The effect of antisymmetric tensor unparticle mediation on the charged lepton electric dipole moment

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Abstract

We study the contribution of antisymmetric tensor unparticle mediation to the charged lepton electric dipole moments and restrict the free parameters of the model by using the experimental upper bounds. We observe that the charged lepton electric dipole moments are strongly sensitive to the the scaling dimension d_U and the fundamental scales M_U and Λ_U. The experimental current limits of electric dipole moments are reached for the small values of the scaling dimension d_U.

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The CP violation which leads to the unequal amounts of matter and antimatter in the universe needs more accurate theoretical explanation. The electric dipole moments (EDMs) of fermions are driven by the CP violating interaction and, therefore, their search, especially the charged lepton EDMs[1], is worthwhile in order to understand the CP violation mechanism. The current experimental limits of the electron, muon and tau EDMs are $d_e = (0.7 \pm 0.7) \times 10^{-27} e\,cm$ [1] $d_\mu = (3.7 \pm 3.4) \times 10^{-19} e\,cm$ [2] and Re$[d_\tau]= -0.22$ to $0.45 \times 10^{-16} e\,cm$; Im$[d_\tau]= -0.25$ to $0.008 \times 10^{-16} e\,cm$ [3], respectively. These experimental results stimulate the search of the lepton EDMs in the framework of various theoretical models. In the standard model (SM) the source of the CP violation and, therefore the EDM, is the complex Cabibo Kobayashi Maskawa (CKM) matrix in the quark sector and the lepton mixing matrix in the lepton sector. However the EDM predictions in the SM are negligible and far from their current experimental limits. Therefore one goes beyond the SM such as multi Higgs doublet models (MHDM), supersymmetric model (SUSY) [4], left-right symmetric model, the seesaw model, the models including the extra dimensions and noncommutative effects,... etc., in order to get the additional CP violating phase (see for example [5]-[9]). Another possibility for a new CP violating phase is to consider the recent unparticle idea which is proposed by Georgi [10, 11]. Unparticles are new degrees of freedom arising from the SM-ultraviolet sector interaction at some scale M_U and, because of the scale invariance, they are massless and have non integral scaling dimension d_U, around the scale $\Lambda_U \sim 1.0\,TeV$. The effective interaction of the SM-ultraviolet (UV) sector at the scale M_U reads

$$\mathcal{L}_{eff} = \frac{C_n}{M_U^{d_{UV}+n-4}} \, O_{SM} \, O_{UV} \, , \tag{1}$$

with the scaling dimension d_{UV} of the UV operator [13] and, around the scale Λ_U, it appears as (see [14], [15] and references therein)

$$\mathcal{L}_{eff} = \frac{C_n^i}{\Lambda_n^{d_U+n-4}} \, O_{SM,i} \, O_U \, , \tag{2}$$

where

$$\Lambda_n = \left(\frac{M_U^{d_{UV}+n-4}}{\Lambda_U^{d_{UV}-d_U}} \right)^{\frac{1}{d_U+n-4}} \, , \tag{3}$$

and n is the scaling dimension of SM operator of type i. Here the scale Λ_n is sensitive to the scaling dimension n of the SM operator $O_{SM,i}$ [14, 15] and depends on the fundamental scales M_U, Λ_U[2].

[1] They are clean theoretically since they are free from strong interactions.

[2] $\Lambda_2 < M_U < \Lambda_4 < \Lambda_3$ with the choice $1 < d_U < 2 < d_{UV}$ (see [14]).

In the present work, we consider that the new CP violating phase is coming from the effective unparticle fermion interaction and we predict the charged lepton EDMs (see [16] for the scalar unparticle contribution to the charged lepton EDM). Here we assume that the antisymmetric tensor unparticle mediation gives the contribution to the lepton EDM[3] by respecting the following conditions:

- The scale Λ_n in the effective Lagrangian depends on the dimension of the SM operator $O_{SM,i}$,
- antisymmetric tensor unparticle-lepton couplings are complex,
- the scale invariance is broken at some scale μ after the electroweak symmetry breaking due to the additional interaction $\sim \frac{\lambda_2}{\Lambda_2^{du-2}}\, O_S\, H^\dagger\, H$ where H (O_S) is the SM Higgs (scalar unparticle operator which exists with the antisymmetric tensor unparticle) [17, 18].

The two point function of antisymmetric tensor unparticle reads (see Appendix for details)

$$\int d^4x\, e^{ipx} \;< 0|T\Big(O_U^{\mu\nu}(x)\, O_U^{\alpha\beta}(0)\Big)0 >= i\, \frac{A_{d_U}}{2\, sin\, (d_U \pi)}\, \Pi^{\mu\nu\alpha\beta}(-p^2 - i\epsilon)^{d_U - 2}\,, \tag{4}$$

where the factor A_{d_U} is

$$A_{d_U} = \frac{16\, \pi^{5/2}}{(2\, \pi)^{2\, d_U}}\, \frac{\Gamma(d_U + \frac{1}{2})}{\Gamma(d_U - 1)\, \Gamma(2\, d_U)}\,. \tag{5}$$

Here $\Pi^{\mu\nu\alpha\beta}$ is the projection operator

$$\Pi_{\mu\nu\alpha\beta} = \frac{1}{2}(g_{\mu\alpha}\, g_{\nu\beta} - g_{\nu\alpha}\, g_{\mu\beta})\,, \tag{6}$$

and it can be divided into the transverse and the longitudinal parts as

$$\Pi^T_{\mu\nu\alpha\beta} = \frac{1}{2}(P^T_{\mu\alpha}\, P^T_{\nu\beta} - P^T_{\nu\alpha}\, P^T_{\mu\beta})\,, \quad \Pi^L_{\mu\nu\alpha\beta} = \Pi_{\mu\nu\alpha\beta} - \Pi^T_{\mu\nu\alpha\beta}\,, \tag{7}$$

with $P^T_{\mu\nu} = g_{\mu\nu} - p_\mu\, p_\nu/p^2$ (see for example [15] and references therein). Furthermore, the scale invariance breaking at the scale μ results in that the antisymmetric tensor unparticle propagator is modified. The propagator is model dependent (see for example [19] for the scalar unparticle case) and we consider the one in the simple model [17, 20]:

$$\int d^4x\, e^{ipx} \;< 0|T\Big(O_U^{\mu\nu}(x)\, O_U^{\alpha\beta}(0)\Big)0 >= i\, \frac{A_{d_U}}{2\, sin\, (d_U \pi)}\, \Pi^{\mu\nu\alpha\beta}(-(p^2 - \mu^2) - i\epsilon)^{d_U - 2}\,. \tag{8}$$

[3]The contribution of the antisymmetric tensor unparticle mediation to the muon anomalous magnetic dipole moment and its effects in Z invisible decays and the electroweak precision observable S has been predicted in [15].

Here μ is the scale where unparticle sector changes in to the particle sector.

Now we start with the effective Lagrangian responsible for the EDM of charged leptons[4]:

$$\begin{aligned} \mathcal{L}_{eff} &= \frac{g'\,\lambda_B}{\Lambda_2^{d_U-2}}\,B_{\mu\nu}\,O_U^{\mu\nu} + \frac{g\,\lambda_W}{\Lambda_4^{d_U}}\,(H^\dagger\,\tau_a\,H)\,W^a_{\mu\nu}\,O_U^{\mu\nu} \\ &+ \frac{y_l}{\Lambda_4^{d_U}}\Big(\lambda_l\,\bar{l}_L\,H\,\sigma_{\mu\nu}\,l_R + \lambda_l^*\,\bar{l}_R\,H^\dagger\,\sigma_{\mu\nu}\,l_L\Big)\,O_U^{\mu\nu}\,, \end{aligned} \tag{9}$$

with the lepton field l and the complex coupling $\lambda_l = |\lambda_l|\,e^{i\,\theta_l}$ where θ_l is the CP violating parameter.

The effective EDM interaction for a charged lepton l reads

$$\mathcal{L}_{EDM} = i d_l\,\bar{l}\,\gamma_5\,\sigma^{\mu\nu}\,l\,F_{\mu\nu}\ , \tag{10}$$

where $F_{\mu\nu}$ is the electromagnetic field tensor and 'd_l', which is a real number by hermiticity, is the EDM of the charged lepton. Finally, the effective Lagrangian in eq.(9) leads to the EDM of charged leptons l after electroweak breaking as (see Appendix for details):

$$d_l = -i(\lambda_l - \lambda_l^*)\,\frac{e\,\mu^{2\,(d_U-2)}\,A_{d_U}\,m_l}{2\,sin\,(d_U\pi)\,\Lambda_4^{d_U}}\left(\frac{\lambda_B}{\Lambda_2^{d_U-2}} - \frac{v^2\,\lambda_W}{4\,\Lambda_4^{d_U}}\right), \tag{11}$$

where v is the vacuum expectation value of the SM Higgs H^0.

Discussion

In this section we predict the intermediate antisymmetric tensor unparticle contribution (see Fig.1) to the charged lepton EDMs by considering that the CP violating phase is carried by the tensor unparticle-charged lepton couplings and try to restrict the free parameters of the model by using the experimental upper bounds of the charged lepton EDMs. The scaling dimension of UV operator O_{UV} (the unparticle operator O_U) d_{UV} (d_U), the fundamental scales of the model, namely the interaction scale M_U of the SM-ultraviolet sector and interaction scale Λ_U of the SM-unparticle sector and the scale μ which is responsible for the flow of unparticle sector in to the particle one are among the free parameters. In our numerical calculations we choose the scale dimension d_U in the range[5] $1 < d_U < 2$ and $d_{UV} > d_U = 3$ (see [14] and [15]) and we choose $\mu \sim 1.0\,GeV$. The couplings λ_B, λ_W and λ_l are other free parameters which should be

[4] Here we used the effective Lagrangian given in [15] and choose the unparticle-lepton coupling complex in order to switch on the CP violation. In this equation H is the Higgs doublet, g and g' are weak couplings, λ_B and λ_W are the unparticle-field tensor couplings, $B_{\mu\nu}$ is the field strength tensor of the $U(1)_Y$ gauge boson $B_\mu = c_W\,A_\mu + s_W\,Z_\mu$ and $W^a_{\mu\nu}$, $a = 1, 2, 3$, are the field strength tensors of the $SU(2)_L$ gauge bosons with $W^3_\mu = s_W\,A_\mu - c_W\,Z_\mu$ where A_μ and Z_μ are photon and Z boson fields respectively.

[5] For antisymmetric tensor unparticle the scale dimension should satisfy $d_U > 2$ not to violate the unitarity

restricted. We take $\lambda_B = \lambda_W = 1$ and choose complex λ_l, $\lambda_l = |\lambda_l|\, e^{i\,\theta_l}$ with the CP violating parameter θ_l, in order to create the EDM. Here we assume that the couplings $|\lambda_l|$ obey the mass hierarchy of charged leptons, $|\lambda_\tau| > |\lambda_\mu| > |\lambda_e|$ and we take $|\lambda_\tau| = 1$, $|\lambda_\mu| = 0.1$ and $|\lambda_e| = 0.005$.

In the first part of the calculation we restrict the CP violating parameter θ_μ by assuming that the antisymmetric unparticle tensor contribution to muon anomalous magnetic moment reaches to the experimental upper limit $a_\mu = 10^{-9}$ and we study its contribution to the EDM of muon d_μ. Furthermore we predict the EDMs of electron and tau lepton and estimate the acceptable values of the free parameters by taking the intermediate numerical value of the CP violating parameter, namely $sin\theta_e = sin\theta_\tau = 0.5$. Finally we study the CP violating parameter dependence of EDMs.

In Fig.2, we present M_U dependence of the EDM d_μ for $a_\mu^U = 10^{-9}$ and different values of the scale parameter d_U and the ratio $r_U = \frac{\Lambda_U}{M_U}$. Here upper-lower-the lowest solid (dashed-long dashed; dotted) line represents the EDM for $d_U = 1.1$, $r_U = 0.40 - 0.10 - 0.05$ ($d_U = 1.3$, $r_U = 0.40 - 0.10$; $d_U = 1.5$, $r_U = 0.40$). It is observed that d_μ is strongly sensitive to the ratio r_U and the increasing values of r_U causes the enhancement in d_μ. To reach the current experimental limit r_U must be at least of the order of $r_U \sim 10^{-1}$ if the scaling dimension satisfies $d_U > 1.1$. For larger values of d_U the higher values of r_U are accepted. The dependence of d_μ to the mass scale M_U is also strong especially for the large values of the scaling dimension and it decreases more than one order in the range $10^3\, GeV < M_U < 10^4\, GeV$ for $d_U \sim 1.5$ and more.

Fig.3 and Fig.4 are devoted to d_μ with respect to the scale parameter d_U for $a_\mu^U = 10^{-9}$ and $a_\mu^U = 10^{-10}$, respectively. Here upper-lower solid (long dashed; dashed; dotted) line represents the EDM for $r_U = 0.05, M_U = 10^3\, GeV$-$r_U = 0.05, M_U = 10^4\, GeV$ ($r_U = 0.1, M_U = 10^3\, GeV$-$r_U = 0.1, M_U = 10^4\, GeV$; $r_U = 0.4, M_U = 10^3\, GeV$-$r_U = 0.4, M_U = 10^4\, GeV$; $r_U = 0.5, M_U = 10^3\, GeV$-$r_U = 0.5, M_U = 10^4\, GeV$). For the decreasing values of the ratio r_U d_U becomes more restricted and with its the increasing values the current experimental value can be reached. If the contribution of the antisymmetric tensor unparticle to the anomalous magnetic moment of muon is taken as $a_\mu^U = 10^{-10}$ (see Fig.4) the restriction of d_U is more relaxed and for higher values of the ratio r_U it would be possible to reach the current experimental value of d_μ similar

(see [21]). Here we assumed that the scale invariance is broken at some scale μ and the restriction on the values of d_U is more relaxed. We used the simple model [17, 20] to define the new propagator. Since this model ensures a connection with the particle sector, we choose d_U in the range $1 < d_U < 2$ and when d_U tends to one one reaches the particle sector and the connection is established. Since this choice brings a rough connection between two sectors, unparticle and particle sectors, we believe that it is worthwhile to study even if it needs more careful analysis whether its is consistent with the QFT.

to the previous case.

Fig.5 (6) represents M_U dependence of the EDM d_e (d_τ) for $sin\theta_e = 0.5$ ($sin\theta_\tau = 0.5$) and for different values of the scale parameter d_U and the ratio r_U. Here the upper most-upper-lower-the lowest solid; dashed line represents the d_e (d_τ) for $d_U = 1.1 - 1.3 - 1.5 - 1.8$, $r_U = 0.05$; $r_U = 0.10$. We see that the increasing values of M_U (r_U) cause the decrease (increase) in the EDM. The current experimental limit of d_e is reached for r_U which is at the order of the magnitude of 10^{-2} in the case of small values of the scaling dimension d_U. r_U can take the values of the order of 10^{-1} for $1.3 < d_U < 1.5$. This can be seen also in Fig.7 which represents d_U dependence of d_e where upper-lower solid (long dashed; dashed; dotted) line represents the EDM for $r_U = 0.05, M_U = 10^3\,GeV$-$r_U = 0.05, M_U = 10^4\,GeV$ ($r_U = 0.1, M_U = 10^3\,GeV$-$r_U = 0.1, M_U = 10^4\,GeV$; $r_U = 0.4, M_U = 10^3\,GeV$-$r_U = 0.4, M_U = 10^4\,GeV$; $r_U = 0.5, M_U = 10^3\,GeV$-$r_U = 0.5, M_U = 10^4\,GeV$). For the large values of the ratio r_U the scaling dimension d_U must be near $d_U \sim 2.0$ in order to get the current experimental value of d_e. On the other hand Fig.6 shows that one needs the ratio $r_U \sim 0.5$ and the small values of the scaling dimension, $d_U \sim 1.1$ in order to reach the current experimental value of d_τ (see also Fig.8 which is the same as the Fig.7 but for d_τ).

Finally we plot the EDM d_e (d_τ) with respect to the CP violating parameter $sin\theta_e$ ($sin\theta_\tau$) in Fig.9 (10). For both figures upper-lower solid; long dashed; dashed; dotted line represents[6] the d_e (d_τ) for $M_U = 10^3\,GeV$-$M_U = 10^4\,GeV$, $r_U = 0.05$, $d_U = 1.1$; $r_U = 0.05$, $d_U = 1.3$; $r_U = 0.1$, $d_U = 1.1$; $r_U = 0.1$, $d_U = 1.3$. These figures show that d_e and d_τ are enhanced at least one order in the range of the CP violating parameter, $0.1 < sin\theta_\tau < 0.9$

Now we would like to summarize our results: The charged lepton EDMs are strongly sensitive to the parameters used, namely the scaling dimension d_U, the ratio r_U and the mass scale M_U. We observe that the experimental current limits of d_e and d_μ are reached in the case that the ratio r_U lies in the range of $0.05 - 0.20$ and the scaling dimension d_U is near $1.1 - 1.2$. However for the current experimental value of d_τ the ratio must reach to the values $r_U \sim 0.5$ for the small values of the scaling dimension, $d_U \sim 1.1$.

For completeness, we compare the theoretical framework and the numerical results of the present work with the study [16] which is related to the contribution of scalar unparticle on the charged lepton EDM. In the present case the tensor unparticle contribution is in the tree level, however in [16] the scalar unparticle contribution is at one loop level. In addition to this, in the present work, we assume that the scale invariance is broken at some scale μ after the

[6]Notice that the dotted line which represents $r_U = 0.1$, $M_U = 10^3\,GeV$, $d_U = 1.3$ almost coincides with the one which represents $r_U = 0.05$, $M_U = 10^3\,GeV$, $d_U = 1.1$ and it is not observed in the figure

electroweak symmetry breaking and, therefore, the antisymmetric tensor unparticle propagator is modified. In [16] the scale invariance is intact and the propagator is the original one. In both cases the charged lepton EDMs are strongly sensitive to the scaling dimension d_U and the experimental current limit of d_e can be reached in the range $1.6 \leq d_U \leq 1.8$ (near $1.1 - 1.2$) for scalar unparticle mediation (tensor unparticle mediation). For d_μ and d_τ the current limits are reached for the small values of the scale d_U, $d_U \leq 1.1$, for both cases.

Hopefully, with in future more accurate measurements of the lepton EDMs it would be possible to eliminate this discrepancy. These new measurements will give strong information about the role of unparticle scenario on the CP violation mechanism and the nature of unparticles.

Appendix

Here we would like to present the calculation of the charged lepton EDM (see eq.(11)) by using the effective lagrangian given in eq.(9). The first (second) term in the effective lagrangian drives the $O_U^{\mu\nu} \to A_\nu$ transition which is carried by the vertex

$$2\,i\,\frac{g'\,c_W\,\lambda_B}{\Lambda_2^{d_U-2}}\,k_\mu\,\epsilon_\nu O_U^{\mu\nu}\;\Big(-i\,\frac{g\,v^2\,s_W\,\lambda_W}{2\,\Lambda_4^{d_U}}\,k_\mu\,\epsilon_\nu O_U^{\mu\nu}\Big)\,,$$

where ϵ_ν is the outgoing photon four polarization vector. On the other hand the third term in the effective lagrangian results in the vertex

$$\frac{y_l\,v}{\sqrt{2}\,\Lambda_4^{d_U}}\,(\lambda_l-\lambda_l^*)\,\bar{l}\,\gamma_5\,\sigma_{\mu\nu}\,l\,,$$

which creates the EDM interaction. Finally these two vertices are connected by the tensor unparticle propagator (see eq.(8)) and, by extracting the coefficient of $i\,\bar{l}\,\gamma_5\,\sigma^{\mu\nu}\,l\,F_{\mu\nu}$, one gets the EDM of charged leptons as in eq.(11). Now we give a brief explanation how to obtain the tensor unparticle propagator. The starting point is the scalar unparticle propagator which is obtained by respecting the scale invariance. The two point function of scalar unparticle operators reads

$$<0|\Big(O_U(x)\,O_U(0)\Big)0>=\int\frac{d^4P}{(2\,\pi)^4}\,e^{-iP.x}\,\rho(P^2)\,, \tag{12}$$

where $\rho(P^2)$ is the spectral density:

$$\rho(P^2)=A_{d_U}\,\theta(P^0)\,\theta(P^2)\,(P^2)^{\xi}\,. \tag{13}$$

The scale invariance[7] requires a restriction on the parameter ξ, $\xi = d_U - 2$, and, therefore, $\rho(P^2)$ becomes

$$\rho(P^2)=A_{d_U}\,\theta(P^0)\,\theta(P^2)\,(P^2)^{d_U-2}\,. \tag{14}$$

Here the factor A_{d_U} reads

$$A_{d_U}=\frac{16\,\pi^{5/2}}{(2\,\pi)^{2\,d_U}}\,\frac{\Gamma(d_U+\frac{1}{2})}{\Gamma(d_U-1)\,\Gamma(2\,d_U)}\,,$$

in order to get the phase space of d_U massless particles, i.e., unparticle stuff having the scale dimension d_U can be represented as non-integral number d_U of invisible particles [10, 11, 12]. Finally, by using spectral formula, the scalar unparticle propagator is obtained as [11, 12]

$$\int d^4x\,e^{iP.x}<0|T\Big(O_U(x)\,O_U(0)\Big)0>=i\frac{A_{d_U}}{2\,\pi}\int_0^\infty ds\,\frac{s^{d_U-2}}{P^2-s+i\epsilon}=i\,\frac{A_{d_U}}{2\,sin\,(d_U\pi)}\,(-P^2-i\epsilon)^{d_U-2}. \tag{15}$$

[7] The spectral density is invariant under the scale transformation $x \to s\,x$ and $O_U(s\,x) \to s^{-d_U}\,O_U(x)$.

Notice that for $P^2 > 0$, the function $\frac{1}{(-P^2-i\epsilon)^{2-d_U}}$ in eq. (15) reads

$$\frac{1}{(-P^2 - i\epsilon)^{2-d_U}} \rightarrow \frac{e^{-i\, d_U\, \pi}}{(P^2)^{2-d_U}} \,, \qquad (16)$$

which shows that there exists a non-trivial phase due to the non-integral scaling dimension. In the case of tensor unparticle one needs a projection operator $\Pi_{\mu\nu\alpha\beta} = \frac{1}{2}(g_{\mu\alpha}\, g_{\nu\beta} - g_{\nu\alpha}\, g_{\mu\beta})$ which contains the transverse and longitudinal parts and one gets the propagator of antisymmetric tensor unparticle as

$$\int d^4x\, e^{ipx} \, < 0|T\Big(O_U^{\mu\nu}(x)\, O_U^{\alpha\beta}(0)\Big)0 >= i\, \frac{A_{d_U}}{2\, sin\,(d_U\pi)}\, \Pi^{\mu\nu\alpha\beta}(-p^2 - i\epsilon)^{d_U-2} \,.$$

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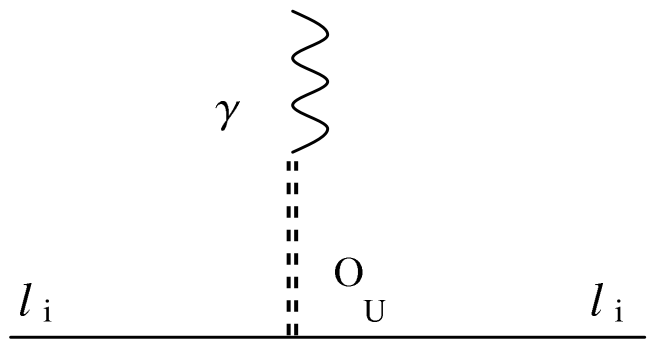

Figure 1: Tree level diagram contributing to the EDM of charged lepton due to tensor unparticle. Wavy (solid) line represents the electromagnetic field (lepton field) and double dashed line the tensor unparticle field.

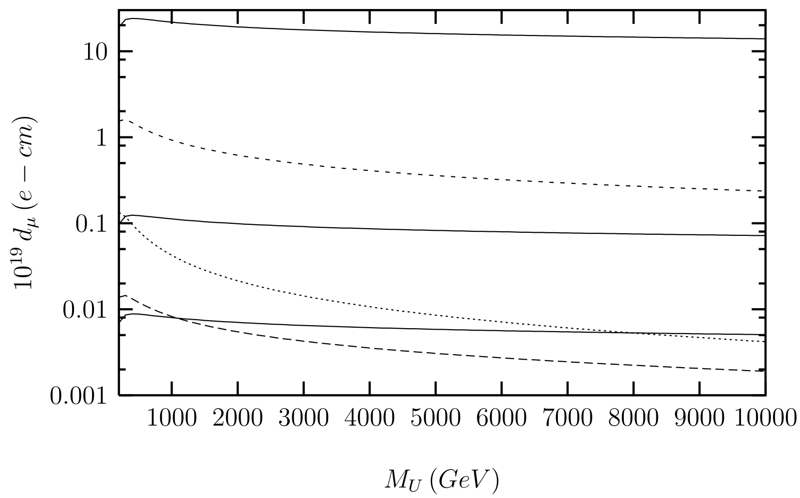

Figure 2: d_μ with respect to M_U for $a_\mu^U = 10^{-9}$. Upper-lower-the lowest solid (dashed-long dashed; dotted) line represents the EDM for $d_U = 1.1$, $r_U = 0.40 - 0.10 - 0.05$ ($d_U = 1.3$, $r_U = 0.40 - 0.10$; $d_U = 1.5$, $r_U = 0.40$).

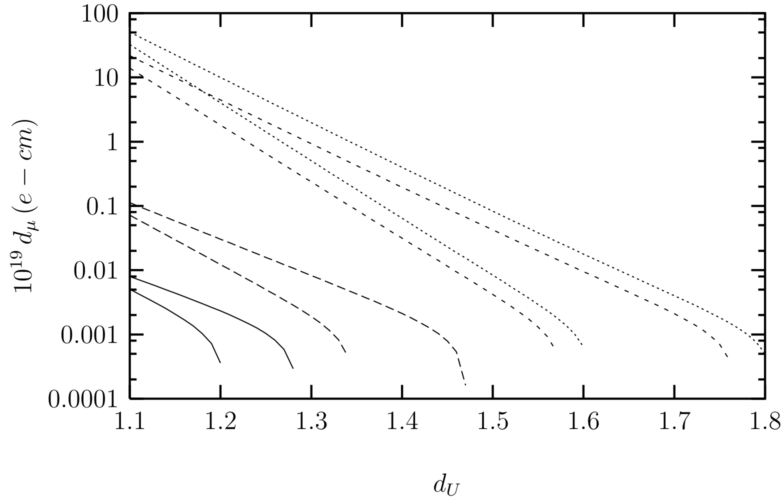

Figure 3: d_μ with respect to the scale parameter d_U for $a_\mu^U = 10^{-9}$. Here upper-lower solid (long dashed; dashed; dotted) line represents the EDM for $r_U = 0.05, M_U = 10^3\, GeV$-$r_U = 0.05, M_U = 10^4\, GeV$ ($r_U = 0.1, M_U = 10^3\, GeV$-$r_U = 0.1, M_U = 10^4\, GeV$; $r_U = 0.4, M_U = 10^3\, GeV$-$r_U = 0.4, M_U = 10^4\, GeV$; $r_U = 0.5, M_U = 10^3\, GeV$-$r_U = 0.5, M_U = 10^4\, GeV$).

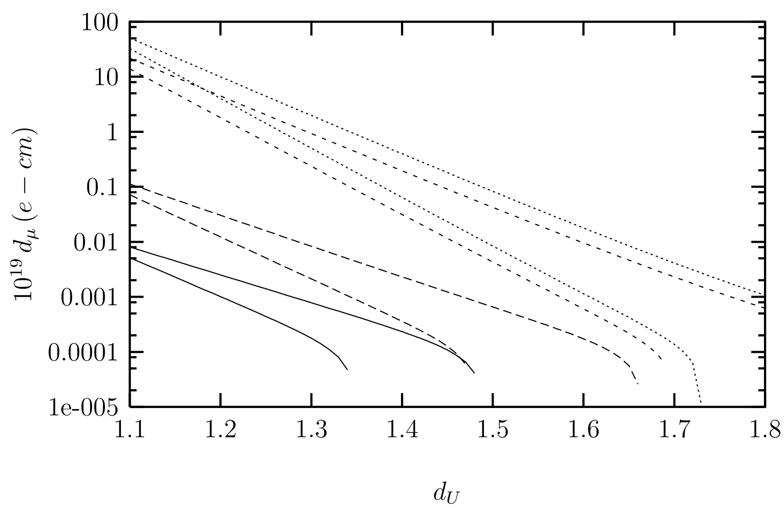

Figure 4: The same as Fig. 3 but for $a_\mu^U = 10^{-10}$.

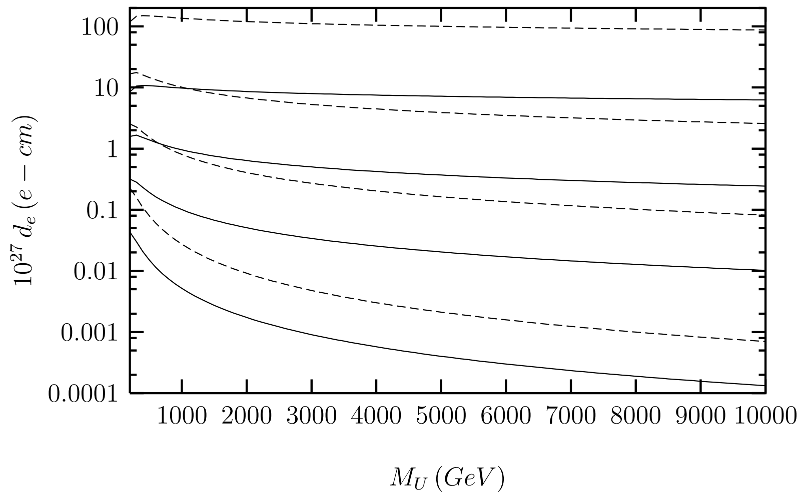

Figure 5: d_e with respect to M_U for $sin\theta_e = 0.5$. Here the upper most-upper-lower-the lowest solid; dashed line represents d_e for $d_U = 1.1 - 1.3 - 1.5 - 1.8$, $r_U = 0.05$; $r_U = 0.10$.

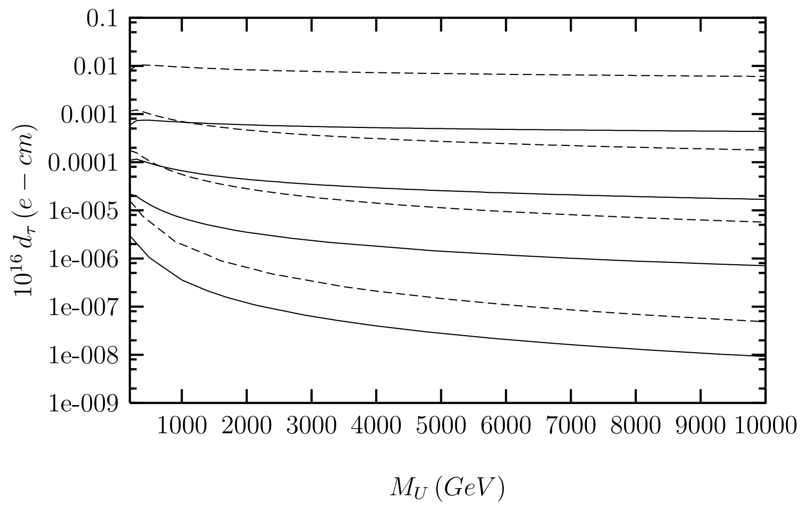

Figure 6: The same as Fig. 5 but for d_τ and $sin\theta_\tau = 0.5$.

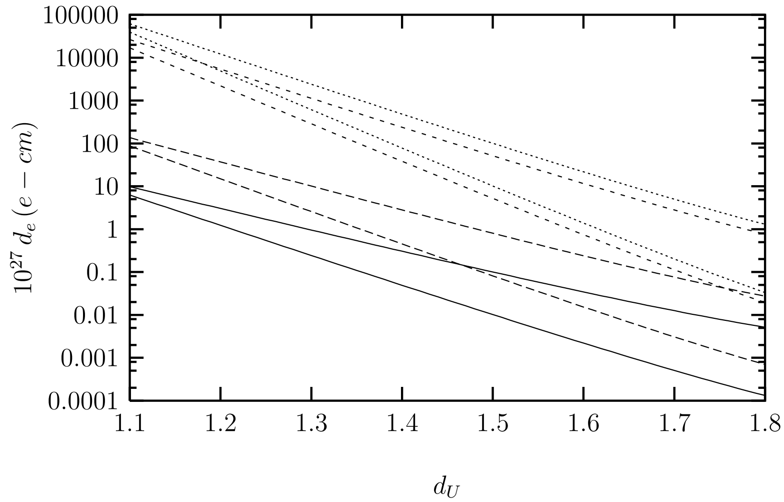

Figure 7: d_e with respect to the scale parameter d_U. Here upper-lower solid (long dashed; dashed; dotted) line represents d_e for $r_U = 0.05, M_U = 10^3\, GeV$-$r_U = 0.05, M_U = 10^4\, GeV$ ($r_U = 0.1, M_U = 10^3\, GeV$-$r_U = 0.1, M_U = 10^4\, GeV$; $r_U = 0.4, M_U = 10^3\, GeV$-$r_U = 0.4, M_U = 10^4\, GeV$; $r_U = 0.5, M_U = 10^3\, GeV$-$r_U = 0.5, M_U = 10^4\, GeV$).

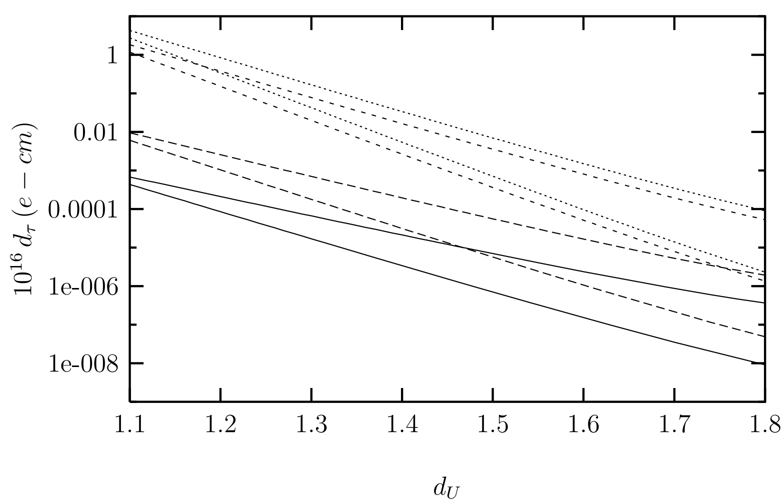

Figure 8: The same as the Fig.7 but for d_τ.

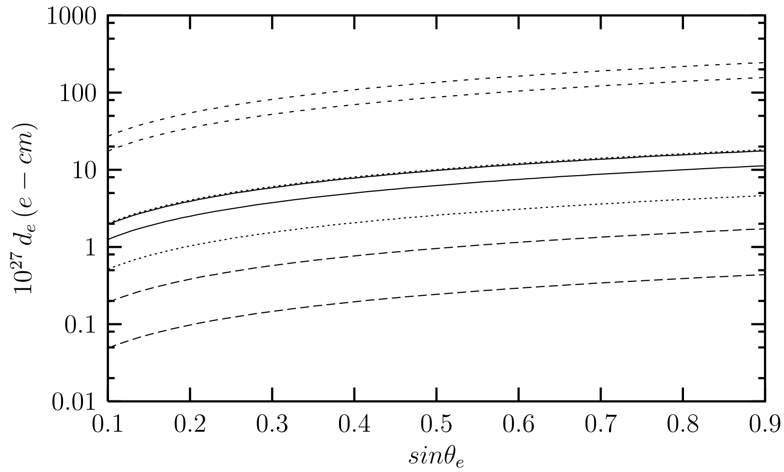

Figure 9: d_e with respect to $sin\theta_e$. Here upper-lower solid; long dashed; dashed; dotted line represents d_e for $M_U = 10^3\, GeV$-$M_U = 10^4\, GeV$, $r_U = 0.05$, $d_U = 1.1$; $r_U = 0.05$, $d_U = 1.3$; $r_U = 0.1$, $d_U = 1.1$; $r_U = 0.1$, $d_U = 1.3$. .

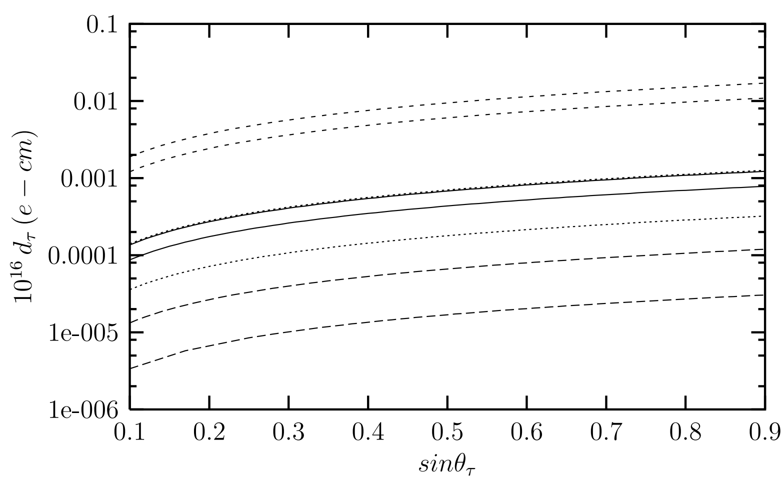

Figure 10: The same as Fig. 9 but for d_τ and with respect to $sin\theta_\tau$.