A Possible Connection Between Dark Matter and Neutrino Masses and Its Implications

Michael A. Schmidt

Institute for Particle Physics Phenomenology
Durham

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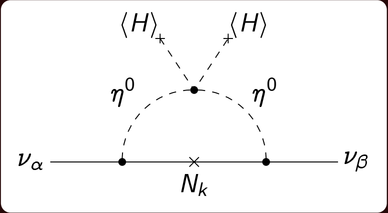
based on:
Y. Farzan, S. Pascoli, MS [1005.5323] and [1006.xxxx]

Radiative Mass Generation

Ma Model[Ma (2006)]



$$(m_\nu)_{\alpha\beta} = \sum_k \frac{Y_{\alpha k} Y_{\beta k} M_k}{16\pi^2} \left[\frac{m_R^2}{m_R^2 - M_k^2} \ln \frac{m_R^2}{M_k^2} - \frac{m_I^2}{m_I^2 - M_k^2} \ln \frac{m_I^2}{M_k^2} \right]$$

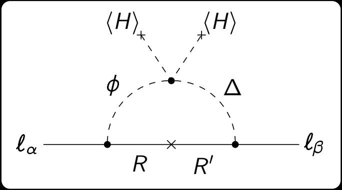
Conditions for Majorana Neutrino Mass Term

- Particle in loop have to couple to $SU(2)_L$ doublet
- Massive scalar and fermion in loop
- Mass splitting between scalar and pseudoscalar in loop
- $\Delta L = 2$ lepton number violation
- Discrete symmetry to avoid FCNCs and Dirac mass term $\Rightarrow \eta^0$ stable particle $\Rightarrow$ DM candidate
- But no symmetry explanation for smallness of couplings

Global U(1)

Particle Content

	SU(2)	U(1)	$U(1)_X$	$\mathbb{Z}_2$
$\ell_L^{(i)}$	2	-1/2	0	+
R_R	2	-1/2	1	-
R'_R	2	1/2	-1	-
Δ	3	1	1	-
ϕ	1	0	-1	-



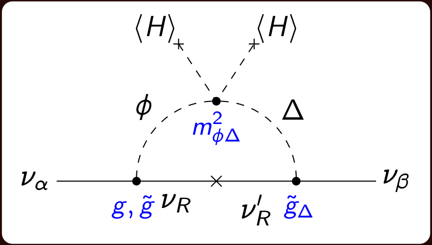
- Symmetry explanation for smallness of couplings U(1)$\to \mathbb{Z}_2$
- $\Rightarrow$ here explicit, later spontaneous
- Symmetry protects smallness from large quantum corrections

Fermion Sector

$$- m_{RR}(R'^C)^\dagger \cdot R - g_\alpha \phi^\dagger R^\dagger \ell_{L\alpha} - \tilde{g}_\alpha \phi R^\dagger \ell_{L\alpha} - (\tilde{g}_\Delta)_\alpha R'^\dagger \cdot \Delta \cdot \ell_{L\alpha} + \text{h. c.}$$

Neutrino Masses

One Loop Diagram Generating Neutrino Masses



- neutral scalar mass eigenstates δ_i
- with scalar masses M_i
- α_1 mixing between $\delta_{1,3}$
- α_2 mixing between $\delta_{2,4}$

$$(m_\nu)_{\alpha\beta} = [g_\alpha(\tilde{g}_\Delta)_\beta + g_\beta(\tilde{g}_\Delta)_\alpha]\tilde{\eta} + [\tilde{g}_\alpha(\tilde{g}_\Delta)_\beta + \tilde{g}_\beta(\tilde{g}_\Delta)_\alpha]\eta$$

$$\tilde{\eta} = \frac{m_{RR}}{64\pi^2}\left(\frac{M_3^2}{m_{RR}^2 - M_3^2}\ln\frac{m_{RR}^2}{M_3^2} - \frac{M_1^2}{m_{RR}^2 - M_1^2}\ln\frac{m_{RR}^2}{M_1^2}\right)\sin 2\alpha_1 + [(1,\,3) \to (2,\,4)]$$

$$\eta = \frac{m_{RR}}{64\pi^2}\left(\frac{M_3^2}{m_{RR}^2 - M_3^2}\ln\frac{m_{RR}^2}{M_3^2} - \frac{M_1^2}{m_{RR}^2 - M_1^2}\ln\frac{m_{RR}^2}{M_1^2}\right)\sin 2\alpha_1 - [(1,\,3) \to (2,\,4)]$$

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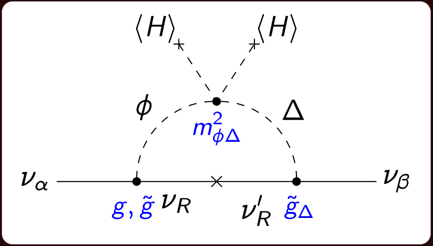

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$$\tilde{\eta} \simeq \frac{m_{RR}}{16\pi^2}\left(\frac{\tilde{m}^2_\phi m^2_{\phi\Delta}}{m^2_{RR} m^2_\Delta}\left(\frac{m^2_{RR}}{m^2_{RR} - m^2_\Delta}\ln\frac{m^2_{RR}}{m^2_\Delta} + 1 - \ln\frac{m^2_{RR}}{M^2_1}\right) - \frac{\tilde{m}^2_{\phi\Delta}}{m^2_{RR} - m^2_\Delta}\ln\frac{m^2_{RR}}{m^2_\Delta}\right)$$

$$\eta \simeq -\frac{m_{RR}}{16\pi^2}\frac{m^2_{\phi\Delta}}{m^2_{RR} - m^2_\Delta}\ln\frac{m^2_{RR}}{m^2_\Delta}$$

Neutrino Masses

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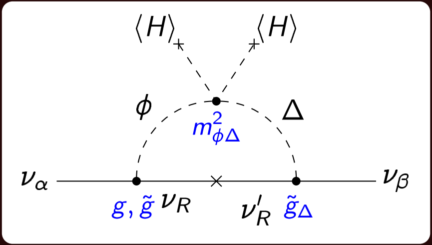

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$$(m_\nu)_{\alpha\beta} = [g_\alpha(\tilde{g}_\Delta)_\beta + g_\beta(\tilde{g}_\Delta)_\alpha]\tilde{\eta} + [\tilde{g}_\alpha(\tilde{g}_\Delta)_\beta + \tilde{g}_\beta(\tilde{g}_\Delta)_\alpha]\eta$$

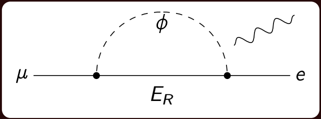
$$g\tilde{g}_\Delta \simeq 4.0\times 10^{-6}\,\frac{m_\nu}{0.05\text{ eV}}\,\frac{70\text{ GeV}}{M_1}\,\frac{50\text{ MeV}}{\delta}\,\frac{m_{RR}}{300\text{ GeV}}\,\frac{0.1}{|\sin\alpha_1|}\left(\frac{m^2_{RR}}{m^2_{RR}-m^2_\Delta}\cdots\right)^{-1}$$

$$g\tilde{g}_\Delta \simeq 4.5\times 10^{-6}\,\frac{m_\nu}{0.05\text{ eV}}\,\frac{300\text{ GeV}}{m_{RR}}\,\frac{1\text{ GeV}^2}{\tilde{m}^2_{\phi\Delta}}\left(\frac{m_\Delta}{500\text{ GeV}}\right)^2\frac{m^2_{RR}-m^2_\Delta}{m^2_\Delta}\left(\log\frac{m^2_{RR}}{m^2_\Delta}\right)^{-1}$$

$$\tilde{g}\tilde{g}_\Delta \simeq 1.8\times 10^{-10}\,\frac{m_\nu}{0.05\text{ eV}}\,\frac{300\text{ GeV}}{m_{RR}}\,\frac{0.1}{\sin\alpha_1}\,\frac{m^2_{RR}-m^2_\Delta}{m^2_\Delta}\left(\log\frac{m^2_{RR}}{m^2_\Delta}\right)^{-1}$$

Lepton Flavour Violation

Lepton Flavour Violation



$$\mathrm{Br}(\mu \to e\gamma) = 2.5 \cdot 10^{-9} \left(\frac{300\ \mathrm{GeV}}{m_{RR}}\right)^4 \left|\frac{g_\mu^*}{0.1}\frac{g_e}{0.1}\right|^2$$

$$\mathrm{Br}(\tau \to \alpha\gamma) = 4.5 \cdot 10^{-10} \left(\frac{300\ \mathrm{GeV}}{m_{RR}}\right)^4 \left|\frac{g_\tau^*}{0.1}\frac{g_\alpha}{0.1}\right|^2$$

Experimental Limits (90% CL)[PDG 2009]

$$\mathrm{Br}(\mu \to e\gamma) < 1.2 \cdot 10^{-11}$$

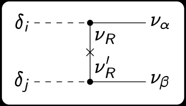
$$\mathrm{Br}(\tau \to e\gamma) < 1.1 \cdot 10^{-7}$$

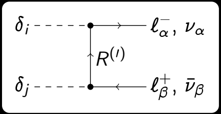
$$\mathrm{Br}(\tau \to \mu\gamma) < 4.5 \cdot 10^{-8}$$

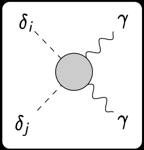
Solutions

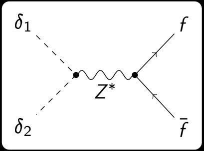
- $m_{RR}/g > 6$ TeV
- $g_e \ll g_\mu$ or $g_\mu \ll g_e$ (allowed by flavour structure)

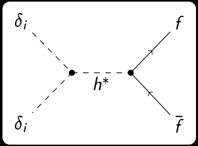
Dark Matter Annihilation





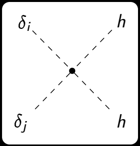






$$\Rightarrow \left\langle \sigma^H_{f\bar{f}} v \right\rangle \simeq N_c \frac{|\lambda_L|^2}{\pi} \frac{m_f^2}{(4\,M_1^2 - m_h^2)^2} \frac{(M_1^2 - m_f^2)^{3/2}}{M_1^3}$$

$$\sim 1.5 \cdot 10^{-26}\ \frac{\mathrm{cm}^3}{\mathrm{sec}} \ \text{for}\ \lambda_L \simeq 0.044;\ \ m_h = 120\ \mathrm{GeV}$$

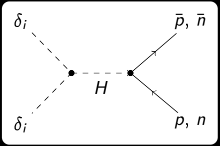


$$\Rightarrow \left\langle \sigma^H_{hh} v \right\rangle \simeq \frac{|\lambda_L|^2 (M_1^2 - m_h^2)^{1/2}}{16\pi M_1^3}$$

- Experimentally required value $\langle \sigma(\delta_1\delta_1 \to \dots) v \rangle \sim 3 \cdot 10^{-26}\ \mathrm{cm}^3/\mathrm{sec}$
- $\sigma_{12} \ll \sigma_{11}, \sigma_{22} \Rightarrow \delta_1$ and δ_2 produced and later $\delta_2 \to \delta_1 \nu\bar{\nu}$ with

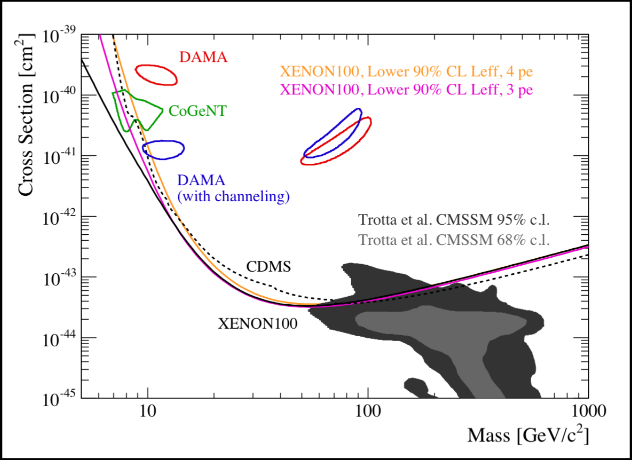
$$\Gamma(\delta_2 \xrightarrow{Z} \delta_1 \nu\bar{\nu}) \approx 14 \left(\frac{\delta}{50\ \mathrm{MeV}}\right)^5 \left(\frac{\sin\alpha_1}{0.1}\right)^4 \mathrm{sec}^{-1}$$

Direct DM Detection



$$\sigma_n = \frac{|\lambda_L|^2}{\pi}\frac{\mu^2_{\delta_1 n} m_p^2}{M_1^2 m_h^4} f^2$$

$$\approx 1.7\cdot 10^{-44}\mathrm{cm}^2 \left(\frac{\lambda_L}{0.044}\right)^2 \left(\frac{70\ \mathrm{GeV}}{M_1}\right)^2 \left(\frac{120\ \mathrm{GeV}}{m_h}\right)^4 \left(\frac{f}{0.3}\right)^2$$



Constraints

Electroweak Precision Tests: Higgs Triplet

$$\hat{S} = \frac{g_{\mathrm{SU}(2)}^2}{24\pi^2}\xi \qquad \hat{T} = \frac{25 g_{\mathrm{SU}(2)}^2}{576\pi^2}\frac{m_\Delta^2}{m_W^2}\xi^2$$

with $\xi := 1 - m_{\Delta^{++}}^2 / m_\Delta^2$ and $m_{\Delta^{++}}^2 = m_\Delta^2 + 2m_{\Delta^+}^2$

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Invisible Z-Decay Width

- DM particle δ_1 couples to Z-boson via mixing of Δ^0
- If $M_1 + M_2 < m_Z$, the corresponding Z-decay width is

$$\Gamma(Z \to \delta_1\delta_2) = \frac{G_F \sin^2\alpha_1 \sin^2\alpha_2}{6\sqrt{2}\pi} m_Z^3$$

- Bound on mixing angle in scalar sector: $\sin\alpha_1 \sin\alpha_2 < 0.07$, i.e. $m_{\phi\Delta}^2 \ll m_\Delta^2$ (protected by $U(1)_\phi \times U(1)_\Delta$)

Collider Physics

Higgs Search

- Higgs might dominantly decay invisibly if $2\,M_1 < m_h$

$$H \to \delta_1\delta_1\,, \quad H \to \delta_2\delta_2 \to (\delta_1\nu\bar{\nu})(\delta_1\nu\bar{\nu})$$

- Displaced vertex if mass splitting large $\delta_2 \to \delta_1\mu^+\mu^-$

Collider Physics

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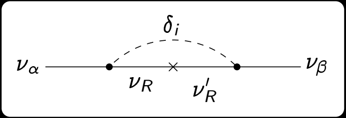
New Particles

- New particles accessible at LHC
- ...decay into the SM particles and DM $\Rightarrow$ missing energy
- Mass relation of triplet $2m_{\Delta^+}^2 = m_{\Delta^{++}}^2 + m_{\Delta}^2$
- Expect small mass splitting $m_{\Delta^{++}}^2 - m_{\Delta^+}^2$
- Determination of g_α: $\mathrm{Br}(E_R^- \to \ell_\alpha^-\delta_{1,2}) \propto |g_\alpha|^2$
- Determination of $\tilde{g}_\Delta$: decay modes of Δ^+ and Δ^{++}, especially $\Gamma(\Delta^{++} \to \ell_\alpha^+\ell_\beta^+\delta_{1,2}) \propto |(\tilde{g}_\Delta)_\alpha g_\beta + (\tilde{g}_\Delta)_\beta g_\alpha|^2$

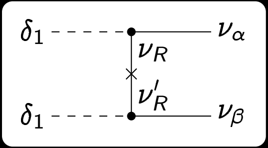
Alternative Scenario [Boehm, Farzan, Hambye, Palomares-Ruiz, Pascoli (2006)]

- Not $U(1)_X$ symmetry but lepton number L or $B - L \Rightarrow \tilde{g}_\Delta$ not small

Neutrino Mass generation



DM annihilation

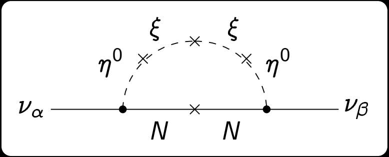


- Direct relation between neutrino mass and DM annihilation
$\Rightarrow$ light dark matter $M_1 \sim \mathcal{O}\,(\mathrm{MeV})$
- MeV scale dark matter might explain the SPI/INTEGRAL signal

Gauge Model

Particle Content

	SU(2)	U(1)	$U(1)_X$	$\mathbb{Z}_2$
$\ell_L^{(i)}$	2	-1	0	+
N_R	1	0	1	-
N_L	1	0	1	-
η	2	-1	-1	-
ξ	1	0	-1	-
ϕ	1	0	-2	+



- Neutrino masses from pseudo Dirac neutrinos N

$$m_{\alpha\beta} \simeq \frac{\kappa\,\lambda^2_{H\eta\xi\phi}}{16\pi^2}\frac{\langle\phi\rangle^4}{m_\eta^4}\frac{\langle H\rangle^2}{m_N^2}\sum_{i,j}(Y_N)_{i\alpha}(Y_N)_{j\beta}\, f_{ij}(m_N, Y_{LL}, Y_{RR}, m_\xi)$$

- LFV similar: $(m_N,\, m_{\eta^-})/Y_N \gtrsim 6\,\text{TeV}$ (unless special flavour structure)

Conclusions

- Neutrino mass can be generated radiatively at the TeV scale and linked to dark matter
- Discrete symmetry seems necessary for radiative neutrino mass generation
- U(1) gauge symmetry might be origin of discrete $\mathbb{Z}_2$ [See also talk by Batell]
- It is testable and the interplay of different experiments imposes strong constraints
- Upcoming experiments may exclude or confirm these models
- Strongest constraints from lepton flavour violating rare decays
- Higgs searches might be more challenging

Thank you very much for your attention.

More Phenomenology

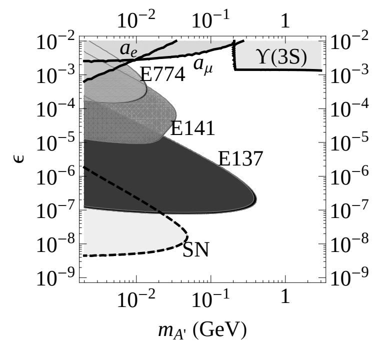
Z'

Gauge kinetic Lagrangian

$$\mathcal{L}_{\mathrm{U(1)}} = \frac{1}{4} F_Y^2 + \frac{1}{4} F_X^2 + \frac{\epsilon}{2} F_X F_Y$$

η in loop induces

$$\epsilon = \frac{g_X g_Y}{3\pi^2} \ln \frac{\Lambda^2}{\mu_\eta^2} \lesssim 1.3 g_X g_Y$$



[Bjorken,Essig,Schuster,Toro (2009)]

Collider

- SM Higgs mixes with $\mathrm{U(1)}_X$-Higgs $\Rightarrow$ Higgs mass bounds weakened
- Invisible Higgs decay like in all DM models in which Higgs exchange dominates