Charming CPV

Yuval Grossman

Cornell

Why are we here?

We are all here to discuss “one” number

$$\mathcal{A}_{CP}(D \to f) \equiv \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})}$$

The data:

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(D \to K^+K^-) - \mathcal{A}_{CP}(D \to \pi^+\pi^-)$$

$$= \begin{cases} (-0.82 \pm 0.21 \pm 0.11)\% & \text{LHCb} \\ (-0.65 \pm 0.18)\% & \text{World average} \end{cases}$$

3.6σ from zero

New physics with charm

The main motivation for meson physics is to look for new physics. Charm decays have several nice properties:

- In the SM charm physics is CP conserving to very good approximation (only two generations)
- Many D mesons are produced in colliders
- It is “easy” to tag the flavor of the D^0
- The sensitivity to new physics is different from that of B physics (let’s talk about it)

Where are we now?

- Many interesting D observables
  - Mixing
  - DCS decays
  - CPV
  - Multi body final states
- The one we care about today is CPV in singly Cabibbo suppressed decays

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

in particular with $f = K^+K^-$ and $\pi^+\pi^-$

Outline

- General formalism
- The SM predictions
- More modes and checks

I will not talk about

- Experimental situation
- New physics explanations

Formalism

The three types of D decay

- Cabibbo Favored (CF)

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

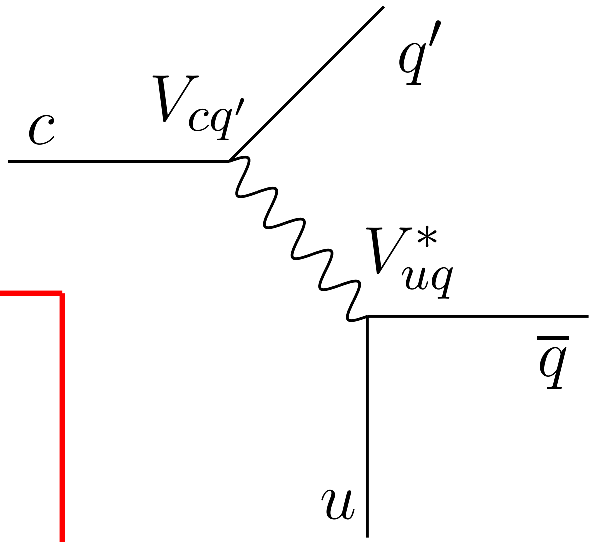
- Singly Cabibbo Suppressed (SCS)

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

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

- Doubly Cabibbo Suppressed (DCS)

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



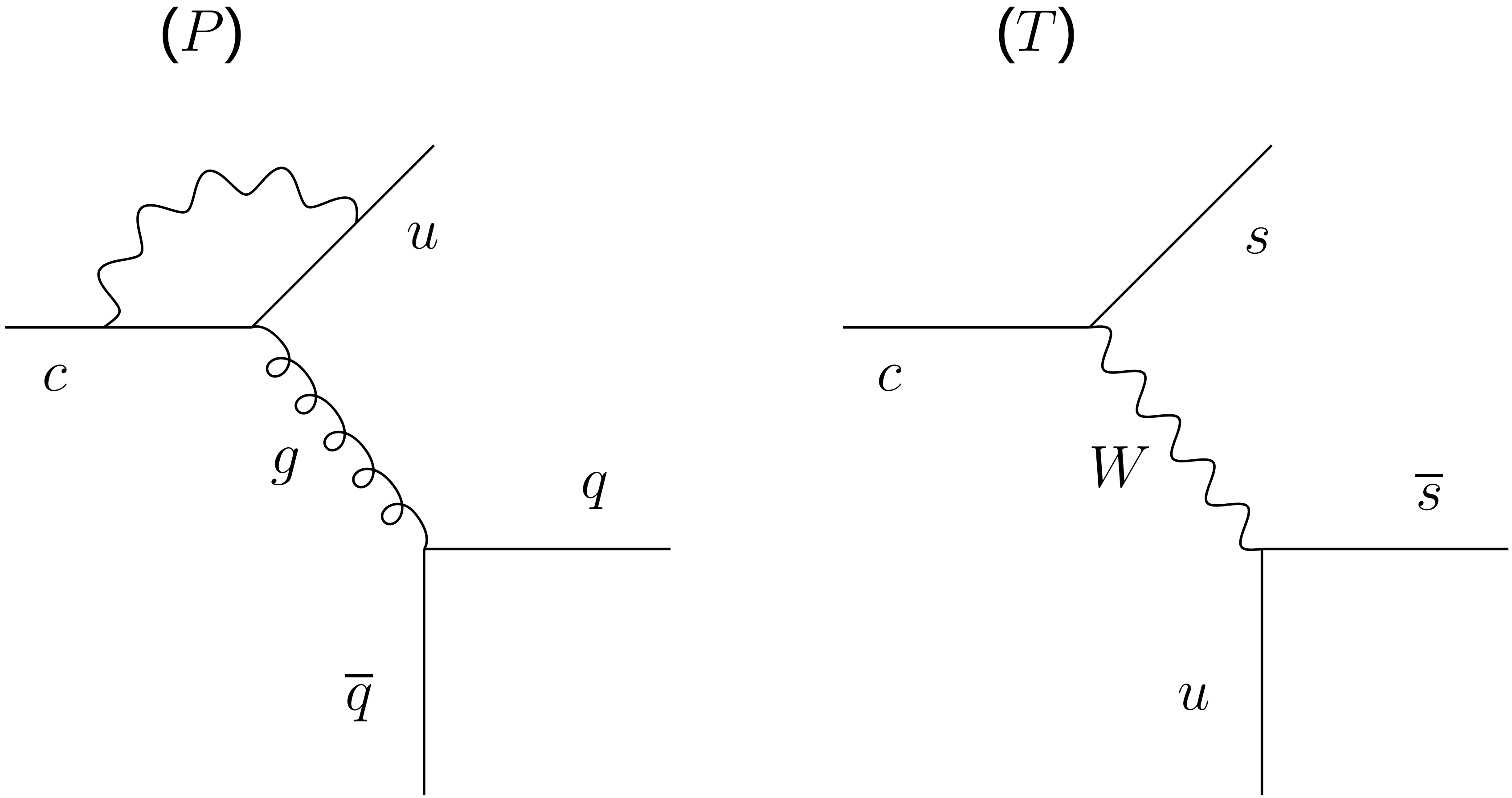
$$q, q' = s, d$$

Penguins

Beside the leading tree amplitudes, there are also loop decays

- Out of the loop decays, penguins are the largest
- Penguins can only contribute to SCS decays
- While they are very small, they carry a weak phase relative to the tree amplitude

$D \to K^+K^-$ diagrams



$D \to f$ amplitudes

We talk only about SCS decay into a CP final state

- We can always write the decay amplitude as

$$\mathcal{A}(D \to f) = A_f \left[1 + r_f e^{i(\delta_f + \phi_f)}\right]$$
$$\mathcal{A}(\bar{D} \to \bar{f}) = A_f \left[1 + r_f e^{i(\delta_f - \phi_f)}\right]$$

- δ_f is a strong phase. ϕ_f is a weak phase
- The whole point is to calculate $r_f \sim P/T$
- The direct CP asymmetry is

$$a_{CP} = 2r_f \sin\delta \sin\phi$$

Direct and indirect CPV

D^0 develop in time $\Rightarrow$ $D-\overline{D}$ mixing can affect the CP asymmetries. Both "indirect" (mixing) and "direct" (decay)

$$a_f = a_f^d + a^{ind}$$

- CP violation in decay (depend on f):

$$a_f^d = 2r_f \sin\phi_f \sin\delta_f$$

- CP violation in mixing (universal):

$$a^{ind} = \left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\left[\frac{x}{2}\sin\varphi - \frac{y}{2}\cos\varphi\right]$$

Separating the CP asymmetries

$$a_f = a_f^d + a^{ind}$$

- Time integrated CP asymmetries are sensitive to both direct and indirect CP violation
- Since a^{ind} is universal

$$\Delta a_{CP} = a_{CP}(KK) - a_{CP}(\pi\pi) = a_{KK}^d - a_{\pi\pi}^d$$

- Mixing grow with time and thus the cut on the decay time enhances the sensitivity to a^{ind}

$$a_f = a_f^d + \frac{\langle t \rangle}{\tau} a^{ind}$$

The SM

SM amplitudes

How to relate the diagrams to the decay amplitudes?

$$\mathcal{A}(D \to K^+K^-) = \lambda_d T_d + \lambda_s T_s + \lambda_b P$$

where

$$\lambda_q = V_{cq}^* V_{uq} \qquad \lambda_d \approx \lambda_s \gg \lambda_b$$

- Unitarity $\Rightarrow \ \lambda_d = -\lambda_s - \lambda_b \ \Rightarrow$

$$\mathcal{A}(D \to K^+K^-) = \lambda_s(T_s - T_d) + \lambda_b(P - T_d) = C\left[1 + r_f e^{i(\delta+\gamma)}\right]$$

where

$$r_f = \left|\frac{V_{cb}V_{ub}}{V_{cs}V_{us}}\right| \times \left|\frac{P - T_d}{T_s - T_d}\right|$$

Direct asymmetry in SCS decays

$$a_f = 2r_f \sin\gamma \sin\delta_f \qquad r_f = \left|\frac{V_{cb}V_{ub}}{V_{cs}V_{us}}\right| \times \left|\frac{P - T_d}{T_s - T_d}\right|$$

- Weak phase is γ
- Hadronic matrix elements (T_q and P) carry only strong phases

$$r_f \approx \left(6 \times 10^{-4}\right) \times X_H$$

What is X_H?

r_f in the SM

$$a_{CP}^f = 2r_f \sin\gamma \sin\delta_f$$

- A rough estimate. SU(3) and $V_{us} = -V_{cd}$ implies

$$a_{CP}(KK) = -a_{CP}(\pi\pi)$$

- $\sin\gamma \approx 1$, and we do not know the strong phase
- To get the central value of $\Delta A_{CP} = 0.8\%$ we then need

$$4r_f \sin\delta \approx 80 \times 10^{-4} \;\Rightarrow\; r_f \sin\delta \approx 20 \times 10^{-4}$$

Can the data be explained by the SM

$$r_f \approx \left(6 \times 10^{-4}\right) \times X_H \qquad X_H \sim P/T$$

- X_H is a ratio of hadronic matrix elements
- The data needs $r_f \sin\delta \sim 20 \times 10^{-4}$
- It can be done if
  - We have large strong phase (seems reasonable)
  - $X_H \gtrsim 3$. Not so easy

At the tropical forest

- Tree?
- Loops?
- Hybrid!

How large can X_H be?

- To explain the data we need $X_H \gtrsim 3$
- Naively

$$X_H \sim \frac{P}{T} \sim \frac{\alpha_S(m_c)}{\pi} \sim 0.1$$

- In B physics we get it from $B \to K\pi$ and $B \to \pi\pi$

$$X_H \sim 0.15$$

- In the heavy quark limit

$$\frac{X_H(D)}{X_H(B)} \sim \frac{\alpha_S(m_c)}{\alpha_S(m_b)} \sim 2 \;\Rightarrow\; X_H \sim 0.3$$

Is the charm heavy?

Is the above estimate reliable?

- Golden and Grinstein (89); Brod, Kagan, Zupan (11): X_H can be large!
- One day I will make a horror movie: “The $\Delta I = 1/2$ rule”
  - Unexplained enhancement of factor of (maybe?) 7
  - Very low energy
- The “penguin” vs “tree” is a perturbative picture. At low energy it is all messed up
- Using ideas like QCD factorization, BKZ found $X_H \sim 0.3$ at leading order. Estimate the breaking of factorization they could go to $X_H \sim 1.2$

SM calculation: Where are we?

$$X_H^{exp} \gtrsim 3 \qquad X_H^{best} \sim 0.3$$

- There seems to be indications that the naive estimate is an underestimate
- Still, very hard to explain the experimental central value by the SM
- Hard to claim that the data is clearly NP, since the theoretical errors on the best estimate are large

What next?

What else we could do?

- More data! The higher the value is, harder to argue that it is the SM
- Measure a_{KK} and $a_{\pi\pi}$ separately
- Look for other D decays: Charged D, multi body, D_s

SU(3) breaking

SU(3) predicts that

$$a_{CP}(KK) = -a_{CP}(\pi\pi) \qquad \Gamma(D \to KK) = \Gamma(D \to \pi\pi)$$

- The latter is broken by $O(1)$
- We may argue that the SU(3) breaking in the asymmetry is smaller (It may also be suggested by CPT arguments)
- If one of the two a_{CP}s dominates ΔA_{CP} then it is more likely that it is NP
  - We need bigger X_H in that one decay
  - The NP can violate the SM SU(3) relation

Other decays

- If we assume that X_H can be anything, what else can we check?
- If it is the SM, we know it is LH penguins
- Penguins are $\Delta I = 1/2$

- CPV in $\Delta I = 3/2$
- RH components to the penguin
- So far no idea of how to find NP if it is in a “SM-like” penguin

$\Delta I = 3/2$

- Similar ideas to Gronau-London in $B \to \pi\pi$
- Using the fact that penguins cannot lead to final states with $I = 2$
- D is $I = 1/2$. CPV in a mode with final $I = 2$ cannot come from penguins
- Several modes

$$D^+ \to \pi^+\pi^0 \qquad D^+ \to \rho^+\rho^0$$

- Probably more can be done in

$$D \to \rho\pi \qquad D \to KK\pi \qquad D_s \to K\pi$$

Conclusions

Conclusions

- CP violation in SCS D decays is very interesting
- Large uncertainties in the SM prediction, but it seems to be NP
- We would like to look for more decays, including non-CP eigenstates and multi-body final states

Can LHCb measure these asymmetries?