One-loop contributions to WWZ from a seesaw variant with radiatively induced light neutrino masses

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Calculation, estimation and analysis of the one loop contributions from **Majorana neutrinos**

⇩

Lorentz-covariant WWZ parametrization

BSM description characterized by $\mathcal{L}_{\mathrm{BSM}}$ [1]

Two phases of spontaneous symmetry breaking

Symmetry breaking at some high-energy scale w

Brout-Englert-Higgs mechanism
$\mathrm{SU}(2)_L \otimes \mathrm{U}(1)_Y \quad \rightarrow \quad \mathrm{U}(1)_e$

at $v = 246\ \mathrm{GeV}$

[1] Pilaftsis, A. (1992). Radiatively induced neutrino masses and large Higgs-neutrino couplings in the Standard Model with Majorana fields. Zeitschrift für Physik C Particles and Fields, **55**(2), 275-282.

Asume that previous chain of events gives rise to the Lagrangian

$$\mathcal{L}_{\text{BSM}} = \mathcal{L}^{\nu}_{\text{mass}} + \mathcal{L}^{\text{SM}}_{\text{CC}} + \mathcal{L}^{\text{SM}}_{\text{NC}} + \mathcal{L}^{\text{SM}}_{\text{HC}} + \cdots$$

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$$\mathcal{L}^{\nu}_{\mathrm{mass}} = -\sum_{j=1}^{3}\sum_{k=1}^{3}\left(\overline{\nu^{0}_{j,L}}(m_{\mathrm{D}})_{jk}\,\nu^{0}_{k,R} + \frac{1}{2}\overline{\nu^{0\,\mathrm{c}}_{j,R}}(m_{\mathrm{M}})_{jk}\,\nu^{0}_{k,R}\right) + \mathrm{H.c.} \quad (1)$$

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$$\nu^{\mathrm{c}}_k = C\overline{\nu_k}^{\mathrm{T}}$$

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3×3 matrix assumed to emerge from EW symmetry breaking

3×3 matrix assumed to emerge from symmetry breaking at w

Defining

$$f_L = \begin{pmatrix} \nu^0_{1,L} \\ \nu^0_{2,L} \\ \nu^0_{3,L} \end{pmatrix} \qquad F_L = \begin{pmatrix} \nu^{0\,c}_{1,R} \\ \nu^{0\,c}_{2,R} \\ \nu^{0\,c}_{3,R} \end{pmatrix}$$

$$f_R = C\overline{f_L}^{\mathrm{T}} \qquad F_R = C\overline{F_L}^{\mathrm{T}}$$

$$\Rightarrow \mathcal{L}^{\nu}_{\mathrm{mass}} = -\frac{1}{2}(\overline{f_L} \ \ \overline{F_L})\mathcal{M}\begin{pmatrix} f_R \\ F_R \end{pmatrix} + \mathrm{H.c.} \qquad (2)$$

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$$\mathcal{M} = \begin{pmatrix} 0 & m_{\mathrm{D}} \\ m^{\mathrm{T}}_{\mathrm{D}} & m_{\mathrm{M}} \end{pmatrix}$$

6×6 matrix
complex
symmetric

✓ Unitary diagonalization transformation

Define the mass eigenspinors base

Assume 6×6 unitary matrix

$$\mathcal{U}_\nu = \begin{pmatrix} \mathcal{U}_{11} & \mathcal{U}_{12} \\ \mathcal{U}_{21} & \mathcal{U}_{22} \end{pmatrix}$$

3×3 matrix blocks $\mathcal{U}_{kj}$

Unitary transformation

$$\mathcal{U}_\nu^{\mathrm{T}} \mathcal{M} \, \mathcal{U}_\nu = \begin{pmatrix} m_\nu & 0 \\ 0 & m_N \end{pmatrix}$$

3×3 real-valued diagonal matrix

$$(m_\nu)_{jk} = m_{\nu_j} \delta_{jk}$$
$$(m_N)_{jk} = m_{N_j} \delta_{jk}$$

Unitary diagonalization transformation

Define the mass eigenspinors base

$$\mathcal{L}^{\nu}_{\text{mass}} = \sum_{j=1}^{3}\Big(-\frac{1}{2}m_{\nu_j}\overline{\nu_j}\nu_j - \frac{1}{2}m_{N_j}\overline{N_j}N_j\Big) \qquad (3)$$

Majorana fields

$$\nu_j^{\text{c}} = \nu_j \qquad N_j^{\text{c}} = N_j$$

Light neutrinos — Heavy neutrinos

$$\mathcal{L}_{\text{BSM}} = \mathcal{L}_{\text{mass}}^{\nu} + \mathcal{L}_{\text{CC}}^{\text{SM}} + \mathcal{L}_{\text{NC}}^{\text{SM}} + \mathcal{L}_{\text{HC}}^{\text{SM}} + \cdots$$

$$\mathcal{L}_{\text{CC}}^{\text{SM}} = \sum_{\alpha} \sum_{j=1}^{3} \left(\frac{g}{\sqrt{2}} \mathcal{B}_{\alpha\nu_j} W_{\rho}^{-} \, \overline{l_\alpha} \gamma^{\rho} P_L \nu_j + \frac{g}{\sqrt{2}} \mathcal{B}_{\alpha N_j} W_{\rho}^{-} \, \overline{l_\alpha} \gamma^{\rho} P_L N_j \right) + \text{H.c.} \quad (4)$$

$$\mathcal{B}_{\alpha\nu_j} = \sum_{k=1}^{3} V_{\alpha k}^{\ell} (\mathcal{U}_{11}^{*})_{kj}$$

$$\mathcal{B}_{\alpha N_j} = \sum_{k=1}^{3} V_{\alpha k}^{\ell} (\mathcal{U}_{12}^{*})_{kj}$$

$$\mathcal{L}_{\rm BSM} = \mathcal{L}_{\rm mass}^{\nu} + \mathcal{L}_{\rm CC}^{\rm SM} + \mathcal{L}_{\rm NC}^{\rm SM} + \mathcal{L}_{\rm HC}^{\rm SM} + \cdots$$

$$\mathcal{L}_{\rm CC}^{\rm SM} = \sum_{\alpha}\sum_{j=1}^{3}\left(\frac{g}{\sqrt{2}}\mathcal{B}_{\alpha\nu_j}W_{\rho}^{-}\,\overline{l_\alpha}\gamma^{\rho}P_L\nu_j + \frac{g}{\sqrt{2}}\mathcal{B}_{\alpha N_j}W_{\rho}^{-}\,\overline{l_\alpha}\gamma^{\rho}P_L N_j\right) + \text{H.c.} \quad (4)$$

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V^{ℓ}

⇩

3×3 matrix

Lepton mixing

$$\mathcal{L}_{\rm BSM} = \mathcal{L}^{\nu}_{\rm mass} + \mathcal{L}^{\rm SM}_{\rm CC} + \mathcal{L}^{\rm SM}_{\rm NC} + \mathcal{L}^{\rm SM}_{\rm HC} + \cdots$$

$$\mathcal{L}^{\rm SM}_{\rm CC} = \sum_{\alpha}\sum_{j=1}^{3}\left(\frac{g}{\sqrt{2}}\mathcal{B}_{\alpha\nu_j}W^{-}_{\rho}\,\overline{l_\alpha}\gamma^{\rho}P_L\nu_j + \frac{g}{\sqrt{2}}\mathcal{B}_{\alpha N_j}W^{-}_{\rho}\,\overline{l_\alpha}\gamma^{\rho}P_L N_j\right) + \text{H.c.} \quad (4)$$

Unitary block parametrization [2,3]

$$\mathcal{B}_{\alpha\nu_j} = \sum_{k=1}^{3} V^{\ell}_{\alpha k}(\mathcal{U}^{*}_{11})_{kj}$$

$$\mathcal{B}_{\alpha N_j} = \sum_{k=1}^{3} V^{\ell}_{\alpha k}(\mathcal{U}^{*}_{12})_{kj}$$

$$\mathcal{U} = \begin{pmatrix} (\mathbf{1}_3 + \xi^{*}\xi^{\rm T})^{-\frac{1}{2}} & \xi^{*}(\mathbf{1}_3 + \xi^{\rm T}\xi^{*})^{-\frac{1}{2}} \\ -\xi^{\rm T}(\mathbf{1}_3 + \xi^{*}\xi^{\rm T})^{-\frac{1}{2}} & (\mathbf{1}_3 + \xi^{\rm T}\xi^{*})^{-\frac{1}{2}} \end{pmatrix} \quad (5)$$

✓ 3×3 complex matrix ξ

Assumption: $|\xi_{jk}|$ are small ➞ $\xi = m_{\rm D} m_{\rm M}^{-1}$

[2] J. G. Korner, A. Pilaftsis, and K. Schilcher, Leptonic CP asymmetries in flavor-changing H0 decays, Phys. Rev. D **47**, 1080 (1993).
[3] P. S. B. Dev and A. Pilaftsis, Minimal radiative neutrino mass mechanism for inverse seesaw models, Phys. Rev. D **86**, 113001 (2012).

$$\mathcal{L}_{\mathrm{BSM}} = \mathcal{L}_{\mathrm{mass}}^{\nu} + \mathcal{L}_{\mathrm{CC}}^{\mathrm{SM}} + \mathcal{L}_{\mathrm{NC}}^{\mathrm{SM}} + \mathcal{L}_{\mathrm{HC}}^{\mathrm{SM}} + \cdots$$

$$\begin{aligned}\mathcal{L}_{\mathrm{NC}}^{\mathrm{SM}} = \sum_{k=1}^{3}\sum_{j=1}^{3}\frac{g}{4c_{\mathrm{W}}}\Big(& Z_\rho \overline{\nu_k}\gamma^\rho \big(i\mathcal{C}_{\nu_k\nu_j}^{\mathrm{Im}} - \mathcal{C}_{\nu_k\nu_j}^{\mathrm{Re}}\gamma_5\big)\nu_j \\ & + \Big(Z_\rho \overline{\nu_k}\gamma^\rho \big(i\mathcal{C}_{\nu_k N_j}^{\mathrm{Im}} - \mathcal{C}_{\nu_k N_j}^{\mathrm{Re}}\gamma_5\big)N_j + \mathrm{H.c.}\Big) \\ & + Z_\rho \overline{N_k}\gamma^\rho \big(i\mathcal{C}_{N_k N_j}^{\mathrm{Im}} - \mathcal{C}_{N_k N_j}^{\mathrm{Re}}\gamma_5\big)N_j\Big)\end{aligned} \quad (6)$$

$$\mathcal{C}_{\nu_i\nu_l} = \sum_{j=1}^{3} (\mathcal{U}_{11})_{ji} (\mathcal{U}^*_{11})_{jl}$$

$$\mathcal{C}_{\nu_i N_l} = \sum_{j=1}^{3} (\mathcal{U}_{11})_{ji} (\mathcal{U}^*_{12})_{jl}$$

$$\mathcal{C}_{N_i\nu_l} = \sum_{j=1}^{3} (\mathcal{U}_{12})_{ji} (\mathcal{U}^*_{11})_{jl}$$

$$\mathcal{C}_{N_i N_l} = \sum_{j=1}^{3} (\mathcal{U}_{12})_{ji} (\mathcal{U}^*_{12})_{jl}$$

6×6 hermitian matrix

$$\mathcal{C} = \begin{pmatrix} \mathcal{C}_{\nu\nu} & \mathcal{C}_{\nu N} \\ \mathcal{C}_{N\nu} & \mathcal{C}_{NN} \end{pmatrix}$$

3×3 matrix blocks

$$\mathcal{C} = \begin{pmatrix} \left(\mathbf{1}_3 + \xi\xi^\dagger\right)^{-1} & \left(\mathbf{1}_3 + \xi\xi^\dagger\right)^{-1}\xi \\ \xi^\dagger\left(\mathbf{1}_3 + \xi\xi^\dagger\right)^{-1} & \xi^\dagger\left(\mathbf{1}_3 + \xi\xi^\dagger\right)^{-1}\xi \end{pmatrix} \quad (7)$$

$$\mathcal{L}_{\mathrm{BSM}} = \mathcal{L}_{\mathrm{mass}}^{\nu} + \mathcal{L}_{\mathrm{CC}}^{\mathrm{SM}} + \mathcal{L}_{\mathrm{NC}}^{\mathrm{SM}} + \mathcal{L}_{\mathrm{HC}}^{\mathrm{SM}} + \cdots$$

$$\begin{aligned}\mathcal{L}_{\mathrm{HC}}^{\mathrm{SM}} = \sum_{k=1}^{3}\sum_{j=1}^{3}\frac{g}{4m_W}\Big(& h\overline{\nu_k}\big((m_{\nu_k}+m_{\nu_j})\mathcal{C}^{\mathrm{Re}}_{\nu_k\nu_j} - i\gamma_5(m_{\nu_k}-m_{\nu_j})\mathcal{C}^{\mathrm{Im}}_{\nu_k\nu_j}\big)\nu_j \\ & + h\overline{\nu_k}\big((m_{\nu_k}+m_{N_j})\mathcal{C}^{\mathrm{Re}}_{\nu_k N_j} - i\gamma_5(m_{\nu_k}-m_{N_j})\mathcal{C}^{\mathrm{Im}}_{\nu_k N_j}\big)N_j \\ & + h\overline{N_k}\big((m_{N_k}+m_{N_j})\mathcal{C}^{\mathrm{Re}}_{N_k N_j} - i\gamma_5(m_{N_k}-m_{N_j})\mathcal{C}^{\mathrm{Im}}_{N_k N_j}\big)N_j\Big)\end{aligned}$$

(8)

Consider the neutrino mass model [1]

Light neutrinos:

$$(\mathcal{M}\mathcal{U}_\nu)_{jk} = 0 \qquad\qquad j = 1,2,3,4,5,6$$

the $k-th$ neutrino mass vanishes at tree level.

Heavy neutrinos:

Tree-level mass are left untouched

$$m_N \simeq m_{\rm M}\left(1 + \frac{1}{2} m_{\rm M}^{-1}\left(\xi^\dagger m_{\rm D} + m_{\rm D}^{\rm T}\xi^*\right)\right) \qquad (9)$$

Smallness of light-neutrino masses comes about if heavy neutrino masses are nearly-degenerate

[1] Pilaftsis, A. (1992). Radiatively induced neutrino masses and large Higgs-neutrino couplings in the Standard Model with Majorana fields. Zeitschrift für Physik C Particles and Fields, **55**(2), 275-282.

One loop effects from Majorana neutrinos on the vertex $\boldsymbol{WWZ}$

The $\boldsymbol{WWZ}$ vertex

Lagrangian

$$\mathcal{L}_{\text{eff}}^{WWZ} = \mathcal{L}_{WWZ}^{\text{even}} + \mathcal{L}_{WWZ}^{\text{odd}}$$

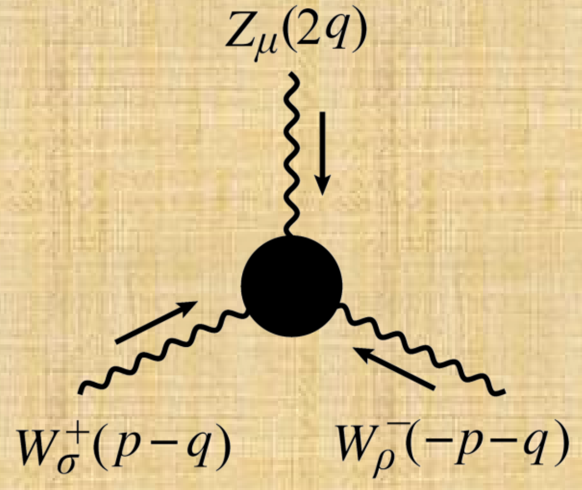
Refer to CP-transformation properties

Where

$$\mathcal{L}_{WWZ}^{\text{even}} = -ig_Z\Big(g_1\big(W_{\mu\nu}^{+}W^{-\mu} - W_{\mu\nu}^{-}W^{+\mu}\big)Z^{\nu} + \kappa\, W_{\mu}^{+}W_{\nu}^{-}Z^{\mu\nu} + \frac{\lambda}{m_W^2}W_{\mu\nu}^{+}W^{-\nu}{}_{\rho}Z^{\rho\mu} - ig_2\epsilon^{\rho\mu\lambda\nu}Z_{\rho}\big(W_{\nu}^{+}\partial_{\lambda}W_{\mu}^{-} - W_{\mu}^{-}\partial_{\lambda}W_{\nu}^{+}\big)\Big) \quad (10)$$

$$\mathcal{L}_{WWZ}^{\text{odd}} = -ig_Z\Big(\tilde{\kappa}W_{\mu}^{+}W_{\nu}^{-}\tilde{Z}^{\mu\nu} + \frac{\tilde{\lambda}}{m_W^2}W_{\mu\nu}^{+}W^{-\nu}{}_{\rho}\tilde{Z}^{\rho\mu} - i\tilde{g}_1W_{\mu}^{+}W_{\nu}^{-}\big(\partial^{\mu}Z^{\nu} + \partial^{\nu}Z^{\mu}\big)\Big) \quad (11)$$

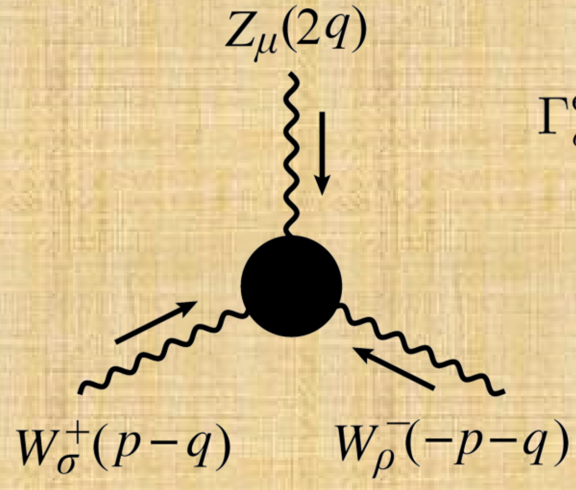
$\boldsymbol{WWZ}$ vertex [4]



SM W bosons on-shell
Z boson off-shell

[4] W. A. Bardeen, R. Gastmans, and B. Lautrup, Static quantities in Weinberg's model of weak and electromagnetic interactions,Nucl. Phys. B **46**, 319 (1972).

CP-even $\boldsymbol{WWZ}$ vertex function



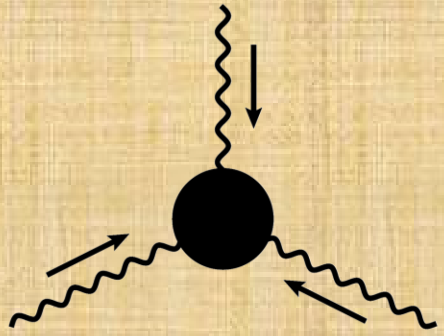
$$\Gamma^{\text{even}}_{\sigma\rho\mu} = ig_Z\Big(g_1\big(2p_\mu g_{\sigma\rho} + 4(q_\rho g_{\sigma\mu} - q_\sigma g_{\rho\mu})\big) + \frac{4\Delta Q}{m_W^2} p_\mu\Big(q_\sigma q_\rho - \frac{q^2}{2} g_{\sigma\rho}\Big) + 2\Delta\kappa(q_\rho g_{\sigma\mu} - q_\sigma g_{\rho\mu}) + i f_1\, \epsilon_{\sigma\rho\mu\alpha} p^\alpha\Big) \quad (12)$$

$$\Delta\kappa = -g_1 + \kappa + \lambda \qquad \Delta Q = -2\lambda$$

$$f_1 = -g_2$$

Anomalous couplings

CP-odd *WWZ* vertex function



$$\Gamma^{\text{odd}}_{\sigma\rho\mu} = i g_Z \Big(2\Delta\tilde{\kappa}\epsilon_{\sigma\rho\mu\alpha} q^\alpha + \frac{4\Delta\tilde{Q}}{m_W^2} q_\rho \epsilon_{\sigma\mu\alpha\beta} p^\alpha q^\beta$$
$$+ i\tilde{f}_1 (q_\rho g_{\sigma\mu} + q_\sigma g_{\rho\mu})$$
$$+ \tilde{f}_2\, p^\lambda \epsilon_{\sigma\rho\lambda\alpha} (q^2 \delta^\alpha{}_\mu - q^\alpha q_\mu) \Big), \quad (13)$$

Anomalous couplings

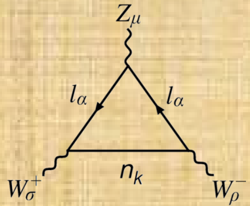
$$\Delta\tilde{\kappa} = \tilde{\kappa} + \frac{m_W^2 - 2q^2}{m_W^2}\tilde{\lambda} \qquad \Delta\tilde{Q} = -2\tilde{\lambda}$$

$$\tilde{f}_1 = 2\tilde{g}_1 \qquad \tilde{f}_2 = -\frac{4\tilde{\lambda}}{m_W^2}$$

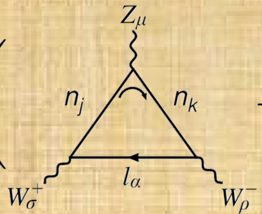
One-loop contributions to $\boldsymbol{WWZ}$

Vertex function $$\Gamma^{WWZ}_{\sigma\rho\mu} = \Gamma^{lln}_{\sigma\rho\mu} + \Gamma^{nnl}_{\sigma\rho\mu} + \Gamma^{nnh}_{\sigma\rho\mu} \qquad (14)$$

$$\Gamma^{lln}_{\sigma\rho\mu} = \sum_{k=1}^{6}\sum_{\alpha}$$



$$\Gamma^{nnl}_{\sigma\rho\mu} = \sum_{k=1}^{6}\sum_{j=1}^{6}\sum_{\alpha}\Bigg($$



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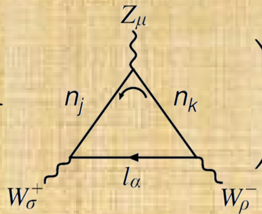
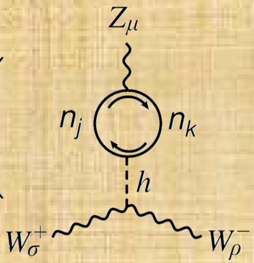


$\Bigg)$

$$\Gamma^{nnh}_{\sigma\rho\mu} = \sum_{k=1}^{6}\sum_{j=1}^{6}\Bigg($$



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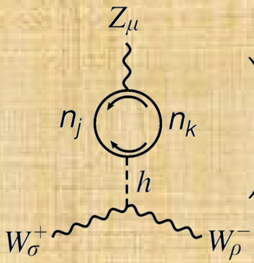

$\Bigg)$

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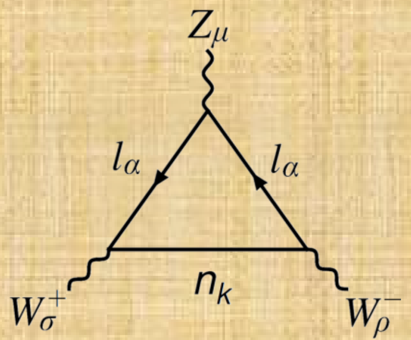
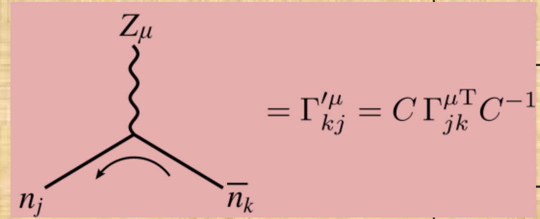


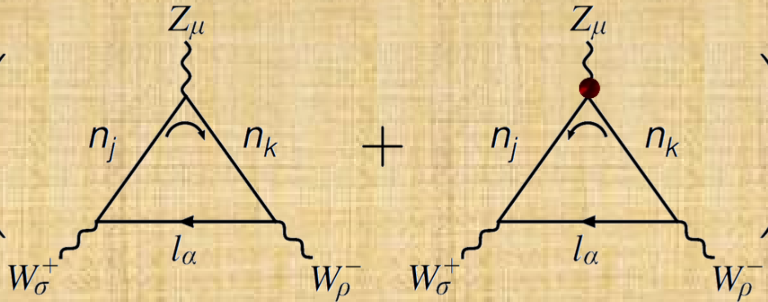
n_k represents both ν_k N_k

One-loop contributions to $\boldsymbol{WWZ}$

Vertex function $$\Gamma^{WWZ}_{\sigma\rho\mu} = \Gamma^{lln}_{\sigma\rho\mu} + \Gamma^{nnl}_{\sigma\rho\mu} + \Gamma^{nnh}_{\sigma\rho\mu} \qquad (14)$$



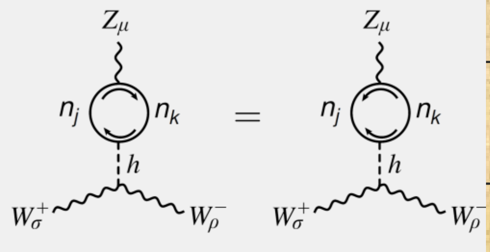
$$\Gamma^{nnl}_{\sigma\rho\mu} = \sum_{k=1}^{6}\sum_{j=1}^{6}\sum_{\alpha}\Bigg($$



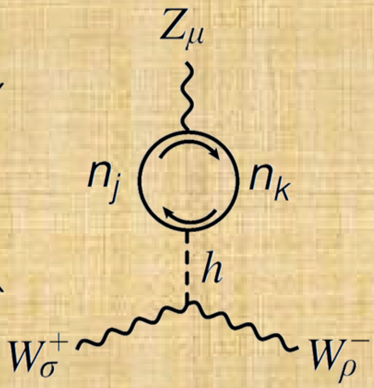
$$\Bigg)$$

One-loop contributions to $\boldsymbol{WWZ}$

Vertex function $$\Gamma^{WWZ}_{\sigma\rho\mu} = \Gamma^{lln}_{\sigma\rho\mu} + \Gamma^{nnl}_{\sigma\rho\mu} + \Gamma^{nnh}_{\sigma\rho\mu} \quad (14)$$



$$\Gamma^{nnh}_{\sigma\rho\mu} = \sum_{k=1}^{6}\sum_{j=1}^{6}\Bigg(\quad + \quad \Bigg)$$



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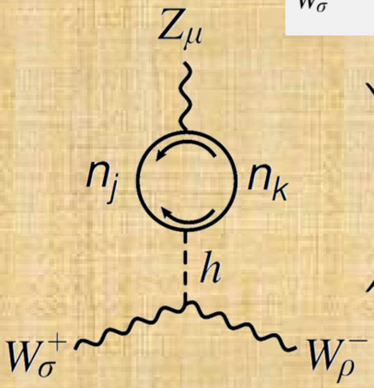


Do not contribute to ΔQ and $\Delta\kappa$

Estimations and discussion

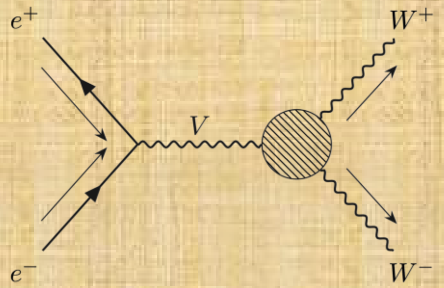
- $$\xi = \hat{\rho} X$$

Considering the matrix texture

$$X = e^{i\varphi} \cdot \mathbf{1}_3$$

- $$V^{\ell} = U_{\nu}$$

$m_{\nu_j} \approx 0.8\text{eV}$ [5]



Nearly degenerated Neutrino spectrum

The International Linear Collider technical design report estimated sensitivity [6]

$$m_{N_1} \approx m_{N_h}$$
$$m_{N_2} \approx m_{N_h}$$
$$m_{N_3} \approx m_{N_h}$$

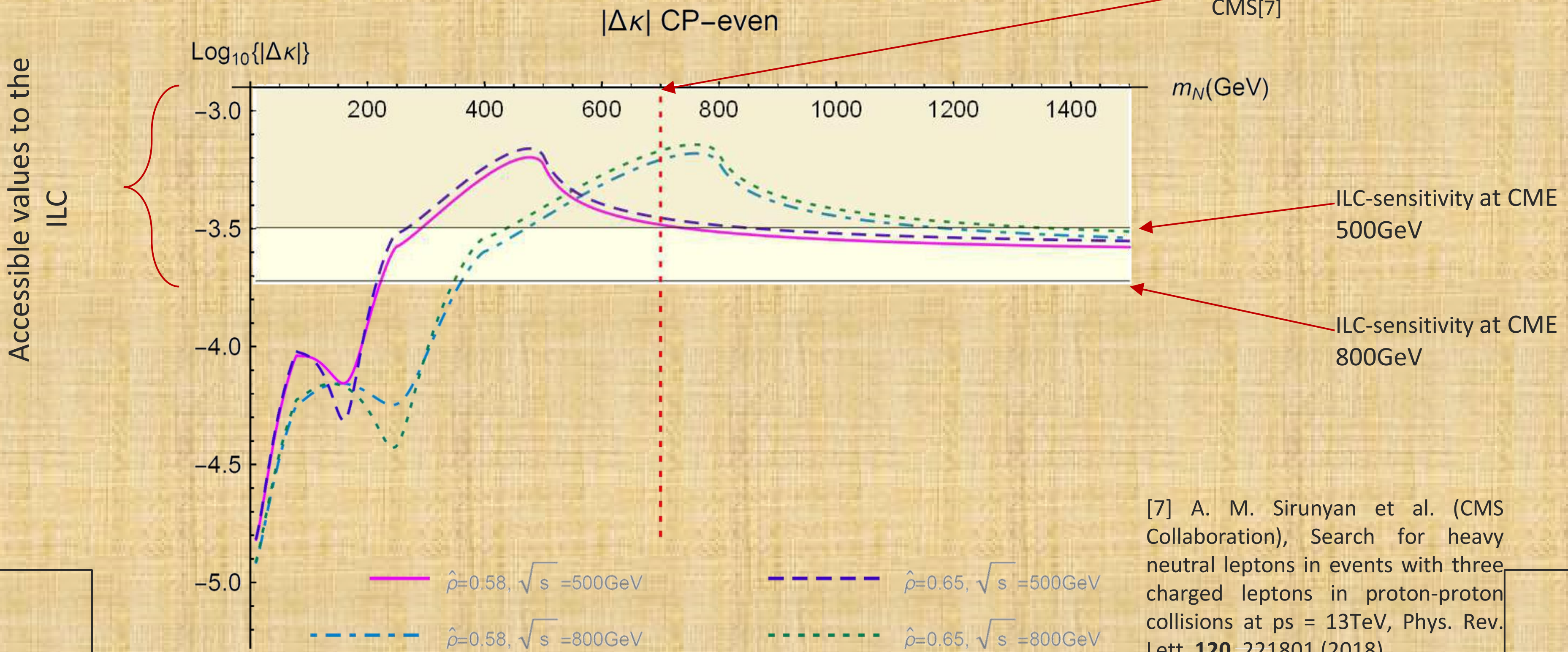
Coupling	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 800$ GeV
$\lvert\Delta\kappa_{\rm ILC}\rvert$	3.20×10^{-4}	1.90×10^{-4}
$\lvert\Delta Q_{\rm ILC}\rvert$	1.34×10^{-3}	6.00×10^{-4}
$\lvert\Delta\tilde{\kappa}_{\rm ILC}\rvert$	5.33×10^{-2}	5.77×10^{-2}
$\lvert\Delta\tilde{Q}_{\rm ILC}\rvert$	1.5×10^{-3}	6.00×10^{-4}

[5] M. Aker et al. (The KATRIN Collaboration), Direct neutrino-mass measurement with sub-electronvolt sensitivity, Nature Phys. 18, 160 (2022)
[6] H. Baer et al. (ILC Collaboration), The international linear collider technical design report-Volume 2: Physics, arXiv:1306.6352.

CP-Even contributions

$$\Delta\kappa = \sum_{\alpha} \Bigg(\frac{1}{1+\hat{\rho}^2} \left(\Delta\kappa^{(1)}_{\alpha\nu} + \hat{\rho}^2 \Delta\kappa^{(1)}_{\alpha N}\right) + \frac{1}{(1+\hat{\rho}^2)^2} \left(\Delta\kappa^{(2)}_{\alpha\nu\nu} + \Delta\kappa^{(3)}_{\alpha\nu\nu}\right) + \frac{\hat{\rho}^4}{(1+\hat{\rho}^2)^2} \left(\Delta\kappa^{(2)}_{\alpha NN} + \Delta\kappa^{(3)}_{\alpha NN}\right) + \frac{2\hat{\rho}^2}{(1+\hat{\rho}^2)^2} \left(\Delta\kappa^{(2)}_{\alpha\nu N} + \cos(2\varphi)\Delta\kappa^{(3)}_{\alpha\nu N}\right) \Bigg) \quad (16)$$

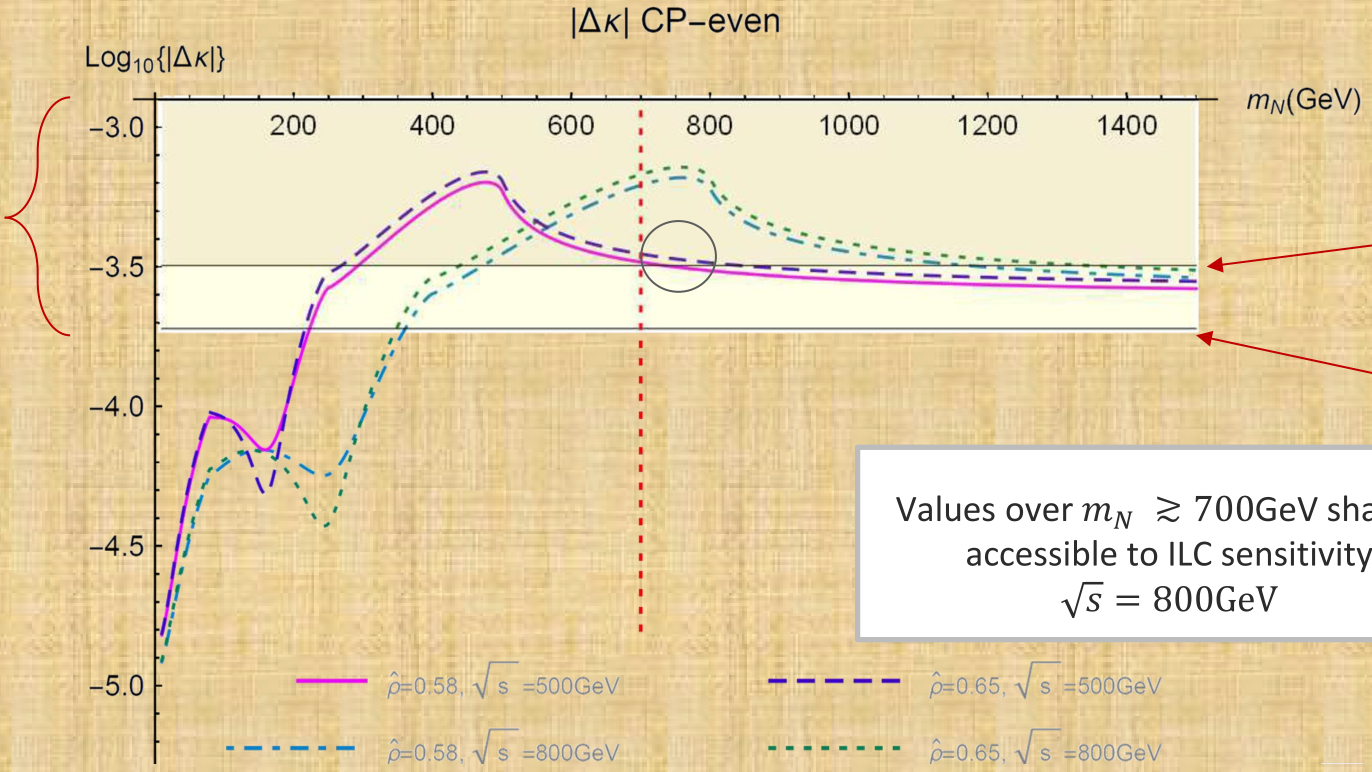
Contributions to the light + heavy neutrinos to the CP-even form factor $\Delta\kappa$



[7] A. M. Sirunyan et al. (CMS Collaboration), Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at ps = 13TeV, Phys. Rev. Lett. **120**, 221801 (2018).

Contributions to the light + heavy neutrinos to the CP-even form factor $\Delta\kappa$

Accessible values to the ILC



ILC-sensitivity at CME 500GeV

ILC-sensitivity at CME 800GeV

Values over $m_N \gtrsim 700$GeV shall be accessible to ILC sensitivity $\sqrt{s} = 800$GeV

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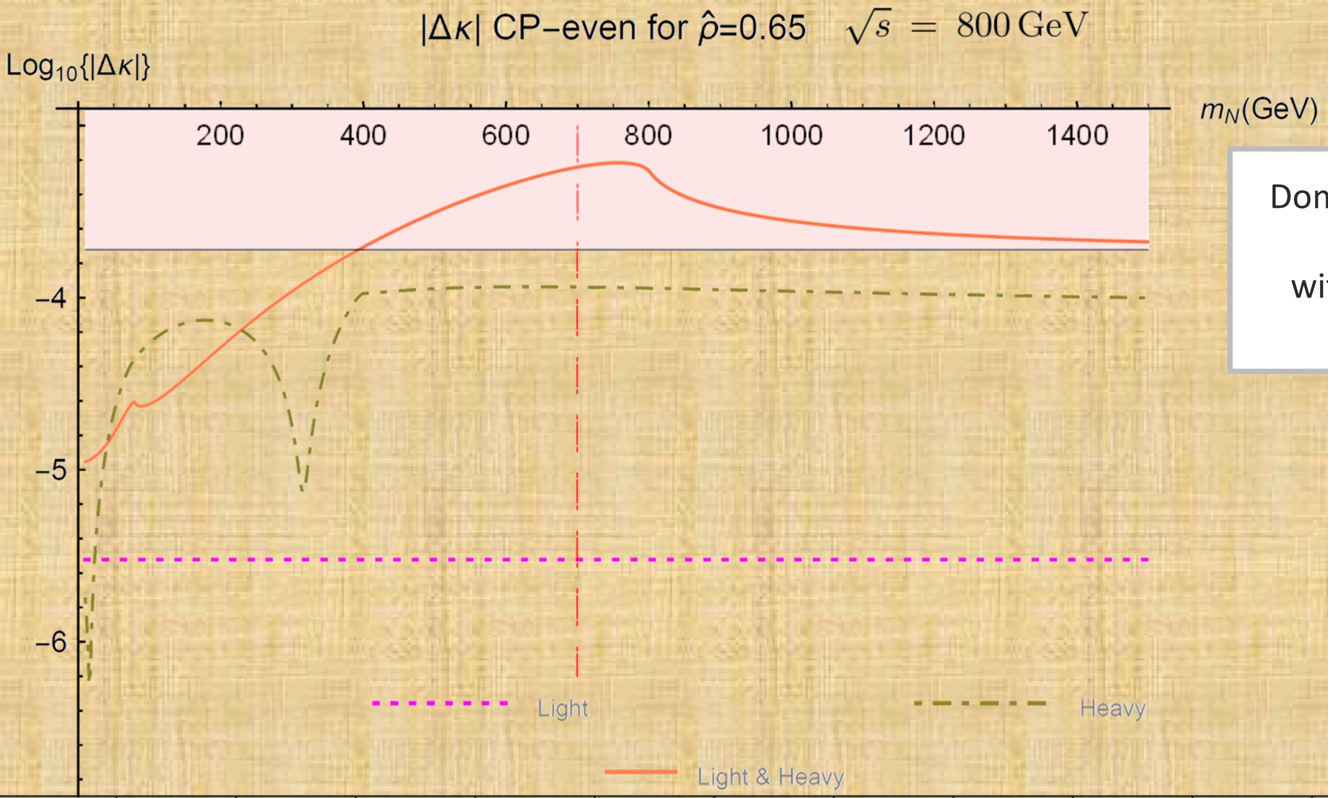

Dominant effect is produced by the diagrams with heavy- and light- virtual neutrinos.

CP-Odd contributions

Implementing the X-matrix texture

$$\Delta\tilde{\kappa} = 3\left(\tilde{\Omega} + \tilde{\mathcal{J}}\right) + \frac{2i\hat{\rho}^2 \sin 2\varphi}{\left(1+\hat{\rho}^2\right)^2} \sum_{\alpha} \Delta\tilde{\kappa}^{(3)}_{\alpha\nu N} \quad (17)$$

$$|\Delta\tilde{\kappa}| = 1.19 \times 10^{-3}$$

Summary and conclusions

- BSM physics effects on the WWZ with virtual Majorana neutrinos at one-loop level.

- SM W bosons on-shell and Z boson off-shell.

$\Delta\kappa$ ← CP-even + CP-odd effects → $\Delta\tilde{\kappa}$

ΔQ ←

- Ultraviolet finite.

- Analytical expressions in terms of three parameters: $m_N, s, \hat{\rho}$.

- Our study is carried out in the context of some future electron-positron collider, perhaps ILC. Sensitive to the CME of the collision.

- $\Delta\kappa$ → Contributions $\mathcal{O}(10^{-3})$
  → We could reach ILC sensitivity at CME of 800 GeV due to the effects from virtual heavy and light neutrinos.

- ΔQ → At least one order of magnitude below the estimated sensitivity for ILC.

- $\Delta\tilde{\kappa}$ → Contributions $\mathcal{O}(10^{-3})$.
  → One order of magnitude beyond expected ILC sensitivity.

Thanks!

[1] Pilaftsis, A. (1992). Radiatively induced neutrino masses and large Higgs-neutrino couplings in the Standard Model with Majorana fields. Zeitschrift für Physik C Particles and Fields, **55**(2), 275-282.

[2] J. G. Korner, A. Pilaftsis, and K. Schilcher, Leptonic CP asymmetries in flavor-changing H0 decays, Phys. Rev. D **47**, 1080 (1993).

[3] P. S. B. Dev and A. Pilaftsis, Minimal radiative neutrino mass mechanism for inverse seesaw models, Phys. Rev. D **86**, 113001 (2012).

[4] W. A. Bardeen, R. Gastmans, and B. Lautrup, Static quantities in Weinberg's model of weak and electromagnetic interactions,Nucl. Phys. B **46**, 319 (1972).

[5] H. Baer et al. (ILC Collaboration), The international linear collider technical design report-Volume 2: Physics, arXiv:1306.6352.

[6] A. M. Sirunyan et al. (CMS Collaboration), Search for heavy neutral leptons in events with three charged leptons in proton-proton collisions at ps = 13TeV, Phys. Rev. Lett. **120**, 221801 (2018).

[7] G. ’t Hooft and M. Veltman, Regularization and renormalization of gauge fields, Nucl. Phys. B **44**, 189 (1972).

[8] F. Jegerlehner, Facts of life with 5, Eur. Phys. J. C **18**, 67 (2001).

[9] G. Weiglein et al., Physics interplay of the LHC and the ILC, Phys. Rept. **426**, 47 (2006).

[10] L. Bian, J. Shu, and Y. Zhang, Prospects for triple gauge coupling measurements at future lepton colliders and the 14 TeV LHC, JHEP **09**, 206 (2015).

Thanks!

Properties

$$\mathcal{B}\mathcal{B}^\dagger = \mathbf{1}_3, \quad \text{or} \quad \sum_{j=1}^{6} \mathcal{B}_{\alpha j}\mathcal{B}^*_{\beta j} = \delta_{\alpha\beta},$$

$$\mathcal{B}^\dagger\mathcal{B} = \mathcal{C}, \quad \text{or} \quad \sum_{\alpha=e,\mu,\tau} \mathcal{B}^*_{\alpha j}\mathcal{B}_{\alpha k} = \mathcal{C}_{jk}$$

$$\mathcal{C}\mathcal{C}^\dagger = \mathcal{C}, \quad \text{or} \quad \sum_{i=1}^{6} \mathcal{C}_{ji}\mathcal{C}^*_{ki} = \mathcal{C}_{jk}$$