New Physics and CP Violation in Singly Cabibbo Suppressed $D$ Decays

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Outline

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**Introduction**

CPV in charm decays provides a unique probe of NP

- SM charm physics is CP conserving (only 2 generations)
  - In mixing, CPV enters at \( O(V_{cb} V_{ub} / V_{cs} V_{us}) \Rightarrow < 10^{-3} \)
  - In decay, penguin CPV enters at \( O(V_{cb} V_{ub} / V_{cs} V_{us} \alpha_s / \pi) \sim 10^{-4} \)

- any signal for CPV would be NP

- uniquely sensitive to the up sector, especially models in which \( \theta_c \) receives a large contribution from the up sector

many \( D' \)'s produced in colliders, and

- easy to tag the flavor of the D, but
- \( D \) lifetime is shorter than \( B \)'s, making time-dependent measurements harder
- \( D \) mixing is very small, therefore mixing induced CPV is very hard to find
We consider time-integrated CPV in singly Cabibbo suppressed decays

\[ \alpha_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(D^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(D^0 \to \bar{f})} \]

Will focus on case where \( f \) is a CP eigenstate, e.g., \( f = K^+K^-, \pi^+\pi^- \), (but non-CP eigenstates, e.g., \( f = K^*K, \rho\pi \) are also very interesting).

- CP asymmetries at the 1% level probe well motivated NP models
- the NP can be in the mixing or in the decay amplitudes
- remarkably, with current experimental reach, sensitivity to CPV gluonic penguins in well motivated NP models is at least as high in \( D \) decays as in \( B \) decays
  - boils down to \( \theta_c m_c \sim V_{cb} m_b \)

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The three types of $D$ decay

- **Cabibbo Favored (CF)**
  \[ c \rightarrow s \bar{d} u \quad (D \rightarrow K^- \pi^+) \]

- **Singly Cabibbo Suppressed (SCS)**
  \[ c \rightarrow s \bar{s} u \quad (D \rightarrow K^- K^+) \]
  \[ c \rightarrow d \bar{d} u \quad (D \rightarrow \pi^- \pi^+) \]

- **Doubly Cabibbo Suppressed (DCS)**
  \[ c \rightarrow d \bar{s} u \quad (D \rightarrow \pi^- K^+) \]
Gluonic penguins from NP

\[ c \rightarrow (\sum q\bar{q})u \] only contributes to SCS \( D \) decays, conversely, only SCS \( D \) decays probe penguins
Formalism
Formalism for CP eigenstates

We use standard notations

\[ x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta \Gamma}{2\Gamma}, \quad \lambda_f \equiv \frac{q}{p} \frac{A_f}{A_f}, \quad \frac{A_{NP}^f}{A^f} = r_f e^{i(\phi_f + \delta_f)} \]

\((\phi_f, \delta_f \text{ are weak and strong phases, respectively})\)

- In the SM \(|q/p| = 1\). With new CPV in mixing, \(|q/p| \neq 1\) is possible
- Experimentally, for SCS decays, \(r_f \lesssim 10^{-2}\)
- Can neglect \(r_f\) in \(\lambda_f\) \(\Rightarrow\) can define

\[ \lambda_f = -|q/p| e^{i\varphi} \]

The phase \(\varphi\) is universal. Its the relative weak phase between the mixing and decay amplitudes. In the SM \(\varphi = 0\).

- Experimentally, \(x, y \lesssim \text{few} \times 10^{-2}\). In the SM \(x, y \sim 10^{-3}\) but due to the large uncertainties \(x, y \sim 10^{-2}\) is possible
Three types of CP violation

Define the time-integrated CP asymmetry

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

\( D^0 \) develops in time \( \Rightarrow D - \overline{D} \) mixing can affect the CP asymmetries. Expanding to leading order in \( r_f \), \( x \), \( y \),

\[ a_f = a_f^d + a_m + a_i \]

- CP violation in decay: \( a_f^d = 2r_f \sin \phi_f \sin \delta_f \)
- CP violation in mixing: \( a_m = -\frac{y}{2}(|q/p| - |p/q|) \cos \varphi \)
- CP violation in the interference of decays with and without mixing: \( a^i = \frac{x}{2}(|q/p| + |p/q|) \sin \varphi \)

the total indirect CP asymmetry \( a^{\text{ind}} = a_m + a^i \) is universal (independent of \( f \))
Separating indirect and direct CP violation

- Can combine with time-dependent CPV measurements for CP eigenstates. To good approximation,

\[ \Gamma(D^0(t) \rightarrow f) \propto \exp[-\hat{\Gamma}_{D^0 \rightarrow f} t], \quad \Gamma(\bar{D}^0(t) \rightarrow f) \propto \exp[-\hat{\Gamma}_{\bar{D}^0 \rightarrow f} t] \]

then the CP violating combination

\[ \Delta Y \equiv \frac{\hat{\Gamma}_{\bar{D}^0 \rightarrow f} - \hat{\Gamma}_{D^0 \rightarrow f}}{2\Gamma_D} = a^m + a^i = a^{\text{ind}} \]

and \( a^d_f = a_f - \Delta Y_f \quad (\Delta Y^{\text{exp}} = (-0.35 \pm 0.47) \times 10^{-2}) \)

- Only using time-integrated info: assuming negligible new CPV in CF or DCS decays, the time-integrated CP asymmetry for CF decay to CP eigenstate gives \( a^{\text{ind}} \), e.g.,

\[ a^d_{P^+P^-} = a_{P^+P^-} - a_{K^0\pi^0}, \quad P = K, \pi \]
New physics
Many NP models can accommodate $D - \overline{D}$ mixing at the 1% level.

The reason is that the bounds on FCNCs in the up sector are not always related to those in the down sector.

One example is the idea of flavor alignment in SUSY. This framework predicts $x \sim 1\%$ with large CP violation.
New physics in decay: tree level

- Tree level exchange can contribute to SCS $D$ decays, e.g., flavor-changing $Z$ exchange (due to extra vectorlike up quarks), $R$-parity violating supersymmetric models, multi-Higgs doublet models

- To get $a_f^d \sim 1\%$ the NP amplitude should satisfy

$$\Im(G_{NP}) \sim 10^{-2} \sin \theta_c G_F$$

- In basically all tree-level exchange models the bounds from $D - \bar{D}$ mixing and other rare processes are very strong

We conclude that new physics models can only make negligible contributions to SCS tree level decay amplitudes
Surprisingly, at one loop there are well-motivated models that can give $a_f^d \sim 1\%$

- At one loop, an effective $c - u - \text{gluon}$ vertex can be generated, the "dipole operator"

$$Q_G = \bar{u}_L \sigma^{\mu\nu} G_{\mu\nu}^a T^a c_R$$

- This operator only contributes to SCS decays

- Model-independent bounds from $D - \bar{D}$ mixing and other processes are very weak
SUSY

An explicit example of a model with a large dipole operator

contours of $M_{12}$ [in units of the upper bound, $6.2 \times 10^{-11}$ MeV] vs. gluino mass for $r_{K^+ K^- \pi^+ \pi^-} = 0.01$. The squark mass $\tilde{m}$ is varied from 300 GeV to 1000 GeV

- The dipole operator is enhanced by $\tilde{m}/m_c$
- Our calculations could have an $O(10)$ upwards correction on the decay amplitude
SUSY Flavor Models

Models of flavor try to explain the SM flavor sector and absence of large FCNC in SUSY

Many flavor models on the market, using various flavor "horizontal" symmetries

given a significant contribution to $\theta_c$ from the up sector,

$$\delta_{LR} \equiv \delta m^2_{\tilde{c}_R \tilde{u}_L} / \tilde{m}^2 \sim \theta_c m_c / \tilde{m}$$

contours of $\delta_{LR}$ vs. gluino mass for $r_{K^+K^-,\pi^+\pi^-} = 0.01$. The squark mass $\tilde{m}$ is varied from 300 GeV to 1000 GeV ⇒

the generic prediction is $a_f^d \lesssim 1\%$ for $m_{\text{susy}} \sim 500$ GeV
**CPV gluonic penguins in SCS $D$ vs charmless $B$ decays**

- compare experimental sensitivities to the $b \to sg$ and $c \to ug$ "dipole operators"

\[ Q^\text{uc}_G = g_s \bar{u}_L \sigma_{\mu\nu} G^{\mu\nu} T^a c_R, \quad Q^\text{sb}_G = g_s \bar{s}_L \sigma_{\mu\nu} G^{\mu\nu} T^a b_R \]

- In models in which $\theta_c$ and $V_{cb}$ receive large contributions in the up and down sectors, respectively, their strengths are proportional to

\[ C^\text{uc}_G \propto \theta_c m_c, \quad C^\text{sb}_G \propto V_{cb} m_b \Rightarrow C^\text{uc}_G \sim C^\text{sb}_G \]

- For example, in SUSY flavor models

\[ \delta m^2_{\tilde{c}_R \tilde{u}_L} \propto \theta_c m_c, \quad \delta m^2_{\tilde{b}_R \tilde{s}_L} \propto V_{cb} m_b \]
**Comparison to experimental sensitivities**

- **sin 2\(\beta_{\text{eff}}\)** measurements in, e.g., \(B \rightarrow \phi K_s, \eta' K_s, K^+ K^- K_s\) are approaching the *10% level* in sensitivity to NP CPV penguin amplitudes (\(r_f \sim 0.10\))

- SCS \(D\) decays are at *1% level* in sensitivity to NP CPV penguin amplitudes (\(r_f \sim 0.01\))

- In terms of the \(b \rightarrow s g\) and \(c \rightarrow u g\) dipole transitions strengths, experimental sensitivities correspond to

\[
|C_{G}^{s b}| \sim 5.3 \times 10^{-9} \text{ GeV}^{-1}, \quad |C_{G}^{u c}| \sim 1.2 \times 10^{-8} \text{ GeV}^{-1}
\]

It's striking that experiment is probing gluonic transitions of comparable strength in \(B\) and SCS \(D\) decays!

- But expect \(C_{G}^{u c} \sim C_{G}^{s b}\) (in models in which \(\theta_c\) receives a significant contribution in the up sector) \(\Rightarrow\) experimental sensitivity to new gluonic penguins at least as large in SCS \(D\) decays
Example: comparison in SUSY flavor models

have fixed $r_f \approx 0.01$ for SCS $D$ decays (left), $r_f \approx 0.1$ for $B$ decays (right), i.e., to experimental sensitivities

- the $c \to ug$ and $b \to sg$ transitions are proportional to

\[
\delta_{LR} \equiv \delta m^2_{c_R \tilde u_L} / \tilde m^2,
\delta_{2L3R}^d \equiv \delta m^2_{b_R \tilde s_L} / \tilde m^2
\]

which in SUSY flavor models are expected to satisfy

\[
\delta_{LR} \sim \theta_c m_c / \tilde m,
\delta_{2L3R}^d \sim V_{cb} m_b / \tilde m
\]
Conclusion
Conclusion

- CP Violation in SCD $D$ decays is a very interesting probe of new physics (Bigi and Pakvasa have been saying this for years)

- there are many such decays, including non-CP eigenstates, and mutli-body final states, e.g. $D \rightarrow VV$

- There is no "SM background" and the new physics models are well motivated

- the sensitivity to gluonic penguins is at least as good as in charmless $B$ decays