Predictive Type-II Neutrino Seesaw Extension of NMSSM from AMSB/GMSB and LFV Constraints

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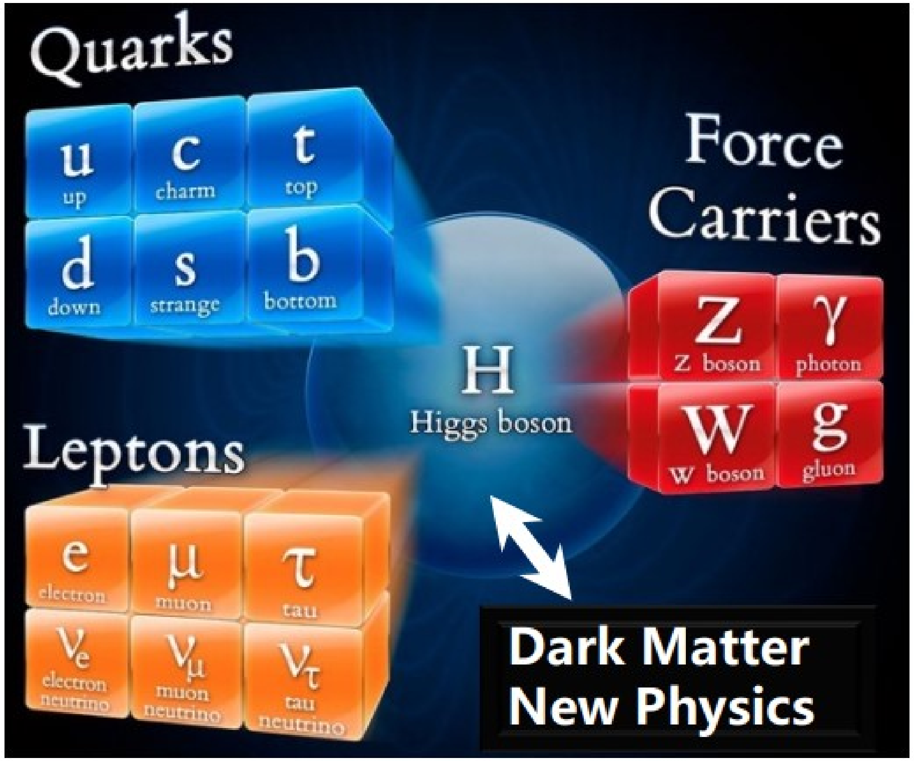
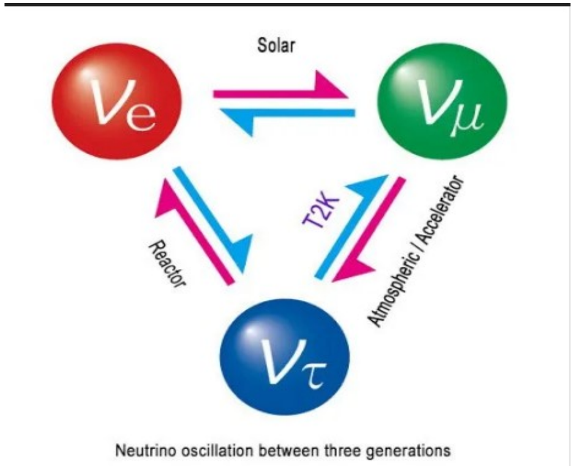
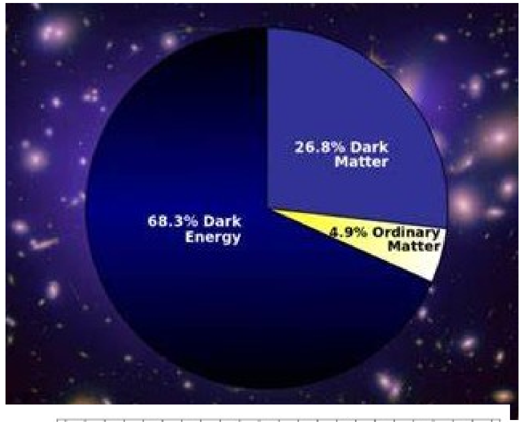
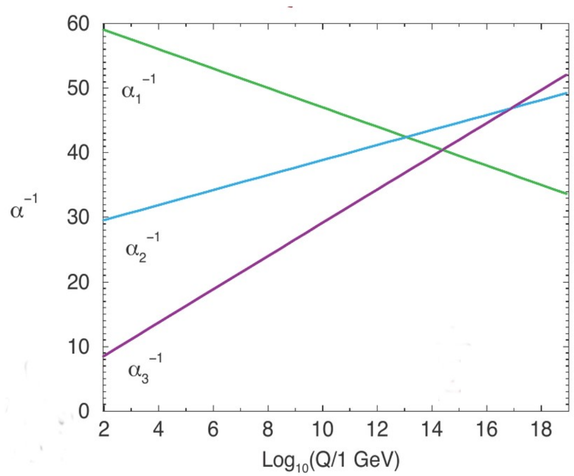
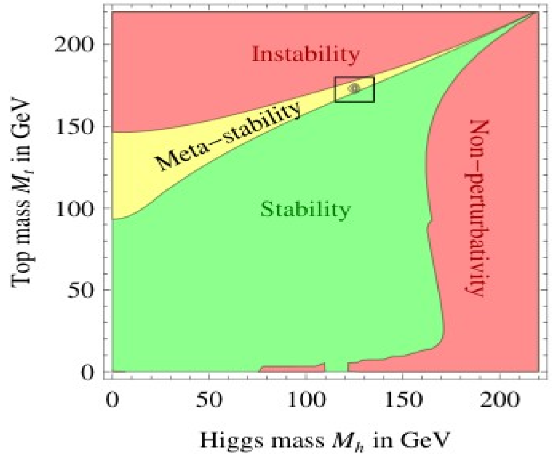
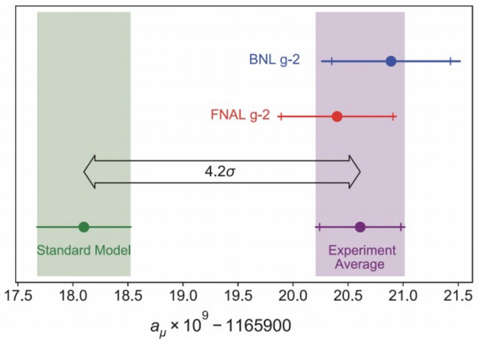

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Force Carriers
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
Leptons
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Dark Matter
New Physics

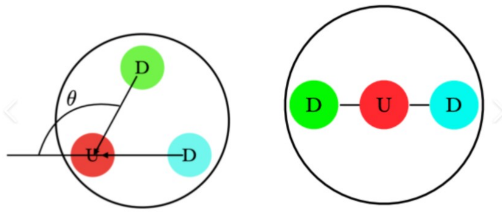

Solar
νe
νμ
ντ
Reactor
T2K
Atmospheric / Accelerator
Neutrino oscillation between three generations


26.8% Dark Matter
68.3% Dark Energy
4.9% Ordinary Matter


α^{-1}
α_1^{-1}
α_2^{-1}
α_3^{-1}
0
10
20
30
40
50
60
2
4
6
8
10
12
14
16
18
$\mathrm{Log}_{10}(Q/1\ \mathrm{GeV})$


Instability
Meta−stability
Stability
Non−perturbativity
Top mass M_t in GeV
Higgs mass M_h in GeV
0
50
100
150
200
0
50
100
150
200


BNL g-2
FNAL g-2
4.2σ
Standard Model
Experiment Average
17.5
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
$a_\mu \times 10^9 - 1165900$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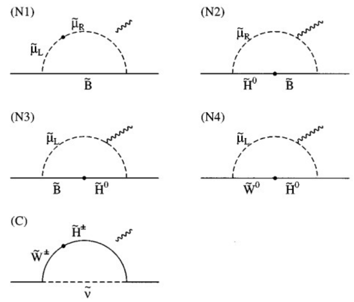
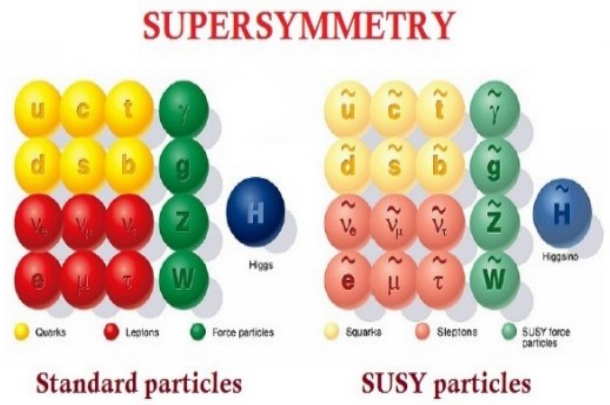
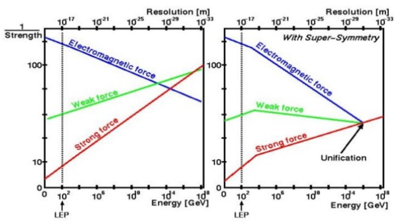
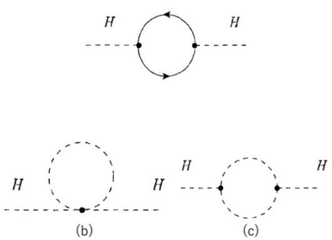
Why Supersymmetry





- Hierarchy problems.
- SUSY GUT.
- Vacuum stability naturally in SUSY at tree-level.
- Possible dark matter candidate.
- Many possible baryogenesis mechanism.
  ---Coincidence of DM and Baryon density.
- Radiative EW symmetry breaking-driven by RGE.
- Predictive-the 125 GeV Higgs favored by SUSY.
- Possibly vanishing CC in SUGRA?
- Good properties: holomorphic in superpotential...





The LHC had a real chance to rule out SUSY, but it failed!

—— Stephen P. Martin

Next-to-Minimal Supersymmetric Standard model

- singlet extension of MSSM to solve the mu-problem

$$W_{MSSM} = \mu H_u H_d + \ldots \quad \longrightarrow \quad W_{NMSSM} = \lambda S H_u H_d + \tfrac{1}{3}\kappa S^3 + \ldots$$

- The most general, renormalizable (R-parity preserving) superpotential

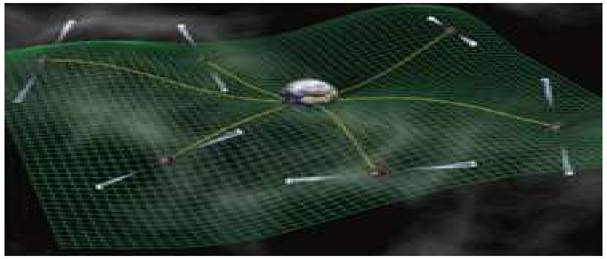
$$\mathcal{W}_S = \mathcal{W}_{\text{Yukawa}} + \frac{1}{3}\kappa \hat{S}^3 + \mu \hat{H}_u \hat{H}_d + \lambda \hat{S} \hat{H}_u \hat{H}_d + \frac{1}{2}\mu_s \hat{S}^2 + t_s \hat{S} \ ,$$

- Discrete Z_3 symmetry can forbide the dimensional terms
- Easily accommodate the 125GeV SM-like Higgs by additional tree-level contributions

$$\begin{aligned} M_{\rm SM}^2 &\simeq M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2} v^2 (\lambda - \kappa \sin 2\beta)^2 \\ &+ \frac{3 m_t^4}{4\pi^2 v^2} \left(\ln\left(\frac{m_T^2}{m_t^2}\right) + \frac{A_t^2}{m_T^2}\left(1 - \frac{A_t^2}{12 m_T^2}\right)\right) \end{aligned}$$

- Relex the bounds on stop masses

Next-to-Minimal Supersymmetric Standard model



Soft SUSY breaking parameters:

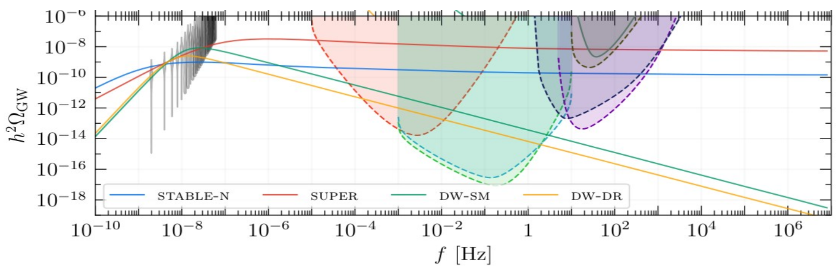
$$
\begin{aligned}
-\mathcal{L}_{\text{soft}} &= m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2 + m_S^2|S|^2 + m_Q^2|Q^2| + m_U^2|U_R^2| \\
&+ m_D^2|D_R^2| + m_L^2|L^2| + m_E^2|E_R^2| \\
&+ (h_u A_u\, Q\cdot H_u\, U_R^c - h_d A_d\, Q\cdot H_d\, D_R^c - h_e A_e\, L\cdot H_d\, E_R^c \\
&+ \lambda A_\lambda\, H_u\cdot H_d\, S + \frac{1}{3}\kappa A_\kappa\, S^3 + m_3^2\, H_u\cdot H_d + \frac{1}{2}m_S'^2\, S^2 + \xi_S\, S + \text{h.c.})\ .
\end{aligned}
$$

Collapse of Z3 Domain wall can explain the Nano-HZ gravitational wave signals by NANOGrav.

Scalar potential: non-trivial to trigger EWSB

$$
\begin{aligned}
V_{\text{Higgs}} &= \left|\lambda\left(H_u^+H_d^- - H_u^0H_d^0\right) + \kappa S^2 + \mu' S + \xi_F\right|^2 \\
&+ \left(m_{H_u}^2 + |\mu + \lambda S|^2\right)\left(\left|H_u^0\right|^2 + \left|H_u^+\right|^2\right) + \left(m_{H_d}^2 + |\mu + \lambda S|^2\right)\left(\left|H_d^0\right|^2 + \left|H_d^-\right|^2\right) \\
&+ \frac{g_1^2 + g_2^2}{8}\left(\left|H_u^0\right|^2 + \left|H_u^+\right|^2 - \left|H_d^0\right|^2 - \left|H_d^-\right|^2\right)^2 + \frac{g_2^2}{2}\left|H_u^+H_d^{0*} + H_u^0H_d^{-*}\right|^2 \\
&+ m_S^2|S|^2 + \left(\lambda A_\lambda\left(H_u^+H_d^- - H_u^0H_d^0\right)S + \frac{1}{3}\kappa A_\kappa\, S^3 + m_3^2\left(H_u^+H_d^- - H_u^0H_d^0\right) \right. \\
&\left. + \frac{1}{2}m_S'^2\, S^2 + \xi_S\, S + \text{h.c.}\right)
\end{aligned}
$$

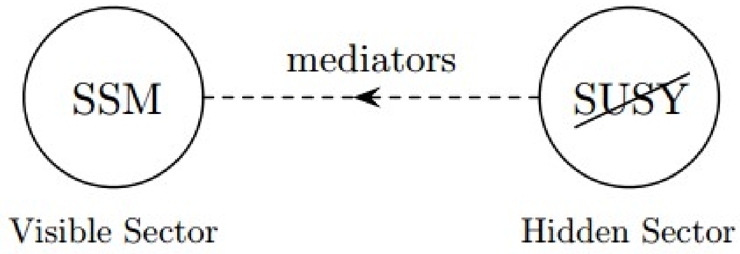
Fei, et al (2023) PRD



Origin of Soft SUSY Breaking Parameters

For tree-level renormalizable couplings

$$\mathrm{STr}\mathcal{M}^2 = \sum_J (-1)^{2J}(2J+1)\mathcal{M}_J^2 = 0$$



$\langle \boldsymbol{X}_{\rm NL} \rangle = \theta^2 F_{\rm hid}$ spontaneous SUSY breaking

$$\mathcal{L} \supset -\int d^4\theta\, \frac{\widetilde{m}_i^2}{F^2} \boldsymbol{X}_{\rm NL}^\dagger \boldsymbol{X}_{\rm NL} \boldsymbol{\Phi}_i^\dagger e^{2\boldsymbol{V}} \boldsymbol{\Phi}_i - \Bigg(\int d^2\theta\, \frac{m_\lambda}{2F_{\rm hid}} \boldsymbol{X}_{\rm NL} \boldsymbol{W}^{\alpha a} \boldsymbol{W}_\alpha^a + \frac{C_i}{F_{\rm hid}} \boldsymbol{X}_{\rm NL} \boldsymbol{\Phi}_i + \frac{B_{ij}}{2F_{\rm hid}} \boldsymbol{X}_{\rm NL} \boldsymbol{\Phi}_i \boldsymbol{\Phi}_j + \frac{A_{ijk}}{6F_{\rm hid}} \boldsymbol{X}_{\rm NL} \boldsymbol{\Phi}_i \boldsymbol{\Phi}_j \boldsymbol{\Phi}_k + \text{h.c.} \Bigg).$$

soft SUSY-breaking terms in the visible sector

$$\mathcal{L}_{\rm soft} = -\widetilde{m}_i^2 |\phi_i|^2 - \left(\frac{m_\lambda}{2} \lambda^a \lambda^a + C_i \phi_i + \frac{B_{ij}}{2} \phi_i \phi_j + \frac{A_{ijk}}{6} \phi_i \phi_j \phi_k + \text{h.c.} \right)$$

Gauge Mediated SUSY Breaking

- In the limit $\alpha_r \to 0$ the theory decouples to two sectors.

Minimal Gauge Mediation:

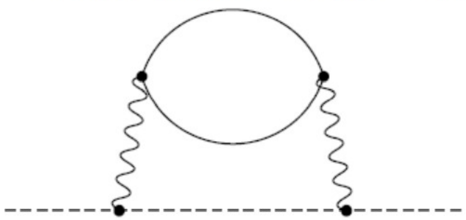
$$\langle X \rangle = X + \theta^2 F,$$

$$W = \lambda_{ij} X \phi_i \widetilde{\phi}_j$$

– Gaugino masses arise at one loop

$$m_{\lambda_r} \sim \alpha_r \frac{F}{M}$$
$$r = 1, 2, 3$$

– Sfermion mass squares arise at two loops (8 graphs).



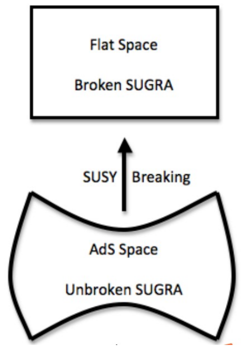
$$m^2_{\tilde{f}} \sim \frac{F^2}{M^2} \sum_{r=1}^{3} \alpha_r^2 c_2^r$$

$$m_{\tilde{f}} \sim m_\lambda \sim \alpha \frac{F}{M}$$

- Relations between gaugino masses and sfermion masses
- Small A-terms   Hard for 125 GeV Higgs
- Hard to generate $\mu \sim B \sim m_\lambda$
- Gravitino LSP

	Gauge mediation
Coupling to MSSM	MSSM gauge interactions
FCNC	Naturally suppressed
Dark matter	Challenging
$\mu/B\mu$ problem	Challenging

Anomaly Mediated SUSY Breaking



✓ A special case of gravity mediation---Most ubiqutious

✓ Combination of Kahler mediation and gravitino mediation

✓ Expressions of the soft terms hold at every renormalization scale, exactly, to all orders in perturbation theory. RG-stable

✓ Keep the information of underlying AdS SUSY--m_{3/2}-inverse radius of AdS space before SUSY breaking.

✓ AMSB is not due to any anomaly of SUSY itself, but due to the need to add local counterterms to preserve SUSY of the 1PI effective action.

	Anomaly?	$m_\lambda \propto$?	SUGRA?	Goldstino?
Gravitino Mediation	Super-Weyl	$(3T_G - T_R)m_{3/2}$	✓	
Kähler Mediation	Super-Weyl	$\frac{1}{3}(3T_G - T_R)K_iF^i$	✓	✓
	Kähler	$-\frac{2}{3}T_R K_i F^i$	✓	✓
	Sigma-Model	$2\frac{T_R}{d_R}(\log\det K\vert''_R)_i F^i$		✓

- Unique input parameter in minimal AMSB: m_{3/2}--inverse AdS radius & SUSY breaking
- Too predictive! ----Tachyonic slepton masses. Necessitate additional contributions.
- Flavor conservation

Anomaly Mediated SUSY Breaking

Simplest derivation in the compensator approach
---- assuming special sequestered form for
Kahler potential

RS-formalism

For global SUSY

$$\mathcal{L} = \int d^4\theta K(\Phi^\dagger, e^V\Phi) + \int d^2\theta \left[W(\Phi) - \frac{i}{16\pi}\tau W^a W_a \right]$$

can couple to gravity via

$$S \sim \int d^4x e \left[\int d^4\theta f(\Phi^\dagger, e^V\Phi) \frac{\Sigma^\dagger\Sigma}{M_{Pl}^2} + \int d^2\theta \{ \frac{\Sigma^3}{M_{pl}^3} W(\Phi) - \frac{i}{16\pi}\tau W^a W_a \} \right]$$

with

$$f(\Phi^\dagger, e^V\Phi) = -3M_{pl}^2 e^{-K/3M_{pl}^2}, \quad \tau \equiv \theta_{YM} + i\frac{4\pi}{g^2}.$$

After re-scaling of the vierbein with

$$e_\mu^a \to e_\mu^a e^{-K/12M_{Pl}^2},$$

we will obtain the resulting Lagrangian with canonical Einstein form.

$$\mathcal{L}_{\rm eff} = \int d^4\theta \psi^\dagger e^V \psi \frac{\Sigma^\dagger\Sigma}{M^2} + \int d^2\theta \frac{\Sigma^3}{M^3}(m_0\psi^2 + y\psi^3) - \frac{i}{16\pi}\int d^2\theta \tau W^\alpha W_\alpha + h.c.\,,$$

$$\frac{\Sigma\psi}{M} \to \psi$$

$$\mathcal{L}_{\rm eff} = \int d^4\theta\, Z\left(\frac{\mu M}{\Lambda\Sigma}, \frac{\mu M}{\Lambda\Sigma^\dagger}\right)\psi^\dagger e^V \psi + \int d^2\theta\, y\psi^3 - \frac{i}{16\pi}\int d^2\theta\, \tau W^\alpha W_\alpha + h.c.$$

$$\tau = i\frac{\tilde{b}}{2\pi}\ln\left(\frac{\mu M}{\Lambda\Sigma}\right)$$

$$\langle\Sigma\rangle = M + \mathcal{F}_\Sigma\theta^2$$

$$M_\lambda = \frac{i}{2\tau}\frac{\partial\tau}{\partial\Sigma}\Big|_{\Sigma=M}\mathcal{F}_\Sigma = \frac{bg^2}{16\pi^2}\frac{\mathcal{F}_\Sigma}{M}$$

$$M_{\tilde{\psi}}^2 = -\frac{1}{4}\left(\frac{\partial\gamma}{\partial g}\beta_g + \frac{\partial\gamma}{\partial y}\beta_y\right)\frac{|\mathcal{F}_\Sigma|^2}{M^2}.$$

Deflected Anomaly Mediation

- Deflect the AMSB Renormalization Group trajectory by thresholds determined by VEV of light fields.

- Natural with vector-like thresholds---non-decouple

- Possible gauge mediation or Yukawa mediation contributions (with interference terms of mAMSB)

- Slepton masses can change into positive after RGE.

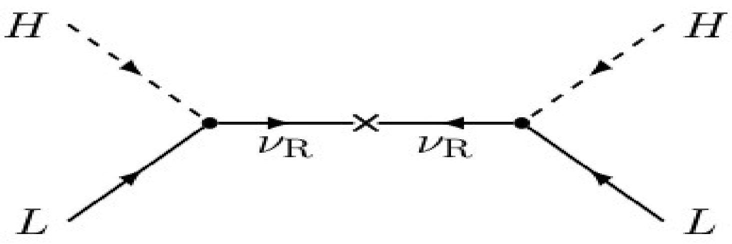
- Natural with neutrino mass generation mechanism:

--- Messengers: Additional triplets or singlet within complete GUT multiplets

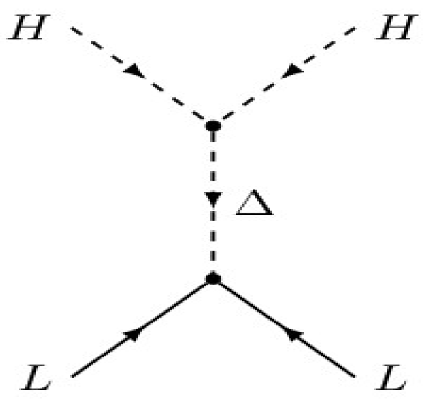
--- Interactions: Couplings of lepton to such messengers

Neutrino Seesaw Mechanism

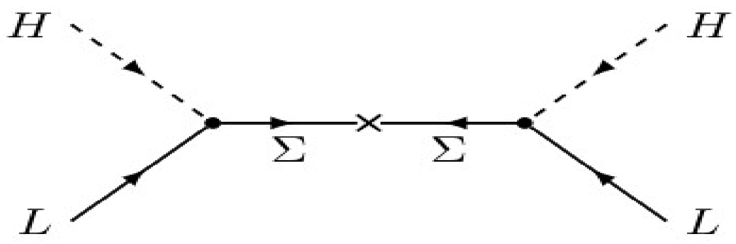
Type I



Type II



Type III



Right handed neutrinos (N_R)

$$N_R \sim (1,1,0)$$

$$m_\nu \approx -m_D M_R^{-1} m_D^T$$

Scalar $SU(2)_L$ triplets (Δ)

$$\Delta_L\,(1,3,1)$$

$$M_\nu = \sqrt{2} Y_\nu \frac{\mu v_0^2}{\sqrt{2} M_\Delta^2}.$$

Fermion $SU(2)_L$ triplets (Σ_R)

$$\Sigma_R\,(1,3,0)$$

$$m_\nu \approx \frac{Y_\Sigma^2 v_0^2}{2 M_\Sigma}$$

Type II Neutrino Seesaw Mechanism-Non SUSY

Consists of SM Higgs $H \sim (1,2,1)$ and an $SU(2)_L$ triplet scalar $\Delta \sim (1,3,2)$

The most general renormalizable potential

$$V = M_\Delta^2 Tr\Delta^\dagger\Delta - m_H^2 H^\dagger H + \frac{\lambda}{4}(H^\dagger H)^2 + \lambda_1 (H^\dagger H) Tr(\Delta^\dagger \Delta)$$
$$+\lambda_2 (Tr\Delta^\dagger\Delta)^2 + \lambda_3 Tr(\Delta^\dagger\Delta)^2 + \lambda_4 H^\dagger \Delta\Delta^\dagger H + \mu H^T i\tau_2 \Delta^\dagger H$$

The μ-term violates the lepton number by 2 unit.

independent of M_Δ

The minimization condition for the scalar potential: $v_\Delta \approx \frac{\mu}{M_\Delta^2} v^2$,

The neutrino mass: $\mathcal{L} \supseteq -iY_\nu L^T C\sigma_2 \Delta L + h.c. \Rightarrow m_\nu = Y_\nu v_\Delta = Y_\nu \frac{\mu v^2}{M_\Delta^2}$.

Modify the ρ-parameter: $\rho = \frac{M_W^2}{c_W^2 M_Z^2} = \frac{v^2 + 2v_\Delta^2}{v^2 + 4v_\Delta^2} \approx 1.0005$

v_Δ must less than $\mathcal{O}(1)$ GeV . Can be relaxed in Georgi-Machacek model.

For example, see Du &Fei Wang, 2409.20198

SUSY Type II Neutrino Seesaw Mechanism

The superpotential involves two $SU(2)_L$ triplets:
----- holomorphism of superpotential

$$T = \begin{pmatrix} T^0 & -\frac{1}{\sqrt{2}}T^+ \\ -\frac{1}{\sqrt{2}}T^+ & -T^{++} \end{pmatrix} \qquad \bar{T} = \begin{pmatrix} \bar{T}^{--} & -\frac{1}{\sqrt{2}}\bar{T}^- \\ -\frac{1}{\sqrt{2}}\bar{T}^- & -\bar{T}^0 \end{pmatrix}$$

$$W = \frac{1}{\sqrt{2}}\mathbf{Y}_T^{ij} L_i T L_j + \frac{1}{\sqrt{2}}\lambda_1 H_1 T H_1 + \frac{1}{\sqrt{2}}\lambda_2 H_2 \bar{T} H_2 + M_T T\bar{T} + \mu H_1 H_2,$$

Vanishing of F-terms for triplets gives: $v_\Delta = -\frac{\lambda_2 v_2^2}{\sqrt{2}M_T}, \quad v_{\bar{\Delta}} = -\frac{\lambda_1 v_1^2}{\sqrt{2}M_T}.$

Economical: Tri-scalar couplings involving the triplets determined also by M_T

Subleading contributions of order M_{SUSY}

Soft SUSY breaking parameters:

$$-\mathcal{L}_{II} \supset m_T^2|T|^2 + m_{\bar{T}}^2|\bar{T}|^2 + \frac{A_T}{\sqrt{2}}Y_T LTL + \frac{A_{\lambda_1}}{\sqrt{2}}\lambda_1 H_1 T H_1 + \frac{A_{\lambda_2}}{\sqrt{2}}\lambda_2 H_2 \bar{T} H_2$$
$$+ B_T M \bar{T} T + \mathcal{L}_{MSSM} \ ,$$

Spoil GUT---needs to be fiited int complete SU(5) representations.

Adopting universal boundary conditions for sfermions (such as mSUGRA), non-vanishing LFV in the mass matrices of the left-handed sleptons will be triggered through radiative corrections

$$(\mathbf{m}_{\tilde{L}}^2)_{ij} \propto m_0^2(\mathbf{Y}_T^\dagger \mathbf{Y}_T)_{ij}\log\frac{M_G}{M_T}, \qquad i \neq j, \qquad \mathrm{Br}(l_i \to l_j\gamma) \propto \alpha^3 m_{l_i}^5 \frac{|(\mathbf{m}_{\tilde{L}}^2)_{ij}|^2}{m_{\mathrm{SUSY}}^8}\tan^2\beta$$

Type II Neutrino Seesaw Mechanism in NMSSM

MSSM+type II--same difficulties as MSSM after the decouplings of triplets! Go to NMSSM+type II model !

The superpotential in type II+NMSSM

$$W_1 \supseteq W_{\rm NMSSM} + y^L_{ij} L_j L_i \Delta_T + y^d_\Delta \Delta_T H_d H_d + m_T \overline{\Delta}_T \Delta_T + y^u_\Delta \overline{\Delta}_T H_u H_u ,$$

$$W_{\rm NMSSM} = W_{{\rm MSSM}/\mu} + \lambda S H_u H_d + \frac{\kappa}{3} S^3 + \xi_S S + \cdots .$$

The scalar potential:

$$V \supset \left| y^L_{ij} L_i L_j + y^d_\Delta H_d H_d + m_T \overline{\Delta}_T \right|^2 + \left| y^u_\Delta H_u H_u + m_T \Delta_T \right|^2 + \left| \lambda S H_u + 2 y^d_\Delta \Delta_T H_d \right| + \left| \lambda S H_d + 2 y^u_\Delta \overline{\Delta}_T H_u \right| + \cdots .$$

The neutrino mass:

$$(m_\nu)_{ij} = -y^L_{ij} \left[y^u_\Delta \frac{v_u^2}{m_T} + y^d_\Delta \frac{A_{H_d H_d \Delta_T} v_d^2}{m_T^2} + y^d_\Delta \frac{2\mu \tan\beta v_d^2}{m_T^2} \right]$$

Soft ~~SUSY~~ parametetrs still constribute to neutrino masses!

Large cancellation? Low m_T large μ or A-term ?

Questions:

1. What are the M_T scale and SUSY breaking scale ?
2. LFV constraints?

Heavy m_T as the messenger scale for deflected AMSB /GMSB

Type-II Seesaw in NMSSM from GMSB/AMSB

Embedding into complete SU(5) representations

$$\Delta(1,3,1) \subset \mathbf{15}, \quad \bar{\Delta}(1,\bar{3},-1) \subset \overline{\mathbf{15}}$$

$$\mathbf{15} = \mathbf{\Delta_S}(\mathbf{6},\mathbf{1})_{-2/3} \oplus \mathbf{\Delta_T}(\mathbf{1},\mathbf{3})_{\mathbf{1}} \oplus \mathbf{\Delta}_{(D)}(\mathbf{3},\mathbf{2})_{1/6},$$
$$\overline{\mathbf{15}} = \overline{\mathbf{\Delta}}_S(\bar{6},1)_{2/3} \oplus \overline{\Delta}_T(1,\bar{3})_{-1} \oplus \overline{\Delta}_{(D)}(\bar{3},2)_{-1/6}.$$

Relevant superpotential:

$$W_0 \supseteq \frac{y^u_{\mathbf{15}}}{2}\overline{\mathbf{15}}_\Delta \cdot \mathbf{5}_H \cdot \mathbf{5}_H + \frac{y^d_{\mathbf{15}}}{2}\mathbf{15}_\Delta \cdot \bar{\mathbf{5}}_H \cdot \bar{\mathbf{5}}_H$$
$$+\frac{y^L_{\mathbf{15};ij}}{2}\mathbf{15}_\Delta \cdot \bar{\mathbf{5}}_i \cdot \bar{\mathbf{5}}_j + \lambda S \cdot \bar{\mathbf{5}}_H \cdot \mathbf{5}_H + \frac{\kappa}{3}S^3 + \cdots$$
$$+y^u_{ij}\mathbf{10}_i \cdot \mathbf{10}_j \cdot \mathbf{5}_H + y^d_{ij}\mathbf{10}_i \cdot \bar{\mathbf{5}}_j \cdot \bar{\mathbf{5}}_H + W_{SB}(\mathbf{24},\cdots)$$
$$+W_{mess;B}, \qquad (3.9)$$

A

$$W_{mess;\Delta} \supseteq y_S S\left(\overline{\Delta}_1\Delta_1 + \overline{\Delta}_2\Delta_2\right) + y_X X\overline{\Delta}_1\Delta_2,$$

$$W_{mess;A} \supseteq \sum_{k=1}^{2n} y_X X\overline{\mathbf{15}}_a \cdot \mathbf{15}_a + \sum_{k=1}^{n} y_S S\overline{\mathbf{15}}_{2k-1} \cdot \mathbf{15}_{2k}.$$

B

$$W_{mess;\Delta} \supseteq y_S S\overline{\Delta}_1\Delta_1 + y_X X\overline{\Delta}_1\Delta_1$$

$$W_{mess;B} \supseteq y_X X\overline{\mathbf{15}} \cdot \mathbf{15} + y_S S\overline{\mathbf{15}} \cdot \mathbf{15}.$$

Trigger mixing between X and S

$$K = 3y_X y_S S X^\dagger \ln\left(\frac{X^\dagger X}{M^2}\right) + h.c.,$$

Contribute a tadpole for S after ~~SUSY~~

$$\mathcal{L} \supseteq 3y_X y_S (S + S^*) M \left|\frac{F_X}{M}\right|^2.$$

Type-II Seesaw in NMSSM from GMSB

Ordinary GMSB realization of NMSSM----Origin of mu-term & explain Higgs mass!

$$V_{\text{Higgs}}(s) \sim m_S^2\, s^2 + \frac{2}{3}\kappa A_\kappa\, s^3 + \kappa^2 s^4$$

Necessary condition for an absolute minimum with $s \neq 0$

$$A_k^2 \gtrsim 9\, m_S^2$$

In general, needs large trilinear couplings A_κ

Yukawa deflection contributions:

$$A_{ab} = -\frac{1}{32\pi^2} d_a^{ij} \Delta\left(\lambda_{aij}^* \lambda_{bij}\right) \Lambda$$

Messenger-matter type interactions!

$$\delta m_{ab}^2 = \frac{1}{256\pi^4}\Big(\frac{1}{2} d_a^{ik} d_i^{\ell m}\left(\Delta\left(\lambda_{aik}^* \lambda_{bjk}\right)\left(\lambda_{i\ell m}\lambda_{j\ell m}^*\right)^+ - \left(\lambda_{aik}^*\lambda_{bjk}\right)^- \Delta\left(\lambda_{i\ell m}\lambda_{j\ell m}^*\right)\right)$$
$$+\frac{1}{4} d_a^{ij} d_b^{k\ell} \Delta\left(\lambda_{aij}^*\lambda_{cij}\right)\Delta\left(\lambda_{ck\ell}^*\lambda_{bk\ell}\right) - d_a^{ij} C_r^{aij} g_r^2 \Delta\left(\lambda_{aij}^*\lambda_{bij}\right)\Big)\Lambda^2$$

Chacko(2001), Shih,JHEP (2013)

1. Ordinary GMSB predict vanishing A-terms at the messenger scale!

2. S-gauge singlet !

Increase simultaneously A-term and m_S^2, still challenging for GMSB.

Better with a tadpole for S.

$$s\left(m_S^2 + m_S'^2 + \mu'^2 + 2\kappa\xi_F + \kappa A_\kappa s + 2\kappa^2 s^2 + 3\kappa s\mu' + \lambda^2(v_u^2 + v_d^2) - 2\lambda\kappa v_u v_d\right)$$
$$+\xi_S + \xi_F \mu' - \lambda v_u v_d (A_\lambda + \mu') = 0\,.$$

Type-II Seesaw in NMSSM from dAMSB

AMSB-naturally large A-terms

Ordinary AMSB realization of NMSSM
---still non-trivial for successful EWSB

Large A_λ, A_κ needs large λ and κ,
induce large positive m_S^2
suppressing the singlet VEV

Triplets act as messengers
--messenger-matter contributions in AMSB
General discussions: see Fei Wang (2016)

New interactions involving H_u, H_d and triplets
will lead to additional contributions to A_κ

----easily EWSB even without S tadpole √

New ingredients in deflected AMSB:

$$\langle X \rangle = M + \theta^2 F_X.$$

pseudo-moduli superpotential

$$W \supset W(X)$$

⟹

Deflection parameter

$$d \equiv \frac{F_X}{M F_\phi} - 1$$

Tachyonic slepton mass

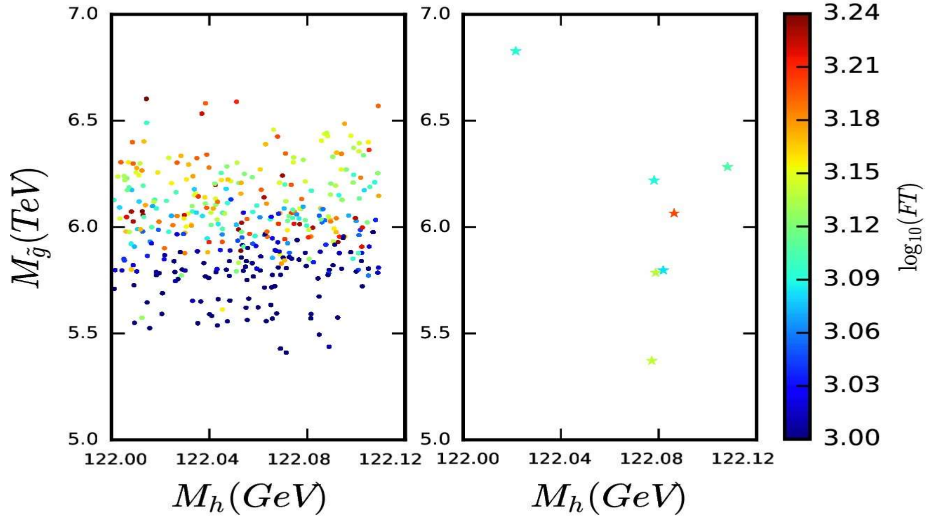
Large A_λ, A_κ

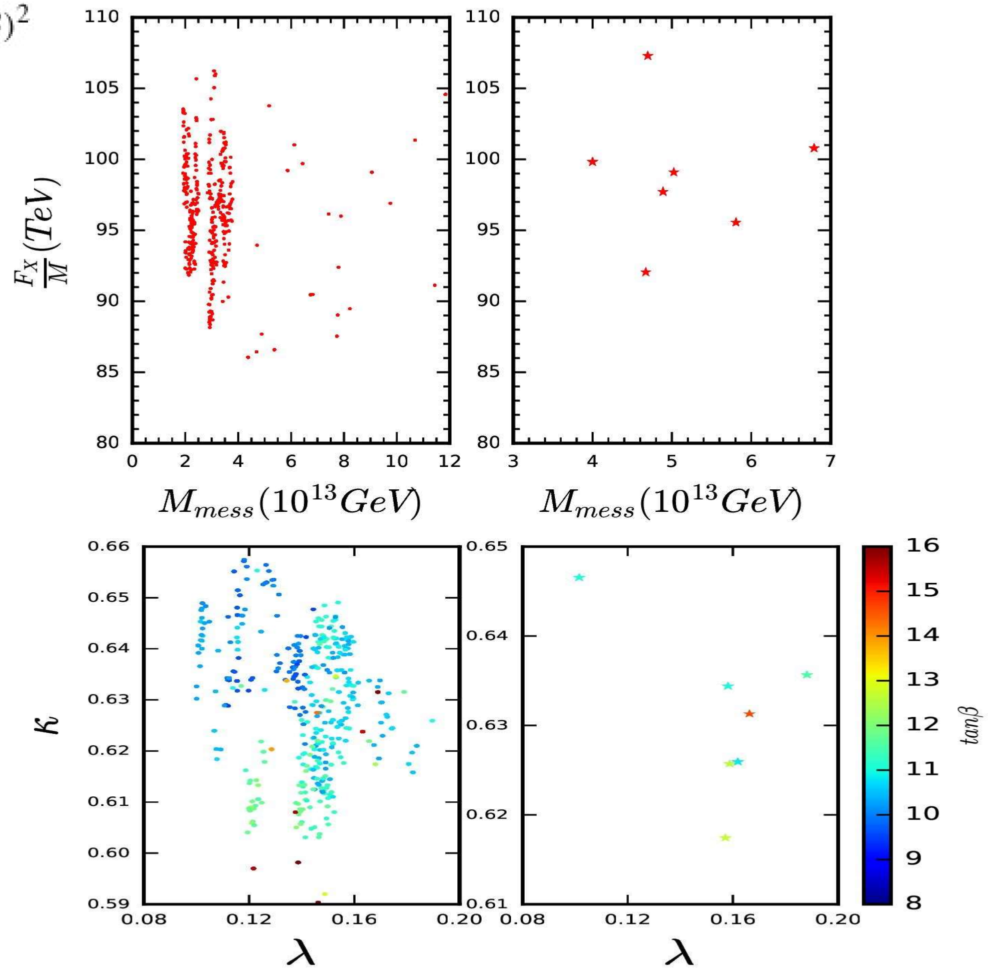
Numerical Results---GMSB case

Higgs mass: $$m_h^2 \simeq M_Z^2\cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta - \frac{\lambda^2}{\kappa^2} v^2(\lambda - \kappa\sin 2\beta)^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\ln\left(\frac{m_{\tilde{T}}^2}{m_t^2}\right) + \frac{A_t^2}{m_{\tilde{T}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{T}}^2}\right)\right],$$

Large A_t--less BG Fine-Tuning.

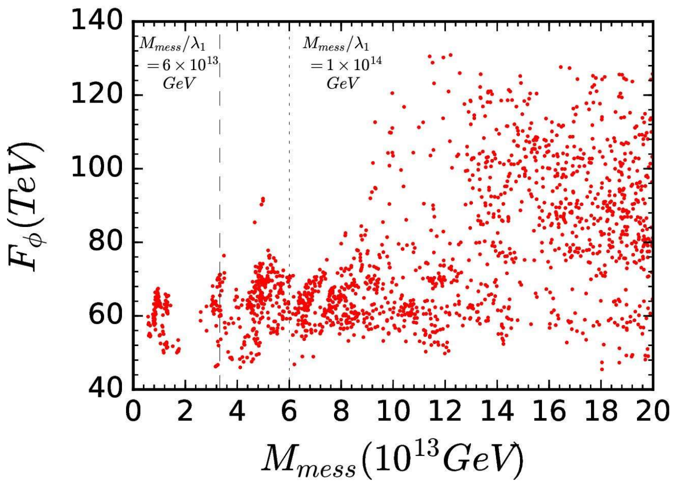
$\frac{m_T}{y_\Delta} \lesssim 1.0\times 10^{14}\text{GeV}$ $\frac{m_T}{y_\Delta} \lesssim 0.6\times 10^{14}\text{GeV}$

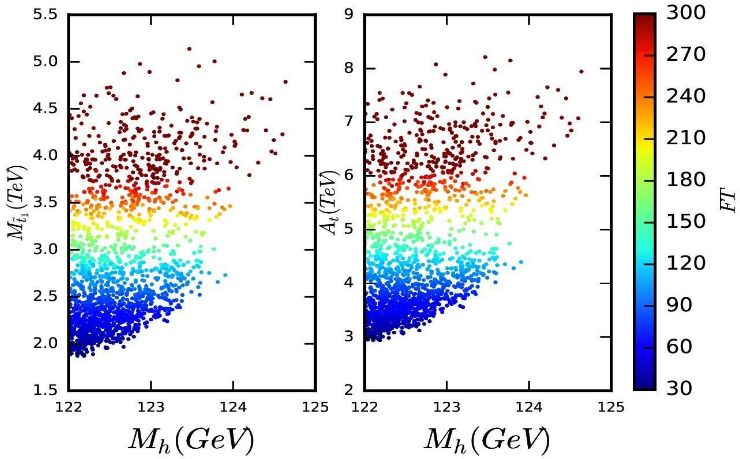


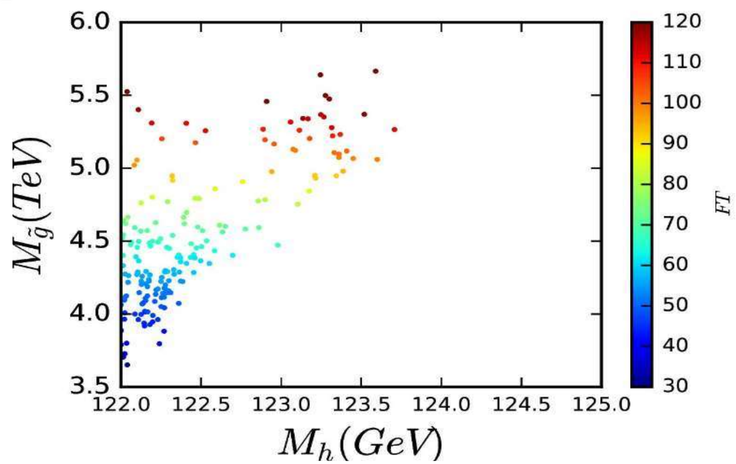


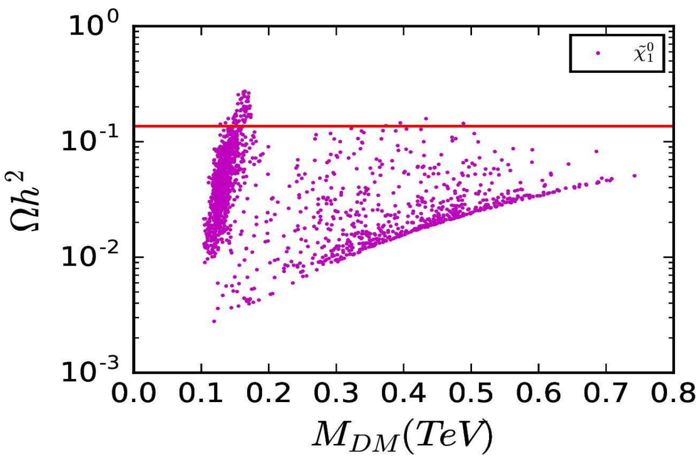
Numerical Results---dAMSB

$$\frac{m_T}{y_\Delta} \lesssim 0.6 \times 10^{14}\mathrm{GeV}$$





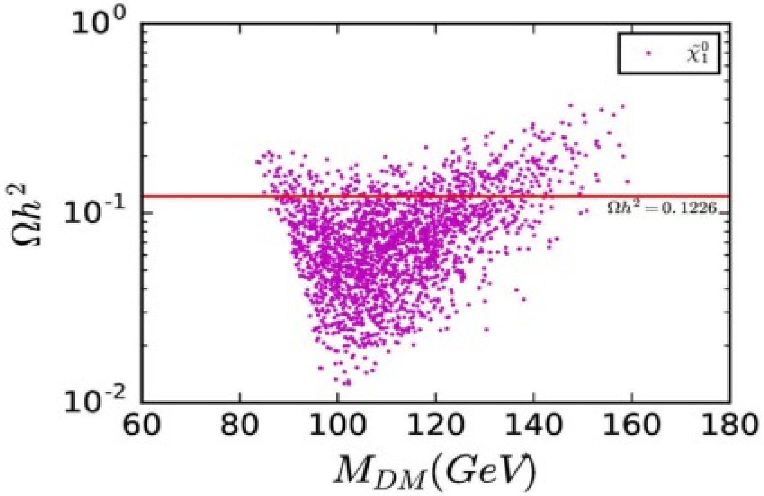




125 GeV Higgs can be:

Lightest (L) or next to Lightest (R)

CP-even scalar



Lepton Flavor Violation constraints

SUGRA-type

- ✓If sfermion masses being universal at high energy, flavour conservation can be broken in the sfermion masses by radiative effects due to flavor-violating Yukawa couplings
- ✓The interactions that generate the neutrino mass also induce LFV in the slepton mass matrices by renormalization effects.
- ✓ Sfermion masses no longer universal at messenger scale.

DAMSB/GMSB-type

- ✓ Non-diagonal sfermion masses for each type at messenger scale!

$$\Delta(m^2_{\tilde{L}})_{ij} \propto \left[(y^L)^\dagger y_L\right]_{ij} \ , \quad \text{for} \quad i \neq j$$

- ✓ LFV interactions decouple with the decouple of messengers
- ✓ LFV effects from RGE suppressed, generated beyond one-loop

$$\Delta\left(m^2_{\tilde{L}}\right)_{ij} \approx -\frac{6}{8\pi^2}\left(3m^2_{\tilde{L}_L}\right)\left[Y^{L\dagger}_{ik} Y^L_{kj}\right]\log\left(\frac{M_U}{m_T}\right) \sim 0$$

- ✓ Relations of LFV processes from $\left[(y^L)^\dagger y_L\right]_{ij}$

See Joaquim& Rossi,PRL (2006)

Lepton Flavor Violation constraints

$$(m_\nu)_{ij} \approx y^L_{ij} \frac{y^u_\Delta v_u^2}{\sqrt{2} m_T} \qquad m_\nu^{diag} = U^T m_\nu U$$

$$\left[(y^L)^\dagger y_L\right] \approx \left(\frac{\sqrt{2} m_T}{y^u_\Delta v_u^2}\right)^2 U (m_\nu^{diag})^2 U^{-1}$$
$$= \left(\frac{\sqrt{2} m_T}{y^u_\Delta v_u^2}\right)^2 \sum_k m_k^2 U_{ik} U^*_{jk}.$$

PMNS matrix:

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

Note: With messenger scale identified with the heavy triplet scalar scale, leading log contribution being

$$\Delta(m^2_{\tilde{L}})^{RGE}_{ij} \propto \frac{1}{(16\pi^2)^2} (m^2_{\tilde{L}})_{mess} \left[(y^L)^\dagger y_L\right]_{ij} \sim 0\ ,$$

GMSB prediction in our case

$$m^2_{\tilde{L}_{L,a}} = \left(\frac{F_X^2}{M^2}\right) \frac{1}{(16\pi^2)^2} \Big[2\left(y_{LL\Delta_T;a}\right)^2 \tilde{G}^+_{LL\Delta_T;a} + 3\left(y_{LD\Delta_{3,2};a}\right)^2 \tilde{G}^+_{LD\Delta_{3,2};a} + \left(\frac{3}{2}g_2^4 + \frac{3}{10}g_1^4\right) 7 \Big]$$

$$\Delta(m^2_{\tilde{L}})_{ij} \propto \left[(y^L)^\dagger y_L\right]_{ij}\ , \quad \text{for} \quad i \neq j$$

whether $(y_{LD\Delta_{3,2}})_{ij} \approx 0$, or $(y_{LD\Delta_{3,2}})_{ij} = (y_{LL\Delta_T})_{ij}$.

$$\frac{Br(l_i \to l_j + \gamma)}{Br(l_i \to l_j + \nu_i \bar{\nu}_j)} \simeq \frac{48\pi^3 \alpha}{G_F^2 m^4_{SUSY}} \left(\frac{g^4 \tan^2\beta}{(16\pi^2)^2} |\Delta(m^2_{\tilde{L}})_{ij}|^2\right)$$

Current best limit from MEG:

$Br(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$, (90% CL)

$\Rightarrow$ $F_X/m_T > 3 \times 10^{-6} m_T$ For GMSB

Lepton Flavor Violation constraints

$$\frac{\mathrm{BR}(\tau\to\mu\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \approx \left[\frac{(\mathbf{m}^2_{\tilde L})_{\tau\mu}}{(\mathbf{m}^2_{\tilde L})_{\mu e}}\right]^2 \frac{\mathrm{BR}(\tau\to\mu\nu_\tau\bar\nu_\mu)}{\mathrm{BR}(\mu\to e\nu_\mu\bar\nu_e)} \approx \begin{cases} 3.48 & (\mathrm{IO}) \\ 3.85 & (\mathrm{NO}) \end{cases}$$

$$\frac{\mathrm{BR}(\tau\to\mu\mu\mu)}{\mathrm{BR}(\mu\to eee)} \approx \begin{cases} 1.16 & (\mathrm{IO}) \\ 1.28 & (\mathrm{NO}) \end{cases}$$

$$\frac{\mathrm{BR}(\tau\to e\gamma)}{\mathrm{BR}(\mu\to e\gamma)} \approx \left[\frac{(\mathbf{m}^2_{\tilde L})_{\tau e}}{(\mathbf{m}^2_{\tilde L})_{\mu e}}\right]^2 \frac{\mathrm{BR}(\tau\to e\nu_\tau\bar\nu_e)}{\mathrm{BR}(\mu\to e\nu_\mu\bar\nu_e)} \approx \begin{cases} 0.15 & (\mathrm{IO}) \\ 0.20 & (\mathrm{NO}) \end{cases}$$

$$\frac{\mathrm{BR}(\tau\to eee)}{\mathrm{BR}(\mu\to eee)} \approx \begin{cases} 0.25 & (\mathrm{IO}) \\ 0.33 & (\mathrm{NO}) \end{cases}$$

$$\mathrm{BR}(\mu\to e\nu_\mu\bar\nu_e)\approx 1$$

$$\mathrm{BR}(\tau\to \mu\nu_\tau\bar\nu_\mu)\approx 17\%$$

$$\mathrm{BR}(\tau\to e\nu_\tau\bar\nu_e)\approx 18\%.$$

IO

$$\begin{cases} (Y_T^\dagger Y_T)_{12} = \tilde m^{-2}(-\ 4.98842586847171 94\times 10^{-14} - 2.707927523936294\times 10^{-13} i) \\ (Y_T^\dagger Y_T)_{13} = \tilde m^{-2}(-\ 8.978389780251289\times 10^{-14} - 2.393322032527885\times 10^{-13} i) \\ (Y_T^\dagger Y_T)_{23} = \tilde m^{-2}(-\ 1.2455893961495833\times 10^{-12} - 4.989638020041978\times 10^{-15} i) \end{cases}$$

NO

$$\begin{cases} (Y_T^\dagger Y_T)_{12} = \tilde m^{-2}(-\ 2.525515609275667\times 10^{-13} - 1.442205288833084\times 10^{-14} i) \\ (Y_T^\dagger Y_T)_{13} = \tilde m^{-2}(-\ 2.690250638429381\times 10^{-13} - 1.2757862388391988\times 10^{-14} i) \\ (Y_T^\dagger Y_T)_{23} = \tilde m^{-2}(\ 1.2038006323809836\times 10^{-12} + 2.6787676694189162\times 10^{-16} i) \end{cases}$$

Similar discussions as for MSSM, Joaquim& Rossi, NPB (2006)

Conclusions

- Type II neutrino seesaw extension of NMSSM can origin from dAMSB/GMSB.
- Combination of Type II seesaw with SUSY breaking mechanism in NMSSM can be advantageous.
- The identification of messenger scale with triplet scale, can be fairly predictive and non-trivial.
- Can set constrains for SUSY breaking parameters by LFV constraints (in addition to predictions on ratios of LFV processes).
- Need more LFV works for dAMSB.

Thanks!

Back Up Slides

$$m^2_{\tilde{U}^c_{L,a}} = \left(\frac{F_X^2}{M^2}\right)\frac{1}{(16\pi^2)^2}\left[-2y_t^2\Delta\tilde{G}_{y_t}\delta_{a,3} + \left(\frac{8}{3}g_3^4 + \frac{8}{15}g_1^4\right)7\right],$$

$$m^2_{\tilde{D}^c_{L,a}} = \left(\frac{F_X^2}{M^2}\right)\frac{1}{(16\pi^2)^2}\left[3\left(y_{DD\Delta_{se};a}\right)^2\tilde{G}^+_{DD\Delta_{se};a} + 2\left(y_{LD\Delta_{3,2};a}\right)^2\tilde{G}^+_{LD\Delta_{3,2};a} - 2y_b^2\Delta\tilde{G}_{y_b}\delta_{a,3} + \left(\frac{8}{3}g_3^4 + \frac{2}{15}g_1^4\right)7\right],$$

$$m^2_{\tilde{L}_{L,a}} = \left(\frac{F_X^2}{M^2}\right)\frac{1}{(16\pi^2)^2}\left[2\left(y_{LL\Delta_T;a}\right)^2\tilde{G}^+_{LL\Delta_T;a} + 3\left(y_{LD\Delta_{3,2};a}\right)^2\tilde{G}^+_{LD\Delta_{3,2};a} + \left(\frac{3}{2}g_2^4 + \frac{3}{10}g_1^4\right)7\right],$$

$$\tilde{G}^+_{DD\Delta_{se};a} = 10\left(y^L_{\mathbf{15;a}}\right)^2 + \sum_c\left(y^L_{\mathbf{15;c}}\right)^2 + (y_X)^2 + 4y_b^2\delta_{a,3} - 12g_3^2 - \frac{4}{3}g_1^2,$$

$$\tilde{G}^+_{LD\Delta_{3,2};a} = 10\left(y^L_{\mathbf{15;a}}\right)^2 + \sum_c\left(y^L_{\mathbf{15;c}}\right)^2 + (y_X)^2 + 2y_b^2\delta_{a,3} - \frac{16}{3}g_3^2 - 3g_2^2 - \frac{7}{15}g_1^2,$$

$$\tilde{G}^+_{LL\Delta_T;a} = 10\left(y^L_{\mathbf{15;a}}\right)^2 + \left(y^d_{\mathbf{15}}\right)^2 + \sum_c\left(y^L_{\mathbf{15;c}}\right)^2 + (y_X)^2 - 7g_2^2 - \frac{9}{5}g_1^2,$$