Natural Supersymmetric Dark Matter in Twin Higgs models

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Based on work with:
Giovanni Grilli di Cortona, Keisuke Harigaya, Michał Łukawski
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JHEP 1710 (2017) 109 [1707.09071]
JHEP 1706 (2017) 065 [1703.02122]

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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 as a natural DM thermal relic in SUSY TH models

Outline

1. Intro to Twin Higgs models

2. Twin Neutralino Dark Matter

   PRL 124 (2020) 121803 [1911.03481]

3. Twin stau as Charged Dark Matter

   2202.10488

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 $\longrightarrow$ $H \overset{\mathbb{Z}_2}{\longleftrightarrow} H'$ $\longleftarrow$ mirror

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

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: $f^2 \equiv v^2 + v'^2$ $\quad \langle H \rangle \equiv v \quad \langle H' \rangle \equiv v'$ $\quad \frac{v'}{v} \gtrsim 3$

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

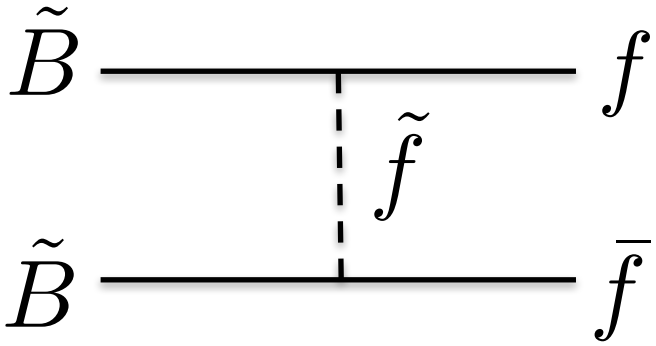
- Pure Bino: generically $\Omega h^2 \gg 1$
- Pure Higgsino: $\Omega h^2 \approx 0.12 \Rightarrow m_{\rm LSP} \approx 1\ {\rm TeV}$
- Pure Wino: $\Omega h^2 \approx 0.12 \Rightarrow m_{\rm LSP} \approx 3\ {\rm TeV}$

Relic abundance of DM from Planck

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

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

Annihilation of MSSM Bino Dark Matter

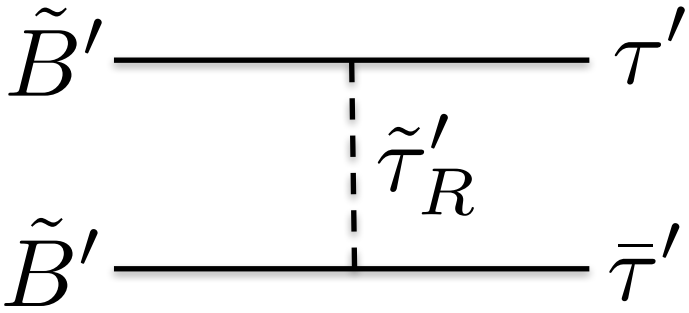


- Annihilation x-sec strongly suppressed due to lower bounds on sfermion masses from LEP/LHC
- chirality suppression of s-wave annihilation into SM fermions

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

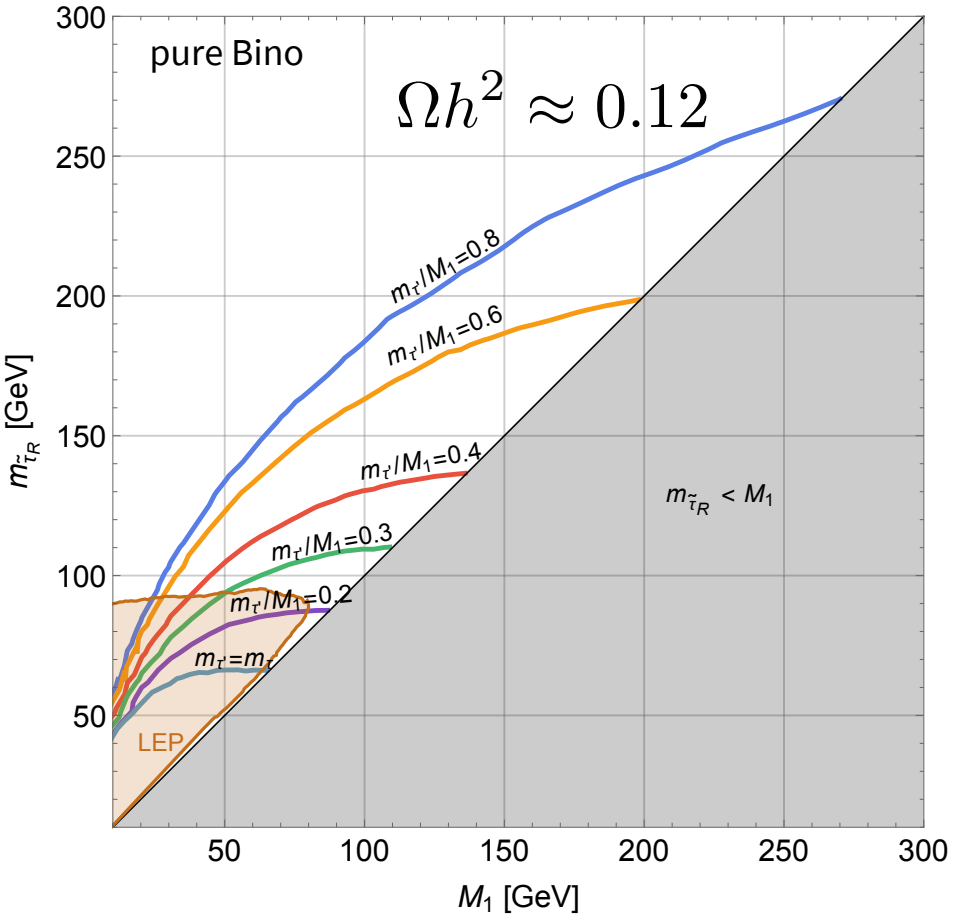


- chirality suppression of s-wave annihilation into twin fermions may be avoided if $m_{f'} \gg m_f$
- Z_2 breaking in Yukawa couplings motivated by the solution to too large N_{eff} problem of TH models

Barbieri, Hall, Harigaya '16, '17

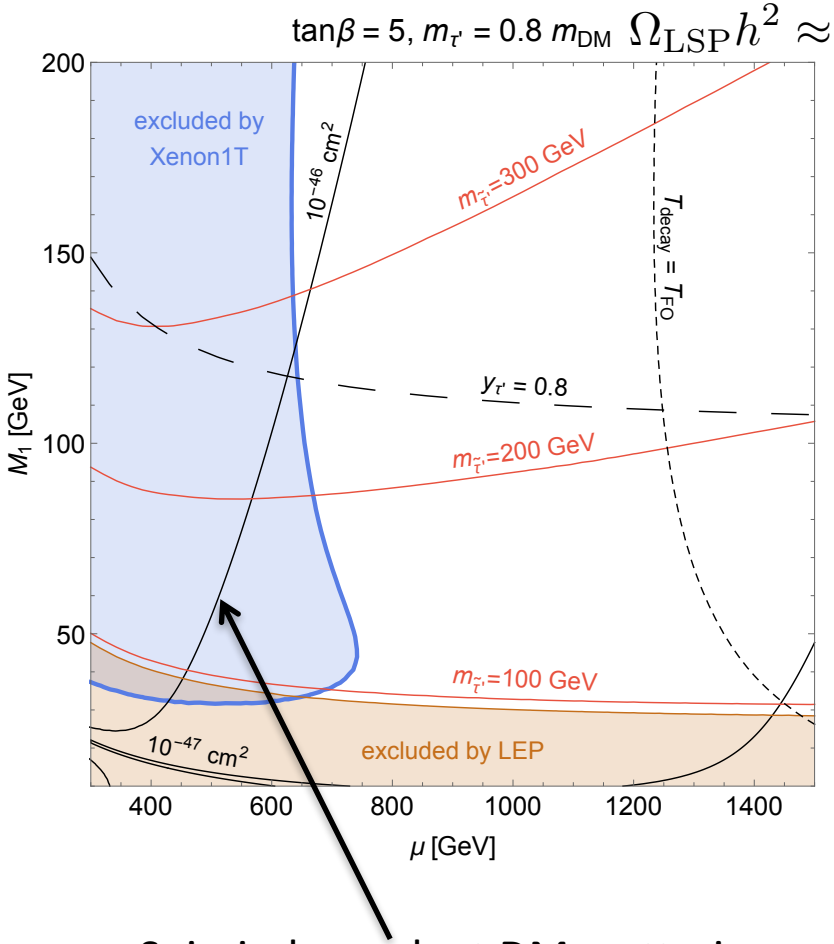
- lower bounds on sfermion masses still relevant but (promptly decaying) right-handed stau remains unconstrained by the LHC

Twin Bino Dark Matter



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

Twin Bino-Higgsino Dark Matter

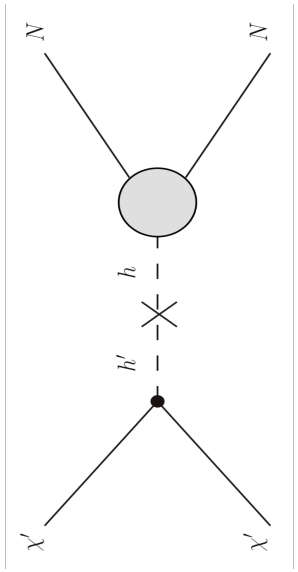


Keeping tuning of the EW scale at 10% level requires μ<1.5 TeV MB, Harigaya '17

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)

Charged dark matter in SUSY TH models

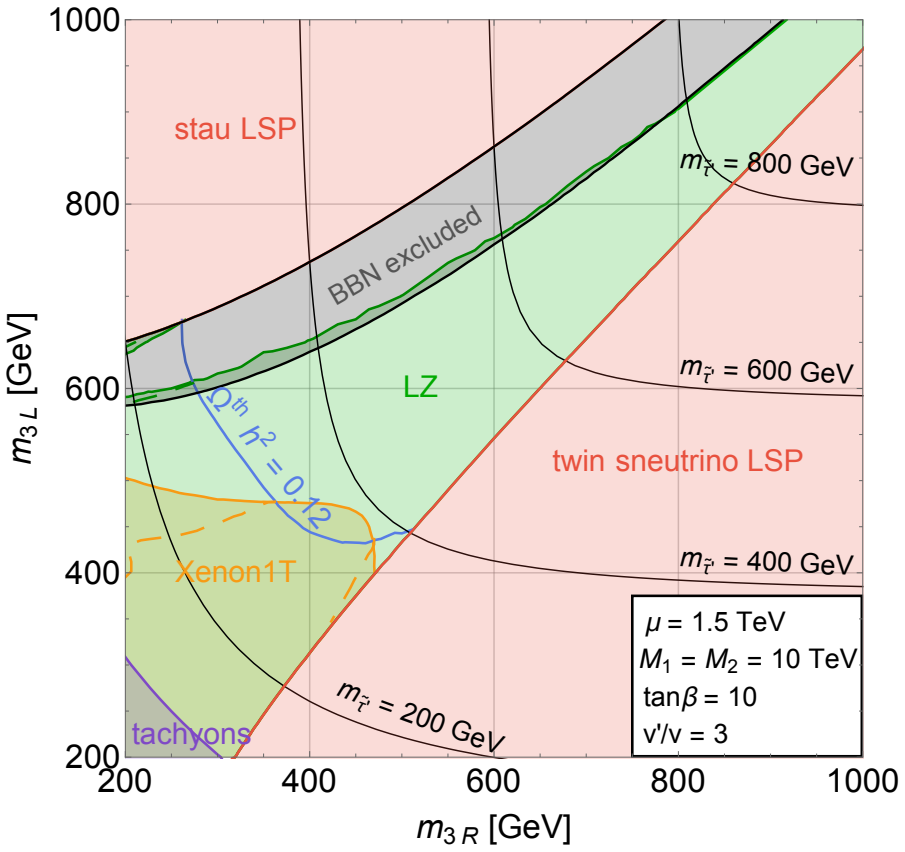
Twin stau dark matter

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

Agrawal, Cyr-Racine, Randall, Scholtz '16

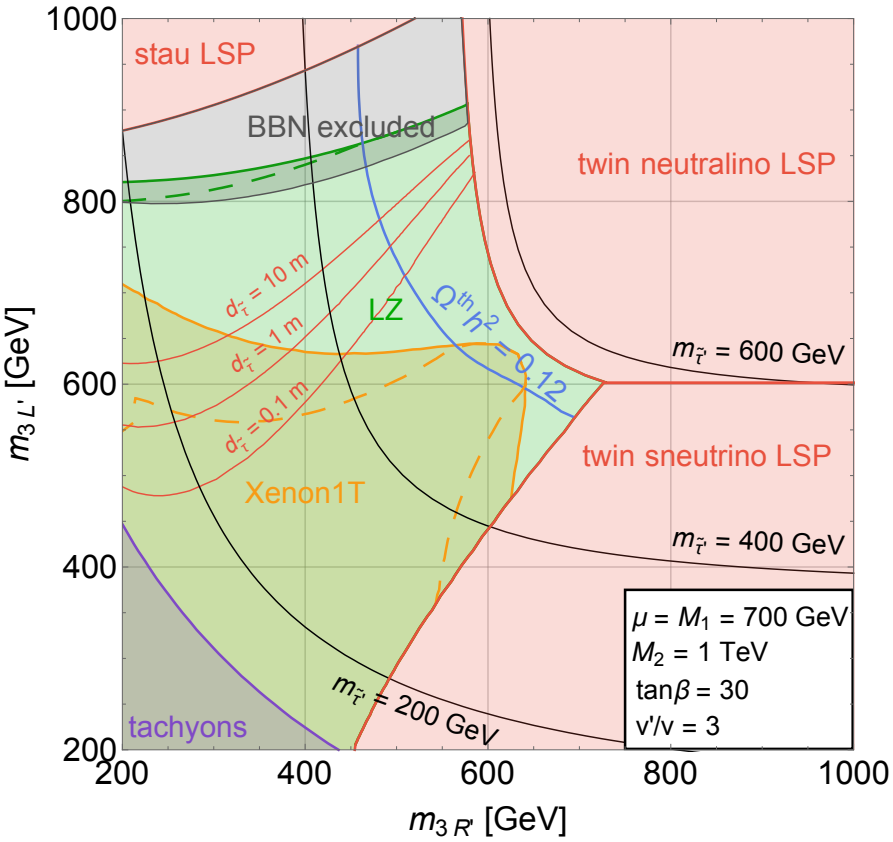
$$m_{\tilde{\tau}'} \gtrsim 200 \text{ GeV required}$$

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 on charged DM)
- Small part of the parameter space excluded by Xenon1T
- Most of the parameter space will be probed by LZ

Twin stau dark matter

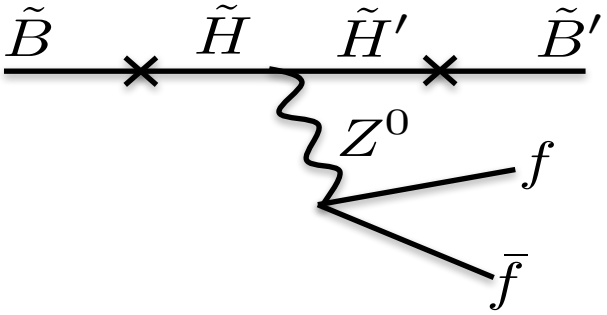


For light bino and wino the mass of twin stau thermal DM can exceed 500 GeV

LHC signatures with long-lived NLSP

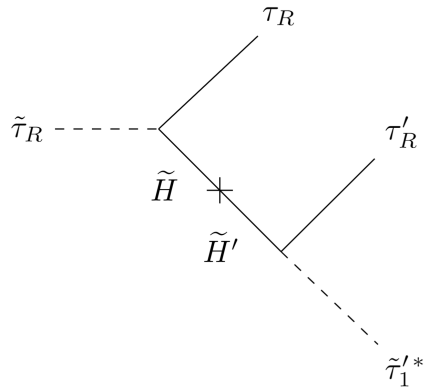
- NLSP is the lightest MSSM sparticle with generically suppressed decay width

Twin neutralino DM



- MSSM bino decay to LSP typically displaced

Twin stau DM



- MSSM stau may be observed as a disappearing track or a long-lived particle at the LHC

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 charged DM
- Spin-independent scattering cross-section for twin neutralino and stau naturally suppressed but within reach of LZ

- Complementary tests at the LHC:

➢ NLSP is the lightest MSSM state which is typically long-lived leading to displaced vertices or (disappearing) charged tracks

➢ right-handed MSSM stau mass in the range of several hundred GeV

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

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

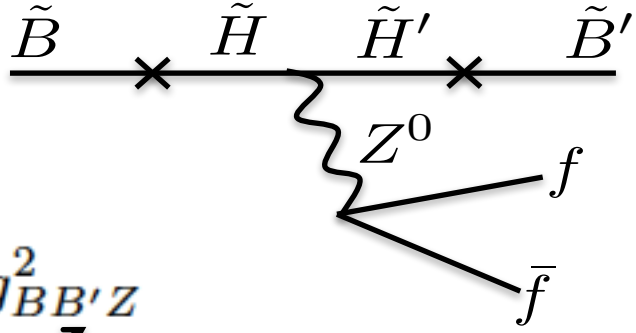
- The Higgs mass enhanced by a factor of $\sqrt{2}$ (after Z_2 breaking which is needed anyway) as compared to MSSM.

- $m_h \approx 125\ \mathrm{GeV}$ obtained at tree level in the limit of large $\tan\beta$!

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

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

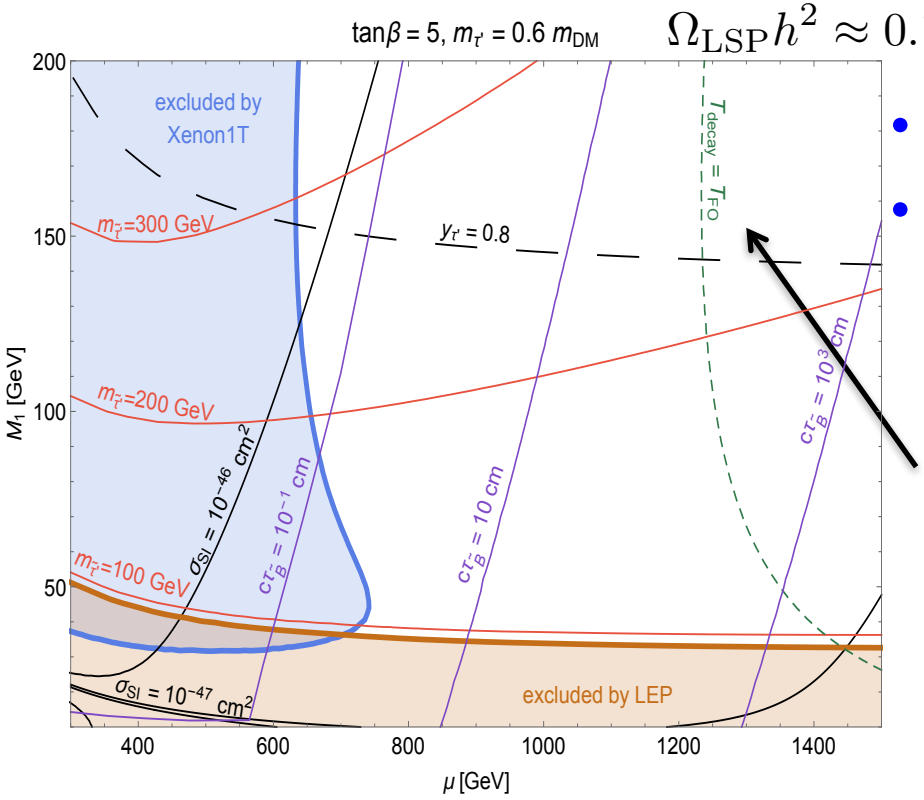


$$\Gamma_{\tilde{B}} \approx 3 \times 10^{-11}\ \mathrm{GeV} \left(\frac{\Delta m_{\tilde{B}}}{\mathrm{GeV}}\right)^5 g^2_{BB'Z}$$

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

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

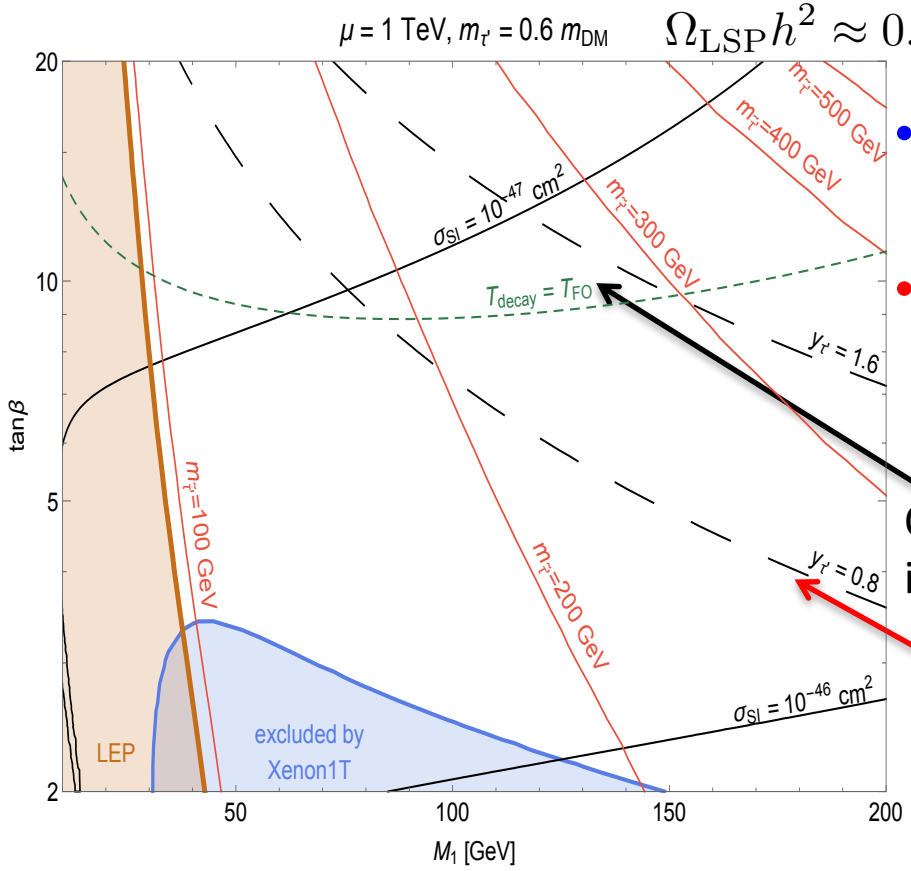
Upper bound on μ



- 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

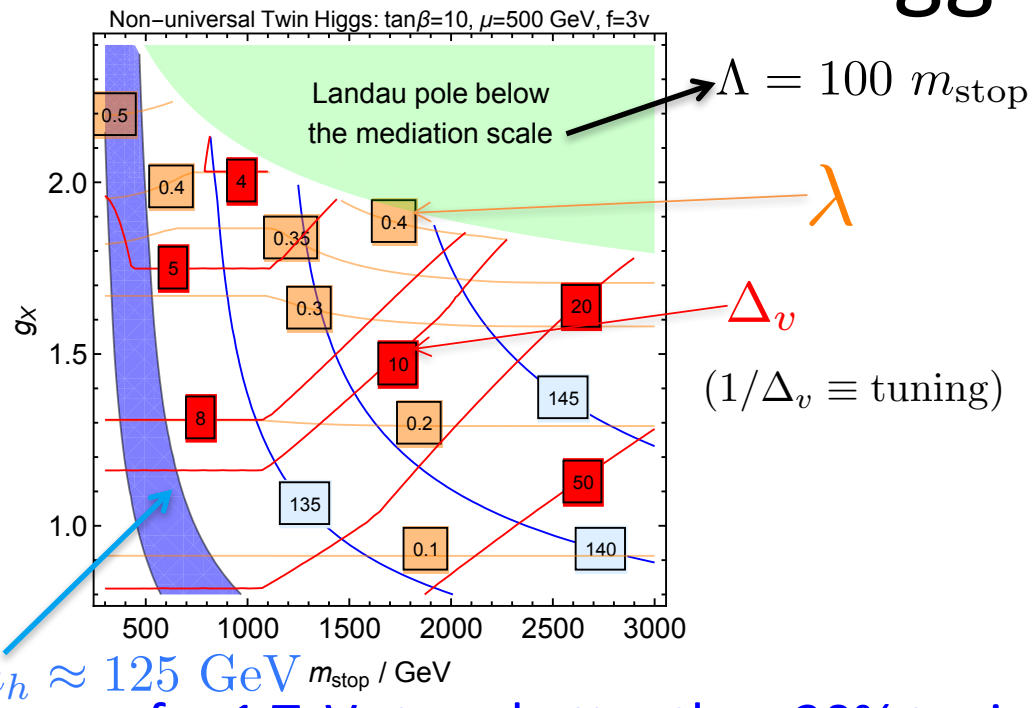


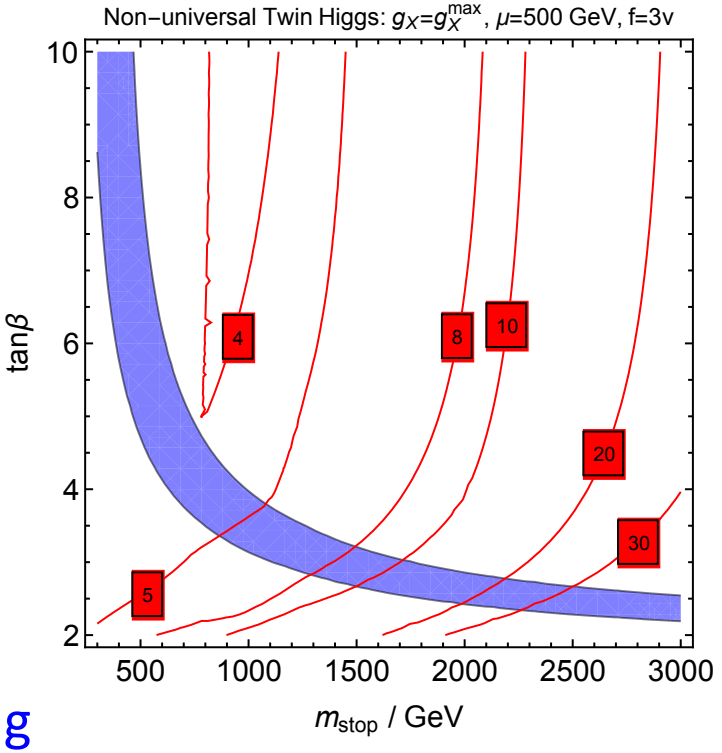
- tanβ below 10 to avoid late-time bino decays
- even stronger bound assuming perturbativity of the twin tau Yukawa coupling up to 10^{16} GeV

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

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!

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

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

$SU(2)_D$

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

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

~~$SU(2)_D$~~

right-handed top & up

	$SU(2)_X$	$SU(2)'_X$	3-2-1	3′-2′-1′
$\mathcal{H}$	**2**		$(\mathbf{1},\mathbf{2},1/2)$	
$\mathcal{H}'$		**2**		$(\mathbf{1},\mathbf{2},1/2)$
Σ	**2**	**2**		
S	**2**			
$\bar{S}$	**2**			
S'		**2**		
$\bar{S}'$		**2**		
$\bar{Q}_R$	**2**		$(\bar{\mathbf{3}},\mathbf{1},-2/3)$	
$\bar{Q}'_R$		**2**		$(\mathbf{3},\mathbf{1},-2/3)$
$\bar{E}$	**2**		$(\mathbf{1},\mathbf{1},1)$	
$\bar{E}'$		**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