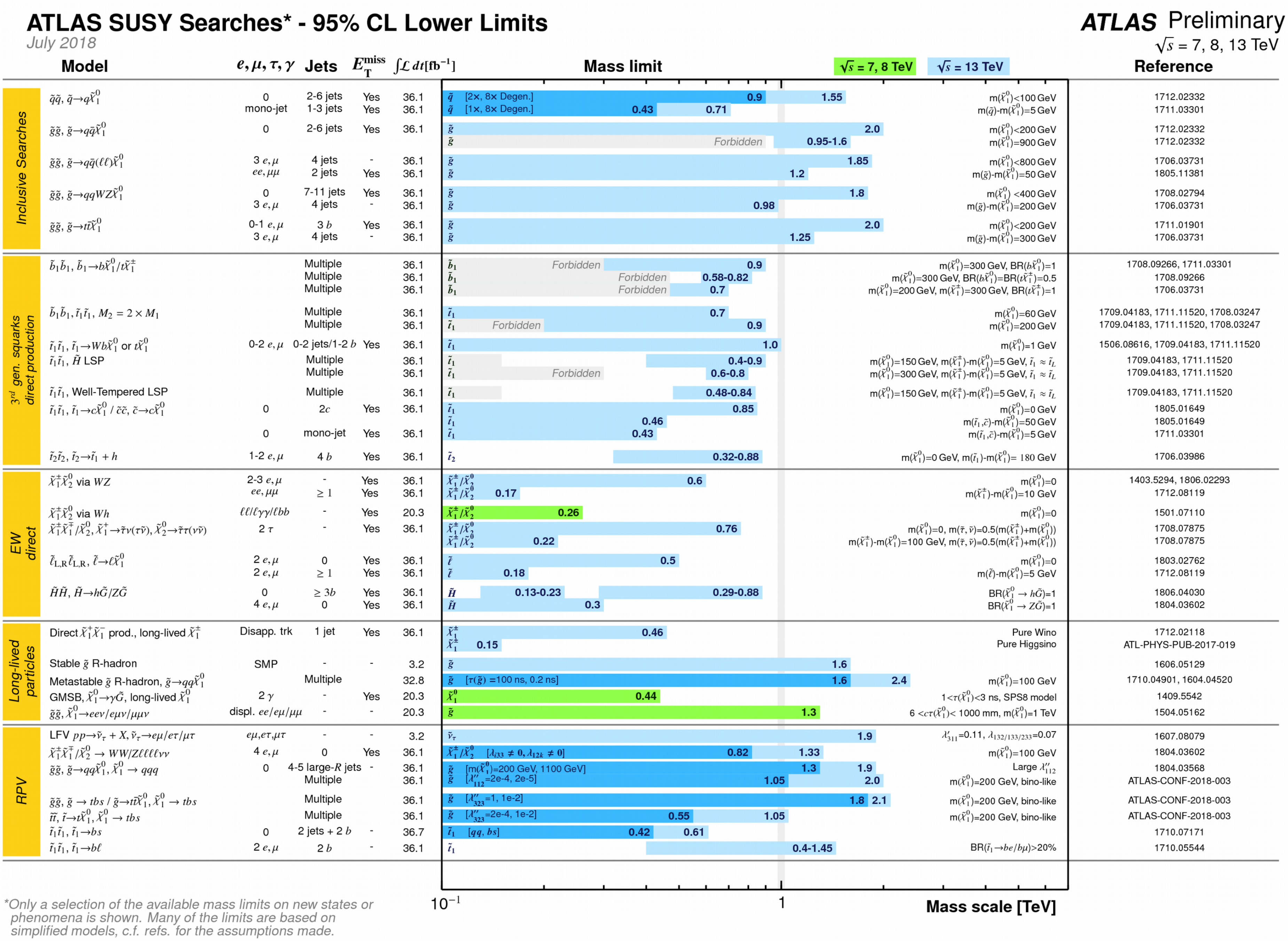
# SUSY – where are we?

Ahmed Ismail
University of Pittsburgh

September 21, 2018

GGI
Beyond Standard Model: where do we go from here?

# Limits



**ATLAS SUSY Searches* - 95% CL Lower Limits**

*July 2018*

***ATLAS*** Preliminary

$\sqrt{s}$ = 7, 8, 13 TeV

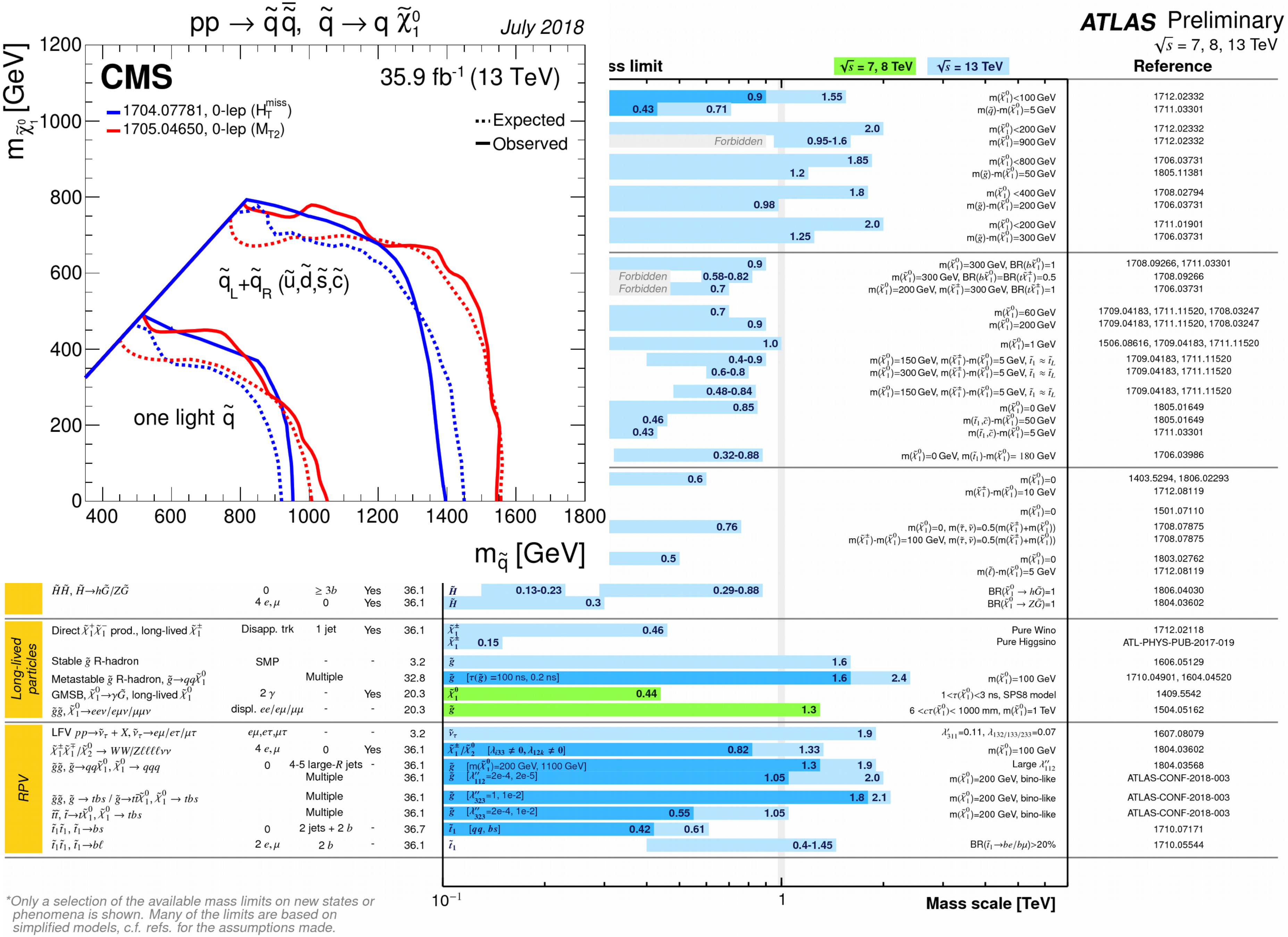
🟩 $\sqrt{s}$ = 7, 8 TeV

🟦 $\sqrt{s}$ = 13 TeV

| | Model | $e, \mu, \tau, \gamma$ | Jets | $E_T^{miss}$ | $\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$ | Mass limit [TeV] | | Reference |
|---|---|---|---|---|---|---|---|---|
| Inclusive Searches | $\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{q}$ [2×, 8× Degen.] 0.9 1.55 | m($\tilde{\chi}_1^0$)<100 GeV | 1712.02332 |
| | | mono-jet | 1-3 jets | Yes | 36.1 | $\tilde{q}$ [1×, 8× Degen.] 0.43 0.71 | m($\tilde{q}$)-m($\tilde{\chi}_1^0$)=5 GeV | 1711.03301 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$ | 0 | 2-6 jets | Yes | 36.1 | $\tilde{g}$ 2.0 | m($\tilde{\chi}_1^0$)<200 GeV | 1712.02332 |
| | | | | | | $\tilde{g}$ *Forbidden* 0.95-1.6 | m($\tilde{\chi}_1^0$)=900 GeV | 1712.02332 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}(\ell\ell)\tilde{\chi}_1^0$ | 3 $e, \mu$ | 4 jets | - | 36.1 | $\tilde{g}$ 1.85 | m($\tilde{\chi}_1^0$)<800 GeV | 1706.03731 |
| | | $ee, \mu\mu$ | 2 jets | Yes | 36.1 | $\tilde{g}$ 1.2 | m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=50 GeV | 1805.11381 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to qqWZ\tilde{\chi}_1^0$ | 0 | 7-11 jets | Yes | 36.1 | $\tilde{g}$ 1.8 | m($\tilde{\chi}_1^0$) <400 GeV | 1708.02794 |
| | | 3 $e, \mu$ | 4 jets | - | 36.1 | $\tilde{g}$ 0.98 | m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=200 GeV | 1706.03731 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to t\bar{t}\tilde{\chi}_1^0$ | 0-1 $e, \mu$ | 3 $b$ | Yes | 36.1 | $\tilde{g}$ 2.0 | m($\tilde{\chi}_1^0$)<200 GeV | 1711.01901 |
| | | 3 $e, \mu$ | 4 jets | - | 36.1 | $\tilde{g}$ 1.25 | m($\tilde{g}$)-m($\tilde{\chi}_1^0$)=300 GeV | 1706.03731 |
| $3^{rd}$ gen. squarks direct production | $\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0/t\tilde{\chi}_1^\pm$ | | Multiple | | 36.1 | $\tilde{b}_1$ *Forbidden* 0.9 | m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=1 | 1708.09266, 1711.03301 |
| | | | Multiple | | 36.1 | $\tilde{b}_1$ *Forbidden* 0.58-0.82 | m($\tilde{\chi}_1^0$)=300 GeV, BR($b\tilde{\chi}_1^0$)=BR($t\tilde{\chi}_1^\pm$)=0.5 | 1708.09266 |
| | | | Multiple | | 36.1 | $\tilde{b}_1$ *Forbidden* 0.7 | m($\tilde{\chi}_1^0$)=200 GeV, m($\tilde{\chi}_1^\pm$)=300 GeV, BR($t\tilde{\chi}_1^\pm$)=1 | 1706.03731 |
| | $\tilde{b}_1\tilde{b}_1, \tilde{t}_1\tilde{t}_1, M_2 = 2\times M_1$ | | Multiple | | 36.1 | $\tilde{t}_1$ 0.7 | m($\tilde{\chi}_1^0$)=60 GeV | 1709.04183, 1711.11520, 1708.03247 |
| | | | Multiple | | 36.1 | $\tilde{t}_1$ *Forbidden* 0.9 | m($\tilde{\chi}_1^0$)=200 GeV | 1709.04183, 1711.11520, 1708.03247 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to Wb\tilde{\chi}_1^0$ or $t\tilde{\chi}_1^0$ | 0-2 $e, \mu$ | 0-2 jets/1-2 $b$ | Yes | 36.1 | $\tilde{t}_1$ 1.0 | m($\tilde{\chi}_1^0$)=1 GeV | 1506.08616, 1709.04183, 1711.11520 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{H}$ LSP | | Multiple | | 36.1 | $\tilde{t}_1$ 0.4-0.9 | m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$ | 1709.04183, 1711.11520 |
| | | | Multiple | | 36.1 | $\tilde{t}_1$ *Forbidden* 0.6-0.8 | m($\tilde{\chi}_1^0$)=300 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$ | 1709.04183, 1711.11520 |
| | $\tilde{t}_1\tilde{t}_1$, Well-Tempered LSP | | Multiple | | 36.1 | $\tilde{t}_1$ 0.48-0.84 | m($\tilde{\chi}_1^0$)=150 GeV, m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=5 GeV, $\tilde{t}_1 \approx \tilde{t}_L$ | 1709.04183, 1711.11520 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$ / $\tilde{c}\tilde{c}, \tilde{c}\to c\tilde{\chi}_1^0$ | 0 | 2$c$ | Yes | 36.1 | $\tilde{t}_1$ 0.85 | m($\tilde{\chi}_1^0$)=0 GeV | 1805.01649 |
| | | | | | | $\tilde{t}_1$ 0.46 | m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=50 GeV | 1805.01649 |
| | | 0 | mono-jet | Yes | 36.1 | $\tilde{t}_1$ 0.43 | m($\tilde{t}_1$,$\tilde{c}$)-m($\tilde{\chi}_1^0$)=5 GeV | 1711.03301 |
| | $\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + h$ | 1-2 $e, \mu$ | 4 $b$ | Yes | 36.1 | $\tilde{t}_2$ 0.32-0.88 | m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)= 180 GeV | 1706.03986 |
| EW direct | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via $WZ$ | 2-3 $e, \mu$ | - | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.6 | m($\tilde{\chi}_1^0$)=0 | 1403.5294, 1806.02293 |
| | | $ee, \mu\mu$ | $\geq 1$ | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.17 | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=10 GeV | 1712.08119 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ via $Wh$ | $\ell\ell/\ell\gamma\gamma/\ell bb$ | - | Yes | 20.3 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.26 | m($\tilde{\chi}_1^0$)=0 | 1501.07110 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu}), \tilde{\chi}_2^0\to\tilde{\tau}\tau(\nu\tilde{\nu})$ | 2 $\tau$ | - | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.76 | m($\tilde{\chi}_1^0$)=0, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | 1708.07875 |
| | | | | | | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ 0.22 | m($\tilde{\chi}_1^\pm$)-m($\tilde{\chi}_1^0$)=100 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^\pm$)+m($\tilde{\chi}_1^0$)) | 1708.07875 |
| | $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$ | 2 $e, \mu$ | 0 | Yes | 36.1 | $\tilde{\ell}$ 0.5 | m($\tilde{\chi}_1^0$)=0 | 1803.02762 |
| | | 2 $e, \mu$ | $\geq 1$ | Yes | 36.1 | $\tilde{\ell}$ 0.18 | m($\tilde{\ell}$)-m($\tilde{\chi}_1^0$)=5 GeV | 1712.08119 |
| | $\tilde{H}\tilde{H}, \tilde{H}\to h\tilde{G}/Z\tilde{G}$ | 0 | $\geq 3b$ | Yes | 36.1 | $\tilde{H}$ 0.13-0.23 0.29-0.88 | BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1 | 1806.04030 |
| | | 4 $e, \mu$ | 0 | Yes | 36.1 | $\tilde{H}$ 0.3 | BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=1 | 1804.03602 |
| Long-lived particles | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 36.1 | $\tilde{\chi}_1^\pm$ 0.46 | Pure Wino | 1712.02118 |
| | | | | | | $\tilde{\chi}_1^\pm$ 0.15 | Pure Higgsino | ATL-PHYS-PUB-2017-019 |
| | Stable $\tilde{g}$ R-hadron | SMP | - | - | 3.2 | $\tilde{g}$ 1.6 | | 1606.05129 |
| | Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$ | | Multiple | | 32.8 | $\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] 1.6 2.4 | m($\tilde{\chi}_1^0$)=100 GeV | 1710.04901, 1604.04520 |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ 0.44 | 1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model | 1409.5542 |
| | $\tilde{g}\tilde{g}, \tilde{\chi}_1^0\to ee\nu/e\mu\nu/\mu\mu\nu$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde{g}$ 1.3 | 6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV | 1504.05162 |
| RPV | LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ | - | - | 3.2 | $\tilde{\nu}_\tau$ 1.9 | $\lambda'_{311}$=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$ | 4 $e, \mu$ | 0 | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] 0.82 1.33 | m($\tilde{\chi}_1^0$)=100 GeV | 1804.03602 |
| | $\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qqq$ | 0 | 4-5 large-$R$ jets | - | 36.1 | $\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV] 1.3 1.9 | Large $\lambda''_{112}$ | 1804.03568 |
| | | | Multiple | | 36.1 | $\tilde{g}$ [$\lambda''_{112}$=2e-4, 2e-5] 1.05 2.0 | m($\tilde{\chi}_1^0$)=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{g}\tilde{g}, \tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$ | | Multiple | | 36.1 | $\tilde{g}$ [$\lambda''_{323}$=1, 1e-2] 1.8 2.1 | m($\tilde{\chi}_1^0$)=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{t}\tilde{t}, \tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$ | | Multiple | | 36.1 | $\tilde{g}$ [$\lambda''_{323}$=2e-4, 1e-2] 0.55 1.05 | m($\tilde{\chi}_1^0$)=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to bs$ | 0 | 2 jets + 2 $b$ | - | 36.7 | $\tilde{t}_1$ [$qq$, $bs$] 0.42 0.61 | | 1710.07171 |
| | $\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to b\ell$ | 2 $e, \mu$ | 2 $b$ | - | 36.1 | $\tilde{t}_1$ 0.4-1.45 | BR($\tilde{t}_1\to be/b\mu$)>20% | 1710.05544 |

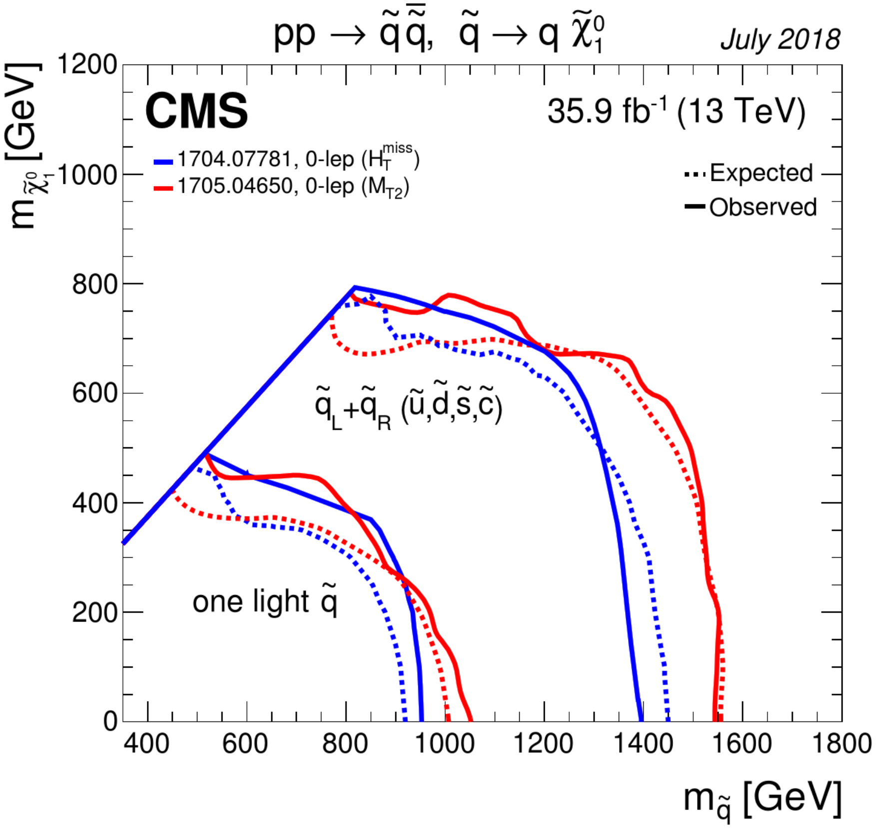
*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

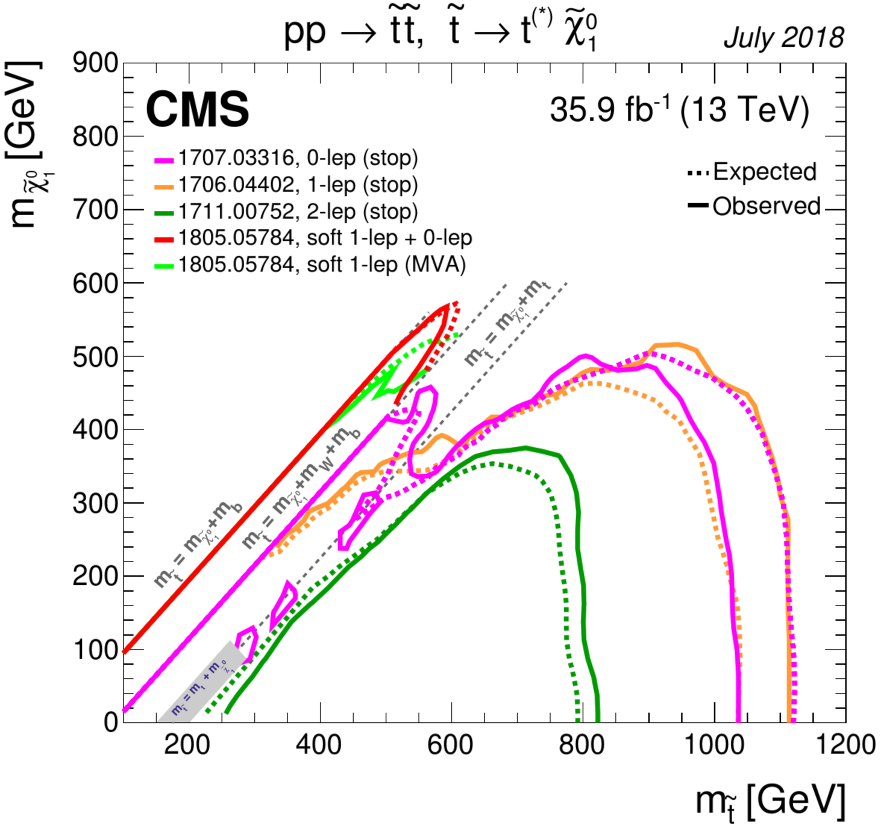
# Limits

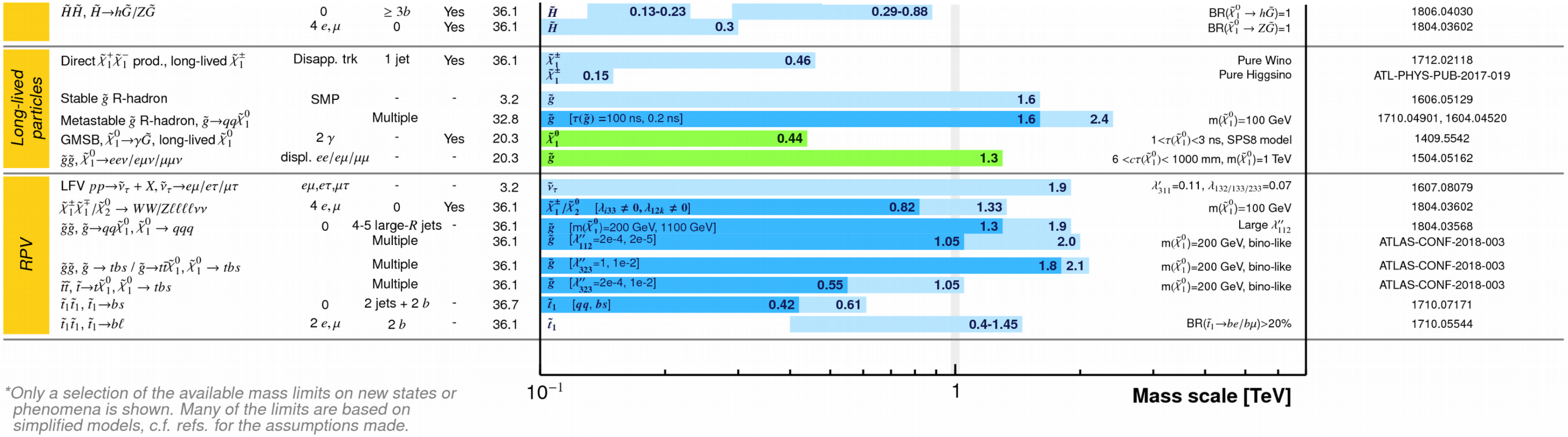


*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

# Limits







| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\tilde{H}\tilde{H}$, $\tilde{H}\to h\tilde{G}/Z\tilde{G}$ | 0<br>4 $e,\mu$ | $\geq 3b$<br>0 | Yes<br>Yes | 36.1<br>36.1 | $\tilde{H}$<br>$\tilde{H}$ | 0.13-0.23 0.29-0.88<br>0.3 | BR($\tilde{\chi}_1^0 \to h\tilde{G}$)=1<br>BR($\tilde{\chi}_1^0 \to Z\tilde{G}$)=1 | 1806.04030<br>1804.03602 |
| *Long-lived particles* | Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ | Disapp. trk | 1 jet | Yes | 36.1 | $\tilde{\chi}_1^\pm$<br>$\tilde{\chi}_1^\pm$ | 0.46<br>0.15 | Pure Wino<br>Pure Higgsino | 1712.02118<br>ATL-PHYS-PUB-2017-019 |
| | Stable $\tilde{g}$ R-hadron | SMP | - | - | 3.2 | $\tilde{g}$ | 1.6 | | 1606.05129 |
| | Metastable $\tilde{g}$ R-hadron, $\tilde{g}\to qq\tilde{\chi}_1^0$ | Multiple | | | 32.8 | $\tilde{g}$ [$\tau(\tilde{g})$ =100 ns, 0.2 ns] | 1.6 2.4 | m($\tilde{\chi}_1^0$)=100 GeV | 1710.04901, 1604.04520 |
| | GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$ | 2 $\gamma$ | - | Yes | 20.3 | $\tilde{\chi}_1^0$ | 0.44 | 1<$\tau(\tilde{\chi}_1^0)$<3 ns, SPS8 model | 1409.5542 |
| | $\tilde{g}\tilde{g}$, $\tilde{\chi}_1^0\to eev/e\mu v/\mu\mu v$ | displ. $ee/e\mu/\mu\mu$ | - | - | 20.3 | $\tilde{g}$ | 1.3 | 6 <$c\tau(\tilde{\chi}_1^0)$< 1000 mm, m($\tilde{\chi}_1^0$)=1 TeV | 1504.05162 |
| *RPV* | LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e\mu/e\tau/\mu\tau$ | $e\mu,e\tau,\mu\tau$ | - | - | 3.2 | $\tilde{\nu}_\tau$ | 1.9 | $\lambda'_{311}$=0.11, $\lambda_{132/133/233}$=0.07 | 1607.08079 |
| | $\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp/\tilde{\chi}_2^0 \to WW/Z\ell\ell\ell\ell\nu\nu$ | 4 $e,\mu$ | 0 | Yes | 36.1 | $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ [$\lambda_{i33} \neq 0, \lambda_{12k} \neq 0$] | 0.82 1.33 | m($\tilde{\chi}_1^0$)=100 GeV | 1804.03602 |
| | $\tilde{g}\tilde{g}$, $\tilde{g}\to qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to qqq$ | 0 | 4-5 large-$R$ jets<br>Multiple | - | 36.1<br>36.1 | $\tilde{g}$ [m($\tilde{\chi}_1^0$)=200 GeV, 1100 GeV]<br>$\tilde{g}$ [$\lambda''_{112}$=2e-4, 2e-5] | 1.3 1.9<br>1.05 2.0 | Large $\lambda''_{112}$<br>m($\tilde{\chi}_1^0$)=200 GeV, bino-like | 1804.03568<br>ATLAS-CONF-2018-003 |
| | $\tilde{g}\tilde{g}$, $\tilde{g} \to tbs$ / $\tilde{g}\to t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$ | Multiple | | | 36.1 | $\tilde{g}$ [$\lambda''_{323}$=1, 1e-2] | 1.8 2.1 | m($\tilde{\chi}_1^0$)=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{t}\tilde{t}$, $\tilde{t}\to t\tilde{\chi}_1^0, \tilde{\chi}_1^0 \to tbs$ | Multiple | | | 36.1 | $\tilde{g}$ [$\lambda''_{323}$=2e-4, 1e-2] | 0.55 1.05 | m($\tilde{\chi}_1^0$)=200 GeV, bino-like | ATLAS-CONF-2018-003 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to bs$ | 0 | 2 jets + 2 $b$ | - | 36.7 | $\tilde{t}_1$ [$qq$, $bs$] | 0.42 0.61 | | 1710.07171 |
| | $\tilde{t}_1\tilde{t}_1$, $\tilde{t}_1\to b\ell$ | 2 $e,\mu$ | 2 $b$ | - | 36.1 | $\tilde{t}_1$ | 0.4-1.45 | BR($\tilde{t}_1\to be/b\mu$)>20% | 1710.05544 |

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

# Naturalness, or *should we care?*

$$\Delta = \frac{\partial \log M_Z^2}{\partial \log x^i}$$

Barbieri, Giudice 1988

$$M_Z^2 = -2\mu^2 + 2\frac{m_{H_d}^2 - \tan^2\beta\, m_{H_u}^2}{\tan^2\beta - 1}$$

Higgsinos
tree level

gluinos, stops
loop level

$$\Delta_\mu \approx 4\mu^2/M_Z^2$$

low scales, $\Lambda < 10^6 M_S$

$$\Delta_{Q_3} \approx \frac{3y_t^2 \log \Lambda/M_S}{\pi^2}\frac{M_{Q_3}^2}{M_Z^2}$$

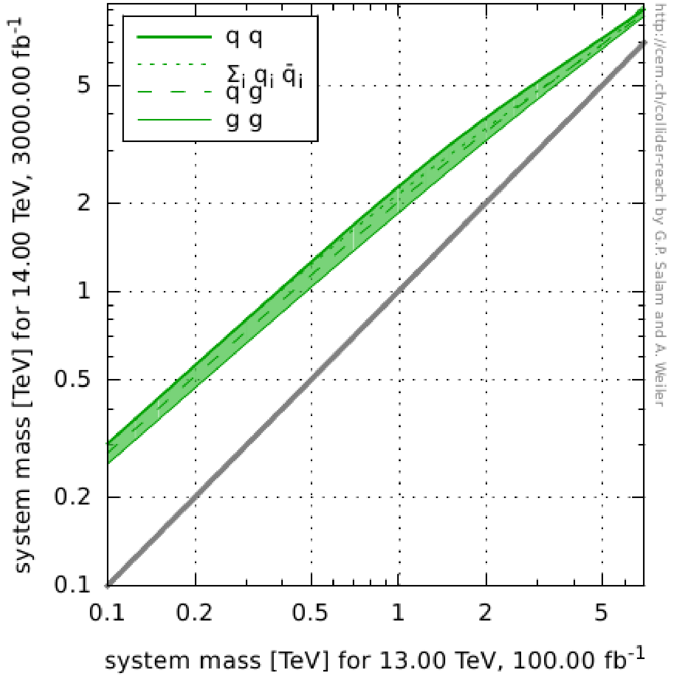
intermediate scales
$10^6 M_S < \Lambda < 10^{13} M_S$

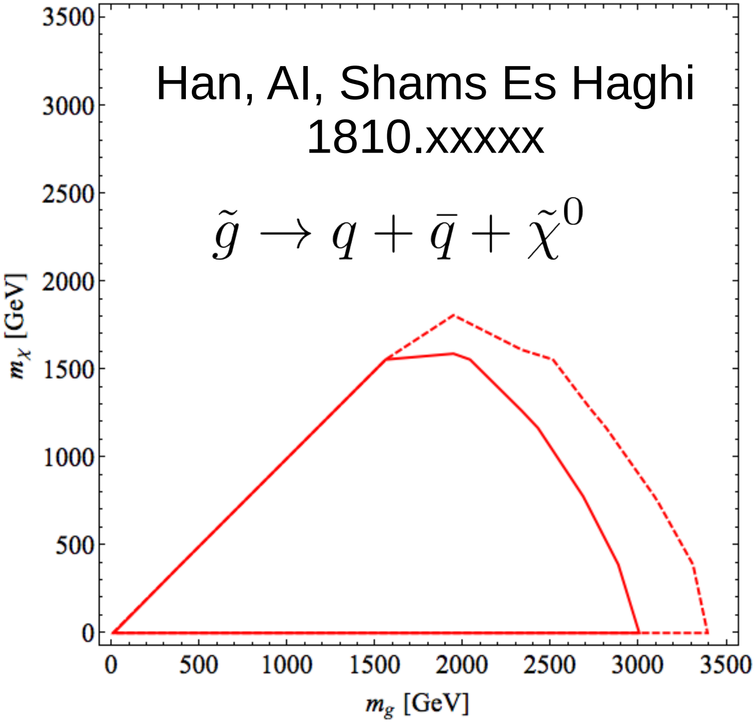
$$\Delta_{M_3} \approx \frac{4\alpha_s y_t^2 \log^2 \Lambda/M_S}{3\pi^3}\frac{M_3^2}{M_Z^2}$$

high scales, $\Lambda > 10^{13} M_S$

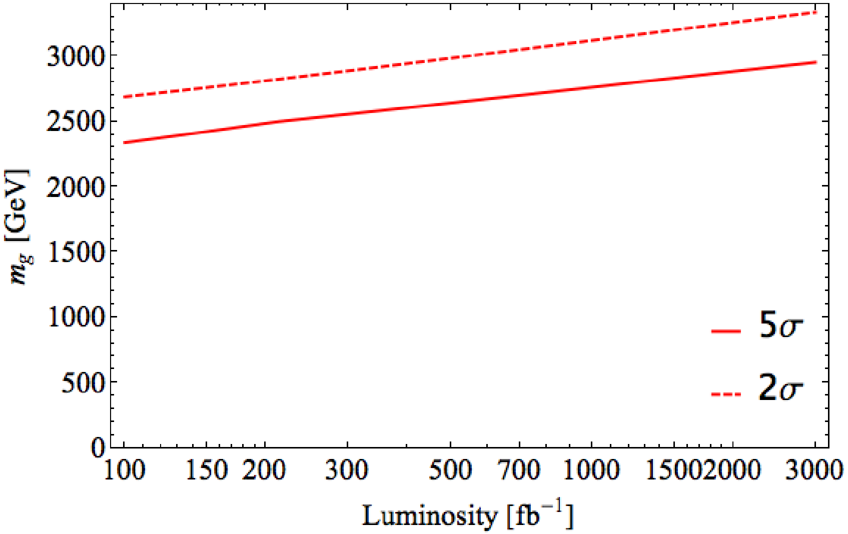
# High luminosity prospects

Estimate from parton
luminosity scaling:
largest gains at low mass for
current LHC → HL-LHC



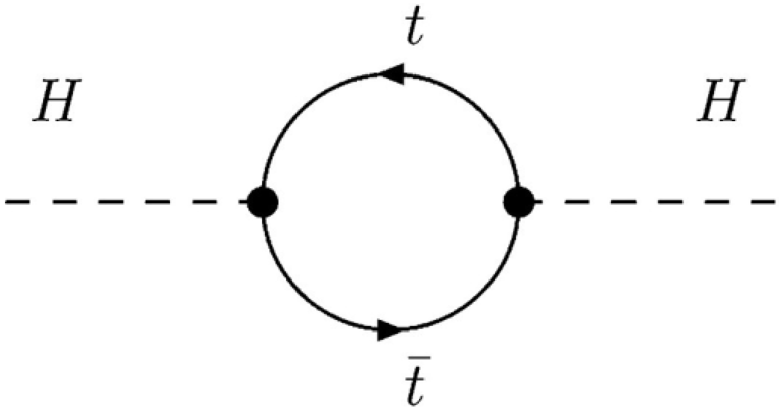

Han, Al, Shams Es Haghi
1810.xxxxx

$$\tilde{g} \to q + \bar{q} + \tilde{\chi}^0$$

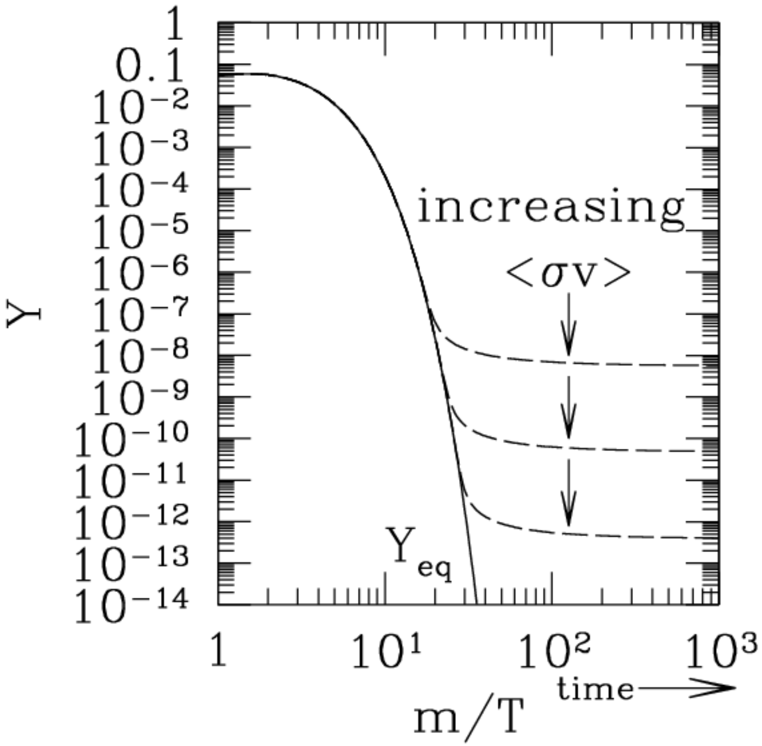


e.g. gluino reach doesn't gain significantly after a few hundred fb$^{-1}$

# EW searches: SUSY and more



Motivation 1, naturalness
In SUSY Higgsino mass affects fine-tuning at *tree* level



Motivation 1', naturalness
top partners charged under *different* SU(3) from color, but still under EW group
folded SUSY Burdman, Chacko, Goh, Harnik hep-ph/0609152
quirky little Higgs Cai, Cheng, Terning 0812.0843

Motivation 2, dark matter
Simple example of WIMP paradigm for dark matter (thermal masses tricky at LHC)

# New electroweak states and MET

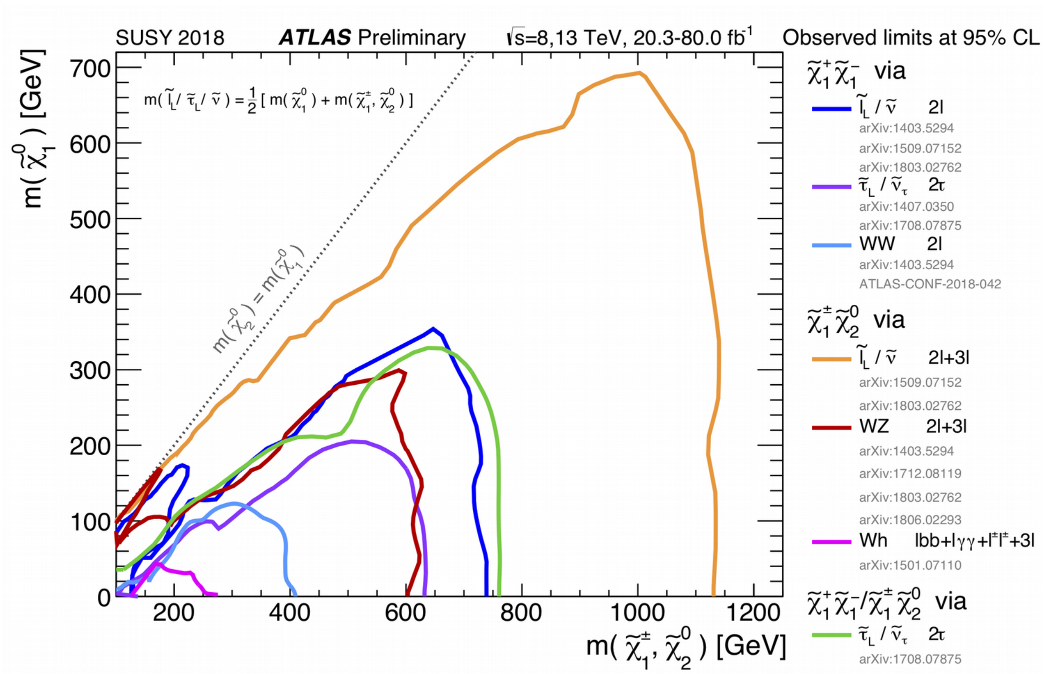
Assume:

EW multiplet odd under $Z_2$ symmetry, to avoid decays into SM particles that are covered by resonance searches (R-parity)

Q = 0 member of multiplet is lightest state, and hence invisible at colliders

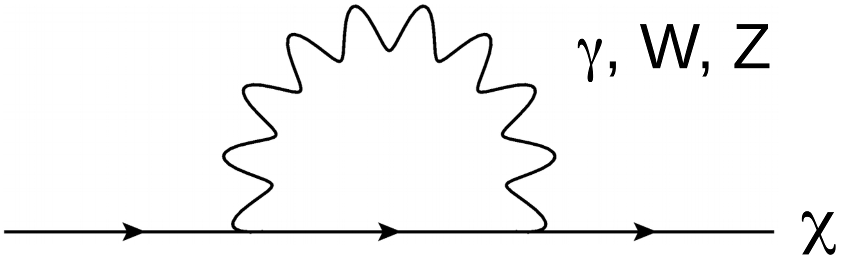
Any non-trivial $SU(2)_L$ multiplet $\chi$ contains at least one charged particle

Can produce charged particle and look for decay products plus MET



# Mass splitting in EW multiplets

Small mass difference from radiative corrections



$$\begin{aligned} M(\chi^+) - M(\chi^0) &= \left(1 + \frac{2Y}{c_w}\right)\frac{\alpha_2}{2} M_W \left(1 - c_w\right) \\ &\approx 166 + 189(2Y)\ \mathrm{MeV} \end{aligned}$$

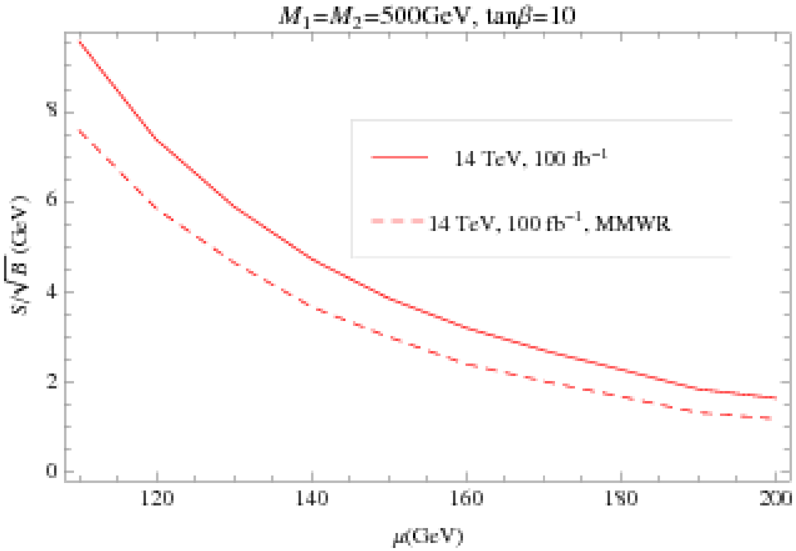
Extra splitting possible from EWSB (SUSY: mixing)

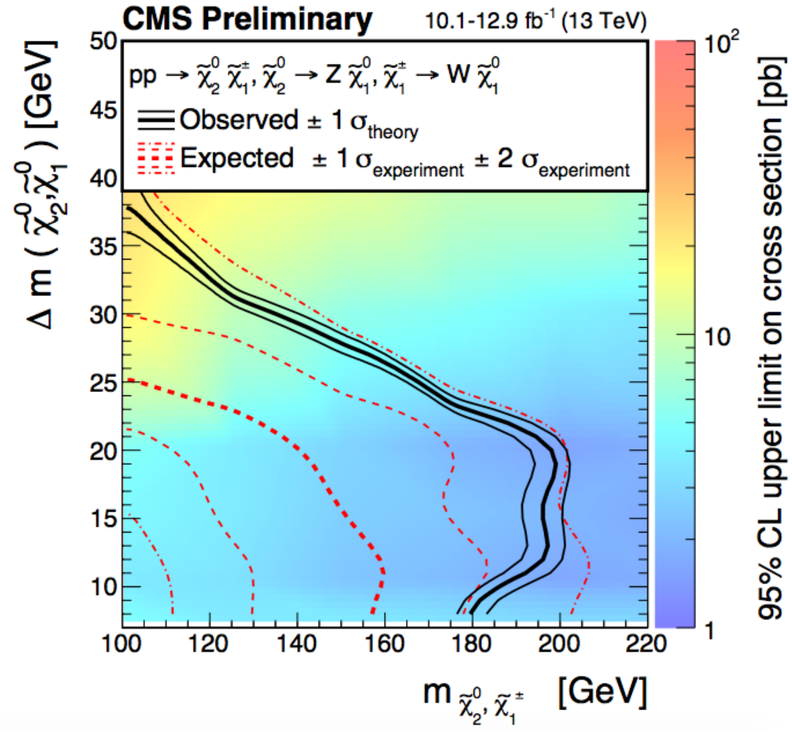
$$\mathcal{L} \supset \frac{1}{\Lambda}\left(\bar{\chi}\vec{\sigma}\chi\right)\left(H^\dagger\vec{\sigma}H\right) \to M(\chi^+) - M(\chi^0) \sim \frac{v^2}{\Lambda m_\chi}$$

# Signatures: large splitting

For several GeV mass splittings, can still use leptons from $\chi^+ \rightarrow \chi^0 + W^*$

Schwaller and Zurita, 1312.7350; Han et al., 1401.1235; Low and Wang, 1404.0682



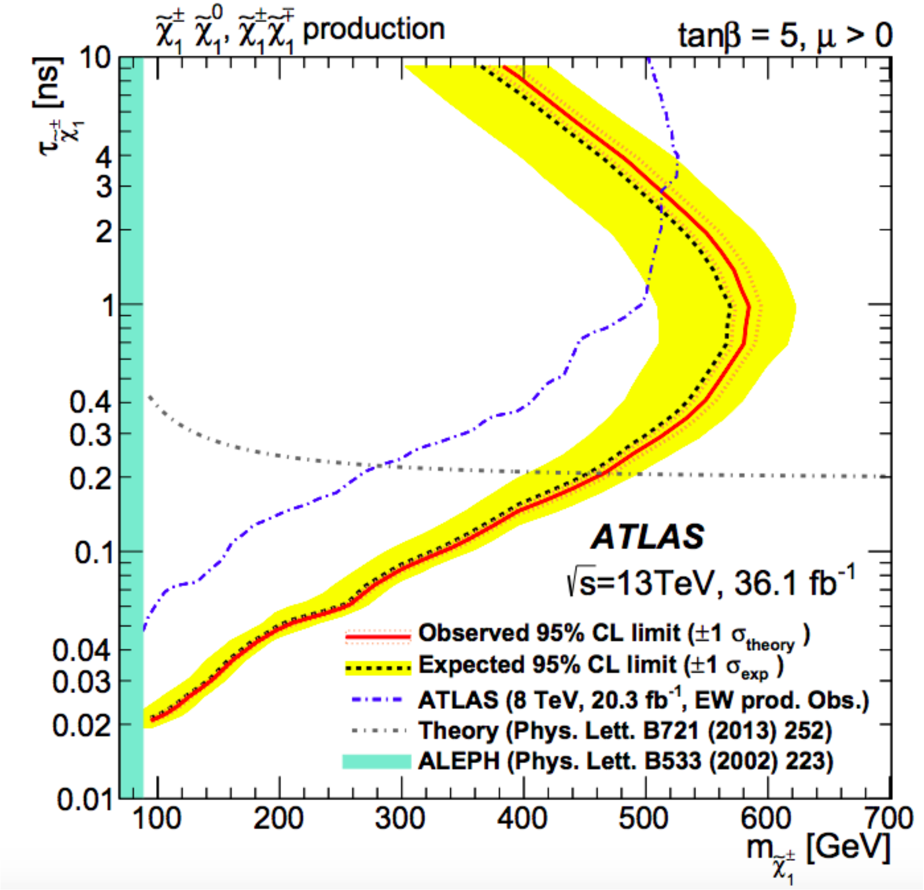


Multiple states also give leptons from off-shell Z

Standard gaugino search

# Signatures: small splitting

For mass difference well below GeV, $\chi^+ \to \chi^0 + \pi^+$ gives disappearing tracks



ATLAS: insertable B-layer allows reconstruction of particles with significantly shorter lifetime, 12 cm rather than 30 cm

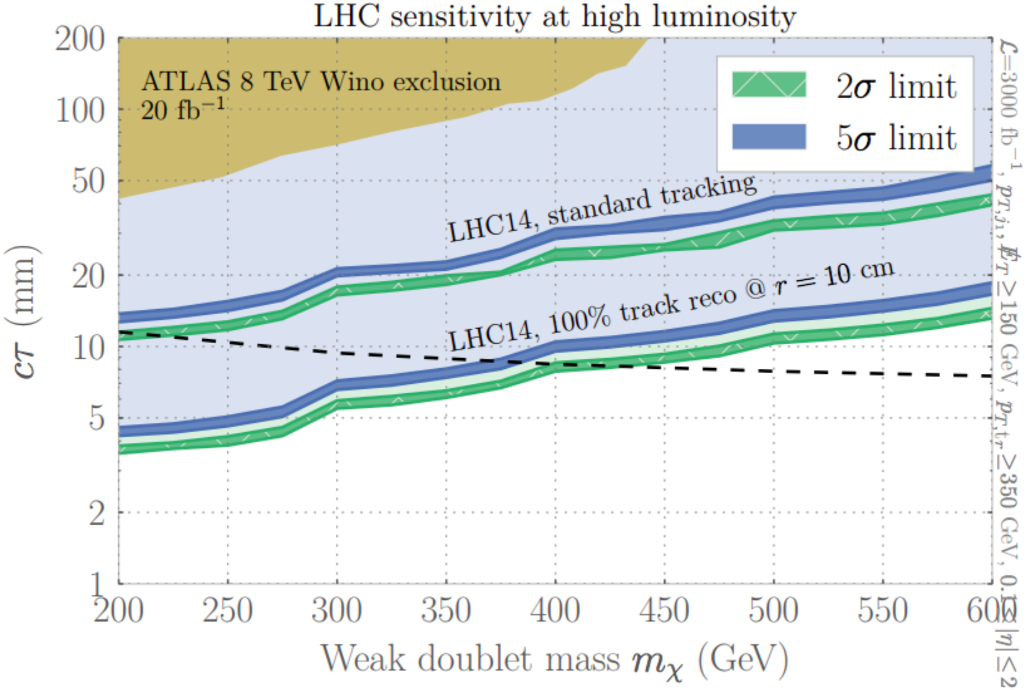
$$\Gamma \quad \propto \quad G_F^2 \Delta M^3 f_\pi^2 \sqrt{1-\frac{m_\pi^2}{\Delta M^2}}$$

$$\to \tau \quad \approx \quad \frac{44\ \text{cm}}{n^2-1}$$

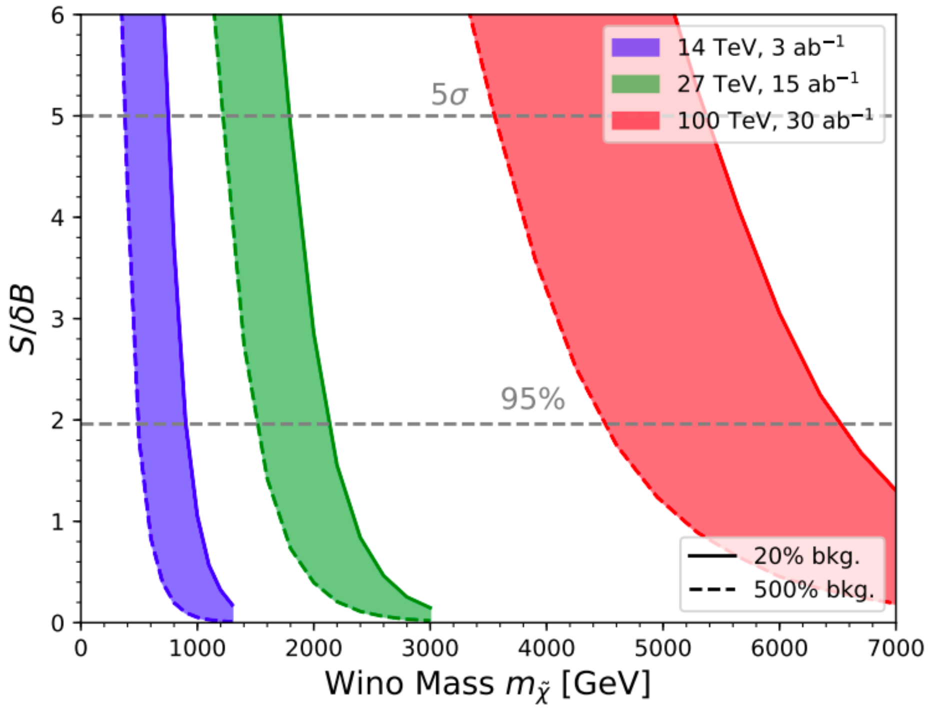
Y = 0 *n*-plet

# The future of disappearing track searches

Prospects for triplet increase to 0.5-0.9 TeV with full luminosity, depending on background



Mahbubani, Schwaller, Zurita 1703.05327



Han, Mukhopadhyay, Wang 1805.00015
see also Low and Wang, 1404.0682

Getting closer to beam would improve reach further

# Intermediate splittings?

For mass differences between ~0.5-5 GeV, leptons from $\chi^+$ decay are too soft to see in detector

But decay is prompt enough to avoid disappearing tracks!

→ alternative: go back to mono-X searches

canonical example: Higgsinos

<u>8 TeV monojet limits</u>

$$\text{ATLAS} : m_\chi > 103\,\text{GeV}\,(\text{SR4})$$

$$\text{CMS} : m_\chi > 73\,\text{GeV}\,(\text{SR5}),$$

Han et al., 1401.1235

Current limits comparable to LEP

# Need to go beyond monojets

Future monojet sensitivity hindered by large V + jet backgrounds

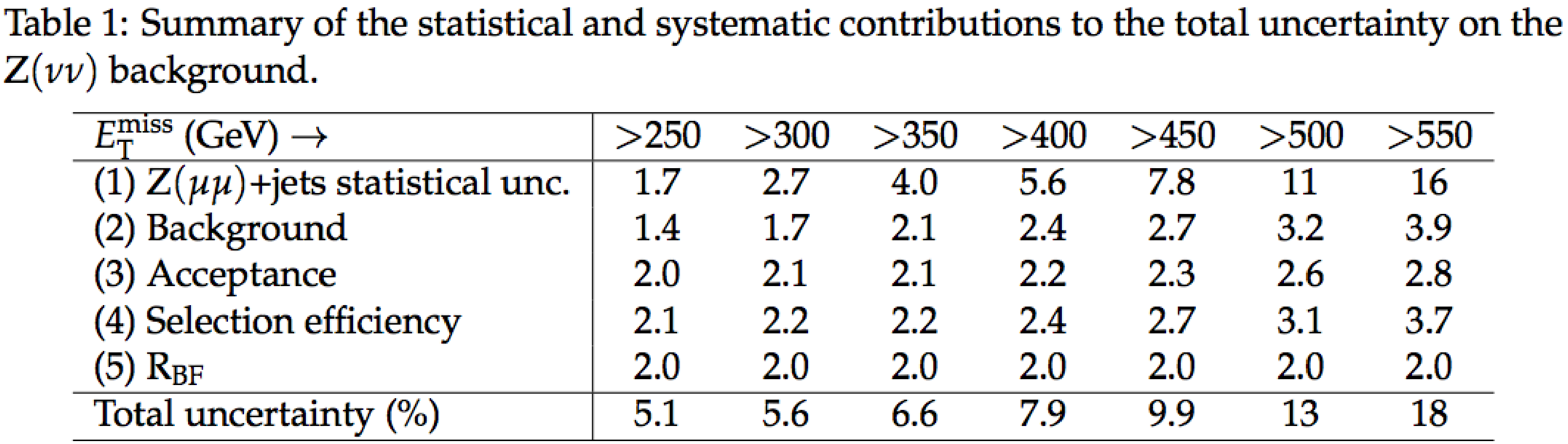
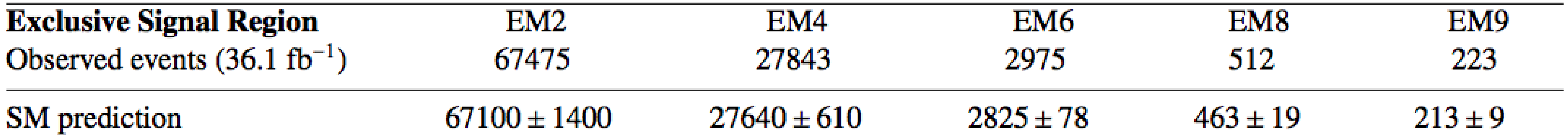


Table 1: Summary of the statistical and systematic contributions to the total uncertainty on the $Z(\nu\nu)$ background.

| $E_T^{miss}$ (GeV) → | >250 | >300 | >350 | >400 | >450 | >500 | >550 |
|---|---|---|---|---|---|---|---|
| (1) $Z(\mu\mu)$+jets statistical unc. | 1.7 | 2.7 | 4.0 | 5.6 | 7.8 | 11 | 16 |
| (2) Background | 1.4 | 1.7 | 2.1 | 2.4 | 2.7 | 3.2 | 3.9 |
| (3) Acceptance | 2.0 | 2.1 | 2.1 | 2.2 | 2.3 | 2.6 | 2.8 |
| (4) Selection efficiency | 2.1 | 2.2 | 2.2 | 2.4 | 2.7 | 3.1 | 3.7 |
| (5) $R_{BF}$ | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| Total uncertainty (%) | 5.1 | 5.6 | 6.6 | 7.9 | 9.9 | 13 | 18 |

CMS, 1408.3583

Current background errors smaller, still above 2%



| **Exclusive Signal Region** | EM2 | EM4 | EM6 | EM8 | EM9 |
|---|---|---|---|---|---|
| Observed events (36.1 $\text{fb}^{-1}$) | 67475 | 27843 | 2975 | 512 | 223 |
| SM prediction | 67100 ± 1400 | 27640 ± 610 | 2825 ± 78 | 463 ± 19 | 213 ± 9 |

ATLAS, 1711.03301

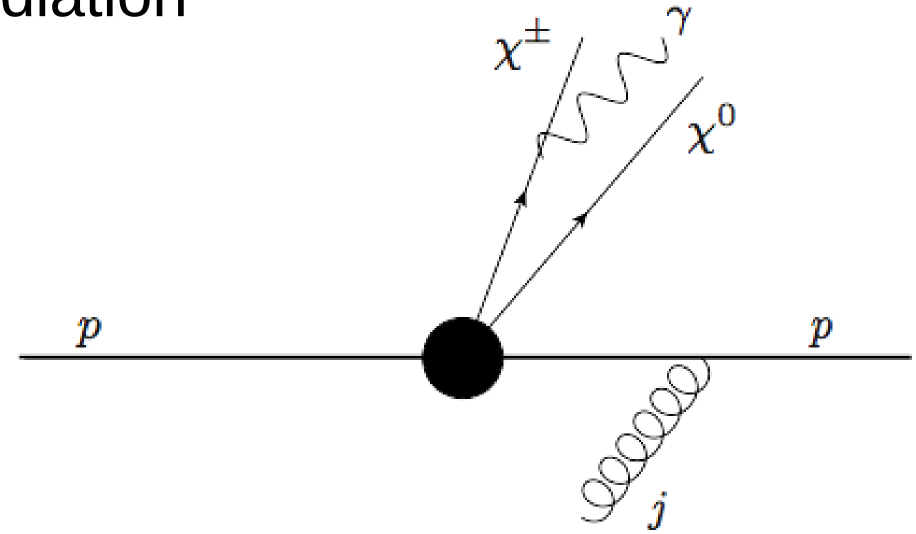
Multiple systematics: jet quality, pile-up, shower modelling, PDFs each near 1%

# Photon final-state radiation

Even if $\chi^+$ decays promptly and invisibly, it can still produce electroweak radiation

Take advantage of photon radiation by boosting

In monojet events with $p_T(j) > m_\chi$, jet recoils against missing energy + any radiation



Al, Izaguirre, Shuve
1605.00658

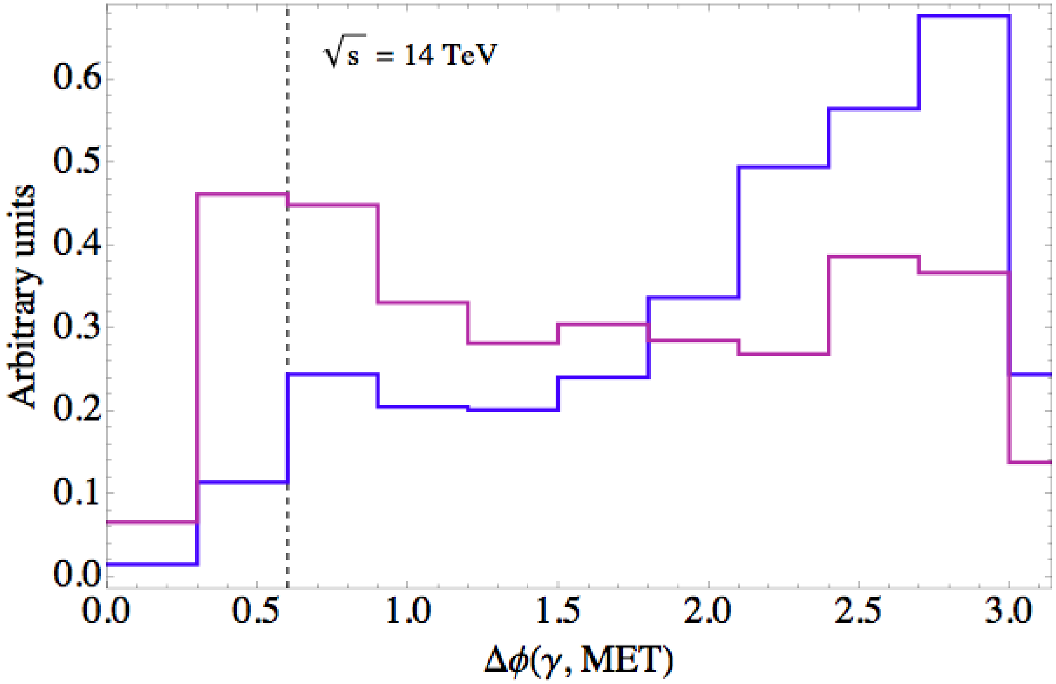
Pay statistical price of $\alpha$ for radiation, but benefit from low backgrounds and extra kinematic handle in $\gamma$ + j + MET

# Photon + jet + MET search

Trigger on hard jet and missing energy, then look for soft photon (15 GeV) with small angular separation from MET

Backgrounds: Z + $\gamma$ + j, W + $\gamma$ + j, tops, QCD fakes

Require photon $m_T > m_W$, $p_T(j_1)$ / MET > 0.5; optimize other cuts

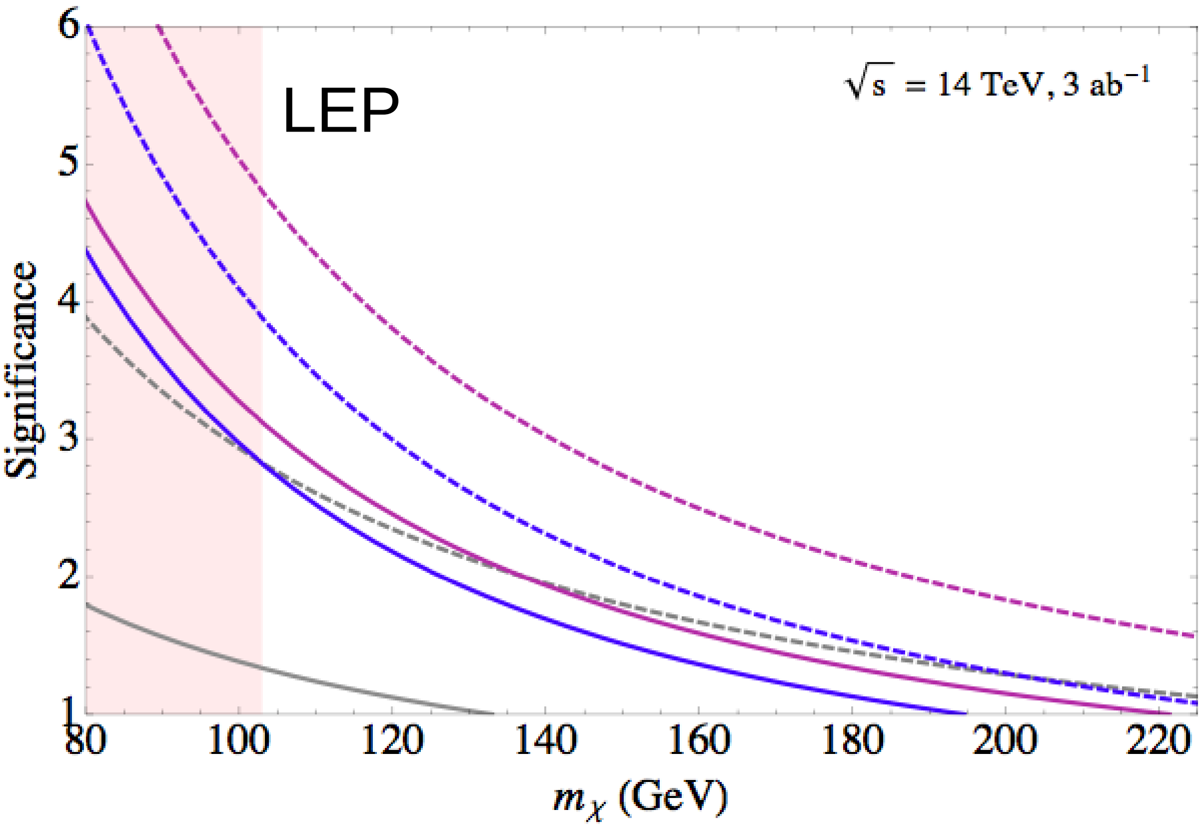


125 GeV Higgsino

Z, W backgrounds

# Better limits on Higgsinos

Adding photon to monojet final state helps, improving search that is independent of model-dependent mass splitting



Photon + jet + MET

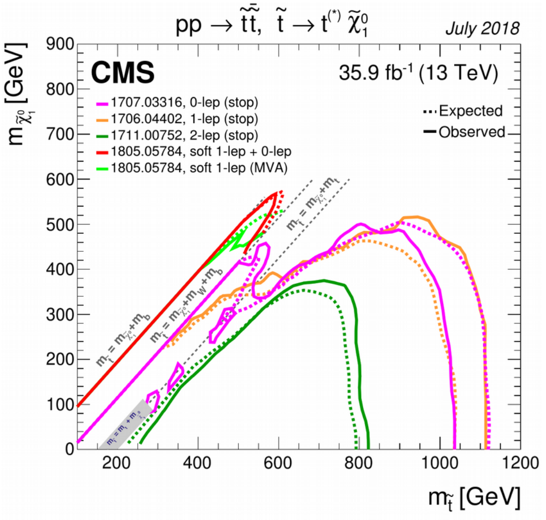
Monojet

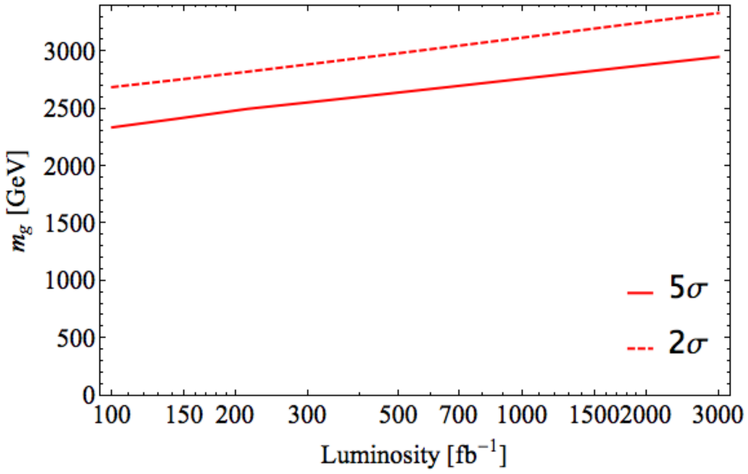
Combination

Solid: 5% systematics
Dashed: 2% systematics

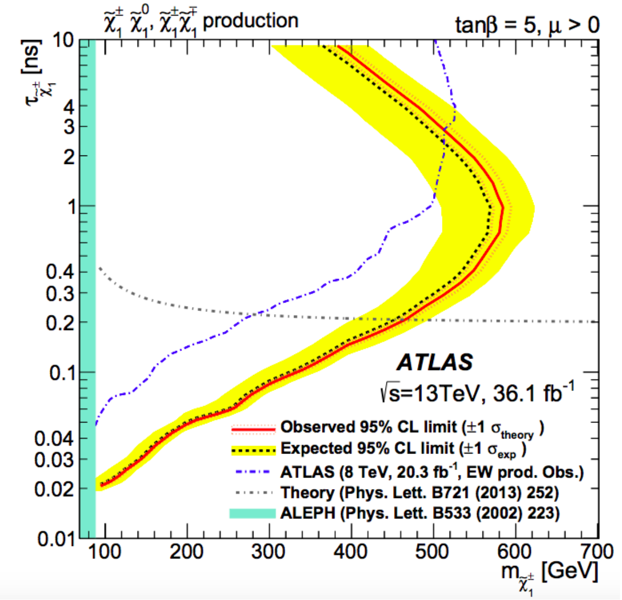
# Summary

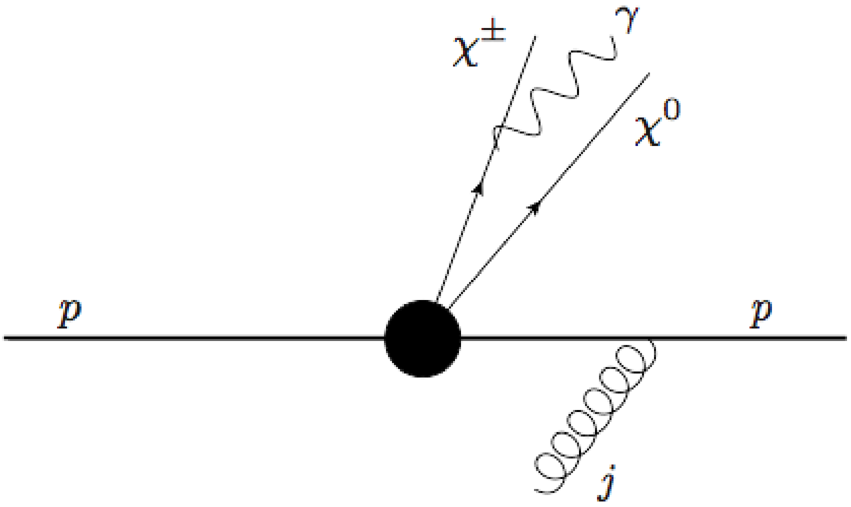
## SUSY: getting harder, but all is not lost





## Interesting strategies left to pursue





# Natural Supersymmetric Twin Higgs

Marcin Badziak

University of Warsaw

Based on:
MB, Keisuke Harigaya
**JHEP 1706 (2017) 065** [1703.02122]
**JHEP 1710 (2017) 109** [1707.09071]
**PRL 120 (2018) 211803** [1711.11040]

NATIONAL SCIENCE CENTRE
POLAND

# Status of Supersymmetry

## in light of LHC data

1. The Higgs mass found to be 125 GeV
2. No BSM particles found

Can SUSY models avoid 1% (or worse) tuning?

Without tuning the spectrum (e.g. pNMSSM islands) or very low mediation scale

| | **125 GeV Higgs** | **LHC limits** |
|---|---|---|
| MSSM | ✗ | ✗ |
| NMSSM | ✓ | ✗ |
| … | ✓ | ✗ |

# Status of Supersymmetry

## in light of LHC data

1. The Higgs mass found to be 125 GeV
2. No BSM particles found

Can SUSY models avoid 1% (or worse) tuning?

Without tuning the spectrum (e.g. pNMSSM islands) or very low mediation scale

| | **125 GeV Higgs** | **LHC limits** |
|---|---|---|
| MSSM | ✗ | ✗ |
| NMSSM | ✓ | ✗ |
| … | ✓ | ✗ |
| ??? | ✓ | ✓ |

Motivation for SUSY model-building

# Status of Supersymmetry

## in light of LHC data

1. The Higgs mass found to be 125 GeV
2. No BSM particles found

Can SUSY models avoid 1% (or worse) tuning?

Without tuning the spectrum (e.g. pNMSSM islands) or very low mediation scale

| | **125 GeV Higgs** | **LHC limits** |
|---|---|---|
| MSSM | ✗ | ✗ |
| NMSSM | ✓ | ✗ |
| … | ✓ | ✗ |
| SUSY Twin Higgs | ✓ | ✓ |

This talk

# 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 → $H \overset{\mathbb{Z}_2}{\longleftrightarrow} H'$ ← 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) spontaneously broken to SU(3) → 7 NGB :
6 eaten + massless Higgs

SU(4) breaking → the Higgs is pNGB maximal mixture of H and H'

$SU(4)\ \&\ \mathbb{Z}_2$ breaking → the Higgs with SM-like couplings

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

# Fine-tuning in Twin Higgs models

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

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

- Large $\lambda$ preferred which suggests non-perturbative UV completions of Twin Higgs model:

Composite Twin Higgs or SUSY with low Landau pole scale

Batra, Chacko ’08 Geller, Telem ’14
Barbieri et al ’15 Low, Tesi, Wang‘15

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

# 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

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

- 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 U(1) D-term Twin Higgs

MB, Harigaya '17

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

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

$$\downarrow$$

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

$$\epsilon^2 = \frac{m_X^2}{2m_S^2 + m_X^2}$$

$$\downarrow$$

$$0 < \epsilon < 1$$

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

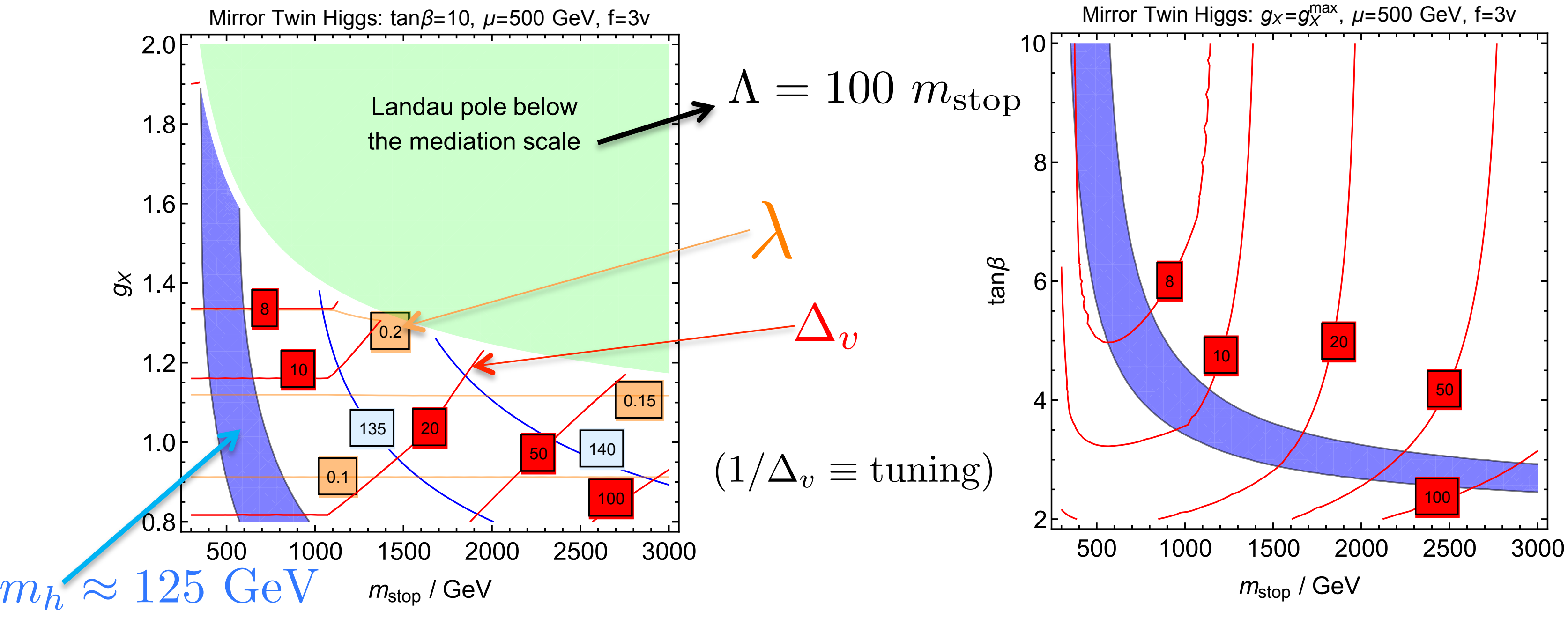
$m_X$- new gauge boson mass

$m_S$- soft mass for $U(1)_X$ breaking fields

- λ grows with tanβ as the Higgs mass does
- Large $g_X$ preferred

# SUSY U(1) D-term Mirror Twin Higgs

- All SM fermions have their mirror counterparts



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

$\lambda$

$\Delta_v$

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

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

- Correct Higgs mass can be obtained for 1 TeV stops (without stop mixing) with better than 10% tuning
- The Landau pole at O(100) TeV – only slightly higher for Fraternal TH or if only 3$^{\text{rd}}$ generation is charged under U(1)$_X$

# SUSY U(1) D-term Twin Higgs: Summary

- The 125 GeV Higgs mass easily obtained for light or heavy stops
- Tuning at the level of 10% for low mediation scales
- Main issue: the Landau pole scale for the new interaction is low
- Can SUSY Twin Higgs model be perturbative up to high scales?

# Non-abelian SUSY Twin Higgs

Slowing down the RG running of the new gauge coupling:

- Non-abelian gauge interaction preferred
- number of fields charged under the new interaction as small as possible

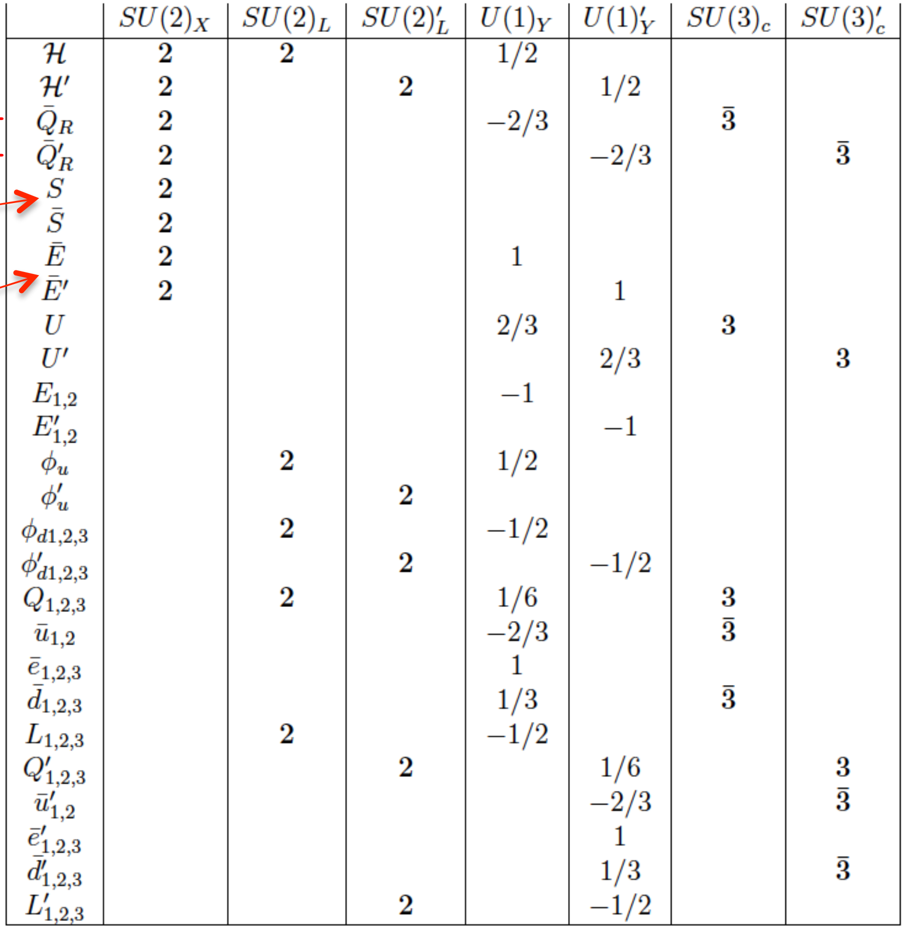
# SUSY SU(2) D-term Twin Higgs

$\mathcal{H} = (H_u, H_2)^T$

right-handed top

$SU(2)_X$ breaking fields

Required by $U(1)_Y$-$SU(2)_X^2$ anomaly cancellation



| | $SU(2)_X$ | $SU(2)_L$ | $SU(2)'_L$ | $U(1)_Y$ | $U(1)'_Y$ | $SU(3)_c$ | $SU(3)'_c$ |
|---|---|---|---|---|---|---|---|
| $\mathcal{H}$ | $\mathbf{2}$ | $\mathbf{2}$ | | $1/2$ | | | |
| $\mathcal{H}'$ | $\mathbf{2}$ | | $\mathbf{2}$ | | $1/2$ | | |
| $\bar{Q}_R$ | $\mathbf{2}$ | | | $-2/3$ | | $\bar{\mathbf{3}}$ | |
| $\bar{Q}'_R$ | $\mathbf{2}$ | | | | $-2/3$ | | $\bar{\mathbf{3}}$ |
| $S$ | $\mathbf{2}$ | | | | | | |
| $\bar{S}$ | $\mathbf{2}$ | | | | | | |
| $\bar{E}$ | $\mathbf{2}$ | | | $1$ | | | |
| $\bar{E}'$ | $\mathbf{2}$ | | | | $1$ | | |
| $U$ | | | | $2/3$ | | $\mathbf{3}$ | |
| $U'$ | | | | | $2/3$ | | $\mathbf{3}$ |
| $E_{1,2}$ | | | | $-1$ | | | |
| $E'_{1,2}$ | | | | | $-1$ | | |
| $\phi_u$ | | $\mathbf{2}$ | | $1/2$ | | | |
| $\phi'_u$ | | | $\mathbf{2}$ | | | | |
| $\phi_{d1,2,3}$ | | $\mathbf{2}$ | | $-1/2$ | | | |
| $\phi'_{d1,2,3}$ | | | $\mathbf{2}$ | | $-1/2$ | | |
| $Q_{1,2,3}$ | | $\mathbf{2}$ | | $1/6$ | | $\mathbf{3}$ | |
| $\bar{u}_{1,2}$ | | | | $-2/3$ | | $\bar{\mathbf{3}}$ | |
| $\bar{e}_{1,2,3}$ | | | | $1$ | | | |
| $\bar{d}_{1,2,3}$ | | | | $1/3$ | | $\bar{\mathbf{3}}$ | |
| $L_{1,2,3}$ | | $\mathbf{2}$ | | $-1/2$ | | | |
| $Q'_{1,2,3}$ | | | $\mathbf{2}$ | | $1/6$ | | $\mathbf{3}$ |
| $\bar{u}'_{1,2}$ | | | | | $-2/3$ | | $\bar{\mathbf{3}}$ |
| $\bar{e}'_{1,2,3}$ | | | | | $1$ | | |
| $\bar{d}'_{1,2,3}$ | | | | | $1/3$ | | $\bar{\mathbf{3}}$ |
| $L'_{1,2,3}$ | | | $\mathbf{2}$ | | $-1/2$ | | |

# Breakdown of the SU(2)$_X$ symmetry

$$W = \kappa Z(S\bar{S} - M^2) \quad V_{\rm soft} = m_S^2(|S|^2 + |\bar{S}|^2)$$

$$\langle S \rangle = \begin{pmatrix} 0 \\ v_S \end{pmatrix}, \ \langle \bar{S} \rangle = \begin{pmatrix} v_S \\ 0 \end{pmatrix}, \quad v_S = \sqrt{M^2 - m_S^2/\kappa^2}$$

- SU(4) invariant term from D-term potential:

$$\frac{g_X^2}{8}\sin^4\beta(1-\epsilon^2)(|H|^2 + |H'|^2)^2 \qquad \epsilon^2 = \frac{m_X^2}{2m_S^2 + m_X^2}$$

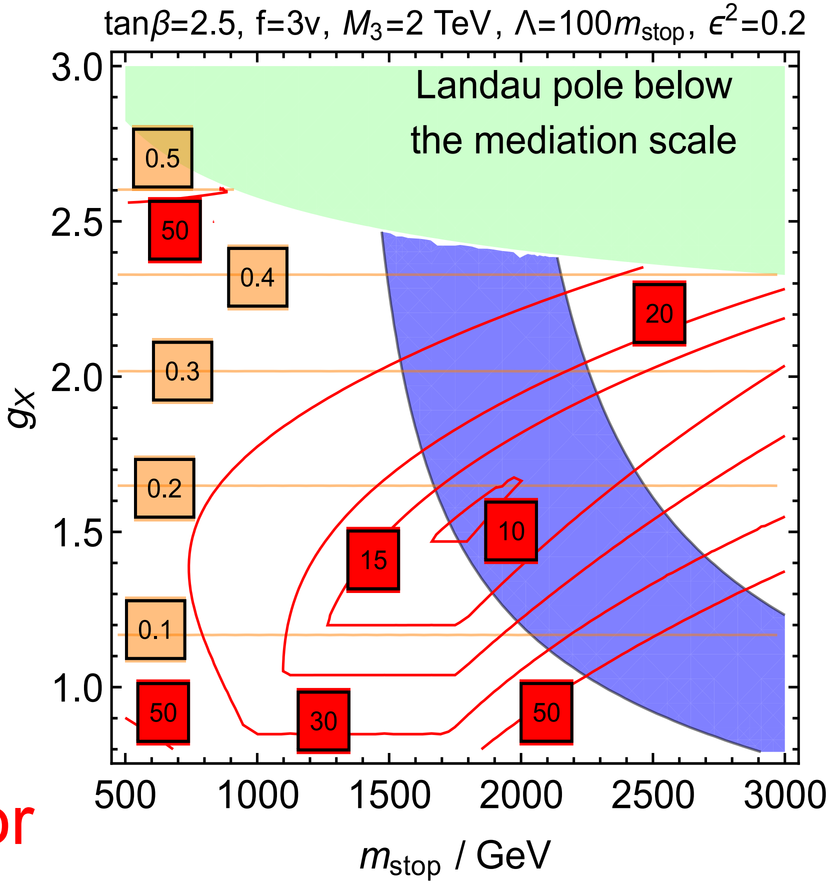
# Low mediation scale of SUSY breaking

- For $\Lambda$=100m$_{\text{stop}}$ much larger g$_{X}$ consistent with perturbativity than in the U(1) model
- For very large g$_{X}$ tuning dominated by the threshold correction:

$$\left(\delta m_{H_u}^2\right)_X = 3\frac{g_X^2}{64\pi^2}m_X^2\ln\left(\epsilon^{-2}\right)$$

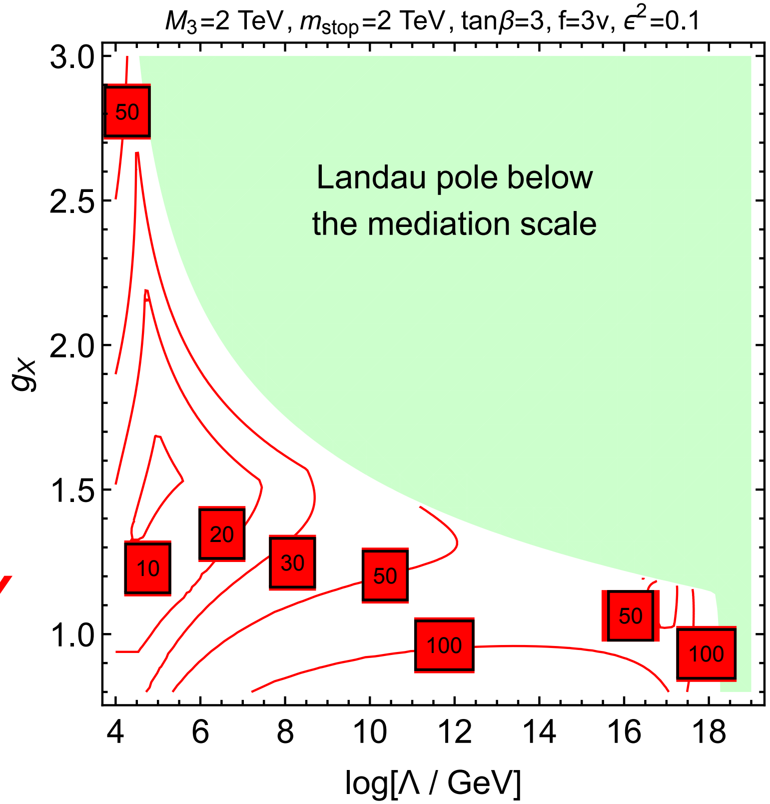
$m_X \gtrsim 4\ \text{TeV} \times g_X$ from LEP

- 10% tuning can be obtained for 2 TeV stops and gluino



# High mediation scale of SUSY breaking

- The Landau pole for the $SU(2)_X$ interaction is much higher than in the U(1) model
- tuning better than 5% can be obtained for mediation scale as high as $10^7$ GeV
- For gravity mediated SUSY breaking 1% tuning



# Asymptotically Free SUSY Twin Higgs

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

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

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

$SU(2)_D$

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

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

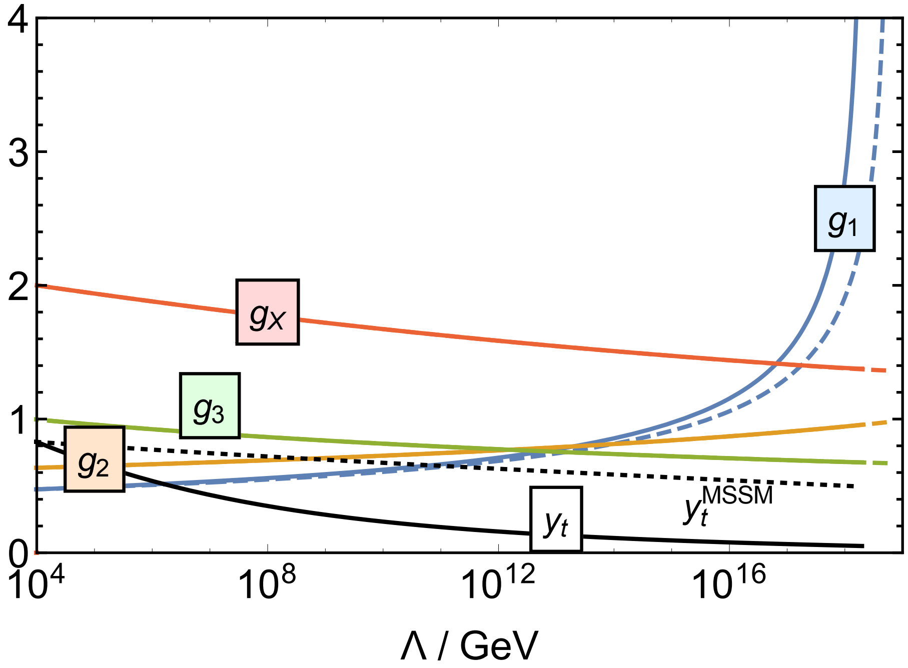
~~$SU(2)_D$~~

|  | $SU(2)_X$ | $SU(2)'_X$ | 3-2-1 | $3'$-$2'$-$1'$ |
|---|---|---|---|---|
| $\mathcal{H}$ | $\mathbf{2}$ |  | $(\mathbf{1},\mathbf{2},1/2)$ |  |
| $\mathcal{H}'$ |  | $\mathbf{2}$ |  | $(\mathbf{1},\mathbf{2},1/2)$ |
| $\Sigma$ | $\mathbf{2}$ | $\mathbf{2}$ |  |  |
| $S$ | $\mathbf{2}$ |  |  |  |
| $\bar{S}$ | $\mathbf{2}$ |  |  |  |
| $S'$ |  | $\mathbf{2}$ |  |  |
| $\bar{S}'$ |  | $\mathbf{2}$ |  |  |
| $\bar{Q}_R$ | $\mathbf{2}$ |  | $(\bar{\mathbf{3}},\mathbf{1},-2/3)$ |  |
| $\bar{Q}'_R$ |  | $\mathbf{2}$ |  | $(\mathbf{3},\mathbf{1},-2/3)$ |
| $\bar{E}$ | $\mathbf{2}$ |  | $(\mathbf{1},\mathbf{1},1)$ |  |
| $\bar{E}'$ |  | $\mathbf{2}$ |  | $(\mathbf{1},\mathbf{1},1)$ |
| $E_{1,2}$ |  |  | $(\mathbf{1},\mathbf{1},-1)$ |  |
| $E'_{1,2}$ |  |  |  | $(\mathbf{1},\mathbf{1},-1)$ |
| $\phi_u$ |  |  | $(\mathbf{1},\mathbf{2},1/2)$ |  |
| $\phi'_u$ |  |  |  | $(\mathbf{1},\mathbf{2},1/2)$ |
| $H_d, \phi_{d,1,2}$ |  |  | $(\mathbf{1},\mathbf{2},-1/2)$ |  |
| $H'_d, \phi'_{d,1,2}$ |  |  |  | $(\mathbf{1},\mathbf{2},-1/2)$ |

right-handed top & up

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

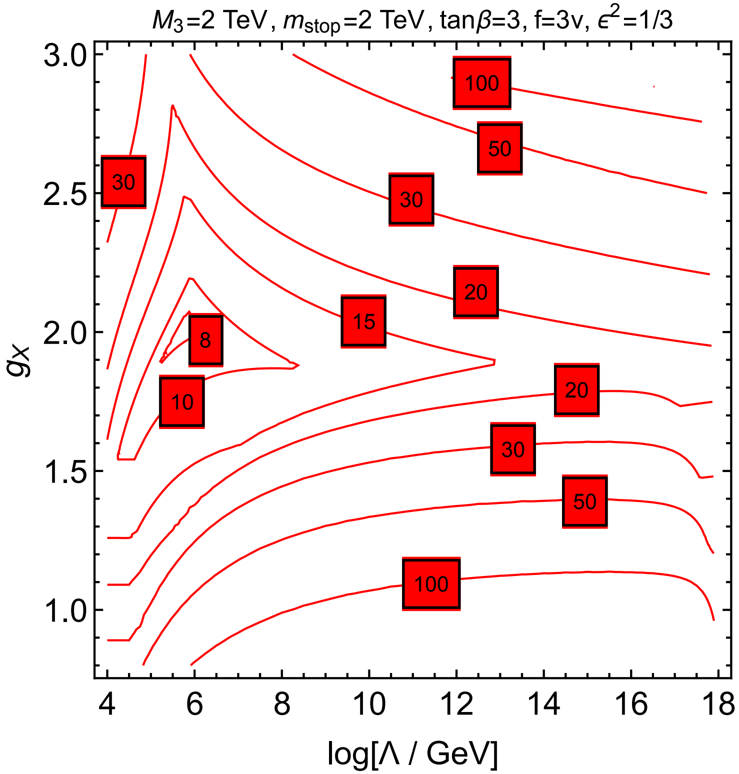
# Asymptotically Free SUSY Twin Higgs: RG running of couplings



- $g_X$ asymptotically free!
- New interaction drives the top Yukawa coupling to small values at high scales – suppressed tuning from stops and gluino (this works also in non-twin SUSY see 1806.07900)

# Asymptotically Free SUSY Twin Higgs

- Twin Higgs mechanism works perturbatively even for mediation around the Planck scale
- Tuning better than 5% (for 2 TeV stops and gluino) even for gravity mediation of SUSY breaking

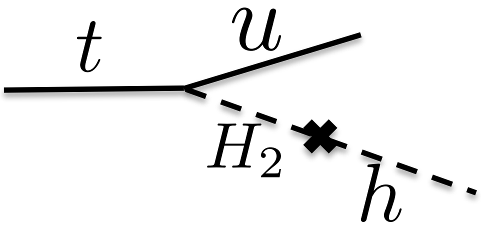


# Asymptotically Free SUSY Twin Higgs: flavor-violating top decays

The model has non-trivial flavor structure

The top Yukawa coupling is generated via $W \sim \mathcal{H}\bar{Q}_R Q_3$

The interaction includes $\mathcal{L} = y_t H_2 \bar{u}_R Q_3$ which generates top decay to the Higgs and the up quark



$$\mathrm{BR}(t \to hu) \sim \left(\frac{\theta_{hH_2}}{0.1}\right)^2 10^{-3}$$

Sizable $\mathrm{BR}(t \to hu)$ even for not large $H_2 - h$ mixing

Current LHC limit on $\mathrm{BR}(t \to hu) \sim 10^{-3}$ may be improved to $10^{-4}$ at HL-LHC

# Final remarks

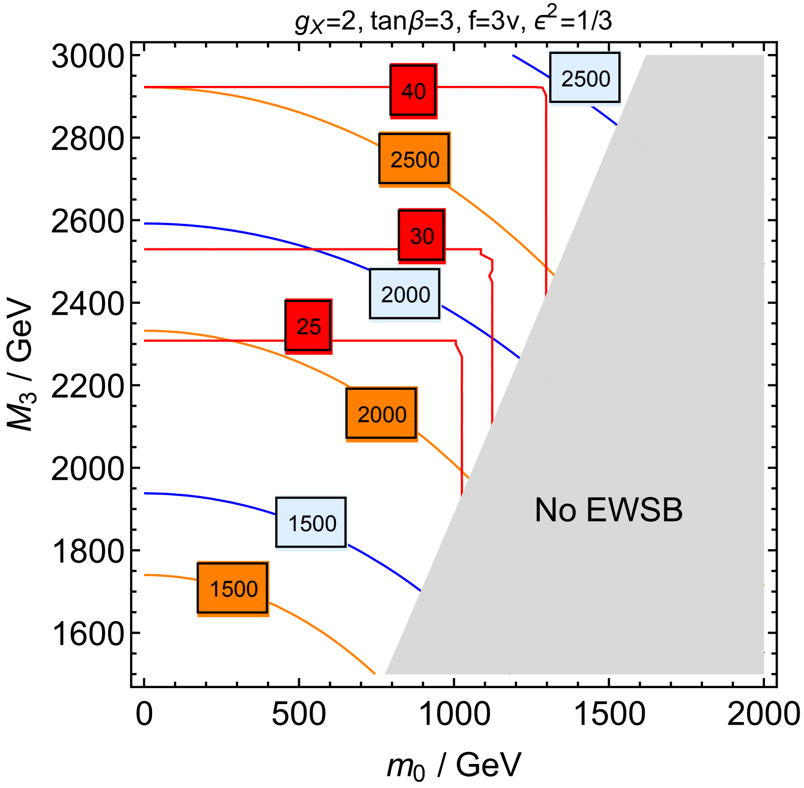
- LHC results should make us think harder on new SUSY model-building
- Twin Higgs and extra gauge interactions make SUSY natural (without sacrifying perturbativity below the Planck scale)
- New models mean new opportunities for pheno/cosmo
- Novel phenomenology from SUSY Twin Higgs (mostly unexplored):
    - Flavor-violating top decays
    - dark matter candidates
    - new phase transitions (1st order?, GW?)
    - Extra gauge bosons (beyond the LHC reach?)
    - …

# BACKUP

# Asymptotically Free SUSY Twin Higgs:

## spectrum for simple UV boundary conditions

- Universal scalar masses
- $M_3$ fixed at the EW scale



# SUSY U(1) D-term Twin Higgs: perturbativity constraints

- $U(1)_X$ charges are a combination of $U(1)_Y$ and $U(1)_{B\text{-}L}$ 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 $g_X$

# Symmetry breaking in U(1) model

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

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

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

- After integrating out $P \text{ and } \bar{P}$: $\epsilon^2$

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

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

# 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:

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

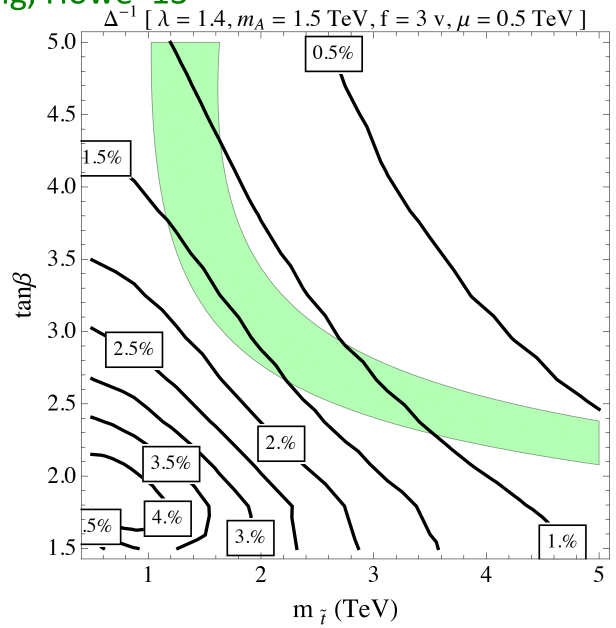
$$V_{SU(4)} = m_{H_u}^2(|H_u|^2 + |H_u'|^2) + m_{H_d}^2(|H_d|^2 + |H_d'|^2) - b(H_u H_d + H_u' H_d' + \text{h.c.}) + m_S^2|S|^2$$

- After integrating out the singlet:

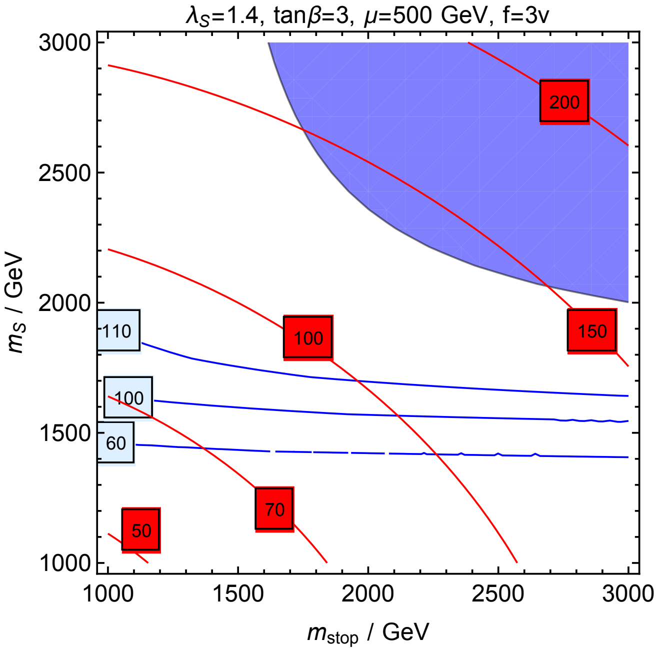
$$\lambda = \lambda_S^2 \frac{\sin^2(2\beta)}{4} \equiv \lambda_F\,.$$

# 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

(assuming very low mediation scale of SUSY breaking $\Lambda=100m_{\rm stop}$)

# 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. $\lambda \approx \lambda_{\rm SM}$
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 )