Virtual heavy neutrinos in low-energy observables

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Neutrinos beyond the Standard Model (SM)

SM gauge symmetry

Sterile right-handed neutrinos (3)

Lepton number violation

A renormalizable Lagrangian:

New-physics scale: $m_{\rm M} \sim \Lambda$

$$\mathcal{L}_{\rm NP} = \mathcal{L}_{\rm SM} - \Big(\underbrace{\frac{1}{2}\overline{\nu_R^{\rm c}}\, \overbrace{m_{\rm M}}\, \nu_R}_{\text{Majorana}} + \underbrace{\overline{L_L}\, \tilde{\phi}\, \mathcal{Y}^\nu \nu_R}_{\text{Dirac}} + {\rm H.c.} \Big)$$

Majorana

Dirac

Electroweak symmetry breaking

$$\Rightarrow m_{\mathrm{D}} = \frac{v}{\sqrt{2}}\mathcal{Y}^{\nu}$$

Then, the type 1 seesaw matrix:

$$\mathcal{L}_{\mathrm{SM}} - \frac{1}{2}\left(\overline{\nu_L} \;\; \overline{\nu_R^{\mathrm{c}}}\right)\underbrace{\begin{pmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}}^{\mathrm{T}} & m_{\mathrm{M}} \end{pmatrix}}\begin{pmatrix} \nu_L^{\mathrm{c}} \\ \nu_R \end{pmatrix} + \mathrm{H.c.} = \mathcal{L}_{\mathrm{SM}} - \sum_{j=1}^{3}\left(\frac{1}{2}m_{n_j}\overline{n_j}n_j + \frac{1}{2}m_{N_j}\overline{N_j}N_j\right)$$

Symmetric $\Longrightarrow$ Takagi diagonalization:

$$\mathcal{U}^{\mathrm{T}}\begin{pmatrix} 0 & m_{\mathrm{D}} \\ m_{\mathrm{D}}^{\mathrm{T}} & m_{\mathrm{M}} \end{pmatrix}\mathcal{U} = \begin{pmatrix} M_{\nu} & 0 \\ 0 & M_N \end{pmatrix}$$

Mass eigenspinor basis:

$$\begin{pmatrix} n_L \\ N_L \end{pmatrix} = \mathcal{U}^{\mathrm{T}}\begin{pmatrix} \nu_L \\ \nu_R^{\mathrm{c}} \end{pmatrix}$$

$$\begin{pmatrix} n_R \\ N_R \end{pmatrix} = \mathcal{U}^{\dagger}\begin{pmatrix} \nu_L^{\mathrm{c}} \\ \nu_R \end{pmatrix}$$

Majorana fields

$$n^{\mathrm{c}} = n$$

$$N^{\mathrm{c}} = N$$

Couplings with SM fields:

$$\mathcal{L}_{W\ell\nu} = \sum_{\chi=n,N} \frac{g}{\sqrt{2}} W_\rho^- \bar{\ell} \mathcal{B}_\chi \gamma^\rho P_L \chi + \text{H.c.}$$

$$\mathcal{L}_{Z\nu\nu} = -\sum_{\chi=n,N} \sum_{\chi'=n,N} \frac{g}{4c_{\text{w}}} Z_\rho \overline{\chi} \big(i\mathcal{C}^{\text{Im}}_{\chi\chi'} - \mathcal{C}^{\text{Re}}_{\chi\chi'} \gamma_5 \big) \gamma^\rho \chi'$$

$$\mathcal{L}_{h\nu\nu} = \sum_{\chi=n,N} \sum_{\chi'=n,N} \frac{g}{4m_W} h\overline{\chi} \big((M_\chi + M_{\chi'}) \mathcal{C}^{\text{Re}}_{\chi\chi'} - i\gamma_5 (M_\chi - M_{\chi'}) \mathcal{C}^{\text{Im}}_{\chi\chi'} \big) \chi'$$

Definitions:

$$\mathcal{B}_n = \left(\mathbf{1}_3 + \xi\xi^\dagger\right)^{-\frac{1}{2}} U_{\text{PMNS}}$$

$$\mathcal{B}_N = \xi\left(\mathbf{1}_3 + \xi^\dagger\xi\right)^{-\frac{1}{2}} V^*$$

$$\begin{pmatrix} \mathcal{B}_n^\dagger \\ \mathcal{B}_N^\dagger \end{pmatrix} \begin{pmatrix} \mathcal{B}_n & \mathcal{B}_N \end{pmatrix} = \begin{pmatrix} \mathcal{C}_{nn} & \mathcal{C}_{nN} \\ \mathcal{C}_{Nn} & \mathcal{C}_{NN} \end{pmatrix}$$

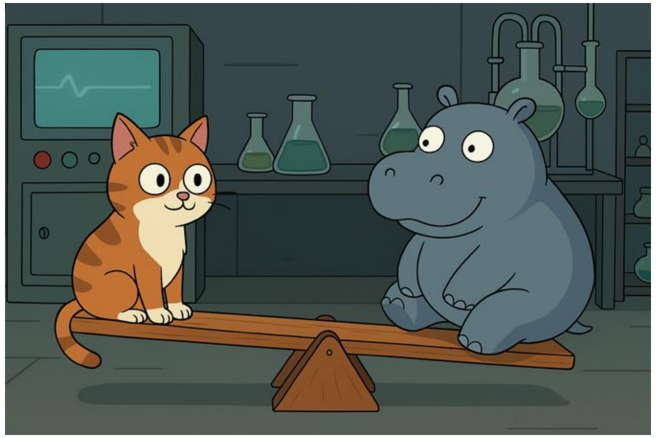
A usual approximation:

$\xi \simeq m_{\text{D}} m_{\text{M}}^{-1}$ as long as $\frac{v}{\Lambda}$ is small

Seesaw neutrino masses

Light neutrinos (observed): $M_n \sim \frac{v^2}{\Lambda}$

Heavy neutrinos (hypothetical): $M_N \sim \Lambda$



Sub-eV bounds on $M_n \Rightarrow \Lambda \sim 10^{13}\,\mathrm{GeV}$

Cannot be directly produced, suppressed virtual effects

Very difficult to probe 

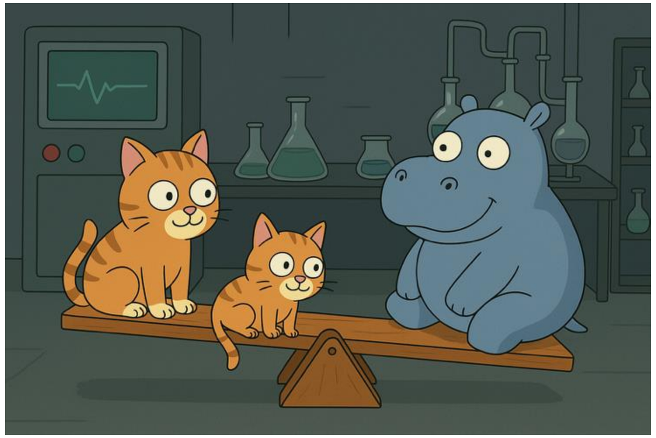
Seesaw variants

Inverse seesaw, linear seesaw, etc

$\Rightarrow$ Attenuation of seesaw relation

$\Rightarrow$ Smaller allowed values for Λ

$\Rightarrow$ New physics within current experimental sensitivity



We considered: a model of radiative masses[1]

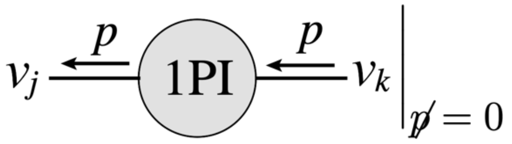
Condition:

$$\begin{pmatrix} 0 & m_{\rm D} \\ m_{\rm D}^{\rm T} & m_{\rm M} \end{pmatrix} \begin{pmatrix} \mathcal{U}_{11} \\ \mathcal{U}_{21} \end{pmatrix} = 0 \;\Rightarrow M_n = 0$$, at the tree level

Seesaw relation is broken

[1] A. Pilaftsis, Radiatively induced neutrino masses and large Higgs-neutrino couplings in the Standard Model with Majorana fields, Z. Phys. C **55**, 275 (1992)

But… radiative masses emerge



$$\Rightarrow \quad (M_n^{1\,\text{loop}})_{ij} = \sum_{k=1}^{3} \frac{g^2 m_{N_k}^3}{64 m_W^2 \pi^2} (\mathcal{C}_{nN})_{ik}(\mathcal{C}_{nN})_{jk}\left(\frac{m_h^2}{m_{N_k}^2-m_h^2}\log\left(\frac{m_{N_k}^2}{m_h^2}\right)+\frac{3m_Z^2}{m_{N_k}^2-m_Z^2}\log\left(\frac{m_{N_k}^2}{m_Z^2}\right)\right)$$

Gauge-independent mass[2]

UV-finite mass

} As long as tree-level light-neutrino masses vanish

New link between masses of heavy and light neutrinos:

Quasi-degenerate heavy-neutrino masses $\Rightarrow$ Light neutrino masses

Much smaller Λ values are allowed $\Rightarrow$ New physics within experimental sensitivity 

[2] I. García-Márquez, Dependencia de la norma en masas de neutrinos inducidas radiativamente (Master thesis).

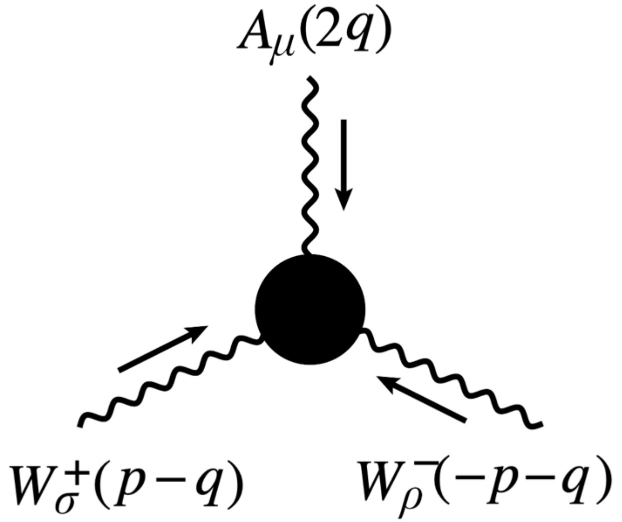
Trilinear gauge-boson couplings

The *WWγ* vertex

Lorentz-covariant *CP*-even parametrization[3]:

$$\Gamma^{\text{even}}_{\sigma\rho\mu} = ie\Big(g_1\big(2p_\mu g_{\sigma\rho} + 4(q_\rho g_{\sigma\mu} - q_\sigma g_{\rho\mu})\big) + \frac{4\Delta Q}{m_W^2}p_\mu\Big(q_\sigma q_\rho - \frac{q^2}{2}g_{\sigma\rho}\Big) + 2\Delta\kappa(q_\rho g_{\sigma\mu} - q_\sigma g_{\rho\mu})\Big)$$

$\Rightarrow$ Contributions to anomalous couplings (ACs) $\Delta\kappa_\gamma^{\text{NP}}$ and $\Delta Q_\gamma^{\text{NP}}$



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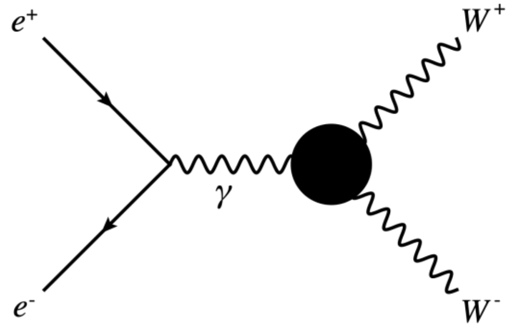
The *WWγ* vertex at the ILC[4]



AC parameters

ξ matrix "size": $\hat{\rho} = 0.58, 0.65$

Heavy-neutrino mass: $m_N \gtrsim 700\,\text{GeV}$ (CMS paper)[5]

Center of mass (CM) energy: $\sqrt{s} = 500\,\text{GeV}, 800\,\text{GeV}$

[3] W.A. Bardeen, R. Gastmans, and B. Lautrup, Static quantities in Weinberg's model of weak and electromagnetic interactions, Nucl. Phys. **B46**, 319 (1972).

[4] H. Baer *et al.*, The international linear collider technical report- Volume 2: Physics, arXiv:1306.6352.

[5] A. M. Sirunyan *et al.*, Search for Heavy Neutral Leptons in Events with Three Charged Leptons in Proton-Proton Collisions at √s = 13 TeV, Phys. Rev. Lett. **120**, 221801 (2018).

Our estimations[6]

GeV-sized heavy-neutrino masses

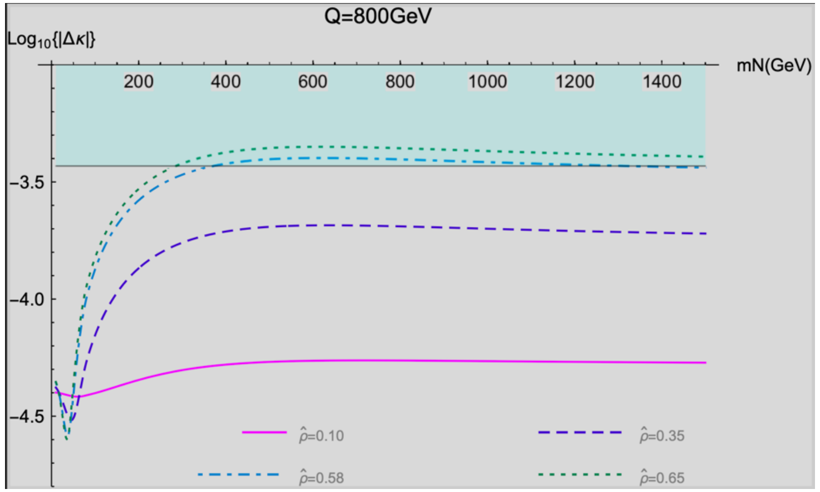
$\Delta\kappa_\gamma^{\mathrm{NP}}$ might be observed at ILC

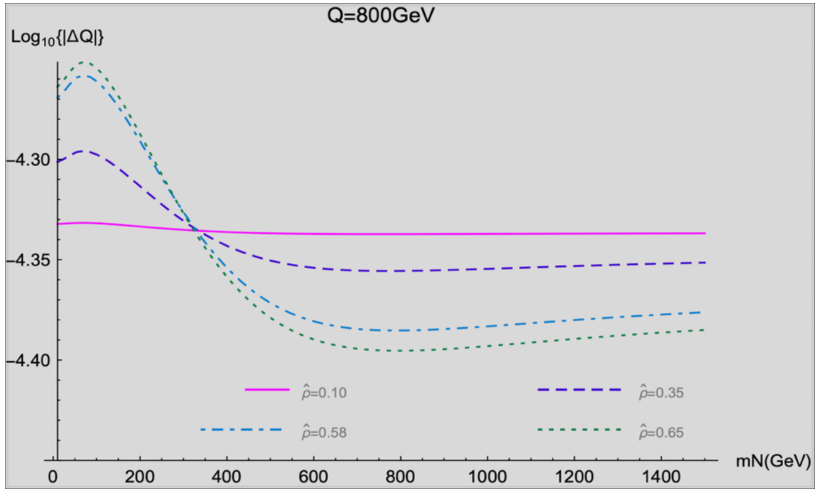
At a CM energy of 800 GeV

$\Delta Q_\gamma^{\mathrm{NP}}$ well below ILC sensitivity

Smaller by about 1 order of magnitude

Conclusion: contributions barely within ILC reach at a CM energy of 800 GeV





[6] E. Martínez, J. Montaño-Domínguez, H. Novales-Sánchez, and M. Salinas, New physics in $WW\gamma$ at one loop via Majorana neutrinos, Phys. Rev. D **107**, 035025 (2023).

Trilinear gauge-boson couplings

The *WWZ* vertex

For details see Monica Salinas' talk (afternoon)

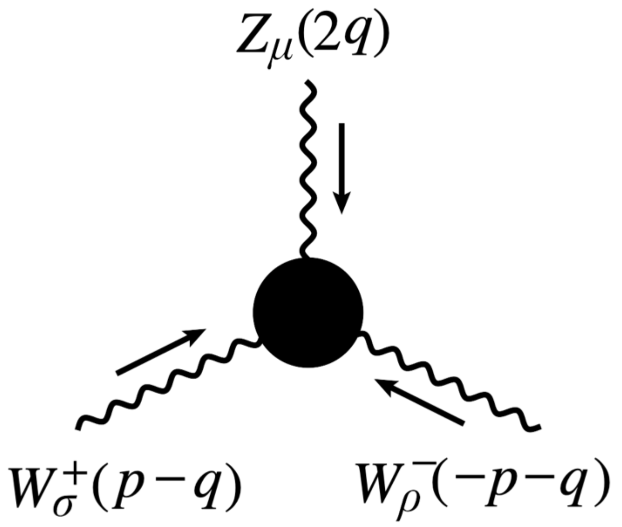
CP-even parametrization:

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

CP-odd parametrization:

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

$\Longrightarrow$ Contributions to ACs $\Delta\kappa_Z^{\text{NP}}$, $\Delta\tilde{\kappa}_Z^{\text{NP}}$, ΔQ_Z^{NP}, and $\Delta\tilde{Q}_Z^{\text{NP}}$



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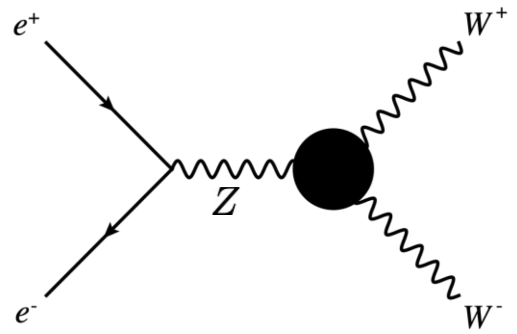
The *WWZ* vertex at the ILC



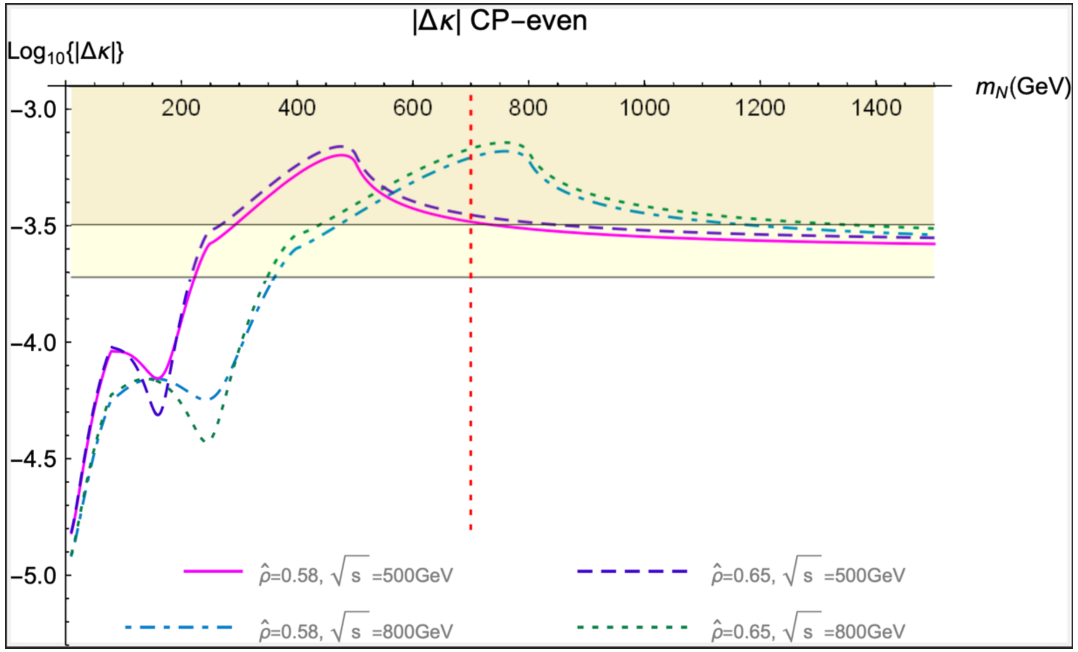
Our estimations

CP-even ACs

GeV-sized heavy-neutrino masses

$\Delta\kappa_Z^{\rm NP}$ might be observed at ILC at 500 GeV, 800 GeV

$\Delta Q_Z^{\rm NP}$ clearly out of the reach of ILC



CP-odd ACs

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

Dominant contribution $\sim 10^{-3}$ $\Longrightarrow$ Below ILC projected sensitivity by ~1 order of magnitude

Conclusion: *CP*-even contributions within ILC projected sensitivity

[7] H. Novales-Sánchez, M. Salinas and H. Vázquez-Castro, One-loop contributions to *WWZ* from a seesaw variant with radiatively light neutrino masses, Phys. Rev. D **110**, 035025 (2024).

Trilinear gauge-boson couplings

The *ZZZ** vertex

Lorentz-covariant parametrization[8]:

$$\Gamma^{ZZZ^*}_{\alpha\beta\mu} = \underbrace{\frac{i(s-m_Z^2)}{m_Z^2}}_{\text{Vanishes on shell}} \left(\underbrace{f_4\,(p_\alpha g_{\beta\mu} + p_\beta g_{\alpha\mu})}_{CP\text{-odd}} - \underbrace{f_5\,\epsilon_{\mu\alpha\beta\rho}\,(q_1^\rho - q_2^\rho)}_{CP\text{-even}} \right)$$

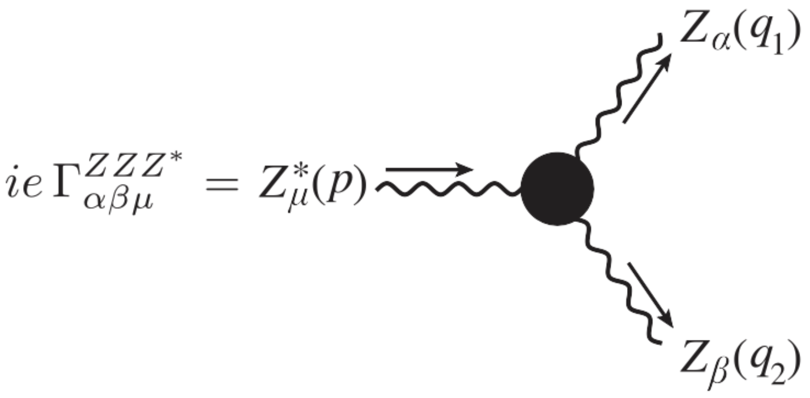
$\Longrightarrow$ Contributions to ACs f_4 and f_5

AC parameters

ξ matrix "size": $\hat{\rho} = 0.65$

Heavy-neutrino mass: $m_N \gtrsim 700\,\mathrm{GeV}$ (CMS paper)

Center of mass (CM) energy: $\sqrt{s} = 500\,\mathrm{GeV}$



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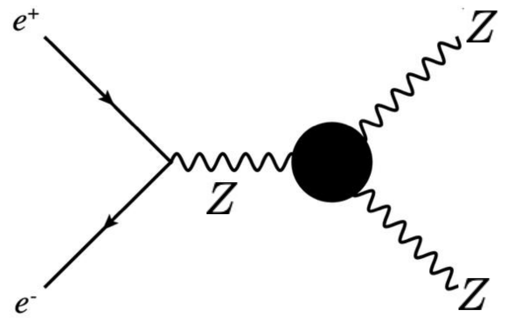
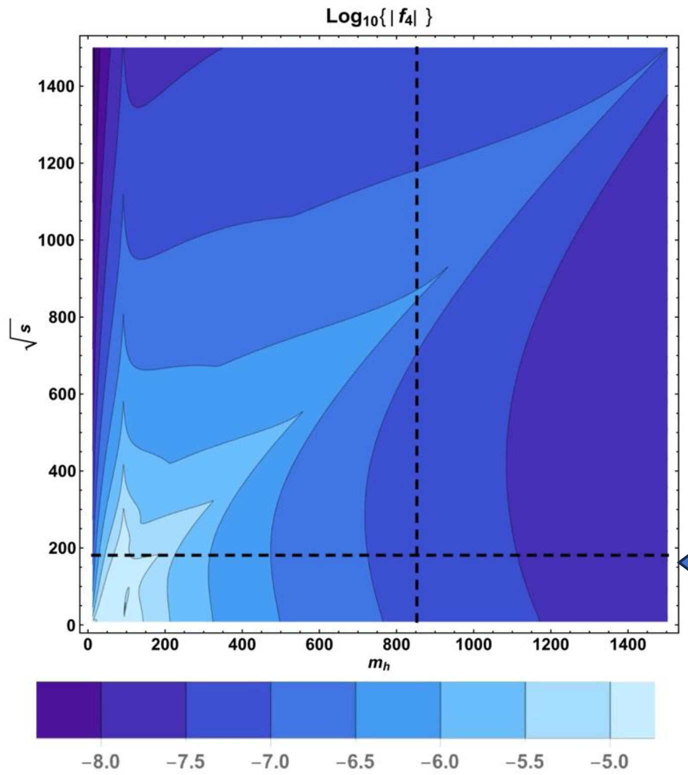
The *ZZZ** vertex at the ILC



[8]G. J. Gounaris, J. Layssac, and F. M. Renard, New and standard physics contributions to anomalous Z and γ self couplings, Phys. Rev. D **62**, 073013 (2000).

Our estimations[9]

***CP*-odd**

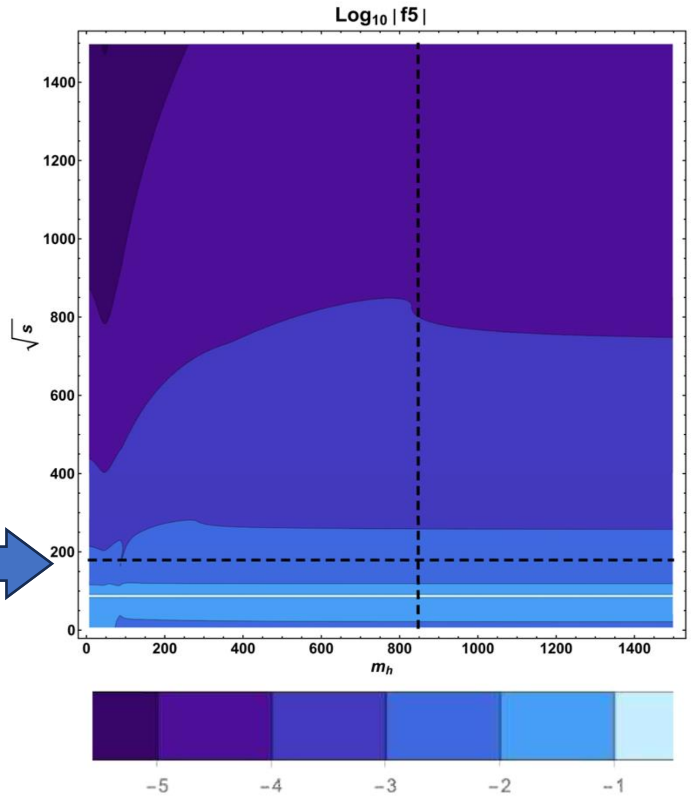


As large as $\sim 10^{-7}$ in the relevant region

Far from ILC sensitivity: $\sim 10^{-4}$

ZZ production threshold

***CP*-even**



As large as $\sim 10^{-3}$ in the relevant region

Can be probed by ILC

Conclusion: CP-even effects to be tested at the ILC

[9]H. Novales-Sánchez and M. Salinas, Majorana neutrinos in the triple gauge boson coupling *ZZZ**, Phys. Rev. D **108**, 075032 (2023).

A gauge-Higgs interaction

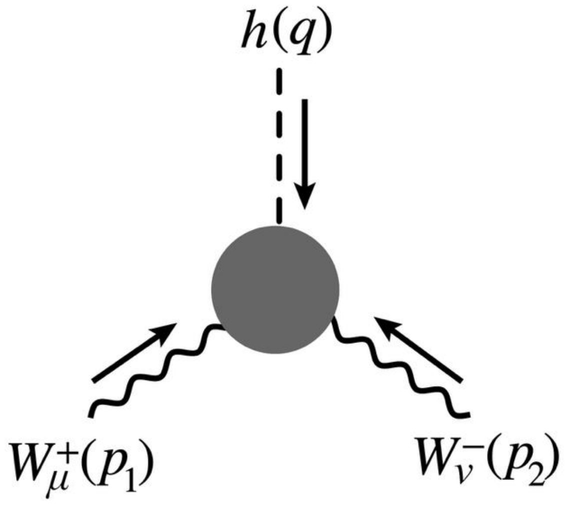
CP-even parametrization[10]:

$$\Gamma^{\text{even}}_{\mu\nu} = g\Big(m_W \lambda_1 g_{\mu\nu} + \frac{\lambda_2}{m_W}\left(p_{1\nu}p_{2\mu} - g_{\mu\nu}\, p_1\cdot p_2\right) - \frac{\lambda_3}{m_W}\left(p_{1\mu}p_{1\nu} + p_{2\mu}p_{2\nu} - g_{\mu\nu}p_1^2 - g_{\mu\nu}p_2^2\right) - \frac{\lambda_4}{m_W^3}\Big(p_{1\mu}p_{1\nu}\left(p_1^2 + p_1\cdot p_2\right) + p_{2\mu}p_{2\nu}\left(p_2^2 + p_1\cdot p_2\right) - g_{\mu\nu}\left(\left(p_2^2 + p_1\cdot p_2\right)^2 + \left(p_1^2 + p_1\cdot p_2\right)^2\right) + p_{1\nu}p_{2\mu}(p_1+p_2)^2\Big) + \frac{\lambda_5}{m_W^3}\Big(p_2^2\, p_{1\mu}p_{1\nu} + p_1^2\, p_{2\mu}p_{2\nu} - (p_1\cdot p_2)p_{1\mu}p_{2\nu} - p_1^2p_2^2 g_{\mu\nu} - \left(p_1^2 + p_1\cdot p_2 + p_2^2\right)\left(p_1\cdot p_2\, g_{\mu\nu} - p_{1\nu}p_{2\mu}\right)\Big)\Big)$$

CP-odd parametrization:

$$\Gamma^{\text{odd}}_{\mu\nu} = g\left(\frac{\tilde\lambda_1}{m_W}\,\epsilon_{\mu\nu\alpha\beta}\, p_2^\alpha p_1^\beta + \frac{i\tilde\lambda_2}{m_W}\left(g_{\mu\nu}p_2^2 - p_{2\mu}p_{2\nu} - g_{\mu\nu}p_1^2 + p_{1\mu}p_{1\nu}\right)\right)$$

The *WWh* vertex



We find: $\lambda_2^{\text{NP}} = 0$

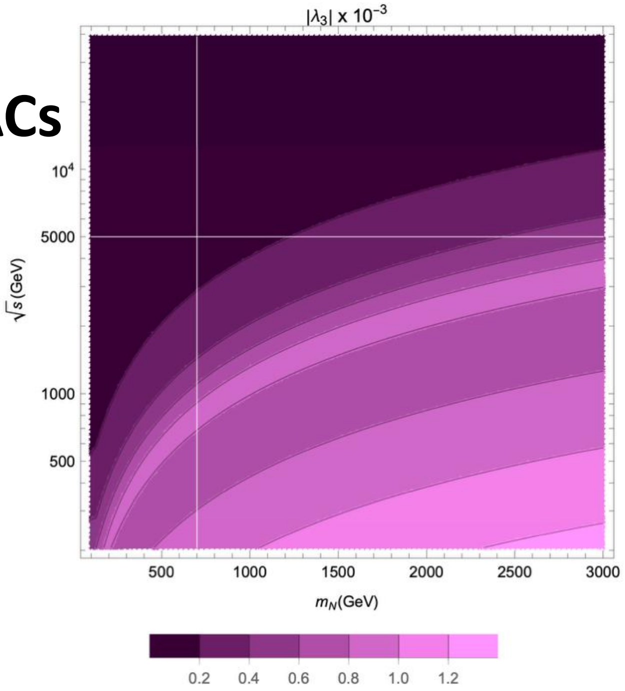
$\lambda_4^{\text{NP}} = \lambda_5^{\text{NP}}$

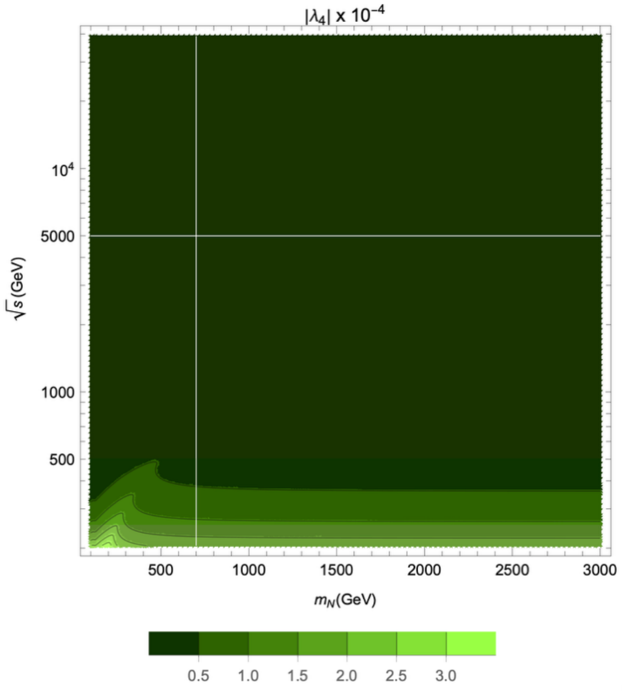
$\Longrightarrow$ Contributions to ACs:

$\lambda_3^{\text{NP}},\ \lambda_4^{\text{NP}},\ \tilde\lambda_1^{\text{NP}},\ \tilde\lambda_2^{\text{NP}}$

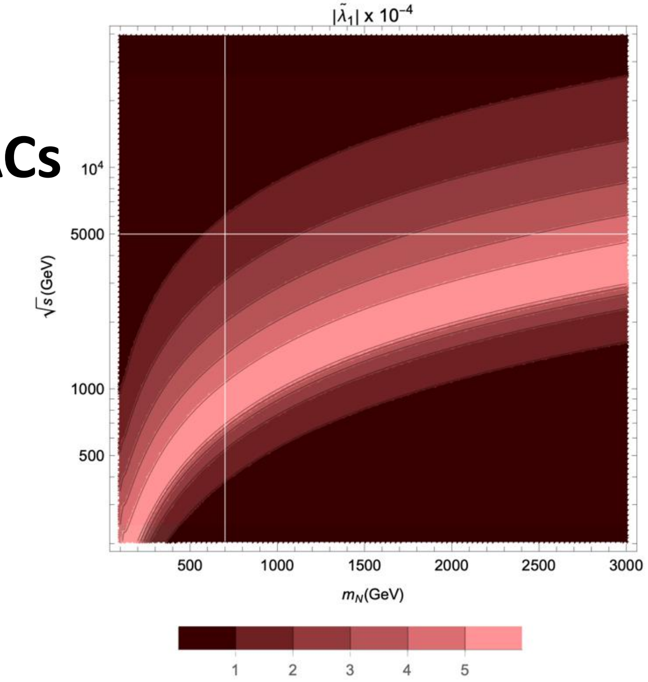
[10] G. F. Giudice, C. Grojean, A. Pomarol, and R. Rattazzi, The strongly-interacting light Higgs, JHEP 06, 045 (2007).

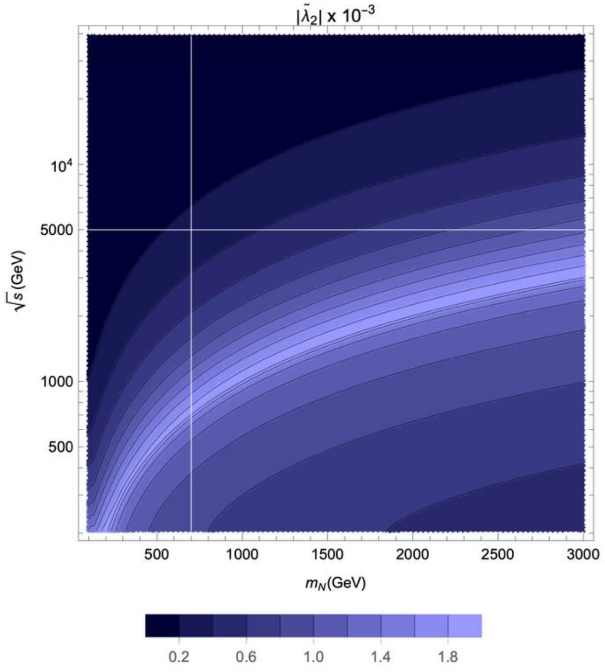
***CP*-even ACs**



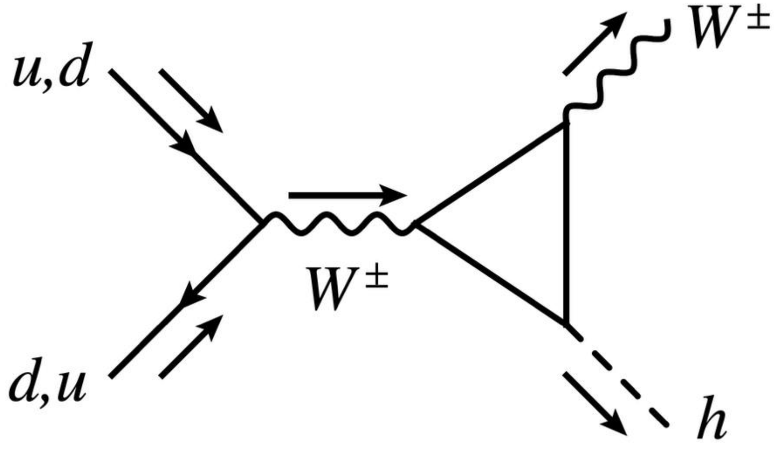


***CP*-odd ACs**





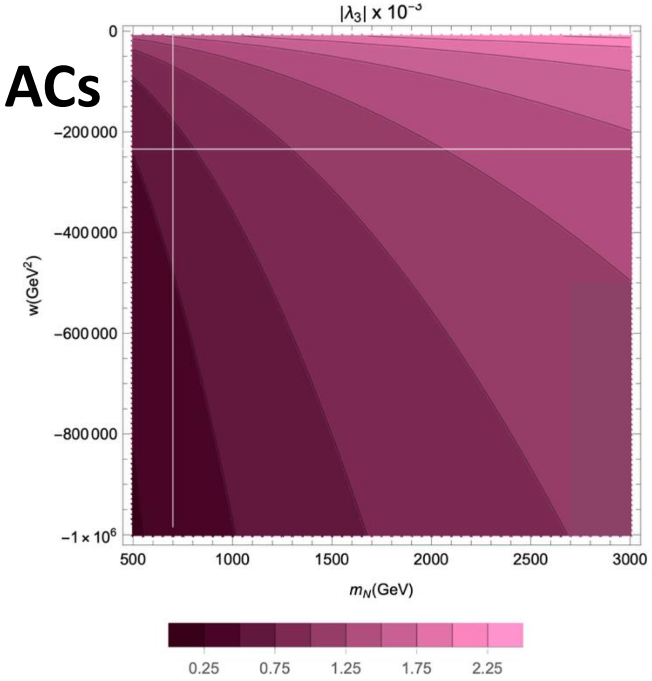
***Wh* production some hadron colliders**

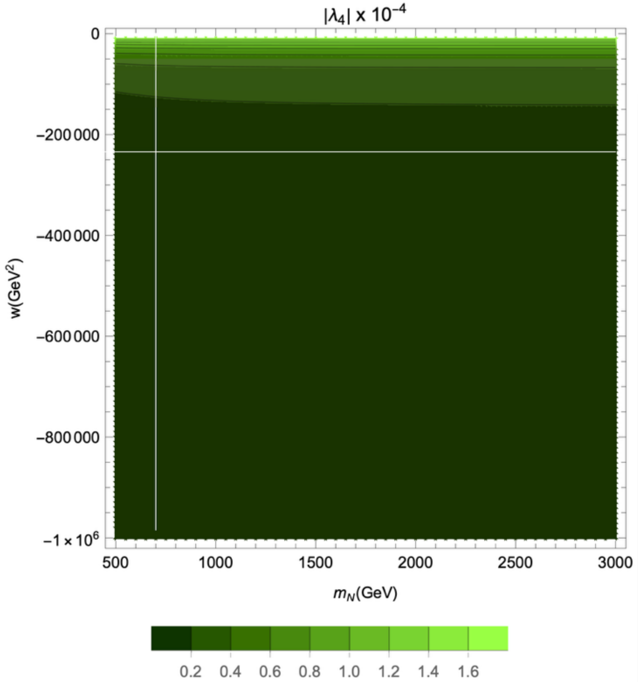


AC	CP	$\lambda^{\text{NP}}_{\text{max}}$	$\lambda^{\text{curr}}_{\text{exp}}$	$\lambda^{\text{NP}}_{\text{fut}}$
λ_3^{NP}	Even	10^{-3}	10^{-2} (LHC+LEP)	10^{-3} (HL-LHC)
λ_4^{NP}	Even	10^{-4}	NA	NA
$\tilde{\lambda}_1^{\text{NP}}$	Odd	10^{-4}	10^{-1} (LHC)	10^{-2} (CLIC)
$\tilde{\lambda}_2^{\text{NP}}$	Odd	10^{-3}	NA	NA

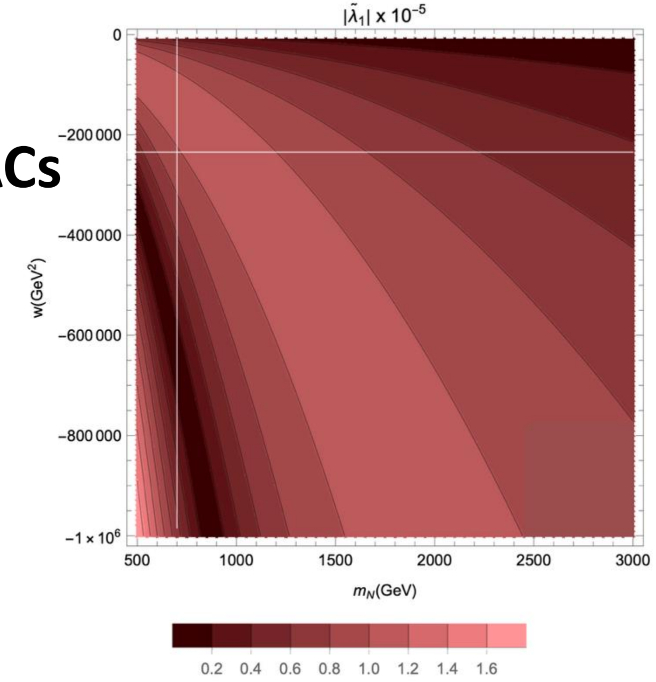
[11]H. Novales-Sánchez, E. Ramírez, M. Salinas, and H. Vázquez-Castro, *WWh* anomalous couplings at one loop from a seesaw variant of radiatively-induced neutrino masses, arXiv:2507.05574.

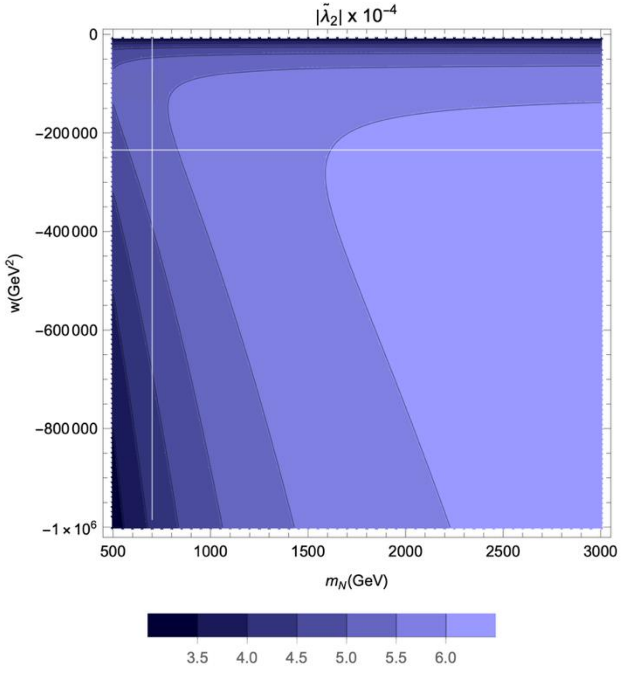
CP-even ACs



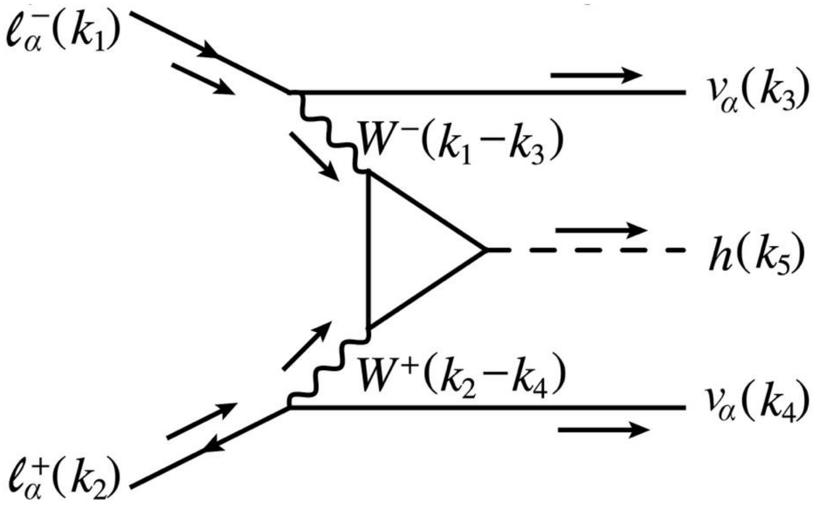


CP-odd ACs





Higgs production by vector boson fusion

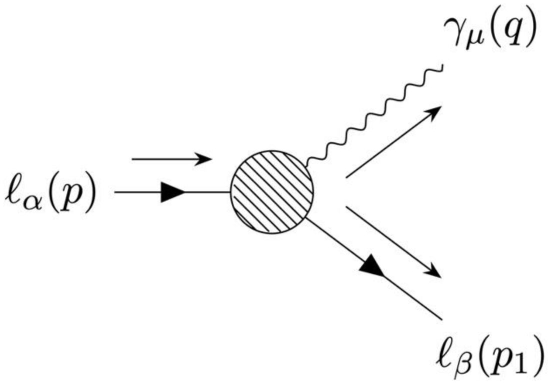


AC	CP	$\lambda_{\rm max}^{\rm NP}$	$\lambda_{\rm exp}^{\rm curr}$	$\lambda_{\rm fut}^{\rm NP}$
$\lambda_3^{\rm NP}$	Even	10^{-3}	10^{-2} (LHC+LEP)	10^{-3} (HL-LHC)
$\lambda_4^{\rm NP}$	Even	10^{-4}	NA	NA
$\tilde{\lambda}_1^{\rm NP}$	Odd	10^{-5}	10^{-1} (LHC)	10^{-2} (CLIC)
$\tilde{\lambda}_2^{\rm NP}$	Odd	10^{-4}	NA	NA

[11]H. Novales-Sánchez, E. Ramírez, M. Salinas, and H. Vázquez-Castro, *WWh* anomalous couplings at one loop from a seesaw variant of radiatively-induced neutrino masses, arXiv:2507.05574.

Lepton flavor violation

The decay $\ell_\alpha \to \ell_\beta \gamma$



$$\Rightarrow \Gamma(\ell_\alpha \to \ell_\beta \gamma) = \frac{\alpha_{\mathrm{w}} \left(m_\alpha^2 - m_\beta^2\right)^3}{2 m_\alpha^3} \Big(\underbrace{\left|F_1^{\alpha\beta}\right|^2}_{\text{Magnetic dipole}} + \underbrace{\left|F_2^{\alpha\beta}\right|^2}_{\text{Electric dipole}} \Big)$$

We considered different ξ textures

An interesting limit

$$\mathcal{L}_{W\ell n} = \frac{g}{\sqrt{2}} W_\rho^- \bar{\ell} (\mathbf{1}_3 - \underbrace{\eta}_{\text{Non-unitarity matrix}}) U_{\mathrm{PMNS}} \gamma^\rho P_L n + \mathrm{H.c.}$$

Limit as $m_n \to 0$

Very large m_N

$$\Rightarrow \Gamma(\ell_\alpha \to \ell_\beta \gamma) = \kappa_{\alpha\beta} \underbrace{\left|\eta_{\alpha\beta}\right|^2}$$

Decay rate determined by non-unitarity matrix

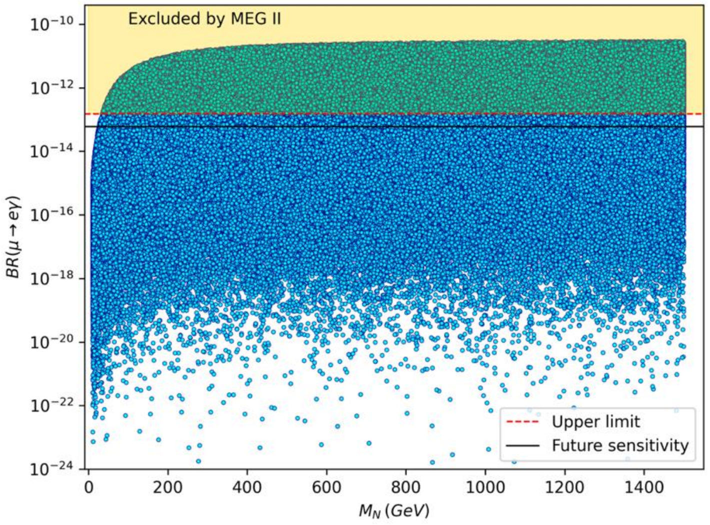
$\Rightarrow$ Upper bounds:

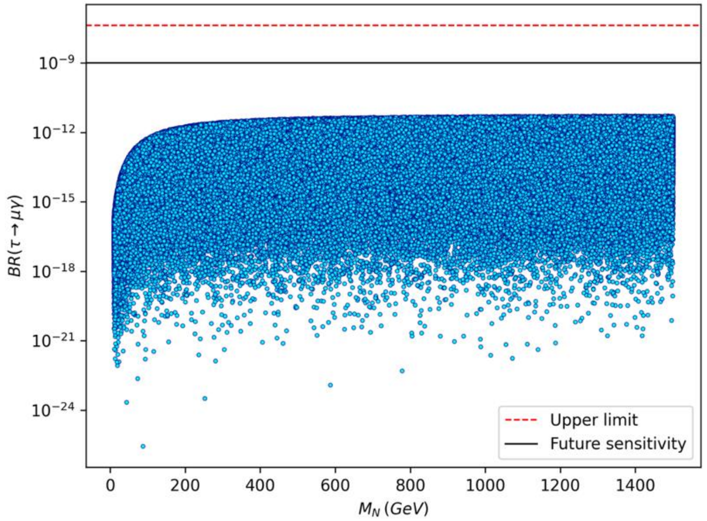
$$\left|\eta_{\mu e}\right| \lesssim 6.6 \times 10^{-6}$$

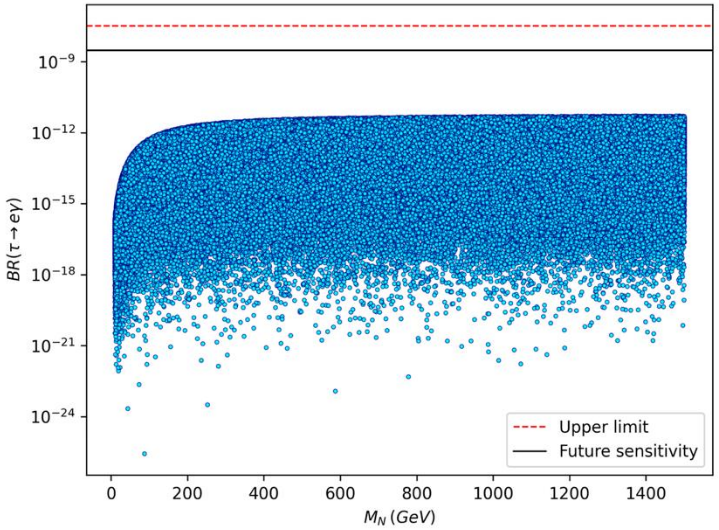
$$\left|\eta_{\tau e}\right| \lesssim 7.5 \times 10^{-3}$$

$$\left|\eta_{\tau \mu}\right| \lesssim 8.5 \times 10^{-3}$$

Our estimations







Can be reached by current experimental sensitivity

Far from future experimental sensitivity

Non-unitarity:

Parameter	η_{ee}	$\eta_{\mu\mu}$	$\eta_{\tau\tau}$	$\lvert\eta_{\mu e}\rvert$	$\lvert\eta_{\tau e}\rvert$	$\lvert\eta_{\tau\mu}\rvert$
Bound	10^{-5}	10^{-5}	10^{-5}	10^{-6}	10^{-6}	10^{-6}

[12]E. Ramírez, H. Novales-Sánchez, H. Vázquez-Castro, M. Salinas, Effects of Majorana neutrinos on charged Lepton Flavor Violation decays from a seesaw variant with radiatively induced light neutrino masses, DOI:10.1088/1361-6471/ae0c24 (accepted for publication by J. Phys. G).

Thank you!!!