SUSY PHENOMENOLOGY AND NATURALNESS

JiJi Fan
Syracuse University

Fermilab, 8/21/14

- Naturalness in SUSY
- Indirect Probes: Higgs couplings, EWPT, ...
- Direct Production at Colliders
- Cosmic Probes

NATURALNESS IN SUSY

There will be intensive discussions of definition of naturalness in this workshop. I will only mention the one that I agree with and focus on the phenomenology.

Let's start with MSSM: at tree-level

$$V = |F|^2 + |D|^2,$$

$$V \supset \frac{1}{8}(g^2 + g'^2)(h_u^{02} - h_d^{02})^2$$

To get a 125 GeV Higgs, one needs a large quantum correction or to go beyond MSSM.

For moderately large tan β, tan β > 2,

$$m_h^2 = -2\left(|\mu|^2 + m_{H_u}^2|_{\mathrm{tree}} + m_{H_u}^2|_{\mathrm{rad}}\right)$$

Natural EWSB means that no large cancellations among terms on the right-hand side to get the correct physical Higgs mass.

This leads to naturalness requirements:

At tree-level: light Higgsinos: $|\mu| \sim m_h$

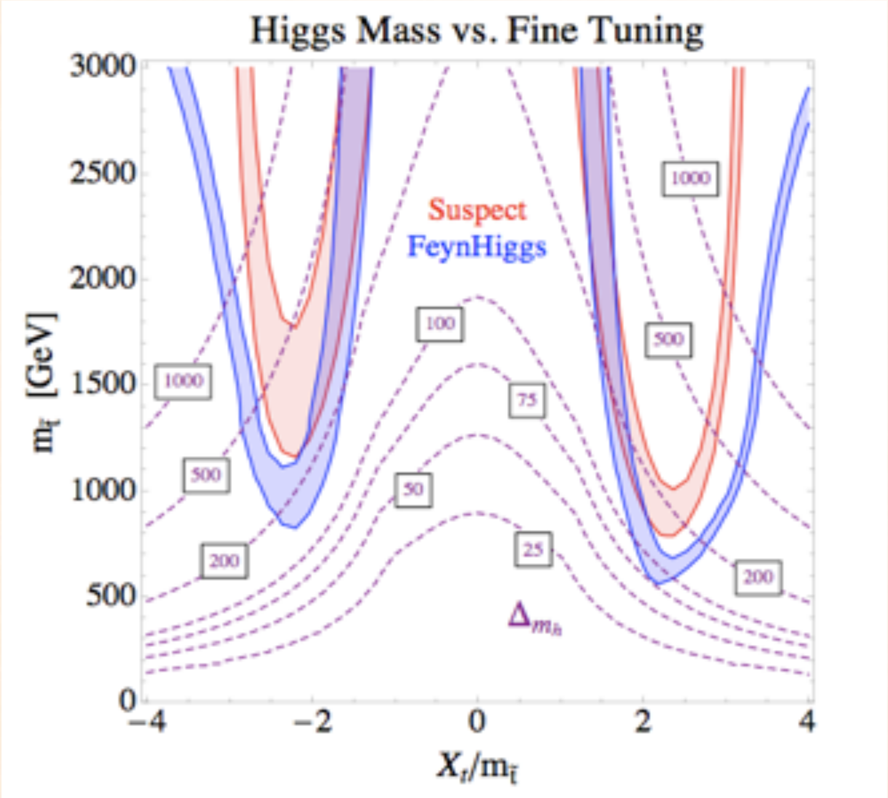
At one-loop level: light stops (with mass ≲ 700 GeV to avoid more than 10 % fine-tuning Papucci, Ruderman and Weiler 2011)

SUSY breaking mediation scale

$$(\Delta^{-1})_{\tilde{t}} = \left|\frac{2\delta m_{H_u}^2}{m_h^2}\right|, \quad \delta m_{H_u}^2|_{\mathrm{stop}} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + A_t^2\right) \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

Kitano, Nomura 2006

$$(\Delta^{-1})_{\tilde{t}} = \left| \frac{2\delta m_{H_u}^2}{m_h^2} \right|, \quad \delta m_{H_u}^2|_{\rm stop} = -\frac{3}{8\pi^2} y_t^2 \left(m_{Q_3}^2 + m_{u_3}^2 + A_t^2\right) \log\left(\frac{\Lambda}{\rm TeV}\right)$$



Hall, Pinner, Ruderman 2011

In MSSM, to get the Higgs mass to be 125 GeV, a large quantum correction must be introduced with multi-TeV SUSY breaking parameters;
the fine-tuning is worse than a few percent.

$$|X_t| \gtrsim 1000 \text{ GeV}, \quad M_S \gtrsim 500 \text{ GeV}.$$

$$M_S \equiv (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}$$

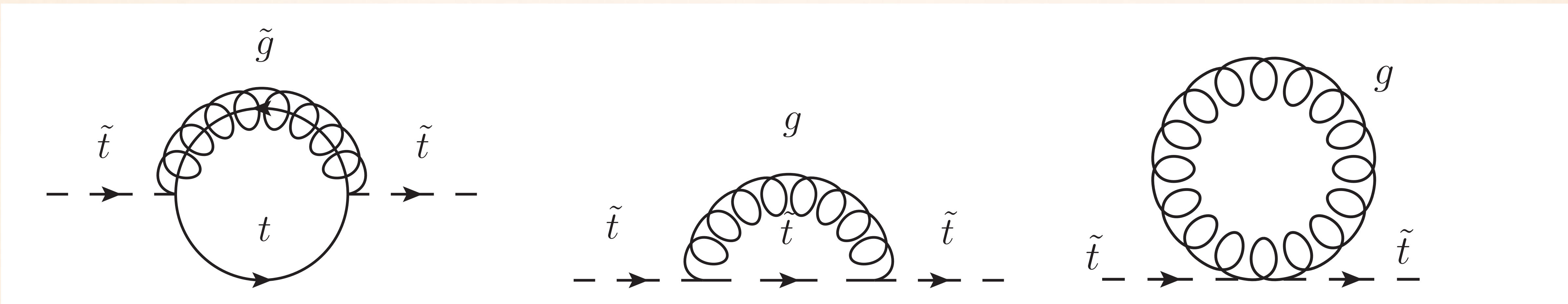
$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

$$\gtrsim (85\text{GeV})^2$$

Caveats: Scherk-Schwarz SUSY breaking models:

Dimopoulos, Howe, March-Russell; Craig, Lou 2014

Stops are scalars themselves and they can receive quadratic corrections from gluinos



To avoid large cancelations, gluinos have to be not too heavy, i.e, below 2 TeV to avoid 10% tuning or worse.

Alternative Routes for SUSY

Keep naturalness: go beyond MSSM: NMSSM, λSUSY...
Alleviate collider constraints: RPV, compressed SUSY, folded SUSY, Stealth SUSY ...

125 GeV Higgs boson

Give up strict naturalness: for example, mini-split SUSY
SUSY still stabilizes most of the hierarchy, preserves gauge coupling unification, provides DM candidate. Ameliorates flavor and CP problem

HIGGS COUPLINGS ON NATURALNESS

Stop effect:

$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & m_t X_t \\ m_t X_t^* & m_{U_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix},$$

Low energy Higgs theorem $$r_G^{\tilde{t}} = \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{\text{SM}}} \approx \frac{1}{4} \frac{\partial \log \text{Det}\, m_{\tilde{t}}^2}{\partial \log v}$$

$$r_G^{\tilde{t}} \equiv \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{\text{SM}}} \approx \frac{1}{4}\left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}\right), \quad \text{stop contribution},$$

These are all well-known results; I just want to present a little cute way to visualize the constraints of the data and extract the bottom line: what do measured Higgs couplings tell us about allowed stop masses?

three free parameters

$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & m_t X_t \\ m_t X_t^* & m_{U_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix},$$

diagonal mass splitting off-diagonal splitting

$$\left| m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2 \right| = \sqrt{(m_{Q_3}^2 + \Delta_{\tilde{u}_L} - m_{U_3}^2 - \Delta_{\tilde{u}_R})^2 + 4 m_t^2 X_t^2},$$

For fixed physical stop masses,

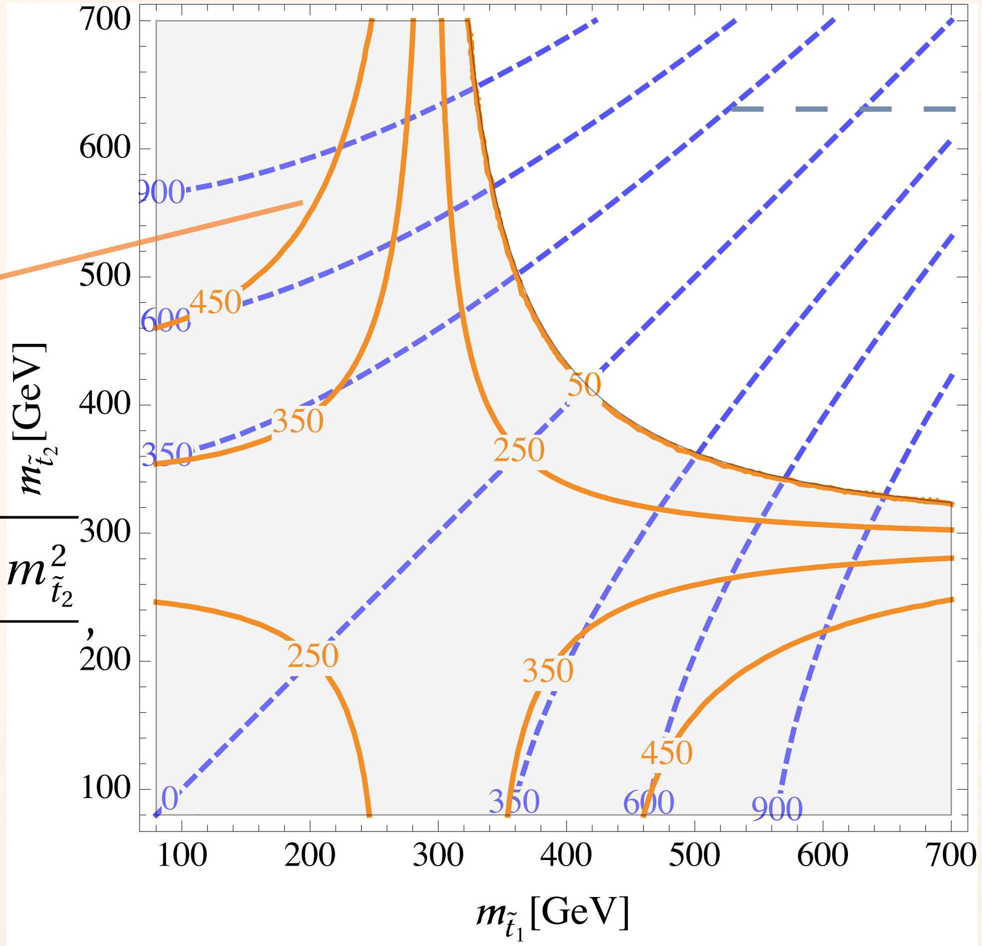
$$\left| X_t^{\max} \right| = \frac{\left| m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2 \right|}{2 m_t},$$

$$r_G^{\tilde{t}} \equiv \frac{c_{hgg}^{\tilde{t}}}{c_{hgg}^{\rm SM}} \approx \frac{1}{4} \left(\frac{m_t^2}{m_{\tilde{t}_1}^2} + \frac{m_t^2}{m_{\tilde{t}_2}^2} - \frac{m_t^2 X_t^2}{m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2} \right), \quad \text{stop contribution,}$$

$$\left| X_t^{\min} \right| = \frac{\sqrt{m_t^2 (m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) - 4 \left(r_G^{\tilde{t}} \right)^{\rm fit;max} m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}}{m_t},$$

$|X_{t;\mathrm{min}}|$

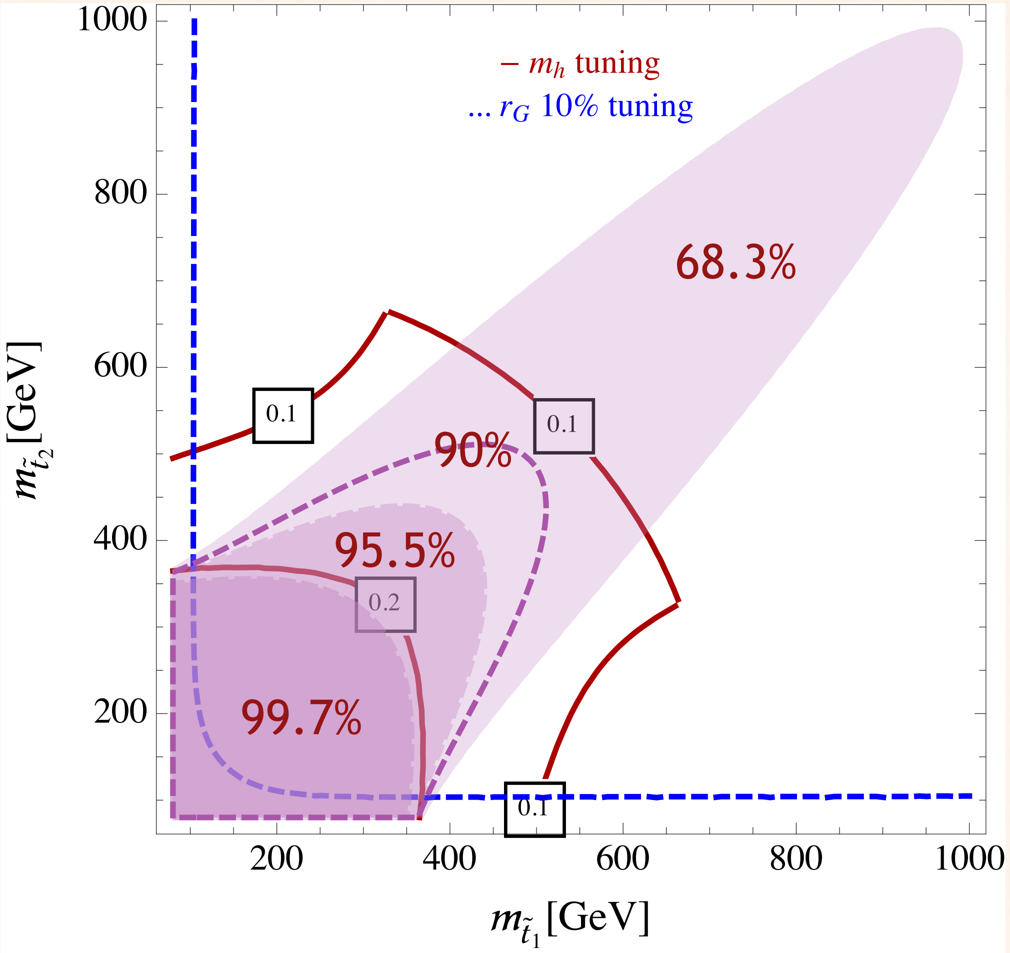
$$\left|X_t^{\mathrm{min}}\right| = \frac{\sqrt{m_t^2(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2) - 4\left(r_G^{\tilde{t}}\right)^{\mathrm{fit;max}} m_{\tilde{t}_1}^2 m_{\tilde{t}_2}^2}}{m_t},$$



$|X_{t;\mathrm{max}}|$

$$\left|X_t^{\mathrm{max}}\right| = \frac{\left|m_{\tilde{t}_1}^2 - m_{\tilde{t}_2}^2\right|}{2m_t},$$

Assume only stops modify Higgs coupling (assuming Yukawa couplings are not modified)



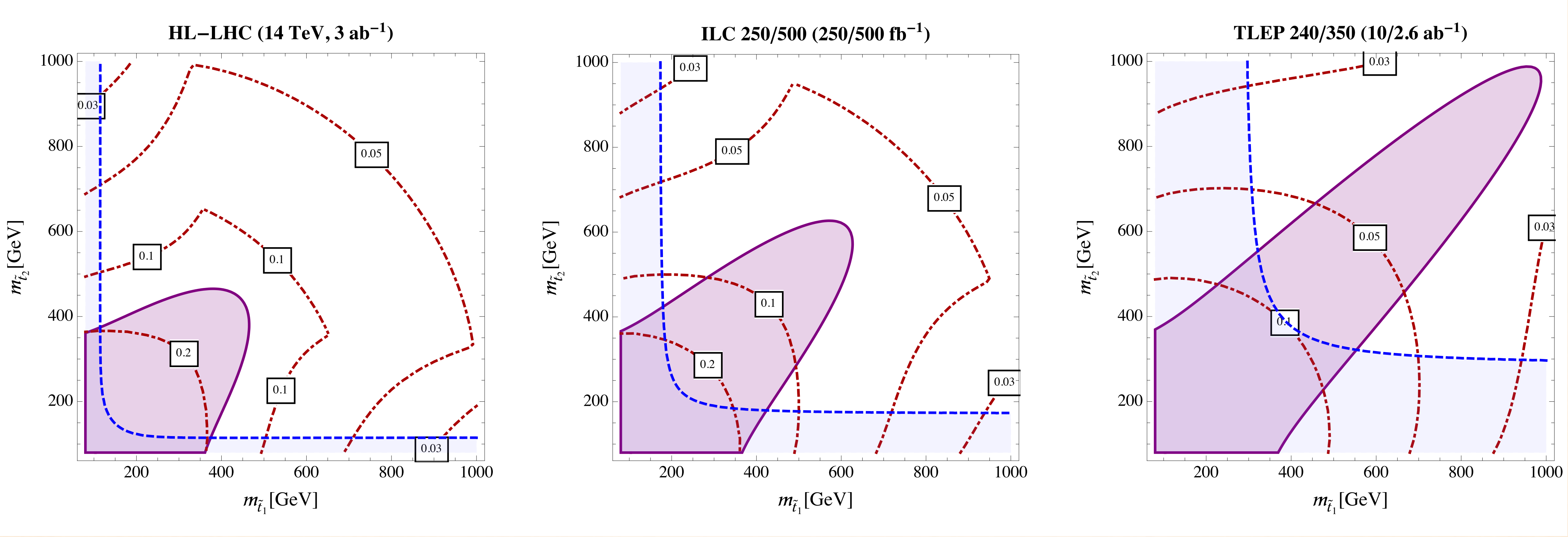
Fan, Reece, 2014

Higgs coupling measurements rules out that **both stops with mass below 400 GeV** in the case when stops are the only contribution to the Higgs coupling modification.

These constraints apply no matter how stops decay and suggest **a minimum electroweak fine-tuning of between a factor of 5 and 10**.

Independent of how stops decay and is complementary to direct searches !

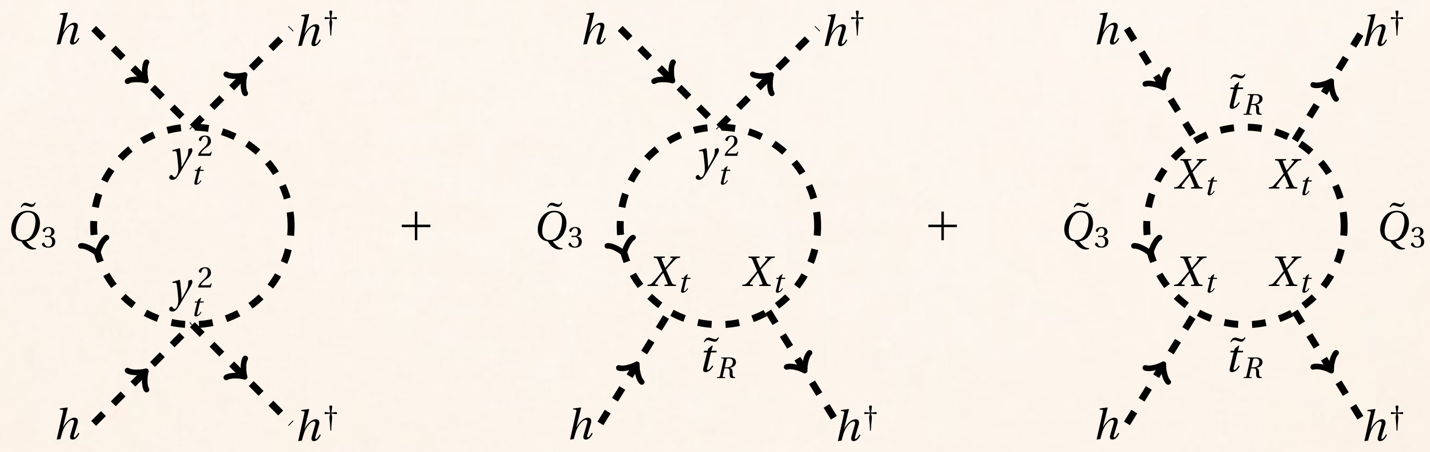
Sensitivities of future experiments

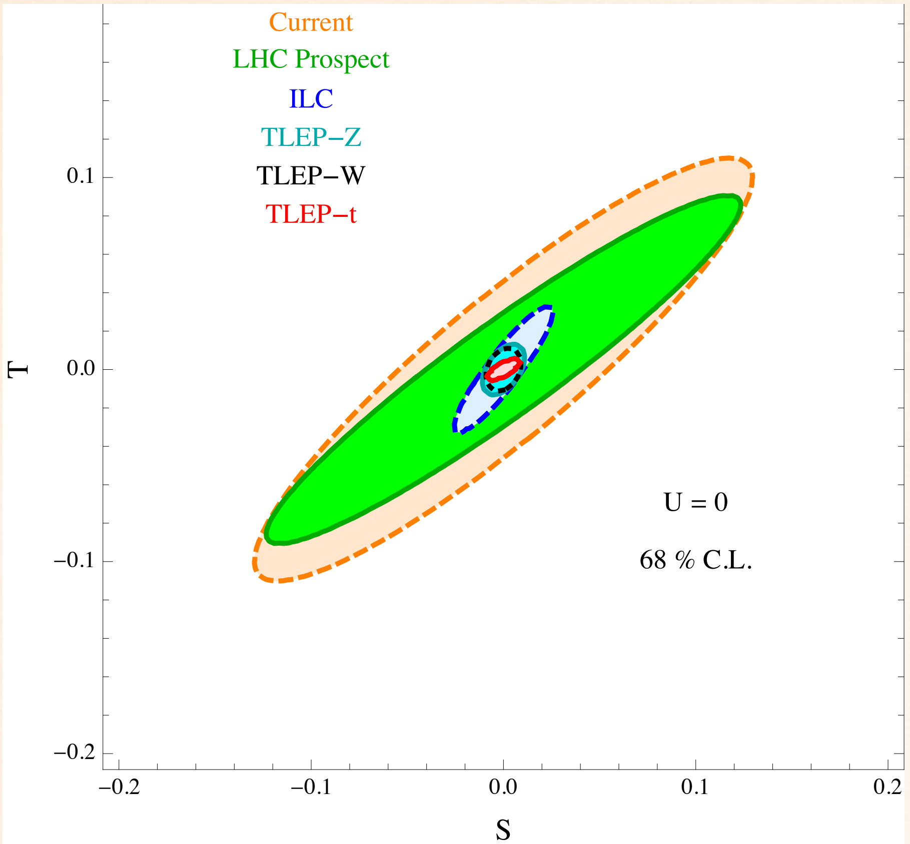


EWPT

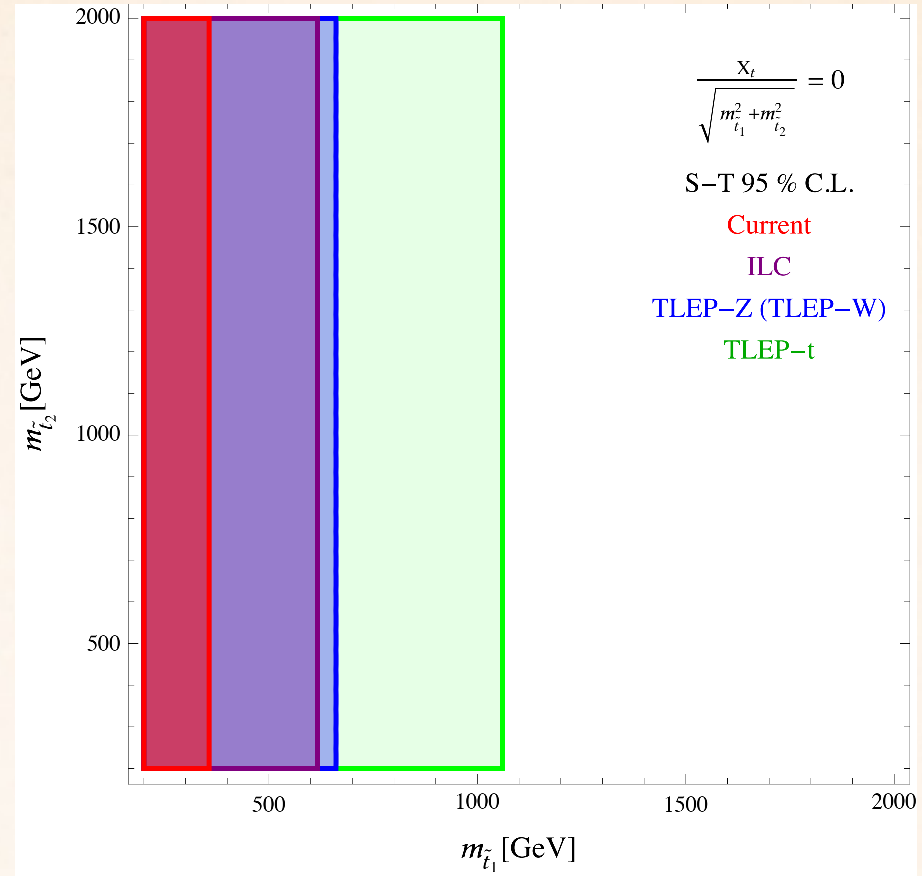
$$|h^\dagger D_\mu h|^2$$

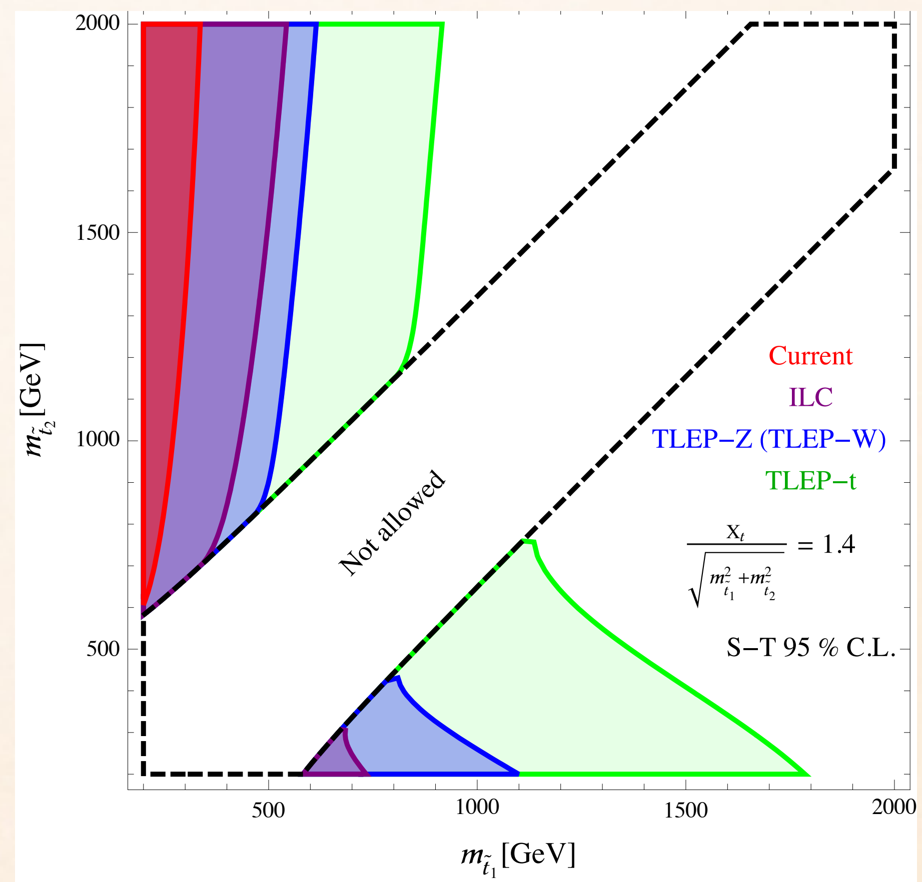
$$T \approx \frac{m_t^4}{16\pi \sin^2\theta_W m_W^2 m_{\tilde{Q}_3}^2} + \mathcal{O}\left(\frac{m_t^2 X_t^2}{4\pi m_{\tilde{Q}_3}^2 m_{\tilde{u}_3}^2}\right).$$





Fan, Reece and Wang, to appear

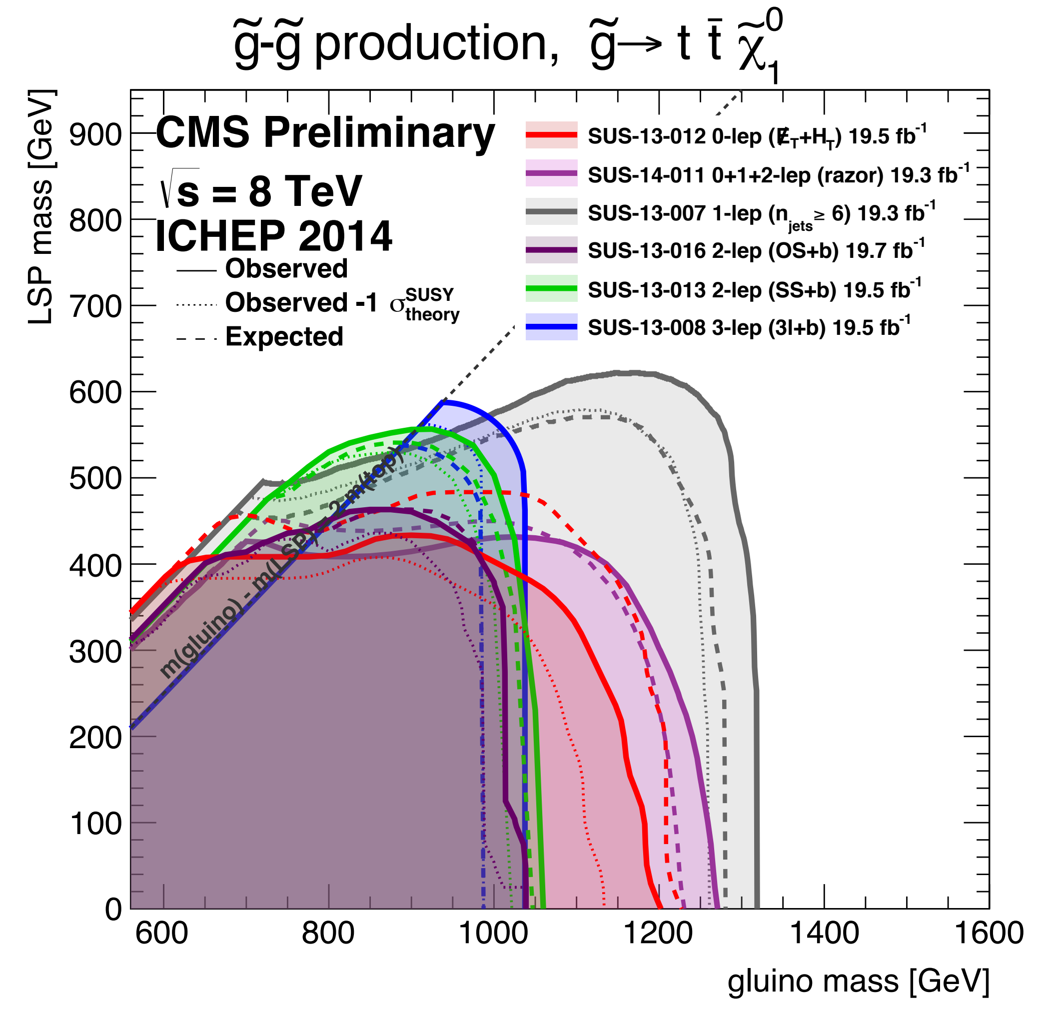


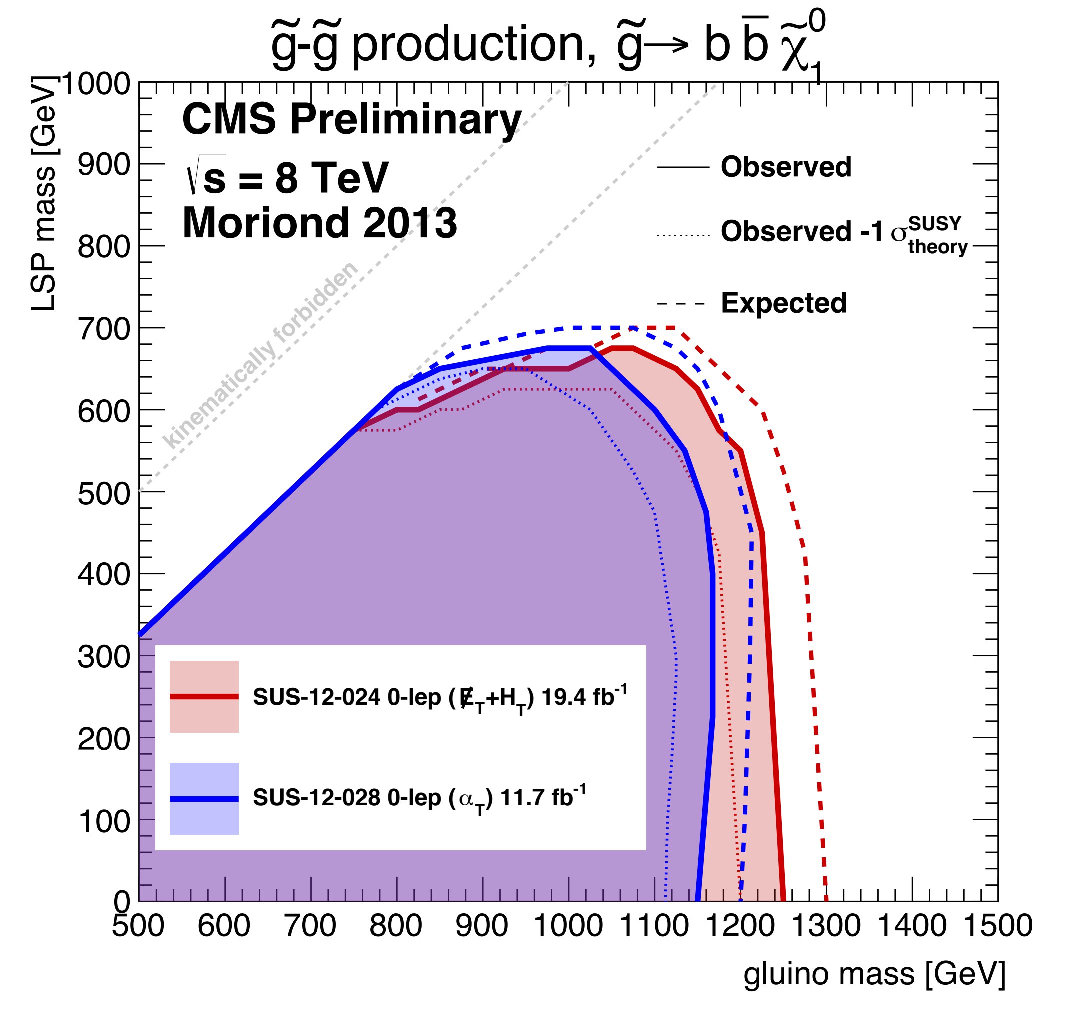


Also holds for non-colored top partners as in folded SUSY

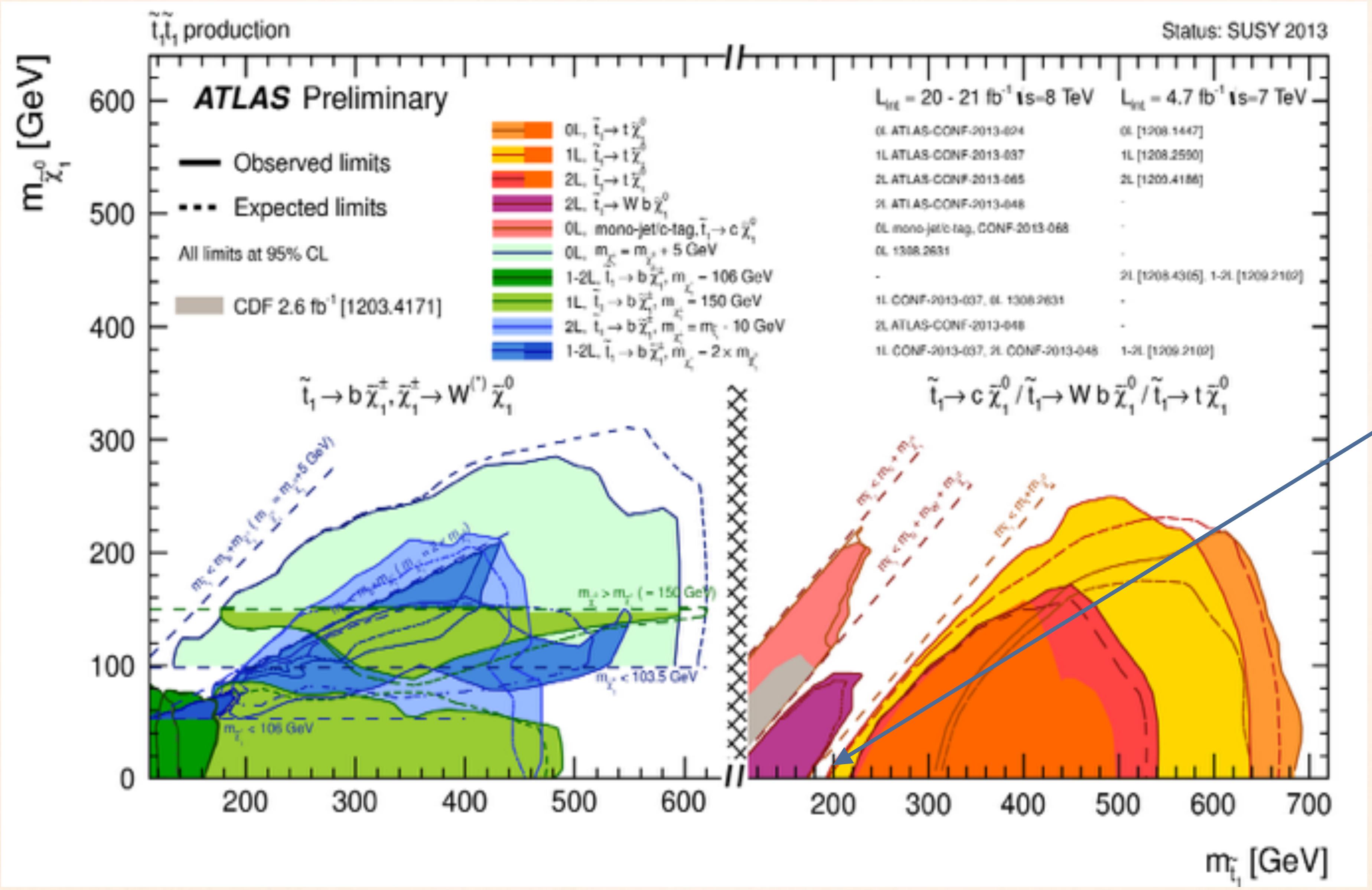
COLLIDER PROBES

Gluinos: current bounds above TeV



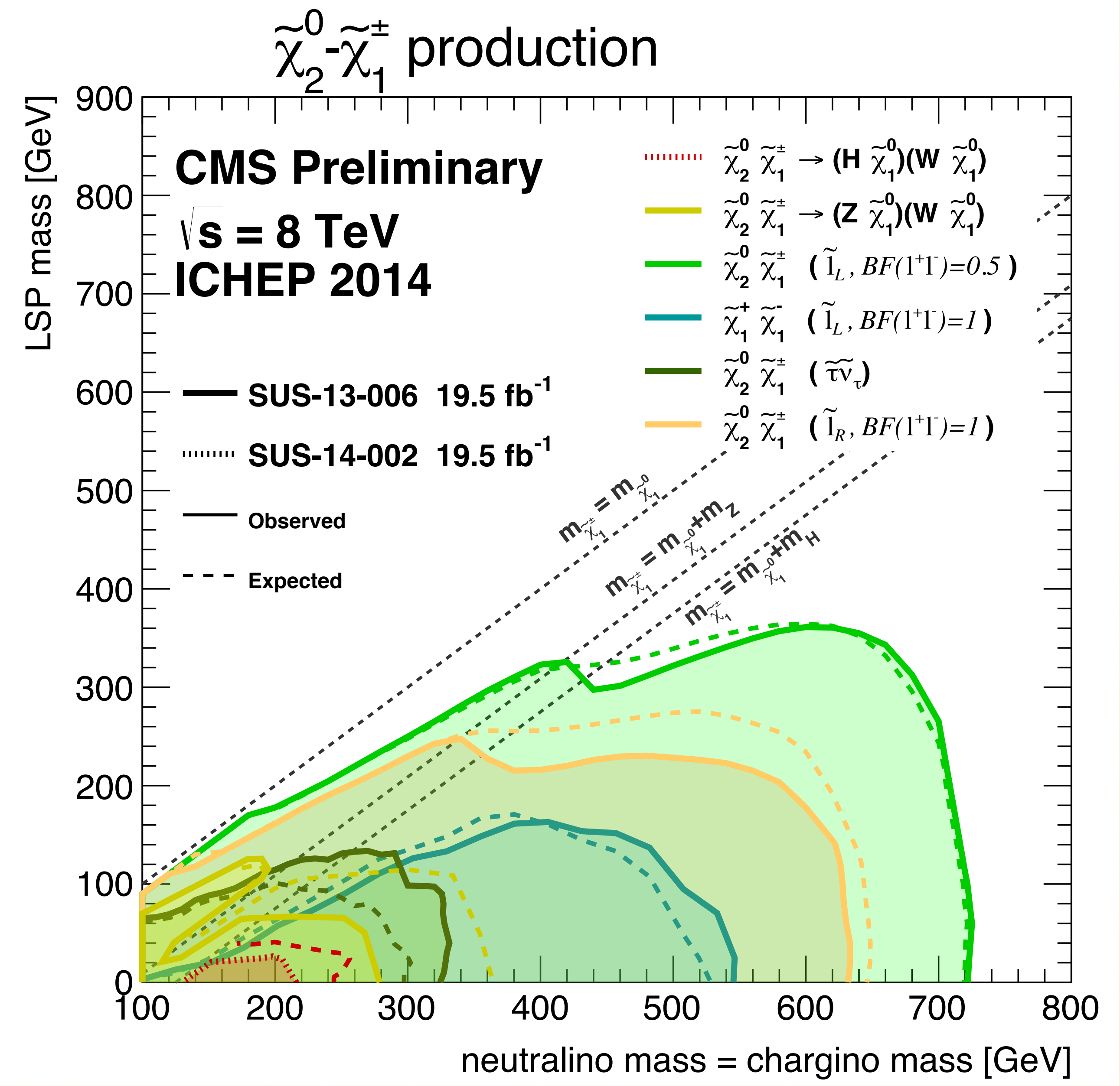


Stops: current bounds close to 700 GeV but with loopholes



Tricky Regions:
Stealth stops

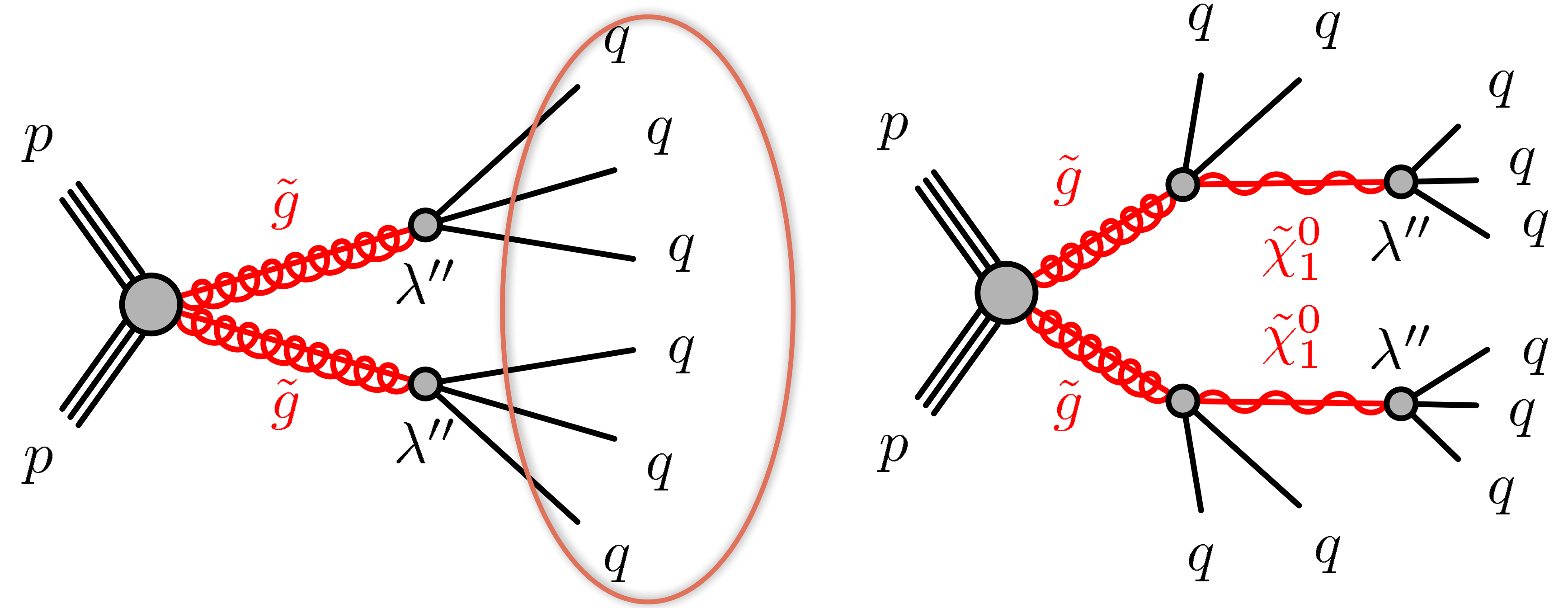
Higgsinos: EW production; relatively less constrained; constraints obtained mostly in scenarios with inflating brs to leptons.



One goal of LHC14: close in the loopholes and search for hidden naturalness

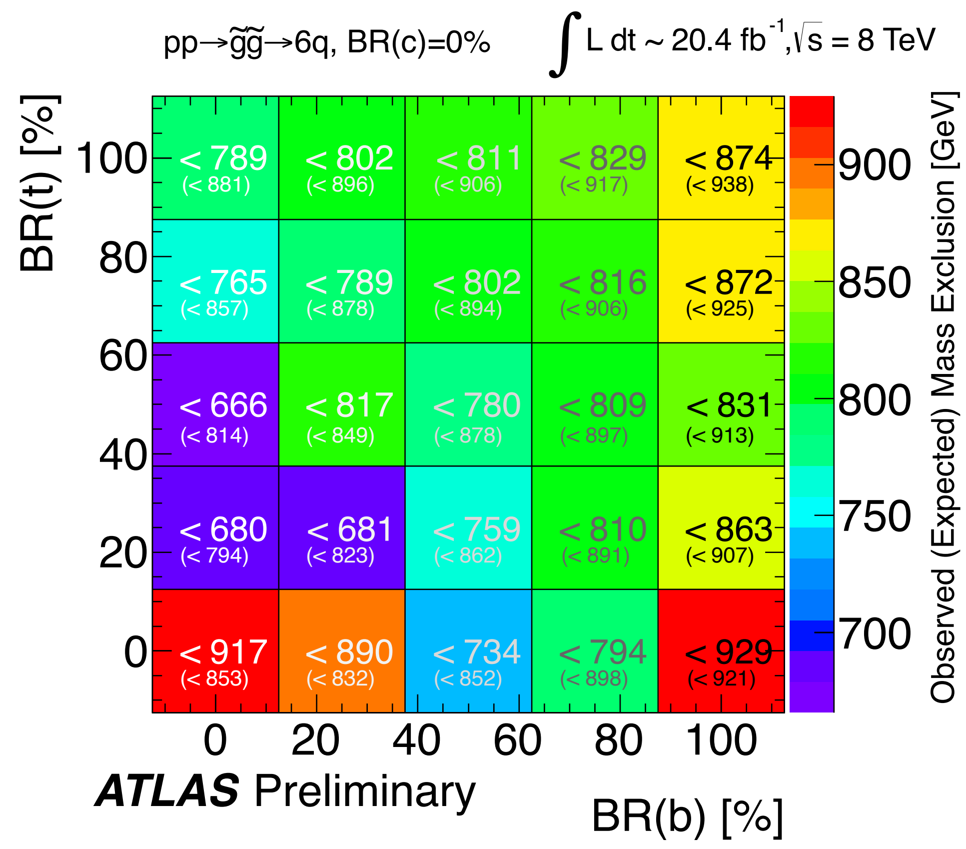
Example 1: RPV Look like QCD bg; but QCD doesn't share energy among jets evenly

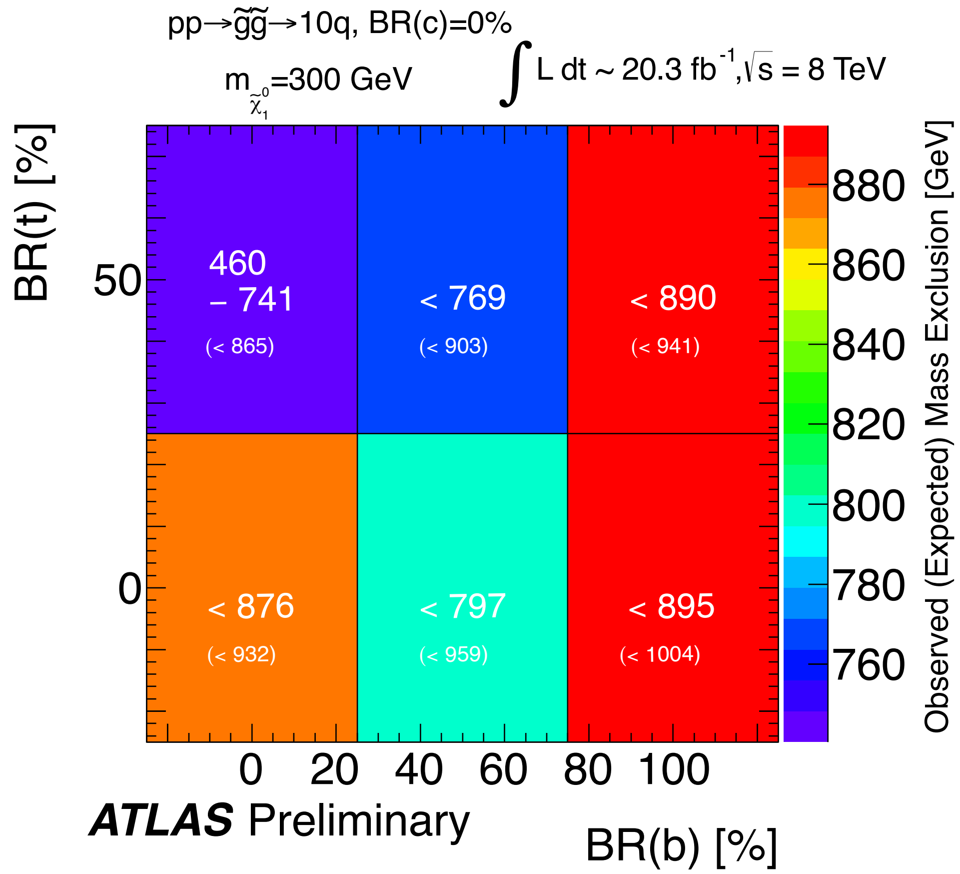
Gluinos



(a) 6-quark model (b) 10-quark model

ATLAS-CONF-2013-091





The bound is roughly about or above 800 GeV

Other simplified models and search strategies:

Same-sign dileptons

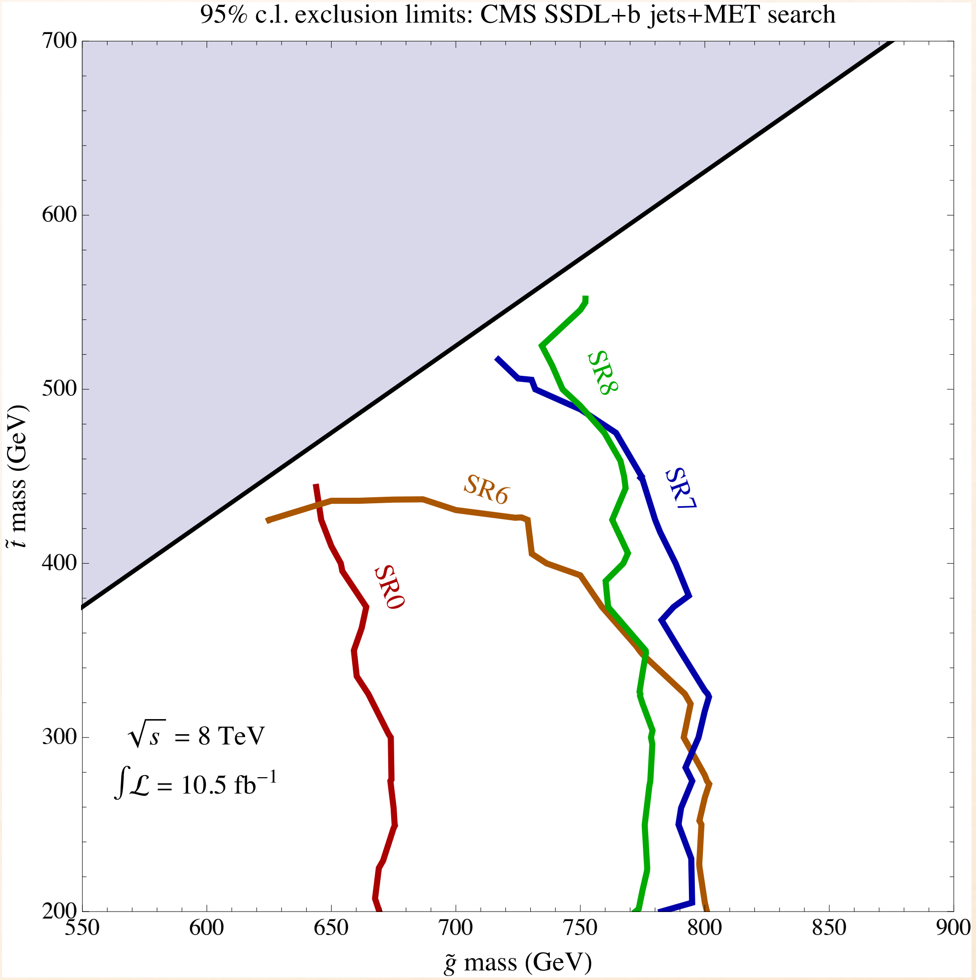
$$\tilde{g} \to \tilde{t}\bar{t}, \quad \tilde{t} \to \bar{b}\bar{s}$$

or

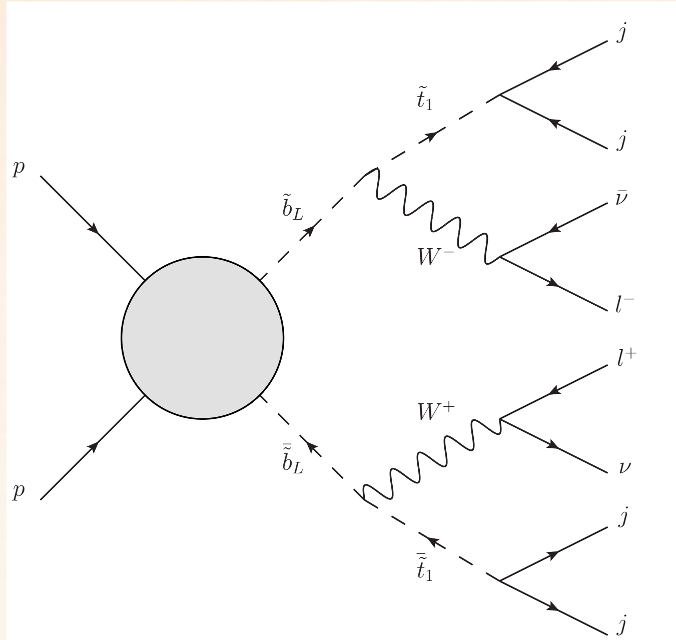
$$\tilde{g} \to \tilde{t}^{*}t, \quad \tilde{t}^{*} \to bs$$

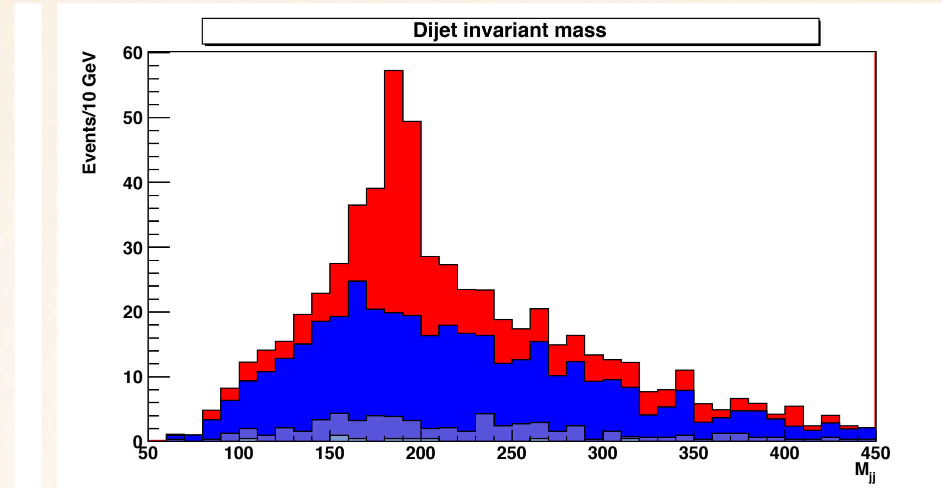
Bounds again up to 800 GeV

(Berger, Perelstein, Saelim and Tanedo 2013)



RPV stops:

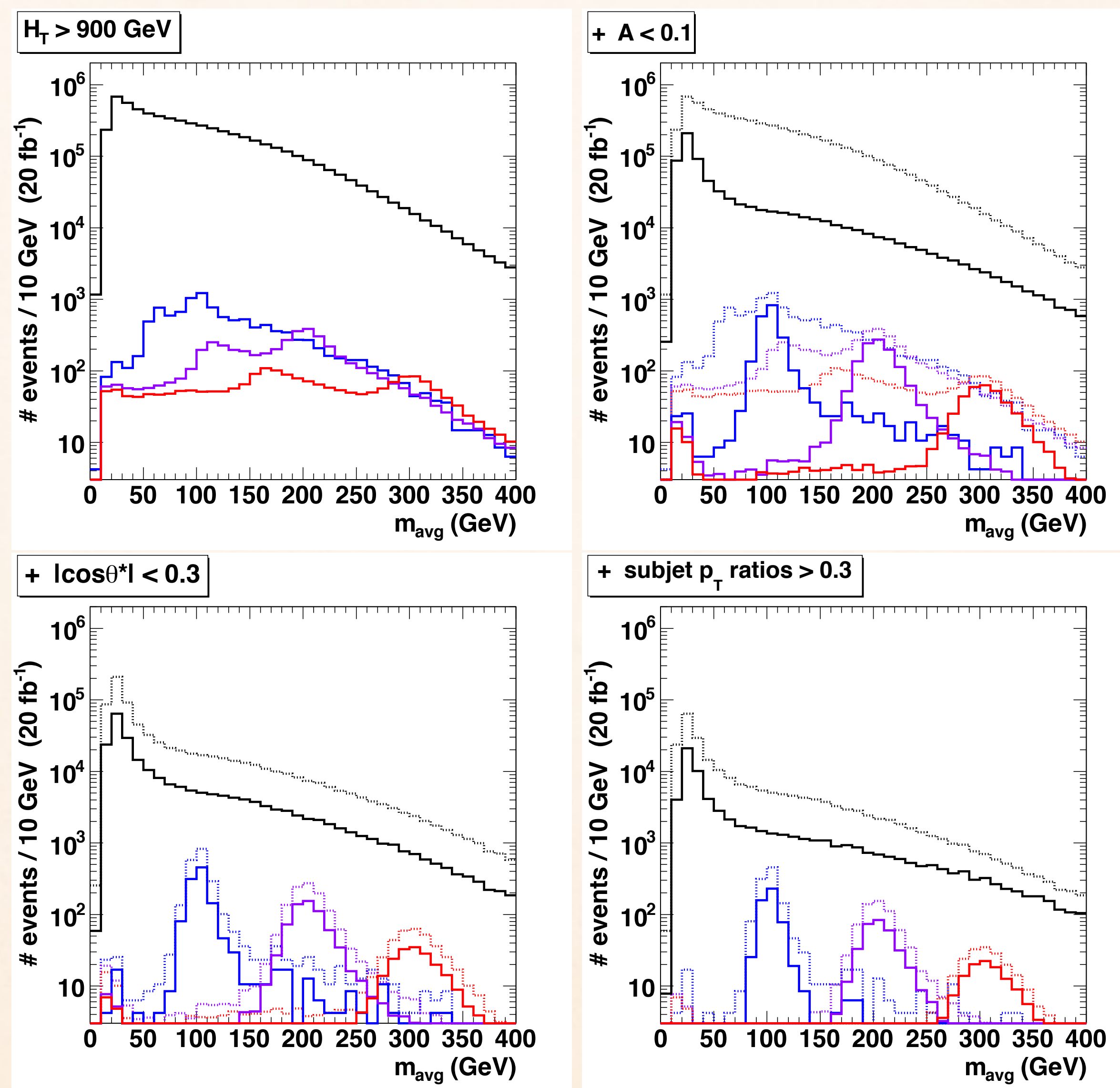




Brust, Katz and Sundrum 2012

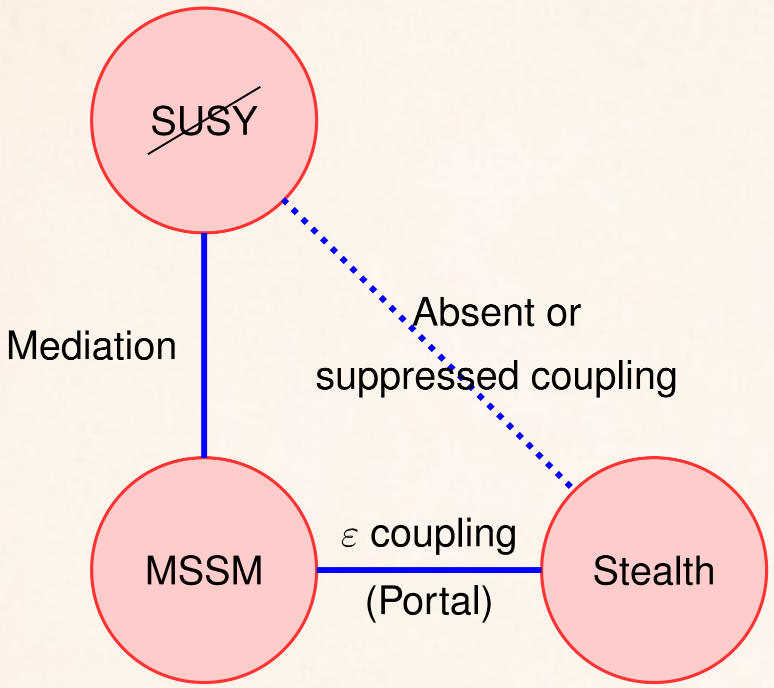
$$pp \to \tilde{t}\tilde{t}^* \to 4j$$

Bai, Katz and Tweedie 2013



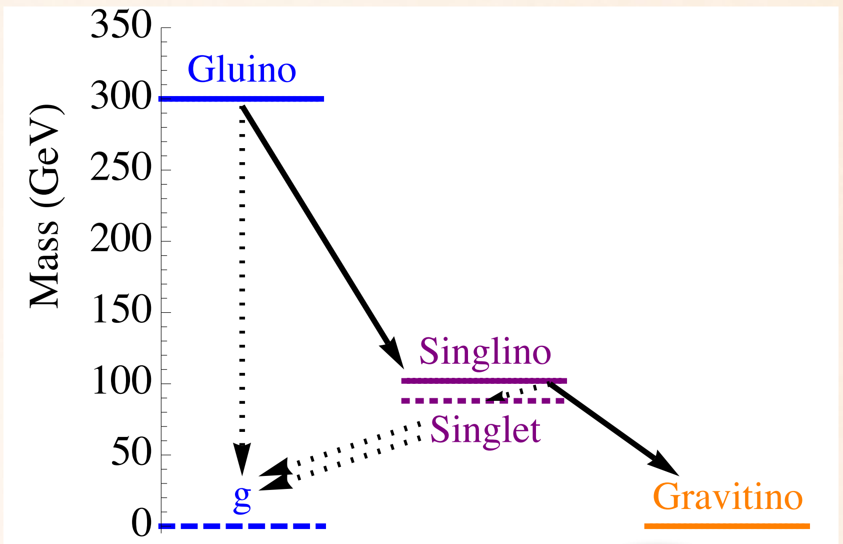
Example 2: Stealth SUSY

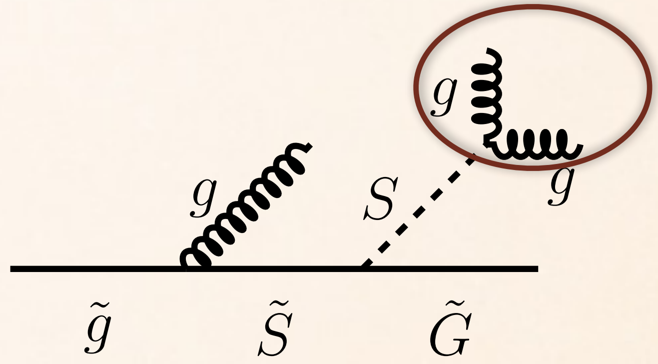
Fan, Reece and Ruderman
2011, 2012



$M_{\rm SUSY} \sim M_{\rm EWK}$

$M_{\not{\rm SUSY}} \sim \varepsilon M_{\rm EWK}$



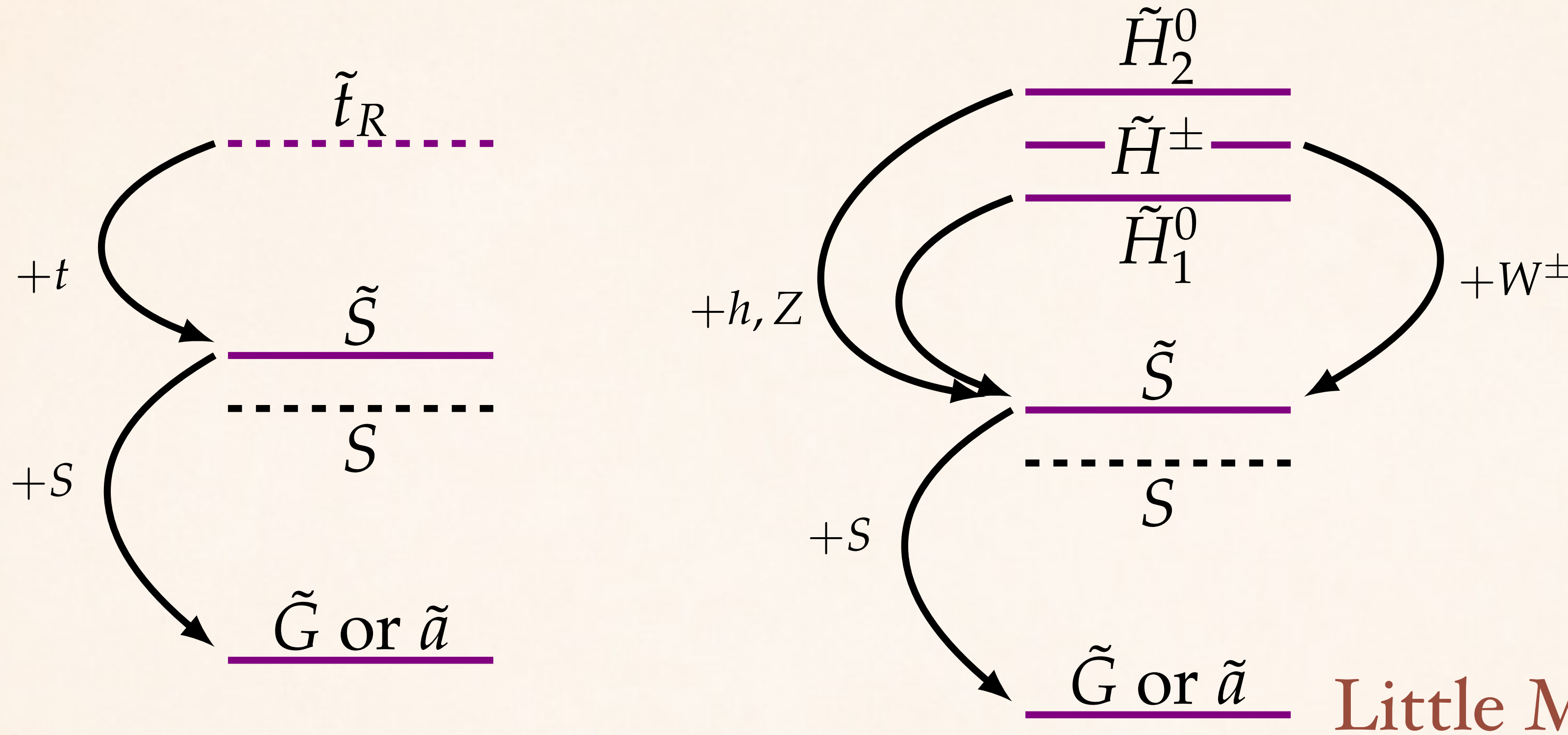


SUSY hides itself!

jets get softer

Parametric limit: hidden sector SUSY breaking, $\varepsilon \to 0$, MET $\to 0$

More new simplified models: decays of lightest superparticle in the visible sector into a hidden sector (S: a SM gauge singlet)

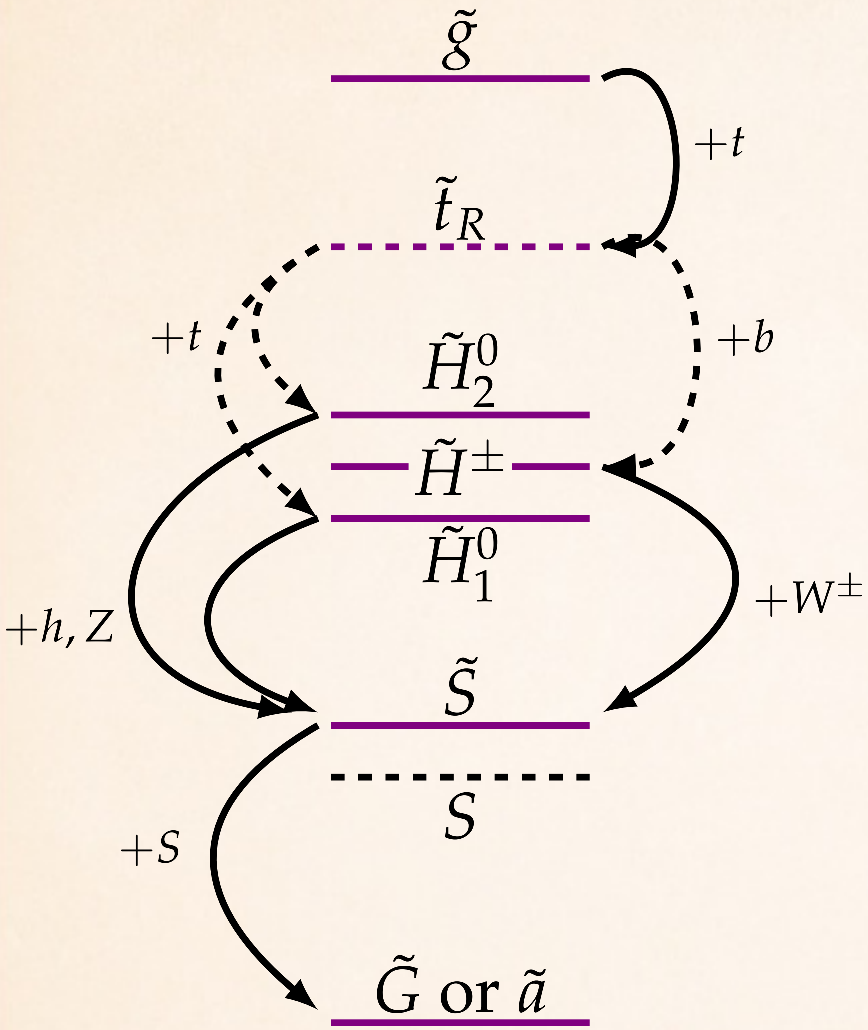


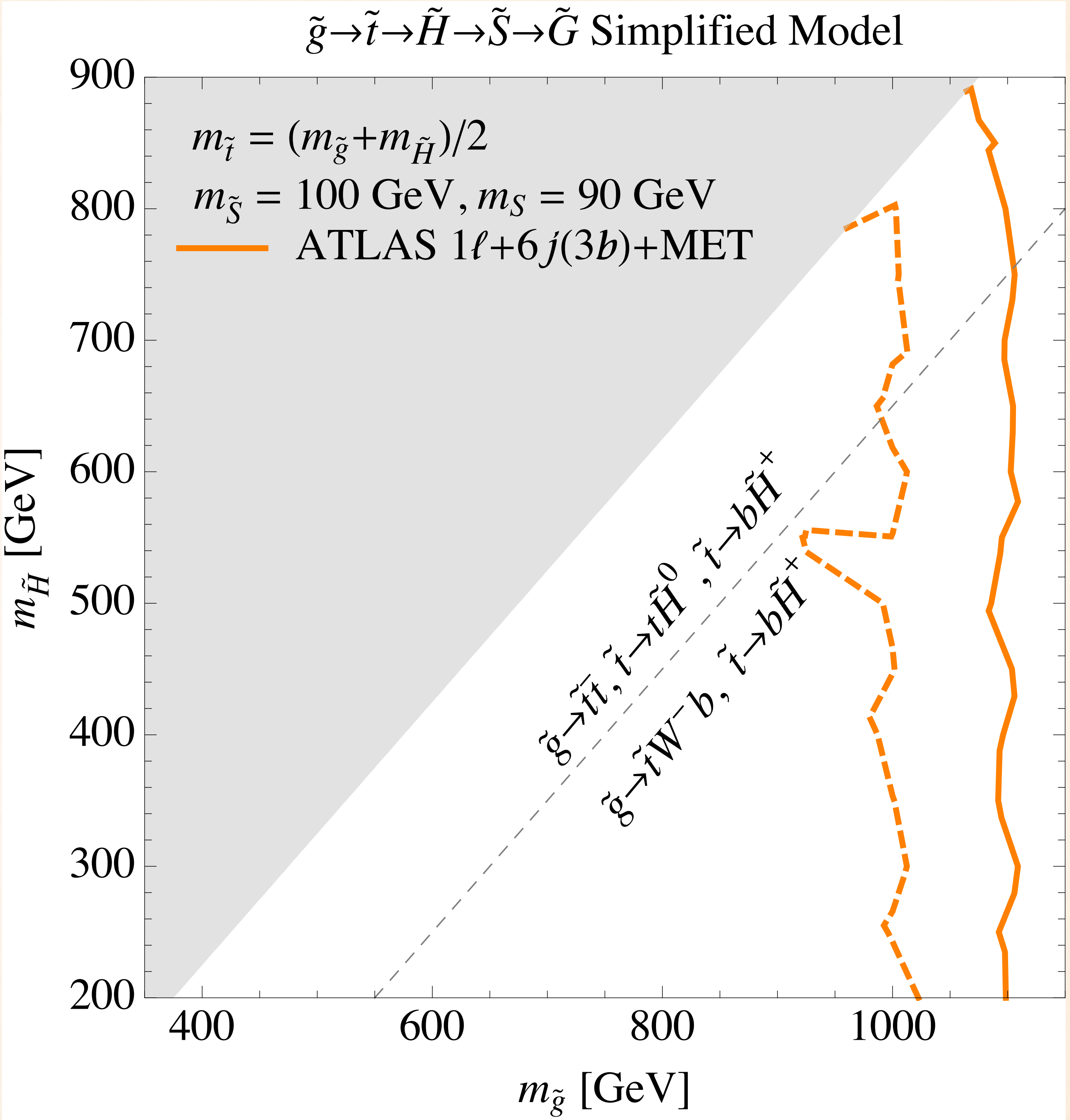
Little MET

Lots of W/Z/h/t !

LSP: gravitino or axino, naturally light and carry away little MET;

Fan, Krall, Pinner, Reece and Ruderman, work in progress



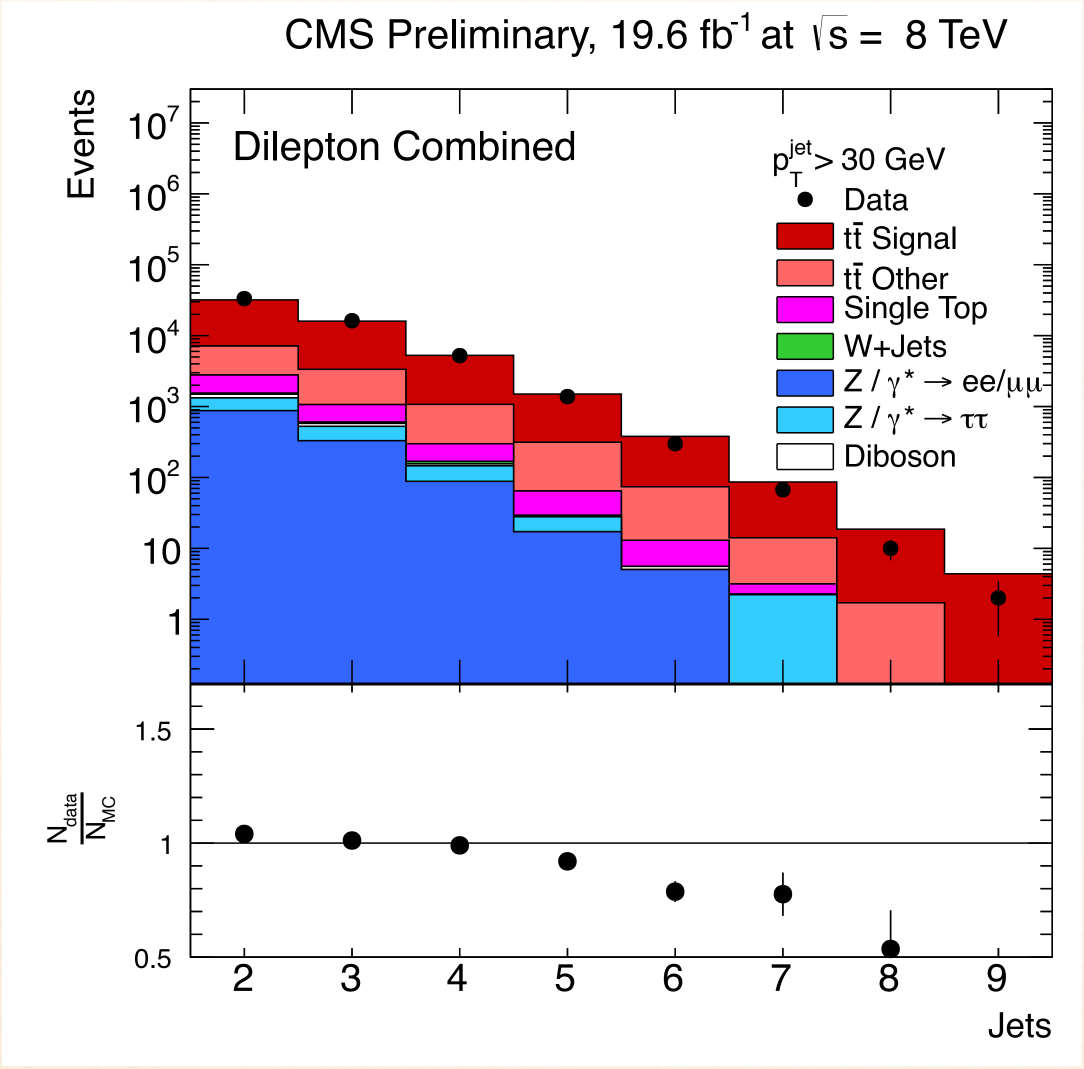


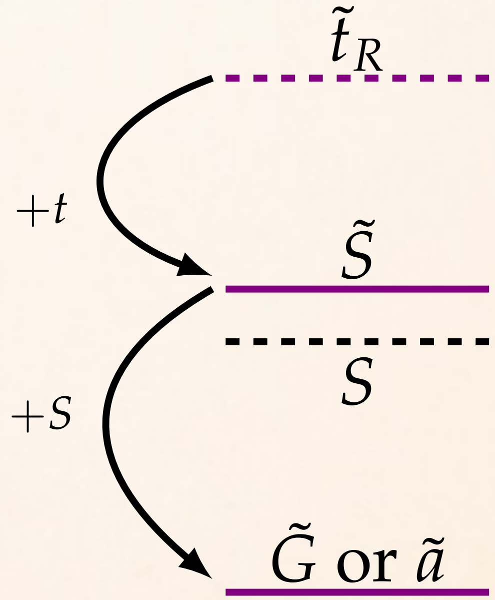
In general, it is hard to hide gluinos!

Other simplified models: Evans, Kats, Shih and Strassler 2013

It is harder to bound with current searches the direct stop productions in the simplified models of stops

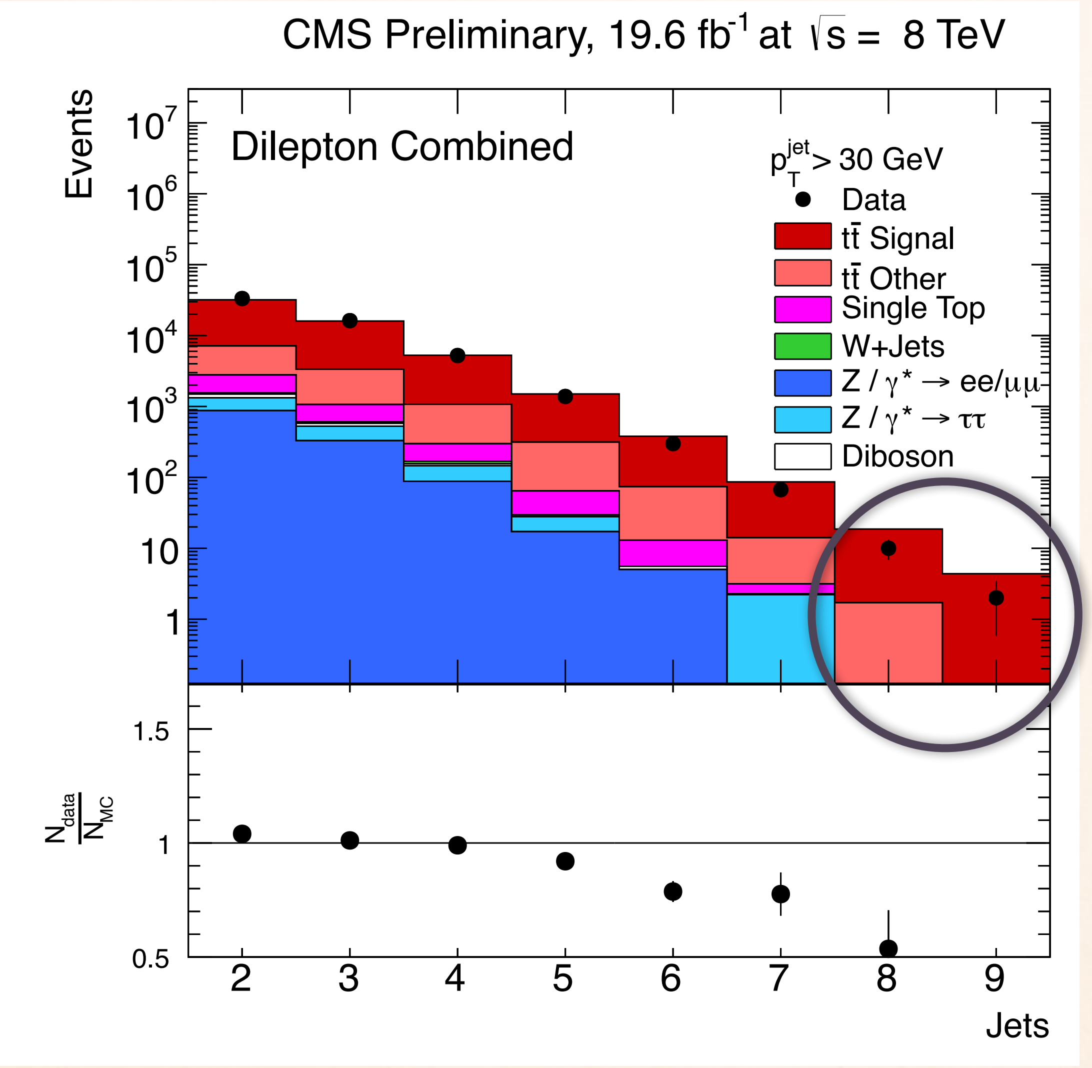
One possible way is to use the jet counts in top events



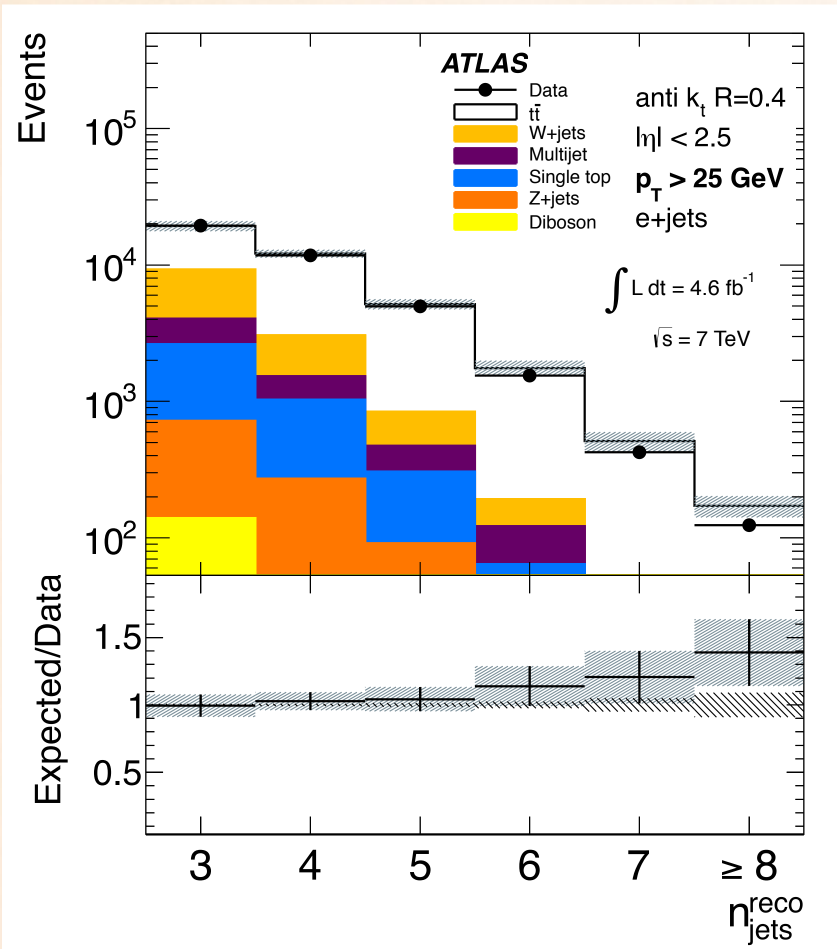


It is harder to bound with current searches the direct stop productions in the simplified models

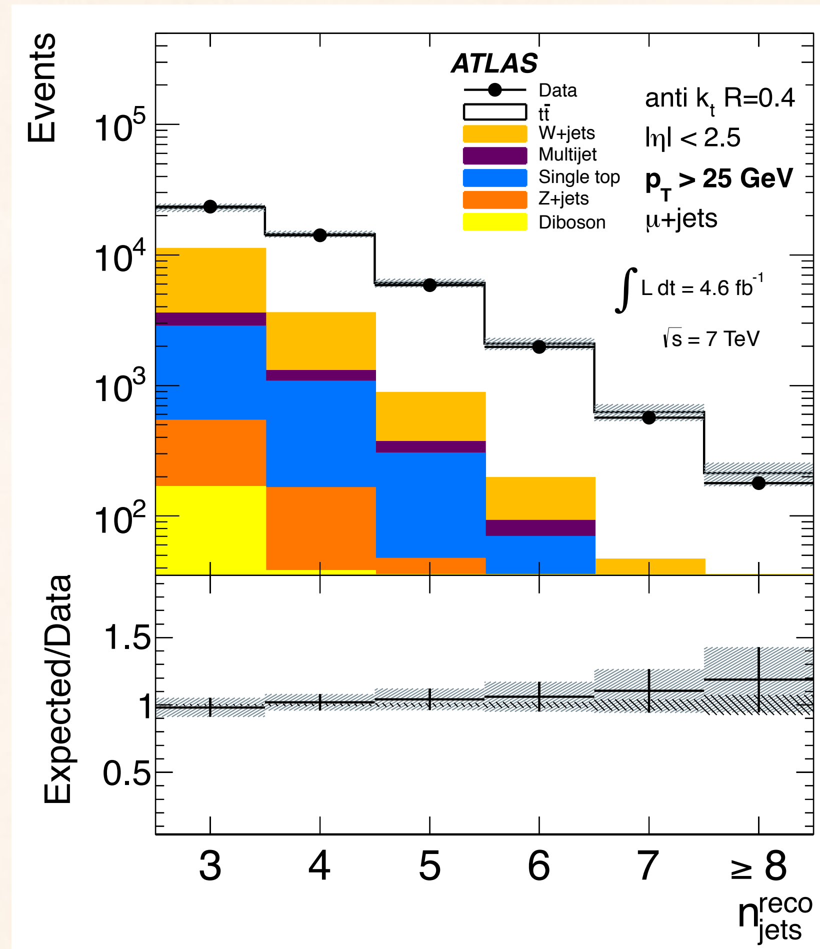
One possible way is to use the jet counts in top events



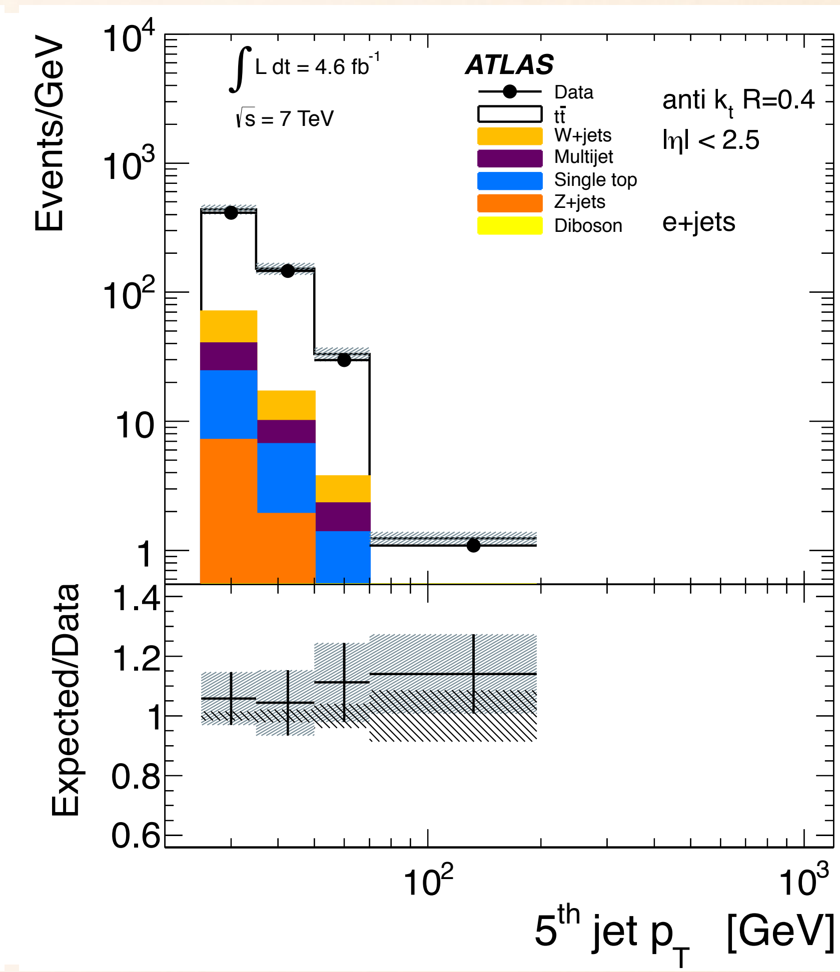
What are the correct error bars?



(a) $e +$ jets, $p_T > 25$ GeV



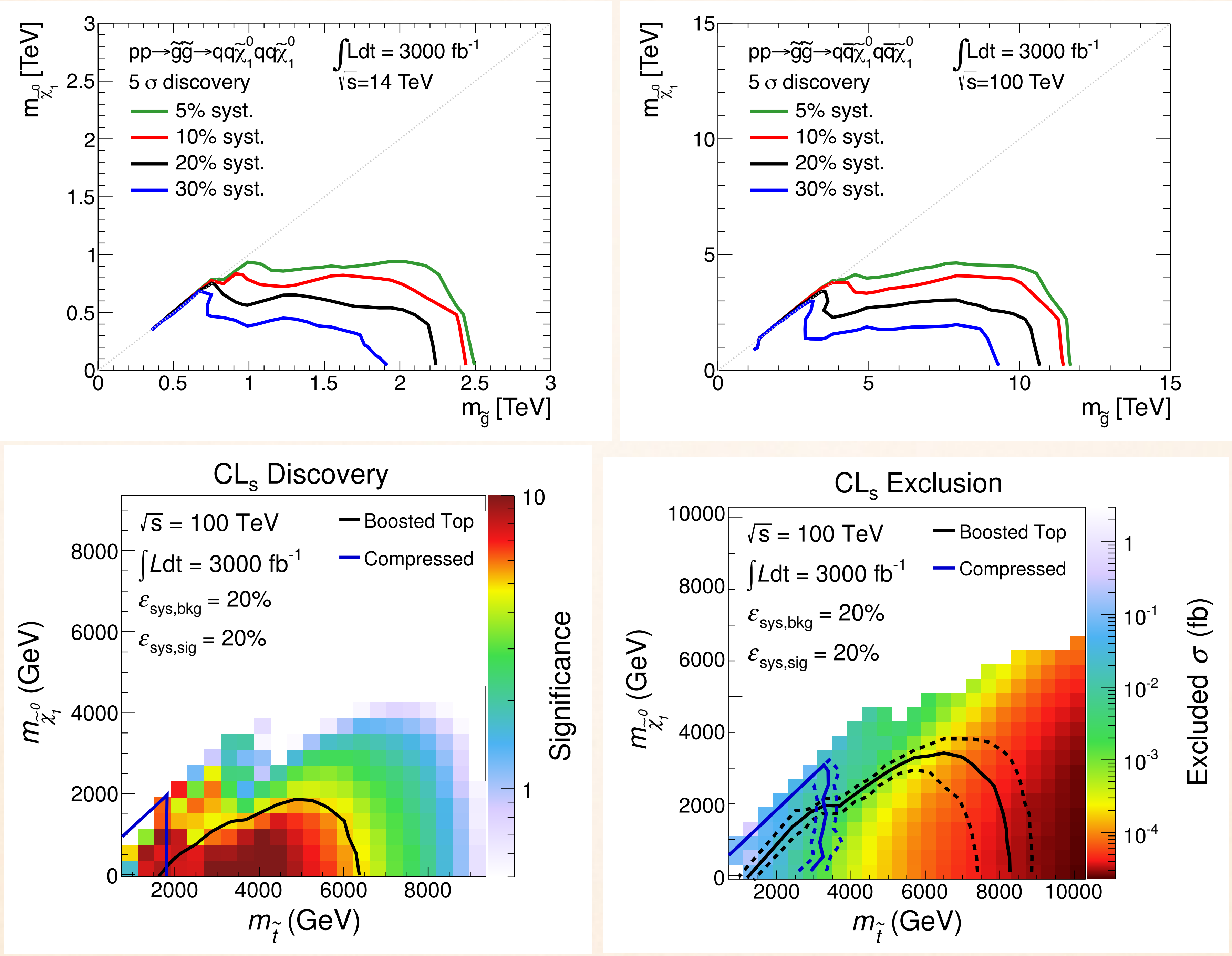
(b) $\mu +$ jets, $p_T > 25$ GeV



(b) $e +$ jets, $p_T > 25$ GeV, 5th jet

ATLAS 1407.0891: jet multiplicity and pT distribution;
Data: SM-like; can be used to bound new physics!

Look forward to the future: Cohen et.al 2013; Cohen et. al 2014



Summary:

It is difficult to hide gluinos even in the hidden natural scenarios!
The bounds are around TeV in most simplified models.
From the naturalness point of view, gluinos shall not be much heavier above 1 TeV:

Discover gluinos around the corner or corner naturalness?

Stops and higgsinos are more challenging due to small production rates. For the stops, close in the gaps of **stops with masses close to top** (e.g: top production cross section:
Czakon, Mitov, Papucci, Ruderman, Weiler 2014; ATLAS 2014)
and **stops with more complicated decay topologies**.

COSMIC PROBES

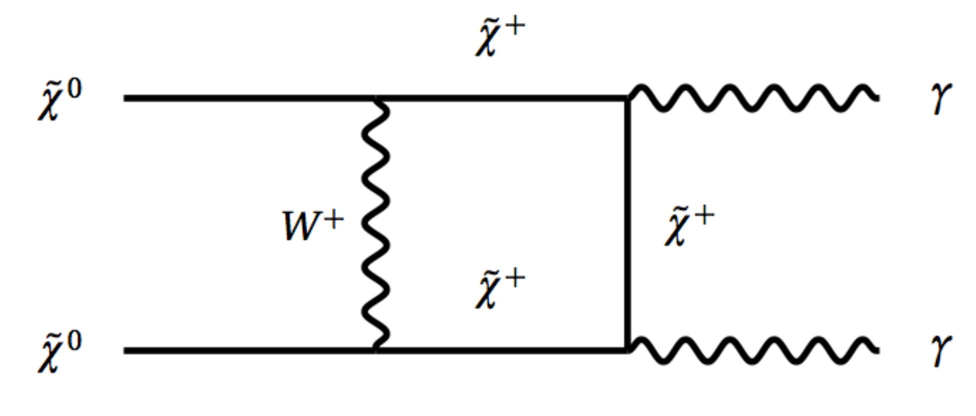
Indirect probes

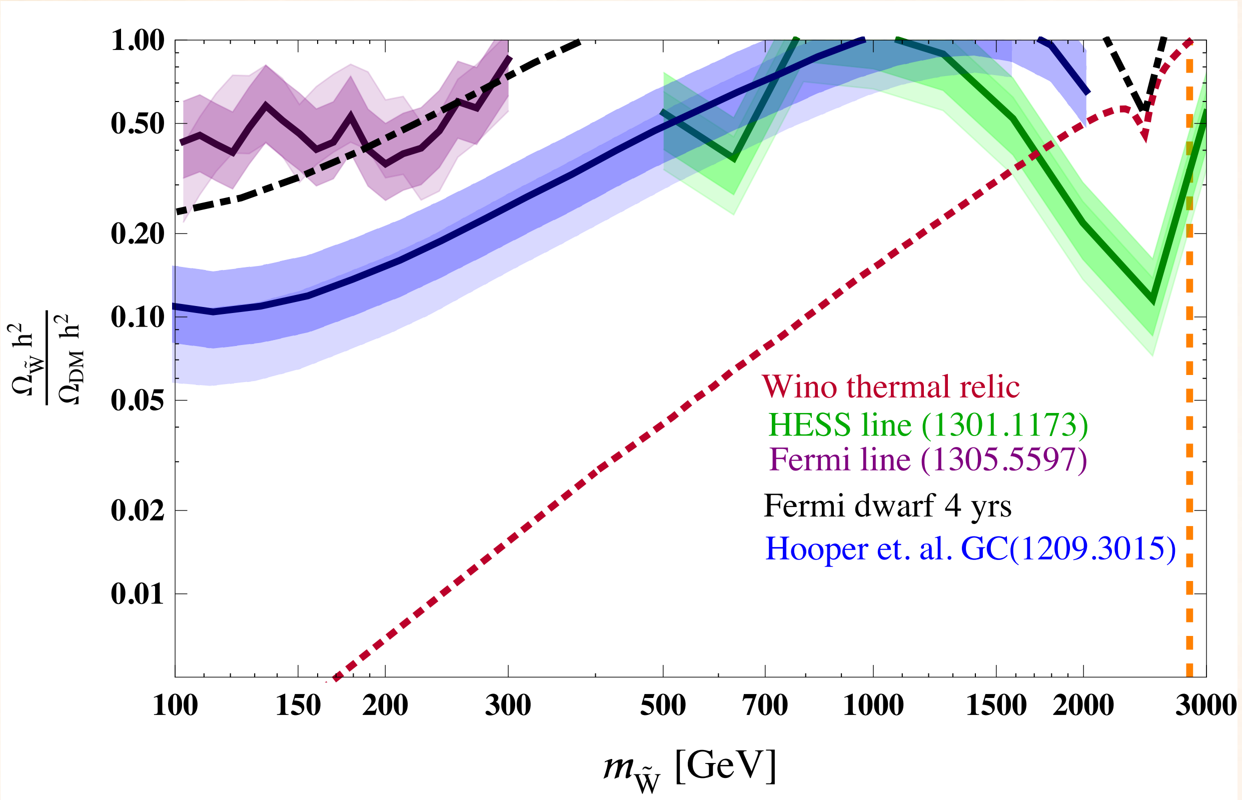
Particularly interesting for wino DM in mini-split scenario based on anomaly mediation;

Direct detection challenging for wino DM $\sigma_p \sim 10^{-47}\ \mathrm{cm}^2$

Hisano, Ishiwata, Nagata and Takesako; Hill, Solon 2011

But wino DM has a large annihilation cross section with Sommerfeld enhancement

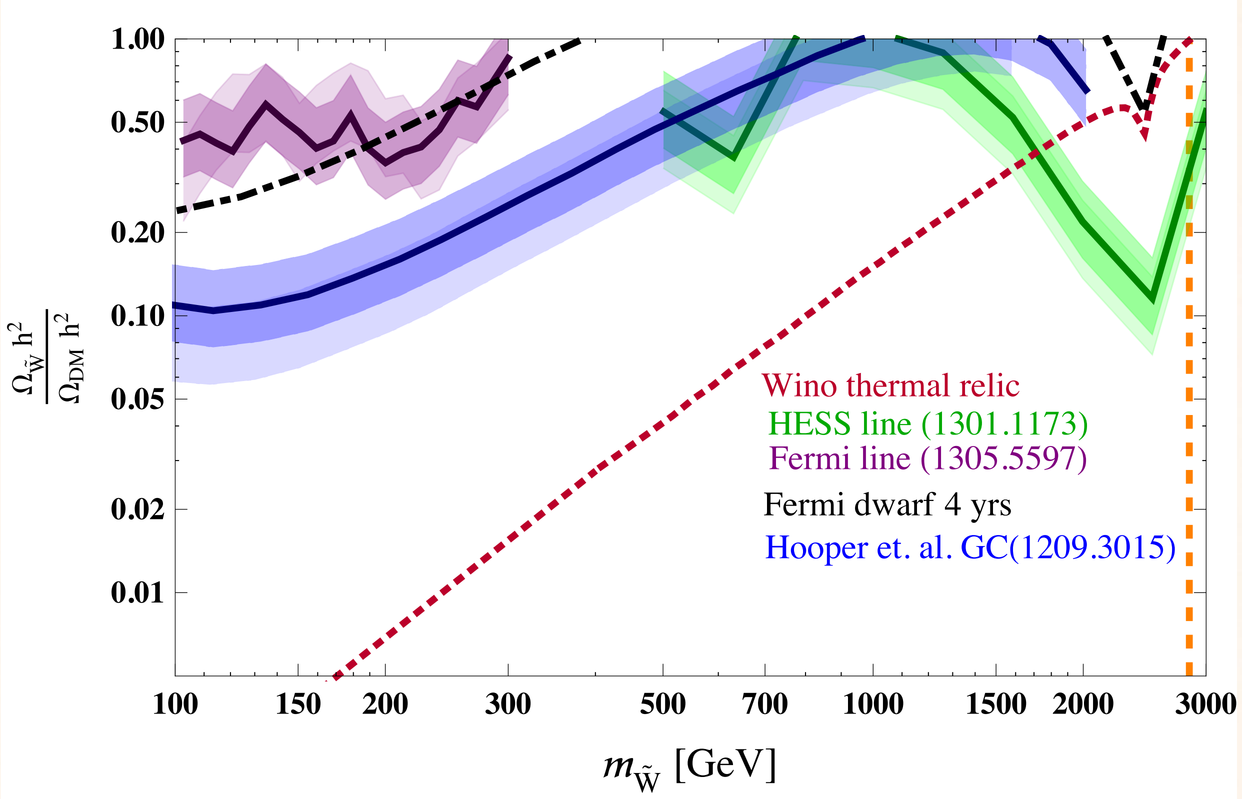


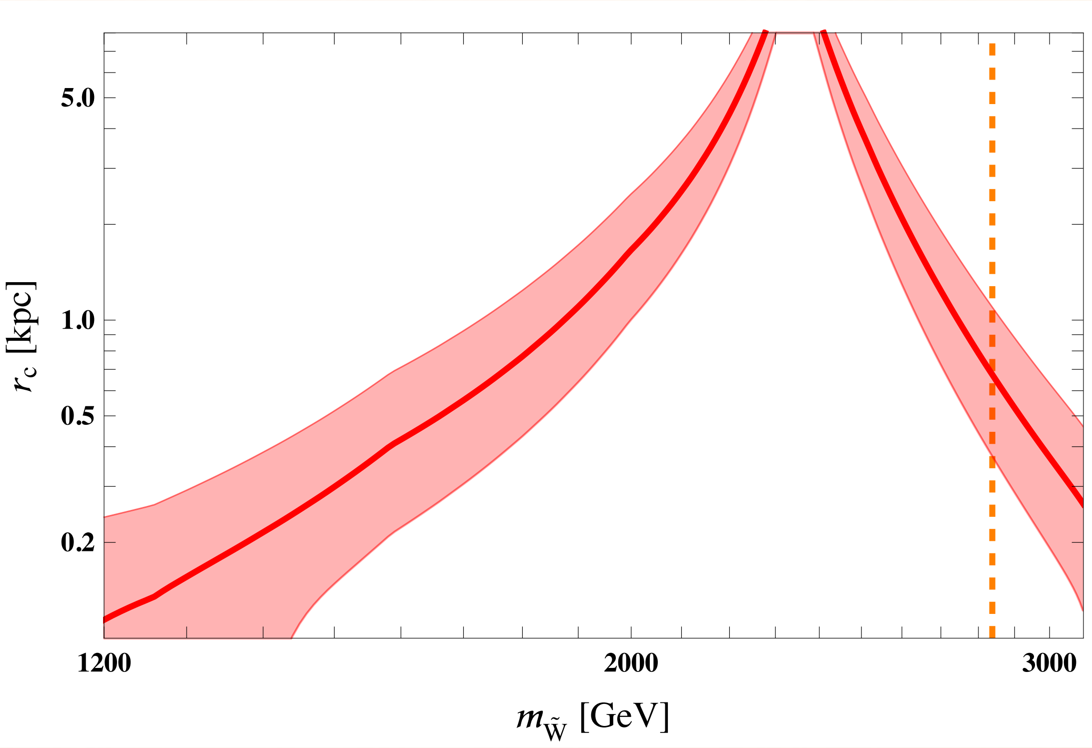


Fan, Reece; Cohen, Lisanti, Pierce and Slatyer 2013; First notice of HESS constraint on wino DM: Cirelli, Stumia and Tamburini 2007

Combined with constraints from continuum photons from galactic center, pure wino DM in the whole range from 100 GeV to 3 TeV (with the possible exception of a range between 700 GeV and 1.4 TeV) is ruled out for both NFW and Einasto profiles.

Cusp or core? Effect of astrophysical uncertainties

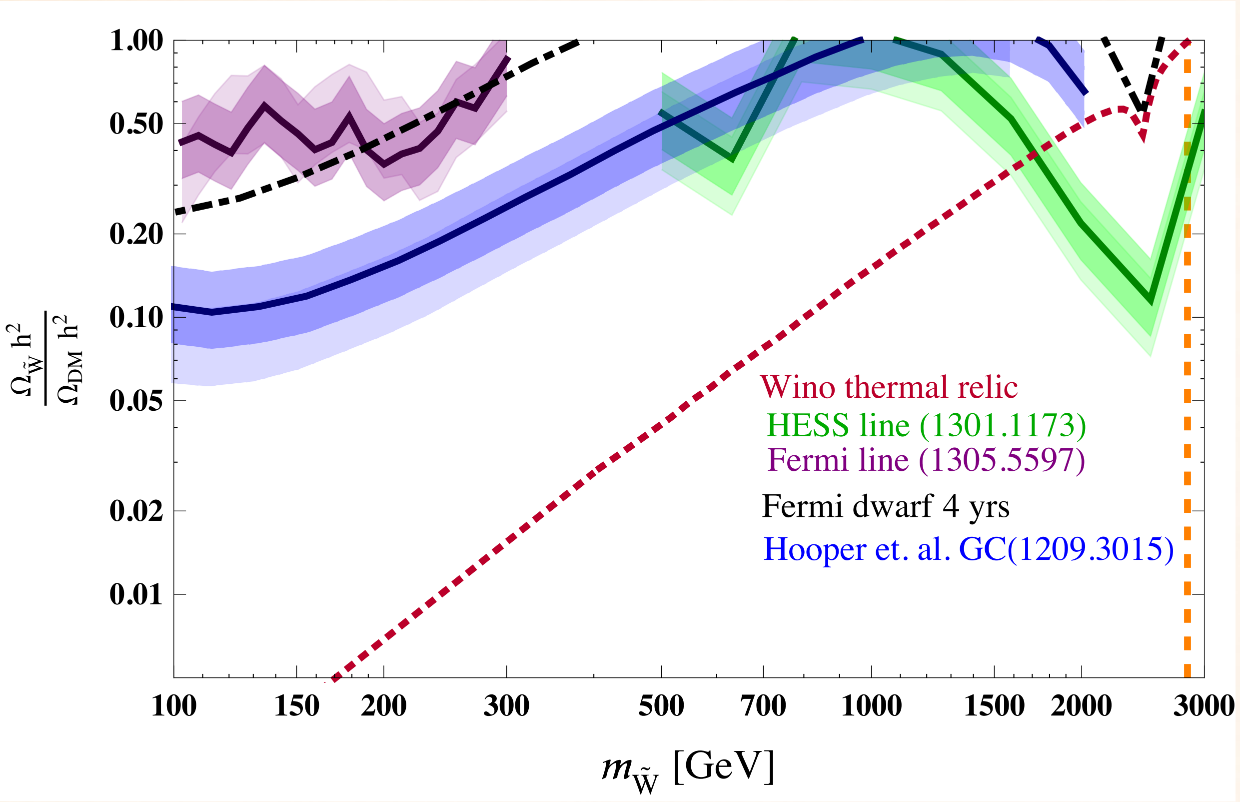


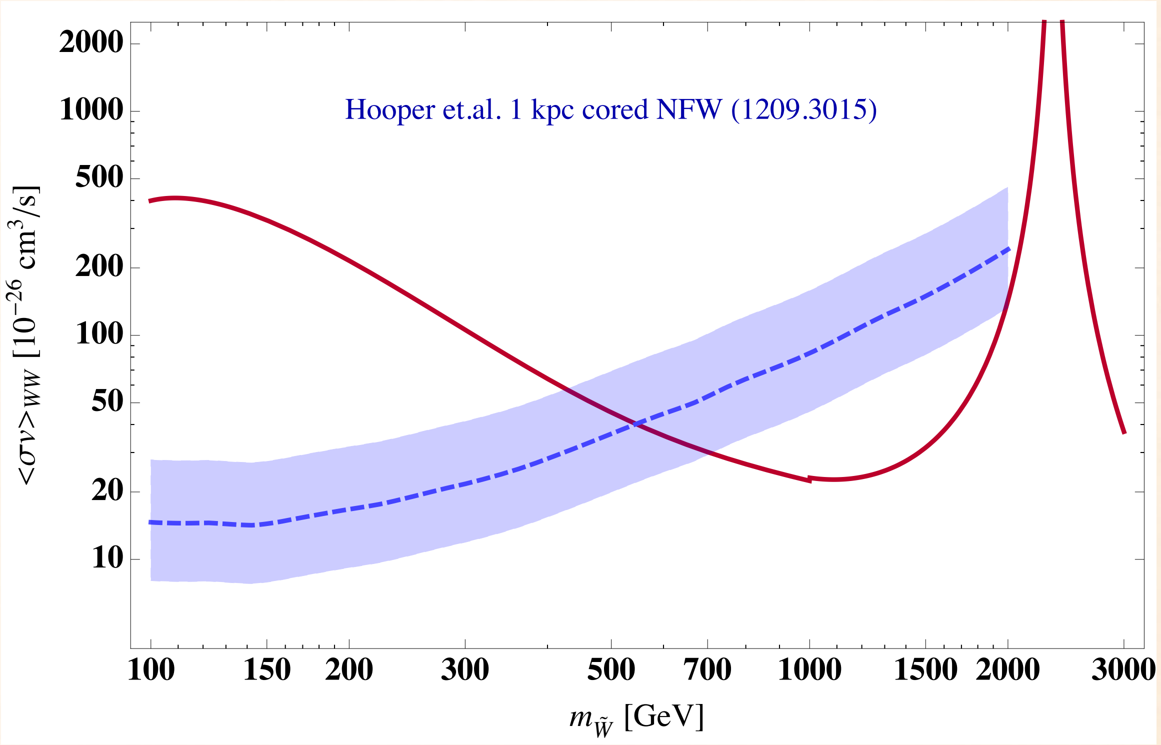


Minimal radius of the inner constant density core that will remove the HESS bound

Decide between two possibilities:
Pure wino DM is ruled out assuming a cusp profile: NFW or Einasto profiles;
Milky Way has a cored profile with a large core radius
(Milky Way's own cusp/core problem?)

Lower mass end: interesting for moduli scenarios





From the top-down view, it is easy to get a non-thermal contribution to the DM relic abundance in high-scale unnatural SUSY.

In high-scale SUSY, there exist ubiquitously heavy particles with masses tied up with the SUSY breaking scale and gravitational coupling strengths: gravitinos, moduli. Their late-time decays before BBN could populate DM!

In this context, non-thermal production arises generically and shall be taken more seriously.

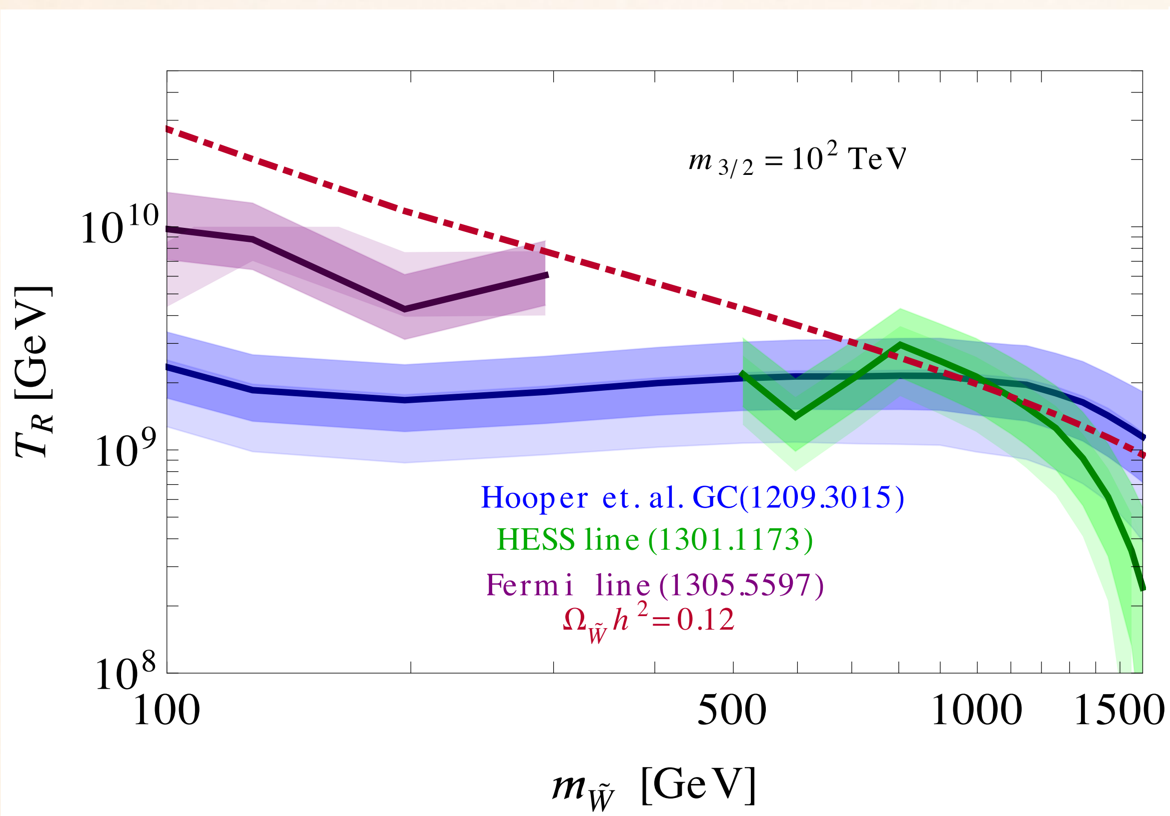
Heavy unstable gravitinos

Fan, Jain, Ozsoy 2014

Gravitinos 10 - 10^4 TeV,
decays of gravitinos populate the DM

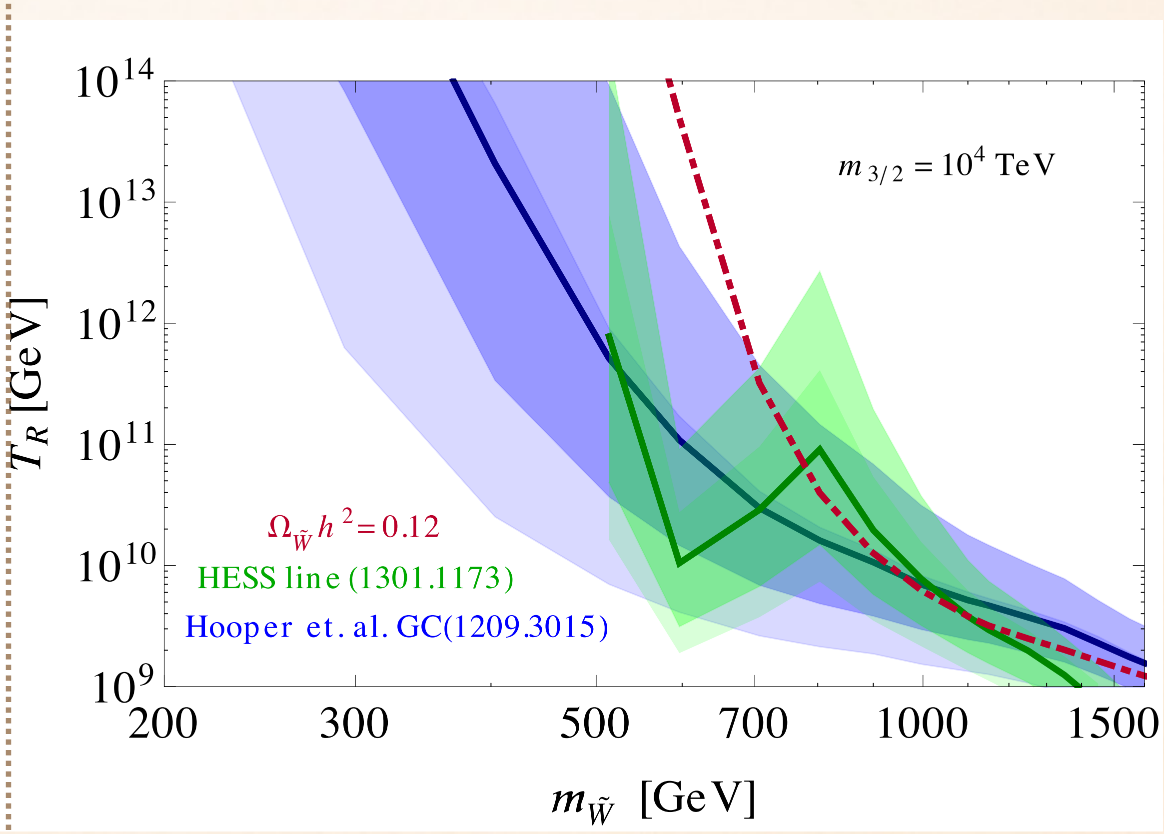
$$\Omega_{\tilde{W}}^{(no-ann)} h^2 = \frac{m_{\tilde{W}}}{m_{3/2}} \left(\Omega_{3/2}^{UV} h^2 + \cdots \right)$$
$$\approx 0.12 \left(\frac{m_{\tilde{W}}}{1\,\mathrm{TeV}} \right) \left[\left(\frac{T_R}{2 \times 10^9\,\mathrm{GeV}} \right) + \cdots \right]$$

Independent of gravitino mass!



For heavier gravitinos with mass above 10^4 TeV;
DM produced from gravitino decays could annihilate effectively,
reducing the number density down to

$$n_{c,\tilde{W}} \simeq 3H / \langle \sigma_{\mathrm{eff}} v \rangle$$



Gravitinos 10 - 10^4 TeV (mini-split),
decays of gravitinos populate the DM

Fan, Jain, Ozsoy 2014

$$\Omega_{\tilde{W}}^{(no-ann)} h^2 = \frac{m_{\tilde{W}}}{m_{3/2}} \left(\Omega_{3/2}^{UV} h^2 + \cdots \right)$$
$$\approx 0.12 \left(\frac{m_{\tilde{W}}}{1\,\text{TeV}} \right) \left[\left(\frac{T_R}{2 \times 10^9\,\text{GeV}} \right) + \cdots \right]$$

Independent of gravitino mass!

In high-scale inflation scenario,
given order O(0.1) tensor-to-scalar ratio

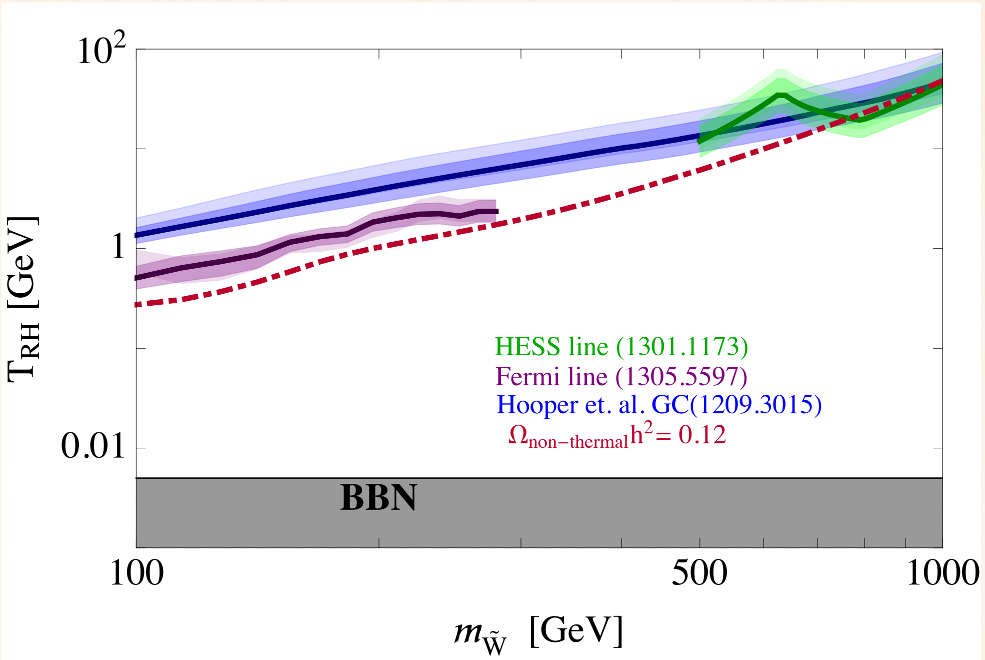
$$m_\phi^2 \sim \frac{V}{(\Delta\phi)^2} \approx \left(2 \times 10^{13}\,\text{GeV}\right)^2,$$

If inflaton decays through dim-5 op. such as $\phi F \tilde{F}$

$$\Gamma_\phi = \frac{c\, m_\phi^3}{M_p^2}, \quad T_R \approx 5 \times 10^9\,\text{GeV} \sqrt{c} \left(\frac{m_\phi}{10^{13}\,\text{GeV}} \right)^{3/2},$$

More dramatic non-thermal history: late-time matter domination phase of moduli Moroi, Randall 1999

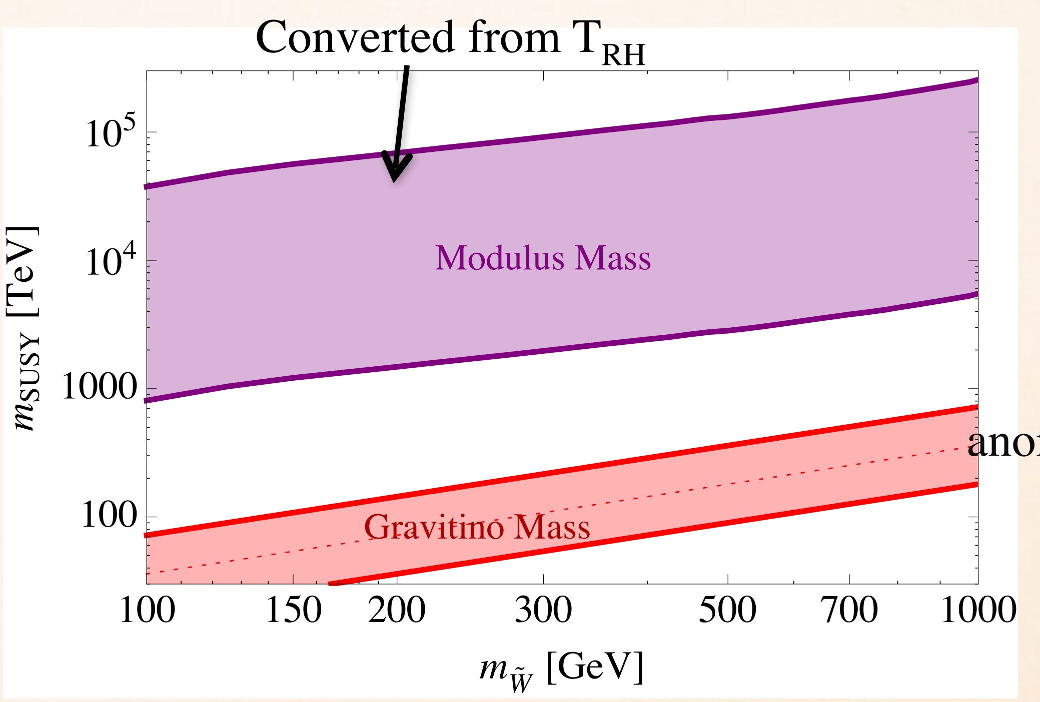
The reheating temperature has to be above 1 GeV!



Fan, Reece 2013

The moduli mass scale compatible with data has to be an order of magnitude or more above $m_{3/2}$

Moduli induced gravitino problem!



More cosmic observables:

Non-gaussianity and squeezed limit scaling Craig, Green 2014

Single field consistency condition

$$\lim_{\mathbf{k}_3 \to 0} \langle \zeta_{\mathbf{k}_1} \zeta_{\mathbf{k}_2} \zeta_{\mathbf{k}_3} \rangle' \to P_\zeta(k_1) P_\zeta(k_3) \left[(n_s - 1) + \mathcal{O}(k_3^2) \right]$$

In the presence of additional massive scalar with m ~ H

$$\frac{12}{5} f_{\rm NL}^{\rm equil.} c_\alpha \times P_\zeta(k_1) P_\zeta(k_3) \left(\frac{k_3}{k_1} \right)^\alpha$$

$$\alpha \equiv \frac{3}{2} - \sqrt{\frac{9}{4} - \frac{m^2}{H^2}}$$

Measuring squeezed limit scaling $\alpha < 2$ could probe scalars in split SUSY that couples to the inflaton.

Conclusion

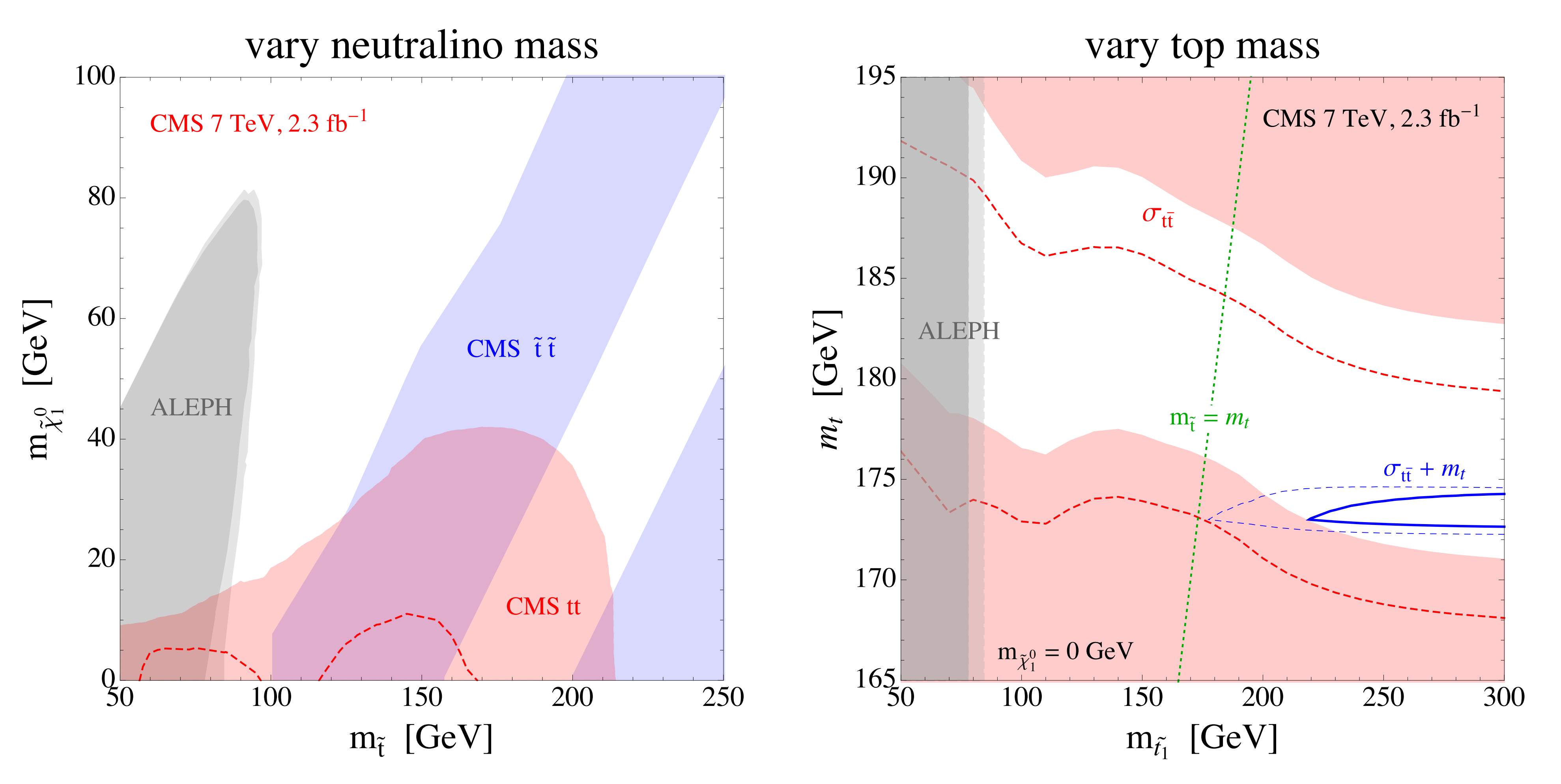
We are lucky to be in a data-rich period.

Naturalness is constrained but not ruled out yet.

It is important for theorists to keep working out new search channels and simplified models as well as better observables.

Backup

Use top cross section to constrain stops



Direct and indirect probes of Higgsino DM