Littlest Higgs Model with T-Parity
Confronting the New Data on $D^0 - \bar{D}^0$ Mixing

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Abstract

Motivated by the first experimental evidence of meson oscillations in the $D$ system, we study $D^0 - \bar{D}^0$ mixing in the Littlest Higgs model with T-parity, we investigate its role in constraining the model parameters and its impact on the most interesting flavour observables. We find that the experimental data are potentially strongly constraining but at present limited by large theoretical uncertainties in the long-distance Standard Model contribution to $D^0 - \bar{D}^0$ mixing.
Note added

An additional contribution to the $Z$ penguin in the Littlest Higgs model with T-parity has been pointed out in [1,2], which has been overlooked in the present analysis. This contribution leads to the cancellation of the left-over quadratic divergence in the calculation of some rare decay amplitudes. Instead of presenting separate errata to the present work and our papers [3–6] partially affected by this omission, we have presented a corrected and updated analysis of flavour changing neutral current processes in the Littlest Higgs model with T-parity in [7].
The phenomenon of meson-antimeson oscillation is very sensitive to heavy degrees of freedom propagating in the mixing amplitude and, therefore, represents one of the most powerful probes of New Physics (NP). In $K$ and $B_{d,s}$ systems the comparison of observed meson mixing with the Standard Model (SM) prediction has achieved a good accuracy and plays a fundamental role in constraining not only the unitarity triangle but also possible extensions of the SM. The evidence for flavour oscillation of the charmed meson $D^0$, instead, has been reported only very recently by BaBar [8] and Belle [9], independently. These experimental results have been combined in [10] to which we refer for details. Here we just mention that the analysis in [10] allows for CP-violation in mixing but not in the decay amplitudes where the SM tree-level contributions are expected to dominate. CP-violation in $D^0 - \bar{D}^0$ mixing is also strongly suppressed, in the SM, by the small combination of CKM matrix elements $V_{cb}V_{ub}^*$. In the presence of NP, however, new CP-violating contributions can occur and spoil this feature.

Combining the new BaBar and Belle measurements of $D^0 - \bar{D}^0$ mixing parameters yields, in particular, an improvement of almost an order of magnitude on the $\Delta M_D$ constraint, which now reads [10]

$$\Delta M_D = (11.7 \pm 6.8) \cdot 10^{-3} \text{ps}^{-1}. \quad (1)$$

This first evidence of $D^0 - \bar{D}^0$ mixing is certainly welcome as, involving mesons with up-type quarks, it is complementary to mixing in $K$ and $B_{d,s}$ systems in providing information on NP. In order to discover a signal for NP in $\Delta M_D$, however, one would need high confidence that the SM predictions lie well below the present experimental limit.

Unfortunately, the SM calculation of $\Delta M_D$ is plagued by long-distance contributions, responsible for very large theoretical uncertainties. In fact, unlike $B^0_{d,s} - \bar{B}^0_{d,s}$ mixing that is completely dominated by short-distance effects generated by the top quark, in $\Delta M_D$ the non-perturbative physics associated with long-distance effects (e.g. propagation of light intermediate states) is potentially large and may even dominate over the short-distance ones [11].

The short-distance contribution in $\Delta M_D$ [12][13], indeed, is highly suppressed both by a factor $(m_2^2 - m_3^2)/M_W^2$ generated by the GIM mechanism and by a further factor $(m_2^2 - m_4^2)/m_c^2$ due to the fact that the external momentum, of the order of $m_c$, is communicated to the internal light quarks in box-diagrams. These factors explain why the box-diagrams are so small for $D$ mesons relative to $K$ and $B_{d,s}$ mesons where the GIM mechanism enters as $m_2^2/M_W^2$ and $m_t^2/M_W^2$ and external momenta can be neglected. Moreover, a recent study of $\Delta M_D$ has found that NLO (QCD) corrections to short-distance contributions interfere destructively with the LO ones, with the net effect $(\Delta M_D)^{SD}_{\text{SM}} \simeq 2 \cdot 10^{-6} \text{ps}^{-1}$ [14].
Within the SM, then, the short-distance contribution is negligible and a reliable theoretical prediction requires an accurate knowledge of the long-distance ones, whose estimates follow at present two approaches. The “inclusive” approach, based on the operator product expansion (OPE), relies on local quark-hadron duality and on $\Lambda_{\text{QCD}}/m_c$ being small enough to allow a truncation of the series after the first few terms. The charm mass, however, may not be large enough for such an approximation. The “exclusive” approach, on the other hand, sums over intermediate hadronic states, which can be modeled or fit to experimental data. These exclusive contributions, however, need to be known with high precision due to cancellations between states within a given $SU(3)$ multiplet and, furthermore, the $D^0$ is not light enough that its decays are dominated by few final states. As a consequence, in the absence of sufficiently precise data, some assumptions are required and yield quite model-dependent results.

While most studies of long-distance contributions find $(\Delta M_D)_{\text{LD}}^{\text{SM}} \lesssim 10^{-3} \text{ ps}^{-1}$, values as high as $10^{-2} \text{ ps}^{-1}$ cannot be excluded [15–17]. The latter estimates, being of the order of magnitude of the experimental constraint in (1), presently prevent revealing an unambiguous sign of NP in $D^0 - \bar{D}^0$ mixing. In spite of that, in view of future theoretical improvements as well as better experimental accuracies, it is certainly interesting to study possible NP contributions to $\Delta M_D$ in specific extensions of the SM. It is important to note that NP contributions appear in box-diagrams with internal new heavy particles and, therefore, are of short-distance only. In predictive NP models, a reliable calculation is then possible and its remaining uncertainty is dominated by the parameters of the model itself.

The aim of the present Letter is to study the phenomenon of $D^0 - \bar{D}^0$ mixing in the Littlest Higgs model with T-parity (LHT) and to investigate its impact on our previous LHT flavour analyses [3,18].

The LHT model [19,20] belongs to the class of the so-called Little Higgs models (LH) [21], whose basic idea for solving the little hierarchy problem is the interpretation of the Higgs as a pseudo-Goldstone boson of a spontaneously broken global symmetry. Diagrammatically, the quadratic divergences that affect the Higgs mass, within the SM, are canceled by the contributions of new heavy particles having the same spin-statistics as the SM ones and masses around 1 TeV. In the LHT model, a discrete symmetry called T-parity is added, in order to satisfy the electroweak precision constraints [22], by avoiding tree-level contributions of the new heavy gauge bosons and restoring the custodial $SU(2)$ symmetry. Under T-parity particle fields are T-even or T-odd. The T-even sector consists of the SM particles and a heavy top $T_+$, while the T-odd sector contains heavy gauge bosons ($W_H^\pm, Z_H, A_H$), a scalar triplet ($\Phi$) and the so-called mirror fermions, i.e. fermions corresponding to the SM ones but with opposite T-parity and $O(1 \text{ TeV})$ mass.
Mirror fermions are characterized by new flavour violating interactions with SM fermions and heavy gauge bosons, which involve two new unitary mixing matrices in the quark sector, analogous to the Cabibbo-Kobayashi-Maskawa (CKM) matrix $V_{\text{CKM}}$. They are $V_{\text{Hd}}$ and $V_{\text{Hu}}$, when the SM quark is of down- or up-type respectively, and they satisfy $V_{\text{Hd}}^\dagger V_{\text{Hu}} = V_{\text{CKM}}^{[23]}$. A similar structure is valid for the lepton sector as discussed in details in [4]. It is important to recall two important features of the LHT model in order to understand its role in flavour physics. The first is that, because of these new mixing matrices, the LHT model does not belong to the Minimal Flavour Violation (MFV) class of models whether constrained [24] or general [25] and significant effects in flavour observables are possible. The second is that no new operators, and no new non-perturbative uncertainties, in addition to the SM ones appear in the LHT model.

Extensive flavour physics analyses in the LHT model have been recently performed in both the quark [3,5,18,23,26,27] and lepton sector [4,28]. In particular, $D^0 - \bar{D}^0$ mixing has been studied in [18,23], before it was experimentally observed. Motivated by the improved experimental constraint on $\Delta M_D$ [8-10] we update and extend here the LHT analysis of $D^0 - \bar{D}^0$ mixing.

As discussed above, at present the large SM long-distance uncertainties prevent to reveal an unambiguous NP contribution to $\Delta M_D$. We choose, therefore, to disentangle our analysis from the large SM uncertainties. To this end, we consider only the LHT contribution to $\Delta M_D$ and determine the range of values that it can assume once the known flavour constraints are imposed as in [3,18]. Once the SM uncertainties are significantly reduced, our strategy can be pushed further to use the experimental $\Delta M_D$ measurement to constrain the parameters of the LHT model. Moreover, if the smaller SM upper bounds ($\Delta M_D)^{\text{LD}}_{\text{SM}} \lesssim 10^{-3}\text{ps}^{-1}$ are confirmed, it will be legitimate to neglect the SM contributions and to use the experimental $\Delta M_D$ measurement as a constraint for the LHT contribution only.

Meson-antimeson mixing in the LHT model is discussed in details in [18,23] where the separate contributions of T-even and T-odd sector to the off-diagonal dispersive matrix elements $M_{i2}^i$ ($i = K, d, s$ for $K$ and $B_{d,s}$ systems) are explicitly given. The $D$ system presents a difference since it involves external SM up-type quarks and therefore the T-even $T_+$ cannot run in the loop, so that the T-even contribution reduces to the SM one. In the T-odd sector, both down-type mirror quarks, together with the charged gauge bosons $W^\pm_H$, and up-type mirror quarks, together with the neutral gauge bosons $Z_H, A_H$, contribute.

Due to the near equality of up- and down-type mirror quark masses the formula for the $\Delta C = 2$ effective Hamiltonian can straightforwardly be obtained from the one
describing $\Delta S = 2$ transitions calculated in [18, 23], yielding
\[
[H_{\text{eff}}(\Delta C = 2)]_{\text{odd}} = \frac{G_F^2}{64 \pi^2} M_W^2 v^2 \eta_D \sum_{i,j} \xi_i^{(D)} \xi_j^{(D)} F_H(z_i, z_j) (\bar{u}c)_{V-A} (\bar{u}c)_{V-A} . \tag{2}
\]
Here, $z_i = m_{H_i}^2 / M_W^2$ with $m_{H_i}$ denoting the mass of the $i$-th mirror quark doublet, and the function $F_H$ has been determined in [18, 23]. The only difference with respect to $[H_{\text{eff}}(\Delta S = 2)]_{\text{odd}}$ is the fact that now the relevant quark mixing is given by the $V_{H_u}$ matrix, leading to the combination $\xi_i^{(D)}$
\[
\xi_i^{(D)} = V_{H_u}^{*i} V_{H_u}^{ij} . \tag{3}
\]
The QCD correction $\eta_D$ can be approximated by [29]
\[
\eta_D \approx \eta_2 = 0.57 \pm 0.01 . \tag{4}
\]
The mirror quark contribution to the off-diagonal element $M_{12}^D$ of the neutral $D$-meson mass matrix is then found to be
\[
(M_{12}^D)_{\text{odd}} \equiv \left| (M_{12}^D)_{\text{odd}} \right| e^{-2i\phi_D} = \frac{G_F^2}{48 \pi^2} F_D^2 \hat{B}_D m_{D^0} M_W^2 v^2 \eta_2 \sum_{i,j} \xi_i^{(D)*} \xi_j^{(D)*} F_H(z_i, z_j) . \tag{5}
\]
Our definition of the phase $\phi_D$ follows from
\[
(M_{12}^D)^* = \langle D^0 | H_{\text{eff}}(\Delta C = 2) | D^0 \rangle \equiv \left| (M_{12}^D) \right| e^{2i\phi_D} , \tag{6}
\]
where we note that it is $(M_{12}^D)^*$ and not $M_{12}^D$, as sometimes found in the literature, that appears on the l.h.s. of (6). We stress that the theoretical uncertainty on the LHT contribution, being of short-distance origin only, comes from the non-perturbative uncertainties in the decay constant $F_D$ and the $B$-parameter $\hat{B}_D$, in addition to the new LHT parameters scanned over in the analysis. For $F_D$ we use the recent experimental determination by the CLEO-c collaboration [30] that turned out to be in agreement with recent lattice calculations [31, 32] and of comparable precision. Concerning the parameter $\hat{B}_D$, we consider the result of the most recent (quenched) lattice calculation [31], compatible within quite large uncertainties with an older lattice determination [33]. Their numerical values are collected together with the other inputs in Table I where some numbers have been updated with respect to [3,18].

Having at hand all the LHT formulae for meson oscillations in $K$, $D$ and $B_{d,s}$ systems and rare $K$ and $B$ decays presented in [3,18] and here, we will now investigate the impact
| Parameter | Value |
|-----------|-------|
| $G_F$     | $1.16637 \cdot 10^{-5} \text{ GeV}^{-2}$ |
| $M_W$     | $80.425(38) \text{ GeV}$ |
| $\alpha$  | $1/127.9$ |
| $\sin^2 \theta_W$ | $0.23120(15)$ |
| $|V_{ub}|$ | $0.00409(25)$ |
| $|V_{cb}|$ | $0.0416(7)$ |
| $\lambda = |V_{us}|$ | $0.2258(14)$ |
| $\gamma$  | $82(20)^\circ$ |
| $m_{K^0}$ | $497.65(2) \text{ MeV}$ |
| $m_{D^0}$ | $1.8645(4) \text{ GeV}$ |
| $m_{B_d}$ | $5.2794(5) \text{ GeV}$ |
| $m_{B_s}$ | $5.370(2) \text{ GeV}$ |
| $|\varepsilon_K|$ | $2.284(14) \cdot 10^{-3}$ |
| $S_{\psi K_S}$ | $0.675(26)$ |
| $\Delta M_K$ | $3.483(6) \cdot 10^{-15} \text{ GeV}$ |
| $\Delta M_d$ | $0.508(4) / \text{ps}$ |
| $\Delta M_s$ | $17.77(12) / \text{ps}$ |
| $F_K \sqrt{B_K}$ | $143(7) \text{ MeV}$ |
| $F_D \sqrt{B_D}$ | $241(24) \text{ MeV}$ |
| $F_{B_s} \sqrt{B_{B_s}}$ | $262(35) \text{ MeV}$ |
| $m_c$     | $1.30(5) \text{ GeV}$ |
| $m_t$     | $161.7(20) \text{ GeV}$ |

Table 1: Values of the experimental and theoretical quantities used as input parameters.

of the measurement $^{(1)}$ and of the constraints on $|M_{D_2}^0|$ and $\phi_D$ derived in $^{[10]}$ on the parameters of the LHT model and our results presented in $^{[3,18]}$. To this end we will consider two frameworks for the SM contributions to $D_0 - \bar{D}_0$ mixing:

**Framework X**

The SM contribution to $M_{D_2}^0$ is set to zero so that the constraint on $|M_{D_2}^0|$ and the phase $\phi_D$ shown in the lower left plot in Fig. 2 of $^{[10]}$ is directly applied to the LHT contribution.

**Framework Y**

The SM contribution is allowed to vary within its large uncertainties as done in $^{[10]}$ and the general constraint on the NP contribution shown in the lower right plot in Fig. 2 of $^{[10]}$ is applied to the LHT model.

In Fig. 1 we show the predictions of the LHT model for $|M_{D_2}^0|$ and $2\phi_D$ obtained in a general scan (blue points) over the parameters of the model in comparison with the allowed $1\sigma$ ranges $^{(3)}$ derived in $^{[10]}$. If we allowed for the $2\sigma$ ranges instead, there would be almost no restrictions on the Little Higgs parameter space from $D_0 - \bar{D}_0$ mixing, i.e. there would be no visible difference between the plots with the points allowed in frameworks X and Y. We therefore restrict ourselves to the $1\sigma$ ranges where the effect is

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2 In practice the constraints derived in $^{[10]}$ have been implemented in our analysis, in the X and Y Frameworks respectively, approximating the $1\sigma$ ranges as: X) $0.0025 \text{ ps}^{-1} \leq |M_{D_2}^0| \leq 0.0125 \text{ ps}^{-1}$ and $2|\phi_D| \leq 50^\circ$; Y) $|M_{D_2}^0| \leq 0.005 \text{ ps}^{-1}$ or $(2|\phi_D| \leq 25^\circ$ and $|M_{D_2}^0| \leq 0.02 \text{ ps}^{-1}$).
Figure 1: $|M_{12}^D|$ versus $2\phi_D$ from a general scan over the LHT parameters, compared to the probability density function derived in [10], for the Framework X (left) and Y (right).

Figure 2: The same as in Fig. 1 but for two LHT specific scenarios: K-Scenario (brown points) and $B_s$-Scenario (green points).

quite pronounced. If in the future the $2\sigma$ ranges come down to where there are now the $1\sigma$ ranges, $D^0 - \bar{D}^0$ mixing and in particular its CP-violating phase will put significant restrictions on the Little Higgs parameter space. Fig. 2 shows analogous results in two specific parameter scenarios identified in [3,18]: the $K$-scenario (brown points) and $B_s$-scenario (green points) that lead to large departures from the SM in $K$ and $B$ decays, respectively. Finally in Figs. 3-5 we show the impact of the experimental $D^0 - \bar{D}^0$ constraint on the most interesting results found in [3,18].

From the inspection of Figs. 1-5 and the comparison with our previous results [3,18] we learn that:

- The $D^0 - \bar{D}^0$ constraint is much weaker in the Framework Y, due to very large long-distance uncertainties present in the SM. In the Framework X the latter are only present in $F_D \sqrt{B_D}$ and, as seen in Figs. 1-2, the impact of the $D^0 - \bar{D}^0$ constraint on the points satisfying all remaining observables is rather significant.

- We observe from Fig. 2 that whereas the $K$-scenario is practically excluded by the $D^0 - \bar{D}^0$ mixing data in the Framework X, the impact on the $B_s$-scenario is only
Figure 3: $\text{Br}(K_L \rightarrow \pi^0\nu\bar{\nu})$ as a function of $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$, after applying the 1σ-constraint on $D^0 - \bar{D}^0$ mixing within the Framework X (left) and Y (right). The shaded area represents the experimental 1σ-range for $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$. The GN-bound [43] is displayed by the dotted line, while the solid line separates the two areas where $\text{Br}(K_L \rightarrow \pi^0\nu\bar{\nu})$ is larger or smaller than $\text{Br}(K^+ \rightarrow \pi^+\nu\bar{\nu})$.

Figure 4: $\text{Br}(K_L \rightarrow \pi^0e^+e^-)$ (upper curve) and $\text{Br}(K_L \rightarrow \pi^0\mu^+\mu^-)$ (lower curve) as functions of $\text{Br}(K_L \rightarrow \pi^0\nu\bar{\nu})$, after applying the 1σ-constraint on $D^0 - \bar{D}^0$ mixing within the Framework X (left) and Y (right).

Figure 5: $\text{Br}(K_L \rightarrow \pi^0\nu\bar{\nu})$ as a function of $S_{\psi\phi}$, after applying the 1σ-constraint on $D^0 - \bar{D}^0$ mixing within the Framework X (left) and Y (right).
moderate in both SM frameworks. Therefore, the impact of the $D^0 - \bar{D}^0$ constraint turns out to be significantly larger on $K$ decays than $B$ decays. The reason is that both $K$ decays and $D^0 - \bar{D}^0$ mixing describe transitions between the first two quark generations, thus involving the same combinations of elements of $V_{Hd}$ and $V_{Hu}$, respectively. Now, as $V_{Hd}$ and $V_{Hu}$ are related via $V_{Hu} = V_{Hd} V_{CKM}^*$ and $V_{CKM} \simeq 1$, it approximately turns out that $V_{Hu} \simeq V_{Hd}$. Therefore, the observed correlation between $K$ and $D$ physics is indeed expected within the LHT model.

- As shown in Figs. 3-5 in the case of the Framework Y and a general scan over the LHT parameters, very large departures from the SM expectations for rare $K$ decays and $S_{\psi\phi}$ are possible. These plots, in fact, are qualitatively similar to those presented in [3, 18].

- On the other hand, if mirror fermion contributions describe the full $D^0 - \bar{D}^0$ mixing as supposed in the Framework X, the enhancements of rare $K$ decay branching ratios are significantly smaller than those found in [3], although they can still be substantial. For instance $Br(K_L \to \pi^0 \nu\bar{\nu})$ can be larger by a factor 5 relative to the SM prediction. On the other hand the CP-conserving decay $Br(K^+ \to \pi^+ \nu\bar{\nu})$ is less affected by the $D^0 - \bar{D}^0$ mixing constraint.

- Finally we observe that a large phase $\phi_D$ can be generated, signaling the possibility of sizeable CP-violating effects in the $D$ meson system within the LHT model. Quantitative predictions for CP-violating observables in the $D$ system would however require a much more detailed analysis which is beyond the scope of the present Letter.

The main message of our paper is that the present data on $D^0 - \bar{D}^0$ mixing put already significant constraints on the predictions of the LHT model for $K$ and $B$ decays. However, without a consistent improvement in the estimate of the SM contribution to $D^0 - \bar{D}^0$ mixing, the role of the $D$ system in constraining the parameters of the LHT model as well as other extensions of the SM will be limited, even if the accuracy of the data improves. The situation is more promising in the case of CP-violation in the $D$ meson system, where due to the absence of SM contributions much cleaner predictions in a given NP model can be made. On the other hand, useful constraints on the parameter space of a given NP model can only be obtained once the data significantly improve.

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