Vacuum Stability in the Extended Standard Model scenarios

Shilpa Jangid
Research Scholar
IIT Hyderabad

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In collaboration with: Priyotosh Bandyopadhyay, Bhupal Dev, Arjun Kumar, Manimala Mitra

भारतीय प्रौद्योगिकी संस्थान हैदराबाद
Indian Institute of Technology Hyderabad

- To ensure the EW Vacuum stability till Planck scale
- Dark matter candidate
- Generation of neutrino mass

Dominant top quark effect in SM

- The effective potential for high field values is written as

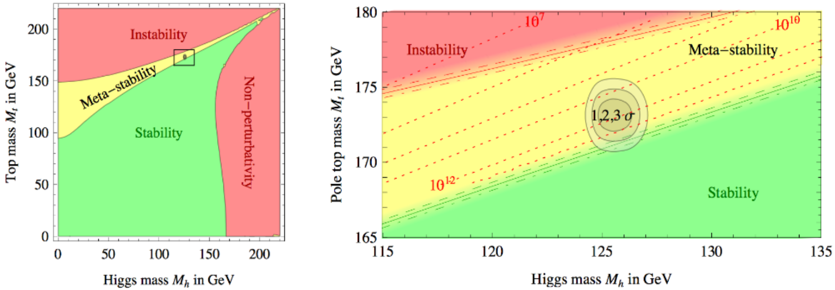
$$V_{\rm eff}(h,\mu) \simeq \lambda_{\rm eff}(h,\mu)\frac{h^4}{4}, \quad \text{with } h \gg v,$$

- Where λ_{eff} is given by

$$\lambda_{\rm eff}(h,\mu) \quad \simeq \underbrace{\lambda_h(\mu)}_{\text{tree-level}} + \underbrace{\frac{1}{16\pi^2}\left[-12Y_t^4\left[\log\frac{Y_t^2 h^2}{\mu^2}-\frac{3}{2}\right]\right]}_{\text{Negative Contribution from top quark}}.$$

- Condition of metastability

$$0 > \lambda_{eff}(\mu) \simeq \frac{-0.065}{1-0.01 log\frac{v}{\mu}}$$



Within the uncertainty of top mass we are in a metastable vacuum

A Strumia, D Buttazzo, G Degrassi et al.

JHEP 12 (2013) 089

Scalar extension with IDM and ITM

- The general Z_2 symmetric Higgs potential for inert 2HDM is

$$\begin{aligned} V_{\text{scalar}} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 + \lambda_1(\Phi_1^\dagger\Phi_1)^2 + \lambda_2(\Phi_2^\dagger\Phi_2)^2 \\ &+\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + [\lambda_5(\Phi_1^\dagger\Phi_2)^2 + \text{H.c}]. \end{aligned}$$

- A Z_2 symmetric potential for ITM can be written as

$$V = m_h^2\Phi^\dagger\Phi + m_T^2 Tr(T^\dagger T) + \lambda_1|\Phi^\dagger\Phi|^2 + \lambda_t(Tr|T^\dagger T|)^2.$$

- The effective potential for high field values is written as

$$V_{\rm eff}(h,\mu)\ \simeq\ \lambda_{\rm eff}(h,\mu)\,\frac{h^4}{4}\,,\quad \text{with } h\gg v\,,$$

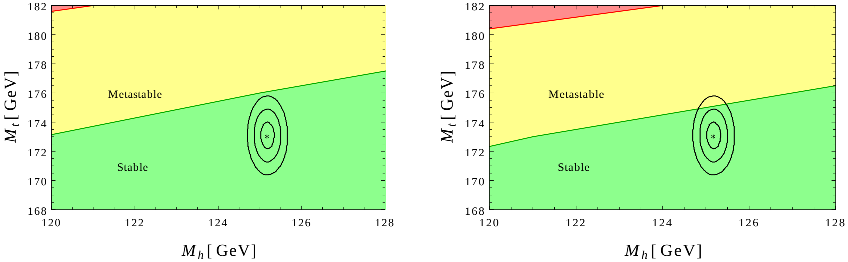
- Where λ_{eff} is given by

$$\lambda_{\rm eff}(h,\mu) \simeq \underbrace{\lambda_h(\mu)}_{\text{tree-level}} + \underbrace{\frac{1}{16\pi^2}\sum_{\substack{i=W^{\pm},Z,t,\\ h,G^{\pm},G^0}} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2}-c_i\right]}_{\text{Contribution from SM}}$$

$$+\underbrace{\frac{1}{16\pi^2}\sum_{i=H,A,H^{\pm}/T_0,T^{\pm}} n_i\kappa_i^2\left[\log\frac{\kappa_i h^2}{\mu^2}-c_i\right]}_{\text{Contribution from IDM/ITM}}.$$

- Condition of metastability

$$0>\lambda_{eff}(\mu)\simeq\frac{-0.065}{1-0.01\,log\,\frac{v}{\mu}}$$



- In both scenarios, Planck scale stability is achievable unlike SM.
- IDM is bit more stable than ITM.

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Seesaw Mechanism

- Seesaw mechanism is motivated for generating small neutrino mass
- Two different scenarios are considered
  Type-I Seesaw- Singlet fermions
  Type-III Seesaw- Triplet fermions with $SU(2)$ gauge charge
- The $SU(2)$ gauge charge of triplet fermions will show drastic change in stability and perturbativity behaviour

- Type-I seesaw Lagrangian

$$\mathcal{L}_{\rm I} = i\overline{N}_{R_i}\partial\!\!\!/ N_{R_i} - \left(Y_{N_{ij}}\overline{L}_i\widetilde{\Phi}_1 N_{R_j} - \frac{1}{2}\overline{N}^c_{R_i} M_{R_i} N_{R_i} + {\rm H.c.}\right),$$

- Neutrino mass matrix

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}$$

- Light neutrino mass

$$m_\nu = -M_D M_R^{-1} M_D^T$$

- Inverse-Seesaw Lagrangian

$$\mathcal{L}_{ISS} = i\bar{N}_R\partial\!\!\!/ N_R + i\bar{S}\partial\!\!\!/ S - \left(Y_N\bar{L}_L\tilde{\Phi}_1 N_R + \bar{N}_R M_R S + \frac{1}{2}\bar{S}^c\mu_s S + H.c.\right),$$

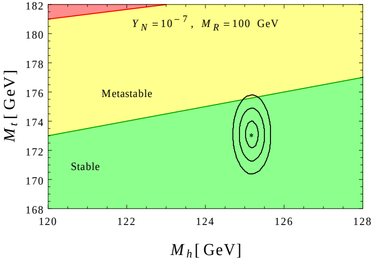
- Neutrino mass matrix

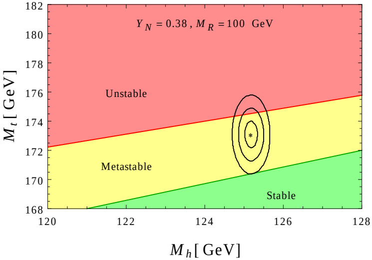
$$\mathcal{M}_\nu = \begin{pmatrix} 0 & M_D & 0 \\ M_D^T & 0 & M_R \\ 0 & M_R^T & \mu_S \end{pmatrix}$$

- Light neutrino mass

$$m_\nu = M_D M_R^{-1}\mu_S (M_R^T)^{-1} M_D^T$$

- Rest are almost degenrate around $M_R \pm \frac{\mu_S}{2}$





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- Lower Y_N corresponds to almost stable region
- Higher Y_N corresponds to large unstable region

- We have SU(2) doublets Φ_1, Φ_2 with same hypercharge $\frac{1}{2}$ and three generations of fermionic triplets Σ_1, Σ_2 with zero hypercharge

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$$

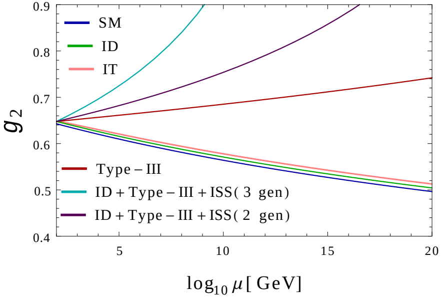
$$\Sigma_1 = \begin{pmatrix} \Sigma_1^0/\sqrt{2} & \Sigma_1^+ \\ \Sigma_1^- & -\Sigma_1^0/\sqrt{2} \end{pmatrix} \qquad \Sigma_2 = \begin{pmatrix} \Sigma_2^0/\sqrt{2} & \Sigma_2^+ \\ \Sigma_2^- & -\Sigma_2^0/\sqrt{2} \end{pmatrix}$$

- The general Higgs potential for Type-III Inverse seesaw

$$\begin{aligned} \mathcal{L}_{\rm ISS} &= Tr[\overline{\Sigma_{1i}} \not{D} \Sigma_{1i}] + Tr[\overline{\Sigma_{2i}} \not{D} \Sigma_{2j}] - \frac{1}{2} Tr[\overline{\Sigma_{2i}} \mu_{\Sigma_{ij}} \Sigma_{2j}^c + \overline{\Sigma_{2i}^c} \mu_{\Sigma_{ij}}^* \Sigma_{2j}] \\ &\quad - \left(\widetilde{\Phi}_1^\dagger \overline{\Sigma_{1i}} \sqrt{2} Y_{N_{ij}} L_j + Tr[\overline{\Sigma}_{1i} M_{N_{ij}} \Sigma_{2j}] + \text{H.c.} \right) \end{aligned}$$

Running of gauge coupling g_2

- Gauge coupling g_2 enhances positively large in Type-III



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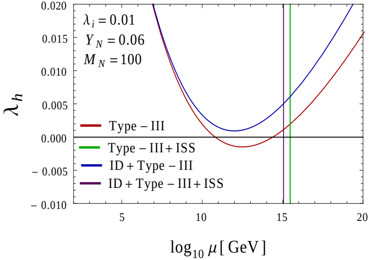
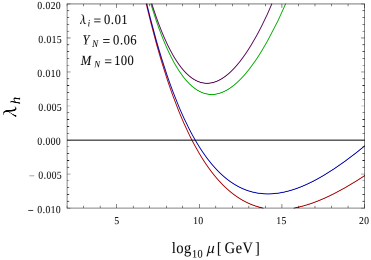
Restriction on number of generations of fermionic triplet

- g_2 contribution is too large with three generations
- Stability gets enhanced with large g_2 contribution





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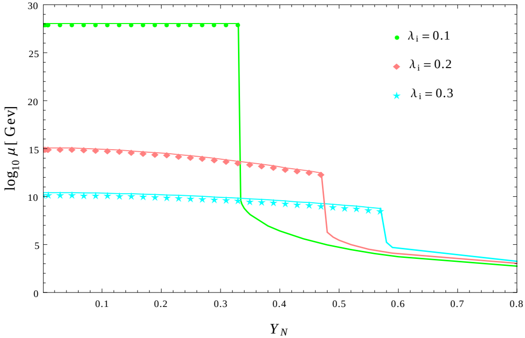
- For $\lambda_i(EW) \leq \lambda_h = 0.1264$, λ_h hits the Landau pole till a particular value of Y_N
- $\lambda_i's$ hits the Landau pole for higher values of Y_N before λ_h
- Stability scale enhances with increase in λ_i



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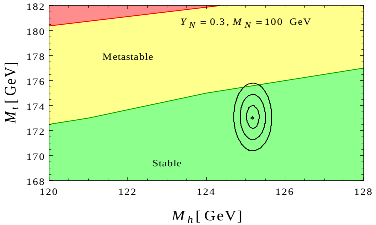
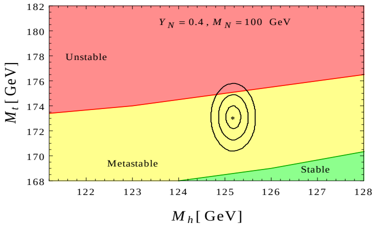
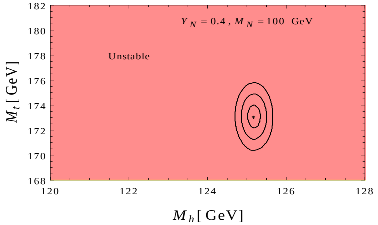
Stability analysis from Effective potential approach

- Type-III seesw is completely unstable
- 3σ contour lies in unstable region for $Y_N = 0.4$







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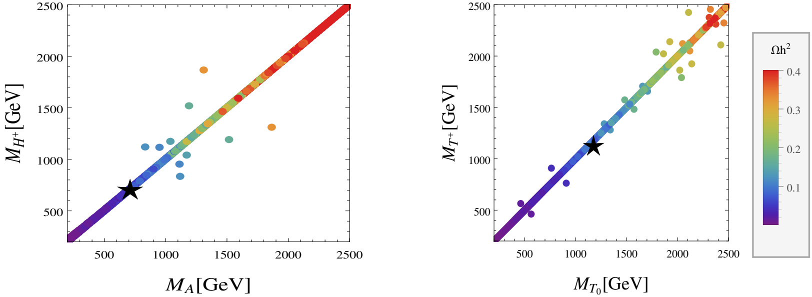

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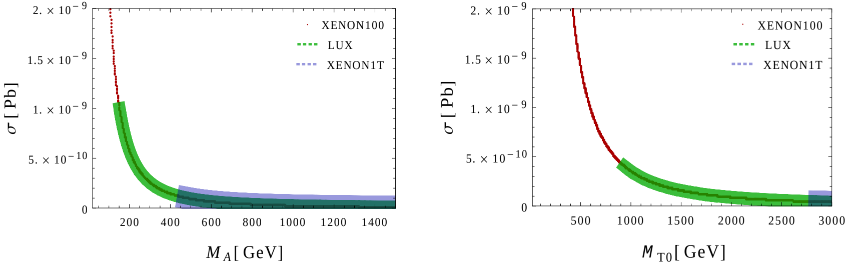
- For IDM, $M_A > 700$ GeV corresponds to correct DM relic value
- For ITM, $M_{T_0} > 1200$ GeV corresponds to correct DM relic value
- The presence of one extra Z_2-odd scalar results into higher DM number density in IDM case, leading to lower mass bound on DM mass for IDM.

$$\text{XENON100}: \sigma_{SI} \leq 2.0 \times 10^{-45}\,\text{cm}^2,$$
$$\text{LUX}: \sigma_{SI} \leq 7.6 \times 10^{-46}\,\text{cm}^2,$$
$$\text{XENON1T}: \sigma_{SI} \leq 1.6 \times 10^{-47}\,\text{cm}^2.$$



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- The cross-section varies with the DM mass and the Higgs quartic coupling λ_{345} for IDM and λ_{ht} for ITM
- In IDM, Higgs quartic coupling $\lambda_{345} = (\lambda_3 + \lambda_4 - 2\lambda_5)$ can be fine-tuned to satisfy the cross-section bounds for much lower DM mass compared to ITM

Decays in IDM and ITM

- The additional Z_2' symmetry restricts the decay modes and only three-body decays are allowed.

- In case of IDM we get prompt decay.
- In case of ITM we have much more compressed spectrum which gives $\mathcal{O}(1-10)$ m decay length (displaced decay).

Conclusions

- The minimal extension to SM necessary for Charged Higgs is $SU(2)$ doublet and triplet in $SU(2)$ representation.
- Planck scale stability is achieved in both IDM and ITM unlike SM.
- IDM and ITM both are safe but in case of ITM we have LHC signatures of displaced vertex which are not so natural in IDM.
- The bound on DM mass from DM relic density is $\geq$ 700 GeV in IDM and $\geq$ 1176 GeV in ITM.
- The additional Z_2' symmetry in IDM and ITM also restricts their decay modes.
- In the case of IDM + Type-I, Y_N=0.32 value is crucial from stability bound.
- IDM and Type-I seesaw do not directly talk to each other so one has to rely on three-body decays.
- Type-III scenario is very interesting because of the $SU(2)$ charge of the fermion.
- The Planck scale stability/perturbativity demands only two generations of Type-III.
- Because of the TeV mass range LHC at ($\sqrt{s} = 100$) TeV is better to probe the signals than 14 TeV.


Thank
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