Charming CPV

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The start of charm CPV

The big news from 3/2019

LHCb found CPV in charm

- It is just the start of charm CPV
- We have many SM predictions to test
- We can probe BSM
- We can learn about QCD

What next for charm CPV?

In this talk

- Is the LHCb signal a hint for BSM?
  - The LHCb signal is well explained in the SM
  - We learn about QCD
- Can we make predictions for time-dependent CPV?
  - We predict approximate universality

A few references

Not the full list

- YG, Kagan, Nir, arXiv:hep-ph/0609178
- YG, Nir, Perez, arXiv:0904.0305
- Bobrowski, Lenz, Riedl, Rohrwild, arXiv:1002.4794
- Khodjamirian, Petrov, arXiv:1706.07780
- Chala, Lenz, Rusov, Scholtz, arXiv:1903.10490
- YG, Schacht, arXiv:1903.10952
- 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 for CPV
  - The 2×2 CKM is not unitary
  - There are NR terms, like four Fermi operators

$$(\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma^\mu d_L)$$

The effective 2×2 CKM

- We think about a 2×2 CKM that is not unitary

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

- Non Unitarity (NU) is given by Δ

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

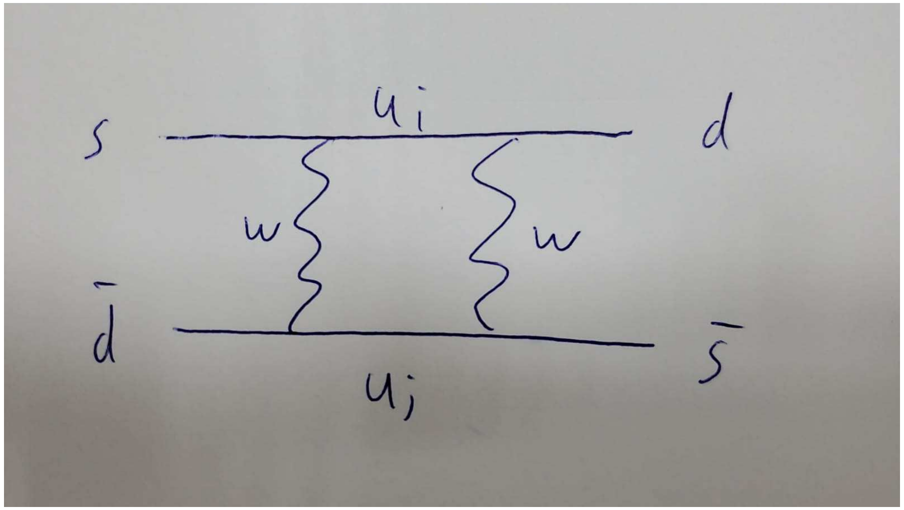
- We also define

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

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

The NR operators

- For example $K - \bar{K}$ mixing from $(\bar{s}_L \gamma_\mu d_L)(\bar{s}_L \gamma^\mu d_L)$
- In the SM it comes from



- Integrating out the W and top gives the NR operator
- The top contributions is CKM suppressed but GIM enhanced compared to the charm

GIM vs CKM

3rd generation terms vs 2nd generation term

- CKM ratio: $$\frac{V_{ts}V_{td}}{V_{cs}V_{cd}} \sim \frac{V_{cb}V_{ub}}{V_{cs}V_{us}} \sim \lambda^4 \sim 10^{-3}$$
- GIM ratio: $$K: \ \frac{m_t^2}{m_c^2} \sim 10^4 \qquad D: \ \frac{m_b^2}{m_s^2} \sim 10^2$$
- K: GIM wins and thus NR is more important
- D: CKM wins and thus NU is more important

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

CPV in charm

The small parameters for charm

All the observables depends on the following small parameters

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

We classify all CPV observables in terms of λ, $\varepsilon_{\rm SU(3)}$, $\varepsilon_{\rm NU}$

Time integrated CP asymmetry

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

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

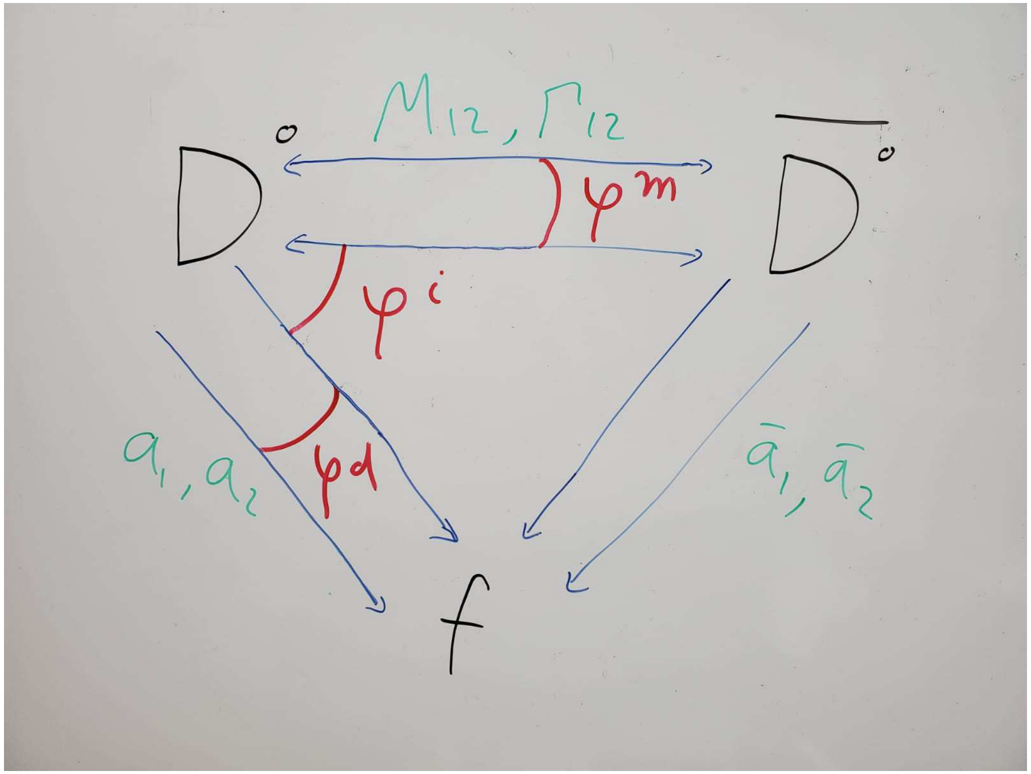
1. $a_f^d \sim r_f \sin \varphi_f^d$
2. $a^m \sim y \sin \varphi^m$
3. $a_f^i \sim x \sin \varphi_f^i$

- 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

What are the phases

All the weak phases depend on $\varepsilon_{\mathrm{NU}}$

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



There is a pattern

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

Direct CPV in charm

The LHCb Measurement

$$\Delta A_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-}$$

Data show a signal that is above 5σ

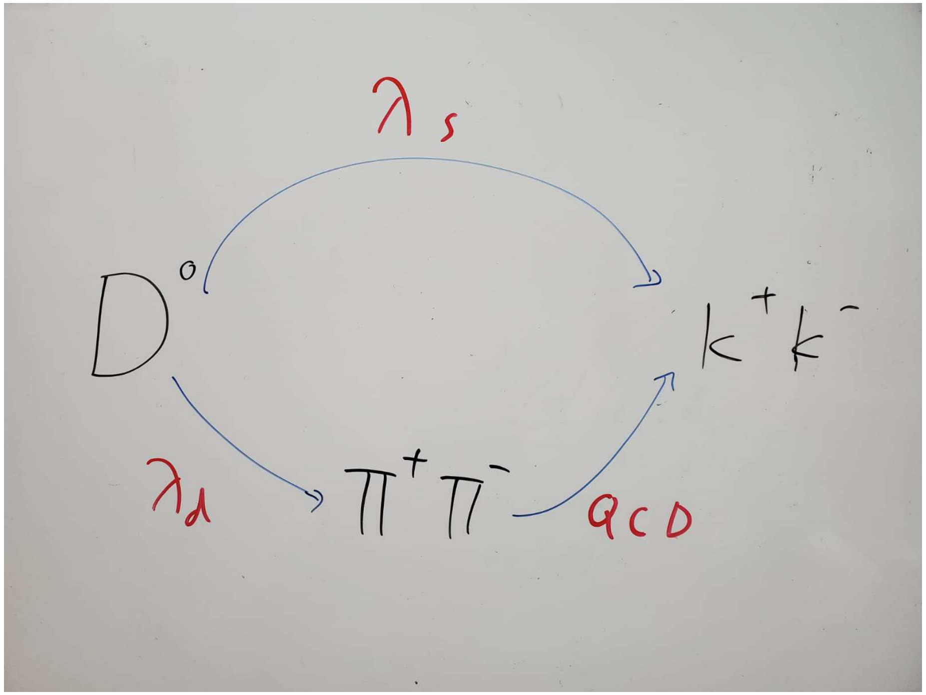
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

- Recall: $a_f = a_f^d + a^m + a_f^i$
- Roghly speaking

$$\Delta A_{CP} \sim 2a_{KK}^d$$

- What the SM predicts?

What interferes? Rescattering



- Interference of trees with λ_s and λ_d
- We do not talk about penguins
- There are many more intermediate states

The factors

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

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

- $r_{\rm QCD}$: 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

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

The ratios

$$a^d \sim 10^{-3} \times r_{\rm QCD} \qquad r_{\rm QCD} \sim \left| \frac{\mathcal{A}(D \to \text{``}\pi\pi\text{''} \to KK)}{\mathcal{A}(D \to KK)} \right|$$

What is $r_{\rm QCD}$?

- Light Cone Sum Rules (LCSR) Khodjamirian, Petrov, 2017

$$r_{\rm QCD} \sim O\left(\frac{\alpha_s}{\pi}\right) \sim 10^{-1}$$

- Low energy QCD, rescattering is $O(1)$

$$r_{\rm QCD} \sim O(1)$$

What we learn from direct CPV

$$a^d_{\rm th} \sim 10^{-3} \times r_{\rm QCD} \qquad a^d_{\rm ex} \sim 10^{-3}$$

We conclude

- Within the SM the data imply $r_{\rm QCD} \sim 1$
- $r_{\rm QCD} \sim 1$ from large rescattering agrees with the data
- It is hard to argue that the LHCb result requires BSM
- Yet, BSM can still be present
- There are more evidences that rescattering is $O(1)$ in charm from $D \to \pi\pi$ decays

CPV involving mixing

What are the phases in mixing

$$a_f \approx a_f^d + a^m + a_f^i$$

We care about a^m and a^i

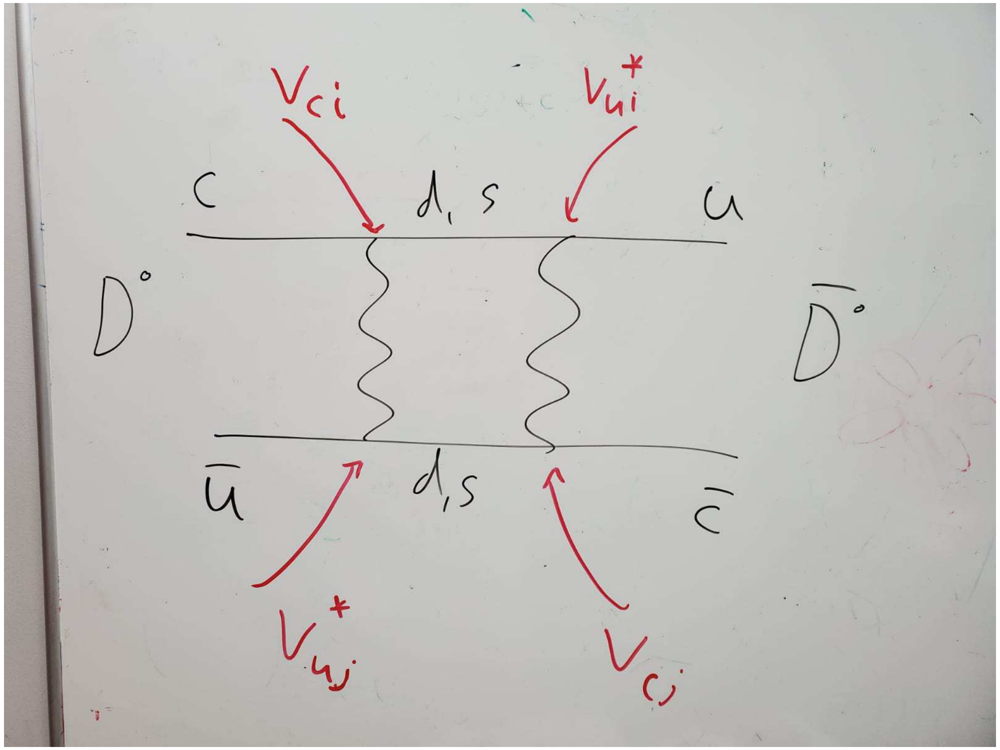
1. $a^m \sim y \sin\varphi^m$ with

$$\sin^2\varphi^m = \frac{x^2}{x^2+y^2}\arg\left(\frac{\Gamma_{12}}{M_{12}}\right)$$

2. $a_f^i \sim x \sin\varphi_f^i$ with φ_f^i is roughly the phase between the decay and the mixing amplitudes

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

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 $f_{ij} \to g_{ij}$
- The SU(3) properties are as follows

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

- Recall

$$\lambda_s - \lambda_d \sim \lambda \qquad \frac{\lambda_s + \lambda_d}{\lambda_s - \lambda_d} \sim \varepsilon_{\mathrm{NU}}$$

- We get

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

The phases of the mixing

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

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

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

The predictions

To leading order in SU(3) breaking the time dependent asymmetries are universal

$$\phi^m \sim \frac{\varepsilon_{\rm NU}}{\varepsilon_{\rm SU(3)}} \qquad \phi^i_f \sim \frac{\varepsilon_{\rm NU}}{\varepsilon_{\rm SU(3)}}\left[1 + O\left(\varepsilon_{\rm SU(3)}\right)_f\right]$$

- Numerically, it is only a rough prediction
- 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

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