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$[\mathrm{SU}(2) \times \mathrm{U}(1)]^2$ Extension

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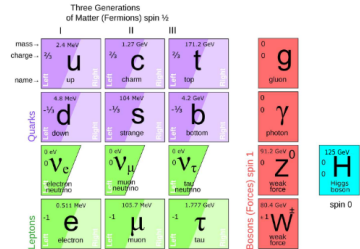
In collaboration with :

Aldo Deandrea, Amine Ahriche, Salah Nasri, and Nabil Baouche

October 20, 2026

Motivations for BSM

- The SM is highly successful,
BUT incomplete



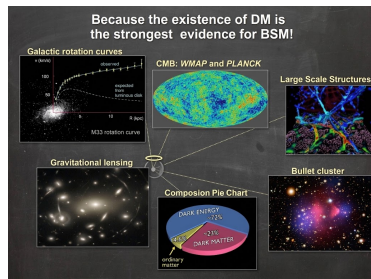
Motivations for BSM

- ▶ The SM is highly successful, BUT incomplete
- ▶ Neutrino masses



Motivations for BSM

- ▶ The SM is highly successful, BUT incomplete
- ▶ Neutrino masses
- ▶ Dark Matter



Our Proposal

Our models is simple SM extension $\Rightarrow$

We propose an extension with an extended gauge sector

Key Model Features

- ▶ Addresses neutrino masses via a scotogenic one-loop mechanism.
- ▶ Viable DM candidates include a Majorana fermion, an inert scalar, and a hidden vector boson

Performs a global parameter scan with theoretical and experimental constraints.

The Model

Theoretical Framework

$$\mathcal{G} = SU(2)_L \times SU(2)_H \times U(1)_1 \times U(1)_2$$

Scalar Sector

- ▶ $SU(2)_L$ inert doublet (η)
- ▶ $SU(2)_H$ doublet (Φ)
- ▶ Complex singlet (S)

Fermion Sector

- ▶ Three singlet fermions ($N_{1,2,3}$)

Gauge Charge Assignments

All SM fields are singlets under $SU(2)_H$ but charged under the $U(1)_{1,2}$ gauge symmetries.

Symmetry Breaking & Charge Representations

$$\begin{array}{ccc} SU(2)_L \times SU(2)_H \times U(1)_1 \times U(1)_2 & \xrightarrow{\langle S \rangle, \langle \Phi \rangle} & \\ & & SU(2)_L \times U(1)_Y \xrightarrow{\langle H \rangle} U(1)_{\text{em}} \end{array}$$

First-Stage Breaking: The extended gauge states associated with $SU(2)_H$ and $U(1)_2$ acquire their masses during the initial symmetry-breaking step.

Particle Content & Quantum Numbers

$$(SU(3)_c, SU(2)_L, SU(2)_H, U(1)_1, U(1)_2)$$

New fields:

- ▶ $\Phi \sim (1, 1, 2, \frac{1}{4}, -\frac{1}{4})$: hidden doublet
- ▶ $S \sim (1, 1, 1, -1, 1)$: complex singlet
- ▶ $\eta \sim (1, 2, 1, \frac{1}{4}, \frac{1}{4})$: inert doublet
- ▶ $N_{1,2,3} \sim (1, 1, 1, \frac{1}{2}, -\frac{1}{2})$: Majorana

Gauge Boson Sector & Mixing

Neutral gauge bosons

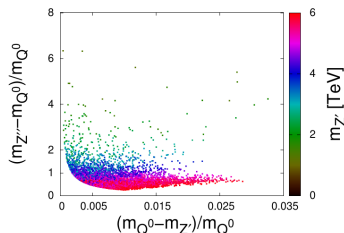
After symmetry breaking:

$$\{W_\mu^3, Q_\mu^3, B_\mu^1, B_\mu^2\} \longrightarrow \{A_\mu, Z_\mu, Z'_\mu, Z''_\mu\}$$

with mixing angle α between Q^3 and $(B^1 - B^2)/\sqrt{2}$.

Mass eigenstates:

- ▶ A : photon (massless)
- ▶ Z : SM Z boson
- ▶ Z', Z'' : heavy neutral gauge bosons
- ▶ $Q^0 = (Q^1 + iQ^2)/\sqrt{2}$: hidden vector boson



Q^0 does not couple to fermions

Scalar Sector: Fields & Potential

Field Parameterizations & VEVs

$$H = \left(\frac{1}{\sqrt{2}} (\chi^+ + \nu + h_1 + ia_1) \right), \quad \Phi = \left(\frac{1}{\sqrt{2}} (\phi_0 + \nu_\Phi + h_3 + ia_3) \right)$$
$$S = \frac{1}{\sqrt{2}} (\nu_s + h_2 + ia_2), \quad \eta = \left(\frac{1}{\sqrt{2}} (H^+ + iA^0) \right)$$

Scalar Potential: Includes H, Φ, S, η with quartic couplings.

$$V = -\mu_H^2 |H|^2 - \mu_\Phi^2 |\Phi|^2 - \mu_S^2 |S|^2 + \mu_\eta^2 |\eta|^2 + \frac{\lambda_H}{6} |H|^4 + \frac{\lambda_\Phi}{6} |\Phi|^4 + \frac{\lambda_S}{6} |S|^4 + \frac{\lambda_\eta}{6} |\eta|^4$$
$$+ \lambda_3 |H|^2 |\eta|^2 + \lambda_4 |H^\dagger \eta|^2 + \omega_1 |H|^2 |\Phi|^2 + \omega_2 |H|^2 |S|^2$$
$$+ \omega_3 |\Phi|^2 |\eta|^2 + \omega_4 |\Phi|^2 |S|^2 + \omega_5 |\eta|^2 |S|^2 + \frac{1}{2} \left\{ \lambda_5 (H^\dagger \eta)^2 + \text{h.c.} \right\}$$

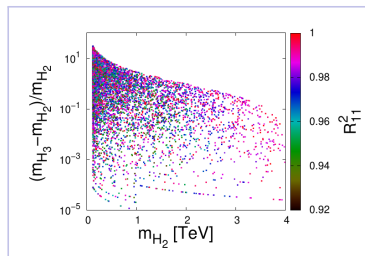
Scalar Sector: Mass Spectra & Mixing

CP-Even Scalar Sector (3×3)

CP-even scalars h_1, h_2, h_3 mix via 3×3 rotation R .

$$M_{\text{even}}^2 = \begin{pmatrix} \frac{1}{3}\lambda_H v^2 & \omega_2 v v_s & \omega_1 v v_\phi \\ \omega_2 v v_s & \frac{1}{3}\lambda_S v_s^2 & \omega_4 v_\phi v_s \\ \omega_1 v v_\phi & \omega_4 v_\phi v_s & \frac{1}{3}\lambda_\Phi v_\phi^2 \end{pmatrix}$$

- Yields physical states H_1, H_2, H_3 .
- H_1 : SM-like Higgs (125 GeV);
 H_2, H_3 : correspond to the heavier Higgs states.



Neutrino Mass Generation

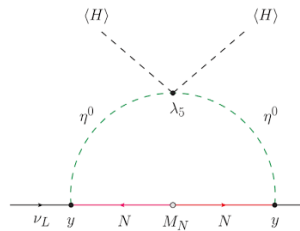
- ▶ Lepton doublets couple to an inert scalar doublet η and singlet fermions N_i via Yukawa interactions

$$\mathcal{L} \supset - f_{i\alpha} \bar{L}_{\alpha L} \tilde{\eta} N_i - \frac{1}{2} y_{N_i} S(N_i^T)^c N_i + \text{h.c.}$$

- ▶ **Z_2 Symmetry:** η and N_i are odd, while all SM fields are even
 - ▶ The Consequence: $\Rightarrow$ The tree-level Dirac mass term $\bar{L}_L \tilde{H} N$ is strictly **forbidden**.

Neutrino Mass Generation

- ▶ Neutrino masses are generated at the **one-loop level** via the exchange of η and N_k .

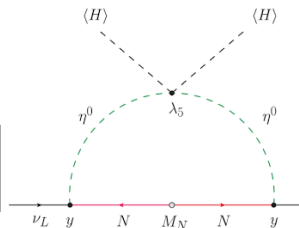


Neutrino Mass Generation

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$$(M_\nu)_{\alpha\beta} = \sum_i \frac{f_{i\alpha} f_{i\beta} M_i}{32\pi^2} \left[\mathcal{F} \left(\frac{m_{H^0}^2}{M_i^2} \right) - \mathcal{F} \left(\frac{m_{A^0}^2}{M_i^2} \right) \right]$$

with the loop function defined as $\mathcal{F}(x) = \frac{x \ln x}{x-1}$



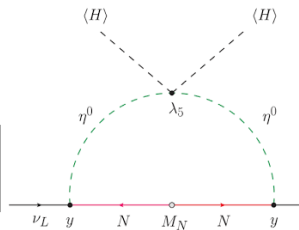
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- ▶ To understand the numerical values in neutrino mass matrix elements $\Rightarrow$ **Estimate the mass scale**



Neutrino Mass Generation



A. Merle and M. Platscher, Phys. Rev. D **92** (2015) 095002 [arXiv:1502.03098 [hep-ph]]



E. Ma, Phys. Rev. D **73** (2006), 077301 [arXiv:0601225 [hep-ph]]

$$\frac{m^{(\nu)}}{0.05 \text{ eV}} \sim \left(\frac{f}{0.01} \right)^2 \left(\frac{M_k}{50 \text{ GeV}} \right) \left(\frac{\Lambda_k/M_k}{10^{-8}} \right)$$

- ▶ The smallness of the parameters Λ_k can be ensured by making the neutral inert masses almost degenerate $\Rightarrow$

$$|m_{H^0}^2 - m_{A^0}^2| = |\lambda_5| v^2 \ll \frac{1}{2} (m_{H^0}^2 + m_{A^0}^2)$$

Neutrino Mass Generation

- ▶ We get $\Rightarrow$

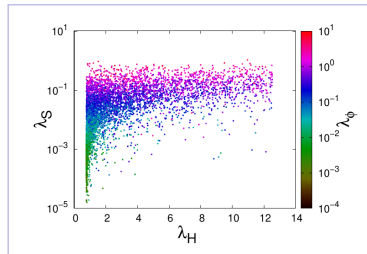
$$\Lambda_k \simeq \frac{|\lambda_5| v^2}{16\pi^2} \frac{M_k}{\bar{m}^2 - M_k^2} \left[1 - \frac{M_k^2}{\bar{m}^2 - M_k^2} \log \left(\frac{\bar{m}^2}{M_k^2} \right) \right]$$

- ▶ This means that for $f \sim O(10^{-3} - 10^{-2})$ required for the DM relic density, the scalar quartic coupling should be of the order $\sim O(10^{-10} - 10^{-9})$
- ▶ This possible fine-tuning issue can be avoided by extending the minimal scotogenic model
- ▶ If λ_5 is absent at tree level, it can be induced at one-loop by introducing additional fields that couple separately to H and η

Theoretical and Experimental Constraints

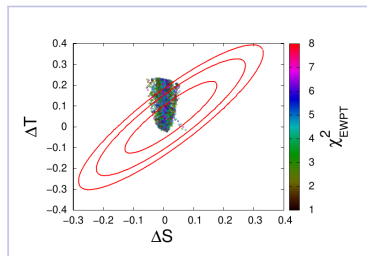
- ▶ **Perturbative Unitarity:**
All eigenvalues of the scattering amplitude matrix obey the condition $|\Lambda_i| < 8\pi$
- ▶ **Vacuum Stability:**
Boundedness from below requires:

$$\begin{aligned}\lambda_H, \lambda_S, \lambda_\Phi &\leq 4\pi, \\ \omega_{1,2,4}, \lambda_3 &\leq 4\pi, \\ |\lambda_3 + \lambda_4|, |\lambda_\pm| &\leq 4\pi\end{aligned}$$



Electroweak Precision Tests

- ▶ Z' and Z'' do not couple to the W and Z bosons $\Rightarrow$ They do not contribute to the oblique parameters.
- ▶ New contributions to ΔS , ΔT , and ΔU arise entirely from the scalar sector.
- ▶ **Global Constraint:** Viable benchmark points satisfy $\chi_{\text{EWPT}}^2 < 3.53$

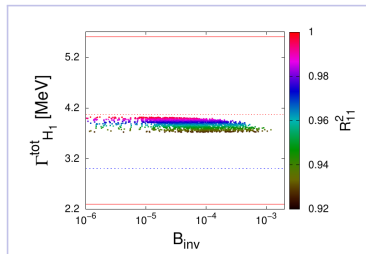


ΔT vs ΔS overlaid with 68%, 95%, and 99% C.L.
experimental fit ellipses.

Higgs Sector Phenomenology

$$\Gamma_{H_1}^{\text{tot}} = \underbrace{\Gamma_{\text{und}}}_{\text{Undetermined}} + \underbrace{\Gamma_{\text{inv}}}_{\text{Invisible}} + \underbrace{\Gamma_{H_1}^{\text{SM}} \sum_{X=\text{SM}} \kappa_X^2 \mathcal{B}(H_1 \rightarrow XX)_{\text{SM}}}_{\text{SM-like Channels}}$$

- ▶ Γ_{und} : Undetermined decays into light scalars ($H_1 \rightarrow SS'$)
- ▶ Γ_{inv} : Invisible decays into dark sector states ($SS, VV', N_i N_i$)
- ▶ κ_X : Higgs coupling modifiers



The mixing parameter R_{11}^2 remains tightly clustered near unity ($0.92 \leq R_{11}^2 \leq 1.0$)

Signal Strength for $H_1 \rightarrow \gamma\gamma$

- ▶ The di-photon signal strength is evaluated relative to the SM:

$$\mu_{\gamma\gamma} = \frac{\sigma(pp \rightarrow H_1) \mathcal{B}(H_1 \rightarrow \gamma\gamma)}{\sigma^{\text{SM}}(pp \rightarrow H_1) \mathcal{B}^{\text{SM}}(H_1 \rightarrow \gamma\gamma)} = \kappa_F^2 \frac{\Gamma_{H_1}^{\text{SM}}}{\Gamma_{H_1}^{\text{tot}}} \left| \frac{\mathcal{A}_{\gamma\gamma}}{\mathcal{A}_{\gamma\gamma}^{\text{SM}}} \right|^2$$

- ▶ The loop amplitude $\mathcal{A}_{\gamma\gamma}$ receives new contributions from the charged scalar $H^\pm$

$$\mathcal{A}_{\gamma\gamma} = \frac{\lambda_{H_1 H^+ H^-} v}{2m_{H^\pm}^2} A_0^{\gamma\gamma}(\tau_{H^\pm}) + \kappa_V A_1^{\gamma\gamma}(\tau_W) + \kappa_F \sum_f N_f Q_e^2 A_{1/2}^{\gamma\gamma}(\tau_f)$$

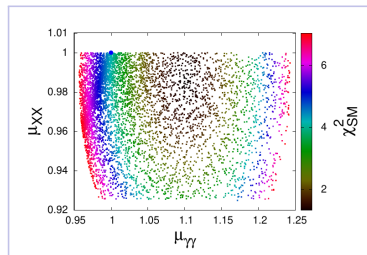
- ▶ The functions $A_{0,1/2,1}^{\gamma\gamma} \Rightarrow$



C. S. Chen, C. Q. Geng, D. Huang and L. H. Tsai, Phys. Rev. D **87** (2013), 075019 [arXiv:1301.4694 [hep-ph]].

Higgs Modifiers Strength μ_{XX}

$$\begin{aligned}\mu_{XX} &= \frac{\sigma(pp \rightarrow H_1 \rightarrow XX)}{\sigma^{\text{SM}}(pp \rightarrow H_1 \rightarrow XX)} \\ &= \kappa_F^2 \kappa_X^2 \frac{\Gamma_{H_1}^{\text{SM}}}{\Gamma_{H_1}^{\text{tot}}}\end{aligned}$$



- Global agreement with data is measured via χ^2

$$\chi_{\text{SM}}^2 = \sum_X \frac{(\mu_{XX} - \mu_{XX}^{\text{exp}})^2}{(\Delta \mu_{XX}^{\text{exp}})^2} < 7.04$$

LHC Constraints on Z' and Z''

- ▶ Z' and Z'' couple to SM fermions and singlet fermions

$$\mathcal{L} \supset \frac{e}{c_W} J^\mu (-s_\alpha Z'_\mu + c_\alpha Z''_\mu)$$

- ▶ The fermion current J^μ

$$J^\mu = -\frac{1}{3} \bar{u} \gamma^\mu u - \frac{1}{3} \bar{d} \gamma^\mu d + \bar{e} \gamma^\mu e \\ + \bar{\nu}_e \gamma^\mu P_L \nu_e + \bar{N}_i \gamma^\mu P_R N_i$$

- ▶ **Key Takeaway:** Couplings are controlled by s_α .

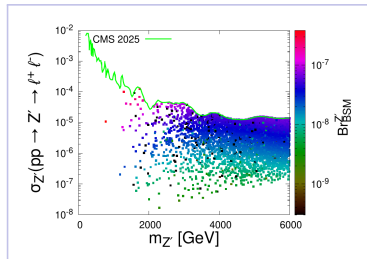
- ▶ At the LHC, Z' and Z'' searched $\Rightarrow$ di-lepton and di-jet resonance
- ▶ We compute $\sigma(pp \rightarrow Z'/Z'')$ multiplied by $\mathcal{B}(Z'/Z'' \rightarrow f\bar{f})$
- ▶ We compare these predicted rates directly against existing exclusion limits from CMS

LHC Constraints on Z' and Z''

- ▶ **Exclusion Limit:** CMS dilepton searches establish a robust lower bound of $m_{Z'} \geq 2$ TeV for moderate gauge mixing
- ▶ **The Decoupling Effect:** Heavily suppressed mixing angles ($|s_\alpha| \ll 1$) dramatically reduce production cross-sections, allowing lighter mass regimes to remain viable.



A. M. Sirunyan *et al.* [CMS], JHEP **07** (2021), 208 [arXiv:2103.02708 [hep-ex]].

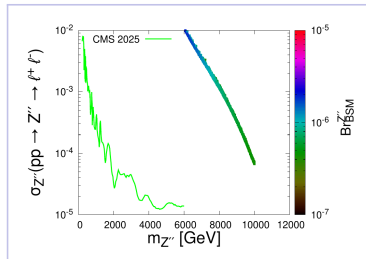


LHC Constraints on Z' and Z''

- ▶ Due to the mass ratio constraint ($m_{Z''}/m_{Z'} \approx 1 - 1.4$), $m_{Z''}$ ranges between 2 TeV and 12 TeV
- ▶ Most Z'' BPs reside well beyond current CMS exclusion limits due to their heavy mass scaling



A. M. Sirunyan *et al.* [CMS], JHEP 07 (2021), 208 [arXiv:2103.02708 [hep-ex]].

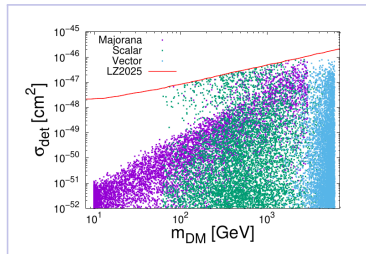


Dark Matter

- ▶ The model accommodates three distinct, stable DM candidates protected by an exact Z_2 symmetry
- ▶ **1. Majorana Fermion**
Lightest singlet fermion from the scotogenic sector
- ▶ **2. Scalar DM**
Neutral component of the inert $SU(2)_L$ scalar doublet (η)
- ▶ **3. Vector DM**
Hidden gauge boson combination from the $SU(2)_H$



J. Aalbers et al. [LZ], Phys. Rev. Lett. **135** (2025) no.1, 011802 [arXiv:2410.17036 [hep-ex]].



- ▶ Cross sections range from 10^{-50} to 10^{-46} cm^2 , satisfying LZ (2025) limits through heavy vector masses and scalar alignment ($R_{11} \approx 1$)

Conclusions

- ▶ Developed a $[SU(2)_L \times SU(2)_H \times U(1)_1 \times U(1)_2]$ gauge extension that naturally addresses several SM shortcomings
- ▶ Generated neutrino masses dynamically via a scotogenic one-loop mechanism involving inert scalars and Majorana fermions
- ▶ Accommodates three distinct stable candidates that satisfy the latest LZ (2025) DD limits
- ▶ **Phenomenological Viability:**
 - ▶ Passes electroweak precision tests ($\Delta S, \Delta T, \Delta U$) and global Higgs signal strength constraints
 - ▶ Respects LHC/CMS Z' and Z'' resonance exclusion bounds via suppressed gauge mixing

Thank You!



Questions??