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

Outline

- The effective 2-generation SM
- Overview of CPV
- Direct CPV (the LHCb signal)
- CPV involving mixing (the future)

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 full 3×3 CKM

- The standard parametrization

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

- There is hierarchy

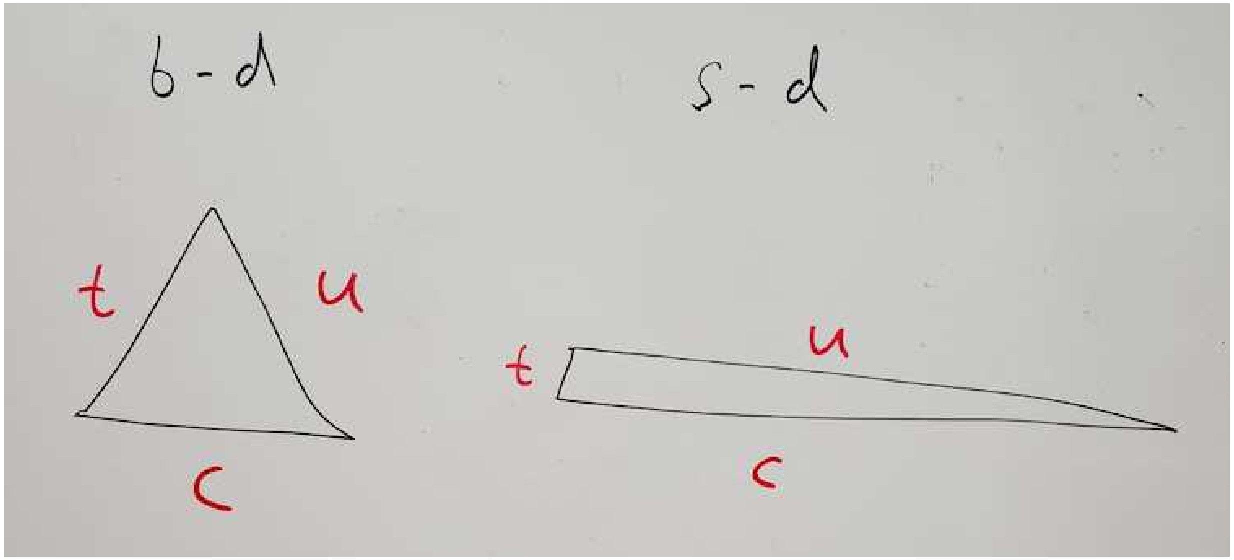
$$\lambda = s_{12} \approx 0.2 \quad s_{23} \sim \lambda^2 \quad s_{13} \sim \lambda^3$$

- Order of magnitude

$$|V| \sim \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix}$$

The unitarity triangles

- All CPV observables are proportional to the Jarlskog invariant, J
- The area of all UTs is $J/2$



- $t \equiv |V_{tb}V_{td}|$ or $t \equiv |V_{ts}V_{td}|$

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

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

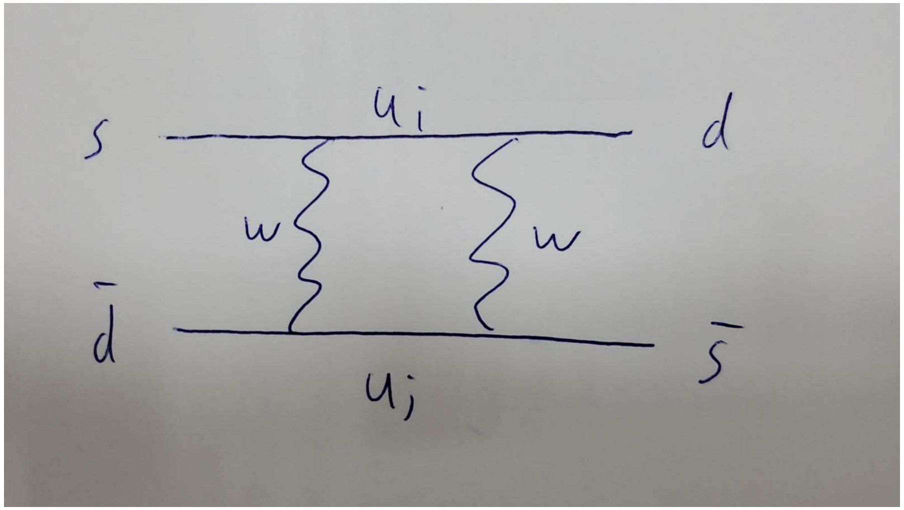
- We also define

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

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

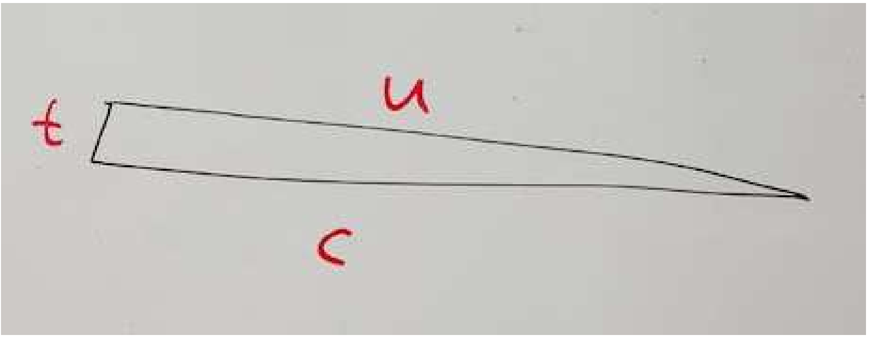
The NR operators

- 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



- CKM ratio: the magnitudes of the sides, $\lambda^4 \sim 10^{-3}$
- GIM ratio: $K: \frac{m_t^2}{m_c^2} \sim 10^4 \quad D: \frac{m_b^2}{m_s^2} \sim 10^2$
- 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

Review of notations

Definitions

- The mass eigenstate D_L and D_H

$$x \equiv \frac{\Delta M}{\Gamma} \qquad y \equiv \frac{\Delta\Gamma}{2\Gamma}$$

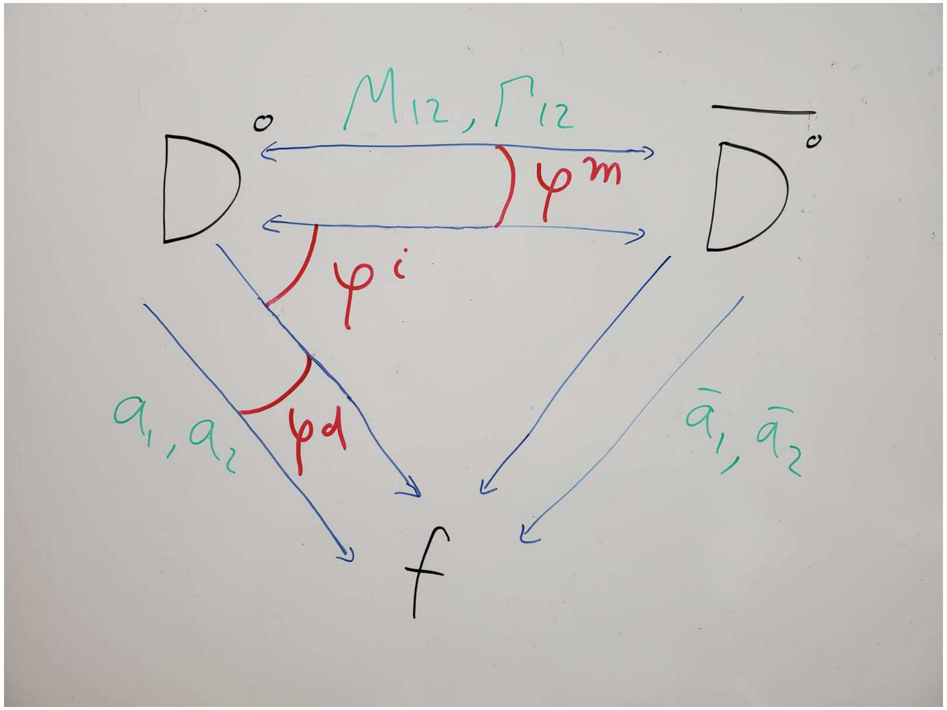
- $x,\ y$ are derived from the mixing amplitude $M_{12},\ \Gamma_{12}$
- In a decay we use

$$\mathcal{A}_f = a_f^1 + a_f^2 = A_f \left[1 + r_f e^{(i\delta_f + \varphi_f)}\right]$$

- δ_f CP-even phase and φ_f CP-odd

The three types of CPV

1. CPV in decay (direct CPV)
2. CPV in mixing (indirect CPV)
3. CPV in interference (also indirect)



The three types of D decay

- Cabibbo Favored (CF)

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

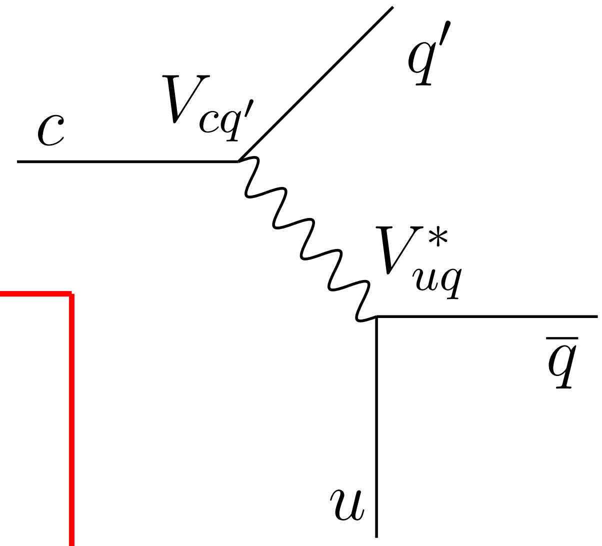
- Singly Cabibbo Suppressed (SCS)

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

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

- Doubly Cabibbo Suppressed (DCS)

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



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

SU(3) flavor

Approximate symmetry of QCD: $s \leftrightarrow d \leftrightarrow u$

- Broken by roughly

$$\varepsilon_{\rm SU(3)} = \frac{m_s}{\Lambda_{QCD}} \sim 0.2$$

- We also talk about U-spin: SU(2) subgroup of SU(3) flavor with $d \leftrightarrow s$
- For D decays, the GIM mechanism is related to U-spin breaking
  - K: GIM gives $m_c^2 - m_u^2$
  - D: GIM gives $m_s^2 - m_d^2$

The small parameters for charm

All the small quantities 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
  - $x_{\rm th} \sim y_{\rm th} \sim \lambda^2 \varepsilon^2_{\rm SU(3)} \sim 0.2\%$
  - $x_{\rm ex} \sim y_{\rm ex} \sim 0.5\%$

Time integrated CP asymmetry

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

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

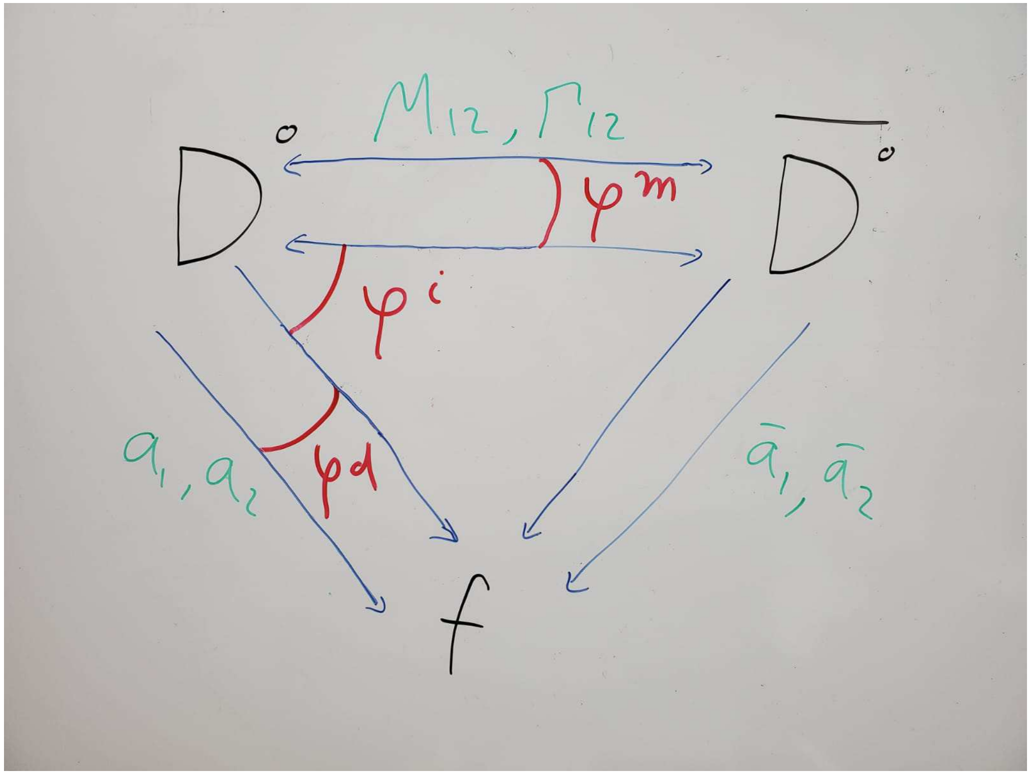
1. $a_f^d \sim r_f \sin\delta_f \sin\varphi_f^d$
2. $a^m \sim y \sin\varphi^m$
3. $a_f^i \sim x \sin\varphi_f^i$

- 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 $\varepsilon_{\rm NU}$

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

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

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

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

Direct CPV in charm

The LHCb Measurement

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

Data gives

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

- Recall: $a_f = a_f^d + a^m + a_f^i$
- a^m is universal. Cancel in ΔA_{CP}
- a_f^i is expected to be small & universal. Cancel in ΔA_{CP}
- SU(3) predicts $a_{KK}^d = -a_{\pi\pi}^d$ and thus $\Delta A_{CP} \approx 2a_{KK}^d$

What can we learn from the dtata? Is it a signal of BSM?

Direct CP Violation for CP eigenstate

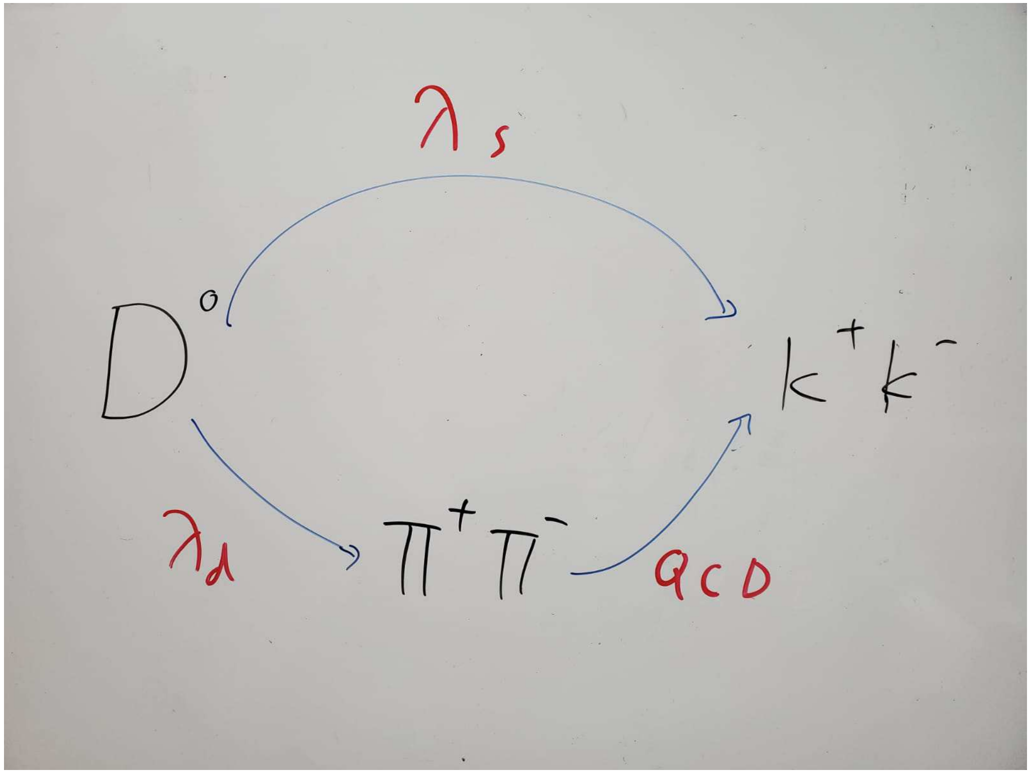
$$a_f^d \equiv \frac{|\mathcal{A}(D^0 \to f)|^2 - |\mathcal{A}(\overline{D}^0 \to f)|^2}{|\mathcal{A}(D^0 \to f)|^2 + |\mathcal{A}(\overline{D}^0 \to f)|^2} \approx 2(r_{\rm CKM} \sin\varphi)(r_{\rm QCD} \sin\delta)$$

The decay amplitude (f CP-eigenstate)

$$\mathcal{A}_f = 1 + r_{\rm CKM}\, r_{\rm QCD}\, e^{i(\varphi+\delta)}$$

- $r_{\rm CKM}$ real ratio of CKM matrix elements
- φ weak phase
- $r_{\rm QCD}$ real ratio of hadronic matrix elements
- δ strong phase

What interferes? Rescattering



- Interference of trees with λ_s and λ_d
- We do not talk about penguins

The factors

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

- $r_{\rm QCD}$: ratio of rescattering amplitudes
- $\delta = O(1)$: strong phase
- $r_{\rm CKM} = 1$: ratio of CKM factors, $|\lambda_d/\lambda_s|$
- $\varphi \approx \varepsilon_{\rm NU} \approx 6 \times 10^{-4}$: deviation from 2×2 unitarity

We predict

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

The ratios

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

What is $r_{\rm QCD}$?

- Light Cone Sum Rules (LCSR)

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

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

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

What we learn from direct CPV

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

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

We conclude

- The assumption of large rescattering agrees with the data
- It is hard to argue that the LHCb result requires BSM
- Yet, BSM can still be present

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

Direct CPV: conclusion

We learn

- I would argue that it is not likely that BSM dominant direct CPV in charm
- Charm is light and rescattering is $O(1)$
- More checks possible in the future

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

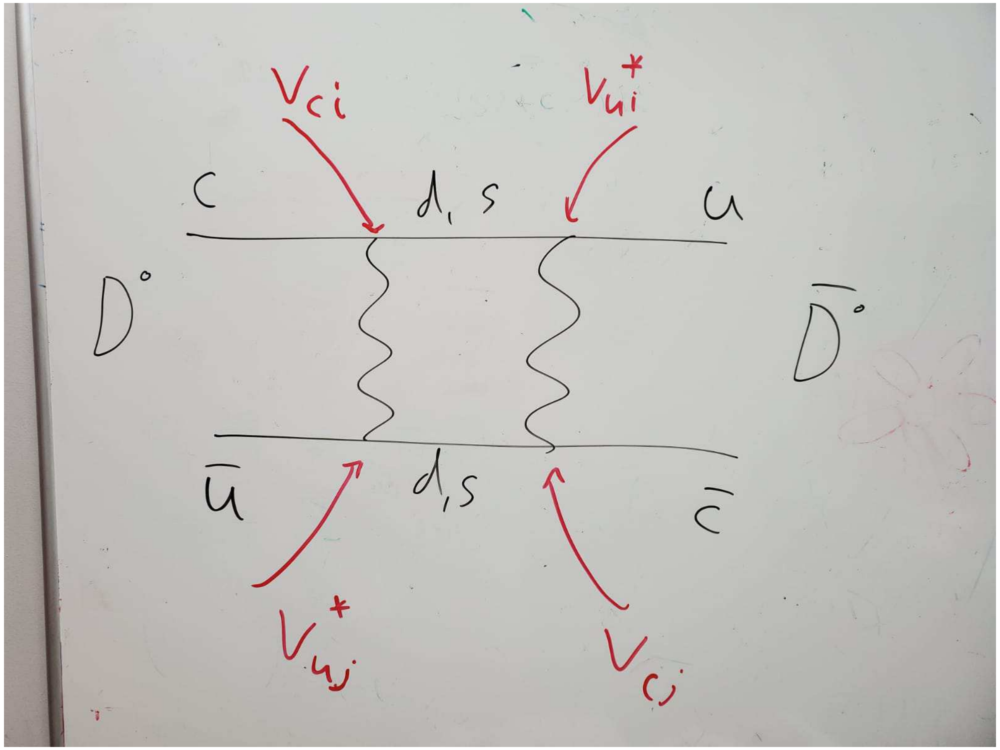
1. $a^m \sim y \sin \varphi^m$ with

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

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

What are the phases of M_{12} and Γ_{12}?



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

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

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

- Recall

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

- 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

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

- The CPV phase enter 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 prediction

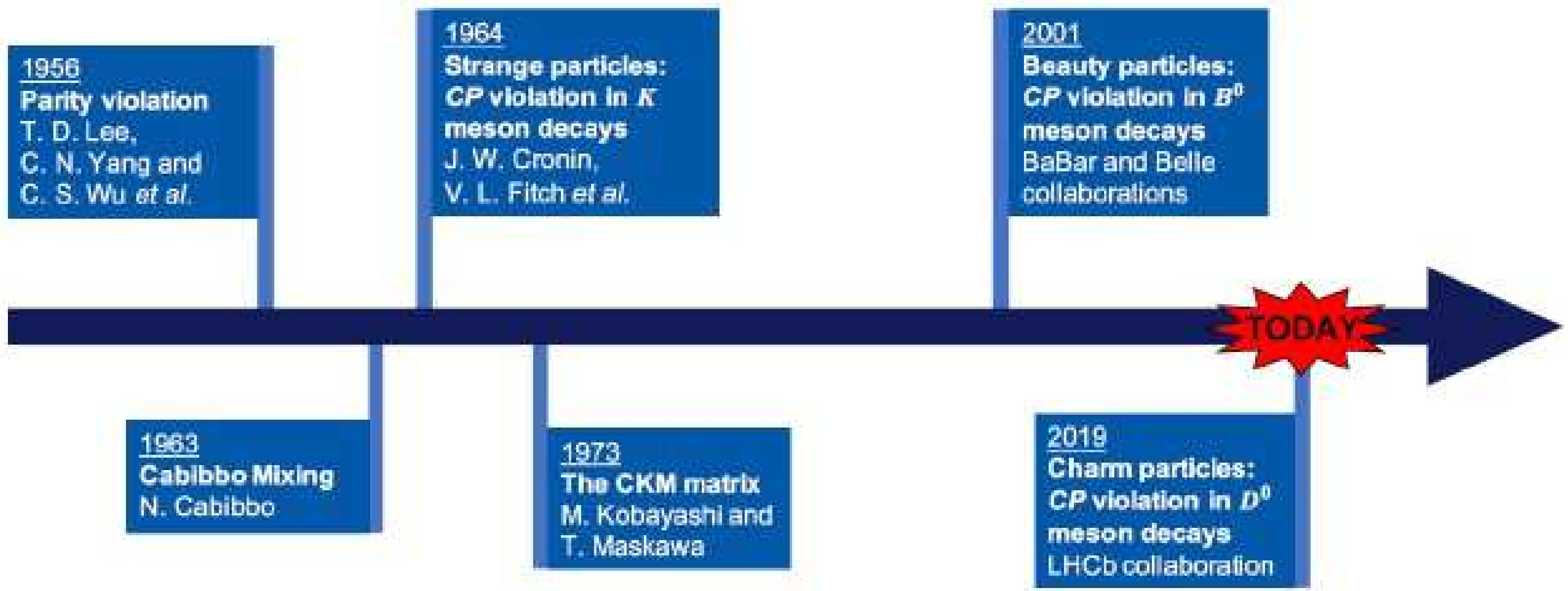
To leading order in SU(3) breaking the time dependent asymmetries are universal

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

- 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

A Short History of CP Violation



This is just the beginning for charm