Supersymmetric D-term Twin Higgs

Marcin Badziak

UC & LBNL Berkeley & University of Warsaw

Based on:
MB, Keisuke Harigaya
1703.02122

Planck 2017, Warsaw, 25 May 2017

Motivation

- LHC set strong constraints on colored top partners (e.g. stops in Supersymmetry)
- Neutral Naturalness (uncolored top partners) becomes a new paradigm to solve the hierarchy problem

See e.g. talks by Chacko, Katz, Harigaya, Najjari,Redigolo

- Twin Higgs idea is a nice implementation of Neutral Naturalness
- Twin Higgs still requires UV completion
- In this talk: Supersymmetric Twin Higgs model

New incarnation of Natural SUSY

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 $\rightarrow H \xleftrightarrow{\mathbb{Z}_2} H' \leftarrow$ 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: $f^2 \equiv v^2 + v'^2 \qquad \langle H \rangle \equiv v \quad \langle H' \rangle \equiv v'$

UV completing Twin Higgs

- Twin Higgs solves only the little hierarchy problem so must be UV completed
- Above the scale of SU(4) breaking colored top partners must enter to avoid fine-tuning
- In SUSY UV completion stops must be light enough to avoid fine-tuning
- How light? Can they naturally avoid current (and future) LHC constraints?

Fine-tuning in Twin Higgs models

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

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

- There is some minimal amount of tuning which depends on the size of Z_2 breaking:

$$\Delta_{v/f} = \frac{1}{2}\left(\frac{f^2}{v^2} - 2\right)$$

- Higgs coupling measurements imply at least 30-50 % tuning ($f/v \gtrsim 2.5 \div 3$ depending on the amount of the Higgs invisible decays to mirror states)

The Higgs mass in SUSY Twin Higgs

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

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

- 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 $\tan\beta$!
- But:
- In explicit models corrections $\mathcal{O}(\Delta\lambda/\lambda)$ are non-negligible

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:

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

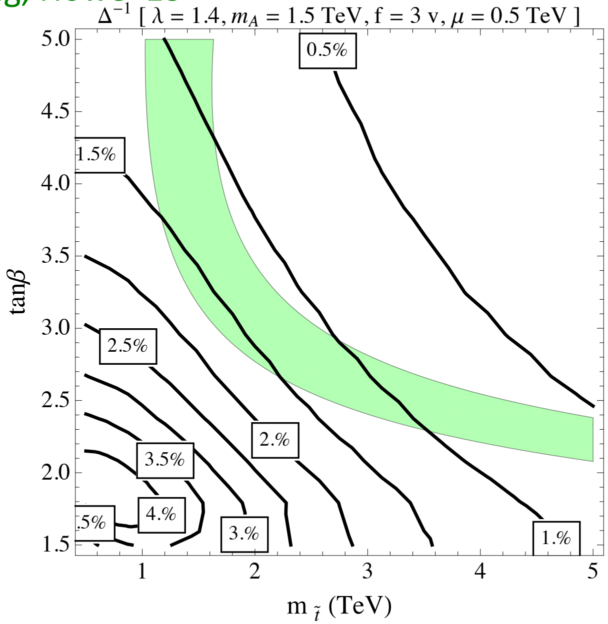
$$V_{SU(4)} = m_{H_u}^2(|H_u|^2 + |H_u'|^2) + m_{H_d}^2(|H_d|^2 + |H_d'|^2) - b(H_u H_d + H_u' H_d' + \text{h.c.}) + m_S^2|S|^2$$

- After integrating out the singlet:

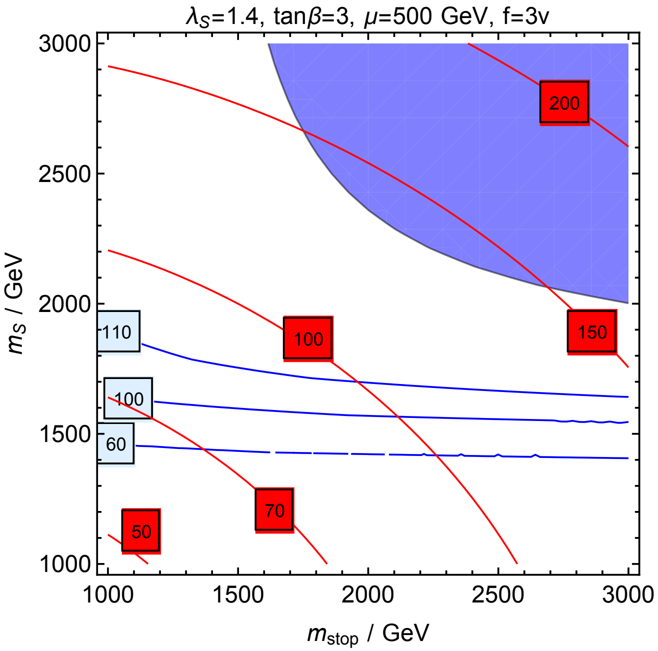
$$\lambda = \lambda_S^2 \frac{\sin^2(2\beta)}{4} \equiv \lambda_F\,.$$

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

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. $\lambda \approx \lambda_{\mathrm{SM}}$

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)

SUSY D-term Twin Higgs

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

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

model dependent

$$0 < \epsilon < 1$$

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

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

- λ grows with $\tan\beta$ as the Higgs mass does
- Large g_X preferred but must be perturbative (at least up to the messenger scale)

SUSY 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

SUSY D-term Twin Higgs: tuning and experimental constraints

- Small ϵ maximizes λ but may introduce tuning via threshold correction:

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

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

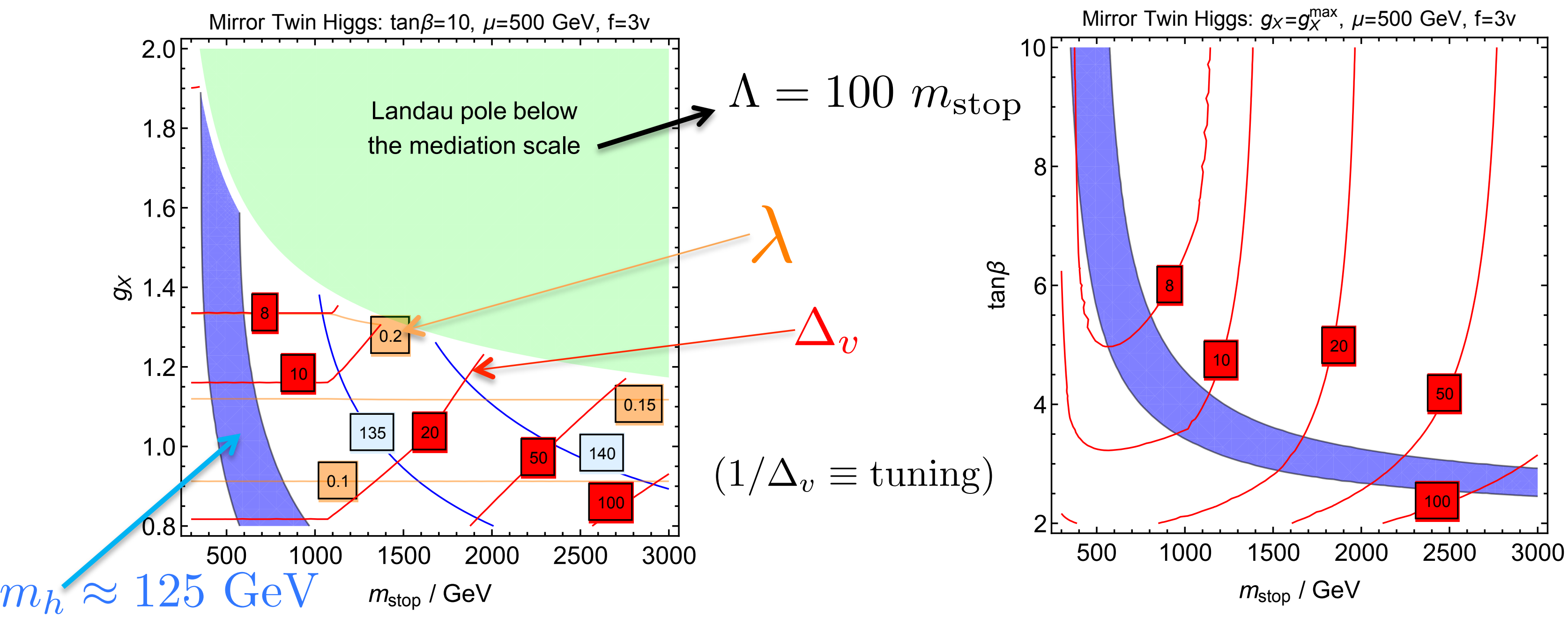
- We take ϵ such that this correction is smaller than the one from stops and exp. lower bound on m_X is satisfied:

$$m_X \gtrsim 4350 \text{ GeV} \times g_X$$

LEP

SUSY D-term Mirror Twin Higgs

- All SM fermions have their mirror counterparts

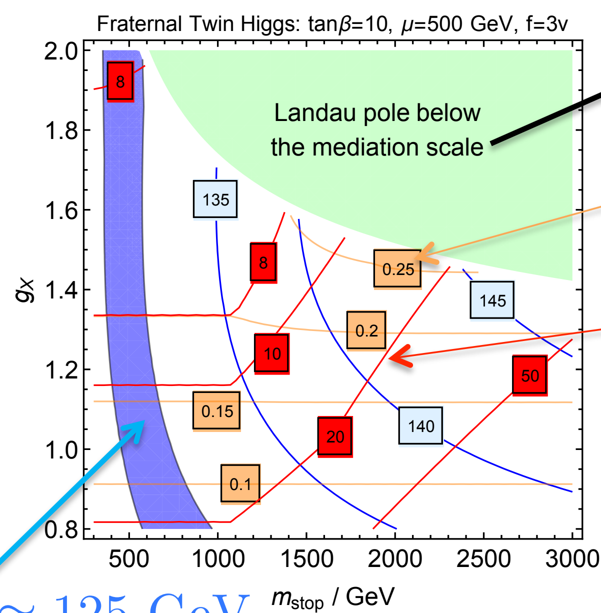


- Correct Higgs mass can be obtained for 1 TeV stops (without stop mixing) with better than 10% tuning
- After HL-LHC the tuning may still be better than 5%

SUSY D-term Fraternal Twin Higgs

Craig, Katz, Strassler, Sundrum '15

- RG running is slower if only 3rd gen. of SM fermions have twins



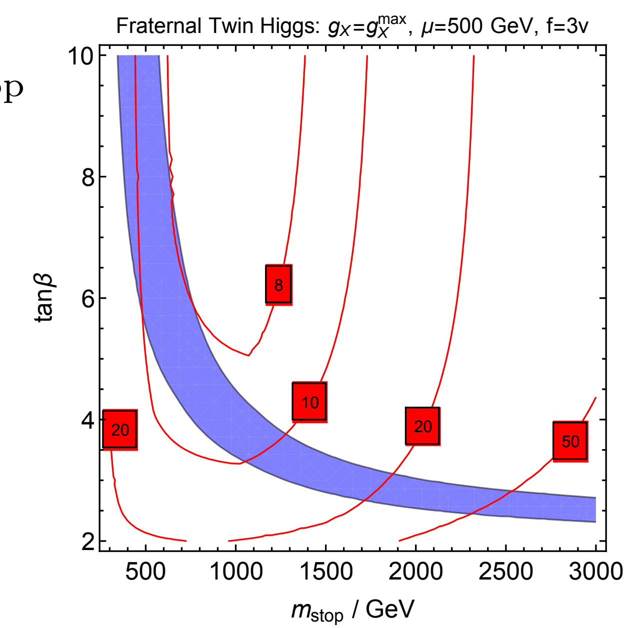
$\Lambda = 100\ m_{\rm stop}$

λ

Δ_v

$(1/\Delta_v \equiv \text{tuning})$

$m_h \approx 125\ \text{GeV}$

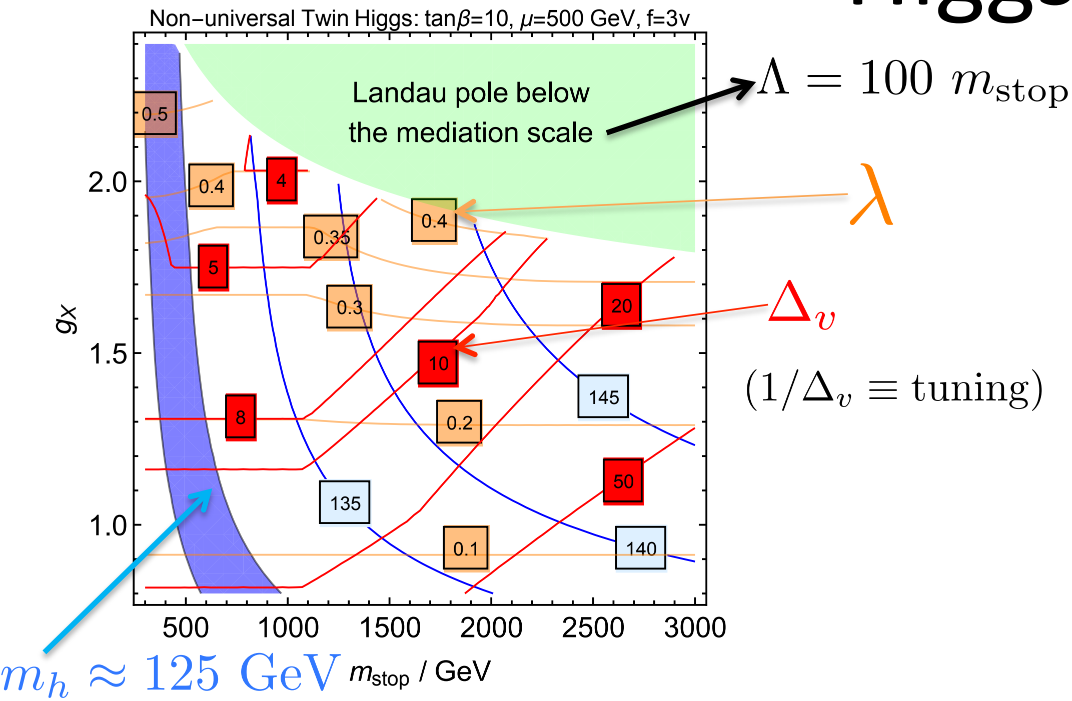


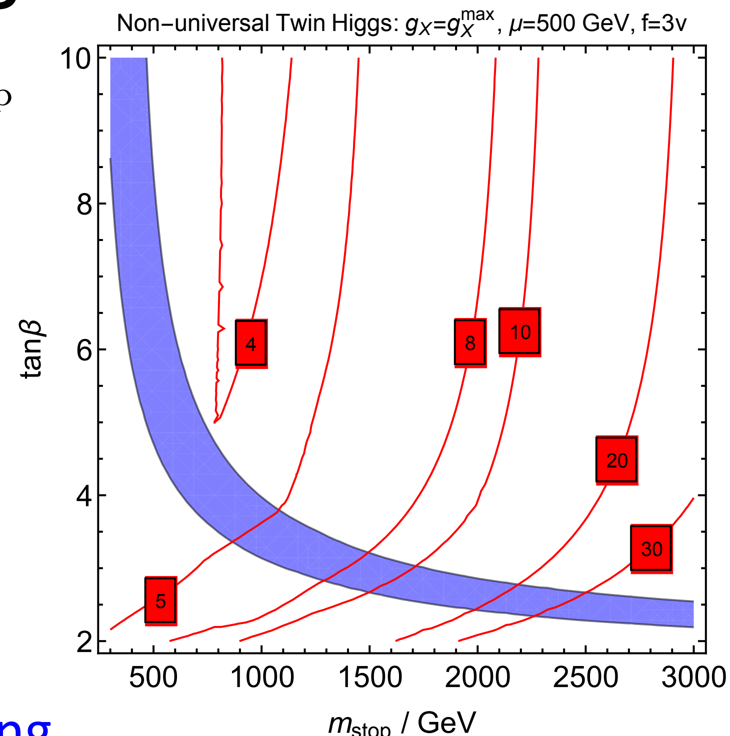
- Bigger g_X allowed $\longrightarrow$ stop masses pushed up by 200-300 GeV with the same amount of tuning as compared to the mirror case

SUSY D-term flavor non-universal Twin Higgs

- Constraints may be substantially relaxed if $U(1)_X$ charges are flavor dependent
- Assume: 1^{st}&2^{nd} generations of the SM and mirror fermions uncharged under $U(1)_X$ (Yukawa couplings generated via mixing with some heavy fermions)
- The RG running of g_X is slower (below heavy fermions scale)
- Production of X gauge boson suppressed so the lower bound on m_X relaxed

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

Conclusions

- D-term of a new $U(1)_X$ gauge symmetry provides approximate SU(4) symmetry for SUSY Twin Higgs
- Fine-tuning may be relaxed by a factor of 7 as compared to the non-twinned version of the model
- Natural SUSY with stop masses up to 2 TeV possible

Conclusions

- D-term of a new $U(1)_X$ gauge symmetry provides approximate SU(4) symmetry for SUSY Twin Higgs
- Fine-tuning may be relaxed by a factor of 7 as compared to the non-twinned version of the model
- Natural SUSY with stop masses up to 2 TeV possible

Natural (twin) SUSY is not dead

BACKUP

Example of a model

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

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

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

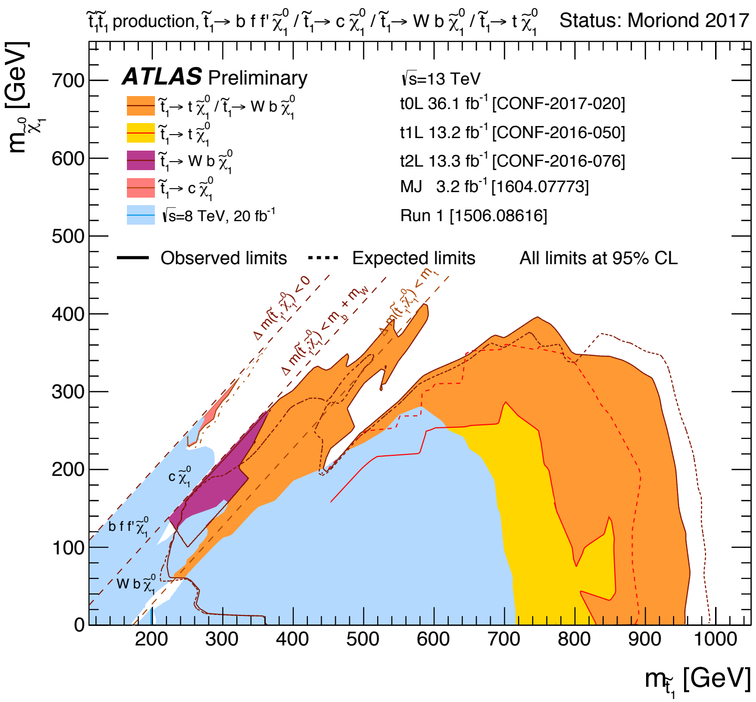
- After integrating out $P \text{ and } \bar{P}$:

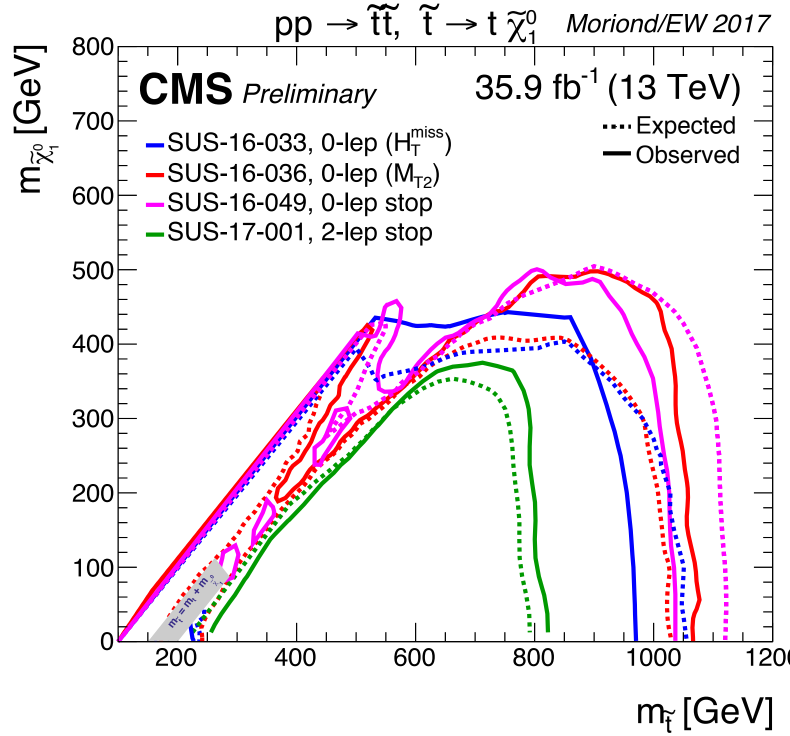
$$\epsilon^2$$

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

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

Moriond stop search results





Acknowledgments

This work has been supported by Polish Ministry of Science Education through its programme Mobility Plus and Department of Energy