Phenomenology of Scotogenic 3-loop Neutrino Mass Models

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Based on **J. High Energ. Phys. 03 (2023) 035 arXiv:2212.06852 [hep-ph]** and **J. High Energ. Phys. 05 (2024) 035 arXiv:2312.14105 [hep-ph]**, with A. Abada, N. Bernal, A. Cárcamo, S. Kovalenko and T. Toma

20 July 2024

Seesaw Mechanism

Weinberg Operator: $$\mathcal{O}_W = \frac{c}{\Lambda} LLHH$$ [Weinberg, 1979]

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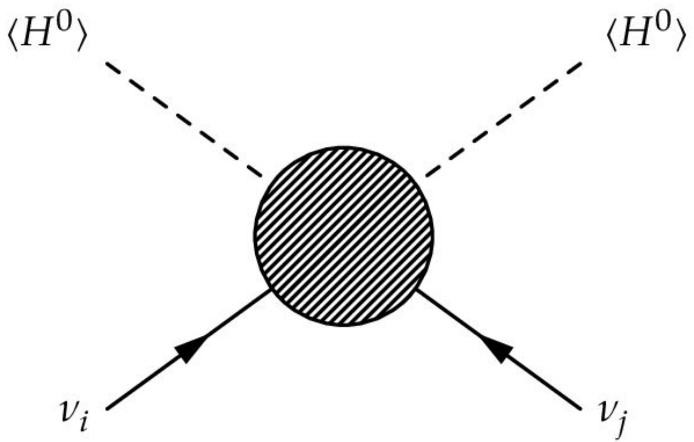
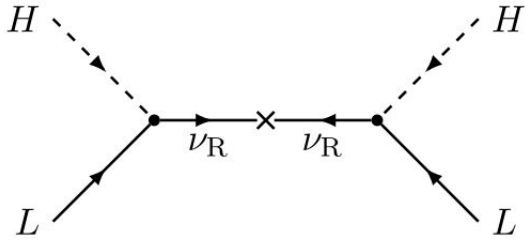


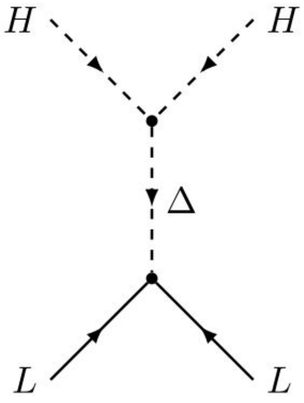
Seesaw Mechanism

Weinberg Operator: $$\mathcal{O}_W = \frac{c}{\Lambda} LLHH$$ [Weinberg, 1979]

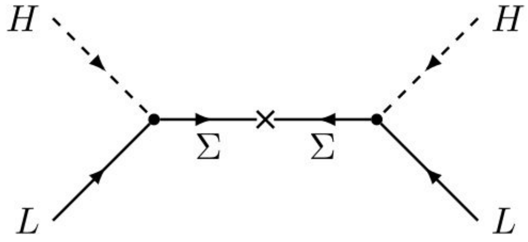
Right-handed singlet:
(type-I seesaw)



Scalar triplet:
(type-II seesaw)



Fermion triplet:
(type-III seesaw)



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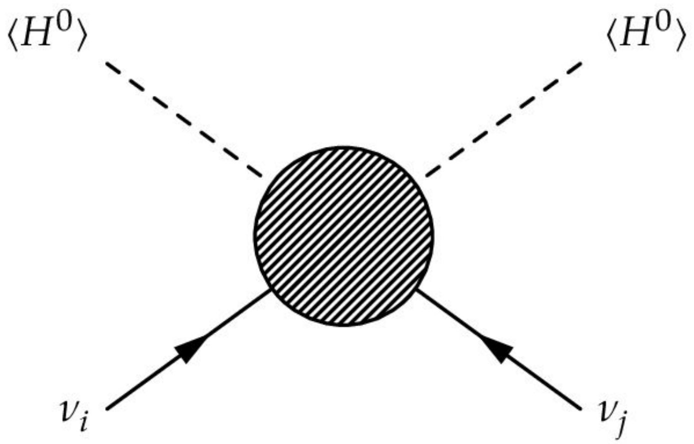
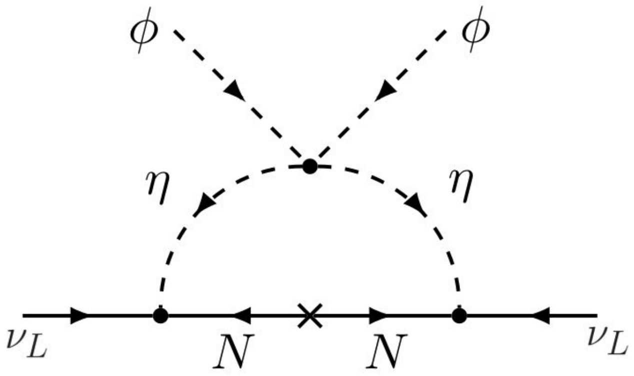


Radiative Seesaw Mechanism

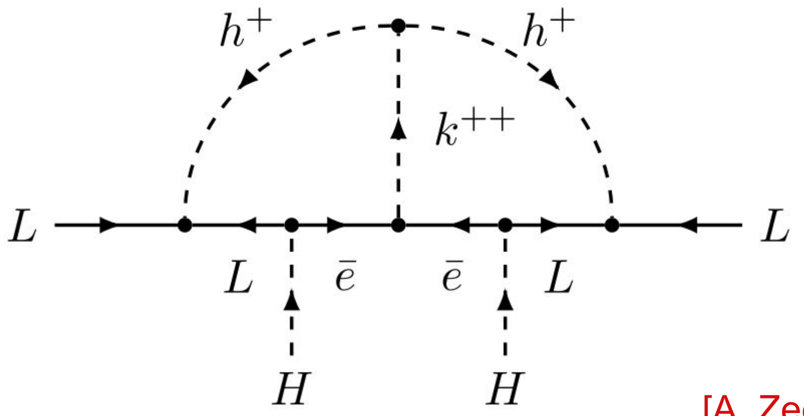
Weinberg Operator: $$\mathcal{O}_W = \frac{c}{\Lambda} LLHH$$ [Weinberg, 1979]

Scotogenic Model (1-loop)



[Ma, 2006]

Zee-Babu Model (2-loop)



[A. Zee, 1986]

[K. Babu, 1988]

Scotogenic Model

[Ma, 2006]

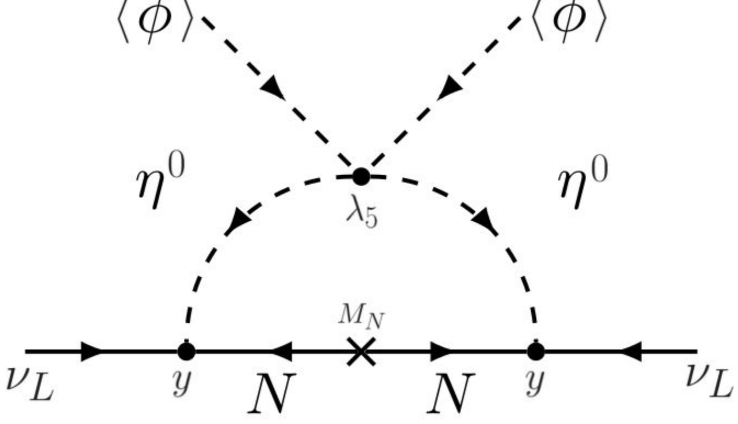
	$SU(2)_L$	$U(1)_Y$	Z_2
η	$\mathbf{2}$	$\frac{1}{2}$	-
N_R	$\mathbf{1}$	0	-

Lepton Sector

$$\mathcal{L} \supset -\frac{m_N}{2}\overline{N_R^c}N_R - y\overline{L}\eta N_R$$

Scalar Sector

$$V \supset \frac{\lambda_5}{2}\left[(\phi^\dagger\eta)^2 + (\eta^\dagger\phi)^2\right]$$



$$m_\nu \simeq \frac{\lambda_5 v^2}{32\pi^2} f_{\rm loop} y^T M_N^{-1} y$$

Scotogenic Model

- The scotogenic model accounts for neutrino masses and dark matter with a very simple and economic setup
- However, λ5 has to be very small if the Yukawa couplings are “natural” (or vice-versa

$$\lambda_5 \sim 5 \times 10^{-8} \left(\frac{m_\nu}{0.1 \text{ eV}}\right) \left(\frac{m_N}{1 \text{ TeV}}\right) \left(\frac{0.1}{y}\right)^2$$

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- This motivates us to go for higher loops. At n-loop order, neutrino masses are typically given by:

$$m_\nu \sim C \left(\frac{1}{16\pi^2}\right)^n \frac{v^2}{\Lambda}$$

3-loop Scotogenic Model

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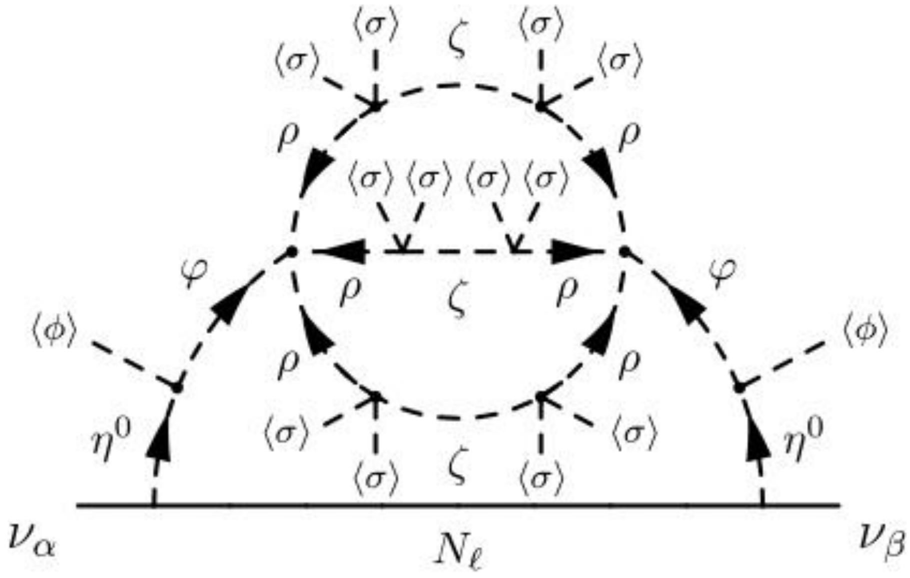

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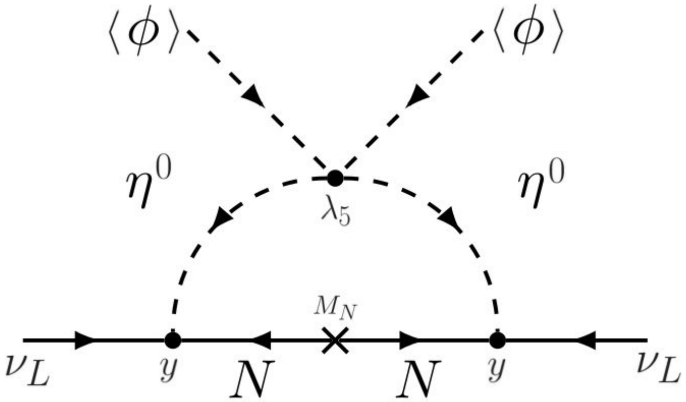
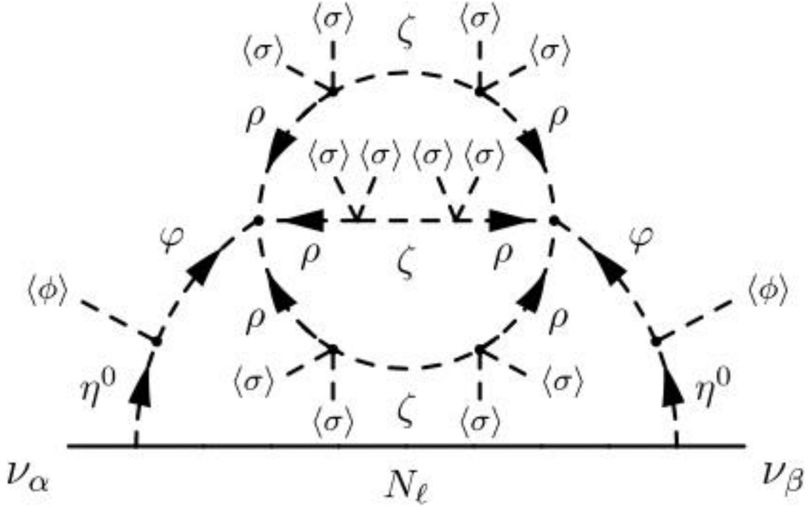
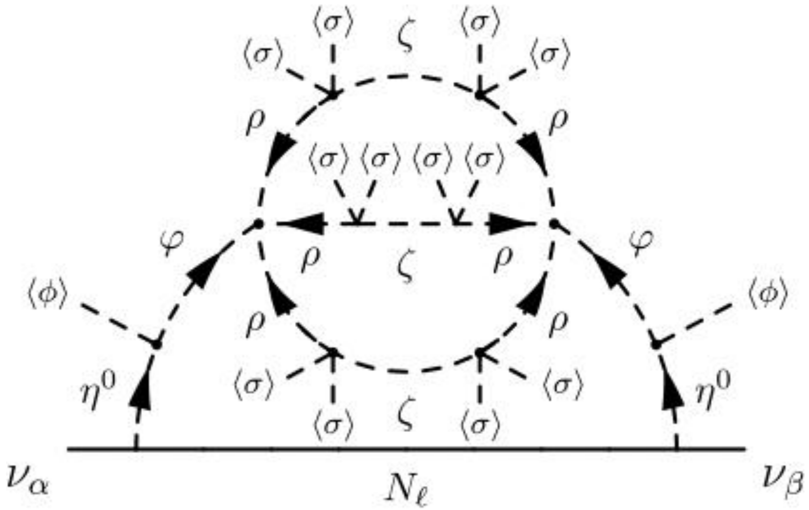




3-loop Scotogenic Model

Field	N_{R_k}	η	φ	ρ	ζ	σ
$SU(2)_L$	$\mathbf{1}$	$\mathbf{2}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$	$\mathbf{1}$
$U(1)_Y$	0	$\frac{1}{2}$	0	0	0	0
$U(1)'$	0	3	3	-1	0	$\frac{1}{2}$
$\mathbb{Z}_2$	-1	-1	-1	-1	-1	1



$$\mathcal{L} \supset -\frac{m_N}{2}\overline{N_R^c}N_R - y\overline{L}\eta N_R - A\left[(\eta^\dagger\phi)\varphi + h.c.\right] - \lambda_{14}(\varphi\rho^3 + h.c.) - \lambda_{15}(\rho\zeta\sigma^2 + h.c.)$$

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3-loop Scotogenic Model

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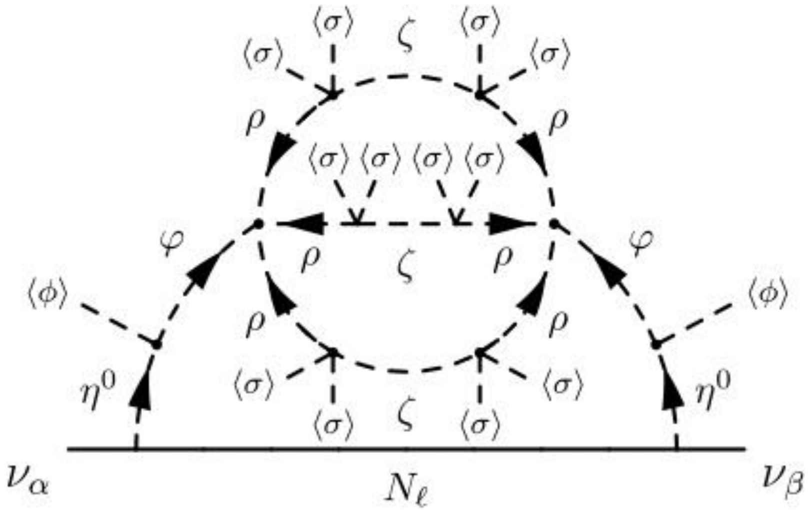
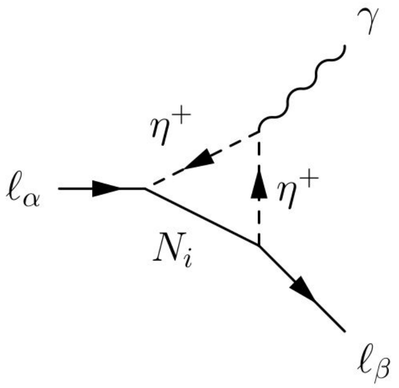
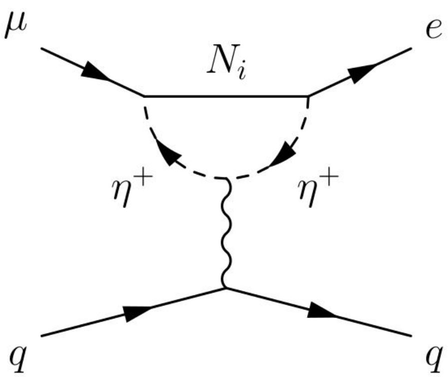
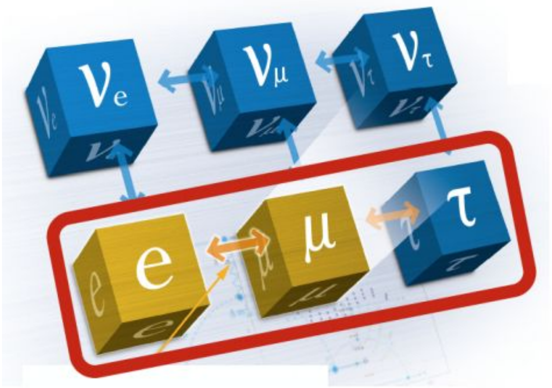


$$m_\nu \simeq \frac{\lambda_{14}^2 A^2 v^2}{(16\pi^2)^3} g_{\rm loop} y^T M^{-1} y$$

Charged Lepton Flavor Violation







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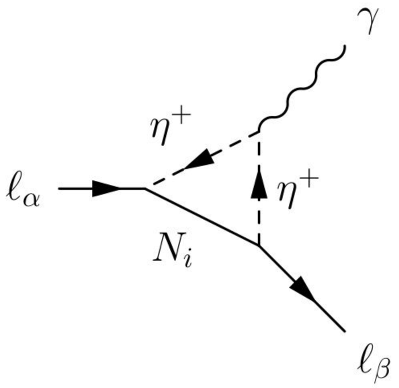

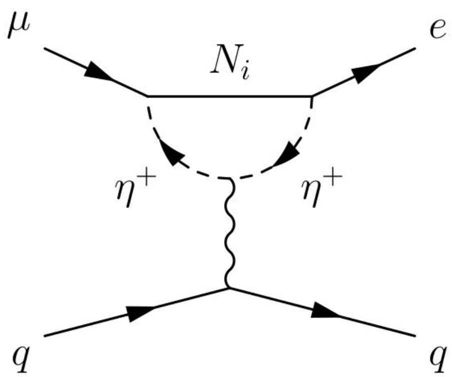

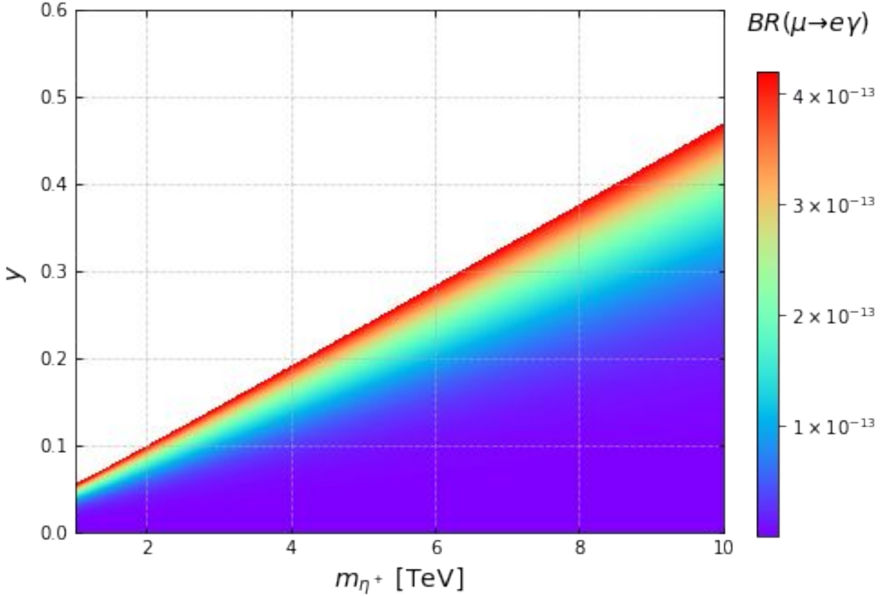

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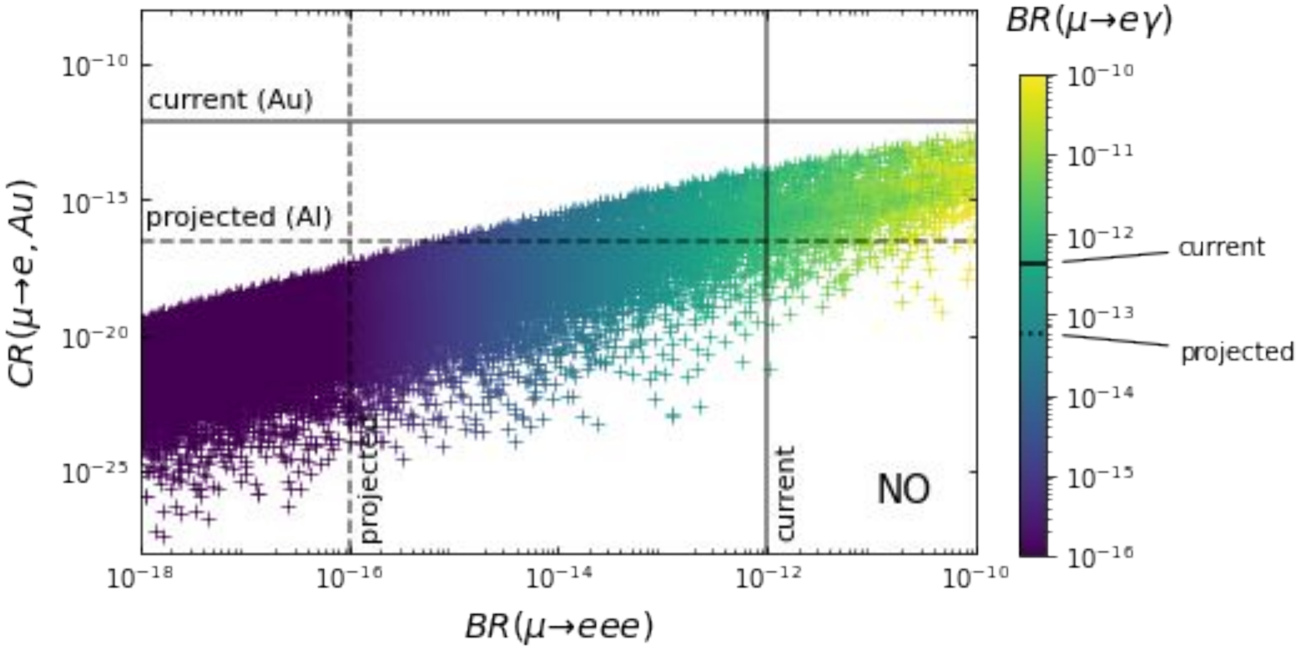

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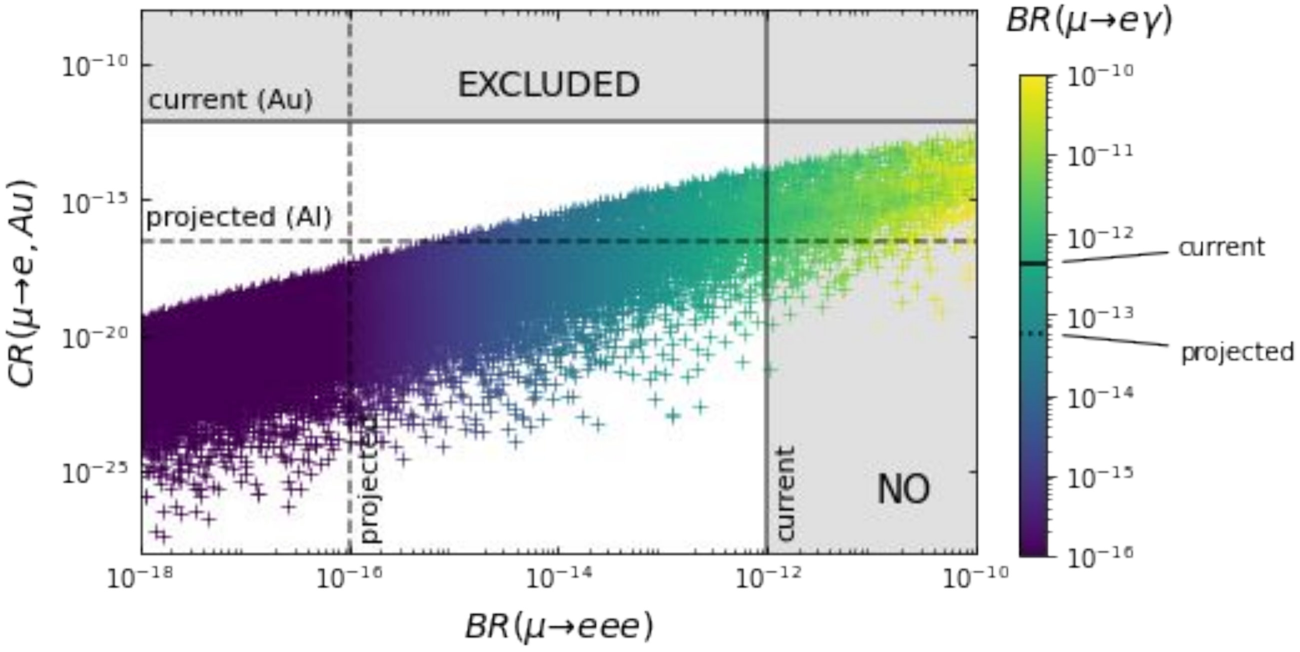

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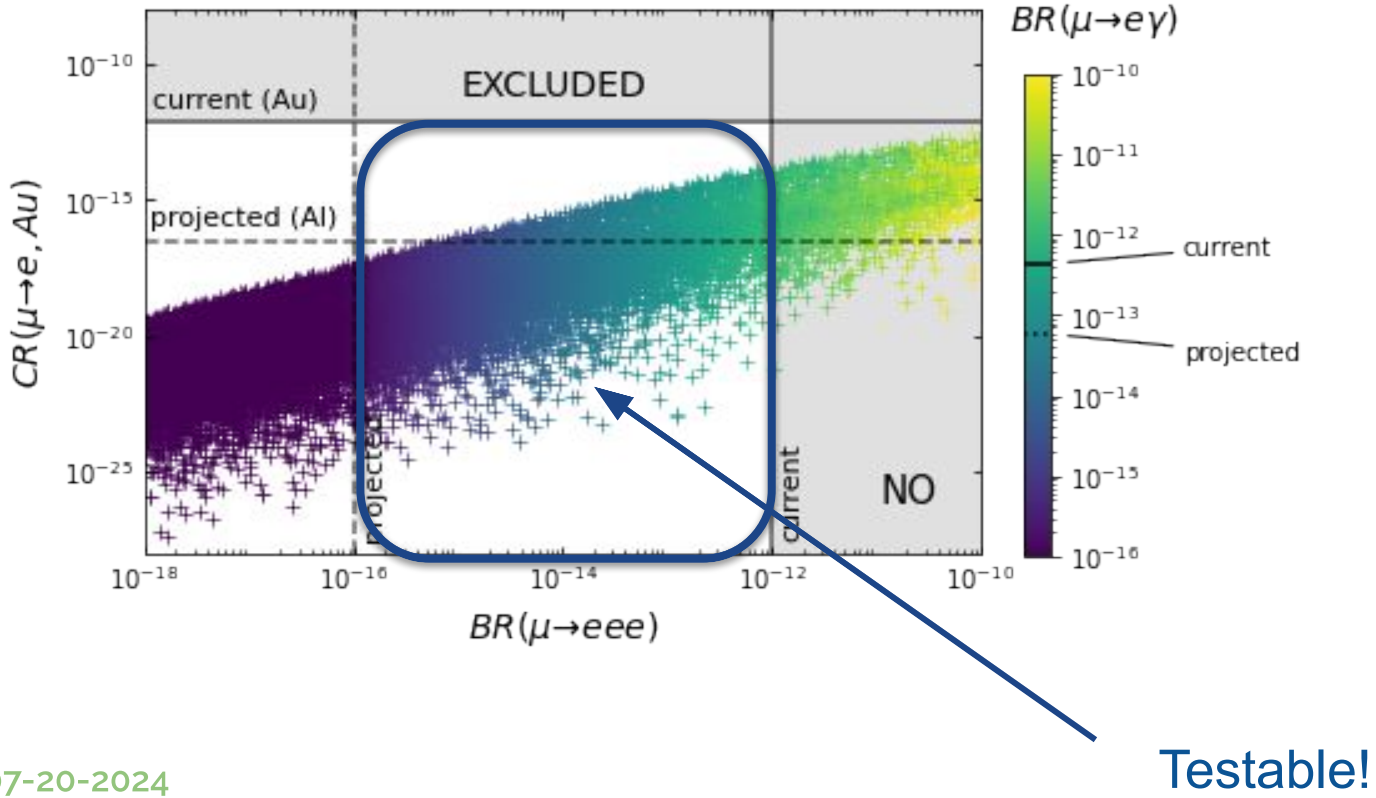
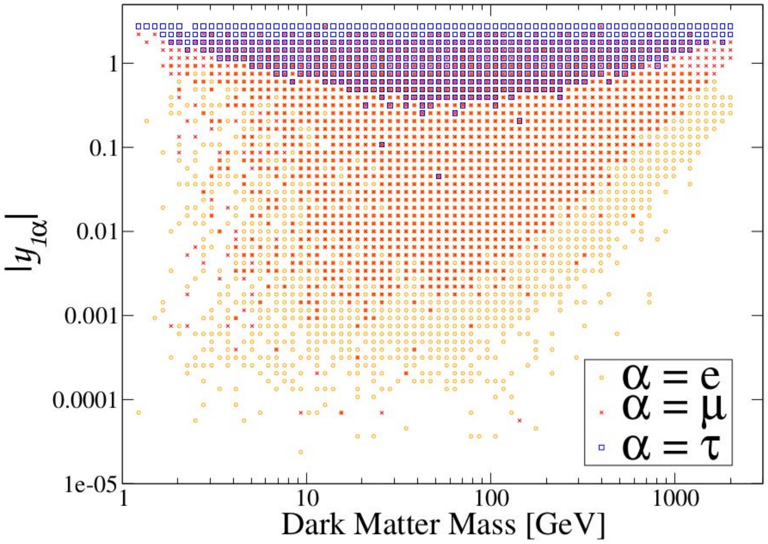
Charged Lepton Flavor Violation



Dark matter

- The lightest particle charged under Z2 is stable: dark matter candidate
- Fermion Dark Matter: NR1
  - It can only be produced via Yukawa interactions
  - It annihilates into a pair of charged leptons or active neutrinos via the η exchange

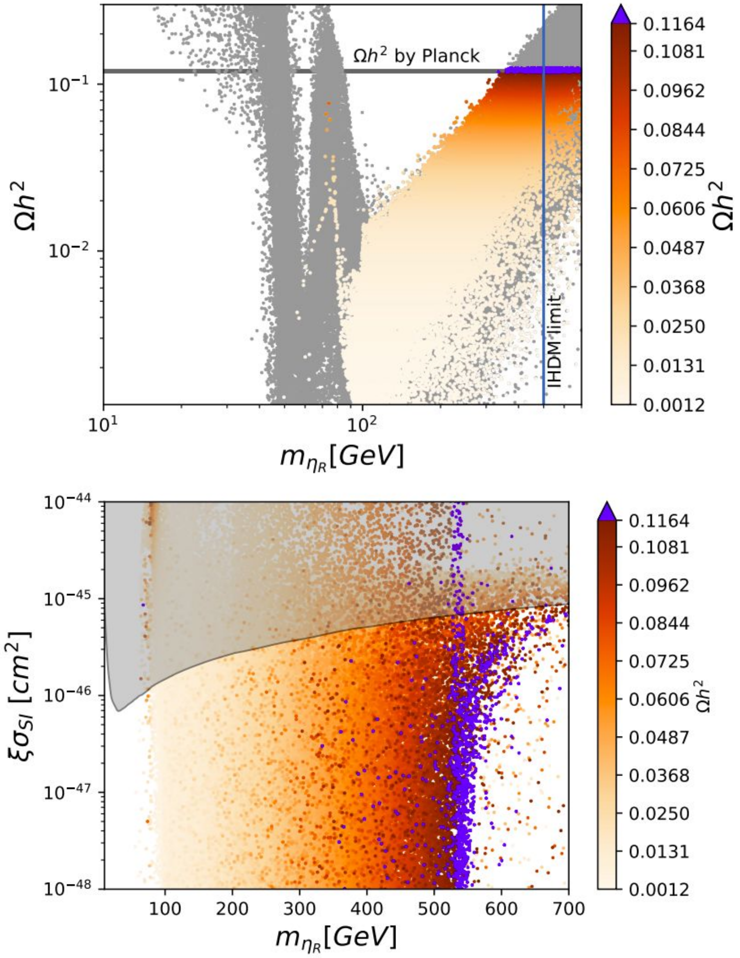


[A. Vicente, C. Yaguna, 2015]

$$\sigma(N_1 N_1 \to \bar{l}_\alpha l_\alpha) \sim {y_{1\alpha}}^4 \implies \Omega_{DM} \Rightarrow y \sim \mathcal{O}(1)$$

Dark matter

- Scalar Dark Matter: the lightest neutral scalar among η0, φ, ρ and ζ
  - Gauge and scalar interactions
  - Not correlated to lepton flavor violation
- If the dominant component is η0
  - DM properties similar to the inert scalar DM
  - Annihilation dominated by gauge interactions
- If DM is dominated by the other components
  - Main annihilation channels into the Higgs bosons via the scalar couplings



[Ávila, Cottin, Díaz, 2022]

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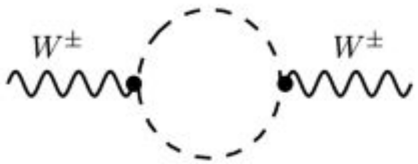
Precision EW and CDF anomaly

- CDF-II measurement of the W mass

[CDF Collaboration, 2022]

$$M_W = (80.433 \pm 0.0064_{\text{stat}} \pm 0.0069_{\text{syst}}) \;\; \text{GeV}$$

$$(M_W)_{\text{SM}} = (80.379 \pm 0.012) \;\; \text{GeV}$$

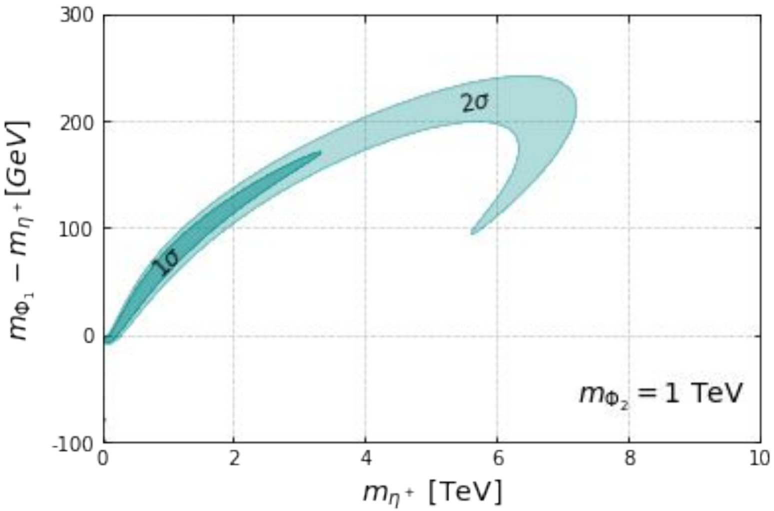


- Non-SM particles provide radiative corrections to the W-boson mass

$$M_W^2 = \left(M_W^2\right)_{\text{SM}} + \frac{\alpha_{\text{EM}}(M_Z)\cos^2\theta_W\, M_Z^2}{\cos^2\theta_W - \sin^2\theta_W}\left[-\frac{S}{2} + \cos^2\theta_W\, T + \frac{\cos^2\theta_W - \sin^2\theta_W}{4\,\sin^2\theta_W} U\right]$$

- CDF-II result can be explained by new physics that contribute to STU parameters

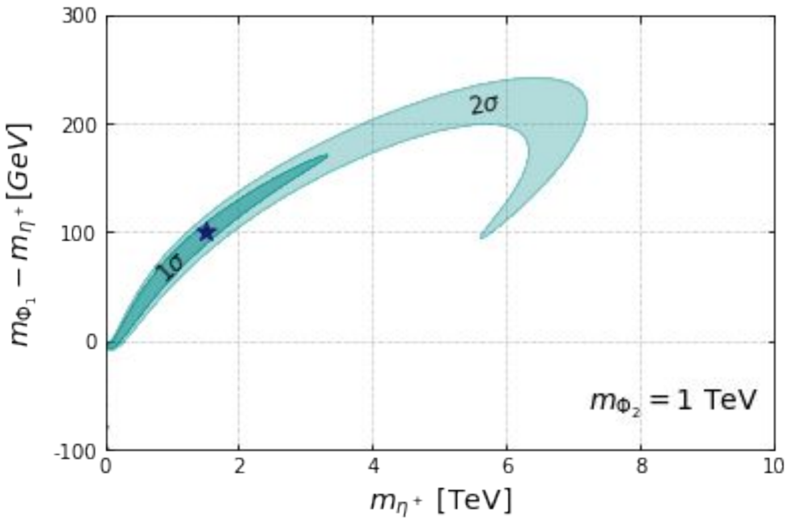
Precision EW and CDF anomaly



	Parameter Value	Correlation S	Correlation T	Correlation U
S	0.06 ± 0.10	1.00	0.90	-0.59
T	0.11 ± 0.12		1.00	-0.85
U	0.14 ± 0.09			1.00

[C. Lu, L. Wu, Y. Wu and B. Zhu, 2022]

Precision EW and CDF anomaly



$m_{\eta^+} = 1500$ GeV $\quad m_{\Phi_1} = 1600$ GeV

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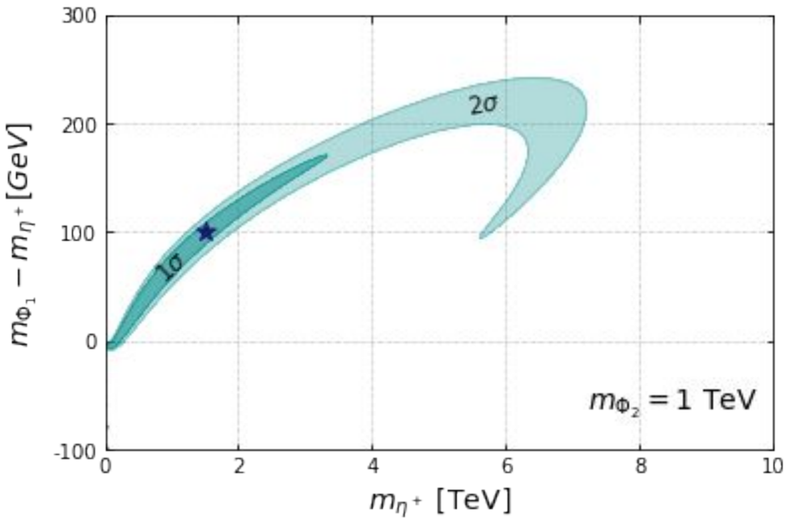

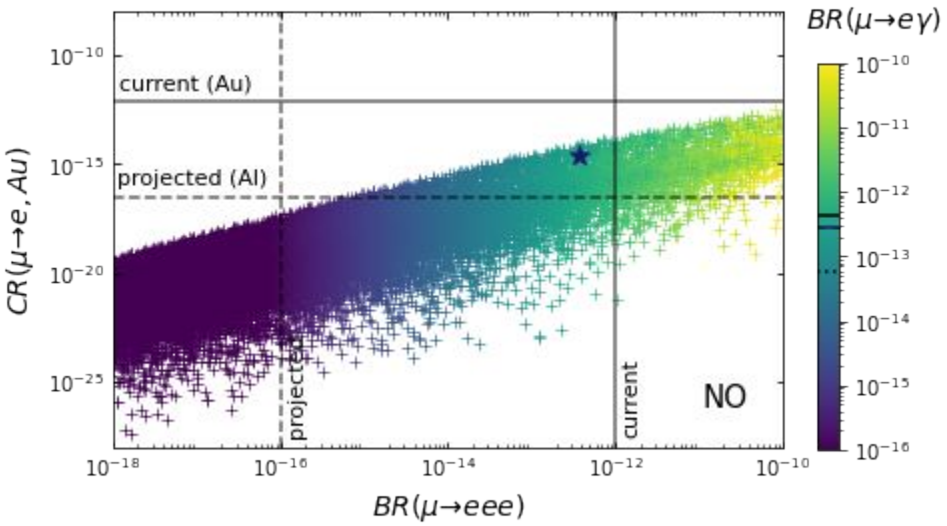

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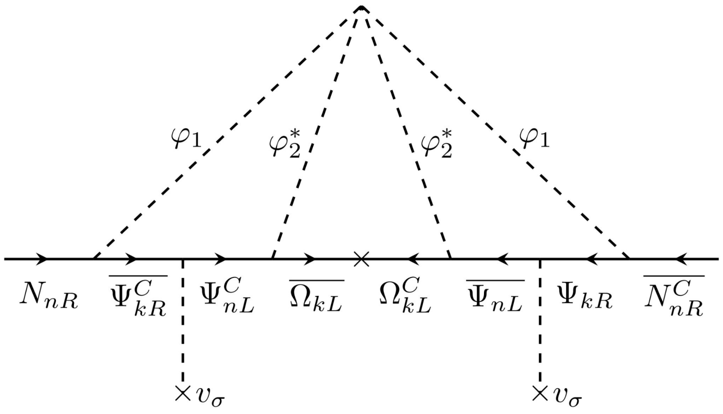
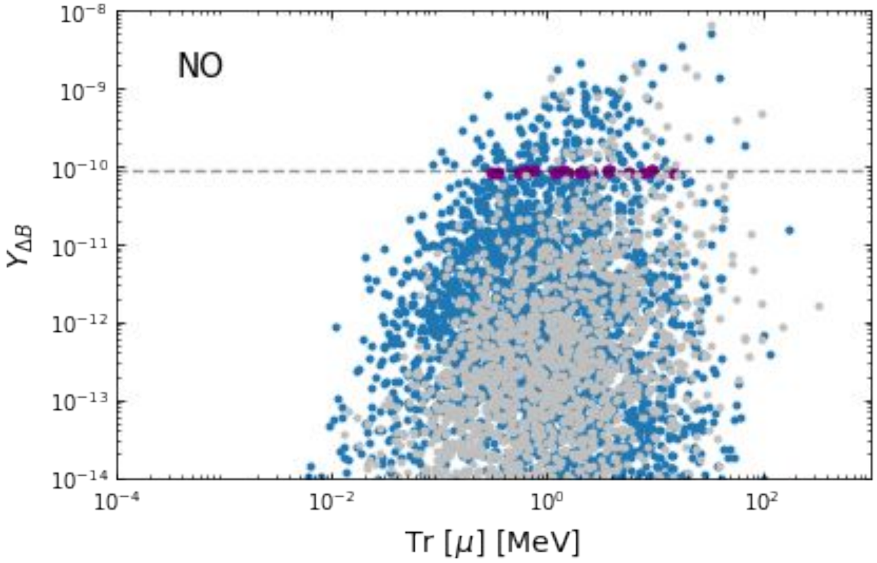
3-loop Scotogenic ISS Model





- ❖ Out-of-equilibrium decays of the pseudo-Dirac neutrinos NR can generate the baryon asymmetry of the universe via leptogenesis

Conclusions

- Radiative seesaw models are well motivated and testable extensions of the SM
- We discussed 2 examples of scotogenic models in which neutrinos masses are generated at the 3-loop level
- The 3-loop suppression allows the new particles to have masses in the TeV scale without fine-tuning the model parameters
- Fermionic or scalar DM can easily be accommodated; stability is ensured by the same symmetries involved in the generation of neutrino masses
- Depending on the realization, the models are capable of accounting for specific problems; here we discussed the W mass anomaly and baryogenesis
- These models lead to sizable cLFV rates which are within the sensitivity of future facilities

Thank you!