Natural Supersymmetric Dark Matter in Twin Higgs models

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Based on work with:
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Motivation

Supersymmetry is a beautiful framework for BSM but its minimal realizations face two major problems:

1. LHC constraints on stops and gluinos impose fine-tuning of the EW scale of at least 1% (typically worse if the Higgs mass constraint is taken into account)
2. The lightest SUSY particle (LSP) can play the role of dark matter only in fine-tuned corners of parameter space

Combining SUSY with Twin Higgs (TH) mechanism provides elegant solution to problem 1

In this talk:

Twin sparticles (twin neutralino, stau) as a natural DM thermal relic in SUSY TH models

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 $\longrightarrow$ $H \xleftrightarrow{\mathbb{Z}_2} H'$ $\longleftarrow$ 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: $f^2 \equiv v^2 + v'^2$ $\quad \langle H \rangle \equiv v \quad \langle H' \rangle \equiv v'$ $\quad \frac{v'}{v} \gtrsim 3$

Fine-tuning in Twin Higgs models

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

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

- TH model solves only the little hierarchy problem so must be UV completed e.g. by SUSY to solve the big hierarchy problem of the SM

- E.g. Tuning from higgsinos (relevant for DM) suppressed for large λ :

$$\Delta_\mu = \frac{\mu^2}{4\lambda v^2}$$

- λ depends on particular SUSY UV completion of TH models

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

SUSY D-term Twin Higgs

MB, Harigaya '17

- SU(4) invariant quartic term generated by a D-term potential of a new 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

- $\lambda \sim 0.5$ can be obtained in D-term TH model
- Only 10% tuning of the EW scale for 2 TeV stop and gluino and 1 TeV Higgsino

Status of MSSM neutralino DM

- In MSSM there are 4 neutralinos:

$$\begin{pmatrix} \text{Bino } M_1 & 0 & -M_Z \sin\theta_W \cos\beta & M_Z \sin\theta_W \sin\beta \\ 0 & \text{Wino } M_2 & M_Z \cos\theta_W \cos\beta & -M_Z \cos\theta_W \sin\beta \\ -M_Z \sin\theta_W \cos\beta & M_Z \cos\theta_W \cos\beta & 0 & -\mu \\ M_Z \sin\theta_W \sin\beta & -M_Z \cos\theta_W \sin\beta & -\mu & 0 \end{pmatrix}$$

Higgsinos

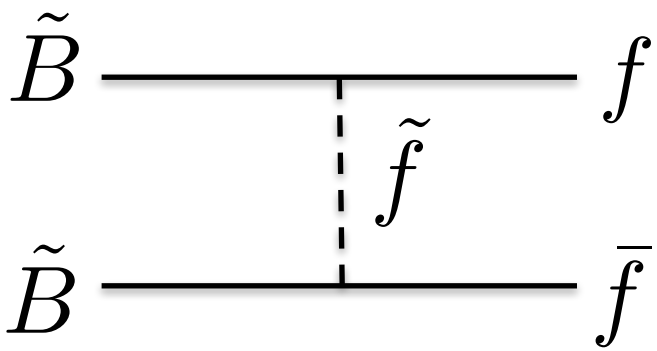
- Pure Bino: generically $\Omega h^2 \gg 1$
- Pure Higgsino: $\Omega h^2 \approx 0.12 \Rightarrow m_{\rm LSP} \approx 1 \text{ TeV}$
- Pure Wino: $\Omega h^2 \approx 0.12 \Rightarrow m_{\rm LSP} \approx 3 \text{ TeV}$

Relic abundance of DM from Planck

require fine-tuning of the EW scale at O(0.1-1) % level

$$\left(\Delta_\mu^{\rm MSSM} = \frac{\mu^2}{2\lambda_{\rm SM} v^2} \approx \left(\frac{\mu}{100 \text{ GeV}} \right)^2 \right)$$

Annihilation of MSSM Bino Dark Matter

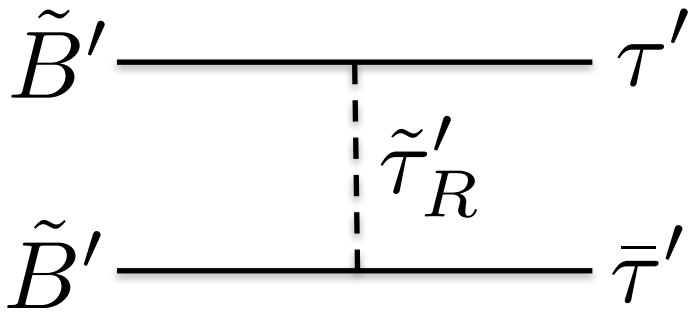


- Annihilation x-sec strongly suppressed due to lower bounds on sfermion masses from LEP/LHC
- chirality suppression of s-wave annihilation into SM fermions

Ways to get $\Omega h^2 \approx 0.12$:

- Include mixing with higgsino (aka well-tempered neutralino) -> excluded by direct detection experiments
- Fine-tuning of the parameter space e.g. small stau-bino mass splitting to allow for stau co-annihilations

Annihilation of Twin Bino Dark Matter

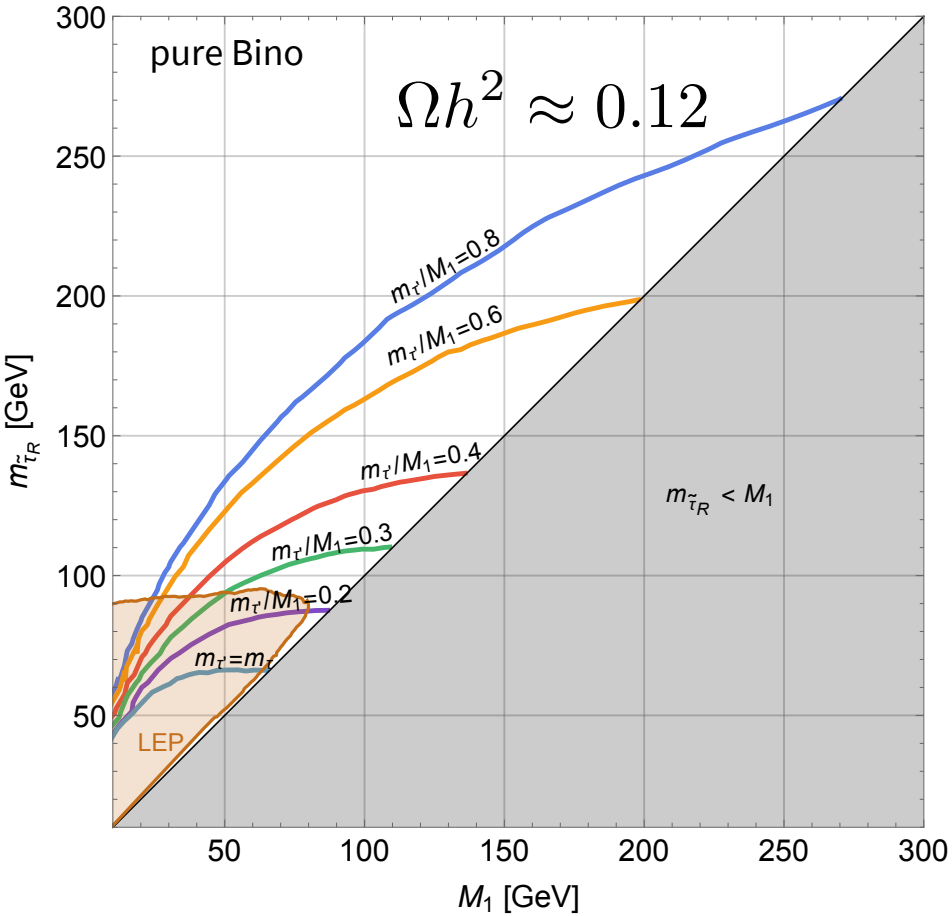


- chirality suppression of s-wave annihilation into twin fermions may be avoided if $m_{f'} \gg m_f$
- Z_2 breaking in Yukawa couplings motivated by the solution to too large N_{eff} problem of TH models

Barbieri, Hall, Harigaya '16, '17

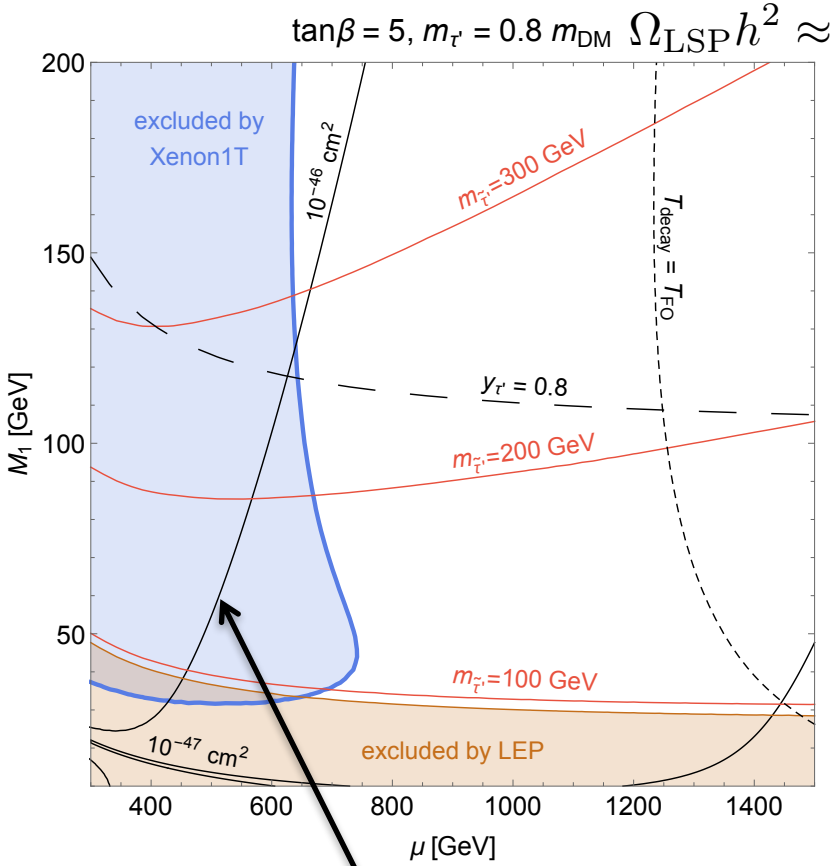
- lower bounds on sfermion masses still relevant but right-handed stau remains unconstrained by the LHC

Twin Bino Dark Matter



For $m_{\tau'}$>30 GeV large range of DM masses allowed without relying on coannihilatons

Twin Bino-Higgsino Dark Matter

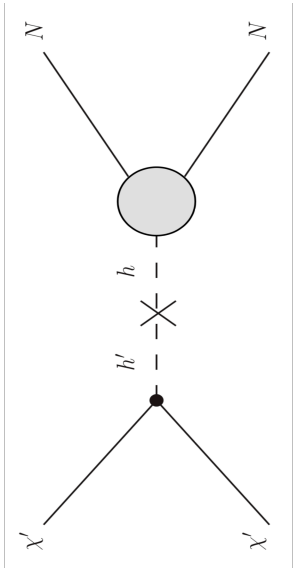


$$\Omega_{\rm LSP} h^2 \approx 0.12$$

Keeping tuning of the EW scale at 10% level requires μ<1 TeV

MB, Harigaya '17

Bino-Higgsino mixing induces DM coupling to nucleons via Higgs portal



Xenon1T excludes μ up to 600-700 GeV

LZ will probe μ up to 3 TeV

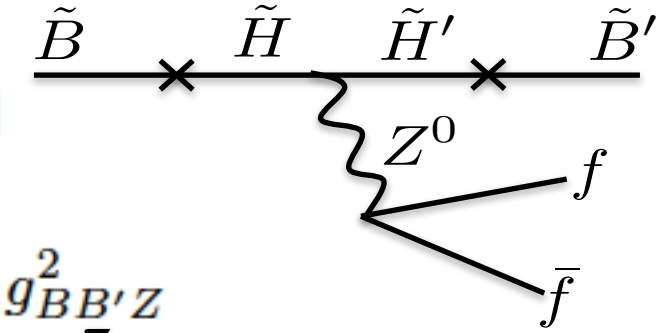
Spin-independent DM scattering on nucleons x-sec

(Spin-dependent DM scattering x-sec strongly suppressed)

Non-thermal production of $\tilde{B}'$ from $\tilde{B}$ decays

- $\tilde{B}$ is typically long lived due to small mass splitting with $\tilde{B}'$and small coupling to the twin sector
- Late $\tilde{B}$ decays overproduce $\tilde{B}'$ if $\tilde{B}$ decays after freeze-out

$$\Delta m_{\tilde{B}} \equiv m_{\tilde{B}} - m_{\tilde{B}'} \approx \frac{g_1^2\left(v'^2 - v^2\right)}{2\mu^2}\,|\mu s_{2\beta} + M_1|$$

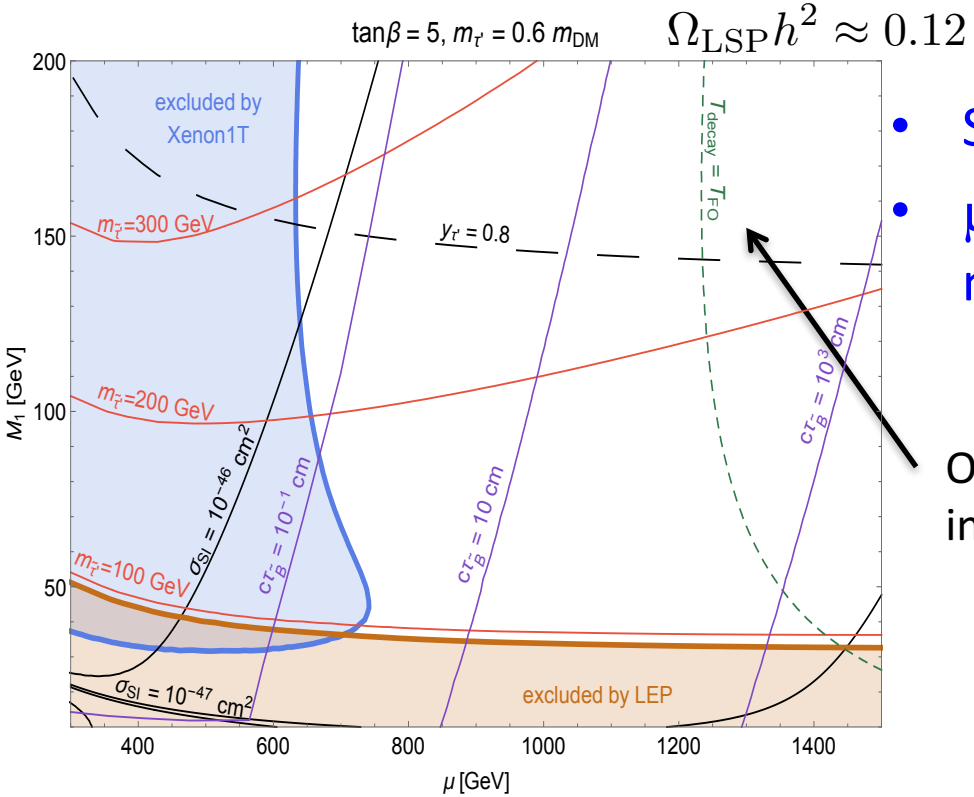


$$\Gamma_{\tilde{B}} \approx 3 \times 10^{-11}\ \mathrm{GeV}\left(\frac{\Delta m_{\tilde{B}}}{\mathrm{GeV}}\right)^5 g^2_{BB'Z}$$

depends on $\tilde{H} - \tilde{H}'$ mixing

- D-term TH model: $g_{BB'Z} \simeq 4 \cdot 10^{-5}\left(\frac{g_X}{2}\right)^2\left(\frac{8\,\mathrm{TeV}}{m_X}\right)\left(\frac{v'/v}{3}\right)\left(\frac{1\,\mathrm{TeV}}{\mu}\right)^3\left(\frac{5}{t_\beta}\right)$

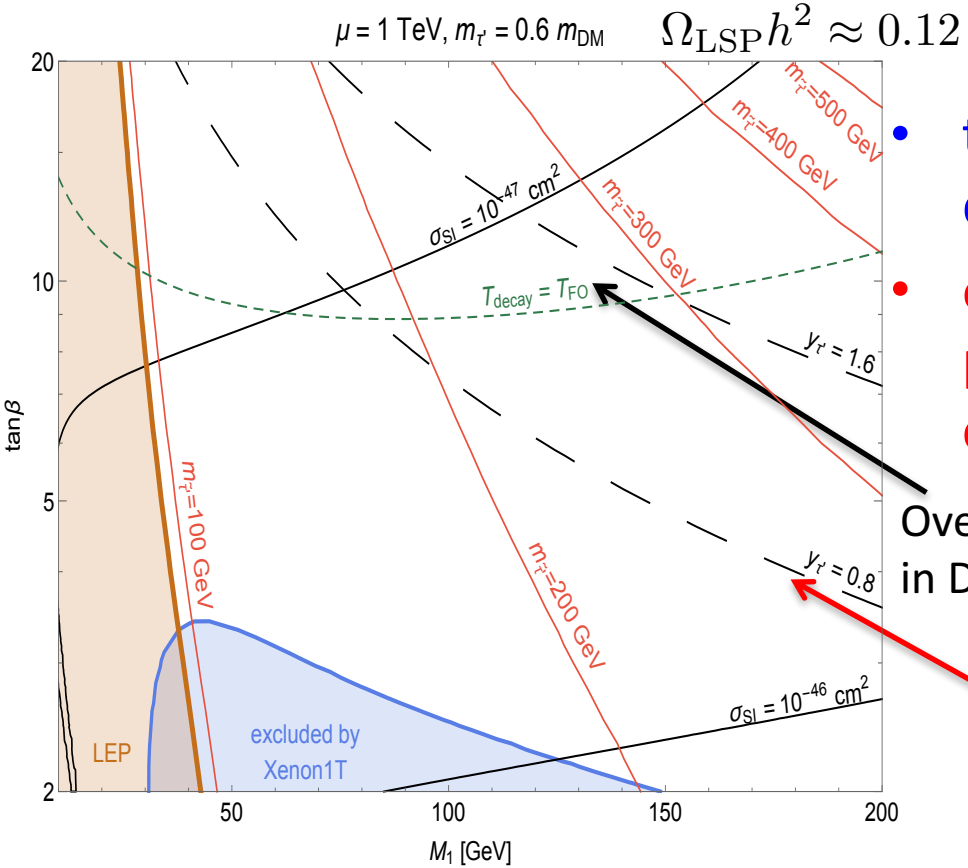
Upper bound on μ



- Strong dependence of $\Gamma_{\tilde{B}}$ on μ
- μ bounded from above not only by naturalness but relic abundance too!

Overabundance from late bino decays in D-term TH model with m_X=8 TeV and g_X=2

Upper bound on tanβ



- tanβ below 10 to avoid late-time bino decays
- even stronger bound assuming perturbativity of the twin tau Yukawa coupling up to 10^{16} GeV

Overabundance from late bino decays in D-term TH model with m_X=8 TeV and g_X=2

Landau pole below 10^{16} GeV

LHC signatures with displaced vertices

- Right-handed stau mass unconstrained by the LHC but most of the parameter space will be probed by HL-LHC
- Higgsino searches also important due to upper bound on μ
- MSSM bino decay to LSP and pair of fermions via off-shell Z typically displaced

Twin stau dark matter: preliminary results

Twin stau dark matter

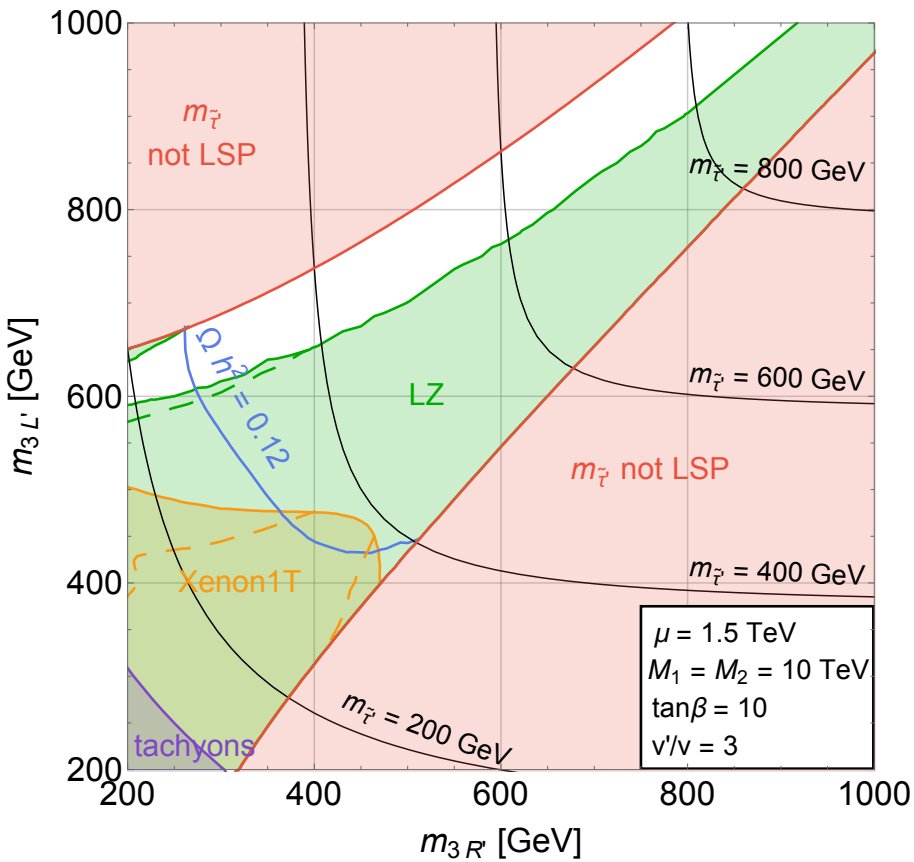
- Twin stau LSP may also play a role of (self-interacting) dark matter
- Twin stau has twin electromagnetic charge
- Charged DM constrained by anistropy of DM velocity distribution in galaxy halos

Agrawal, Cyr-Racine, Randall, Scholtz '16

$\Downarrow$

$m_{\tilde{\tau}'} \gtrsim 200$ GeV required

Twin stau dark matter



- Twin stau can be the LSP only for large enough left-right mixing
- Correct relic abundance picks the twin stau mass of about 300-400 GeV (above the bound from self-interactions)
- Small part of the parameter space excluded by Xenon1T
- Most of the parameter space will be probed by LZ

Summary

- SUSY Twin Higgs models can elegantly solve the hierarchy problem of the SM and provide new natural dark matter candidates

- Twin neutralino LSP is a natural DM candidate fixing shortcomings of the MSSM neutralino
- Twin stau LSP is a natural candidate for self-interacting DM
- Spin-independent scattering cross-section for twin neutralino and stau naturally suppressed but within reach of LZ

- Complementary tests at the LHC:
- ➢ right-handed MSSM stau mass in the range of several hundred GeV
- ➢ In the twin neutralino LSP scenario: the lightest MSSM neutralino unstable with a decay length leading typically to displaced vertices

BACKUP

The Higgs mass miracle in SUSY Twin Higgs models

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

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

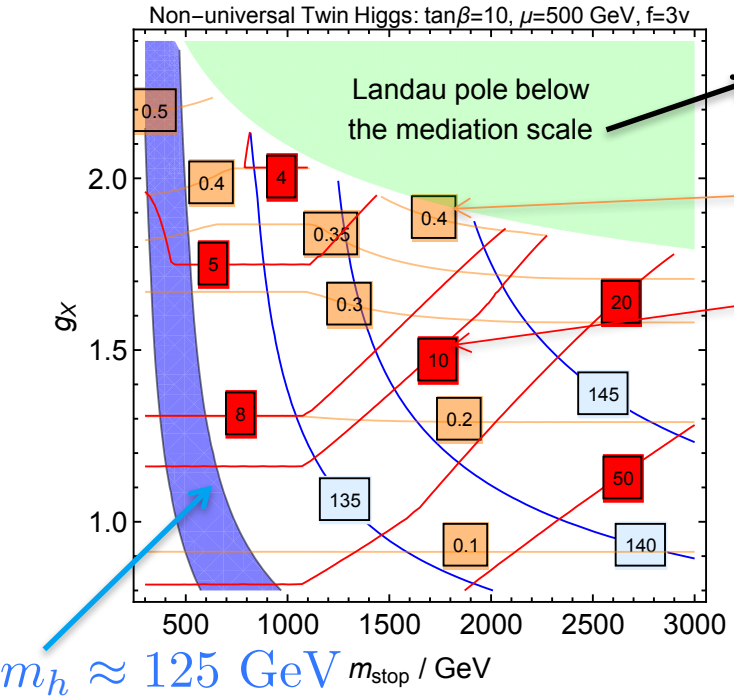
- The tree-level Higgs mass is given by

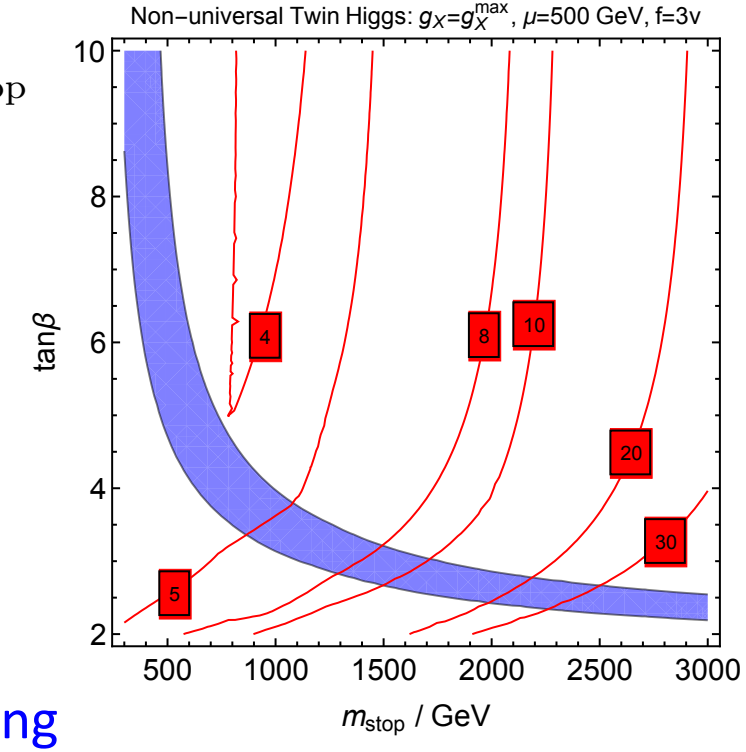
$$\left(m_h^2\right)_{\rm tree} \approx 2 M_Z^2 \cos^2(2\beta)\left(1-\frac{v^2}{f^2}\right) + \mathcal{O}(\Delta\lambda/\lambda)$$

- 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 $\tan\beta$!

SUSY D-term flavor non-universal Twin Higgs





- for 1 TeV stops better than 20% tuning
- 10% tuning beyond the reach of HL-LHC
- Improvement by a factor 7 as compared to MSSM with non-decoupling D-term

Asymptotically Free SUSY Twin Higgs

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

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

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

$SU(2)_D$

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

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

~~$SU(2)_D$~~

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

- Twin Higgs mechanism works perturbatively even for mediation around the Planck scale
- Tuning better than 5% even for gravity mediation of SUSY breaking