Fermion Electric Dipole Moments in R-parity violating Supersymmetry.

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In this talk I discuss some aspects of the study of electric dipole moments (EDMs) of the fermions, in the context of R-parity violating ($R\!\!\!/_p$) Supersymmetry (SUSY). I will start with a brief general discussion of how dipole moments, in general, serve as a probe of physics beyond the Standard Model (SM) and an even briefer summary of $R\!\!\!/_p$ SUSY. I will follow by discussing a general method of analysis for obtaining the leading fermion mass dependence of the dipole moments and present its application to $R\!\!\!/_p$ SUSY case. Then I will summarise the constraints that the analysis of e, n and Hg EDMs provide for the case of trilinear $R\!\!\!/_p$ SUSY couplings and make a few comments on the case of bilinear $R\!\!\!/_p$, where the general method of analysis proposed by us does not work.

I. INTRODUCTION

A. Fermion Dipole Moments

Dipole moments of fermions in general, whether magnetic or electric and diagonal or transition, provide a very interesting probe of physics at the loop level, since different invariance principles make very precise tree level predictions for them. Any deviation from these then can give information about loop-physics. Indeed electric dipole moments of the electron and neutron [1, 2] are an excellent probe of sources of CP-violation beyond that available in the SM described by the CKM parametrisation. The incredibly accurate test of Quantum Electro Dynamics (QED) provided by the measurement of $(g-2)_e$, possible signals for physics beyond the Standard Model (SM) implied by the accurate measurement of $(g-2)_\mu$ [3] or constraints on all lepton number violating BSM physics from the lepton and flavour violating transition moments [4] as well as from the Majorana ν masses [5], all show the very important role that the dipole moments of fermions, in general, play in probing the loop level effects of BSM physics that may be CP and flavour violating.

In the SM the CP odd neutron electric dipole moment (edm) d_n vanishes at two loops [6]. At three loops it has been estimated [2, 7] to be $d_n \sim 10^{-32\pm1}$ e cm. Since there are no purely leptonic sources of CP violation in the SM, an electron dipole moment can only be induced from d_n at second order in G_F and thus may be estimated to be $d_e \sim (G_F m_n^2)^2 d_n \sim 10^{-42}$ e cm, to be compared to the estimate 8×10^{-41} e cm quoted in the literature [1, 8]. A nonzero d_n can also induce an edm for Hg or Deuteron. The current experimental limits on the diagonal, fermion EDMs are $\sim 10^{-25} - 10^{-26}$. For example, for the neutron, $d_n < 6.3 \times 10^{-25}$ e cm [9]. Given the much lower estimates for the same in the SM, it is clear that the fermion EDMs are a very promising place to look for footprints of CP violation in physics beyond the SM: BSM physics. The experimental situation for the Deuteron and Mercury EDMs is more competitive with respect to the theoretical predictions in the SM. Hence, these can be a test of the SM and can also put nontrivial constraints on BSM physics. Further, with additional sources of CP-violation, beyond the one present in the SM, EDMs for fermions (e or n) may arise even at the one-loop or two-loop level and thus provide strong constrains for the additional CP-violating phases and/or new particle masses in the particular version of BSM. Supersymmetric theories [10] with or without R–parity violation [11, 12], lepto-quark models, extended Higgs sectors are examples of different types of BSM physics wherein additional sources of CP violation, which may or may not be flavour conserving, are strongly constrained by considerations of the EDMs of fermions and neutral atoms like Hg [13, 14].

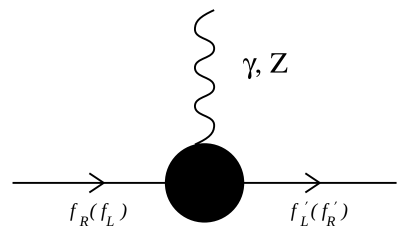

FIG. 1: Generic diagram which will contribute to the dipole moment.

Figure 1 shows a generic diagram which will contribute to the fermion dipole moment. One calculates in any theory the matrix element of the current (electromagnetic or weak) as $q^\mu \to 0$. The EDMs, magnetic and electric, are then the tensor form factors $F_T^{\mathcal{V}}, F_T^{\prime\mathcal{V}}$, given by:

$$\bar{u}_{f_1}(p-q)\sigma_{\mu\nu}q^\nu(F_T^{\mathcal{V}} + \gamma_5 F_T^{\prime\mathcal{V}})u_{f_2}(p),\ (\mathcal{V} = \gamma, Z)$$

Dipole moment operators flip chirality, and hence have either to be proportional to *some* fermion mass (this may not be the mass of the external fermion), or to a chirality flipping Yukawa type coupling [15]. The theoretical predictions for the moments of the heavier fermions like the t, b or the τ, are larger than those for the first generation particles due to the linear dependence on m_f [16]. In models with lepto-quarks, particularly large enhancements of the predicted values of the τ moments, by a factor of m_t/m_τ, are possible [17] and thus can be tested in collider experiments. In this talk I will discuss a method of analysis [18], which allows to extract the leading fermion mass dependence of the coefficient of the induced dipole moment in any theory. The method is illustrated using the example of $R\!\!\!/_p$ [11, 12] SUSY interactions.

B. $R\!\!\!/_p$ Supersymmetric Theories

Supersymmetry, arguably, is the most attractive option for physics beyond the SM. In these theories there exists a discrete symmetry R_p ($R_p = (-1)^{3B+L+2S}$) such that all the SM particles are even under it and all the superpartners are odd. The B, L and S in the definition of R_p above, are the Baryon number, Lepton number and the spin of the particle respectively. Neither the conservation nor the violation of R_p, is mandatory from a theoretical viewpoint. B, L are symmetries of the SM but NOT of the MSSM. Hence the completely general superpotential obtained by the requirement of gauge invariance and supersymmetry (SUSY), contains the $R\!\!\!/_p$ terms given by,

$$\begin{aligned} W_{R\!\!\!/_p} = & \frac{1}{2}\ \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k + \\ & \frac{1}{2}\ \lambda''_{ijk} U^c_i D^c_j D^c_k + \kappa_i L_i H_2. \end{aligned} \quad (1)$$

Here, L_i, Q_i are the doublet Lepton and Quark superfields, E_i, U_i, D_i are the singlet Lepton and Quark superfields. In general, this superpotential contains terms violating Baryon number (e.g. λ'' terms) as well as the Lepton number (e.g. l, λ'). For supersymmetric particles with masses around a TeV, the former can cause very rapid proton decay. This can be, however, cured by adopting $\lambda'' = 0$, corresponding to B conservation. This choice is also preferred if we do not want the $R\!\!\!/_p$ terms to wash out Baryon asymmetry generated through EW Baryogenesis. As a matter of fact, unified string theories actually prefer models with B conservation and R_p violation [19], as the former also suppresses the dimension five proton decay operators. In addition, non-zero ν masses can be generated in an economical way without introducing any new fields, only the $R\!\!\!/_p$ couplings are 'new'. The bilinear $\kappa'_i s$ can generate the masses at tree level whereas the trilinear λ, λ' terms generate them through quantum effects at one or two loop level [20]. Superkamiokande and SNO have provided us with an unambiguous proof of ν masses. In the $R\!\!\!/_p$ Supersymmetric theories, there exists enough freedom to generate the mass patterns indicated by all the data. Furthermore it leads to testable predictions at the colliders. All this makes $R\!\!\!/_p$ SUSY worth detailed investigations. $R\!\!\!/_p$ interactions can give rise to both the CP-conserving and CP-violating dipole moments of fermions; the latter of course only when the couplings have non zero phases.

All the above positive things notwithstanding, one has to contend with the fact that allowing for this most general, $R\!\!\!/_p$ superpotential, gives us a large number (total 48) Yukawa type couplings, with NO theoretical indications about their sizes. On the positive note, many of these unknown couplings are constrained by a host of low energy processes [10, 12, 14], such as the nucleon decay, N–$\bar{N}$ oscillations, μ decay,$B-$ physics,collider searches and last but not the least the fermion EDMs: the topic of present discussion. For the $L-$ violating coupling the severest of the constraints come from ν masses [20]. In addition to this, serious constraints also exist from cosmology from considerations of Baryogenesis. The EDMs provide some of the strongest constraints on the CP phases.

In the next sections I would like to describe our work where we had developed a general method of analysis to obtain the leading fermion mass dependence of dipole moment operators in general, and of the EDMs, in particular. As mentioned before, large mass enhancements of the dipole moments were observed in the lepto-quark models [17]. Since in $R\!\!\!/_p$ models the sfermions behave like lepto-quarks, it was interesting to check whether similar enhancements obtain for $R\!\!\!/_p$ SUSY as well.

II. FORMALISM AND APPLICATION TO d_e IN $R\!\!\!/_P$ SUSY.

A. Formalism

Let us define five global charges $Q_{l_L}, Q_{e_R}, Q_{q_L}, Q_{d_R}$ and Q_{u_R} corresponding to five different $U(1)$ transformations, taking following values:

$$\begin{aligned} Q_{l_L} &= 1 \text{ for } e_{iL}, \nu_i, \widetilde{e}_{iL}, \widetilde{\nu}_i \ \ (i = 1-3) \\ &= 0 \text{ for all the other (s)particles.} \end{aligned} \quad (2)$$

The charge is independent of the generation. The value of all the charges for all the Gauge bosons and Higgs bosons (plus their SUSY partners) are zero. Note that the superpotential Yukawa interactions, A terms and $R\!\!\!/_p$ terms do not conserve these charges where as the gauge (and gaugino) interactions do. These charges are some kind of 'superchirality' in that they are nonzero even for spin zero sfermions. They differentiate fermions of different chirality, and also right handed quarks of different electrical charge. They do not, however, differentiate between flavours of leptons or quarks with the same chirality, and so are conserved by inter-generational quark mixing.

Having introduced these charges, now we are ready to derive selection rules that must be obeyed, for example, for the dipole moment operators. As mentioned already and shown in Figure 1, these operators require an interaction which will give rise to a flip in chirality of the fermion. In the SM of course it is only the Yukawa interaction terms. Once we go to the MSSM we also have the Higgsino mass term as well as the trilinear A term, which are proportional to the same Yukawa coupling. In the MSSM the gaugino masses can also flip the chirality of gauginos, but in order for the chirality-flipped gaugino component to couple, one also needs $\tilde{f}_L - \tilde{f}_R$ mixing which has its origin in Yukawa interactions. In addition to these, in $\not{R}_p$ SUSY, there are also the $\not{R}_p$ interactions which can flip the fermion chirality. We will call all these interactions 'Yukawa' interactions in a generalised sense in what follows.

For (say) a leptonic dipole moment to be generated we need Q_{l_L} and Q_{e_R} to change by one unit in equal and opposite directions, with no change in the other charges. Similar change in Q_{q_L} and Q_{u_R} (Q_{d_R} and Q_{q_L}) is required for $u(d)$ dipole moments. To be specific for the case of leptonic moments, where f, f' of Figure 1 are leptons, we must have:

$$\Delta Q_{l_L} = -1, \Delta Q_{e_R} = 1. \tag{3}$$

or vice versa and all the other charges uncharged, i.e.

$$\Delta Q_{q_L} = 0, \Delta Q_{u_R} = 0, \Delta Q_{d_R} = 0. \tag{4}$$

Similar equations will hold for the case of the u, d moments as well. Then, knowing the change induced in each of these charges by any (chirality-flipping) interaction, it is straightforward to derive relations between the number of vertices of various types of chirality flipping interactions in order that these collectively induce a dipole moment for any particular matter fermion. Of course it clear that these would only be necessary conditions since, without further study, it cannot be guaranteed that the answer would not vanish. All this tells us is that it *need* not *vanish*. Solving these conditions one can then estimate the expected mass dependence of the contribution of the diagram to the dipole moment operator. Note also that our method does not distinguish between the direct and transitional dipole moments. So the results we obtain will be equally applicable to the case of (say) EDMs (in case of nonzero phases of the BSM couplings), as for the ν Majorana mass as well as the lepton number violating decay like $\mu \to e\gamma$ etc.

Table I shows the changes in various charges caused by different interaction terms, for the SUSY model with the MSSM field content, allowing for the possibility of $\not{R}_p$. Out of the Higgs-squark interaction terms arising from the D–term and the F–term, the trilinear Higgs-squark-squark and the Higgs-Higgs-squark-squark interaction terms cause the charges to change in a manner different from the above mentioned Yukawa interaction terms, as can be seen from the table.

Using these, total change in a given charge in terms of the number of vertices of a given type present in the diagram can be written down trivially. Let P, S and R be the number of down-quark, up-quark and lepton Yukawa interactions, and P^*, S^*, R^* the number of insertions corresponding to the Hermitean conjugate ($h.c.$) of these interactions. $N, M, L(N^*, M^*, L^*)$ denote the number of vertices corresponding to interactions proportional to l, λ', λ'' of Eq. 1 respectively and $T(T^*)$ denote the number of trilinear or quartic scalar vertices corresponding to the interactions in the fourth row of Table I.

The net change in various charges are given by

$$\begin{aligned} \Delta Q_{l_L} &= -2\Delta N - \Delta M - \Delta R \\ \Delta Q_{e_R} &= \Delta N + \Delta R \\ \Delta Q_{q_L} &= -\Delta M - \Delta P - \Delta S \\ \Delta Q_{d_R} &= 2\Delta L + \Delta P + \Delta M + \Delta T \\ \Delta Q_{u_R} &= \Delta L + \Delta S - \Delta T, \end{aligned} \tag{5}$$

where ΔM, is given by $\Delta M = M - M^*$, *etc.*

Now we can solve this general system of equations for the special cases of the moments of (say) leptons, by demanding that Eqs. 3 and 4 are satisfied. This general analysis and some numerical results for the case of d_e, d_n for the trlinear $\not{R}_p$ case are presented in the next section.

B. Expected fermion mass dependencies of the dipole moments.

Leptonic Moments:
Let us start with the case of lepton moments. For any diagram to give a nonzero contribution to the dipole moment of a lepton, Eqs. 3 and 4 need to be satisfied. Using Eqs. 5 we then get,

$$\begin{aligned} \Delta N &= 1 - \Delta R \\ \Delta M &= \Delta R - 1 \\ \Delta P &= 1 - \Delta R - \Delta T \\ \Delta L &= 0, \Delta S = \Delta T. \end{aligned} \tag{6}$$

It is clear that any dipole moment $\mathcal{D}_l$ that this diagram can give rise to will be

$$\mathcal{D}_l \propto m_{l_i}^{R+R^*} m_{d_j}^{P+P^*} m_{u_k}^{S+S^*} (m_{u_l} m_{d_l})^{T+T^*}$$

with an appropriate numbers of the large masses (at least M_W or M_{SUSY} depending on the graph) coming from the loops in the denominator to give the right dimension. Here, m_{l_i}, m_{u_k} and m_{d_j} denote *some* lepton, up type quark and down type quark mass.

Notice that in the SM or in SUSY in absence of $\not{R}_p$ interactions, we have $\Delta L = \Delta M = \Delta N = 0$. This in turn means that $\Delta R = 1$. I.e., R or R^* must be

TABLE I: The change in the charges $Q_{l_L}, Q_{e_R}, Q_{q_L}, Q_{u_R}$ and Q_{d_R} as defined in the text for different interactions that might be present in SUSY models with MSSM field content. Gauge and gaugino interactions or Higgs and Higgsino self interactions do not change any of these charges.$\mathcal{H}^0$ indicates any of the neutral Higgs bosons in the MSSM.

Interaction	ΔQ_{l_L}	ΔQ_{e_R}	ΔQ_{q_L}	ΔQ_{u_R}	ΔQ_{d_R}
Lepton Yukawa Interactions	-1	+1	0	0	0
Up quark Yukawa Interactions	0	0	-1	+1	0
Down quark Yukawa Interactions	0	0	-1	0	+1
$\mathcal{H}^0 H^- \tilde{d}_R^* \tilde{u}_R$, $H^- \tilde{d}_R^* \tilde{u}_R$	0	0	0	-1	+1
$l_{ijk} L_i L_j E_k^c$ interactions	-2	+1	0	0	0
$\lambda'_{ijk} L_i Q_j D_k^c$ interactions	-1	0	-1	0	1
$\lambda''_{ijk} U_i^c D_j^c D_k^c$ interactions	0	0	0	1	2

non-zero and hence the dipole moment has to be proportional to *some* lepton mass. Since there is no lepton flavour violation in the SM or the MSSM, the moment $\propto m_l$. Further, in presence of $\not{R}_p$, i.e, with nontrivial values of $\Delta M, \Delta N$, nonzero lepton moment is possible ONLY with an insertion of down-type OR lepton Yukawa insertion. With $\not{R}_p$ there is also lepton flavour violation and one may get an enhancement of the lepton moment **relative to SM/MSSM** by m_b/m_l. The last of Eqs. 6 tells us further that up-type quark masses enter only as even powers so that these can never be the sole source of the required chirality flip for a lepton dipole moment. Indeed these masses have to be *in addition to* the lepton or down type mass as mentioned above, and so will necessarily be accompanied by the same power of some high mass in the denominator, and so will actually suppress the moment.

down-type quark moments:

For this case it is the Eqs. 7 analogous to the earlier Eqs. 6 that need to be satisfied.

$$\begin{aligned} \Delta M &= 1 - \Delta P - \Delta T \\ \Delta N &= \Delta P - 1 + \Delta T \\ \Delta R &= 1 - \Delta P - \Delta T \\ \Delta L &= 0, \Delta S = \Delta T. \end{aligned} \quad (7)$$

As in the previous case, we can easily see that for the SM/MSSM, the dipole moments will be proportional to *some* down type quark mass, as it would vanish in the absence of all down-type Yukawa couplings. Again the $\not{R}_p$ contributions to the dipole moments of down-type quarks are nonzero only if either ΔR or ΔP are non-zero, and thus are proportional either to a lepton mass or a down-type quark mass. Thus again no big enhancement involving the large top quark mass is possible.

up-type quark moments:

Now the conditions for the edm to be nonzero are given by

$$\begin{aligned} \Delta R &= -\Delta N \\ \Delta P &= \Delta N - \Delta T \\ \Delta M &= -\Delta N \\ \Delta L &= 0, \Delta S = 1 + \Delta T. \end{aligned} \quad (8)$$

In this case a solution *without* an up-type Yukawa interaction is not allowed as opposed to the earlier two cases where a solution was allowed where a single power of quark (lepton) mass could appear for the lepton (quark) moment. Further, the leading mass dependence of an up-quark moment generated by $\not{R}_p$ interactions is necessarily an up-type mass.This happens because neither the ł or the λ' interactions involve a $\tilde{u}_R$ or u_R.

We also see that for contributions that will involve only the λ'' part of the $\not{R}_p$ interactions, the dipole moment for the down quark will thus be proportional to $m_{d_i} m_{u_i}^{2n}$ as opposed to the up quark moment which will be proportional to $m_{u_i} m_{d_i}^{2n}$ $(n = 0, 1, 2...)$. This is in agreement with the result for the edm due to the λ'' couplings that was derived long ago [21].

One can make a few more general comments. We observe that it is not possible to get an enhancement of the dipole moments by a factor of m_t/m_f in $\not{R}_p$ theories similar to the case of theories with general lepto-quarks [17], even though the squarks/sleptons do play the role of lepto-quarks which have $\not{L}$ or $\not{B}$ interactions. This is simply due to the fact that as opposed to the case of a general lepto-quark, in SUSY with $\not{R}_p$ the couplings of the sfermions are chiral as a result of the supersymmetry. This allowed the charge assignment made in Eqs. 2 in the first place. The chiral nature of the couplings, therefore, forbids the enhancement of dipole moments of the leptons and down-type quarks as compared to the expectations in the SM/MSSM, by a factor of m_t/m_l or m_t/m_d. Let us also add here that the mass dependencies obtained

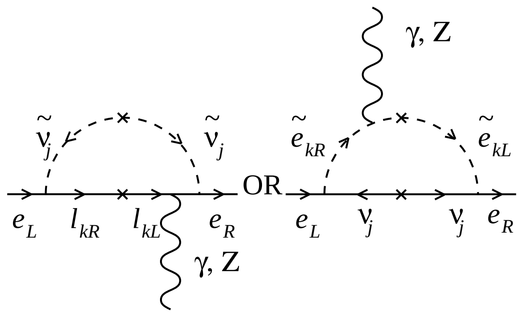

FIG. 2: Possible one loop diagrams diagram in $\not{R}_p$ theories, which may contribute to the edm.

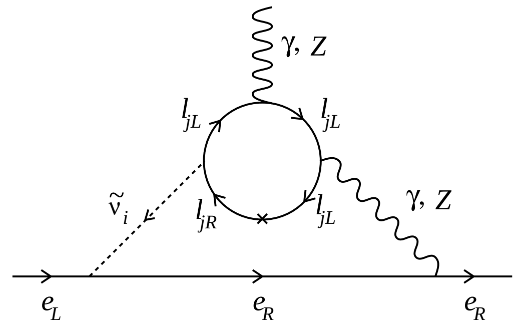

FIG. 3: An example of the leading two-loop contribution to the edm of electron due to ł couplings.

by our analysis match with the results in the literature whenever explicit computations are available. Refs. [21, 22] are examples of such earlier computations.

Numerical estimates for EDMs

Of course nowhere in the analysis so far we specialised to the case of the edm. For the edm to be nonzero, the diagram should be complex. Again, if we look at the various conditions given by Eqs. 6, 7 and 8, we see that to the lowest order, the $\not{R}_p$ contribution to a dipole moment needs $N = N^* = 1$ or $M = M^* = 1$. Our framework then tells us that the diagram $\propto |\lambda|^2$ or $\lambda'|^2$. Thus it is clear that one loop diagram thus can not contribute to edm, with just the trilinear $\not{R}_p$ couplings.

This analysis assumed NO lepton number violation in the sneutrino masses. In the presence of such a violation, Majorana type ν masses required by SUSY and a left-right mixing in the charged slepton masses, one loop diagrams shown in Figure 2 can exist and may give rise to an edm of the electron. However, we expect such contribution to be severely limited by the constraints on the ν masses. For bilinear $\not{R}_p$ violation the situation is different [23] and I shall comment on it later.

Having established that the dominant contributions to the fermion EDMs from the trilinear $\not{R}_p$ couplings, can arise only at the two loop level, we studied various different types of two loop diagrams which would achieve this. Here I discuss a few examples.

The diagram in Figure 3 corresponds to the case $N = N^* = 1$. As mentioned before, the contribution to the dipole moment then should be proportional to some m_{l_j} which need not be the mass of the external lepton (electron in this case). This amplitude involves two *different* ł couplings and hence is complex in general. Here the source of the complex nature of the amplitude and hence for the edm, is the irremovable phases of the $\not{R}_p$ couplings. The order of magnitude of the real part of the edm is estimated as the product of explicit factors of couplings, mass insertions and colour factors, a factor of $1/(4\pi^2)$ for each loop, and finally appropriate powers of the "large mass" ($m_{\tilde{\nu}}$ in this case) in the denominator to get the appropriate dimension. We then take the edm to be the imaginary part ($\Im$) of this product. What we obtain is clearly an overestimate since in practice the different diagrams may interfere destructively with each other. For the diagram shown in Figure 3 the contribution can be estimated to be:

$$d_e \sim \frac{(e^2, g_Z^2)}{4\pi^2}\frac{1}{4\pi^2}\Im\left[\sum_{ij,i\neq 1,j} m_{l_j}\lambda^*_{ijj}\lambda_{i11}\frac{1}{m^2_{\tilde{\nu}_i}}\right]. \quad (9)$$

Eq. 9 reflects the enhancement by m_τ/m_e as expected from our earlier general analysis and it is noteworthy that this enhancement is obtained without paying any price for mixing angles.

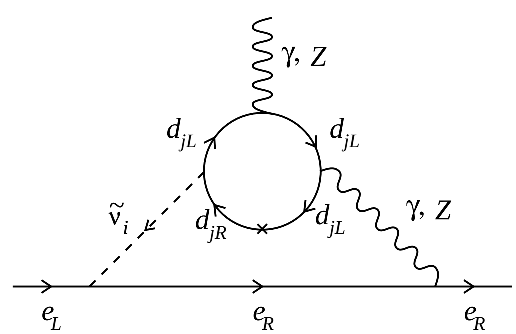

FIG. 4: An example of the leading two-loop contribution to the edm of electron due to ł and λ' couplings.

The diagram shown in Figure 4 corresponds to $\Delta M = -1, \Delta N = 1, \Delta P = 1$ but with $\Delta R = 0$. This gives an enhancement of the edm of the electron by a factor of m_b/m_e as we have already discussed and the dominant part of the corresponding estimated contribution to d_e is given by,

$$d_e \sim \frac{(e^2, g_Z^2)}{4\pi^2}\frac{1}{4\pi^2}m_b\Im\left[\sum_{i\neq 1} 3\lambda'^*_{i33}\lambda_{i11}\frac{1}{m^2_{\tilde{\nu}_i}}\right], \quad (10)$$

where a colour factor of 3 has been inserted.

Among the large number of possible two loop diagrams, those involving the Higgs exchanges will all lead to contributions proportional to m_e or even higher powers in agreement with the expectations from our general rules and others will be similar to the one given by Eq. 10 with the masses of the charged sleptons replacing those of the sneutrino etc.

These two represent the dominant contributions and the current constraints on the edm of the electron can be translated into a limit on products of ł and λ' couplings, as given by Eq. 11 below.

$$\Im\left(l_{211} l^*_{233}\right) \ < \ 5\times 10^{-4}\left(\frac{\tilde{m}}{1TeV}\right)^2$$
$$\Im \sum_{i\neq 1} l_{i11}\lambda'^*_{i33} \ < \ 0.6\times 10^{-4}\left(\frac{\tilde{m}}{1TeV}\right)^2. \quad (11)$$

Here $\tilde{m}$ stands for the mass of the appropriate SUSY scalar.

We can analyse the EDMs of the d-type quark and u-type quark in a similar fashion and then use those results in conjunction with the neutron edm to constrain the different $R\!\!\!/_p$ couplings. For example, diagrams for the d quark similar to the one shown in Figure 3, replacing the ł couplings by λ' couplings and the sparticle masses appropriately, lead using current experimental result $d_n < 6.0\times 10^{-26}$ e cm, to

$$\Im\left[\sum_k \lambda'_{k11}\lambda'^*_{k33}\right] < 10^{-2}\left(\frac{\tilde{m}}{1TeV}\right)^2. \quad (12)$$

Given the level of (justified) approximations made in getting our theoretical estimates for the quark edms, it did not make sense to include in our analysis the long distance effects in relating the neutron edm d_n to d_u, d_d. We further approximated d_n by d_d [18].

C. Limits obtained using d_{Hg}

As already mentioned in the introduction, for d_{Hg} the SM predictions themselves can be competitive with the accuracy of the experimental measurements. A recent analysis of the hadronic edm in the presence of $R\!\!\!/_p$ interactions [14], invokes one particular model to relate the CP violation in the effective quark interactions to that giving rise to a hadronic edm. They use a one pion-exchange model with CP-odd pion-nucleon interactions, generated through CP violating four quark interactions which in turn are caused λ' couplings. Limits on the $R\!\!\!/_p$ couplings improve using the predictions for d_{Hg} as compared to those from d_n, by an order of magnitude. Of course this limit has a model dependence.

D. Bilinear $R\!\!\!/_p$

As mentioned already, in the presence of bilinear $R\!\!\!/_p$, there are also soft SUSY breaking scalar bilinear terms and our analysis needs to be modified. An important difference is that in the presence of the scalar bilinear terms the sneutrino fields generically acquire a *vev*, so that the charge Q_{l_L} is now no longer conserved. In principle, it would be possible to include modifications to our analysis by allowing diagrams where sneutrino fields disappear or are created from the vacuum: but the result then depends on the number of fields that disappear into, or are created from, the vacuum and the simple predictions that we have obtained are lost. Our analysis clearly is inadequate when the bilinear mass term and the sneutrino VEV's are of the same order. In fact for the case of bilinear $R\!\!\!/_p$, dominant one loop $R\!\!\!/_p$ contributions to the EDMs can exist [23] and can usefully constrain, along with ν masses, the $R\!\!\!/_p$ couplings. It may be interesting to do a more general analysis including both the bilinear and the trilinear $R\!\!\!/_p$ interaction terms and understand the issue in an unified fashion.

III. CONCLUSIONS

In conclusion we presented a general analysis for obtaining the fermion mass dependence of the induced dipole moment operator. We illustrated it with an example for the case of trilinear $R\!\!\!/_p$ interactions. The estimates we obtain agree with the ones present in literature when they are available. Our results show that the unlike the lepto-quark model big enhancements by factors of m_t/m_f do not occur in this case. The analysis needs to be modified for including the bilinear $R\!\!\!/_p$ terms.

IV. ACKNOWLEDGMENTS

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