Electroweak-scale Right-handed Neutrino Model: Contributions to Oblique Parameters

Part I

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(paper in preparation)

University of Virginia

21^{st} December, 2012

VIII^{th} Rencontres du Vietnam, Quy Nhon, Vietnam

Outline

- Motivation

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- Overview of the Electroweak-scale Right-handed Neutrino (EWν_R/EWNR) model

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- New Physics contributions to oblique parameters due to EWNR model

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Majorana mass

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possible! **[PQ, PLB 649 (2007)]**

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$$m_\nu^D = g_{Sl} v_S$$

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$$m_\nu \leq 1 eV \Rightarrow v_S \sim 10^{5-6} eV$$

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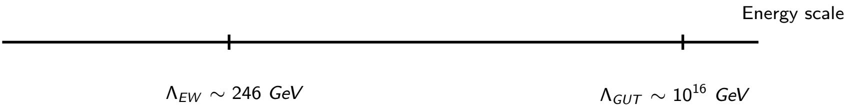
Z width

$$\Rightarrow\; M_R > M_Z \,/\, 2$$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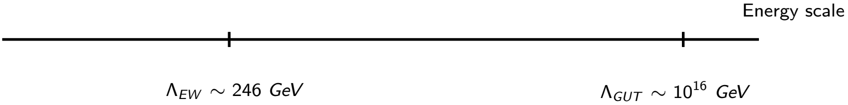
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$$\rho = \frac{M_W^2}{M_Z^2 cos\theta_W^2} = 1 \quad \Rightarrow$$

Tree level

$$\rho = \frac{M_W^2}{M_Z^2 cos\theta_W^2} = 1 \quad \Rightarrow \text{add} \quad \xi \quad (3,\ Y/2 = 0)$$

Tree level

Fermions

SM Fermions			EWν_R Mirror Fermions		
SM Fields	$SU(2)_W$	$U(1)_Y$	Additional Fields	$SU(2)_W$	$U(1)_Y$
$L_{Li} = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_i$	2	-1	$L^M_{Ri} = \begin{pmatrix} \nu_R \\ e^M_R \end{pmatrix}_i$	2	-1
$Q_{Li} = \begin{pmatrix} u_L \\ d_L \end{pmatrix}_i$	2	$(1/3)$	$Q^M_{Ri} = \begin{pmatrix} u^M_R \\ d^M_R \end{pmatrix}_i$	2	$(1/3)$
e_{Ri}	1	-2	e^M_{Li}	1	-2
u_{Ri}	1	$(4/3)$	u^M_{Li}	1	$(4/3)$
d_{Ri}	1	$-(2/3)$	d^M_{Li}	1	$-(2/3)$

Scalars

Field	$SU(2)_W$	$U(1)_Y$	VEV
χ	3	2	v_M
ξ	3	0	v_M
Φ	2	-1	$v_2/\sqrt{2}$
ϕ_S	1	0	v_S

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0\star} \end{pmatrix} \qquad \Phi = \begin{pmatrix} \phi^{0\star} & \phi^+ \\ \phi^- & \phi^0 \end{pmatrix}$$

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$$\begin{aligned} V(\Phi,\chi) &= \lambda_1(Tr\Phi^\dagger\Phi - v_2^2)^2 + \lambda_2(Tr\chi^\dagger\chi - 3v_M^2)^2 \\ &+ \lambda_3(Tr\Phi^\dagger\Phi - v_2^2 + Tr\chi^\dagger\chi - 3v_M^2)^2 \\ &+ \lambda_4(Tr\Phi^\dagger\Phi\, Tr\chi^\dagger\chi - 2\,Tr\Phi^\dagger T^i\Phi T^j \cdot Tr\chi^\dagger T^i\chi T^j) \\ &+ \lambda_5(3\,Tr\chi^\dagger\chi\chi^\dagger\chi) - (Tr\chi^\dagger\chi)^2. \end{aligned}$$

To make sure it is positive semidefinite the following conditions are imposed: $\lambda_1 + \lambda_2 + 2\lambda_3 > 0,\ \lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3 > 0,\ \lambda_4 > 0,\ \lambda_5 > 0.$

$$\phi^0 \equiv \frac{1}{\sqrt{2}}(v_2 + \phi^{0r} + i\phi^{0i}), \qquad \chi^0 \equiv v_M + \frac{1}{\sqrt{2}}(\chi^{0r} + i\chi^{0i}),$$

$$v = \sqrt{v_2^2 + 8v_M^2} \approx 246\text{GeV}$$

$$cos(\theta_H) = c_H \equiv v_2/v \qquad sin(\theta_H) = s_H \equiv 2\sqrt{2}v_M/v$$

$$SU(2)_L \times SU(2)_R$$

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with $H_5^{--} = (H_5^{++})^\star$, $H_5^{-} = -(H_5^{+})^\star$, $H_3^{-} = -(H_3^{+})^\star$ and $H_3^0 = -(H_3^0)^\star$

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doublet ϕ & triplet χ; 0^-

Only doublet ϕ; 0^+

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Electroweak Constraints

Oblique Parameters

S, T, U

Oblique Parameters

[Peskin, Takeuchi, PRD 46, 1992]

- $\alpha S \equiv 4e^2[\Pi'_{33}(0) - \Pi'_{3Q}(0)]$

- $\alpha T \equiv \dfrac{e^2}{s_W^2 c_W^2 M_Z^2}[\Pi_{11}(0) - \Pi_{33}(0)]$

- $\alpha U \equiv 4e^2[\Pi'_{11}(0) - \Pi'_{33}(0)]$.

Oblique Parameters

$S \rightarrow$ **Difference between** Z **self-energy at** $q^2 = M_Z^2$ **and at** $q^2 = 0$

$T \rightarrow \sim \left(1 - \rho\right)$; **Difference between isospin currents** Π_{11} **and** Π_{33} **at** $q^2 = 0$

$U \rightarrow$ **Difference between** W **and** Z **self-energies at** $q^2 = M_Z^2$ **and at** $q^2 = 0$

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- Although $\widetilde{T}$ can be made small by having degenerate multiplets, it will be useful to see whether
    - $|\text{Multiplet Mass splitting}| \uparrow \quad \Rightarrow \quad |\text{Contribution}| \uparrow$
    - $\widetilde{T}_{scalar}$ negative enough to cancel positive $\widetilde{T}_{Fermion}$

EWNR Contributions to Oblique Parameters

$$\frac{\widehat{\alpha}}{4\widehat{s}_W^2\widehat{c}_W^2}\widetilde{S} = \frac{1}{M_Z^2}\left[\overline{\Pi}_{ZZ}(M_Z^2) - \left(\frac{\widehat{c}_W^2 - \widehat{s}_W^2}{\widehat{c}_W\widehat{s}_W}\right)\overline{\Pi}_{Z\gamma}(M_Z^2) - \overline{\Pi}_{\gamma\gamma}(M_Z^2)\right]^{EW\nu_R}$$

$$-\frac{1}{M_Z^2}\left[\overline{\Pi}_{ZZ}(M_Z^2) - \left(\frac{\widehat{c}_W^2 - \widehat{s}_W^2}{\widehat{c}_W\widehat{s}_W}\right)\overline{\Pi}_{Z\gamma}(M_Z^2) - \overline{\Pi}_{\gamma\gamma}(M_Z^2)\right]^{SM}$$

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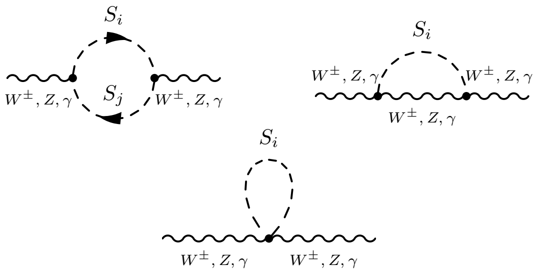
Types of contributing loops (one loop)



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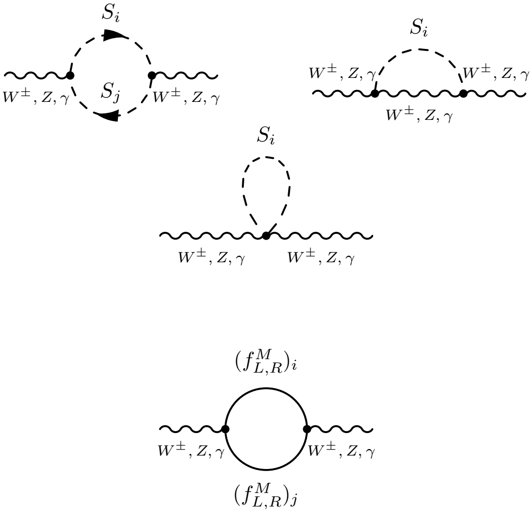
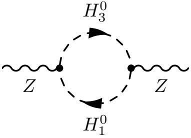
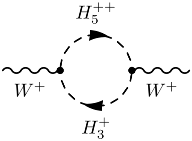


Examples of NP Scalar loops

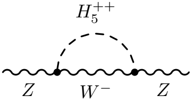
$$\mathcal{L}_{kin} = \frac{1}{2} Tr \left[(D_\mu \Phi)^\dagger (D^\mu \Phi) \right] + \frac{1}{2} Tr \left[(D_\mu \chi)^\dagger (D^\mu \chi) \right] + |\partial_\mu \phi_S|^2 \tag{1}$$



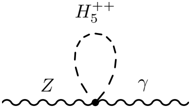
$$\frac{s_H^2}{c_W^2} B_{22}(q^2;\ m_{3^0}^2,\ m_{1^0}^2)$$



$$2c_H^2 B_{22}(q^2;\ m_{5^{++}}^2,\ m_{3^+}^2)$$



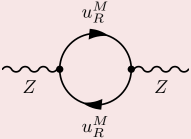
$$-2s_H^2 M_W^2 B_0(q^2;\ M_W^2,\ m_{5^{++}}^2)$$



$$-4\frac{s_W}{c_W} c_{2W} A_0(m_{5^{++}}^2)$$

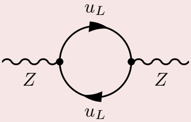
$$
\begin{aligned}
\widetilde{S}_{scalar} &= S^{EW\nu_R}_{scalar} - S^{SM}_{scalar} \\
&= \frac{1}{M_Z^2 \pi} \Bigg\{ \frac{4}{3}\, s_H^2 \Big[\overline{B}_{22}(M_Z^2; M_Z^2, m_{50}^2) - M_Z^2\, \overline{B}_0(M_Z^2; M_Z^2, m_{50}^2) \Big] + 2\, s_H^2 \Big[\overline{B}_{22}(M_Z^2; M_Z^2, m_{5+}^2) \\
&- M_W^2\, \overline{B}_0(M_Z^2; M_Z^2, m_{5+}^2) \Big] + c_H^2 \Big[\overline{B}_{22}(M_Z^2; M_Z^2, m_{10}^2) - M_Z^2\, \overline{B}_0(M_Z^2; M_Z^2, m_{10}^2) \Big] \\
&+ \frac{8}{3}\, s_H^2 \Big[\overline{B}_{22}(M_Z^2; M_Z^2, m_{10'}^2) - M_Z^2\, \overline{B}_0(M_Z^2; M_Z^2, m_{10'}^2) \Big] + \frac{4}{3} c_H^2\, \overline{B}_{22}(M_Z^2; m_{50}^2, m_{30}^2) \\
&+2\, c_H^2\, \overline{B}_{22}(M_Z^2; m_{5+}^2, m_{3+}^2) + s_H^2\, \overline{B}_{22}(M_Z^2; m_{30}^2, m_{10}^2) + \frac{8}{3}\, c_H^2\, \overline{B}_{22}(M_Z^2; m_{30}^2, m_{10'}^2) \\
&- 4\, \overline{B}_{22}(M_Z^2; m_{5++}^2, m_{5++}^2) - \overline{B}_{22}(M_Z^2; m_{5+}^2, m_{5+}^2) - \overline{B}_{22}(M_Z^2; m_{3+}^2, m_{3+}^2) \\
&- \Big[\overline{B}_{22}(M_Z^2; M_Z^2, m_H^2) - M_Z^2\, \overline{B}_0(M_Z^2; M_Z^2, m_H^2) \Big] \Bigg\}
\end{aligned}
$$

$$\begin{aligned}
\widetilde{T}_{scalar} &= T^{EW\nu_R}_{scalar} - T^{SM}_{scalar} \\
&= \frac{1}{4\pi s_W^2 M_W^2}\Bigg\{ \frac{1}{2}\mathcal{F}(m^2_{5++}, m^2_{50}) + \frac{3}{4}\mathcal{F}(m^2_{5+}, m^2_{50}) + \frac{1}{4}\mathcal{F}(m^2_{3+}, m^2_{30}) + \frac{c_H^2}{2}\mathcal{F}(m^2_{5++}, m^2_{3+}) \\
&+ \frac{c_H^2}{4}\mathcal{F}(m^2_{5+}, m^2_{30}) + \frac{c_H^2}{12}\mathcal{F}(m^2_{50}, m^2_{3+}) - \frac{c_H^2}{2}\mathcal{F}(m^2_{5_+}, m^2_{3+}) - \frac{c_H^2}{3}\mathcal{F}(m^2_{50}, m^2_{30}) \\
&+ \frac{s_H^2}{4}\left[\mathcal{F}(m^2_{3+}, m^2_{10}) - \mathcal{F}(m^2_{30}, m^2_{10})\right] + \frac{2}{3}\, c_H^2 \left[\mathcal{F}(m^2_{3+}, m^2_{10'}) - \mathcal{F}(m^2_{30}, m^2_{10'})\right] \\
&+ \frac{s_H^2}{2}\mathcal{F}(M_W^2, m^2_{5++}) - \frac{s_H^2}{4}\mathcal{F}(M_W^2, m^2_{5+}) - \frac{s_H^2}{4}\mathcal{F}(M_W^2, m^2_{50}) \\
&+ M_W^2 s_H^2 B_0(0; M_W^2, m^2_{50}) + M_W^2 s_H^2 B_0(0; M_W^2, m^2_{5+}) - M_W^2 s_H^2 B_0(0; M_W^2, m^2_{5++}) \Bigg\}
\end{aligned}$$



$$= -\frac{4}{c_W^2}(T_3^{u^M} - s_W^2 Q_{u^M})^2 \Big[(\frac{q^2}{6} - \frac{m_{u^M}^2}{2})\Delta$$

$$-q^2 B_2(q^2;\ m_{u^M}^2,\ m_{u^M}^2) + m_{u^M}^2 B_1(q^2;\ m_{u^M}^2,\ m_{u^M}^2) \Big]$$



$$= -\frac{4}{c_W^2}(T_3^{u} - s_W^2 Q_{u})^2 \Big[(\frac{q^2}{6} - \frac{m_{u}^2}{2})\Delta$$

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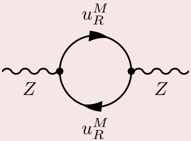
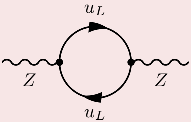


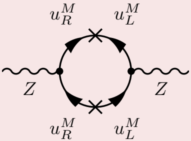
$$= -\frac{4}{c_W^2}(T_3^{u^M} - s_W^2 Q_{u^M})^2 \Big[(\frac{q^2}{6} - \frac{m^2_{u^M}}{2})\Delta$$

$$-q^2 B_2(q^2;\ m^2_{u^M},\ m^2_{u^M}) + m^2_{u^M} B_1(q^2;\ m^2_{u^M},\ m^2_{u^M}) \Big]$$



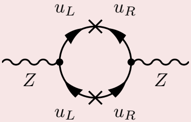
$$= -\frac{4}{c_W^2}(T_3^{u} - s_W^2 Q_{u})^2 \Big[(\frac{q^2}{6} - \frac{m^2_{u}}{2})\Delta$$

$$-q^2 B_2(q^2;\ m^2_{u},\ m^2_{u}) + m^2_{u} B_1(q^2;\ m^2_{u},\ m^2_{u}) \Big]$$



$$= -\frac{2}{c_W^2} m^2_{u^M} (T_3^{u^M} - s_W^2 Q_{u^M}) s_W^2 Q_{u^M}$$

$$\times \Big[\Delta - 2B_1(q^2;\ m^2_{u^M},\ m^2_{u^M}) \Big]$$



$$= -\frac{2}{c_W^2} m^2_{u} (T_3^{u} - s_W^2 Q_{u}) s_W^2 Q_{u} \Big[\Delta - 2B_1(q^2;\ m^2_{u},\ m^2_{u}) \Big]$$

$$
\begin{aligned}
\widetilde{S}_{lepton} &= S^{EW\nu_R}_{lepton} - S^{SM}_{lepton} \\
&= \frac{(N_C)_{lepton}}{6\pi} \sum_{i=1}^{3} \Bigg\{ -2\; Y_{lepton}\; x_{\nu_R i} + 2\left(-4\frac{Y_{lepton}}{2} + 3\right) x_{eM_i} - Y_{lepton}\; ln\left(\frac{x_{\nu_R i}}{x_{eM_i}}\right) \\
&\quad + \left(1 - x_{\nu_R i}\right) \frac{Y_{lepton}}{2} G(x_{\nu_R i}) + \left[\left(\frac{3}{2} - \frac{Y_{lepton}}{2}\right) x_{eM_i} - \frac{Y_{lepton}}{2}\right] G(x_{eM_i}) \Bigg\}
\end{aligned}
$$

$$
\begin{aligned}
\widetilde{T}_{lepton} &= T^{EW\nu_R}_{lepton} - T^{SM}_{lepton} \\
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\end{aligned}
$$

$$\boxed{= \frac{m^2_{\nu_R i}}{M_Z^2}}$$

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\end{aligned}$$

Always positive

$$\boxed{= \frac{m^2_{\nu_R i}}{M_Z^2}}$$

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&\quad + \left(1 - x_{\nu_R i} \right) \frac{Y_{lepton}}{2} G(x_{\nu_R i}) + \left[\left(\frac{3}{2} - \frac{Y_{lepton}}{2} \right) x_{eM_i} - \frac{Y_{lepton}}{2} \right] G(x_{eM_i}) \Bigg\}
\end{aligned}$$

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\widetilde{T}_{lepton} &= T^{EW\nu_R}_{lepton} - T^{SM}_{lepton} \\
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\end{aligned}$$

$\boxed{\textit{Always} \text{ positive}}$

$$\widetilde{S}_{quark} = S^{EW\nu_R}_{quark} - S^{SM}_{quark}$$

$$= \frac{(N_C)_{quark}}{6\pi} \sum_{i=1}^{3} \left\{ 2\left(4\frac{Y_{quark}}{2} + 3\right) x_{uM_i} + 2\left(-4\frac{Y_{quark}}{2} + 3\right) x_{dM_i} - Y_{quark}\ ln\left(\frac{x_{uM_i}}{x_{dM_i}}\right) \right.$$

$$\left. + \left[\left(\frac{3}{2} + Y_{quark}\right) x_{uM_i} + \frac{Y_{quark}}{2}\right] G(x_{uM_i}) + \left[\left(\frac{3}{2} - Y_{quark}\right) x_{dM_i} - \frac{Y_{quark}}{2}\right] G(x_{dM_i}) \right\}$$

$$\widetilde{T}_{quark} = T^{EW\nu_R}_{quark} - T^{SM}_{quark}$$

$$= \frac{(N_C)_{quark}}{8\pi s_W^2 c_W^2} \sum_{i=1}^{3} F(x_{uM_i}, x_{dM_i})$$

$$= \frac{m^2_{u M_i}}{M_Z^2}$$

$$\widetilde{S}_{quark} = S^{EW\nu_R}_{quark} - S^{SM}_{quark}$$

$$= \frac{(N_C)_{quark}}{6\pi} \sum_{i=1}^{3} \left\{ 2\left(4\frac{Y_{quark}}{2} + 3\right) x_{u M_i} + 2\left(-4\frac{Y_{quark}}{2} + 3\right) x_{d M_i} - Y_{quark}\, ln\left(\frac{x_{u M_i}}{x_{d M_i}}\right) \right.$$

$$\left. + \left[\left(\frac{3}{2} + Y_{quark}\right) x_{u M_i} + \frac{Y_{quark}}{2}\right] G(x_{u M_i}) + \left[\left(\frac{3}{2} - Y_{quark}\right) x_{d M_i} - \frac{Y_{quark}}{2}\right] G(x_{d M_i}) \right\}$$

$$\widetilde{T}_{quark} = T^{EW\nu_R}_{quark} - T^{SM}_{quark}$$

Always positive

$$= \frac{(N_C)_{quark}}{8\pi s^2_W c^2_W} \sum_{i=1}^{3} F(x_{u M_i}, x_{d M_i})$$

$= 3 \Rightarrow$ Large Contribution

Experimental Constraints on $\tilde{S}$, $\widetilde{T}$

At SM $m_H = 125 GeV$[PDG, 2012 and work of Tim Tait] (1σ)

Experimental Constraints on $\tilde{S}$, $\widetilde{T}$

At SM $m_H = 125 GeV$[PDG, 2012 and work of Tim Tait] (1σ)

$$\widetilde{S} = 0.02 \pm 0.14$$

$$\widetilde{T} = 0.06 \pm 0.14$$

Summary *so far*

- We have a model with Electroweak-scale Right-handed Neutrino (EWν_R/EWNR) with Majorana mass

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Summary *so far*

- We have a model with Electroweak-scale Right-handed Neutrino (EWν_R/EWNR) with Majorana mass
- Scale like $10^{16}\,GeV$ not required
- Theoretically predicts
  - Mirror Fermion sector with opposite chirality to SM Fermions
  - BSM Higgs sector with doubly charged Higgs
  - BSM contributions to the oblique parameters

Stay tuned for next talk!

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Backup Slides

- To forbid left-handed ν's from getting large Majorana mass (terms like $g_L l_L^T \sigma_2 \tau_2 \widetilde{\chi} l_L$) and $l_L^T \sigma_2 \tau_2 \widetilde{\chi} l_R^M$)
$U(1)_M$ symmetry,

$$\begin{aligned}
(l_R^M,\ \ e_L^M) &\rightarrow e^{i\theta_M}(l_R^M,\ \ e_L^M), \\
\widetilde{\chi} &\rightarrow e^{-2i\theta_M}\widetilde{\chi}, \\
\phi_S &\rightarrow e^{-i\theta_M}\phi_S
\end{aligned}$$

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\phi_S &\rightarrow e^{-i\theta_M}\phi_S
\end{aligned}$$

- Terms like $\overline{q}_L q_R^M$, $\overline{u}_R u_R^M$, $\overline{d}_R d_R^M$ also don't occur

SM Fermions Yukawa couplings:

$$\mathcal{L} = -h_{ij}\overline{\Psi}_{Li}\Phi\Psi_{Rj} + h.c.$$

Feynman Rules [PQ, Aranda, Hernández-Sánchez, JHEP11, 2008]

- $$g_{H_1^0 q\bar{q}} = -i\frac{m_q g}{2M_W c_H} \;....(q = t, b)$$
- $$g_{H_3^0 t\bar{t}} = i\frac{m_t g s_H}{2M_W c_H}$$
- $$g_{H_3^0 b\bar{b}} = -i\frac{m_b g s_H}{2M_W c_H}$$
- $$g_{H_3^0 - t\bar{b}} = i\frac{g s_H}{2M_W c_H}(m_t(1+\gamma_5) - m_b(1+\gamma_5))$$

Similar couplings for SM leptons and mirror quarks.

Mirror Fermions' kinetic Lagrangian

$$(\mathcal{L}_{F^M})_{int}$$

$$= \frac{g}{\sqrt{2}} \left[\left(\overline{u}_R^{Mi} \, \gamma^\mu d_{Ri}^M + \overline{\nu}_R^i \, \gamma^\mu e_{Ri}^M \right) W_\mu^+ + \left(\overline{d}_R^{M\,i} \, \gamma^\mu u_{R\,i}^M + \overline{e}_R^{M\,i} \, \gamma^\mu \nu_{R\,i}^M \right) W_\mu^- \right]$$

$$+ \frac{g}{c_W} \left[\sum_{f^M = u^M, d^M, \nu^M, e^M} \left(T_3^{f^M} - s_W^2 Q_{f^M} \right) \overline{f}_R^{M\,i} \, \gamma^\mu f_{R\,i}^M \right.$$

$$\left. + \sum_{f^M = u^M, d^M, e^M} s_W^2 Q_{f^M} \, \overline{f}_L^{M\,i} \, \gamma^\mu f_{L\,i}^M \right] Z_\mu$$

$$+ e \sum_{f^M = u^M, d^M, e^M} Q_{f^M} \left(\overline{f}_R^{M\,i} \, \gamma^\mu f_{R\,i}^M - \overline{f}_L^{M\,i} \, \gamma^\mu f_{L\,i}^M \right) A_\mu$$