Some Recent Results from the Complete Theory of Supersymmetry without R-parity

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Supersymmetry without R-parity
IS
the Generic Supersymmetric SM

- minimal superfield spectrum
- SM (gauge) symmetries

as Vs R-parity Violations

R-parity Violating Parameters

- trilinear (superpotential) : λ_{ijk}, λ'_{ijk}, λ''_{ijk}
- bilinear (superpotential) : μ_i
- trilinear & bilinear (soft SUSY breaking) :
- scalar mass mixing (soft SUSY breaking) :

⋆ "sneutrino VEVs"

⟹ **the Complete Theory**

A Purely Phenomenological Approach :-

— a formulation that relies on no *a priori* assumption

— study admissible phenomenology

— check experimental constraints on the various parameters

• need optimal set of independent parameters

— to simplfy analysis

— to remove ambiguity

• **SINGLE-VEV parametrization**

— such an optimal choice of flavor bases

— with RPV effects on tree-level mass matrices for all states (scalars and fermions) maintaining the simplest structure

Supersymmetrizing the SM Matter Fields

— minimal list of **superfields** :-

- holomorphy of superpotential requires
  (at least) two independent Higgs doublets

	fermion	*scalar*
$(3,2)_{1/3}$	$3\ \boldsymbol{Q_i} \longrightarrow$	
$(\bar{3},1)_{-4/3}$	$3\ \boldsymbol{U_i^c} \longrightarrow$	
$(\bar{3},1)_{2/3}$	$3\ \boldsymbol{D_i^c} \longrightarrow$	
$(1,2)_1$		$\longleftarrow \boldsymbol{H_u}$
$(1,2)_{-1}$	$3\ \boldsymbol{L_i} \longrightarrow$	$\longleftarrow \boldsymbol{H_d}$
$(1,1)_2$	$3\ \boldsymbol{E_i^c} \longrightarrow$	

$3\ \hat{Q}_i$

$3\ \hat{U}_i^c$

$3\ \hat{D}_i^c$

$\hat{H}_u$

$4\ \hat{L}_\alpha$

$3\ \hat{E}_i^c$

* extra fermion (higgsino) doublet needed for gauge anomaly cancellation*

WHAT IS R-PARITY ?

- (SM) particles — even
- superparticles — odd

$$\mathcal{R} = (-1)^{3B+L+2S}$$

— B - baryon number
— L - lepton number
— S - spin (of component)

As superfields :-

- $\hat{Q}_i$, $\hat{U}^c_i$, $\hat{D}^c_i$, $\hat{L}_i$, $\hat{E}^c_i$ — odd
- $\hat{H}_u$, $\hat{H}_d$ — even

* $\hat{L}_i$ and $\hat{H}_d$ NOT the same quantum numbers *

R-parity conserving MSSM :

- superparticles have a *categorically different* quantum number
- NO NEUTRINO MASSES !!

Life without R-parity :-

— B violation and L violation

$$W = \varepsilon_{ab}\Big[\mu_\alpha \hat{H}_u^a \hat{L}_\alpha^b + h_{ik}^u \hat{Q}_i^a \hat{H}_u^b \hat{U}_k^C + \lambda'_{\alpha jk} \hat{L}_\alpha^a \hat{Q}_j^b \hat{D}_k^C$$
$$+\lambda_{\alpha\beta k} \hat{L}_\alpha^a \hat{L}_\beta^b \hat{E}_k^C\Big] + \lambda''_{ijk} \hat{U}_i^C \hat{D}_j^C \hat{D}_k^C$$

- proton \(><)/
- neutrinos \(^0^)/ \(^o^)/ \(^0^)/

$$\Downarrow$$

listen to the neutrinos

+

impose **B** (*or baryon parity*)

\(><)/ ⟶ ··· ⟶ \(^0^)/

Parametrization — choice of flavor bases :-

e.g. two 3×3 quark Yukawas $\rightarrow$ 10 parameters

- $h^u_{ik} = \frac{\sqrt{2}}{v_u} V^\dagger_{CKM} \mathrm{diag}\{m_u, m_c, m_t\}$
- $h^d_{jk} = \frac{\sqrt{2}}{v_d} \mathrm{diag}\{m_d, m_s, m_b\}$

SINGLE-VEV parametrization

for SUSY w/o R-parity :-

- **4 $\hat{L}$ flavors $\rightarrow$ SINGLE VEV** $(v_0 \equiv v_d)$

— *no* $\lambda, \lambda', \lambda''$ in fermion mass matrices

— h^u_{ik} and $h^d_{jk} (\equiv \lambda'_{0jk})$ as above

- $+ 3\ \hat{E}^C \longrightarrow h^e_{jk} = \frac{\sqrt{2}}{v_0} \mathrm{diag}\{m_1, m_2, m_3\}$

— but the three m_i's correspond to the physical charged lepton masses *only* when $\mu_i = 0$

(Color-singlet) Charged Fermion Sector :-

$$\mathcal{M}_C = \begin{pmatrix} M_2 & \frac{g_2 v_0}{\sqrt{2}} & 0 & 0 & 0 \\ \frac{g_2 v_u}{\sqrt{2}} & \mu_0 & \mu_1 & \mu_2 & \mu_3 \\ 0 & 0 & m_1 & 0 & 0 \\ 0 & 0 & 0 & m_2 & 0 \\ 0 & 0 & 0 & 0 & m_3 \end{pmatrix}$$

INSTEAD OF

$$\begin{pmatrix} M_2 & \frac{g_2 v_0}{\sqrt{2}} & \frac{g_2 v_1}{\sqrt{2}} & \frac{g_2 v_2}{\sqrt{2}} & \frac{g_2 v_3}{\sqrt{2}} \\ \frac{g_2 v_u}{\sqrt{2}} & \mu_0 & \mu_1 & \mu_2 & \mu_3 \\ 0 & 2\lambda_{\alpha 01} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 11} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 12} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 13} \frac{v_\alpha}{\sqrt{2}} \\ 0 & 2\lambda_{\alpha 02} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 21} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 22} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 23} \frac{v_\alpha}{\sqrt{2}} \\ 0 & 2\lambda_{\alpha 03} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 31} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 32} \frac{v_\alpha}{\sqrt{2}} & 2\lambda_{\alpha 33} \frac{v_\alpha}{\sqrt{2}} \end{pmatrix}$$

⋆ μ_i's *cannot* be set to zero in general ⋆

• m_i's have to be determined by imposing the correct ℓ_i masses for the mass eigenstates

Neutral Fermion Sector :-

$$\mathcal{M}_{\mathcal{N}} = \begin{pmatrix} M_1 & 0 & \frac{g_1 v_u}{2} & -\frac{g_1 v_0}{2} & 0 & 0 & 0 \\ 0 & M_2 & -\frac{g_2 v_u}{2} & \frac{g_2 v_0}{2} & 0 & 0 & 0 \\ \frac{g_1 v_u}{2} & -\frac{g_2 v_u}{2} & 0 & -\mu_0 & -\mu_1 & -\mu_2 & -\mu_3 \\ -\frac{g_1 v_0}{2} & \frac{g_2 v_0}{2} & -\mu_0 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\mu_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\mu_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & -\mu_3 & 0 & 0 & 0 & 0 \end{pmatrix}$$

- one massive neutrino state :

$$\begin{aligned} |\nu_5\rangle &= \frac{\mu_1}{\mu_5}\left|\psi^1_{L_1}\right\rangle + \frac{\mu_2}{\mu_5}\left|\psi^1_{L_2}\right\rangle + \frac{\mu_3}{\mu_5}\left|\psi^1_{L_3}\right\rangle \\ \mu_5 &= \sqrt{\mu_1^2 + \mu_2^2 + \mu_3^2} \end{aligned}$$

- it is an admixture of the "ν_e, ν_μ, ν_τ"
- sub-eV (oscillation) masses $\longrightarrow$ very small μ_i

  our basis gives e, μ and τ
- Super-K atmospheric result

$\Longrightarrow$ **maximal mixing**

Vs usual hierarchical flavor structure

Constraints from Leptonic Phenomenology

Quantity	μ_i combo. constrained	Experimental bounds
Z^0-coupling:		
• $U_{br}^{e\mu}$ (e-μ universality)	$\mu_1^2 - \mu_2^2$	$(0.596 \pm 4.37) \times 10^{-3}$
• $U_{br}^{e\tau}$ (e-τ universality)	$\mu_1^2 - \mu_3^2$	$(0.955 \pm 4.98) \times 10^{-3}$
• $U_{br}^{\mu\tau}$ (μ-τ universality)	$\mu_2^2 - \mu_3^2$	$(1.55 \pm 5.60) \times 10^{-3}$
• $\Delta\mathcal{A}_{e\mu}$ (e-μ L-R asymmetry)	$\mu_1^2 - \mu_2^2$ + Rt. contrib.	$(0.346 \pm 2.54) \times 10^{-2}$
• $\Delta\mathcal{A}_{\tau e}$ (τ-e L-R asymmetry)	$\mu_3^2 - \mu_1^2$ + Rt. contrib.	0.0043 ± 0.104
• $\Delta\mathcal{A}_{\tau\mu}$ (τ-μ L-R asymmetry)	$\mu_3^2 - \mu_2^2$ + Rt. contrib.	0.082 ± 0.25
• $Br(Z^0 \to e^\pm \mu^\mp)$	$\lvert\mu_1\mu_2\rvert$	$< 1.7 \times 10^{-6}$
• $Br(Z^0 \to e^\pm \tau^\mp)$	$\lvert\mu_1\mu_3\rvert$	$< 9.8 \times 10^{-6}$
• $Br(Z^0 \to \mu^\pm \tau^\mp)$	$\lvert\mu_2\mu_3\rvert$	$< 1.2 \times 10^{-5}$
• $Br(\mu^- \to e^- e^+ e^-)$	$\lvert\mu_1\mu_2\rvert$	$< 1.0 \times 10^{-12}$
• $Br(\tau^- \to e^- e^+ e^-)$	$\lvert\mu_1\mu_3\rvert$	$< 2.9 \times 10^{-6}$
• $Br(\tau^- \to \mu^- e^+ e^-)$	$\lvert\mu_2\mu_3\rvert$	$< 1.7 \times 10^{-6}$
• $Br(\tau^- \to \mu^+ e^- e^-)$	$\lvert\mu_1^2\mu_2\mu_3\rvert$	$< 1.5 \times 10^{-6}$
• $Br(\tau^- \to e^- \mu^+ \mu^-)$	$\lvert\mu_1\mu_3\rvert$	$< 1.8 \times 10^{-6}$
• $Br(\tau^- \to e^+ \mu^- \mu^-)$	$\lvert\mu_1\mu_2^2\mu_3\rvert$	$< 1.5 \times 10^{-6}$
• $Br(\tau^- \to \mu^- \mu^+ \mu^-)$	$\lvert\mu_2\mu_3\rvert$	$< 1.9 \times 10^{-6}$
• $Br(Z^0 \to \chi^\pm \ell^\mp)$	μ_5	$< 1.0 \times 10^{-5}$
• $Br(Z^0 \to \chi^\pm \chi^\mp)$	μ_5	$< 1.0 \times 10^{-5}$
• $Br(Z^0 \to \chi_i^0 \chi_j^0, \chi_j^0 \nu)$; $j \neq 1$	μ_5	$< 1.0 \times 10^{-5}$
• Γ_z (total Z^0-width)	μ_5	$2.4948 \pm .0075$ GeV
• Γ_z^{inv} (*)	μ_5	500.1 ± 5.4 MeV
$W^\pm$-coupling:		
• $\overline{\Gamma}^{\mu e}$ ($\mu \to e\nu\nu$)	m_{ν_3} / μ_i ratio	0.983 ± 0.111
• $\overline{\Gamma}^{\tau e}$ ($\tau \to e\nu\nu$)	m_{ν_3} / μ_i ratio	0.979 ± 0.111
• $\overline{\Gamma}^{\tau\mu}$ ($\tau \to \mu\nu\nu$)	m_{ν_3} / μ_i ratio	0.954 ± 0.108
• $R_{\pi\mu}^{\pi e}$ (π decays)	m_{ν_3} / $\frac{\mu_1}{\mu_5}$ and $\frac{\mu_2}{\mu_5}$	$(1.230 \pm 0.012) \times 10^{-4}$
• $R_{\tau\mu}^{\tau e}$ (τ decays)	m_{ν_3} / μ_i ratio	1.0265 ± 0.0222
• $R_{\tau e}^{\mu e}$ (decays to e's)	m_{ν_3} / μ_i ratio	1.0038 ± 0.0219
• $m_{\nu_3} \lvert\tilde{B}_{e\nu_3}^L\rvert^2$ $[(\beta\beta)_{0\nu}]$	m_{ν_3} / $\frac{\mu_1}{\mu_5}$	< 0.46 eV (only for $m_{\nu_3} < 10$ MeV)
• BEBC expt.	m_{ν_3} / $\frac{\mu_1}{\mu_5}$ and $\frac{\mu_2}{\mu_5}$	
mass constraints:		
• ν_3 mass	μ_5	< 18.2 MeV if $\nu_3 = \nu_\tau$
	μ_6	< 149 MeV if $\nu_3 \neq \nu_\tau$
• $\chi^\pm$ mass	μ_5	> 70 GeV

Studies on Various Phenomenological Issues :-

• unconventional Z^0 and $W^{\pm}$ couplings

$\longrightarrow$ leptonic universality violations

$\longrightarrow$ lepton number violating rare decays

used to give overall constraint on μ_i's
(with Bisset,Macesanu, and Orr)

(NEUTRINO OSCILLATIONS :)

• bilinear (μ_i's) or trilinear (λ and λ') only

— implications on flavor structure

• bilinear and trilinear together

— give new contributions (SUSY Zee diagram)
(with Cheung)

• full neutrino mass contributions up to 1-loop

• new contribution to LR-mixing squark and slepton masses (bilinear and trilinear together)

$\longrightarrow$ neutron and electron EDM at 1-loop

$\longrightarrow$ $B \rightarrow s\gamma$, $\mu \rightarrow e\gamma$, ...
(with Keum)

• direct CP violation in B-decay (with Tseng)

• scalar sector

• charginos, $\cdots\cdots$

Complete Soft SUSY Breaking Terms :-

$$
\begin{aligned}
V_{\rm soft} &= \epsilon_{ab}\Big[B_0\, H_u^a H_d^b + A^U_{ij}\, \tilde{Q}^a_i H^b_u \tilde{U}^C_j + A^D_{ij} H^a_d \tilde{Q}^b_i \tilde{D}^C_j \\
&+ A^E_{ij} H^a_d \tilde{L}^b_i \tilde{E}^C_j + B_i\, H^a_u \tilde{L}^b_i + A^{\lambda'}_{ijk} \tilde{L}^a_i \tilde{Q}^b_j \tilde{D}^C_k \\
&+ A^{\lambda}_{ijk} \tilde{L}^a_i \tilde{L}^b_j \tilde{E}^C_k \Big] + A^{\lambda''}_{ijk} \tilde{U}^C_i \tilde{D}^C_j \tilde{D}^C_k \\
&+ \tilde{Q}^\dagger \tilde{m}^2_Q\, \tilde{Q} + \tilde{U}^\dagger \tilde{m}^2_U\, \tilde{U} + \tilde{D}^\dagger \tilde{m}^2_D\, \tilde{D} \\
&+ \tilde{L}^\dagger \tilde{m}^2_L \tilde{L} + \tilde{E}^\dagger \tilde{m}^2_E\, \tilde{E} + \tilde{m}^2_{H_u}\, |H_u|^2 \\
&+ \frac{M_1}{2} \tilde{B}\tilde{B} + \frac{M_2}{2} \tilde{W}\tilde{W} + \frac{M_3}{2} \tilde{g}\tilde{g}
\end{aligned}
$$

Note that $\tilde{m}^2_{L_{00}} \longrightarrow \tilde{m}^2_{H_d} \qquad (H_d \equiv L_0)$

Squark mass — new (RPV) contribution

$$
\mathcal{M}^2_D = \begin{pmatrix} \mathcal{M}^2_{LL} & \mathcal{M}^{2\dagger}_{RL} \\ \mathcal{M}^2_{RL} & \mathcal{M}^2_{RR} \end{pmatrix}
$$

where

$$
(\mathcal{M}^2_{RL})^T = A^D \frac{v_0}{\sqrt{2}} - m_D\, \mu^*_0\, \tan\beta \; - (\, \mu^*_i \lambda'_{ijk}\,)\, \frac{v_u}{\sqrt{2}}
$$

$(\mu_i^* \lambda'_{ijk})$ is interesting

- 3×3 matrix $(\ )_{jk}$ with elements listed

- **SUSY conserving R-parity violating** contributions

- **no** natural mechanism for suppression of off-diagonal part

Vs e.g.

$$A^D \frac{v_0}{\sqrt{2}} = A_d \, m_D + \delta A^D \frac{v_0}{\sqrt{2}}$$

— soft SUSY breaking part (proportionality)

$\mathcal{M}^2_{RL}$ contributes to FCNC

e.g. $b \longrightarrow s\gamma$

also neutron EDM, neutrino masses

Similarly, we have $(\mu_i^* \lambda_{ijk})$ for charged leptons *e.g.* **Neutron EDM** $[(d_n)^{\exp} < 6.3 \cdot 10^{-26}\, e \cdot \mathrm{cm}]$:-

— gluino diagram

$$\left(\frac{d_d}{e}\right)_{\tilde{g}} = -\frac{2\alpha_s}{3\pi}\,\frac{M_{\tilde{g}}}{M_{\tilde{d}}^2}\,Q_{\tilde{d}}\,\mathrm{Im}(\delta_{11}^{D})\,F\left(\frac{M_{\tilde{g}}^2}{M_{\tilde{d}}^2}\right)$$

$$\delta_{11}^{D}\,M_{\tilde{d}}^2 = [A_d - \mu_0^*\,\tan\beta]\,m_d + \frac{\sqrt{2}\,M_W\,\cos\beta}{g_2}\,\delta A_{11}^{D}$$

$$-\frac{\sqrt{2}\,M_W\,\sin\beta}{g_2}\,(\,\mu_i^* X_{i11}\,)$$

- neutrino mass bound (super-K)

— X_{311} (also $\tau \to \pi\nu$) $\lesssim$ $0.05 \sim 0.1$

— $\mu_i\ \cos\beta \lesssim 10^{-4}\,\mathrm{GeV}$

EDM : $M_{\tilde{d}} = 100\,\mathrm{GeV}$ and $M_{\tilde{g}} = 300\,\mathrm{GeV}$ gives
$\mathrm{Im}(\mu_i^* X_{i11}) \lesssim 10^{-6}\,\mathrm{GeV}$

⋆ RPV contribution could be larger then MSSM part

⋆ new bound interesting

Slepton-Higgs Masses :-

Charged particles — $4+3+1$ matrix :

$$\mathcal{M}_E^2 = \begin{pmatrix} \widetilde{\mathcal{M}}_{LL}^2 & \widetilde{\mathcal{M}}_{RL}^{2\dagger} & \widetilde{\mathcal{M}}_{LH}^2 \\ \widetilde{\mathcal{M}}_{RL}^2 & \widetilde{\mathcal{M}}_{RR}^2 & \widetilde{\mathcal{M}}_{RH}^2 \\ \widetilde{\mathcal{M}}_{LH}^{2\dagger} & \widetilde{\mathcal{M}}_{RH}^{2\dagger} & \widetilde{\mathcal{M}}_{H_u}^2 \end{pmatrix} ,$$

where

$$\widetilde{\mathcal{M}}_{LL}^2 = \tilde{m}_L^2 + m_L^\dagger m_L + (\mu_\alpha^* \mu_\beta) + M_Z^2 \cos 2\beta \left[-\frac{1}{2} + \sin^2\theta_W \right]$$
$$+ \begin{pmatrix} M_Z^2 \cos^2\beta \, [1-\sin^2\theta_W] & 0_{1\times 3} \\ 0_{3\times 1} & 0_{3\times 3} \end{pmatrix} ,$$
$$\widetilde{\mathcal{M}}_{RR}^2 = \tilde{m}_E^2 + m_E m_E^\dagger + M_Z^2 \cos 2\beta \left[-\sin^2\theta_W \right] ,$$
$$\widetilde{\mathcal{M}}_{H_u}^2 = \tilde{m}_{H_u}^2 + \mu_\alpha^* \mu_\alpha + M_Z^2 \cos 2\beta \left[\frac{1}{2} - \sin^2\theta_W \right]$$
$$+ \; M_Z^2 \sin^2\beta \, [1-\sin^2\theta_W] \, .$$

- $\tilde{m}_L^2$ is a 4×4 matrix with $\tilde{m}_{L_{0i}}^2$ being RPV
- $\mu_\alpha^* \mu_\beta$ contains RPV flavor mixings, *e.g.* $\mu_i^* \mu_j$

$$(\widetilde{\mathcal{M}}^2_{RL})^T = \begin{pmatrix} 0 \\ A^E \end{pmatrix} \frac{v_0}{\sqrt{2}} - (\, \mu^*_\alpha \lambda_{\alpha\beta k} \,) \, \frac{v_u}{\sqrt{2}}$$

$$= [A_e - \mu^*_0 \, \tan\beta] \begin{pmatrix} 0 \\ m_E \end{pmatrix} + \frac{v_0}{\sqrt{2}} \begin{pmatrix} 0 \\ \delta A^E \end{pmatrix}$$

$$- \begin{pmatrix} -\mu^*_k \, m_k \, \tan\beta \\ \frac{\sqrt{2} \, M_W \, \sin\beta}{g_2} \, (\, \mu^*_i \lambda_{ijk} \,) \end{pmatrix},$$

$$\widetilde{\mathcal{M}}^2_{RH} = -(\, \mu^*_i \lambda_{i0k} \,) \, \frac{v_0}{\sqrt{2}} = (\, \mu^*_k \, m_k \,) \quad \text{(no sum over } k\text{)},$$

$$\widetilde{\mathcal{M}}^2_{LH} = \begin{pmatrix} B^*_0 \\ (B^*_k) \end{pmatrix} + \begin{pmatrix} \frac{1}{2} \, M_Z^2 \, \sin 2\beta \, [1 - \sin^2\theta_W] \\ 0_{3\times 1} \end{pmatrix}.$$

- $m_L = \text{diag}\{0, m_E\} = \text{diag}\{0, m_1, m_2, m_3\}$
- 4×3 matrix $(\, \mu^*_i \lambda_{i\beta k} \,)$

— first row : $\tilde{l}^c_R \, h^-_d$ mass

plays a role in SUSY Zee model where a right-handed slepton becomes the Zee scalar

$\mathcal{M}_S^2 =$

$$\begin{pmatrix} \tilde{m}_L^2 + (\mu_\alpha^* \mu_\beta) + \frac{M_Z^2 \cos 2\beta}{2} & -(B_\alpha^*) \\ -(B_\alpha) & \tilde{m}_{H_u}^2 + \mu_\alpha^* \mu_\alpha - \frac{M_Z^2 \cos 2\beta}{2} \end{pmatrix}$$

$$+\frac{1}{2} M_Z^2 \begin{pmatrix} \cos^2\beta & 0_{1\times 3} & -\cos\beta \sin\beta \\ 0_{3\times 1} & 0_{3\times 3} & 0_{3\times 1} \\ -\cos\beta \sin\beta & 0_{1\times 3} & \sin^2\beta \end{pmatrix}$$

$+$ Majorana-like mass terms for Higgses :

$$\frac{1}{4} M_Z^2 \cos^2\beta\, h_d^0 h_d^0 - \frac{1}{2} M_Z^2 \cos\beta \sin\beta\, h_u^{0\dagger} h_d^0 + \frac{1}{4} M_Z^2 \sin^2\beta\, h_u^0 h_u^0$$

$+h.c.$

- B_i's lead to (seesaw type) Majorana-like mass terms for "sneutrinos"

$\longrightarrow$ gauge loop neutrino mass Haber/Grossman

$\longrightarrow$ RPV contribution to quark-scalar (Higgs) loop of EDM, FCNC under study