SUPERSYMMETRY: WHERE DO WE STAND?

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At LHCP, Barcelona, May 16, 2013

WHY SUPERSYMMETRY?

- Naturalness
- Gauge Coupling Unification
- Dark Matter

Recent experimental results make this look shakier than before....

(This is a review talk; apologies for omissions and idiosyncracies)

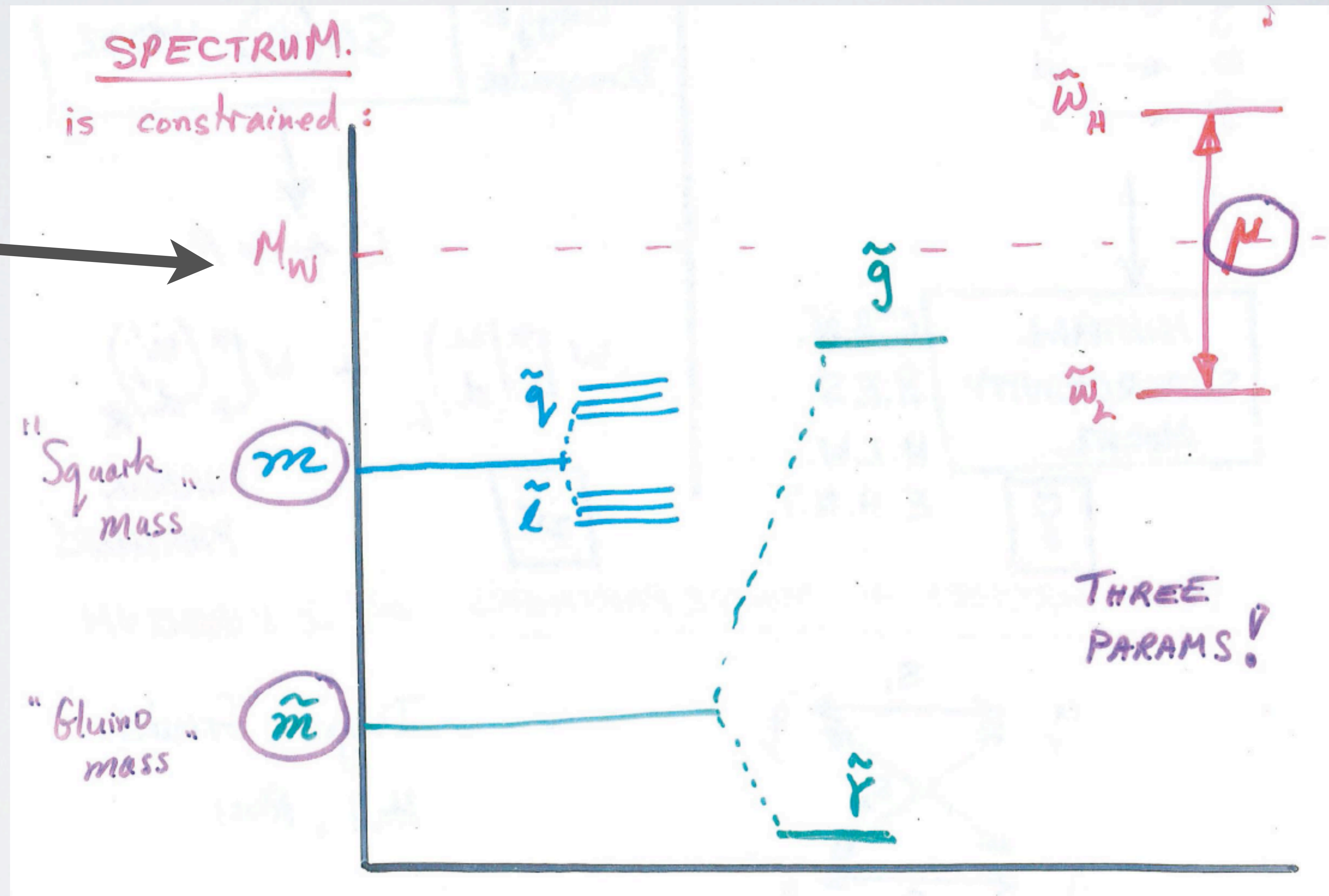
NATURAL SUSY, 1984

From Lawrence Hall's talk at SavasFest

W boson near the top of the spectrum....

1984 was a utopian year for SUSY.

Times have changed!



125 GEV HIGGS AND SUSY

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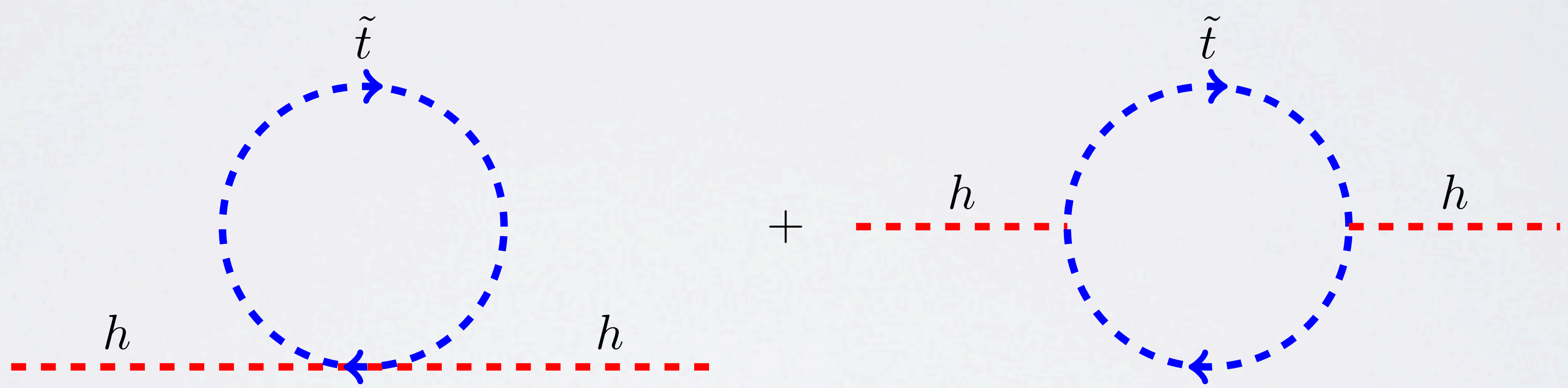
Very interesting! Light enough that SUSY still seems sane, but heavy enough that many *models* don't.

MSSM:



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

Haber, Hempfling '91

more: Haber, Hempfling, Hoang, Ellis, Ridolfi, Zwirner, Casas, Espinosa, Quiros, Riotto, Carena, Wagner, Degrassi, Heinemeyer, Hollik, Slavich, Weiglein

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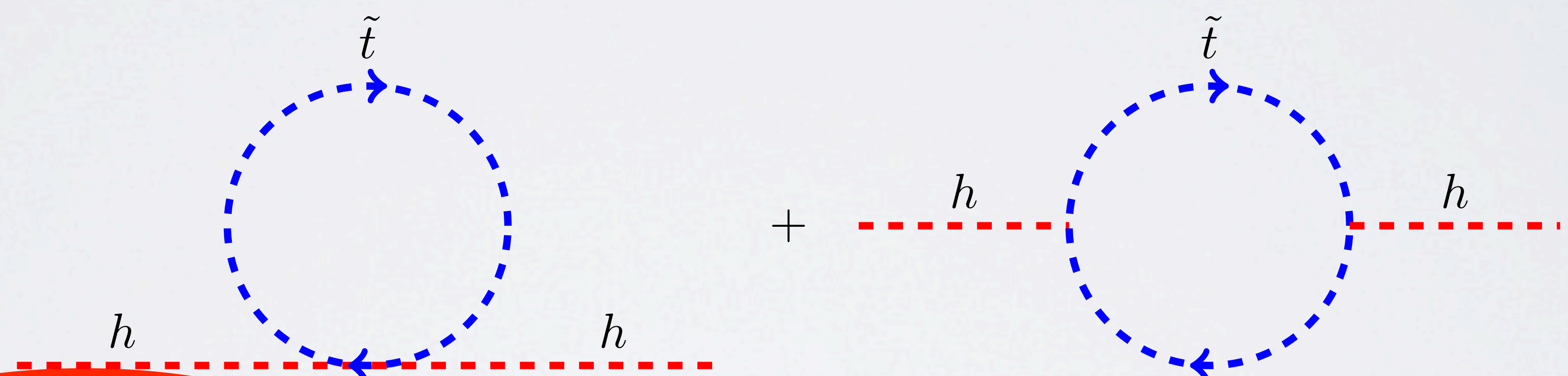

$$m_h^2 = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left(\log\left(\frac{M_S^2}{m_t^2}\right) + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12M_S^2}\right)\right)$$

Tree-level bound: 90 GeV

more: Haber, Hempfling, Hoang, Ellis, Ridolfi, Zwirner, Casas, Espinosa, Quiros, Riotto, Carena, Wagner, Degrassi, Heinemeyer, Hollik, Slavich, Weiglein

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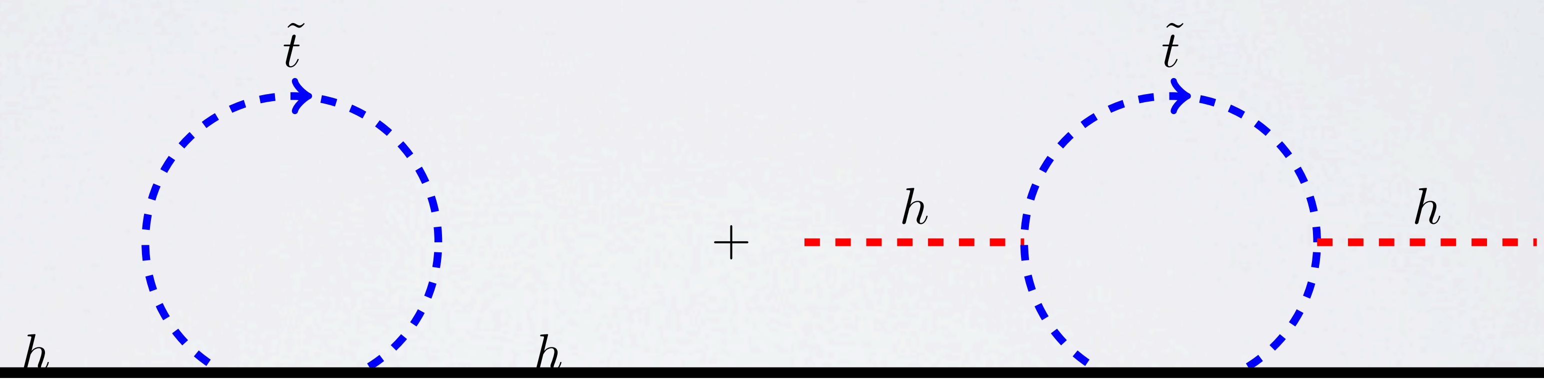

Logarithmic growth with stop mass

$$m_h^2 = m_Z^2 c_{2\beta}^2$$

Haber, Hempfling '91

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

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MSSM:

Polynomial growth with X_t, a mixing between left- and right- handed stops.

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

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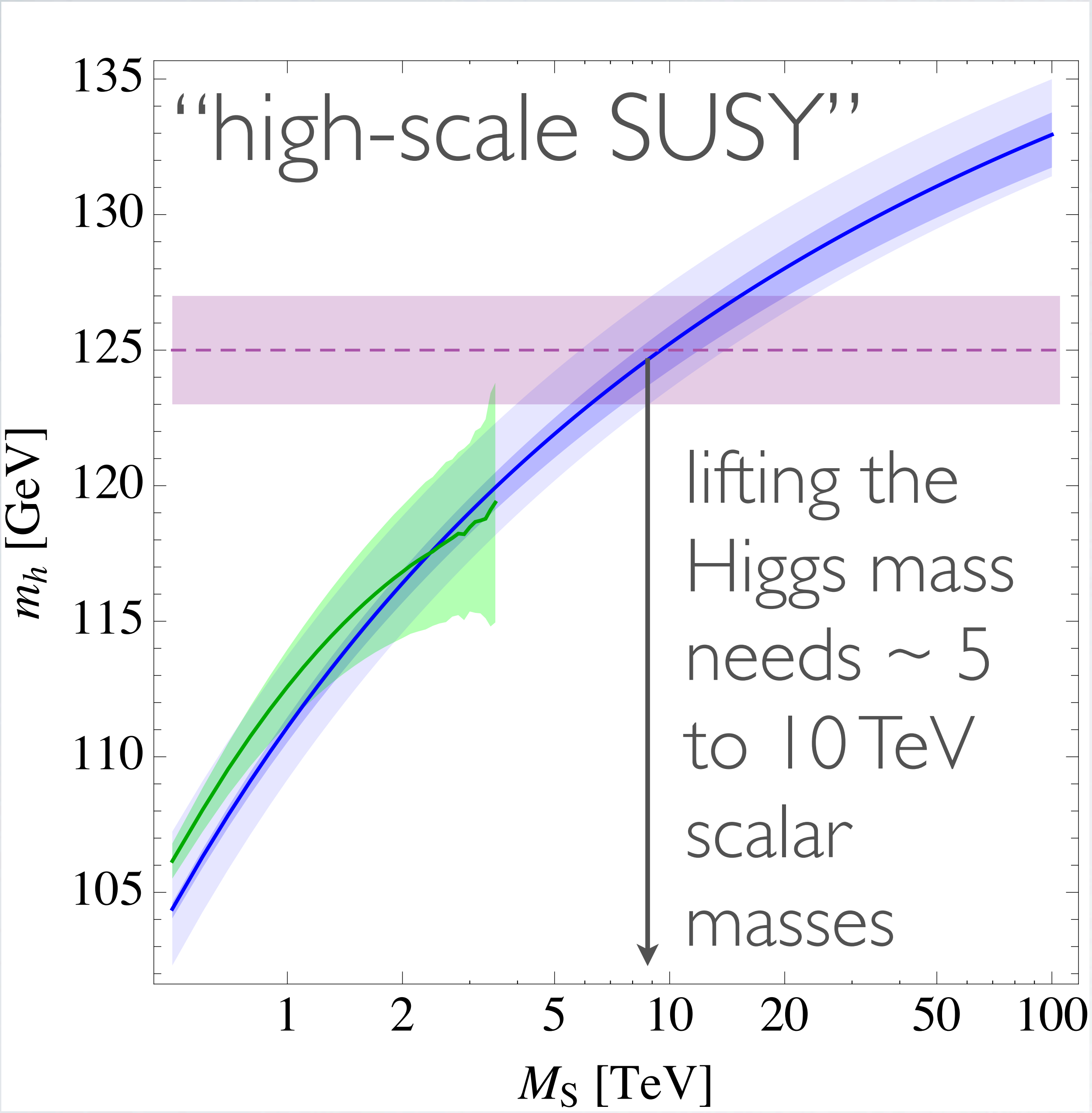
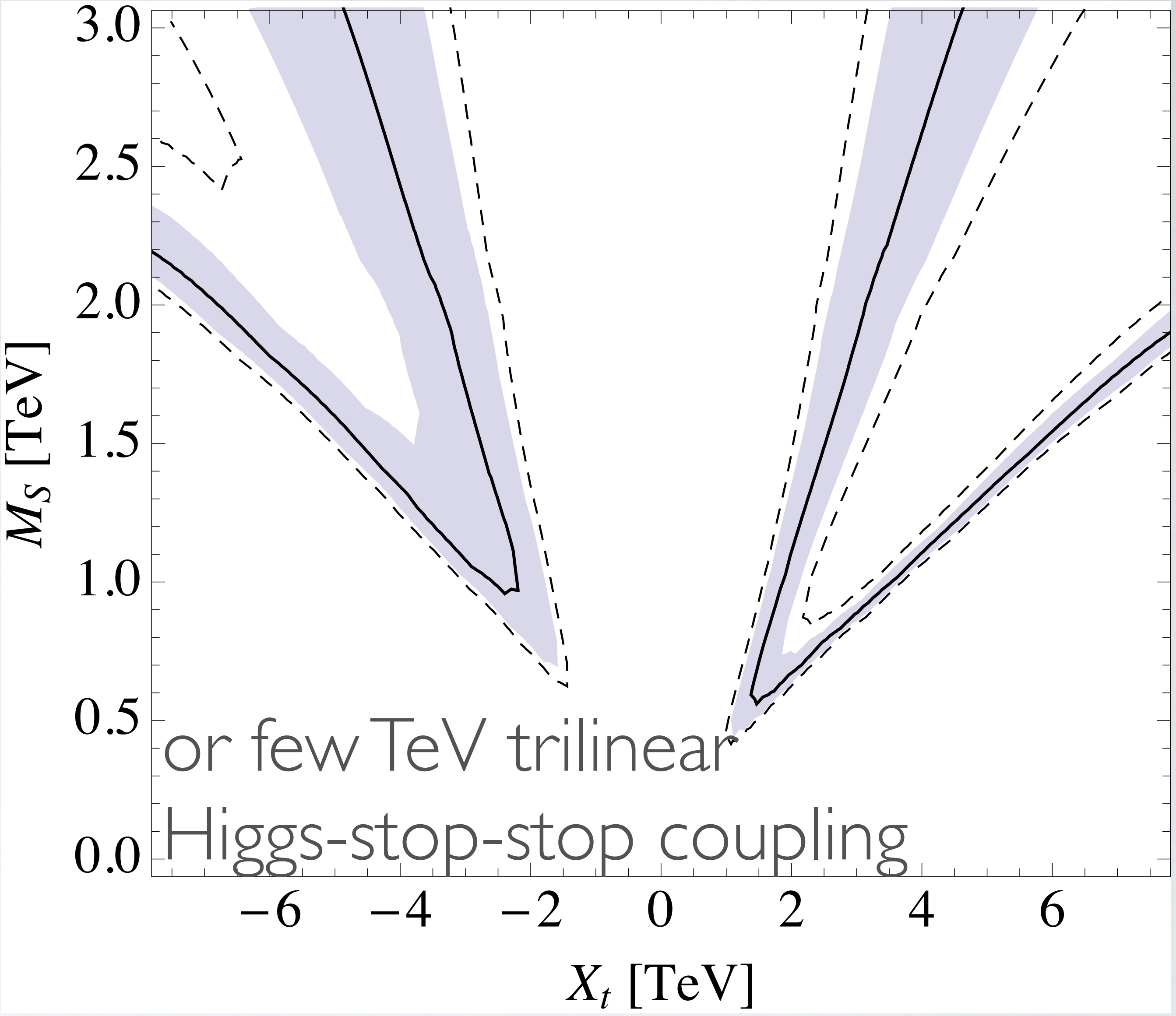
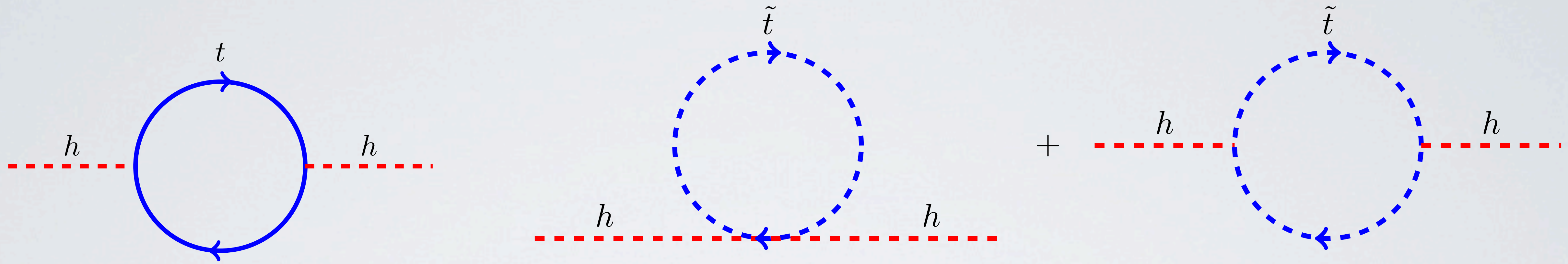




In the MSSM, a 125 GeV Higgs requires large quantum corrections, with multi-TeV SUSY-breaking parameters, **reintroducing** *(part of)* the hierarchy.

P. Draper, P. Meade, MR, D. Shih '11; similar work by many others

NATURALNESS



Higgs potential $-\mu^2|H|^2+\lambda|H|^4$: large quantum corrections to the mass^2 term. **Direct searches** constrain them:

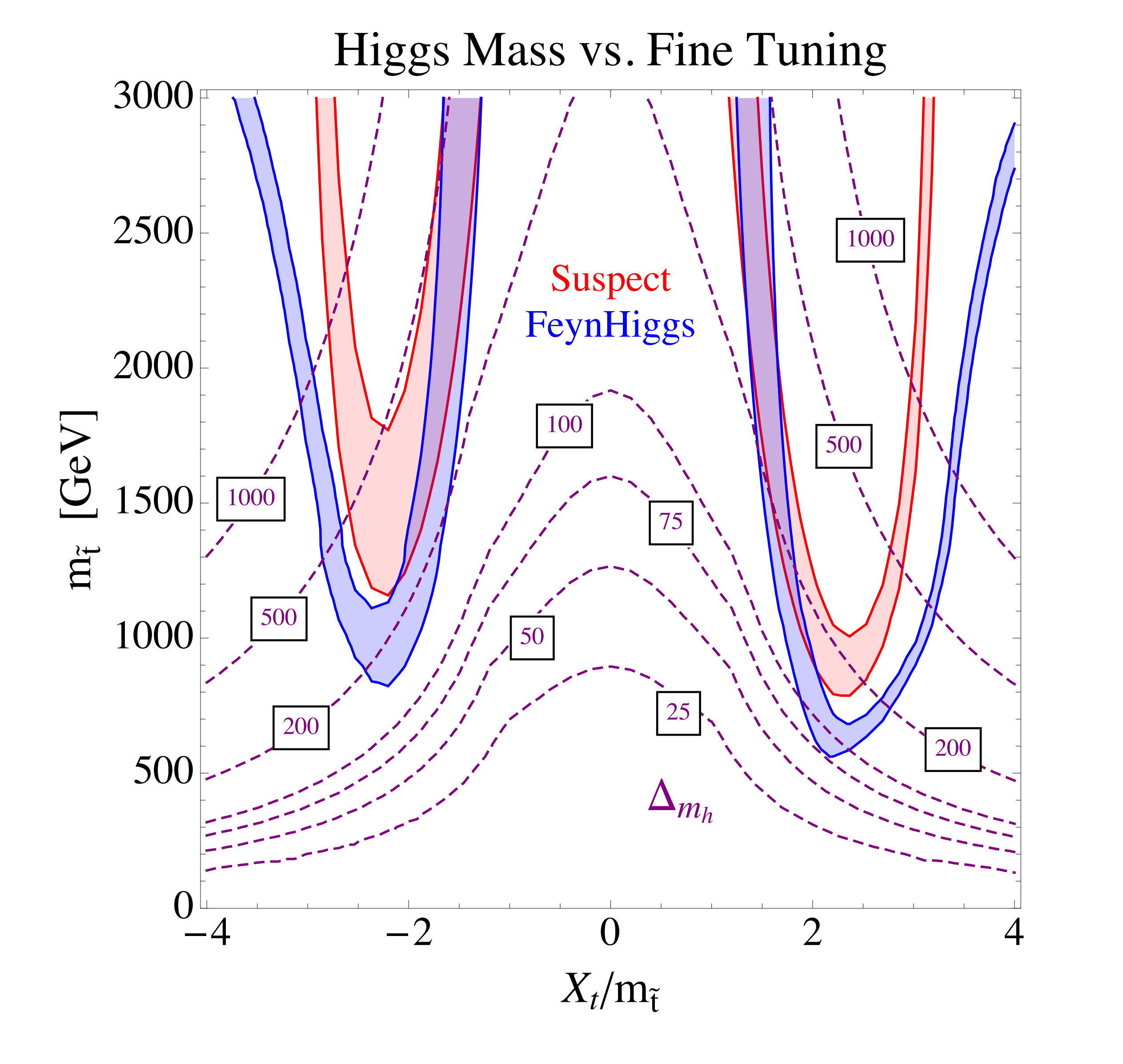
$$\delta m^2_{H_u} = -\frac{3}{8\pi^2} y_t^2 \left(m^2_{\tilde{t}_L} + m^2_{\tilde{t}_R} + |A_t|^2 \right) \log \frac{\Lambda}{\mathrm{TeV}}.$$

Either the stop is light, or Higgs potential is finely-tuned.

Two stops (LH/RH), one sbottom (LH) should be below about 500 - 700 GeV (e.g. 1110.6926 Papucci et al.)

THE MSSM IS UNNATURAL

In the MSSM, a 125 GeV Higgs mass requires heavy stops / large *A*-terms, but those **directly** undermine the naturalness argument for SUSY.



Tuning contours (Hall/Pinner/Ruderman 1112.2703) for **low-scale mediation**, $\Lambda = 10$ TeV.

Always **at least** a factor of 100 tuning.

DICHOTOMY

Higgs at 125 GeV

Beyond MSSM,
natural

MSSM, tuned with heavy scalars

robust experimental connection

Stop search;
Higgs sector
(rates, decays)

Models?
(NMSSM, D-terms, compositeness....)

Gluino search

Top-down theory

NATURAL SUSY

NATURAL SUSY

Have to complicate the MSSM in two ways:

1. Raise the Higgs mass to 125 GeV. Typically new tree-level interactions.

2. Explain lack of squark signals. Usually splitting 1st/2nd gen from third. Example: $U(2)^3$ flavor models (e.g. 1206.1327 by Barbieri, Buttazzo, Sala, Straub, "less minimal flavor violation")

or hide the decays, so all squarks can be light: e.g. R-parity violation (Barbier *et al.* review hep-ph/0406039, "MFV RPV" by Csaki, Grossman, Heidenreich), stealth supersymmetry (Fan, MR, Ruderman)

125 GEV, NATURALLY

The Higgs mass could be raised to 125 GeV by beyond-MSSM tree-level interactions (quartic terms).

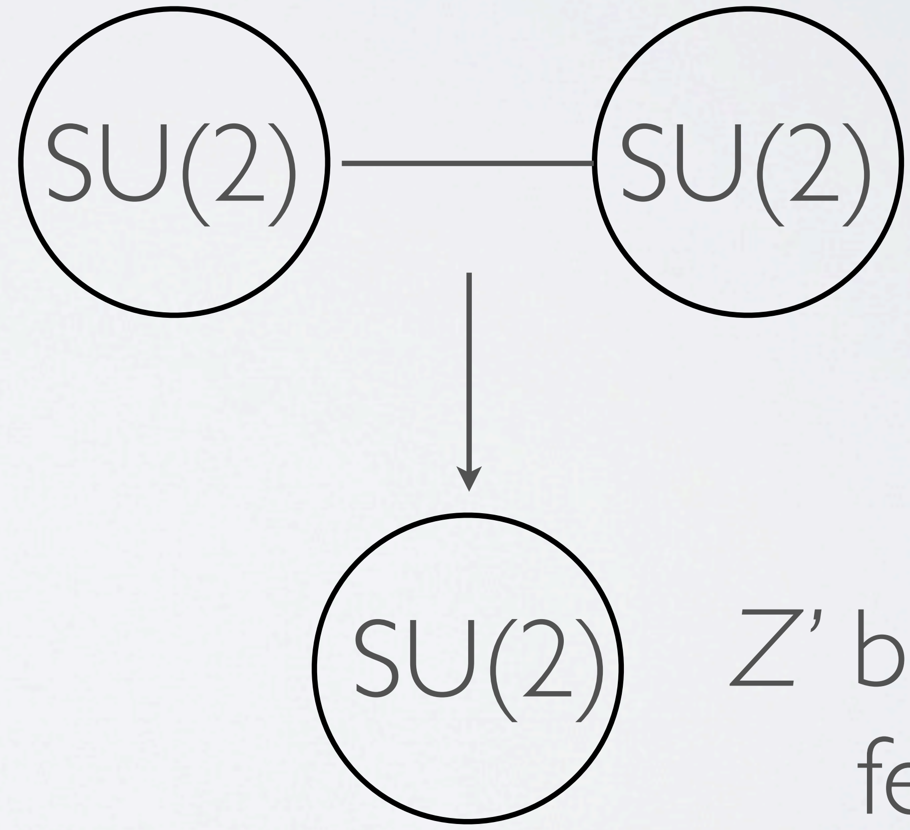
NMSSM / Fat Higgs / lambdaSUSY

$$W = \lambda S H_u H_d + f(S)$$

works best with low-scale compositeness: higher-dim operators around the corner?

Look for more Higgses!

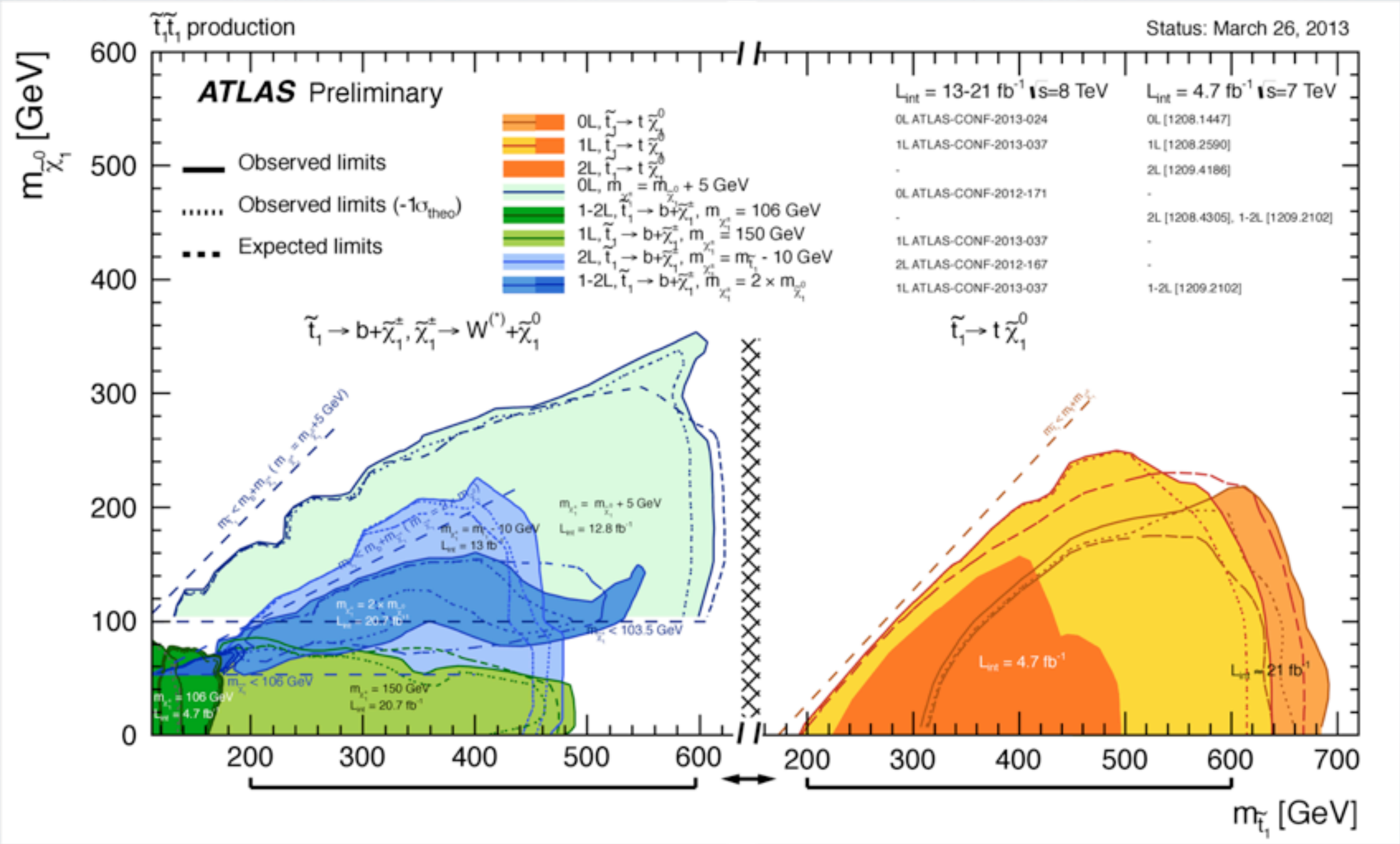
New *D*-terms:



Z' bosons at a few TeV?

DIRECT STOP LIMITS

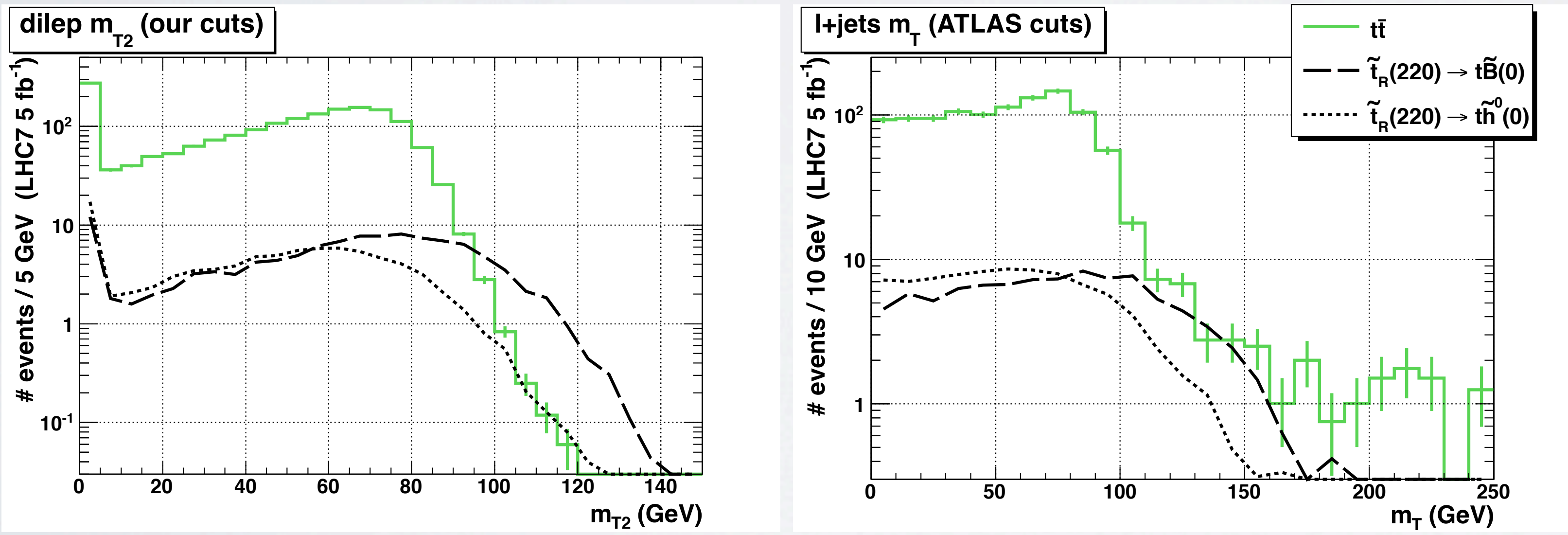
2013 update: ATLAS and CMS are aggressively pursuing the direct signatures of naturalness. **No hints so far.**



TARGETING STOPS
NEXT STEPS

Probe the scalar nature through **spin correlations** or rapidity differences (Z. Han, A. Katz, D. Krohn, MR, 1205.5808)

Allow for **asymmetric decays** $\tilde{t}\tilde{t} \to (t\chi^0)\,(b\chi^+)$
(Graesser, Shelton 1212.4495)

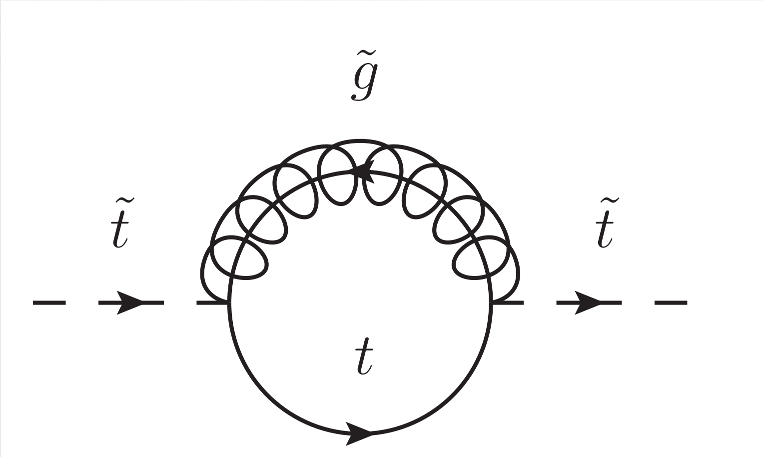


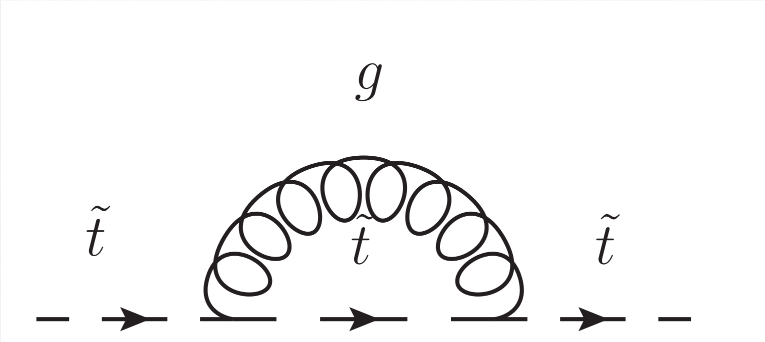
Dileptonic m_{T2}
(Kilic/Tweedie 1211.6106)

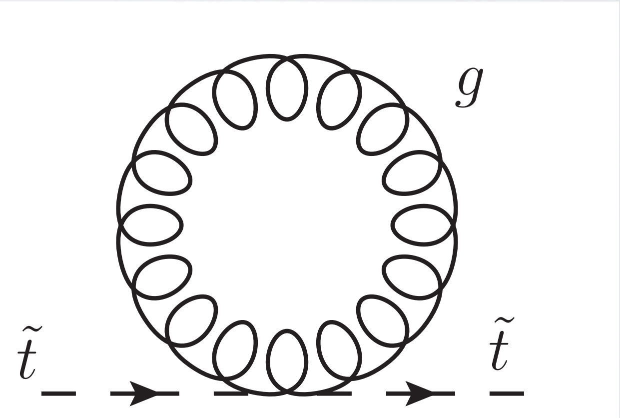
and more, for instance: Plehn et al 1102.0557 & 1205.2696; Bai et al 1203.4813; Alves et al. 1205.5805; Kaplan et al. 1205.5816, ...

NATURALNESS AND GLUINOS

We need the stop to be relatively light for naturalness of a light Higgs. But the stop is *itself* a scalar field, and can get quadratic corrections!



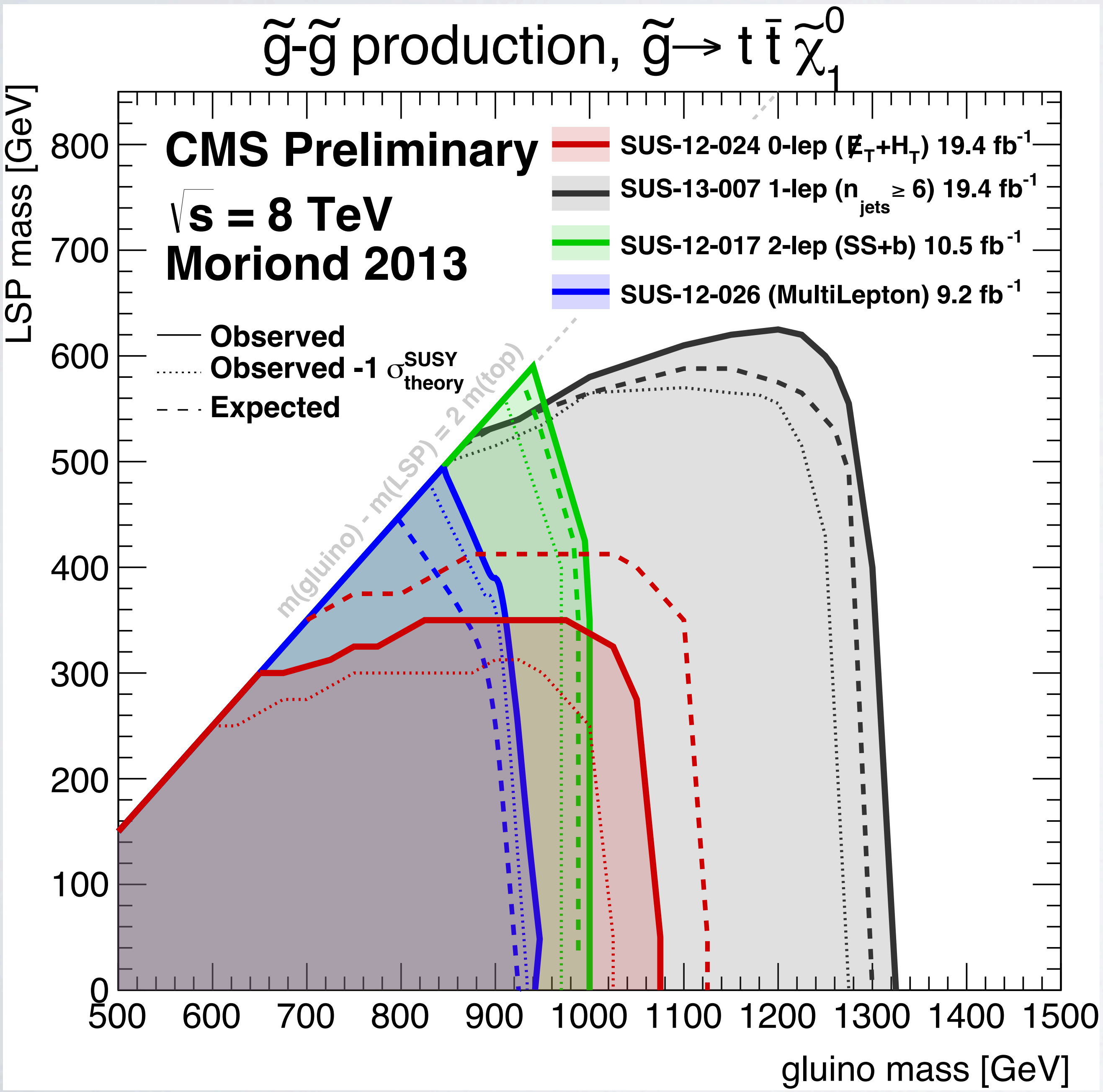


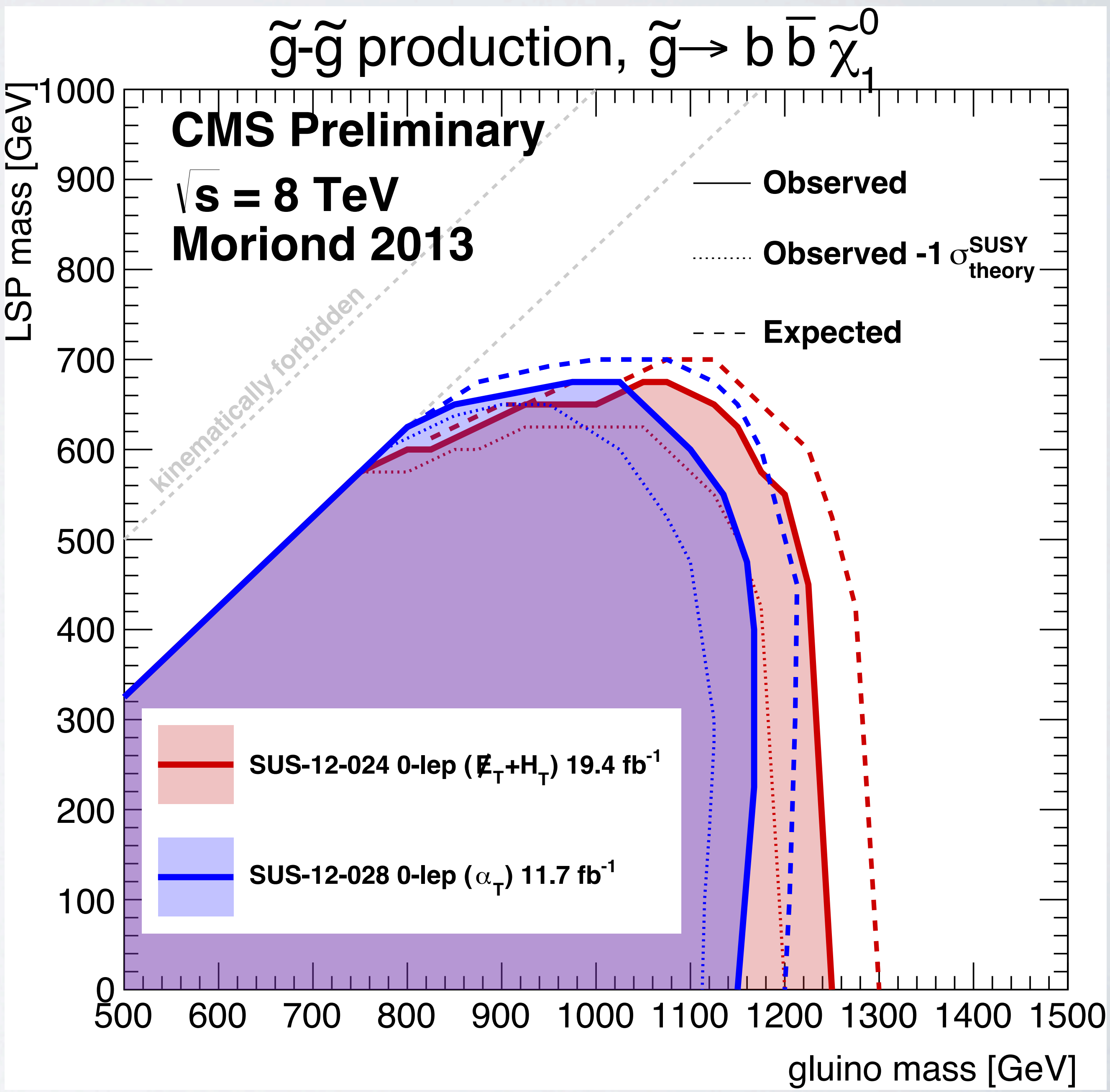


Large corrections come from the **gluino**, which hence should be light (below about 1.5 TeV). As a **color octet**, the gluino has a **large** production cross section at the LHC.

GLUINOS

Gluino mass bounds are now above a TeV; e.g., 1.3 TeV if gluino decays through stops.





NATURAL SUSY: SUMMARY

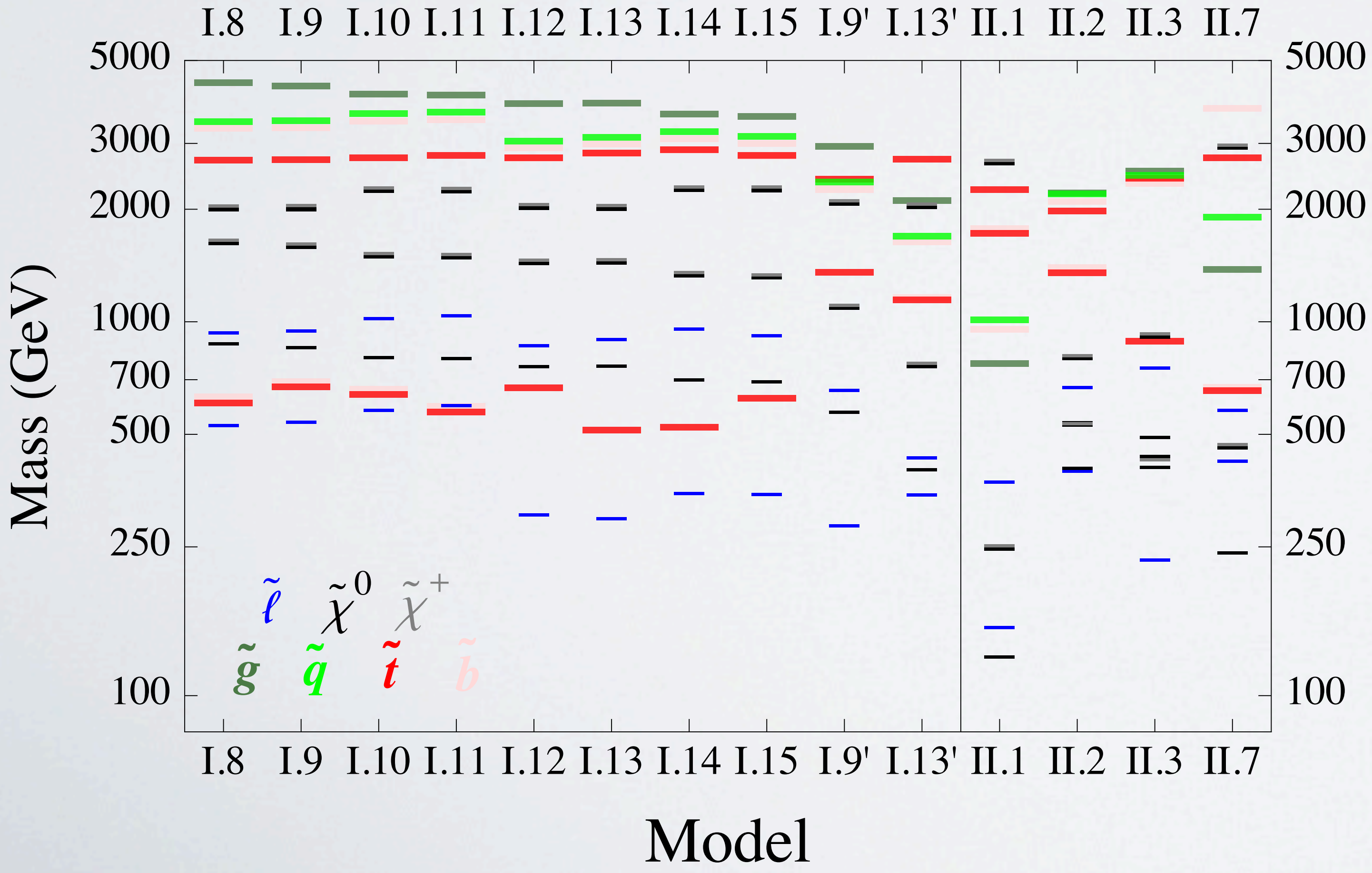
- Requires more complicated model-building: new Higgs interactions, possible flavor problems / new flavor structures
- *those predict signals* -- look for them!
- Standard decay modes of stops, sbottoms, gluinos are being ruled out to uncomfortably high masses. *Look for higgsinos!*
- RPV, stealth, other models could alter decays enough to evade bounds, for now...
- Are we complicating the models so much that they're less appealing than tuning?

UNNATURAL SUSY

MSSM WITH LARGE A-TERMS

The least-tuned corner of the MSSM has large A_t.

This doesn't happen in "General Gauge Mediation," but can happen in extended models that add "Yukawa mediation": new couplings of messengers to matter.



Evans/Shih 1303.0228: spectra of some models. Keep searching for stops and/or gluinos; slepton NLSPs.

SEMI-SPLIT SUSY

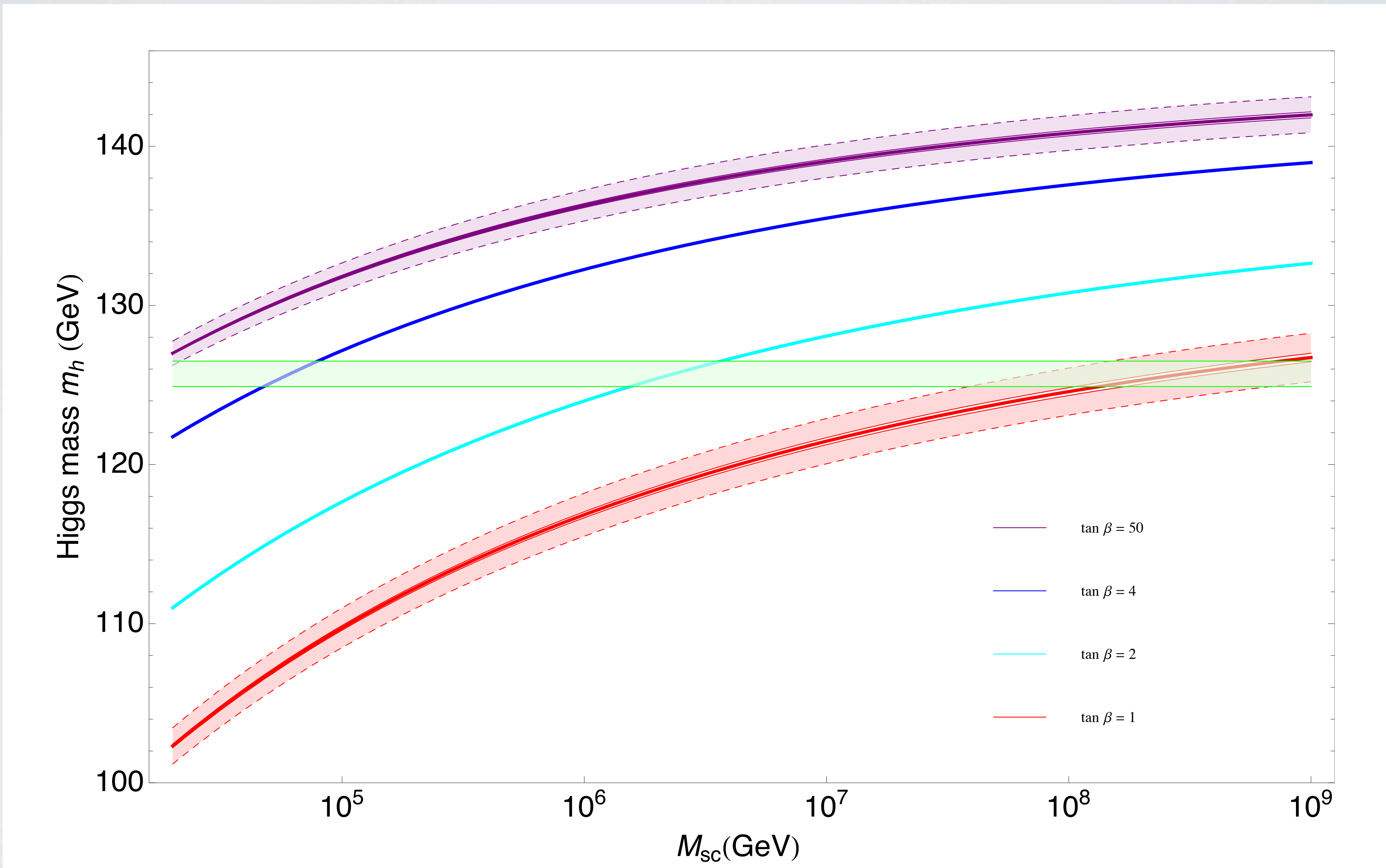
Many models predict $m_{\text{gaugino}} \sim \frac{g^2}{16\pi^2} m_{\text{scalar}}$.

Tuned EWSB. But: solves "most" of hierarchy problem (Planck down to ~100 TeV).

Gauge coupling unification works. SUSY dark matter also possible. **Helps flavor/CP problems.**

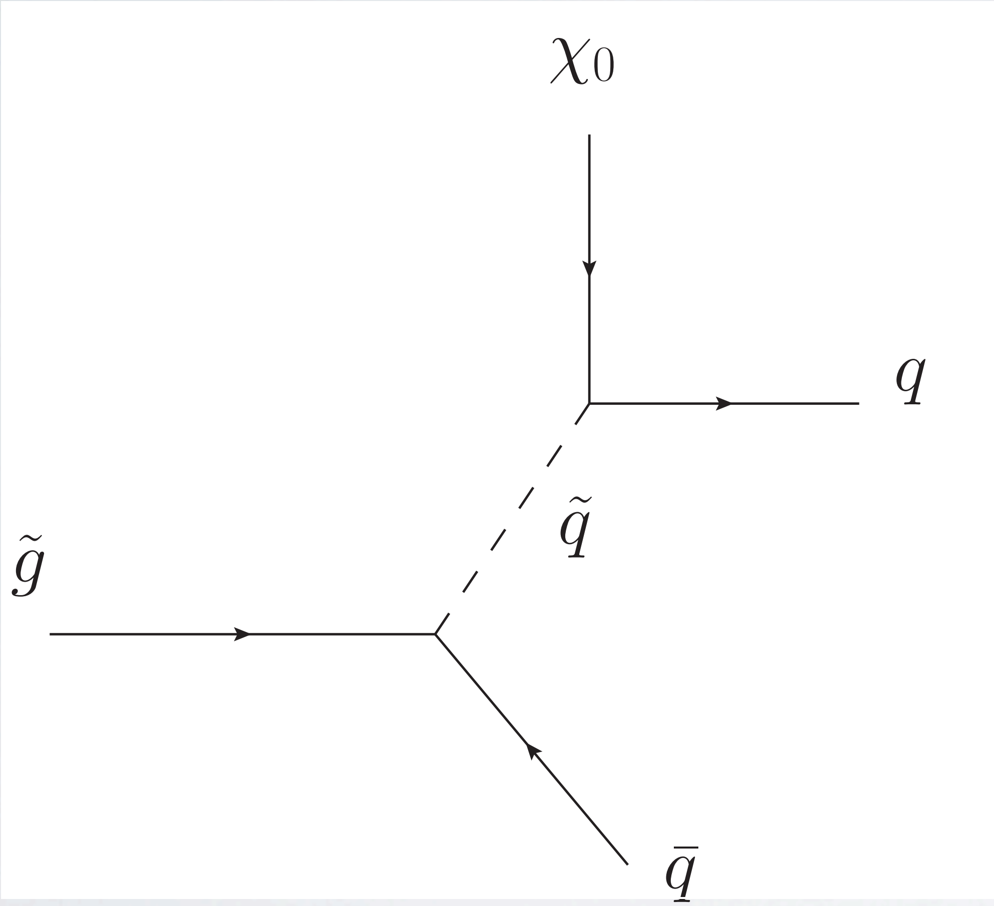
Taken seriously early on by James Wells: hep-ph/0306127. Followed by Arkani-Hamed / Dimopoulos "split SUSY," others....

HIGGS MASS IN SPLIT MODELS



Arkani-Hamed et al 1212.6971; also see Acharya/Kane et al, Arvanitaki et al, Hall/Nomura

POTENTIAL SIGNALS



$$c\tau \approx 10^{-5}\mathrm{m}\left(\frac{m_{\tilde{q}}}{\mathrm{PeV}}\right)^4\left(\frac{\mathrm{TeV}}{m_{\tilde{g}}}\right)^5 .$$

Arkani-Hamed et al 1212.6971

The gluino remains the best bet, possibly with a somewhat displaced vertex.

Also, neutralino dark matter could give signals in direct or indirect detection experiments.

WHY THE HIGH SCALE?

Why couldn't the whole spectrum have been lighter, both semi-split *and* natural? (1 TeV scalars, 1 GeV gauginos)

One possibility: **moduli**, scalar fields interacting with gravitational strength, tend to have mass $m_\phi \sim m_{3/2}$ and decay width $\Gamma_\phi \sim \frac{m_\phi^3}{M_{\rm Pl}^2}$

Coherent moduli oscillations ruin cosmology unless they decay early enough for BBN:

$$T_{\rm reheat} \sim \sqrt{\Gamma_\phi M_{\rm Pl}} \sim 10 \text{ MeV} \Rightarrow m_\phi \sim 100 \text{ TeV}$$

But 100 TeV soft scalar masses imply tuned EWSB!

NONTHERMAL DARK MATTER

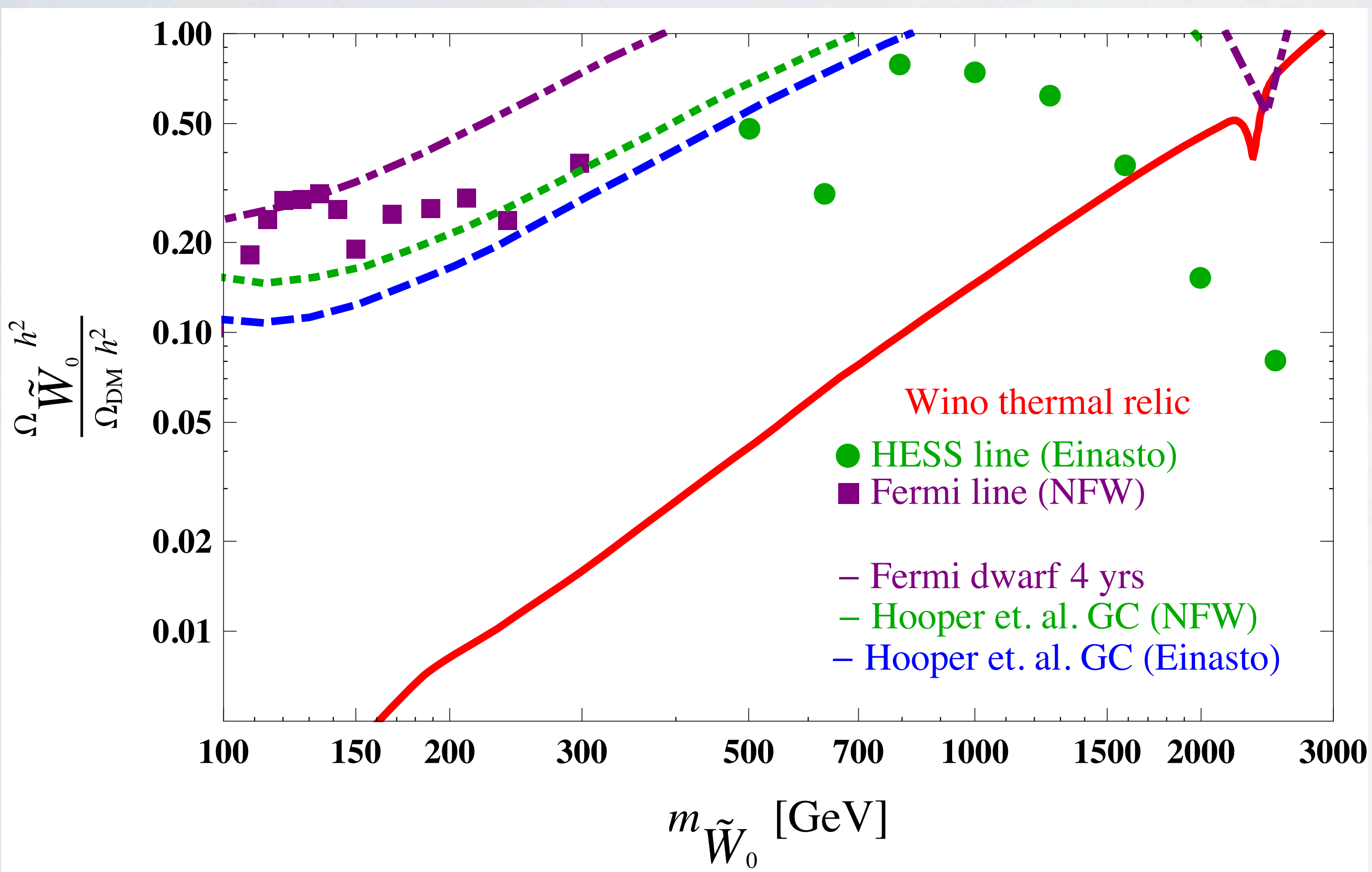
Considering moduli cosmology motivates pairing **semi-split SUSY** with **nonthermal dark matter** generated through moduli decay.

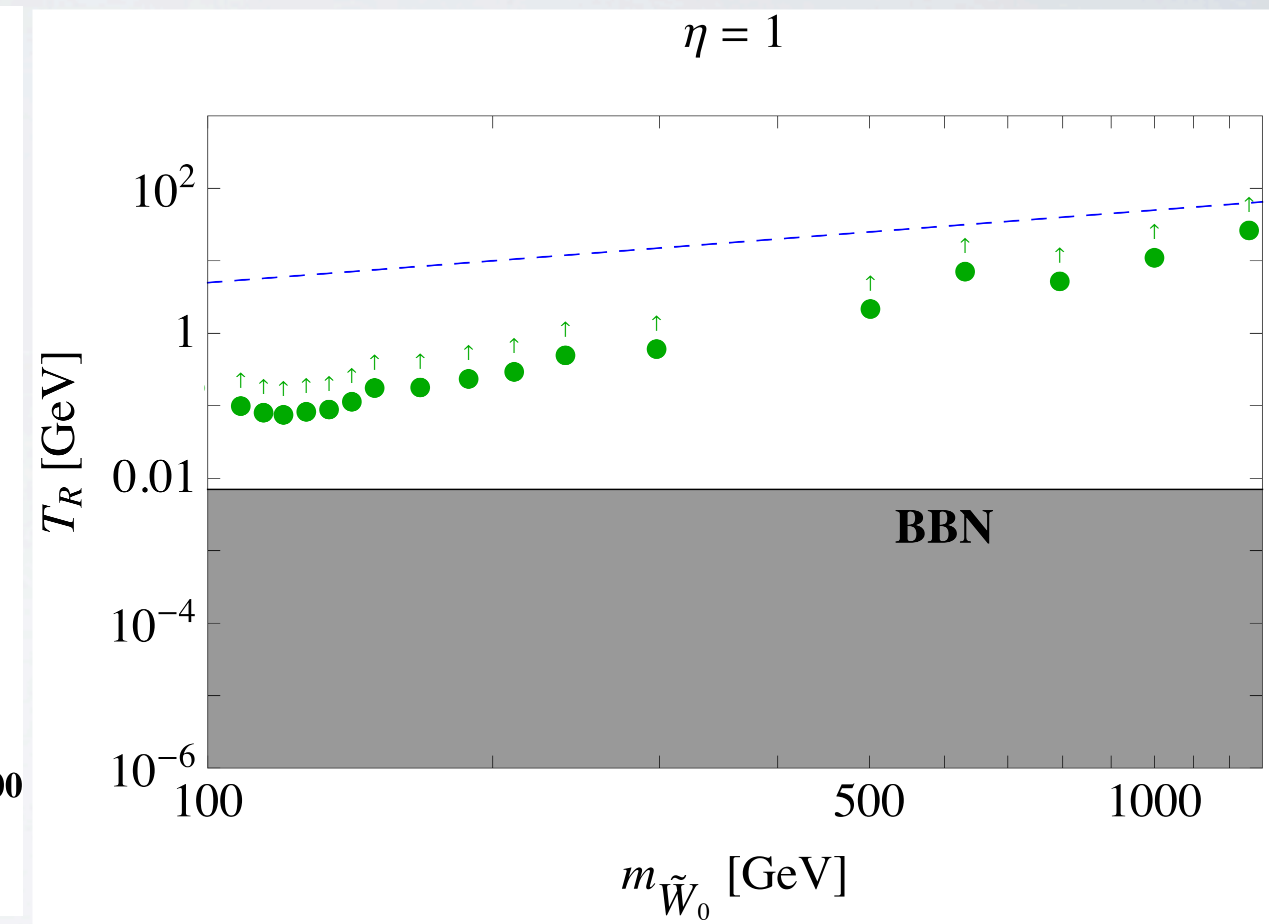
see: Moroi/Randall hep-ph/9906527; J. Kaplan hep-ph/0601262; Gelmini/Gondolo hep-ph/0602230, Acharya/Kane/Kuflik 1006.3272, others....

For given $\langle \sigma v \rangle$, DM abundance is enhanced by a factor of $T_{freezeout}/T_{RH}$. **Ideal for light wino DM**, with large annihilation rate.

IN WINO VERITAS?

Both thermal and nonthermal wino DM are in some trouble from observations of the gamma-ray sky:





Hard not to overproduce DM without *even heavier* moduli, RPV, or more complex cosmology.

Preliminary work in progress, J. Fan and MR.

WHAT'S NEXT?

- If SUSY is right, could well be **beyond the MSSM.** If SUSY is **natural**, it *must* be beyond MSSM.
- Important to keep pushing stop and gluino searches, also broadening to RPV, etc, to really rule out naturalness.
- "Mildly split" SUSY: scalars at ~100 to ~1000 TeV? Now some tension with dark matter / moduli constraints. Add RPV?
- Keep looking for hard-to-find but theoretically motivated options: displaced gluinos, light higgsino, pure higgsino DM....
- Still hoping for more surprises!