NATURALNESS AND SUPERSYMMETRY

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November 11, 2013

I was asked to give an overview of natural supersymmetry. This is a big topic, so I apologize in advance for all the important things I won't have time to say, and for not fully referencing all the literature.

For further reading, I'd point you to Nathaniel Craig's up-to-date review article at arXiv:1309.0528.

TREE-LEVEL NATURALNESS

There is some model-dependence, e.g. in choosing new quartics to lift the Higgs mass or mixing with new singlets/ doublets/triplets. For example, with new $|H_u|^4$ quartic,

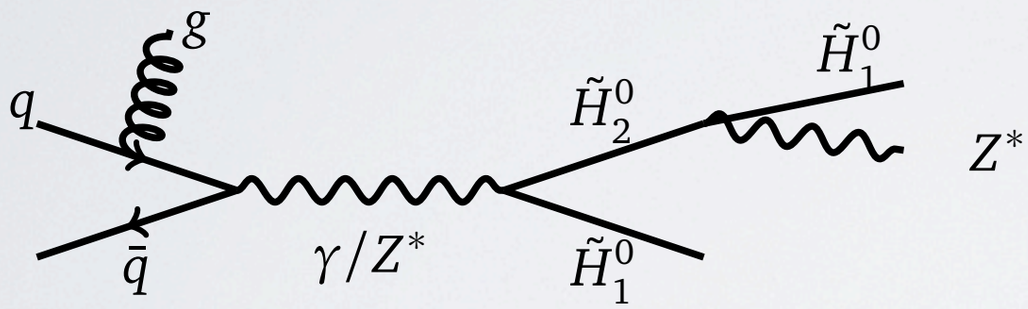
$$\left(m_{H_u}^2 + |\mu|^2\right) - b/t_\beta - m_Z^2 c_{2\beta}/2 + \lambda_u v^2 s_\beta^2 = 0$$

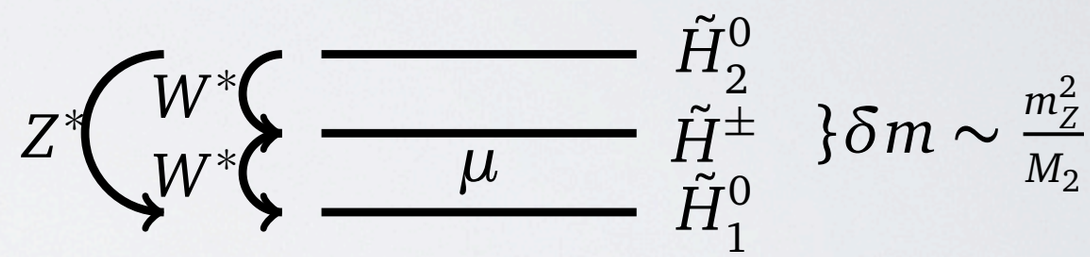
$$\left(m_{H_d}^2 + |\mu|^2\right) - b t_\beta + m_Z^2 c_{2\beta}/2 = 0$$

Learn: **higgsinos** must be light; at large tan beta, heavy Higgses ($H^{0,+,-}, A^0$) can be heavy, but at order-one tan beta (e.g. NMSSM / **λ**SUSY), naturalness also requires the **heavy Higgses** to be light.

HIGGSINOS

A natural spectrum should have light higgsinos, but the wino and bino might be significantly heavier. It's important to try to directly probe the higgsino states.

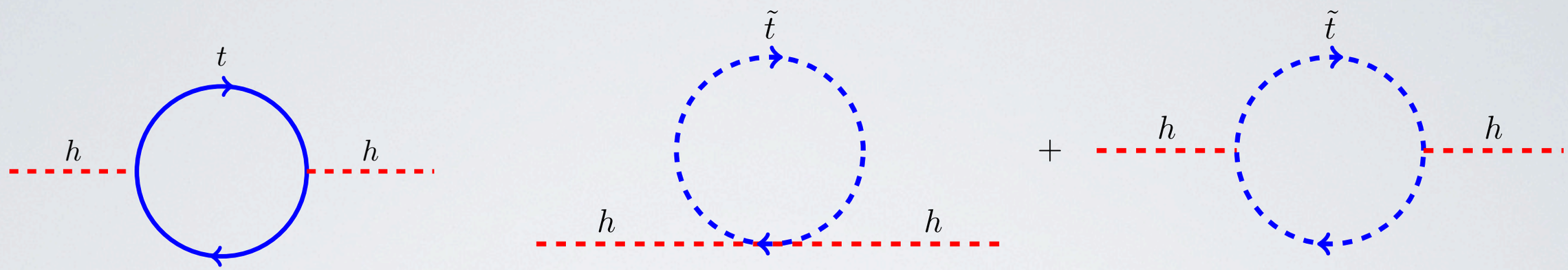




Slightly different masses: split by a dim-5 operator.

Monojet or VBF to tag the event, plus soft leptons from off-shell Z or W could be useful.
No strong constraints so far. Important to fill in!

1-LOOP NATURALNESS



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

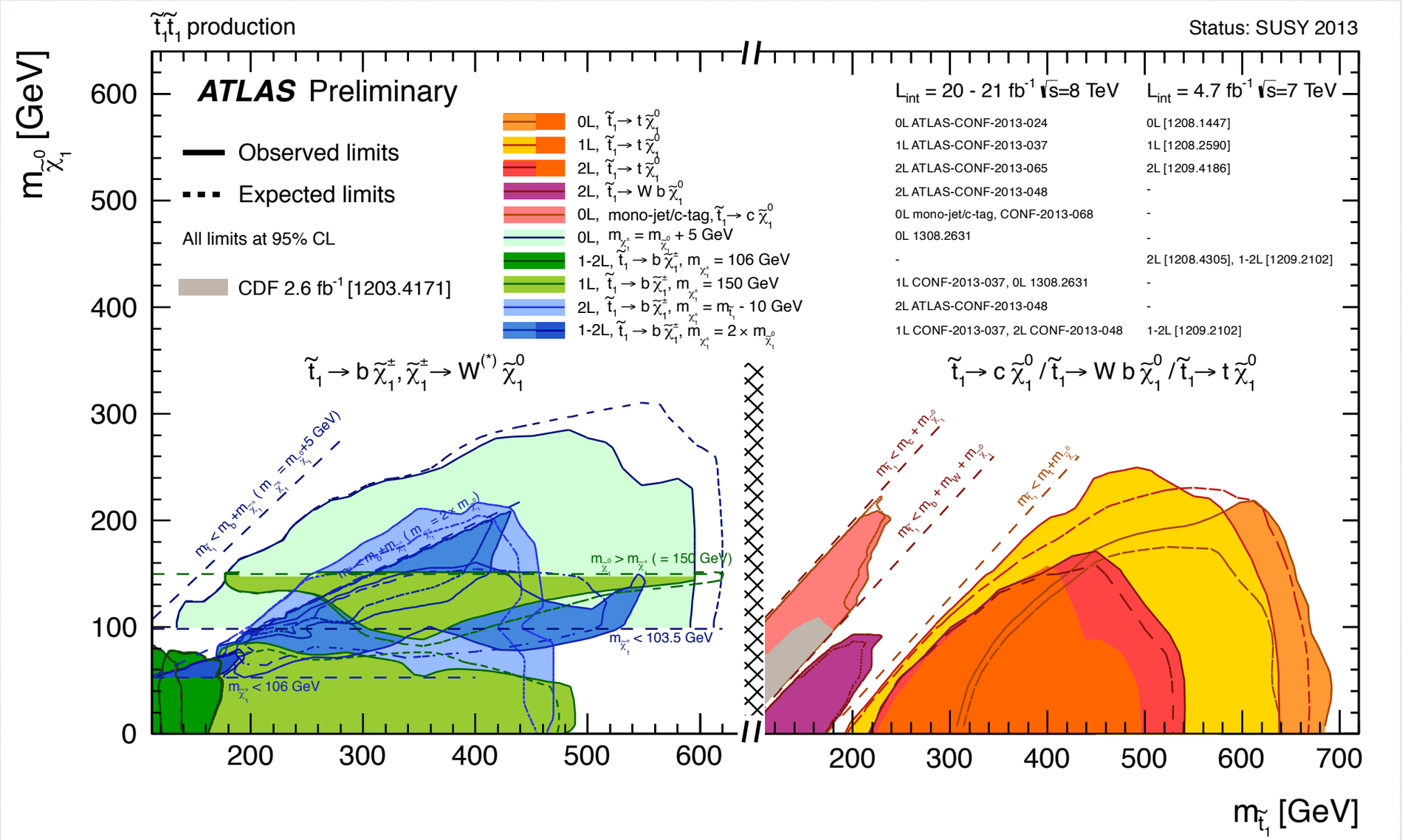
$$\delta m_{H_u}^2 = -\frac{3}{8\pi^2} y_t^2 \left(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + |A_t|^2 \right) \log \frac{\Lambda}{\mathrm{TeV}}.$$

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.)

DIRECT STOP LIMITS

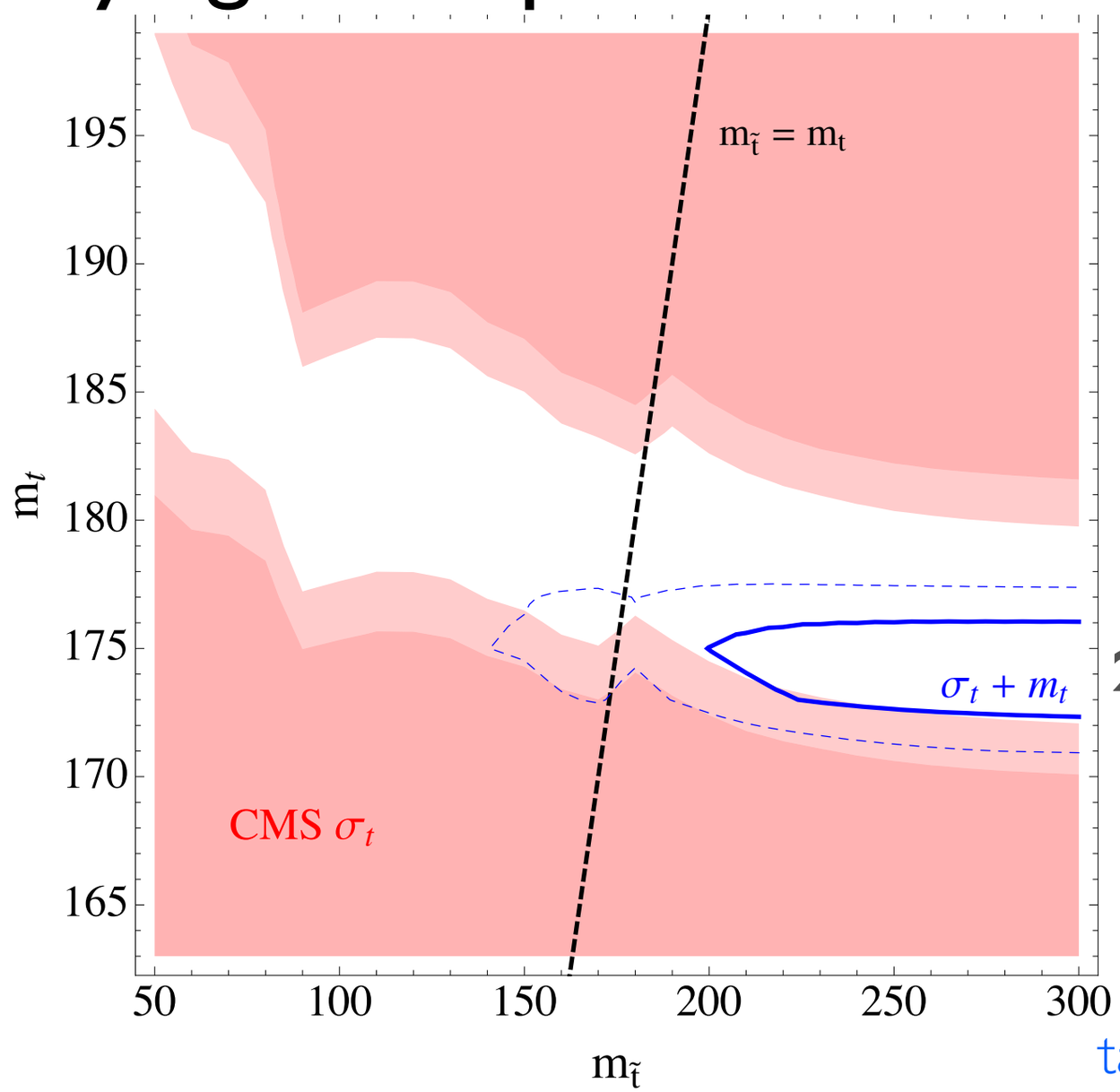
ATLAS and CMS are aggressively pursuing the direct signatures of naturalness. **No hints so far.** Could the stops be hiding?



via Josh Ruderman, NNLO theory applied to SUSY:

stop + top

varying the top mass:



LHC top mass
(5/fb)

$$173.3 \pm 0.5 \pm 1.3 \text{ GeV}$$

2 and 3 sigma contours

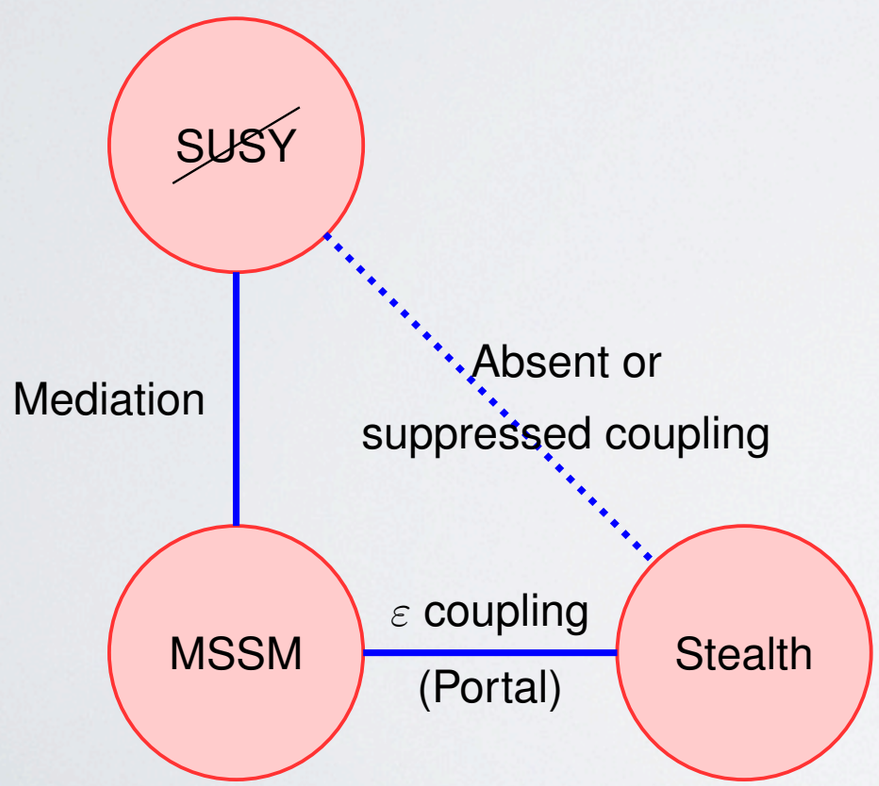
what is m_t in the presence of stop contamination?

take blue curve as guide to what might be accomplished when this is answered

Czakon, Mitov, Papucci, JTR, Weiler, *to appear.*

STOPS IN STEALTH SUSY

Unlike the minimal "stealthy stop" scenario, $\tilde{t} \to t\tilde{\chi}^0$ with the stop mass just above the top mass, here we mean a cascade through a stealthy "hidden sector."

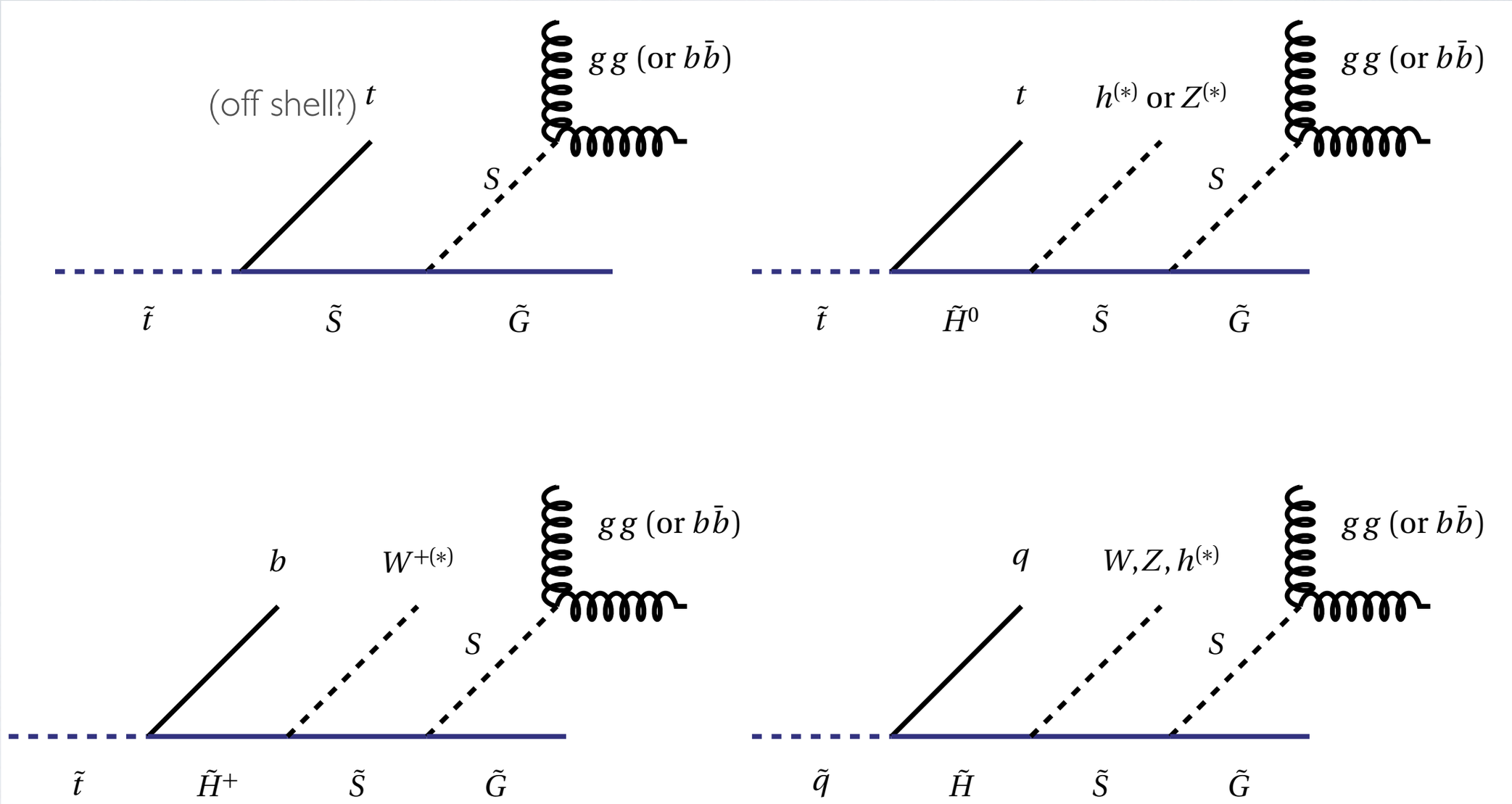


$$M_{\rm SUSY} \sim M_{\rm EWK}$$

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

Inside the hidden sector, a near-degeneracy of *R*-odd and *R*-even particles (due to approximate SUSY) leads to small missing momentum.

STOPS IN STEALTH SUSY

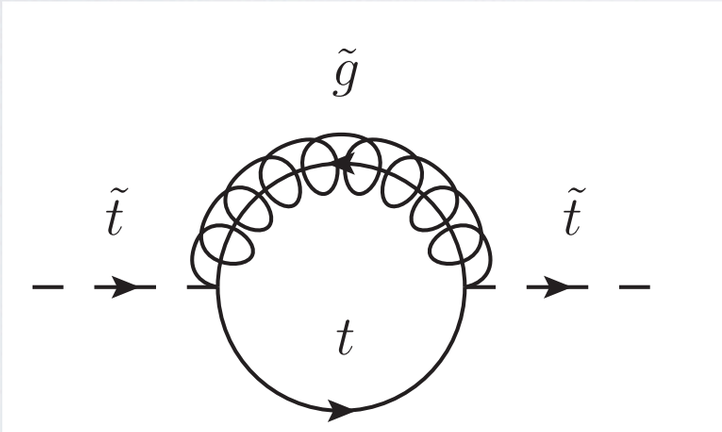


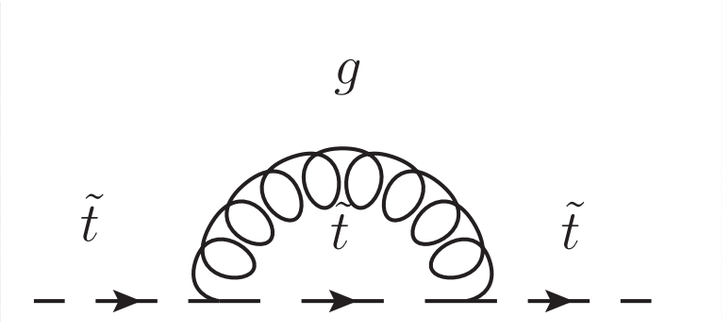
In stealth SUSY models, the signal of stops might be tops + extra jets (possibly with weak bosons). Also 1st, 2nd gen squarks: many-jet events, possibly with weak bosons.

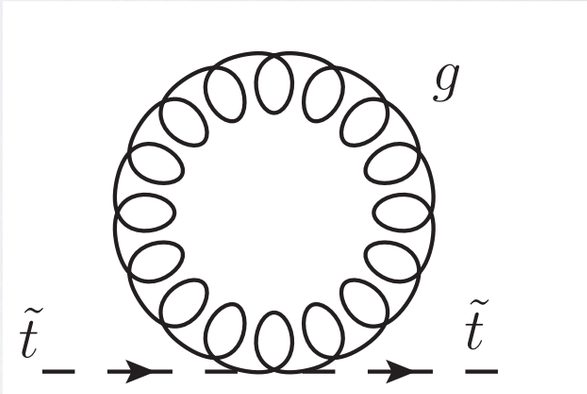
(Limits already exist by recasting: J. Fan, R. Krall, D. Pinner, MR, J. Ruderman, work in progress)

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!



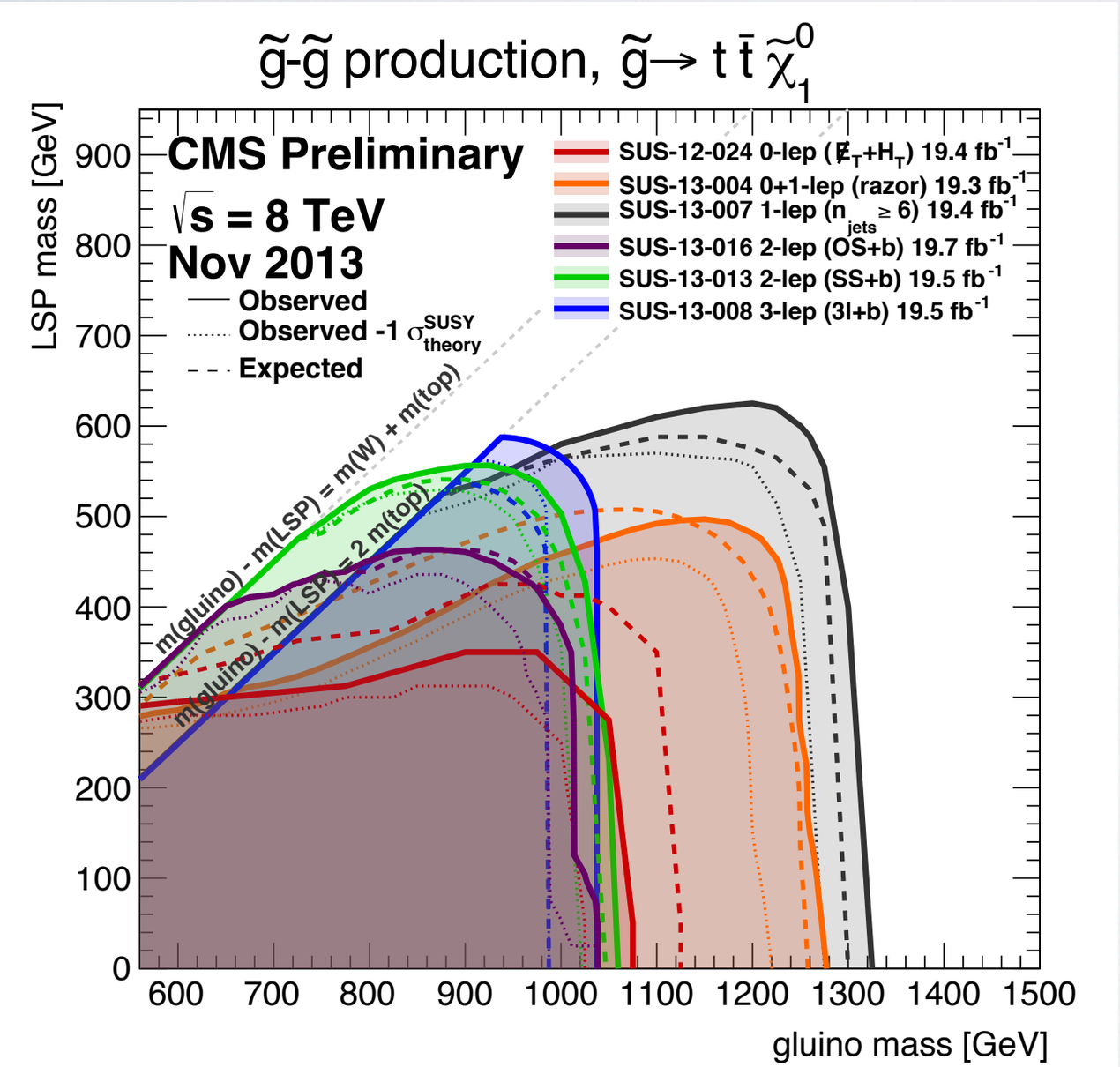


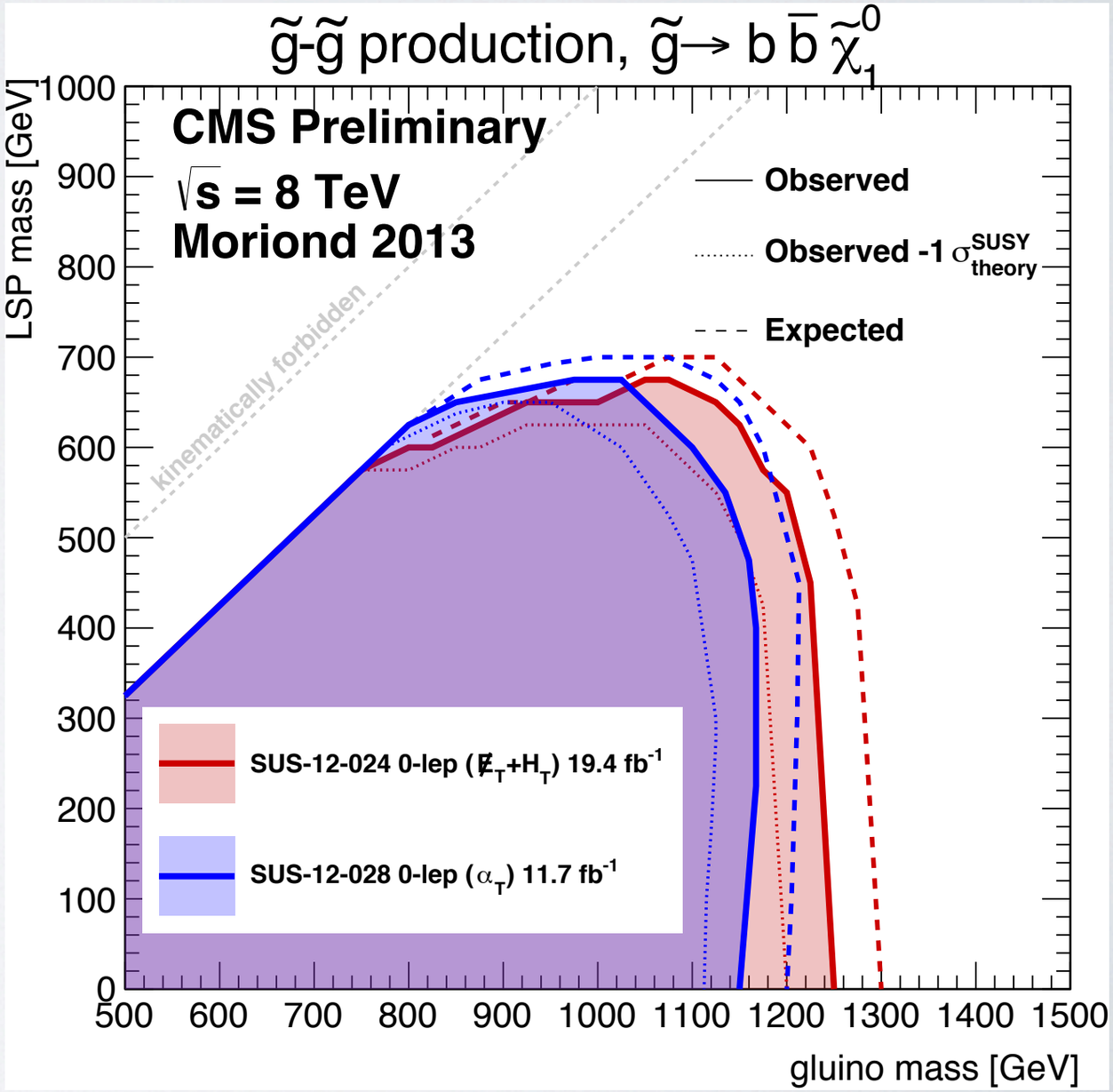


Large corrections come from the **gluino**, which hence should be light (below about 1.5 TeV). As a **color octet**, the gluino has a **large** production cross section at the LHC.

GLUINOS

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





INDIRECT CONSTRAINTS

Direct searches are powerful and exclude much of the expected natural parameter space. However, they fail if the decay modes change (e.g. stealth, RPV) or the theory changes significantly (e.g., Dirac gluinos are less tied to naturalness).

Naturalness is all about the Higgs boson, so another avenue is open to us: use measured Higgs properties to indirectly constrain naturalness. The SM Higgs is not natural, so *a natural Higgs will always differ from an SM Higgs*.

HIGGS COUPLINGS

The Higgs-gluon-gluon and Higgs-photon-photon couplings are related to beta function coefficients:

(Shifman et al.)

View mass thresholds in RG as spatially-varying.

In particular, if $M(x)$ depends on the Higgs, $M = M(h(x))$, then we extract an effective coupling:

$$\frac{\Delta b}{32\pi^2} h G^a_{\mu\nu} G^{a\mu\nu} \frac{\partial \log M(v)}{\partial v}$$

If a particle's mass increases with larger Higgs VEV, contributes with sign of top loop. But *mixing* can alter the sign.

STOPS

$$M^2_{\tilde{t}} = \begin{pmatrix} \tilde{m}^2_Q + \left(y_t^2 + \mathcal{O}(g^2)\right) v^2 & y_t v \sin\beta X_t \\ y_t v \sin\beta X_t & \tilde{m}^2_u + \left(y_t^2 + \mathcal{O}(g'^2)\right) v^2 \end{pmatrix}$$

Here $X_t = A_t - \mu \cot\beta$, the O($g^2$) parts are D-terms I will hereafter ignore, and the key point is that **the Higgs VEV appears in both diagonal and off-diagonal terms.**

For large soft masses:

$$\frac{1}{2}\frac{\partial \log\det M^2_{\tilde{t}}}{\partial v} \sim y_t m_t \frac{\tilde{m}^2_Q + \tilde{m}^2_u - X_t^2 \sin^2\beta}{\tilde{m}^2_Q \tilde{m}^2_u - X_t^2 m_t^2 \sin^2\beta}$$

STOPS

Things to note:

$$\frac{1}{2}\frac{\partial \log\det M_{\tilde{t}}^2}{\partial v} \sim y_t m_t \frac{\tilde{m}_Q^2 + \tilde{m}_u^2 - X_t^2 \sin^2\beta}{\tilde{m}_Q^2 \tilde{m}_u^2 - X_t^2 m_t^2 \sin^2\beta}$$

Small numerator factor (for heavy stops): decoupling

Minus sign: large mixing leads to opposite-sign couplings

If the measured correction is small, *either* stops are heavy, or we have fine-tuned the correction:

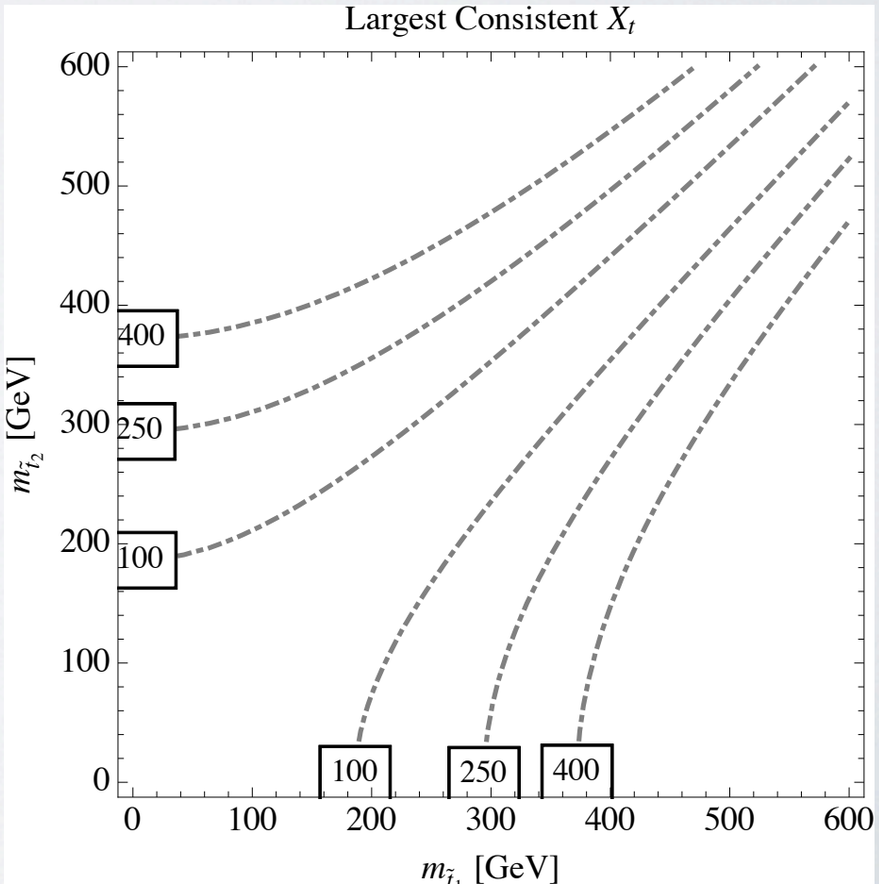
$$X_t^2 \sin^2\beta \gg \tilde{m}_Q^2 + \tilde{m}_u^2 - X_t^2 \sin^2\beta$$

LEFT/RIGHT STOP MIXING VS. MASS EIGENVALUES

The difference of two *physical* stop mass^2 eigenvalues is a sum of two positive definite quantities:

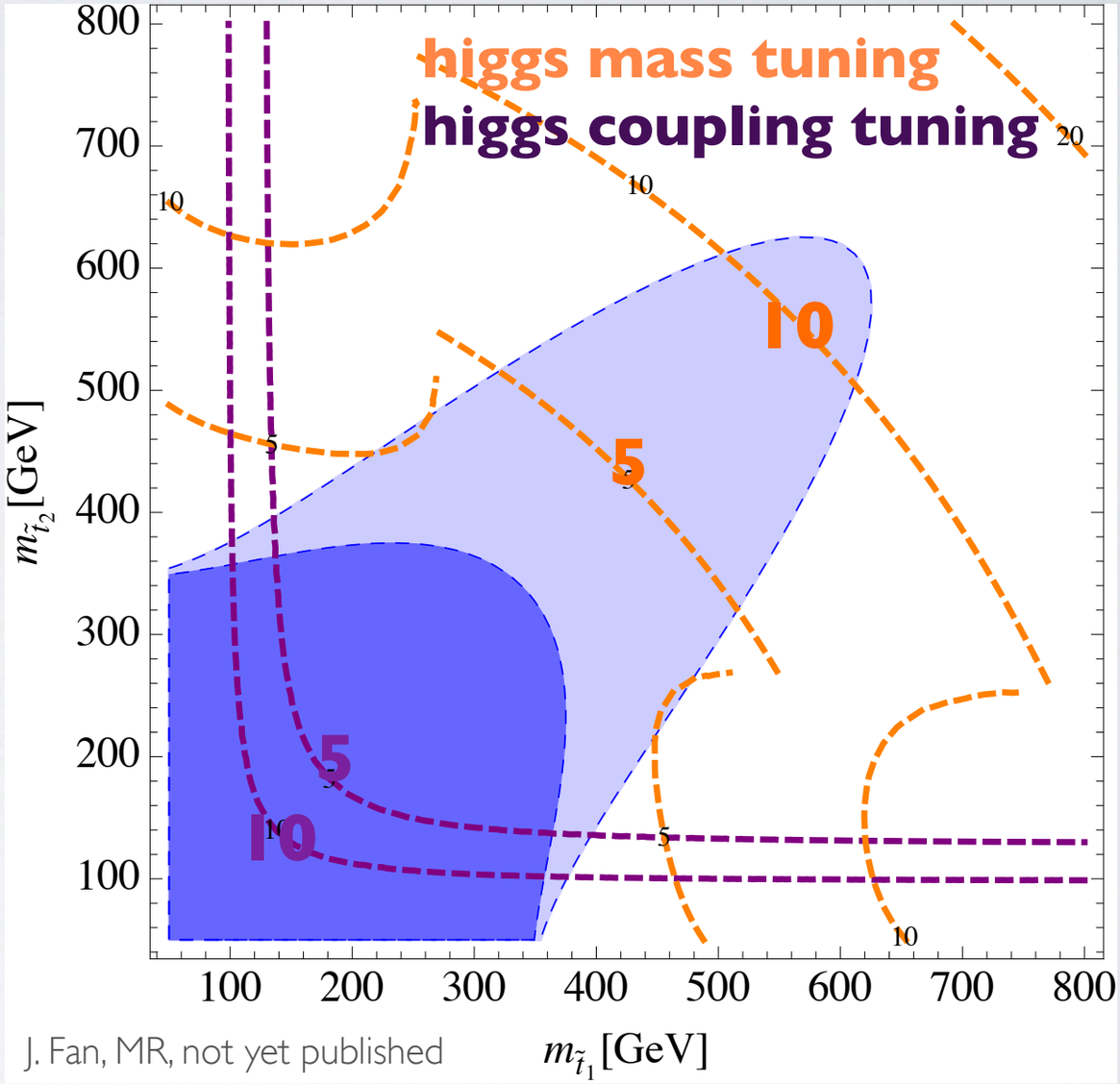
$$\left(m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2\right)^2 = \left(m_{\tilde{Q}_3}^2 - m_{\tilde{u}_3^c}^2 + m_Z^2\left(\frac{1}{2} - \frac{4}{3}\sin^2\theta_W\right)\cos(2\beta)\right)^2 + 4m_t^4 X_t^4 \sin^4\beta$$

Thus, anywhere in the $\left(m_{\tilde{t}_1}, m_{\tilde{t}_2}\right)$ plane, there is a largest consistent X_t (0 on the diagonal.)



STOP BOUNDS FROM HIGGS

Fitting data with light stops requires a *minimum* X_t to cancel the correction. Part of parameter space is simply ruled out because this minimum is inconsistent with the eigenvalues. More space is tuned, either to get the Higgs coupling right, or the usual 1-loop Higgs mass tuning.



J. Fan, MR, not yet published

Even without direct searches, know stop/Higgs tuned by factor ~ 5 or more.

Impact of N^nLO K-factors?

HIGGS MEASUREMENTS

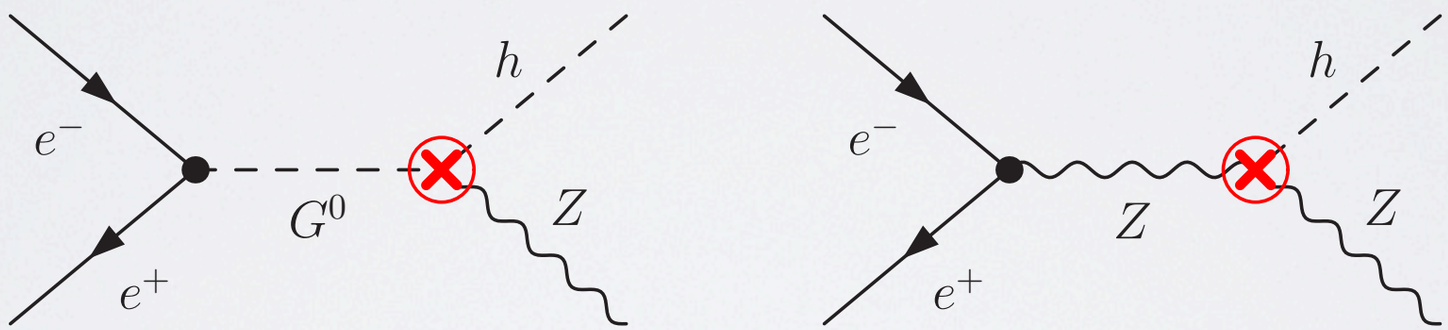
One of the most challenging conceivable natural scenarios is one in which the top partners do not have QCD color. "Folded Supersymmetry" (Burdman, Chacko, Goh, Harnik hep-ph/0609152) is an existence proof for such theories.

It can be extremely challenging to directly probe these theories. But Folded SUSY top partners still have electroweak quantum numbers and affect $h \to \gamma\gamma$ decays. An argument just like the one we've just considered could eventually rule out natural Folded SUSY. But need better measurements (ILC? TLEP?).

A "NO-HIDE" THEOREM?

Model builders can build increasingly byzantine constructions to hide natural physics from direct searches, but *anything enforcing naturalness must couple to the Higgs*.

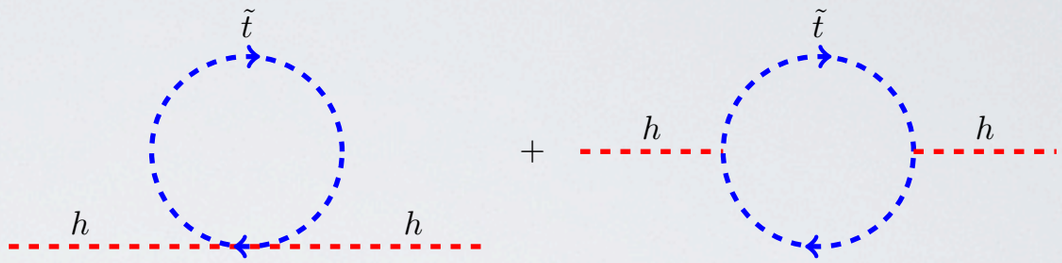
Craig, Englert, McCullough 1305.5251:



Anything that modifies the Higgs wave function renormalization (anything coupling to the Higgs) should alter the *Zh* associated production rate. TLEP could rule out naturalness at the 10%-tuned level.

125 GEV HIGGS AND SUSY

MSSM must be tuned to fit 125 GeV:



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

Haber, Hempfling '91

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

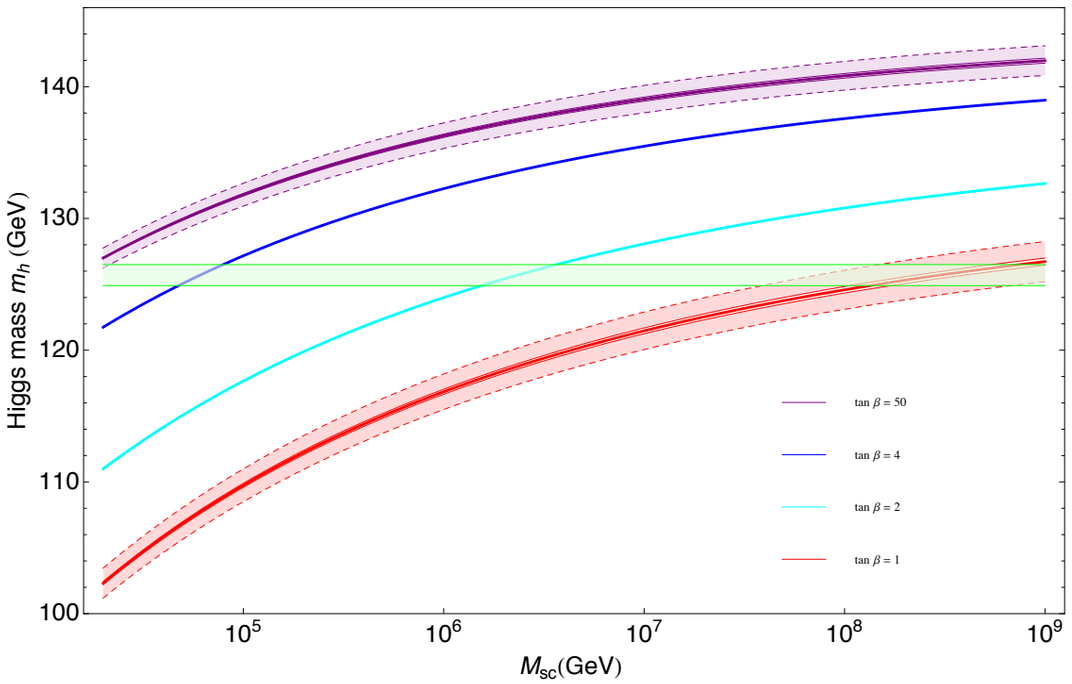
Higgs at 125 GeV

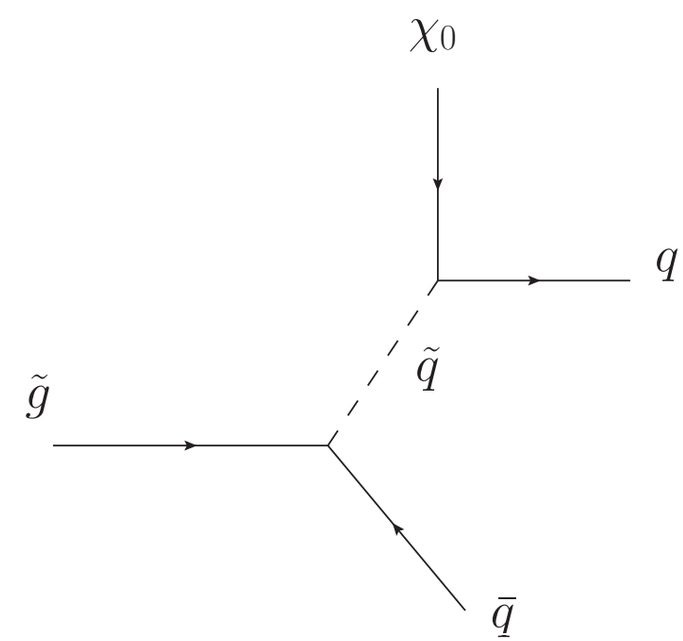
Beyond MSSM, *natural*: new D-terms? NMSSM?

MSSM, tuned with heavy scalars

MILDLY SPLIT SUSY?

Many scenarios predict scalars heavier (e.g., by a loop factor) than gauginos. **Tuned EWSB.** But, solves most of the hierarchy problem (Planck to 100 TeV, e.g.), helps flavor/CP problems, keeps gauge coupling unification. First taken seriously by James Wells: hep-ph/0306127





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

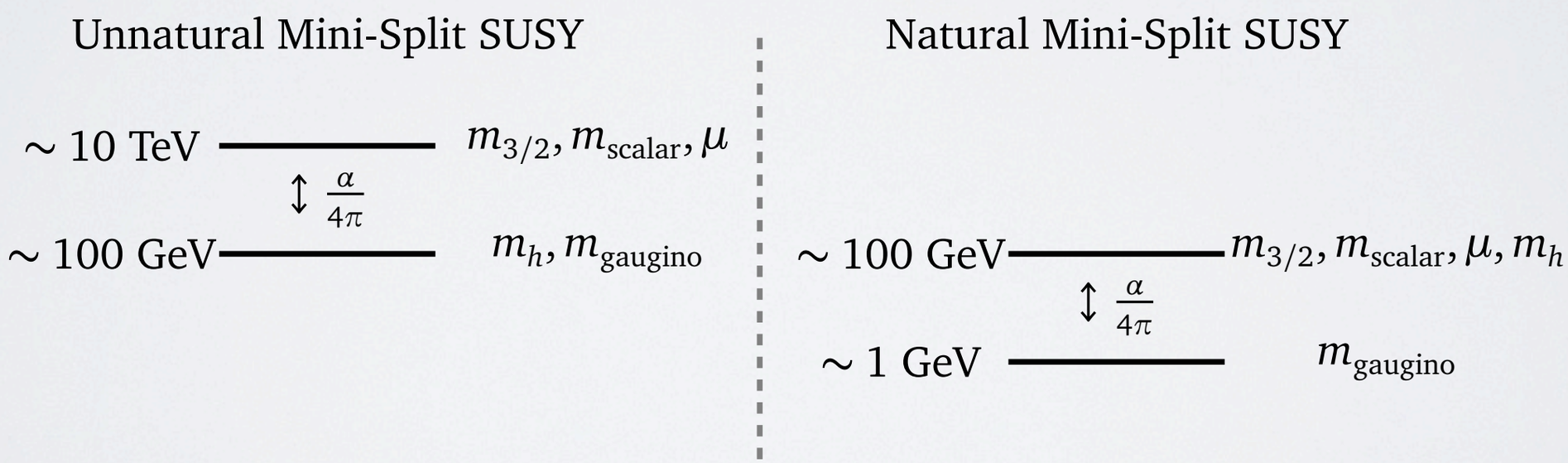
Arkani-Hamed et al 1212.6971; also see Acharya/Kane et al, Arvanitaki et al, Hall/Nomura

A QUESTION FOR MINI-SPLIT

It's very plausible that SUSY-breaking happens in such a way that:

$$m_{\rm scalar} \approx m_{3/2}, \; m_{\rm gaugino} \approx \frac{\alpha}{4\pi} m_{3/2}$$

(e.g. anomaly mediation with no sequestering). But why isn't the world split *and* natural?



An anthropic argument for living in the world on the left vs the right is not obvious. Linked to cosmology? Moduli?

OPINIONS

If naturalness were the right explanation for the weak scale, I think we would have seen signs of it by now.

Doesn't mean naturalness is irrelevant, e.g.:

anthropics $\longrightarrow$ (BBN? dark matter?)

minimal tuning? (10 TeV?)

naturalness $\longleftarrow$ scalar masses

If we're going to rule strict naturalness out---and this *is* an important goal---we should be thorough and careful about it, considering even some of the more contrived models. Let's not overlook a discovery due to our preconceptions!

SUMMARY

Searches for stops & gluinos have put strong bounds on natural SUSY. Higgs coupling measurements are also beginning to be important constraints.

Various things I'd like to see more of:

- Strong effort to find Higgsino LSPs.
- Set limits on simplified models with hidden sectors (e.g. stealth SUSY).
- On the theory end: can we make a more appealing Folded SUSY-like model? How would we search for it?
- If the right answer is unnatural, do we understand *why*? What does this tell us?