$D - \overline{D}$ mixing and indirect CPV

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Based on: K. Blum, YG, Y. Nir, G. Perez, arXiv:0903.2118

YG, Y. Nir, G. Perez, arXiv:0904.0305

Motivation

- $D - \overline{D}$ mixing has been observed

$$x = (1.00 \pm 0.25) \times 10^{-2}$$
$$y = (0.77 \pm 0.18) \times 10^{-2}$$
$$1 - |q/p| = +0.06 \pm 0.14$$
$$\phi = -0.05 \pm 0.09$$

- CP conserving: $x \sim y \sim 1\%$, CPV: $1 - |q/p| \sim \phi \sim 0 \pm 0.1$
- The SM predictions have large uncertainties (but they roughly agree with the data)

Question: Do we care about $D - \overline{D}$ mixing?

Answer: Yes

Outline (or why do we care)

We like to measure D mixing and CPV despite the fact that we cannot predict x and y in the SM

- In the SM we have basically no CPV. Any signal of CPV is NP. One subtle point to discuss
- We can test for indirect CPV (not only in charm)
- The combination of $D-\overline{D}$ and $K-\overline{K}$ data is powerful in probing NP

Tests of indirect CPV

Introduction: Meson Mixing formalism

Of course, we all know it, but...

- “Experimental” parameters vs “theoretical” parameters
- Experimental parameters are what we measure (for example, x)
- Theoretical parameters are what we calculate in any given model (for example $|M_{12}|$)
- Of course, they are related

Experimental parameters

The experimental parameters are

$$x, \quad y, \quad |q/p|, \quad \phi_f$$

- For any final state we have a different CP violating phase

$$\phi(B \to \psi K_S) = \beta, \qquad \phi(B \to \pi\pi) = \alpha$$

- If all the decay amplitudes can be real, ϕ is universal
  - In the B system ϕ is not universal
  - In the K system ϕ is (basically) universal
  - In the D and B_s system ϕ can be universal if we have NP only in the mixing

Theoretical parameters

Parameters that can be calculated (in principle) for a given model

- Mixing parameters

$$|M_{12}|, \quad |\Gamma_{12}|, \quad \arg(M_{12}/\Gamma_{12})$$

- Decay parameters

$$|A_f|, \quad \phi_f$$

- In the case on no direct CPV $\phi_f = 0$ and all we have are the mixing parameters

From theory to experiment

Consider the case of no direct CPV

- There are 4 experimental parameters

$$x \equiv \frac{\Delta m}{\Gamma}, \quad y \equiv \frac{\Delta \Gamma}{\Gamma}, \quad |q/p|, \quad \phi$$

- There are 3 theoretical parameters

$$x_{12} \equiv \frac{2|M_{12}|}{\Gamma}, \quad y_{12} \equiv \frac{|\Gamma_{12}|}{\Gamma}, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

- The relations between them are not trivial. The intuition from B may be misleading for D
- $4 - 3 = 1$. One relation between the exp. parameters. A check on the assumption of no direct CPV

Relations between the. and exp.

- In the case of no direct CPV, A_f and Γ_{12} have the same phase (can be set to zero)
- Then we get the following relations

$$
\begin{aligned}
xy &= x_{12} y_{12} \cos\phi_{12} \\
x^2 - y^2 &= x_{12}^2 - y_{12}^2 \\
(x^2 + y^2)\,|q/p|^2 &= x_{12}^2 + y_{12}^2 + 2x_{12} y_{12} \sin\phi_{12} \\
x^2 \cos^2\phi - y^2 \sin^2\phi &= x_{12}^2 \cos^2\phi_{12}
\end{aligned}
$$

- When $y \ll x$ we get the known results for the B_s

$$
x = x_{12}, \qquad y = y_{12}\cos\phi_{12}, \qquad \phi = \phi_{12}
$$

- In particular, $\phi = \phi_{12}$ is nice

Relations for the D case

In the D case we know that ϕ is small

- In that case we get

$$\sin^2\phi_{12} = \frac{(x^2+y^2)^2}{x^4}\sin^2\phi$$

- For the case that $y \gg x$ we have

$$\sin\phi_{12} = \frac{y^2}{x^2}\sin\phi$$

- Small ϕ does not imply small ϕ_{12}!
- The current strong bound on ϕ does not give a very strong bound on the phase of the NP

Test for indirect CPV

Since there are 3 theoretical and 4 experimental parameters, there is one relation

$$\frac{(1-|q/p|^4)^2}{\sin^2\phi} = \frac{16(y/x)^2|q/p|^4 + [1+(y/x)^2]^2(1-|q/p|^4)^2}{1+(y/x)^4\tan^2\phi}$$

- If this relation is violated $\Rightarrow$ direct CPV
- If $y \ll x$ (as is the case for B_s) or $\phi_{12} \ll 1$ (K and maybe D) the relation is very simple

$$\frac{y}{x} = \frac{1-|q/p|}{\tan\phi}.$$

Indirect CPV

For no direct CPV we have

$$\frac{y}{x} = \frac{1 - |q/p|}{\tan\phi}.$$

- For kaons this relation was confirmed experimentally

$$-\tan[\arg(\varepsilon_K)] = \frac{x}{y}$$

  The ratio between the semileptonic asymmetry and $K_L \to \pi\pi$ is the same as y/x.
- Could be used as a test for D and B_s
- For the B_d, however, we know there is direct CPV so it will not work

Combination of D and K data

New physics

- NP can affect meson mixing amplitudes
- Such operators can give very large effects
- We parametrize it by the scale of the effective operator

$$\frac{1}{\Lambda_{\rm NP}^2}\left[z_1^K(\overline{d_L}\gamma_\mu s_L)(\overline{d_L}\gamma^\mu s_L)+z_1^D(\overline{u_L}\gamma_\mu c_L)(\overline{u_L}\gamma^\mu c_L)\right]$$

- In one case, that of a $(V-A)^2$ operator, the combination of K and D data is powerful
- The reason is that this operator works on the quark doublets and it affects both K and D

New physics effects

Consider some new heavy particles. In general they are OK with the data if

- Their masses are large (heavy); or
- They are degenerate (universality); or
- Their mixing angles are the same as the SM ones (alignment)

For example in SUSY the effect on $B-\bar{B}$ mixing is

$$\frac{\Delta m_{\rm SUSY}}{\Delta m_{\rm SM}} \sim 10^4 \left(\frac{100\ \mathrm{GeV}}{m_{\tilde{Q}}}\right)^2 \left(\frac{\Delta m^2_{\tilde{Q}}}{m^2_{\tilde{Q}}}\right)^2 \mathrm{Re}\left[(K_L)_{13}(K_R)_{13}\right]$$

NP effects on doublets

- Consider a NP operator that involves only doublets

$$\frac{1}{\Lambda_{\rm NP}^2}(\overline{Q_{Li}}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q_{Li}}(X_Q)_{ij}\gamma^\mu Q_{Lj})$$

- It contributes to both K and D mixing
- Consider the mechanism that make sure it is not too big. Does it do it for both D and K?
  - Yes, for heavy and universality
  - Kind of, for alignment (because of the built in CKM misalignment)

Alignment

- After electroweak breaking

$$\frac{1}{\Lambda_{\rm NP}^2}(\overline{Q_{Li}}(X_Q)_{ij}\gamma_\mu Q_{Lj})(\overline{Q_{Li}}(X_Q)_{ij}\gamma^\mu Q_{Lj}) \;\Rightarrow$$

$$\frac{1}{\Lambda_{\rm NP}^2}\left[z_1^K(\overline{d_L}\gamma_\mu s_L)(\overline{d_L}\gamma^\mu s_L) + z_1^D(\overline{u_L}\gamma_\mu c_L)(\overline{u_L}\gamma^\mu c_L)\right]$$

- How small we can make z_1^K and z_1^D using alignment?
- For the simple case of 2 generations and no CPV

$$z_1^K \propto \sin^2 2\alpha \qquad z_1^D \propto \sin^2 2(\alpha-\theta_c)$$

- Cannot make both of them much smaller than θ_c

Examples

Alignment cannot make the contribution to D and K both zero

- This result is generic. It also applies to the case of 3 generations and CPV
- SUSY (with $m_{\tilde{Q}} \leq 1$ TeV):

$$\frac{m_{\tilde{Q}_2} - m_{\tilde{Q}_1}}{m_{\tilde{Q}_2} + m_{\tilde{Q}_1}} \leq \begin{cases} 0.034 & \text{maximal phases} \\ 0.27 & \text{vanishing phases} \end{cases}$$

- RS:

$$f_{Q^2} \leq \sqrt{\frac{m_{\mathrm{KK}}}{\mathrm{TeV}}} \begin{cases} 0.020 & \text{maximal phases} \\ 0.056 & \text{vanishing phases} \end{cases}$$

Conclusions

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Of course, charm is interesting...

- CPV in charm implies NP, but be careful, it is not like B
- Relation to probe direct CPV
- The combination of D and K is powerful