Hidden new physics in meson decays

M. M. Guzzo ,* L. J. F. Leite, ,† S. W. P. Novelo, ,‡ and O. L. G. Peres , Instituto de Física Gleb Wataghin - UNICAMP, 13083-859, Campinas-SP, Brazil

Instituto de Física Teórica, Universidade Estadual Paulista, R. Dr. Bento Teobaldo Ferraz 271, Barra Funda, São Paulo - SP, 01140-070 Brazil. (Dated: 12/01/2021)

A model-independent analysis of a non-standard pseudoscalar contribution to leptonic meson decays (π,K,D,D_s) and B) is presented. As also seen from similar analyses in the literature, we find that two distinct regions in the parameter space arise, a region where the standard model contribution is predominant and a region where the new physics terms cancel precisely. The latter has been regarded as a fine-tuning, and for this reason, it was neglected from the very beginning. This paper argues that this cancellation appears naturally in a class of models, most notably those that realize the Glashow-Weinberg-Paschos mechanism for avoiding flavor-changing neutral currents, particularly in the lepton sector. Thus, such a region that allows for larger Yukawa couplings $(10^{-4} \lesssim (G_\eta^P/G_F)U^{-1}m_l^{-1} \lesssim 10^{-3}~{\rm MeV}^{-1})$ cannot be readily ruled out solely by the meson leptonic decays and is degenerated with the Standard Model prediction in these decays.

Introduction.—In most possible new physics beyond the Standard Model (BSM), even when considering their minimal versions, a richer scalar sector is encountered than the simple neutral Higgs present in the particle spectrum of the Standard Model (SM) [1]. Even in the context of the $SU(2) \times U(1)$ gauge symmetry, nothing limits the number of scalar fields, though at least a single doublet is necessary for the usual spontaneous symmetry breaking pattern. Thus, one cannot rule out the possibility that extra scalars, heavier than the observed Higgs (or lighter, but with sufficiently weak couplings), do exist. Moreover, many mechanisms to generate neutrino masses require additional scalars [2–4]. Such particles can also be used, in principle, to solve some anomalies in high-energy experiments, like those in B-meson decays [5, 6] or the muon anomalous magnetic moment [7, 8], for example.

In case those extra scalars do exist, they possibly modify several well-known processes. Among others, this would be the case of a charged meson decaying into a charged lepton and a neutrino. Take, for example, leptonic pion decay, π_{l2} . Such a process has an astonishing agreement between the experimental results and the SM theoretical calculations, often used as a hallmark of the weak interactions' V-A structure. Its helicity suppression explains the dominant decay in muons (99.99%) and not electrons. Therefore, strong constraints on new physics are expected in this decay [5, 9–34].

If a pseudoscalar interaction is assumed to contribute to the charged meson decay $P \to l\nu[\gamma]$ (P_{l2}), the effective

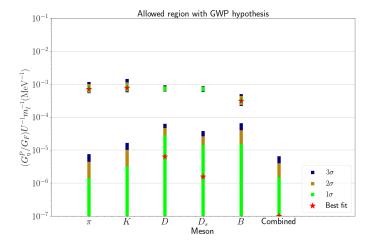


FIG. 1. Allowed Yukawa couplings at up to 3σ for each charged pseudoscalar meson $(\pi, K, D, D_s \text{ and } B)$. Note that we are factoring out the leptonic GWP structure of G_{η}^{P} . In other words, following Equation (5), the constant shown here is $\kappa \lambda_q / v \, m_{\eta}^2 G_F$. Two distinct regions arise, a Glashow-Weinberg-Paschos [35–37] region around 10^{-3} MeV⁻¹ and a SM-like region below around 10^{-5} MeV⁻¹. A combined χ^2 analysis considering an universal coupling in quark sector is also shown.

Lagrangian that describes this process is given by

$$-\mathcal{L} = \frac{G_F}{\sqrt{2}} J_{\alpha}^5 U_{li} \overline{\ell}_l \gamma^{\alpha} (1 - \gamma^5) \nu_i + \frac{(G_{\eta}^P)_{li}}{\sqrt{2}} j^5 \overline{\ell}_l (1 - \gamma^5) \nu_i + \text{H.c.},$$
(1)

where U is the PMNS matrix [38, 39] and $G_{\eta}^{P} = \lambda_{q} \lambda_{\ell} / m_{\eta}^{2}$, with $\lambda_{q}(\lambda_{\ell})$ being the Yukawa couplings for quarks (leptons), and m_{η} the charged

scalar mass. The quark currents and hadronizations read.

$$\langle 0|J_{\alpha}^{5}|P(k)\rangle = V_{pq} \langle 0|\overline{u_{p}}\gamma_{\alpha}\gamma^{5}d_{q}|P(k)\rangle = ik_{\alpha}V_{pq}f_{P}, \quad (2)$$

$$\langle 0|j^5|P(k)\rangle = V_{pq} \langle 0|\overline{u_p}\gamma^5 d_q|P(k)\rangle = iV_{pq}\tilde{f}_P, \tag{3}$$

with f_P the corresponding meson decay constant, and V the CKM mixing matrix. The quantities \tilde{f}_P and f_P are related by [10, 40]

$$\tilde{f}_P = f_P \frac{m_P^2}{m_{u_p} + m_{d_q}},$$
(4)

where m_P is the charged meson mass, and m_{u_p} and m_{d_q} are the bare masses of its constituent quarks.

It can be shown that if we assume a particular structure to the leptonic Yukawa coupling, $G_{\eta}^{P} \propto \hat{M}^{(\ell)}U$, where $\hat{M}^{(\ell)} = \text{diag}(m_e, m_\mu, m_\tau)$ is the diagonal mass matrix for the charged leptons, the full decay rate for P_{l2} coincides with the SM result. The degenerate solution of the standard model and the extension with a charged scalar can be seen in Figure 1, where the analysis of leptonic decay of different mesons have two distinct solutions, one compatible with SM (the lower end of the plot, for $(G_{\eta}^{P}/G_{F})U^{-1}m_{l}^{-1} < 10^{-5} \text{ MeV}^{-1})$ and another solution with $(G_{\eta}^{P}/G_{F})U^{-1}m_{l}^{-1} \sim 10^{-3} \text{ MeV}^{-1}$. In previous works [5, 11, 12, 15, 16, 18, 23, 30], such region of the parameter space was neglected as an unlikely finetuning of the coupling constants. In this letter, we would like to point out that such condition can naturally happen and can be viewed as a consequence of the Glashow-Weinberg-Paschos (GWP) theorem [35–37], which state that if a single scalar gives mass to leptons, the leptonic flavor-changing neutral currents (FCNC) are suppressed in the scalar sector. As a consequence of the GWP theorem, the effective Yukawa coupling constant for a charged scalar takes the form

$$G_{\eta}^{P} = \kappa \lambda_{q} \left(\frac{\hat{M}^{(\ell)}}{v} \right) \left(\frac{U}{m_{\eta}^{2}} \right),$$
 (5)

where v is the corresponding vacuum expectation value (VEV) in the model that gives masses to leptons and κ is a dimensionless model-dependent parameter that accounts for scalar mixing and normalizations [41].

We perform a detailed model-independent analysis of this situation for the mesons $P=\pi,K,D,D_s,B$, and show that, even under restricted circumstances, an allowed region corresponding to the condition in Eq. (5) still exists and is slightly preferred by our statistical analysis for π , K and B. The result of this analysis is shown in Figure 1.

Charged meson decay.—With the above assumptions, the total decay rate for P_{l2} , in the meson rest frame, is given by

$$\Gamma_l = \Gamma_{\rm SM} \times (1 + \Delta_l), \tag{6}$$

where $\Gamma_{\rm SM}$ corresponds to the usual Standard Model rate (including radiative corrections for soft photons) [42] and

$$\Delta_{l} = \frac{1}{m_{l}} \left(\frac{\tilde{f}_{P}}{f_{P}} \right) \sum_{i=1}^{3} \left[\left(\frac{\left| (G_{\eta}^{P})_{li} \right|}{G_{F}} \right)^{2} \left(\frac{\tilde{f}_{P}}{f_{P}} \right) \frac{1}{m_{l}} - 2 \operatorname{Re} \left(U_{li} \frac{(G_{\eta}^{P})_{li}^{*}}{G_{F}} \right) \right], \quad (l = e, \mu, \tau)$$
 (7)

quantifies the presence of new physics beyond the SM. Terms proportional to the neutrino masses were negligible, and, for each charged lepton state, we summed over all the active neutrino mass eigenstates (i=1,2,3). In Eq. (7), the first term inside square brackets comes purely from the pseudoscalar interaction, while the latter corresponds to the interference between the SM contribution and the new interaction.

Demanding the result in Eq. (6) to be close to the SM value, we obtain $\Delta_l \ll 1$. A trivial solution would then be $G_p^P \approx 0$. That is, no significant new physics arises.

However, another degenerated solution that have the same rate as in SM is also possible for $\Delta_l = 0$, namely

$$\frac{G_{\eta}^{P}}{G_{F}} = \frac{2}{(\tilde{f}_{P}/f_{P})}\hat{M}^{(\ell)}U. \tag{8}$$

Which allows for an exact cancellation of the direct scalar and the interference terms. Note that the lepton mass here coming from the helicity suppression in the pseudoscalar leptonic decays has the same dependency which arises from the charged scalar coupling within the GWP framework. Comparing Eq. (8) with Eq. (5), we see that

$$\frac{\kappa \lambda_q}{v \, m_\eta^2} = \frac{2G_F}{(\tilde{f}_P/f_P)} \sim 9(3) \times 10^{-6} \,\text{GeV}^{-3},$$
 (9)

which sets an order of magnitude for the new physics constants [43].

Suppose, for estimation purposes, that $\kappa \sim 1$ and $\lambda_q \sim 1$. Considering also a typical value for v in order to suitably give mass to τ , $v \sim 2$ GeV, then, in this case we find by Eq. (9) that $m_{\eta} \approx 240$ GeV, which is well within the reach of current collider experiments.

Glashow-Weinberg-Paschos region.—Figure 1 shows two solutions compatible with experimental values, arising from $\Delta_l=0$, the SM-like region, $(G_\eta^P/G_F)U^{-1}m_l^{-1}\lesssim 10^{-5}~{\rm MeV^{-1}}$ and the region where the condition of Equation (8) is satisfied, $(G_\eta^P/G_F)U^{-1}m_l^{-1}\sim 10^{-3}~{\rm MeV^{-1}}$, which we call Glashow-Weinberg-Paschos region.

This region is not unknown in the literature [5, 11, 12, 15, 16, 18, 23, 30], but, so far, has been regarded as a fine-tuning of the parameters. As we have shown previously, this is not the case. Lepton flavor conserving models have naturally satisfied the condition Eq. (5).

Consider the general Lagrangian in Eq. (1), where, as previously stated, $G_{\eta}^{P} = \lambda_{q} \lambda_{\ell}/m_{\eta}^{2}$. The Yukawa coupling matrix for the leptons has the form $\lambda_{\ell} = (V_{R})^{\dagger} Y V_{N}$, where Y is a general Yukawa matrix (or a sum of Yukawa matrices with their respective VEVs) in the lepton sector, and V_{R} and V_{N} are, respectively, the matrices that rotate the right-handed charged leptons and left-handed neutrinos.

Now, assume that the charged field η^{\pm} is part of a multiplet that contains a neutral field with non-zero VEV and that such neutral fields generate the charged lepton masses in the Higgs mechanism. Then the charged lepton mass matrix, on the physical basis, is given by

$$\hat{M}^{\ell} = \text{diag}(m_e, m_{\mu}, m_{\tau}) = (V_R)^{\dagger} [Y + A] V_L,$$
 (10)

where $V_L(V_R)$ is the matrix that rotates the left-handed (right-handed) charged leptons, and A corresponds to other contributions to the charged lepton masses. Assuming that the GWP hypotheses hold, that is, only one scalar contributes to the charged lepton masses, the second term is A=0. This happens when (i) a discrete symmetry, for example, Z_2 [20, 24, 34, 44], is present, (ii) there is an alignment condition on the flavor space of the Yukawa matrices, where the different Yukawa couplings are proportional to each other $Y_1 \propto Y_2$ [20, 45–50], or (iii) we have natural flavor conservation or BGL model [51], where the Yukawa entries are dependent only on CKM matrix elements and on lepton masses [24, 34, 46, 51]. Using Eq. (10), we obtain Eq. (5),

$$G_{\eta}^{P} = \frac{1}{m_{\eta}^{2}} \frac{\lambda_{q}}{v} \hat{M}^{(\ell)} U. \tag{11}$$

We stress that, in this work, we consider the GWP structure in the lepton sector only. The quark sector is assumed to be an arbitrary constant for each meson, λ_q (factoring out the CKM matrix).

Statistical analysis.—We perform a statistical analysis using the standard definition of the χ^2 function,

$$\chi^{2}(G_{\eta}^{P}) = \sum_{l} \frac{(\Gamma_{l} - \Gamma_{l}^{\exp})^{2}}{(\sigma_{\Gamma_{l}}^{SM})^{2} + (\sigma_{\Gamma_{l}}^{\eta})^{2} + (\sigma_{\Gamma_{l}}^{\exp})^{2}}, \quad (12)$$

where $\sigma^{\mathrm{SM}}_{\Gamma_l}$ is the uncertainty in SM theoretical calculations for the leptonic meson rate given in Eq. (6), $\sigma^{\eta}_{\Gamma_l}$ is the propagated uncertainty in the new physics terms due the charged scalar, and $\sigma^{\mathrm{exp}}_{\Gamma_l}$ is the experimental uncertainty of decay rate, $\Gamma^{\mathrm{exp}}_{l}$ [42].

In the last column of Figure 1, inspired by the similarity among the ratio f_P/\tilde{f}_P , we did a combined χ^2 -analysis for the five mesons made considering a universal coupling for the quark sector. Figure 1 shows that no universal coupling exists within the context of the GWP theorem, and only a minor modification of the SM can be accommodated in this scenario.

Consequences.—It is interesting to note from Figure 1 that the GWP theorem well describes all mesons, and the best fit even falls within this region for π , K and B mesons. This is a shred of substantial evidence that this region is a feasible range for the Yukawa coupling, and both solutions, the SM-like and GWP theorem-region, yield the exact predictions for leptonic decays. Therefore, a relatively large coupling cannot be excluded from the leptonic decays alone.

Although different experiments could restrain this GWP parameter region, it is remarkable that decays as known and studied as pions and kaons, could contain hidden new physics with relatively strong coupling. Therefore, exploring potential constraints coming from beta decays, β^- [16], neutral pseudoscalar mesons [20] or the muon decays should be considered in light of this specific parameter region to exclude it definitively or to consolidate this region as a possible candidate of new physics.

Conclusion.—In this work, we obtained a solution that allows for a universal quark Yukawa coupling for the decay of π , K, D, D_s and B. We conclude that a degenerate solution, which occurs naturally for a wide range of models, most notably those that satisfy the Glashow-Weinberg-Paschos mechanism, can be obtained and provides a good fit for experimental data SM, considering this decay solely. Thus, new physics could be hidden in the leptonic pion decay measurements, and the implications of coupling within this region should be explored in different experiments to break this parameter space degeneracy.

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- * guzzo@ifi.unicamp.br
- † lfleite@ifi.unicamp.br
- [‡] wnovelo@ifi.unicamp.br
- § orlando@ifi.unicamp.br
- ¶ v.pleitez@unesp.br
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