Exploring Scotogenic Signals in Higgs Boson Decays

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SY Ho & JT, arXiv:1303.5700 [PRD 87 (2013) 095015]

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Outline

- Introduction
  - Scotogenic model
- Interactions, neutrino masses, Yukawa couplings
- Constraints from low energy & dark matter data
- Implications for exotic & nonexotic decays of the Higgs boson
- Conclusions

Recent experimental developments

- Recent discovery of a Higgs boson with mass ~125 GeV at the LHC

- Numerous experimental data show that neutrinos have mass and mix
  - The latest measurements have confirmed that the neutrino mixing parameter $\sin\theta_{13}$ is not negligibly small

DAYA-BAY, 2012
RENO, 2012

- Astronomical observations imply that about a quarter of the total cosmic energy density is attributable to matter that is dark (nonluminous and nonabsorbing).

- Any realistic model of new physics needs to take into account all of these data.

- One of the simplest scenarios that can accommodate them is the scotogenic model

Ingredients of scotogenic model

Ma, 2006

- Beyond the standard model (SM), there are new particles
  - one scalar doublet, η
  - three singlet fermions, N_k
- Both η and N_k are odd under an exactly conserved Z_2 symmetry
  - but SM particles are even under Z_2.
- Being Z_2 odd, the lightest one of the new particles is stable and can serve as a dark matter (DM) candidate.
  - We shall choose N_1 to be the DM.
- Neutrino mass is generated radiatively at the one-loop level.

Interactions of new scalars

Ma, 2006

The interactions of the scalar particles with each other and the SM gauge bosons, $\boldsymbol{W}_\rho$ and B_ρ, are described by

$$\mathcal{L} = (\mathcal{D}^\rho \Phi)^\dagger \mathcal{D}_\rho \Phi + (\mathcal{D}^\rho \eta)^\dagger \mathcal{D}_\rho \eta - \mathcal{V}$$

$$\mathcal{D}_\rho = \partial_\rho + ig\frac{\boldsymbol{\tau}}{2}\cdot\boldsymbol{W}_\rho + ig_Y \mathcal{Q}_Y B_\rho$$

$$\mathcal{V} = \mu_1^2 \Phi^\dagger \Phi + \mu_2^2 \eta^\dagger \eta + \tfrac{1}{2}\lambda_1 (\Phi^\dagger \Phi)^2 + \tfrac{1}{2}\lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) + \tfrac{1}{2}\lambda_5 \left[(\Phi^\dagger \eta)^2 + (\eta^\dagger \Phi)^2\right]$$

Deshpande & Ma, 1978

and, after electroweak symmetry breaking,

$$\Phi = \begin{pmatrix} 0 \\ \frac{1}{\sqrt{2}}(h+v) \end{pmatrix}, \qquad \eta = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(\mathcal{S} + i\mathcal{P}) \end{pmatrix}$$

v is the vacuum expectation value (VEV) of Φ. The VEV of η is zero due to the Z_2 symmetry.

Masses of new scalars

$$\mathcal{L} = (\mathcal{D}^\rho \Phi)^\dagger \mathcal{D}_\rho \Phi + (\mathcal{D}^\rho \eta)^\dagger \mathcal{D}_\rho \eta - \mathcal{V}$$

$$\mathcal{V} = \mu_1^2 \Phi^\dagger \Phi + \mu_2^2 \eta^\dagger \eta + \tfrac{1}{2}\lambda_1 (\Phi^\dagger \Phi)^2 + \tfrac{1}{2}\lambda_2 (\eta^\dagger \eta)^2 + \lambda_3 (\Phi^\dagger \Phi)(\eta^\dagger \eta) + \lambda_4 (\Phi^\dagger \eta)(\eta^\dagger \Phi) + \tfrac{1}{2}\lambda_5 \left[(\Phi^\dagger \eta)^2 + (\eta^\dagger \Phi)^2\right]$$

- The masses of $\mathcal{S}$, $\mathcal{P}$, and $H^\pm$ are then

$$m_\mathcal{S}^2 = \mu_2^2 + \tfrac{1}{2}(\lambda_3 + \lambda_4 + \lambda_5) v^2 , \qquad m_\mathcal{P}^2 = \mu_2^2 + \tfrac{1}{2}(\lambda_3 + \lambda_4 - \lambda_5) v^2$$

$$m_H^2 = \mu_2^2 + \tfrac{1}{2}\lambda_3 v^2$$

- We will assume $|\lambda_5| \ll |\lambda_3 + \lambda_4|$ $\Rightarrow$ $|m_\mathcal{S}^2 - m_\mathcal{P}^2| = |\lambda_5| v^2 \ll m_\mathcal{S}^2 \simeq m_\mathcal{P}^2$

This is needed in order to satisfy both neutrino mass and relic density constraints

Interactions of new scalars

The couplings of η to h, the photon A, and the Z boson are described by

$$\mathcal{L} \supset \left[(\mu_2^2 - m_\mathcal{S}^2)\mathcal{S}^2 + (\mu_2^2 - m_\mathcal{P}^2)\mathcal{P}^2 + 2(\mu_2^2 - m_H^2)H^+H^- \right]\frac{h}{v}$$

$$+ ie\,(H^+\,\partial^\rho H^- - H^-\,\partial^\rho H^+)A_\rho + e^2\,H^+H^-A^2 + \frac{eg\,(1-2s_\mathrm{w}^2)}{c_\mathrm{w}}\,H^+H^-A^\rho Z_\rho$$

$$+ \frac{g}{2c_\mathrm{w}}\left[\mathcal{P}\,\partial^\rho\mathcal{S} - \mathcal{S}\,\partial^\rho\mathcal{P} + i(1-2s_\mathrm{w}^2)(H^+\,\partial^\rho H^- - H^-\,\partial^\rho H^+)\right]Z_\rho + \cdots$$

Interactions of new singlet fermions

- The new singlet fermions N_k can have Majorana masses and interact with other particles according to

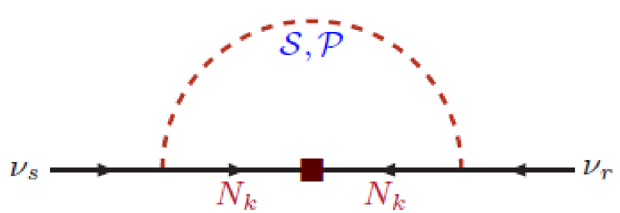
$$\mathcal{L}_N = -\tfrac{1}{2} M_k \overline{N_k^c} P_R N_k + \mathcal{Y}_{jk} \Big[\bar{\ell}_j H^- - \tfrac{1}{\sqrt{2}} \bar{\nu}_j (\mathcal{S} - i\mathcal{P}) \Big] P_R N_k + \text{H.c.}$$

$j, k = 1,2,3$ are summed over, $P_R = \frac{1}{2}(1+\gamma_5)$, and $\ell_{1,2,3} = e, \mu, \tau$.

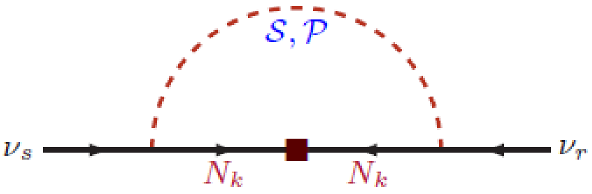
With $\mathcal{Y}_{jk} = Y_{\ell_j k}$, we have
$$\mathcal{Y} = \begin{pmatrix} Y_{e1} & Y_{e2} & Y_{e3} \\ Y_{\mu 1} & Y_{\mu 2} & Y_{\mu 3} \\ Y_{\tau 1} & Y_{\tau 2} & Y_{\tau 3} \end{pmatrix}$$

- The Z_2 symmetry does not allow Φ to couple to ν_j and N_k.

- The light neutrinos get mass via one-loop diagrams involving internal $\mathcal{S}$ or $\mathcal{P}$ and N_k.



Radiative neutrino masses



Ma, 2006

- The elements of the neutrino mass matrix from the one-loop diagram are

$$(\mathcal{M}_\nu)_{ij} = \frac{\mathcal{Y}_{ik}\mathcal{Y}_{jk} M_k}{16\pi^2}\left(\frac{m_\mathcal{S}^2}{m_\mathcal{S}^2 - M_k^2}\ln\frac{m_\mathcal{S}^2}{M_k^2} - \frac{m_\mathcal{P}^2}{m_\mathcal{P}^2 - M_k^2}\ln\frac{m_\mathcal{P}^2}{M_k^2}\right)$$

summation over $k = 1, 2, 3$ being implicit.

- In matrix form $\mathcal{M}_\nu = \mathcal{Y}\,\mathrm{diag}(\Lambda_1, \Lambda_2, \Lambda_3)\,\mathcal{Y}^\mathrm{T}$

$$\mathcal{Y} = \begin{pmatrix} Y_{e1} & Y_{e2} & Y_{e3} \\ Y_{\mu 1} & Y_{\mu 2} & Y_{\mu 3} \\ Y_{\tau 1} & Y_{\tau 2} & Y_{\tau 3} \end{pmatrix}$$

- For $m_\mathcal{S} \simeq m_\mathcal{P}$

$$\Lambda_k = \frac{\lambda_5 v^2}{16\pi^2 M_k}\mathcal{I}\left(\frac{M_k^2}{m_0^2}\right), \qquad \mathcal{I}(x) = \frac{x}{1-x} + \frac{x^2 \ln x}{(1-x)^2}$$

$$2m_0^2 = m_\mathcal{S}^2 + m_\mathcal{P}^2$$

PMNS neutrino mixing matrix

- The mass eigenvalues m_j of the neutrinos are given by

$$\mathrm{diag}(m_1, m_2, m_3) \; = \; \mathcal{U}^{\mathrm{T}} \mathcal{M}_\nu \mathcal{U}$$

$$\mathcal{M}_\nu \; = \; \mathcal{Y} \, \mathrm{diag}(\Lambda_1, \Lambda_2, \Lambda_3) \, \mathcal{Y}^{\mathrm{T}}$$

- $\mathcal{U}$ is the PMNS (Pontecorvo-Maki-Nakagawa-Sakata) unitary matrix.

- $\mathcal{U}$ relates the flavor states to the mass eigenstates: $\nu_{\ell_i} \; = \; \sum_{k=1}^{3} \mathcal{U}_{ik} \nu_k$

- Conventional parametrization (PDG)

$$\mathcal{U} \; = \; \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\, e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}\, e^{i\delta} & c_{12}c_{23} - s_{12}s_{13}s_{23}\, e^{i\delta} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}\, e^{-i\delta} & -c_{12}s_{23} - s_{12}s_{13}c_{23} & c_{13}c_{23} \end{pmatrix}$$

$$c_{kl} = \cos\theta_{kl}, \quad s_{kl} = \sin\theta_{kl}, \quad 0 \le \theta_{kl} \le \pi/2, \quad 0 \le \delta \le 2\pi.$$

Some simple forms of U

- $$\mathcal{U} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ \frac{-1}{\sqrt{2}}\sin\theta & \frac{1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}}\sin\theta & \frac{-1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}} \end{pmatrix}$$

  Suematsu, Toma, Yoshida, 2009

  If $\sin\theta = \frac{1}{\sqrt{3}}$, this $\mathcal{U}$ has the tribimaximal form.

- $$\mathcal{U} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ \frac{-1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{6}} & \frac{-1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \cos\varsigma & 0 & e^{i\delta}\sin\varsigma \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\varsigma & 0 & \cos\varsigma \end{pmatrix}$$

  He & Zee, 2011

- Both of these possibilities for $\mathcal{U}$ are no longer compatible with the latest findings, especially that $\sin\theta_{13}$ is not negligibly small : $\sin^2\theta_{13} = 0.0227^{+0.0023}_{-0.0024}$

  Gonzalez-Garcia *et al.*, 2012

Good choice of U

Ho & JT, 2013

- $$\mathcal{U} = \begin{pmatrix} \cos\theta & \sin\theta & 0 \\ \frac{-1}{\sqrt{2}}\sin\theta & \frac{1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}} \\ \frac{1}{\sqrt{2}}\sin\theta & \frac{-1}{\sqrt{2}}\cos\theta & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \cos\varsigma & 0 & e^{i\delta}\sin\varsigma \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\varsigma & 0 & \cos\varsigma \end{pmatrix}$$

  $$= \frac{1}{\sqrt{2}} \begin{pmatrix} \sqrt{2}\,\cos\theta\,\cos\varsigma & \sqrt{2}\,\sin\theta & \sqrt{2}\,e^{i\delta}\cos\theta\,\sin\varsigma \\ -\sin\theta\,\cos\varsigma - e^{-i\delta}\sin\varsigma & \cos\theta & -e^{i\delta}\sin\theta\,\sin\varsigma + \cos\varsigma \\ \sin\theta\,\cos\varsigma - e^{-i\delta}\sin\varsigma & -\cos\theta & e^{i\delta}\sin\theta\,\sin\varsigma + \cos\varsigma \end{pmatrix}$$

  involves only two mixing angles, θ and ς, and a CP-violating phase δ

- For simplicity, we fix $e^{i\delta} = 1$ compatible with the value $\delta = (300^{+66}_{-138})^\circ$ from the latest fit to the global data.

  Gonzalez-Garcia *et al.*, 2012

- Taking $\cos\theta\,\sin\varsigma = \sin\theta_{13}^{\rm exp}$ and $\theta \sim \theta_{12}^{\rm exp}$ leads numerically to elements of $\mathcal{U}$ consistent with their empirical counterparts within one sigma.

Neutrino mass eigenvalues

- Diagonalization equation

$$\mathrm{diag}(m_1, m_2, m_3) = \mathcal{U}^{\mathrm{T}} \mathcal{M}_\nu \mathcal{U}$$

$$\mathcal{M}_\nu = \mathcal{Y}\, \mathrm{diag}(\Lambda_1, \Lambda_2, \Lambda_3)\, \mathcal{Y}^{\mathrm{T}}$$

- Eigenvalues

$$\begin{aligned} m_1 &= \Big\{ Y_{ek}^2\, c_\theta^2\, c_\varsigma^2 - \sqrt{2}\, Y_{ek} [(Y_{\mu k} - Y_{\tau k}) s_\theta\, c_\varsigma + (Y_{\mu k} + Y_{\tau k}) s_\varsigma] c_\theta\, c_\varsigma \\ &\quad + \tfrac{1}{2} [(Y_{\mu k} - Y_{\tau k}) s_\theta\, c_\varsigma + (Y_{\mu k} + Y_{\tau k}) s_\varsigma]^2 \Big\} \Lambda_k \end{aligned}$$

$$m_2 = \Big[\tfrac{1}{2} (Y_{\mu k} - Y_{\tau k})^2 c_\theta^2 + \sqrt{2}\, Y_{ek} (Y_{\mu k} - Y_{\tau k}) c_\theta\, s_\theta + Y_{ek}^2\, s_\theta^2 \Big] \Lambda_k$$

$$\begin{aligned} m_3 &= \Big\{ Y_{ek}^2\, c_\theta^2\, s_\varsigma^2 + \sqrt{2}\, Y_{ek} [(Y_{\mu k} + Y_{\tau k}) c_\varsigma - (Y_{\mu k} - Y_{\tau k}) s_\theta\, s_\varsigma] c_\theta\, s_\varsigma \\ &\quad + \tfrac{1}{2} [(Y_{\mu k} + Y_{\tau k}) c_\varsigma - (Y_{\mu k} - Y_{\tau k}) s_\theta\, s_\varsigma]^2 \Big\} \Lambda_k \end{aligned}$$

summation over $k = 1, 2, 3$ is implicit, $c_\theta = \cos\theta$, $s_\theta = \sin\theta$, $c_\varsigma = \cos\varsigma$, $s_\varsigma = \sin\varsigma$

Neutrino mass diagonalization conditions

- The vanishing of the off-diagonal elements of $\mathrm{diag}(m_1, m_2, m_3) = \mathcal{U}^{\rm T}\mathcal{M}_\nu\mathcal{U}$ implies

$$
\begin{aligned}
0 \;=\; & \Big\{\sqrt{2}\,Y_{ek}\,(Y_{\mu k}-Y_{\tau k})(c_\theta^2-s_\theta^2)c_\varsigma+\Big[2Y_{ek}^2-(Y_{\mu k}-Y_{\tau k})^2\Big]c_\theta s_\theta\,c_\varsigma \\
& -(Y_{\mu k}^2-Y_{\tau k}^2)c_\theta\,s_\varsigma-\sqrt{2}\,Y_{ek}\,(Y_{\mu k}+Y_{\tau k})s_\theta\,s_\varsigma\Big\}\Lambda_k
\end{aligned}
$$

$$
\begin{aligned}
0 \;=\; & \Big\{\sqrt{2}\,Y_{ek}\,(Y_{\mu k}-Y_{\tau k})(c_\theta^2-s_\theta^2)s_\varsigma+\Big[2Y_{ek}^2-(Y_{\mu k}-Y_{\tau k})^2\Big]c_\theta s_\theta\,s_\varsigma \\
& +(Y_{\mu k}^2-Y_{\tau k}^2)c_\theta\,c_\varsigma+\sqrt{2}\,Y_{ek}\,(Y_{\mu k}+Y_{\tau k})s_\theta\,c_\varsigma\Big\}\Lambda_k
\end{aligned}
$$

$$
\begin{aligned}
0 \;=\; & \Big\{\Big[\Big(2Y_{ek}^2-Y_{\mu k}^2-Y_{\tau k}^2\Big)c_\theta^2-\sqrt{8}\,Y_{ek}\,(Y_{\mu k}-Y_{\tau k})c_\theta s_\theta-2Y_{\mu k}Y_{\tau k}\,(1+s_\theta^2)\Big]c_\varsigma s_\varsigma \\
& +\Big[\sqrt{2}\,Y_{ek}\,c_\theta-(Y_{\mu k}-Y_{\tau k})s_\theta\Big](Y_{\mu k}+Y_{\tau k})(c_\varsigma^2-s_\varsigma^2)\Big\}\Lambda_k
\end{aligned}
$$

summation over $k=1,2,3$ is again implicit

- These equations turn out to be exactly solvable for Y_{ek} and $Y_{\mu k}$ in terms of $Y_k = Y_{\tau k}$

Solutions for Yukawa couplings

- There is more than one set of the solutions.
- They each can be expressed as $(Y_{ek}, Y_{\mu k}) = (\bar{e}_z, \bar{\mu}_z) Y_k$, where $z = a, b,$ or c and

$$\bar{e}_a = \frac{\sqrt{2}\, c_\theta\, c_\varsigma}{s_\theta\, c_\varsigma - s_\varsigma}\,, \qquad \bar{e}_b = \frac{-\sqrt{2}\, s_\theta}{c_\theta}\,, \qquad \bar{e}_c = \frac{\sqrt{2}\, c_\theta\, s_\varsigma}{s_\theta\, s_\varsigma + c_\varsigma}$$

$$\bar{\mu}_a = \frac{s_\varsigma + s_\theta\, c_\varsigma}{s_\varsigma - s_\theta\, c_\varsigma}\,, \qquad \bar{\mu}_b = -1\,, \qquad \bar{\mu}_c = \frac{c_\varsigma - s_\theta\, s_\varsigma}{s_\theta\, s_\varsigma + c_\varsigma}$$

- In total there are 27 possible sets of solutions
  - 3 sets can each give only 1 nonzero *ν* mass
  - 18 sets can each give 2 nonzero *ν* masses
  - 6 sets can each give 3 nonzero *ν* masses

Sample solutions

- One of the solution sets that each yield 2 nonzero masses (set I)

$$Y_{ei} = \frac{\sqrt{2}\, c_\theta\, s_\varsigma\, Y_i}{s_\theta\, s_\varsigma + c_\varsigma}\,, \qquad i = 1,2\,, \qquad Y_{e3} = \frac{-\sqrt{2}\, s_\theta\, Y_3}{c_\theta}$$

$$Y_{\mu i} = \frac{c_\varsigma - s_\theta\, s_\varsigma}{s_\theta\, s_\varsigma + c_\varsigma}\, Y_i\,, \qquad Y_{\mu 3} = -Y_3$$

$$m_1 = 0\,, \qquad m_2 = \frac{2\Lambda_3\, Y_3^2}{c_\theta^2}\,, \qquad m_3 = \frac{2(\Lambda_1\, Y_1^2 + \Lambda_2\, Y_2^2)}{(s_\theta\, s_\varsigma + c_\varsigma)^2}$$

- Hereafter we employ one of the solution sets that each yield 3 nonzero masses (set II)

$$Y_{e1} = \frac{\sqrt{2}\, c_\theta\, c_\varsigma\, Y_1}{s_\theta\, c_\varsigma - s_\varsigma}\,, \qquad Y_{e2} = \frac{-\sqrt{2}\, s_\theta\, Y_2}{c_\theta}\,, \qquad Y_{e3} = \frac{\sqrt{2}\, c_\theta\, s_\varsigma\, Y_3}{s_\theta\, s_\varsigma + c_\varsigma}$$

$$Y_{\mu 1} = \frac{s_\varsigma + s_\theta\, c_\varsigma}{s_\varsigma - s_\theta\, c_\varsigma}\, Y_1\,, \qquad Y_{\mu 2} = -Y_2\,, \qquad Y_{\mu 3} = \frac{c_\varsigma - s_\theta\, s_\varsigma}{s_\theta\, s_\varsigma + c_\varsigma}\, Y_3$$

$$m_1 = \frac{2\Lambda_1\, Y_1^2}{(s_\varsigma - s_\theta\, c_\varsigma)^2}\,, \qquad m_2 = \frac{2\Lambda_2\, Y_2^2}{c_\theta^2}\,, \qquad m_3 = \frac{2\Lambda_3\, Y_3^2}{(c_\varsigma + s_\theta\, s_\varsigma)^2}$$

Some numbers

Numerically, we adopt for definiteness $\cos\theta \, \sin\varsigma \;=\; \sqrt{0.0227}\,, \qquad \theta \;=\; 32.89^\circ$

implying that $\theta_{12} \;=\; 33.32^\circ$ and $\theta_{23} \;=\; 39.34^\circ$

For comparison $\theta_{12}^{\rm exp} \;=\; \left(33.36^{+0.81}_{-0.78}\right)^\circ$ and $\theta_{23}^{\rm exp} \;=\; \left(40.0^{+2.1}_{-1.5}\right)^\circ$

Gonzalez-Garcia *et al.*, 2012

- For solution sets I & II

Numerical values of $\hat{Y}_{\ell k} = Y_{\ell k}/Y_k$ and neutrino masses in terms of $\tilde{\Lambda}_k = \Lambda_k Y_k^2$.

Set	$\hat{Y}_{e1}$	$\hat{Y}_{\mu 1}$	$\hat{Y}_{e2}$	$\hat{Y}_{\mu 2}$	$\hat{Y}_{e3}$	$\hat{Y}_{\mu 3}$	m_1	m_2	m_3
I	0.197	0.820	0.197	0.820	−0.915	−1	0	$2.84\,\tilde{\Lambda}_3$	$1.71(\tilde{\Lambda}_1+\tilde{\Lambda}_2)$
II	3.293	−2.011	−0.915	−1	0.197	0.820	$15.89\,\tilde{\Lambda}_1$	$2.84\,\tilde{\Lambda}_2$	$1.71\,\tilde{\Lambda}_3$

Mass constraints

- Neutrino oscillation measurements determine the differences $\Delta^2_{ji} = m_j^2 - m_i^2$.
  From the latest fit to the data (for normal hierarchy of the masses)

$$\Delta^2_{21,\mathrm{exp}} = (7.50^{+0.18}_{-0.19}) \times 10^{-5}\ \mathrm{eV}^2\ , \qquad \Delta^2_{31,\mathrm{exp}} = (2.473^{+0.070}_{-0.067}) \times 10^{-3}\ \mathrm{eV}^2$$

Gonzalez-Garcia *et al.*, 2012

$$31.0 < \frac{\Delta^2_{31}}{\Delta^2_{21}} < 35.0$$

based on the 90% CL ranges of the data

- There are also constraints on the effective mass parameters $\langle m_\beta \rangle$ and $\langle m_{\beta\beta} \rangle$ from beta decay and neutrinoless double-beta decay experiments, respectively, and on the sum of masses, $\Sigma_k m_k$, from astrophysical and cosmological observations.

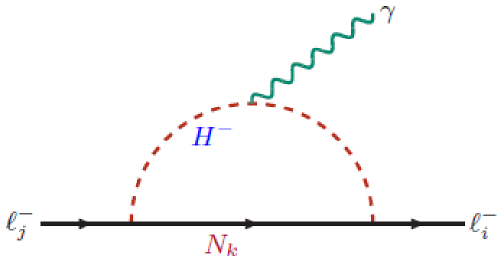
  But the limits are still too weak

$$\langle m_\beta \rangle = \sqrt{\sum_k |\mathcal{U}_{1k}|^2 m_k^2} < 2.1\ \mathrm{eV}\ , \qquad \langle m_{\beta\beta} \rangle = |\sum_k \mathcal{U}_{1k}^2 m_k| < 0.25\ \mathrm{eV}$$

$$\sum_k m_k < (0.5\text{-}1.5)\ \mathrm{eV}$$

Rodejohan, 2012
KamLAND-Zen, 2013

Constraints from loop induced transitions



- Radiative decay

Branching ratio $\mathcal{B}(\ell_j \to \ell_i \gamma) \; = \; \dfrac{3\alpha\,\mathcal{B}(\ell_j \to \ell_i \nu\bar{\nu})}{64\pi\, G_F^2\, m_H^4} \Big|\sum_k \mathcal{Y}_{ik}\mathcal{Y}_{jk}^*\, \mathcal{F}(M_k^2/m_H^2)\Big|^2$

Ma & Raidal, 2001

$G_F \; = \; \dfrac{1}{\sqrt{2}\, v^2}$ is the Fermi constant, $\alpha \; = \; \dfrac{e^2}{4\pi}$, $\mathcal{F}(x) \; = \; \dfrac{1 - 6x + 3x^2 + 2x^3 - 6x^2 \ln x}{6(1-x)^4}$

The experimental bounds on their branching ratios are at 90% CL

$$\mathcal{B}(\mu \to e\gamma)_{\rm exp} \; < \; 5.7 \times 10^{-13}$$

$$\mathcal{B}(\tau \to e\gamma)_{\rm exp} \; < \; 3.3 \times 10^{-8}\,, \qquad \mathcal{B}(\tau \to \mu\gamma)_{\rm exp} \; < \; 4.4 \times 10^{-8}$$

MEG, 2013
PDG, 2012

For $\mathcal{B}(\ell_j \to \ell_i \nu\bar{\nu})$ we use the central values of their data: $\mathcal{B}(\mu \to e\nu\bar{\nu})_{\rm exp} \simeq 1$, $\mathcal{B}(\tau \to e\nu\bar{\nu})_{\rm exp} = 0.1783 \pm 0.0004$, and $\mathcal{B}(\tau \to \mu\nu\bar{\nu})_{\rm exp} = 0.1741 \pm 0.0004$

- Lepton anomalous magnetic moment

$$\Delta a_{\ell_i} \; = \; \frac{-m_{\ell_i}^2}{16\pi^2 m_H^2} \sum_k |\mathcal{Y}_{ik}|^2\, \mathcal{F}(M_k^2/m_H^2)$$

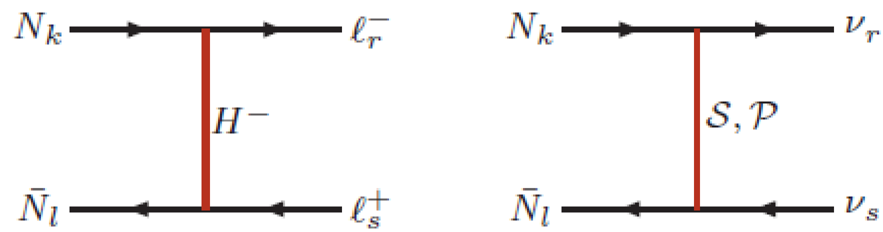
$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = (249 \pm 87) \times 10^{-11} \qquad \Rightarrow \qquad |\Delta a_\mu| \; < \; 9 \times 10^{-10}$$

Aoyama *et al.*, 2012

Dark matter constraints

- Since N_1 has been chosen to be the lightest of the new particles and serve as cold dark matter, it needs to account for the observed relic abundance, which therefore imposes bounds on $Y_{\ell 1}$ and hence Y_1.

- N_1 annihilation diagrams



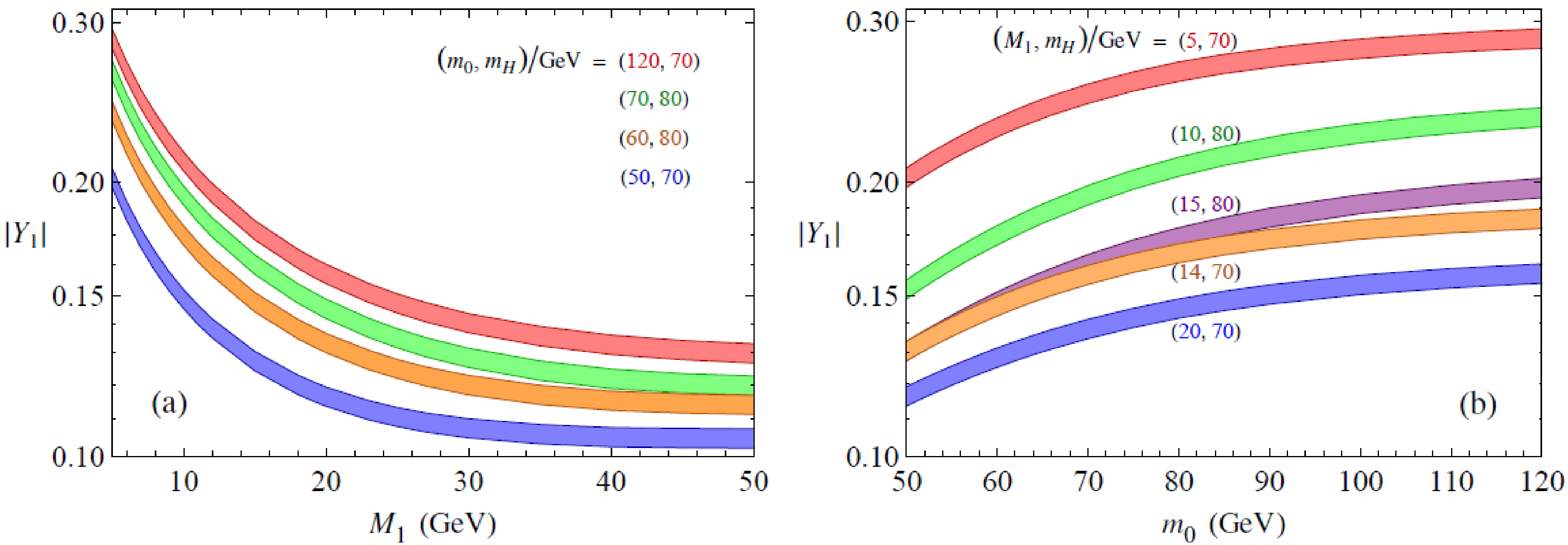
- Annihilation cross-section (if the final leptons are massless)

$$\sigma_{\rm ann} v_{\rm rel} = \sum_{i,j=1,2,3} \frac{|\mathcal{Y}_{i1}\mathcal{Y}_{j1}|^2 M_1^2 v_{\rm rel}^2}{48\pi} \left[\frac{M_1^4 + m_H^4}{(M_1^2 + m_H^2)^4} + \frac{M_1^4 + m_0^4}{(M_1^2 + m_0^2)^4} \right]$$

- Relic data (PDG) $\quad \Omega \hat{h}^2 = 0.111 \pm 0.006 \quad \Rightarrow \quad 0.101 \le \Omega \hat{h}^2 \le 0.121$

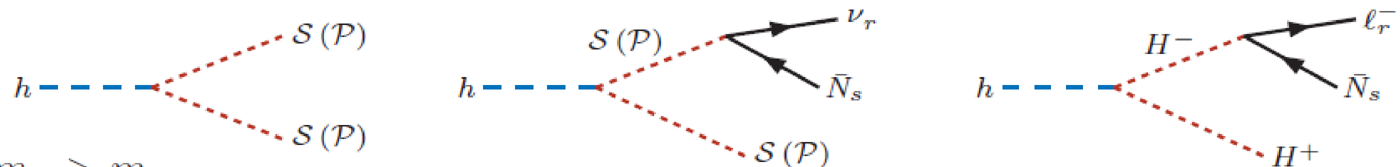
Dark matter constraints on Y_1

- Illustrations of the relic constraints on $|Y_1|$



- Direct search constraints are still too weak. Since N_1 can scatter off a nucleon mainly via its one-loop Z-mediated axial-vector interactions with quarks, the process is characterized by a spin-dependent cross-section that is relatively suppressed and in this case still orders of magnitude below the strictest limit to date, measured by XENON100 (2013).

Scotogenic exotic decays of Higgs boson



Collider and Z data imply $m_{\mathcal{S}} + m_{\mathcal{P}} > m_Z$

- $$\mathcal{M}_{h\to\mathcal{SS}} \simeq \mathcal{M}_{h\to\mathcal{PP}} \simeq \frac{2(m_0^2-\mu_2^2)}{v}$$

$$\Gamma(h\to\eta^0\eta^0) = \Gamma(h\to\mathcal{SS}) + \Gamma(h\to\mathcal{PP}) \simeq \frac{(m_0^2-\mu_2^2)^2}{4\pi\, m_h v^2}\sqrt{1-\frac{4m_0^2}{m_h^2}}$$

- $$\mathcal{M}_{h\to\mathcal{S}(\mathcal{P})\nu_j\bar{N}_k} = (-i)\frac{\sqrt{2}}{v}\frac{(\mu_2^2-m_0^2)\,\mathcal{Y}_{jk}\,\bar{\nu}_j P_R N_k}{m_0^2-(p_\nu+p_N)^2}$$

$$\Gamma(h\to\eta^0\nu N) = \sum_{\hat{\eta}=\mathcal{S},\mathcal{P}}\ \sum_{j,k=1,2,3}\left[\Gamma(h\to\hat{\eta}\,\nu_j\bar{N}_k)+\Gamma(h\to\hat{\eta}\,\bar{\nu}_j N_k)\right]$$

- Since collider data require $m_H \gtrsim 70\,\mathrm{GeV}$, the 3-body decays $h\to H^+\ell_j^-\bar{N}_k$ and their charge-conjugated parners dominate the charged modes for $m_H + m_\ell + m_N < m_h$.

$$\mathcal{M}_{h\to H^+\ell_j^-\bar{N}_k} = \frac{2}{v}\frac{(m_H^2-\mu_2^2)\,\mathcal{Y}_{jk}\,\bar{\ell}_j P_R N_k}{m_H^2-(p_\ell+p_N)^2}$$

$$\Gamma(h\to H\ell N) = \sum_{j,k=1,2,3}\left[\Gamma(h\to H^+\ell_j^-\bar{N}_k)+\Gamma(h\to H^-\ell_j^+ N_k)\right]$$

- Examples of branching ratio of scotogenic exotic decays of a 125.5-GeV Higgs boson with couplings satisfying the various constraints.

$$\mathcal{B}_{\mathcal{SPH}} = \frac{\Gamma_{\mathcal{SPH}}}{\Gamma_h^{\rm SM} + \Gamma_{\mathcal{SPH}}}$$

$\Gamma_{\mathcal{SPH}}$ is the sum of $\Gamma(h \to \eta^0\eta^0)$ or $\Gamma(h \to \eta^0\nu N)$, depending on m_0, and $\Gamma(h \to H\ell N)$.

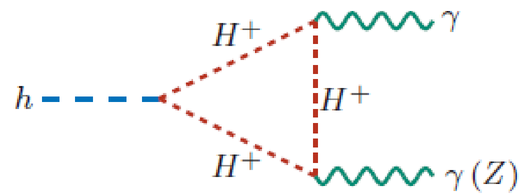
m_0	m_H	μ_2	M_1	M_2	M_3	Y_1	Y_2	Y_3	$\mathcal{B}_{\mathcal{SPH}}$
50	70	46 (47)	9	13	63	0.155	0.372	0.632	21 (14)
60	80	54 (56)	10	15	71	0.172	0.413	0.700	26 (14)
70	70	$40i$ (25)	14	20	80	0.155	0.378	0.677	23 (11)
70	80	111 (99)	12	17	78	0.180	0.437	0.730	24 (12)
80	80	159 ($88i$)	15	22	82	0.175	0.422	0.760	22 (13)
120	70	123 (111)	20	29	85	0.157	0.386	0.715	20 (12)

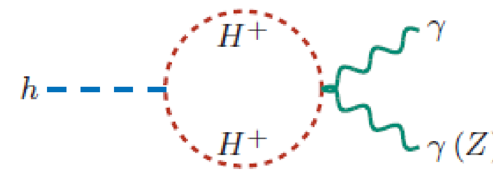
- LHC data allow the branching ratio of nonstandard decays of the Higgs into invisible or undetected final-states to be as high as 19%-22% at 95% CL.
  - This restriction is not yet strong for the scenario considered.

Cheung, Lee, Tseng, 2013
Falkowski, Riva, Urbano, 2013
Giordano *et al.*, 2013
Ellis & You, 2013

Scotogenic effects on $h \to \gamma\gamma$ and $h \to \gamma Z$

- Scotogenic contributions





- Decay rates including SM contributions

$$\Gamma(h \to \gamma\gamma) = \frac{\alpha^2 G_{\rm F}\, m_h^3}{128\sqrt{2}\,\pi^3} \left| \frac{4}{3} A_{1/2}^{\gamma\gamma}(\kappa_t) + A_1^{\gamma\gamma}(\kappa_W) + \frac{m_H^2 - \mu_2^2}{m_H^2} A_0^{\gamma\gamma}(\kappa_H) \right|^2$$

$$\Gamma(h \to \gamma Z) = \frac{\alpha G_{\rm F}^2\, m_W^2 (m_h^2 - m_Z^2)^3}{64\pi^4\, m_h^3} \left| \left(\frac{2}{c_{\rm w}} - \frac{16 s_{\rm w}^2}{3 c_{\rm w}} \right) A_{1/2}^{\gamma Z}(\kappa_t, \lambda_t) + c_{\rm w}\, A_1^{\gamma Z}(\kappa_W, \lambda_W) - \frac{(1 - 2s_{\rm w}^2)(m_H^2 - \mu_2^2)}{c_{\rm w}\, m_H^2} A_0^{\gamma Z}(\kappa_H, \lambda_H) \right|^2$$

$$\kappa_X = 4m_X^2/m_h^2 \,, \qquad \lambda_X = 4m_X^2/m_Z^2$$

Scotogenic effects on $h \to \gamma\gamma$ and $h \to \gamma Z$

- $$\mathcal{R}_{\gamma\mathcal{V}^0} = \frac{\Gamma(h \to \gamma\mathcal{V}^0)}{\Gamma(h \to \gamma\mathcal{V}^0)_{\rm SM}}, \qquad \mathcal{V}^0 = \gamma, Z$$

m_0	m_H	μ_2	M_1	M_2	M_3	Y_1	Y_2	Y_3	$\mathcal{B}_{\mathcal{SPH}}$	$\mathcal{R}_{\gamma\gamma}$	$\mathcal{R}_{\gamma Z}$
50	70	46 (47)	9	13	63	0.155	0.372	0.632	21 (14)	0.89 (0.89)	0.95 (0.95)
60	80	54 (56)	10	15	71	0.172	0.413	0.700	26 (14)	0.91 (0.92)	0.96 (0.97)
70	70	$40i$ (25)	14	20	80	0.155	0.378	0.677	23 (11)	0.75 (0.83)	0.88 (0.92)
70	80	111 (99)	12	17	78	0.180	0.437	0.730	24 (12)	1.15 (1.09)	1.06 (1.04)
80	80	159 ($88i$)	15	22	82	0.175	0.422	0.760	22 (13)	1.53 (0.68)	1.21 (0.86)
120	70	123 (111)	20	29	85	0.157	0.386	0.715	20 (12)	1.48 (1.34)	1.20 (1.14)

- The scotogenic effects on the $\gamma\gamma$ and γZ modes are positively correlated.
- There does not appear to be a clear correlation between $\mathcal{B}_{\mathcal{SPH}}$ and the scotogenic effects on the $\gamma\gamma$ and γZ modes.
- The $\gamma\gamma$ predictions are compatible with one or more of the LHC data

  The signal strength is $\sigma/\sigma_{\rm sm} = 1.55^{+0.33}_{-0.28}$ from ATLAS and $\sigma/\sigma_{\rm SM} = 0.78^{+0.28}_{-0.26}$ and $1.11^{+0.32}_{-0.30}$ from CMS.

  Talk by A. De Roeck
- Future data on the γZ channel will provide supplementary information.

Conclusions

- We have explored for the scotogenic model of radiative neutrino mass some implications of the recent discovery of a Higgs boson at the LHC and experimental determination of $\sin\theta_{13}$ that is not very small.
- Employing a 2-parameter neutrino-mixing matrix consistent with the latest data, we derive simple solutions for the Yukawa couplings of the nonstandard particles in the model.
  - Such solutions are applicable to some other models of radiative neutrino mass.
- Taking into account various constraints, we use the solutions to consider Higgs decays into final states containing the new particles.
  - Within the allowed parameter space the rates of such decays can be significant and are already bounded by the latest Higgs data.
- We also look at how these exotic channels may correlate with the scotogenic effects on Higgs decays into $\gamma\gamma$ and γZ.
- Upcoming Higgs data can then be expected to reveal hints of the new particles or impose further restrictions on the model.