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

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

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

SU(4) symmetric

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

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

$\frac{v'}{v} \gtrsim 3$

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Fine-tuning in Twin Higgs models

• Maximal gain in fine-tuning depends on the size of $\lambda$:

$$\frac{2\lambda}{\lambda_{SM}} \quad \lambda_{SM} \approx 0.13$$

• 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 $\lambda$:

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

• $\lambda$ 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

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

\[ V_{U(1)_X} = \frac{g_X^2}{8} (|H_u|^2 - |H_d|^2 + |H'_u|^2 - |H'_d|^2)^2 (1 - \epsilon^2) \]

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

• \( \lambda \approx 0.5 \) 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:

\[
\begin{pmatrix}
M_1 & 0 & -M_Z \sin \theta_W \cos \beta & M_Z \sin \theta_W \sin \beta \\
0 & M_2 & M_Z \cos \theta_W \cos \beta & 0 \\
-M_Z \sin \theta_W \cos \beta & M_Z \cos \theta_W \cos \beta & 0 & -\mu \\
M_Z \sin \theta_W \sin \beta & -M_Z \cos \theta_W \sin \beta & -\mu & 0
\end{pmatrix}
\]

• Pure Bino: generically \( \Omega h^2 \gg 1 \)

• Pure Higgsino: \( \Omega h^2 \approx 0.12 \Rightarrow m_{LSP} \approx 1 \) TeV

• Pure Wino: \( \Omega h^2 \approx 0.12 \Rightarrow m_{LSP} \approx 3 \) TeV

\[
\Delta^\text{MSSM}_\mu = \frac{\mu^2}{2\lambda_{SM} v^2} \approx \left( \frac{\mu}{100 \text{ GeV}} \right)^2
\]

require fine-tuning of the EW scale at O(0.1-1) % level
Annihilation of MSSM Bino Dark Matter

\[ \tilde{B} \rightarrow f \]

- 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

\[ \tilde{B}' \quad \tilde{\tau}' \]

- 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 \( N_{\text{eff}} \) problem of TH models
- lower bounds on sfermion masses still relevant but right-handed stau remains unconstrained by the LHC

Barbieri, Hall, Harigaya ’16, ’17
For $m_\tau > 30$ GeV large range of DM masses allowed without relying on coannihilations.
Twin Bino-Higgsino Dark Matter

Keeping tuning of the EW scale at 10% level requires $\mu < 1$ TeV

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

Xenon1T excludes $\mu$ up to 600-700 GeV

LZ will probe $\mu$ 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.

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

\[
\Gamma_{\tilde{B}} \approx 3 \times 10^{-11} \text{ GeV} \left(\frac{\Delta m_{\tilde{B}}}{\text{GeV}}\right)^5 g_{BB'Z}^2
\]

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

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

Overabundance from late bino decays in D-term TH model with $m_{\chi}=8$ TeV and $g_{\chi}=2$
Upper bound on $\tan\beta$

- $\tan\beta$ 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 $m_\chi=8$ TeV and $g_\chi=2$

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 \( \mu \)
• 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 anisotropy of DM velocity distribution in galaxy halos

\[ m_{\tilde{\tau}} \gtrsim 200 \text{ GeV required} \]

Agrawal, Cyr-Racine, Randall, Scholtz ‘16
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

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

• The tree-level Higgs mass is given by

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

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

• \(m_h \approx 125\) 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

\[ m_h \approx 125 \text{ GeV} \]

\[ m_{\text{stop}} \text{ / GeV} \]

\[ \Lambda = 100 \, m_{\text{stop}} \]

\[ \Delta \nu \]

\[ (1/\Delta \nu \equiv \text{tuning}) \]
Asymptotically Free SUSY Twin Higgs

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

\[ W = Y (\Sigma^2 - v^2_\Sigma) \]

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

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

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

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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

\[ M_3=2 \text{ TeV}, \ m_{\text{stop}}=2 \text{ TeV}, \ \tan\beta=3, \ f=3v, \ \epsilon^2=1/3 \]