Mass Matrices and Couplings for the ϵ–Model

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Abstract

We write down the mass matrices and couplings needed for the ϵ–model calculations. These include the mass matrices for **all** the particles in the model, the charged and neutral current couplings of the spin $\frac{1}{2}$ particles with the gauge bosons, and the couplings of the charged and neutral scalars with the spin $\frac{1}{2}$ particles. We have not included the couplings of the gauge bosons with themselves, because these are the same as in the SM. Missing are still the couplings of the scalars with the gauge bosons, and the couplings of the scalars among themselves.

Contents

1 The Superpotential and the Soft Breaking Terms

Using the conventions of refs. [1, 2, 3] we introduce the model by specifying the superpotential, which includes BRpV [4] in three generations. It is given by

$$W = \varepsilon_{ab}\left[h_U^{ij}\widehat{Q}_i^a\widehat{U}_j\widehat{H}_u^b + h_D^{ij}\widehat{Q}_i^b\widehat{D}_j\widehat{H}_d^a + h_E^{ij}\widehat{L}_i^b\widehat{R}_j\widehat{H}_d^a - \mu\widehat{H}_d^a\widehat{H}_u^b + \epsilon_i\widehat{L}_i^a\widehat{H}_u^b\right] \tag{1}$$

where $i,j = 1,2,3$ are generation indices, $a,b = 1,2$ are $SU(2)$ indices, and ε is a completely antisymmetric 2×2 matrix, with $\varepsilon_{12} = 1$. The symbol "hat" over each letter indicates a superfield, with $\widehat{Q}_i$, $\widehat{L}_i$, $\widehat{H}_d$, and $\widehat{H}_u$ being $SU(2)$ doublets with hypercharges $\frac{1}{3}$, -1, -1, and 1 respectively, and $\widehat{U}$, $\widehat{D}$, and $\widehat{R}$ being $SU(2)$ singlets with hypercharges $-\frac{4}{3}$, $\frac{2}{3}$, and 2 respectively. The couplings h_U, h_D and h_E are 3×3 Yukawa matrices, and μ and ϵ_i are parameters with units of mass. The last term in eq. (1) is the only R–parity violating term.

Supersymmetry breaking is parameterized with a set of soft supersymmetry breaking terms. In the MSSM these are given by

$$\begin{aligned} V_{soft}^{MSSM} &= M_Q^{ij2}\widetilde{Q}_i^{a*}\widetilde{Q}_j^a + M_U^{ij2}\widetilde{U}_i\widetilde{U}_j^* + M_D^{ij2}\widetilde{D}_i\widetilde{D}_j^* + M_L^{ij2}\widetilde{L}_i^{a*}\widetilde{L}_j^a + M_R^{ij2}\widetilde{R}_i\widetilde{R}_j^* \\ &\quad + m_{H_d}^2 H_d^{a*}H_d^a + m_{H_u}^2 H_u^{a*}H_u^a - \left[\tfrac{1}{2}M_s\lambda_s\lambda_s + \tfrac{1}{2}M\lambda\lambda + \tfrac{1}{2}M'\lambda'\lambda' + h.c.\right] \\ &\quad + \varepsilon_{ab}\left[A_U^{ij}\widetilde{Q}_i^a\widetilde{U}_j H_u^b + A_D^{ij}\widetilde{Q}_i^b\widetilde{D}_j H_d^a + A_E^{ij}\widetilde{L}_i^b\widetilde{R}_j H_d^a - B\mu H_d^a H_u^b\right]. \end{aligned} \tag{2}$$

In addition to the MSSM soft SUSY breaking terms in $\mathcal{L}_{soft}^{MSSM}$ the BRpV model contains the following extra term

$$V_{soft}^{BRpV} = B_i\epsilon_i\varepsilon_{ab}\widetilde{L}_i^a H_u^b\,, \tag{3}$$

where the B_i have units of mass. In what follows, we neglect intergenerational mixing in the soft terms in eq. (2).

The electroweak symmetry is broken when the two Higgs doublets H_d and H_u, and the neutral component of the slepton doublets $\widetilde{L}_i^1$ acquire vacuum expectation values. We introduce the notation:

$$H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}, \qquad H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \qquad \widetilde{L}_i = \begin{pmatrix} \tilde{L}_i^0 \\ \tilde{\ell}_i^- \end{pmatrix}, \tag{4}$$

where we shift the neutral fields with non–zero vevs as

$$H_d^0 \equiv \frac{1}{\sqrt{2}}[\sigma_d^0 + v_d + i\varphi_d^0]\,, \quad H_u^0 \equiv \frac{1}{\sqrt{2}}[\sigma_u^0 + v_u + i\varphi_u^0]\,, \quad \tilde{L}_i^0 \equiv \frac{1}{\sqrt{2}}[\tilde{\nu}_i^R + v_i + i\tilde{\nu}_i^I]\,. \tag{5}$$

Note that the W boson acquires a mass $m_W^2 = \frac{1}{4}g^2v^2$, where $v^2 \equiv v_d^2 + v_u^2 + v_1^2 + v_2^2 + v_3^2 \simeq (246\text{ GeV})^2$. We introduce the following notation in spherical coordinates for the vacuum expectation values:

$$\begin{aligned} v_d &= v\sin\theta_1\sin\theta_2\sin\theta_3\cos\beta \\ v_u &= v\sin\theta_1\sin\theta_2\sin\theta_3\sin\beta \end{aligned}$$

$$
\begin{aligned}
v_3 &= v \sin\theta_1 \sin\theta_2 \cos\theta_3 \\
v_2 &= v \sin\theta_1 \cos\theta_2 \\
v_1 &= v \cos\theta_1
\end{aligned} \tag{6}
$$

which preserves the MSSM definition $\tan\beta = v_u/v_d$. In the MSSM limit, where $\epsilon_i = v_i = 0$, the angles θ_i are equal to $\pi/2$. In addition to the above MSSM parameters, our model contains nine new parameters, ϵ_i, v_i and B_i. The three vevs are determined by the one–loop tadpole equations, and we will assume universality of the B–terms, $B = B_i$ at the unification scale. Therefore, the only new and free parameters can be chosen as the ϵ_i.

2 The Scalar Potential

The electroweak symmetry is broken when the Higgs and lepton fields acquire non–zero vevs. These are calculated via the minimization of the effective potential or, in the diagramatic method, via the tadpole equations. The full scalar potential at tree level is

$$
V^0_{total} = \sum_i \left| \frac{\partial W}{\partial z_i} \right|^2 + V_D + V^{MSSM}_{soft} + V^{BRpV}_{soft} \tag{7}
$$

where z_i is any one of the scalar fields in the superpotential in eq. (1), V_D are the D-terms, and V^{BRpV}_{soft} is given in eq. (3).

The tree level scalar potential contains the following linear terms

$$
V^0_{linear} = t^0_d \sigma^0_d + t^0_u \sigma^0_u + t^0_1 \tilde{\nu}^R_1 + t^0_2 \tilde{\nu}^R_2 + t^0_3 \tilde{\nu}^R_3 \,, \tag{8}
$$

where the different t^0 are the tadpoles at tree level. They are given by

$$
\begin{aligned}
t^0_d &= \Big(m^2_{H_d} + \mu^2\Big) v_d + v_d D - \mu\Big(B v_u + v_i \epsilon_i\Big) \\
t^0_u &= -B\mu v_d + \Big(m^2_{H_u} + \mu^2\Big) v_u - v_u D + v_i B_i \epsilon_i + v_u \epsilon^2 \\
t^0_1 &= v_1 D + \epsilon_1\Big(-\mu v_d + v_u B_1 + v_i \epsilon_i\Big) + \tfrac{1}{2}\Big(v_i M^2_{Li1} + M^2_{L1i} v_i\Big) \\
t^0_2 &= v_2 D + \epsilon_2\Big(-\mu v_d + v_u B_2 + v_i \epsilon_i\Big) + \tfrac{1}{2}\Big(v_i M^2_{Li2} + M^2_{L2i} v_i\Big) \\
t^0_3 &= v_3 D + \epsilon_3\Big(-\mu v_d + v_u B_3 + v_i \epsilon_i\Big) + \tfrac{1}{2}\Big(v_i M^2_{Li3} + M^2_{L3i} v_i\Big)
\end{aligned} \tag{9}
$$

where we have defined $D = \frac{1}{8}(g^2 + g'^2)(v_1^2 + v_2^2 + v_3^2 + v_d^2 - v_u^2)$ and $\epsilon^2 = \epsilon_1^2 + \epsilon_2^2 + \epsilon_3^2$. A repeated index i in eq. (9) implies summation over $i = 1, 2, 3$. The five tree level tadpoles t^0_α are equal to zero at the minimum of the tree level potential, and from there one can determine the five tree level vacuum expectation values.

It is well known that in order to find reliable results for the electroweak symmetry breaking it is necessary to include the one–loop radiative corrections. The full scalar potential at one loop level, called effective potential, is

$$
V_{total} = V^0_{total} + V_{RC} \tag{10}
$$

where V_{RC} include the quantum corrections. In this paper we use the diagramatic method, which incorporates the radiative corrections through the one–loop corrected tadpole equations. The one loop tadpoles are

$$t_\alpha = t_\alpha^0 - \delta t_\alpha^{\overline{DR}} + T_\alpha(Q) = t_\alpha^0 + \widetilde{T}_\alpha^{\overline{DR}}(Q) \tag{11}$$

where $\alpha = d, u, 1, 2, 3$ and $\widetilde{T}_\alpha^{\overline{DR}}(Q) \equiv -\delta t_\alpha^{\overline{MS}} + T_\alpha(Q)$ are the finite one loop tadpoles. At the minimum of the potential we have $t_\alpha = 0$, and the vevs calculated from these equations are the renormalized vevs.

3 Mass Matrices

3.1 Scalar Mass Matrices

3.1.1 Charged Scalars

The mass matrix of the charged scalar sector follows from the quadratic terms in the scalar potential

$$V_{quadratic} = S'^{-} \boldsymbol{M^2_{S^\pm}} S'^{+} \tag{12}$$

where the unrotated charged scalars are $S'^{+} = (H_d^+, H_u^+, \widetilde{e}_L^+, \widetilde{\mu}_L^+ \widetilde{\tau}_L^+, \widetilde{e}_R^+, \widetilde{\mu}_R^+ \widetilde{\tau}_R^+)$. For convenience we will divide this (8×8) matrix into blocks in the following way:

$$\boldsymbol{M^2_{S^\pm}} = \begin{bmatrix} \boldsymbol{M}^2_{HH} & \boldsymbol{M}^{2T}_{H\tilde{\ell}} \\ \boldsymbol{M}^2_{H\tilde{\ell}} & \boldsymbol{M}^2_{\tilde{\ell}\tilde{\ell}} \end{bmatrix} + \xi m_W^2 \begin{bmatrix} \boldsymbol{M}^2_A & \boldsymbol{M}^{2T}_B \\ \boldsymbol{M}^2_B & \boldsymbol{M}^2_C \end{bmatrix} \tag{13}$$

where the charged Higgs block is

$$\boldsymbol{M}^2_{HH} = \begin{bmatrix} \begin{array}{c} B\mu \frac{v_u}{v_d} + \frac{1}{4} g^2 (v_2^2 - \sum_{i=1}^3 v_i^2) + \frac{t_d}{v_d} \\ +\mu \sum_{i=1}^3 \epsilon_i \frac{v_i}{v_d} + \frac{1}{2} \sum_{i,j=1}^3 v_i \left(h_E h_E^\dagger\right)_{ij} v_j \end{array} & B\mu + \frac{1}{4} g^2 v_d v_u \\ B\mu + \frac{1}{4} g^2 v_d v_u & \begin{array}{c} B\mu \frac{v_d}{v_u} + \frac{1}{4} g^2 (v_d^2 + \sum_{i=1}^3 v_i^2) \\ - \sum_{i=1}^3 B_i \epsilon_i \frac{v_i}{v_u} + \frac{t_u}{v_u} \end{array} \end{bmatrix} \tag{14}$$

This matrix reduces to the usual charged Higgs mass matrix in the MSSM when we set $v_i = \epsilon_i = 0$ and we call $m_{12}^2 = B\mu$. The slepton block is given by

$$\boldsymbol{M}^2_{\tilde{\ell}\tilde{\ell}} = \begin{bmatrix} \boldsymbol{M}^2_{LL} & \boldsymbol{M}^2_{LR} \\ \boldsymbol{M}^2_{RL} & \boldsymbol{M}^2_{RR} \end{bmatrix} \tag{15}$$

where

$$\left(\boldsymbol{M}^2_{LL}\right)_{ij} = \tfrac{1}{2} v_d^2 \left(h_E^* h_E^T\right)_{ij} + \tfrac{1}{4} g^2 \left(-\sum_{k=1}^3 v_k^2 - v_d^2 + v_u^2\right) \delta_{ij} + \tfrac{1}{4} g^2 v_i v_j - \frac{v_u}{v_i} B_i \epsilon_i \delta_{ij} + \frac{t_i}{v_i} \delta_{ij}$$

$$+\mu\frac{v_d}{v_i}\epsilon_i\delta_{ij}-\epsilon_i\left(\sum_{k=1}^{3}\frac{v_k}{v_i}\epsilon_k\right)\delta_{ij}+\epsilon_i\epsilon_j+M^2_{Lji}$$
$$-\tfrac{1}{2}\sum_{k=1}^{3}\frac{v_k}{v_i}\left(M^2_{Lik}+M^2_{Lki}\right)\delta_{ij} \tag{16}$$

$$\boldsymbol{M}^2_{LR}=\frac{1}{\sqrt{2}}\left(v_dA_E-\mu v_u h_E\right) \tag{17}$$

$$\boldsymbol{M}^2_{RL}=\left(\boldsymbol{M}^2_{LR}\right)^\dagger \tag{18}$$

$$\begin{aligned}\left(\boldsymbol{M}^2_{RR}\right)_{ij} &= \tfrac{1}{4}g'^2\left(-\sum_{k=1}^{3}v_k^2-v_d^2+v_u^2\right)\delta_{ij}+\tfrac{1}{2}v_d^2\left(h_E^Th_E^*\right)_{ij}\\ &+\left(\sum_{k=1}^{3}\left(h_E^T\right)_{ik}v_k\right)\left(\sum_{s=1}^{3}\left(h_E^*\right)_{sj}v_s\right)+M^2_{Rji}\end{aligned} \tag{19}$$

We recover the usual stau mass matrix again by replacing $v_i=\epsilon_i=0$ (note that we need to replace the expression of the tadpole t_i in eq. (9) before taking the limit). The mixing between the charged Higgs sector and the slepton sector is given by the following 6×2 block (repeated indices are not summed unless an explicit sum appears):

$$\boldsymbol{M}^2_{H\tilde{\ell}}=\begin{bmatrix}-\mu\epsilon_i-\tfrac{1}{2}v_d\sum_{k=1}^{3}\left(h_E^*h_E^T\right)_{ik}v_k+\tfrac{1}{4}g^2v_dv_i & -B_i\epsilon_i+\tfrac{1}{4}g^2v_uv_i\\ -\tfrac{1}{\sqrt{2}}v_u\sum_{k=1}^{3}\left(h_E^T\right)_{ik}\epsilon_k-\tfrac{1}{\sqrt{2}}\sum_{k=1}^{3}\left(A_E^T\right)_{ik}v_k & -\tfrac{1}{\sqrt{2}}\sum_{k=1}^{3}\left(h_E^T\right)_{ik}\left(\mu v_k+\epsilon_kv_d\right)\end{bmatrix} \tag{20}$$

and as expected, this mixing vanishes in the limit $v_i=\epsilon_i=0$. The charged scalar mass matrix in eq. (13), after setting $t_u=t_d=t_i=0$, has determinant equal to zero for $\xi=0$, since one of the eigenvectors corresponds to the charged Goldstone boson with zero eigenvalue.

For our one loop calculations one has to had the gauge fixing. The part of the mass matrix in Eq. (13) that comes from the gauge fixing reads for the (2×2) A block

$$\boldsymbol{M}^2_A=\begin{bmatrix}\frac{v_d^2}{v^2} & \frac{-v_uv_d}{v^2}\\ \frac{-v_uv_d}{v^2} & \frac{v_u^2}{v^2}\end{bmatrix} \tag{21}$$

for the (6×2) B and the (6×6) C blocks

$$\boldsymbol{M}^2_B=\begin{bmatrix}\frac{v_iv_d}{v^2} & \frac{-v_iv_u}{v^2}\\ 0 & 0\end{bmatrix}\qquad;\qquad \boldsymbol{M}^2_C=\begin{bmatrix}\boldsymbol{M}^2_D & 0\\ 0 & 0\end{bmatrix} \tag{22}$$

where the (3×3) D block is

$$\boldsymbol{M}^2_D=\begin{bmatrix}\frac{v_1^2}{v^2} & \frac{v_1v_2}{v^2} & \frac{v_1v_3}{v^2}\\ \frac{v_2v_1}{v^2} & \frac{v_2^2}{v^2} & \frac{v_2v_3}{v^2}\\ \frac{v_3v_1}{v^2} & \frac{v_2v_3}{v^2} & \frac{v_3^2}{v^2}\end{bmatrix} \tag{23}$$

The charged scalar mass matrices are diagonalized by the following rotation matrices,

$$S_i^{\pm} = \boldsymbol{R}_{ij}^{S^{\pm}} S_j^{\pm\prime} \tag{24}$$

with the eigenvalues $\mathrm{diag}(\mathrm{m}_{\mathrm{S}_1}^2, \ldots, \mathrm{m}_{\mathrm{S}_8}^2) = \boldsymbol{R}^{\mathrm{S}^{\pm}} \boldsymbol{M}_{\mathrm{S}^{\pm}}^2 \left(\boldsymbol{R}^{\mathrm{S}^{\pm}}\right)^{\mathrm{T}}$.

3.1.2 CP–Even Neutral Scalars

The quadratic scalar potential includes

$$V_{quadratic} = \tfrac{1}{2}[\sigma_d^0, \sigma_u^0, \tilde{\nu}_i^R] \boldsymbol{M}_{S^0}^2 \begin{bmatrix} \sigma_d^0 \\ \sigma_u^0 \\ \tilde{\nu}_i^R \end{bmatrix} + \cdots \tag{25}$$

where the neutral CP-even scalar sector mass matrix in eq. (25) is given by

$$\boldsymbol{M}_{S^0}^2 = \begin{bmatrix} \boldsymbol{M}_{SS}^2 & \boldsymbol{M}_{S\widetilde{\nu}_R}^2 \\ \boldsymbol{M}_{S\widetilde{\nu}_R}^{2\;T} & \boldsymbol{M}_{\widetilde{\nu}_R\widetilde{\nu}_R}^2 \end{bmatrix} \tag{26}$$

where

$$\boldsymbol{M}_{SS}^2 = \begin{bmatrix} B\mu\frac{v_u}{v_d} + \frac{1}{4}g_Z^2 v_d^2 + \mu\sum\limits_{k=1}^{3}\epsilon_k\frac{v_k}{v_1} + \frac{t_d}{v_d} & -B\mu - \frac{1}{4}g_Z^2 v_d v_u \\ -B\mu - \frac{1}{4}g_Z^2 v_d v_u & B\mu\frac{v_d}{v_u} + \frac{1}{4}g_Z^2 v_u^2 - \sum\limits_{k=1}^{3} B_k\epsilon_k\frac{v_k}{v_2} + \frac{t_u}{v_u} \end{bmatrix} \tag{27}$$

$$\boldsymbol{M}_{S\widetilde{\nu}_R}^2 = \begin{bmatrix} -\mu\epsilon_i + \frac{1}{4}g_Z^2 v_d v_i \\ B_i\epsilon_i - \frac{1}{4}g_Z^2 v_u v_i \end{bmatrix} \tag{28}$$

and

$$\begin{aligned}\left(\boldsymbol{M}_{\widetilde{\nu}_R\widetilde{\nu}_R}^2\right)_{ij} = &\left(\mu\epsilon_i\frac{v_d}{v_i} - B_i\epsilon_i\frac{v_u}{v_i} - \epsilon_i\sum_{k=1}^{3}\epsilon_k\frac{v_k}{v_i} - \frac{1}{2}\sum_{k=1}^{3}\frac{v_k}{v_i}\left(M_{Lik}^2 + M_{Lki}^2\right) + \frac{t_i}{v_i}\right)\delta_{ij} + \frac{1}{4}g_Z^2 v_i v_j \\ &+\epsilon_i\epsilon_j + \frac{1}{2}\left(M_{Lij}^2 + M_{Lji}^2\right)\end{aligned} \tag{29}$$

where we have defined $g_Z^2 \equiv g^2 + g'^2$. In the upper–left 2×2 block, in the limit $v_i = \epsilon_i = 0$, the reader can recognize the MSSM mass matrix corresponding to the CP–even neutral Higgs sector. To define the rotation matrices let us define the unrotated fields by

$$S'^0 = (\sigma_d^0, \sigma_u^0, \tilde{\nu}_1^R, \tilde{\nu}_2^R, \tilde{\nu}_2^R) \tag{30}$$

Then the mass eigenstates are S_i^0 given by

$$S_i^0 = \boldsymbol{R}_{ij}^{S^0} S_j'^0 \tag{31}$$

with the eigenvalues $\mathrm{diag}(\mathrm{m}_{\mathrm{S}_1}^2, \ldots, \mathrm{m}_{\mathrm{S}_5}^2) = \boldsymbol{R}^{\mathrm{S}^0} \boldsymbol{M}_{\mathrm{S}^0}^2 \left(\boldsymbol{R}^{\mathrm{S}^0}\right)^{\mathrm{T}}$.

3.1.3 CP–Odd Neutral Scalars

The quadratic scalar potential includes

$$V_{quadratic} = \tfrac{1}{2}[\varphi_1^0, \varphi_2^0, \tilde{\nu}_i^I]\boldsymbol{M}^2_{P^0}\begin{bmatrix}\varphi_1^0\\ \varphi_2^0\\ \tilde{\nu}_i^I\end{bmatrix} + \cdots \tag{32}$$

where the CP-odd neutral scalar mass matrix is

$$\boldsymbol{M}^2_{P^0} = \begin{bmatrix}\boldsymbol{M}^2_{PP} & \boldsymbol{M}^2_{P\widetilde{\nu}_I}\\ \boldsymbol{M}^{2\ \ T}_{P\widetilde{\nu}_I} & \boldsymbol{M}^2_{\widetilde{\nu}_I\widetilde{\nu}_I}\end{bmatrix} + \xi m_Z^2\begin{bmatrix}\boldsymbol{M}^2_E & \boldsymbol{M}^{2T}_F\\ \boldsymbol{M}^2_F & \boldsymbol{M}^2_G\end{bmatrix} \tag{33}$$

where

$$\boldsymbol{M}^2_{PP} = \begin{bmatrix} B\mu\dfrac{v_u}{v_d} + \mu\displaystyle\sum_{k=1}^{3}\epsilon_k\frac{v_k}{v_d} + \frac{t_d}{v_d} & B\mu \\ B\mu & B\mu\dfrac{v_d}{v_u} - \displaystyle\sum_{k=1}^{3}B_k\epsilon_k\frac{v_k}{v_u} + \frac{t_u}{v_u}\end{bmatrix} \tag{34}$$

$$\boldsymbol{M}^2_{P\widetilde{\nu}_I} = \begin{bmatrix} -\mu\epsilon_i \\ -\ B_i\epsilon_i\end{bmatrix} \tag{35}$$

and

$$\begin{aligned}\left(\boldsymbol{M}^2_{\widetilde{\nu}_I\widetilde{\nu}_I}\right)_{ij} &= \left(\mu\epsilon_i\frac{v_d}{v_i} - B_i\epsilon_i\frac{v_u}{v_i} - \epsilon_i\sum_{k=1}^{3}\epsilon_k\frac{v_k}{v_i} - \tfrac{1}{2}\sum_{k=1}^{3}\frac{v_k}{v_i}\left(M^2_{Lik} + M^2_{Lki}\right) + \frac{t_i}{v_i}\right)\delta_{ij} \\ &\quad +\epsilon_i\epsilon_j + \tfrac{1}{2}\left(M^2_{Lij} + M^2_{Lji}\right)\end{aligned} \tag{36}$$

Finally the part of the mass matrix in Eq. (33) that comes from the gauge fixing reads for the (2×2) E block

$$\boldsymbol{M}^2_E = \begin{bmatrix}\dfrac{v_d^2}{v^2} & \dfrac{-v_u v_d}{v^2}\\ \dfrac{-v_u v_d}{v^2} & \dfrac{v_u^2}{v^2}\end{bmatrix} \tag{37}$$

for the (3×2) F block

$$\boldsymbol{M}^2_F = \begin{bmatrix}\dfrac{v_i v_d}{v^2} & \dfrac{-v_i v_u}{v^2}\end{bmatrix} \tag{38}$$

and for the (3×3) G block

$$\boldsymbol{M}^2_G = \begin{bmatrix}\dfrac{v_1^2}{v^2} & \dfrac{v_1 v_2}{v^2} & \dfrac{v_1 v_3}{v^2}\\ \dfrac{v_2 v_1}{v^2} & \dfrac{v_2^2}{v^2} & \dfrac{v_2 v_3}{v^2}\\ \dfrac{v_3 v_1}{v^2} & \dfrac{v_3 v_2}{v^2} & \dfrac{v_3^2}{v^2}\end{bmatrix} \tag{39}$$

The charged pseudo–scalar mass matrices are diagonalized by the following rotation matrices,

$$P_i = \boldsymbol{R}^{P0}_{ij} P'_j \tag{40}$$

with the eigenvalues $\mathrm{diag}(\mathrm{m}^2_{\mathrm{A}_1}, \ldots, \mathrm{m}^2_{\mathrm{A}_5}) = \boldsymbol{R}^{\mathrm{P}^0} \boldsymbol{M}^2_{\mathrm{P}^0} \left(\boldsymbol{R}^{\mathrm{P}^0}\right)^{\mathrm{T}}$. where the unrotated fields are

$$P'^0 = (\varphi^0_d, \varphi^0_u, \widetilde{\nu}^I_1, \widetilde{\nu}^I_2, \widetilde{\nu}^I_2) \tag{41}$$

3.1.4 Squark Mass Matrices

In the unrotated basis $\widetilde{u}'_i = (\widetilde{u}_{Li}, \widetilde{u}^*_{Ri})$ and $\widetilde{d}'_i = (\widetilde{d}_{Li}, \widetilde{d}^*_{Ri})$ we get

$$V_{quadratic} = \tfrac{1}{2}\widetilde{u}'^{\dagger} \boldsymbol{M_{\widetilde{u}}}^2 \, \widetilde{u}' + \tfrac{1}{2}\widetilde{d}'^{\dagger} \boldsymbol{M_{\widetilde{d}}}^2 \, \widetilde{d}' \tag{42}$$

where

$$\boldsymbol{M_{\widetilde{q}}}^2 = \begin{pmatrix} \boldsymbol{M^2_{\widetilde{q}LL}} & \boldsymbol{M^2_{\widetilde{q}LR}} \\ \boldsymbol{M^2_{\widetilde{q}RL}} & \boldsymbol{M^2_{\widetilde{q}RR}} \end{pmatrix} \tag{43}$$

with $\widetilde{q} = (\widetilde{u}, \widetilde{d})$. The blocks are different for up and down type squarks. We have

$$\begin{aligned}
\boldsymbol{M^2_{\widetilde{u}LL}} &= \tfrac{1}{2}\, v_u^2 \, h_U^* h_U^T + M_Q^2 + \tfrac{1}{6}\,(4m_W^2 - m_Z^2)\, \frac{1}{v^2} \left(v_d^2 - v_u^2 + \sum_i v_i^2 \right) \\
\boldsymbol{M^2_{\widetilde{u}RR}} &= \tfrac{1}{2}\, v_u^2 \, h_U^T h_U^* + M_U^2 + \tfrac{2}{3}(m_Z^2 - m_W^2)\, \frac{1}{v^2} \left(v_d^2 - v_u^2 + \sum_i v_i^2 \right) \\
\boldsymbol{M^2_{\widetilde{u}LR}} &= \frac{v_u}{\sqrt{2}}\, A_U^* - \mu \frac{v_d}{\sqrt{2}}\, h_U^* + \sum_{i=1}^{3} \frac{v_i}{\sqrt{2}}\, \epsilon_i \, h_U^* \\
\boldsymbol{M^2_{\widetilde{u}RL}} &= \boldsymbol{M^2_{\widetilde{u}LR}}^{\dagger}
\end{aligned} \tag{44}$$

and

$$\begin{aligned}
\boldsymbol{M^2_{\widetilde{d}LL}} &= \frac{1}{2}\, v_d^2 \, h_D^* h_D^T + M_Q^2 - \tfrac{1}{6}\,(2m_W^2 + m_Z^2)\, \frac{1}{v^2} \left(v_d^2 - v_u^2 + \sum_i v_i^2 \right) \\
\boldsymbol{M^2_{\widetilde{d}RR}} &= \tfrac{1}{2}\, v_d^2 \, h_D^T h_D^* + M_D^2 - \tfrac{1}{3}(m_Z^2 - m_W^2)\, \frac{1}{v^2} \left(v_d^2 - v_u^2 + \sum_i v_i^2 \right) \\
\boldsymbol{M^2_{\widetilde{d}LR}} &= \frac{v_d}{\sqrt{2}}\, A_D^* - \mu \frac{v_u}{\sqrt{2}}\, h_D^* \\
\boldsymbol{M^2_{\widetilde{d}RL}} &= \boldsymbol{M^2_{\widetilde{d}LR}}^{\dagger}
\end{aligned} \tag{45}$$

We define the mass eigenstates

$$\widetilde{q} = \boldsymbol{R^{\widetilde{q}}} \, \widetilde{q}' \tag{46}$$

which implies

$$\widetilde{q}'_i = \boldsymbol{R^{\widetilde{q}}}^{*}_{ji} \, \widetilde{q}_j \tag{47}$$

The rotation matrices are obtained from

$$\boldsymbol{R^{\widetilde{q}}}^{\dagger} \left(\boldsymbol{M^{diag}_{\widetilde{q}}} \right)^2 \boldsymbol{R^{\widetilde{q}}} = \boldsymbol{M_{\widetilde{q}}}^2 \tag{48}$$

In our case the matrices in Eq. (43) are real and therefore the rotation matrices $\boldsymbol{R^{\widetilde{q}}}$ are orthogonal matrices.

3.2 Chargino Mass Matrix

The charginos mix with the charged leptons forming a set of five charged fermions $F_i^{\pm}$, $i = 1,\ldots,5$ in two component spinor notation. In a basis where $\psi^{+T} = (-i\lambda^+, \widetilde{H}_u^+, e_R^+, \mu_R^+, \tau_R^+)$ and $\psi^{-T} = (-i\lambda^-, \widetilde{H}_d^-, e_L^-, \mu_L^-, \tau_L^-)$, the charged fermion mass terms in the Lagrangian are

$$\mathcal{L}_m = -\frac{1}{2}(\psi^{+T}, \psi^{-T}) \begin{pmatrix} \mathbf{0} & \boldsymbol{M}_C^T \\ \boldsymbol{M}_C & \mathbf{0} \end{pmatrix} \begin{pmatrix} \psi^+ \\ \psi^- \end{pmatrix} + h.c. \tag{49}$$

where the chargino/lepton mass matrix is given by

$$\boldsymbol{M}_C = \begin{bmatrix} M & \frac{1}{\sqrt{2}} g v_u & 0 & 0 & 0 \\ \frac{1}{\sqrt{2}} g v_d & \mu & -\frac{1}{\sqrt{2}} v_i \left(h_E\right)_{i1} & -\frac{1}{\sqrt{2}} v_i \left(h_E\right)_{i2} & -\frac{1}{\sqrt{2}} v_i \left(h_E\right)_{i3} \\ \frac{1}{\sqrt{2}} g v_1 & -\epsilon_1 & \frac{1}{\sqrt{2}} \left(h_E\right)_{11} v_d & \frac{1}{\sqrt{2}} \left(h_E\right)_{12} v_d & \frac{1}{\sqrt{2}} \left(h_E\right)_{13} v_d \\ \frac{1}{\sqrt{2}} g v_2 & -\epsilon_2 & \frac{1}{\sqrt{2}} \left(h_E\right)_{21} v_d & \frac{1}{\sqrt{2}} \left(h_E\right)_{22} v_d & \frac{1}{\sqrt{2}} \left(h_E\right)_{23} v_d \\ \frac{1}{\sqrt{2}} g v_3 & -\epsilon_3 & \frac{1}{\sqrt{2}} \left(h_E\right)_{31} v_d & \frac{1}{\sqrt{2}} \left(h_E\right)_{32} v_d & \frac{1}{\sqrt{2}} \left(h_E\right)_{33} v_d \end{bmatrix} \tag{50}$$

and M is the $SU(2)$ gaugino soft mass. We note that chargino sector decouples from the lepton sector in the limit $\epsilon_i = v_i = 0$. As in the MSSM, the chargino mass matrix is diagonalized by two rotation matrices $\boldsymbol{U}$ and $\boldsymbol{V}$ defined by

$$F_i^- = U_{ij}\, \psi_j^- \quad ; \quad F_i^+ = V_{ij}\, \psi_j^+ \tag{51}$$

Then

$$\boldsymbol{U}^* \boldsymbol{M_C} \boldsymbol{V}^{-1} = \boldsymbol{M_{CD}} \tag{52}$$

where $\boldsymbol{M_{CD}}$ is the diagonal charged fermion mass matrix. To determine $\boldsymbol{U}$ and $\boldsymbol{V}$ we note that

$$\boldsymbol{M^2_{CD}} = \boldsymbol{V} \boldsymbol{M_C^\dagger} \boldsymbol{M_C} \boldsymbol{V}^{-1} = \boldsymbol{U^*} \boldsymbol{M_C} \boldsymbol{M_C^\dagger} (\boldsymbol{U^*})^{-1} \tag{53}$$

implying that $\boldsymbol{V}$ diagonalizes $\boldsymbol{M_C^\dagger M_C}$ and $\boldsymbol{U^*}$ diagonalizes $\boldsymbol{M_C M_C^\dagger}$. For future reference we note that

$$\psi_j^- = \boldsymbol{U^*}_{kj}\, F_k^- \quad ; \quad \psi_j^+ = \boldsymbol{V^*}_{kj}\, F_k^+ \tag{54}$$

In the previous expressions the $F_i^{\pm}$ are two component spinors. We construct the four component Dirac spinors out of the two component spinors with the conventions*,

$$\chi_i^- = \begin{pmatrix} F_i^- \\ \overline{F_i^+} \end{pmatrix} \tag{55}$$

The chargino masses coming from Eq. (52) can have a negative sign. We fix that by defining a sign parameter

$$\eta_i = \frac{m_{\chi_i^-}}{|m_{\chi_i^-}|} \tag{56}$$

*Here we depart from the conventions of ref. [2] because we want the e^-, μ^- and τ^- to be the particles and not the anti–particles.

This corresponds to the following substitution

$$\chi_i^- \to \gamma_5\,\chi_i^- \tag{57}$$

and therefore

$$\begin{array}{lcl} \chi_i^- \to (\eta_i P_L + P_R)\,\chi_i^- & ; & \overline{\chi^-}_i \to \overline{\chi^-}_i\,(P_L + \eta_i P_R) \\ \chi_i^+ \to (P_L + \eta_i P_R)\,\chi_i^+ & ; & \overline{\chi^+}_i \to \overline{\chi^+}_i\,(\eta_i P_L + P_R) \end{array} \tag{58}$$

3.3 Neutralino Mass Matrix

In our model, the neutrinos acquires mass [5], and this is due to a mixing between the neutralino sector and the neutrinos, forming a set of seven neutral two component fermions F_i^0, $i = 1, ...7$. In the basis $\psi^{0T} = (-i\lambda', -i\lambda^3, \widetilde{H}_d^1, \widetilde{H}_u^2, \nu_e, \nu_\mu, \nu_\tau)$ the neutral fermions mass terms in the Lagrangian are given by

$$\mathcal{L}_m = -\frac{1}{2}(\psi^0)^T \boldsymbol{M}_N \psi^0 + h.c. \tag{59}$$

where the neutralino/neutrino mass matrix is

$$\boldsymbol{M}_N = \begin{bmatrix} M' & 0 & -\frac{1}{2}g'v_d & \frac{1}{2}g'v_u & -\frac{1}{2}g'v_1 & -\frac{1}{2}g'v_2 & -\frac{1}{2}g'v_3 \\ 0 & M & \frac{1}{2}gv_d & -\frac{1}{2}gv_u & \frac{1}{2}gv_1 & \frac{1}{2}gv_2 & \frac{1}{2}gv_3 \\ -\frac{1}{2}g'v_d & \frac{1}{2}gv_d & 0 & -\mu & 0 & 0 & 0 \\ \frac{1}{2}g'v_u & -\frac{1}{2}gv_u & -\mu & 0 & \epsilon_1 & \epsilon_2 & \epsilon_3 \\ -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & \epsilon_1 & 0 & 0 & 0 \\ -\frac{1}{2}g'v_2 & \frac{1}{2}gv_2 & 0 & \epsilon_2 & 0 & 0 & 0 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \epsilon_3 & 0 & 0 & 0 \end{bmatrix} \tag{60}$$

and M' is the $U(1)$ gaugino soft mass. This neutralino/neutrino mass matrix is diagonalized by a 7×7 rotation matrix $\boldsymbol{N}$ such that

$$\boldsymbol{N}^* \boldsymbol{M}_N \boldsymbol{N}^{-1} = \mathrm{diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}, m_{\chi_4^0}, m_{\nu_e}, m_{\nu_\mu}, m_{\nu_\tau}) \tag{61}$$

For future reference we note that

$$\psi_j^0 = \boldsymbol{N^*}_{kj}\, F_k^0 \tag{62}$$

and the four component Majorana neutral fermions are obtained from the two component via the relation

$$\chi_i^0 = \begin{pmatrix} F_i^0 \\ \overline{F_i^0} \end{pmatrix} \tag{63}$$

The neutralino masses coming from Eq. (61) can have a negative sign. We fix that by defining a sign parameter

$$\epsilon_i = \frac{m_{\chi_i^0}}{|m_{\chi_i^0}|} \tag{64}$$

This corresponds to the following substitution

$$\chi_i^0 \to \gamma_5 \chi_i^0 \tag{65}$$

and therefore

$$\chi_i^0 \to (\epsilon_i P_L + P_R)\,\chi_i^0 \quad ; \quad \overline{\chi^0}_i \to \overline{\chi^0}_i\,(P_L + \epsilon_i P_R) \tag{66}$$

3.4 Quark Mass Matrices

In two component spinor notation the relevant terms in the Lagrangian are

$$\mathcal{L}_M = -\frac{v_1}{\sqrt{2}}\,(h_D)_{ij}\;d'_{Li}\,d'^c_{Lj} - \frac{v_2}{\sqrt{2}}\,(h_U)_{ij}\;u'_{Li}\,u'^c_{Lj} + h.c. \tag{67}$$

where the primed states are again the interaction eigenstates. In 4–component spinor notation with the definitions

$$d' = \begin{pmatrix} d'_L \\ \overline{d'^c_L} \end{pmatrix} \qquad ; \qquad u' = \begin{pmatrix} u'_L \\ \overline{u'^c_L} \end{pmatrix} \tag{68}$$

we get

$$\mathcal{L}_M = -\overline{d'_L}\,\boldsymbol{M_D} d'_R - \overline{u'_L}\,\boldsymbol{M_U} u'_R + h.c. \tag{69}$$

where

$$(\boldsymbol{M_D})_{ij} = \frac{v_1}{\sqrt{2}}\,(h^*_D)_{ij} \qquad ; \qquad (\boldsymbol{M_U})_{ij} = \frac{v_2}{\sqrt{2}}\,(h^*_U)_{ij} \tag{70}$$

To obtain the eigenstates of the mass we rotate the quark fields through

$$d_R = \boldsymbol{R^d_R}\,d'_R \quad ; \quad d_L = \boldsymbol{R^d_L}\,d'_L \quad ; \quad u_R = \boldsymbol{R^u_R}\,u'_R \quad ; \quad u_L = \boldsymbol{R^u_L}\,u'_L \tag{71}$$

For future reference we write the relations between the mass and the interaction eigenstates. We have

$$\begin{array}{lcl} q'_{Ri} = (\boldsymbol{R^q_R})^*_{ji}\;q_{Rj} & ; & \overline{q'_{Ri}} = \overline{q_{Rj}}\;(\boldsymbol{R^q_R})_{ji} \\ & & \qquad\qquad q = (d,u) \\ q'_{Li} = (\boldsymbol{R^q_L})^*_{ji}\;q_{Lj} & ; & \overline{q'_{Li}} = \overline{q_{Lj}}\;(\boldsymbol{R^q_L})_{ji} \end{array} \tag{72}$$

Then

$$\boldsymbol{R^d_L}\,\boldsymbol{M_D}\boldsymbol{R^{d\dagger}_R} = \boldsymbol{M^{diag}_D} \qquad \text{and} \qquad \boldsymbol{R^u_L}\,\boldsymbol{M_U}\boldsymbol{R^{u\dagger}_R} = \boldsymbol{M^{diag}_U} \tag{73}$$

where $\boldsymbol{M^{diag}_{D(U)}}$ are a diagonal matrices. These are diagonalized by noticing that

$$\begin{array}{lcl} \boldsymbol{R^d_L}\,\boldsymbol{M_D}\boldsymbol{M_D}^\dagger\,\boldsymbol{R^d_L}^\dagger = \left(\boldsymbol{M^{diag}_D}\right)^2 & ; & \boldsymbol{R^d_R}\,\boldsymbol{M_D}^\dagger\boldsymbol{M_D}\,\boldsymbol{R^d_R}^\dagger = \left(\boldsymbol{M^{diag}_D}\right)^2 \\ \boldsymbol{R^u_L}\,\boldsymbol{M_U}\boldsymbol{M_U}^\dagger\,\boldsymbol{R^u_L}^\dagger = \left(\boldsymbol{M^{diag}_U}\right)^2 & ; & \boldsymbol{R^u_R}\,\boldsymbol{M_U}^\dagger\boldsymbol{M_U}\,\boldsymbol{R^u_R}^\dagger = \left(\boldsymbol{M^{diag}_U}\right)^2 \end{array} \tag{74}$$

Before we close this section let us write down the Cabibbo-Kobayashi-Maskawa (CKM) mixing matrix with our conventions. The couplings of the $W^{\pm}$ with the quarks are

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\, W_\mu^- \overline{d'_{Li}}\, \gamma^\mu\, u'_{Li} - \frac{g}{\sqrt{2}}\, W_\mu^+ \overline{u'_{Li}}\, \gamma^\mu\, d'_{Li} \tag{75}$$

Then in terms of the mass eigenstates the charged current Lagrangian reads

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} \boldsymbol{V}_{ij}^{\text{CKM}*}\, W_\mu^-\, \overline{d_{Lj}}\, \gamma^\mu\, u_{Li} - \frac{g}{\sqrt{2}} \boldsymbol{V}_{ij}^{\text{CKM}}\, W_\mu^+\, \overline{u_{Li}}\, \gamma^\mu\, d_{Lj} \tag{76}$$

where the CKM matrix $\boldsymbol{V}^{\text{CKM}}$ is defined through

$$\boldsymbol{V}^{\text{CKM}} = \boldsymbol{R_L^u}\, \boldsymbol{R_L^d}^\dagger \tag{77}$$

4 Couplings in the ϵ-model

In this section we give a list of all the couplings of the ϵ-model. In Table 1 we give a guide to the various couplings of the model†.

4.1 Gauge Self-Interactions

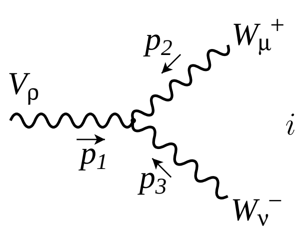
The gauge sector of the ϵ-model is exactly the same as the SM and the MSSM. So we refer the reader to ref. [3] for details and just give here the vertices for completeness and to fix our notation.

4.1.1 VVV

We have

$$\begin{aligned}
\mathcal{L} \; = \; & i\, e \Big[\left(\partial_\mu W_\nu^- - \partial_\nu W_\mu^-\right) W^{+\mu} A^\nu - \left(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+\right) W^{-\mu} A^\nu \\
& \qquad - \left(\partial_\mu A_\nu - \partial_\nu A_\mu\right) W^{+\mu} W^{-\nu} \Big] \\
& + i\, g\, \cos\theta_W \Big[\left(\partial_\mu W_\nu^- - \partial_\nu W_\mu^-\right) W^{+\mu} Z^\nu - \left(\partial_\mu W_\nu^+ - \partial_\nu W_\mu^+\right) W^{-\mu} Z^\nu \\
& \qquad - \left(\partial_\mu Z_\nu - \partial_\nu Z_\mu\right) W^{+\mu} W^{-\nu} \Big]
\end{aligned} \tag{78}$$

which gives the following Feynman rule for the vertices



$$i\, g_V \left[g^{\mu\nu} (p_2 - p_3)^\rho + g^{\nu\rho} (p_3 - p_1)^\mu + g^{\rho\mu} (p_1 - p_2)^\nu \right] \tag{79}$$

†This is work in progress, therefore the list is still incomplete.

Name	Type	Equations	Explanation Section	Notes
3-Point Gauge Coupling	$V\chi\chi$	(89), (101)	4.2, 4.3	$V = A_\mu, Z^0_\mu, W^\pm_\mu$
	Vqq	(91)	4.2	$q = u, d, c, s, t, b$
	$V\tilde{q}\tilde{q}$			$\tilde{q} = \tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}$
	VHH	(96)	4.2.4	$H = S^0, P^0, H^\pm$
3-Point Higgs Coupling	$H\chi\chi$	(108),(109),(117), (119)	4.4.1, 4.4.2	
	Hqq	(125)	4.4.3	
	$H\tilde{q}\tilde{q}$			
	HVV			
Other 3-Point	$\tilde{f}f\chi$			
	$\tilde{q}q\chi$	(135),(141),(148),(154)	4.5	
4-Point Coupling	$VV\chi\chi$			
	$HHVV$			
	$HH\tilde{q}\tilde{q}$			
Gauge	VVV	(79)	4.1	
Self-Interaction	$VVVV$	(81),(82)	4.1	
Higgs Interaction	HHH			
	$HHHH$			
Ghost	$\overline{\omega}\omega V$			
	$\overline{\omega}\omega H$			

Table 1: List of the couplings of the ϵ-model

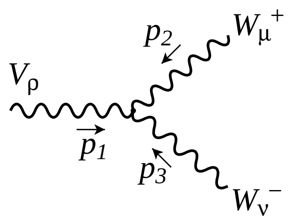
where $V = A(Z)$ and $g_A = e, g_Z = g \cos\theta_W$.

4.1.2 $VVVV$

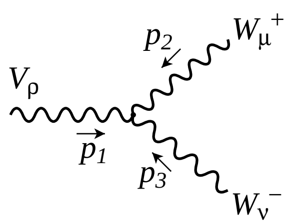
For the quartic self–interactions we have

$$
\begin{aligned}
\mathcal{L}_{VVVV} \;=\;& \tfrac{1}{2} g^2 \left[\left(W^+_\mu W^{+\mu}\right)\left(W^-_\nu W^{-\nu}\right) - \left(W^+_\mu W^{-\mu}\right)^2\right] \\
&+ g^2 \cos^2\theta_W \left[W^+_\mu W^-_\nu Z^\mu Z^\nu - W^+_\mu W^{-\mu} Z_\nu Z^\nu\right] \\
&+ e^2 \left[W^+_\mu W^-_\nu A^\mu A^\nu - W^+_\mu W^{-\mu} A_\nu A^\nu\right] \\
&+ e\, g \cos\theta_W \left[W^+_\mu W^-_\nu \left(Z^\mu A^\nu + Z^\nu A^\mu\right) - 2 W^+_\mu W^{-\mu} A_\nu Z^\nu\right] \qquad (80)
\end{aligned}
$$

which gives the following Feynman rules for the quartic vertices,



$$i\, g^2 \left[2\, g^{\mu\alpha} g^{\nu\beta} - g^{\alpha\nu} g^{\mu\beta} - g^{\mu\nu} g^{\alpha\beta}\right] \qquad (81)$$



$$i\, g_V\, g_V \left[g^{\mu\alpha} g^{\nu\beta} + g^{\mu\beta} g^{\alpha\nu} - 2\, g^{\mu\nu} g^{\alpha\beta}\right] \qquad (82)$$

where $V = A(Z)$ and $g_A = e, g_Z = g \cos\theta_W$.

4.2 Charged Current Couplings

4.2.1 $W\chi\chi$

In the ϵ-model the charged leptons and the neutrinos are mixed with the charginos and neutralinos. Hence the couplings in this subsection also include those. Using two component spinors and following the notation of ref. [2] the relevant part of the Lagrangian can be written as

$$\mathcal{L} = g\, W^-_\mu \left[\left(\overline{\lambda^3}\, \overline{\sigma}^\mu \lambda^+ - \overline{\lambda^-}\, \overline{\sigma}^\mu \lambda^3\right) - \frac{1}{\sqrt{2}} \left(\overline{\widetilde{H}^0_u}\, \overline{\sigma}^\mu \widetilde{H}^+_u + \overline{\widetilde{H}^-_d}\, \overline{\sigma}^\mu \widetilde{H}^0_d + \sum_{i=1}^{3} \overline{L^-_i}\, \overline{\sigma}^\mu L^0_i\right)\right]$$

$$+ g\, W_\mu^+ \left[\left(\overline{\lambda^+}\, \overline{\sigma}^\mu\, \lambda^3 - \overline{\lambda^3}\, \overline{\sigma}^\mu\, \lambda^- \right) - \frac{1}{\sqrt{2}} \left(\overline{\widetilde{H}_u^+}\, \overline{\sigma}^\mu\, \widetilde{H}_u^0 + \overline{\widetilde{H}_d^0}\, \overline{\sigma}^\mu\, \widetilde{H}_d^- + \sum_{i=1}^{3} \overline{L_i^0}\, \overline{\sigma}^\mu\, L_i^- \right) \right] \tag{83}$$

To obtain the couplings in four component notation we first write eq.(83) in terms of the mass eigenstates in two component notation, $F_i^\pm$ and F_i^0. In order to do that we recall that

$$\begin{array}{rclcrcl}
-i\lambda' &=& \boldsymbol{N}^*{}_{i1} F_i^0 && i\overline{\lambda'} &=& \boldsymbol{N}_{i1} \overline{F_i^0} \\
-\,i\lambda^3 &=& \boldsymbol{N}^*{}_{i2} F_i^0 && i\overline{\lambda^3} &=& \boldsymbol{N}_{i2} \overline{F_i^0} \\
\widetilde{H}_d^0 &=& \boldsymbol{N}^*{}_{i3} F_i^0 && \overline{\widetilde{H}_d^0} &=& \boldsymbol{N}_{i3} \overline{F_i^0} \\
\widetilde{H}_u^0 &=& \boldsymbol{N}^*{}_{i4} F_i^0 && \overline{\widetilde{H}_u^0} &=& \boldsymbol{N}_{i4} \overline{F_i^0} \\
\widetilde{L}_k^0 &=& \boldsymbol{N}^*{}_{i,4+k} F_i^0 && \overline{\widetilde{L}_k^0} &=& \boldsymbol{N}_{i,4+k} \overline{F_i^0}
\end{array} \tag{84}$$

$$\begin{array}{rclcrcl}
-i\lambda^- &=& \boldsymbol{U}^*{}_{j1} F_j^- && i\overline{\lambda^-} &=& \boldsymbol{U}_{j1} \overline{F_j^-} \\
\widetilde{H}_d^- &=& \boldsymbol{U}^*{}_{j2} F_j^- && \overline{\widetilde{H}_d^-} &=& \boldsymbol{U}_{j2} \overline{F_j^-} \\
L_k^- &=& \boldsymbol{U}^*{}_{j,2+k} F_j^- && \overline{L_k^-} &=& \boldsymbol{U}_{j,2+k} \overline{F_j^-}
\end{array} \tag{85}$$

$$\begin{array}{rclcrcl}
-i\lambda^+ &=& \boldsymbol{V}^*{}_{j1} F_j^+ && i\overline{\lambda^+} &=& \boldsymbol{V}_{j1} \overline{F_j^+} \\
\widetilde{H}_u^+ &=& \boldsymbol{V}^*{}_{j2} F_j^+ && \overline{\widetilde{H}_u^+} &=& \boldsymbol{V}_{j2} \overline{F_j^+} \\
R_k^+ &=& \boldsymbol{V}^*{}_{j,2+k} F_j^+ && \overline{R_k^+} &=& \boldsymbol{V}_{j,2+k} \overline{F_j^+}
\end{array} \tag{86}$$

We obtain then

$$\begin{aligned}
\mathcal{L} \;=\; & g\, W_\mu^- \Big[\; \overline{F_i^0}\, \overline{\sigma}^\mu\, F_j^+ \left(\boldsymbol{N}_{i2} \boldsymbol{V}^*{}_{j1} - \frac{1}{\sqrt{2}} \boldsymbol{N}_{i4} \boldsymbol{V}^*{}_{j2} \right) \\
& \qquad + \overline{F_j^-}\, \overline{\sigma}^\mu\, F_i^0 \left(-\boldsymbol{N}^*{}_{i2} \boldsymbol{U}_{j1} - \frac{1}{\sqrt{2}} \left(\boldsymbol{N}^*{}_{i3} \boldsymbol{U}_{j2} + \sum_{k=1}^{3} \boldsymbol{N}^*{}_{i,4+k} \boldsymbol{U}_{j,2+k} \right) \right) \Big] \\
+ \; & g\, W_\mu^+ \Big[\; \overline{F_j^+}\, \overline{\sigma}^\mu\, F_i^0 \left(\boldsymbol{N}^*{}_{i2} \boldsymbol{V}_{j1} - \frac{1}{\sqrt{2}} \boldsymbol{N}^*{}_{i4} \boldsymbol{V}_{j2} \right) \\
& \qquad + \overline{F_i^0}\, \overline{\sigma}^\mu\, F_j^- \left(-\boldsymbol{N}_{i2} \boldsymbol{U}^*{}_{j1} - \frac{1}{\sqrt{2}} \left(\boldsymbol{N}_{i3} \boldsymbol{U}^*{}_{j2} + \sum_{k=1}^{3} \boldsymbol{N}_{i,4+k} \boldsymbol{U}^*{}_{j,2+k} \right) \right) \Big]
\end{aligned} \tag{87}$$

Finally using

$$\begin{aligned}
\overline{F_i^0}\, \overline{\sigma}^\mu\, F_j^+ &= -\overline{\chi_j^-}\, \gamma^\mu P_R \chi_i^0 \\
\overline{F_j^-}\, \overline{\sigma}^\mu\, F_i^0 &= \overline{\chi_j^-}\, \gamma^\mu P_L \chi_i^0 \\
\overline{F_i^0}\, \overline{\sigma}^\mu\, F_j^- &= \overline{\chi_i^0} \gamma^\mu P_L \chi_j^- \\
\overline{F_j^+}\, \overline{\sigma}^\mu\, F_i^0 &= -\overline{\chi_i^0} \gamma^\mu P_R \chi_j^-
\end{aligned} \tag{88}$$

and remembering the sign conventions, Eq. (57) and Eq. (65), we get

$$\mathcal{L} = \overline{\chi_i^-}\, \gamma^\mu \left(O_{Lij}^{\text{cnw}} P_L + O_{Rij}^{\text{cnw}} P_R \right) \chi_j^0\; W_\mu^- + \overline{\chi_i^0}\, \gamma^\mu \left(O_{Lij}^{\text{ncw}} P_L + O_{Lij}^{\text{ncw}} P_R \right) \chi_j^-\; W_\mu^+ \tag{89}$$

where

$$
\begin{aligned}
O^{\rm cnw}_{Lij} &= g\,\eta_i \epsilon_j \left[-\boldsymbol{N}^*{}_{j2}\boldsymbol{U}_{i1} - \tfrac{1}{\sqrt{2}} \left(\boldsymbol{N}^*{}_{j3}\boldsymbol{U}_{i2} + \sum_{k=1}^{3} \boldsymbol{N}^*{}_{j,4+k}\,\boldsymbol{U}_{i,2+k} \right) \right] \\
O^{\rm cnw}_{Rij} &= g\,\left(-\boldsymbol{N}_{j2}\boldsymbol{V}^*{}_{i1} + \tfrac{1}{\sqrt{2}}\,\boldsymbol{N}_{j4}\boldsymbol{V}^*{}_{i2} \right) \\
O^{\rm ncw}_{Lij} &= \left(O^{\rm cnw}_{Lji} \right)^* \quad ; \quad O^{\rm ncw}_{Rij} = \left(O^{\rm cnw}_{Rji} \right)^*
\end{aligned}
\tag{90}
$$

4.2.2 Wqq'

This couplings were already presented before when we discussed the quark mass matrices and the $\boldsymbol{V}^{\rm CKM}$ matrix in Section 3.4. We just copy the result without further discussion. In terms of the mass eigenstates the charged current Lagrangian reads

$$
\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}}\boldsymbol{V}^{\rm CKM*}_{ij}\, W^-_\mu\, \overline{d_{Lj}}\,\gamma^\mu\, u_{Li} - \frac{g}{\sqrt{2}}\boldsymbol{V}^{\rm CKM}_{ij}\, W^+_\mu\, \overline{u_{Li}}\,\gamma^\mu\, d_{Lj} \tag{91}
$$

where the CKM matrix $\boldsymbol{V}^{\rm CKM}$ is defined in Eq. (77).

4.2.3 $W\tilde{q}\tilde{q}'$

4.2.4 WHH

The trilinear couplings of the W bosons with the charged and neutral scalars result from the following terms written in terms of the unrotated doublets

$$
\mathcal{L}_{\rm WHH} \subset (D_\mu H_d)^\dagger\, D^\mu + H_d\,(D_\mu H_u)^\dagger\, D^\mu H_u + \sum_{i=1}^{3}\left(D_\mu \widetilde{L}_i\right)^\dagger D^\mu \widetilde{L}_i \tag{92}
$$

In terms of the unrotated fields we get

$$
\begin{aligned}
\mathcal{L}_{\rm WHH} \;=\; & i\frac{g}{\sqrt{2}} W^-_\mu \Big[H'^0_d\,\partial^\mu H'^+_d - H'^+_d \partial^\mu H'^0_d - H'^{0*}_u\,\partial^\mu H'^+_u + H'^+_u\,\partial^\mu H'^{0*}_u \\
& + \sum_{i=1}^{3}\left(\widetilde{L'}^0_i \partial^\mu \widetilde{L'}^+_i - \widetilde{L'}^+_i \partial^\mu \widetilde{L'}^0_i \right) \Big] + \text{h.c.}
\end{aligned}
\tag{93}
$$

which can be written as

$$
\mathcal{L}_{\rm WHH} = O'^{\rm wc\,s}_{ij}\, W^-_\mu\, \left(S'^0_i \partial^\mu S'^+_j - S'^+_j \partial^\mu S'^0_i\right) + O'^{\rm wcp}_{ij}\, W^-_\mu\, \left(P'^0_i \partial^\mu S'^+_j - S'^+_j \partial^\mu P'^0_i\right) + \text{h.c.} \tag{94}
$$

where

$$
\begin{aligned}
O'^{\rm wc\,s}_{11} &= \frac{ig}{2} & \qquad O'^{\rm wc\,p}_{11} &= -\frac{g}{2} \\
O'^{\rm wc\,s}_{22} &= -\frac{ig}{2} & \qquad O'^{\rm wc\,p}_{22} &= -\frac{g}{2} \\
O'^{\rm wc\,s}_{jj} &= \frac{ig}{2} \quad j=1,2,3 & \qquad O'^{\rm wc\,p}_{jj} &= -\frac{g}{2} \quad j=1,2,3
\end{aligned}
\tag{95}
$$

all other entries vanishing. In terms of the mass eigenstates we have

$$O_{ij}^{\text{wc s}} = \boldsymbol{R}_{im}^{S^0\,*}\boldsymbol{R}_{jn}^{S^\pm\,*}O_{mn}^{\prime\text{wc s}} \quad , \quad O_{ij}^{\text{wc p}} = \boldsymbol{R}_{im}^{P^0\,*}\boldsymbol{R}_{jn}^{S^\pm\,*}O_{mn}^{\prime\text{wc p}} \tag{96}$$

4.3 Neutral Current Couplings

4.3.1 $(A,Z)\chi\chi$

In the ϵ-model the charged leptons and the neutrinos are mixed with the charginos and neutralinos. Hence the couplings in this subsection also include those. Using two component spinors and following the notation of ref. [2] the relevant part of the Lagrangian can be written as

$$\begin{aligned}
\mathcal{L} = &-\frac{1}{2}\left(gW_\mu^3 + g'B_\mu\right)\left(\overline{\widetilde{H}_u^+}\,\overline{\sigma}^\mu\,\widetilde{H}_u^+ - \overline{\widetilde{H}_d^0}\,\overline{\sigma}^\mu\,\widetilde{H}_d^-\right)\\
&-\frac{1}{2}\left(-gW_\mu^3 + g'B_\mu\right)\left(\overline{\widetilde{H}_u^0}\,\overline{\sigma}^\mu\,\widetilde{H}_u^0 - \overline{\widetilde{H}_d^0}\,\overline{\sigma}^\mu\,\widetilde{H}_d^0\right)\\
&-gW_\mu^3\left(\overline{\lambda^+}\,\overline{\sigma}^\mu\,\lambda^+ - \overline{\lambda^-}\,\overline{\sigma}^\mu\,\lambda^-\right) - g'B_\mu\sum_{i=1}^3\overline{R_i^+}\,\overline{\sigma}^\mu\,R_i^+\\
&+\frac{1}{2}\sum_{i=1}^3\left(-gW_\mu^3 + g'B_\mu\right)\,\overline{L_i^0}\,\overline{\sigma}^\mu\,L_i^0 + \frac{1}{2}\sum_{i=1}^3\left(gW_\mu^3 + g'B_\mu\right)\,\overline{L_i^-}\,\overline{\sigma}^\mu\,L_i^-
\end{aligned}\tag{97}$$

To obtain the couplings in four component notation we first write eq.(83) in terms of the mass eigenstates in two component notation, $F_i^\pm$ and F_i^0. We also use

$$\begin{aligned}
gW_\mu^3 &= eA_\mu + \frac{g}{\cos\theta_w}\left(1-\sin^2\theta_w\right)Z_\mu\\
g'B_\mu^3 &= eA_\mu - \frac{g}{\cos\theta_w}\sin^2\theta_w Z_\mu
\end{aligned}\tag{98}$$

We get in two component notation

$$\begin{aligned}
\mathcal{L} = &-eA_\mu\left[\sum_{k=1}^5\boldsymbol{V}_{ik}\boldsymbol{V}^*{}_{jk}\overline{F_i^+}\,\overline{\sigma}^\mu\,F_j^+ - \sum_{k=1}^5\boldsymbol{U}_{ik}\boldsymbol{U}^*{}_{jk}\overline{F_i^-}\,\overline{\sigma}^\mu\,F_j^-\right]\\
&+\frac{g}{\cos\theta_w}Z_\mu\Bigg[\tfrac{1}{2}\left(\boldsymbol{N}_{i4}\boldsymbol{N}^*{}_{j4} - \boldsymbol{N}_{i3}\boldsymbol{N}^*{}_{j3} - \sum_{k=1}^3\boldsymbol{N}_{i,4+k}\boldsymbol{N}^*{}_{j,4+k}\right)\overline{F_i^0}\overline{\sigma}^\mu\,F_j^0\\
&\left(\tfrac{1}{2}\boldsymbol{U}_{i2}\boldsymbol{U}^*{}_{j2} + \boldsymbol{U}_{i1}\boldsymbol{U}^*{}_{j1} + \tfrac{1}{2}\sum_{k=1}^3\boldsymbol{U}_{i,2+k}\boldsymbol{U}^*{}_{j,2+k} - \sin^2\theta_w\sum_{k=1}^5\boldsymbol{U}_{ik}\boldsymbol{U}^*{}_{jk}\right)\overline{F_i^-}\,\overline{\sigma}^\mu\,F_j^-\\
&\left(-\tfrac{1}{2}\boldsymbol{V}_{i2}\boldsymbol{V}^*{}_{j2} - \boldsymbol{V}_{i1}\boldsymbol{V}^*{}_{j1} + \sin^2\theta_w\sum_{k=1}^5\boldsymbol{V}_{ik}\boldsymbol{V}^*{}_{jk}\right)\overline{F_i^+}\,\overline{\sigma}^\mu\,F_j^+\Bigg]
\end{aligned}\tag{99}$$

Now using the unitarity of the diagonalization matrices we get, still in two component spinor notation,

$$\mathcal{L} = eA_\mu\left[\sum_{i=1}^5\left(\overline{F_i^-}\,\overline{\sigma}^\mu\,F_i^- - \overline{F_i^+}\,\overline{\sigma}^\mu\,F_i^+\right)\right]$$

$$
\begin{aligned}
&+ \frac{g}{\cos\theta_w} Z_\mu \Bigg[\tfrac{1}{2}\left(\boldsymbol{N}_{i4}\boldsymbol{N}^*{}_{j4} - \boldsymbol{N}_{i3}\boldsymbol{N}^*{}_{j3} - \sum_{k=1}^{3} \boldsymbol{N}_{i,4+k}\boldsymbol{N}^*{}_{j,4+k} \right) \overline{F_i^0}\overline{\sigma}^\mu F_j^0 \\
&\qquad \left(\tfrac{1}{2}\boldsymbol{U}_{i2}\boldsymbol{U}^*{}_{j2} + \boldsymbol{U}_{i1}\boldsymbol{U}^*{}_{j1} + \sum_{k=1}^{3} \tfrac{1}{2}\boldsymbol{U}_{i,2+k}\boldsymbol{U}^*{}_{j,2+k} - \sin^2\theta_w\,\delta_{ij} \right) \overline{F_i^-}\,\overline{\sigma}^\mu F_j^- \\
&\qquad \left(-\tfrac{1}{2}\boldsymbol{V}_{i2}\boldsymbol{V}^*{}_{j2} - \boldsymbol{V}_{i1}\boldsymbol{V}^*{}_{j1} + \sin^2\theta_w\,\delta_{ij} \right) \overline{F_i^+}\,\overline{\sigma}^\mu F_j^+ \Bigg]
\end{aligned}
\tag{100}
$$

Finally we get in four component notation

$$
\begin{aligned}
\mathcal{L} &= eA_\mu \sum_{i=1}^{3} \overline{\chi_i^-}\,\gamma^\mu \chi_i^- \\
&\quad + Z_\mu^0\, \tfrac{1}{2}\overline{\chi_i^0}\gamma^\mu \left(O^{\rm nnz}_{Lij} P_L + O^{\rm nnz}_{Rij} P_R \right) \chi_j^0 + Z_\mu^0\, \overline{\chi_i^-}\,\gamma^\mu \left(O^{\rm ccz}_{Lij} P_L + O^{\rm ccz}_{Rij} P_R \right) \chi_j^-
\end{aligned}
\tag{101}
$$

where

$$
\begin{aligned}
O^{\rm nnz}_{Lij} &= \frac{g}{\cos\theta_w}\, \epsilon_i\epsilon_j \tfrac{1}{2} \left(\boldsymbol{N}_{i4}\boldsymbol{N}^*{}_{j4} - \boldsymbol{N}_{i3}\boldsymbol{N}^*{}_{j3} - \sum_{k=1}^{3} \boldsymbol{N}_{i,4+k}\boldsymbol{N}^*{}_{j,4+k} \right) \\
O^{\rm nnz}_{Rij} &= -\left(O^{\rm nnz}_{Lji} \right)^*
\end{aligned}
\tag{102}
$$

and

$$
\begin{aligned}
O^{\rm ccz}_{Lij} &= \frac{g}{\cos\theta_w}\, \eta_i\eta_j \left(\tfrac{1}{2}\boldsymbol{U}_{i2}\boldsymbol{U}^*{}_{j2} + \boldsymbol{U}_{i1}\boldsymbol{U}^*{}_{j1} + \sum_{k=1}^{3} \tfrac{1}{2}\boldsymbol{U}_{i,2+k}\boldsymbol{U}^*{}_{j,2+k} - \sin^2\theta_w\,\delta_{ij} \right) \\
O^{\rm ccz}_{Rij} &= \frac{g}{\cos\theta_w} \left(\tfrac{1}{2}\boldsymbol{V}_{j2}\boldsymbol{V}^*{}_{i2} + \boldsymbol{V}_{j1}\boldsymbol{V}^*{}_{i1} - \sin^2\theta_w\,\delta_{ij} \right)
\end{aligned}
\tag{103}
$$

4.3.2 $(A, Z)qq$

4.3.3 $(A, Z)\tilde{q}\tilde{q}$

4.3.4 $(A, Z)HH$

4.4 Scalar 3-Point Interactions

4.4.1 $S^{\mp}\chi^0\chi^{\pm}$

Using two component spinors and following the notation of ref. [2] the relevant part of the Lagrangian can be written as

$$
\begin{aligned}
\mathcal{L} &= H_d^+ \left[\frac{g}{\sqrt{2}} (-i\lambda^3)\, \widetilde{H}_d^- + \frac{g'}{\sqrt{2}} (-i\lambda')\, \widetilde{H}_d^- - g\,(-i\lambda^-)\, \widetilde{H}_d^0 + h_E^{ij} \overline{L_i^0}\; \overline{R_j^+} \right] \\
&\quad + H_u^+ \left[-\frac{g}{\sqrt{2}} (i\overline{\lambda^3})\; \overline{\widetilde{H}_u^+} - \frac{g'}{\sqrt{2}} (i\overline{\lambda'})\; \overline{\widetilde{H}_u^+} - g\,(i\overline{\lambda^+})\; \overline{\widetilde{H}_u^0} \right] \\
&\quad + \widetilde{L_i^-}^* \left[\left(\frac{g}{\sqrt{2}} (-i\lambda^3) + \frac{g'}{\sqrt{2}} (-i\lambda') \right) L_i^- - g\,(-i\lambda^-)\, L_i^0 - h_E^{ij} \overline{R_j^+}\; \overline{\widetilde{H}_d^0} \right]
\end{aligned}
$$

$$+ \widetilde{R_j^+} \left[-g'\sqrt{2}\,(i\overline{\lambda'})\ \overline{R_j^+} - h_E^{ij}\, L_i^- \widetilde{H}_d^0 + h_E^{ij}\, L_i^0 \widetilde{H}_d^- \right] + \text{h.c.} \tag{104}$$

The previous expression can be written in terms of the two component fermions $F_i^{\pm}$and F_i^0

$$\begin{aligned}
\mathcal{L} = H_d^+ & \left[\left(\frac{g}{\sqrt{2}} \boldsymbol{N^*}_{i2} \boldsymbol{U^*}_{j2} + \frac{g'}{\sqrt{2}} \boldsymbol{N^*}_{i1} \boldsymbol{U^*}_{j2} - g \boldsymbol{N^*}_{i3} \boldsymbol{U^*}_{j1} \right) F_i^0 F_j^- + h_E^{km}\, \boldsymbol{N}_{i,4+k} \boldsymbol{V}_{j,2+m}\, \overline{F_j^+}\ \overline{F_i^0} \right] \\
+ H_u^+ & \left[\left(-\frac{g}{\sqrt{2}} \boldsymbol{N}_{i2} \boldsymbol{V}_{j2} - \frac{g'}{\sqrt{2}} \boldsymbol{N}_{i1} \boldsymbol{V}_{j2} - g \boldsymbol{N}_{i4} \boldsymbol{V}_{j1} \right) \overline{F_j^+}\ \overline{F_i^0} \right] \\
+ \widetilde{L_k^-}^* & \left[\left(\frac{g}{\sqrt{2}} \boldsymbol{N^*}_{i2} \boldsymbol{U^*}_{j,2+k} + \frac{g'}{\sqrt{2}} \boldsymbol{N^*}_{i1} \boldsymbol{U^*}_{j,2+k} - g \boldsymbol{N^*}_{i,4+k} \boldsymbol{U^*}_{j1} \right) F_i^0 F_j^- - h_E^{km}\, \boldsymbol{N}_{i3} \boldsymbol{V}_{j,2+m} \overline{F_j^+}\, \overline{F_i^0} \right] \\
+ \widetilde{R_k^+} & \left[-g'\sqrt{2}\, \boldsymbol{N}_{i1} \boldsymbol{V}_{j,2+k}\, \overline{F_j^+}\ \overline{F_i^0} + h_E^{mk}\, (\boldsymbol{N^*}_{i,4+m} \boldsymbol{U^*}_{j2} - \boldsymbol{N^*}_{i3} \boldsymbol{U^*}_{j,2+m})\, F_i^0 F_j^- \right] + \text{h.c.}
\end{aligned} \tag{105}$$

Now we define the weak basis charged scalars $S_i'^+ = (H_d^+, H_u^+, \widetilde{L_i^+}, \widetilde{R_j^+})$. The mass eigenstates $S_i^{\pm}$ are obtained from $S_i'^{\pm}$ through the rotation matrix $\boldsymbol{R_{S^\pm}}$. Then in terms of the unrotated fields $S_i'^{\pm}$ and in terms of the mass eigenstates $S_i^{\pm}$, the Lagrangian reads

$$\begin{aligned}
\mathcal{L} &= \overline{\chi_i^-} \left(O'^{cns}_{Lijk}\ P_L + O'^{cns}_{Rijk}\ P_R \right) \chi_j^0 S_k'^- + \overline{\chi_i^0} \left(O'^{ncs}_{Lijk}\ P_L + O'^{ncs}_{Rijk}\ P_R \right) \chi_j^- S_k'^+ \\
&= \overline{\chi_i^-} \left(O^{cns}_{Lijk}\ P_L + O^{cns}_{Rijk}\ P_R \right) \chi_j^0 S_k^- + \overline{\chi_i^0} \left(O^{ncs}_{Lijk}\ P_L + O^{ncs}_{Rijk}\ P_R \right) \chi_j^- S_k^+
\end{aligned} \tag{106}$$

where

$$\begin{aligned}
O^{cns}_{Lijk} = \boldsymbol{R}^{S^{\pm *}}_{km}\ O'^{cns}_{Lijm} \quad ; \quad O^{cns}_{Rijk} = \boldsymbol{R}^{S^{\pm *}}_{km}\ O'^{cns}_{Rijm} \\
O^{ncs}_{Lijk} = \boldsymbol{R}^{S^{\pm *}}_{km}\ O'^{ncs}_{Lijm} \quad ; \quad O^{ncs}_{Rijk} = \boldsymbol{R}^{S^{\pm *}}_{km}\ O'^{ncs}_{Rijm}
\end{aligned} \tag{107}$$

The coupling matrices can be read from eq.(105). We get

$$\begin{aligned}
O'^{cns}_{Lij1} &= \epsilon_j \left(h_E^{mn} \boldsymbol{N}^*_{j,4+m} \boldsymbol{V}^*_{i,2+n} \right) \\
O'^{cns}_{Lij2} &= \epsilon_j \left(-\frac{g}{\sqrt{2}}\, \boldsymbol{N}^*_{j2} \boldsymbol{V}^*_{i2} - \frac{g'}{\sqrt{2}}\, \boldsymbol{N}^*_{j1} \boldsymbol{V}^*_{i2} - g \boldsymbol{N}^*_{j4} \boldsymbol{V}^*_{i1} \right) \\
O'^{cns}_{Lij,2+m} &= \epsilon_j \left(-h_E^{mr} \boldsymbol{N}^*_{j3} \boldsymbol{V}^*_{i,2+r} \right) \quad ; \quad (m = 1,2,3) \\
O'^{cns}_{Lij,5+m} &= \epsilon_j \left(-g'\sqrt{2}\, \boldsymbol{N}^*_{j1} \boldsymbol{V}^*_{i,2+m} \right) \quad ; \quad (m = 1,2,3)
\end{aligned} \tag{108}$$

and

$$\begin{aligned}
O'^{cns}_{Rij1} &= \eta_i \left(\frac{g}{\sqrt{2}}\, \boldsymbol{N}_{j2} \boldsymbol{U}_{i2} + \frac{g'}{\sqrt{2}}\, \boldsymbol{N}_{j1} \boldsymbol{U}_{i2} - g \boldsymbol{N}_{j3} \boldsymbol{U}_{i1} \right) \\
O'^{cns}_{Rij2} &= 0 \\
O'^{cns}_{Rij,2+m} &= \eta_i \left(\frac{g}{\sqrt{2}} \boldsymbol{N}_{j2} \boldsymbol{U}_{i,2+m} + \frac{g'}{\sqrt{2}} \boldsymbol{N}_{j1} \boldsymbol{U}_{i,2+m} - g \boldsymbol{N}_{j,4+m} \boldsymbol{U}_{i1} \right) \quad ; \quad (m = 1,2,3) \\
O'^{cns}_{Rij,5+m} &= \eta_i\, h_E^{rm} \left(\boldsymbol{N}_{j,4+r} \boldsymbol{U}_{i2} - \boldsymbol{N}_{j3} \boldsymbol{U}_{i,2+r} \right) \quad ; \quad (m = 1,2,3)
\end{aligned} \tag{109}$$

For the couplings with $S_k'^+$ we have the relations, in an obvious notation

$$\begin{aligned}
O'^{ncs}_{Lijk} &= \left(O'^{cns}_{Rjik} \right)^* \\
O'^{ncs}_{Rijk} &= \left(O'^{cns}_{Ljik} \right)^*
\end{aligned} \tag{110}$$

4.4.2 $S^0\chi\chi$ and $P^0\chi\chi$

Using two component spinors and following the notation of ref. [2] the relevant part of the Lagrangian can be written as

$$\begin{aligned}
\mathcal{L} = & \left(H_d^0\right)^* \left[-\frac{g}{\sqrt{2}}\left(-i\lambda^3\right)\widetilde{H}_d^0 + \frac{g'}{\sqrt{2}}\left(-i\lambda'\right)\widetilde{H}_d^0 - g\left(-i\lambda^+\right)\widetilde{H}_d^- - h_E^{ij}\,\overline{L_i^-}\;\overline{R_j^+}\right] \\
& + \left(H_u^0\right)^* \left[\frac{g}{\sqrt{2}}\left(-i\lambda^3\right)\widetilde{H}_u^0 - \frac{g'}{\sqrt{2}}\left(-i\lambda'\right)\widetilde{H}_u^0 - g\left(-i\lambda^-\right)\widetilde{H}_u^+\right] \\
& + \left(\widetilde{L}_k^0\right)^* \left[-\frac{g}{\sqrt{2}}\left(-i\lambda^3\right)L_k^0 + \frac{g'}{\sqrt{2}}\left(-i\lambda'\right)L_k^0 - g\left(-i\lambda^+\right)L_k^- + h_E^{kj}\,\overline{R_j^+}\;\overline{\widetilde{H}_d^-}\right] \\
& + \text{h.c.}
\end{aligned} \tag{111}$$

Now we write this expression in terms of the two component fermion eigenstates

$$\begin{aligned}
\mathcal{L} = & \left(H_d^0\right)^* \Bigg[\left(-\frac{g}{\sqrt{2}}\boldsymbol{N^*}_{i2}\boldsymbol{N^*}_{j3} + \frac{g'}{\sqrt{2}}\boldsymbol{N^*}_{i1}\boldsymbol{N^*}_{j3}\right) F_i^0F_j^0 - g\boldsymbol{V^*}_{i1}\boldsymbol{U^*}_{j2}\,F_i^+F_j^- \\
& \qquad - h_E^{mn}\,\boldsymbol{U}_{j,2+m}\boldsymbol{V}_{i,2+n}\,\overline{F_j^-}\;\overline{F_i^+}\Bigg] \\
& + \left(H_u^0\right)^* \left[\left(\frac{g}{\sqrt{2}}\boldsymbol{N^*}_{i2}\boldsymbol{N^*}_{j4} - \frac{g'}{\sqrt{2}}\boldsymbol{N^*}_{i1}\boldsymbol{N^*}_{j4}\right) F_i^0F_j^0 - g\,\boldsymbol{V^*}_{i2}\boldsymbol{U^*}_{j1}\,F_i^+F_j^-\right] \\
& + \left(\widetilde{L}_k^0\right)^* \Bigg[\left(-\frac{g}{\sqrt{2}}\boldsymbol{N^*}_{i2}\boldsymbol{N^*}_{j,4+k} + \frac{g'}{\sqrt{2}}\boldsymbol{N^*}_{i1}\boldsymbol{N^*}_{j,4+k}\right) F_i^0F_j^0 - g\,\boldsymbol{V^*}_{i1}\boldsymbol{U^*}_{j,2+k}\,F_i^+F_j^- \\
& \qquad + h_E^{km}\,\boldsymbol{U}_{j2}\boldsymbol{V}_{i,2+m}\,\overline{F_j^-}\;\overline{F_i^+}\Bigg] \\
& + \text{h.c.}
\end{aligned} \tag{112}$$

To proceed we separate the real and imaginary parts of the complex scalars. Using

$$\widetilde{L}_k^0 = \frac{\widetilde{L}_k^{0R} + i\,\widetilde{L}_k^{0I}}{\sqrt{2}} \tag{113}$$

we get

$$\begin{aligned}
\mathcal{L} = & \frac{\sigma_1^0}{\sqrt{2}} \Bigg[\left(-\frac{g}{\sqrt{2}}\boldsymbol{N^*}_{i2}\boldsymbol{N^*}_{j3} + \frac{g'}{\sqrt{2}}\boldsymbol{N^*}_{i1}\boldsymbol{N^*}_{j3}\right) F_i^0F_j^0 - g\boldsymbol{V^*}_{i1}\boldsymbol{U^*}_{j2}\,F_i^+F_j^- \\
& \qquad - h_E^{mn}\,\boldsymbol{U}_{j,2+m}\boldsymbol{V}_{i,2+n}\,\overline{F_j^-}\;\overline{F_i^+} + \text{h.c}\Bigg] \\
& + \frac{\sigma_2^0}{\sqrt{2}} \left[\left(\frac{g}{\sqrt{2}}\boldsymbol{N^*}_{i2}\boldsymbol{N^*}_{j4} - \frac{g'}{\sqrt{2}}\boldsymbol{N^*}_{i1}\boldsymbol{N^*}_{j4}\right) F_i^0F_j^0 - g\,\boldsymbol{V^*}_{i2}\boldsymbol{U^*}_{j1}\,F_i^+F_j^- + \text{h.c}\right] \\
& + \frac{\widetilde{L}_k^{0R}}{\sqrt{2}} \Bigg[\left(-\frac{g}{\sqrt{2}}\boldsymbol{N^*}_{i2}\boldsymbol{N^*}_{j,4+k} + \frac{g'}{\sqrt{2}}\boldsymbol{N^*}_{i1}\boldsymbol{N^*}_{j,4+k}\right) F_i^0F_j^0 - g\boldsymbol{V^*}_{i1}\boldsymbol{U^*}_{j,2+k}\,F_i^+F_j^- \\
& \qquad + h_E^{km}\,\boldsymbol{U}_{j2}\boldsymbol{V}_{i,2+m}\,\overline{F_j^-}\;\overline{F_i^+} + \text{h.c}\Bigg]
\end{aligned}$$

$$
\begin{aligned}
&-i\,\frac{\varphi_1^0}{\sqrt{2}}\,\Bigg[\left(-\frac{g}{\sqrt{2}}\boldsymbol{N}^*{}_{i2}\boldsymbol{N}^*{}_{j3}+\frac{g'}{\sqrt{2}}\boldsymbol{N}^*{}_{i1}\boldsymbol{N}^*{}_{j3}\right)\,F_i^0F_j^0-g\,\boldsymbol{V}^*{}_{i1}\boldsymbol{U}^*{}_{j2}\,F_i^+F_j^-\\
&\qquad\qquad -h_E^{mn}\boldsymbol{U}_{j,2+m}\boldsymbol{V}_{i,2+n}\,\overline{F_j^-}\;\overline{F_i^+}-\text{h.c}\Bigg]\\
&-i\,\frac{\varphi_2^0}{\sqrt{2}}\,\Bigg[\left(\frac{g}{\sqrt{2}}\boldsymbol{N}^*{}_{i2}\boldsymbol{N}^*{}_{j4}-\frac{g'}{\sqrt{2}}\boldsymbol{N}^*{}_{i1}\boldsymbol{N}^*{}_{j4}\right)\,F_i^0F_j^0-g\,\boldsymbol{V}^*{}_{i2}\boldsymbol{U}^*{}_{j1}\,F_i^+F_j^--\text{h.c}\Bigg]\\
&-i\,\frac{\widetilde{L}_k^{0I}}{\sqrt{2}}\,\Bigg[\left(-\frac{g}{\sqrt{2}}\boldsymbol{N}^*{}_{i2}\boldsymbol{N}^*{}_{j,4+k}+\frac{g'}{\sqrt{2}}\boldsymbol{N}^*{}_{i1}\boldsymbol{N}^*{}_{j,4+k}\right)\,F_i^0F_j^0-g\,\boldsymbol{V}^*{}_{i1}\boldsymbol{U}^*{}_{j,2+k}\,F_i^+F_j^-\\
&\qquad\qquad +h_E^{km}\,\boldsymbol{U}_{j2}\boldsymbol{V}_{i,2+m}\,\overline{F_j^-}\;\overline{F_i^+}-\text{h.c}\Bigg]
\end{aligned}
\tag{114}
$$

Introducing the notation $S_i'^0=(\sigma_1^0,\sigma_2^0,\widetilde{L}_k^{0R})$ and $P_i'^0=(\varphi_1^0,\varphi_2^0,\widetilde{L}_k^{0I})$ for the unrotated scalar and pseudoscalar fields, we can write the Lagrangian in the form,

$$
\begin{aligned}
\mathcal{L}=&\tfrac{1}{2}\overline{\chi_i^0}\left(O_{Lijk}'^{nns}\,P_L+O_{Rijk}'^{nns}\;P_R\right)\chi_j^0\,S_k'^0+\tfrac{1}{2}\overline{\chi_i^0}\left(O_{Lijk}'^{nnp}\,P_L+O_{Rijk}'^{nnp}\,P_R\right)\chi_j^0\,P_k'^0\\
&+\overline{\chi_i^-}\left(O_{Lijk}'^{ccs}\,P_L+O_{Rijk}'^{ccs}\;P_R\right)\chi_j^-\;S_k'^0+\overline{\chi_i^-}\left(O_{Lijk}'^{ccp}\,P_L+O_{Rijk}'^{ccp}\,P_R\right)\chi_j^-\;P_k'^0\\
=&\tfrac{1}{2}\overline{\chi_i^0}\left(O_{Lijk}^{nns}\,P_L+O_{Rijk}^{nns}\;P_R\right)\chi_j^0\,S_k^0+\tfrac{1}{2}\overline{\chi_i^0}\left(O_{Lijk}^{nnp}\,P_L+O_{Rijk}^{nnp}\,P_R\right)\chi_j^0\,P_k^0\\
&+\overline{\chi_i^-}\left(O_{Lijk}^{ccs}\,P_L+O_{Rijk}^{ccs}\;P_R\right)\chi_j^-\;S_k^0+\overline{\chi_i^-}\left(O_{Lijk}^{ccp}\,P_L+O_{Rijk}^{ccp}\,P_R\right)\chi_j^-\;P_k^0
\end{aligned}
\tag{115}
$$

where

$$
\begin{aligned}
O_{L(R)\,ijk}^{nns}&=\boldsymbol{R}_{km}^{S^0\,*}\;O_{L(R)\,ijm}'^{nns}\quad;\quad O_{L(R)\,ijk}^{nnp}=\boldsymbol{R}_{km}^{P^0\,*}\;O_{L(R)\,ijm}'^{nnp}\\
O_{L(R)\,ijk}^{ccs}&=\boldsymbol{R}_{km}^{S^0\,*}\;O_{L(R)\,ijm}'^{ccs}\quad;\quad O_{L(R)\,ijk}^{ccp}=\boldsymbol{R}_{km}^{P^0\,*}\;O_{L(R)\,ijm}'^{ccp}
\end{aligned}
\tag{116}
$$

The unrotated couplings can be read from eq. (114). We get for the couplings with neutral fermions,

$$
\begin{aligned}
O_{Lij1}'^{nns}&=\epsilon_i\left(-\frac{g}{2}\boldsymbol{N}^*{}_{i2}\boldsymbol{N}^*{}_{j3}+\frac{g'}{2}\boldsymbol{N}^*{}_{i1}\boldsymbol{N}^*{}_{j3}+(i\leftrightarrow j)\right)\\
O_{Lij2}'^{nns}&=\epsilon_i\left(\frac{g}{2}\boldsymbol{N}^*{}_{i2}\boldsymbol{N}^*{}_{j4}-\frac{g'}{2}\boldsymbol{N}^*{}_{i1}\boldsymbol{N}^*{}_{j4}+(i\leftrightarrow j)\right)\\
O_{Lij,2+k}'^{nns}&=\epsilon_i\left(-\frac{g}{2}\boldsymbol{N}^*{}_{i2}\boldsymbol{N}^*{}_{j,4+k}+\frac{g'}{2}\boldsymbol{N}^*{}_{i1}\boldsymbol{N}^*{}_{j,4+k}+(i\leftrightarrow j)\right)\\
O_{Lijk}'^{nnp}&=-i\;O_{Lijk}'^{nns}
\end{aligned}
\tag{117}
$$

and

$$
\begin{aligned}
O_{Rijk}'^{nns}&=\left(O_{Ljik}'^{nns}\right)^*\\
O_{Rijk}'^{nnp}&=\left(O_{Ljik}'^{nnp}\right)^*
\end{aligned}
\tag{118}
$$

The couplings with the charged fermions are

$$
O_{Lij1}'^{ccs}=\eta_j\left(-\frac{g}{\sqrt{2}}\boldsymbol{V}^*{}_{i1}\boldsymbol{U}^*{}_{j2}-\frac{h_E^{mn}}{\sqrt{2}}\,\boldsymbol{U}^*{}_{j,2+m}\,\boldsymbol{V}^*{}_{i,2+n}\right)
$$

$$
\begin{aligned}
O'^{ccs}_{Lij2} &= \eta_j \left(-\frac{g}{\sqrt{2}} \boldsymbol{V^*}_{i2} \boldsymbol{U^*}_{j1} \right) \\
O'^{ccs}_{Lij,2+k} &= \eta_j \left(-\frac{g}{\sqrt{2}} \boldsymbol{V^*}_{i1} \boldsymbol{U^*}_{j,2+k} + \frac{h_E^{km}}{\sqrt{2}} \boldsymbol{V^*}_{i,2+m} \boldsymbol{U^*}_{j2} \right)
\end{aligned}
\tag{119}
$$

$$
\begin{aligned}
O'^{ccp}_{Lij1} &= -i\,\eta_j \left(-\frac{g}{\sqrt{2}} \boldsymbol{V^*}_{i1} \boldsymbol{U^*}_{j2} + \frac{h_E^{mn}}{\sqrt{2}} \boldsymbol{U^*}_{j,2+m} \boldsymbol{V^*}_{i,2+n} \right) \\
O'^{ccp}_{Lij2} &= i\,\eta_j \frac{g}{\sqrt{2}} \boldsymbol{V^*}_{i2} \boldsymbol{U^*}_{j1} \\
O'^{ccp}_{Lij,2+k} &= -i\,\eta_j \left(-\frac{g}{\sqrt{2}} \boldsymbol{V^*}_{i1} \boldsymbol{U^*}_{j,2+k} - \frac{h_E^{km}}{\sqrt{2}} \boldsymbol{V^*}_{i,2+m} \boldsymbol{U^*}_{j2} \right)
\end{aligned}
\tag{120}
$$

and

$$
\begin{aligned}
O'^{ccs}_{Rijk} &= \left(O'^{ccs}_{Ljik} \right)^* \\
O'^{ccp}_{Rijk} &= \left(O'^{ccp}_{Ljik} \right)^*
\end{aligned}
\tag{121}
$$

4.4.3 $S^+ qq'$

The couplings of the charged scalars in the ϵ–model to the quarks come from the corresponding couplings of the MSSM charged Higgs bosons. They originate from the following Yukawa Lagrangian [3],

$$
\mathcal{L}_{\text{Yukawa}} = (h_D)_{ij}\, H_1^-\, u'_{Li}\, d'^c_{Lj} + (h_U)_{ij}\, H_2^+\, d'_{Li}\, u'^c_{Lj} + \text{h.c.} \tag{122}
$$

which reads in four component notation,

$$
\mathcal{L}_{\text{Yukawa}} = (h_D)_{ij}\, H_1^-\, \overline{d'_{Ri}}\, u'_{Li} + (h_U)_{ij}\, H_2^+\, \overline{u'_{Rj}}\, d'_{Li} + \text{h.c.} \tag{123}
$$

Now using Eq. (72) we can write,

$$
\mathcal{L}_{\text{Yukawa}} = H_2^+\, V_{ij}^{\text{CKM}}\, m_i^u\, \frac{\sqrt{2}}{v_u}\, \overline{u_{Ri}}\, d_{Lj} + H_1^+\, V_{ij}^{\text{CKM}}\, m_j^d\, \frac{\sqrt{2}}{v_d}\, \overline{u_{Li}}\, d_{Rj} + \text{h.c.} \tag{124}
$$

In terms of the charged scalars mass eigenstates we obtain

$$
\mathcal{L}_{\text{Yukawa}} = S_k^+\, \overline{u_i} \left(O^{sqq}_{Lijk} P_L + O^{sqq}_{Rijk} P_R \right) d_j \; + \text{h.c.} \tag{125}
$$

where

$$
O^{sqq}_{L,Rijk} = \boldsymbol{R}^{S^\pm *}_{km}\, O'^{sqq}_{L,Rijm} \tag{126}
$$

and

$$
O'^{sqq}_{Rij1} = V_{ij}^{\text{CKM}}\, m_j^d\, \frac{\sqrt{2}}{v_d} \tag{127}
$$

$$
O'^{sqq}_{Rijk} = 0, \quad \forall k \neq 1 \tag{128}
$$

$$
O'^{sqq}_{Lij2} = V_{ij}^{\text{CKM}}\, m_i^u\, \frac{\sqrt{2}}{v_u} \tag{129}
$$

$$
O'^{sqq}_{Lijk} = 0, \quad \forall k \neq 2 \tag{130}
$$

4.4.4 $S^0 qq$ and $P^0 qq$

4.4.5 $H\tilde{q}\tilde{q}$

4.4.6 HVV

4.5 Gaugino-Fermion-Sfermion

4.5.1 $\chi^0 q\tilde{q}$: Neutralino-Quark up-Squark up

In two component spinor notation the relevant part of the Lagrangian is

$$\begin{aligned}\mathcal{L} &= i\,g\,\frac{\sqrt{2}}{2}\,\lambda^3 u'_{Li}\,\widetilde{u}^*_{Li} + i\,g'\,\frac{\sqrt{2}}{6}\,\lambda' u'_{Li}\,\widetilde{u}^*_{Li} - i\,g'\,\frac{2\sqrt{2}}{3}\,\lambda' u'^c_{Li}\,\widetilde{u}^*_{Ri} \\ &\quad -h_U^{ij}\,\widetilde{H}^0_u u'_{Li}\,\widetilde{u}_{Rj} - h_U^{ij}\,\widetilde{H}^0_u u'^c_{Lj}\,\widetilde{u}_{Li} + \text{h.c.}\end{aligned} \tag{131}$$

We first use Eq. (84) to obtain

$$\begin{aligned}\mathcal{L} &= F^0_i u'_{Lm}\left(-\frac{g}{\sqrt{2}}\,\boldsymbol{N^*}_{i2}\,\widetilde{u}^*_{Lm} - \frac{g'}{\sqrt{2}}\,\frac{1}{3}\,\boldsymbol{N^*}_{i1}\,\widetilde{u}^*_{Lm} - h_U^{mn}\,\boldsymbol{N^*}_{i4}\,\widetilde{u}_{Rn}\right) \\ &\quad +F^0_i u'^c_{Lm}\left(\frac{g'}{\sqrt{2}}\,\frac{4}{3}\,\boldsymbol{N^*}_{i1}\,\widetilde{u}^*_{Rm} - h_U^{nm}\,\boldsymbol{N^*}_{i4}\,\widetilde{u}_{Ln}\right) + \text{h.c.}\end{aligned} \tag{132}$$

which can be written in four component notation as

$$\begin{aligned}\mathcal{L} &= \overline{u'}_m\,P_L\chi^0_i\left(\frac{4}{3}\,\frac{g}{\sqrt{2}}\,\tan\theta_w\,\boldsymbol{N^*}_{i1}\,\widetilde{u}^*_{Rm} - h_U^{nm}\,\boldsymbol{N^*}_{i4}\,\widetilde{u}_{Ln}\right) \\ &\quad -\overline{u'}_m\,P_R\chi^0_i\left[\frac{g}{\sqrt{2}}\left(\boldsymbol{N}_{i2} + \frac{1}{3}\,\tan\theta_w\,\boldsymbol{N}_{i1}\right)\widetilde{u}_{Lm} + h_U^{*\,mn}\,\boldsymbol{N}_{i4}\,\widetilde{u}^*_{Rn}\right] + \text{h.c.}\end{aligned} \tag{133}$$

Now we use Eq. (47) and Eq. (72) to rotate to the quark and squark mass eigenstates. We obtain,

$$\mathcal{L} = \overline{u}_i\left(O^{uns}_{Lijk}P_L + O^{uns}_{Rijk}P_R\right)\chi^0_j\,\widetilde{u}^*_k + \overline{\chi^0_j}\left(O^{nus}_{Ljik}P_L + O^{nus}_{Rjik}P_R\right)u_i\,\widetilde{u}_k \tag{134}$$

where

$$\begin{aligned}O^{uns}_{Lijk} &= \epsilon_j\left(\frac{4}{3}\,\frac{g}{\sqrt{2}}\,\tan\theta_w\,\boldsymbol{N^*}_{j1}\,\boldsymbol{R^{\widetilde{u}}}^*_{k,m+3}\,\boldsymbol{R^u_R}_{im} - h_U^{nm}\,\boldsymbol{N^*}_{j4}\,\boldsymbol{R^{\widetilde{u}}}^*_{kn}\,\boldsymbol{R^u_R}_{im}\right) \\ O^{uns}_{Rijk} &= \eta^u_i\left(-\frac{g}{\sqrt{2}}\left(\boldsymbol{N}_{j2} + \frac{1}{3}\,\tan\theta_w\,\boldsymbol{N}_{j1}\right)\boldsymbol{R^{\widetilde{u}}}^*_{km}\,\boldsymbol{R^u_L}_{im} - h_U^{*\,mn}\,\boldsymbol{N}_{j4}\,\boldsymbol{R^{\widetilde{u}}}^*_{k,n+3}\,\boldsymbol{R^u_L}_{im}\right)\end{aligned} \tag{135}$$

and

$$O^{nus}_{Ljik} = \left(O^{uns}_{Rijk}\right)^* \quad ; \quad O^{nus}_{Rjik} = \left(O^{uns}_{Lijk}\right)^* \tag{136}$$

In Eq. (135) we have introduced the sign factor η^u_i for the up–quarks defined in the same way as for the charginos.

4.5.2 $\chi^0 q\tilde{q}$: Neutralino-Quark down-Squark down

In two component spinor notation the relevant part of the Lagrangian is

$$
\begin{aligned}
\mathcal{L} &= -i\, g\, \frac{\sqrt{2}}{2}\, \lambda^3 d'_{Li}\, \widetilde{d}^*_{Li} + i\, g'\, \frac{\sqrt{2}}{6}\, \lambda' d'_{Li}\, \widetilde{d}^*_{Li} + i\, g'\, \frac{\sqrt{2}}{3}\, \lambda' d'^c_{Li}\, \widetilde{d}^*_{Ri} \\
&\quad - h_D^{ij}\, \widetilde{H}^0_d d'_{Li}\, \widetilde{d}_{Rj} - h_D^{ij}\, \widetilde{H}^0_d d'^c_{Lj}\, \widetilde{d}_{Li} + \text{h.c.}
\end{aligned} \tag{137}
$$

We first use Eq. (84) to obtain

$$
\begin{aligned}
\mathcal{L} &= F^0_i d'_{Lm} \left[\left(\frac{g}{\sqrt{2}} \boldsymbol{N^*}_{i2} - \frac{g'}{\sqrt{2}} \frac{1}{3} \boldsymbol{N^*}_{i1} \right) \widetilde{d}^*_{Lm} - h_D^{mn}\, \boldsymbol{N^*}_{i3}\, \widetilde{d}_{Rn} \right] \\
&\quad + F^0_i d'^c_{Lm} \left(-\frac{g'}{\sqrt{2}} \frac{2}{3} \boldsymbol{N^*}_{i1}\, \widetilde{d}^*_{Rm} - h_D^{nm}\, \boldsymbol{N^*}_{i3}\, \widetilde{d}_{Ln} \right) + \text{h.c.}
\end{aligned} \tag{138}
$$

which can be written in four component notation as

$$
\begin{aligned}
\mathcal{L} &= \overline{d'}_m\, P_L \chi^0_i \left(-\frac{2}{3} \frac{g}{\sqrt{2}}\, \tan\theta_w\, \boldsymbol{N^*}_{i1}\, \widetilde{d}^*_{Rm} - h_D^{nm}\, \boldsymbol{N^*}_{i3}\, \widetilde{d}_{Ln} \right) \\
&\quad + \overline{d'}_m\, P_R \chi^0_i \left[\frac{g}{\sqrt{2}} \left(\boldsymbol{N}_{i2} - \frac{1}{3}\, \tan\theta_w\, \boldsymbol{N}_{i1} \right) \widetilde{d}_{Lm} - h_D^{*\,mn}\, \boldsymbol{N}_{i3}\, \widetilde{d}^*_{Rn} \right] + \text{h.c.}
\end{aligned} \tag{139}
$$

Now we use Eq. (47) and Eq. (72) to rotate to the quark and squark mass eigenstates. We obtain,

$$
\mathcal{L} = \overline{d}_i \left(O^{dns}_{Lijk} P_L + O^{dns}_{Rijk} P_R \right) \chi^0_j\, \widetilde{d}^*_k + \overline{\chi^0_j} \left(O^{nds}_{Ljik} P_L + O^{nds}_{Rjik} P_R \right) d_i\, \widetilde{d}_k \tag{140}
$$

where

$$
\begin{aligned}
O^{dns}_{Lijk} &= \epsilon_j \left(-\frac{2}{3} \frac{g}{\sqrt{2}}\, \tan\theta_w\, \boldsymbol{N^*}_{j1}\, \boldsymbol{R}^{\widetilde{\boldsymbol{d}}^*}_{k,m+3}\, \boldsymbol{R}^{\boldsymbol{d}}_{\boldsymbol{R}im} - h_D^{nm}\, \boldsymbol{N^*}_{j3}\, \boldsymbol{R}^{\widetilde{\boldsymbol{d}}^*}_{kn}\, \boldsymbol{R}^{\boldsymbol{d}}_{\boldsymbol{R}im} \right) \\
O^{dns}_{Rijk} &= \eta^d_i \left(\frac{g}{\sqrt{2}} \left(\boldsymbol{N}_{j2} - \frac{1}{3}\, \tan\theta_w\, \boldsymbol{N}_{j1} \right) \boldsymbol{R}^{\widetilde{\boldsymbol{d}}^*}_{km}\, \boldsymbol{R}^{\boldsymbol{d}}_{\boldsymbol{L}im} - h_D^{*\,mn}\, \boldsymbol{N}_{j3}\, \boldsymbol{R}^{\widetilde{\boldsymbol{d}}^*}_{k,n+3}\, \boldsymbol{R}^{\boldsymbol{d}}_{\boldsymbol{L}im} \right)
\end{aligned} \tag{141}
$$

and

$$
O^{nds}_{Ljik} = \left(O^{dns}_{Rijk} \right)^* \quad ; \quad O^{nds}_{Rjik} = \left(O^{dns}_{Lijk} \right)^* \tag{142}
$$

4.5.3 $\chi^- q\tilde{q}'$: Chargino-Quark up-Squark down

In two component spinor notation the relevant part of the Lagrangian is

$$
\mathcal{L} = i\, g\, \lambda^- u'_{Lm}\, \widetilde{d}^*_{Lm} + h_U^{mn}\, \widetilde{H}^+_u u'^c_{Ln}\, \widetilde{d}_{Lm} + h_D^{mn}\, \widetilde{H}^-_d u'_{Lm}\, \widetilde{d}_{Rn} + \text{h.c.} \tag{143}
$$

We first use Eq. (84) to obtain

$$
\mathcal{L} = -g\, \boldsymbol{U^*}_{i1}\, F^-_i u'_{Lm}\, \widetilde{d}^*_{Lm} + h_U^{*\,mn}\, \boldsymbol{V}_{i2}\, \overline{F^+_i}\, \overline{u'^c}_{Ln}\, \widetilde{d}^*_{Lm} + h_D^{mn}\, \boldsymbol{U^*}_{i2}\, F^-_i u'_{Lm}\, \widetilde{d}_{Rn} + \text{h.c.} \tag{144}
$$

which can be written in four component notation as

$$\mathcal{L} = \overline{\chi_i^+} P_L u'_m \left(-g\, \boldsymbol{U^*}_{i1}\, \widetilde{d}^*_{Lm} + h_D^{mn}\, \boldsymbol{U^*}_{i2}\, \widetilde{d}_{Rn} \right) + \overline{\chi_i^+} P_R u'_n \left(h_U^{*mn}\, \boldsymbol{V}_{i2}\, \widetilde{d}^*_{Lm} \right) + \text{h.c.} \qquad (145)$$

where we have introduced χ^+, the antiparticle of χ^- in Eq. (55),

$$\chi_i^+ = \begin{pmatrix} F_i^+ \\ \hline \overline{F_i^-} \end{pmatrix} \qquad (146)$$

Now we use Eq. (47) and Eq. (72) to rotate to the quark and squark mass eigenstates. We obtain,

$$\mathcal{L} = \overline{\chi_i^+} \left(O^{cus}_{Lijk} P_L + O^{cus}_{Rijk} P_R \right) u_j\, \widetilde{d}^*_k + \overline{u}_j \left(O^{ucs}_{Ljik} P_L + O^{ucs}_{Rjik} P_R \right) \chi_i^+\, \widetilde{d}_k \qquad (147)$$

where

$$\begin{aligned} O^{cus}_{Lijk} &= \eta_i\, \eta^u_j \left(-g\, \boldsymbol{U^*}_{i1}\, \boldsymbol{R^{\widetilde{d}}}_{km}\, \boldsymbol{R^{u}_{L}}^*_{jm} + h_D^{mn}\, \boldsymbol{U^*}_{i2}\, \boldsymbol{R^{\widetilde{d}}}_{k,n+3}\, \boldsymbol{R^{u}_{L}}^*_{jm} \right) \\ O^{cus}_{Rijk} &= h_U^{*mn}\, \boldsymbol{V}_{i2}\, \boldsymbol{R^{\widetilde{d}}}_{km}\, \boldsymbol{R^{u}_{R}}^*_{jn} \end{aligned} \qquad (148)$$

and

$$O^{ucs}_{Ljik} = \left(O^{cus}_{Rijk} \right)^* \quad ; \quad O^{ucs}_{Rjik} = \left(O^{cus}_{Lijk} \right)^* \qquad (149)$$

4.5.4 $\chi^- q \tilde{q}'$: Chargino-Quark down-Squark up

In two component spinor notation the relevant part of the Lagrangian is

$$\mathcal{L} = i\, g\, \lambda^+ d'_{Li}\, \widetilde{u}^*_{Li} + h_U^{ij}\, \widetilde{H}_u^+ d'_{Li}\, \widetilde{u}_{Rj} + h_D^{ij}\, \widetilde{H}_d^- d'^c_{Lj}\, \widetilde{u}_{Li} + \text{h.c.} \qquad (150)$$

We first use Eq. (84) to obtain

$$\mathcal{L} = -g\, \boldsymbol{V^*}_{i1}\, F_i^+ d'_{Lm}\, \widetilde{u}^*_{Lm} + h_U^{mn}\, \boldsymbol{V^*}_{i2}\, F_i^+ d'_{Lm}\, \widetilde{u}_{Rn} + h_D^{*mn}\, \boldsymbol{U}_{i2}\, \overline{F_i^-}\, \overline{d'^c}_{Ln}\, \widetilde{u}^*_{Lm} + \text{h.c.} \qquad (151)$$

which can be written in four component notation as

$$\mathcal{L} = \overline{\chi_i^-} P_L d'_m \left(-g\, \boldsymbol{V^*}_{i1}\, \widetilde{u}^*_{Lm} + h_D^{mn}\, \boldsymbol{V^*}_{i2}\, \widetilde{u}_{Rn} \right) + \overline{\chi_i^-} P_R d'_n \left(h_U^{*mn}\, \boldsymbol{U}_{i2}\, \widetilde{u}^*_{Lm} \right) + \text{h.c.} \qquad (152)$$

Now we use Eq. (47) and Eq. (72) to rotate to the quark and squark mass eigenstates. We obtain,

$$\mathcal{L} = \overline{\chi_i^-} \left(O^{cds}_{Lijk} P_L + O^{cds}_{Rijk} P_R \right) d_j\, \widetilde{u}^*_k + \overline{d}_j \left(O^{dcs}_{Ljik} P_L + O^{dcs}_{Rjik} P_R \right) \chi_i^-\, \widetilde{u}_k \qquad (153)$$

where

$$\begin{aligned} O^{cds}_{Lijk} &= \eta^d_j \left(-g\, \boldsymbol{V^*}_{i1}\, \boldsymbol{R^{\widetilde{u}}}_{km}\, \boldsymbol{R^{d}_{L}}^*_{jm} + h_U^{mn}\, \boldsymbol{V^*}_{i2}\, \boldsymbol{R^{\widetilde{u}}}_{k,n+3}\, \boldsymbol{R^{d}_{L}}^*_{jm} \right) \\ O^{cds}_{Rijk} &= \eta_i\, h_D^{*mn}\, \boldsymbol{U}_{i2}\, \boldsymbol{R^{\widetilde{u}}}_{km}\, \boldsymbol{R^{d}_{R}}^*_{jn} \end{aligned} \qquad (154)$$

and

$$O^{dcs}_{Ljik} = \left(O^{cds}_{Rijk} \right)^* \quad ; \quad O^{dcs}_{Rjik} = \left(O^{cds}_{Lijk} \right)^* \qquad (155)$$

4.6 4-Point Interactions

4.6.1 $VV\chi\chi$

4.6.2 $VVHH$

4.6.3 $VV\tilde{q}\tilde{q}$

4.7 Higgs Self-Interactions

4.7.1 HHH

4.7.2 $HHHH$

4.8 Ghost Interactions

4.8.1 $\overline{\omega}\omega V$

4.8.2 $\overline{\omega}\omega H$

A Changelog

- 13/11/2006
  - Introduced the couplings of charged scalars to W and neutral scalars in Section 4.2.4
- 30/10/2006
  - Introduced the couplings of charged scalars to quarks in Section 4.4.3.
- 10/7/2003
  - Corrected signs in Eq. (2) and Eq. (3).
- 17/6/2001
  - The gauge self–interactions in Section 4.1 were introduced.
- 15/6/2001
  - The sign factors were introduced in Eq. (117) and Eq. (119) and in all vertices in Section 4.5.
- 12/6/2001
  - Some mistakes were correcetd in Eq. (117) and Eq. (119).
- 6/6/2001
  - Introduced neutralino and chargino couplings to neutral scalars, in Section 4.4.2.
- 1/6/2001
  - Indices corrected in Eq. (148) and Eq. (154).
- 30/5/2001
  - Introduced neutralino and chargino couplings to quarks and squarks, in Section 4.5.
- 29/5/2001
  - Delete in Eq. (67) an extra factor $(h_U^*)_{ij}$.
  - Change $\overline{L_3^-} \to \overline{L_k^-}$ in Eq. (85).
  - Change $L \to R$ and $R \to L$ in Eq. (110) and correct also the indices.
- 27/5/2001

- Introduced the section on the quark mass matrices.

- 24/4/2001
  - Change $v_2 \longrightarrow v_u$ in Eq. (14).
  - Change $A_E^* \longrightarrow A_E$; $h_E^* \longrightarrow h_E$ in Eq. (17).
  - Change $\cos 2\beta \longrightarrow \frac{1}{v^2}\,(v_d^2 - v_u^2 + \sum_i v_i^2)$ in Eq. (44) and Eq. (45).

- 20/4/2001
  - Introduced the version numbering convention.

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