UNIVERSALITY VIOLATION IN LEPTONIC W DECAYS: AN EFFECTIVE FIELD THEORY APPROACH*

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We analyse the deviation from universality in leptonic W decays suggested by current PDG data within a general effective field theory approach. Considering the constraints to the New Physics effects coming from Electroweak precision observables we are able to set limits on the amount of universality violation that can be accounted for in a broad class of New Physics models. Our approach starts from a usual Single Operator analysis and extends up to considering the interplay of all the effective operators defined by our EFT.

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1. Introduction

The latest experimental results from LEP-II on leptonic W decays show a slight deviation from universality coming from the third family [1]

$$R^W_{\tau\ell} = \frac{2\,\mathrm{BR}\,(W \to \tau\,\overline{\nu}_\tau)}{\mathrm{BR}\,(W \to e\,\overline{\nu}_e) + \mathrm{BR}\,(W \to \mu\,\overline{\nu}_\mu)} = 1.055 \pm 0.021\,, \tag{1}$$

resulting in a 2.6 standard deviations departure from Standard Model (SM) expectations. Recalling also the ratio [1] $R^W_{\mu e} = 0.983 \pm 0.018$, it can be concluded that, contrary to the third one, the two lightest families seem to attach to the universality principle. Such a violation by the third family, if confirmed, would be clear indication of Beyond the Standard Model (BSM) dynamics.

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Within the SM the $W \to \ell\,\overline{\nu}_\ell$ and $Z \to \ell\,\overline{\ell}$ processes are tightly connected by the gauge symmetry. However, data do not show any deviation from lepton universality in the later vertex [1]. Given this conspicuous observation we think that our analysis should include a joint study of both W and Z decays in order to get possible hints on the origin of the discrepancy.

Precision electroweak measurements, as well as other precise low energy observables, provide constraints on new models looking for deviations that could foresee a BSM structure. Therefore, we think that it is important to try to accommodate the apparent discrepancy on the leptonic W decays within the present situation provided by LHC and the hunt of New Physics (NP) hints. However, instead of adhering to a specific model, we think that the use of an Effective Field Theory (EFT) system provides a more useful setting.

Previous studies of this deviation from universality in W decays have focused on the possibility that pair production of supersymmetric light charged Higgs bosons, almost degenerate with the W and decaying largely into heavy fermions, could mimic $W \to \tau\,\overline{\nu}_\tau$ decays [2]. Modifications of the electroweak gauge group in order to singularize the third family have also been considered [3].

If any violation of universality is at work it also should be exposed in other observables. We will comment on this possibility in the last part of the present work, taking into account the leptonic decays of pseudoscalar mesons and the anomalous magnetic moment of the tau lepton.

2. The Effective Field Theory framework

The astonishing performance of the SM implies that, whatever theory we find at higher energies, it has to reduce, upon integration of the relevant heavier degrees of freedom, to the key properties of the SM. For this reason we use the SM fields, including the SM Higgs doublet, as the low energy particle content of our effective theory. Furthermore, we take the lepton and baryon total numbers as conserved symmetries and we impose that the CKM matrix is the only source of CP violation. In order to properly define our EFT setting, we need moreover to assume that there exists a mass gap between the SM and NP scales and that the new theory above the SM is weakly coupled at the weak scale, so that we can use a linear realization of the gauge $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ symmetry.

The trail left in the procedure of integrating out heavy degrees of freedom is a Lagrangian theory with higher dimensional operators that respect its symmetry and content [4, 5]. Incidentally, there is only one dimension 5 operator and, as it violates lepton number, we neglect it. Then the first order corrections to the SM prediction come from dimension 6 operators, deviations that, at present we know, are tiny in many electroweak and low energy observables.

The experimental data suggest that the NP effects related to the first and second generations of leptons are similar and probably very small. We then choose to impose on the operator coefficients a $[\mathrm{U}(2)\otimes\mathrm{U}(1)]^5$ flavour symmetry that reflects these experimental observations and, moreover, to set to zero the coupling constants for electron and muon. The use of the flavour symmetry allow us to reduce, in a systematic way, the number of operators we need to consider (for details see the discussion on the $[\mathrm{U}(3)]^5$ flavour symmetry in [6] that apply also in our case), although we will break it because we introduce the tensor operators $\mathcal{O}^t_{\ell W}$ and $\mathcal{O}^t_{\ell B}$, relevant in our analysis. The complete list of the operators we will consider can be found in [7].

Of particular interest for our research will be the specific dimension 6 operators contributing to $W\to\ell\,\overline{\nu}_\ell$

$$\begin{aligned}\left[\mathcal{O}^3_{h\ell}\right]_{ij} &= i\left(h^\dagger D_\mu \tau^a h\right)\left(\overline{\ell}_i\,\gamma^\mu\,\tau^a\,\ell_j\right)+\text{h.c.}\,,\\ \left[\mathcal{O}^t_{\ell W}\right]_{ij} &= \left(\overline{\ell}_i\,\sigma^{\mu\nu}\,\tau^a\,e_j\right)h\,W^a_{\mu\nu}+\text{h.c.}\end{aligned} \tag{2}$$

plus three similar operators $(\mathcal{O}^1_{h\ell},\mathcal{O}_{he},\mathcal{O}^t_{\ell B})$, that contribute, together with the previous two, to $Z\to\ell\,\overline{\ell}$. Here i,j are family flavour indices. Our notation is the one introduced in [4].

Although our EFT Lagrangian can provide a loopwise perturbative expansion in the determination of the relevant observables, here we will only consider its leading tree-level contribution, up to linear order in the dimension 6 operator coefficients. In this limit the full width for the leptonic W decay $W\to\ell\,\overline{\nu}_\ell$ reads

$$\varGamma_{W_\ell}=\frac{G_\mathrm{F}M_W^3}{6\sqrt{2}\pi}\left(1-r_\ell^2\right)^2\left[\left(1+4\left[\alpha^3_{h\ell}\right]_{ii}\right)\left(1+\frac{r_\ell^2}{2}\right)+6\sqrt{2}r_\ell\left[\alpha^t_{\ell W}\right]_{ii}\right], \tag{3}$$

where ℓ is the charged lepton in the doublet ℓ_i and $r_\ell=m_\ell/M_W$. The αs are the effective coefficients describing the short distance physics effects in our EFT. The new contributions to the decay width have interesting features: *(i)* there are only two dimension six operators contributing to this process; *(ii)* the operator $\mathcal{O}^3_{h\ell}$ gives, after spontaneous symmetry breaking, a similar structure to the SM one, *i.e.* it modifies the SM couplings; *(iii)* the addition of $\mathcal{O}^t_{\ell W}$ provides a new structure not present in the SM: it gives an anomalous $\ell\,\overline{\nu}_\ell\,W$ coupling [8, 9, 10]. Contrarily to the other ones, this is a left–right operator and its contribution is suppressed by m_ℓ/M_W due to the derivative dependence.

With slight modifications the 2-nd and 3-rd comment applies also to the NP contributions to the leptonic Z decay rate, but, for the sake of brevity, we will not report here the formulas related to this case.

3. Analyses of the observables

In order to constrain the effects of the operators contributing to W and Z leptonic decays, we take into account the observables most precisely measured related to the gauge bosons and tau lepton. Apart from the precise electroweak observables (see Table 1 of [7]), we use the leptonic tau decays and the decays of tau into one charged pion, both with an experimental error well below the 1% level and a theoretical error under control. Given the present uncertainties [1,11] and their tiny capacity to constraint the NP couplings, we do not consider the anomalous magnetic moment of the tau and the pseudoscalar meson decay ($B^{\pm}$, $D^{\pm}$, $D_S^{\pm}$) as observables able to enforce information in our analyses.

To proceed we have then made use of the `Mathematica` code provided in [7] and for obvious reasons we chose to use the flavour $[\mathrm{U}(2)\otimes \mathrm{U}(1)]^5$ approach. Beside updating the experimental data [1], we included into the analyses $\mathcal{O}^t_{\ell W}$ and $\mathcal{O}^t_{\ell B}$ operators in Eq. (2). We included also the tau decays rates as new observables. Given a set of observables O^i, the procedure lies in constructing a χ^2 function and to minimize it in order to get bounds and correlations between the different operator coefficients (in particular on the $[\alpha]_{33}$ couplings, *i.e.* those corresponding to the tau lepton) that are the free parameters of our theory. With these values for the couplings we will give an estimate of the ratio between the BSM contributions and the SM ones: $\Delta R^W_\tau = \mathrm{BR}\,(W\to\tau\,\overline{\nu}_\tau)_{\mathrm{BSM}}\,/\mathrm{BR}\,(W\to\tau\,\overline{\nu}_\tau)_{\mathrm{SM}}$, that can be directly compared with the experimental results.

4. Results and discussion

We have performed three different analysis:

Global analysis: We consider all the dimension six operators allowed by gauge and flavour symmetries (plus the two tensor operators $\mathcal{O}^t_{\ell W}$ and $\mathcal{O}^t_{\ell B}$) and all the observables we discussed in the previous section. Figure 1 shows the allowed regions for the two coefficients contributing to W decays. We want to stress that the weak bounds on the tensor operators are due mainly to the suppression these operators face because of their derivative dependence. From these bounds we get a prediction for the NP contribution to the universality ratio: $\Delta R^W_\tau = 0.01(5)$. Saturating the bounds on ΔR^W_τ we can fully explain the deviation from lepton universality in Eq. (1) in terms of NP effects. However, taking into account that the NP contribution to $R^W_{\tau\ell}$ comes almost entirely from the tensor operator $\mathcal{O}^t_{eW}$, the actual NP contribution can be significatively smaller than the largest one.

Five operator analysis: This case provides a joint result for $W\to\tau\,\overline{\nu}_\tau$ and $Z\to\tau^+\tau^-$, avoiding the problems related to the big number of parameters in the fit. The analysis of these results shows that the coupling $\alpha^3_{h\ell}$ for the

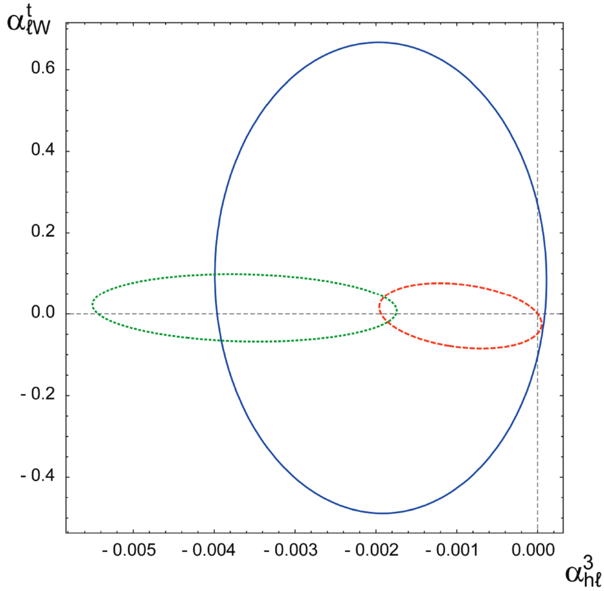

Fig. 1. Allowed region for the couplings $\alpha^3_{h\ell}$ and $\alpha^t_{\ell W}$, at 90% C.L. in the Global case (black ellipse), Five operator case (dotted ellipse) and Two operator case (dashed ellipse).

third family is consistently negative. This gives a negative contribution to the universality ratio: $\Delta R^W_\tau = -0.012(8)$. We conclude from these analyses that the violation of universality in W decays can be only partially explained by the presence of New Physics, at least if the new theory above SM can be described at low energies within our EFT framework.

Two operator analysis: An even more simplified inquiry would be to consider only the two operators contributing in the leptonic decay of the W gauge boson, *i.e.* $\mathcal{O}^3_{h\ell}$ and $\mathcal{O}^t_{\ell W}$ in Eq. (2). In this case we get: $\Delta R^W_\tau = -0.005(7)$ that again, as in the Five operator case, sets a very tight constraint on the NP contribution.

4.1. Predictions for other observables

Leptonic decays of heavy mesons

The leading SM contribution to the $P^- \to \ell^- \overline{\nu}_\ell$ decays is given by the W exchange. Hence it is interesting to point out how these decays get modified by possible deviations from family universality in the $\ell\overline{\nu}W$ coupling. In fact, we will only be interested in the decays of the D^-, D^-_S and B^- because the issue of violation of the lepton couplings arises with the decay into the tau lepton. We see that, though two dimension 6 operators modify the $\ell\bar{\nu}W$ vertex, only the first one contributes to the leptonic decay of the P meson, as the tensor coupling has no spin-0 component. We define the universality ratios

$$R^P_{\tau\ell} = \frac{\mathrm{BR}\,(P\to\tau\overline{\nu}_\tau)}{\mathrm{BR}\,(P\to\ell\,\overline{\nu}_\ell)} = \left(\frac{m_\tau\left(1-m_\tau^2/M_P^2\right)}{m_\ell\left(1-m_\ell^2/M_P^2\right)}\right)^2\left(1+4\left[\alpha^3_{h\ell}\right]_{33}\right). \qquad (4)$$

Due to the lack of precise experimental measurements for the rates of the heavy meson decays, at the moment, we cannot compare our predictions with experimental data. There is just one exception: the D_s ratio with an experimental value equal to $R^{D_s}_{\tau\mu}|_{\mathrm{exp}} = 9.2(7)$ [1]. In the Global case our prediction is $R^{D_s}_{\tau\mu}|_{\mathrm{Global}} = 9.76(1)$. The error on the theoretical prediction is more than one order of magnitude smaller than the experimental one, preventing us from using this observables as universality test. However, it is clear that these will be good observables to look at when new data will be made available by future B-factories.

Anomalous magnetic moment of tau

The tensor operators $\mathcal{O}^t_{\ell W}$ and $\mathcal{O}^t_{\ell B}$ also provide a local contribution to the anomalous magnetic moment of the charged leptons. We find for a lepton of the i family

$$a_\ell \,=\, a_\ell^{\mathrm{SM}} + \frac{2\sqrt{2}}{s_W}\frac{m_\ell}{M_W}\Big(c_W\left[\alpha^t_{\ell B}\right]_{ii} - s_W\left[\alpha^t_{\ell W}\right]_{ii}\Big)\,, \qquad (5)$$

where the first term in the right-hand side is the contribution of the SM. For the τ lepton, that is our main interest here, the present status on a_τ sets, at 95% C.L., $-0.052 < a_\tau < 0.013$ [11]. From the results of the analysis with five operators we can provide a result for the BSM contribution to this observable. We find: $a_\tau^{\mathrm{BSM}} = a_\tau - a_\tau^{\mathrm{SM}} = (1.5\pm5.9)\times10^{-3}$ that still does not provide any relevant information on this observable. A more stringent constraint on the tensor couplings would be needed.

5. Conclusions

The alleged violation of the universality in the lepton couplings in the decay $W\to\tau\,\overline{\nu}_\tau$ [1], opens a window to BSM contributions that could settle the observed deviation. As we do not wish to attach to any specific model, we propose the use of an appropriate EFT framework [4] to analyse those decays and other correlated high-energy electroweak processes, with the purpose of bringing some light to this issue.

We have performed several analyses taking into account different scenarios characterized by the operators and observables that we consider. We find that a global analysis including all the relevant precision measurements by LEP-I and LEP-II, the precisely measured tau decay rates and the appropriate operators in $\mathcal{L}_{\rm EFT}$ leaves the door open to an explanation of the universality departure in terms of NP. However, in other analyses with a better sensitivity, in which we reduced the number of operators, the constraints coming from precise electroweak observables and tau decays are stronger and the allowed NP contribution become too small to explain the lepton universality violation. Possible systematic improvements, like the addition of dimension 8 operators into the EFT framework, are not expected to change our conclusion.

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