Searching for new physics in $D^0 \to \mu^+\mu^-$, e^+e^-, $\mu^\pm e^\mp$ at BES and/or the super charm-tau factory *

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Abstract: In contrast with B^0-$\bar{B}^0$, B_s-$\bar{B}_s$ mixing where the standard model (SM) contributions overwhelm that of the new physics beyond standard model (BSM), a measured relatively large D^0-$\bar{D}^0$ mixing where the SM contribution is negligible, definitely implies the existence of the new physics BSM. It is natural to consider that the rare decays of D meson might be more sensitive to new physics, and the decay mode $D^0 \to \mu^+\mu^-$ could be an ideal area to search for new physics because it is a flavor changing process. In this work we look for a trace of the new physics BSM in the leptonic decays of D^0. Concretely we discuss the contributions of unparticle or an extra gauge boson Z' while imposing the constraints set by fitting the D^0-$\bar{D}^0$ mixing data. We find that the long-distance SM effects for $D^0 \to l\bar{l}$ still exceed those contributions of the BSM under consideration, but for a double-flavor changing process such as $D^0 \to \mu^\pm e^\mp$, the new physics contribution would be significant.

Key words: unparticle, non-universal Z', leptonic rare decay, FCNC, BSM

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1 Introduction

One of the main goals of the study on lower energy processes is to look for traces of the new physics beyond standard model (BSM) and it is mutually complementary with the very high energy processes at the LHC. It is believed that the standard model (SM) is very successful in that its predictions are well consistent with all the present experimental data. But the SM is still an effective theory. The consistency is because at lower energy scales the contributions from the new physics BSM are much smaller than that of the SM which dominates all the processes. Even though the effects of new physics are small, they may manifest in some precise measurements and leave traces. Generally, BSM effects may show up at rare processes where the SM contributions are forbidden or strongly suppressed. Therefore more theorists and experimentalists have growing interests in the rare decays of heavy flavor mesons and baryons. Such studies may find traces of BSM and provide valuable information to the LHC for designing new experiments.

As is well understood, the SM dominates the B^0-$\bar{B}^0$ and B_s-$\bar{B}_s$ mixing due to an enhancement factor m_t^2/M_W^2 in the box-diagrams, thus contributions of the new physics BSM are much smaller than that of the SM. On the contrary, the SM contributions to D^0-$\bar{D}^0$ mixing are negligible because the intermediate quarks in the box are b and s which are much lighter than M_W. The first evidence of D^0-$\bar{D}^0$ oscillation is presented by the BaBar [1] and Belle [2] Collaborations and later further confirmed by the CDF Collaboration [3] in 2007. The relatively large mixing implies the existence of the new physics BSM. There have been many models which offer a flavor-changing-neutral current (FCNC) and enhance the mixing to the observational level. For example, the Littlest Higgs Model [4], the fourth generation [5], the non-universal Z' [6] and the unparticle [7] etc., can result in larger D^0-$\bar{D}^0$ mixing. Thus it motivates people to look for rare decay processes where the SM contributions are suppressed, so that the new physics effects would not be buried in the SM background. Taking into account the constraints set by D^0-$\bar{D}^0$ mixing, we turn to investigate the new physics contributions to the rare decays $D^0 \to l'^+ l^-$.

Recently, an intensive study of the leptonic decays of $B^0(\bar{B}^0)$ and $B_s(\bar{B}_s)$ was carried out. It seems that no evidence of the new physics BSM is needed to explain the present data obtained by the LHCb [8, 9] and CMS [10].

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One may wonder if D is more sensitive to new physics as it happens to the D^0-$\bar{D}^0$ mixing. As the existence of a flavor changing neutral current can explain the D^0-$\bar{D}^0$ mixing, the same mechanism should apply to the leptonic decays $D^0\to\mu^+\mu^-$, e^+e^-, and it might cause sizable effects to enhance the rates of the leptonic decays. Definitely, such a mechanism would also apply to leptonic decays of B^0 and B_s even though they do not manifest for the B-$\bar{B}$ mixing.

In this work we calculate the decay rates of $D^0\to\mu^+\mu^-$, e^+e^- in terms of both the unparticle model and an extra gauge boson Z′. Our numerical results indicate that the contributions of the new physics of concern to the decay rates do not exceed that coming from the long-distance SM effects. But it is not the end of the story, as we proceed to study the lepton-flavor changing decay $D^0\to\mu^+e^-(\mu^-e^+)$ which is a double-flavor changing process, the new physics may be significant. Moreover, when we consider the possible CP violation, the role of new physics might also be important.

Our strategy is that we employ the model parameters obtained by fitting the data of D^0-$\bar{D}^0$ mixing for both unparticle and extra gauge boson Z′ scenarios, then apply them to estimate the decay rates under consideration.

This work is organized as follows: after this short introduction, we formulate the decay rates of $D^0\to\mu^+\mu^-$, e^+e^- and $\mu^\pm e^\mp$ in Section 2. In Section 3, we present our numerical results along with all the input model parameters. In Section 4, we discuss possible measurement schemes on the leptonic decays and the lepton-flavor-changing decay, and the last section is devoted to our conclusion and a brief discussion.

2 Contributions of the new physics BSM to $D^0\to l'^+l^-$

The SM contribution to the decay of $D^0\to l'^+l^-$ has been estimated as the short distance contribution to $\mathcal{B}_{D^0\to\mu^+\mu^-}$ is of the order 10^{-19}–10^{-18} [11–13], while taking into account the long distance contributions, the branching ratio can reach a level of 10^{-13} [12, 13]. The branching ratio of $D^0\to e^+e^-$ is of order 10^{-23} [13], and the decay mode $D^0\to\mu^\pm e^\mp$ is deeply suppressed in the SM. Obviously, these rates are too small to be detected by the present facilities. Our goal of this work is to investigate if the new physics BSM would result in larger rates for those decays. In this work we only let ourselves concentrate on two possible models: the unparticle [14] and non-universal boson Z′ [15–20]. These models have been thoroughly discussed in literature, so that first we briefly show how to extract model parameters from D^0-$\bar{D}^0$ mixing data, then we formulate the new physics contributions to the rare decays $D^0\to l'^+l^-$.

2.1 Determination of the new physics parameters by fitting D^0-$\bar{D}^0$ mixing

A detectable D^0-$\bar{D}^0$ mixing has been measured, but as indicated the SM contribution cannot induce a detectable mixing. There are two crucial parameters for the D^0-$\bar{D}^0$ mixing which are experimentally measured via the D^0-$\bar{D}^0$ oscillation. The physical eigen-states are

$$|D_{1,2}\rangle=p|D^0\rangle\pm q|\bar{D}^0\rangle, \tag{1}$$

and the measurable parameters x, y are defined as

$$x\equiv\frac{m_1-m_2}{\Gamma}=\frac{\Delta m_D}{\Gamma}$$

and

$$y\equiv\frac{\Gamma_1-\Gamma_2}{2\Gamma}=\frac{\Delta\Gamma_D}{2\Gamma},$$

where

$$\Gamma=(\Gamma_1+\Gamma_2)/2.$$

Experimentally, the "rotated" parameters x', y' are also used (for more details, see, e.g., [21]). The updated Belle results [22] are $x=(0.56\pm0.19^{+0.03+0.06}_{-0.09-0.09})\%$, $y=(0.30\pm0.15^{+0.04+0.03}_{-0.05-0.06})\%$. No evidence of CP violation was observed at Belle so far and it is consistent with the observed results at the LHCb [23, 24].

2.1.1 Constraints on the parameters of the unparticle scenario

The scale invariant unparticle scenario was proposed by Georgi [14], which has a non-integral scale dimension $d_\mathcal{U}$ below a typical energy scale $\Lambda_\mathcal{U}$. In the scenario of the unparticle, different flavors can be coupled to unparticle, so that FCNC can be induced at tree level. The scalar, vector unparticle fields are denoted as $O_\mathcal{U}$, $O^\mu_\mathcal{U}$. The propagator of the scalar unparticle is [25–27]

$$\int d^4x e^{iP.x}\langle0|TO_\mathcal{U}(x)O_\mathcal{U}(0)|0\rangle$$
$$=i\frac{A_{d_\mathcal{U}}}{2\sin(d_\mathcal{U}\pi)}\frac{1}{(P^2+i\epsilon)^{2-d_\mathcal{U}}}e^{-i(d_\mathcal{U}-2)\pi}, \tag{2}$$

where $A_{d_\mathcal{U}}$ is

$$A_{d_\mathcal{U}}=\frac{16\pi^{5/2}}{(2\pi)^{2d_\mathcal{U}}}\frac{\Gamma(d_\mathcal{U}+1/2)}{\Gamma(d_\mathcal{U}-1)\Gamma(2d_\mathcal{U})}. \tag{3}$$

The vector unparticle propagator is [28]

$$\int d^4x e^{iP.x}\langle0|TO^\mu_\mathcal{U}(x)O^\nu_\mathcal{U}(0)|0\rangle$$
$$=i\frac{A_{d_\mathcal{U}}}{2\sin(d_\mathcal{U}\pi)}\frac{-g^{\mu\nu}+\frac{2(d_\mathcal{U}-2)}{d_\mathcal{U}-1}\frac{P^\mu P^\nu}{P^2}}{(P^2+i\epsilon)^{2-d_\mathcal{U}}}e^{-i(d_\mathcal{U}-2)\pi}. \tag{4}$$

The unitarity bounds on the non-integral scale dimension $d_\mathcal{U}$ below the typical energy scale $\Lambda_\mathcal{U}$ are that $d_\mathcal{U}\geqslant1$ for the scalar unparticle and $d_\mathcal{U}\geqslant3$ for the vector unparticle [28].

The mass and width differences are related to the mixing elements, $\Delta m_{\rm D}=2|M_{12}|$ and $\Delta\Gamma_{\rm D}=2|\Gamma_{12}|$. In the case of CP conservation, the scalar unparticle's contribution to the mass difference (for more, see e.g. [7, 29]) is

$$\Delta m_{\rm D}^{\mathcal{U}}=\frac{5}{3}\frac{f_{\rm D}^2\hat{B}_{\rm D}}{m_{\rm D}}\frac{A_{d_{\mathcal{U}}}}{4}\left(\frac{m_{\rm D}}{\Lambda_{\mathcal{U}}}\right)^{2d_{\mathcal{U}}}\left(\frac{m_{\rm D}}{m_{\rm c}}\right)^2|c_{\rm S}^{\rm uc}|^2|\cot d_{\mathcal{U}}\pi|. \tag{5}$$

For the vector unparticle, the result is

$$\begin{aligned}\Delta m_{\rm D}^{\mathcal{U}} &= \frac{f_{\rm D}^2\hat{B}_{\rm D}}{m_{\rm D}}\frac{A_{d_{\mathcal{U}}}}{4}\left(\frac{m_{\rm D}}{\Lambda_{\mathcal{U}}}\right)^{2d_{\mathcal{U}}-2}|c_{\rm V}^{\rm uc}|^2\\ &\times\left[\frac{8}{3}-\frac{2(d_{\mathcal{U}}-2)}{d_{\mathcal{U}}-1}\frac{5}{3}\left(\frac{m_{\rm D}}{m_{\rm c}}\right)^2\right]|\cot d_{\mathcal{U}}\pi|. \end{aligned}\tag{6}$$

Here the Wick contraction factors have been taken into consideration. $f_{\rm D}$ is the decay constant, $f_{\rm D}\approx 0.2$ GeV, and $\hat{B}_{\rm D}$ is a factor related to a non-perturbative quantum chromodynamics (QCD) with the order of unity, $\hat{B}_{\rm D}\approx 1$ corresponding to the vacuum saturation [30]. $m_{\rm D}$ is D^0 meson mass, and $\Lambda_{\mathcal{U}}$ is of the order TeV. $c_{\rm S}$, $c_{\rm V}$ are the coupling parameters.

For the mixing induced by the unparticle, the relation $\Gamma_{12}^{\mathcal{U}}/2=M_{12}^{\mathcal{U}}\tan(d_{\mathcal{U}}\pi)$ holds, as given in Ref. [29]. Thus $\Delta\Gamma_{\rm D}^{\mathcal{U}}/2=\Delta m_{\rm D}^{\mathcal{U}}|\tan(d_{\mathcal{U}}\pi)|$. As the contributions to the mass and width differences are totally from the unparticle, i.e. ignoring the contributions from the SM and other BSMs, $\Delta m_{\rm D}^{\mathcal{U}}\sim\Delta m_{\rm D}$ and $\Delta\Gamma_{\rm D}^{\mathcal{U}}\sim\Delta\Gamma_{\rm D}$. The measurement values of x,y can be used to determine the unparticle parameters and then applied to calculate the rates of $D^0\to l'^{+}l^{-}$.

2.1.2 Constraints on the parameters of the non-universal Z′

Instead of the unparticle scenario, let us turn to another possible BSM. In this scenario, a tree-level FCNC is induced by the new non-universal gauge boson Z′. Some phenomenological applications of the non-universal Z′ have been widely studied [15–20]. It was applied to the D^0-$\bar{D}^0$ mixing by the authors of [6]. The flavor-changing couplings of Z′ to quarks and leptons are in the form

$$\begin{aligned}\mathcal{L} &= \frac{g}{2}\tan\theta_{\rm W}(\tan\theta_{\rm R}+\cot\theta_{\rm R})(\sin\xi_{\rm Z}Z_\mu+\cos\xi_Z Z'_\mu)\\ &\times(V_{\rm Rbi}^{\rm d*}V_{\rm Rbj}^{\rm d}\bar{d}_{\rm Ri}\Gamma^\mu d_{\rm Rj}-V_{\rm Rti}^{\rm u*}V_{\rm Rtj}^{\rm u}\bar{u}_{\rm Ri}\Gamma^\mu u_{\rm Rj}\\ &+\bar{\tau}_{\rm R}\Gamma^\mu\tau_{\rm R}-\bar{\nu}_{\rm R\tau}\Gamma^\mu\nu_{\rm R\tau}),\end{aligned}\tag{7}$$

where g is the $SU(2)_{\rm L}$ coupling, and θ_W is the Weinberg angle, as in the SM. $\theta_{\rm R}$ is related to the right-handed interaction strength, and $\xi_{\rm Z}$ parameterizes the Z-Z′ mixing angle. $V_{\rm Rij}^{\rm u,d}$ are the matrix rotating the right-handed up(down)-type quarks from their weak eigen-states to their mass eigen-states.

The bound set by the LEP-Ⅱ measurements can be approximated in a relation form [31, 32],

$$\tan\theta_{\rm W}\cot\theta_{\rm R}\frac{M_{\rm W}}{M_{\rm Z'}}\sim 1.$$

Supposing that the measured x is fully determined by the contribution of Z′, the D^0-$\bar{D}^0$ mixing constrains the matrix element $|V_{\rm Rtu}^{\rm u*}V_{\rm Rtc}^{\rm u}|$ is [6]

$$|V_{\rm Rtu}^{\rm u*}V_{\rm Rtc}^{\rm u}|\lesssim 2.0\times 10^{-4}. \tag{8}$$

This bound will be used for evaluating the rates of $D^0\to l'^{+}l^{-}$ decays.

2.2 The unparticle contribution to $D^0\to l'^{+}l^{-}$

For the mixing, as shown in Eqs. (5), (6), the vector unparticle's contribution is more suppressed by a factor $\left(\frac{m_{\rm D}}{\Lambda_{\mathcal{U}}}\right)^{2d_{\mathcal{U}}}$ compared with the scalar unparticle. The unparticle effect on $B_s\to\mu^+\mu^-$ was discussed in Ref. [33]. The leptonic decay $D^0\to l'^{+}l^{-}$ is similar. Therefore, here we just consider the scalar unparticle contribution, and the Feynman diagram is presented in Fig. 1.

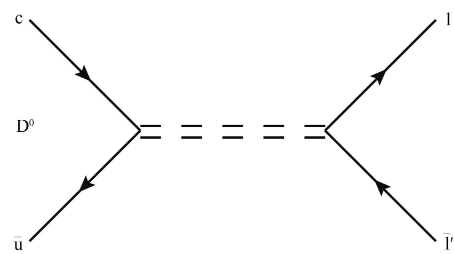

Fig. 1. Unparticle induced $D^0\to l'^{+}l^{-}$ decays.

The effective interaction of the scalar unparticle with quarks and/or leptons is

$$\frac{c_{\rm S}^{\rm q'q}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}}\bar{q}'\gamma_\mu(1-\gamma_5)q\partial^\mu O_{\mathcal{U}}+\frac{c_{\rm S}^{\rm l'l}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}}}\bar{l}'\gamma_\mu(1-\gamma_5)l\partial^\mu O_{\mathcal{U}}+\text{h.c.}, \tag{9}$$

where $c_{\rm S}^{\rm q'q}$, $c_{\rm S}^{\rm l'l}$ are the coupling constants for quarks and leptons respectively.

Including the contributions of the SM and the unparticle, the decay width of $D^0\to l'^{+}l^{-}$ is

$$\Gamma_{D^0\to l'^{+}l^{-}}=\frac{1}{16\pi m_{\rm D}}\beta_{\rm f}|\langle l'^{+}l^{-}|\mathcal{H}_{\rm SM}+\mathcal{H}_{\mathcal{U}}|D^0\rangle|^2, \tag{10}$$

where

$$\beta_{\rm f}=\sqrt{1-\frac{2(m_{\rm l'}^2+m_{\rm l}^2)}{m_{\rm D}^2}+\frac{(m_{\rm l'}^2-m_{\rm l}^2)^2}{m_{\rm D}^4}}, \tag{11}$$

$\mathcal{H}_{\rm SM}$, $\mathcal{H}_{\mathcal{U}}$ are SM and unparticle Hamiltonians respectively. $\mathcal{H}_{\mathcal{U}}$ is in the form

$$\begin{aligned}\mathcal{H}_{\mathcal{U}} &= -\frac{A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)}\frac{1}{m_{\rm D}^4}{\rm e}^{-{\rm i}(d_{\mathcal{U}}-2)\pi}\left(\frac{m_{\rm D}^2}{\Lambda_{\mathcal{U}}^2}\right)^{d_{\mathcal{U}}}c_{\rm S}^{\rm uc}c_{\rm S}^{\rm l'l}\\ &\times[m_{\rm l}\bar{l}(1-\gamma_5)l'-m_{\rm l'}\bar{l}(1+\gamma_5)l']\\ &\times[m_{\rm u}\bar{u}(1-\gamma_5)c-m_{\rm c}\bar{u}(1+\gamma_5)c],\end{aligned}\tag{12}$$

where the relation $P^2=m_{\rm D}^2$ has been used. Let us first consider only the unparticle contribution to the decay rate. The decay width is

$$\Gamma^{\mathcal{U}}_{\rm D^0\to l'^+l^-}=\frac{1}{16\pi m_{\rm D}}\beta_{\rm f}\left|\frac{A_{d_{\mathcal{U}}}}{2\sin(d_{\mathcal{U}}\pi)}\frac{1}{m_{\rm D}^4}{\rm e}^{-{\rm i}(d_{\mathcal{U}}-2)\pi}\left(\frac{m_{\rm D}^2}{\Lambda_{\mathcal{U}}^2}\right)^{d_{\mathcal{U}}}\right. \times c_{\rm S}^{\rm uc}c_{\rm S}^{\rm l'l}\Big|^2\times[4(m_{\rm l}'^2+m_{\rm l}^2)(m_{\rm D}^2-m_{\rm l}'^2-m_{\rm l}^2) +16m_{\rm l}'^2m_{\rm l}^2]\times f_{\rm D}^2m_{\rm D}^4. \quad (13)$$

Taking $\Delta m_D^{\mathcal{U}}$, $\Delta\Gamma_D^{\mathcal{U}}$ into the above formula (13), we have

$$\Gamma^{\mathcal{U}}_{\rm D^0\to l'^+l^-}=\frac{1}{16\pi m_{\rm D}}\beta_{\rm f}\left|\frac{c_{\rm S}^{\rm l'l}}{c_{\rm S}^{\rm uc}}\right|^2\left[\left(\frac{6}{5}\Delta m_{\rm D}^{\mathcal{U}}\right)^2+\left(\frac{6}{5}\frac{\Delta\Gamma_{\rm D}^{\mathcal{U}}}{2}\right)^2\right] \times\frac{1}{f_{\rm D}^2m_{\rm D}^2}\left(\frac{m_{\rm c}}{m_{\rm D}}\right)^4[4(m_{\rm l}'^2+m_{\rm l}^2)(m_{\rm D}^2-m_{\rm l}'^2-m_{\rm l}^2) +16m_{\rm l}'^2m_{\rm l}^2]. \quad (14)$$

2.3 Non-universal Z′ contribution to $\rm D^0\to l'^+l^-$

In the limit of the mixing angle $\xi_{\rm Z}\sim0$, we only consider the contribution of Z′. The decay width of $\rm D^0\to\mu^+\mu^-$ can be formulated as [6]

$$\Gamma_{\rm D^0\to\mu^+\mu^-}\approx\frac{G_{\rm F}^2m_{\rm D}m_{\mu}^2f_{\rm D}^2}{16\pi}|V_{\rm Rtu}^{\rm u*}V_{\rm Rtc}^{\rm u}|^2 \times\left(\tan\theta_{\rm W}\cot\theta_{\rm R}\frac{M_{\rm W}}{M_{\rm Z'}}\right)^4\tan^4\theta_{\rm R}. \quad (15)$$

For the process $\rm D^0\to e^+e^-$, the decay width is proportional to the lepton mass square, so it is suppressed compared to $\rm D^0\to\mu^+\mu^-$.

In formula (7), the rotation only applies to the quark sector, one may naturally generalize the lagrangian to involve a rotation at the lepton sector. The lagrangian can be re-written as

$$\mathcal{L}=\frac{g}{2}\tan\theta_{\rm W}(\tan\theta_{\rm R}+\cot\theta_{\rm R})(\sin\xi_{\rm Z}Z_{\mu}+\cos\xi_{\rm Z}Z'_{\mu}) \times(V_{\rm R\tau i}^{\rm l^c*}V_{\rm R\tau j}^{\rm l^c}\bar{\tau}_{\rm Ri}\Gamma^{\mu}\tau_{\rm Rj}-V_{\rm R\tau i}^{\nu*}V_{\rm R\tau j}^{\nu}\bar{\nu}_{\rm Ri}\Gamma^{\mu}\nu_{\rm Rj}), \quad (16)$$

where $V_{\rm Rij}^{\rm l^c,\nu}$ are matrix elements rotating the lepton weak eigen-states to the mass eigen-states, moreover, this lagrangian allows flavor changes as it is not necessary to be equal to j. In this case, the lepton-flavor-changing interaction induced by Z′ would occur at tree level. The decay width of $\rm D^0\to\mu^+e^-$ can be obtained,

$$\Gamma_{\rm D^0\to\mu^+e^-}\approx\frac{G_{\rm F}^2m_{\rm D}m_{\mu}^2f_{\rm D}^2}{32\pi}|V_{\rm Rtu}^{\rm u*}V_{\rm Rtc}^{\rm u}|^2|V_{\rm R\tau e}^{\rm l^c*}V_{\rm R\tau\mu}^{\rm l^c}|^2 \times\left(\tan\theta_{\rm W}\cot\theta_{\rm R}\frac{M_{\rm W}}{M_{\rm Z'}}\right)^4. \quad (17)$$

In the subsequent computations, we are simply going to employ the model parameters obtained by others and will list them in the next section.

3 Numeral analysis on $\rm D^0\to l'^+l^-$

In the following, we present our numeral results of the decay $\rm D^0\to l'^+l^-$ based on the new physics BSM, both unparticle and non-universal Z′.

3.1 The unparticle

First we discuss the unparticle contribution to the decays $\rm D^0\to l'^+l^-$. Relevant parameters are input as $m_{\rm c}=1.275\pm0.025$ GeV, $m_{\rm D}=1.86486\pm0.00013$ GeV, and the mean lifetime of $\rm D^0$ meson $(410.1\pm1.5)\times10^{-15}$ s [34]. The updated Belle results [22] are used to constrain the new physics contributions, taking the central values, $x\sim0.056$, $y\sim0.030$, and $x^2+y^2\sim4.0\times10^{-5}$. Though with a large uncertainty of x^2+y^2, it should be taken as an upper bound of the unparticle contribution. The branching ratios $\mathcal{B}^{\mathcal{U}}_{\rm D^0\to l'^+l^-}$ with the contributions from only the unparticle are

$$\mathcal{B}^{\mathcal{U}}_{\rm D^0\to\mu^+\mu^-}\lesssim4.8\times10^{-19}\left|\frac{c_{\rm S}^{\mu^+\mu^-}}{c_{\rm S}^{\rm uc}}\right|^2, \quad (18)$$

$$\mathcal{B}^{\mathcal{U}}_{\rm D^0\to e^+e^-}\lesssim1.1\times10^{-23}\left|\frac{c_{\rm S}^{\rm e^+e^-}}{c_{\rm S}^{\rm uc}}\right|^2, \quad (19)$$

$$\mathcal{B}^{\mathcal{U}}_{\rm D^0\to\mu^+e^-}\lesssim2.4\times10^{-19}\left|\frac{c_{\rm S}^{\mu^+\rm e^-}}{c_{\rm S}^{\rm uc}}\right|^2. \quad (20)$$

As is well recognized, due to the large experimental errors, only the order of magnitude of these theoretical evaluations are meaningful.

The lagrangian determines that l(q) can be equal or unequal to l′(q′), thus, it is natural to assume the couplings to be universal, namely a coupling takes a value for all the same flavors and another value for all different flavors, as discussed in Ref. [35],

$$c_{\rm S}^{\rm f'f}=\begin{cases}c_{\rm S}, & f\neq f'\\ \kappa c_{\rm S}, & f=f',\end{cases} \quad (21)$$

where $\kappa>1$. To estimate the branching ratios, $\kappa=3$ is taken as suggested by the authors of Ref. [35]. The branching ratios $\mathcal{B}^{\mathcal{U}}_{\rm D^0\to l'^+l^-}$ are

$$\mathcal{B}^{\mathcal{U}}_{\rm D^0\to\mu^+\mu^-}\lesssim4.3\times10^{-18}, \quad (22)$$

$$\mathcal{B}^{\mathcal{U}}_{\rm D^0\to e^+e^-}\lesssim1.0\times10^{-22}, \quad (23)$$

$$\mathcal{B}^{\mathcal{U}}_{\rm D^0\to\mu^+e^-}\lesssim2.4\times10^{-19}. \quad (24)$$

3.2 Non-universal Z′

Next let us turn to the non-universal Z′ contribution to the decays $\rm D^0\to l'^+l^-$. Taking $m_{\rm Z'}\sim500$ GeV [6], and just accounting the contributions from the non-universal Z′, with $\tan\theta_{\rm R}\sim0.088$, the branching ratios

$\mathcal{B}_{\mathrm{D}^0\to\mu^+\mu^-,\mathrm{e}^+\mathrm{e}^-}$ are

$$\mathcal{B}_{D^0\to\mu^+\mu^-}\lesssim 3.4\times10^{-15}, \tag{25}$$

$$\mathcal{B}_{\mathrm{D}^0\to\mathrm{e}^+\mathrm{e}^-}\lesssim 7.9\times10^{-20}. \tag{26}$$

For the lepton flavor violation case, we take the bound given in Ref. [36] for our discussions. That is

$$\left|\frac{b_{\mathrm{R}}^{\mathrm{e}\mu}}{m_{\mathrm{Z}'}}\right|\lesssim 1.8\times10^{-7}, \tag{27}$$

in a unit of GeV^{-1}. The constraint is

$$\left|\frac{g}{2m_{\mathrm{Z}'}}\tan\theta_{\mathrm{W}}\cot\theta_{\mathrm{R}}V_{\mathrm{R}\tau\mathrm{e}}^{\mathrm{l^c}*}V_{\mathrm{R}\tau\mu}^{\mathrm{l^c}}\right|\lesssim 1.8\times10^{-7}, \tag{28}$$

or

$$\left|V_{\mathrm{R}\tau\mathrm{e}}^{\mathrm{l^c}*}V_{\mathrm{R}\tau\mu}^{\mathrm{l^c}}\right|\lesssim\frac{1}{\sqrt{\sqrt{2}G_{\mathrm{F}}}}\times1.8\times10^{-7}. \tag{29}$$

The branching ratio $\mathcal{B}_{\mathrm{D}^0\to\mu^+\mathrm{e}^-}$ is

$$\mathcal{B}_{\mathrm{D}^0\to\mu^+\mathrm{e}^-}\lesssim 5.5\times10^{-20}. \tag{30}$$

4 The $\mathrm{D}^0\to\mathrm{l}'^+\mathrm{l}^-$ decay search at BESⅢ and future charm-tau factory

Since the first effort on limiting the branching fraction of the FCNC process $\mathrm{D}^0\to\mu^+\mu^-$ was carried out by the European Muon Collaboration [37] in 1985, and there have been many experimental groups searchings for $\mathrm{D}^0\to\mu^+\mu^-$, $\mathrm{D}^0\to\mu^\pm\mathrm{e}^\mp$, and $\mathrm{D}^0\to\mathrm{e}^+\mathrm{e}^-$ during the past thirty years. Table 1 summarizes their results, where the 1st column refers the name of the experiments; the 2nd column is for the year when the results were published; the 3rd to 5th columns present the Upper Limit of the branching fractions; the 6th column shows the experiment style, i.e. fixed target, leptonic collider, hadronic collider, or heavy ion collider; and the last two columns correspond to the center-of-mass energies and data samples in use. Most of the measurements suffered from high background contaminations, and so the detection efficiency is rather low. The important task for gaining meaningful conclusion is to enhance the ability of distinguishing the background and signal events. While, in the experiments whose center-of-mass energy is near the $\mathrm{D}^0\bar{\mathrm{D}}^0$ threshold, the neutral charm mesons are produced in pairs, one can measure the di-lepton decays absolutely based on a technical treatment namely the double tagging method (i.e. to properly reconstruct double D mesons). In the $\mathrm{e}^+\mathrm{e}^-$ annihilation experiment around 3.773 GeV, which is just above the $\mathrm{D}\bar{\mathrm{D}}$ production threshold, $\mathrm{D}\bar{\mathrm{D}}$ pair is produced via a decay of the resonance $\psi(3770)$ ($\psi(3770)\to\mathrm{D}\bar{\mathrm{D}}$). If we only identify a fully reconstructed $\bar{\mathrm{D}}$ meson in one event, called a singly tagged $\bar{\mathrm{D}}$ meson, there must exist a D meson at the recoiling side. And if we reconstructed the whole $\mathrm{D}\bar{\mathrm{D}}$ pair in the analysis procedure, the event will be called a doubly tagged event. Thus, with the data sample consisting of the identified singly tagged $\bar{\mathrm{D}}^0$ events, the di-leptonic final states from the decay of neutral D mesons can be

Table 1. Historical measurements on searching for dilepton decays.

experiment	year	$\mathrm{D}^0\to\mu^+\mu^-$ [$\times10^{-6}$]	$\mathrm{D}^0\to\mu^\pm\mathrm{e}^\mp$ [$\times10^{-6}$]	$\mathrm{D}^0\to\mathrm{e}^+\mathrm{e}^-$ [$\times10^{-6}$]	style	energy	note
EMC[37]	1985	340	—	—	μ^-N	280 GeV	1.3×10^{12} events
E615[38]	1986	11	—	—	π^-W	225 GeV	Norm. to D decay
MARK2[39]	1987	—	2100	—	$\mathrm{e}^+\mathrm{e}^-$	29 GeV	
ACCMOR[40]	1987	—	900	—	πp	200 GeV	
MARK3[41]	1987	—	120	—	$\mathrm{e}^+\mathrm{e}^-$	3.77 GeV	9.3 pb^{-1}
CLEO[42]	1988	—	270	220	$\mathrm{e}^+\mathrm{e}^-$	10 GeV	
ARGUS[43]	1988	70	100	170	$\mathrm{e}^+\mathrm{e}^-$	10 GeV	
MARK3[44]	1988	—	—	130	$\mathrm{e}^+\mathrm{e}^-$	3.77 GeV	9.6 pb^{-1}
E789[45]	1994	31	—	—	pN	—	
E653[46]	1995	44	—	—	π^- emulsion	600 GeV	
BEATRICE[47]	1995	7.6	—	—	$\pi^-\mathrm{C_u}$	350 GeV	
CLEO2[48]	1996	34	19	13	$\mathrm{e}^+\mathrm{e}^-$	$\Upsilon(4S)$	3.85 fb^{-1}
E771[49]	1996	4.2	—	—	$\mathrm{pS_i}$	800 GeV	
BEATRICE[50]	1997	4.1	—	—	$\pi^-\mathrm{C_u}$	350 GeV	
E791[51]	1999	5.2	8.1	6.2	π^-N	500 GeV	2×10^{10} events
E789[52]	2000	15.6	17.2	8.19	pN	800 GeV	Norm. to $\mathrm{D}^0\to\mathrm{K}\pi$
CDF[53]	2003	2.5	—	—	$\mathrm{p}\bar{\mathrm{p}}$	1.96 TeV	
BABAR[54]	2004	2.0	0.81	1.2	$\mathrm{e}^+\mathrm{e}^-$	$\Upsilon(4S)$	122 fb^{-1}
HERA-B[55]	2004	2.0	—	—	pA	920 GeV	
BELLE[56]	2010	0.14	0.26	0.079	$\mathrm{e}^+\mathrm{e}^-$	$\Upsilon(4S)$	660 fb^{-1}
CDF[57]	2010	0.21	—	—	$\mathrm{p}\bar{\mathrm{p}}$	1.96 TeV	
LHCb[58]	2013	0.0062	—	—	pp	—	0.9 fb^{-1}
BABAR[59]	2012	0.81	0.33	0.17	$\mathrm{e}^+\mathrm{e}^-$	10.58 GeV	468 fb^{-1}
PDG[34]	2012	0.14	0.26	0.079	—	—	—

indubitably selected, and the absolute branching fractions would be well measured. The advantage of the double tagging method can extremely reduce the background by tagging the D meson pairs. Historically, there were only two measurements of $D^0 \to e^+e^-$ and $D^0 \to \mu^\pm e^\mp$ using the threshold data by the MARK3 Collaboration, while they proceeded the analysis with the single tagging method (i.e. reconstructing only one D meson) with a large background, the threshold data did not bring up any advantages at all.

Until now, the BESIII collaboration has accumulated 2.92 fb^{-1} [60] ψ(3770) data samples near its production threshold during 11 month's data taking. There is about 2.15×10^7 neutral D mesons among 3.84×10^7 D mesons assuming $\sigma^{obs}_{D\bar{D}}$=6.57 nb [61]. And we can eventually have more than 20 fb^{-1} ψ(3770) data according to the data taking plan of the experiment, resulting in a D^0 sample of about 1.47×10^8. Then, the key issue will be, how many singly tagged $\bar{D}^0$ events we can reconstruct, and how well we can carry out the measurement. To answer this question, here we present a full simulation of searching for di-leptonic decays at the BESIII experiment with the Monte Carlo method to discuss the experimental sensitivities that can be reached in the future.

The Monte Carlo samples are obtained with the BESIII offline Software System [62], where the particle trajectories are simulated with a GEANT4 [63] based package [64] for the BESIII detector [65] at the BEPC-II collider. The events used in this discussion, named generic MC events, are generated as $e^+e^- \to \psi(3770) \to D\bar{D}$ at the c.m. energy $\sqrt{s}$=3.773 GeV with the $D\bar{D}$ mesons decaying into all possible final states with the branching fractions cited from Particle Data Group (PDG) [34]. Totally $\sim1.31\times10^8$ $D\bar{D}$ events are produced at $\sqrt{s}$=3.773 GeV, corresponding to an integrated luminosity of ∼20 fb^{-1} ψ(3770) data assuming $\sigma^{obs}_{D\bar{D}}$=6.57 nb [61], which contains $\sim7.35\times10^7$ $D^0\bar{D}^0$ pairs, $\sim6.08\times10^7$ D^+D^- pairs.

The singly tagged $\bar{D}^0$ events are reconstructed in 4 golden hadronic decays of $\bar{D}^0 \to K^+\pi^-$(69%), $\bar{D}^0 \to K^+\pi^-\pi^0$(35%), $\bar{D}^0 \to K^+\pi^-\pi^-\pi^+$(39%), and $\bar{D}^0 \to K^+\pi^-\pi^-\pi^+\pi^0$(14%), constituting more than 30% of all $\bar{D}^0$ decays, where the numbers in brackets are reconstruction efficiencies. Tagged $\bar{D}^0$ events are filtered by two kinematic variables based on the principles of energy and momentum conservations: (1) Difference in energy

$$\Delta E \equiv E_f - E_b,$$

where E_f is the total energy of the daughter particles from $\bar{D}^0$ in one event and E_b is the e^+/e^- beam energy for the experiment, is recorded to describe the deviation from energy conservation caused by experimental errors. (2) Beam-constrained mass

$$M_{BC} \equiv \sqrt{E_b^2 - (\Sigma_i \vec{p}_i)}$$

is calculated to reduce the uncertainty caused by experimental errors when measuring the momenta of the produced particles. In this definition, the energy E_f in the expression of

$$M^2_{inv.} \equiv E_f^2 - p_f^2$$

for the $\bar{D}$ invariant mass is replaced by $E_b = E_{c.m.}/2$, where $E_{c.m.}$ is the c.m. energy that $D^0\bar{D}^0$ produced. The total energy and momentum of all the daughter particles in $\bar{D}^0$ decays must satisfy the Energy Conservation (EC) principle, generally one needs to introduce a kinematic fit, including energy and momentum constraints and some correlated corrections, to reject those not satisfying the EC which are caused by the uncertainty of experimental measurement. This replacement of the real invariant mass by M_{BC} partly plays the role. Moreover, events are rejected if they fail to satisfy the selection constraint $|\Delta E| < 3\times\sigma_{\Delta E}$, which is tailored for each individual decay mode, and $\sigma_{\Delta E}$ is the standard deviation of the ΔE distribution. If the $\bar{D}^0$ events were correctly tagged, a peak in the M_{BC} spectrum would emerge at the nominal mass of $\bar{D}^0$. Thus, if there is more than one combination in one tagged event, the one with the smallest $|\Delta E|$ is retained. After considering the detection efficiencies of each tag mode, 16856207±8874 tagged $\bar{D}^0$ events have been obtained based on a simulated sample of about 20 fb^{-1}.

With the tagged $\bar{D}^0$ mesons, the D^0 decays into a lepton pair is reconstructed in the recoiling side, i.e. $D^0 \to l'^+l^-$, where two charged tracks are identified as electrons or muons. To suppress the contamination from γ conversion, the angle between electron and other charged tracks should be greater than 30°. And it is required that the ΔE distribution of the lepton pairs should fall into the range of $|\Delta E| < 3\times\sigma_{\Delta E}$, where $\sigma_{\Delta E}$ is obtained by fitting the ΔE distribution determined by the signal MC events. And the valid signals would produce a peak at the D^0 nominal mass within $3\sigma_{M_{BC}}$ at the M_{BC} spectra. For the processes of $D^0 \to \mu^+\mu^-$, $D^0 \to \mu^\pm e^\mp$, and $D^0 \to e^+e^-$, the numbers of estimated background events are found to be all zero, by counting the signal window of $|M_{e^+e^-} - M_{D^0}| < 3\sigma_{M_{BC}}$.

To examine the sensitivities of the measurement, we evaluate the upper limits of the possible observed signal events, s_{90}, at a 90% confidence level, based on the expected background events assuming zero signals. The upper limits are obtained by using the Poissonian Limit Estimator (POLE) program [66], which is developed with an extended version [66] of the Feldman-Cousins method [67]. Thus, the upper limit on the branching fractions are calculated to be

$$\begin{aligned} &\mathcal{B}(D^0 \to \mu^+\mu^-) < 4.7\times10^{-7}, \\ &\mathcal{B}(D^0 \to \mu^\pm e^\mp) < 3.4\times10^{-7}, \\ &\mathcal{B}(D^0 \to e^+e^-) < 2.6\times10^{-7}, \end{aligned} \quad (31)$$

respectively, with

$$\mathcal{B}=\frac{s_{90}/\epsilon}{N_{\bar{D}^0}^{\rm tag}},$$

by inserting the s_{90}, the detection efficiencies ϵ(31% for $D^0 \to \mu^+\mu^-$, 43% for $D^0 \to \mu^\pm e^\mp$, 55% for $D^0 \to e^+e^-$), and the number of singly tagged $\bar{D}^0$ events $N_{\bar{D}^0}^{\rm tag}$. The detection efficiencies are obtained by analyzing the simulated events which are generated as $D^0 \to l'^+l^-$ and $\bar{D}^0 \to$ anything with the same procedure to the generic MC events.

The BEPCⅡ collider is designed to work at the c.m. energy of $\sqrt{s}$=3.773 GeV with an instantaneous luminosity of 10^{33} cm^{-2}·s^{-1}. As a conservative estimate, a data sample with the integrated luminosity of about 20 fb^{-1} can be collected during less than 10 years' running. As the World's largest threshold data sample, it will deliver an experimental sensitivity for searching di-leptonic decays of D^0 meson at about the 10^{-7} level. It seems that there will be a desperate running time for the threshold experiment to challenge the sensitivities from experiments at higher energies (e.g. 10^{-8} at Belle), however, it will not be a problem if one can have a τ-charm factory with an increasing of the luminosity of more than 100 times.

5 Conclusions

In this article we give some discussions about the search of flavor-changing interactions caused by new physics in D^0 leptonic decays. Considering the constraints set by the D^0-$\bar{D}^0$ mixing, we derive the new physics contributions: the unparticle and non-universal Z' concerned in this work, to the decay modes $D^0 \to \mu^+\mu^-$, e^+e^-, μ^+e^-, and estimate the numerical results of the rare decays $D^0 \to l'^+l^-$. The theoretical predictions of branching ratios are shown in Table 2, including contributions from the SM and the new physics from the unparticle and non-universal Z'.

For the decay $D^0 \to \mu^+\mu^-$, it is shown that the long-distance effect of the SM still exceeds the contributions from the unparticle and non-universal Z', therefore the two models do not manifest in the decays. But if the leptonic decay $D^0 \to \mu^+\mu^-$ is observed with a larger branching ratio (larger that 10^{-13}), it indicates that there exist BSM contributions, but not from the unparticle or non-universal Z'. Since $D^0 \to e^+e^-$ suffers from the helicity suppression in the SM, so that the new physics contribution may exceed the SM contribution, but this branching ratio is very small to be observed with the present facilities. A simple analysis indicates that the decay mode $D^0 \to \mu^\pm e^\mp$ is much suppressed in the SM. Therefore a sizable or at least observable mode $D^0 \to \mu^\pm e^\mp$ must be due to new physics contributions.

Table 2. The branching ratio predictions in $D^0 \to l'^+l^-$ decays, with the contributions from SM and new physics unparticle, non-universal Z'.

branching ratios	SM predictions	unparticle	non-universal Z'
$\mathcal{B}_{D^0\to\mu^+\mu^-}$	10^{-13}	$\lesssim 4.3\times10^{-18}$	$\lesssim 3.4\times10^{-15}$
$\mathcal{B}_{D^0\to e^+e^-}$	10^{-23}	$\lesssim 1.0\times10^{-22}$	$\lesssim 7.9\times10^{-20}$
$\mathcal{B}_{D^0\to\mu^\pm e^\mp}$	0	$\lesssim 2.4\times10^{-19}$	$\lesssim 5.5\times10^{-20}$

As discussed in this work, even though the leptonic decays of D^0 are sensitive to the new physics as implied by the measured D^0-$\bar{D}^0$ mixing, the contributions from the unparticle and non-universal Z' cannot exceed the SM contribution. The favorable modes which may distinguish between the SM and BSM contributions are the lepton-flavor violation processes which are much suppressed in the SM. However, the branching ratio of such modes are very small and far below the reach of any presently available facilities, even though some BSM mechanisms such as the unparticle and non-universal Z' are taken into account. In fact there are many new physics models which might cause a larger branching ratio (other schemes, see e.g. [68]). The measurement of the leptonic decay $D^0 \to \mu^+\mu^-$ is worthwhile and one might find a trace of new physics. Meanwhile, $D^0 \to \mu^+e^-(\mu^-e^+)$ is a much better place to look for new physics.

Though the present facilities cannot provide large amount of D^0, one may expect that the future super charm-tau factory and the LHC may do the job.

References

1 Aubert B et al. (BaBar collaboration). Phys. Rev. Lett., 2007, **98**: 211802; arXiv: hep-ex/0703020 [HEP-EX]
2 Staric M et al. (Belle collaboration). Phys. Rev. Lett., 2007, **98**: 211803; arXiv: hep-ex/0703036
3 Aaltonen T et al. (CDF collaboration). Phys. Rev. Lett., 2008, **100**: 121802; arXiv: 0712.1567 [hep-ex]
4 CHEN C H, GENG C Q, YUAN T C. Phys. Lett. B, 2007, **655**: 50; arXiv: 0704.0601 [hep-ph]
5 HOU W S, Nagashima M, Soddu A. Phys. Rev. D, 2007, **76**: 016004; arXiv: hep-ph/0610385
6 HE X G, Valencia G. Phys. Lett. B, 2007, **651**: 135; arXiv: hep-ph/0703270
7 LI X Q, WEI Z T. Phys. Lett. B, 2007, **651**: 380; arXiv: 0705.1821 [hep-ph]
8 RAaij et al. (LHCb collaboration). Phys. Rev. Lett., 2013, **110**: 021801; arXiv: 1211.2674 [hep-ex]
9 RAaij et al. (LHCb collaboration). Phys. Rev. Lett., 2013, **111**: 101805; arXiv: 1307.5024 [hep-ex]
10 Chatrchyan S et al. (CMS collaboration). Phys. Rev. Lett., 2013, **111**: 101804; arXiv: 1307.5025 [hep-ex]
11 Gorn M. Phys. Rev. D, 1979, **20**: 2380
12 Pakvasa S. Chin. J. Phys., 1994, **32**: 1163; arXiv: hep-ph/9408270
13 Burdman G, Golowich E, Hewett J L, Pakvasa S. Phys. Rev. D, 2002, **66**: 014009; arXiv: hep-ph/0112235
14 Georgi H. Phys. Rev. Lett., 2007, **98**: 221601; arXiv: hep-ph/0703260
15 Barger V, CHIANG C W, Langacker P, LEE H S. Phys. Lett. B, 2004, **580**: 186; arXiv: hep-ph/0310073
16 HE X G, Valencia G. Phys. Rev. D, 2004, **70**: 053003; arXiv: hep-ph/0404229
17 CHEUNG K, CHIANG C W, Deshpande N G, JIANG J. Phys. Lett. B, 2007, **652**: 285; arXiv: hep-ph/0604223
18 HE X G, Valencia G. Phys. Rev. D, 2006, **74**: 013011; arXiv: hep-ph/0605202
19 CHIANG C W, Deshpande N G, JIANG J. JHEP, 2006, **0608**: 075; arXiv: hep-ph/0606122
20 Baek S, Jeon J H, Kim C S. Phys. Lett. B, 2006, **641**: 183; arXiv: hep-ph/0607113
21 LI H B, YANG M Z. Sci. China G, 2010, **53**: 1953
22 PENG T. (Belle collaboration). PoS ICHEP, 2013, **2012**: 357; LI L. arXiv: 1310.6142 [hep-ex]
23 RAaij et al. (LHCb collaboration). arXiv: 1309.6534 [hep-ex]
24 RAaij et al. (LHCb collaboration). arXiv: 1310.7201 [hep-ex]
25 Georgi H. Phys. Lett. B, 2007, **650**: 275; arXiv: 0704.2457 [hep-ph]
26 CHEUNG K, KEUNG W Y, YUAN T C. Phys. Rev. Lett., 2007, **99**: 051803; arXiv: 0704.2588 [hep-ph]
27 LUO M, ZHU G. Phys. Lett. B, 2008, **659**: 341; arXiv: 0704.3532 [hep-ph]
28 Grinstein B, Intriligator K A, Rothstein I Z. Phys. Lett. B, 2008, **662**: 367; arXiv: 0801.1140 [hep-ph]
29 CHEN S L, HE X G, LI X Q, TSAI H C, WEI Z T. Eur. Phys. J. C, 2009, **59**: 899; arXiv: 0710.3663 [hep-ph]
30 Burdman G, Shipsey I. Ann. Rev. Nucl. Part. Sci., 2003, **53**: 431; arXiv: hep-ph/0310076
31 HE X G, Valencia G. Phys. Rev. D, 2002, **66**: 013004; 079901; arXiv: hep-ph/0203036
32 HE X G, Valencia G. Phys. Rev. D, 2003, **68**: 033011; arXiv: hep-ph/0304215
33 Lee J P. Phys. Rev. D, 2013, **88**: 116003; arXiv: 1303.4858 [hep-ph]
34 Beringer J et al. (Particle Data Group collaboration). Phys. Rev. D, 2012, **86**: 010001
35 DING G J, YAN M L. Phys. Rev. D, 2008, **77**: 014005
36 CHIANG C W, LIN Y F, Tandean J. JHEP, 2011, **1111**: 083; arXiv: 1108.3969 [hep-ph]
37 Aubert J J et al. (European Muon collaboration). Phys. Lett. B, 1985, **155**: 461
38 Biino C, Greenhalgh J F, Louis W C et al. Phys. Rev. Lett., 1986, **56**: 1027
39 Riles K, Dorfan J, Abrams G S et al. Phys. Rev. D, 1987, **35**: 2914
40 Palka H et al. (ACCMOR collaboration). Phys. Lett. B, 1987, **189**: 238
41 Becker J et al. (MARK-III collaboration). Phys. Lett. B, 1987, **193**: 147; **198**: 590
42 Haas P et al. (Cleo collaboration). Phys. Rev. Lett., 1988, **60**: 1614
43 Albrecht H et al. (ARGUS collaboration). Phys. Lett. B, 1988, **209**: 380
44 Adler J et al. (MARK-III collaboration). Phys. Rev. D, 1988, **37**: 2023; 1989, **40**: 3788
45 Mishra C S et al. (E789 collaboration). Phys. Rev. D, 1994, **50**: 9
46 Kodama K et al. (E653 collaboration). Phys. Lett. B, 1995, **345**: 85
47 Adamovich M et al. (BEATRICE collaboration). Phys. Lett. B, 1995, **353**: 563
48 Freyberger A et al. (CLEO collaboration). Phys. Rev. Lett., 1996, **76**: 3065; **77**: 2147
49 Alexopoulos T et al. (E771 collaboration). Phys. Rev. Lett., 1996, **77**: 2380
50 Adamovich M et al. (BEATRICE collaboration). Phys. Lett. B, 1997, **408**: 469
51 Aitala E M et al. (E791 collaboration). Phys. Lett. B, 1999, **462**: 401; arXiv: hep-ex/9906045
52 Pripstein D et al. (E789 collaboration). Phys. Rev. D, 2000, **61**: 032005; arXiv: hep-ex/9906022
53 Acosta D et al. (CDF collaboration). Phys. Rev. D, 2003, **68**: 091101; arXiv: hep-ex/0308059
54 Aubert B et al. (BaBar collaboration). Phys. Rev. Lett., 2004, **93**: 191801; arXiv: hep-ex/0408023
55 Abt I et al. (HERA-B collaboration). Phys. Lett. B, 2004, **596**: 173; arXiv: hep-ex/0405059
56 Petric M et al. (Belle collaboration). Phys. Rev. D, 2010, **81**: 091102; arXiv: 1003.2345 [hep-ex]
57 Aaltonen T et al. (CDF collaboration). Phys. Rev. D, 2010, **82**: 091105; arXiv: 1008.5077 [hep-ex]
58 RAaij et al. (LHCb collaboration). Phys. Lett. B, 2013, **725**: 15; arXiv: 1305.5059 [HEP-ex]
59 Lees J P et al. (BaBar collaboration). Phys. Rev. D, 2012, **86**: 032001; arXiv: 1206.5419 [hep-ex]
60 Ablikim M et al. (BESIII collaboration). Chin. Phys. C, 2013, **37**: 063001; arXiv: 1209.6199 [hep-ex]
61 Dobbs S et al. (CLEO collaboration). Phys. Rev. D, 2007, **76**: 112001; arXiv: 0709.3783 [hep-ex]
62 LI W D et al. The Offine Software for the BESIII Experiment, Proceeding of CHEP06 (Mumbai, India, February 2006)
63 Agostinelli S et al. (GEANT4 collaboration). Nucl. Instrum. Methods A, 2003, **506**: 250
64 DENG Zi-Yan, CAO Guo-Fu, FU Cheng-Dong, et al. High Energy Physics and Nuclear Physics, 2006, **30**(05): 371-377 (in Chinese)
65 Ablikim M et al. (BESIII collaboration). Nucl. Instrum. Methods A, 2010, **614**: 345; arXiv: 0911.4960 [physics.ins-det]
66 Conrad J, Botner O, Hallgren A, Perez de los Heros C. Phys. Rev. D, 2003, **67**: 012002; arXiv: hep-ex/0202013
67 Feldman G J, Cousins R D. Phys. Rev. D, 1998, **57**: 3873; arXiv: physics/9711021 [physics.data-an]
68 Golowich E, Hewett J, Pakvasa S, Petrov A A. Phys. Rev. D, 2009, **79**: 114030; arXiv: 0903.2830 [hep-ph]