DIMENSION 7 NEUTRINO MASS GENERATION AND ITS IMPLICATIONS FOR THE LHC AND THE DARK MATTER

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K.S. Babu, S. Nandi, Z. Tavartkiladze, Phys. Rev. D **80**, 071702 (2009)

S. Bhattacharya, S. Jana and S. Nandi, Phys. Rev. D **95**, no. 5, 055003 (2017)

K. Ghosh, S. Jana and S. Nandi, arXiv:1705.01121

T. Ghosh, S. Jana, S. Nandi, (to appear)

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Goals

- To provide a new mechanism for light neutrino mass generation with new mass scale at the TeV.
- To connect the neutrino physics with the physics that can be explored at the LHC.
- To connect neutrino physics to dark matter.

Outline of Talk

- Introduction
- Model and the Formalism
- Phenomenological Implications
  - for LHC
  - for Dark Matter
- Conclusions and Outlook

Introduction

- The existence of neutrino masses are now firmly established.
  $m_\nu \sim 10^{-2}$ eV $\Rightarrow$ 1st and only indication for physics beyond the SM

- m_ν is about a billion times smaller the quark and charged lepton masses

- What is the mechanism for such a tiny neutrino mass generation ?

Introduction

- Most popular mechanism : see-saw, $m_\nu \sim \frac{m_D^2}{M}$
  $\Rightarrow$ dimension 5 operator : $L_{eff} = \frac{f}{M} LLHH$
  The observed neutrino mass, $m_\nu \sim 10^{-2}$ eV.

- If $M = M_{PL}$, then m_ν is too small

- If $M = M_{GUT}$, then m_ν is still too small

- $M \sim 10^{14}$ GeV is needed
  $\rightarrow$ A new symmetry breaking scale (N_R)

- This scale is too high $\rightarrow$ No connection can be made to the physics to be explored at the LHC or Tevatron
  $\Rightarrow$ need $M \sim$ TeV.

Introduction

- It is possible that the dimension 5 operator does not contribute to neutrino masses in a significant way.
  $\Rightarrow$ next operator (dimension 7) : $L_{eff} = \frac{f}{M^3} LLHH(H^\dagger H)$

- If $M = M_{PL}$, This by itself is not enough to make $M \sim$ TeV, need $f \sim 10^{-9}$

- We propose a model in which $f \sim y_1 y_2 \lambda_4$ with each $\sim 10^{-3}$ (domain of natural values)

- This gives $M \sim$ TeV scale to obtain neutrino masses in the range $10^{-2} - 10^{-1}$ eV.
  $\Rightarrow$ Connect to physics at the LHC, as well as dark matter

Model & Formaism

- Gauge Symmetry : $SU(3)_C \times SU(2)_L \times U(1)_Y$

- Usual SM particles
  +a pair of vector-like $SU(2)$ triplet leptons,
  $$\Sigma \equiv \begin{pmatrix} \Sigma^{++} \\ \Sigma^{+} \\ \Sigma^{0} \end{pmatrix} \sim (1,3,2),\ \bar{\Sigma} \equiv \begin{pmatrix} \bar{\Sigma}^{0} \\ \bar{\Sigma}^{-} \\ \bar{\Sigma}^{--} \end{pmatrix} \sim (1,3,-2)$$
  +a new isospin $\frac{3}{2}$ scalar quadruplet,
  $$\Delta \equiv \begin{pmatrix} \Delta^{+++} \\ \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix} \sim (1,4,3)$$
  +a new scalar singlet, $S \sim (1,1,0)$.

- Δ has positive mass square, but acquires a tiny induced VEV through Higgs potential via interaction with H.

- Σ has interactions with SM lepton doublets, H as well as Δ.

Model & Formalism

- Higgs Potential

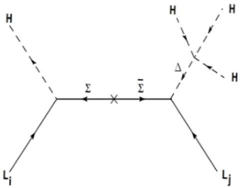
$$V(H,\Delta) = \mu_H^2 H^\dagger H + \mu_\Delta^2 \Delta^\dagger \Delta + \frac{\lambda_1}{2}(H^\dagger H)^2 + \frac{\lambda_2}{2}(\Delta^\dagger \Delta)^2 \\ +\lambda_3 (H^\dagger H)(\Delta^\dagger \Delta) + \lambda_4 (H^\dagger \tau_a H)(\Delta^\dagger T_a \Delta) + \{\lambda_5 H^3 \Delta^\star + h.c.\}, \tag{1}$$

$$V(H,\Delta,S) = V(H,\Delta) + \mu_S^2 S^2 + \frac{\lambda_7}{2} S^4 + \lambda_8 (H^\dagger H) S^2 \\ +\lambda_9 (\Delta^\dagger \Delta) S^2, \tag{2}$$

- Minimization of V $\Rightarrow$ Neutral component of Δ acquires an induced VEV at the tree level, $v_\Delta = -\lambda_5 v^3 / M_\Delta^2$

Model & Formalism

Neutrino Mass Generation in the Model



$$\mathcal{L}_{\nu-\text{mass}} = Y_i L_i H^* \Sigma + \overline{Y}_i L_i \Delta \overline{\Sigma} + M_\Sigma \Sigma \overline{\Sigma} + h.c.,$$

Integrating out the $\Sigma, \overline{\Sigma}$ fermions

$$\mathcal{L}_{\text{eff}} = -\frac{(Y_i \overline{Y}_j + Y_j \overline{Y}_i) L_i L_j H^* \Delta}{M_\Sigma} + h.c.$$

- EWSB induces a VEV on the *CP*-even neutral component of the quadruplet

$$v_\Delta \;=\; -\lambda_5 v^3 / M_\Delta^2$$

- This leads to dimension 7 neutrino mass at tree level with Δ replaced by HHH/M_Δ^2.

$$(m_\nu)_{ij} = \frac{(Y_i Y_j' + Y_i' Y_j) v_\Delta v}{M_\Sigma} = -\frac{\lambda_5 (Y_i Y_j' + Y_i' Y_j) v^4}{(M_\Sigma M_{\Delta^0}^2)}.$$

- $m_\nu \sim 10^{-2} - 10^{-1}$ eV range with M_Σ and M_Δ at the TeV scale with $(Y_1, Y_2, \lambda_5) \sim 10^{-3}$

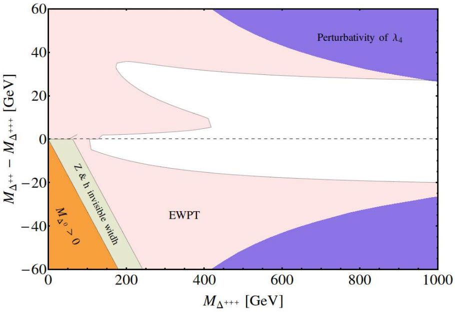
Phenomenological Implications

Signals at LHC :

- Productions of Δ's in the model
- Decay modes
- Mass Bounds
- Signals
- Other Implications

Phenomenological Implications

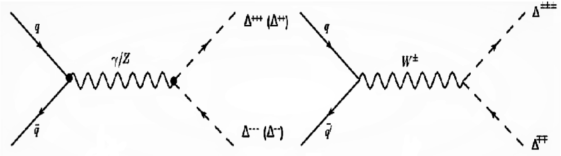
Constraints

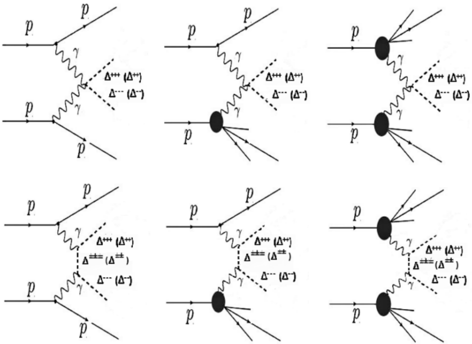


- $M^2_{\Delta_i} = M^2_{\Delta^0} - q_i \frac{\lambda_4}{2} v^2 \, (q_i = 1, 2, 3)$
- $\Delta M > 0 \implies M_{\Delta^{+++}} < M_{\Delta^{++}} < M_{\Delta^{+}} < M_{\Delta^0}$
- $\Delta M < 0 \implies M_{\Delta^{+++}} > M_{\Delta^{++}} > M_{\Delta^{+}} > M_{\Delta^0}$
- EWPT $\implies$ S, T parameters constrains the parameter space in $M_{\Delta^{\pm\pm\pm}} - \Delta M$ plane

Phenomenological Implications

A. Productions

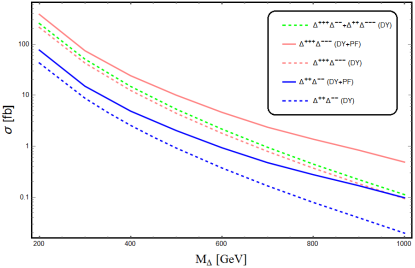


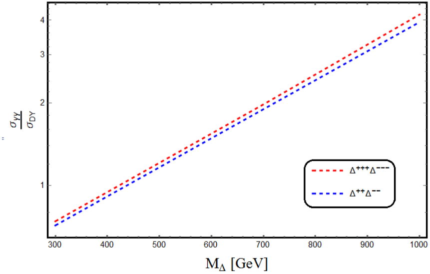


- Drell Yan Production
- Photon Photon Fusion

Phenomenological Implications

A. Productions

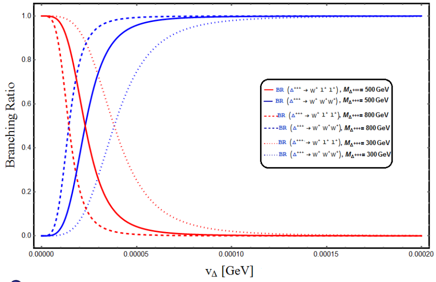


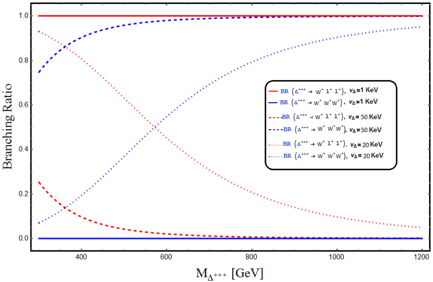


- $\Delta^{\pm\pm\pm}(\Delta^{\pm\pm})$ pair and associated production at the LHC happens via Drell-Yan (DY)
- Photon fusion (PF) is another process
  $\Rightarrow$ Photon PDF is available from `NNPDF`, `CTEQ`, `MRST`
- For larger $\Delta^{\pm\pm\pm}(\Delta^{\pm\pm})$ PF contribution is significant
  $\rightarrow$ However uncertainty in available photon PDFs are significant ($\sim$25 - 30%)

Babu, Jana, (2016) [arXiv:1612.09224], K.Ghosh, Jana, Nandi, (2017) [arXiv:1705.01121]

B. Decay Modes of Triply Charged Scalar

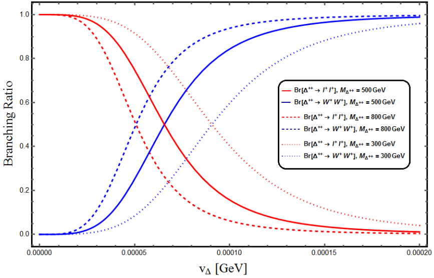


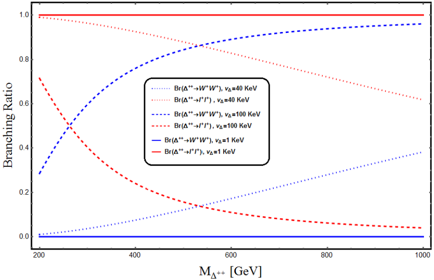


- Depends on ΔM and v_Δ
- For $\Delta M \geq 0 \implies$
  - $\Delta^{\pm\pm\pm} \to l^\pm l^\pm W^\pm (W^\pm W^\pm W^\pm)$ dominates for small (large) v_Δ
  - $\Delta^{\pm\pm} \to l^\pm l^\pm (W^\pm W^\pm)$ dominates for small (large) v_Δ
  - Crossover happens at $\sim 10^{-4}$ GeV
  - For $\Delta M \gtrsim 2 - 20$ GeV Cascade Decay $\Delta^{\pm\pm} \to H^{\pm\pm\pm} W^{*\mp}$ dominates
- For $\Delta M < 0 \implies$
  - $\Delta^{\pm\pm\pm} \to \Delta^{\pm\pm} W^\pm$ always happens
  - $\Delta^{\pm\pm} \to l^\pm l^\pm (W^\pm W^\pm)$ dominates for small (large) v_Δ
  - For $\Delta M \gtrsim 2 - 20$ GeV Cascade Decay $\Delta^{\pm\pm} \to H^\pm W^{*\pm}$ dominates

Phenomenological Implications

B. Decay Modes of Doubly Charged Scalar





- Depends on ΔM and v_Δ
- For $\Delta M \geq 0 \implies$
  - $\Delta^{\pm\pm\pm} \to l^\pm l^\pm W^\pm (W^\pm W^\pm W^\pm)$ dominates for small (large) v_Δ
  - $\Delta^{\pm\pm} \to l^\pm l^\pm (W^\pm W^\pm)$ dominates for small (large) v_Δ
  - Crossover happens at $\sim 10^{-4}$ GeV
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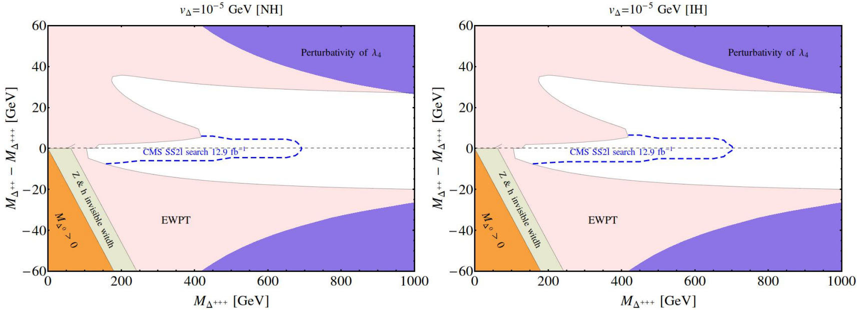
- For $\Delta M < 0 \implies$
  - $\Delta^{\pm\pm\pm} \to \Delta^{\pm\pm} W^\pm$ always happens
  - $\Delta^{\pm\pm} \to l^\pm l^\pm (W^\pm W^\pm)$ dominates for small (large) v_Δ
  - For $\Delta M \gtrsim 2 - 20$ GeV Cascade Decay $\Delta^{\pm\pm} \to H^\pm W^{*\pm}$ dominates

Phenomenological Implications

C. Mass Bounds

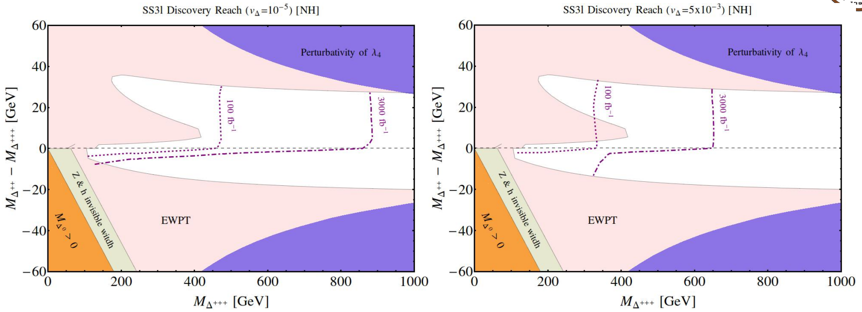


- CMS and ATLAS searches for $\Delta^{\pm\pm}$ in SS2l final states
- However they assume 100% BR in various leptonic channel
- CMS analysis at 12.9 fb^{-1} provides strongest limit CMS PAS HIG-16-036
- We obtain the strongest limits from $\mu^\pm\mu^\pm(e^\pm e^\pm)$ for NH (IH)
- No bound for $W^\pm W^\pm$ dominated channel

D. Searching for $\Delta^{\pm\pm\pm}$ at the LHC

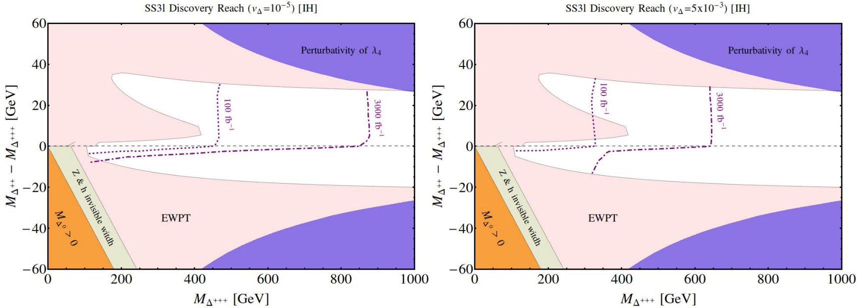
- Although $\Delta^{\pm\pm}$ has a better prospect to be found at the LHC, this particle is not exclusive to this model
- To verify/falsify this model we also need to search for $\Delta^{\pm\pm\pm}$
- $\Delta^{\pm\pm}$ searches looses sensitivity for $\Delta M \gtrsim 5$ GeV
- For $\Delta^{\pm\pm\pm}$ one needs to look at SS3l channel $\implies$ sensitivity remains the same for all $\Delta M > 0$
- Search Strategy $\implies$ 3 isolated SS leptons (e, μ), $p_T(l_1, l_2, l_3) > (30, 30, 20)$ GeV, $\not{E}_T > 30$ GeV, Z-veto
- Major BGs $\rightarrow t\bar{t}(Z/\gamma^*)$, $t\bar{t}W^\pm$, $t\bar{t}t\bar{t}$, $l^+l^-VV(V = Z, W^\pm)$
- After cut $t\bar{t}W^\pm$ dominates $\rightarrow \sigma_{BG}^{total} \approx 5 \times 10^{-3}$ fb

E. Future Prospects of SS3l Search



- Discovery potential upto 450 (950) GeV at 100 (3000) fb^{-1} for *llW* dominated region Discovery potential upto 500 (950) GeV at 100 (3000) fb^{-1} for *llW* dominated region
- Discovery potential upto 350 (700) GeV at 100 (3000) fb^{-1} for *WWW* dominated region
- Covers the whole area available for $\Delta M > 0$ scenarios
- Similar results for NH and IH

E. Future Prospects of SS3l Search



- Discovery potential upto 450 (850) GeV at 100 (3000) fb^{-1} for *llW* dominated region
- Discovery potential upto 350 (650) GeV at 100 (3000) fb^{-1} for *WWW* dominated region
- Covers the whole area available for $\Delta M > 0$ scenarios
- Similar results for NH and IH

Dark Matter

- To bring both the issues of neutrino masses and DM together under one umbrella with a minimal possible extension of the SM

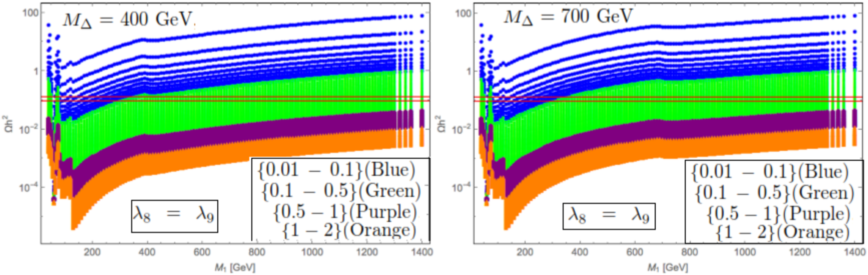
- The DM is an electroweak (EW) singlet scalar S, odd under an imposed exact Z_2 symmetry, interacting to SM through 'Higgs-portal' coupling, while all other particles are even under Z_2.

- Additional interactions with Δ, the scalar singlet DM S survives a large region of parameter space by relic density constraints from WMAP/PLANCK and direct search bounds from updated LUX data.

- The relevant parameter space of this model is spanned by :
  $\Rightarrow \{M_s,\ M_\Delta,\ \lambda_8,\ \lambda_9\}$

Dark Matter

Relic Density

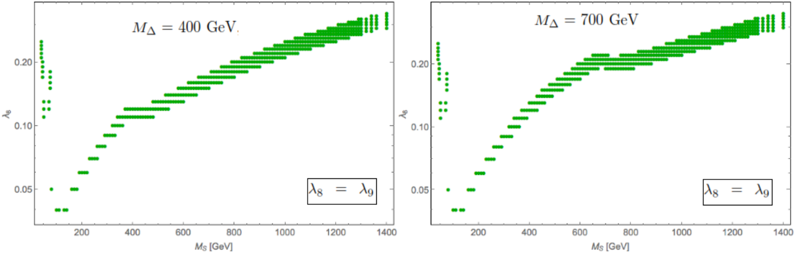


- The scalar singlet S introduced here interacts with the scalar quadruplet Δ and can annihilate through $SS \to \Delta^0\Delta^0, \Delta^+\Delta^-, \Delta^{++}\Delta^{--}, \Delta^{+++}\Delta^{---}$ on top of annihilations to SM particles through Higgs portal interactions.
- Relic density of the DM in the present universe is obtained by the annihilation cross-section of the DM as

$$\Omega h^2 = \frac{0.1\text{pb}}{\langle \sigma v \rangle}. \quad (3)$$

$\Rightarrow$ Annihilation cross-section : $\langle \sigma v \rangle = \langle \sigma v \rangle_{SS\to SM} + \langle \sigma v \rangle_{SS\to\Delta\Delta}$

Dark Matter
Relic Density



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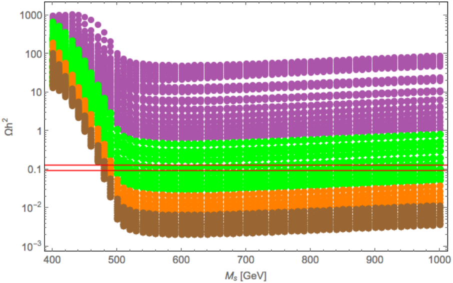
- Relic density of the DM in the present universe is obtained by the annihilation cross-section of the DM as

$$\Omega h^2 = \frac{0.1\text{pb}}{\langle \sigma v \rangle}. \tag{4}$$

$\Rightarrow$ Annihilation cross-section : $\langle \sigma v \rangle = \langle \sigma v \rangle_{SS \to SM} + \langle \sigma v \rangle_{SS \to \Delta\Delta}$

Dark Matter

Relic Density



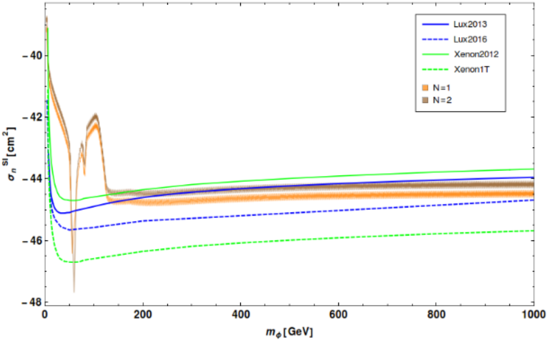
- The scalar singlet S introduced here interacts with the scalar quadruplet Δ and can annihilate through $SS \to \Delta^0\Delta^0, \Delta^+\Delta^-, \Delta^{++}\Delta^{--}, \Delta^{+++}\Delta^{---}$ on top of annihilations to SM particles through Higgs portal interactions.
- Relic density of the DM in the present universe is obtained by the annihilation cross-section of the DM as

$$\Omega h^2 = \frac{0.1\text{pb}}{\langle \sigma v \rangle}. \tag{5}$$

$\Rightarrow$ Annihilation cross-section : $\langle \sigma v \rangle = \langle \sigma v \rangle_{SS \to SM} + \langle \sigma v \rangle_{SS \to \Delta\Delta}$

Dark Matter

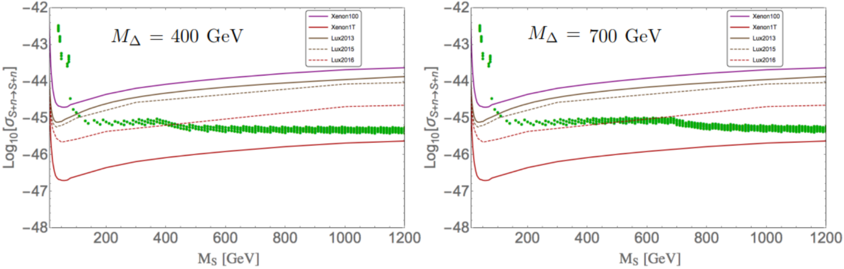
Direct Detection Constraints



- Scalar singlet extension of SM to accommodate DM through Higgs portal interaction is under tension as the allowed region of relic density space has been ruled out to a very large DM mass excepting for the Higgs resonance by non-observation in direct search experiment, especially the LUX and XENON data

Dark Matter

Direct Detection Constraints



- Thanks to the additional interactions with Δ, the scalar singlet DM S survives a large region of parameter space by relic density constraints from WMAP/PLANCK and direct search bounds from updated LUX data.

Conclusion

- Presented a model to generate tiny neutrino masses via tree-level d=7 operator
- The scale of new physics $\simeq$ TeV
- The model has doubly charged, as well as tripply charged scalar
- The decay of the triply charged scalar can produce diplaced vertex at the LHC
- The doubly charged scalar can be probed upto 1 TeV at the LHC in the SS2l channel
- The triply charged scalar can be probed upto 500 GeV at the LHC in the SS3l model
- A singlet scalar is a viable dark matter candidate in this model.

The End