LHCb CP-violation in D meson decays

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Overview

- CP-violation in D meson;
- Experiments and calculations in SM;
- R-parity violation induced CP asymmetry;
- some consequences.

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CP-violation in D meson

- 3 types of CP-violation
  - In decay: amplitudes for a process and its CP conjugate differ.
  - In mixing: rate of $D^0 \to \bar{D}^0$ and $\bar{D}^0 \to D^0$ differ.
  - In interference between decay and mixing.
- In the SM, indirect CP-violation in charm is expected to be small and universal between CP eigenstates.
- direct CP-violation can be large in SM, dependent on final states.

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Direct CPV of D meson

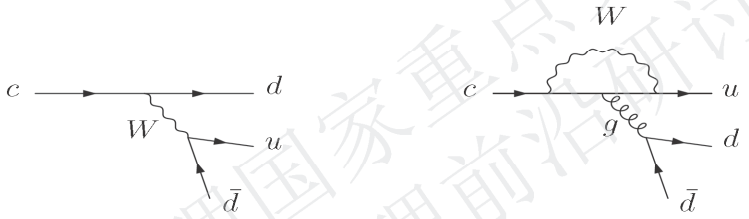

Figure: SM D^0 decay

$$A_f(D \to f) = A_f^T[1 + r_f e^{i(\delta_f - \gamma)}]; \qquad (1)$$
$$\bar{A}_{\bar{f}}(\bar{D} \to \bar{f}) = A_f^T[1 + r_f e^{i(\delta_f + \gamma)}].$$

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Direct CPV of D meson

where A_f^T is the tree amplitude, and r_f is the relative magnitude of penguin diagram. γ is the weak phase and δ_f refers to the strong phase, which arises when the internal quarks are on the mass shell.

$$\mathcal{A}_f^{dir} \equiv \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2} = 2r_f \sin\gamma \sin\delta_f \tag{2}$$

$$\sin\gamma = 0.92, \quad r_{K^+K^-} \sim \frac{\alpha_s}{\pi}\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*} \sim \mathcal{O}(10^{-4}); \tag{3}$$

$$\mathcal{A}_f^{dir} \sim \mathcal{O}(10^{-4}), \quad \mathcal{A}_{\pi^+\pi^-}^{dir} = -\mathcal{A}_{K^+K^-}^{dir}. \tag{4}$$

therefore

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{K^+K^-}^{dir} - \mathcal{A}_{\pi^+\pi^-}^{dir} \sim \mathcal{O}(10^{-4}). \tag{5}$$

Previous experimental results

Year	Experiment	CP Asymmetry in the decay mode D0 to π+π-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2010	CDF	M.J. Morello (CDF Collab.), Preprint (CHARM 2010).	+0.0022 ± 0.0024 ± 0.0011
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 2008).	+0.0043 ± 0.0052 ± 0.0012
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
.	.	COMBOS average	+0.0020 ± 0.0022

Year	Experiment	CP Asymmetry in the decay mode D0 to K+K-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2011	CDF	A. Di Canto (CDF Collab.), Preprint (BEAUTY 2011).	-0.0024 ± 0.0022 ± 0.0010
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).	-0.0043 ± 0.0030 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	+0.0000 ± 0.0034 ± 0.0013
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.000 ± 0.022 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	-0.001 ± 0.022 ± 0.015
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.010 ± 0.049 ± 0.012
1995	CLEO	J.E. Bartelt et al. (CLEO Collab.), Phys. Rev. D 52, 4860 (1995).	+0.080 ± 0.061
1994	E687	P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).	+0.024 ± 0.084
.	.	COMBOS average	-0.0023 ± 0.0017

Figure: Experiments in past years

LHCb measurement

The latest LHCb result:

$$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}^{dir}_{K^+K^-} - \mathcal{A}^{dir}_{\pi^+\pi^-} = [-0.82 \pm 0.21(\texttt{stat.}) \pm 0.11(\texttt{sys.})]\% \quad (6)$$

Significance: 3.5 σ.
It is obvious that this result significantly deviate from our previous estimation.

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Brute-force calculation in SM

$$\begin{aligned}\mathcal{A}_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-) &= \frac{\alpha_s(\mu)}{6}\left[-1+\frac{2m_\pi^2}{m_c(m_u+m_d)}\right]\frac{{\rm Im}(V_{ub}V_{cb}^*)}{V_{ud}V_{cd}^*} \\ &\simeq 0.0127\%,\end{aligned} \tag{7}$$

similarly, we have $\mathcal{A}_{CP}^{\rm dir}(D^0 \to K^+K^-) \simeq -0.0116\%$.
Then,

$$\Delta\mathcal{A}_{CP}^{\rm dir}({\rm SM}) = -0.024\%, \tag{8}$$

which is consistent with our previous estimation.

Some hints for New Physics

Unlike in D system, the CP-violations in K and B systems are thought to be consistent with the SM, especially the measurement of $\mathcal{A}_{CP}(B \to \psi K_s)$ is consistent with SM prediction.

Therefore, some NP mechanism might be responsible for the CP-violation in the up-type quark (D meson) decays, while leaving the down-type quark (K an B mesons) decays not affected.

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R-parity violation(RPV) terms

The general SM related trilinear RPV interactions in SUSY are

$$\mathcal{W}_{\not R} = \epsilon_{\alpha\beta}(\frac{1}{2}\lambda_{ijk}L_i^\alpha L_j^\beta E_k^c + \lambda'_{ijk}L_i^\alpha Q_j^\beta D_k^c) + \frac{1}{2}\lambda''_{ijk}U_i^c D_j^c D_k^c \ , \tag{9}$$

where $\lambda_{ijk} = -\lambda_{jik}$, $\lambda''_{ijk} = -\lambda''_{ikj}$, and λ'_{ijk}'s are completely free. It is obvious that the charm quark nonleptonic decays could be induced by λ', λ'' terms, the related Lagrangian is

$$\mathcal{L} \supset \lambda'_{ijk}\tilde{l}_{iL}\bar{d}_{kR}u_{jL} - \frac{1}{2}\lambda''_{ijk}(\widetilde{d}^*_{kR}\bar{u}_{iR}d^c_{jL} + \widetilde{d}^*_{jR}\bar{u}_{iR}d^c_{kL}) + \text{ h.c. } . \tag{10}$$

Some constraints of the couplings

- Only λ' terms would be taken into account, since otherwise violations of baryon numbers would have to be considered.
- Among various λ'_{ijk}, there are only two nonzero terms: λ'_{112} and λ'_{122}, while λ'_{112} is real and λ'_{122} is complex.
- To be quantitatively correct, the following relation could be assumed, as

$$\frac{\mathrm{Im}(\lambda'_{122}\lambda'^{*}_{112})}{\widetilde{m}_e^2} = \frac{\lambda'_{112}\mathrm{Im}(\lambda'_{122})}{\widetilde{m}_e^2} \simeq 33 \times \frac{\mathrm{Im}(V_{ub}V_{cb}^{*})}{m_W^2} g_2^2 \ . \tag{11}$$

Related Feynman diagrams

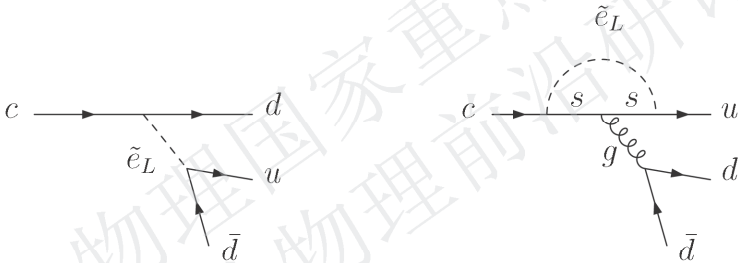

Figure: RPV D^0 decay

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Total CP asymmetry

The total direct CP violation in $D^0 \to \pi^+\pi^-$ transition is now

$$A_{CP}^{\rm dir}(D^0 \to \pi^+\pi^-) \simeq 0.43\%. \tag{12}$$

Similar calculation results to total CP violation in $D^0 \to K^+K^-$ transition

$$A_{CP}^{\rm dir}(D^0 \to K^+K^-) \simeq -0.39\%. \tag{13}$$

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Some explanations

- To elude constraints from the branching ratio of $\mu \to e + \gamma$, only first generation of leptons have been taken into account.
- These new couplings would not affected the mixing of mesons, either in D or in K, since they are negligible (the new couplings are actually CKM suppressed), compared to the couplings responsible for the mixing in SM, which are CKM favored.
- The RPV induced direct CP-violation in K system is also negligible. In SM, top-quark is responsible for the direct CP-violation in K meson, whereas new contributions mainly come from strange-quark.

Conclusion and discussions

- There are many constraints in RPV , among which the following constraints are of the most interest to us, as

$$|\lambda'_{i22}\lambda'^{*}_{i12}| < 2.11 \times 10^{-5}\Big[\frac{m_{\widetilde{d}_{kR}}}{100\mathrm{GeV}}\Big]^2 , \qquad (14)$$

which combined with Eq. (11), would deduce another interesting constraint, as $m_{\widetilde{d}_R} \geq 10\, m_{\widetilde{e}}$, which is acceptable for the present.

Conclusion and discussions

- The most direct inference is that, since we have introduced some RPV terms, the tree level transition such as $\widetilde{q} \to q' + e$, would be observable once the SUSY is discovered. Simple estimation indicates that the decay rates would be at least 0.1 GeV, which can be tested in future.

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The end

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