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Charged dark matter in supersymmetric Twin Higgs models

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Supersymmetric implementations of the Twin Higgs mechnism solve the hierarchy problem, while alleviating fine-tuning present in supersymmetry. We propose twin stau as a charged candidate for dark matter. The correct relic abundance is obtained for masses between 450 and 500 GeV. Self-interaction constraints from ellipticity measurements are easily satisfied due to large contributions to twin stau mass from supersymmetry breaking. We also show the effects of increasing the breaking scale of accidental $SU(4)$, which controls the fine-tuning of the scenario. Interestingly, this scale is bounded from above, which corresponds to the worst tuning of the scenario around 1%.

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1. Introduction

The electroweak (EW) scale is unstable under loop corrections, which is manifested via quadratic sensitivity to scales, such as Planck scale. The reason is, that the mass of the Higgs is not technically natural parameter of the Standard Model (SM) - there is no enhancement of the symmetry in the limit $m_h \to 0$. This sensitivity to UV scales indicates that there is a special structure of new physics, which protects the EW scale from large corrections. The instability of EW scale in Standard Model is called the hierarchy problem.

Perhaps the most prominent solution to the hierarchy problem is supersymmetry (SUSY), which relates bosons to fermions via continuous, spacetime transformation. SUSY predicts the existence of a SUSY partners to each known particle. Phenomenologically, SUSY must be broken at some scale m_{SUSY}, which sets the masses of SUSY partners, including sparticles, which cancel the quadratic contributions to the mass of the Higgs above SUSY breaking. However, null results from the LHC indicate that the m_{SUSY} is much larger than the EW scale [1, 2]. A natural question arises of how could supersymmetric theory characterized by scale m_{SUSY} yield the observed mass of the Higgs without fine-tuning of parameters [3].

Twin Higgs (TH) mechanism [4] can be successfully implemented in supersymmetry to yield the mass of the Higgs naturally low compared to the m_{SUSY} [5–9]. It introduces a second, twin sector, which is related to the visible sector by the Z_2 symmetry, interchanging particles between sectors. Z_2 symmetry induces accidental, global symmetry of the scalar potential, which undergoes spontaneous symmetry breaking (SSB). The standard model Higgs is one of the pseudo-Nambu-Goldstone-bosons (pNGBs) and its mass is protected from large divergences below the scale of SSB. Twin Higgs Supersymmetry (TH SUSY) is a UV complete solution to the hierarchy problem, with little fine-tuning of the parameters. Its rich phenomenology is reflected in the numerous particle species, some of which could be candidates for the dark matter.

2. Supersymmetric Twin Higgs

TH mechanism relies on the existence of a mirror sector, which we will denote with prime, e.g. τ' is twin tau. The gauge symmetry of the twin sector is $SU_C(3)' \times SU_L(2)' \times U_Y(1)'$. Consider the case of the non-SUSY TH, with scalar potential

$$V(H, H') = \lambda\left(H^2 + H'^2\right)^2 - m_{\mathcal{H}}^2\left(H^2 + H'^2\right) + \Delta\lambda\left(H^4 + H'^4\right) + \Delta m^2 H^2 \tag{1}$$

Due to the Z_2 symmetry, Higgs doublets constitute components of accidental $SU(4)$ fundamental $\mathcal{H} = (H, H')^T$. Clearly, λ and $m_{\mathcal{H}}$ parametrize the $SU(4)$ invariant part of the potential, responsible for the SSB. The Higgs is massive, so the symmetry cannot be exact, and its explicit breaking is parametrized by $\Delta\lambda$. The explicit breaking can be generated by loop corrections, or be present already at tree level. If Z_2 is exact, the masses and VEVs of Higgs and twin Higgs are equal. The mixing between the Higgs and the twin Higgs is bounded by the Higgs invisible decays, thus Z_2 breaking is necessary and is parametrized by Δm^2. This term misaligns VEVs of Higgses and, relates the masses of twin particles to masses of particles by simple relation $m_{\phi'} = m_\phi f/v$. It is also a dominant source of tuning of order $f^2/2v^2$.

After $\mathcal{H}$ obtains VEV $\langle\mathcal{H}\rangle = f$, which breaks the $SU(4)$ down to $SU(3)$, 7 NGBs appear.

Electroweak gauge bosons eat 6 NGB, 3 for each sector and the remaining one, a mixture of neutral components of Higgs doublets H and H', is identified with the SM higgs. The orthogonal, mostly primed mixture is the twin Higgs.
Embedding of the TH mechanism in the supersymmetry can be achieved in two ways. The $SU(4)$ invariant quartic term can be generated either by the F-term of new chiral supermultiplet [5, 6], or by the D-term of new gauge interaction [7–9]. The latter allows for significant reduction of fine-tuning of EW scale with respect to m_{SUSY}. Most of our analysis of twin stau DM is UV independent, and is applicable to both cases.

3. Twin stau

We will consider twin stau as a candidate for the dark matter (DM) [10, 11]. Given that $\tilde{\tau}'$ is charged under the unbroken twin electromagnetism, the massless twin photon mediates long-range interactions between twin stau particles. Hence, twin stau is constrained by the ellipticity measurements of the DM halo [12], and for Z_2 symmetric EM coupling $m_{\tilde{\tau}'} > 210$ GeV. Non-supersymmetric charged candidates for the DM in TH models [13–17], necessarily need broken twin EM to avoid this constraint. On the other hand, twin stau obtains large contributions to its mass from supersymmetry breaking, easily satisfying the bound with unbroken twin EM.

The mass matrix of twin stau is given by

$$m^2_{\tilde{\tau}'} = \begin{pmatrix} m^2_{L_3} + \Delta_{\tilde{\tau}_L} + m^2_{\tau'} & -\mu v' y_\tau \sin(\beta) \\ -\mu v' y_\tau \sin(\beta)) & m^2_{\tilde{e}_3} + \Delta_{\tilde{\tau}_R} + m^2_{\tau'} \end{pmatrix} \tag{2}$$

where m_{3L} and m_{3R} are twin stau soft masses, which are assumed to be Z_2 (we assume that the only Z_2 breaking comes from the scalar potential). Diagonal $\Delta_{\tilde{\tau}'_i}$ terms are the EW D-term contributions proportional to v'^2. The off-diagonal contribution is proportional to higgsino mixing μ and v'. It is clear that the off-diagonal contribution is larger in twin sector by a factor v'/v, and one of the mass matrix eigenvalues can be smaller in twin sector. We have set the soft trilinear term $A_\tau = 0$ for simplicity, since its effects can be imitated by adjusting μ and $\tan\beta$.

First, we will consider a case of minimal tuning introduced through Z_2 breaking compatible with invisible Higgs decay choosing $v'/v = 3$. The plot in Fig. 1 presents results in m_{3R}-m_{3L} plane, the colouring is explained in the caption. Natural values of μ and M_1 are chosen, while large $\tan\beta$ is necessary, to provide the mixing required for twin stau LSP. Large $\tan\beta$ is also preferred due to naturalness in D-term SUSY TH, since it maximizes the $SU(4)$ invariant quartic term in the potential. Regions with small mixing have sparticles lighter than twin stau (stau and twin sneutrino) and are of no interest in this work.

We have computed the relic abundance using `Micromegas` [18–20] which has been adjusted to include all states in the twin sector. Neglecting the interactions with visible sector, which are mediated by Higgs portal, is a good approximation in most parts of the parameter space. However, in regions where stau and twin stau are nearly degenerate, coannihilation may change relic abundance by $O(1)$. We have included this effect using the procedure described in details in [10].

The relic abundance is relatively boosted by light bino, which mediates annihilation into twin taus. The observed abundance $\Omega_{\text{DM}} = 0.12$ [21] is obtained for masses $m_{\tilde{\tau}'} = 450 - 500$ GeV, way above the ellipticity constraint.

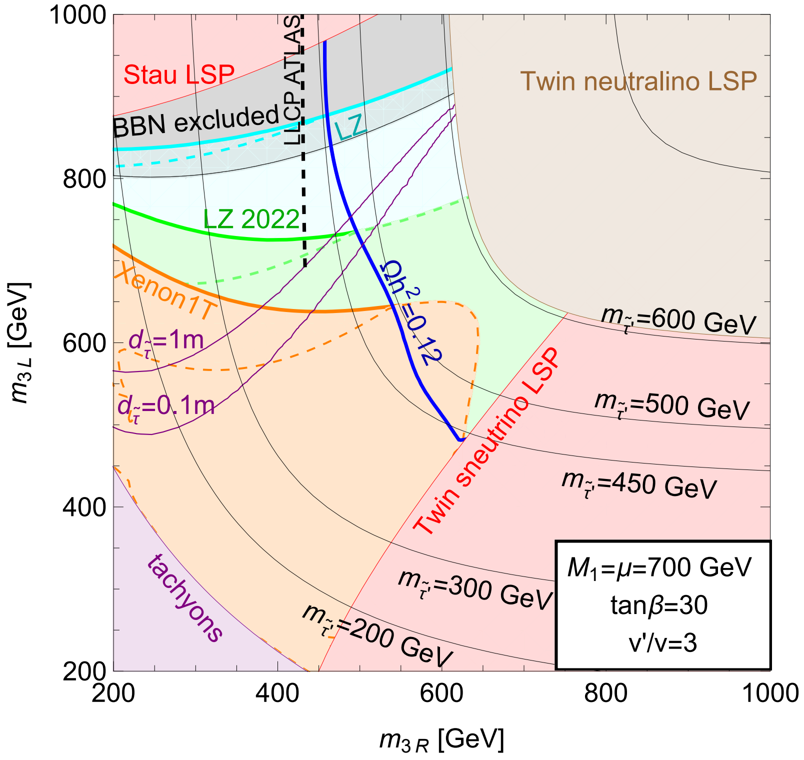

Figure 1: Thermal abundance of twin stau $\Omega^{\text{th}}h^2 = 0.12$ (blue), twin stau mass contours (black solid), stau decay length (purple) in soft masses plane $m_{3R} - m_{3L}$ with $\mu = M_1 = 700$ GeV and $\tan\beta = 30$, ensuring large mixing. Direct detection bounds from Xenon1T [25] (orange), current LZ [26] (green) are presented along with predicted sensitivity of LZ [24] (blue). ATLAS bound on long-lived charged particles is indicated by dashed black line. The region with purple colouring contains tachyons in the spectrum. Regions with twin stau not LSP are coloured red (for stau and twin sneutrino LSP) and brown (twin neutralino LSP). This plot has been first published in [11]

The signature of this scenario, relevant to collider searches as well as cosmological bounds, is relatively light stau. Long-lived charged particles are constrained by ATLAS [22], and for decay length $d_{\tilde\tau} > 1$ m give lower bound $m_{\tilde\tau} > 430$ GeV. For stau decay length below 1 m, the disappearing charged tracks become most sensitive, however current limits on the mass of the stau give $m_{\tilde\tau} \gtrsim 200$ GeV [23], which is weaker than the ellipticity bound and thus always satisfied in this scenario.

If the lifetime of stau becomes large on cosmological scales, stau may decay after Big-Bang Nucleosynthesis (BBN), altering the abundance of light elements. However, cosmologically stable stau is possible only for small mass splitting between stau and twin stau, when $\tilde\tau \to \tilde\tau'\tau\tau'$ is nearly kinematically closed.

Most notably, the direct detection excludes equal mixtures of $\tilde\tau'_L$ and $\tilde\tau'_R$, preferring mostly right-handed twin stau. It should be noted, that even though in this region of parameter space, stau decay length is above 1 m, observed relic abundance is obtained for soft masses yielding $m_{\tilde\tau} > 430$ GeV, above ATLAS bounds. The predicted sensitivity of LZ [24] will probe the scenario with minimal Z_2 tuning. There is a blind spot in the DD bounds, due to vanishing coupling between twin stau and Higgs. It should be stressed, that the blind spot in the DD is excluded by the BBN bounds, as it overlaps with the region of long-lived stau.

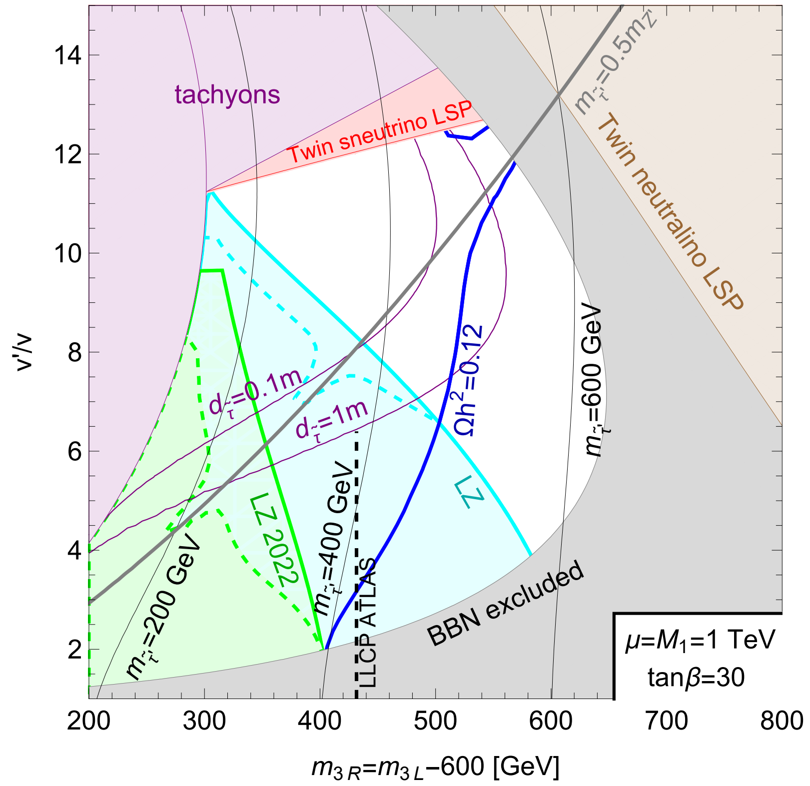

Figure 2: Thermal abundance of twin stau in $m_{3R} - v'/v$ plane with $\mu = M_1 = 1$ TeV and $\tan\beta = 30$.The colouring is the same as in Fig. 1. This plot has been first published in [11]

The coupling of twin stau to quarks is mediated by the Higgs portal, and the mixing between the Higgs and the twin Higgs is well approximated by v/v'. Thus, the scale of $SU(4)$ breaking can suppress the DD bounds. The plot on Fig. 2 shows parameter space in $m_{3R} - v'/v$ plane setting $\mu = M_1 = 1$ TeV to accommodate light bino. The difference between stau soft masses $m_{3R} - m_{3L} = 600$ GeV is kept constant to account for mostly right-handed stau.

For moderate scale of $SU(4)$ breaking, increasing v'/v leads to larger twin stau masses reproducing the correct relic abundance, because the mass splitting between stau and twin stau decreases, enhancing the coannihilation. There is a resonance due to twin stau annihilation into twin fermions via Z'.

Interestingly, the BBN sets an upper bound on the ratio $v'/v \lesssim 12$, because the D-term contribution to the diagonal term in the twin stau mass matrix is proportional to v'^2, while the off-diagonal term is linear in v'. At low v'/v, the suppression of small gauge couplings dominates and twin stau mass is smaller than stau mass. However, for large ratio v'/v the gauge suppression is overcome and the splitting between stau and twin stau decreases, leading to cosmologically stable stau. The upper bound on v'/v can be translated to the worst possible tuning compatible with this scenario of about 1%.

As expected, DD bounds weaken with increasing v'/v. For chosen difference between stau soft masses $m_{3R} - m_{3L} = 600$ GeV, new LZ results don't constrain this scenario. The predicted sensitivity

will probe this scenario up to $v'/v \simeq 6.5$, corresponding to approximately 5% tuning.
Even though much part of the parameter space has decay length above 1 m, the correct relic abundance is usually obtained for $m_{\tilde{\tau}} > 430$ GeV, which is above current LHC limits [22].

4. Conclusions

We have considered twin stau as a candidate for dark matter in SUSY TH models. Although the twin stau is charged under twin electromagnetism, it acquires significant mass contributions from supersymmetry breaking, avoiding constraints for self-interacting dark matter.

Typically, the mass range of the twin stau that reproduces the correct relic abundance is between 450 and 500 GeV. Relic abundance is partially controlled by coannihilation with stau (controlled by mass splitting between $\tilde{\tau}'$ and $\tilde{\tau}$) and annihilations via bino exchange (controlled by bino mass).

We have shown, that direct detection experiments, in particular Lux-Zepelin, prefer mostly right-handed twin stau LSP. The sensitivity of LZ will completely probe parameter space with minimal scale of $SU(4)$ breaking, $v'/v = 3$.

We have also presented the effect of increasing the scale of $SU(4)$ breaking, which reduces mixing between Higgs and twin Higgs. On the other hand, a large scale of $SU(4)$ breaking leads to fine-tuning. Interestingly, there exists an upper limit on $v'/v \simeq 12$, which implies the worst possible tuning of the scenario around 1%. Predicted sensitivity of the LZ will probe twin stau DM up to $v'/v \simeq 6.5$, corresponding to tuning around 5%.

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