Effects of littlest Higgs model in rare D meson decays

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A tree-level flavor changing neutral current in the uplike quark sector appears in one of the variations of the littlest Higgs model. We investigate the effects of this coupling in the $D^+ \to \pi^+ l^+ l^-$ and $D^0 \to \rho^0 l^+ l^-$ decays, which are the most appropriate candidates for the experimental studies. However, the effects are found to be too small to be observed in the current and the foreseen experimental facilities. These decays are still dominated by the standard model long-distance contributions, which are reevaluated based on the new experimental input.

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I. INTRODUCTION

The effects of new physics in hadronic phenomena are most likely to be seen in the downlike quark sector. Many new scenarios modify the flavor changing natural currents (FCNC) with respect to standard model (SM) framework. This might lead to observable effects in the processes which do not appear at tree level within SM like $b \to s$, $b \to d$, $s \to d$, $b\bar{s} \leftrightarrow \bar{b}s$, $b\bar{d} \leftrightarrow \bar{b}d$, and $s\bar{d} \leftrightarrow \bar{s}d$ transitions. Most of the charm meson processes, where $c \to u$ and $c\bar{u} \leftrightarrow \bar{c}u$ transitions occur, are however dominated by the standard model long-distance (LD) contributions [1–10].

On the experimental side there are many studies of rare charm meson decays. The first observed rare D meson decay was the radiative weak decay $D \to \phi\gamma$. Its rate $\mathrm{Br}(D \to \phi\gamma) = 2.6^{+0.7}_{-0.6} \times 10^{-5}$ has been measured by the Belle Collaboration [11] and hopefully other radiative weak charm decays will be observed soon [12]. The hadronic decays, in which the $c \to u$ transition occur, are interesting for the searches of new physics. The $c \to u\gamma$ decay rate is strongly Glashow-Iliopoulos-Maiani (GIM) suppressed at the leading order in the SM, while the QCD effects enhance it up to the order of 10^{-8} [13]. The minimal supersymmetric standard model (MSSM) can increase this rate by a factor of 100 [14]. On the other hand, the long-distance contributions in the relevant $D \to V\gamma$ decays (V is a light vector meson) give the branching ratios of the order $\mathrm{Br} \sim 10^{-6}$ [1,7], which makes the search for new physics in radiative charm decays almost impossible.

Another possibility to search for the effects of new physics in the charm sector is offered in the studies of $D \to Xl^+l^-$ decays which might be results of the $c \to ul^+l^-$ FCNC transition [2,3,6,8,9]. Here X is a light vector meson V or pseudoscalar meson P. The leading order rate for the inclusive $c \to ul^+l^-$ calculated within SM [9] was found to be suppressed by QCD corrections [2]. The inclusion of the renormalization group equations for the Wilson coefficients gave an additional significant suppression leading to the rates $\Gamma(c \to ue^+e^-)/\Gamma_{D^0} = 2.4 \times 10^{-10}$ and $\Gamma(c \to u\mu^+\mu^-)/\Gamma_{D^0} = 0.5 \times 10^{-10}$ [15]. These transitions are largely driven by a virtual photon at low dilepton mass $m_{ll} \equiv \sqrt{(p_+ + p_-)^2}$. The total rate for $D \to Xl^+l^-$ is dominated by the long-distance resonant contributions at dilepton mass $m_{ll} = m_\rho,\ m_\omega,\ m_\phi$ and even the largest contributions from new physics are not expected to affect the total rate significantly [2,9]. New physics could only modify the dilepton mass distribution below ρ or distribution above ϕ. In the case of $D \to \pi l^+l^-$ there is a broad kinematical region of dilepton mass above ϕ resonance which presents an unique possibility to study $c \to ul^+l^-$ at high m_{ll} [9]. The leading contribution to $c \to ul^+l^-$ in general MSSM with the conserved R parity comes from a one-loop diagram with gluino and squarks in the loop [2,9,14]. It proceeds via virtual photon and significantly enhances the $c \to ul^+l^-$ spectrum at small m_{ll}. This MSSM enhancement is not so drastic in the hadronic decays, since the gauge invariance in $D \to Pl^+l^-$ imposes an additional factor of m_{ll}^2 [2,9], while $D \to Vl^+l^-$ has large long-distance contributions at small m_{ll} just like $D \to V\gamma$. The R-parity violating supersymmetry contributions can induce $c \to ul^+l^-$ at tree level via sparticle exchange. This can give a sizable enhancement of decay width distribution at low and at high m_{ll} [2,3]. The presence of the R-parity violating couplings modifies also the forward-backward asymmetry in the case of $D \to Vl^+l^-$ decay. There are intensive experimental efforts by CLEO [12,16] and Fermilab [17,18] collaborations to improve the upper limits on the rates for $D \to Xl^+l^-$ decays. Two events in the channel $D^+ \to \pi^+e^+e^-$ with m_{ee} close to m_ϕ already have been observed by CLEO [12].

The other rare D meson decays are not so easily accessible by experimental searches. The $c \to u$ transition occurs also in $D^0 \to l^+l^-$ decay. However, in the SM this mode is helicity suppressed and also dominated by the long-distance contributions [2,6,10] leading to the rate of the order 10^{-13}.

Among many extensions of the standard model, the littlest Higgs (LH) model (see e.g. [19–25]) offers a simple and appealing solution to the gauge hierarchy problem. The Higgs boson of this model is a pseudo Goldstone boson of a new global symmetry, which is spontaneously broken at the scale $4\pi f$. This protects Higgs mass against quadratic divergences from self interactions. The quadratic divergences in the Higgs mass due to the SM gauge bosons are cancelled by the contributions of the new heavy gauge bosons with spin 1. The divergence due to top quark is cancelled by the contribution of the new heavy quark with the charge $2/3$ and spin $1/2$. There are two interesting consequences that arise from the existence of this new quark which is a $SU(2)_L$ singlet [22]. It extends the 3×3 Cabibbo-Kobayashi-Maskawa (CKM) matrix in the SM to a 4×3 matrix. It also allows Z-mediated FCNC at tree level in the up sector but not in the down sector [22]. The magnitude of the relevant tree level $c\to uZ$ coupling $|V_{ub}||V_{cb}|v^2/f^2$ is constrained via the scale $f\geq \mathcal{O}(1\ \mathrm{TeV})$ by the precision electroweak observables [25]. In Ref. [22] the author has studied effects of this new FCNC coupling in $D\to\mu^+\mu^-$, $D^0\leftrightarrow\bar{D}^0$ oscillations and $t\to cZ$ decay. The effects were found to be insignificant for the current experimental studies and the testability of the model requires more stringent measurements of the mixing angles at the Large Hadron Collider.

In this paper we investigate possible effects of the tree level $c\to uZ$ coupling from the littlest Higgs model in charm meson decays. We focus on the decays $D^+\to\pi^+l^+l^-$ and $D^0\to\rho^0 l^+l^-$, which are the most suitable for the experimental studies among all $D\to Xl^+l^-$ decay modes, and they have the most stringent upper bounds on the rates at present [26]. We show that the effects of the LH model [22] can slightly modify the dilepton mass distribution for the inclusive decay $c\to ul^+l^-$. This effect is screened by the long-distance contributions in the hadronic channels. The total rate and the dilepton mass distribution for the decays $D^+\to\pi^+l^+l^-$ and $D^0\to\rho^0l^+l^-$ are found to be completely dominated by the standard model long-distance contributions. For this reason we also reexamine the long-distance contributions to $D^+\to\pi^+l^+l^-$ using the most recent experimental results on charm meson decays. We also consider the forward-backward asymmetry for the decay $D^0\to\rho^0l^+l^-$, which is equal to zero in SM. The forward-backward asymmetry is different from zero in the LH model, but it is not large enough to be seen in the present or planned experiments.

The paper is organized as follows: In Sec. II we present the main results of the LH model by Lee [22]. In Sec. III we discuss the influence of this model on the $c\to ul^+l^-$ transition. Sections IV and V are devoted to effects of the LH model on decays $D^+\to\pi^+l^+l^-$ and $D^0\to\rho^0l^+l^-$, respectively. Our results are summarized in Sec. VI.

II. FCNC IN THE LITTLEST HIGGS MODEL

The littlest Higgs models [19–25] offer an interesting and rather simple solution to the gauge hierarchy problem. These models contain new massive gauge bosons and a new heavy uplike quark $\tilde{t}$ together with its conjugate $\tilde{t}^c$. This quark is a singlet under $SU(2)_L$, triplet under $SU(3)_{\mathrm{color}}$, and carries charge $2/3$ [22]. Its presence modifies the weak currents [22]. The charged currents have SM contributions from the W boson as well as the new contributions from a new gauge boson W_H. The SM CKM matrix is extended to a 4×3 matrix.

The neutral-current interactions in the SM do not change flavor at the tree level due to the GIM mechanism. The FCNC appears at a one-loop level as a result of GIM cancellation and the difference of the quark masses. However, in the littlest Higgs model the neutral-current interactions change the flavor already at the tree level. The Lagrangian which describes this interaction within the LH model is given by [22]

$$\mathcal{L}_{\mathrm{NC}}=\frac{g}{\cos\theta_W}Z_\mu(J^\mu_{W^3}-\sin^2\theta_W J^\mu_{\mathrm{EM}}), \qquad (1)$$

where J^μ_{EM} is the same electromagnetic current as in the SM, while $J^\mu_{W^3}$ is given by [22]

$$J^\mu_{W^3}=\tfrac{1}{2}\bar{U}^m_L\gamma^\mu\Omega U^m_L-\tfrac{1}{2}\bar{D}^m_L\gamma^\mu D^m_L, \qquad (2)$$

with $L=\frac{1}{2}(1-\gamma_5)$ and mass eigenstates $U^m_L=(u_L,c_L,t_L,T_L)^T$, $D^m_L=(d_L,s_L,b_L)^T$. The neutral current for the downlike quarks is the same as in the SM, while the up sector has additional currents since $\Omega\neq I$ due to the new heavy quark [22]

$$\Omega=\begin{pmatrix}1-|\Theta_u|^2 & -\Theta_u\Theta_c^* & -\Theta_u\Theta_t^* & -\Theta_u\Theta_T^*\\ -\Theta_c\Theta_u^* & 1-|\Theta_c|^2 & -\Theta_c\Theta_t^* & -\Theta_c\Theta_T^*\\ -\Theta_t\Theta_u^* & -\Theta_t\Theta_c^* & 1-|\Theta_t|^2 & -\Theta_t\Theta_T^*\\ -\Theta_T\Theta_u^* & -\Theta_T\Theta_c^* & -\Theta_T\Theta_t^* & 1-|\Theta_T|^2\end{pmatrix}. \qquad (3)$$

The elements of Ω satisfy the following unitarity relations [22]:

$$|V_{id}|^2+|V_{is}|^2+|V_{ib}|^2+|\Theta_i|^2=1, \qquad i=u,c,t,T, \qquad (4)$$

$$V_{id}V^*_{jd}+V_{is}V^*_{js}+V_{ib}V^*_{jb}+\Theta_i\Theta^*_j=0, \qquad i,j=u,c,t,T, \qquad i\neq j, \qquad (5)$$

where V_{ij} are CKM matrix elements. The SM unitarity triangle is replaced by a unitary quadrangle in the LH model.

There is a tree-level flavor changing neutral coupling $\bar{u}_L\gamma_\mu c_L Z^\mu$ given by $ig\Omega_{uc}/(2\cos\theta_W)$, and we explore its possible effect in rare charm meson decays. The magnitude of this effect depends on the value of $\Omega_{uc}=-\Theta_u\Theta^*_c$, which is constrained by the unitarity of CKM matrix via (4). A more stringent upper bound on Ω_{uc} follows from the equality derived within the LH model [22]

$$|\Omega_{uc}|\simeq|V_{ub}||V_{cb}|\frac{v^2}{f^2}\simeq 10^{-5}\left(\frac{1\ \mathrm{TeV}}{f}\right)^2, \qquad (6)$$

since the scale f cannot be arbitrarily small. At present, the scale f is already severely constrained by the precision electroweak observables. The lowest bound on f ranges between 1 TeV to 4 TeV or even higher, depending on the specific model [25], and we will vary the scale between

$$0.5\ \text{TeV} \leq f \leq 4\ \text{TeV}. \tag{7}$$

The scales below 1 TeV are already excluded by the precision electroweak observables [25], but we use them in order to demonstrate that even for the scale as low as $f = 0.5$ TeV the effect of the LH model on the rare charm meson decays is insignificant.

III. EFFECTS ON $c \to ul^+l^-$ TRANSITION

The tree-level coupling $\bar{u}_L\gamma_\mu c_L Z^\mu$ in the LH model introduces new contributions in the effective weak Lagrangian relevant for $c \to ul^+l^-$ decay. Here we write only contributions which are relevant for our further study of charm meson decays[1]:

$$\mathcal{L}_{\text{eff}} = -\frac{G_F}{\sqrt{2}}\Big[V_{cd}^*V_{ud}\sum_{i=1,2} C_i Q_i^d + V_{cs}^*V_{us}\sum_{i=1,2} C_i Q_i^s - V_{cb}^*V_{ub}\sum_{i=7,9,10} C_i Q_i\Big], \tag{8}$$

where quark operators are

$$Q_9 = \frac{e^2}{16\pi^2}\bar{u}_L\gamma_\mu c_L \bar{l}\gamma^\mu l, \qquad Q_{10} = \frac{e^2}{16\pi^2}\bar{u}_L\gamma_\mu c_L \bar{l}\gamma^\mu\gamma_5 l,$$
$$Q_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu}\bar{u}\sigma^{\mu\nu}(1+\gamma_5)c, \tag{9}$$
$$Q_1^q = \bar{q}_L\gamma^\mu q_L \bar{u}_L\gamma_\mu c_L, \qquad Q_2^q = \bar{u}_L\gamma^\mu q_L \bar{q}_L\gamma_\mu c_L.$$

The SM calculation leads to the prediction [15][2]

$$\frac{\Gamma^{\text{SM}}(c \to ue^+e^-)}{\Gamma_{D^+}} = 6.0\times 10^{-10}, \qquad \frac{\Gamma^{\text{SM}}(c \to u\mu^+\mu^-)}{\Gamma_{D^+}} = 1.3\times 10^{-10}. \tag{10}$$

Let us briefly describe the dominant contributions that lead to this rate, since we will need the SM values of coefficients $C_{7,9,10}$ in the following sections. The SM rate is dominated by the photon exchange, where $c \to u\gamma$ is a two-loop diagram induced by Q_2 and a gluon exchange [13,15]. The corresponding dominant piece in the amplitude is given by the coefficient $V_{cb}^*V_{ub}\hat{C}_7^{\text{eff}} = V_{cs}^*V_{us}(0.007 + 0.020i)(1 \pm 0.2)$ [13,15][3] and tree-level matrix element $\langle Q_7\rangle_0$. The contribution of $\hat{C}_9^{\text{eff}}$, given by Eq. (7) of [15],

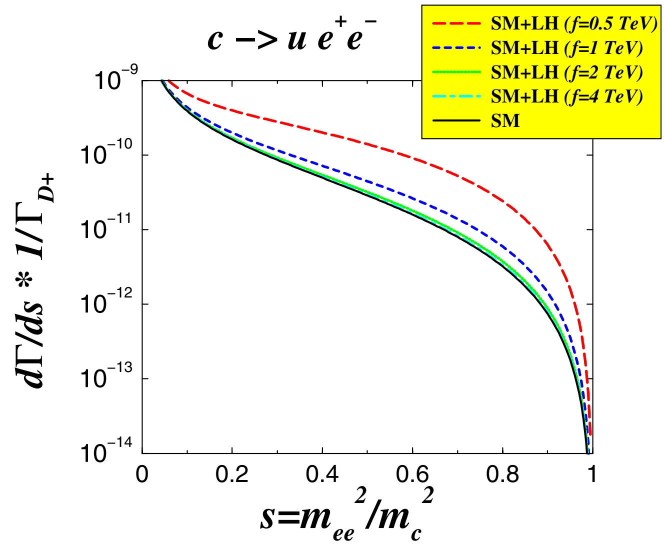

FIG. 1 (color online). The dilepton mass distribution for the decay width of $c \to ue^+e^-$. The SM prediction [15] is shown together with possible modifications within LH model for various scales f.

is small since it was found to be significantly suppressed by the effects of the renormalization group equations for the Wilson coefficients. The coefficient $C_{10} \simeq 0$ is completely negligible in the SM in contrast to the LH model, where it has the same magnitude as C_9 (11).

The LH model contains the tree-level coupling $\bar{u}_L\gamma_\mu c_L Z^\mu$ (1) and modifies coefficients C_9 and C_{10}

$$V_{cb}^*V_{ub}\delta C_9^{\text{LH}} = \frac{8\pi}{\alpha}\Omega_{uc} g_V^l, \qquad V_{cb}^*V_{ub}\delta C_{10}^{\text{LH}} = -\frac{8\pi}{\alpha}\Omega_{uc} g_A^l, \tag{11}$$

with $g_V^l = -1/2 + 2\sin^2\theta_W$ and $g_A = -1/2$. This model can moderately enhance the rate for the inclusive decay $c \to ul^+l^-$, as illustrated for various scales f in Fig. 1.[4] The enhancement over the SM rate is practically negligible for the scales f of few TeV or more. The enhancement is appreciable for $f \simeq 0.5$ TeV and we explore whether this could lead to any modifications of hadron observables in the following two sections.

IV. EFFECTS ON $D^+ \to \pi^+l^+l^-$ DECAY

The possible modification of $c \to ul^+l^-$ rates due to new physics can be probed experimentally only in the hadronic decays. First we focus on the $D^+ \to \pi^+l^+l^-$ ($l = e, \mu$) decay, which has the most stringent experimental upper bound and is the most promising for future experimental investigations among all $D \to Xl^+l^-$ decays. The present experimental upper bounds are [12,17,26]

[1]The notation for $C_{7,9,10}$ and $Q_{7,9,10}$ follows one given in Ref. [15].

[2]The branching ratio is expressed in terms of coefficients C_i in [9,15]. We use $m_c = 1.4$ GeV.

[3]$\hat{C}_7^{\text{eff}}$ and $\hat{C}_9^{\text{eff}}$ are effective Wilson coefficients [13,15].

[4]The phase of Ω_{uc} (6) is unknown and we take the value that maximizes the rates in Figs. 1 and 2.

$$\mathrm{B\,r}^{\mathrm{exp}}(D^+ \to \pi^+ e^+ e^-) < 7.4 \times 10^{-6},$$
$$Br^{\mathrm{exp}}(D^+ \to \pi^+ \mu^+ \mu^-) < 8.8 \times 10^{-6}. \quad (12)$$

The first rate concerns m_{ee} outside the narrow region near $m_{ee} \simeq m_\phi$, while two events already have been observed in the region where the dilepton mass is close to the mass of ϕ meson $m_{ee} \simeq m_\phi$ [12] giving

$$\mathrm{B\,r}^{\mathrm{exp}}(D^+ \to \pi^+ \phi \to \pi^+ e^+ e^-) = (2.8 \pm 1.9 \pm 0.2) \times 10^{-6}, \quad (13)$$

which is consistent with $\mathrm{Br}(D^+ \to \phi\pi^+ \to \pi^+ e^+ e^-) = \mathrm{Br}(D^+ \to \phi\pi^+) \times \mathrm{Br}(\phi \to e^+ e^-) = (1.9 \pm 0.2) \times 10^{-6}$ [26].

This indicates that the resonant decay channels $D^+ \to \pi^+ V_0 \to \pi^+ l^+ l^-$ with intermediate vector resonances $V_0 = \rho^0, \omega, \phi$ constitute an important long-distance contribution to the hadronic decay, which may shadow interesting short-distance (SD) contributions induced a by $c \to u l^+ l^-$ transition. Our determination of short and long-distance contributions to $D^+ \to \pi^+ l^+ l^-$ takes advantage of the available experimental data. This is a fortunate circumstance for this particular decay since the analogous experimental input is not available for determination of the other $D \to X l^+ l^-$ rates in a similar way.

The size of the short-distance contribution is dictated by the coefficients $C_{7,9,10}$ in the SM or LH model via

$$\mathcal{A}^{\mathrm{SD}}[D(p) \to \pi(p-q) l^+ l^-] = i\frac{G_F}{\sqrt{2}} e^2 V_{cb}^* V_{ub}\Big[\frac{C_{10}}{16\pi^2} f_+(q^2)\bar{u}(p_-)\not{p}\gamma_5 v(p_+) + \Big\{\frac{C_7}{2\pi^2} m_c s(q^2) + \frac{C_9}{16\pi^2} f_+(q^2)\Big\} \times \bar{u}(p_-)\not{p} v(p_+)\Big], \quad (14)$$

where $q^2 = m_{ll}^2$ and form factors $f_+(q^2)$ and $s(q^2)$ are defined by

$$\langle \pi(p_\pi)|\bar{u}\gamma^\mu(1-\gamma_5)c|D(p)\rangle = (p+p_\pi)^\mu f_+(q^2) + (p-p_\pi)^\mu f_-(q^2),$$
$$\langle \pi(p_\pi)|\bar{u}\sigma^{\mu\nu}(1\pm\gamma_5)c|D(p)\rangle = is(q^2)[(p+p_\pi)^\mu q^\nu - q^\mu(p+p_\pi)^\nu \pm i\epsilon^{\mu\nu\lambda\sigma}(p+p_\pi)_\lambda q_\sigma]. \quad (15)$$

We apply the information coming from recently measured decay distribution for $D \to \pi$ semileptonic decay [27,28]. They lead to the $D \to \pi$ form factor $f_+(q^2) = f_+(0)/(1 - q^2/m_{D^*}^2)$ with $f_+(0) = 0.73 \pm 0.14 \pm 0.06$ [27], which is consistent with D^*-pole dominance at present experimental accuracy [28]. The experimental data for the form factor $s(q^2)$ is not available and we use the relation $s(q^2) = f_+(q^2)/m_D$ [29], which strictly holds in the heavy quark limit and at zero recoil. The amplitude (14) gives the rates for the short-distance contribution in standard and littlest Higgs models by using the values of coefficients $C_{7,9,10}$ from the previous section. The resulting rates in Table I and Fig. 2 indicate that the LH model can moderately enhance the short-distance contribution in comparison with the SM result.

The long-distance contributions arise from the $D^+ \to \pi^+ V^0$ decay followed by $V_0 \to \gamma \to e^+ e^-$ where $V_0 = \rho^0, \omega\phi$. The theoretical model for the long-distance (and also short-distance) contributions to all $D \to P l^+ l^-$ decays has been presented in [9]. The gauge invariance and Lorentz symmetry prohibit the decay $D \to \pi\gamma$ to a real photon and there is no $1/m_{ll}^2$ pole in the $D \to P l^+ l^-$ amplitude [6,9]. Instead of using the theoretical model [9], we take the full advantage of experimental input that is available for the decay of interest here. Our estimation is based on the measured rates for $D^+ \to \pi^+ \rho^0$, $\rho^0 \to l^+ l^-$, $D^+ \to \pi^+ \phi$, $\phi \to l^+ l^-$ [26] and the fact that the decay width for a cascade $D \to \pi V_0$ followed by $V_0 \to l^+ l^-$ can be generally expressed as [30][5]

$$\frac{d\Gamma_{D\to\pi V_0\to\pi l^+ l^-}}{dq^2} = \Gamma_{D\to\pi V_0}(q^2)\frac{1}{\pi} \times \frac{\sqrt{q^2}}{(m_{V_0}^2 - q^2)^2 + m_{V_0}^2\Gamma_{V_0}^2}\Gamma_{V_0\to l^+ l^-}(q^2). \quad (16)$$

Here $\Gamma_{D\to\pi V_0}(q^2)$ and $\Gamma_{V_0\to l^+l^-}(q^2)$ denote rates if V_0 had a mass $\sqrt{q^2}$ and these rates are known experimentally only at $\sqrt{q^2} = m_{V_0}$. Since vector resonances are relatively narrow, the relation (16) can be further simplified using the narrow width approximation $\Gamma_{V_0} \ll M_{V_0}$ leading to

$$\mathrm{Br}\,(D \to \pi V_0 \to \pi l^+ l^-) = \mathrm{Br}(D \to \pi V_0)\mathrm{Br}(V_0 \to l^+ l^-), \quad (17)$$

which is in agreement with the experimental result (13). This indicates that the amplitude for a cascade via resonance ρ^0 or ϕ can be written as

$$\mathcal{A}^{\mathrm{LD}}[D(p) \to \pi V_0 \to \pi(p-q) l^+ l^-] = e^{i\varphi_{V_0}} a_{V_0}\frac{1}{q^2 - m_{V_0}^2 + i m_{V_0}\Gamma_{V_0}}\bar{u}(p_-)\not{p} v(p_+), \quad (18)$$

where the values $a_\rho = 2.9 \times 10^{-9}\ \mathrm{GeV}^{-2}$ and $a_\phi = 4.2 \times 10^{-9}\ \mathrm{GeV}^{-2}$ are determined from experimental data [26] via (17) and the only assumption here is that a_{V_0} does not depend on q^2. Since the amplitude can be

[5]Relation (16) applies for scalar resonances and also for vector resonances since $l\not{q}l = 0$ [30].

TABLE I. Branching ratios for the hadronic decays, which are most suitable to probe $c \to u l^+ l^-$ transition experimentally. The total rates in the standard and littlest Higgs models are completely dominated by the resonant long-distance contribution $D \to X V_0 \to X l^+ l^-$. We also provide the short-distance contribution in the SM together with its maximal modification in the LH model for the scale $f = 0.5$ TeV. The SM short-distance contribution for $D^0 \to \rho^0 l^+ l^-$ is not shown since it is completely negligible in comparison to the long-distance contribution.

Br	Short-distance contribution only SM	SM + LH ($f = 0.5$ TeV)	Total rate $\simeq$ long-distance contr.	Experiment
$D^+ \to \pi^+ e^+ e^-$	6×10^{-12}	8×10^{-11}	1.9×10^{-6}	$<7.4 \times 10^{-6}$
$D^+ \to \pi^+ \mu^+ \mu^-$	6×10^{-12}	8×10^{-11}	1.9×10^{-6}	$<8.8 \times 10^{-6}$
$D^0 \to \rho^0 e^+ e^-$	negligible	5×10^{-12}	1.6×10^{-7}	$<1.0 \times 10^{-4}$
$D^0 \to \rho^0 \mu^+ \mu^-$	negligible	5×10^{-12}	1.5×10^{-7}	$<2.2 \times 10^{-5}$

determined up to the overall phase $e^{i\varphi_{V_0}}$ we keep it in our expressions. The contribution of the cascade via ω cannot be determined in such a way since only the upper limit on the $D^+ \to \pi^+ \omega$ rate is experimentally known.

The long-distance amplitude is a sum of amplitudes for separate resonant channels, but their relative sign is not known since only the absolute value of a_{V_0} can be determined from (17). We will argue that the relative signs as well as the ratio of ω/ρ^0 amplitudes can be determined by considering the mechanism of the cascade decays. Our result is

$$\mathcal{A}^{\rm LD}[D(p) \to \pi(p-q) l^+ l^-] = e^{i\varphi}\bigg[a_\rho\bigg(\frac{1}{q^2 - m_\rho^2 + i m_\rho \Gamma_\rho} - \frac{1}{3}\frac{1}{q^2 - m_\omega^2 + i m_\omega \Gamma_\omega}\bigg) - a_\phi \frac{1}{q^2 - m_\phi^2 + i m_\phi \Gamma_\phi}\bigg] \times \bar{u}(p_-)\not{p} v(p_+), \qquad (19)$$

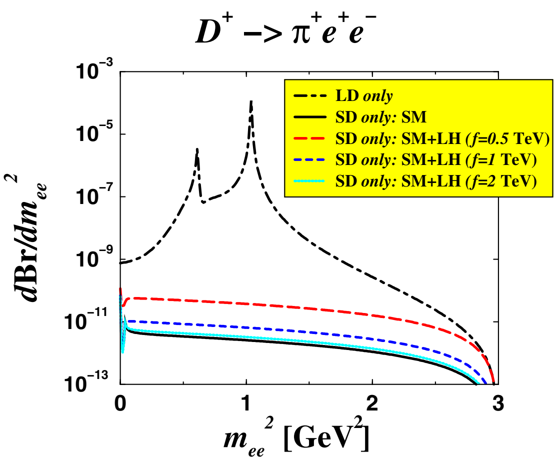

FIG. 2 (color online). The dilepton mass distribution $d\mathrm{Br}/dm_{ee}^2$ for the decay $D^+ \to \pi^+ e^+ e^-$ as a function of the dilepton mass square $m_{ee}^2 = (p_+ + p_-)^2$. In the standard and littlest Higgs models the rate is largely dominated by the long-distance contribution, shown by the dotted-dashed line. The other lines represent the short-distance contribution in the SM and its modifications in the LH model for various scales f.

where the values $a_{\rho,\phi}$ are given above, while the overall phase φ is unknown but it is irrelevant since the phase of Ω_{uc} (6) in $\mathcal{A}^{\rm SD}$ (14) is unknown as well.

The relative signs and the ratio of ω/ρ^0 amplitudes can be derived by considering the mechanism of the decay $D^+ \to \pi^+ V^0 \to \pi^+ l^+ l^-$. Part of the difference between amplitudes which proceed via ρ^0, ω, ϕ comes from the electromagnetic (EM) transition $V^0 \to \gamma \to l^+ l^-$, which depends on the quark content of the mesons in the EM current $e_u \bar{u}u + e_d \bar{d}d + e_s \bar{s}s \to \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{3\sqrt{2}}\omega - \frac{1}{3}\phi$. The remaining part of the difference is due to the weak transition $D^+ \to \pi^+ V^0$, which is induced by the operators $Q_{1,2}^{d,s}$ (9) and can proceed via three ways within the factorization approximation:

(1) The first possibility is due to the operator $V_{cd}^* V_{ud} Q_1^d + V_{cs}^* V_{us} Q_1^s \simeq V_{cd}^* V_{ud} \bar{u}_L \gamma^\mu c_L \times (\bar{d}_L \gamma_\mu d_L - \bar{s}_L \gamma_\mu s_L)$, which induces the $D^+ \to \pi^+$ transition via the $\bar{u}_L \gamma^\mu c_L$ current and produces ρ^0, ω, ϕ due to the acting of the $\bar{d}\gamma_\mu d - \bar{s}\gamma_\mu s$ current. The $\bar{d}d \sim -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega$ current renders ρ^0 and ω with the opposite phase, while their amplitudes for the EM transition differ by factor 1/3, so $A_1(\omega)/A_1(\rho^0) = -1/3$ for this mechanism in the limit of $SU(3)$ flavor symmetry. Along the same lines $A_1(\phi)/A_1(\rho^0) = -2/3$.

(2) The operator Q_2^d can induce $D^+ \to \rho^0$ or $D^+ \to \omega$ transition via the $\bar{d}_L \gamma^\mu c_L$ current and produce π^+ via $\bar{u}_L \gamma^\mu d_L$. Since ρ^0 and ω arise from $\bar{d}d$ again, this mechanism gives the same ratio $A_2(\omega)/A_2(\rho^0) = -1/3$, while there is no intermediate ϕ in this case.

(3) The third possibility arises from D^+ which is annihilated by the $\bar{d}_L \gamma^\mu c_L$ operator and $V^0 \pi^+$ created by the $\bar{u}_L \gamma^\mu d_L$ operator. It was shown within a model of [9] that this gives rise only to bremsstrahlung diagrams and that the total bremsstrahlung amplitude is equal to zero for $D \to P l^+ l^-$ decays. So the model of [9] indicates that the contribution from this mechanism is small and will be neglected.

Since the ratio of ω/ρ^0 amplitudes is equal for the first two mechanisms, the ratio for the total amplitudes employed in (19) is $A(\omega)/A(\rho^0) = -1/3$. The magnitude

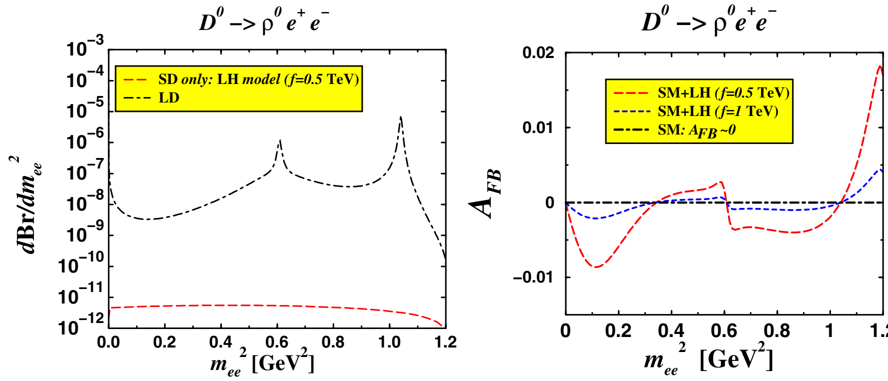

FIG. 3 (color online). The left figure shows the dilepton mass distribution for $D^0 \to \rho^0 e^+ e^-$. It is completely dominated by the standard model long-distance contributions, shown by the dotted-dashed line. The dashed line illustrates the short-distance contribution within the LH model for $f = 0.5$ TeV. The figure on the right shows the forward-backward asymmetry (20), which is zero in the SM and small but nonzero in the LH model.

$|A(\phi)/A(\rho^0)| = a_\phi/a_\rho$ is taken from the experimental data as explained above, while the relative sign between $A(\phi)$ and $A(\rho^0)$ in (19) is negative due to the first mechanism, which is the only one that allows ϕ intermediate state. This explains the structure of amplitude presented in Eq. (19).

We point out that the long-distance amplitude cannot be determined in such a way for most of the remaining $D \to Pl^+l^-$ decays. This is due to the lack of experimental data or to the fact that $A_1(\omega, \phi)/A_1(\rho^0)$ for the first mechanism may be different from $A_2(\omega, \phi)/A_2(\rho^0)$ for the second mechanism.

The amplitudes (14) and (19) give decay distributions in Fig. 2, while the corresponding total rates are given in Table I. The rates in standard and littlest Higgs models are dominated by the resonant long-distance contribution over the entire kinematical region of m_{ll}^2. Although the LH model with scale as low as $f = 0.5$ TeV would enhance the short-distance contribution, it would not affect appreciably the dilepton mass distribution for $D^+ \to \pi^+ l^+ l^-$.

V. EFFECTS ON $D^0 \to \rho^0 l^+ l^-$ DECAY

The $c \to ul^+l^-$ transition in principle also could be probed in $D \to Vl^+l^-$ decays with a vector meson V in the final state. In this section we explore possible effects of the LH model on the rate of $D^0 \to \rho^0 l^+ l^-$, which has most strict experimental upper bound at present [16,18,26] (see Table I) and best prospects for future investigations.

The long-distance contribution $D^0 \to \rho^0 V_0 \to \rho^0 l^+ l^-$ ($V_0 = \rho^0, \omega, \phi$) is induced by $V_{cd}^* V_{ud} Q_1^d + V_{cs}^* V_{us} Q_1^s$ (9). We are unable to determine its amplitude using the measured rates for $D^0 \to \rho^0 V_0$ since only the rate of $D^0 \to \rho^0 \phi$ is known experimentally. We are forced to use a model and we apply the approach of [6] (an improved version of [8]), which was developed to describe all $D \to Vl^+l^-$ and $D \to V\gamma$ decays. It is an effective model with mesonic degrees of freedom (heavy and light, pseudoscalar and vector) and is based on the heavy quark and chiral symmetries. The matrix elements are evaluated using the factorization approximation and they are invariant under EM gauge transformation by construction. We apply the model and the values of the parameters from Sec. 5.4 of [6] to evaluate the matrix elements for long- and short-distance contributions of $D^0 \to \rho^0 l^+ l^-$.

The resulting long-distance contribution in Fig. 3 indicates that there is a pole at $m_{ll} \simeq 0$ in addition to the poles at $m_{ll} = m_{\rho,\omega,\phi}$. This pole is due to the photon propagator and arises since the decay $D^0 \to \rho^0 \gamma$ to a real photon is allowed.[6] The long-distance contribution completely dominates the dilepton mass distributions in SM and LH models. It also dominates the total rate given in Table I. The short-distance contributions are completely negligible in the SM [6,8] as well as in the LH model even for the scale as low as $f = 0.5$ TeV.

Our study shows that the LH model has a negligible effect on the rate of $D^0 \to \rho^0 l^+ l^-$, but it might have a sizable effect on forward-backward asymmetry defined as

$$A_{\rm FB}(m_{ll}^2) = \frac{\int_0^1 \frac{d^2\Gamma}{d\cos\theta dm_{ll}^2} d\cos\theta - \int_{-1}^0 \frac{d^2\Gamma}{d\cos\theta dm_{ll}^2} d\cos\theta}{\frac{d\Gamma}{dm_{ll}^2}}, \quad (20)$$

where θ is the angle between l^+ and D^0 in the l^+l^- rest frame. We did not present $A_{\rm FB}$ in the case of the $D \to \pi l^+ l^-$ decay since it is equal to zero for the given amplitudes (14) and (19). The nonzero asymmetry in $D \to \rho l^+ l^-$ decay arises only when $C_{10} \neq 0$ (assuming $m_l \to 0$), so the asymmetry is practically zero in SM where $C_{10} \simeq 0$. The enhancement of the C_{10} in the LH model (11) is due

[6]The EM gauge invariance requires that $\langle\gamma|\bar{d}\gamma^\mu d - \bar{s}\gamma^\mu s|0\rangle\langle\rho^0|\bar{u}_L\gamma_\mu c_L|D^0\rangle$ is zero for the real photon in the factorization approximation [31]. The nonzero amplitude for $D^0 \to \rho^0\gamma$ within the factorization approximation comes from the mechanism, where $\bar{u}_L\gamma_\mu c_L$ annihilates D^0, $\bar{d}_L\gamma^\mu d_L$ creates ρ^0 and a photon is emitted before or after the weak transition.

to the tree level $\bar{u}_L \gamma_\mu c_L Z^\mu$ coupling and leads to nonzero asymmetry $A_{\rm FB}(m_{ll}^2)$ shown in Fig. 3.[7] The asymmetry is of the order of 10^{-3} for $f \simeq 1$ TeV, but this is still too small to be observed in the present and foreseen experiments due to the smallness of the $D^0 \to \rho^0 l^+ l^-$ rate.

VI. CONCLUSIONS

The tree-level flavor changing neutral transition $c \to uZ$ appears within a particular variation of the littlest Higgs model [22]. The magnitude of the relevant $c \to uZ$ coupling $|V_{ub}||V_{cb}|v^2/f^2$ is constrained via the scale $f \geq \mathcal{O}(1\ \text{TeV})$ by the precision electroweak data. We have investigated its impact on the rare D meson decay observables. First we determined the effects of the LH model on the effective Wilson coefficients $C_9^{\rm eff}$ and $C_{10}^{\rm eff}$. Both coefficients have the same magnitude in the LH model, contrary to the result of SM where $C_{10}^{\rm eff} \simeq 0$. The LH model can appreciably modify the inclusive $c \to ul^+ l^-$ decay only for the scales close to $f = 1$ TeV or less.

Among exclusive rare $D \to Xl^+ l^-$ decays, the $D^+ \to \pi^+ l^+ l^-$ and $D^0 \to \rho^0 l^+ l^-$ decays are the best candidates for the experimental searches and have most stringent upper bounds at present. However, these decays are found to be completely dominated by the long-distance contributions in the SM as well as in the LH models. Even the LH model with a scale as low as $f = 0.5$ TeV cannot sizably modify the total rates and the dilepton mass distributions for $D^+ \to \pi^+ l^+ l^-$ and $D^0 \to \rho^0 l^+ l^-$. The forward-backward asymmetry for $D^0 \to \rho^0 l^+ l^-$ vanishes in SM, while it is of the order of 10^{-3} in the LH model with the scale f around 1 TeV. Such asymmetry is still too small to be observed in the present or planned experiments given that the rate itself is already small.

We conclude that the LH model has insignificant effects on the charm meson observables in spite of its tree-level flavor changing couplings among uplike quarks. The eventual observation of the dilepton mass distribution and forward-backward asymmetry that disagree with the standard model prediction would indicate the presence of some other scenario of physics beyond the standard model.

[7]The asymmetry depends on the relative phase between short-distance and long-distance contributions, and we fix this phase using $\arg(\Omega_{uc}) = 0$ in Fig. 3.

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