Higgs Beyond the Standard Model: Expectations in Strongly vs Weakly Interacting Theories

Matthew Reece
Harvard University
at Higgs Couplings, Freiburg, October 2013

The organizers asked me 'to present a REVIEW TALK about "Strongly interacting physics versus weakly interacting SUSY and/or non-SUSY approaches"'

A big topic! There are many new physics models of both types.

I'll discuss the two general ideas I think are most plausible: composite Higgs and SUSY.

Both are becoming at least moderately tuned in light of data.

A COMPOSITE HIGGS

A generic composite Higgs would come with many other composite resonances. So we usually consider composite Higgses that are ***pseudo-Nambu-Goldstone*** bosons.

(Georgi, Kaplan 80s; recent review: R. Contino, 1005.4269)

$$G \xrightarrow[f]{} H$$

E.g. SO(5) $\rightarrow$ SO(4): one complex Higgs doublet.

EWSB FOR COMPOSITES

A potential is generated for the Higgs by *G*-violating couplings. Usually this is done with elementary top quarks coupled to composite top-like fermions.

$$V(h) \sim \frac{a\lambda^2}{16\pi^2}\cos(h/f) + \frac{b\lambda^2}{16\pi^2}\sin^2(h/f)$$

Both terms contain h^2 and h^4 pieces, so $v << f$ is always a *tuning*: $-2\cos(h/f) - (1+\epsilon)\sin^2(h/f) \Rightarrow \langle h \rangle^2 \approx 2\epsilon f^2$

(Exception: "little Higgs" theories with extended symmetry structure.)

Expect *v/f* corrections to be large, if EWSB is natural.

WHERE IS THE SCALE?

Before even looking at Higgs properties, we had strong bounds on the composite scale, e.g. from the *S*-parameter:

$$\sim \frac{1}{m_\rho^2} H^\dagger \sigma^i H W^i_{\mu\nu} B^{\mu\nu}$$

or $S \approx 4\pi(v/m_\rho)^2$. This puts the resonance masses at about 3 TeV or above.

Implies some tuning, e.g. the quadratically divergent *W* loop:

$$\delta m_h^2 \approx \frac{9}{64\pi^2} g^2 m_\rho^2 \gtrsim (250\ \mathrm{GeV})^2$$

Also via $m_\rho \sim 4\pi f/\sqrt{N}$ it means minimum factor ~3 tree-level tuning of the Higgs potential.

COMPOSITE HIGGS COUPLINGS

The lighter the composites, the more they affect Higgs couplings. E.g. coupling to vectors (see e.g. recent Azatov/Galloway review 1212.1380):

$$a = \frac{g_{VVh}}{g_{VVh^{(\mathrm{SM})}}} = \sqrt{1 - \frac{v^2}{f^2}}.$$

Given the *S*-parameter bound on *f*, this correction ends up at ~6% for $N = 3$ and $m_\rho = 3$ TeV. So it's not surprising there's no deviation observed.

Interestingly, Goldstone shift symmetry favors larger deviations in $Z\gamma$ than $\gamma\gamma$ or gg. Choose good basis: $O_{HW} = \frac{ig}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu}$
(Giudice et al. hep-ph/0703164; Montull et al. 1308.0559; Azatov et al. 1308.2676)

A LESSON?

Strongly-interacting new physics predicts a large set of new higher-dimension operators, many of which were already highly constrained. May have a large "footprint" in terms of signals showing up across a number of channels.

Weakly-interacting new physics can predict more localized discrepancies. Because of this, Higgs measurements so far may tell us more *new* information about weakly-interacting new physics than strongly interacting new physics (which was already quite constrained).

WHY LIGHT TOP PARTNERS?

Elementary/composite mixing for top: $\lambda_L q_L \mathcal{O}_R + \mathrm{h.c.}$

Puzzles: 1. need large top Yukawa; operator of dim 5/2?

2. why a light bound state?

P: $x_1 \to -x_1, \quad \psi(x_1) \to \gamma_1 \psi(-x_1), \quad \bar{\psi}(x_1) \to -\bar{\psi}(-x_1)\gamma_1$

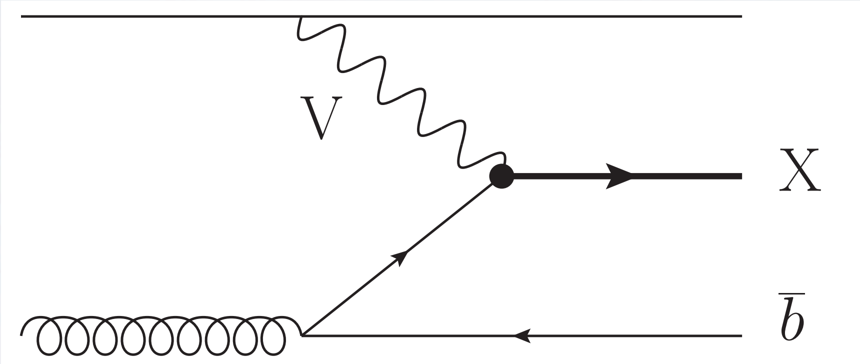
"Bulk naturalness puzzle": 5D fermions are unprotected by chiral symmetry. Mass terms violate *parity*, but it's broken by heavier masses. Why a light bulk fermion? (6D? 10D?)

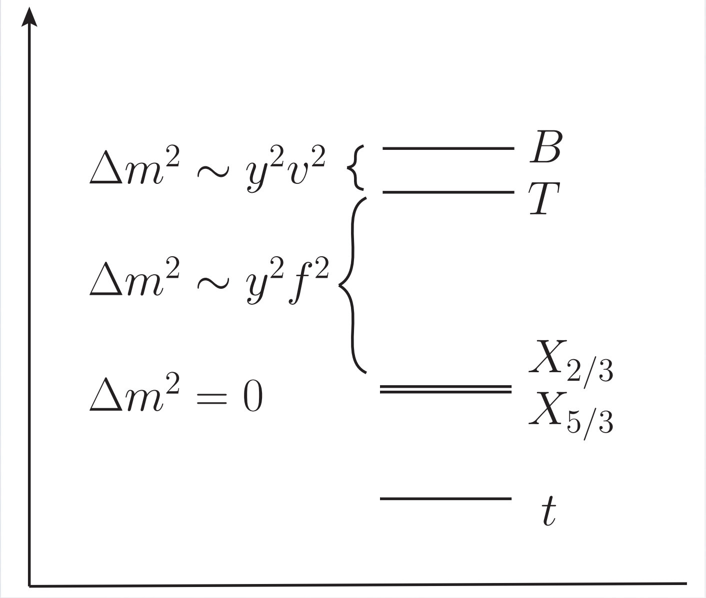
(Could have light bound states from anomaly matching: example in hep-ph/0312287, "A Composite Little Higgs Model," by E. Katz, J. Lee, A. Nelson, D. Walker)

FERMIONIC TOP PARTNERS

recent survey of models / limits in 1211.5663: de Simone, Matsedonskyi, Rattazzi, Wulzer

Single production can be important:





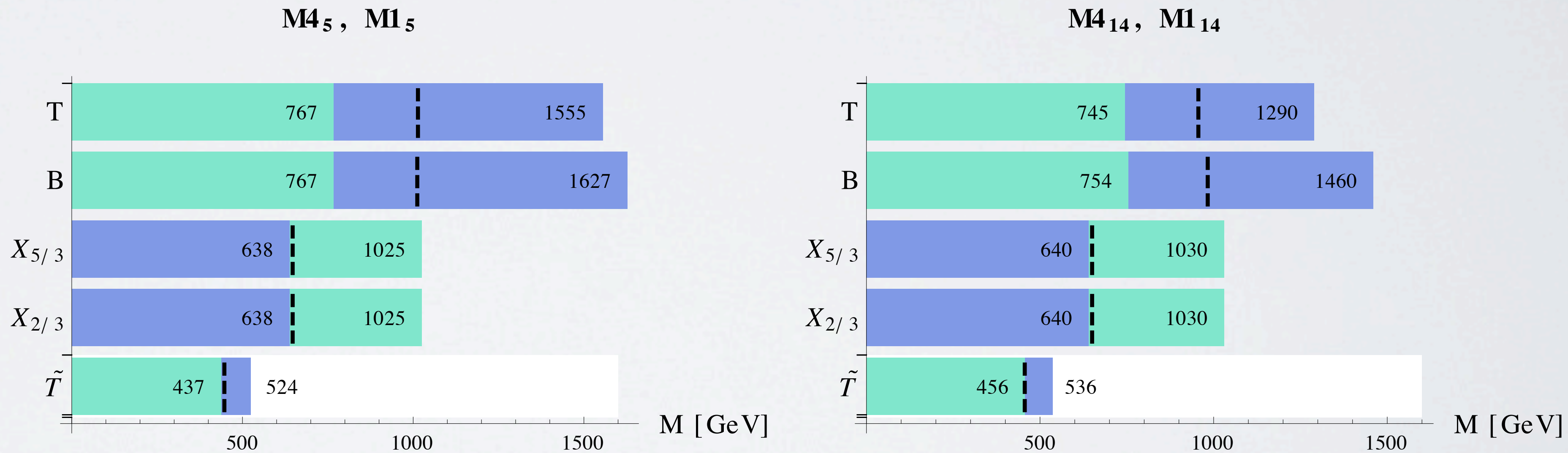


Figure 11: Maxmal and minimal bounds on the masses of top partners for $y \in [0.3, 3]$, $c_1 \in [0.3, 3]$ and $\xi \in [0.1, 0.3]$ for the models $\mathbf{M4}_5$, $\mathbf{M1}_5$ (left pannel) and $\mathbf{M4}_{14}$, $\mathbf{M1}_{14}$ (right pannel). Blue and green bars correspond respectively to high and low values of y. Black dashed lines correspond to the exclusions for the reference values $\xi = 0.1$, $c_1 = 1$, $y = 1$.

Want below 1 TeV for tuning: Panico, Redi, Tesi, Wulzer 1210.7114

LITTLE HIGGS

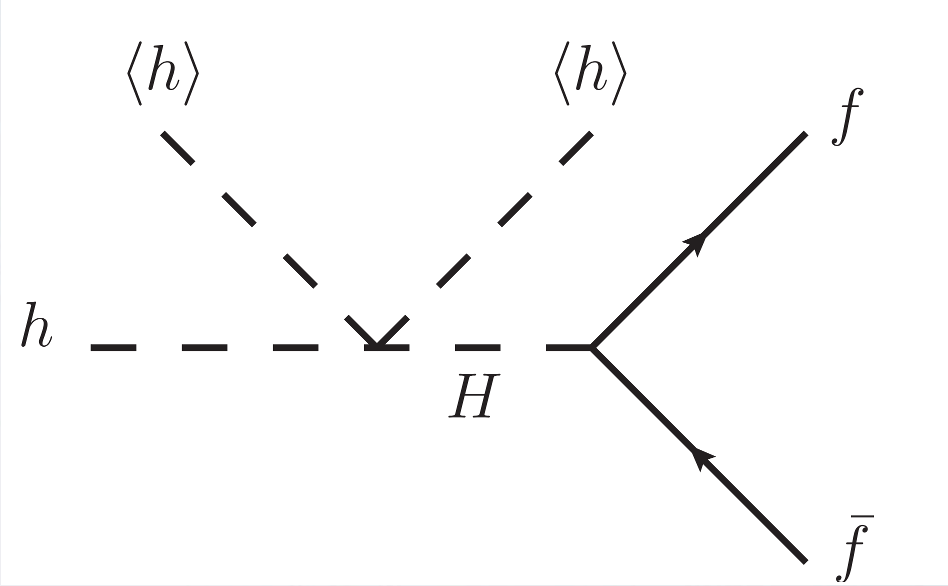
Little Higgs models have an extra symmetry, *naturally* parametrically separating f and v. EWPT can be protected with T-parity (similar to SUSY with R-parity).

Here there are generally new *elementary* fermionic top partners. At least 20% tuning (Berger, Hubisz, Perelstein 1205.0013).

Pay a price in model complexity, and still we haven't seen top partners.

SUSY: TREE-LEVEL HIGGS COUPLINGS

In SUSY have (at least) a 2HDM. Useful way to think about the physics: Gupta, Montull, Riva 1212.5240. Go to **Higgs vev basis**, rather than mass basis.

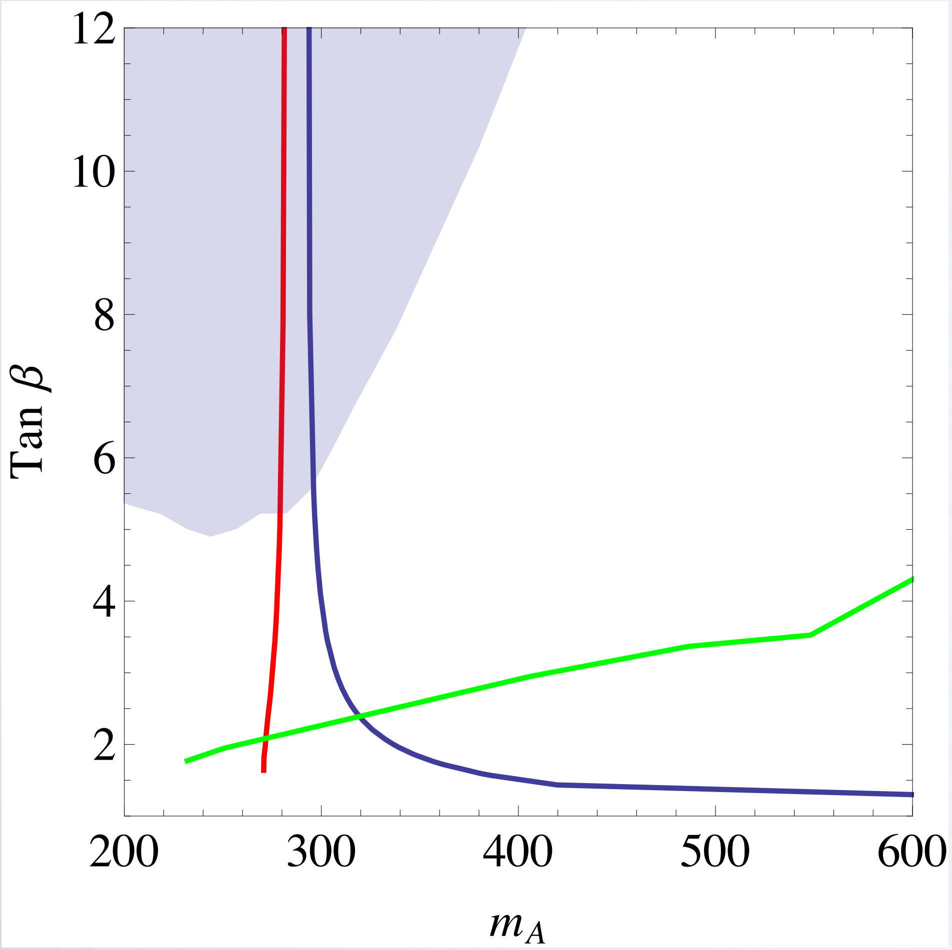


Eigenstate with VEV has SM couplings. Deviations in fermion couplings ~ v^2/m_H^2 suppressed.

MSSM: $$c_b \approx 1 - \frac{m_Z^2}{2m_H^2} \sin 4\beta \tan\beta$$ enhances other branching ratios

TREE-LEVEL 2HDM EFFECTS

Even though these are weakly-coupled theories, corrections can be very important. *Affecting the Higgs coupling to b quarks can dramatically change other branching ratios*. In SUSY, can be correlated with m_h = 125 GeV.



Gupta, Montull, Riva 1212.5240

Exclusion to left of lines, depending on source of new Higgs quartic

red: MSSM (heavy stops)

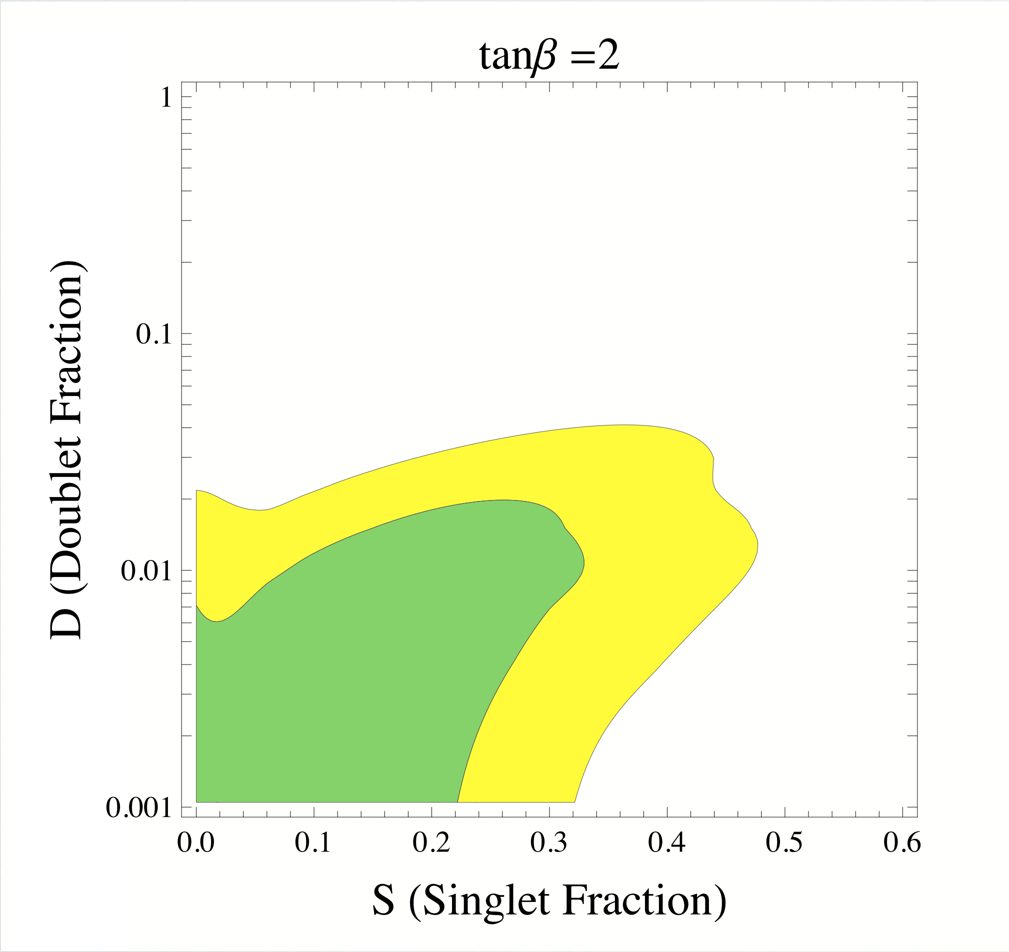
blue: D-terms $\Delta V = \kappa \left(|H_1^0|^2 - |H_2^0|^2\right)^2$

green: F-terms $\mathcal{L}_5 = \int d^2\theta \left(\frac{\lambda_1}{M}(H_1 H_2)^2 + \mathcal{Z}\frac{\lambda_2}{M}(H_1 H_2)^2\right)$

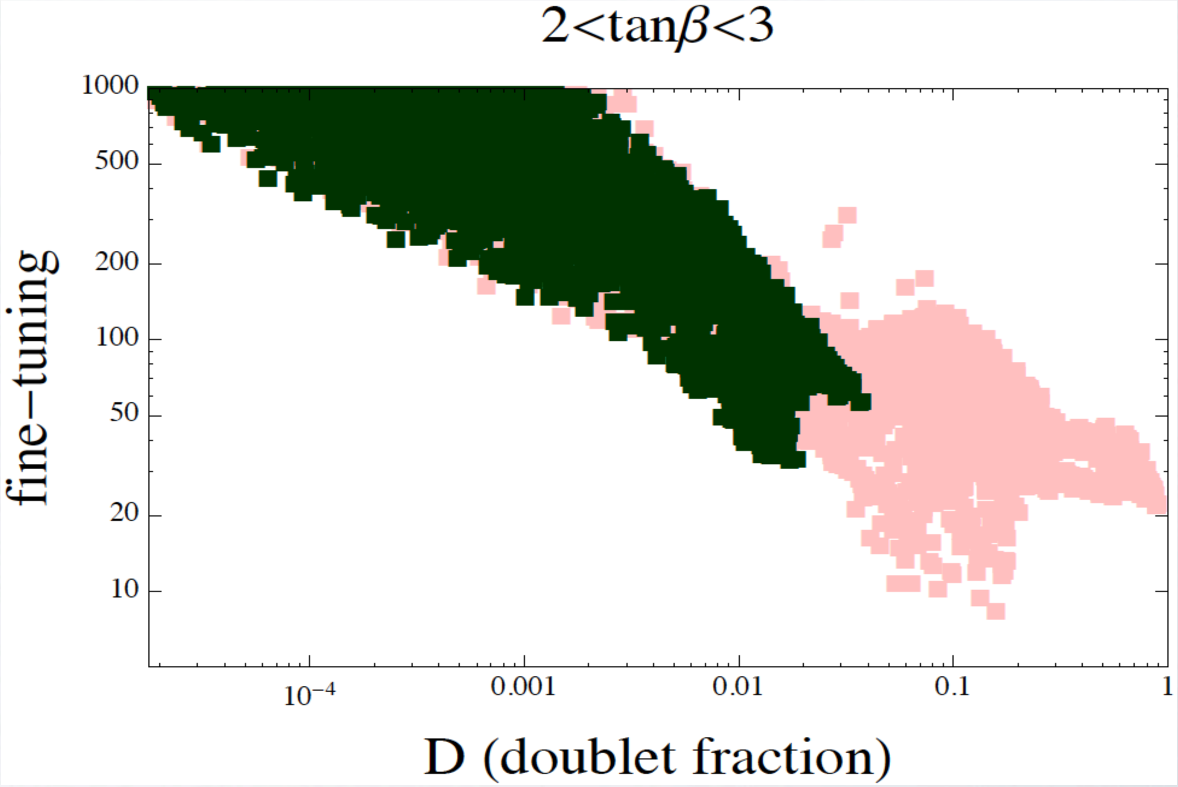
All rule out regions not probed by direct searches

NMSSM TROUBLE?

Farina, Perelstein, Shakya 1310.0549: look at λSUSY (Barbieri/Hall/Nomura/Rychkov), where $\lambda S H_u H_d$ coupling is large.



Fits to Higgs couplings show that large mixing is not allowed; forces fine-tuning for $m_h = 126$ GeV.



ONE-LOOP COUPLINGS: LOW-ENERGY THEOREM

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

Gauge theory: $\mathcal{L} = -\frac{1}{4g^2} G^a_{\mu\nu} G^{a\mu\nu}$

Run from Λ down to μ with an intermediate threshold $\mu < M < \Lambda$ at which the beta function changes from b to $b + \Delta b$.

RG:

$$\frac{1}{g^2(\mu)} = \frac{1}{g^2(\Lambda)} + \frac{b}{8\pi^2} \log \frac{\Lambda}{\mu} + \frac{\Delta b}{8\pi^2} \log \frac{\Lambda}{M}$$

LOW-ENERGY THEOREM

Suppose the mass threshold is actually a function of space and time:

$$M \rightarrow M + \delta M(x)$$

Then we have a spatially varying gauge coupling:

$$\frac{1}{g^2(\mu,x)} = \frac{1}{g^2(\mu)} + \frac{\Delta b}{8\pi^2}\log\frac{M}{M(x)} = \frac{1}{g^2(\mu)} - \frac{\Delta b}{8\pi^2}\frac{\delta M(x)}{M}$$

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

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

Shifman, Vainshtein, ...

STOPS

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

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:

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

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): no longer nondecoupling

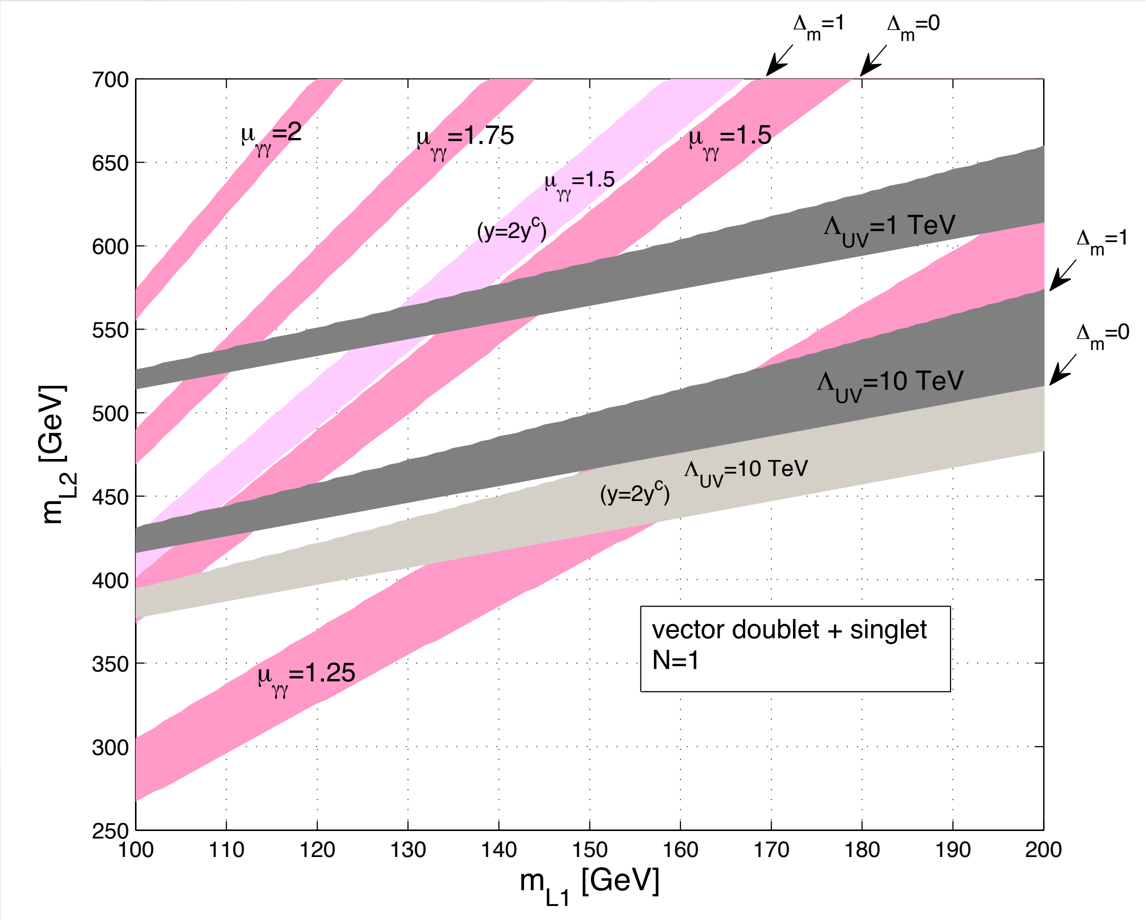
Minus sign: large mixing leads to opposite-sign couplings

Intuition: in the highly mixed case, larger VEV means more mixing, splitting light and heavy stops more. The light one contributes more, and is pushed lighter, so the overall sign reverses.

DANGER IN LOOPS

Fermions generically cause Higgs vacuum stability problems (Arkani-Hamed, Blum, D'Agnolo, Fan 1207.4482)

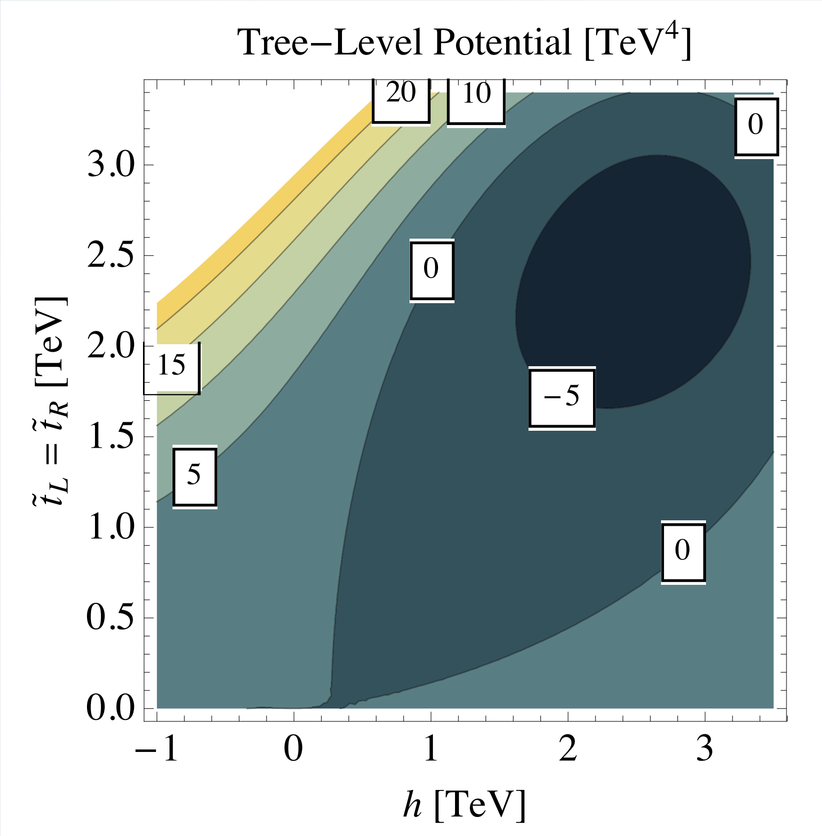
$$16\pi^2 \frac{d\lambda}{dt} = \lambda\left(24\lambda - 9g_2^2 - \frac{9g_1^2}{5} + 12y_t^2 + 4\mathcal{N}\left(y_n^2 + y_n^{c2} + y^2 + y^{c2}\right)\right) - 2\mathcal{N}\left(y^4 + y^{c4} + y_n^4 + y_n^{c4}\right) - 6y_t^4$$
$$+\frac{3}{8}\left(2g_2^4 + \left(g_2^2 + \frac{3g_1^2}{5}\right)^2\right). \qquad \text{(A.1)}$$



Any *large* deviation in *h*γγ coupling arising from *fermions* would imply a low cutoff to prevent rapid vacuum decay.

DANGER IN LOOPS

Large deviations from *scalars* in loops are also dangerous:

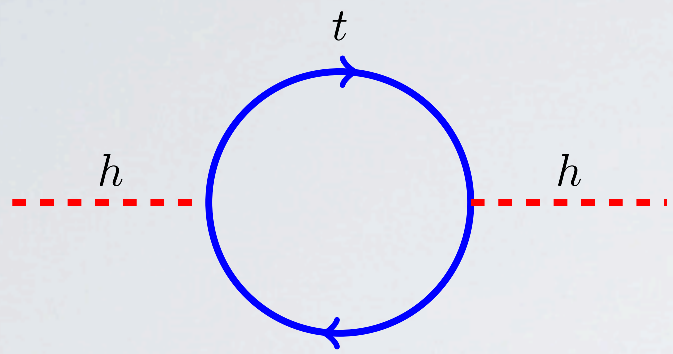


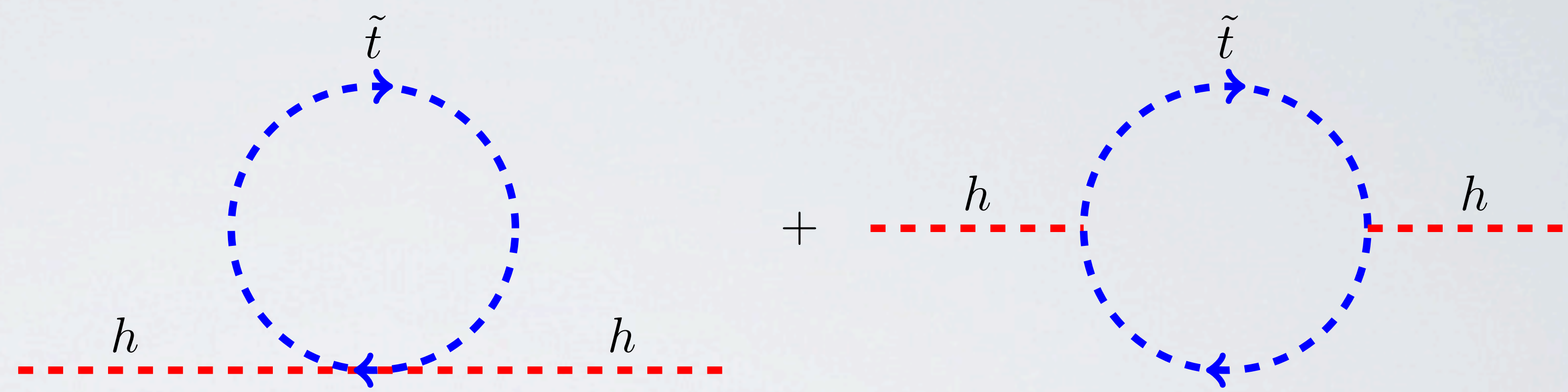
Large trilinears (e.g. *A*-terms in SUSY theories) or large negative quartics both imply *tree-level* instabilities.

Can have rapid tunneling.
MR 1208.1765; earlier: Kusenko, Langacker, Segre hep-ph/9602414

One lesson: even though changing sign of *hGG* amplitude could preserve the rate, theories that do it are usually ruled out. Large *hγγ* enhancements are *a priori* unlikely.

NATURALNESS





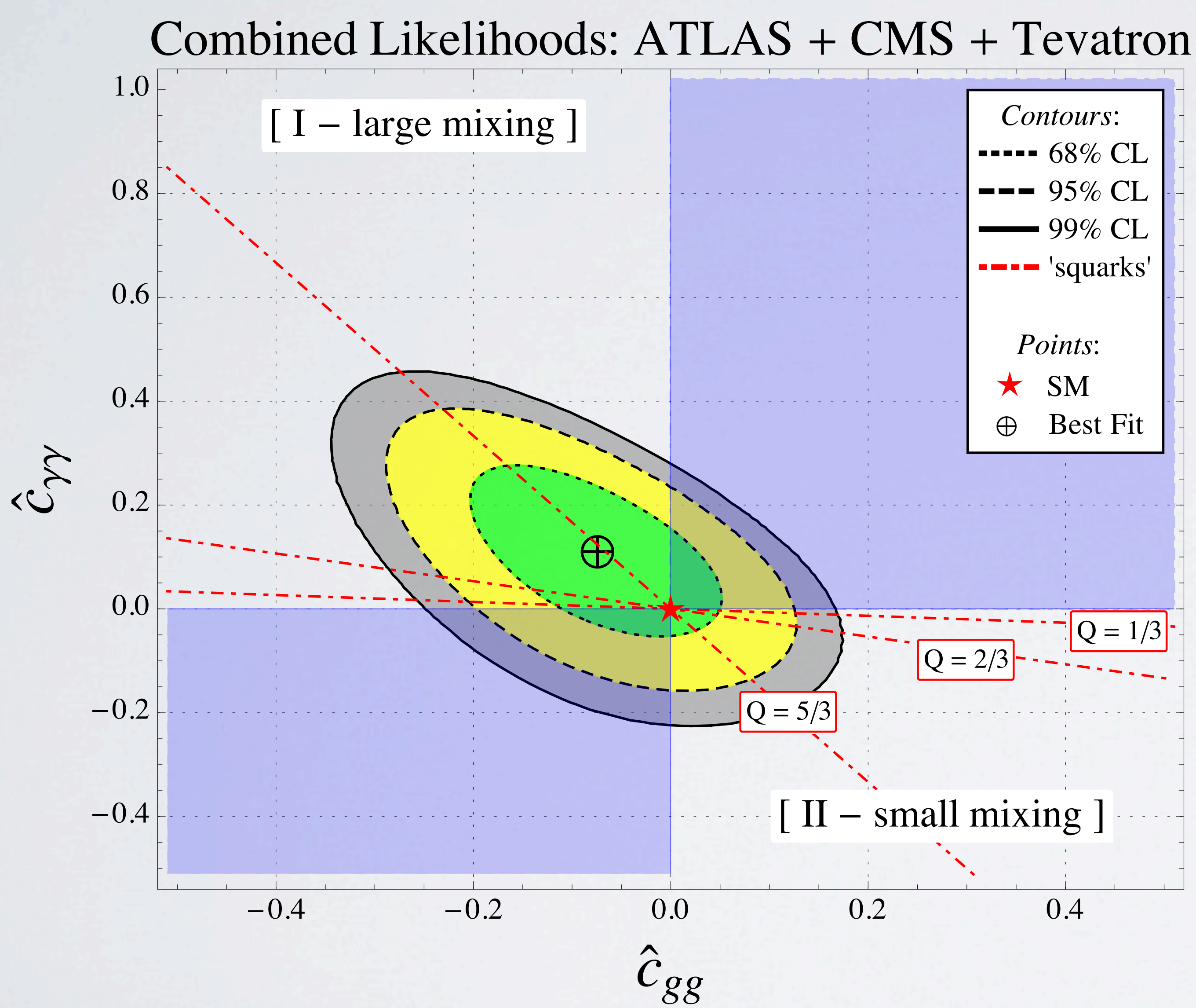
Higgs potential $-\mu^2|H|^2+\lambda|H|^4$: large quantum corrections to the mass^2 term. **Direct searches** constrain them:

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

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

Two stops (LH/RH), one sbottom (LH) should all be light!

THE DATA SO FAR



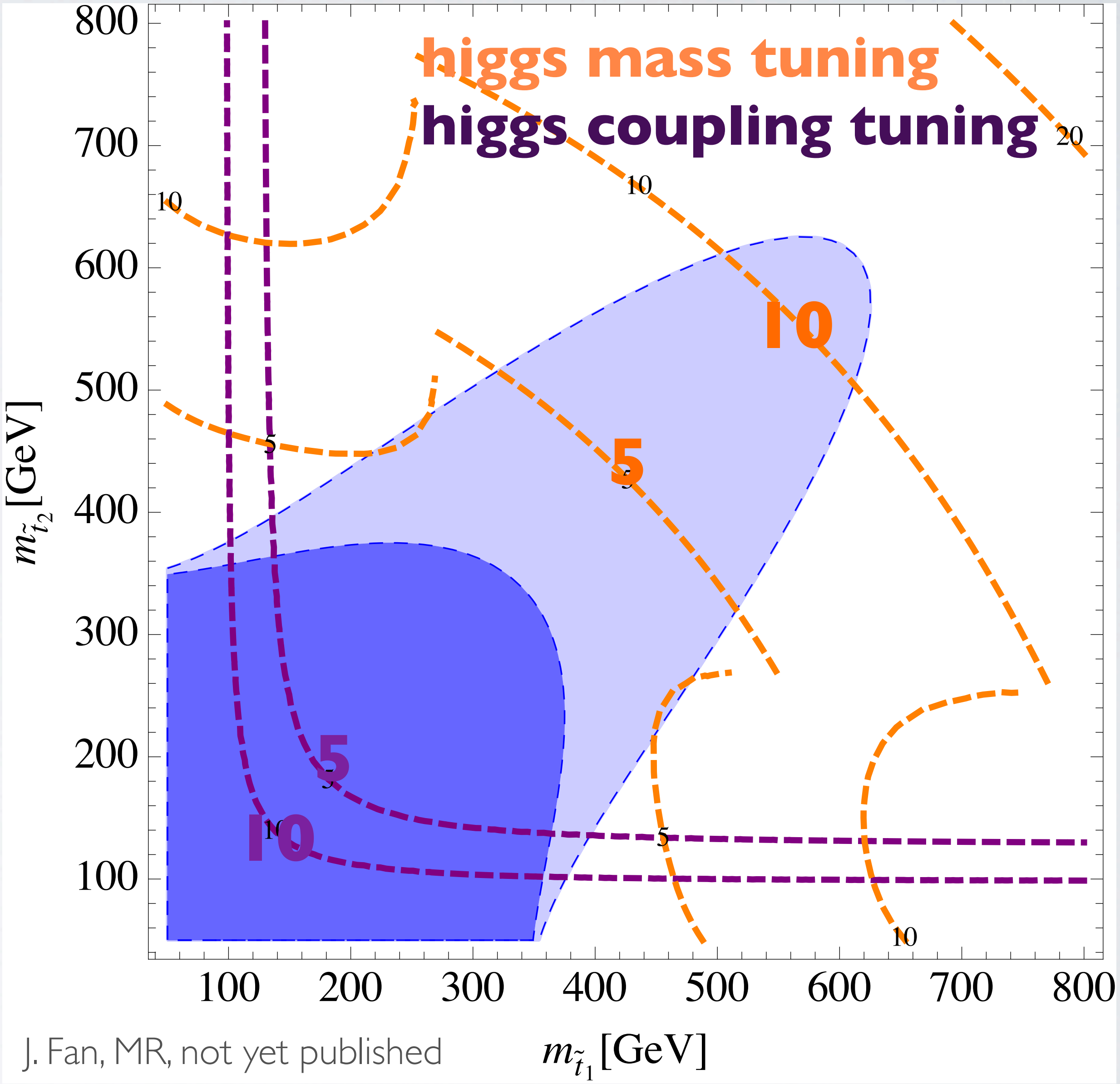
Azatov & Galloway, fit in 1212.1380 (updated post-Moriond)

Consistent with SM! Puts bounds on new physics.

STOP BOUNDS FROM HIGGS

A pair of stop masses is associated with a maximum X_t (property of 2x2 matrices: can't have equal eigenvalues if nonzero off-diagonal term).

Fitting data with light stops requires a *minimum* X_t. Part of parameter space is simply ruled out; more is tuned, even running from only 10 TeV.



J. Fan, MR, not yet published

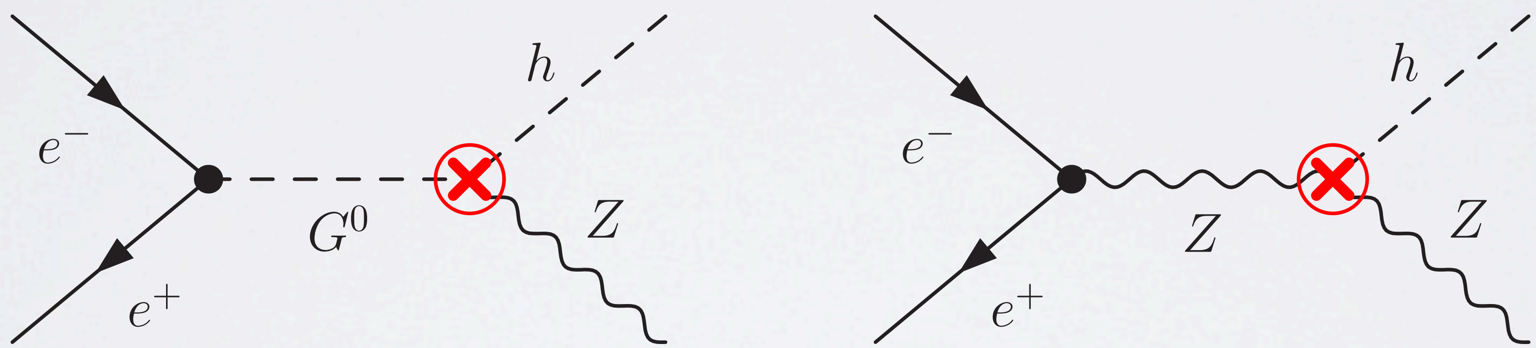
Even without direct searches, know stop/Higgs tuned by factor ~ 5 or more.

Impact of N^nLO K-factors?

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*.

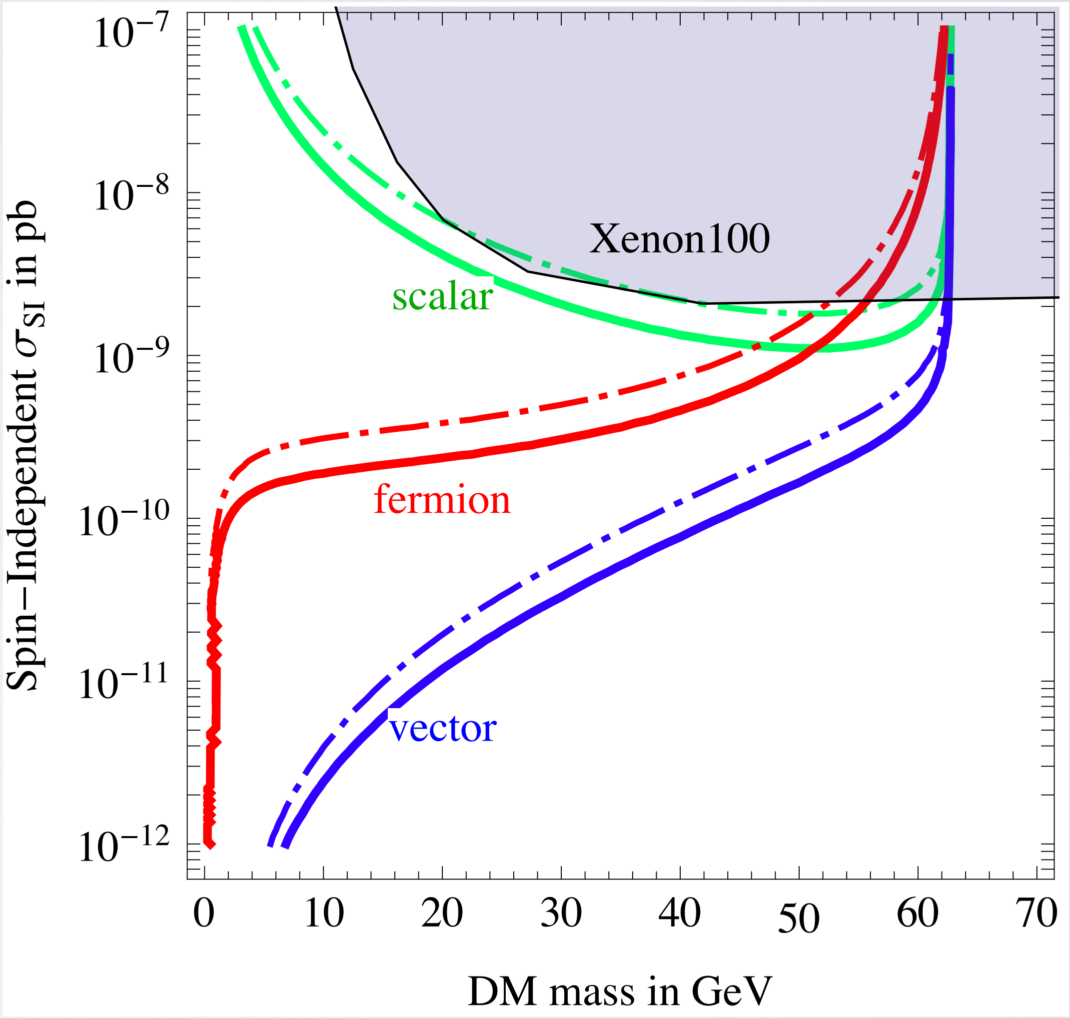
Craig, Englert, McCullough 1305.5251:



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

RARE HIGGS DECAYS

One exciting result of the relatively small SM Higgs couplings is that the Higgs could have a large width into non-SM (e.g. "hidden valley"), even with small couplings.



Most familiar: invisible Higgs. Complementary to direct DM detection. Right: Giardino, Kannike, Masina, Raidal, Strumia 1303.3570.

Many other possibilities: e.g. decays to dark photons, light pseudoscalars, exotic fermions.... Search broadly!

See Stefania Gori's talk for more.

CONCLUSIONS

Higgs couplings provide a very interesting probe of new physics, complementary to direct searches. Directly probe naturalness.

Example: some light stops may not be excluded by direct searches if they decay in unusual ways, but they *are* excluded because they change *ggH* coupling.

Strongly-coupled models were already pushed by EWPT into a range where large deviations in Higgs properties are not expected. But Higgs offers a new set of EWPT observables.

The Higgs completes the SM; perhaps it will also be a window to beyond the SM.

HIGGS COUPLINGS FOR NATURAL MODELS

Two effects we've discussed impact the Higgs production and decay:

Mixing alters $b\bar{b}$ rate, thus changing all other smaller branching ratios. No signal: bad for λSUSY.

Loops alter *gg* and γγ couplings. No signal: bad for stops.

"Typically," in natural models, would like to have seen effects ~20%.

WHAT NEXT?

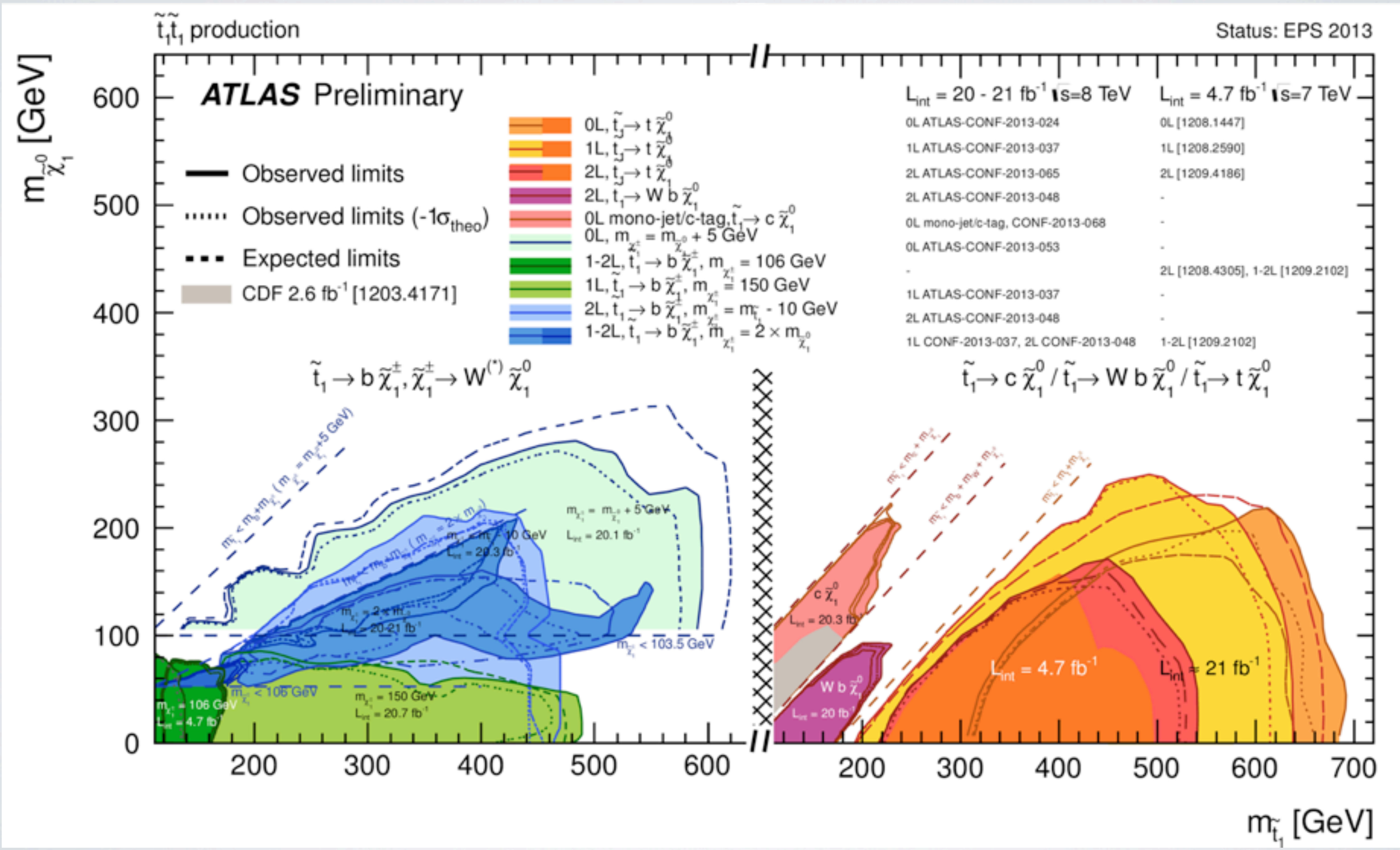
It's interesting that very conservative and general arguments already put most of our favorite models at *at least* ~20% tuning.

For composite Higgs, the *S*-parameter alone does approximately that.

For SUSY, absence of large stop loop corrections to Higgs properties also does approximately that.

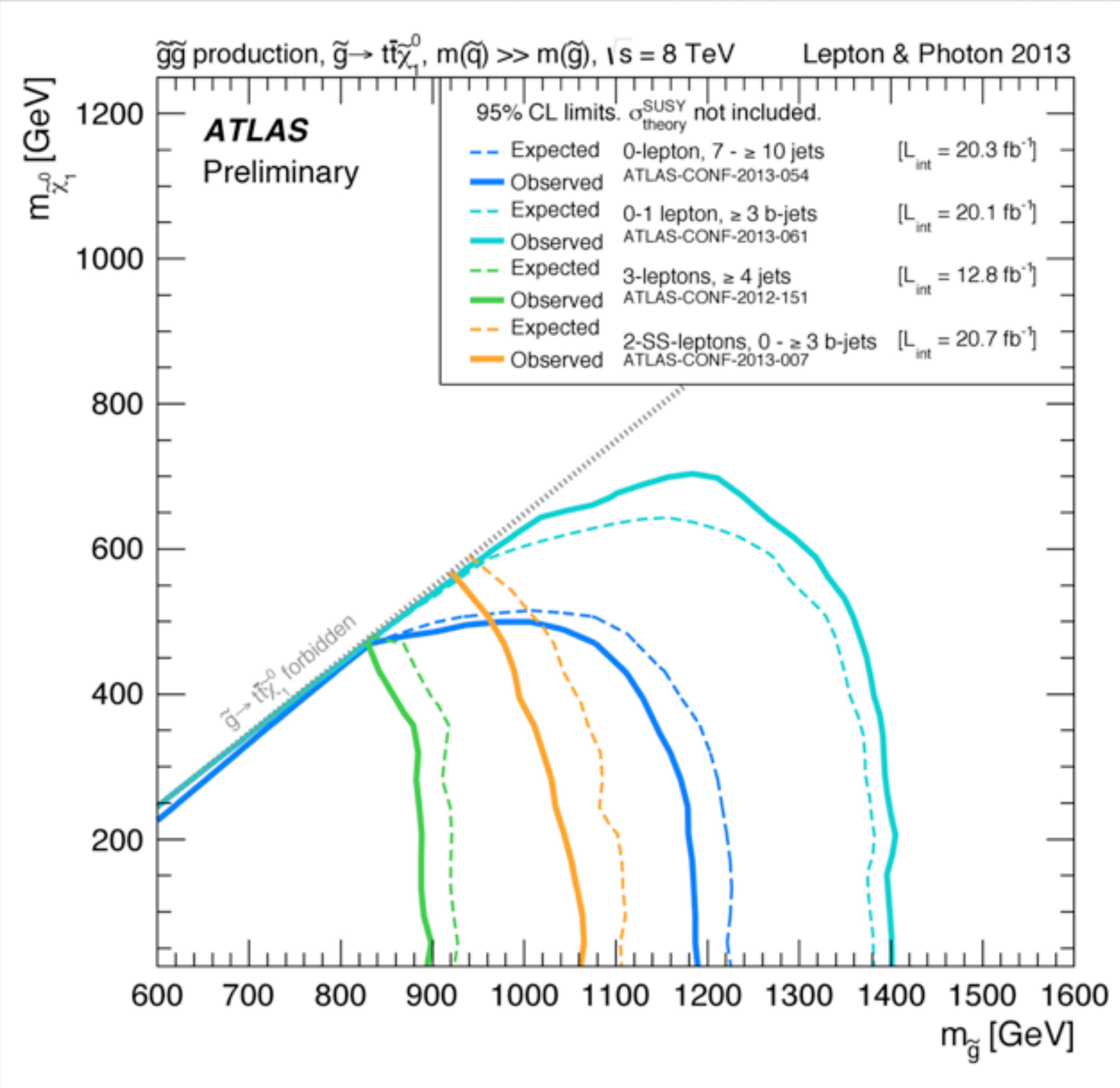
In most specific models, combining constraints (e.g. direct searches) requires a much worse tuning!

STOP BOUNDS



t̃1t̃1 production
Status: EPS 2013
ATLAS Preliminary
Observed limits
Observed limits (-1σtheo)
Expected limits
CDF 2.6 fb-1 [1203.4171]
0L, t̃1→ t χ̃10
1L, t̃1→ t χ̃10
2L, t̃1→ t χ̃10
2L, t̃1→ W b χ̃10
0L mono-jet/c-tag, t̃1→ c χ̃10
0L, mχ̃1± = mχ̃10 + 5 GeV
1-2L, t̃1 → b χ̃1±, mχ̃1± = 106 GeV
1L, t̃1 → b χ̃1±, mχ̃1± = 150 GeV
2L, t̃1 → b χ̃1±, mχ̃1± = mt̃1 - 10 GeV
1-2L, t̃1 → b χ̃1±, mχ̃1± = 2 × mχ̃10
Lint = 20 - 21 fb-1 √s=8 TeV
Lint = 4.7 fb-1 √s=7 TeV
0L ATLAS-CONF-2013-024
1L ATLAS-CONF-2013-037
2L ATLAS-CONF-2013-065
2L ATLAS-CONF-2013-048
0L mono-jet/c-tag, CONF-2013-068
0L ATLAS-CONF-2013-053
1L ATLAS-CONF-2013-037
2L ATLAS-CONF-2013-048
1L CONF-2013-037, 2L CONF-2013-048
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
2L [1208.4305], 1-2L [1209.2102]
1-2L [1209.2102]
t̃1 → b χ̃1±, χ̃1± → W(*) χ̃10
t̃1→ c χ̃10 / t̃1→ W b χ̃10 / t̃1→ t χ̃10
mχ̃1± < 103.5 GeV
mχ̃1± < 106 GeV
mχ̃1± = 150 GeV
Lint = 20.7 fb-1
Lint = 20.1 fb-1
Lint = 20.3 fb-1
Lint = 20-21 fb-1
Lint = 4.7 fb
Lint = 4.7 fb-1
Lint = 21 fb-1
Lint = 20 fb-1
c χ̃10
W b χ̃10
mχ̃10 [GeV]
mt̃1 [GeV]
0
100
200
300
400
500
600
700

GLUINO TO STOP BOUNDS



Great progress here. We have many complementary channels and the bounds are one of the biggest worries for natural SUSY.

But: Dirac gluino could be heavier and natural....

NATURAL HIDDEN SUSY?

This "split generations" scenario is increasingly constrained by stop & sbottom searches and has tension with flavor. But natural SUSY doesn't *require* splitting the squark generations if they're hidden.

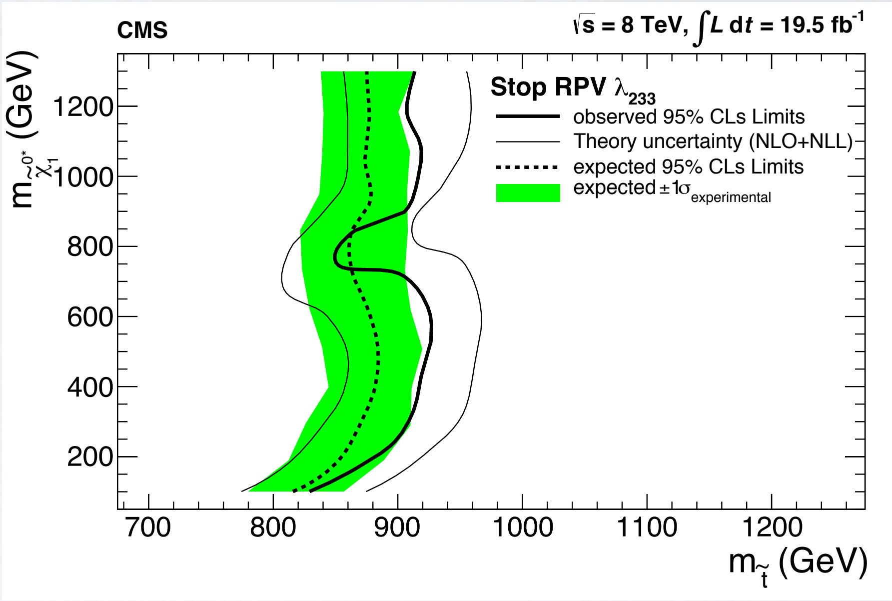
Some ways to hide superpartners:
- decay through RPV
- decay through hidden valley (large multiplicity, less phase space for missing momentum)
- decay through lepton jets (special case of hidden valley)
- decay through stealth SUSY (another special case, with a nearly-supersymmetric hidden sector)

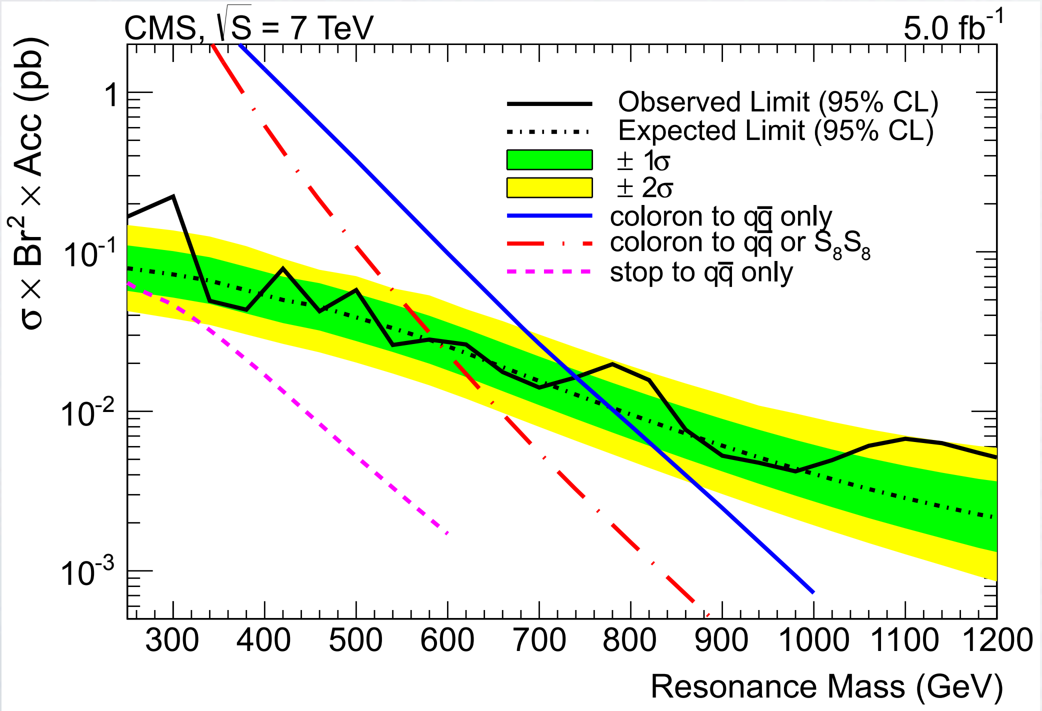
STOPS WITH *R*-PARITY VIOLATION

Some experimental results are already appearing, e.g. CMS 1306.6643 with LQD operator (muon/top/bottom)

Table 2: Kinematically allowed stop decay modes with RPV coupling λ'_{233}. The allowed neutralino decay modes for $m_{\mathrm{t}} < m_{\tilde\chi_1^0} < m_{\tilde{\mathrm{t}}_1}$ are $\tilde\chi_1^0 \to \mu \mathrm{t}\bar{\mathrm{b}}$ and $\nu \mathrm{b}\bar{\mathrm{b}}$.

Label	Kinematic region	Decay mode
A	$m_{\mathrm{t}} < m_{\tilde{\mathrm{t}}_1} < 2m_{\mathrm{t}}, m_{\tilde\chi_1^0}$	$\tilde{\mathrm{t}}_1 \to \mathrm{t}\nu\mathrm{b}\bar{\mathrm{b}}$
B	$2m_{\mathrm{t}} < m_{\tilde{\mathrm{t}}_1} < m_{\tilde\chi_1^0}$	$\tilde{\mathrm{t}}_1 \to \mathrm{t}\mu\mathrm{t}\bar{\mathrm{b}}$ or $\mathrm{t}\nu\mathrm{b}\bar{\mathrm{b}}$
C	$m_{\tilde\chi_1^0} < m_{\tilde{\mathrm{t}}_1} < m_{\mathrm{W}^\pm} + m_{\tilde\chi_1^0}$	$\tilde{\mathrm{t}}_1 \to \ell\nu\mathrm{b}\tilde\chi_1^0$ or $\mathrm{jjb}\tilde\chi_1^0$
D	$m_{\mathrm{W}^\pm} + m_{\tilde\chi_1^0} < m_{\tilde{\mathrm{t}}_1} < m_{\mathrm{t}} + m_{\tilde\chi_1^0}$	$\tilde{\mathrm{t}}_1 \to \mathrm{bW}^\pm\tilde\chi_1^0$
E	$m_{\mathrm{t}} + m_{\tilde\chi_1^0} < m_{\tilde{\mathrm{t}}_1}$	$\tilde{\mathrm{t}}_1 \to \mathrm{t}\tilde\chi_1^0$

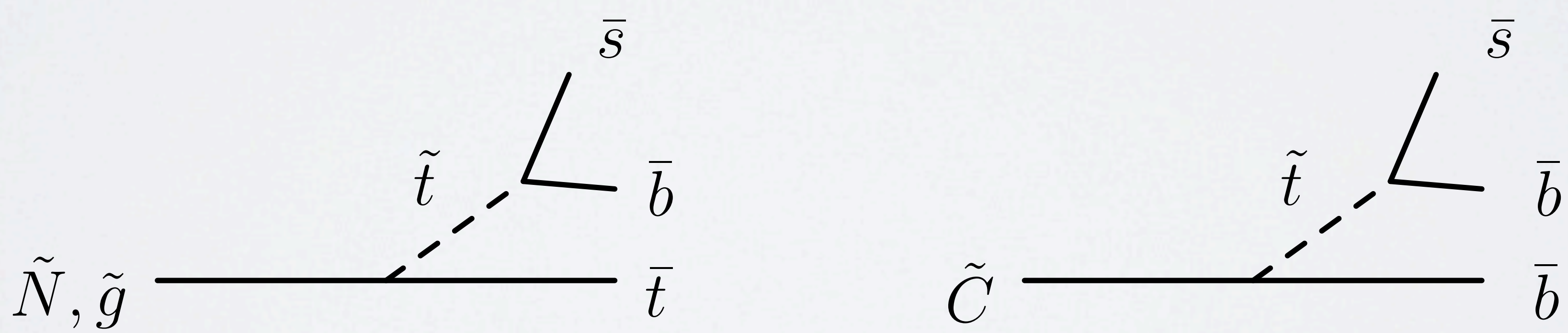




Or 1302.0531 paired dijets (e.g. stop via UDD)

WHICH RPV?

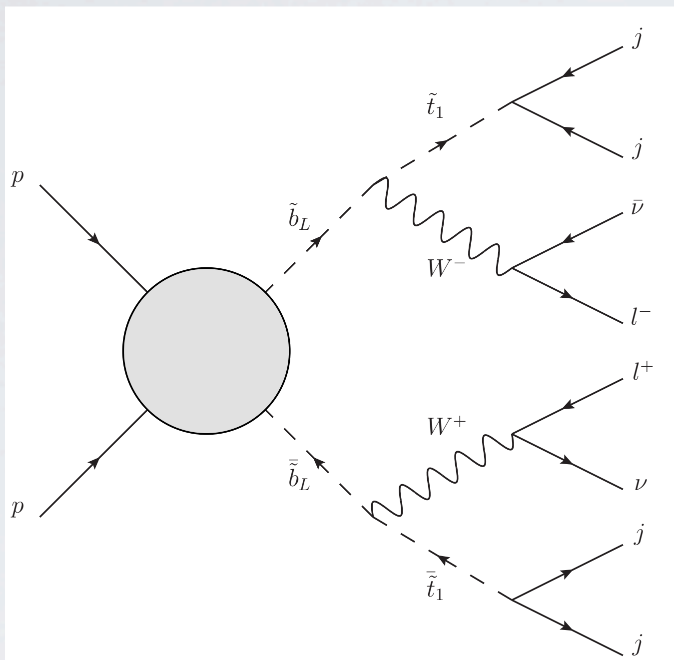
RPV is a huge space of models. The "MFV RPV" framework (Csaki, Grossman, Heidenreich 1111.1239) and the "Bilinear RPV" case (only *LH* operators; Graham, Kaplan, Rajendran, Saraswat 1204.6038) seem like two of the most reasonable to me. Long lifetimes evade some bounds?

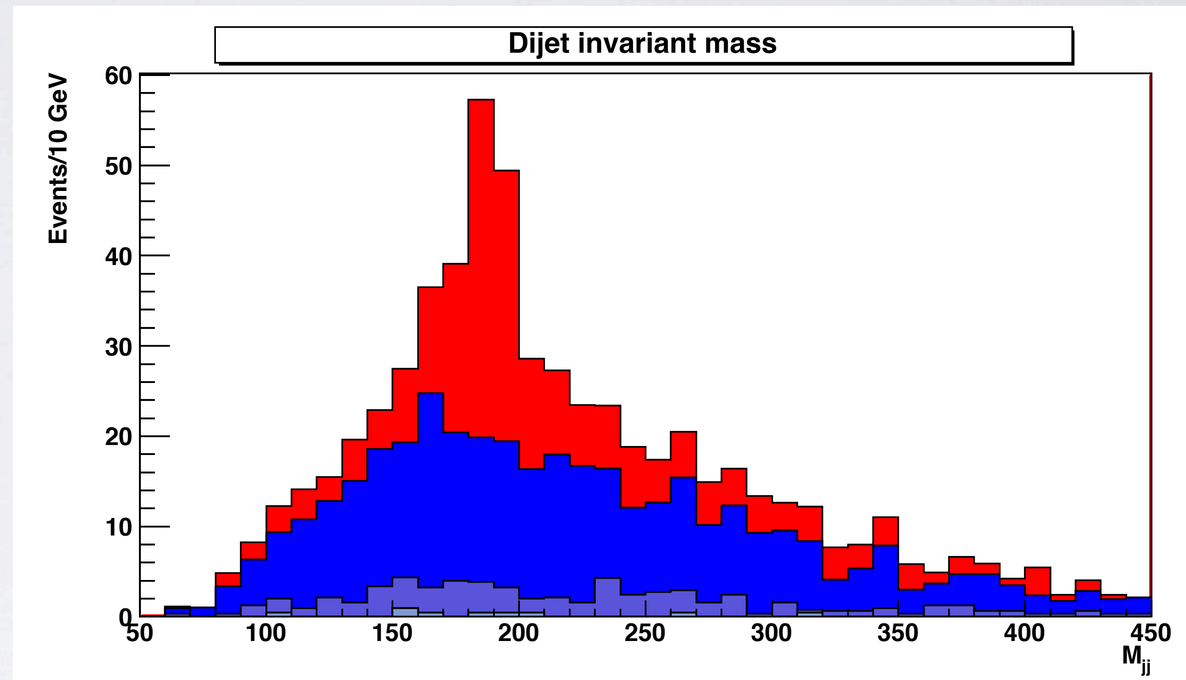


Multi-jet resonances (possibly top+jets) as a signal of naturalness?

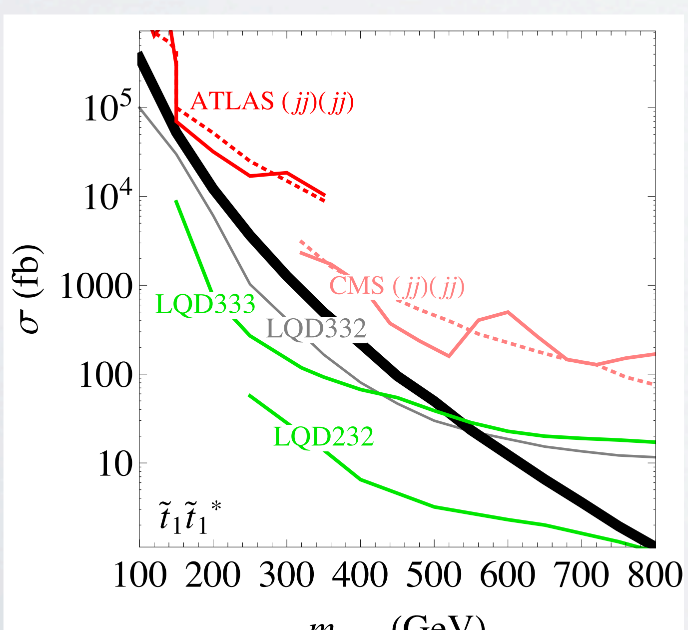
RPV STOPS

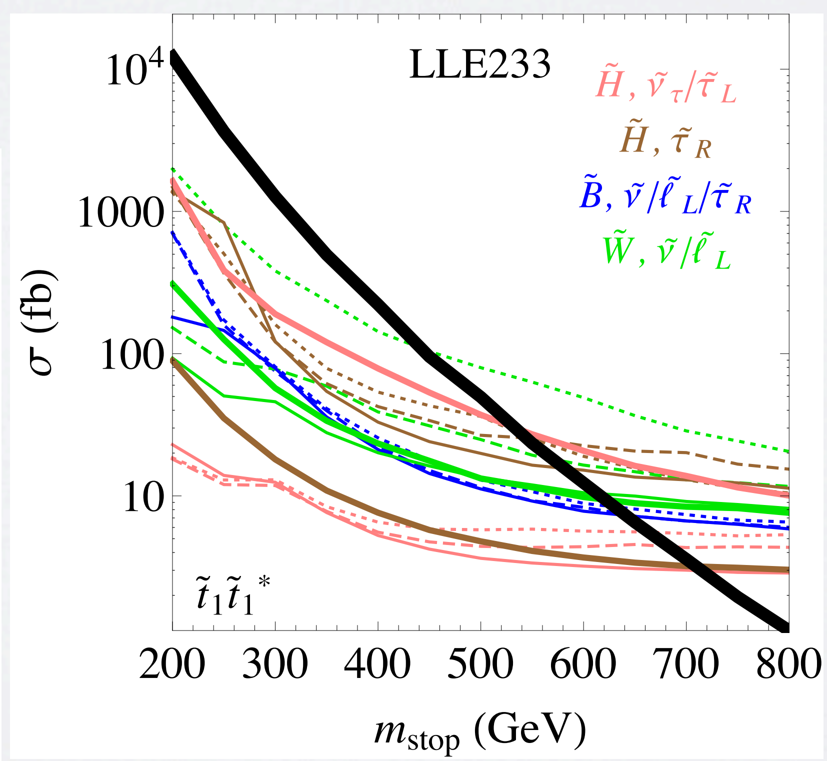
Brust, Katz, Sundrum 1206.2353

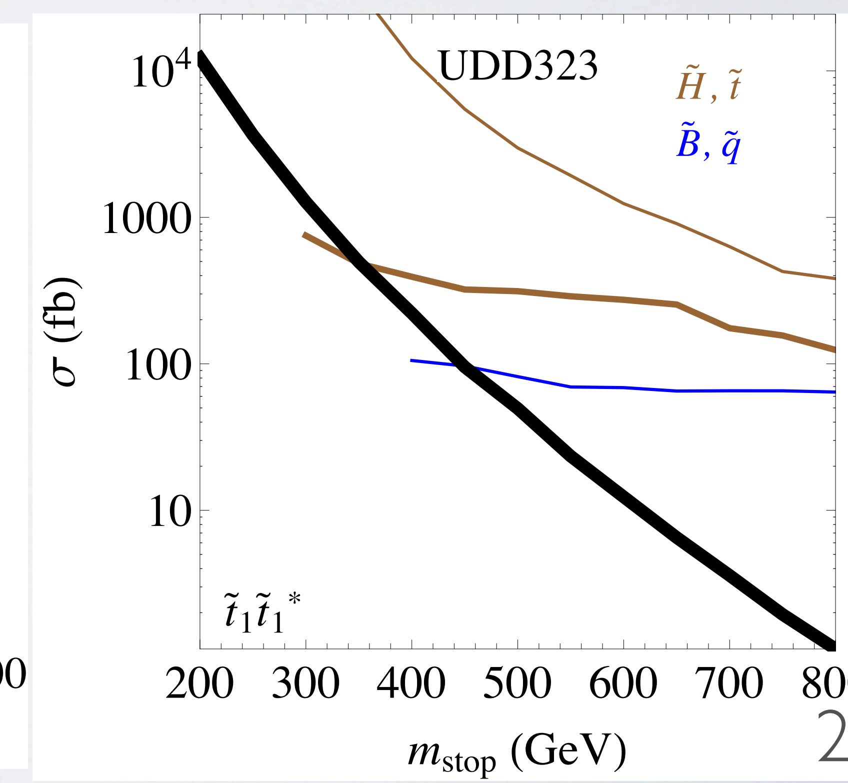




Evans, Kats 1209.0764

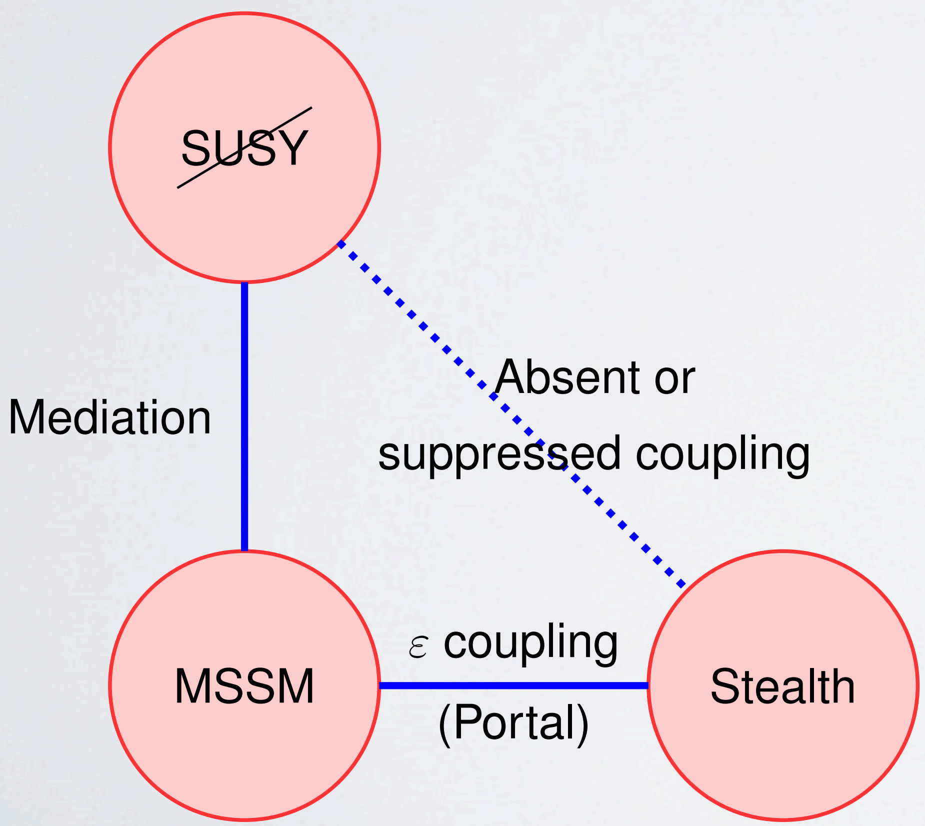






STOPS IN STEALTH SUSY

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."

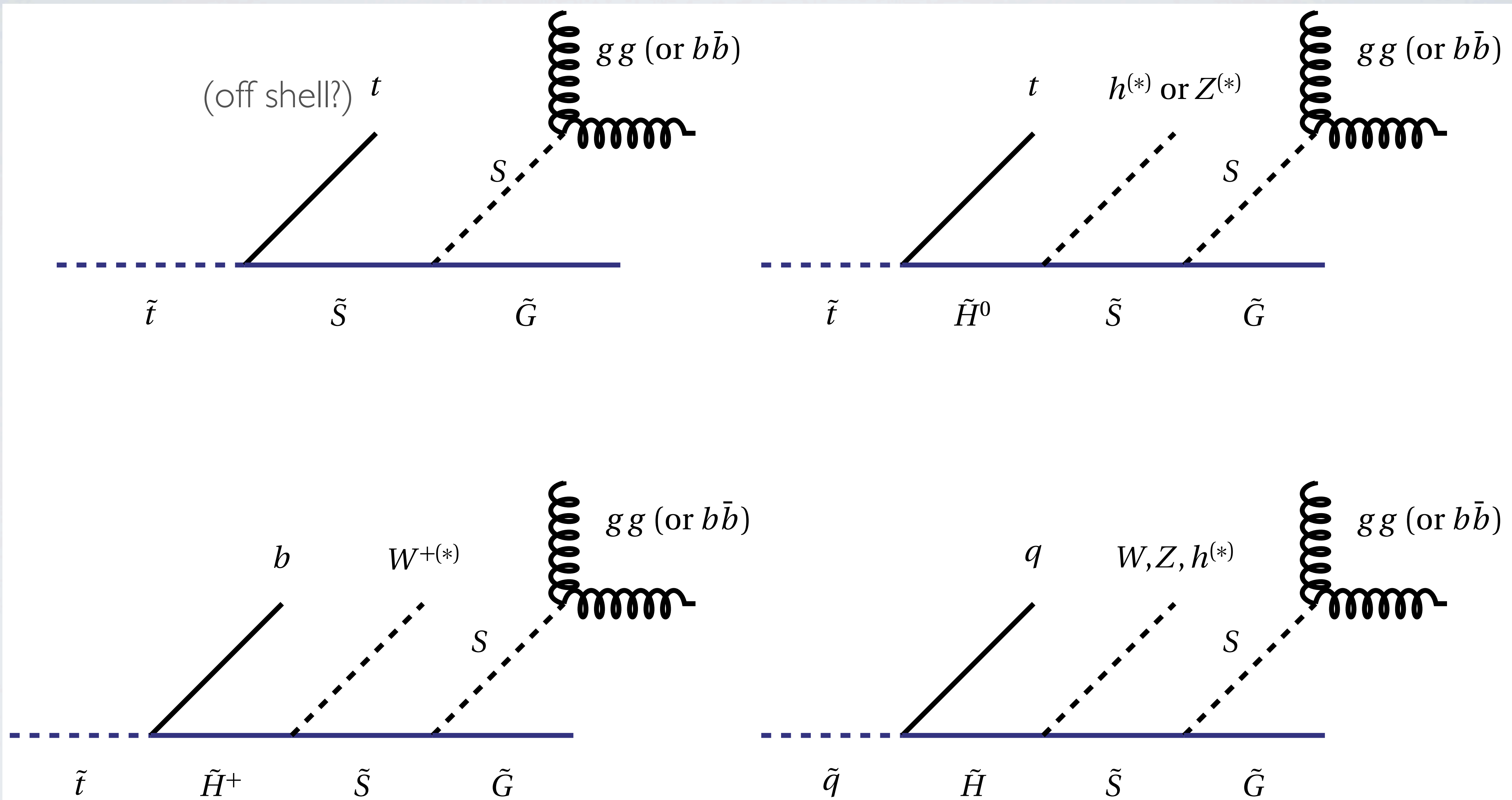


$M_{\rm SUSY} \sim M_{\rm EWK}$

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

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.