LHCb ACP of D meson and R-Parity Violation Postprint

Authors: Xue Chang, Ming-Kai Du, Chun Liu, Jia-Shu Lu, Shuo Yang

Date: 2017-09-17T00:00:00+00:00

Abstract

LHCb collaboration has recently announced a measurement of the difference of time-integrated CP asymmetries between D → K+K− and D → #25;+#25;−. This result provides the evidence of large direct CP violation in D meson and reveals some important implications on underlying new physics. It is shown that the direct CP violation in D meson can be enhanced by R-parityviolating supersymmetry, while CP violations in K and B mesons are suppressed by this newphysics, which is in consistence with previous experiments. Constraints on the model parametersand some consequences are also discussed.

Full Text

Preamble

CP Asymmetry of D Meson and R-Parity Violation

Xue Chang[1], Ming-Kai Du[1], Chun Liu[1], Jia-Shu Lu[1], Shuo Yang[2,3]

[1]State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, P.O. Box 2735, Beijing 100190, P.R. China
[2]Department of Physics, Dalian University, Dalian 116622, P.R. China
[3]Center for High-Energy Physics, Peking University, Beijing, 100871, P.R. China

Abstract

The LHCb collaboration has recently announced a measurement of the difference in time-integrated CP asymmetries between $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays. This result provides evidence for large direct CP violation in the D meson system and reveals important implications for underlying new physics. We demonstrate that direct CP violation in D meson decays can be enhanced by R-parity violating supersymmetry, while CP violations in K and B mesons remain suppressed by this new physics, consistent with previous experimental results. Constraints on the model parameters and associated consequences are also discussed.

PACS numbers: 11.30.Er, 13.25.Ft, 14.40.Lb, 12.60.Jv

Electronic address: chxue@itp.ac.cn, mkdu@itp.ac.cn, liuc@mail.itp.ac.cn, lujiashu@itp.ac.cn, yangshuo@dlu.edu.cn

Introduction

New physics may be discovered either through direct searches at colliders or via indirect observations in precision measurements at "low" energies. The key motivations for CP violation (CPV) measurements at LHCb are precisely to conduct precision tests of the Standard Model (SM) and to search for new physics. CP violation in D mesons is highly suppressed in the SM, providing a background-free environment for new physics searches. Furthermore, hadrons containing charm quarks represent the only playground for studying CP violation in the up-type quark sector, as top quarks decay before hadronization. Hadrons built from u or $\bar{u}$ quarks, such as π^0 and η, are their own antiparticles, and therefore no CP violation occurs in these systems.

Recently, the LHCb collaboration announced a measurement of the difference between CP asymmetries in two D meson decay channels [**?**]: $A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-) = [0.21(\text{stat.}) \pm 0.11(\text{syst.})]\%$. This measurement is robust against systematic uncertainties and is primarily sensitive to direct CP violation. The result deviates significantly from SM predictions, which place this quantity at the order of 10^{-4} \cite{2-5}. Although ATLAS and CMS have not found evidence for new physics, this large CP asymmetry at LHCb may provide a hint of underlying new physics.

In this work, we present a tentative interpretation of the enhanced direct CP violation in D mesons within R-parity violating (RPV) supersymmetry, while leaving CP violation in K and B mesons nearly unaffected, since SM predictions for these systems are consistent with experimental data. In Section II, we provide a brief estimate of direct CP violation in the SM, which allows us to extract essential RPV parameters. Section III presents our conclusions and discusses relevant implications.

II. R-Parity Violating SUSY and Direct CP Violation in D Decay

Before discussing R-parity violating supersymmetry, we briefly review the SM calculation for this CPV observable \cite{2-5}. In the SM, CP violations in $D^0(\bar{D}^0) \to K^+K^-$ decays are significantly suppressed by CKM parameters, loop effects, and the GIM mechanism. At the quark-gluon level, the $\pi^+\pi^-$ case is depicted in Fig. 1 [Figure 1: see original paper], with the K^+K^- case described by the same diagrams with the replacement $d \to s$. CP violation in these decays arises from interference between the tree amplitude (Fig. 1 left) and the penguin diagram amplitude (Fig. 1 right). The CP asymmetry is defined as [?]:

$$A_{CP} \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \simeq \frac{2\mathrm{Im}(\alpha_T^* \alpha_P)}{|\alpha_T|^2}$$

where α_T and α_P represent the tree and penguin amplitudes, respectively. For $D^0 \to \pi^+\pi^-$, we have $\alpha_T(D^0 \to \pi^+\pi^-) = V_{ud}V_{cd}^*\mathcal{T}$ and $\alpha_P(D^0 \to \pi^+\pi^-) = V_{ub}V_{cb}^*\mathcal{P}$. To $\mathcal{O}(\alpha_s)$, the direct CP asymmetry can be simplified as:

$$A_{CP}^{\mathrm{dir}}(\mathrm{SM}) \simeq 2\frac{\mathrm{Im}(\alpha_T^* \alpha_P)}{|\alpha_T|^2}$$

The tree-level diagram amplitude is:

$$T(D^0 \to \pi^+\pi^-) \approx -\frac{G_F}{\sqrt{2}} V_{ud}V_{cd}^* \langle \pi^+\pi^- | \bar{d}\gamma_\mu c \bar{u}\gamma^\mu\gamma_5 d | D^0 \rangle$$

where the hadronic matrix elements are parameterized as:

$$\langle \pi^- | \bar{u}\gamma_\mu\gamma_5 d | 0 \rangle = i f_\pi p_\mu$$
$$\langle \pi^+ | \bar{d}\gamma_\mu c | D^0 \rangle = f_+(q^2)(p_{D^0} + p_{\pi^+})_\mu + f_-(q^2)(p_{D^0} - p_{\pi^+})_\mu$$

The imaginary parts of penguin diagrams arise from cuts on internal lines involving on-shell particles and thus long-distance physics, making them difficult to estimate. Nevertheless, we can first calculate the penguin diagram assuming the gluon momentum is spacelike (which is calculable), then carefully analytically continue the momentum to timelike to extract the imaginary part. While the result is not as accurate as in QED, it can still be considered a reasonable estimation. The result is:

$$\mathcal{P}(D^0 \to \pi^+\pi^-) = i\alpha_s(\mu)\frac{G_F}{\sqrt{2}} V_{ub}V_{cb}^* \langle \pi^+\pi^- | \bar{d}\gamma_\mu c \bar{u}\gamma^\mu\gamma_5 d | D^0 \rangle \frac{(m_u + m_d)}{(m_c - m_d)(m_u + m_d)}$$

where μ is the typical energy scale in this transition. Substituting the relevant expressions, the final result is:

$$A_{CP}(D^0 \to \pi^+\pi^-) = \frac{\alpha_s(\mu)}{27}\frac{(m_u + m_d)}{(m_c - m_d)}\mathrm{Im}\left(\frac{V_{ub}V_{cb}^*}{V_{ud}V_{cd}^*}\right) \approx 0.0086\%$$

$$A_{CP}(D^0 \to K^+K^-) = \frac{\alpha_s(\mu)}{27}\frac{(m_u + m_s)}{(m_c - m_s)}\mathrm{Im}\left(\frac{V_{ub}V_{cb}^*}{V_{us}V_{cs}^*}\right) \approx 0.0087\%$$

where we have taken $\mu = m_c$, $\alpha_s(m_c) = 0.396$, $\lambda = 0.2253$, $A = 0.808$, $\eta = 0.341$, $m_K = 493.677$ MeV, $m_\pi = 140$ MeV, $m_s(m_c) = 122$ MeV, $m_c = 1290$ MeV, $m_d(m_c) = 6.1$ MeV, and $m_u(m_c) = 3.05$ MeV [?, ?]. The U-spin relation $A_{CP}^{\mathrm{SM}}(D^0 \to K^+K^-) \approx A_{CP}^{\mathrm{SM}}(D^0 \to \pi^+\pi^-)$ is guaranteed by approximate $\mathrm{SU}(3)_F$ symmetry. The difference between the two asymmetries is:

$$\Delta A_{CP}^{\mathrm{SM}} = A_{CP}^{\mathrm{SM}}(D^0 \to K^+K^-) - A_{CP}^{\mathrm{SM}}(D^0 \to \pi^+\pi^-) \approx 0.02\%$$

While uncertainties due to nonperturbative QCD might be considerable [?, ?], the experimental central value from LHCb remains difficult to understand within the SM.

It is well known that CP violation in D meson decays provides a clean probe of new physics, which has drawn considerable attention \cite{3,4,6,10-14}. In light of the recent experimental result for ΔA_{CP}, we expect that such new physics would enhance direct CP violation in charm quark decays \cite{15-18} while leaving beauty and strange quarks nearly unaffected. We will show that RPV SUSY can provide such an opportunity.

In supersymmetry, the general trilinear RPV superpotential is:

$$W_{\mathrm{RPV}} = \epsilon_{\alpha\beta}\left(\lambda_{ijk}L_i^\alpha L_j^\beta E_k^c + \lambda'_{ijk}L_i^\alpha Q_j^\beta D_k^c + \lambda''_{ijk}U_i^c D_j^c D_k^c\right)$$

where λ_{ijk}, λ'_{ijk}, and λ''_{ijk} are completely free parameters. Here L and E^c (Q, U^c and D^c) correspond respectively to the lepton doublet and anti-lepton singlet (quark doublet and antiquark singlet) left-handed superfields. Charm quark nonleptonic decays can be induced by λ' and λ'' terms [?, ?]. The relevant Lagrangian is:

$$\mathcal{L}_{\mathrm{RPV}} = \lambda'_{ijk}\left(\tilde{\nu}_L^i \bar{d}_k u_L^j + \tilde{e}_L^i \bar{d}_k d_L^j - \tilde{d}_L^j \bar{d}_k \nu_L^i - \tilde{d}_L^k \bar{d}_k e_L^i\right) + \text{h.c.}$$

For simplicity, we assume baryon number conservation and consider only the λ' terms. The new charm quark decay diagrams are shown in Fig. 2 [Figure 2: see original paper].

We find that the following requirements are essential to explain the LHCb CPV anomaly: (1) Among various λ'_{ijk} couplings, only two terms are introduced: λ'_{112} and λ'_{122}, with λ'_{112} real and λ'_{122} complex. (2) The following relation is assumed:

$$\mathrm{Im}(\lambda'_{112})\mathrm{Im}(\lambda'_{122}) \sim \frac{g^2}{16\pi^2}\mathrm{Im}(V_{ub}V_{cb}^*)$$

where g is the weak interaction coupling, and the numerical factor is inferred from the SM calculation above.

Because of this relation, the new RPV tree diagrams are negligible compared to the SM tree diagram:

$$\frac{T_{\mathrm{RPV}}(D^0 \to K^+K^-)}{T_{\mathrm{SM}}(D^0 \to K^+K^-)} \sim \frac{\mathrm{Im}(V_{ub}V_{cb}^*)}{\mathrm{Im}(V_{us}V_{cs}^*)} \ll 1$$

Consequently, RPV contributions to the branching ratios of various D and K decays are negligible compared to their SM values.

With all necessary ingredients prepared, the calculations are straightforward. First, consider the $D^0 \to \pi^+\pi^-$ transition. The total amplitude is:

$$\mathcal{A}(D^0 \to \pi^+\pi^-) = \alpha_T^{\mathrm{SM}} + \alpha_T^{\mathrm{RPV}} + \alpha_P^{\mathrm{SM}} + \alpha_P^{\mathrm{RPV}}$$

where $\alpha_T^{\mathrm{RPV}}(D^0 \to \pi^+\pi^-) = \lambda'_{112}\lambda'_{122}$. Due to the hierarchy in Eq. (15), the total direct CP asymmetry simplifies to:

$$A_{CP}(D^0 \to \pi^+\pi^-) \approx 2\frac{\mathrm{Im}[(\alpha_T^{\mathrm{SM}} + \alpha_T^{\mathrm{RPV}})^*(\alpha_P^{\mathrm{SM}} + \alpha_P^{\mathrm{RPV}})]}{|\alpha_T^{\mathrm{SM}}|^2}$$

Following analogous procedures, the imaginary part of the RPV penguin diagram is:

$$\mathrm{Im}(\alpha_P^{\mathrm{RPV}}(D^0 \to \pi^+\pi^-)) = \frac{G_F}{\sqrt{2}} f_+(m_\pi^2) f_\pi \frac{\alpha_s(\mu)}{27} \frac{(m_u + m_d)}{(m_c - m_d)} \mathrm{Im}(\lambda'_{112}\lambda'_{122})$$

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

$$A_{CP}(D^0 \to \pi^+\pi^-) \approx 0.35\%$$

A similar calculation yields the total CP violation in the $D^0 \to K^+K^-$ transition:

$$A_{CP}(D^0 \to K^+K^-) \approx 0.36\%$$

Thus, our requirements indeed produce a considerable enhancement of direct CP violation in D meson decays. To maintain consistency with current experiments on K and B mesons, we must keep new contributions to these sectors suppressed. B meson decays are unaffected because only λ'_{122} and λ'_{112} have been introduced. For K mesons, the RPV interactions $\lambda'_{ijk}\tilde{\nu}_L^i \bar{d}_k u_L^j$ would generate new diagrams for $s \to du\bar{u}$ with s-quarks as internal lines. However, direct CP violation in K decays remains unaffected, since the internal quarks cannot all be on-shell and thus no imaginary part arises through these additional diagrams. Furthermore, strict experimental constraints on lepton flavor violation are evaded, as only the first generation of leptons and their SUSY partners participate in the new interactions.

III. Conclusions

In this paper, we investigate supersymmetry without R-parity as an interpretation of the recently observed large $\Delta A_{CP} = A_{CP}(D^0 \to K^+K^-) - A_{CP}(D^0 \to \pi^+\pi^-)$ at LHCb, which corresponds to 3.5σ significance. We find that significant enhancement of CP violation in D mesons is feasible after introducing specific R-parity violating terms λ'_{122} and λ'_{112}.

Phenomenological implications are discussed below:

1. There are many constraints on RPV parameters [**?**]. Among them, the following is particularly relevant to this work:

$$\frac{\lambda'_{112}}{m_{\tilde{d}_R}} < 2.11 \times 10^{-2} \left(\frac{100 \text{ GeV}}{m_{\tilde{d}_R}} \right)$$

Combining this with Eq. (13), we obtain the relation $m_{\tilde{d}_R} \geq 13$ TeV. This strongly constrains the parameter space of RPV SUSY. After introducing λ'_{122} and λ'_{112}, some exotic phenomenology emerges [**?**]. At the LHC, both pair production of scalar quarks ($pp \to \tilde{q}\tilde{q}$) and single production ($pp \to \tilde{q}e$ followed by $\tilde{q} \to q' + e$) have large cross sections and exotic final states. The signal can be distinguished from backgrounds (mainly Z+jets) by reconstructing the invariant mass of $\tilde{q}$ from one jet and an electron, together with delicate kinematic cuts [**?**]. It is expected that the LHC could discover this exotic signal or further constrain the model' s parameter space.

2. For singly Cabibbo-suppressed decay modes such as $D^+ \to \pi^+ + K^0$, we expect direct CP violation of the same order to be observed. In addition to direct CP violation, there is a small enhancement in $D^0 - \bar{D}^0$ mixing from new physics. However, this effect is negligible compared to the SM contribution, since the new couplings are CKM-suppressed, as shown in Eq. (14). Similarly, mixing in the K system remains essentially unaffected.

Although still far from a complete theoretical description, RPV SUSY provides a very natural mechanism to induce differentiated CP violations, as up-type and down-type quarks are treated differently in RPV terms. This is essential for extending the SM, which cannot easily explain why D mesons are more special than K and B mesons. As experimental data accumulates, more fundamental mechanisms may be discovered that could explain why the λ'_{ijk} parameters take the specific structure shown in Eq. (13).

Acknowledgments

We thank Prof. Hai-Yang Cheng and Hua Shao for helpful discussions. This work was supported in part by the National Natural Science Foundation of China under grant numbers 11075193, 10821504, and 11175251.

[1] M. Charles, Talk at HCP conference, LHCb-CONF-2011-061; A.I. Golutvin, Talk at Nuclear Physics Section of Physics Division of RAN Session, ITEP, November 21, 2011.
[2] For reviews, see I. I. Y. Bigi and A. I. Sanda, "CP violation," Cambridge Monographs on Particles Physics, Nuclear Physics and Cosmology 9, 1 (2000); G. C. Branco, L. Lavoura and J. P. Silva, "CP Violation," International Series of Monographs on Physics 103, 1 (1999).
[3] S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. 26N7, 1 (2003).
[4] F. Buccella, M. Lusignoli, G. Miele, A. Pugliese and P. Santorelli, Phys. Rev. D 51, 3478 (1995).
[5] Hai-Yang Cheng, Cheng-Wei Chiang, arXiv:1201.0785v1 [hep-ph].
[6] L. T. Handoko and J. Hashida, Phys. Rev. D 58, 094008 (1998).
[7] K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010).
[8] A. J. Buras, arXiv:hep-ph/9806471.
[9] G. Buchalla, A. J. Buras and M. E. Lautenbacher, Rev. Mod. Phys. 68, 1125 (1996).
[10] Y. Grossman, A. L. Kagan and Y. Nir, Phys. Rev. D 75, 036008 (2007).
[11] I. I. Bigi, A. Paul and S. Recksiegel, JHEP 1106, 089 (2011) [arXiv:1103.5785 [hep-ph]].
[12] S. Bergmann, Y. Grossman, Z. Ligeti, Y. Nir and A. A. Petrov, Phys. Lett. B 486, 418 (2000).
[13] I. I. Bigi, arXiv:0907.2950 [hep-ph].
[14] G. Blaylock, A. Seiden and Y. Nir, Phys. Lett. B 355, 555 (1995); M. Bobrowski, A. Lenz, J. Riedl and J. Rohrwild, JHEP 1003, 009 (2010); I. I. Bigi, M. Blanke, A. J. Buras and S. Recksiegel, the Littlest Higgs Model with T-Parity, JHEP 0907, 097 (2009).
[15] G. Isidori, J. F. Kamenik, Z. Ligeti, G. Perez, arXiv:1111.4987 [hep-ph].
[16] J. Brod, A. L. Kagan, J. Zupan, arXiv:1111.5000 [hep-ph].
[17] K. Wang and G.-h. Zhu, arXiv:1111.5196 [hep-ph].
[18] Y. Hochberg and Y. Nir, arXiv:1112.5268 [hep-ph].
[19] For a review see, R. Barbier, C. Brat, M. Besanon, M. Chemtob, A. Deandrea, E. Dudas, P. Fayet, S. Lavignac, G. Moreau, E. Perez, Y. Sirois, Phys. Rept. 420, 1 (2005).
[20] A. Belyaev, C. Leroy, R. Mehdiyev, A. Pukhov, JHEP 0509, 005 (2005); P. Fileviez Perez, T. Han, T. Li, M. J. Ramsey-Musolf, Nucl. Phys. B819, 139 (2009).

Note: Figure translations are in progress. See original paper for figures.