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Constraining New Physics with D meson decays

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ABSTRACT

Latest Lattice results on D form factors evaluation from first principles show that the Standard Model (SM) branching ratios prediction for the leptonic $D_s \to \ell\nu_\ell$ decays and the semileptonic SM branching ratios of the D^0 and D^+ meson decays are in good agreement with the world average experimental measurements. It is possible to disprove New Physics hypothesis or find bounds over several models beyond the SM. Using the observed leptonic and semileptonic branching ratios for the D meson decays, we performed a combined analysis to constrain non-standard interactions which mediate the $c\bar{s} \to l\bar{\nu}$ transition. This is done either by a model-independent way through the corresponding Wilson coefficients or in a model-dependent way by finding the respective bounds over the relevant parameters for some models beyond the Standard Model. In particular, we obtain bounds for the Two Higgs Doublet Model Type-II and Type III, the Left–Right model, the Minimal Supersymmetric Standard Model with explicit R-parity violation and Leptoquarks. Finally, we estimate the transverse polarization of the lepton in the D^0 decay and we found it can be as high as $P_T = 0.23$.

1. Introduction

In spite of the Standard Model (SM) success, now favored by the probable recent discovery of the Higgs boson [1], the search of a fundamental theory at an energy scale much bigger than the electroweak scale is still open. Interestingly, low energy scale experiments may shed some light in the search for such fundamental theory due to their possibility of getting high statistics and hence indirect observables of New Physics (NP). We will use D meson decays as an illustration. Charmed hadronic states are in the unique mass range of $O(2\text{ GeV})$, which allows for strong non-perturbative hadronic physics. Moreover, the calculations for the relevant form factors, which parameterize all QCD effects within the hadronic state, have been improved significantly reaching a remarkable precision [2,3]. The SM predictions for the D meson decays computed with latest lattice results are in agreement with the world average experimental measurements [3], allowing us to disprove New Physics hypothesis or find restrictive bounds over several models beyond the SM.

At low energies, most of the extensions to the Standard Model reduce to an effective four Fermi interaction, usually called Non-Standard Interaction NSI, that can be parameterized by a generic coefficient (Fig. 1). For the $\Delta C = \Delta S$ leptonic and semileptonic D meson decays, the new particle state should couple to the leptons and the second generation of quarks, leaving such effective interaction. Any kind of intermediate state, such as scalars, vectors or even tensors, is allowed. Examples are the Two Higgs Doublet Model Type-II (THDM-II) and Type III (THDM-III) [4], the Left–Right model (LR)) [5], the Minimal Supersymmetric Standard Model with explicit R-parity violation (MSSM-$\not{R}$) [6,7], and the Leptoquark model [8,9], also illustrated in Fig. 1.

NSIs from a model-independent approach had been considered and constrained with D_s leptonic decays [10,11], and independently, using semileptonic decays [11,12]. In this work we make a model-independent analysis and a model-dependent analysis in order to constrain NSIs combining the total leptonic and semileptonic branching ratios of D meson decays. The q^2 distributions for the $D^+ \to \bar{K}^0 e^+ \nu_e$ and $D^0 \to K^- e^+ \nu$ decays are also considered. We restrict our analysis to three fermion family models of physics BSM, as the CKM matrix element is deduced from unitarity constraints, $W \to cs$ decay and neutrino–nucleon scattering [13]. We use the latest Lattice results on the form factors[3] which have reached a significant precision. We show the usefulness of the model-independent constraints as well as specific cases when a model-dependent analysis is needed. Using the respective bounds for the Wilson coefficients, we compute as well the transverse polarization of the charged lepton in the semileptonic decay of the D meson. This T-violating observable has not been measured but may provide significant constraints over the complex character of the new physics parameters, as in the case of the B meson semileptonic decay [14] and other meson decays [15].

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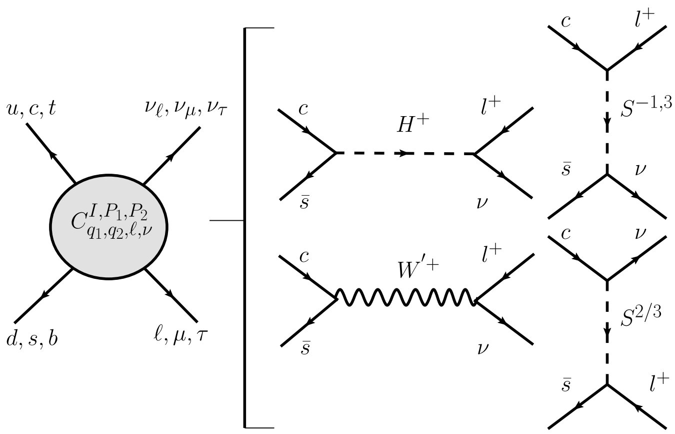

Fig. 1. Generic charged current non-standard interaction between two quarks and the leptonic sector. Some Feynman diagrams for models beyond SM involving the $c\bar{s} \to l\bar{\nu}$ transition involved in D meson decays are shown.

The Letter is organized as follows. In Section 2 we describe the general effective Lagrangian for the semileptonic transition $c \to s$ when non-standard interactions are included and show the theoretical branching ratios and the transverse polarization of the D meson semileptonic decay. In Section 3 we show the experimental constraints over the Wilson coefficients, and the theoretical predictions for the transverse polarization of the D meson semileptonic decay. Finally, in Section 4 we constrain the relevant parameters of the THDM-II and THDM-III, LR, and the MSSM-$\not{R}$, and the Leptoquark model.

2. Non-standard interactions and relevant observables

Flavor-changing meson transitions in the SM have at least two scales involved, the electroweak scale that is responsible of the flavor changing and the scale of strong interactions [16]. When NSI are considered, we assume that the new physics energy scale is higher than the electroweak scale, thus the operator product expansion formalism (OPE) [17] is suitable since it allows the separation between long-distance (low energy) and short-distance (high energy) interactions. In the OPE the degrees of freedom corresponding to higher energies scales are integrated out [18], resulting an effective Lagrangian where all high energy physics effects are parameterized by Wilson's coefficients, namely the effective couplings multiplying the operators of the Lagrangian. In this spirit, the non-standard effective Lagrangian for a semileptonic transition as the one illustrated in Fig. 1 is:

$$-\frac{\mathcal{L}_{\rm NP}}{G_F} = \sum_{\substack{c,s,\ell,\nu \\ I=S,V,T \\ P_{1,2}=L,R}} C^{I,P_1P_2}_{q_1q_2\ell\nu} \left(\bar{q_1}\Gamma^I P_1 q_2\right) \cdot \left(\bar{\nu}_L \Gamma_I P_2 \ell\right), \tag{1}$$

where the indexes q_1 and q_2 represent down-type and up-type quarks respectively, ℓ is the charged lepton flavor and ν its corresponding neutrino. $P_{1,2}$ represent the chiral projectors $L = (1-\gamma^5)/2$ and $R = (1+\gamma^5)/2$. The current operators Γ's are determined by the Dirac field bilinears, namely: $\Gamma_S = 1$, $\Gamma_V = \gamma_\mu$ and $\Gamma_T = (i/2)[\gamma^\mu, \gamma^\nu]$. The dimensionless coefficients $C^{I,P_1P_2}_{q_1q_2\ell\nu}$ have a clean interpretation: they are a measurement of how big can the NSI be as compared to the SM current, since they are weighted by the Fermi constant G_F.

The decay rate of $D_s \to \ell\nu_\ell$ including the SM Lagrangian plus the NSI Lagrangian of Eq. (1), is thus given by

$$\Gamma_{D_s\to\ell\nu} = \frac{|G_F f_{D_s}(M_{D_s}^2 - m_l^2)|^2}{8\pi M_{D_s}^3} \left| V_{cs} m_l + \frac{m_l(C^{V,LL}_{sc\ell\nu} - C^{V,RL}_{sc\ell\nu})}{2\sqrt{2}} + \frac{M_{D_s}^2 (C^{S,RR}_{sc\ell\nu} - C^{S,LR}_{sc\ell\nu})}{2\sqrt{2}(m_c+m_s)} \right|^2. \tag{2}$$

On the other hand, in the rest frame of the decaying meson, the partial decay rate for the $D^0 \to K^\pm l^\mp \nu$ decay channel with NSIs is given by

$$\begin{aligned} \frac{d\Gamma}{dE_K} = {} & \frac{G_F^2 m_D (E_K^2 - m_K^2)^{3/2}}{(2\pi)^3} \left\{ \frac{2q^2 + m_\ell^2}{3q^2} \left|G_V f_+(q^2)\right|^2 \right. \\ & - |G_T f_2(q^2)|^2 \frac{q^2 + 2m_l^2}{3m_D^2} + \frac{m_l}{m_D} \operatorname{Re}\left(G_V G_T^* f_2(q^2) f_+(q^2)\right) \\ & \left. + \frac{|(m_D^2 - m_K^2) q f_0(q^2)|^2}{4m_D^2(E_K^2 - m_K^2)} \left| \frac{m_\ell}{q^2} G_V + \frac{G_S}{m_c - m_s} \right|^2 \right\} \\ & \times \left(1 - \frac{m_\ell^2}{q^2}\right)^2, \end{aligned} \tag{3}$$

where in the later expression we have defined $G_V = V_{cs}^* + (C^{V,LL}_{sc\ell\nu} + C^{V,RL}_{sc\ell\nu})/2\sqrt{2}$, $G_S = (C^{S,RR}_{sc\ell\nu} + C^{S,LR}_{sc\ell\nu})/2\sqrt{2}$ and $G_T = (C^{T,RR}_{sc\ell\nu} + C^{T,LR}_{sc\ell\nu})/2\sqrt{2}$. Other constants involved in Eqs. (2), (3) are: G_F the Fermi constant, V_{cs}^* the CKM matrix element, $m_\ell, m_c, m_s, m_K, m_{D_s}, m_D$ the masses of the leptons, charm and strange quarks, the kaon and D meson respectively as reported by PDG [13]. The transferred energy is $q^2 = m_D^2 + m_K^2 - 2m_D E_K$ and E_K is the final energy of the kaon meson, $m_K < E_K < (m_D^2 + m_K^2 - m_\ell^2)/2m_D$. The decay constant f_{D_s} in the leptonic decay rate is defined by $\langle 0|\bar{s}\gamma_\mu\gamma_5 c|D_s(p)\rangle = i f_{D_s} p_\mu$. In the semileptonic decays, the scalar, vector and tensor form factors $f_0(q^2)$ and $f_+(q^2)$, $f_2(q^2)$ are defined via $\langle K|\bar{s}\gamma^\mu c|D\rangle = f_+(q^2)(p_D + p_K - \Delta)^\mu + f_0(q^2)\Delta^\mu$, with $\Delta^\mu = (m_D^2 - m_K^2)q^\mu/q^2$, $\langle K|\bar{s}c|D\rangle = (m_D^2 - m_K^2)/(m_c - m_s) f_0(q^2)$ and $\langle K(k)|\bar{s}\sigma^{\mu\nu}c|D(p)\rangle = i m_D^{-1} f_2(q^2)(p^\mu k^\nu - p^\nu k^\mu)$.

The transverse polarization of the charged lepton in the decay $D \to K l \nu$ is a sensitive T-violating or CP-violating observable when CPT is conserved. This observable was first computed in the semileptonic decay $K^+ \to \pi^0 \mu^+ \nu$ as a useful tool for studying non-standard CP violation [19,20]. The SM contribution to P_T is expected to be highly suppressed, as in the case of the charged kaon $K_{\mu 3}$ [21] or neutral kaon K^0 [22]. Given the similarities with the K^+ decay, we can compute the transverse polarization for the semileptonic decay of the D meson $D(p)^0 \to K^\mp(k)\nu(p_1)l(p_2)^\pm$. The transverse polarization is given by $P_T^S = \frac{|A_T^S|^2 - |A_T^{-S}|^2}{|A_T^S|^2 + |A_T^{-S}|^2}$, where S represents the spin of the lepton. In general, one measures the spin perpendicular to the decay plane defined by the final particles [15]. Given that $S_\mu = (0, \mathbf{s})^T$, with $\mathbf{s}$ perpendicular to the decay plane we can construct the transverse polarization averaged over the charged lepton energy. Written in the decay frame of the D meson,

$$\begin{aligned} \langle P_T^S \rangle = {} & \frac{G_F^2 M_D^4}{4\pi^3} \left\{ \left(f_+(q^2) \frac{M_D^2 - M_K^2}{M_D(m_c - m_s)} \operatorname{Im}\left(G_V G_S^*\right) \right. \right. \\ & \left. + f_2(q^2) \frac{m_\ell}{M_D^2} \frac{M_D^2 - M_K^2}{m_c - m_s} \operatorname{Im}\left(G_T G_S^*\right) \right) f_0(q^2) g_0(q^2) \\ & + f_2(q^2) \left[f_0(q^2) \frac{m_\ell^2}{M_D^2} \frac{(M_D^2 - M_K^2)}{q^2} g_0(q^2) \right. \\ & \left. + f_+(q^2) \left(g_1(q^2) - \frac{m_\ell^2 + q^2}{M_D^2} \frac{(M_D^2 - M_K^2 - q^2)}{q^2} g_0(q^2) \right) \right] \\ & \left. \times \operatorname{Im}\left(G_T G_V^*\right) \right\} \left(\frac{d\Gamma}{dE_K} \right)^{-1}, \end{aligned} \tag{4}$$

where we have defined the dimensionless kinematical functions

Table 1
Theoretical and experimental branching ratios.

i	Decay	Theor. BR $\mathcal{B}_i^{th}$	Exp. BR $\mathcal{B}_i^{exp}$
1	$D^0 \to K^- e^+ \nu_e$	$(3.28 \pm 0.11)\%$.	$(3.55 \pm 0.04)\%$
2	$D^0 \to K^- \mu^+ \nu_\mu$	$(3.22 \pm 0.11)\%$	$(3.30 \pm 0.13)\%$
3	$D^+ \to \bar{K}^0 e^+ \nu_e$	$(8.40 \pm 0.32)\%$.	$(8.83 \pm 0.22)\%$
4	$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	$(8.24 \pm 0.31)\%$	$(9.2 \pm 0.6)\%$
5	$D_s^+ \to \tau^+ \nu_\tau$	$(5.10 \pm 0.22)\%$	$(5.43 \pm 0.31)\%$
6	$D_s^+ \to \mu^+ \nu_\mu$	$(5.20 \pm 0.20) \times 10^{-3}$	$(5.90 \pm 0.33) \times 10^{-3}$

$$g_n(q^2) \equiv \frac{1}{M_D^{n+3}} \int_{E_\ell^{\min}}^{E_\ell^{\max}} dE_\ell\, E_\ell^n |\mathbf{p_1} \times \mathbf{p_2}|, \tag{5}$$

with

$$E_\ell^{\max(\min)} = \frac{1}{2}(m_D - E_K)\left(\frac{m_\ell^2}{q^2} + 1\right) \pm \frac{1}{2}\sqrt{E_K^2 - m_K^2}\left(1 - \frac{m_\ell^2}{q^2}\right).$$

3. Model-independent analysis and experimental constraints

D_s leptonic decays have been measured by a number of experiments, namely CLEO [23] and Belle [24] among others. Semileptonic decays have been observed with an integrated luminosity of 818 pb^{-1} [25]. In particular, the q^2 distribution for the semileptonic decays $D^+ \to \bar{K}^0 e^+ \nu_e$, $D^0 \to K^- e^+ \nu_e$ has been measured by CLEO [26,27]. From those measurements it is possible to extract the lifetimes for the mesons. In summary, total branching ratios for semileptonic decays of the D^0 and D^+ and for the leptonic decays of the D_s are shown in Table 1. The theoretical decay rates $\Gamma^{th}_{D_s \to \ell\nu}$, $\Gamma^{th}_{D^0 \to K^+ \ell^- \nu_\ell}$ and $\Gamma^{th}_{D^+ \to \bar{K}^0 \ell^+ \nu_\ell}$, given by Eqs. (2), (3), are computed by fixing all the Wilson's coefficients to zero. We ignore all radiative corrections since they are expected to be below the 1% [28]. Other relevant physical inputs needed for the SM computation of the theoretical BRs are:

The CKM element V_{cs}

As we are looking for New Physics, we have to be very careful on the value of the CKM element we will use in our numerical analysis. In order to avoid that leptonic and semi leptonic of D mesons have been used to fix the V_{cs} value, we use the central value of the CKM element which comes from $W \to cs$ decay, neutrino–nucleon scattering and unitary constraints coming from $b - s$ transitions relating $|V_{cd}|$ and $|V_{cs}|$ through unitarity. This last constraint gives the strongest constraint. So our central value for V_{cs} is 0.97344 ± 0.00016 [29]. Using this unitary constraint means that automatically our results will not apply to any model with more than three fermion families.

Hadronic form factors

Lattice QCD has reached an excellent precision [3]. Therefore, for our analysis, we fix the hadronic form factors and leptonic decay constant to the value estimated with Lattice QCD simulations. The leptonic decay constant f_{D_s} has been computed with a precision of the order of 2% by the HPQCD Collaboration, i.e. $f_{D_s} = 248 \pm 2.5$ MeV [2]. On the other hand, less is known about $f_0(q^2)$, $f_+(q^2)$. Dramatic progress has been made over the last decade on lattice calculations of for those form factors [2,3]. We use the latest results by the HPQCD Collaboration [3] as input for the calculation of the theoretical decay rate.

The results for the theoretical BRs are listed in Table 1. with their corresponding uncertainties. The total theoretical uncertainties are calculated straightforward: propagating each uncertainty for every physical constant as reported in PDG [13], and the theoretical uncertainties coming from the Lattice QCD calculations of the form factors. The main contribution in the theoretical error comes from the leptonic decay constant f_{D_s} and the semileptonic form factors $f_+(q^2)$ and $f_0(q^2)$. Error values are listed in Table 1 as well. World average measurements of the total BRs as reported by PDG [13] are shown in Table 1 for comparison. In the same way, the theoretical partial decays for the $D^0 \to K^+ e^- \nu_e$ and $D^+ \to \bar{K}^0 e^+ \nu_e$ and the CLEO data points are shown in Fig. 2. Note the good agreement between experiment and theory.

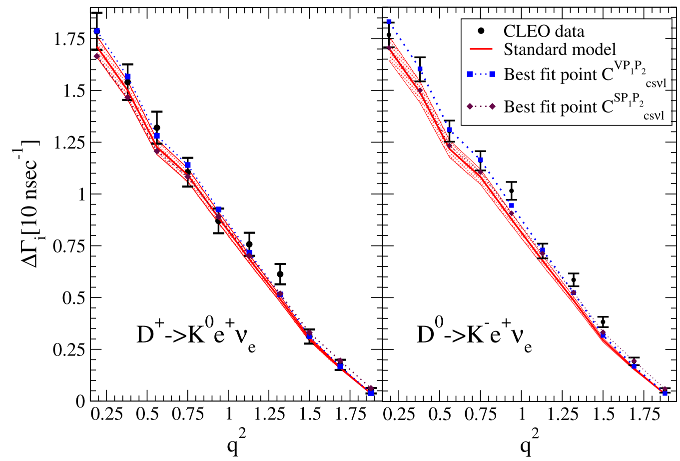

Fig. 2. Partial decays measured by CLEO [27] and the theoretical partial decay computed with the Standard Model using the latest form factors from [3]. Shadowed region represents one sigma theoretical error.

3.1. Constraining real NSI

Let us assume that the new physics effects are parameterized, as described in Section 2, by the Wilson coefficients. In this first part of our analysis we suppose the non-standard physical phases are aligned with those of the SM in such a way that in general we can consider the Wilson coefficients real. We compute the range of the Wilson coefficients to exactly match the theory and the experiment. In order to do so, we perform a simple χ^2 analysis, with $\chi^2 = \sum_i (\mathcal{B}_i^{th} - \mathcal{B}_i^{exp})^2 / \delta\mathcal{B}_i^2$. Here, $\delta\mathcal{B}_i$ is calculated adding in quadratures the experimental and theoretical uncertainties shown in Table 1.

We shall consider first a combined analysis of the leptonic and semileptonic BRs and the experimental data from CLEO assuming only scalar (S) and vector (V) NSI. An analysis including all the New Physics operators at a time, scalar, vector and tensor, shows that the tensor contribution is negligible as compared to the former operators. Hence, the relevant parameters with the above considerations are: $C^{V,LL}_{sc\ell\nu}$, $C^{V,RL}_{sc\ell\nu}$, $C^{S,RR}_{sc\ell\nu}$ and $C^{S,LR}_{sc\ell\nu}$. Although this is a restrictive hypothesis, this analysis is useful for models where no CP-violating phases or models in which the physical phases are aligned with the CKM phase, e.g. THDM-II or some specific MSSM-$\not{R}$ as we will show later. The results for the relevant Wilson coefficients, assuming these are flavor universal or flavor-dependent, are shown in Table 2.

Flavor-independent NSI

The upper part of Table 2 corresponds to flavor-independent interactions e.g. universal NSI. Notice that Eqs. (2), (3) have a different dependence on the Wilson coefficients, hence, when combining the leptonic decay rates and the semileptonic decay rates it is possible to extract a bound for each parameter even if we analyze the four parameters at a time. We have computed the allowed values for those universal coefficients at 95% C.L. by varying the four parameters at-a-time, i.e. those are the most general cases, this is because both scalar and vector universal NSI may affect the BRs.

Table 2
Model-independent constraints at 95% C.L. for either universal scalar and vector NSIs or flavor-dependent NSIs from the leptonic and semileptonic D meson decays.

	95% C.L.	$\frac{\chi^2_{\min}}{\text{d.o.f.}}$
Universal	NSIs 4 pars. at-a-time	
$C^{V,LL}_{sc\ell\nu}$	$[-.094, 0.42]$	0.62
$C^{V,RL}_{sc\ell\nu}$	$[-0.34, 0.17]$	0.62
$C^{S,RR}_{sc\ell\nu}$	$[-0.33, 0.21]$	0.62
$C^{S,LR}_{sc\ell\nu}$	$[-0.23, 0.33]$	0.62
Universal	NSIs 1 pars. at-a-time	
$C^{V,LL}_{sc\ell\nu}$	$[0.072, 0.14]$	0.89
$C^{V,RL}_{sc\ell\nu}$	$[0.057, 0.13]$	1.29
$C^{S,RR}_{sc\ell\nu}$	$[-0.22, -0.21] \cup [0.00, 0.13]$	2.19
$C^{S,LR}_{sc\ell\nu}$	$[-0.012, 0.00] \cup [0.20, 0.22]$	2.17
Flavor	dependent scalar	NSIs
$C^{S,RR}_{sce\nu_e} + C^{S,LR}_{sce\nu_e}$	$[-0.47, -0.33] \cup [0.32, 0.47]$	1.05
$C^{S,RR}_{sc\mu\nu_\mu}$	$[-0.77, 0.25]$	1.30
$C^{S,LR}_{sc\mu\nu_\mu}$	$[-0.63, 0.38]$	1.30
$C^{S,RR}_{sc\tau\nu_\tau} - C^{S,LR}_{sc\tau\nu_\tau}$	$[-0.075, 0.175]$	1.0
Flavor	dependent vector	NSIs
$C^{V,LL}_{sce\nu_e} + C^{V,RL}_{sce\nu_e}$	$[0.07, 0.14]$	0.99
$C^{V,LL}_{sc\mu\nu_\mu}$	$[-0.025, 0.255]$	0.93
$C^{V,RL}_{sc\mu\nu_\mu}$	$[-0.19, 0.095]$	0.93
$C^{V,LL}_{sc\tau\nu_\tau} - C^{V,RL}_{sc\tau\nu_\tau}$	$[-0.12, 0.28]$	1.0

On the other hand, we have also estimated the allowed regions by varying only one parameter at a time (right column in Table 2), this is when only one lepton flavor-independent NSI contributes to the physical process.

Flavor-dependent NSI

Some models may induce only vector, as well as only scalar NSI at a time. As we will show in the next section, the left-right model or the two Higgs doublet model are examples of each type of NSI, respectively. In those cases, we can obtain the bounds for the corresponding Wilson coefficients. Those coefficients may depend on the flavor of the lepton involved. Since we have only six $\mathcal{B}_i^{th}$s, we can perform the χ^2 analysis only if we assume scalar NSI or vector NSI at a time. In each case, for the electron NSI, we use the channels $i = 1, 3$ and the CLEO data points from the kinematic distribution, for the muon $i = 2, 4, 6$ and for the tau, only a fit can be performed with $i = 5$; channel i as shown in Table 1. Results for both cases, scalar and vector flavor-dependent NSI are listed Table 2.

3.2. Complex Wilson coefficients

We shall consider now complex flavor universal Wilson coefficients. Many models of New Physics introduce CP-violating phases which are in general not aligned with the SM CP-violating phase, therefore we also analyze such scenario. Here, we assume that only one non-standard operator is dominant besides the Standard Model operator, either scalar, vector or tensor NSIs. This means we will take into account only one complex Wilson coefficient at a time, i.e. two independent parameters for each operator. We consider again a combined analysis of the leptonic and semileptonic BRs and the experimental data from CLEO.

Contrary to the scalar or vector NSI, tensor NSI can not be separated from the unknown form factor $f_T(0) \equiv f_2(0)$. Moreover we found there is no sensitivity to the q^2 dependence of the tensor form factor. Hence, we can only obtain the bounds for $\text{Re}[f_T G_T]$ and $\text{Im}[f_T G_T]$ for $f_T(q^2) = f_T(0)$. In summary, the allowed regions at 95% C.L. are the following:

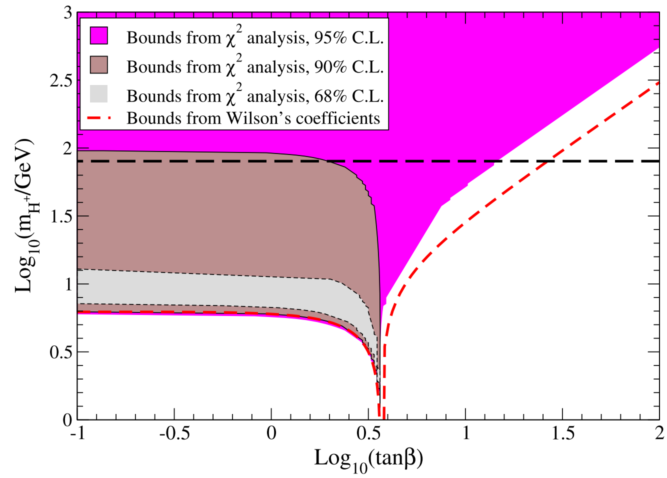

Fig. 3. Allowed regions for $\tan\beta$ and the mass of the charged Higgs to be consistent with the D meson decays at 68% C.L., 90% C.L. and 95% C.L. obtained performing a complete χ^2 analysis of the BRs. Dashed lines are the limits at 90% C.L. using the bounds on Wilson coefficients (Table 2) showing good agreement. As a reference, the LEP limit on the mass of a charged Higgs is also plotted [32].

Vector NSI: $\chi^2/\text{d.o.f.} = 0.96$

$$-0.5 < \text{Re}\big[C^{V,LL}_{sc\ell\nu}\big] < 0.21, \qquad -1.63 < \text{Im}\big[C^{V,LL}_{sc\ell\nu}\big] < 1.63,$$
$$-0.9 < \text{Re}\big[C^{V,RL}_{sc\ell\nu}\big] < 0.7, \qquad -2.10 < \text{Im}\big[C^{V,RL}_{sc\ell\nu}\big] < 2.10,$$

Scalar NSI: $\chi^2/\text{d.o.f.} = 1.20$

$$-0.24 < \text{Re}\big[C^{S,RR}_{sc\ell\nu}\big] < 0.23, \qquad -0.28 < \text{Im}\big[C^{S,RR}_{sc\ell\nu}\big] < 0.28,$$
$$-0.23 < \text{Re}\big[C^{S,LR}_{sc\ell\nu}\big] < 0.26, \qquad -0.29 < \text{Im}\big[C^{S,LR}_{sc\ell\nu}\big] < 0.29,$$

Tensor NSI: $\chi^2/\text{d.o.f.} = 2.33$

$$-0.18 < \text{Re}[f_T G_T] < 0.27, \qquad -0.24 < \text{Im}[f_T G_T] < 0.24.$$

We use the best fit points to compute the partial decays of the D meson, $D^+ \to \bar{K}^0 e^+ \nu_e$ and $D^0 \to K^- e^+ \nu_e$, and we show them in Fig. 2, compared with the experimental data and the Standard Model prediction. For those points we see there is better agreement with the experimental data.

3.3. Transverse polarization estimation

As an application of our results we give a prediction for a T-odd observable, the transverse polarization of the charged lepton for the decay $D^+ \to \bar{K}^0 \ell^+ \nu_\ell$. This observable has not been measured. We chose this semileptonic decay thinking the experimental measurement could be done as in the case of the K^+ meson, [15]. The K^+ decays as $K^+ \to \pi^0 \ell^+ \nu_\ell$ and the BR of the $\pi^0 \to \gamma\gamma$ is $\text{BR}(\pi^0 \to \gamma\gamma) = 98.823 \pm 0.034\%$ [13], this allows for a clean distinction of the angular distribution of the charged lepton, hence the transverse polarization. In our case, the $\bar{K}^0$ decays with a BR of $\text{BR}(\bar{K}^0 \to \pi^0\pi^0) = 30.69 \pm 0.05\%$ [13], allowing possibly for a distinction of the angular distribution of the charged lepton. In the SM, P_T is expected to be highly suppressed, as in the case of the charged kaon $K_{\mu 3}$ [21] and neutral kaon K^0 [22]. This implies that a large value, i.e. $P_T \gtrsim \mathcal{O}(10^{-3})$, is a signal of new physics. As we performed the analysis for the complex universal Wilson coefficients taking into account only one dominant non-standard operator the transverse polarization (4) can only be computed for each case. Furthermore, notice that the vector contribution does not contribute for P_T. For these reason, the only non-vanishing transverse polarizations including New Physics are given for scalar

Table 3
Low energy effective Lagrangians and Wilson coefficients.

Model	Low energy effective Lagrangian	Wilson coefficient
THDM	$-\mathcal{L}_{H^\pm} = \sqrt{2}/v H^+[V_{u_i d_j}\bar{u}_i(m_{u_i} X P_L + m_{d_j} Y P_R)d_j + +m_\ell Z\bar{\nu}_L \ell_R] + \text{H.c.}$	$\frac{C^{S,RR}_{sc\ell\nu}}{2\sqrt{2}} = V^*_{cs}\frac{m_\ell m_c}{M_H^2}ZX, \quad \frac{C^{S,LR}_{sc\ell\nu}}{2\sqrt{2}} = V^*_{cs}\frac{m_\ell m_s}{M_H^2}ZY$
Left–right	$-\mathcal{L}_{LR} = g_L/\sqrt{2}\bar{u}_i\gamma^\mu[(c_\xi V_{u_i d_j}P_L + \frac{g_R}{g_L}s_\xi \bar{V}^R_{u_i d_j}P_R)W^+_\mu q(-s_\xi V_{u_i d_j}P_L + \frac{g_R}{g_L}c_\xi \bar{V}^R_{u_i d_j}P_R)W'^+_\mu]d_j + \frac{g_L}{\sqrt{2}}\bar{\nu}_L\gamma^\mu(c_\xi W^+_\mu - s_\xi W'^+_\mu)\ell_L + \text{H.c.}$	$C^{V,LL}_{sc\ell\nu} = \sin^2\xi(\frac{M_W^2}{M_{W'}^2} - 1)V_{cs}$ $C^{V,RL}_{sc\ell\nu} = \frac{g_L}{2g_R}\sin(2\xi)(1 - \frac{M_W^2}{M_{W'}})\bar{V}^R_{cs}$
MSSM-$\not{R}$	$\mathcal{L}_S = V^*_{cs}\frac{\sum_k \lvert\lambda'_{i2k}\rvert^2}{m^2_{\tilde{d}^{k*}_R}}(\bar{\nu_L}^i s^c_R \bar{l^c_R} c_L) \xrightarrow{\text{Fierz}} V^*_{cs}\frac{\sum_k \lvert\lambda'_{i2k}\rvert^2}{2m^2_{\tilde{d}^{k*}_R}}(\bar{\nu_L}^i\gamma^\mu l^i_L \bar{s_L}\gamma_\mu c_L)$	$C^{V,LL}_{sc\ell\nu} = \sqrt{2}V_{cs}/G_F\sum_k\lvert\lambda'_{i2k}\rvert^2/m^2_{\tilde{d}^{k*}_R}$
Leptoquarks	$\mathcal{L}^{LQ}_{Eff} = \frac{1}{2}V^*_{cs}[(\frac{\kappa^{R*}_{i2}\kappa^L_{i2}}{m^2_{S^{2/3}_{1/2}}} + \frac{\kappa'^{R*}_{i2}\kappa'^L_{i2}}{m^2_{S^{-1/3}_0}})(\overline{\nu_L}^i l_{iR}\overline{s_L}c_R - \frac{1}{4}\overline{\nu_L}^i\sigma_{\mu\nu}l_{iR}\overline{s_L}\sigma^{\mu\nu}c_R) + \frac{\lvert\kappa'^L_{i2}\rvert}{m^2_{S^{-1/3}_0}}(\bar{\nu}^i\gamma^\mu P_L l_i \bar{s}\gamma_\mu P_L c)]$	$C^{TRR}_{sc\ell\nu} = \frac{\sqrt{2}V_{cs}}{G_F}(\frac{\kappa^{R*}_{i2}\kappa^L_{i2}}{m^2_{S^{2/3}_{1/2}}} + \frac{\kappa'^{R*}_{i2}\kappa'^L_{i2}}{m^2_{S^{-1/3}_0}})$ $C^{VLL}_{sc\ell\nu} = \frac{\sqrt{2}V_{cs}}{G_F}(\frac{\lvert\kappa'^L_{i2}\rvert^2}{m^2_{S^{-1/3}_0}})$

or tensor NSI only. The largest value of the transverse polarization allowed from the previous constraints over the complex universal Wilson coefficients is $P_T = 0.23$, which is not negligible.

4. Model-dependent analysis

Let us consider now different models of New Physics. The low energy effective Lagrangians and the corresponding Wilson coefficients are listed in Table 3. We perform a χ^2 analysis in a model-dependent way by finding the respective bounds over the relevant parameters for those models. We show that under some simplifying assumptions, the model-independent constraints can be mapped to some particular models, exemplifying the usefulness of this kind of analysis.

Two Higgs doublet model (THDM)

For D meson decays, the only two parameters involved are the new scalar mass (m_{H^+}) and the ratio of the vacuum expectation values $\tan\beta$ of the two Higgs doublets. At low energies, the Lagrangian for THDM, in the Higgs basis for the charge scalars and the mass basis for fermions is shown in Table 3. There, X, Y, Z are functions of m_{H^+} and $\tan\beta$ for each version of THDM [30]. For THDM-II, $X = \cot\beta$, $Y = Z = \tan\beta$. Interesting bounds have been obtained with meson decay experiments [31] and recently LEP has reported a lower bound on the mass of the charged Higgs of 80 GeV [32]. Here, we performed a χ^2 analysis using the 26 observables from the leptonic and semileptonic BRs and the kinematical distribution from CLEO. The result is shown in Fig. 3. We can see from this figure that D meson decays favor lower masses for the charged Higgs at 90% C.L., 6.3 GeV $< m_{H^+} <$ 63.1 GeV. However at 95%, there is good agreement with LEP bounds.

Now we will illustrate the effectiveness of our model-independent bounds, once we apply them to Wilson coefficients of THDM. There is a flavor dependence coming from the mass of the leptons involved. Since this is an scalar interaction, we can use the bounds on flavor dependent scalar NSI. From $C^{S,RR}_{sc\tau\nu_\tau} - C^{S,LR}_{sc\tau\nu_\tau}$ we get the region -1.8×10^{-3} GeV$^{-1} < (m_c - m_s\tan^2\beta)/M_H^2 < 0.023$ GeV^{-1} at 68% C.L., which gives the outer region of an ellipse and the inner region of an hyperbole in the plane $(m_H, \tan\beta)$ illustrated in Fig. 3. Those regions are in excellent agreement with the region obtained by a complete χ^2 analysis performed with all D meson decays. The allowed values for $\tan\beta$ and m_H^+ are plotted in Fig. 3 in a shadow gray area. This agreement illustrates the effectiveness of using generic Wilson coefficient to constrain the relevant parameters of models beyond the SM. Our analysis agrees with the analysis for the THDM-II model using different observables from flavor physics in [33].

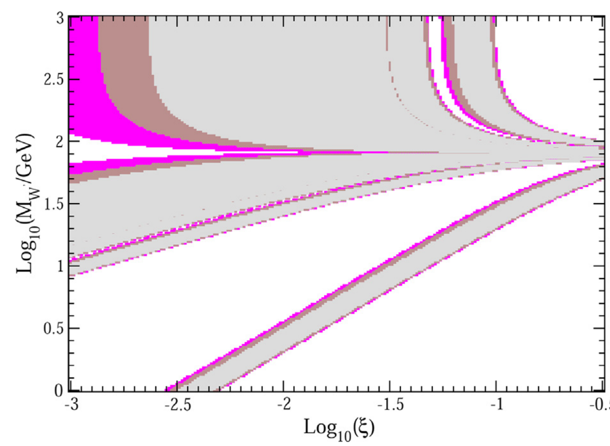

Fig. 4. Bounds at 68% ,90% and 95% C.L. on ξ and the mass of the W' boson obtained by using D meson decays data.

For completeness, let us briefly mention the THDM-III which can be analyzed by noting that the Wilson coefficients in this case correspond to the following definitions: $X = \cot\beta - \csc\beta/(2^{3/4}G_F^{1/2} m_c)(\tilde{Y}^u_{1,22} + V_{us}/V_{cs}\tilde{Y}^u_{1,21} + V_{ts}/V_{cs}\tilde{Y}^u_{1,23})$, $Y = \tan\beta - \sec\beta/(2^{3/4} G_F^{1/2}m_s)(\tilde{Y}^d_{2,22} + V_{cd}/V_{cs}\tilde{Y}^d_{2,12} + V_{cb}/V_{cs}\tilde{Y}^d_{2,32})$, $Z = \tan\beta - \sec\beta/ 2^{3/4}G_F^{1/2}m_\ell)\tilde{Y}^\ell_{2,\nu_\ell\ell}$, where $\tilde{Y}^f_{a,ij}$ are the Yukawa elements as were defined in [34,35]. The corresponding bounds are interesting since they show relations between $\tilde{Y}^f_{a,ij}$, β and the mass of the charged Higgs.

Left–right model

Here we consider the scenario where Left–Right is not manifest, that is $g_L \neq g_R$ at unification scale, with the presence of mixing between left and right bosons through a mixing angle ξ. This LR mixing is restricted by deviation to non-unitarity of the CKM quark mixing matrix. In case of manifest LR model, it is well known that ξ has to be smaller than 0.005 [36] and $M_{W'}$ bigger than 2.5 TeV [37]. But in the no manifest case, the constraint on $M_{W'}$ are much less restrictive as $M_{W'}$ could be as light as 0.3 TeV [38] and ξ can be as large as 0.02 [39–42]. The Lagrangian for this case and the relevant Wilson coefficients are shown in Table 3, where $c_\xi = \cos\xi$ and $s_\xi = \sin\xi$ and W^+, W'^+ are the mass states of gauge bosons. Likewise $\bar{V}^R_{u_i d_j} = \exp^{-i\omega}V^R_{u_i d_j}$, where ω is a CP-violating phase. Such scenarios were studied for instance in [43]. In our case, the relevant parameters are: ξ, $M_{W'}$, $g_L/g_R\,\mathrm{Re}[V^R_{cs}]$ and $g_L/g_R\,\mathrm{Im}[V^R_{cs}]$. By performing the combined analysis for all our 26 observables, by varying these four parameters at a time we found the allowed regions for ξ and $M_{W'}$ which are shown in Fig. 4. There is only one viable restriction for the following parameters: $-71.0 < g_L/g_R\,\mathrm{Re}[V^R_{cs}] < 83$, while the analysis is insensitive to the imaginary part.

MSSM-$\not R$

In particular, for D meson decays [44–48], the corresponding Wilson coefficients which constructively interfere with the Standard Model, i.e. through the exchange of a $-1/3$ electrically charged squark in a t-channel, which fixes the neutrino flavor are shown in Table 3 where a Fierz transformation was done to rearrange the former operator in terms of the product of a leptonic and a hadronic current. Using the conservative bounds for the model-independent constraints (Table 2) we get the following constraints at 95% confidence level and expressed in GeV^{-2}:

$$\begin{aligned}
&0.05 < \sum_k \left|\lambda'_{12k}\right|^2/(m_{\tilde{d}_R^{k*}}/300\ \mathrm{GeV})^2 < 0.11,\\
&\sum_k \left|\lambda'_{22k}\right|^2/(m_{\tilde{d}_R^{k*}}/300\ \mathrm{GeV})^2 < 0.17,\\
&\sum_k \left|\lambda'_{32k}\right|^2/(m_{\tilde{d}_R^{k*}}/300\ \mathrm{GeV})^2 < 0.22.
\end{aligned} \tag{6}$$

Our bounds agree with those found in [48] for muon and tau flavor. Nevertheless it is interesting to note that for the electron flavor we find more restrictive bounds. This is taking into account the latest and more accurate values of the form factors from Lattice QCD as previously mentioned.

Leptoquarks

Effective interactions induced by leptoquark exchange can be manifest in meson decays, in particular, for the second generation of quarks in D meson decays. A vast majority of observables have been used to set the corresponding bounds to these effective couplings; in particular, for D meson decays [10,49,50]. When we rearrange the effective interactions in order to have external quark and lepton currents we do some Fierz transformations that lead to tensor, scalar and vector interactions, that we shall take into account in a model-dependent analysis. We will consider the exchange of the scalar leptoquarks: S_0 with charge $-1/3$ and $(3, 1, -2/3)$ gauge numbers; and the $S_{1/2}$ with charge $2/3$ and $(3, 2, 7/3)$ gauge numbers. Hence, the effective Lagrangian for the $c \to s$ transition (Fig. 1) and the corresponding Wilson coefficients are listed in the last line of Table 3. Note that $C^{SRR}_{sc\ell\nu} = -4C^{TRR}_{sc\ell\nu}$

In the following we show the respective bounds as a result from our χ analysis considering the 26 observables: the leptonic and semileptonic decays of the D meson and the CLEO data points of the q^2 distribution. Notice here that we have one complex and one real independent Wilson coefficients (as the tensor operator is proportional to the scalar operator), and the tensor form factor f_T. However this analysis is not sensitive to the tensor form factor as the tensor contribution is negligible when the scalar and vector interactions are taken into account, which are the dominant contributions. Hence the model-dependent analysis is done varying 3 parameters at a time. At 95% C.L. and expressed in GeV^{-2} these are given by:

$$\begin{aligned}
&-0.17 < \mathrm{Re}\big(\kappa^{R*}_{i2}\kappa^{L}_{i2} + \kappa'^{R*}_{i2}\kappa'^{L}_{i2}\big)/(m_S/300\ \mathrm{GeV})^2 < 0.01,\\
&-0.09 < \mathrm{Im}\big(\kappa^{R*}_{i2}\kappa^{L}_{i2} + \kappa'^{R*}_{i2}\kappa'^{L}_{i2}\big)/(m_S/300\ \mathrm{GeV})^2 < 0.10,\\
&0.04 < \left|\kappa'^{L}_{i2}\right|^2/(m_{S_0}/300\ \mathrm{GeV})^2 < 0.11.
\end{aligned} \tag{7}$$

As an example we can consider the leptoquark states that couple to the second generation of left handed quarks (chiral generation leptoquarks) and the first generation of left handed leptons. Therefore the Wilson coefficient is real and flavor-dependent on the first generation of leptons, hence, we use the model-independent constraints obtained in Section 3 for flavor-dependent parameters, given in Table 2 which corresponds to the first constraint in Eq. (6). The allowed region at 95% C.L. from the semileptonic decays of the D mesons is given by:

$$0.05\left(\frac{m_{S_0}}{300\ \mathrm{GeV}}\right)^2 < |\kappa'_{12}|^2 < 0.11\left(\frac{m_{S_0}}{300\ \mathrm{GeV}}\right)^2. \tag{8}$$

Previous bounds [13] for the second generation of left handed quarks coupling to the first generation of left handed leptons, are reported to be $\kappa'^2 < 5 \times (M_{LQ}/300\ \mathrm{GeV})^2$ for S_0. As stated in the previous subsection (for the MSSM-$\not R$), for the electron flavor and the second generation of quarks, this former constraint is more restrictive than previous bounds.

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