Phenomenology of the Higgs sector of Dimension-7 Neutrino Mass Generation

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T. G., S. Jana, S. Nandi, arXiv:17xx.xxxxx

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Overview

1. Neutrino Mass and the Model
2. Higgs Sector
3. Probing Higgs Sector at the LHC

Summary of what we know now

- Convincing evidence of neutrino oscillations obtained in:
  - SK, SNO, KamLAND
  - Other solar and atmospheric neutrino experiments
  - Accelerator K2K experiment

- Neutrino oscillations are direct consequence of small neutrino masses and mixing

MIXINGS Defined as:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\alpha i} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \qquad c_{ij} = \cos\theta_{ij} \qquad s_{ij} = \sin\theta_{ij}$$

$$P = \mathrm{diag}\{1, 1, e^{i\alpha}\}$$

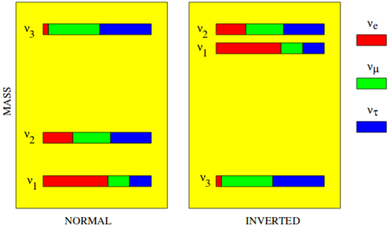
$$U = \begin{pmatrix} c_{12}\,c_{13} & s_{12}\,c_{13} & s_{13}\,e^{-i\delta} \\ -c_{23}\,s_{12} - s_{23}\,s_{13}\,c_{12}\,e^{i\delta} & c_{23}\,c_{12} - s_{23}\,s_{13}\,s_{12}\,e^{i\delta} & s_{23}\,c_{13} \\ s_{23}\,s_{12} - c_{23}\,s_{13}\,c_{12}\,e^{i\delta} & -s_{23}\,c_{12} - c_{23}\,s_{13}\,s_{12}\,e^{i\delta}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

- $\sin^2\theta_{12} \simeq 0.304 \pm 0.013$, $\sin^2\theta_{23} \simeq 0.452^{+0.052}_{-0.028}$, $\sin^2\theta_{13} \simeq 0.0218 \pm 0.0010$
- $\delta \simeq 306^{+39}_{-70}$

M.C. Gonzalez-Garcia *et al.*, Nuclear Physics B 00 (2015)

Masses

- We only know two mass difference squares:
    - Atmospheric: $\Delta m^2_{31} \approx (2.457 \pm 0.047) \times 10^{-3}$ ev^2
    - Solar: $\Delta m^2_{21} \approx (7.50^{+0.19}_{-0.17}) \times 10^{-5}$ ev^2
    - Mass pattern still unknown
- Possibilities:
    - Normal: $m_1 \ll m_2 \ll m_3$
    - Inverted: $m_1 \simeq m_2 \gg m_3$



Neutrino Mass Generation

- No neutrino mass in SM
- Neutrino mass term can be – Dirac or Majorana
  We focus on Majorana $\Longrightarrow$ lepton number violated
- In an effective theory of neutrino mass generation
  $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{NP}}\mathcal{O}^{d=5} + \frac{1}{\Lambda_{NP}^2}\mathcal{O}^{d=6} + \frac{1}{\Lambda_{NP}^3}\mathcal{O}^{d=7} + \ldots$
- Neutrino mass: $m_\nu \sim v \times \left(\frac{v}{\Lambda_{NP}}\right)^{d-4}$
- Lowest higher dim. operator $\mathcal{O}^{d=5}$: $\mathcal{L}_{d=5} = \frac{1}{\Lambda_{NP}} LLHH$

Weinberg, PRL43 (1979) 1566

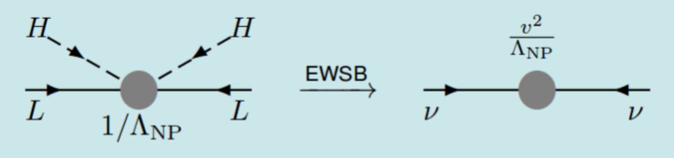


Fig. Credit: T. Ota

d=5 Neutrino Mass Generation

- Lowest higher dim. operator $\mathcal{O}^{d=5}$: $\mathcal{L}_{d=5} = \frac{1}{\Lambda_{NP}} LLHH$

Weinberg, PRL43 (79) 1566

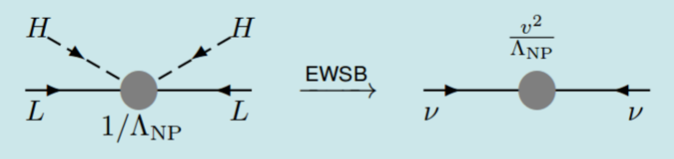


Fig. Credit: T. Ota

- Realization of Weinberg op. –
  - See-saw: there are many seesaw realizations –
    - ★ Type-I Minkowski (77), Ramond,Slansky (79), Yanagida (79), Glashow (79), Mohapatra, Senjanovic (80)
    - ★ Type-II Schechter,Valle (80), Lazarides, Shafi, Wetterich (81), Mohapatra, Senjanovic (81)
    - ★ Type-III Foot, Lew, He, Joshi (89), Ma (98)
    - ★ Linear, Inverse, etc ...
  - Loop-induced:
    - ★ 1-loop Zee (80), Ma (99)
    - ★ 2-loop Babu (88)

d=7 Neutrino Mass Generation

- Next higher dim. operator $\mathcal{O}^{d=7}$: $\mathcal{L}_{d=7} = \frac{1}{\Lambda_{NP}^3} LLHHH^\dagger H$

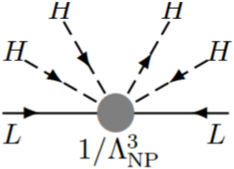
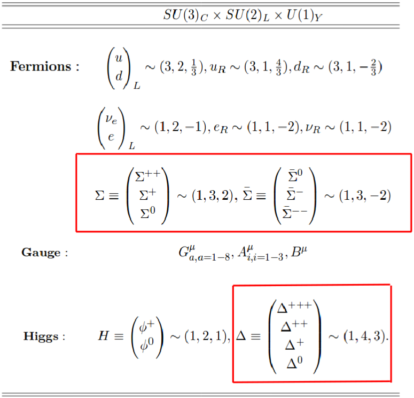


Fig. Credit: T. Ota

- Advantage: $m_\nu \sim (\frac{v^4}{\Lambda_{NP}^3})$
  More suppression → lower Λ_{NP} → Collider testable
- We focus on the model proposed by –
  Babu, Nandi and Tavartkiladze, Phys. Rev.D 80, 071702 (2009)
- Tree-level d=7 neutrino mass generation

The Model

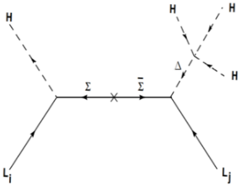
- We focus on the model proposed by –
  Babu, Nandi and Tavartkiladze, Phys. Rev.D 80, 071702 (2009)
- Particle content of the model:



	$SU(3)_C \times SU(2)_L \times U(1)_Y$
Fermions :	$\begin{pmatrix} u \\ d \end{pmatrix}_L \sim (3, 2, \frac{1}{3}), u_R \sim (3, 1, \frac{4}{3}), d_R \sim (3, 1, -\frac{2}{3})$
	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \sim (1, 2, -1), e_R \sim (1, 1, -2), \nu_R \sim (1, 1, -2)$
	$\Sigma \equiv \begin{pmatrix} \Sigma^{++} \\ \Sigma^{+} \\ \Sigma^{0} \end{pmatrix} \sim (1, 3, 2), \bar{\Sigma} \equiv \begin{pmatrix} \bar{\Sigma}^{0} \\ \bar{\Sigma}^{-} \\ \bar{\Sigma}^{--} \end{pmatrix} \sim (1, 3, -2)$
Gauge :	$G^{\mu}_{a, a=1-8}, A^{\mu}_{i, i=1-3}, B^{\mu}$
Higgs :	$H \equiv \begin{pmatrix} \phi^{+} \\ \phi^{0} \end{pmatrix} \sim (1, 2, 1), \Delta \equiv \begin{pmatrix} \Delta^{+++} \\ \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix} \sim (1, 4, 3).$

- One $Y = 3$, $SU(2)$-quadruplet scalar; and two $SU(2)$-triplet vector-like leptons with $Y = 2$, and -2

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

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

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

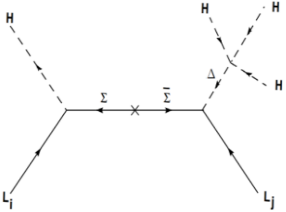
EWSB induces a VEV on the *CP*-even neutral component of the quadruplet

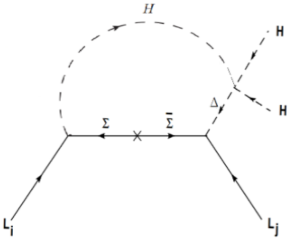
$$v_\Delta \;=\; -\lambda_5 v^3 / M_\Delta^2$$

This leads to d=7 neutrino mass at tree level –

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

However





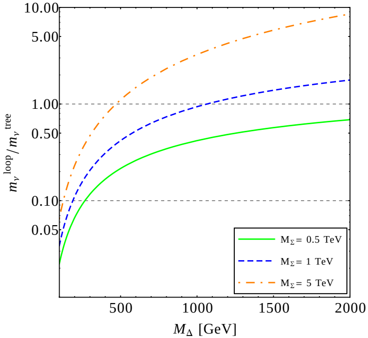
$$(m_\nu)_{ij} = \frac{(Y_i Y_j' + Y_i' Y_j) v_\Delta v}{M_\Sigma} = -\frac{\lambda_5 (Y_i Y_j' + Y_i' Y_j) v^4}{(M_\Sigma M_{\Delta^0}^2)}.$$

$$(m_\nu)_{ij}^{loop} = \frac{\left(3+\sqrt{3}\right) \lambda_5 v^2 M_\Sigma \left(Y_i Y_j' + Y_i' Y_j\right)}{16\pi^2 \left(M_\Delta^2 - M_H^2\right)} \left(\frac{M_\Delta^2 \log\left(\frac{M_\Sigma^2}{M_\Delta^2}\right)}{M_\Sigma^2 - M_\Delta^2} - \frac{M_H^2 \log\left(\frac{M_\Sigma^2}{M_H^2}\right)}{M_\Sigma^2 - M_H^2} \right)$$

- This model does not prevent loop-level $d = 5$ mass generation

Bambhaniya, Chakrabortty, Goswami, Konar, arXiv:1305.2795

d=7 v d=5 Mass Generation



- This model does not prevent loop-level $d = 5$ mass generation
- $m_\nu^{loop}/m_\nu^{tree} \sim 1$ upto $M_\Delta \approx 500$ GeV for $M_\Sigma \sim 5$ TeV
- Regardless of neutrino mass origin, Higgs sector offers reach phenomenology
- We choose $M_\Sigma = 5$ TeV $\implies$ Integrate out M_Σ $\implies$ computationally less expensive

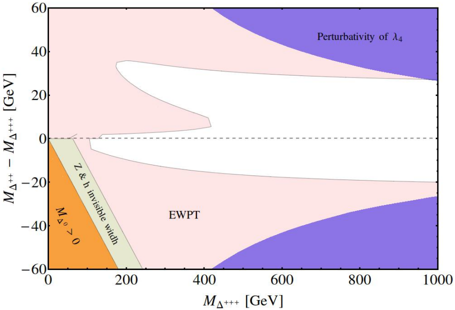
Higgs Sector of the Model

$$\textbf{Higgs}: \qquad H \equiv \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \sim (1,2,1),\ \Delta \equiv \begin{pmatrix} \Delta^{+++} \\ \Delta^{++} \\ \Delta^{+} \\ \Delta^{0} \end{pmatrix} \sim (1,4,3).$$

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

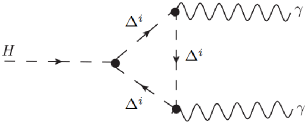
- The Higgs sector contains exotic doubly and triply-charged Higgs
- Striking SS2l or SS3l signatures at the LHC from $\Delta^{\pm\pm}$ and $\Delta^{\pm\pm\pm}$ decay
- Neutral Sector: mixing between h and Δ^{0r} is proportional to v_Δ or λ_5
- $v_\Delta \lesssim 2$ GeV from ρ parameter
- $M^2_{\Delta^{0r}} \approx M^2_{\Delta^{0i}} \approx -\lambda_5 v^3/v_\Delta \implies \lambda_5 \lesssim -v_\Delta$ to generate $\mathcal{O}(100-1000)$ GeV mass
- Mixing is negligible except for $v_\Delta \sim \mathcal{O}(1)$ GeV

Mass Splitting of the Quadruplet



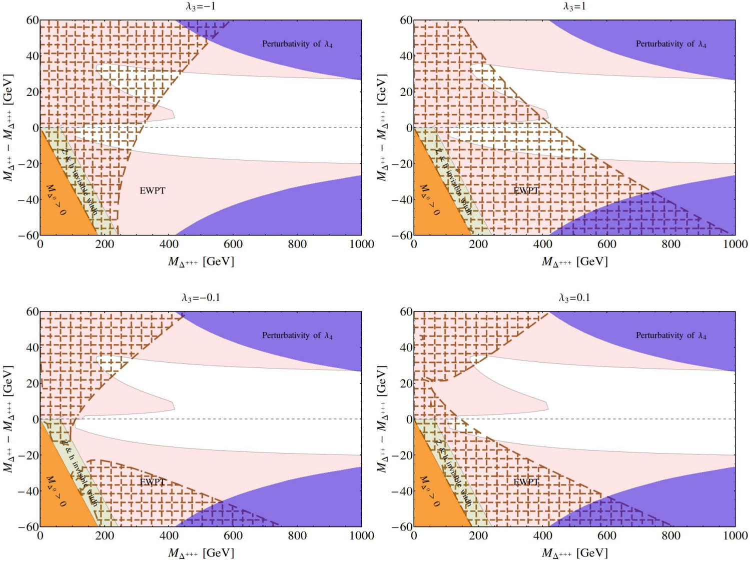
- $M_i^2 = M_{\Delta^0}^2 - q_i \frac{\lambda_4}{2} v^2 \, (q_i = 1, 2, 3)$
- $\Delta M > 0 \implies M_{\Delta^{+++}} < M_{\Delta^{++}} < M_{\Delta^{+}} < M_{\Delta^0}$
- $\Delta M < 0 \implies M_{\Delta^{+++}} > M_{\Delta^{++}} > M_{\Delta^{+}} > M_{\Delta^0}$
- EWPT $\implies$ S, T parameters constrains the parameter space in $M_{\Delta^{\pm\pm\pm}} - \Delta M$ plane
- Gives rise to potentially difficult mass-spectra at the LHC

$H \to \gamma\gamma$



- Presence of doubly and triply-charged scalars can significantly increase/decrease the decay width of SM Higgs into di-photon
- $h\Delta\Delta$ coupling depends on combination of quartic couplings λ_3 and λ_4
- λ_4 is constrained by EWPT
- Measured $\mu^{\gamma\gamma} = BR^{\gamma\gamma}_{NP}/BR^{\gamma\gamma}_{SM}$ at the LHC can strongly constrain on Δ mass-spectra (depends on the value of λ_3)
- LHC combined Run-I → $\mu^{\gamma\gamma} = 1.16 \pm 0.18$

$H \to \gamma\gamma$ constraint from Run-I



Brown shaded regions ruled out – highly λ_3 dependent

Direct and Associated production of $\Delta^{\pm\pm\pm}(\Delta^{\pm\pm})$

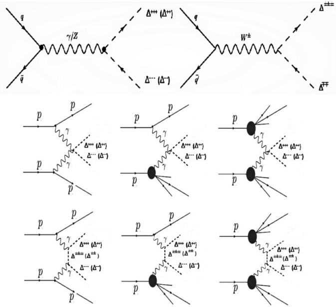


Fig. Credit: S. Jana

- $\Delta^{\pm\pm\pm}(\Delta^{\pm\pm})$ pair and associated production at the LHC happens via Drell-Yan (DY)
- Photon fusion (PF) is a secondary process → Photon PDF is available from `NNPDF, CTEQ, MRST`
- For larger $\Delta^{\pm\pm\pm}(\Delta^{\pm\pm})$ PF contribution is significant → However uncertainty in available photon PDFs are significantly large

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

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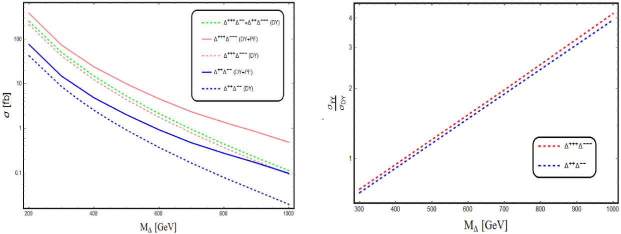

14 TeV cross-section [arXiv:1705.01121]

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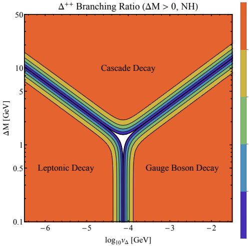
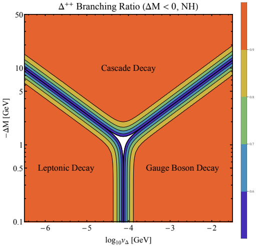
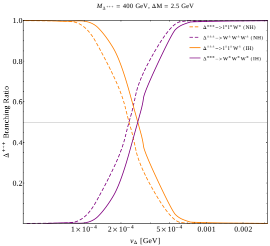
Decay of $\Delta^{\pm\pm\pm}(\Delta^{\pm\pm})$







- 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 $\Delta^{\pm\pm} \to \Delta^{\pm\pm\pm} W^{*\mp}$ 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
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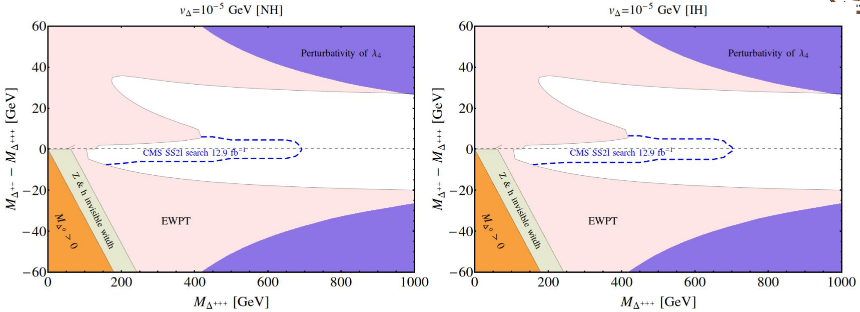
Constraint from SS2l Searches at LHC



- CMS and ATLAS searches for $\Delta^{\pm\pm}$ in SS2l final states
- However they assume 100% BR in various leptonic channel
- In a realistic fitting of neutrino masses it never happens

  We use $\Delta m^2_{21} = 7.50 \times 10^{-5}$ev^2,$\Delta m^2_{31} = 2.50 \times 10^{-3}$ev^2,$\sin^2\theta_{12} = 0.320$,$\sin^2\theta_{23} = 0.500$,$\sin^2\theta_{13} = 0.025$,$\delta = 0$
- 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

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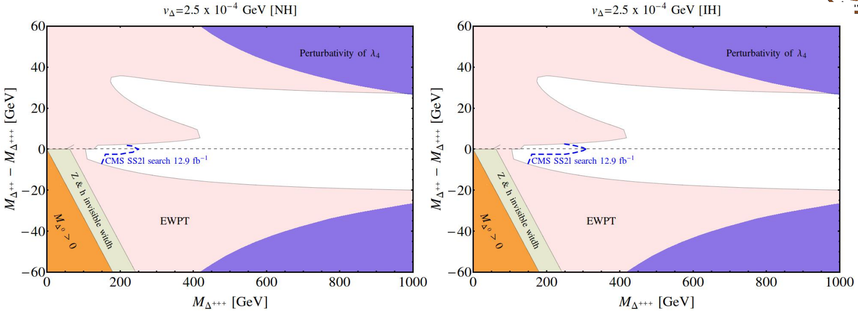

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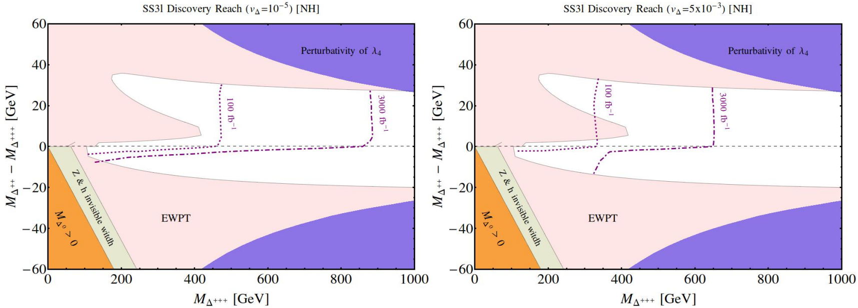
Searching for $\Delta^{\pm\pm\pm}$ at the LHC

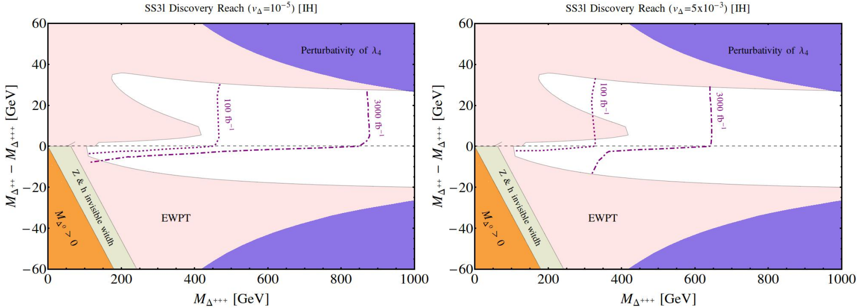
- Although $\Delta^{\pm\pm}$ has a better prospect to be found at the LHC, this particle is not exclusive to this model
- To verify/falsify this model we also need to search for $\Delta^{\pm\pm\pm}$
- $\Delta^{\pm\pm}$ searches looses sensitivity for $\Delta M \gtrsim 5$ GeV
- For $\Delta^{\pm\pm\pm}$ one needs to look at SS3l channel $\Longrightarrow$ sensitivity remains the same for all $\Delta M > 0$
- Search Strategy $\Longrightarrow$ 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 cuts $t\bar{t}W^{\pm}$ dominates $\rightarrow \sigma_{BG}^{total} \approx 5 \times 10^{-3}$ fb

Future Prospects of SS3l Search



- Discovery potential upto 450 (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

Future Prospects of SS3l Search



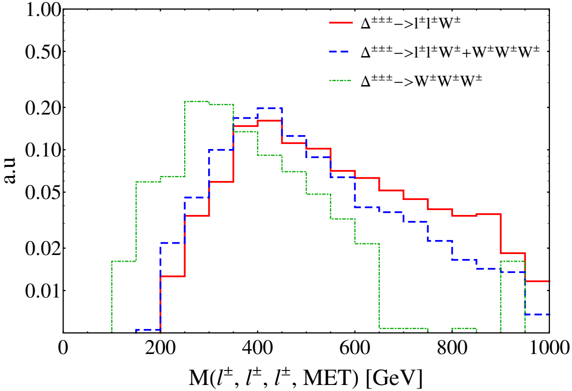
- Discovery potential upto 450 (850) GeV at 100 (3000) fb^{-1} for *llW* dominated region
- Discovery potential upto 350 (650) GeV at 100 (3000) fb^{-1} for *WWW* dominated region
- Covers the whole area available for $\Delta M > 0$ scenarios
- Similar results for NH and IH

Conclusion

- This model can provide an avenue to generate tiny neutrino masses via tree-level d=7 operator
- M_Σ has to be light upto $\lesssim$ 500 GeV for d=7 to dominate → regardless of d=7 or d=5 operator – this model predict TeV scale doubly-triply charged Higgs at the LHC
- $\Delta^{\pm\pm\pm}$ can be discovered upto 350–500 GeV in SS3l channel at 100 fb^{-1}.... for all $\Delta M \geq 0$
- Large $\Delta M < 0$ poses serious problem → Cascade Decay → Innovative Search Strategy needed
- Improved result from $H \to \gamma\gamma$ can close this window .... albeit only for large λ_3 values

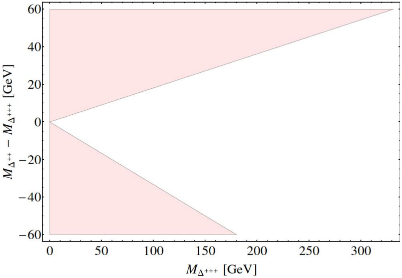
The End

Backup-I



$$\mathcal{L}_{m_\nu} = Y_i \overline{l_{iL}}^C H^* \Sigma_L + Y_i' \overline{\Sigma_R} \Phi l_{iL} + \overline{\Sigma_R} M_\Sigma \Sigma_L + h.c.,$$

Backup-II


60
40
20
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−60
$M_{\Delta^{++}} - M_{\Delta^{+++}}$ [GeV]
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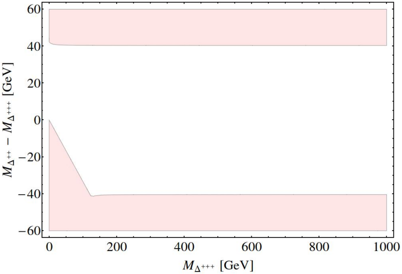
100
150
200
250
300
$M_{\Delta^{+++}}$ [GeV]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$M_{\Delta^{++}} - M_{\Delta^{+++}}$ [GeV]
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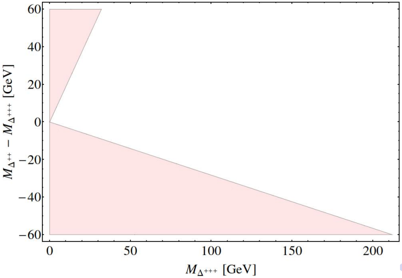
$M_{\Delta^{+++}}$ [GeV]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−60
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