Towards determination of the weak/strong phases in neutral D-meson decays into $K^{*+}K^-/K^{*-}K^+$

Zhi-zhong Xing

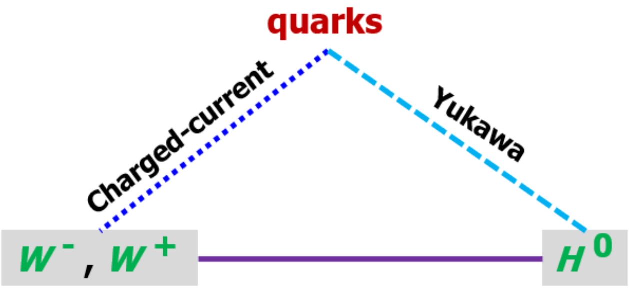
【IHEP Beijing】

- Why CPV so small in charm?
- The D → $K^-/K^{*-}K^+$ decays
- Further discussions

The 11th International Workshop on Charm Physics, 17~21 July 2023, Siegen

The origin of CPV in the SM

♦ **In the SM, the masses of three quark families originate from their interactions with the Higgs field, while flavor mixing and CP violation come from the mismatch between their simultaneous interactions with the Higgs and gauge fields.**



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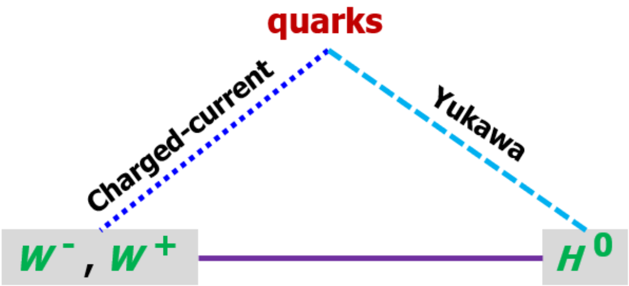
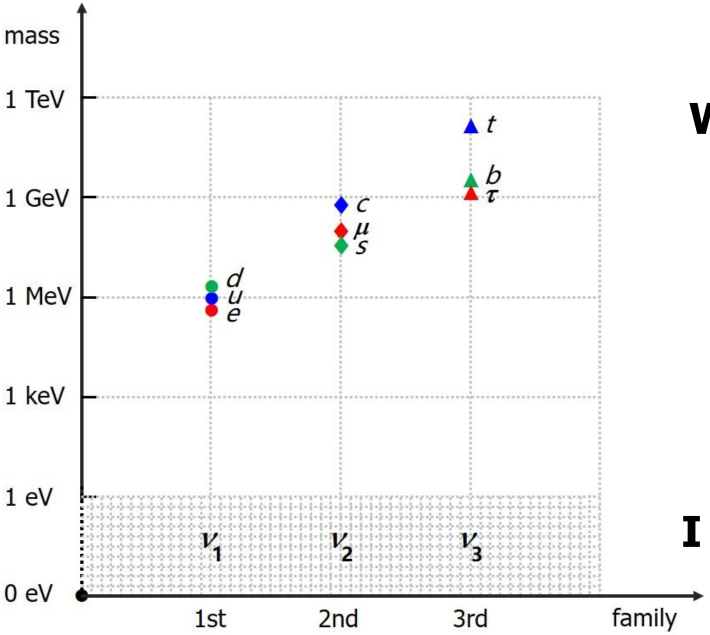
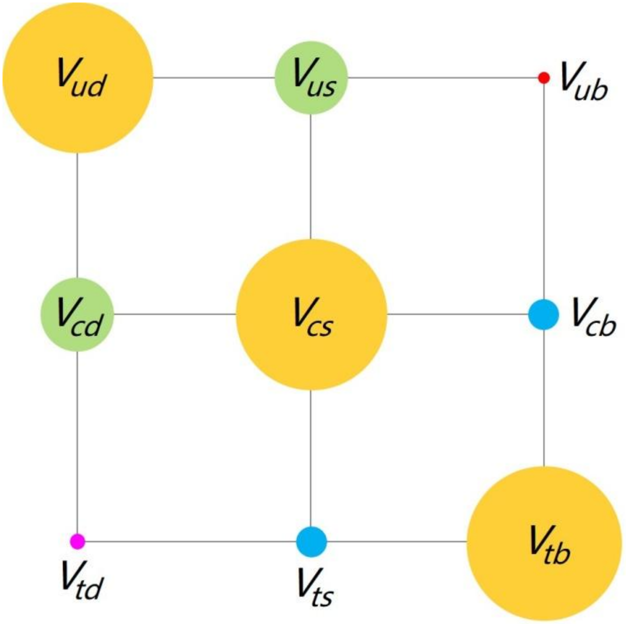




Why that *hierarchical* ?

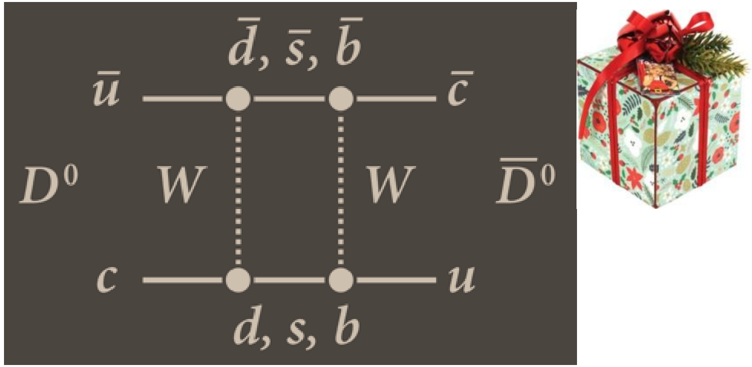
I lost in my own thought

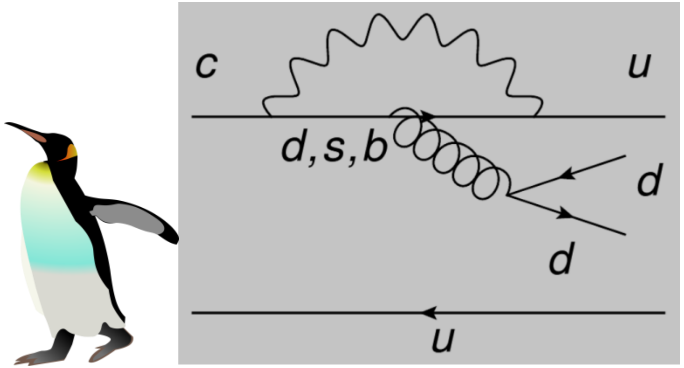


Salient features of CPV in charm

- In the SM, CPV arises from the interplay of all the three families of quarks.

- The 3rd family of quarks are so heavy that they are kinematically forbidden to contribute to the decays of D mesons at the tree level. And hence CPV can either arise from quantum effects where the 3rd family participate as *virtual* (intermediate) particles, or from tiny unitarity violation of the *u*-*d*-*c*-*s* block.





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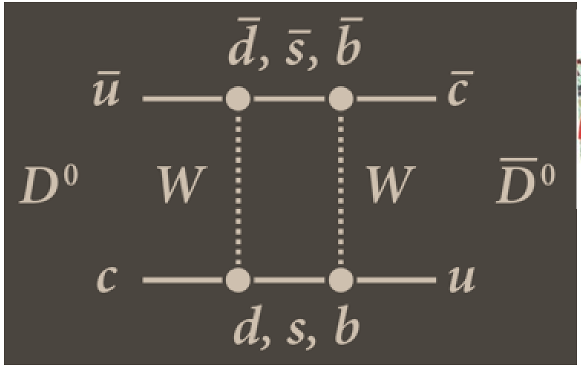
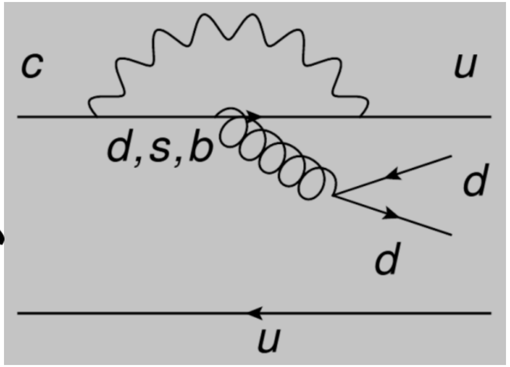




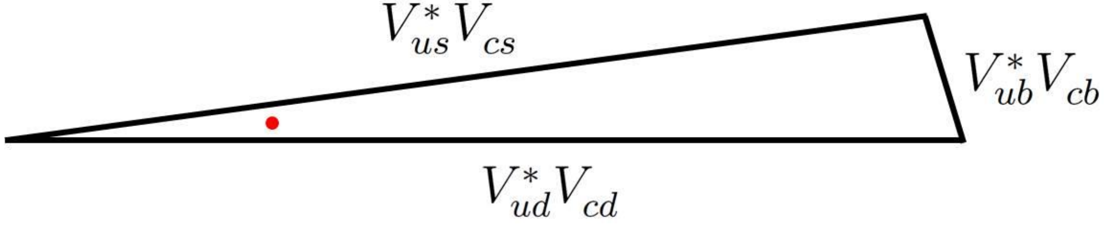
Unfortunately, the 3rd family *b*-quark plays a negligibly *tiny* role in the FCNC box and penguin diagrams.

$$m_b^2/m_W^2 \sim \mathcal{O}(10^{-3})\,, \quad |V_{ub}V_{cb}|^2/|V_{ud}V_{cd}|^2 \sim |V_{ub}V_{cb}|^2/|V_{us}V_{cs}|^2 \sim \mathcal{O}(10^{-6})$$

Both direct and indirect CPV are small

- **Geometric reason: the charm-associated CKM unitarity triangle is so sharp.**

$$\underbrace{V_{ud}^*V_{cd} + V_{us}^*V_{cs}}_{+\lambda^6\sin\gamma} + \underbrace{V_{ub}^*V_{cb}}_{-\,\lambda^6\sin\gamma} = 0$$



imaginary parts highly suppressed

$$V_{ub}^*V_{cb}/|V_{ud}^*V_{cd}| \simeq V_{ub}^*V_{cb}/|V_{us}^*V_{cs}| \simeq A^2\lambda^4\sqrt{\rho^2+\eta^2}\,e^{-i\gamma} \simeq \lambda^5\,e^{-i\gamma} \sim 5\times10^{-4}\,e^{-i\gamma}$$

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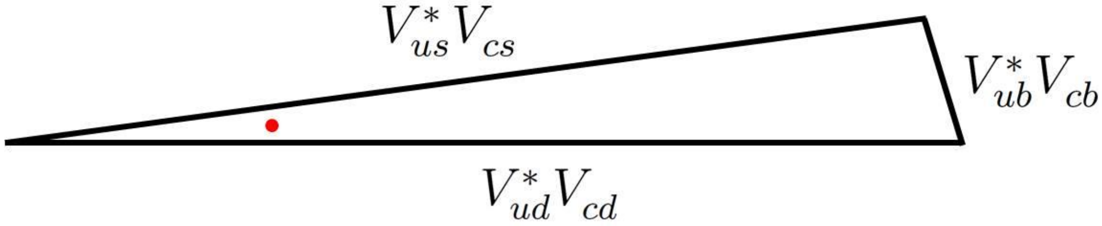

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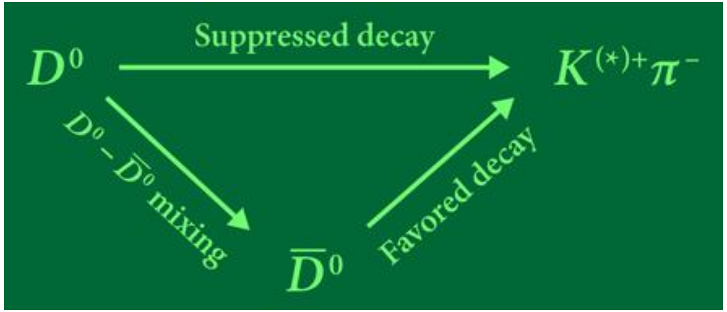
◆ **The magnitude of CPV in D decays is at most of order 0.1% in the SM, even if there are large final-state interactions.**

◆ **In general, the SCSDs may have larger CPV than the Cabibbo-favored decays and DCSDs.**

◆ **Indirect CPV is also *small*, at most of order 0.1%, due to suppressed D0-D0bar mixing.**

◆ **The unique experimental result at present:**

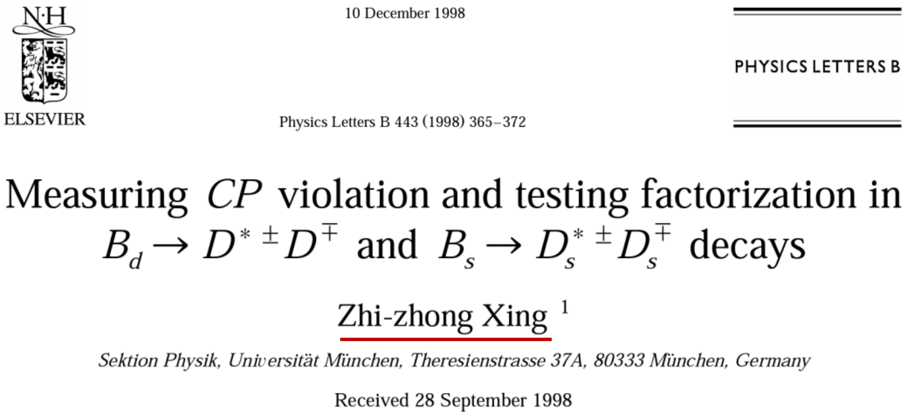
$$\mathcal{A}(D^0 \to K^+K^-) - \mathcal{A}(D^0 \to \pi^+\pi^-) = (-1.54 \pm 0.29) \times 10^{-3}$$



Then how about $K^{*+}K^-$/$K^{*-}K^+$?

Motivated by an analogue in B decays

- **CPV in B decays into $D^{*+}D^{-}$ or $D^{*-}D^{+}$:**



10 December 1998

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Physics Letters B 443 (1998) 365–372

PHYSICS LETTERS B

Measuring *CP* violation and testing factorization in $B_d \to D^{*\pm}D^{\mp}$ and $B_s \to D_s^{*\pm}D_s^{\mp}$ decays

Zhi-zhong Xing [1]

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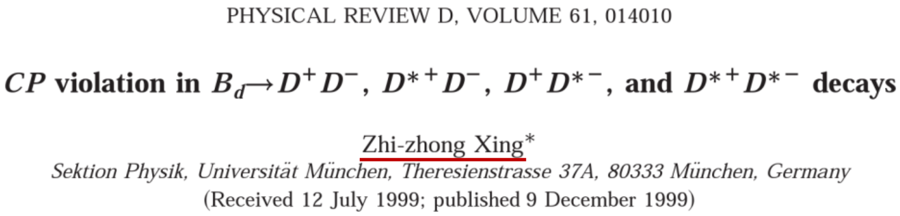

PHYSICAL REVIEW D, VOLUME 61, 014010

CP violation in $B_d \to D^+D^-$, $D^{*+}D^-$, D^+D^{*-}, and $D^{*+}D^{*-}$ decays

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BaBar, Belle and LHCb collaborations paid attention to such B decay modes and CPV, and reported some interesting results.

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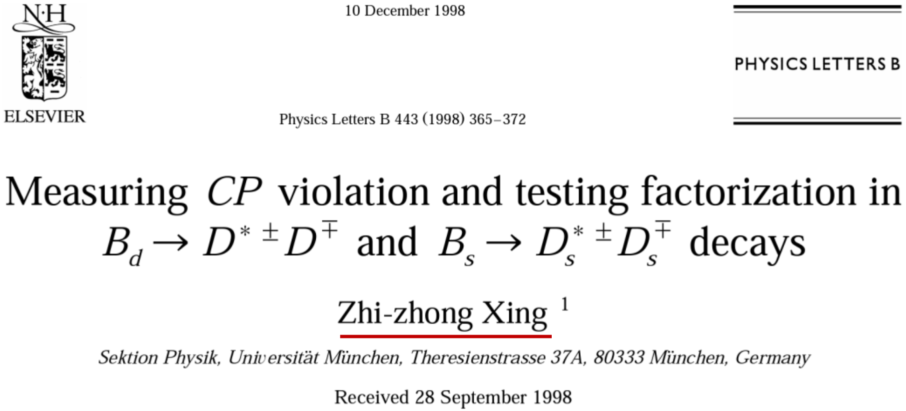

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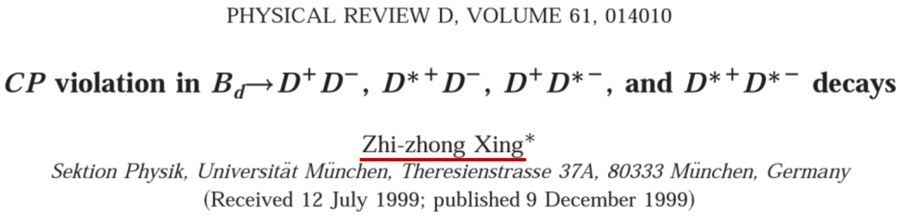

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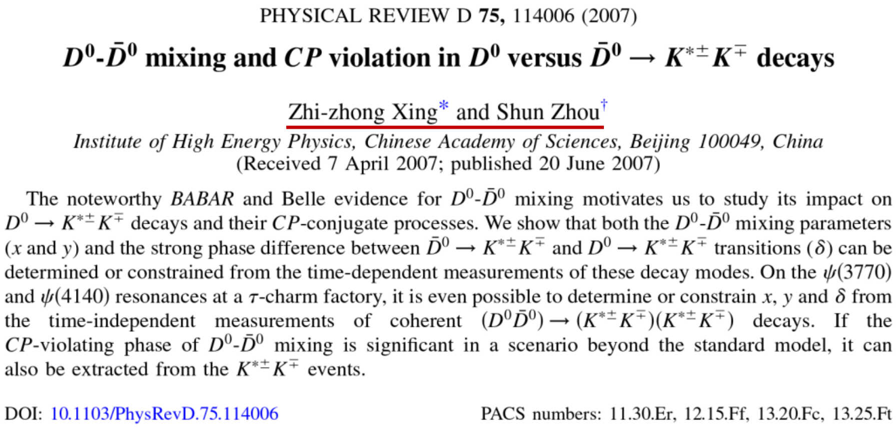
- **We did something similar in 2008:**



PHYSICAL REVIEW D **75**, 114006 (2007)

D^0-$\bar{D}^0$ mixing and *CP* violation in D^0 versus $\bar{D}^0 \to K^{*\pm}K^{\mp}$ decays

Zhi-zhong Xing* and Shun Zhou†

Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

(Received 7 April 2007; published 20 June 2007)

The noteworthy *BABAR* and Belle evidence for D^0-$\bar{D}^0$ mixing motivates us to study its impact on $D^0 \to K^{*\pm}K^{\mp}$ decays and their *CP*-conjugate processes. We show that both the D^0-$\bar{D}^0$ mixing parameters (x and y) and the strong phase difference between $\bar{D}^0 \to K^{*\pm}K^{\mp}$ and $D^0 \to K^{*\pm}K^{\mp}$ transitions (δ) can be determined or constrained from the time-dependent measurements of these decay modes. On the $\psi(3770)$ and $\psi(4140)$ resonances at a τ-charm factory, it is even possible to determine or constrain x, y and δ from the time-independent measurements of coherent $(D^0\bar{D}^0) \to (K^{*\pm}K^{\mp})(K^{*\pm}K^{\mp})$ decays. If the *CP*-violating phase of D^0-$\bar{D}^0$ mixing is significant in a scenario beyond the standard model, it can also be extracted from the $K^{*\pm}K^{\mp}$ events.

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In this talk, I will

- **reiterate the usefulness of $K^{*+}K^{-}$/$K^{*-}K^{+}$;**
- **update the previous calculations;**
- **comment on the coherent case;**
- **learn more from colleagues.**

Some preliminaries

◆ **Different from the CP state K^+K^-, $K^{*+}K^-$ or $K^{*-}K^+$ mode may have a big strong phase.**

◆ **The tree-level amplitude is essentially CP-conserving in the PDG phase convention, and the loop-level (penguin-diagram) amplitude is highly suppressed in magnitude so it can be safely neglected in the SM and some natural extensions of the SM.**

$$\left.\begin{aligned} A_{K^{*+}K^-} &\equiv \langle K^{*+}K^-|\mathcal{H}|D^0\rangle \\ \bar{A}_{K^{*+}K^-} &\equiv \langle K^{*+}K^-|\mathcal{H}|\bar{D}^0\rangle \\ A_{K^{*-}K^+} &\equiv \langle K^{*-}K^+|\mathcal{H}|D^0\rangle \\ \bar{A}_{K^{*-}K^+} &\equiv \langle K^{*-}K^+|\mathcal{H}|\bar{D}^0\rangle \end{aligned}\right] \Rightarrow \begin{aligned} \bar{A}_{K^{*-}K^+} &= A_{K^{*+}K^-} \\ A_{K^{*-}K^+} &= \bar{A}_{K^{*+}K^-} \end{aligned} \Rightarrow \boxed{\frac{\bar{A}_{K^{*+}K^-}}{A_{K^{*+}K^-}} = \frac{A_{K^{*-}K^+}}{\bar{A}_{K^{*-}K^+}} \equiv \underset{\substack{\uparrow \\ >0}}{\rho} e^{i\delta}}$$

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- ◆ **The neutral D-meson mixing via the box diagrams may introduce a new weak phase beyond the SM, although its phase ϕ in the SM is almost zero. In this case indirect CPV effects are governed by the following rephasing-invariant quantities:**

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\bar{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\bar{D}^0\rangle \end{aligned} \quad \xrightarrow[y \equiv (\Gamma_2 - \Gamma_1)/(2\Gamma)]{x \equiv (m_2 - m_1)/\Gamma} \quad \left\{\begin{aligned} \lambda_{K^{*+}K^-} &\equiv \frac{q}{p}\cdot\frac{\bar{A}_{K^{*+}K^-}}{A_{K^{*+}K^-}} = \rho\left|\frac{q}{p}\right| e^{i(\delta+\phi)} \\ \bar{\lambda}_{K^{*-}K^+} &\equiv \frac{p}{q}\cdot\frac{A_{K^{*-}K^+}}{\bar{A}_{K^{*-}K^+}} = \rho\left|\frac{p}{q}\right| e^{i(\delta-\phi)} \end{aligned}\right.$$

Time-dependent decay rates

- ◆ **The very small *D0-D0bar mixing* allows for a safe analytical approximation for the decay rates.**
- ◆ **Given *t* ≤ 1/Γ for the proper time, we obtain**

$$\Gamma[D^0(t) \to K^{*+}K^-] \;\propto\; |A_{K^{*+}K^-}|^2 e^{-\Gamma t}\left[1+\rho\left|\frac{q}{p}\right|\left(y'_-\cos\phi - x'_+\sin\phi\right)\Gamma t\right]$$

$$\Gamma[\bar{D}^0(t) \to K^{*-}K^+] \;\propto\; |\bar{A}_{K^{*-}K^+}|^2 e^{-\Gamma t}\left[1+\rho\left|\frac{p}{q}\right|\left(y'_-\cos\phi + x'_+\sin\phi\right)\Gamma t\right]$$

and

$$\Gamma[D^0(t) \to K^{*-}K^+] \;\propto\; |\bar{A}_{K^{*-}K^+}|^2 e^{-\Gamma t}\left[\rho^2+\rho\left|\frac{q}{p}\right|\left(y'_+\cos\phi - x'_-\sin\phi\right)\Gamma t\right]$$

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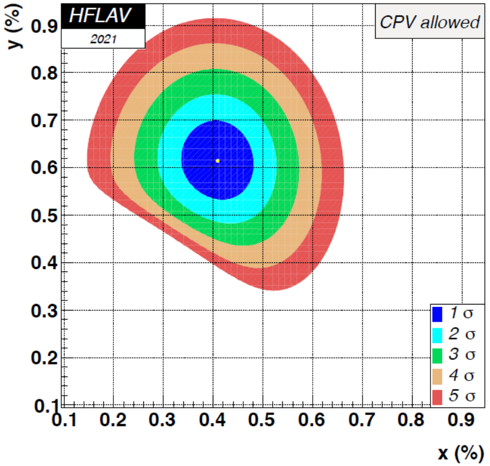
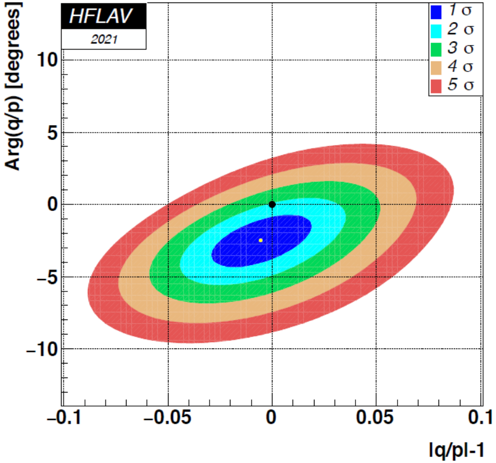
here the two effective (strong-phase-rotated) D0-D0bar mixing parameters are defined as

$$x'_\pm = x\cos\delta \pm y\sin\delta, \qquad y'_\pm = y\cos\delta \pm x\sin\delta$$

Within the SM, $\phi \approx 0$ and $|p/q| \approx 1$, it is possible to determine δ.





Time-independent coherent decays (1)

- On the resonance ψ**(3770)** with **C = -1**, or on the resonance ψ**(4140)** with **C = +1**, a pair of neutral D mesons can be coherently produced. So their decay will be well studied in the super-tau-charm factory:

$$(D^0\bar{D}^0)_C \to (K^{*\pm}K^{\mp})(K^{*\pm}K^{\mp})$$

$$\Gamma_C^{++} \equiv \Gamma(K^{*+}K^-, K^{*+}K^-)_C$$
$$\Gamma_C^{--} \equiv \Gamma(K^{*-}K^+, K^{*-}K^+)_C$$
$$\Gamma_C^{-+} \equiv \Gamma(K^{*-}K^+, K^{*+}K^-)_C$$

- The time-integrated joint decay rates are expressed as follows:

$$r \equiv (x^2 + y^2)/2$$

$$\Gamma_C^{++} \propto 2|A_{K^{*+}K^-}|^4 \left\{ (2+C)\, r \left[\left|\frac{p}{q}\right|^2 + 2C\rho^2 \cos(\delta+\phi) + \rho^4 \left|\frac{q}{p}\right|^2 \right] + (1+C)^2 \rho \left[\rho + \left|\frac{p}{q}\right| \left(y'_+ \cos\phi + x'_- \sin\phi \right) + \rho^2 \left|\frac{q}{p}\right| \left(y'_- \cos\phi - x'_+ \sin\phi \right) \right] \right\}$$

$$\Gamma_C^{--} \propto 2|\bar{A}_{K^{*-}K^+}|^4 \left\{ (2+C)\, r \left[\left|\frac{q}{p}\right|^2 + 2C\rho^2 \cos(\delta-\phi) + \rho^4 \left|\frac{p}{q}\right|^2 \right] + (1+C)^2 \rho \left[\rho + \left|\frac{q}{p}\right| \left(y'_+ \cos\phi - x'_- \sin\phi \right) + \rho^2 \left|\frac{p}{q}\right| \left(y'_- \cos\phi + x'_+ \sin\phi \right) \right] \right\}$$

Time-independent coherent decays (2)

- **The time-integrated joint decay rates are expressed as follows (continued):**

$$\begin{aligned}\Gamma^{+-}_{C} \quad \propto \quad & 2|A_{K^{*+}K^{-}}|^{4}\left\{(2+C)\, r\rho^{2}\left[\left|\frac{p}{q}\right|^{2}+2C\cos\left(2\phi\right)+\left|\frac{q}{p}\right|^{2}\right]+\left[1+2C\rho^{2}\cos\left(2\delta\right)+\rho^{4}\right]\right. \\ & +(1+C)\,\rho\left|\frac{p}{q}\right|\left[\left(y'_{-}\cos\phi+x'_{+}\sin\phi\right)+\rho^{2}\left(y'_{+}\cos\phi+x'_{-}\sin\phi\right)\right] \\ & \left.+(1+C)\,\rho\left|\frac{q}{p}\right|\left[\left(y'_{-}\cos\phi-x'_{+}\sin\phi\right)+\rho^{2}\left(y'_{+}\cos\phi-x'_{-}\sin\phi\right)\right]\right\}\;.\end{aligned}$$

- **On the resonance ψ(3770):**

$$\frac{\Gamma^{++}_{-}}{\Gamma^{+-}_{-}} \approx r\frac{1-2\rho^{2}\cos(\delta+\phi)+\rho^{4}}{1-2\rho^{2}\cos(2\delta)+\rho^{4}}$$

$$\frac{\Gamma^{--}_{-}}{\Gamma^{+-}_{-}} \approx r\frac{1-2\rho^{2}\cos(\delta-\phi)+\rho^{4}}{1-2\rho^{2}\cos(2\delta)+\rho^{4}}$$

- **On the resonance ψ(4140):**

$$\frac{\Gamma^{++}_{+}}{\Gamma^{+-}_{+}} \approx \frac{\Gamma^{--}_{+}}{\Gamma^{+-}_{+}} \approx \frac{4\rho^{2}}{1+2\rho^{2}\cos(2\delta)+\rho^{4}}$$

- **We hope that $K^{*+}K^{-}$ and $K^{*-}K^{+}$ modes are complementary to the $K^{+}K^{-}$ and $\pi^{+}\pi^{-}$ modes or $K^{+}\pi^{-}$ and $K^{-}\pi^{+}$ modes in the study of charmed CPV, both direct and indirect.**

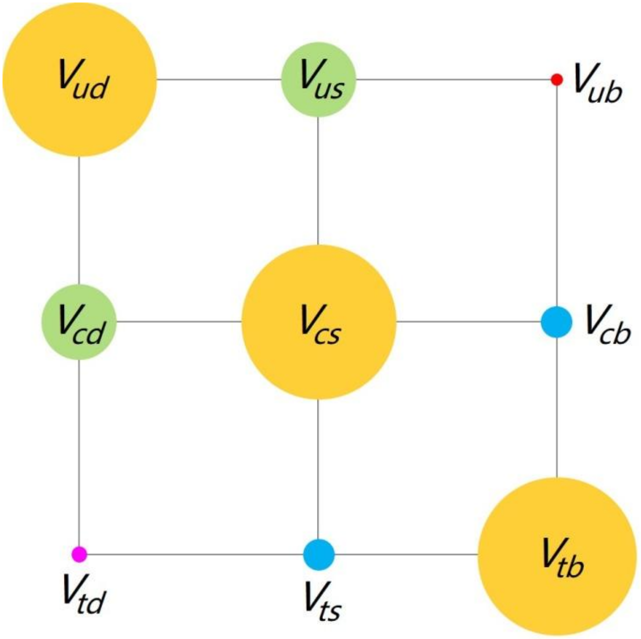
Further discussions

- **The strength of CPV in the SM is characterized by the universal Jarlskog invariant, a small quantity :**

$$\boxed{J \simeq A^2\lambda^6\eta \sim 3 \times 10^{-5}}$$

- **The asymmetry between a decay and its CP-conjugated process is measured by the ratio of *J* to its CP-conserving counterpart. In the charm sector, e.g.,**

$$\mathrm{Asymmetry} = \frac{J}{\mathrm{Re}(V_{ud}V_{cs}V_{us}^{*}V_{cd}^{*})} \simeq A^2\lambda^4\eta \sim 6 \times 10^{-4}$$



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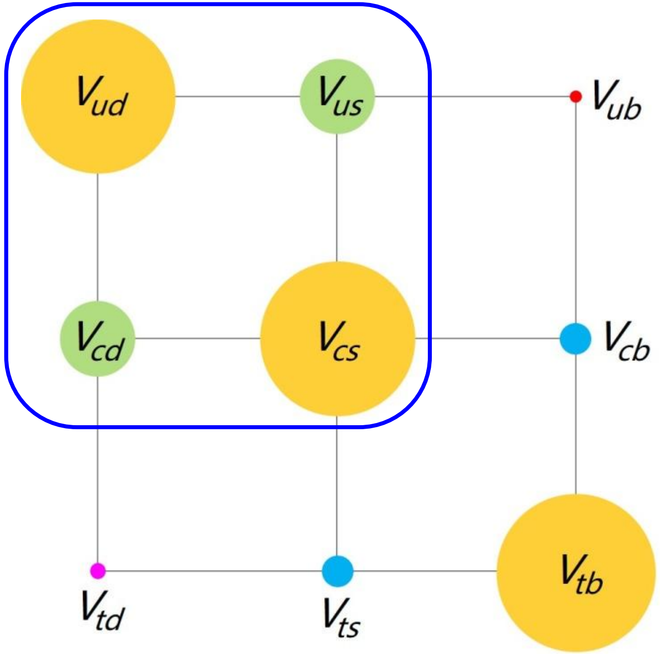
- ♦ **A *stupid* question: why there is CPV in the presence of only four flavor indices?**

- ♦ **Answer: since unitarity of the 2 × 2 block's is slightly violated by the two extra flavor indices (namely the 3rd family of quarks).**



- ♦ **Because the top quark's lifetime is much smaller than its *hadronization* time, it is absolutely impossible to see all the six flavors appearing in a single process. It is also hopeless to see any new physics?**

Thank you for your attention