Riding the Seesaw Part I

Neutrinos and Higgsstrahlung

Adam Lackner

In collaboration with **Tobias Felkl & Michael A. Schmidt**
~~Cool Particle Physicists Collaborating in Sydney (CPPC Sydney)~~
Consortium of Particle Physics and Cosmology Sydney (CPPC Sydney)
School of Physics, University of New South Wales

UNSW SYDNEY

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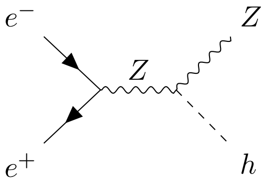
Based on hep-ph/2211.15954

Overview

- Neutrinos have mass
- We would like to find good probes of mass models
- One potential probe is *Higgsstrahlung* $(e^+e^- \to Zh)$ at a next-gen collider



- We look at the prospects for Type-I and Type-III Seesaw

This talk is part one of two – to be followed up by Tobias.

Part I: Assembling the Pieces

Context: Seesaw Mechanism

Right-handed neutrinos (Type-I Seesaw)

$$\mathcal{L} = \overline{N} i \partial\!\!\!/ N - \left(\widetilde{Y} \overline{L} \widetilde{H} N + \frac{1}{2} M \overline{N^c} N + \text{h.c.} \right)$$

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Mass matrix

$$\mathcal{L}_{\nu\ \text{mass}} = \frac{1}{2} \begin{pmatrix} \overline{\nu} & \overline{N^c} \end{pmatrix} \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} \begin{pmatrix} \nu^c \\ N \end{pmatrix} + \text{h.c.}, \qquad m = \frac{\widetilde{Y} v}{\sqrt{2}}$$

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Seesaw masses

$$m_{\text{light}} \approx \frac{m^2}{M}, \qquad m_{\text{heavy}} \approx M$$

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Seesaw masses

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See next talk for Type-III

Mass Matrix Texture

We adopt the following texture for the mass matrix:

$$\begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & \theta_e M & 0 \\ 0 & 0 & 0 & \theta_\mu M & 0 \\ 0 & 0 & 0 & \theta_\tau M & 0 \\ \theta_e M & \theta_\mu M & \theta_\tau M & 0 & M \\ 0 & 0 & 0 & M & 0 \end{pmatrix}$$

See e.g. *Abada et. al.* 0707.4058

For concreteness we fix $M = 1\,\text{TeV}$ and explore the parameter space of the **mixing angles** θ_e, θ_μ and θ_τ.

Standard Model Effective Field Theory

To study the Seesaw models we use EFT.

SMEFT Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathsf{SM}} + \sum_i C_i \mathcal{O}_i$$

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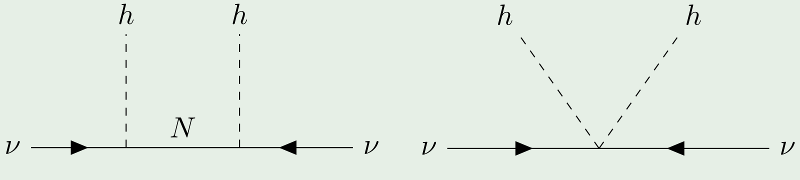
Example: Weinberg Operator



Full theory: LHN interactions

SMEFT: $\mathcal{O}_5 \sim LHLH$

SMEFT Procedure

- Step 1: Match the Seesaw models to SMEFT

Operator	Coefficient	Type-I	Type-III
$(\widetilde{H}^\dagger L_i)^T C (\widetilde{H}^\dagger L_j)$	$C_{5,ij}$	$\frac{1}{2}\left(\tilde{Y}^*(M^\dagger)^{-1}\tilde{Y}^\dagger\right)_{ij}$	$\frac{1}{2}(\tilde{Y}^*(M^\dagger)^{-1}\tilde{Y}^\dagger)_{ij}$
$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{L_i}\gamma^\mu L_j)$	$C^{(1)}_{HL,ij}$	$\frac{1}{4}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger\right)_{ij}$	$\frac{3}{4}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger\right)_{ij}$
$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{L_i}\sigma^a\gamma^\mu L_j)$	$C^{(3)}_{HL,ij}$	$-\frac{1}{4}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger\right)_{ij}$	$\frac{1}{4}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger\right)_{ij}$
$(H^\dagger H)(\overline{L_i}e_{Rj}H)$	$C_{eH,ij}$	0	$\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$
$(\overline{L_i}\sigma^{\mu\nu}e_{Rj})HB_{\mu\nu}$	$C_{eB,ij}$	$\frac{1}{16\pi^2}\frac{g_1}{24}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$	$\frac{1}{16\pi^2}\frac{g_1}{8}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$
$(\overline{L_i}\sigma^{\mu\nu}\sigma^a e_{Rj})HW^a_{\mu\nu}$	$C_{eW,ij}$	$\frac{1}{16\pi^2}\frac{5g_2}{24}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$	$\frac{1}{16\pi^2}\frac{3g_2}{8}\left(\tilde{Y}(M^\dagger M)^{-1}\tilde{Y}^\dagger Y_e\right)_{ij}$

Du et. al. 2201.04646, *Zhang & Zhou*, 2107.12133, *Coy & Frigerio*, 2110.09126

- Step 2: Use `DsixTools` to perform RG running to the relevant scale. *Celis et. al.* 1704.04504

- (Step 3: Match to LEFT at the electroweak scale and run to a low scale. Next talk!)

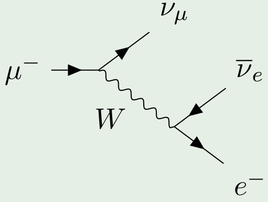
STOP

STOP

Did you know that introducing BSM physics means you're wrong about most, if not all, SM parameters?

An effect we can't ignore: Parameter Shifts

Example: muon decay



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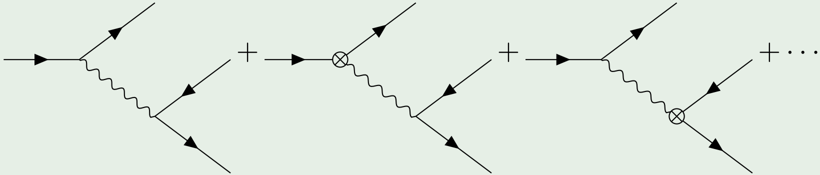

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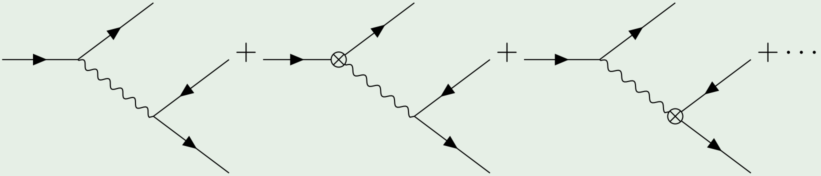


Fermi constant extracted from muon decay is shifted!

$$\hat{G}_F = G_F\left[1 + v^2\left(C^{(3)}_{HL,\mu\mu} + C^{(3)}_{HL,ee} - \frac{1}{2}C_{LL,e\mu\mu e} - \frac{1}{2}C_{LL,\mu ee\mu}\right)\right]$$

Parameter shifts (continued)

Virtually all parameters receive shifts: $g \to g + \delta g$

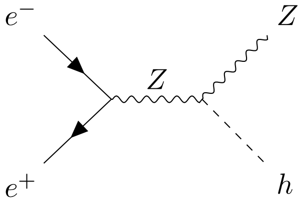
The upshot

For any observable σ, such as a cross-section,

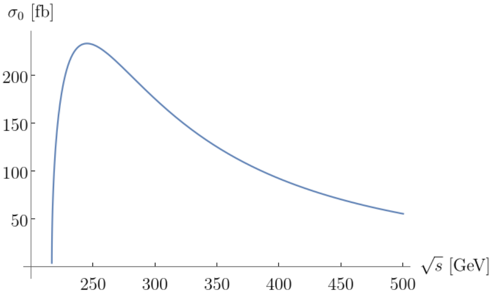
$$\Delta\sigma = \sigma_{\mathsf{SMEFT}} - \sigma_{\mathsf{SM}} = \Delta\sigma_{\mathsf{Direct}} + \sum_i \frac{\partial \sigma_{\mathsf{SM}}}{\partial g_i}\delta g_i$$

Part II: Higgsstrahlung and Seesaws

Higgsstrahlung



(a) The dominant diagram



(b) SM cross section

$$\sigma_0 = \frac{\sqrt{\lambda}}{32\pi s}(g_L^2 + g_R^2)\left(\frac{g_{ZZh}}{s - m_Z^2}\right)^2\left(1 + \frac{\lambda}{12 s m_Z^2}\right)$$

where $\lambda = (s - m_Z^2 - m_h^2)^2 - 4 m_Z^2 m_h^2$

Higgsstrahlung

Higgsstrahung cross section is shifted from its SM value:

$$\frac{\Delta\sigma}{\sigma_0} \approx \left(0.90\, C^{(1)}_{HL,ee} + 0.77\, C^{(3)}_{HL,ee} - 0.13\, C^{(3)}_{HL,\mu\mu}\right) \times (1\,\text{TeV})^2$$

$$\text{at } \sqrt{s} = 240\,\text{GeV}$$

Craig et. al. 1411.0676

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Craig et. al. 1411.0676

In terms of mixing angles:

$$\frac{\Delta\sigma}{\sigma_0}(240\,\text{GeV}) = \begin{cases} 0.95\,|\theta_e|^2 + 1.10\,|\theta_\mu|^2 + 0.02\,|\theta_\tau|^2 & \text{Type-I} \\ 27.59\,|\theta_e|^2 - 1.08\,|\theta_\mu|^2 - 0.01\,|\theta_\tau|^2 & \text{Type-III} \end{cases}$$

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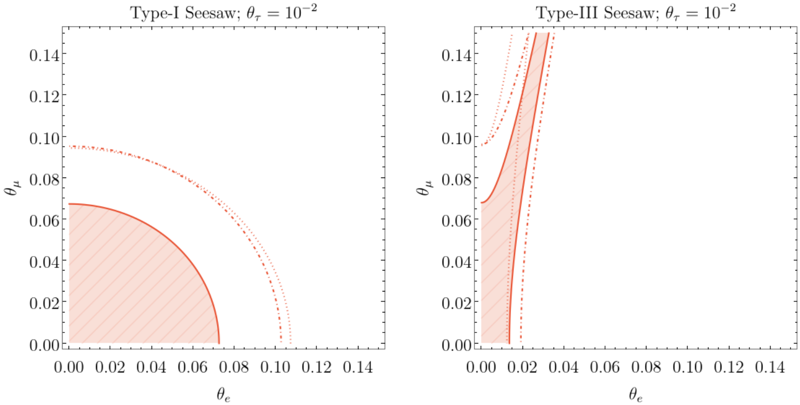

Electroweak Observables

W-boson mass and the weak mixing angle, $s_w = \sin\theta_w$ are shifted by

$$\delta m_W^2 = \frac{-m_W^2}{2(c_w^2 - s_w^2)} v^2 \left(4 c_w s_w C_{HWB} + c_w^2 C_{HD} + 2\sqrt{2} s_w^2 \delta G_F\right)$$

$$\delta s_w^2 = \frac{c_w s_w}{c_w^2 - s_w^2} v^2 \left(\frac{1}{2} c_w s_w C_{HD} + C_{HWB} + \sqrt{2} c_w s_w \delta G_F\right)$$

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We also know the following:

Observable	SM prediction	Measurement
$\sin^2(\theta_{\text{eff}}^{\text{lept}})$	0.231534 ± 0.000030	0.23153 ± 0.00026
m_W [GeV]	80.356 ± 0.006	80.377 ± 0.012

de Blas et. al. 2112.07274 *Schael et. al.* hep-ex/0509008 *PDG 2022*

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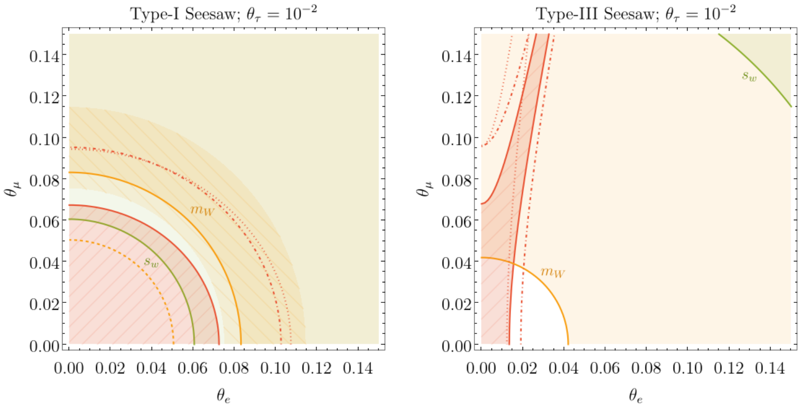
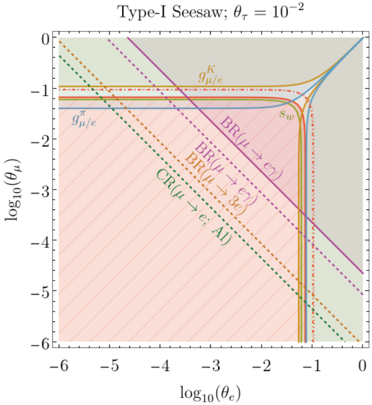
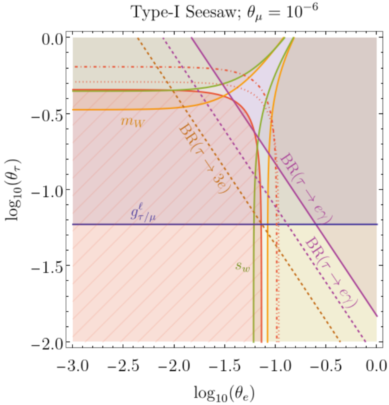


Figure: Constraints from m_W and s_w at 2σ vs. Higgsstrahlung prospects.

Type-I Full Results

Skipping to the full results...





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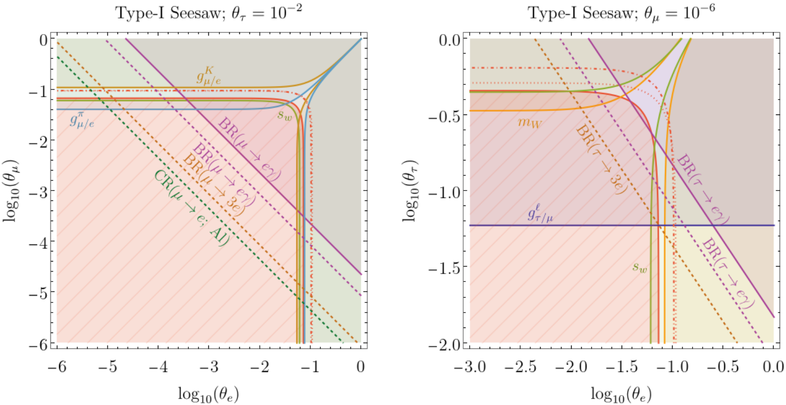

Upshot: we are not likely to see shifts to $\sigma(e^+e^- \to Zh)$ in Type-I Seesaw.

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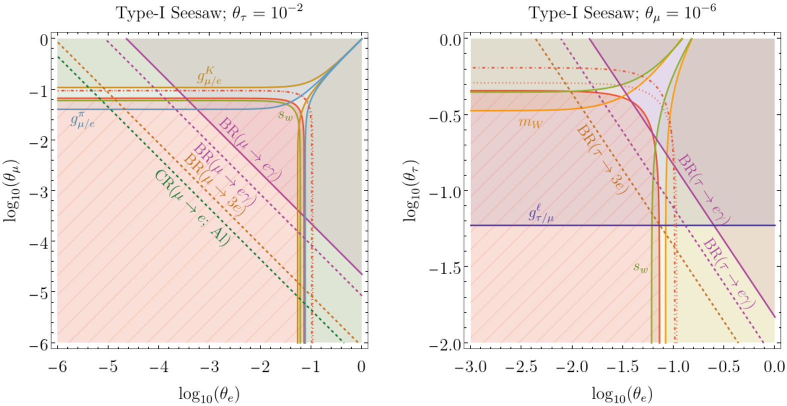

Upshot: we are not likely to see shifts to $\sigma(e^+e^- \to Zh)$ in Type-I Seesaw.

That's all folks! (...until Tobias' turn)

Backup Slides

Backup: SMEFT Operators

$\mathcal{O}_{HW}$	$H^\dagger H W^I_{\mu\nu} W^{I\mu\nu}$
$\mathcal{O}_{HB}$	$H^\dagger H B_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HWB}$	$H^\dagger \sigma^I H W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
$\mathcal{O}_{HD}$	$(H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$
$\mathcal{O}^{(1)}_{HL,ij}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\overline{L_i}\gamma^\mu L_j)$
$\mathcal{O}^{(3)}_{HL,ij}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{L_i}\sigma^a\gamma^\mu L_j)$
$\mathcal{O}_{He,ij}$	$(H^\dagger i\overleftrightarrow{D}^a_\mu H)(\overline{e_{Ri}}\gamma^\mu e_{Rj})$
$\mathcal{O}_{LL,ijkl}$	$(\overline{L_i}\gamma^\mu L_j)(\overline{L_k}\gamma_\mu L_l)$

Backup: Higgsstrahlung in the SM

$$\sigma_0 = \frac{\sqrt{\lambda}}{32\pi s}(g_L^2 + g_R^2)\left(\frac{g_{ZZh}}{s - m_Z^2}\right)^2\left(1 + \frac{\lambda}{12sm_Z^2}\right).$$

$$\begin{aligned} g_{ZZh} &= \frac{g_2 m_Z}{\cos\theta_w} \\ g_L &= g_Z(-\tfrac{1}{2} + \sin^2\theta_w) \\ g_R &= g_Z\sin^2\theta_w \\ g_Z &= \frac{g_2}{\cos\theta_w} \\ \lambda &= (s - m_Z^2 - m_h^2)^2 - 4m_Z^2 m_h^2 \end{aligned}$$

Backup: Higgstrahlung Shift

$$\frac{\Delta\sigma}{\sigma_0} = 2\left(\frac{\delta g_{ZZh}}{g_{ZZh}} + \frac{g_L \delta g_L + g_R \delta g_R}{g_L^2 + g_R^2}\right) + \frac{v}{g_{ZZh}} \sum_{i=2}^{5} d_i f_i .$$

See *Craig et. al.* 1411.0676

Parameter shifts:

$$\frac{\delta g_{ZZh}}{g_{ZZh}} = v^2\left(C_{H\Box} + \frac{1}{4}C_{HD} - \frac{1}{\sqrt{2}}\delta G_F\right),$$

$$\frac{\delta g_L}{g_Z} = \frac{1}{8(c_w^2 - s_w^2)} v^2\left(8 s_w c_w C_{HWB} + C_{HD} + 2\sqrt{2}\delta G_F\right) - \frac{1}{2}v^2\left(C_{HL,11}^{(1)} + C_{HL,11}^{(3)}\right), \quad \text{and}$$

$$\frac{\delta g_R}{g_Z} = \frac{s_w^2}{4(c_w^2 - s_w^2)} v^2\left(4\frac{c_w}{s_w} C_{HWB} + C_{HD} + 2\sqrt{2}\delta G_F\right) - \frac{1}{2}v^2 C_{He,11}.$$

'Direct' contributions:

$$d_2 = 4(s_w^2 C_{HB} + s_w c_w C_{HWB} + c_w^2 C_{HW}), \qquad f_2 = 12 m_Z^2 \frac{s(s + m_Z^2 - m_h^2)}{12 s m_Z^2 + \lambda},$$

$$d_3 = -4 s_w c_w C_{HB} - 2(c_w^2 - s_w^2) C_{HWB} + 4 s_w c_w C_{HW},$$

$$f_3 = -12 e m_Z^2 \frac{g_L + g_R}{g_L^2 + g_R^2} \frac{(s - m_Z^2)(s + m_Z^2 - m_h^2)}{12 s m_Z^2 + \lambda},$$

$$d_4 = -g_Z(C_{HL,11}^{(1)} + C_{HL,11}^{(3)}), \qquad f_4 = \frac{2 g_L}{g_L^2 + g_R^2}(s - m_Z^2),$$

$$d_5 = -g_Z C_{He,11}, \quad \text{and} \qquad f_5 = \frac{2 g_R}{g_L^2 + g_R^2}(s - m_Z^2).$$

Backup: Weak Mixing Angle

Left-right asymmetry $\mathcal{A}_f = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{2(1-4s_w^2)}{1+(1-4s_w^2)^2}$

$$\delta g_{L,ij}^{\text{direct}} = -\frac{1}{2} g_Z v^2 \left(C_{HL,ij}^{(1)} + C_{HL,ij}^{(3)} \right)$$
$$\delta g_{R,ij}^{\text{direct}} = -\frac{1}{2} g_Z v^2 C_{He,ij},$$

$$s_{w,\text{eff}}^2 = s_{w,\text{SM}}^2 + \delta s_w^2 + \frac{1}{3}\frac{\partial s_w^2}{\partial \mathcal{A}_\ell} \left(\frac{\partial \mathcal{A}_\ell}{\partial g_L} \sum_{i=1}^{3} \delta g_{L,ii}^{\text{direct}} + \frac{\partial \mathcal{A}_\ell}{\partial g_R} \sum_{i=1}^{3} \delta g_{R,ii}^{\text{direct}} \right)$$
$$\approx s_{w,\text{SM}}^2 + 0.020 \left(\hat{C}_{HL,11}^{(3)} + \hat{C}_{HL,22}^{(3)} \right)$$
$$- 0.005 \sum_{i=1}^{3} \left(\hat{C}_{HL,ii}^{(1)} + \hat{C}_{HL,ii}^{(3)} \right)$$

Backup: Shifts in terms of mixing angles

	Type-I	Type-III
$\Delta\sigma/\sigma_0$ (240 GeV)	$0.95\,\lvert\theta_e\rvert^2 + 1.10\,\lvert\theta_\mu\rvert^2 + 0.02\,\lvert\theta_\tau\rvert^2$	$27.59\,\lvert\theta_e\rvert^2 - 1.08\,\lvert\theta_\mu\rvert^2 - 0.01\,\lvert\theta_\tau\rvert^2$
$\Delta\sigma/\sigma_0$ (365 GeV)	$0.87\,\lvert\theta_e\rvert^2 + 1.12\,\lvert\theta_\mu\rvert^2 + 0.04\,\lvert\theta_\tau\rvert^2$	$66.15\,\lvert\theta_e\rvert^2 - 1.09\,\lvert\theta_\mu\rvert^2 - 0.01\,\lvert\theta_\tau\rvert^2$
$\Delta\sigma/\sigma_0$ (500 GeV)	$0.80\,\lvert\theta_e\rvert^2 + 1.14\,\lvert\theta_\mu\rvert^2 + 0.05\,\lvert\theta_\tau\rvert^2$	$126.39\,\lvert\theta_e\rvert^2 - 1.10\,\lvert\theta_\mu\rvert^2 - 0.01\,\lvert\theta_\tau\rvert^2$

Shift	Type-I	Type-III
Δs_w^2	$-0.157(\lvert\theta_e\rvert^2 + \lvert\theta_\mu\rvert^2) + 0.003\,\lvert\theta_\tau\rvert^2$	$0.017(\lvert\theta_e\rvert^2 + \lvert\theta_\mu\rvert^2) - 0.143\,\lvert\theta_\tau\rvert^2$
$\Delta m_W/$GeV	$8.24(\lvert\theta_e\rvert^2 + \lvert\theta_\mu\rvert^2) - 0.13\,\lvert\theta_\tau\rvert^2$	$-8.51(\lvert\theta_e\rvert^2 + \lvert\theta_\mu\rvert^2) - 0.13\,\lvert\theta_\tau\rvert^2$