Natural Supersymmetric Twin Higgs

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Based on:
MB, Keisuke Harigaya
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JHEP 1710 (2017) 109 [1707.09071]
PRL 120 (2018) 211803 [1711.11040]

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Status of Supersymmetry
in light of LHC data

1. The Higgs mass found to be 125 GeV
2. No BSM particles found

Can SUSY models avoid 1% (or worse) tuning?

Without tuning the spectrum or very low mediation scale

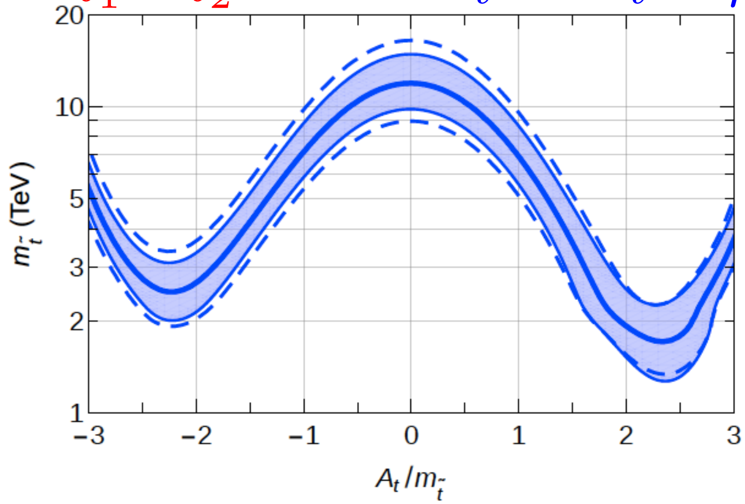
	125 GeV Higgs	LHC limits
MSSM	✗	✗
NMSSM	✓	✗
…	✓	✗

The Higgs mass in MSSM

SUSY models predict the Higgs mass:

$$m_h^2 \approx M_Z^2 \cos^2 2\beta + \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_{\tilde{t}}^2}{m_t^2}\right) + \frac{X_t^2}{M_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12M_{\tilde{t}}^2}\right)\right]$$

$$M_{\tilde{t}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \qquad X_t = A_t - \mu/\tan\beta$$



SUSYHD: Vega, Villadoro

Multi-TeV stops required to get 125 GeV Higgs in the MSSM!

Heavy sparticles introduce fine-tuning of the EW scale

- Heavy stops introduce fine-tuning:

Mediation scale of SUSY breaking

$$\delta m_H^2 \sim -\frac{3}{8\pi^2} y_t^2 m_{\mathrm{stop}}^2 \log\frac{\Lambda}{Q}$$

- So does heavy gluino:

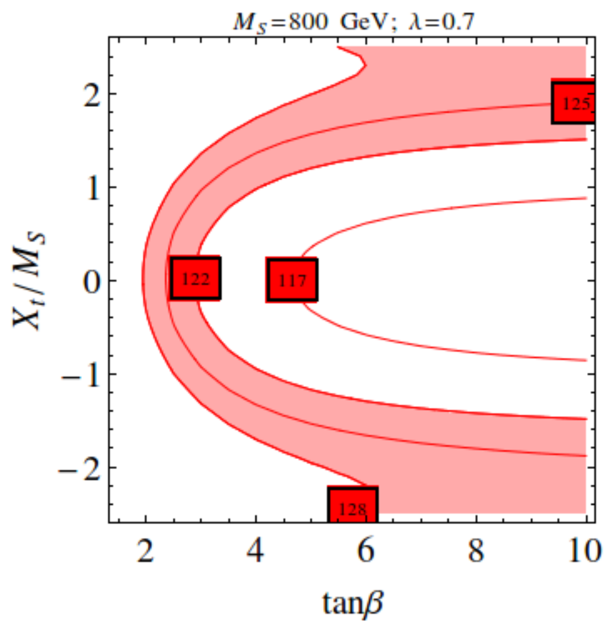
$$\delta m_H^2 \sim -\frac{g_3^2 y_t^2}{4\pi^4} |M_3|^2 \left(\log\frac{\Lambda}{Q}\right)^2$$

The 125 GeV Higgs can live with light stops in extensions of MSSM

- E.g. NMSSM: MSSM + singlet superfield S:

$$W_{\text{NMSSM}} = \lambda S H_u H_d + \kappa S^3/3$$

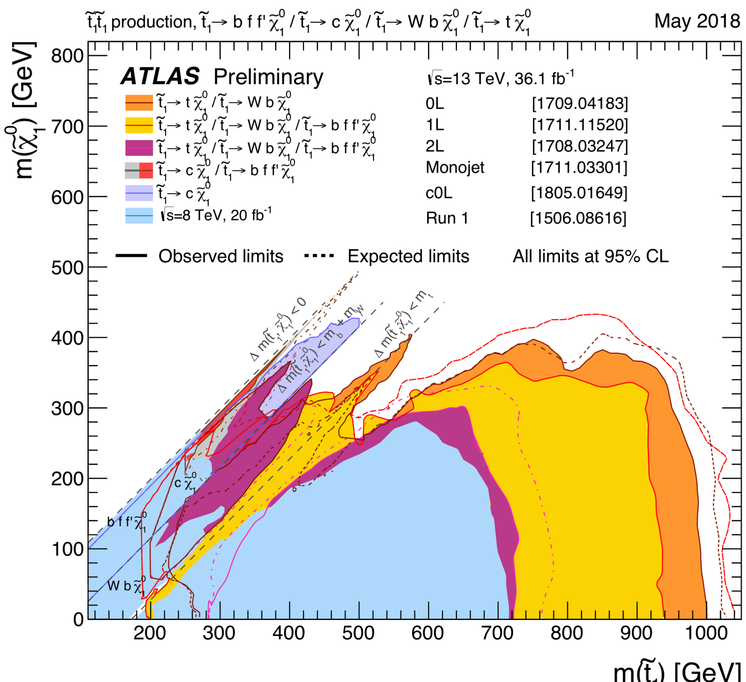
$$m_h^2 = M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + m_{h,\text{mix}}^2 + m_{h,\text{loop}}^2$$

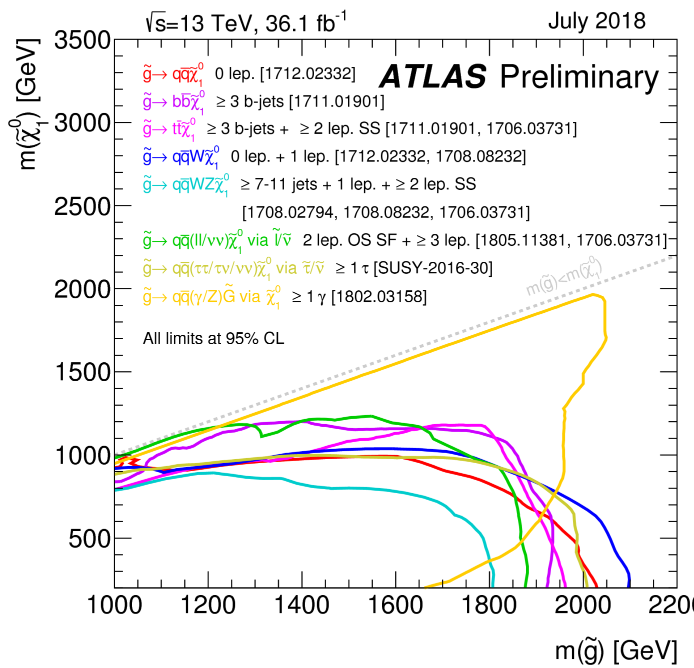


but...

LHC constraints on stops and gluino

the fine-tuning remains due to LHC constraints





Stops (gluinos) generically excluded up to 1 (2) TeV

Fine-tuning of the EW scale at least 1%

(independently from the Higgs mass constraint)

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…	✓	✗
???	✓	✓

Motivation for SUSY model-building

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MSSM	✗	✗
NMSSM	✓	✗
…	✓	✗
SUSY Twin Higgs	✓	✓

marriage of SUSY with Neutral Naturalness (uncolored top partners)

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 $\rightarrow H \overset{\mathbb{Z}_2}{\longleftrightarrow} H' \leftarrow$ mirror

$$V = \underbrace{\lambda(|H'|^2 + |H|^2)^2 - m^2(|H'|^2 + |H|^2)} + \underbrace{\Delta\lambda(|H'|^4 + |H|^4)} + \underbrace{\Delta m^2 |H^2|}$$

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:

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

- 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

The Higgs mass in SUSY Twin Higgs

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

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

- The tree-level Higgs mass is given by

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

- 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 $\tan\beta$!

SUSY U(1) D-term Twin Higgs

MB, Harigaya '17

- SU(4) invariant quartic term generated by a D-term potential of a new $U(1)_X$ gauge symmetry

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

$$\epsilon^2 = \frac{m_X^2}{2m_S^2 + m_X^2}$$

$$0 < \epsilon < 1$$

$$\epsilon \ll 1 \text{ preferred}$$

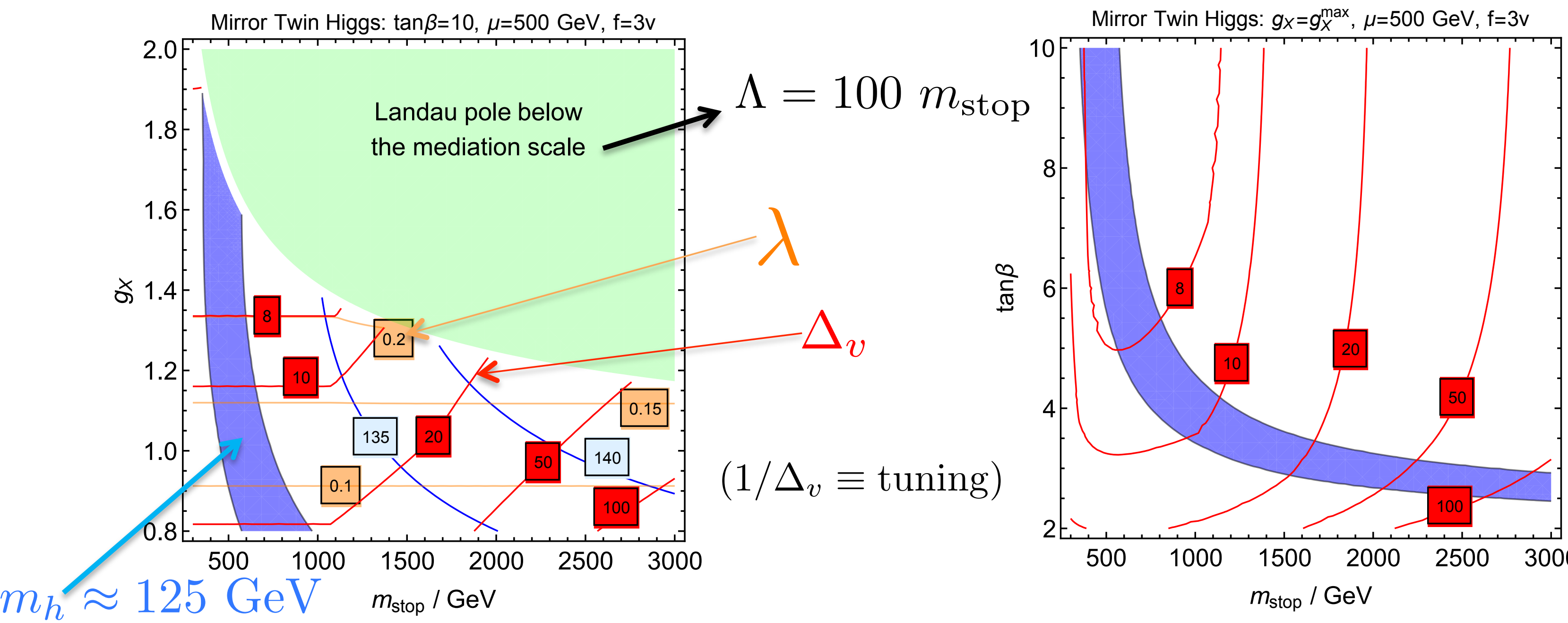
$$\lambda = g_X^2 \frac{\cos^2(2\beta)}{8}\left(1-\epsilon^2\right) \equiv \lambda_D$$

m_X- new gauge boson mass
m_S- soft mass for $U(1)_X$ breaking fields

- λ grows with $\tan\beta$ as the Higgs mass does
- Large g_X preferred

SUSY U(1) D-term Mirror Twin Higgs

- All SM fermions have their mirror counterparts



- Correct Higgs mass can be obtained for 1 TeV stops (without stop mixing) with better than 10% tuning

SUSY U(1) D-term Twin Higgs: Summary

- The 125 GeV Higgs mass easily obtained for light or heavy stops
- Tuning at the level of 10% for low mediation scales
- Main issue: the Landau pole scale for the new interaction is low
- Can SUSY Twin Higgs model be perturbative up to high scales?

Non-abelian SUSY Twin Higgs

Slowing down the RG running of the new gauge coupling:

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

SUSY SU(2) D-term Twin Higgs

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

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

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

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

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

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

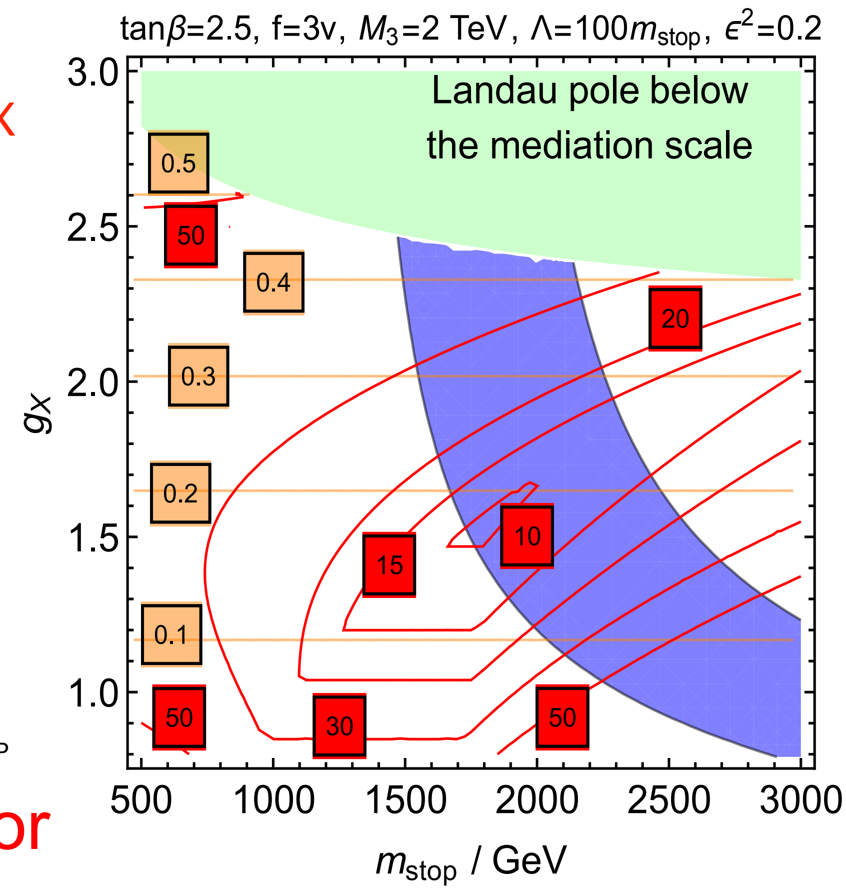
Low mediation scale of SUSY breaking

- For Λ=100m$_{stop}$ much larger g$_X$ consistent with perturbativity than in the U(1) model
- For very large g$_X$ tuning dominated by the threshold correction:

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

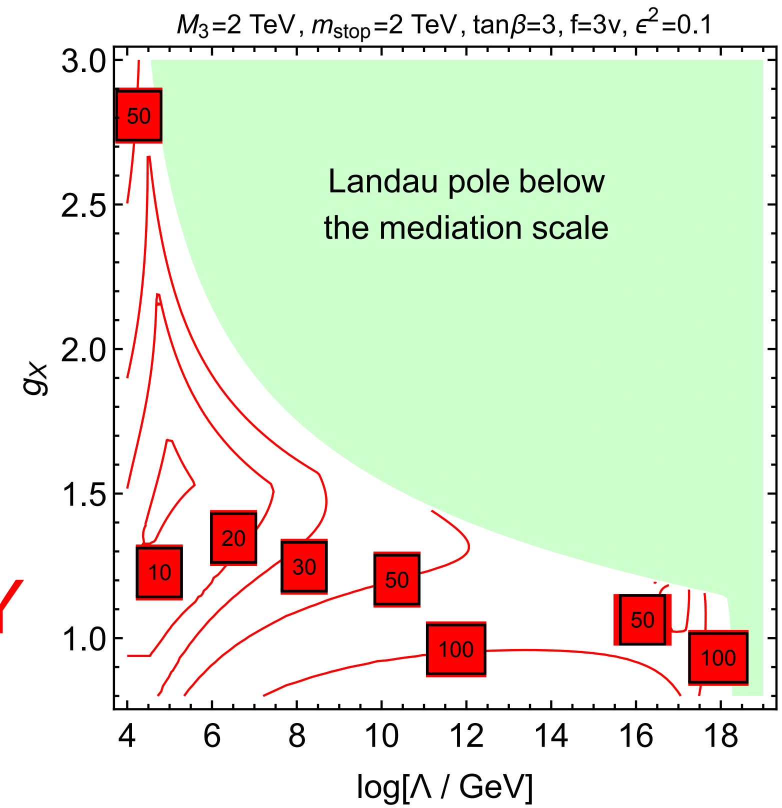
$m_X \gtrsim 4\ \mathrm{TeV} \times g_X$ from LEP

- 10% tuning can be obtained for 2 TeV stops and gluino



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!

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

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

$SU(2)_D$

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

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

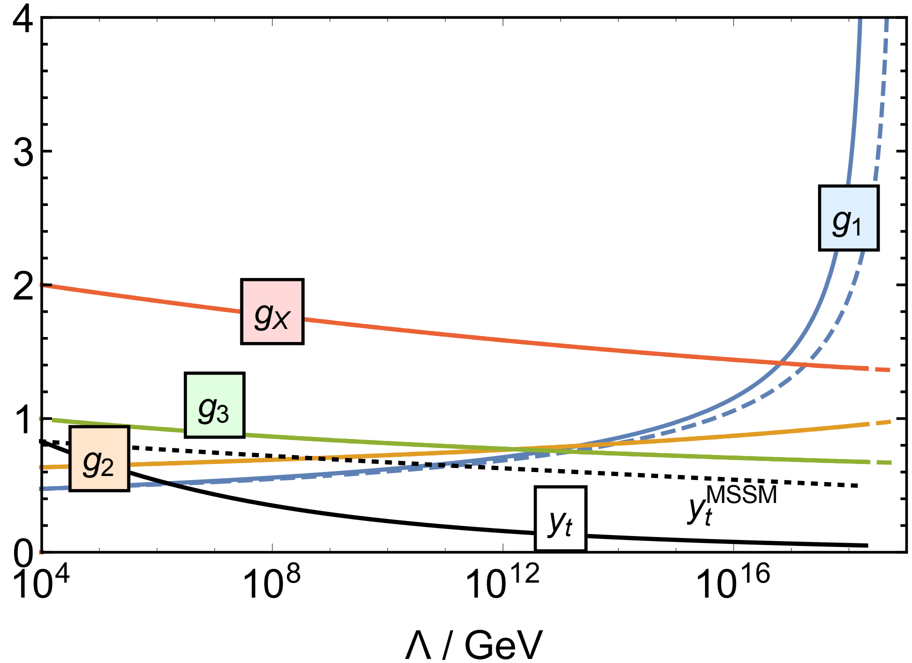
$\cancel{SU(2)_D}$

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

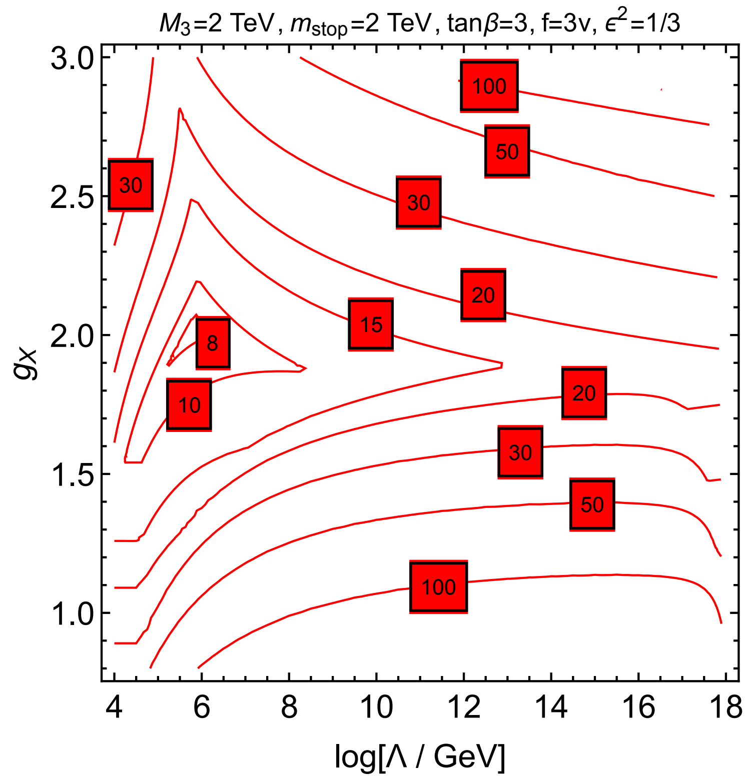
Asymptotically Free SUSY Twin Higgs: RG running of couplings



- g_X asymptotically free!
- New interaction drives the top Yukawa coupling to small values at high scales – suppressed tuning from stops and gluino (this works also in non-twin SUSY see 1806.07900)

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

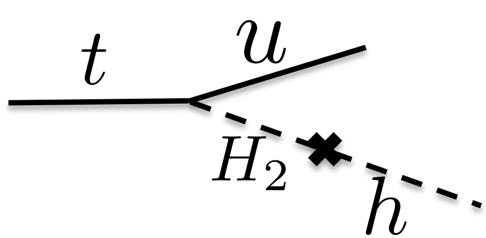


Asymptotically Free SUSY Twin Higgs: flavor-violating top decays

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

Concluding remarks

- LHC results should make us think harder on new SUSY model-building
- Twin Higgs mechanism and extra gauge interactions make SUSY natural (without sacrifying perturbativity below the Planck scale)
- New models mean new opportunities for pheno/cosmo
- Novel phenomenology from SUSY Twin Higgs (mostly unexplored):
  - Flavor-violating top decays
  - New dark matter candidates
  - Extra gauge bosons (beyond the LHC reach?)
  - …

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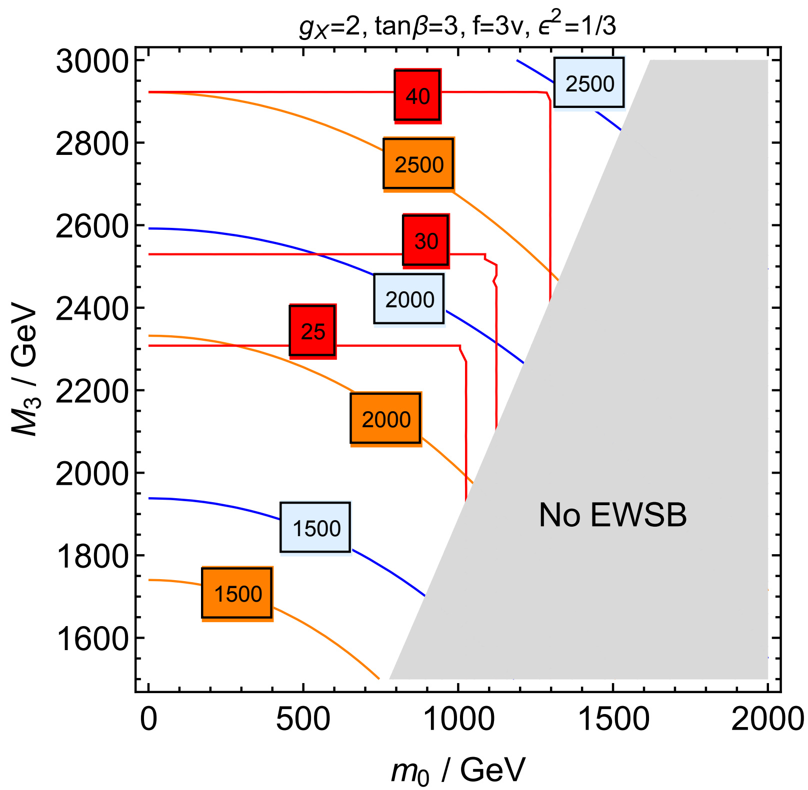
  - …

Supersymmetry can be still natural!

BACKUP

Asymptotically Free SUSY Twin Higgs: spectrum for simple UV boundary conditions

- Universal scalar masses
- M_3 fixed at the EW scale



SUSY U(1) D-term Twin Higgs: perturbativity constraints

- $U(1)_X$ charges are a combination of $U(1)_Y$ and $U(1)_{B-L}$ charges to ensure anomaly cancellation (with the help of right-handed neutrinos)

$$q_X = q_Y + x q_{\mathrm{B-L}}$$

- Fast RG running of g_X due to SM and twin states charged under $U(1)_X$
- We assume x=-1/2 to maximize the Landau pole scale for g_X

Symmetry breaking in U(1) model

- Chiral multiplets $Z, P \text{ and } \bar{P}$ with $U(1)_X$ charges 0,q,-q, respectively:

$$W = \kappa Z(P\bar{P} - M^2)$$

$$V_{\rm soft} = m_P^2 \left(|P|^2 + |\bar{P}|^2\right)$$

- After integrating out $P \text{ and } \bar{P}$:

ϵ^2

$$V_D = \frac{1}{8} g_X^2 \left(|H_u|^2 - |H_d|^2\right)^2 \left(1 - \frac{m_X^2}{2m_P^2 + m_X^2}\right)$$

$$m_P \gg m_X \Rightarrow \epsilon \ll 1$$

SUSY F-term Twin Higgs

Falkowski, Pokorski, Schmaltz; Chang, Hall, Weiner '06
Craig, Howe '13 ; Katz, Pokorski, Redigolo, Ziegler '16

- SU(4) invariant quartic term generated via F-term of a singlet:

$$W_{SU(4)} = (\mu + \lambda_S S)(H_u H_d + H'_u H'_d) + \mu' S^2 \,,$$

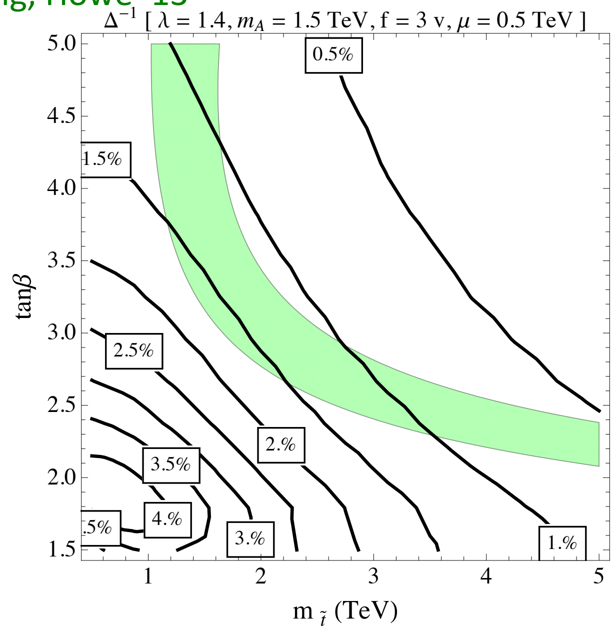
$$V_{SU(4)} = m^2_{H_u}(|H_u|^2 + |H'_u|^2) + m^2_{H_d}(|H_d|^2 + |H'_d|^2) - b(H_u H_d + H'_u H'_d + \mathrm{h.c.}) + m^2_S |S|^2$$

- After integrating out the singlet:

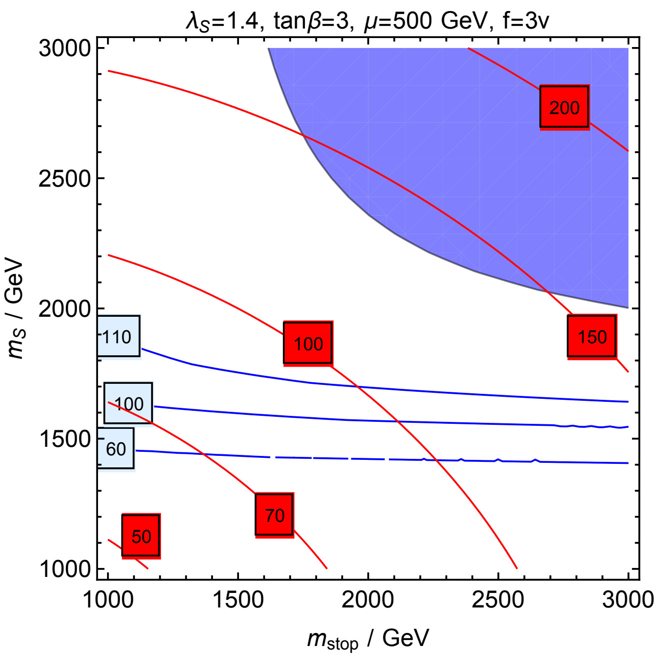
$$\lambda = \lambda_S^2 \frac{\sin^2(2\beta)}{4} \equiv \lambda_F \,.$$

SUSY F-term Twin Higgs

Craig, Howe '13



MB, Harigaya '17



- Fine-tuning at the level of 1% - no improvement with respect to non-twinned NMSSM

(assuming very low mediation scale of SUSY breaking Λ=100m_{stop})

SUSY F-term Twin Higgs: why it is fine-tuned?

- The 125 GeV Higgs mass prefers large $\tan\beta$
- λ is maximized at small $\tan\beta$

$$\lambda = \lambda_S^2 \frac{\sin^2(2\beta)}{4}$$

In the region with the correct Higgs mass ($\tan\beta \approx 3$ for 2 TeV stops):

1. $\lambda \approx \lambda_{\rm SM}$
2. Correction from heavy singlet to $m_{H_u}^2$ is larger than the one from stops (lighter singlet gives large negative correction to m_h via Higgs-singlet mixing)