Asymptotically Free Supersymmetric Twin Higgs

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Based on:
MB, Keisuke Harigaya
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Motivation

- LHC set strong constraints on colored top partners (e.g. stops in Supersymmetry)
- Neutral Naturalness (uncolored top partners) becomes a new paradigm to solve the hierarchy problem
- Twin Higgs idea is a nice implementation of Neutral Naturalness but still requires UV completion to solve the big hierarchy problem of the SM
- All known UV completions involve some non-perturbative dynamics not far above the EW scale
- In this talk: Supersymmetric Twin Higgs model perturbative up to around the Planck scale

Twin Higgs model in a nutshell

Chacko, Goh, Harnik '05

- The Higgs is a pNGB of a global SU(4) symmetry
- SU(4) enforced by Z_2 symmetry exchanging two copies of the SM

SM $\rightarrow$ $H \xleftrightarrow{\mathbb{Z}_2} H'$ $\leftarrow$ mirror

$$V = \underbrace{\lambda(|H'|^2 + |H|^2)^2 - m^2(|H'|^2 + |H|^2)}_{\text{SU(4) symmetric}} + \underbrace{\Delta\lambda(|H'|^4 + |H|^4)}_{\text{SU(4) breaking}} + \underbrace{\Delta m^2 |H^2|}_{SU(4)\ \&\ \mathbb{Z}_2\ \text{breaking}}$$

SU(4) symmetric

SU(4) spontaneously broken to SU(3) $\longrightarrow$ 7 NGB :
6 eaten + massless Higgs

SU(4) breaking $\downarrow$

the Higgs is pNGB
maximal mixture
of H and H'

$SU(4)$ & $\mathbb{Z}_2$ breaking $\downarrow$

the Higgs
with SM-like
couplings

Scale of SU(4) breaking: $f^2 \equiv v^2 + v'^2 \qquad \langle H \rangle \equiv v \quad \langle H' \rangle \equiv v'$

Fine-tuning in Twin Higgs models

- Maximal gain in fine-tuning depends on the size of λ:

$$\frac{2\lambda}{\lambda_{\mathrm{SM}}} \qquad \lambda_{\mathrm{SM}} \approx 0.13$$

- Large λ preferred which suggests non-perturbative UV completions of Twin Higgs model:

Composite Twin Higgs or SUSY with low Landau pole scale

Batra, Chacko ’08 Geller, Telem ’14 Barbieri et al ’15 Low, Tesi, Wang‘15

Falkowski, Pokorski, Schmaltz ’06 Chang, Hall, Weiner ’06 Craig, Howe ’13 Katz et al. ’16 MB, Harigaya ‘17

How to make UV completed Twin Higgs perturbative up to high scales?

Supersymmetry with new gauge symmetry

SUSY D-term Twin Higgs

- SU(4) invariant quartic term generated by a D-term potential of a new gauge symmetry MB, Harigaya '17

$$V_{U(1)_X} = \frac{g_X^2}{8}\left(|H_u|^2 - |H_d|^2 + |H_u'|^2 - |H_d'|^2\right)^2 (1-\epsilon^2)$$

model dependent

$0 < \epsilon < 1$

$\epsilon \ll 1$ preferred

must be large

$$\lambda = g_X^2 \frac{\cos^2(2\beta)}{8}(1-\epsilon^2) \equiv \lambda_D$$

- New U(1) works well for low mediation scale of SUSY breaking – better than 10% tuning but Landau Pole at O(100) TeV

Keeping new gauge coupling in the perturbative regime prefers:

- Non-abelian gauge interaction preferred
- number of fields charged under the new interaction as small as possible

Particle Content of the Minimal Model

$\mathcal{H} = (H_u, H_2)^T$

right-handed top

SU(2)$_X$ breaking fields

Required by U(1)$_Y$-SU(2)$_X^2$ anomaly cancellation

	$SU(2)_X$	$SU(2)_L$	$SU(2)'_L$	$U(1)_Y$	$U(1)'_Y$	$SU(3)_c$	$SU(3)'_c$
$\mathcal{H}$	$\mathbf{2}$	$\mathbf{2}$		$1/2$			
$\mathcal{H}'$	$\mathbf{2}$		$\mathbf{2}$		$1/2$		
$\bar{Q}_R$	$\mathbf{2}$			$-2/3$		$\bar{\mathbf{3}}$	
$\bar{Q}'_R$	$\mathbf{2}$				$-2/3$		$\bar{\mathbf{3}}$
S	$\mathbf{2}$						
$\bar{S}$	$\mathbf{2}$						
$\bar{E}$	$\mathbf{2}$			1			
$\bar{E}'$	$\mathbf{2}$				1		
U				$2/3$		$\mathbf{3}$	
U'					$2/3$		$\mathbf{3}$
$E_{1,2}$				-1			
$E'_{1,2}$					-1		
ϕ_u		$\mathbf{2}$		$1/2$			
ϕ'_u			$\mathbf{2}$				
$\phi_{d1,2,3}$		$\mathbf{2}$		$-1/2$			
$\phi'_{d1,2,3}$			$\mathbf{2}$		$-1/2$		
$Q_{1,2,3}$		$\mathbf{2}$		$1/6$		$\mathbf{3}$	
$\bar{u}_{1,2}$				$-2/3$		$\bar{\mathbf{3}}$	
$\bar{e}_{1,2,3}$				1			
$\bar{d}_{1,2,3}$				$1/3$		$\bar{\mathbf{3}}$	
$L_{1,2,3}$		$\mathbf{2}$		$-1/2$			
$Q'_{1,2,3}$			$\mathbf{2}$		$1/6$		$\mathbf{3}$
$\bar{u}'_{1,2}$					$-2/3$		$\bar{\mathbf{3}}$
$\bar{e}'_{1,2,3}$					1		
$\bar{d}'_{1,2,3}$					$1/3$		$\bar{\mathbf{3}}$
$L'_{1,2,3}$			$\mathbf{2}$		$-1/2$		

Breakdown of the SU(2)$_X$ symmetry

$$W = \kappa Z(S\bar{S} - M^2) \quad V_{\rm soft} = m_S^2(|S|^2 + |\bar{S}|^2)$$

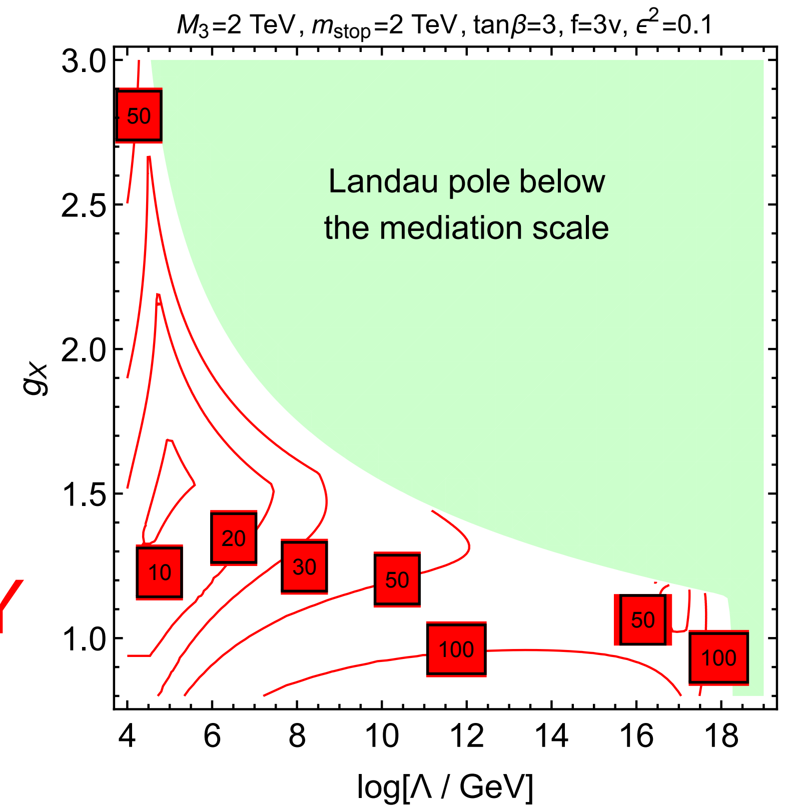
$$\langle S \rangle = \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \;\; \langle \bar{S} \rangle = \begin{pmatrix} v_S \\ 0 \end{pmatrix}, \;\; v_S = \sqrt{M^2 - m_S^2/\kappa^2}$$

- SU(4) invariant term from D-term potential:

$$\frac{g_X^2}{8} \sin^4\beta (1-\epsilon^2)(|H|^2 + |H'|^2)^2 \qquad \epsilon^2 = \frac{m_X^2}{2m_S^2 + m_X^2}$$

High mediation scale of SUSY breaking

- The Landau pole for the $SU(2)_X$ interaction is much higher than in the U(1) model
- tuning better than 5% can be obtained for mediation scale as high as 10^7 GeV
- For gravity mediated SUSY breaking 1% tuning



Asymptotically Free SUSY Twin Higgs

The non-abelian model can be extended to make the new interaction asymptotically free!

$SU(2)_X \times SU(2)'_X$

$$W = Y(\Sigma^2 - v_\Sigma^2)$$

$SU(2)_D$

$$W = \kappa\Xi(S\bar{S} - M^2) + \kappa\Xi'(S'\bar{S}' - M^2)$$

$$V_{\rm soft} = m_S^2(|S|^2 + |\bar{S}|^2 + |S'|^2 + |\bar{S}'|^2)$$

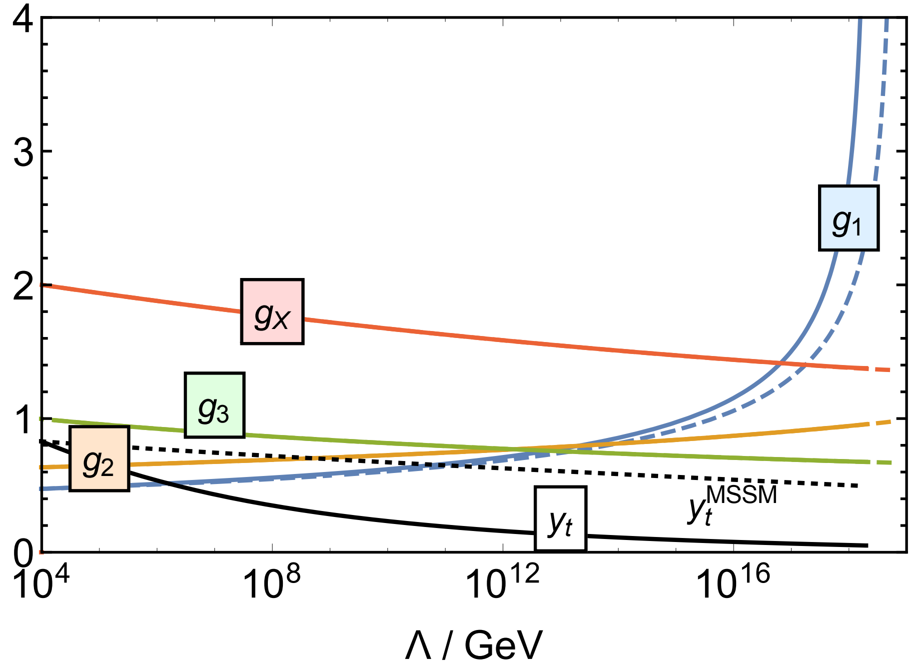
$\cancel{SU(2)_D}$

right-handed top & up

	$SU(2)_X$	$SU(2)'_X$	3-2-1	$3'$-$2'$-$1'$
$\mathcal{H}$	$\mathbf{2}$		$(\mathbf{1},\mathbf{2},1/2)$	
$\mathcal{H}'$		$\mathbf{2}$		$(\mathbf{1},\mathbf{2},1/2)$
Σ	$\mathbf{2}$	$\mathbf{2}$		
S	$\mathbf{2}$			
$\bar{S}$	$\mathbf{2}$			
S'		$\mathbf{2}$		
$\bar{S}'$		$\mathbf{2}$		
$\bar{Q}_R$	$\mathbf{2}$		$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	
$\bar{Q}'_R$		$\mathbf{2}$		$(\mathbf{3},\mathbf{1},-2/3)$
$\bar{E}$	$\mathbf{2}$		$(\mathbf{1},\mathbf{1},1)$	
$\bar{E}'$		$\mathbf{2}$		$(\mathbf{1},\mathbf{1},1)$
$E_{1,2}$			$(\mathbf{1},\mathbf{1},-1)$	
$E'_{1,2}$				$(\mathbf{1},\mathbf{1},-1)$
ϕ_u			$(\mathbf{1},\mathbf{2},1/2)$	
ϕ'_u				$(\mathbf{1},\mathbf{2},1/2)$
$H_d, \phi_{d,1,2}$			$(\mathbf{1},\mathbf{2},-1/2)$	
$H'_d, \phi'_{d,1,2}$				$(\mathbf{1},\mathbf{2},-1/2)$

Twin states charged under different SU(2)s at high scales

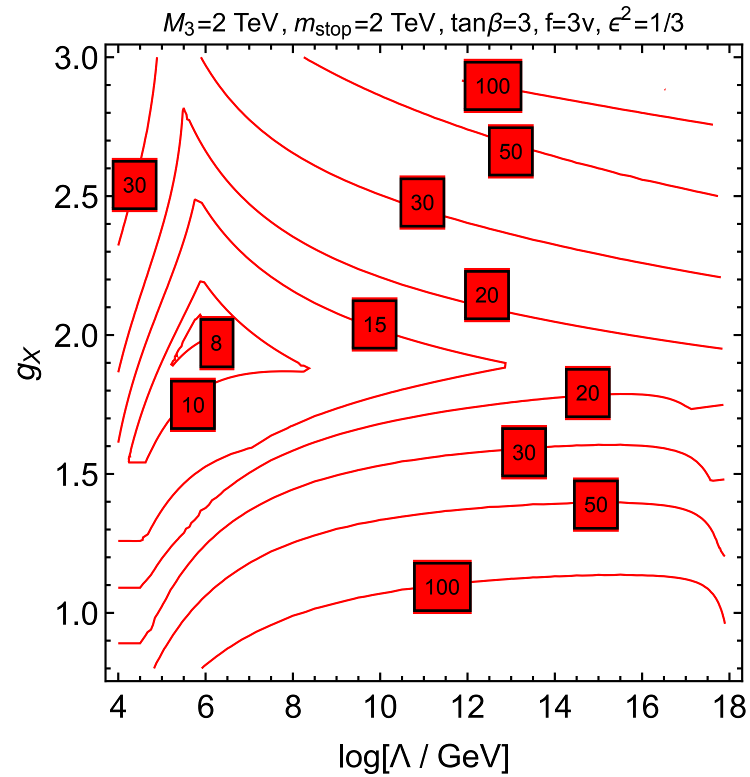
Asymptotically Free SUSY Twin Higgs: RG running of couplings



- g_X asymptotically free!
- New interaction drives the top Yukawa coupling to small values at high scales – suppressed tuning from stops and gluino

Asymptotically Free SUSY Twin Higgs

- Twin Higgs mechanism works perturbatively even for mediation around the Planck scale
- Tuning better than 5% (for 2 TeV stops and gluino) even for gravity mediation of SUSY breaking

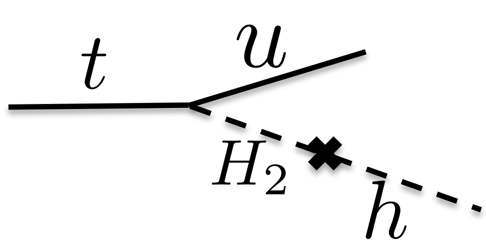


Asymptotically Free SUSY Twin Higgs: flavor-violating top decays

The model has non-trivial flavor structure

The top Yukawa coupling is generated via $W \sim \mathcal{H}\bar{Q}_R Q_3$

The interaction includes $\mathcal{L} = y_t H_2 \bar{u}_R Q_3$ which generates top decay to the Higgs and the up quark



$$\mathrm{BR}(t \to hu) \sim \left(\frac{\theta_{hH_2}}{0.1}\right)^2 10^{-3}$$

Sizable $\mathrm{BR}(t \to hu)$ even for not large $H_2 - h$ mixing

Current LHC limit on $\mathrm{BR}(t \to hu) \sim 10^{-3}$ may be improved to 10^{-4} at HL-LHC

Conclusions

- Twin Higgs mechanism is the leading idea of Neutral Naturalness that used to be thought to require some non-perturbative dynamics
- I presented natural SUSY UV completion of Twin Higgs in which D-term of a new gauge symmetry provides approximate SU(4) symmetry for the Higgs sector
- Fine-tuning may be relaxed by a factor of 10 as compared to SUSY models without Twin Higgs mechanism
- EW scale is obtained naturally for stop and gluino masses that easily satisfy current constraint and may even escape detection at HL-LHC
- The model with new non-abelian interactions is perturbative and does not require any further UV completion below the energy scale of gravity
- Perturbativity up to the Planck scale enforces non-trivial flavor structure leading e.g. to $t \to hu$ decay which may be discovered at the LHC

BACKUP

The Higgs mass in SUSY Twin Higgs

- In SUSY Twin Higgs SU(4) is broken by the EW gauge interaction

$$V_D = \frac{g^2 + g'^2}{8} \left[(|H_u|^2 - |H_d|^2)^2 + (|H'_u|^2 - |H'_d|^2)^2 \right] \longrightarrow \frac{g^2 + g'^2}{8} \cos^2(2\beta) \equiv \Delta\lambda_{\rm SUSY} \approx 0.07 \cos^2(2\beta)$$

- The tree-level Higgs mass is given by

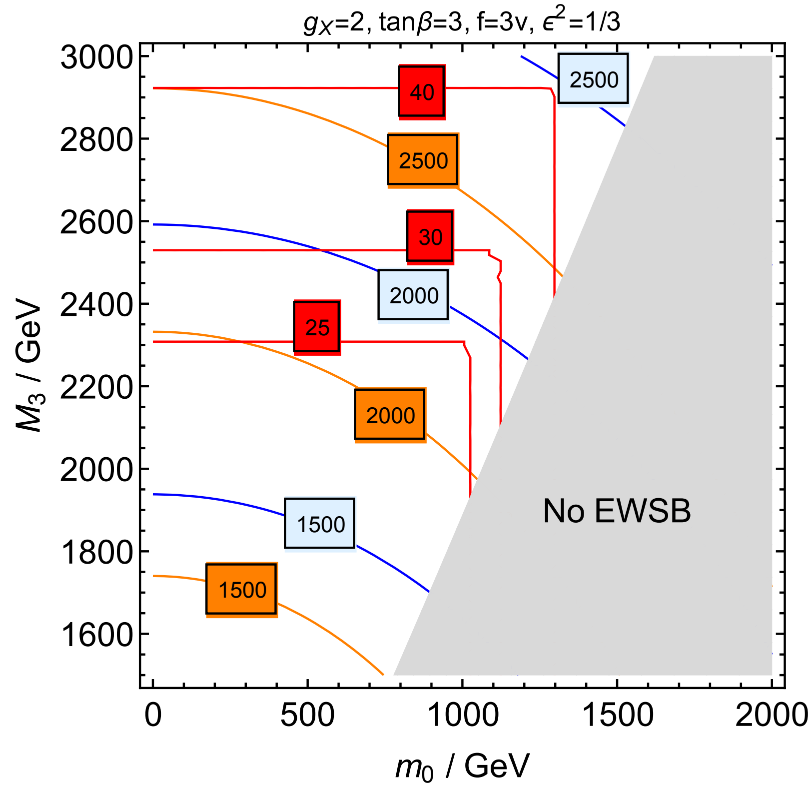
$$\left(m_h^2\right)_{\rm tree} \approx 2 M_Z^2 \cos^2(2\beta) \left(1 - \frac{v^2}{f^2}\right) + \mathcal{O}(\Delta\lambda/\lambda)$$

- The Higgs mass enhanced by a factor of $\sqrt{2}$ (after Z_2 breaking which is needed anyway) as compared to MSSM.
- $m_h \approx 125\ \mathrm{GeV}$ obtained at tree level in the limit of large $\tan\beta$!
- But:
- In explicit models corrections $\mathcal{O}(\Delta\lambda/\lambda)$ are non-negligible

Asymptotically Free SUSY Twin Higgs:

spectrum for simple UV boundary conditions

- Universal scalar masses
- M_3 fixed at the EW scale

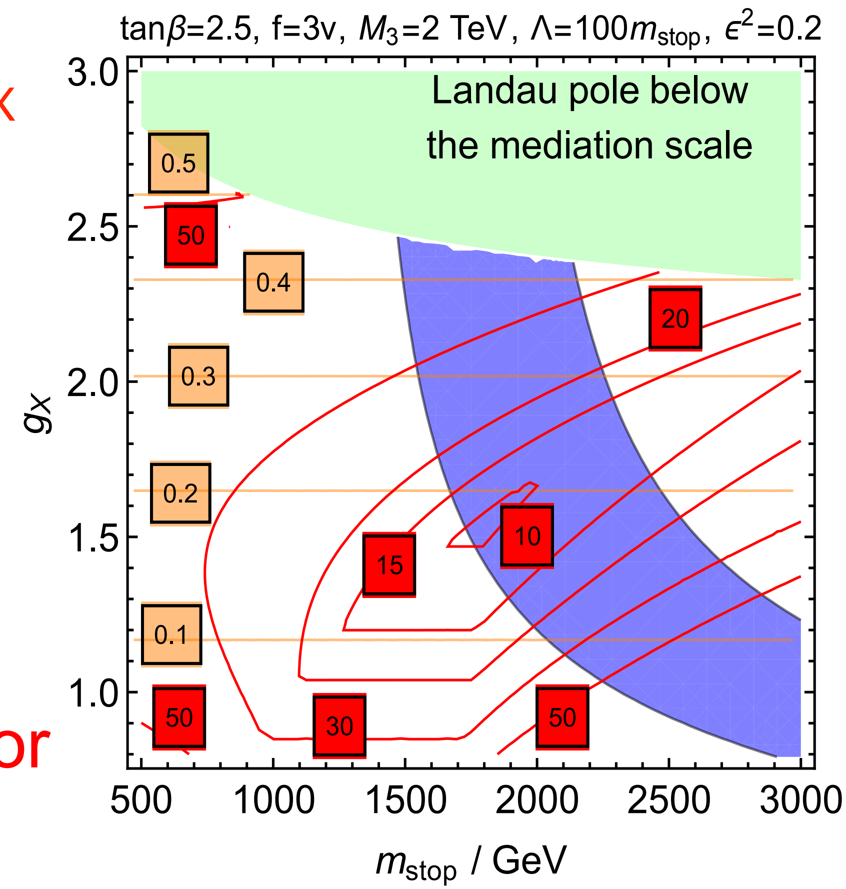


Low mediation scale of SUSY breaking

- For $\Lambda = 100 m_{stop}$ much larger g_X consistent with perturbativity than in the U(1) model
- For very large g_X tuning dominated by the threshold correction:

$$\left(\delta m_{H_u}^2\right)_X = 3 \frac{g_X^2}{64\pi^2} m_X^2 \ln\left(\epsilon^{-2}\right)$$

- 10% tuning can be obtained for 2 TeV stops and gluino (similarly to the U(1) model)



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