New Physics and CP Violation in Singly Cabibbo Suppressed D Decays

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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 θ_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

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

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 $\theta_c m_c \sim V_{cb} m_b$

The three types of D decay

- Cabibbo Favored (CF)

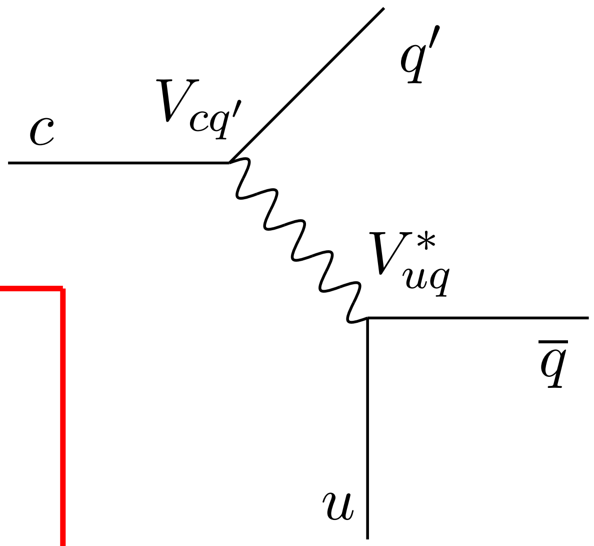
$$c \to s\bar{d}u \ \ (D \to K^- \pi^+)$$

- Singly Cabibbo Suppressed (SCS)

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

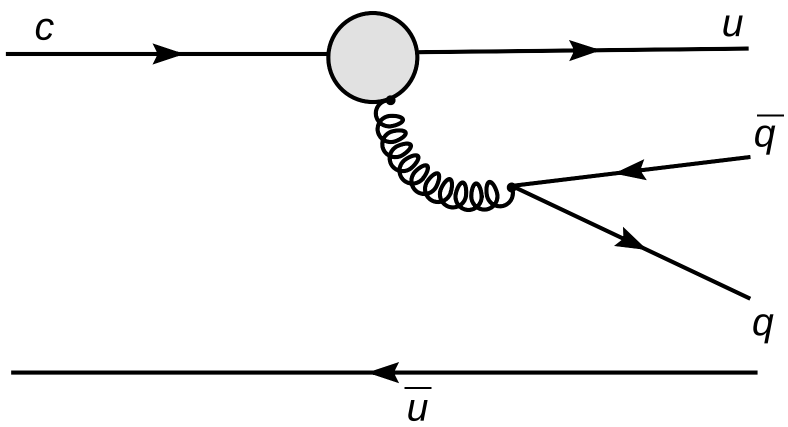
- Doubly Cabibbo Suppressed (DCS)

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



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

Gluonic penguins from NP



$c \to (\sum q\bar{q})u$ only contributes to SCS D decays,

conversely, only SCS D decays probe penguins

Formalism

Formalism for CP eigenstates

We use standard notations

$$x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta\Gamma}{2\Gamma}, \quad \lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}, \quad \frac{A_f^{\rm NP}}{A_f} = r_f e^{i(\phi_f+\delta_f)}$$

(ϕ_f, δ_f 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 λ_f $\Rightarrow$ can define

$$\lambda_f = -|q/p|\, e^{i\varphi}$$

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

- Experimentally, $x, y \lesssim \mathrm{few} \times 10^{-2}$. 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: $a_f^d = 2 r_f \sin\phi_f \sin\delta_f$
- 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,

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

  then the CP violating combination

$$\Delta Y \equiv \frac{\hat{\Gamma}_{\overline{D}^0\to f} - \hat{\Gamma}_{D^0\to f}}{2\Gamma_D} = a^m + a^i = a^{\rm ind}$$

  and $a_f^d = a_f - \Delta Y_f$ $\qquad$ ($\Delta Y^{\rm exp} = (-0.35 \pm 0.47) \times 10^{-2}$)

- 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 $a^{\rm ind}$, e.g.,

$$a^d_{P^+P^-} = a_{P^+P^-} - a_{K_s\pi^0}, \qquad P = K,\, \pi$$

New physics

New Physics in mixing

- 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

$$\mathcal{I}\text{m}(G_{NP}) \sim 10^{-2} \sin\theta_c G_F$$

- In basically all tree-level exchange models the bounds from $D - \overline{D}$ 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

New Physics in decay: one loop

Surprisingly, at one loop there are well-motivated models that can give $a_f^d \sim 1\%$

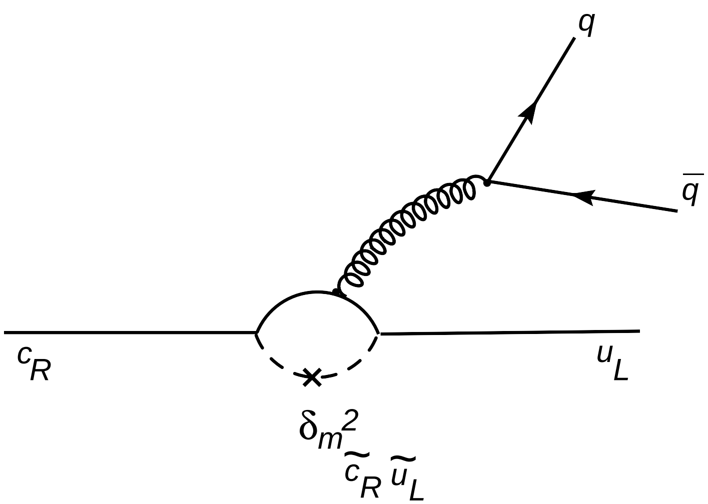
- At one loop, an effective $c - u - gluon$ vertex can be generated, the "dipole operator”

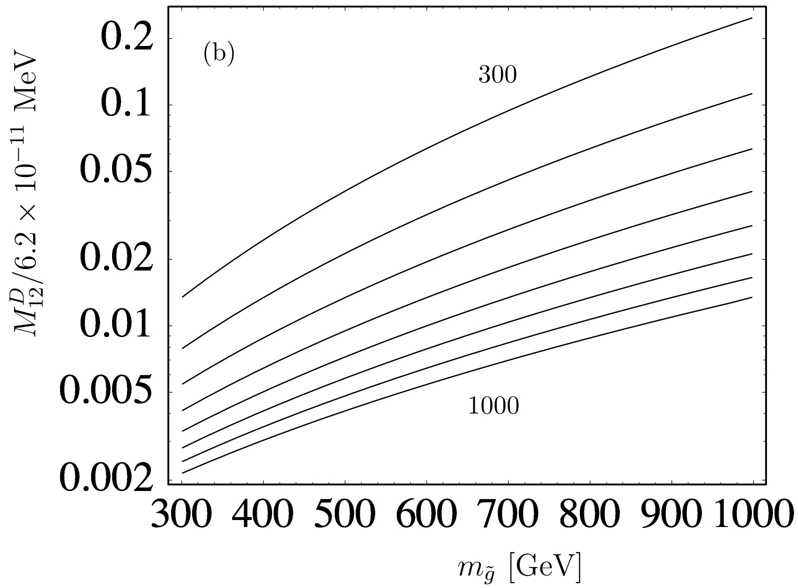
$$Q_G = \bar{u}_L \sigma^{\mu\nu} G^a_{\mu\nu} T^a c_R$$

- This operator only contributes to SCS decays
- Model-independent bounds from $D - \overline{D}$ mixing and other processes are very weak

SUSY

An explicit example of a model with a large dipole operator



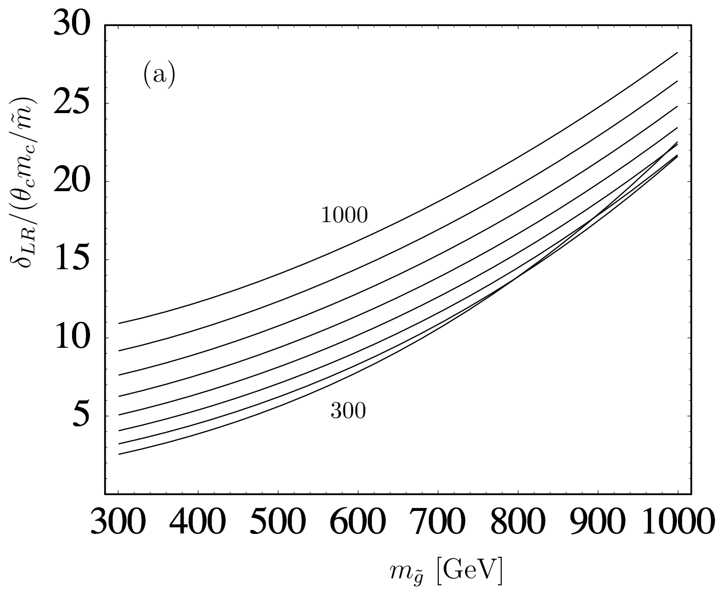


contours of M_{12} [in units of the upper bound, 6.2×10^{-11} MeV] vs. gluino mass for $r_{K^+K^- \ \pi^+\pi^-} = 0.01$. The squark mass $\tilde{m}$ is varied from 300 GeV to 1000 GeV

- 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 θ_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 δ_{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 $\Rightarrow$

the generic prediction is $a_f^d \lesssim 1\%$ for $m_{susy} \sim 500$ GeV

CPV gluonic penguins in SCS D vs charmless B decays

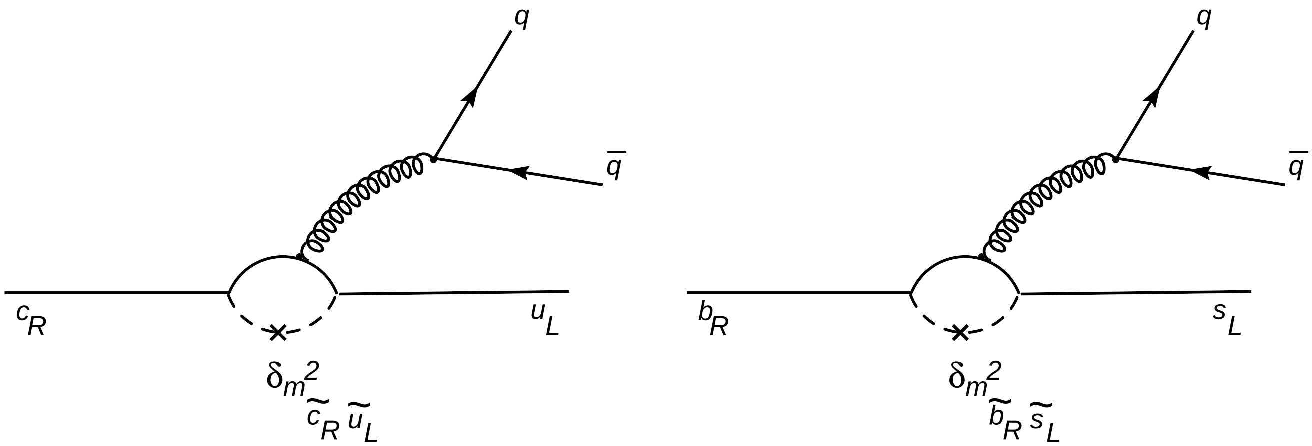
- compare experimental sensitivities to the $b \to sg$ and $c \to ug$ "dipole operators"

$$Q_G^{uc} = g_s \bar{u}_L \sigma_{\mu\nu} G^{\mu\nu} T^a c_R \,, \quad Q_G^{sb} = g_s \bar{s}_L \sigma_{\mu\nu} G^{\mu\nu} T^a b_R$$

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

$$C_G^{uc} \propto \theta_c m_c, \quad C_G^{sb} \propto V_{cb} m_b \Rightarrow C_G^{uc} \sim C_G^{sb}$$

- For example, in SUSY flavor models



$$\delta m^2_{\tilde{c}_R \tilde{u}_L} \propto \theta_c m_c, \quad \delta m^2_{\tilde{b}_R \tilde{s}_L} \propto V_{cb} m_b$$

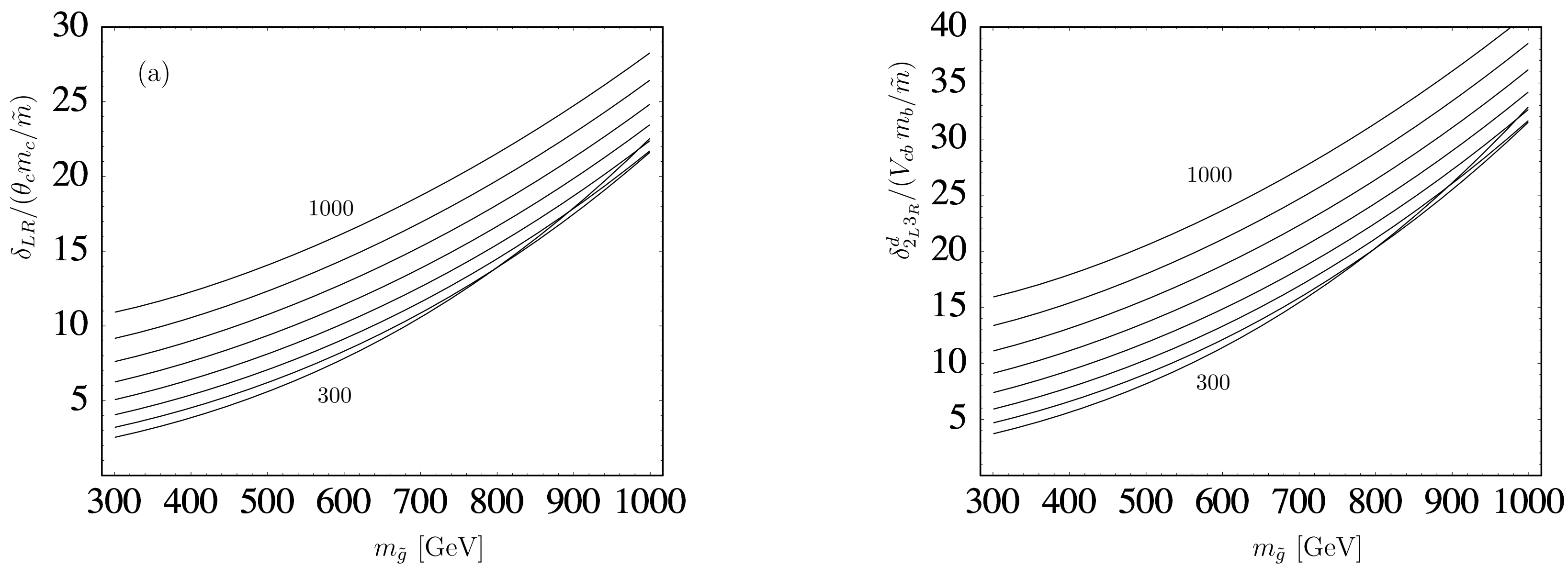
Comparison to experimental sensitivities

- $\sin 2\beta^{\rm eff}$ measurements in, e.g., $B \to \phi K_s,\ \eta' K_s,\ K^+K^-K_s$ 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 $b \to sg$ and $c \to ug$ dipole transitions stengths, experimental sensitivities correspond to

$$|C_G^{sb}| \sim 5.3 \times 10^{-9}\ {\rm GeV}^{-1}\,, \quad |C_G^{uc}| \sim 1.2 \times 10^{-8}\ {\rm GeV}^{-1}$$

  Its striking that experiment is probing gluonic transitions of comparable strength in B and SCS D decays!
- But expect $C_G^{uc} \sim C_G^{sb}$ (in models in which θ_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 Bdecays (right), i.e., to experimental sensitivities

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

$$\delta_{LR} \equiv \delta m^2_{\tilde{c}_R \tilde{u}_L}/\tilde{m}^2, \quad \delta^d_{2_L 3_R} \equiv \delta m^2_{\tilde{b}_R \tilde{s}_L}/\tilde{m}^2$$

which in SUSY flavor models are expected to satisfy

$$\delta_{LR} \sim \theta_c m_c/\tilde{m}, \quad \delta^d_{2_L 3_R} \sim V_{cb} m_b/\tilde{m}$$

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. $D \to VV$
- 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