58th Rencontres de Moriond

Pheno & Cosmo Implications of Scotogenic 3-loop Neutrino Mass Models

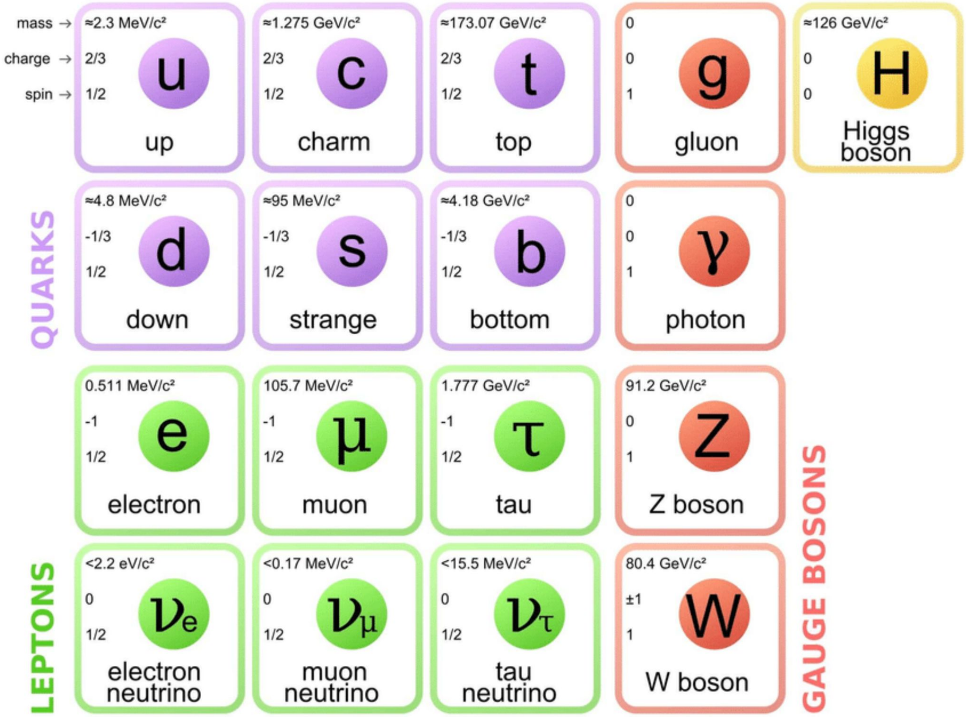
Téssio de Melo

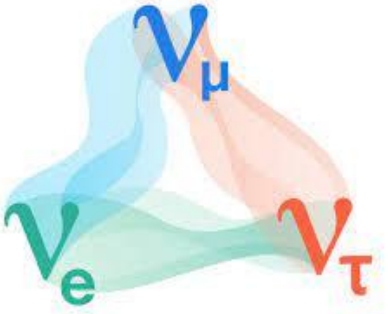
Universidad Andrés Bello/Millenium SAPHIR Institute

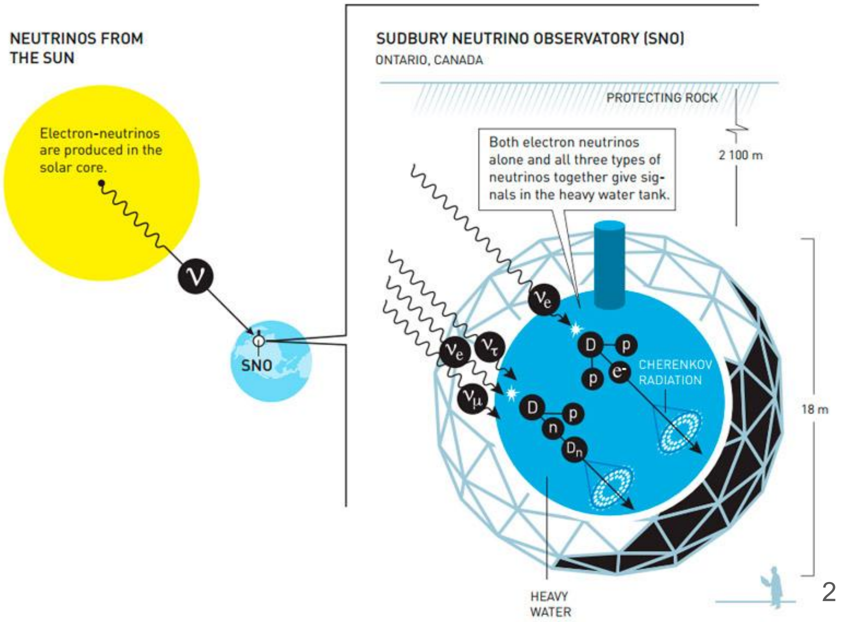
Based on **arXiv:2312.14105 [hep-ph]**, with A. Abada, N. Bernal, A. Cárcamo, S. Kovalenko and
J. High Energ. Phys. 03 (2023) 035 arXiv:2212.06852 [hep-ph], with A. Abada, N. Bernal, A. Cárcamo, S. Kovalenko and T. Toma

29 March 2024

Introduction







Introduction

Including vR fields:

$$\mathcal{L} \supset y_\nu \bar{L}_L \tilde{H} \nu_R$$

Dirac mass: $m_\nu \bar{\nu}_L \nu_R$

Small neutrino masses O(0.1) eV requires:

$$y_\nu \sim \mathcal{O}(10^{-12})$$

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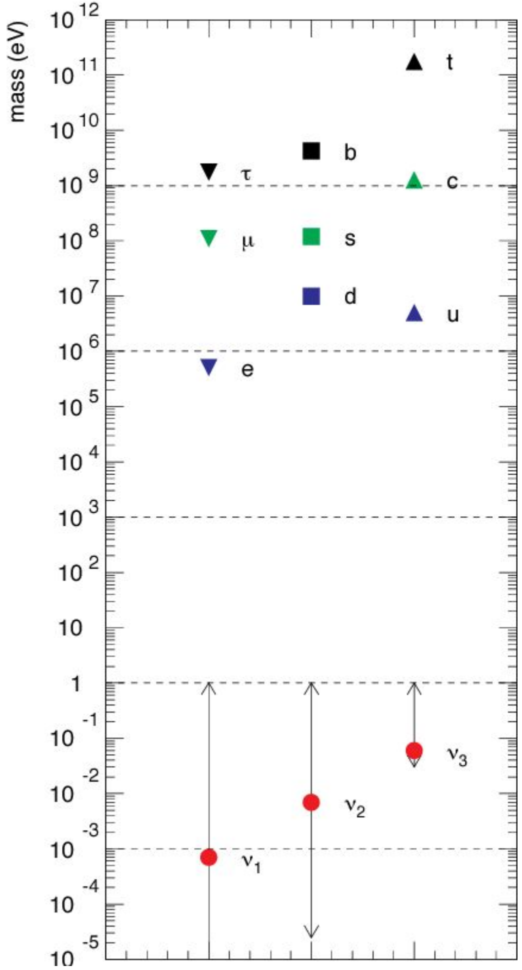
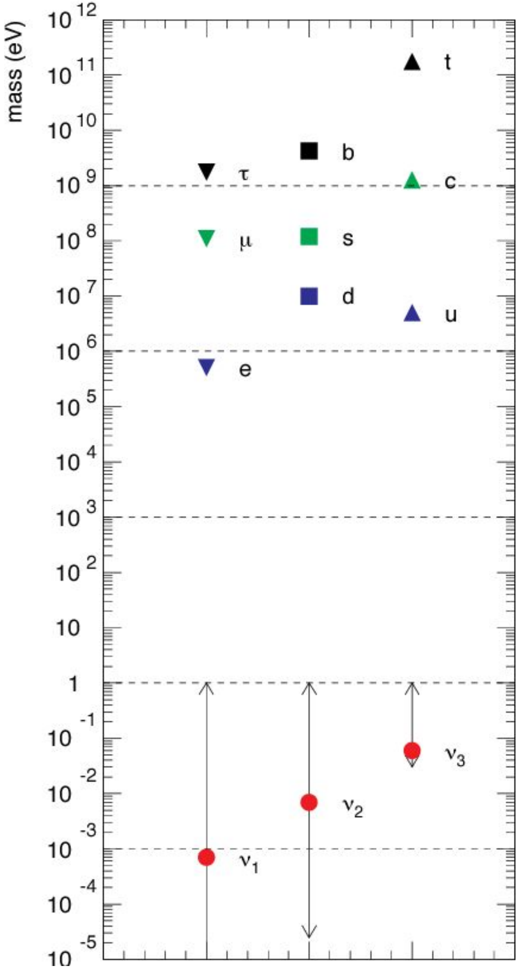


Introduction

ν_R are singlets under all the symmetries of the SM

Majorana mass term is not forbidden:

$$\mathcal{L} \supset y_\nu \bar{L}_L \tilde{H} \nu_R + \boxed{M_R \overline{\nu_R{}^c} \nu_R}$$



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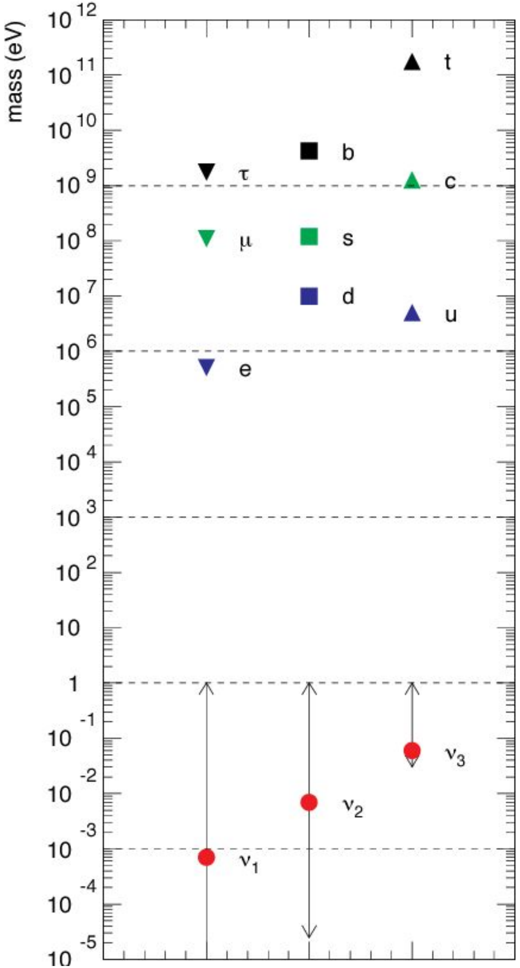
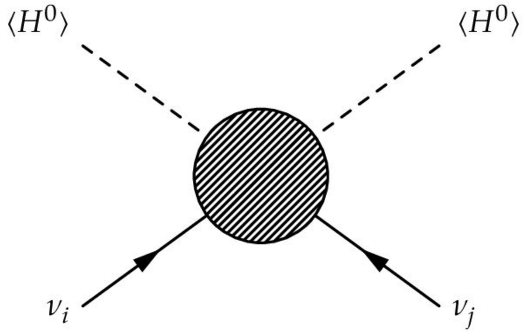
$$M_R \gg v \qquad\qquad m_\nu \simeq \frac{y_\nu^2 v^2}{M_R}$$



Introduction

Weinberg Operator:

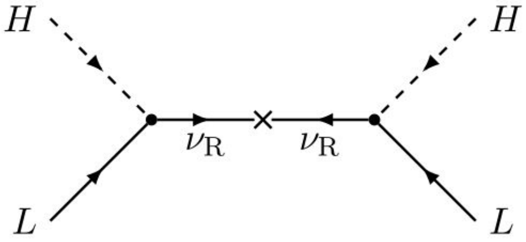
$$\mathcal{O}_W = \frac{c}{\Lambda} LLHH$$

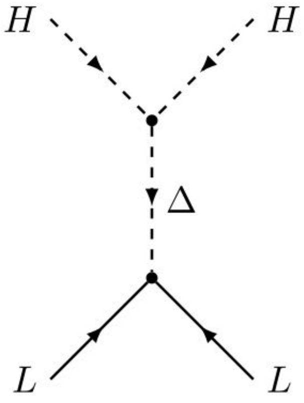


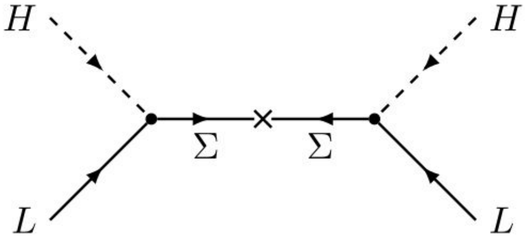
Right-handed singlet:
(type-I seesaw)

Scalar triplet:
(type-II seesaw)

Fermion triplet:
(type-III seesaw)







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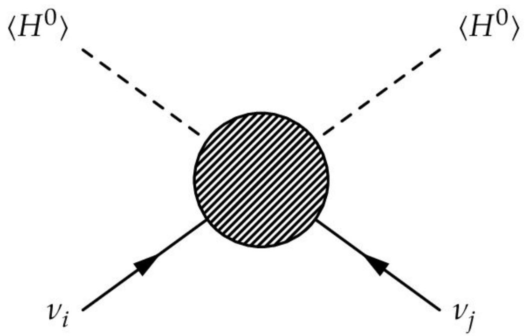
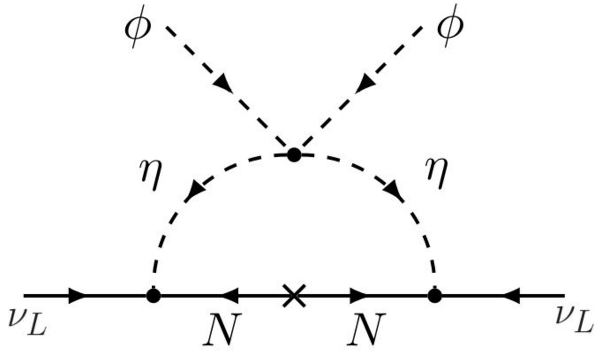
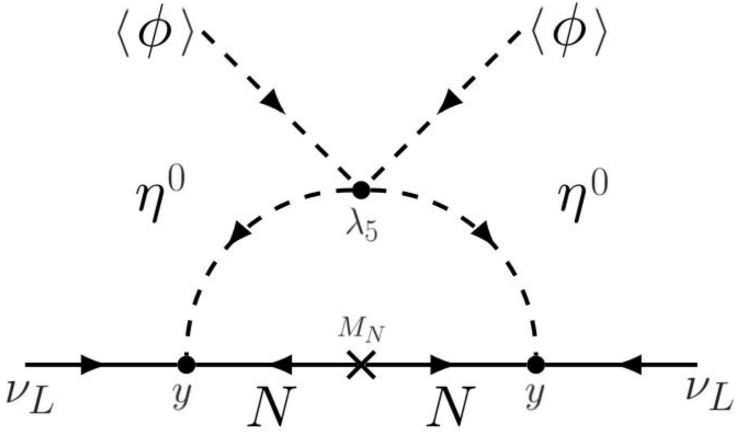




Scotogenic Model



[Ma, 2006]

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

Lepton Sector

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

Scalar Sector

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

Scotogenic Model

- The scotogenic model accounts for neutrino masses and dark matter with a very simple and economic setup
- However, λ_5 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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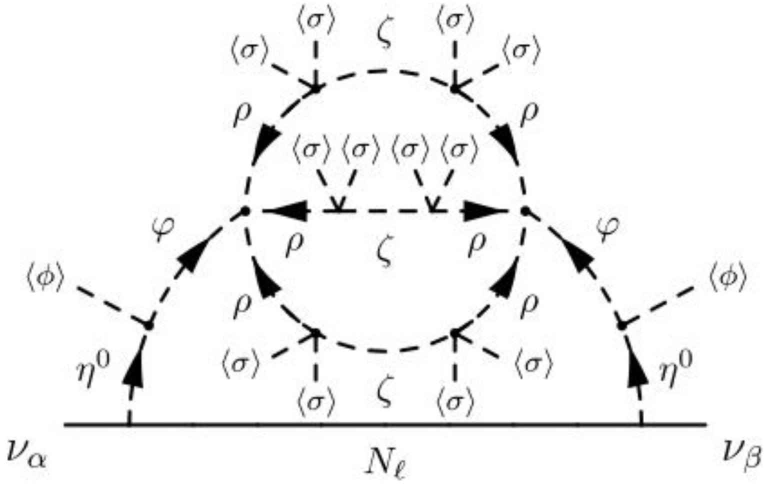
- This motivates us to go for higher loops. At n-loop order, neutrino masses are typically given by:

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

3-loop Scotogenic Model

Field	N_{R_k}	η	φ	ρ	ζ	σ
$SU(2)_L$	**1**	**2**	**1**	**1**	**1**	**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



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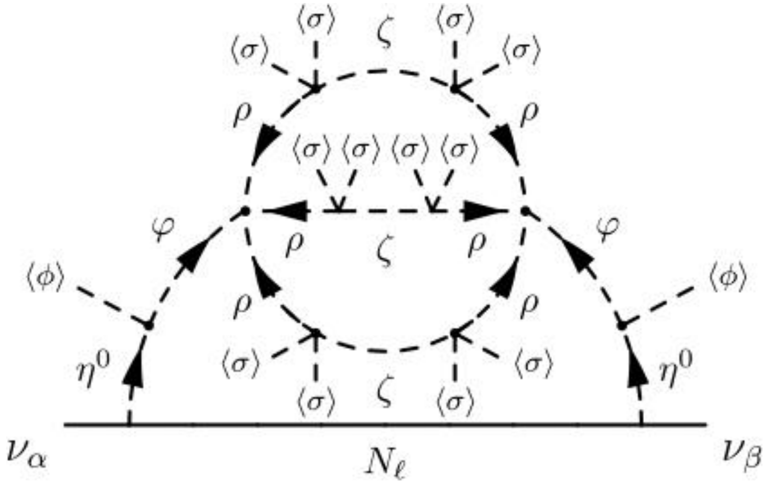

- Right-handed neutrinos
- Scalar doublet
- Singlet scalars

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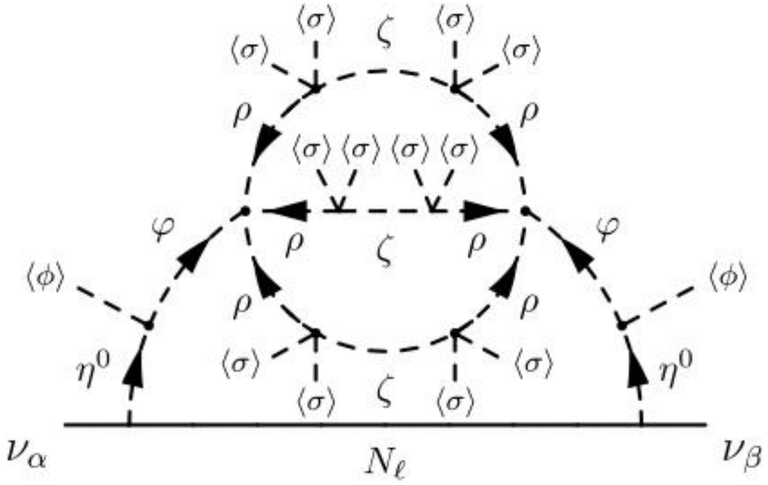

❖ Z2 symmetry forbids tree level Dirac mass term

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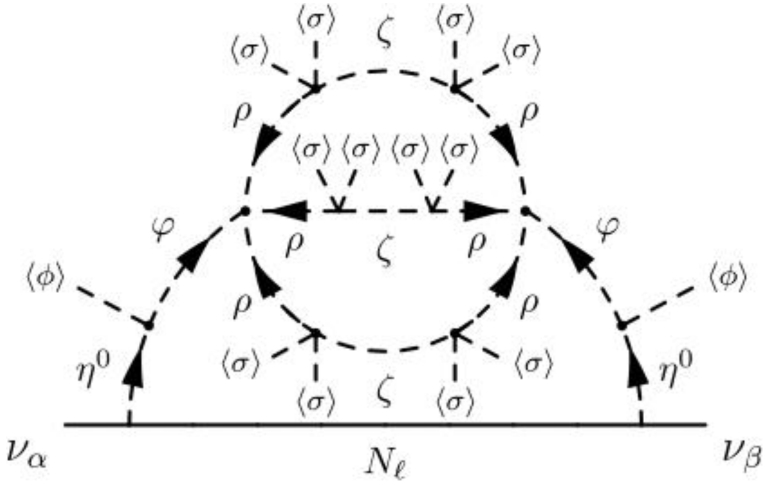
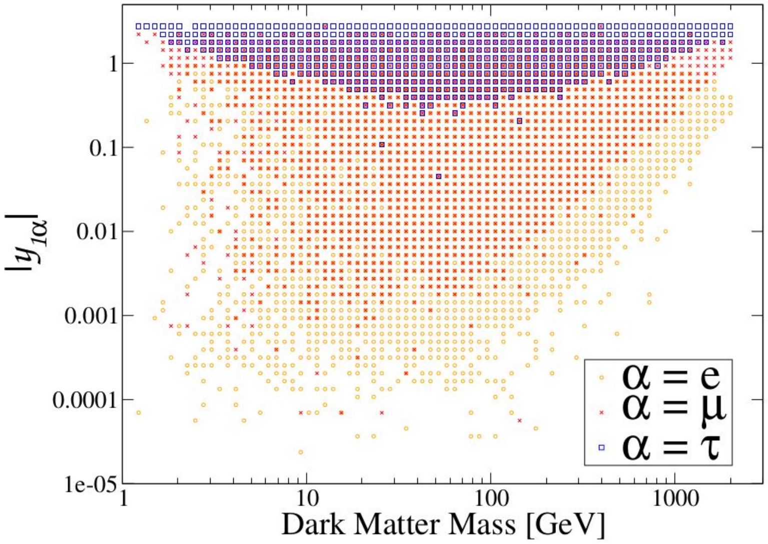


- Z2 symmetry forbids tree level Dirac mass term
- U(1)' symmetry forbids 1- and 2-loop mass terms

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

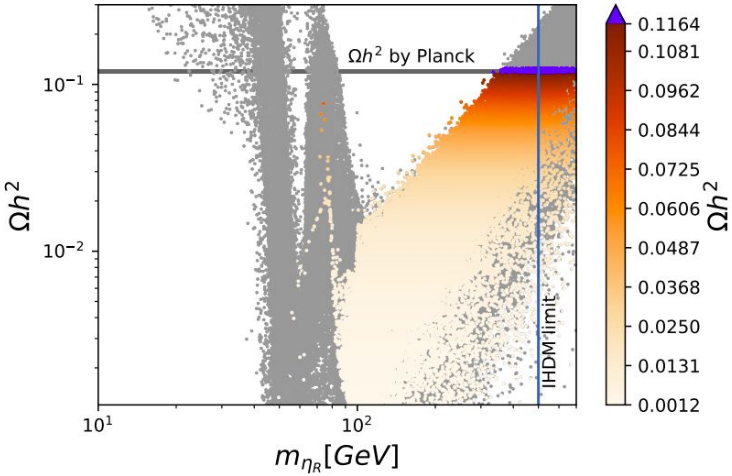
$$\sigma(N_1 N_1 \to \bar{l}_\alpha l_\alpha) \sim {y_{1\alpha}}^4 \quad \Longrightarrow \quad \Omega_{DM} \Rightarrow y \sim \mathcal{O}(1)$$

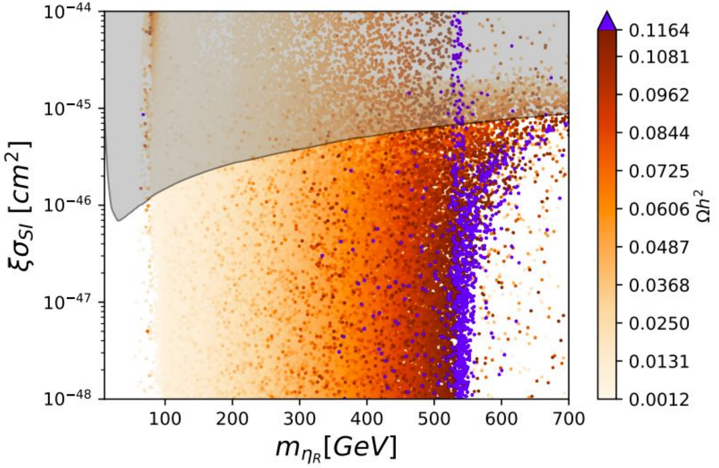


[A. Vicente, C. Yaguna, 2015]

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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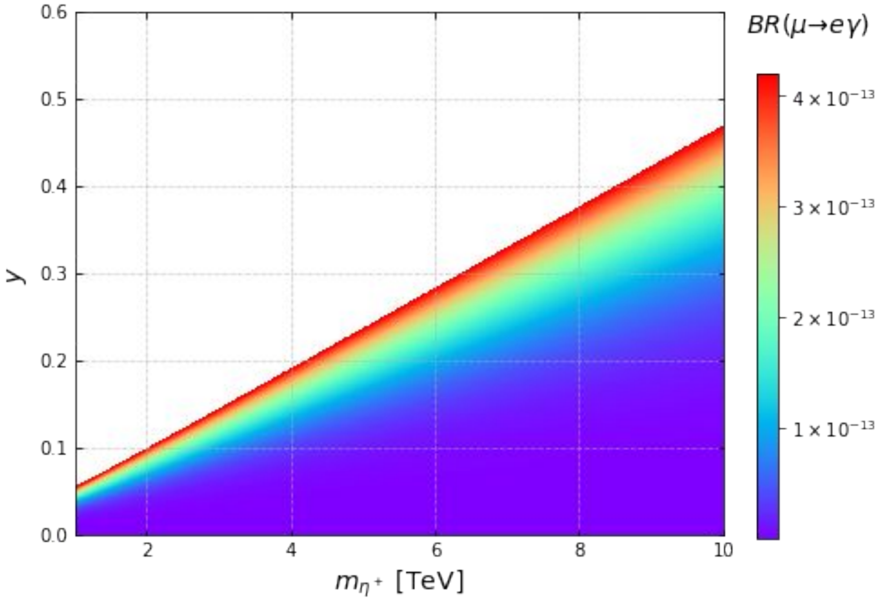
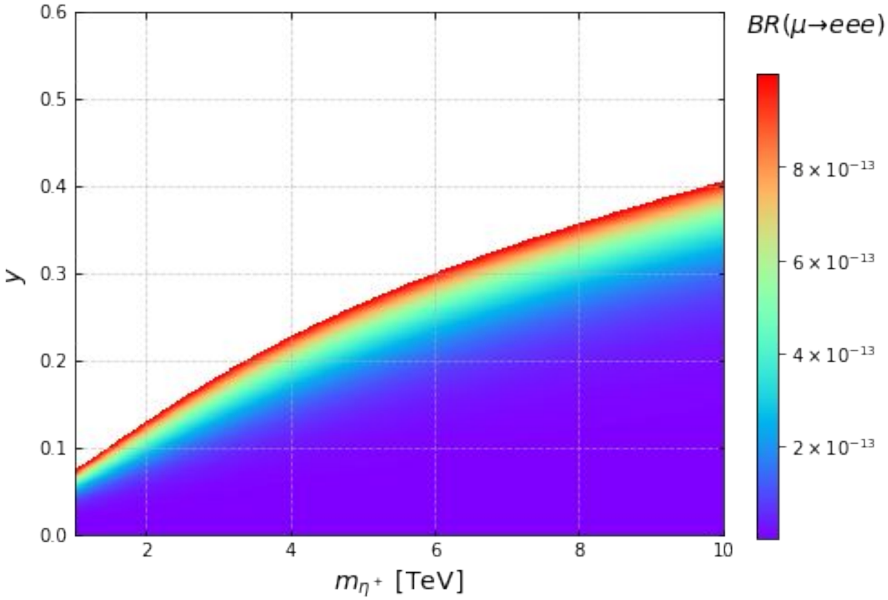
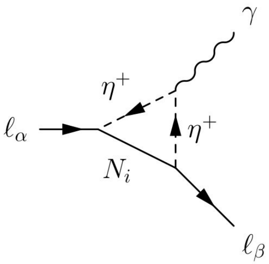
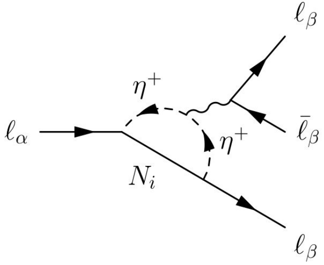
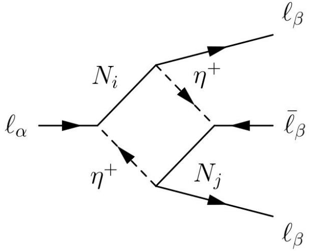
Charged Lepton Flavor Violation











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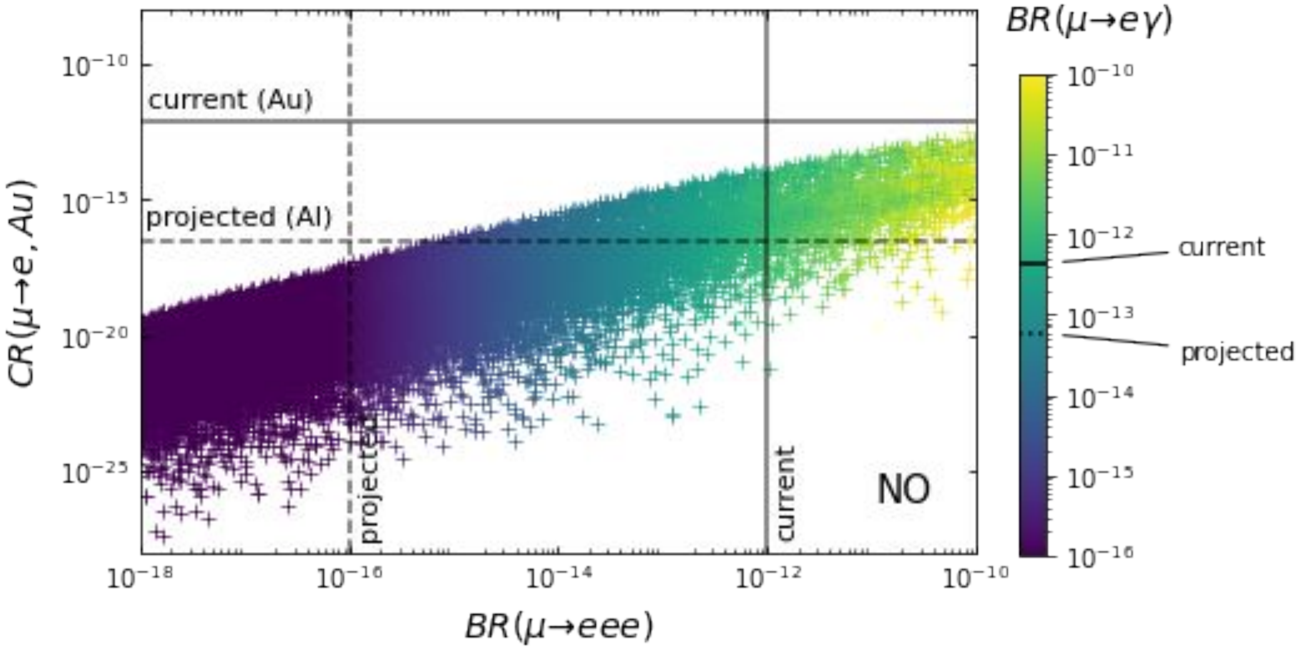

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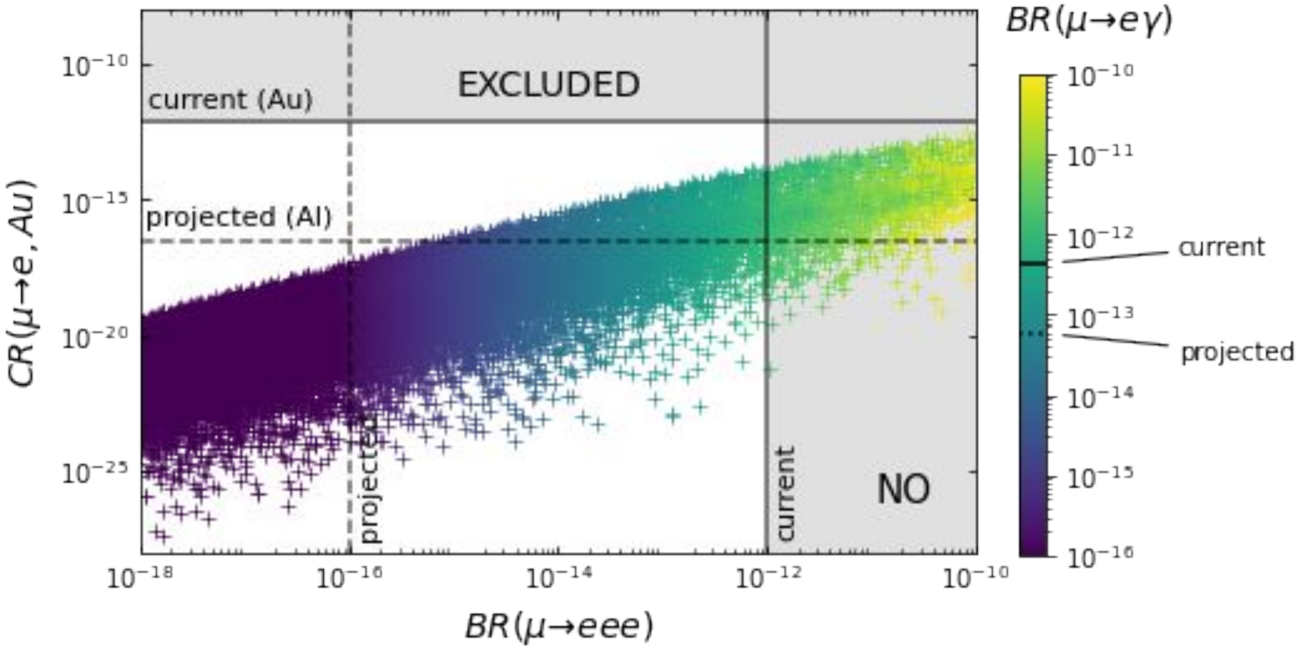

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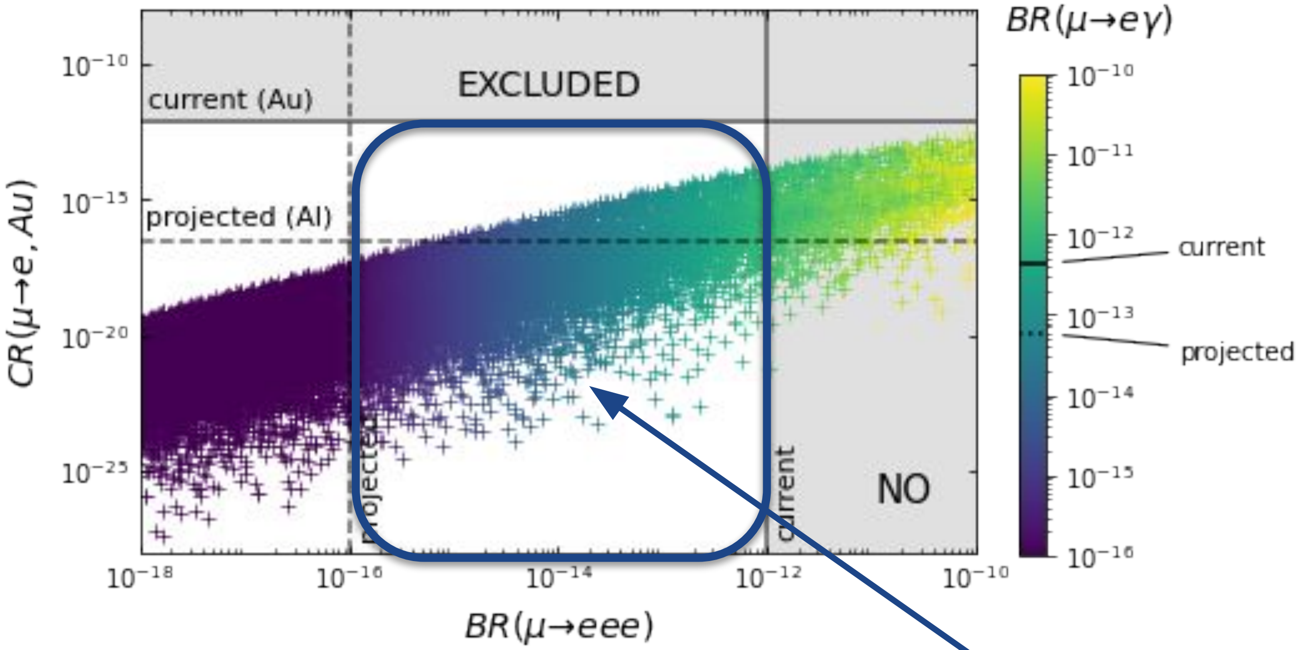


Testable!

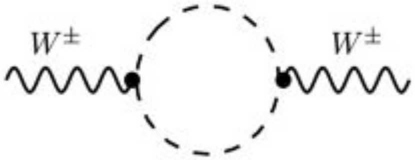
Precision EW and CDF anomaly

❖ CDF-II measurement of the W mass

[CDF Collaboration, 2022]

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

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

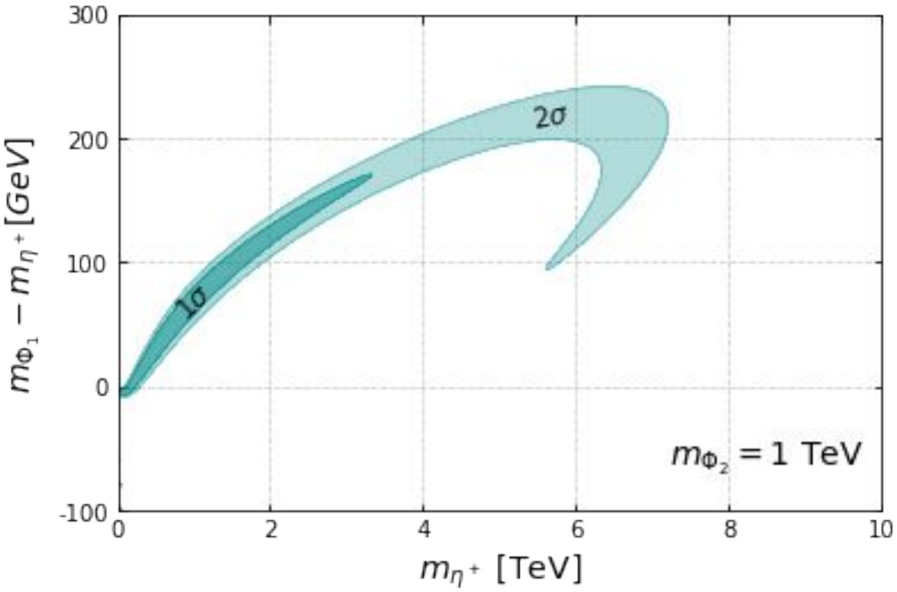


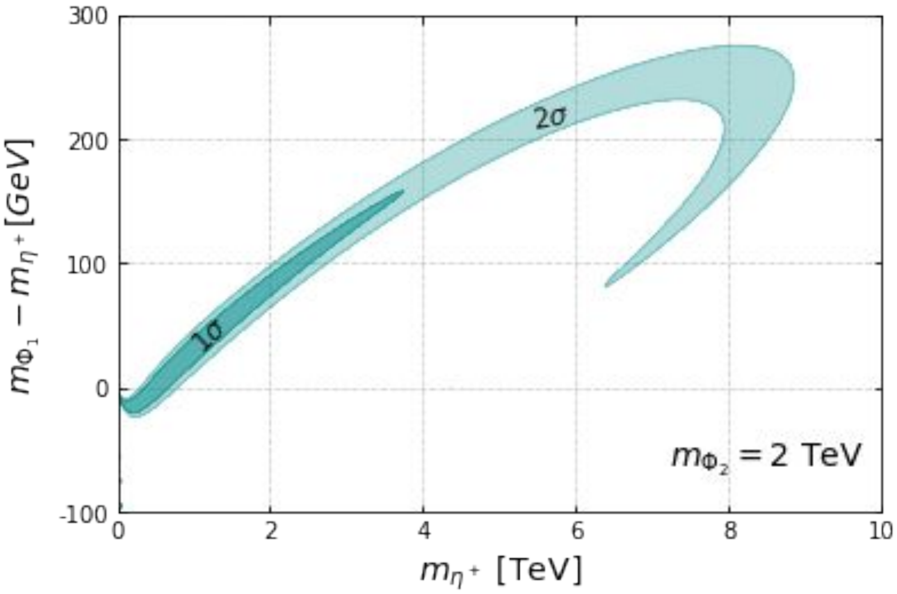
❖ Non-SM particles provide radiative corrections to the W-boson mass

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

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

Precision EW and CDF anomaly





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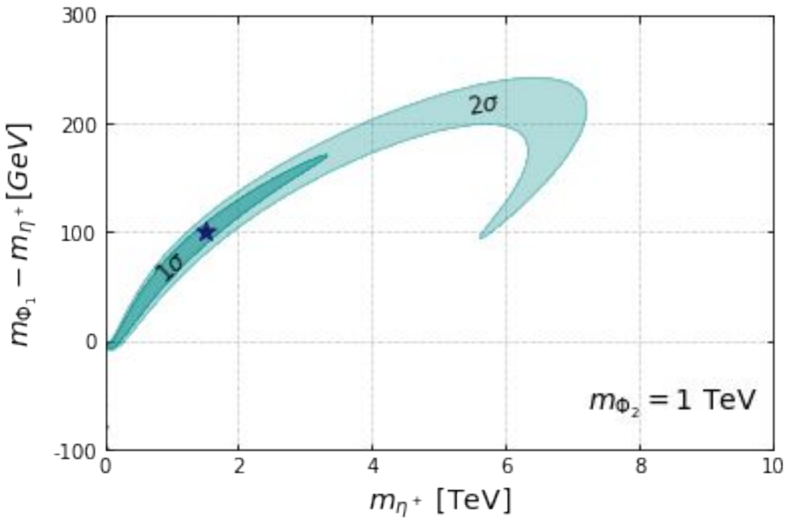

$$m_{\eta^+} = 1500 \text{ GeV} \qquad m_{\Phi_1} = 1600 \text{ GeV}$$

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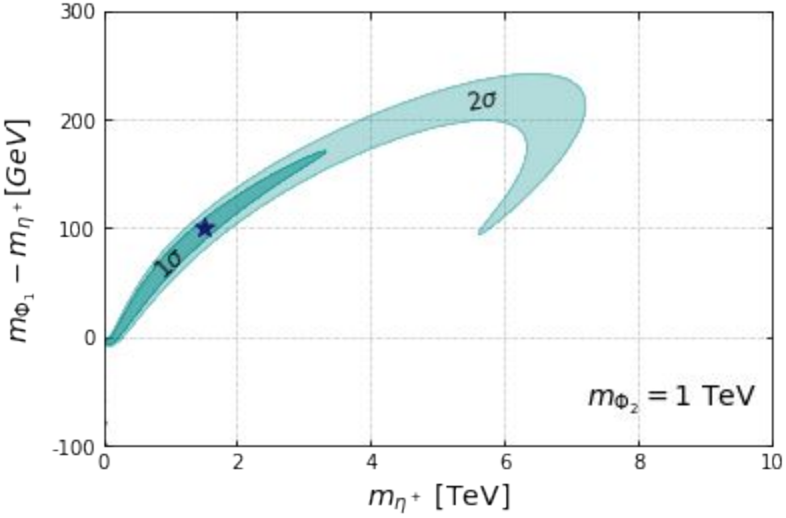

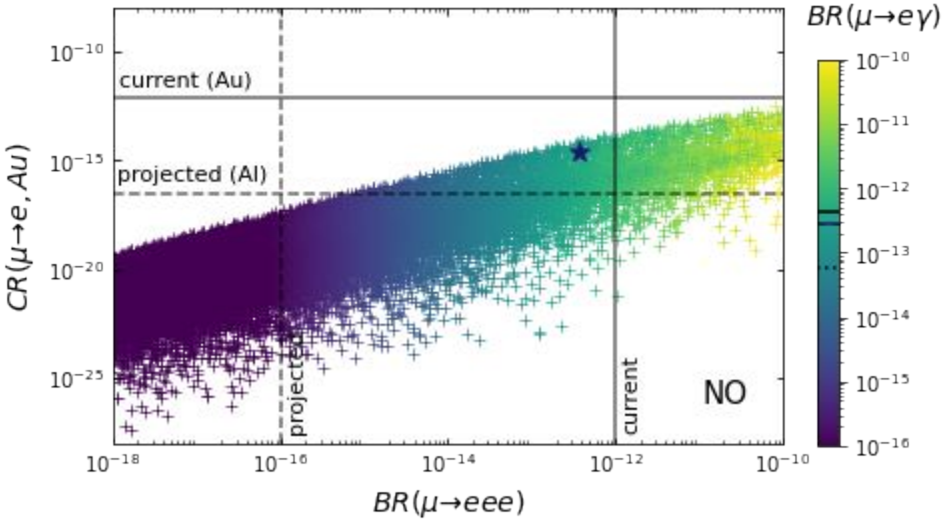

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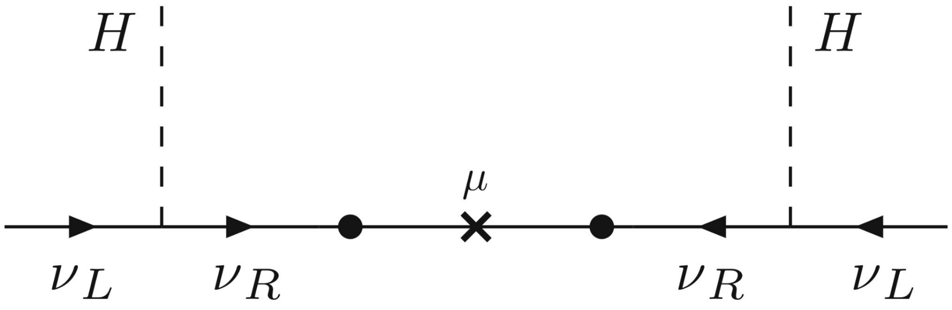
3-loop Scotogenic ISS Model



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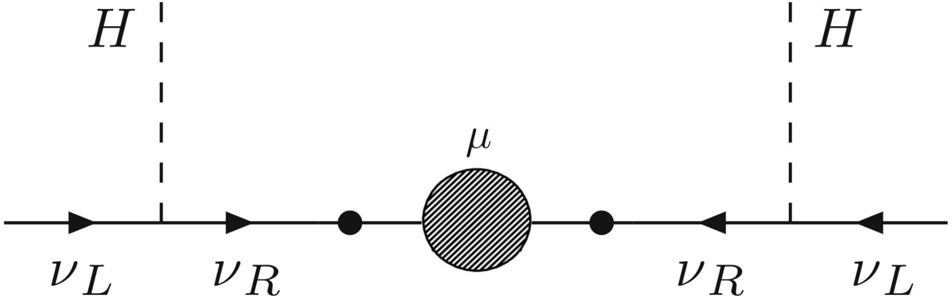

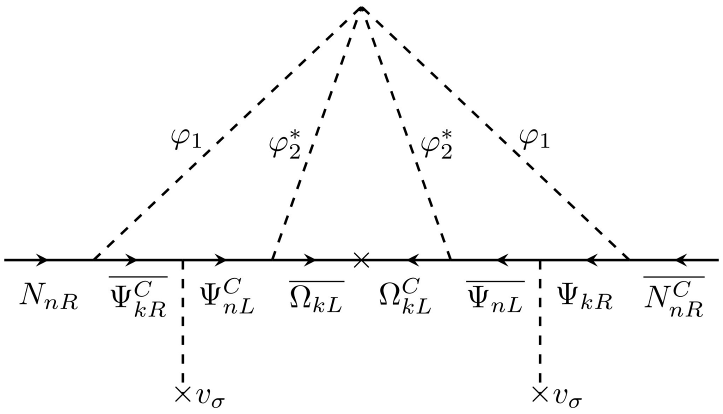

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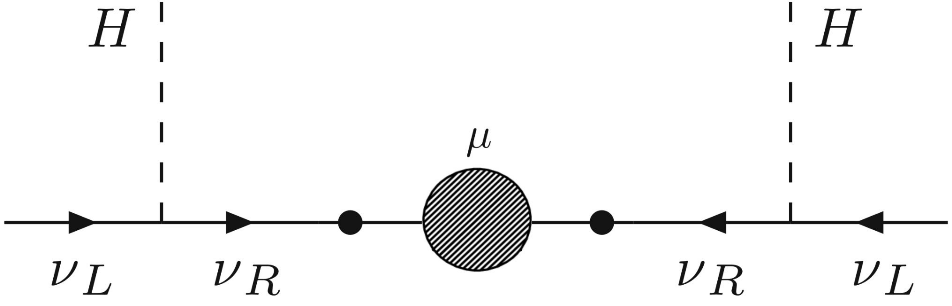

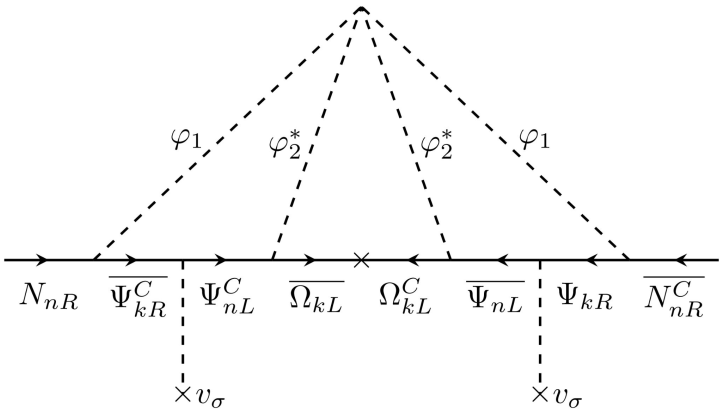

- Right-handed neutrinos
- Extra neutral singlet fermions
- Vector-like fermion pair
- Singlet scalars

Field	ν_{kR}	N_{kR}	Ω_{kL}	Ψ_{kR}	Ψ_{kL}	φ_1	φ_2	σ
$SU(2)_L$	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**
$U(1)_Y$	0	0	0	0	0	0	0	0
$U(1)'$	-4	4	0	-5	-1	-1	-1	4
$\mathbb{Z}_2$	1	1	-1	-1	-1	-1	1	1

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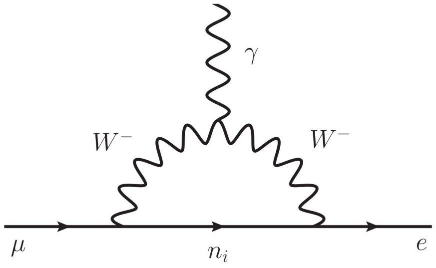
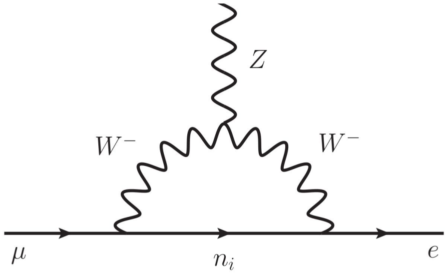
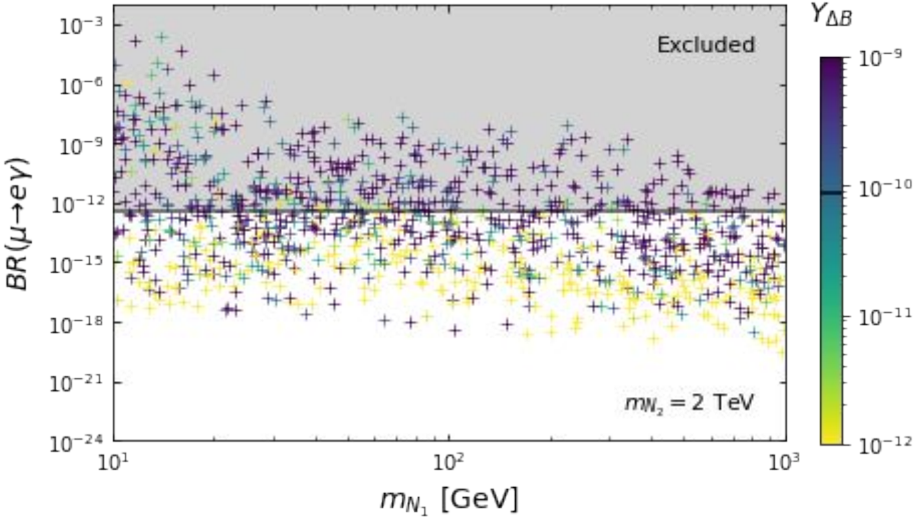
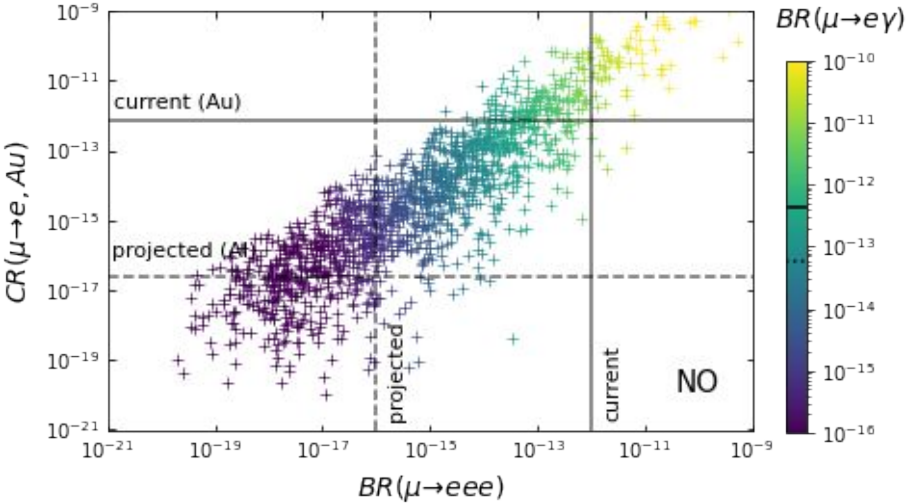
Charged Lepton Flavor Violation

- ❖ Photon and Z penguin diagrams mediated by neutrinos and W



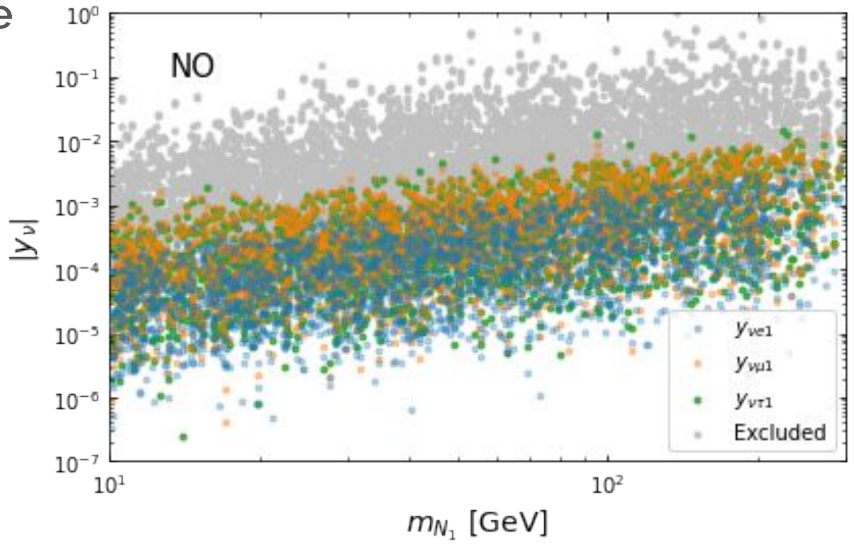






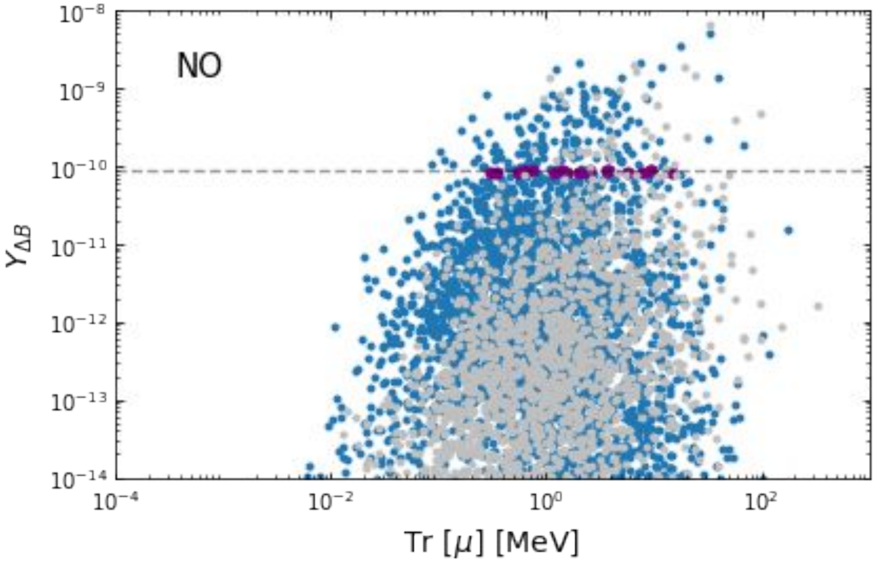
Dark matter

- Fermion or scalar DM candidates are possible
- For definiteness, here we assume the neutral lepton Ψ1 is the DM, and that N1 (which is Z2-even) is lighter than Ψ1
- Ψ1 annihilate mainly into N1 through the t-channel exchange of φ1. Later, N1 decays into Higgs and leptons
- All the points in the scan comply with neutrino oscillation data and DM relic abundance



Leptogenesis

- Out-of-equilibrium decays of the pseudo-Dirac neutrinos NR can generate the baryon asymmetry of the universe via leptogenesis
- All the points in the plot generate correct neutrino masses and DM relic abundance. Grey points are excluded by cLFV constraints. Purple points generate the correct baryon asymmetry



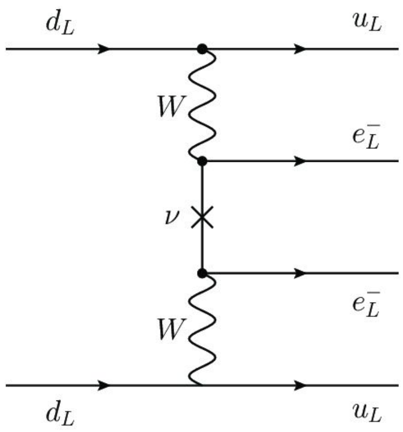
Conclusions

- 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!

Back Up

Neutrinoless double beta decay



- Effective mass for neutrinoless double beta decay

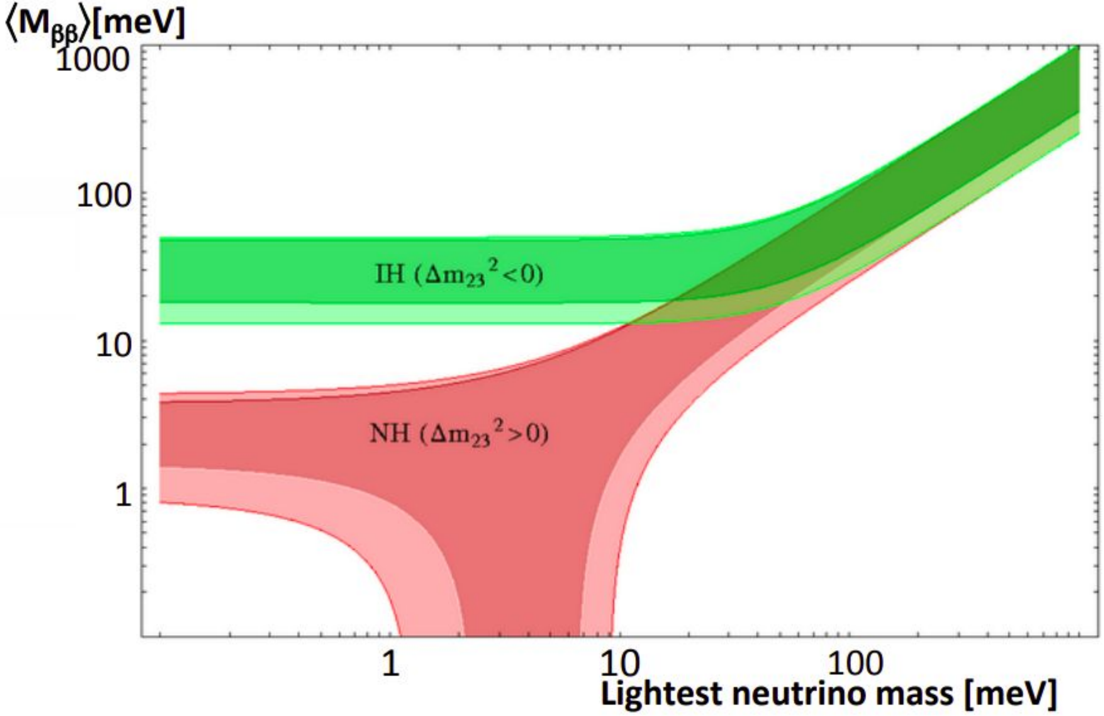
$$m_{ee} = \left| \sum_{i=1}^{3} \mathbf{U}_{ei}^2 \, m_i \right|$$

- RH neutrinos do not contribute due to the Z2 symmetry
- With one massless neutrino implies a definite prediction (depending on the mass ordering):

$$m_{ee}^{\rm NO} = 3.67 \ \text{meV} \ \ (\text{for NO}) \qquad m_{ee}^{\rm IO} = 48.36 \ \text{meV} \ \ (\text{for IO})$$

- Both satisfy the bound from KamLAND-ZEN $m_{ee} \lesssim 61 \ \text{meV}$
- Inverted ordering is within reach of experiments such as LEGEND and NEXT

Neutrinoless double beta decay



3-loop Scotogenic Model

$$
\begin{aligned}
V = & -\mu_\phi^2(\phi^\dagger\phi) - \mu_\sigma^2(\sigma^*\sigma) + \mu_\eta^2(\eta^\dagger\eta) + \mu_\varphi^2(\varphi^*\varphi) + \mu_\rho^2(\rho^*\rho) + \mu_\zeta^2(\zeta^*\zeta) + \tilde{\mu}_\zeta^2\left(\zeta^2 + \text{H.c.}\right) \\
& + \lambda_1(\phi^\dagger\phi)^2 + \lambda_2(\sigma^*\sigma)^2 + \lambda_3(\phi^\dagger\phi)(\sigma^*\sigma) + \lambda_4(\eta^\dagger\eta)^2 + \lambda_5(\varphi^*\varphi)^2 + \lambda_6(\rho^*\rho)^2 \\
& + \lambda_7(\zeta^*\zeta)^2 + \left(\kappa_1\zeta^4 + \text{H.c.}\right) + \left(\kappa_2\zeta^2 + \text{H.c.}\right)(\zeta^*\zeta) + \lambda_8(\eta^\dagger\eta)(\varphi^*\varphi) + \lambda_9(\eta^\dagger\eta)(\rho^*\rho) \\
& + \lambda_{10}(\eta^\dagger\eta)\zeta^2 + \left(\kappa_3\zeta^2 + \text{H.c.}\right)(\eta^\dagger\eta) + \lambda_{11}(\varphi^*\varphi)(\rho^*\rho) + \lambda_{12}(\varphi^*\varphi)(\zeta^*\zeta) \\
& + \left(\kappa_4\zeta^2 + \text{H.c.}\right)(\varphi^*\varphi) + \lambda_{13}(\rho^*\rho)(\zeta^*\zeta) + \left(\kappa_5\zeta^2 + \text{H.c.}\right)(\rho^*\rho) + \lambda_{14}\left(\varphi\rho^3 + \text{H.c.}\right) \\
& + \lambda_{15}\left(\rho\zeta\sigma^2 + \text{H.c.}\right) + \lambda_{16}(\phi^\dagger\phi)(\eta^\dagger\eta) + \lambda_{17}(\phi^\dagger\eta)(\eta^\dagger\phi) + \lambda_{18}(\phi^\dagger\phi)(\varphi^*\varphi) \\
& + \lambda_{19}(\phi^\dagger\phi)(\rho^*\rho) + \lambda_{20}(\phi^\dagger\phi)(\zeta^*\zeta) + \left(\kappa_6\zeta^2 + \text{H.c.}\right)(\phi^\dagger\phi) + \lambda_{21}(\sigma^*\sigma)(\eta^\dagger\eta) \\
& + \lambda_{22}(\sigma^*\sigma)(\varphi^*\varphi) + \lambda_{23}(\sigma^*\sigma)(\rho^*\rho) + \lambda_{24}(\sigma^*\sigma)(\zeta^*\zeta) + \left(\kappa_7\zeta^2 + \text{H.c.}\right)(\sigma^*\sigma) \\
& + A\left[(\eta^\dagger\phi)\varphi + \text{H.c.}\right]
\end{aligned}
$$

3-loop Scotogenic Model

$$\begin{pmatrix} \eta^0 \\ \varphi \end{pmatrix} = \begin{pmatrix} \cos\theta_\Phi & \sin\theta_\Phi \\ -\sin\theta_\Phi & \cos\theta_\Phi \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix}$$

$$\begin{pmatrix} \rho_R \\ \zeta_R \end{pmatrix} = \begin{pmatrix} \cos\theta_\Xi & \sin\theta_\Xi \\ -\sin\theta_\Xi & \cos\theta_\Xi \end{pmatrix} \begin{pmatrix} \Xi_1 \\ \Xi_2 \end{pmatrix}$$

$$\begin{pmatrix} \rho_I \\ \zeta_I \end{pmatrix} = \begin{pmatrix} \cos\theta'_\Xi & \sin\theta'_\Xi \\ -\sin\theta'_\Xi & \cos\theta'_\Xi \end{pmatrix} \begin{pmatrix} \Xi_3 \\ \Xi_4 \end{pmatrix}$$

3-loop Scotogenic Model

- We scan the parameter space of the model enforcing agreement with neutrino oscillation data via an adapted Casas-Ibarra parametrization

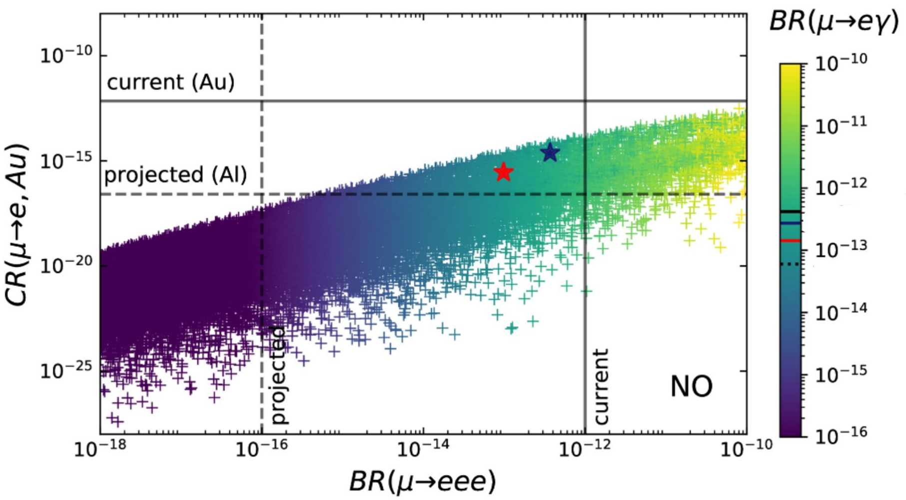
$$y_\eta = \sqrt{\Lambda}^{-1} R \begin{pmatrix} 0 & \sqrt{m_2} & 0 \\ 0 & 0 & \sqrt{m_3} \end{pmatrix} P\, U^\dagger_{\text{PMNS}}$$

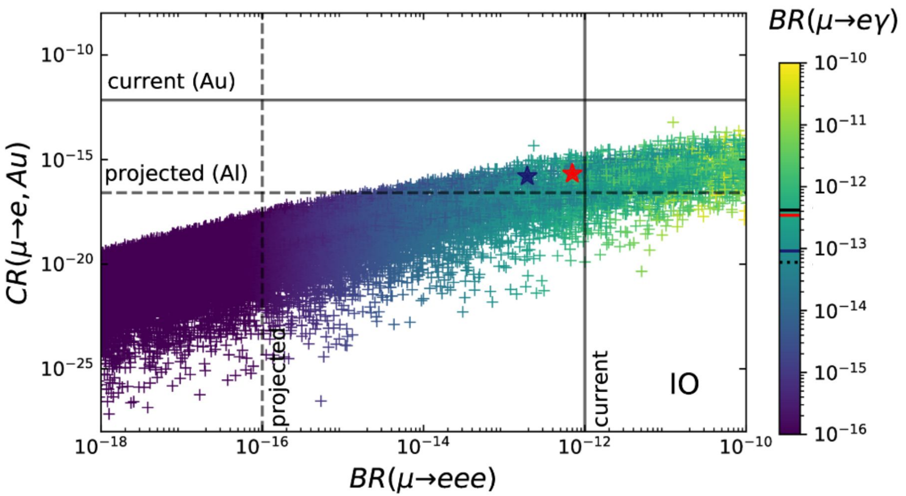
Parameters	**Scanned ranges**
θ_R	$[0, 2\pi]$
λ_{14}	$[0.01, 1]$
m_{N_R}, m_{η^+}, $m_{\Phi_{1,2}}$, $m_{\Xi_{1,2,3,4}}$	$[500, 10000]$ GeV

Benchmark Points

Parameters	BP1		BP2	
θ_Φ	0.2		0.2	
θ_Ξ	0.3		0.3	
θ'_Ξ	0.1		0.1	
m_{η^+} [GeV]	1500		1700	
m_{Φ_1} [GeV]	1600		1765	
m_{Φ_2} [GeV]	1000		2000	
	NO	**IO**	**NO**	**IO**
m_{N_R} [GeV]	8954.5	4246.9	5040.0	3450.7
m_{Ξ_1} [GeV]	8130.4	2925.0	8244.0	3282.9
m_{Ξ_2} [GeV]	1452.5	4748.5	2431.6	1815.4
m_{Ξ_3} [GeV]	8932.4	2763.1	6392.1	3637.6
m_{Ξ_4} [GeV]	7127.2	9336.4	1296.0	1458.4
λ_{14}	0.729	0.726	0.363	0.504
y_η^{e1}	0.124	0.346	-0.009	0.639
y_η^{e2}	-0.253	0.389	0.154	0.152
$y_\eta^{\mu 1}$	0.746	0.220	-0.313	0.031
$y_\eta^{\mu 2}$	-0.307	-0.272	0.312	-0.440
$y_\eta^{\tau 1}$	0.705	-0.335	-0.400	-0.183
$y_\eta^{\tau 2}$	0.207	0.225	0.043	0.475

3-loop Scotogenic Model





3-loop Scotogenic ISS Model

$$
\begin{aligned}
-\mathcal{L}_Y^{(\nu)} = & \sum_{i=1}^{3}\sum_{k=1}^{2} (y_\nu)_{ik}\, \bar{l}_{iL}\, \widetilde{\phi}\, \nu_{kR} + \sum_{n=1}^{2}\sum_{k=1}^{2} M_{nk}\, \overline{\nu}_{nR}\, N_{kR}^C \\
& + \sum_{n=1}^{2}\sum_{k=1}^{2} (y_N)_{nk}\, N_{nR}\, \varphi_1^*\, \overline{\Psi_{kR}^C} + \sum_{n=1}^{2}\sum_{k=1}^{2} (y_\Omega)_{nk}\, \Psi_{nL}^C\, \varphi_2 \overline{\Omega}_{kL} \\
& + \sum_{n=1}^{2}\sum_{k=1}^{2} (y_\Psi)_{nk}\, \overline{\Psi}_{nL}\, \sigma\, \Psi_{kR} + \sum_{n=1}^{2}\sum_{k=1}^{2} (m_\Omega)_{nk}\, \overline{\Omega}_{kL}\, \Omega_{nL}^C + \text{H.c.}
\end{aligned}
$$

3-loop Scotogenic ISS Model

$$-\mathcal{L}_{\rm mass}^{(\nu)} = \frac{1}{2}\begin{pmatrix} \overline{\nu_L^C} & \overline{\nu_R} & \overline{N_R} \end{pmatrix} M_\nu \begin{pmatrix} \nu_L \\ \nu_R^C \\ N_R^C \end{pmatrix} + \sum_{n=1}^{2}\sum_{k=1}^{2}(m_\Psi)_{nk}\,\overline{\Psi}_{nL}\Psi_{kR} + \sum_{n=1}^{2}\sum_{k=1}^{2}(m_\Omega)_{nk}\,\overline{\Omega}_{kL}\,\Omega_{nL}^C + H.c.$$

$$M_\nu = \begin{pmatrix} 0_{3\times3} & m_{\nu D} & 0_{3\times2} \\ m_{\nu D}^T & 0_{2\times2} & M \\ 0_{2\times3} & M^T & \mu \end{pmatrix}$$

$$\widetilde{\mathbf{M}}_\nu = m_{\nu D}\left(M^T\right)^{-1}\mu\, M^{-1} m_{\nu D}^T, \quad \mathbf{M}_\nu^{(-)} = -\frac{M+M^T}{2}+\frac{\mu}{2}, \quad \mathbf{M}_\nu^{(+)} = \frac{M+M^T}{2}+\frac{\mu}{2}$$

$$\mu_{sp} = \sum_{k=1}^{2}\sum_{n=1}^{2}\sum_{r=1}^{2}\frac{\lambda_{10} m_{\Psi_R} m_{\Psi_k}}{8\left(4\pi^2\right)^3 m_{\varphi_2}}(y_N)_{sr}(y_N)_{pk}(y_\Omega)_{rn}(y_\Omega)_{kn}\,F\left(\frac{m_{\Omega_n}^2}{m_{\varphi_2}^2}, \frac{m_{\varphi_1}^2}{m_{\varphi_2}^2}\right)$$

3-loop Scotogenic ISS Model

- Casas-Ibarra parametrization

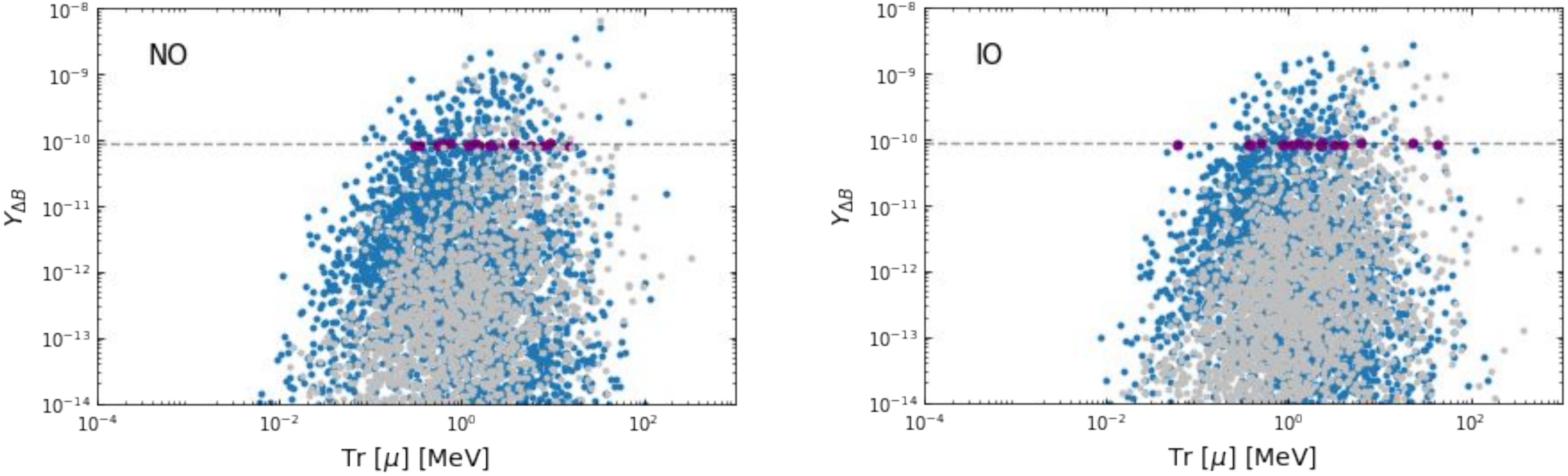
$$m_{\nu D} = R_\nu \left(\left(\widetilde{\mathbf{M}}_\nu \right)_{\rm diag} \right)^{\frac{1}{2}} O \mu^{-\frac{1}{2}} M$$

- μ-parametrization

$$\mu = M^T m_{\nu D}^{-1} \widetilde{\mathbf{M}}_\nu \left(m_{\nu D}^T \right)^{-1} M = M^T m_{\nu D}^{-1} U_{\rm PMNS} \left(\widetilde{\mathbf{M}}_\nu \right)_{\rm diag} U_{\rm PMNS}^T \left(m_{\nu D}^T \right)^{-1} M$$

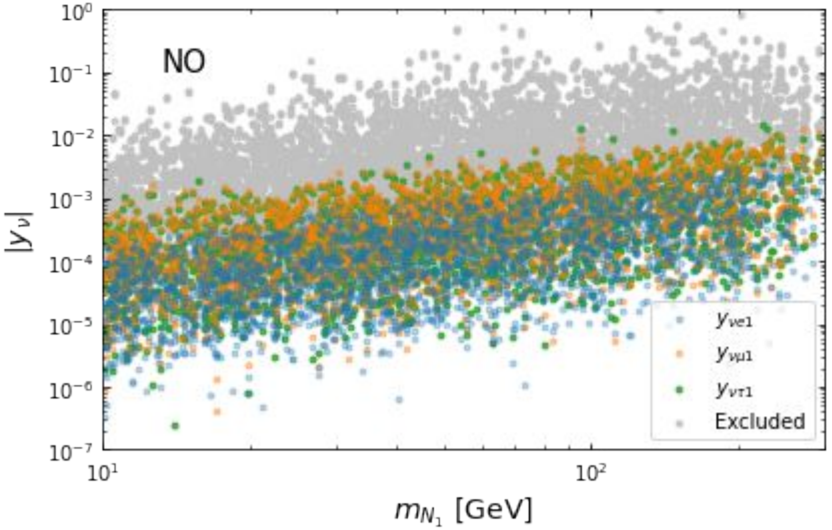
Téssio de Melo

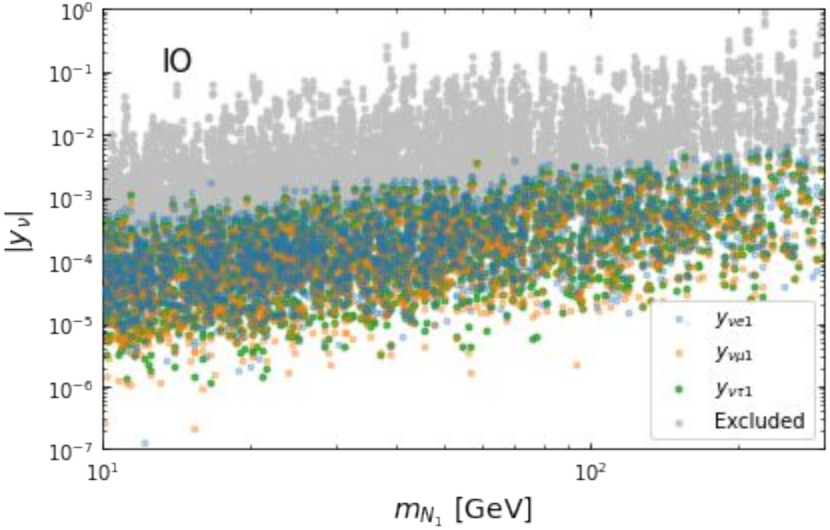
3-loop Scotogenic ISS Model



Téssio de Melo

3-loop Scotogenic ISS Model





3-loop Scotogenic ISS Model