\ell\bar{L}EH_d \\ &+ X_u\bar{Q}UH_d^\dagger + X_d\bar{Q}DH_u^\dagger + X_\ell\bar{L}EH_u^\dagger + \text{ h.c. }.\end{aligned}$$

Two Higgs Doublet Model

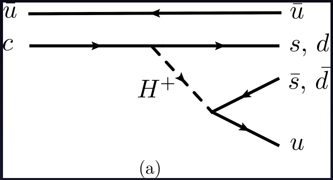
We perform a Minimal Flavor Violation expansion of the X's:

$$\begin{aligned} X_u &= \epsilon_u Y_u + \epsilon'_u Y_u Y_u^\dagger Y_u + \epsilon''_u Y_d Y_d^\dagger Y_u + \ldots \ , \\ X_d &= \epsilon_d Y_d + \epsilon'_d Y_u Y_u^\dagger Y_d + \epsilon''_d Y_d Y_d^\dagger Y_d + \ldots \ , \\ X_\ell &= \epsilon_\ell Y_\ell . \end{aligned}$$

Assumptions:

- We choose a basis $\epsilon_d = 0$.
- We work in the regime of large $\tan\beta \equiv v_u/v_d$ and assume $\epsilon''_u, \epsilon'_d \lll 1$.
- We allow the parameters ϵ_u, ϵ'_u, ϵ''_d, and ϵ_ℓ to be $\mathcal{O}(1)$.

Two Higgs Doublet Model



$$\tilde{C}_{S1}^{(1)} = \frac{m_c m_s}{v^2} \epsilon_u \frac{\tan\beta}{1 + \tilde{\epsilon}_s \tan\beta} \frac{V_{us} V_{cs}^*}{M_{H^\pm}^2}$$

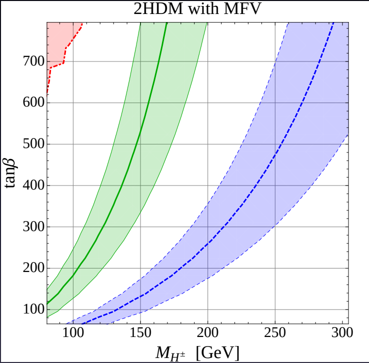
where $\tilde{\epsilon}_s \equiv \epsilon_d'' y_s^2$.

Two Higgs Doublet Model

Bounds considered:

- Direct searches at LEP for a charged Higgs.
- $B^+ \to \tau^+\nu$ and $K^+ \to \mu^+\nu$ decays. (ϵ_ℓ)
- $D^0 - \bar{D}^0$ and $K - \bar{K}$ mixing.
- $B_d \to X_s\gamma$ decay. $(\epsilon_u, \epsilon'_u, \epsilon''_d)$
- Electric dipole moments.
- Top quark decay $t \to H^+b$.
- Direct searches for neutral Higgs bosons.

Two Higgs Doublet Model



We set $\epsilon_u = i$, $\tilde{\epsilon}_t = 0.05i$, $\epsilon_\ell = -1$ and chose ϵ''_d such that $\tilde{\epsilon}_s = 10^{-3}$. All other ϵ_i are set to zero.

Conclusion

- Models with tree level contributions to CP asymmetry in D decays are still allowed.
- We show that flavor changing heavy gluon and 2HDM can explain the LHCb data.

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- Models with tree level contributions to CP asymmetry in D decays are still allowed.
- We show that flavor changing heavy gluon and 2HDM can explain the LHCb data.
- Other models: scalar octet, fermion + scalar loop without GIM mechanism, fermion + scalar loop with GIM mechanism, chirally enhanced magnetic penguin.