Dirac Triplet Extension of the MSSM*

Carlos Alvarado

University of Notre Dame

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*arXiv:1504.03683v1
CA, Delgado, Martin, Ostdiek

Introduction: MSSM Higgs mass

- **LHC**: A Higgs boson $m_h \approx 125$ GeV.
- **MSSM (Standard model + low scale SUSY)**:
  - Radiatively stable scalar potential
  - Unification
  - Radiative EWSB
  - DM candidate
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- **Fine tuning**: $m_{H_u}^2$ controls EWSB. Consider $\delta m_{H_u}^2 / m_h^2$,

  $$\delta m_{H_u}^2 \propto (m_{Q_3}^2 + m_{\bar{u}_3}^2 + A_t^2)$$

  Large stop masses/stop mixing $\Rightarrow$ $\sim 1\%$ fine-tuned Higgs sector.

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$$\lambda S H_u H_d + \boldsymbol{M S \bar{S}}$$

$$m^2_{h,\text{tree}} = m_Z^2 \cos^2 2\beta + \lambda^2 \mathcal{F}(\beta) \frac{m^2_{\bar{S}}}{M^2 + m^2_{\bar{S}}} - \lambda^2 \mathcal{G}(\beta) \frac{1}{M^2 + m^2_S}$$

Sizable, positive contribution to m_h if $m^2_{\bar{S}} \gg M^2$. Expect large FT?
No, $m^2_{\bar{S}}$ does not enter $\beta\left(m^2_{H_{u,d}}\right)$ at 1-loop .

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- Room for improvement in the DiracNMSSM: $\tan\beta$ dependence

$$SH_u \cdot H_d \sim \sin 2\beta \qquad (\text{ enhances } m_h^2 \text{ at } \textbf{low} \ \tan\beta)$$

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- $SU(2)_L$ multiplets other than singlets/doublets: **triplets**
  - Gauge-invariant couplings to $H_{u,d}$
  - phenomenology ($h \to \gamma\gamma$, stop decay)
  - constrained by EWPT (vevs must be small)

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$$\mu_\Sigma \mathsf{Tr}\left[\Sigma_1 \cdot \Sigma_2\right] + \lambda H \Sigma_1 H$$

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	$Y = 0$	$Y = \pm 1$	
	$\lambda H_d \cdot \Sigma_1 H_u$	$\lambda H_d \cdot \Sigma_1 H_d$	$\lambda H_u \cdot \Sigma_1 H_u$
δm_h^2	$\sim \sin^2 2\beta$	$\sim \cos^4 \beta$	$\sim \sin^4 \beta$

Hypercharge choice $\Rightarrow$ fixed $\tan\beta$ dependence in m_h

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- **Tree-level Higgs mass**: Let T^0, χ^0 be the neutral components of $\Sigma^0_{1,2}$, with soft masses $m^2_{T,\chi}$

$$m^2_{h,\text{tree}} = m_Z^2 \cos^2 2\beta + \delta^+ - \delta^-, \qquad \delta^{+(-)} \propto \frac{m^2_\chi(1)}{\mu^2_\Sigma + m^2_{\chi(T)}}$$

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The task: maximize δ^+ while minimizing δ^-

$m_\chi \gg \mu^2_\Sigma$ preferred

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- The $\mathcal{T}$-parameter favors
  - $m_\chi^2 \gg \mu_\Sigma^2$
  - $m_T^2 \gtrsim \mu_\Sigma^2$
  - $\boldsymbol{Y = \pm 1}$ due to λ and $\tan\beta$ dependence.

The model: fine tuning

A measure of fine tuning ($L = \log \Lambda / m_{\text{stop}}$)

$$\Delta \equiv \frac{2}{m_h^2} \max \left(m_{H_u}^2, m_{H_d}^2, L \frac{dm_{H_u}^2}{d\log(u)}, L \frac{m_{H_d}^2}{\log(u)}, \delta m_{H_u^0}^2, \mu B_{\mu \text{eff}} \right)$$

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Dominated by

$$\frac{dm_{H_u}^2}{d \log (u)} \ni 6 y_t^2 (m_{Q_3}^2 + m_{\bar{u}_3}^2) + 6 \lambda^2 m_T^2 + \text{(two-loop pieces)}^*$$

* Contains m_χ^2.

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m_χ^2 **absent** at 1-loop $\Rightarrow m_\chi^2 \gg \mu_\Sigma^2$ lifts m_h^2 **without** introducing large Δ

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The model: stop mass & benchmark

- δm_h^2(triplets), $\mathcal{T}$-parameter and Δ **all** prefer $Y = \pm 1$

  Drop $\boldsymbol{Y = 0}$, focus **on $\boldsymbol{Y = \pm 1}$** type $\lambda H_u \Sigma_1 \cdot H_u$

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- **benchmark**:

$\tan\beta = 10$	$m_A = 300$ GeV	$A_t = 0$
$\mu = 250$ GeV	$B_\Sigma = 100$ GeV	$A_\lambda = 0$

λ, m_T, m_χ, μ_Σ to be set numerically

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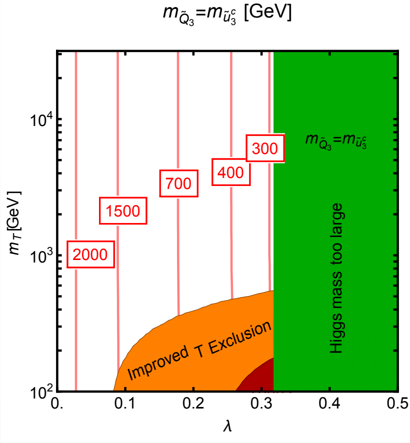
- **Stop mass**: adjust $m_{\tilde{Q}_3}$ and $m_{\tilde{u}_3^c}$ so that

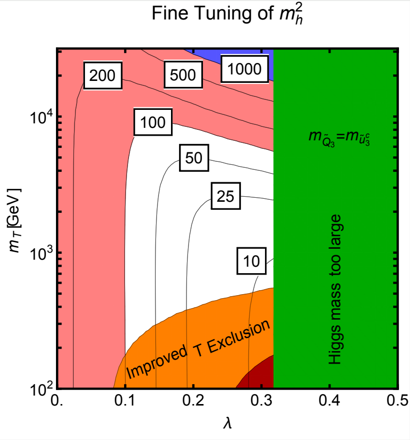
$$(125\ \text{GeV})^2 = \delta m_h^2(\text{triplets}) + \delta m_h^2(\text{stops})$$

$m_{\tilde{Q}_3} = m_{\tilde{u}_3^c}$ vary, or only $m_{\tilde{u}_3^c}$ varies.

Results: stop mass & fine tuning

Fix $m_\chi(10\ \text{TeV})$ and $\mu_\Sigma(300\ \text{GeV})$





$\lambda = 0.25$, $m_T = 800$ GeV join the benchmark set.

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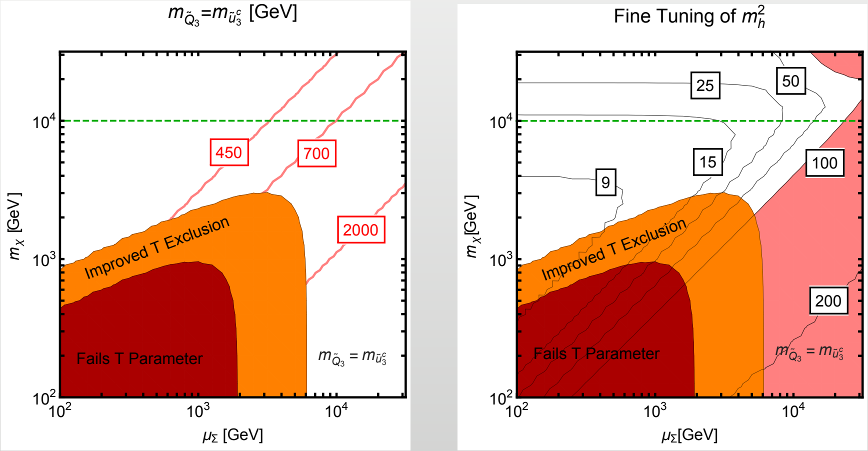
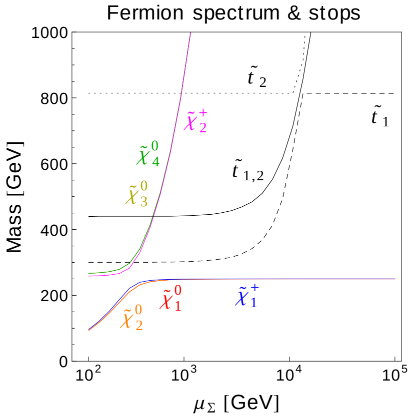
SUSY-breaking m_χ v.s. SUSY mass μ_Σ



Low $\Delta(\approx 15)$ and light stops $(\approx 450\text{ GeV})$ at $\mu_\Sigma = m_\chi = 10$ TeV

Results: stop decay

Phenomenology **at $m_\chi = 10$ TeV, $\mu_\Sigma = 250$ GeV** (gauginos decoupled)

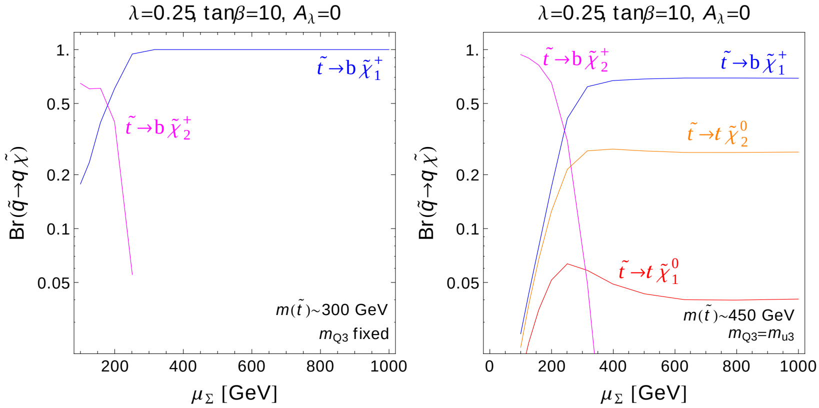


Lighter electroweakinos

$\mu_\Sigma < \mu$: mostly tripletino, $\mu_\Sigma > \mu$: mostly Higgsino.

Results: stop decay

Two-body final states



- $\mu_\Sigma < \mu$: stop $\rightarrow$ Higgsino $\rightarrow$ tripletino
- $\mu_\Sigma > \mu$: stop $\rightarrow$ Higgsino

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- MSSM + Dirac-mass triplets raise $m_h^{(\text{tree})}$ efficiently (no large Δ) with large uncoupled triplet soft mass.
- **$Y = \pm 1$ model**: parameter values keeping low Δ also maintain $\mathcal{T}$-parameter under control.
- **Light stops**: ~ 300 or 450 GeV.
    - Light RH stop: safe by $\mu_\Sigma > 200$ GeV.
    - Light $L = R$ stop: $\tilde{b}$-searches demand compressed spectra (either greater $m_{\tilde{t}}$ or greater μ).
- **Light tripletinos**: $\mu_\Sigma \sim 150$ GeV due tiny splitting within the multiplet. Must be looked for at the LHC.

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Thank you

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Examples involving a SM singlet S (non-exhaustive)

NMSSM	$\lambda S H_u H_d + \frac{\kappa}{3} S^3$	$\mathbb{Z}^3$	Ellis :1988er
G-NMSSM	$\lambda S H_u H_d + \frac{\mu}{2} S^2$	$--$	Kolda, 1005.1282
UMSSM	$\lambda S H_u H_d$	$U(1)'$	Langacker, hep-ph/703317

Backup: $Y = 0$ model

$$\Delta m_h^2 = \frac{v^2\lambda^2}{2}\sin^2(2\beta)\frac{m_\chi^2}{\mu_\Sigma^2 + m_\chi^2} - \frac{v^2\lambda^2}{2}\frac{|2\mu^* - A_\lambda \sin(2\beta)|^2}{\mu_\Sigma^2 + m_T^2}.$$

$$\delta m^2_{H_u^0} \simeq \frac{3}{2}\frac{\lambda^2\mu_\Sigma^2}{16\pi^2}\log\frac{m_\chi^2 + \mu_\Sigma^2}{\mu_\Sigma^2}$$

$$\mathcal{T}_{Y=0} = \frac{1}{\alpha}\;\frac{4\big(\langle\chi^0\rangle^2 + \langle T^0\rangle^2\big)}{v^2 - 4\big(\langle\chi^0\rangle^2 + \langle T^0\rangle^2\big)}$$

$$\left\langle T^0\right\rangle_{Y=0} \approx \frac{v^2\lambda}{2\sqrt{2}}\frac{2\mu^* - A_\lambda \sin(2\beta)}{\mu_\Sigma^2 + m_T^2}$$

$$\left\langle \chi^0\right\rangle_{Y=0} \approx -\frac{v^2\lambda}{2\sqrt{2}}\frac{\mu_\Sigma \sin(2\beta)}{\mu_\Sigma^2 + m_\chi^2},$$

Backup: $Y = \pm 1$ model

$$\Delta m_h^2 = 4v^2\lambda^2 \sin^4(\beta)\left(\frac{m_{T_1}^2}{\mu_\Sigma^2 + m_\chi^2}\right) - \frac{4v^2\lambda^2\sin^2(\beta)}{\mu_\Sigma^2 + m_T^2}\left|2\mu^*\cos(\beta) - A_\lambda \sin(\beta)\right|^2 .$$

$$\delta m_{H_u^0}^2 \simeq 6\frac{\lambda^2\mu_\Sigma^2}{16\pi^2}\log\frac{m_\chi^2 + \mu_\Sigma^2}{\mu_\Sigma^2}.$$

$$\left\langle T^0 \right\rangle_{Y=-1} \approx -\frac{v^2\lambda}{2}\frac{\sin(2\beta)\left(2\mu^* - A_\lambda \tan(\beta)\right)}{\mu_\Sigma^2 + m_T^2}$$

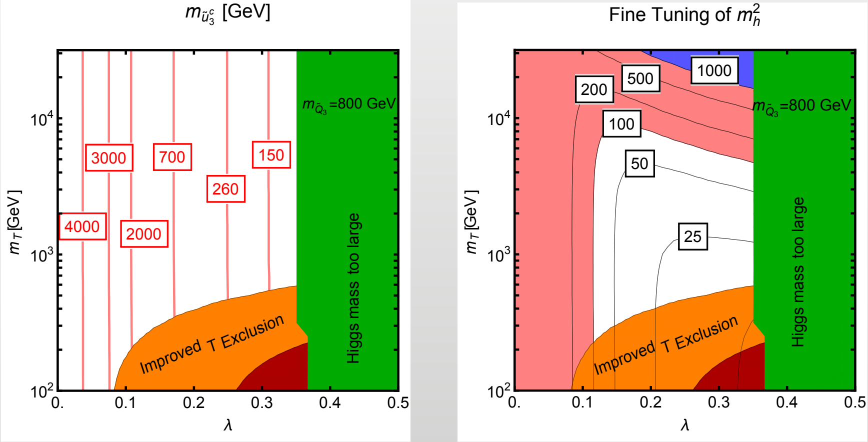
$$\left\langle \chi^0 \right\rangle_{Y=1} \approx v^2\frac{-\lambda\mu_\Sigma\sin^2(\beta)}{\mu_\Sigma^2 + m_\chi^2}.$$

Backup: Two-loop RGE in $Y = \pm 1$

$$\frac{dm_{H_u}^2}{dt} \supset \frac{1}{(4\pi)^2}\left(6h_t^2\left(m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2\right) + 6\lambda^2\left(2m_{H_u}^2 + m_T^2 + A_\lambda^2\right)\right)$$
$$+ \frac{1}{(4\pi)^4}\left(\frac{162}{25}g_1^4 + \frac{72}{5}g_1^2 g_2^2 + 12 g_2^4\right) m_\chi^2$$
$$\frac{dm_{H_d}^2}{dt} \supset \frac{1}{(4\pi)^2}\left(6h_b^2\left(m_{Q_3}^2 + m_{D_3}^2 + m_{H_u}^2\right)\right)$$
$$+ \frac{1}{(4\pi)^4}\left(-\frac{54}{25}g_1^4 - \frac{72}{5}g_1^2 g_2^2 + 12 g_2^4\right) m_\chi^2$$

Backup: varying $m_{u_3^c}$ only

Fix $m_\chi(10\ \text{TeV})$ and $\mu_\Sigma(300\ \text{GeV})$



$$\lambda = 0.25,\ m_T = 800\ \text{GeV still good}$$

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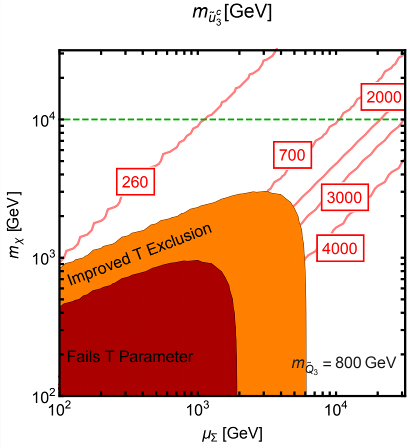
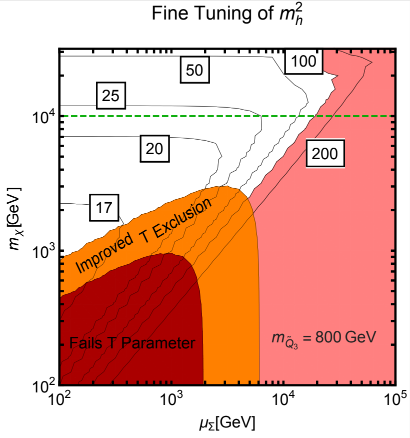
m_χ vs μ_Σ





Light stops (≈ 300 GeV) at $\mu_\Sigma = m_\chi = 10$ TeV

Backup: $Y = \pm 1$ mixing matrices

Neutralino mixing

$$\begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z & -\sqrt{2} g' v_T & \sqrt{2} g' v_\chi \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z & -\sqrt{2} g v_T & \sqrt{2} g v_\chi \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu & 0 & 0 \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & -2 v_T \lambda & -2 v \lambda s_\beta & 0 \\ -\sqrt{2} g' v_T & -\sqrt{2} g v_T & 0 & -2 v \lambda s_\beta & 0 & -\mu_\Sigma \\ \sqrt{2} g' v_\chi & \sqrt{2} g v_\chi & 0 & 0 & -\mu_\Sigma & 0 \end{pmatrix}$$

Chargino mixing

$$\mathcal{M}_C = \begin{pmatrix} M_2 & g v s_\beta & -\sqrt{2} g v_\chi \\ g v c_\beta & \mu & 0 \\ -\sqrt{2} g v_T & \sqrt{2} \lambda v s_\beta & \mu_\Sigma \end{pmatrix}$$

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- $m_{\psi_\Sigma^{++}} > m_{\psi_\Sigma^{+}} > m_{\psi_\Sigma^{0}}$ all about $\mu_\Sigma = 150$ GeV.

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- No LO effect on $h \to \gamma\gamma$.