Right-handed neutrinos and the CDF II anomaly

Mattias Blennow ,[1,*] Pilar Coloma ,[2,†] Enrique Fernández-Martínez ,[2,3,‡] and Manuel González-López [2,3,§]

[1]*Department of Physics, School of Engineering Sciences, KTH Royal Institute of Technology, AlbaNova University Center, Roslagstullsbacken 21, SE-106 91 Stockholm, Sweden*
[2]*Instituto de Física Teórica UAM-CSIC, Calle Nicolás Cabrera 13-15, Cantoblanco, E-28049 Madrid, Spain*
[3]*Departamento de Física Teórica, Universidad Autónoma de Madrid, Cantoblanco, E-28049, Madrid, Spain*

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We point out that right-handed neutrinos can resolve the tension between the latest CDF II measurement of M_W and the SM. Integrating out the new states yields a single $d = 6$ operator, which translates into a nonunitary leptonic mixing matrix. This alters the extraction of G_F from muon decay and increases the prediction for M_W, in line with the CDF II result. We find that this explanation worsens the so-called Cabibbo anomaly, which could still be explained through the same $d = 6$ operator if it is not generated by right-handed neutrinos. Exploiting the flavor dependence, a common explanation of both anomalies would *a priori* be possible, but is ruled out by weak universality constraints.

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I. INTRODUCTION

The Standard Model (SM) of particle physics is an extremely successful theory, having made countless predictions that have been experimentally verified, the crowning achievement being the discovery of the Higgs boson a decade ago [1,2]. With this in mind, any indications for physics beyond the SM (BSM) generally attract significant attention from the particle physics community. In particular, the so-called Cabibbo anomaly [3–6] has attracted a lot of attention, and the recent release of the CDF II result for the mass of the W boson [7], including a seven standard deviation discrepancy relative to the SM prediction, is certain to do the same.

It would be particularly appealing to relate these budding new anomalies to longstanding open problems of the SM. The simplest extension of the SM able to accommodate the experimental evidence for neutrino masses and mixings, observed in neutrino oscillations, is arguably the addition of right-handed neutrinos to the SM particle content. If their Majorana masses (allowed by the SM gauge symmetry) are heavy, integrating them out yields the ($d = 5$) Weinberg operator [8], which generates the light neutrino masses after electroweak symmetry breaking. Following in the operator expansion, a single $d = 6$ operator is generated at tree level [9]:

$$\mathcal{O}_{d=6} = \overline{\ell_L}\,\tilde{H}\,c_{\mathcal{O}_{d=6}} i\partial\!\!\!/(\tilde{H}^\dagger \ell_L) \qquad (1)$$

with

$$c_{\mathcal{O}_{d=6}} = Y_\nu \frac{1}{\Lambda^2} Y_\nu^\dagger, \qquad (2)$$

where Λ is the Majorana mass of the right-handed neutrino and Y_ν is the matrix of Yukawa couplings between the right-handed neutrinos, the left-handed lepton doublets ℓ_L, and the Higgs H.

When the Higgs develops its vacuum expectation value, this $d = 6$ operator induces a deviation from unitarity of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [10–34], which we will dub N [35]:

$$N_{\alpha i} = (\delta_{\alpha\beta} - \eta_{\alpha\beta})U_{\beta i}, \qquad (3)$$

where $\eta = c_{\mathcal{O}_{d=6}} v^2/4$ is a Hermitian positive semidefinite matrix and U is the unitary rotation that diagonalizes the Weinberg operator.

In the canonical type-I seesaw mechanism [36–39], where the lightness of neutrino masses derives from the hierarchy between the Dirac and Majorana masses, the $d = 6$ operator will be highly suppressed, making its phenomenological impact negligible. However, naturally small neutrino masses may also arise from a symmetry

*emb@kth.se
†pilar.coloma@ift.csic.es
‡enrique.fernandez-martinez@uam.es
§Manuel.gonzalezl@uam.es

argument. Indeed, the Weinberg operator is protected by the lepton number symmetry [40–42], while the $d = 6$ one is not. Thus, low-scale seesaw variants with an approximately conserved lepton number symmetry are characterized by both naturally light neutrino masses and sizable Yukawa couplings, even for sterile neutrinos lying close to the electroweak scale. This is the case of the inverse [43,44] or linear [45] seesaw mechanisms. In these scenarios the heavy neutrinos arrange in pseudo-Dirac pairs, with sizable mixing with the active neutrinos and significant unitarity deviations of the PMNS matrix [15,23,31,46]. All interactions involving neutrinos, both through charged and neutral currents, are consequently affected.

In this paper we discuss how these modifications affect the extraction of the Fermi constant in such a way that the prediction for the W-boson mass (M_W) shifts to larger values, reducing the tension with the new CDF II measurement. Conversely, the impact of the unitarity deviation in the extraction of V_{ud} worsens the so-called Cabibbo anomaly as long as the coefficient of the $d = 6$ operator in Eq. (1) is positive semidefinite, as required by its generation from the inclusion of right-handed neutrinos. Nevertheless, if this assumption is relaxed and the coefficient of the operator is allowed to be indefinite, it has been shown that a solution of the Cabibbo anomaly can also be found [47,48]. This would however imply more elaborate additions to the SM particle content beyond only right-handed neutrinos (see Ref. [47] for a dedicated discussion). We will also relax this assumption when performing our global fit to the different relevant observables. In particular, we will show that bounds on lepton flavor universality are very important, and that the proposed $d = 6$ operator can provide a very good fit to any two out of the three sets of observables: M_W from CDF II, lepton flavor universality, and unitarity of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. For the first two, a positive definite η provides a good fit, and therefore only right-handed neutrinos are required for the UV completion. Interestingly, the common best fit is also in perfect agreement with the measurement of the invisible width of the Z.

II. IMPACT OF NONUNITARITY ON ELECTROWEAK OBSERVABLES

A nonunitary PMNS matrix would directly affect the dominant decay channel of the muon, from which the Fermi constant is extracted. This translates into the following relation between G_F (the parameter that enters the Fermi Lagrangian) and G_μ (the value of the parameter extracted from the muon lifetime):

$$G_F = G_\mu(1 + \eta_{ee} + \eta_{\mu\mu}). \tag{4}$$

As the prediction of the mass of the W stems from the Fermi constant, the nonunitarity corrections in G_F propagate to the prediction of M_W as

$$M_W = M_Z\sqrt{\frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha(1 - \eta_{\mu\mu} - \eta_{ee})}{\sqrt{2}G_\mu M_Z^2(1 - \Delta r)}}}, \tag{5}$$

where α is the fine-structure constant, M_Z is the mass of the Z gauge boson, and Δr accounts for loop corrections. The latter would also receive η-dependent corrections through the gauge boson self-energies involving heavy neutrinos in the loop. However, as it was shown in Ref. [49], these modifications can generally be neglected with respect to the tree level effects of η.

Similarly, the invisible decay of the Z is yet another observable, precisely measured, which is affected by nonunitarity. In particular, the number of active neutrinos extracted from this process is corrected to [46]

$$N_\nu = 3 - 4\eta_{\tau\tau} - \eta_{ee} - \eta_{\mu\mu}. \tag{6}$$

Its value, measured at LEP [50], constitutes a further source of information to constrain the entries of η. Notice that, disregarding the effect of $\eta_{\tau\tau}$, N_ν has the same functional dependence on the η parameters as M_W. The resulting errors from the invisible width of the Z are significantly larger and we will therefore not include this measurement in our fits (we have checked numerically that including it leads to a negligible effect in the fit). However, the current central value for N_ν is very compatible with the CDF II result at just above a 1σ difference in the resulting value of $\eta_{ee} + \eta_{\mu\mu}$.

If the η matrix is positive semidefinite, then its diagonal entries must be positive. Nonzero values of η_{ee} and/or $\eta_{\mu\mu}$ would therefore increase the prediction for M_W. This would improve the agreement with the latest CDF II measurement, pointing to a nonunitary PMNS matrix as a possible explanation to the strong tension with the SM.

Nevertheless, these unitarity deviations are also strongly constrained by other observables. In particular, some of the strongest bounds arise from beta and kaon decays, from which the CKM matrix elements V_{ud} and V_{us} are extracted. The determination of V_{ud} from superallowed beta decays would receive a nonunitarity correction with η_{ee} entering the lepton vertex. This contribution is canceled upon inclusion of G_μ, since the same vertex is present in its determination, so that the final correction is

$$|V_{ud}^\beta| = (1 + \eta_{\mu\mu})|V_{ud}|, \tag{7}$$

where V_{ud}^β is the experimentally measured value and V_{ud} the actual entry of the CKM matrix.

The value of V_{us} is determined through semileptonic kaon decays. The nonunitarity correction will in this case be different depending on the flavor of the final state lepton:

$$|V_{us}^{K\to\pi e\bar{\nu}_e}| = (1+\eta_{\mu\mu})|V_{us}|, \tag{8}$$

$$|V_{us}^{K\to\pi\mu\bar{\nu}_\mu}| = (1+\eta_{ee})|V_{us}|. \tag{9}$$

These kind of semileptonic decays are controlled by a form factor, $f_+(q^2)$, which depends on the momentum transfer between the mesons. Experimental measurements are not able to disentangle $|V_{us}|$ from the form factor evaluated at zero momentum transfer, $f_+(0)$. An independent determination of the latter, arising from lattice QCD, is therefore needed.

While the new physics effects do affect the measurements of V_{ud} and V_{us}, to alleviate the $\sim 3\sigma$ tension of the Cabibbo anomaly, negative values of $\eta_{\mu\mu}$ would be required. As discussed in the introduction, this would imply a more complex extension of the SM than simply introducing right-handed neutrinos, but it is indeed a viable possibility [47] that will also be considered in our fit.

Finally, lepton flavor universality bounds also provide competitive limits on nonunitarity. These are derived from the relative branching ratios to different flavors,

$$R^P_{\alpha/\beta} = \Gamma(P\to\ell_\alpha\bar{\nu}_\alpha)/\Gamma(P\to\ell_\beta\bar{\nu}_\beta), \tag{10}$$

so as to cancel uncertainties. Measurements of pion, kaon, and tau lepton decays provide the strongest constraints[1] on ratios of η elements [52]:

$$\left(\frac{1-\eta_{\mu\mu}}{1-\eta_{ee}}\right)_\pi = 1.0010(9),$$
$$\left(\frac{1-\eta_{\mu\mu}}{1-\eta_{ee}}\right)_K = 0.9978(18),$$
$$\left(\frac{1-\eta_{\mu\mu}}{1-\eta_{ee}}\right)_\tau = 1.0018(14). \tag{11}$$

Notice that the CDF II measurement is in $\sim 3.6\sigma$ tension with previous determinations of M_W, which are in agreement with the SM expectation. We will therefore not include them in our fit, since the proposed scenario will not be able to alleviate that tension. Similarly, measurements of $\sin\theta_W$ will not be included, since they are affected by the same combinations of elements of η as M_W and are less precise. Instead, we will quantify the level of compatibility of observables sensitive to different combinations of elements of η. Nevertheless, in case the new result does not pan out, we will also perform our fit assuming the current global determination [53] of $M_W = 80.379(12)$ GeV, instead of the CDF II one.

Similarly, lepton flavor violating decays have also been shown to be excellent probes of the lepton mixing matrix unitarity deviations. However, these only constrain the off-diagonal elements of η, which are not relevant to the present discussion. For example, very strong constraints on $\eta_{e\mu}$ exist from the nonobservation of the lepton flavor violating $\mu\to e\gamma$ decay or $\mu\to e$ conversion in nuclei [26]. For a limited number of right-handed neutrinos, the structure of the $d=6$ operator can be constrained, or even derived, from that of the observed neutrino masses and mixings [49,54]. Conversely, when three or more pseudo-Dirac pairs are considered, there are no constraints on the structure of η; in particular, $\eta_{e\mu}$ should only satisfy the Cauchy-Schwarz inequality $\eta_{e\mu} \le \sqrt{\eta_{ee}\eta_{\mu\mu}}$. Therefore, we will consider that η_{ee} and $\eta_{\mu\mu}$ are not bounded by lepton flavor violating processes.

[1]Bounds on W decays from colliders are also available; however, they are an order of magnitude weaker, see Ref. [51].

III. RESULTS

In order to perform a fit to M_W along with the results from beta and kaon decays, as well as with the universality constraints, we adopt a χ^2 approach, where we add a Gaussian term for each of the observables listed in Table I. Apart from the target parameters η_{ee} and $\eta_{\mu\mu}$, the Z boson mass M_Z, the value of Δr, the value of $f_+(0)$, and the true value of V_{ud} were used as nuisance parameters, with the experimental bounds on the first three being introduced into the χ^2 through pull terms. The true value of V_{ud} was allowed to vary freely apart from the constraints introduced by the beta and kaon decays. The correlation matrix among the kaon decay observables from [55] has also been taken into account.

In the upper panel of Fig. 1 we show the results for our fit to the η coefficients. Our results show separately the preferred regions for the different sets of observables. As expected, the area in which the CDF-II measurement of M_W would be reconciled with the prediction is very far from the SM, which corresponds to $\eta_{ee} = \eta_{\mu\mu} = 0$.

TABLE I. List of relevant observables and their experimental determinations. All the values have been taken from Ref. [53] except explicitly stated otherwise.

Observable	Experimental measurement
α	$7.2973525693(11)\times 10^{-3}$
G_μ	$1.1663787(6)\times 10^{-5}$ GeV^{-2}
M_Z	91.1876(21) GeV
M_W (PDG)	80.379(12) GeV
M_W (CDF II) [7]	80.4335(94) GeV
Δr	0.03652(22)
N_ν [50]	2.9963(74)
$\|V_{ud}\|$	0.97370(14)
$\|V_{us}\| f_+(0)(K^\pm e3)$	0.2169(8)
$\|V_{us}\| f_+(0)(K^\pm \mu3)$	0.2167(11)
$\|V_{us}\| f_+(0)(K^L e3)$	0.2164(6)
$\|V_{us}\| f_+(0)(K^L \mu3)$	0.2167(6)
$\|V_{us}\| f_+(0)(K^S e3)$	0.2156(13)
$f_+(0)$ [56]	0.9698(17)

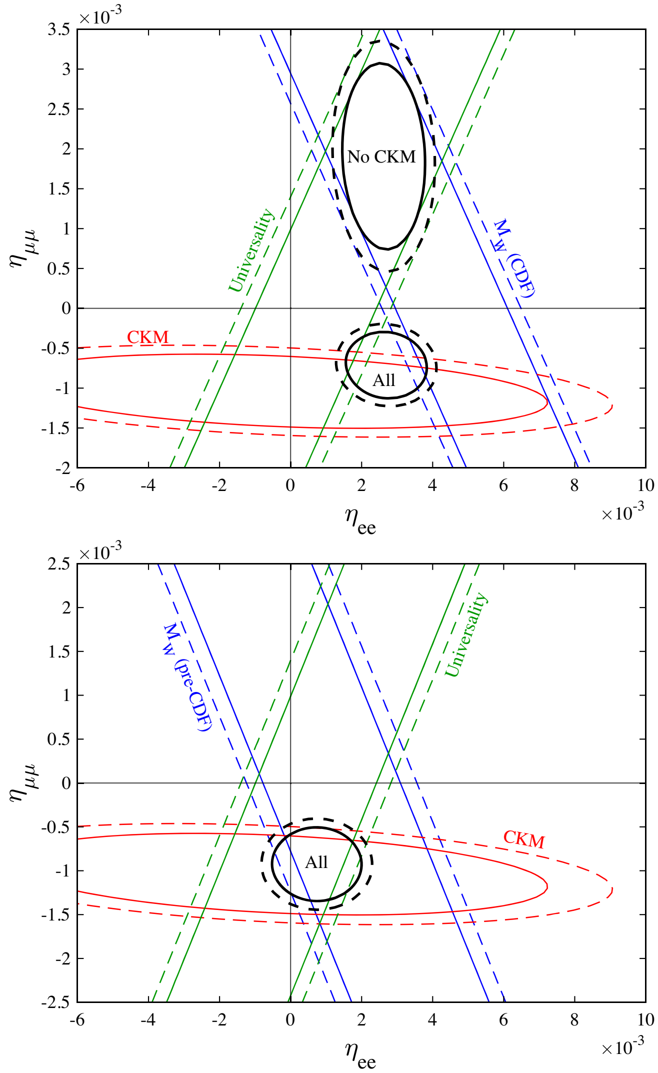

FIG. 1. Results of our fit, projected onto the η_{ee}-$\eta_{\mu\mu}$ plane. The solid (dashed) curves correspond to the allowed regions at 95% C.L. (99% C.L.), for 2 d.o.f. The constraints are labeled as "M_W" for the measurement of the W mass, "Universality" for the lepton flavor universality bounds, and "CKM" for the bounds coming from beta and kaon decays. In the upper (lower) panel we take the constraints on M_W from CDF II [7] (the global average before CDF II [53]). The black contours correspond to combinations of different data sets, see text for details.

Similarly, the area in which the beta and kaon decay measurements would be reconciled with a unitary CKM matrix upon extraction of V_{ud} and V_{us} does not contain the SM expectation either. Finally, the bounds from the universality constraints prefer $\eta_{ee} \sim \eta_{\mu\mu}$. As can be seen, there is no common region where all three measurements overlap simultaneously. In fact, the global fit using all datasets is in some tension with all three sets and thus has its global minimum at a $\chi^2_{\rm min}/n_{\rm dof} = 40.1/7$, where $n_{\rm dof}$ is the number of degrees of freedom of the χ^2. Nevertheless, the addition of new physics does provide a significant improvement with respect to the result obtained under the SM hypothesis: specifically, we find $\Delta\chi^2 = \chi^2_{\rm SM} - \chi^2_{\rm min} = 48.1$ with $n_{\rm dof} = 2$.

It is therefore interesting to also consider scenarios in which one of the two present anomalies is not confirmed. In the lower panel of Fig. 1 we focus on the solution of the Cabibbo anomaly assuming that the M_W measurement by CDF II will not be confirmed. The contours are therefore the same as for the upper panel except for the constraint from M_W, which now corresponds to the present global fit without CDF II of $M_W = 80.379(12)$ GeV [53]. As can be seen, a satisfactory explanation of the Cabibbo anomaly can be found for positive values of η_{ee} and negative values of $\eta_{\mu\mu}$, which is in agreement with previous results in Refs. [47,48,52]. The best fit in this scenario has a $\chi^2/n_{\rm dof} = 9.7/7$. Notice that the preferred negative value for $\eta_{\mu\mu}$ foregoes the appealing simple explanation in terms of just right-handed neutrinos, which would require $\eta > 0$, see Eq. (2).

Conversely, in the upper panel of Fig. 1 we also show that the new M_W anomaly from the CDF II measurement can be explained if the Cabibbo anomaly is not confirmed. This corresponds to the black contours labeled "No CKM," which provide a very good fit to both sets of observables and is also in excellent agreement with the invisible width of the Z. The best fit in this scenario has a $\chi^2/n_{\rm dof} = 3.3/2$.

IV. SUMMARY AND DISCUSSION

In this paper we have explored the tantalizing possibility of a common explanation to the new M_W measurement by CDF II and the Cabibbo anomalies, also linking them with the origin of neutrino masses and mixings by the inclusion of right-handed neutrinos in the particle spectrum. This induces a unique $d = 6$ operator at tree level, whose coefficient η may help to reconcile these measurements with predictions. We point out that, apart from these two sets of observables, the lepton universality constraints from the relative branching ratios of meson and tau lepton decays to different flavors are also very relevant to constrain the allowed parameter space. We find that the global fit including all constraints does offer a significant improvement over the SM only. Indeed, with the addition of only two parameters (η_{ee} and $\eta_{\mu\mu}$), the global minimum of the χ^2 is reduced by roughly 48 units when using all of the datasets. Nevertheless, significant tension between the three sets of observables remain, with a global minimum at $\chi^2/n_{\rm dof} = 40.1/7$, corresponding to a p value of only 1.3×10^{-6}.

Thus, we also explored the possibility of explaining a single anomaly with the proposed scenario. When the CDF-II measurement of M_W is not considered and replaced by the present determination of M_W from other data, a very good fit to all observables is found for positive (negative) values of η_{ee} ($\eta_{\mu\mu}$), confirming earlier analyses [47,48,52]. Since the inclusion of right-handed neutrinos implies that η

should be positive semidefinite, this scenario would require a more complex UV completion [47].

More interestingly, when assuming that a different explanation will be found for the Cabibbo anomaly and removing it from the fit, we obtained excellent fits to the M_W measurement by CDF II in agreement with the lepton universality constraints as well as the invisible width of the Z. Furthermore, all diagonal elements of η are positive in this case, in agreement with the type-I seesaw expectation. They are also significantly different from 0, with the SM hypothesis disfavored at 6.8σ, possibly linking the new determination of M_W by CDF II to the origin of neutrino masses. This interpretation of the new CDF II results implies $\eta_{ee} \sim \eta_{\mu\mu} \sim 3 \times 10^{-3}$, or, equivalently, a mixing of the heavy neutrinos with ν_e and ν_μ of order 0.07. For Yukawa couplings $\mathcal{O}(1)$, the heavy neutrino mass would be around the TeV scale, within reach of future collider searches [57].

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