Charming CP Violation

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The birth of charm CPV

Charm CPV is still a baby

What is next for charm CPV?

- We have many SU(3) based rough SM predictions to test

Kagan, Silvestrini, arXiv:2001.07207

YG et al. in preparation

The effective 2-gen SM

The 2-generation SM

- Kaon and charm physics: only the first two generation are on-shell
- In many cases we can forget about the 3rd generation
- In some cases, like for CPV, we cannot do it
- The effective 2-generation model: We work with an EFT with two generation that is valid below m_b
- There are two main effects
  - The 2×2 CKM is not unitary (NU)
  - There are NR terms, like four Fermi operators (box diagram)

In charm we only care about the NU of the 2×2 CKM

The effective 2×2 CKM

- Consider the 2×2 block of the CKM that is not unitary

$$V \approx \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C + \cos\theta_C \Delta e^{i\gamma} & \cos\theta_C + \sin\theta_C \Delta e^{i\gamma} \end{pmatrix}$$

- CPV effects are proportional to the Non Unitarity (NU) parameter

$$\Delta = |V_{cb} V_{ub}| \sim \lambda^5$$

- We also define

$$\lambda_i = V_{ci}^* V_{ui}, \qquad \lambda_s + \lambda_d = \Delta e^{i\gamma}, \qquad \lambda_s - \lambda_d = 2 \sin\theta_C \cos\theta_C$$

$$\varepsilon_{\mathrm{NU}} \equiv \frac{\lambda_s + \lambda_d}{\lambda_s - \lambda_d} \approx 6 \times 10^{-4}$$

The small parameters for charm

We can map all the parameters in charm based on the following small parameters

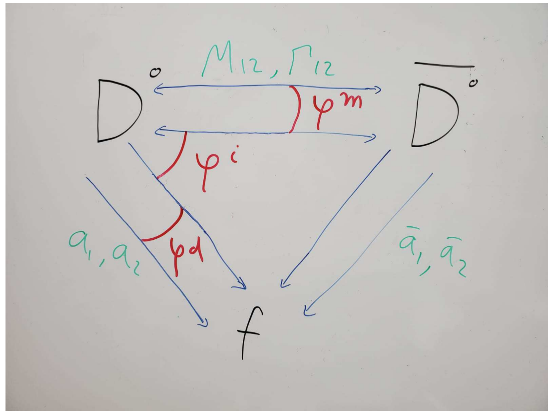
- Non-unitarity of the 2×2 CKM: $\varepsilon_{\rm NU} \sim 10^{-3}$
- SU(3)/U–spin breaking: $\varepsilon_{\rm SU(3)} \sim 0.2$
- The Wolfenstein parameter of the CKM: $\lambda \sim 0.2$
- For example
  - $x_{\rm th} \sim y_{\rm th} \sim \lambda^2 \varepsilon^2_{\rm SU(3)} \sim 0.2\%$
  - $x_{\rm ex} \sim y_{\rm ex} \sim 0.5\%$

Time integrated CP asymmetry

The time integrated CP asymmetry to leading order in x, y

$$a_f \equiv \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \approx a_f^d + a^m + a_f^i$$

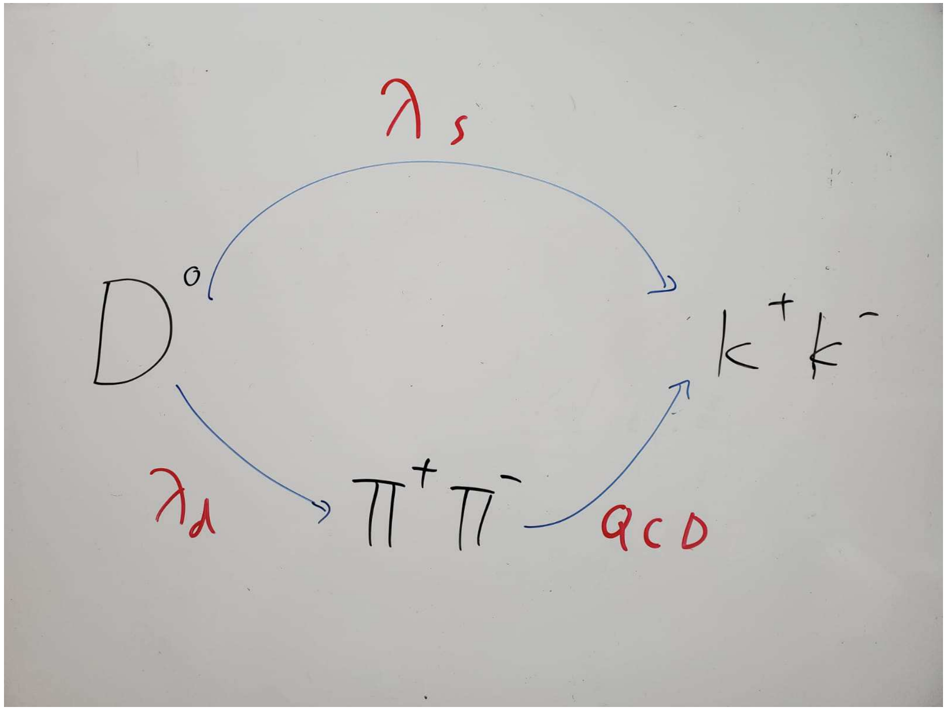
1. $a_f^d \sim r_f \sin\varphi_f^d$
2. $a^m \sim y \sin\varphi^m$
3. $a_f^i \sim x \sin\varphi_f^i$



- a^m is universal but a_f^d and a_f^i depend on f
- Using time dependence we can separate the three terms. Each is a separate observable

Direct CPV in charm

What interferes? Rescattering



- $\pi\pi$ represents many similar states like $\pi\rho$, $\rho\rho$
- Interference of trees with λ_s and λ_d
- We do not talk about penguins

The factors

$$\frac{\mathcal{A}(D \to \text{``}\pi\pi\text{''} \to KK)}{\mathcal{A}(D \to KK)} = \left(r_{\rm QCD} e^{i\delta}\right) \left(r_{\rm CKM} e^{i\varphi}\right)$$

$$a^d = 2(r_{\rm CKM} \sin\varphi)(r_{\rm QCD} \sin\delta)$$

- $r_{\rm QCD}$: ratio of rescattering amplitudes
- $\sin\delta = O(1)$: strong phase
- $r_{\rm CKM} = 1$: ratio of CKM factors, $|\lambda_d/\lambda_s|$
- $\sin\varphi \sim \varepsilon_{\rm NU} \sim 10^{-3}$: deviation from 2×2 unitarity

$$a^d \sim \varepsilon_{\rm NU} \times r_{\rm QCD} \sim 10^{-3} \times r_{\rm QCD}$$

What we learn from direct CPV

Within the SM the data implies $r_{\rm QCD} \sim 1$

- Theory: $a^d \sim 10^{-3} \times r_{\rm QCD}$
- Data: $a^d \sim 10^{-3}$

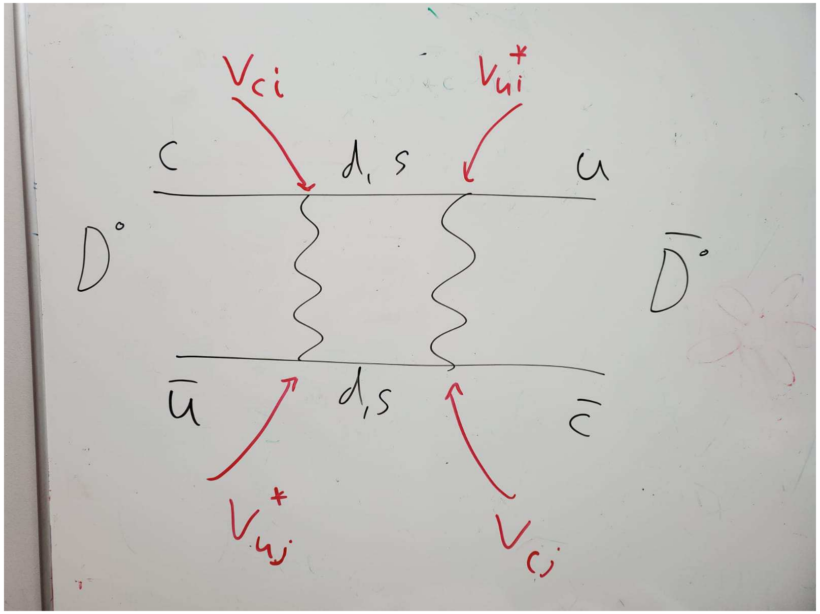
We conclude

The SM with $O(1)$ rescattering explains the data

CPV involving mixing (future)

The mixing amplitude

$$M_{12} \propto \lambda_s^2 f_{ss} + 2\lambda_s \lambda_d f_{sd} + \lambda_d^2 f_{dd}$$



- We cannot calculate f_{ij} reliably
- We can use SU(3)

Evaluation of the mixing amplitude

$$M_{12} \propto \lambda_s^2 f_{ss} + 2\lambda_s \lambda_d f_{sd} + \lambda_d^2 f_{dd}$$

- Same for Γ_{12} but with $f_{ij} \to g_{ij}$
- In the SU(3) limit: $f_{ss} = f_{dd} = f_{sd}$
- Including SU(3) breaking we get

$$f_{ss} - f_{sd} \sim f_{dd} - f_{sd} \sim \varepsilon_{\rm SU(3)} \qquad f_{ss} + f_{dd} - 2f_{sd} \sim \varepsilon_{\rm SU(3)}^2$$

- Recall

$$\lambda_s + \lambda_d \sim \lambda \times \varepsilon_{\rm NU}$$

- Using the CKM we get

$$M_{12}, \Gamma_{12} \sim \lambda^2 \left[\varepsilon_{\rm SU(3)}^2 + 2\varepsilon_{\rm SU(3)}\varepsilon_{\rm NU} + \varepsilon_{\rm NU}^2\right]$$

The phases of the mixing

$$M_{12}, \Gamma_{12} \sim \lambda^2 \left[\varepsilon_{\mathrm{SU(3)}}^2 + 2\varepsilon_{\mathrm{SU(3)}}\varepsilon_{\mathrm{NU}} + \varepsilon_{\mathrm{NU}}^2\right]$$

- The CPV phase enters with $\varepsilon_{\mathrm{NU}}$
- We can neglect the $\varepsilon_{\mathrm{NU}}^2$ term
- The mixing phases are

$$\arg(M_{12}) \sim \arg(\Gamma_{12}) \sim \frac{\varepsilon_{\mathrm{NU}}}{\varepsilon_{\mathrm{SU(3)}}}$$

- The phases of the decays are $O(\varepsilon_{\mathrm{NU}})$

The universal phase is enhanced

The prediction

- The relevant phases are

$$\phi^m \sim \frac{\varepsilon_{\rm NU}}{\varepsilon_{\rm SU(3)}} \qquad \phi^i_f \sim \frac{\varepsilon_{\rm NU}}{\varepsilon_{\rm SU(3)}} + (\varepsilon_{\rm NU})_f \qquad \phi^d_f \sim (\varepsilon_{\rm NU})_f$$

- To leading order in SU(3) breaking the time dependent asymmetries are universal
- Numerically, it is only a rough prediction
- It can be tested, hopefully soon
- We will learn something
  - If it fail, we found BSM
  - If it is confirmed, we will understand QCD better

Conclusion

There is a pattern

1. a_f^d. For SCS

$$a_f^d \sim \varepsilon_{\rm NU} \times O(1)_f \sim 10^{-3}$$

2. a^m. Universal

$$a^m \sim y \, \frac{\varepsilon_{\rm NU}}{\varepsilon_{\rm SU(3)}} \sim \varepsilon_{\rm NU} \times \varepsilon_{\rm SU(3)} \sim 10^{-4}$$

3. a_f^i. Approximate universality

$$a_f^i \sim x \, \frac{\varepsilon_{\rm NU}}{\varepsilon_{\rm SU(3)}} \times \left[1 + O(\varepsilon_{\rm SU(3)})_f\right] \sim 10^{-4} \pm 10^{-5}$$

Back up

What next for direct CPV?

- Seperating $\pi\pi$ and KK
- Use multi body decays

More checks

At low energy, we know that rescattering is important. The $\Delta I = 1/2$ rule in kaon decay is a prime example

- We find that $\Delta I = 1/2$ in D decays also requires $O(1)$ rescattering
- It needs to be checked if LCSR can explain the $\Delta I = 1/2$ in D decays within the SM
- We expect similar size of a^d in other modes