SUPERSYMMETRY: WHERE DO WE STAND?

Matthew Reece
Harvard University
At IDM, Chicago, July 26, 2012

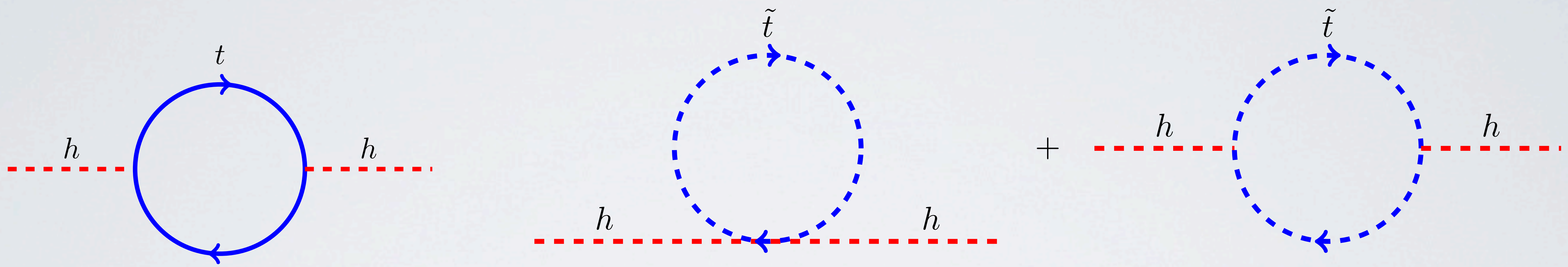
WHY SUPERSYMMETRY?

- Naturalness
- Gauge Coupling Unification
- Dark Matter

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

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

NATURALNESS

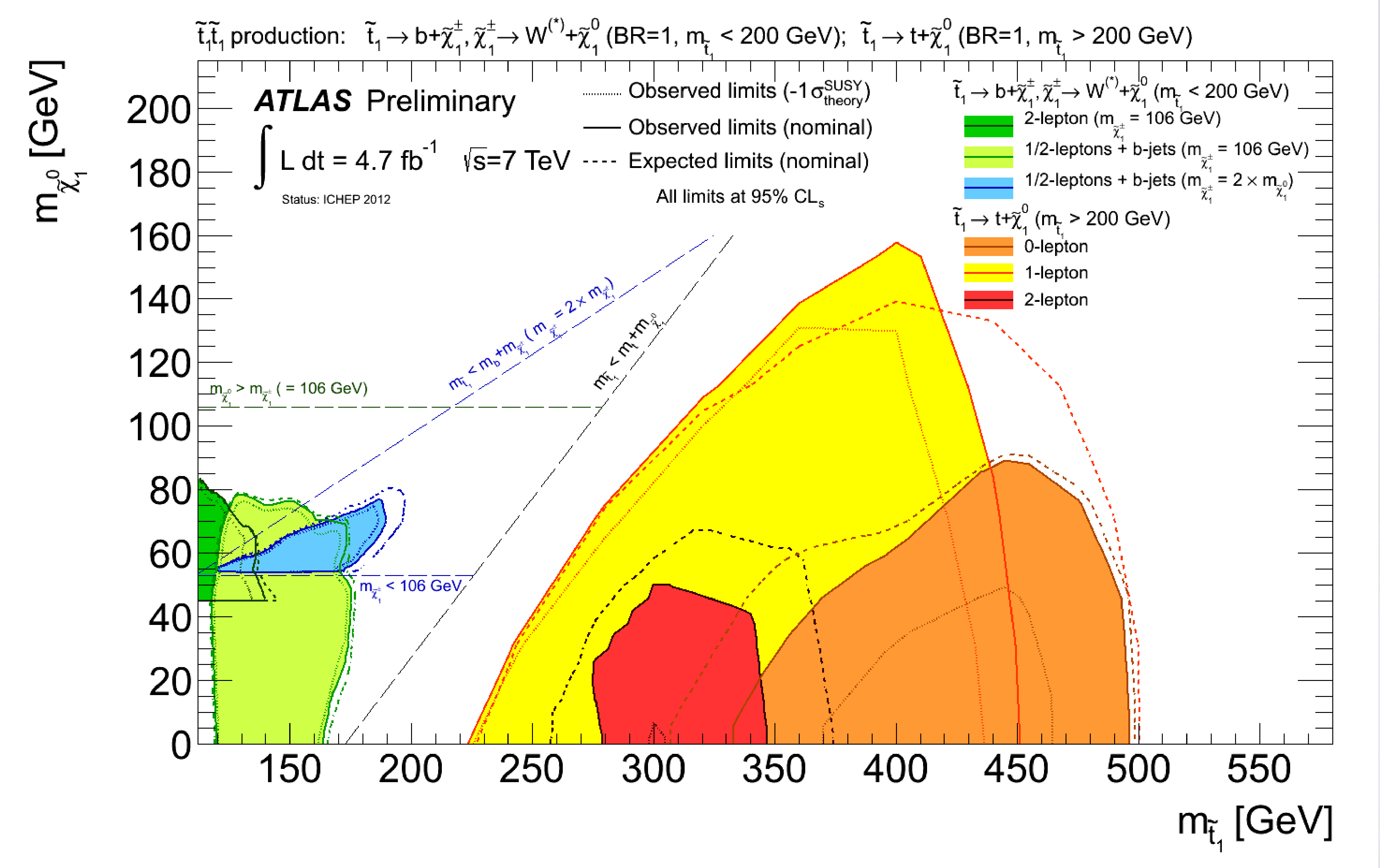


Higgs potential -$\mu^2|H|^2+\lambda|H|^4$: large quantum corrections to the mass^2 term.

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

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

DIRECT STOP LIMITS



NEW this summer! ATLAS-CONF-2012-070/071/073/074; CMS-PAS-SUS-12-009, SUS-11-022, ...

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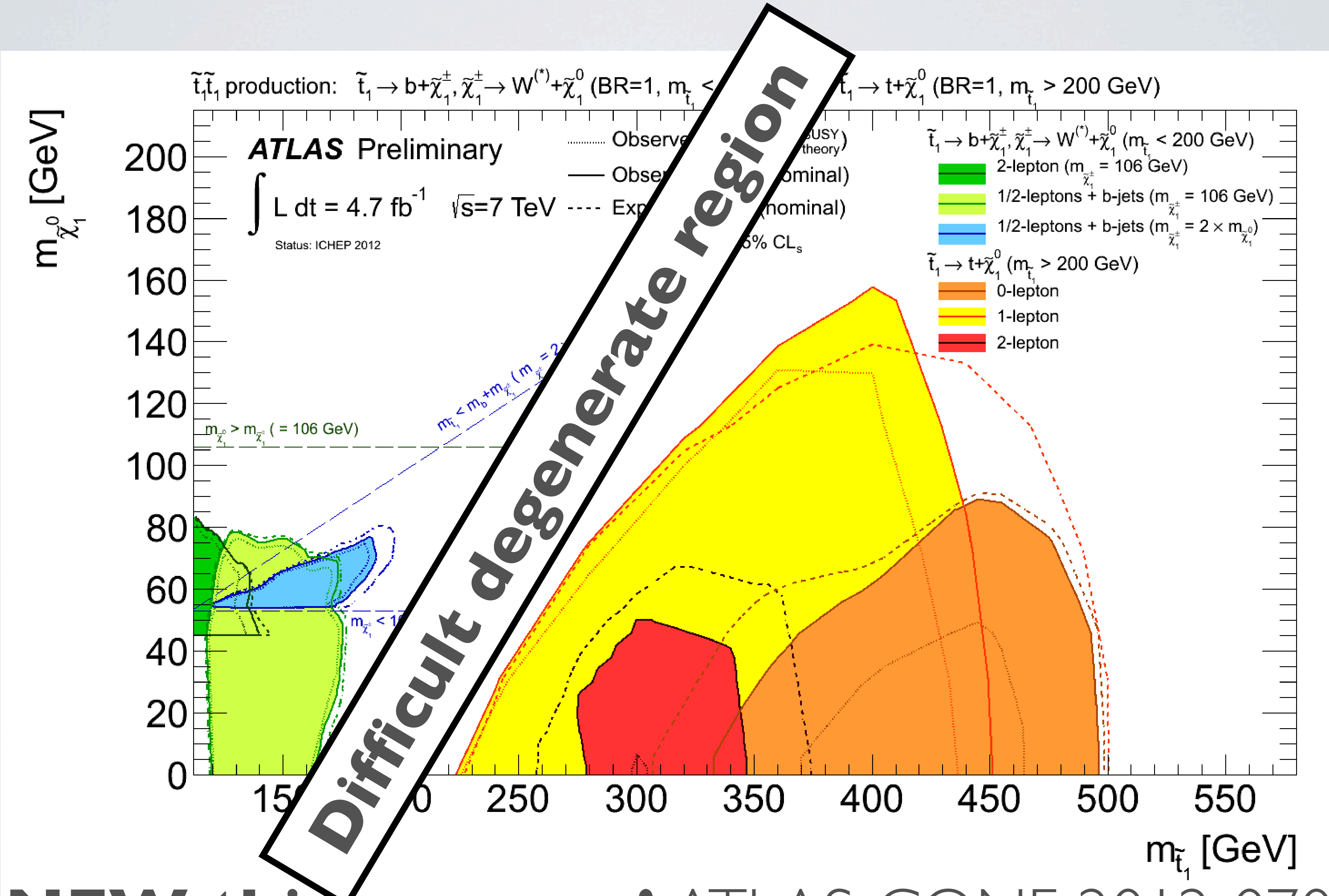

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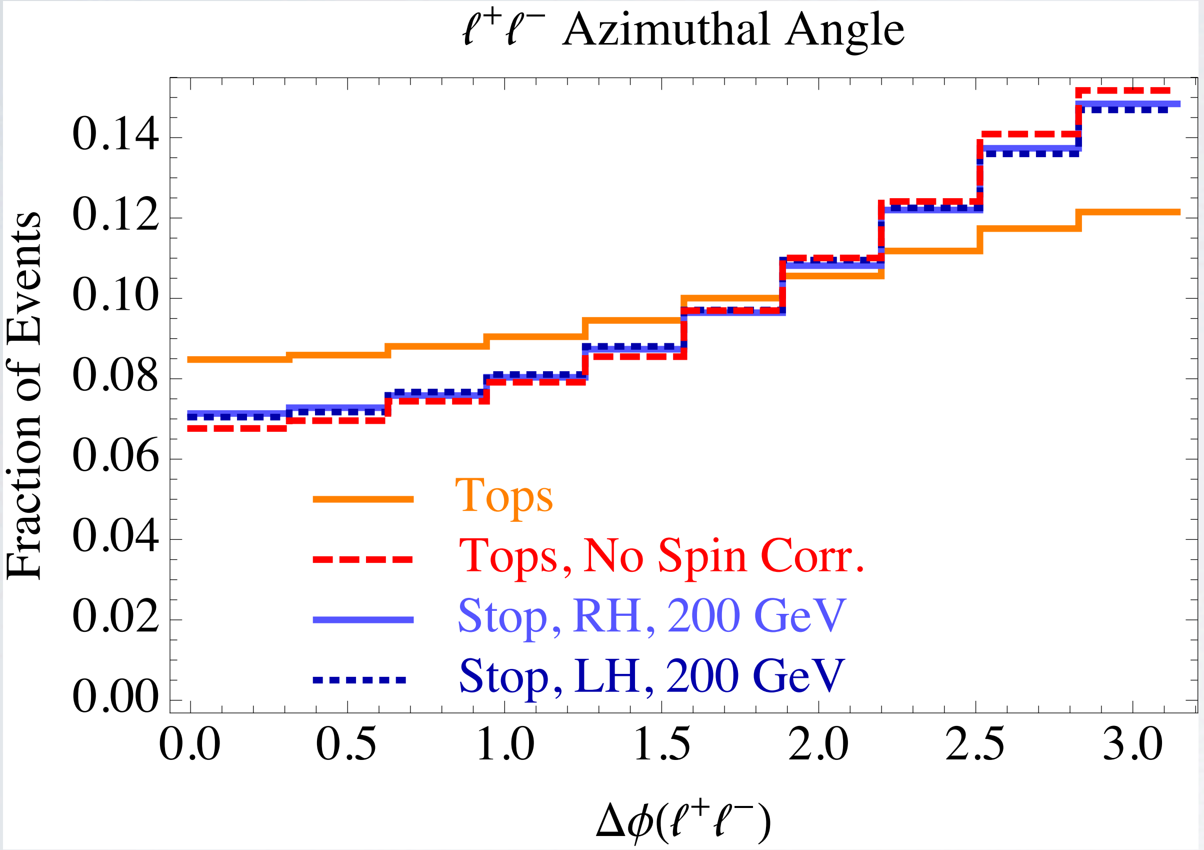
TARGETING STOPS

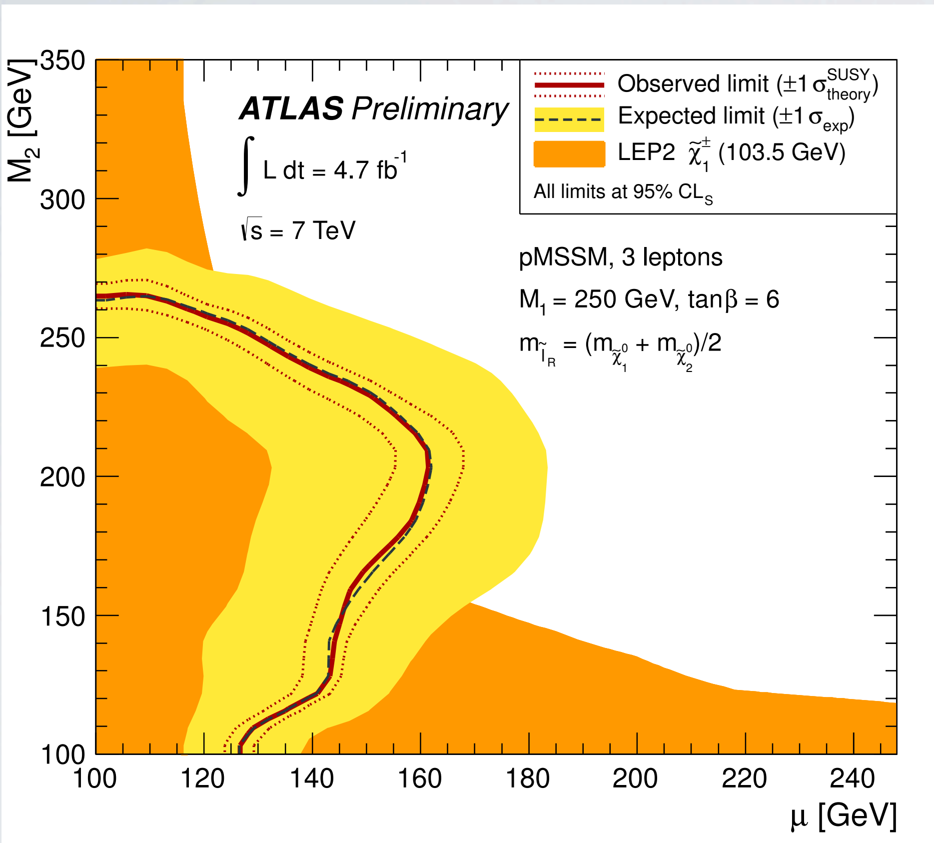
NEXT STEPS



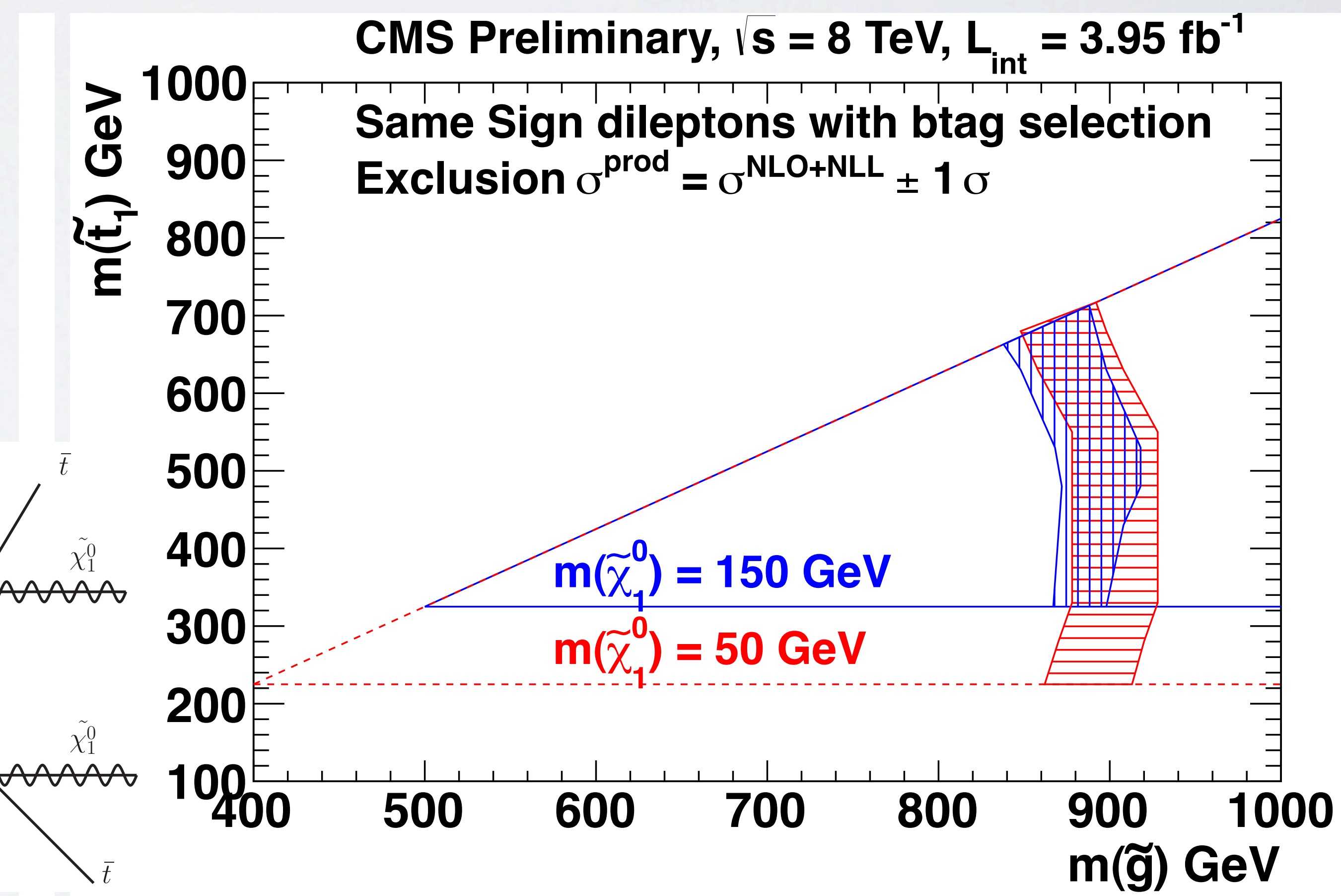
In the degenerate region that isn't being probed well by missing energy searches, may be useful to supplement with spin correlations or rapidity differences (Z. Han, A. Katz, D. Krohn, M. Reece, 1205.5808)

Can be combined with various proposals using missing energy and boosts: Plehn et al 1102.0557 & 1205.2696; Bai et al 1203.4813; Alves et al. 1205.5805; Kaplan et al. 1205.5816, ...

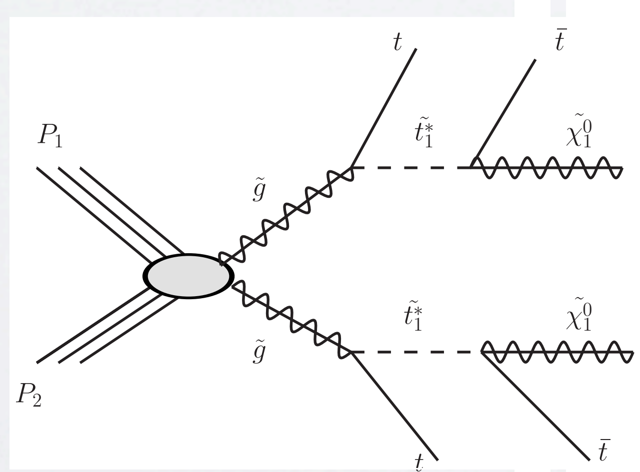
OTHER RECENT RESULTS



Electroweak production beginning to be probed (ATLAS-CONF-2012-077)



Gluinos decaying through tops (CMS PAS-SUS-12-017)



DIRECT SUSY SEARCHES

So far, no evidence. "Vanilla" gluinos ruled out up to around 1 TeV, *whether or not* they decay through third generation (progress over the last year). **Ways out:**

- **"Natural"**: gluinos not too far above 1 TeV, third gen. lighter than first two. Where are the stops?
- **Compressed** spectrum leads to less visible energy (LeCompte & Martin, 1111.6897)
- **"Stealth"**: degenerate SUSY multiplets lead to less missing energy (Fan, Reece, Ruderman, 1105.5135 & 1201.4875)
- **R-parity violation**: lightest states decay (hep-ph/0406039, recently Csaki et al.1111.1239, Brust et al.1206.2353, Ruderman et al. 1207.5787)

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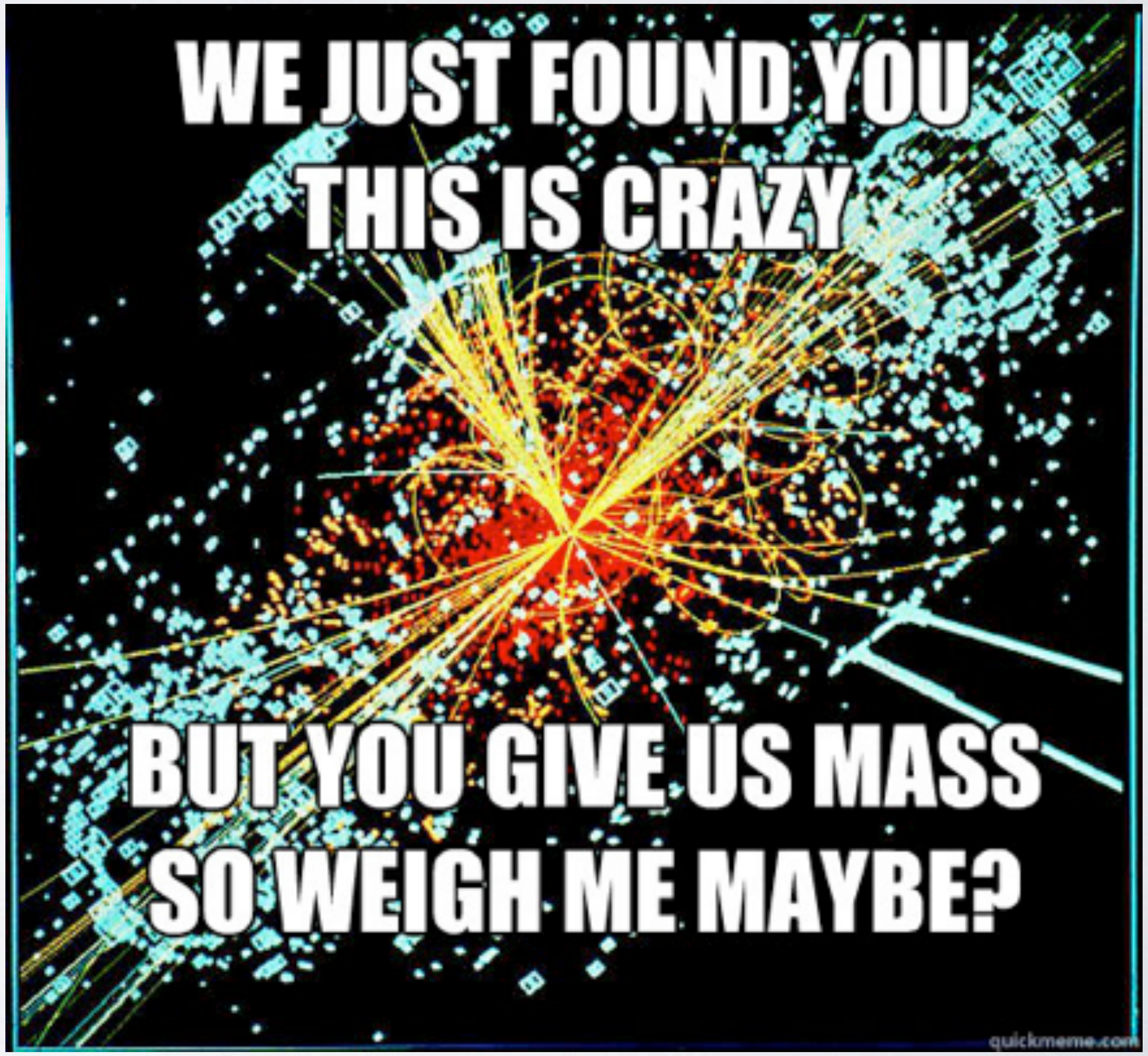
These two don't play well with traditional SUSY dark matter

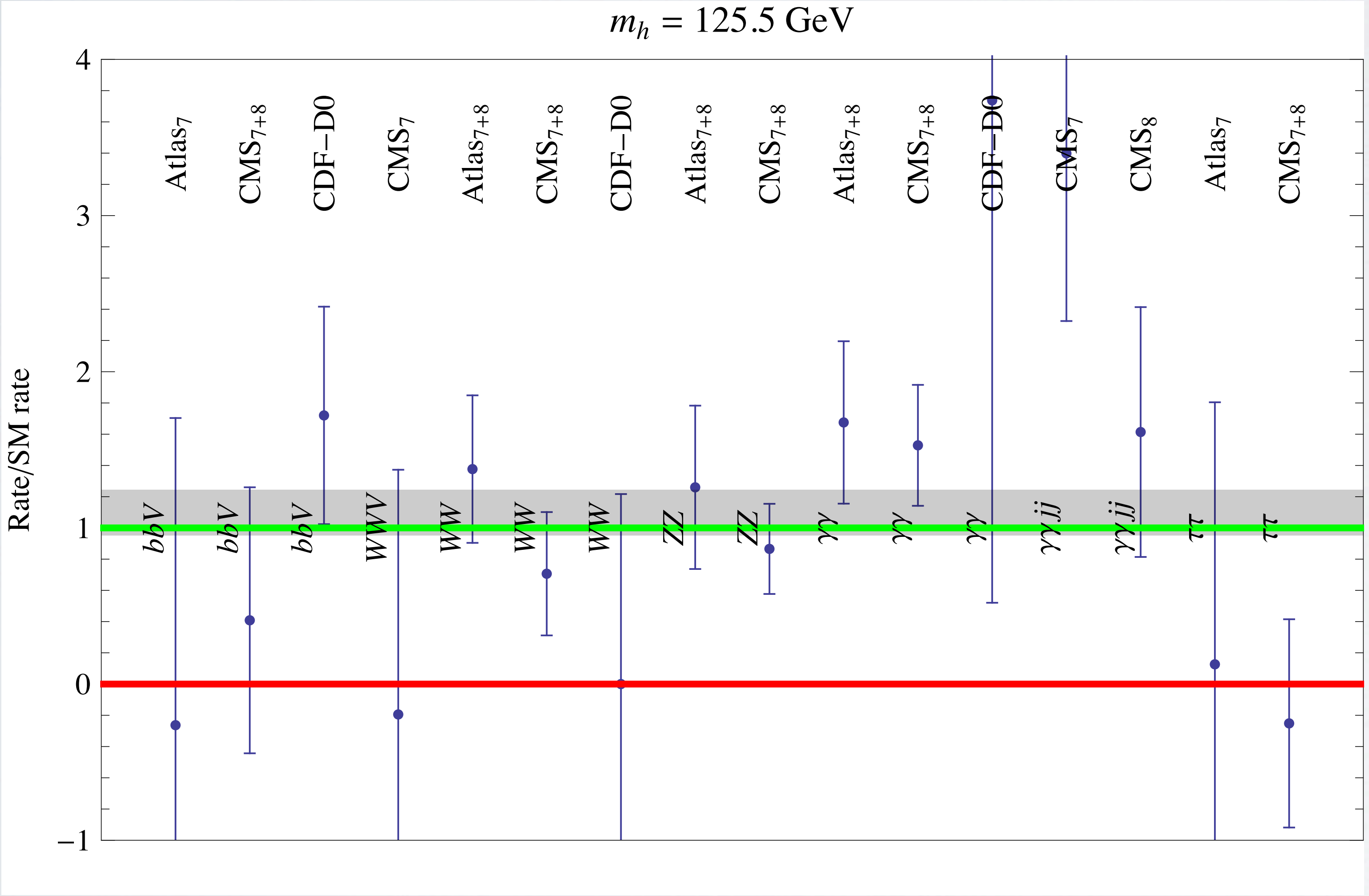
HIGGS DISCOVERY

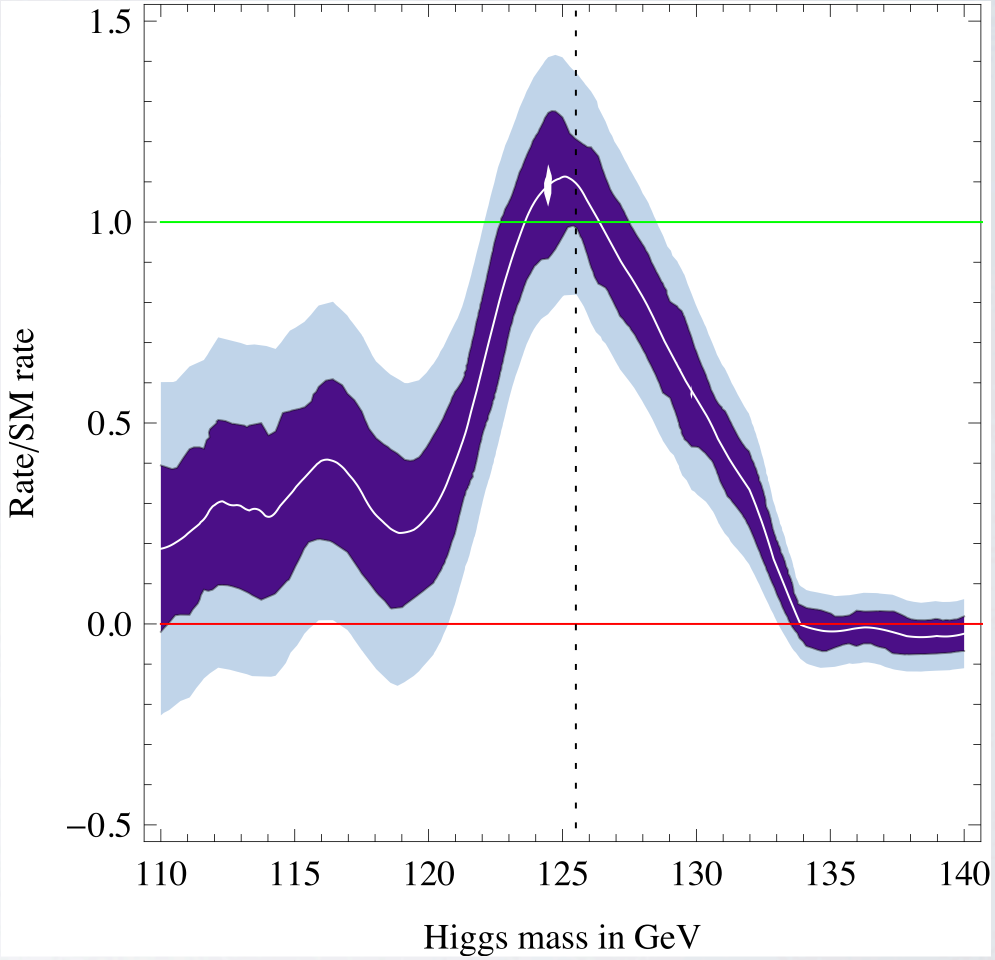
The Higgs is real, and its mass is about 125 GeV.
This is ambiguous news for SUSY partisans....



HIGGS PROPERTIES

Data summarized in Giardino / Kannike / Raidal / Strumia, 1207.1347.





Photons are high, taus are low, *WW/ZZ* just about right.

Error bars are big. But more data is coming in quickly.

HIGGS DISCOVERY

It's a weakly coupled Higgs boson and approximately Standard-Model like. **Nightmare scenario?**

Anything resembling traditional technicolor is **ruled out**. But still a little room for a pseudo-Goldstone composite.

Only SUSY really predicts Higgs mass near Z mass.

But...

MSSM HIGGS MASS

- Just as in the Standard Model, Higgs mass is related to quartic coupling.

- Supersymmetry: gauge interactions always come with quartic scalar interactions (*D*-term potential)

$$\frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

- Implication: Higgs quartic related to gauge couplings, which also determine *W*, *Z* masses: tree-level bound

$$m_h \leq m_Z \cos(2\beta)$$

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Higgs mass maximized at *large* tan beta.

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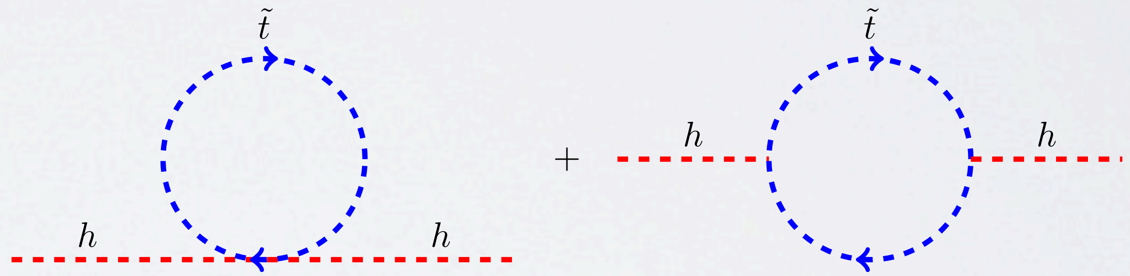
125 GEV HIGGS AND SUSY

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

Many options to fit it, but most feel a little contrived.

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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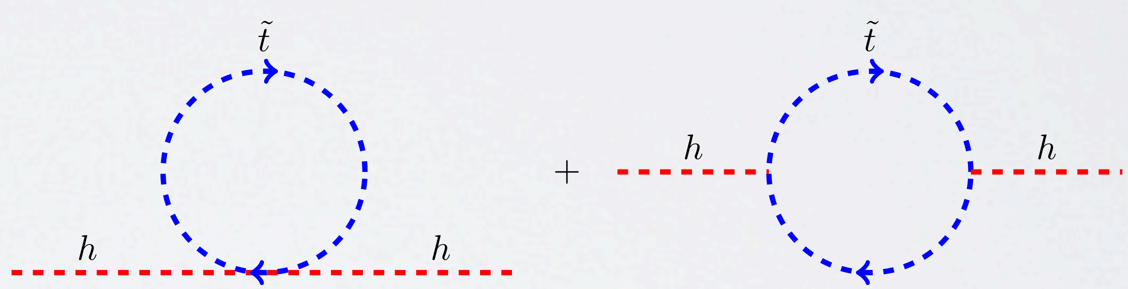

Tree-level bound: 90 GeV

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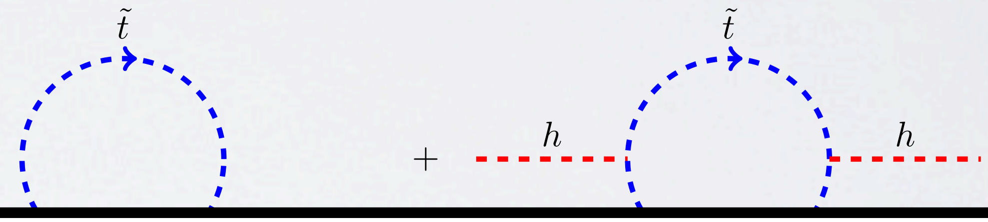

Logarithmic growth with stop mass

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

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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MS

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

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

Haber, Hempfling '91

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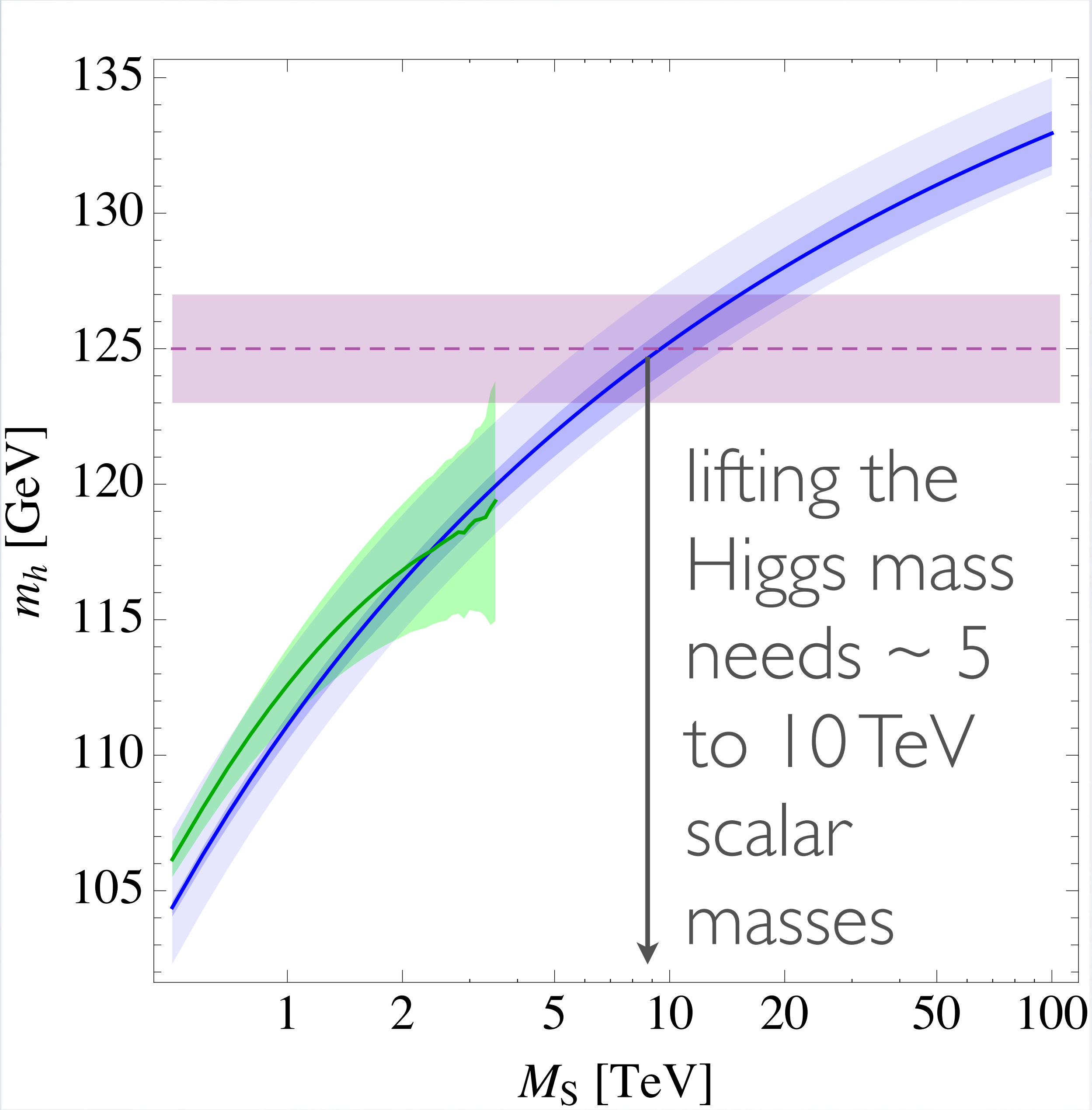
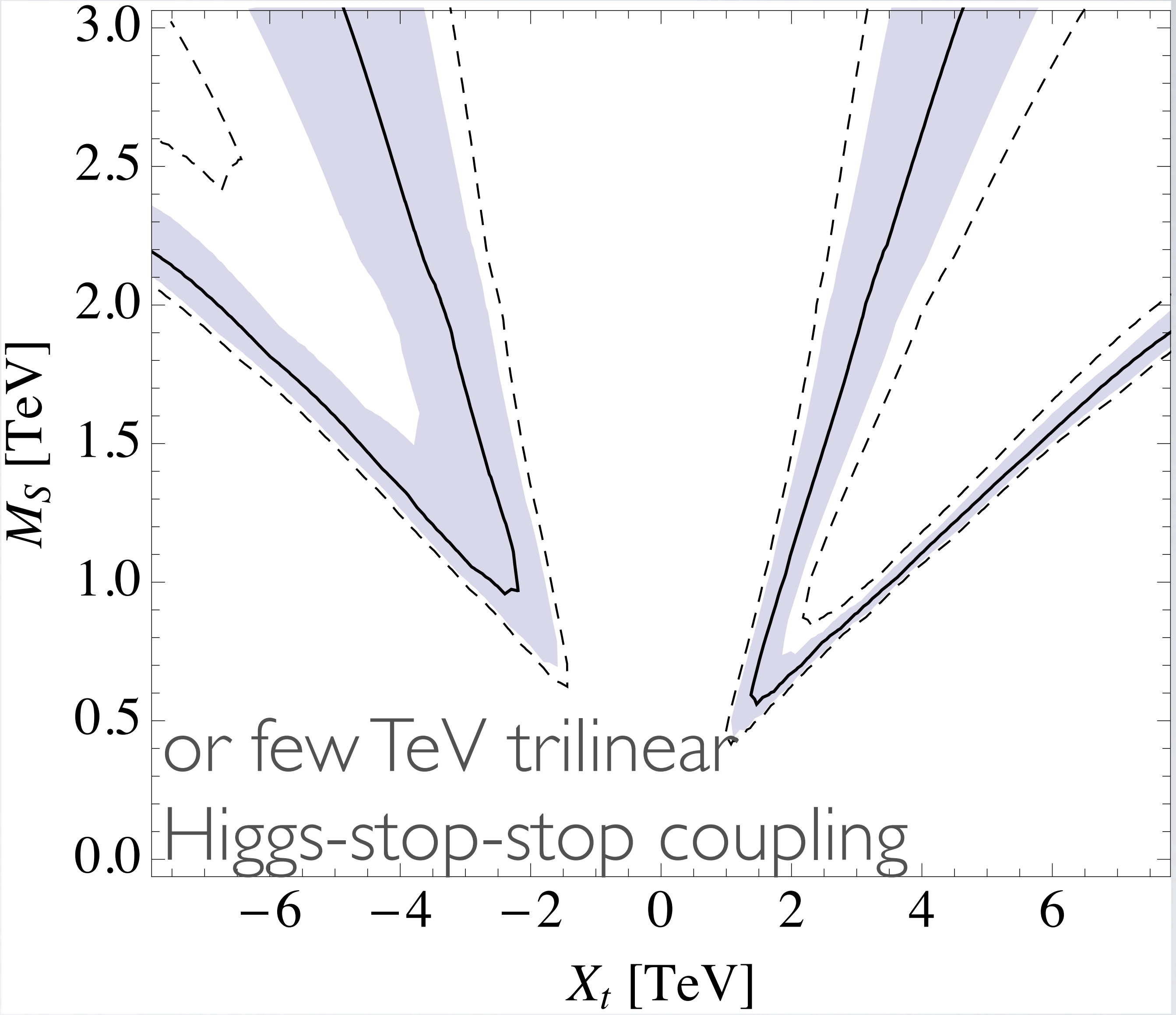




In the MSSM, a 125 GeV Higgs requires large quantum corrections, with multi-TeV SUSY-breaking parameters, **reintroducing** *(part of)* the hierarchy.

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

DICHOTOMY

Higgs at 125 GeV

Beyond MSSM,
natural

MSSM, tuned
with heavy
scalars

robust experimental connection

Stop search;
Higgs sector
(rates, decays)

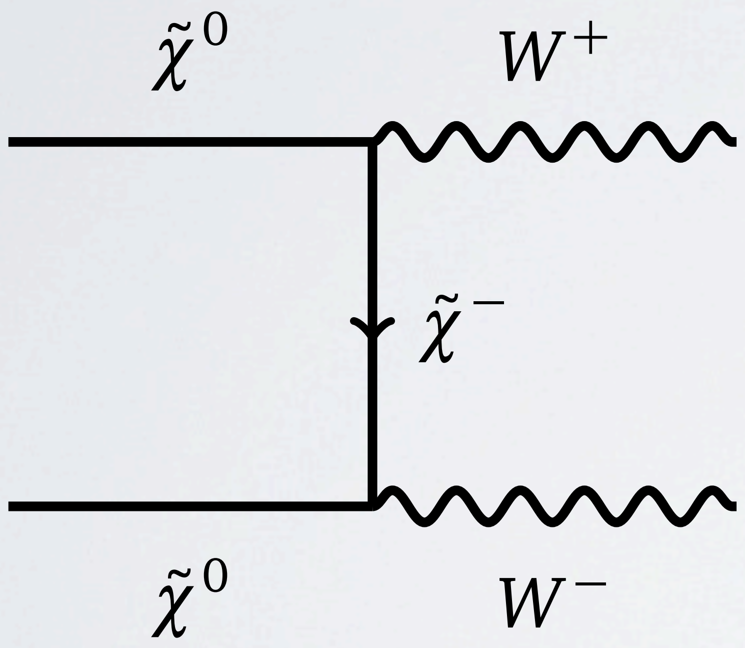
Models?
(NMSSM, D-terms,
compositeness....)

Gluino
search

Top-down
theory

MSSM DARK MATTER

Neutralinos: superpartners of photon, Z, and Higgs.



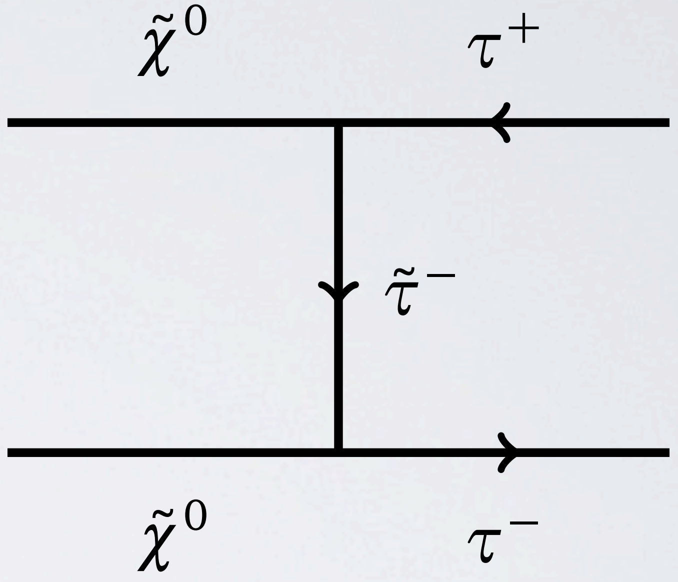
Wino and higgsino: in SU(2) multiplets; can annihilate a lot.

Thermal relic abundance is underpopulated unless they're heavy (about 1 TeV for higgsinos or 2.7 TeV for winos), e.g.:

$$\langle \sigma v(\chi\chi \to W^+W^-)\rangle \approx 3 \times 10^{-24} \frac{\mathrm{cm}^3}{\mathrm{s}} \text{ for } m_\chi \approx 140 \text{ GeV}$$

MSSM DARK MATTER

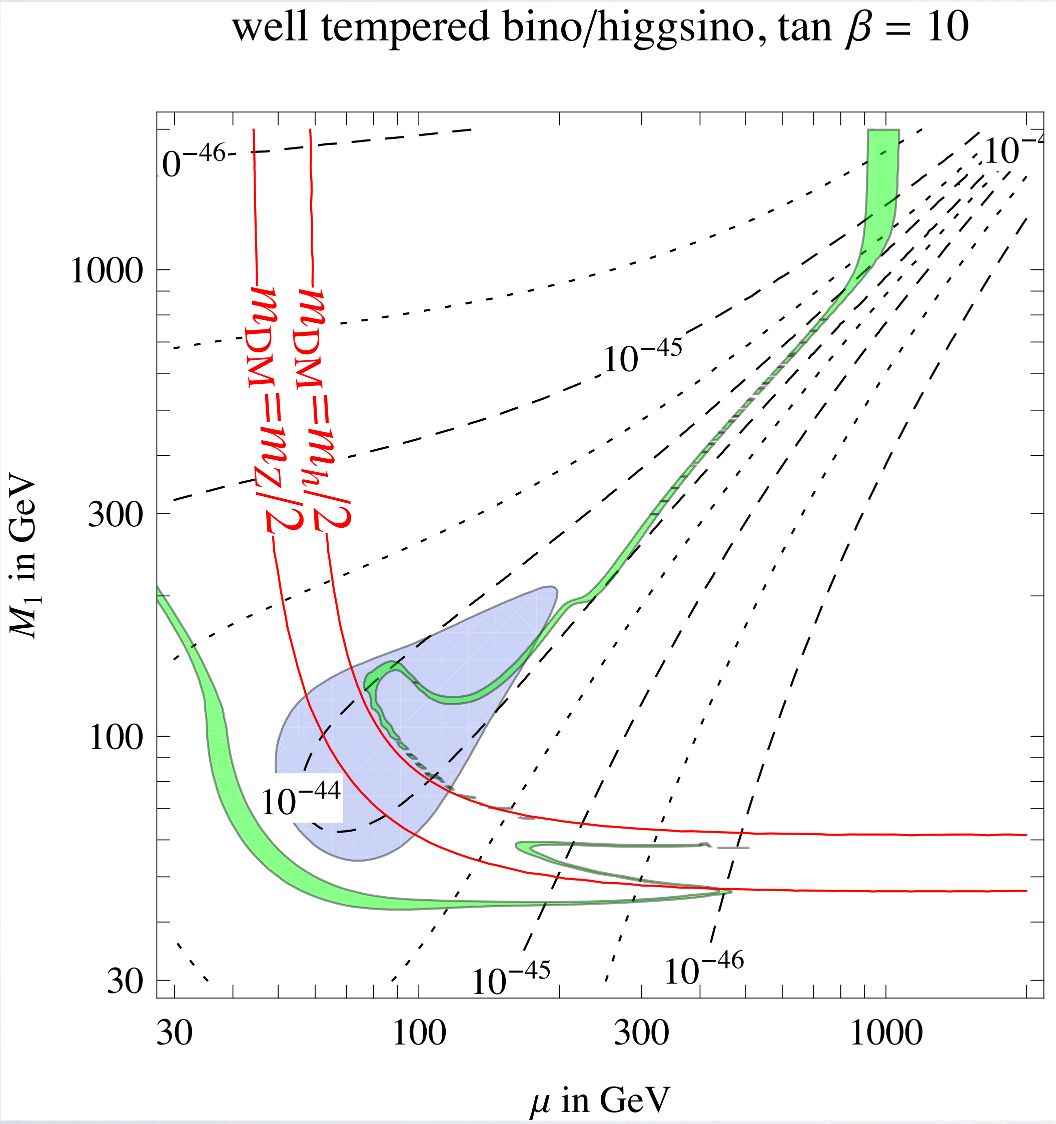
Bino: overpopulates, unless slepton is very light or degenerate within 5% for coannihilation.



Viable MSSM dark matter:
- **coannihilation** to boost relic abundance of a mostly-bino state
- delicate **mixing** of wino/higgsino and bino to get thermal abundance (“well-tempered”)
- **non-thermal relic abundance**

WELL-TEMPERED NEUTRALINO

The right mixture of bino/higgsino or bino/wino can have a thermal relic abundance. Arkani-Hamed/Delgado/Giudice hep-ph/0601041: "Well-tempered neutralino."

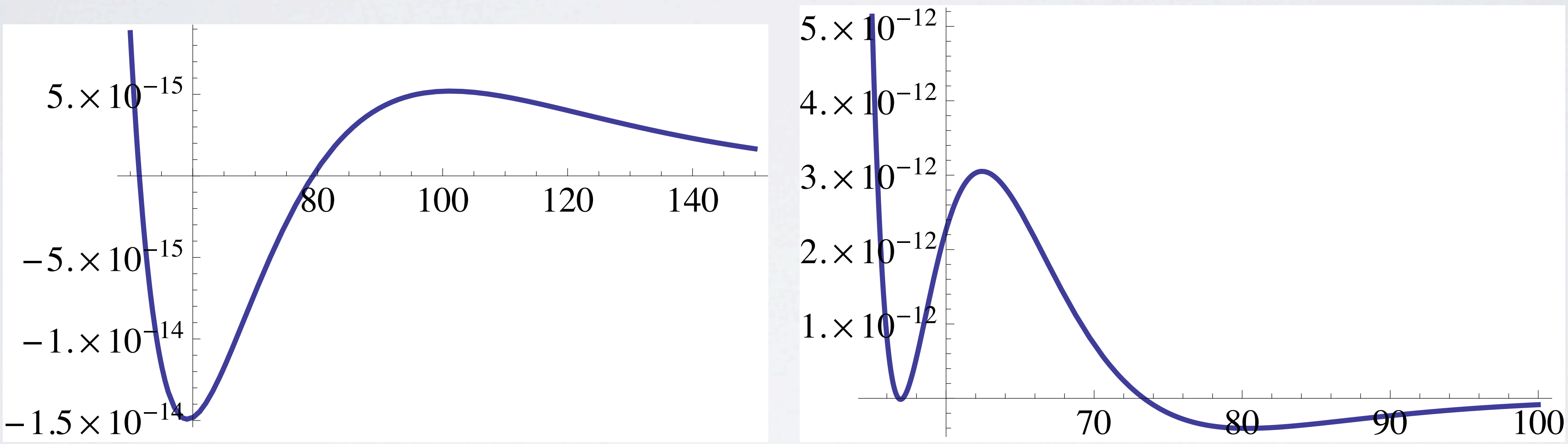


XENON100 is significantly eating into the parameter space: Farina et al., 1104.3572.

See also: Perelstein & Shakya, 1107.5048; talk by B. Shakya tomorrow.

NON-THERMAL DM

Supergravity theories are generically expected to have a **moduli problem**. New scalar fields with gravitational-strength couplings.



Moduli masses ~ $m_{3/2}$ from effective field theory after canceling the c.c. (de Carlos et al. hep-ph/9308325; Fan et al. 1106.6044). This is one strike against gravitino dark matter.

MODULI TO DM?

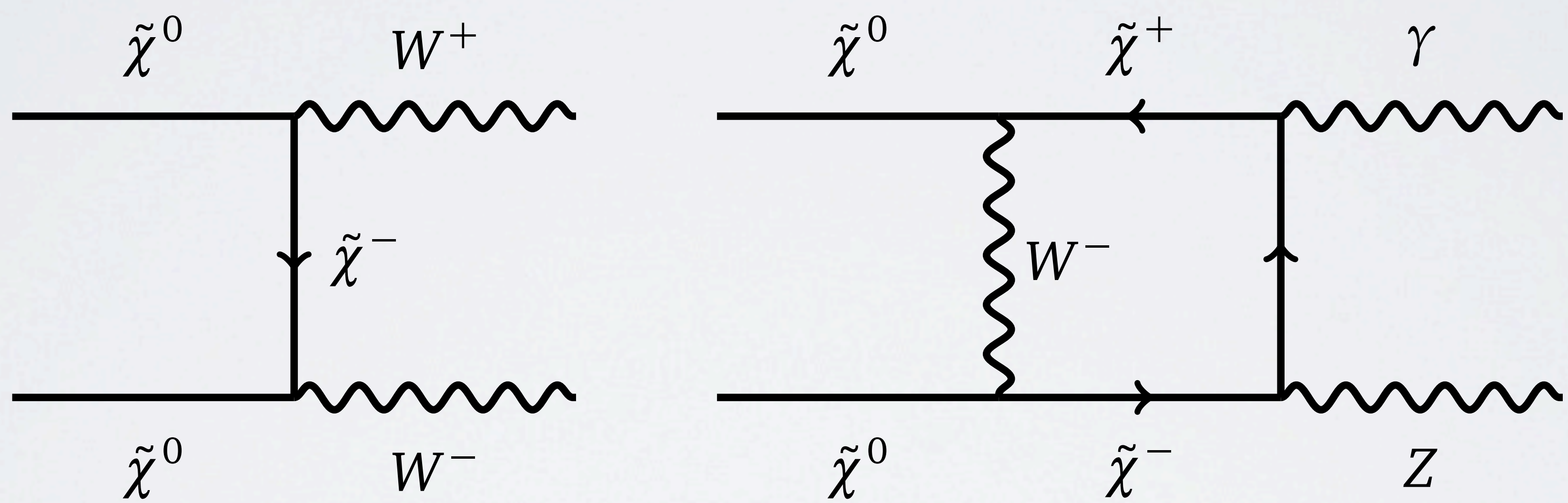
Moduli oscillate coherently, ruining cosmology, unless they are heavy enough that their decays reheat the universe above the BBN temperature.

Suggests $m_{3/2}$ ~ 30 to 100 TeV. **Moduli decays produce neutralinos**, allowing winos to have a larger relic abundance (Moroi & Randall, hep-ph/9906527; J. Kaplan, hep-ph/0601262; Gelmini & Gondolo, hep-ph/0602230; Acharya, Kane, et al., many papers)

Lesson: don't rely too much on the assumption of thermal relic abundance.

IN WINO VERITAS?

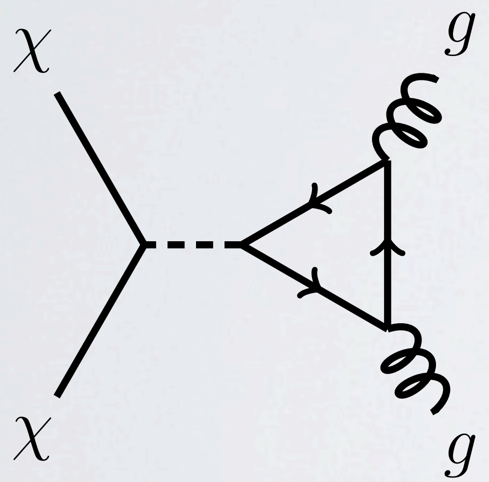
The non-thermal scenario makes winos a compelling possibility for dark matter. Their large annihilation rate doesn't necessarily imply under-abundance.



Direct detection is **loop-suppressed** and hard to see. Indirect detection: **antiprotons, continuum gamma rays, gamma ray line.** Bounds exist (safe above ~ 300 GeV). Keep looking!

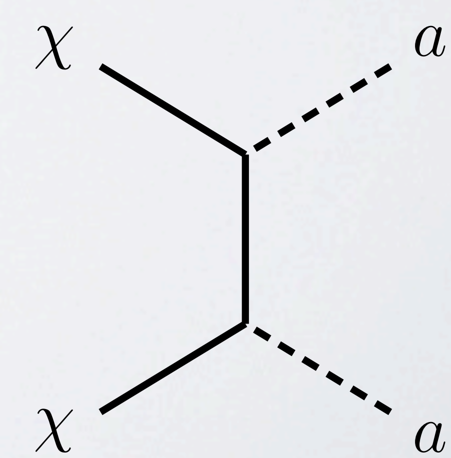
NON-MSSM SUSY DM

Supersymmetry need not be **minimal** SUSY. Can have extended models with new DM candidates. For instance, **axino** dark matter or (Bellazzini, Csaki, Hubisz, Shao, Tanedo 1106.2162) **Goldstone fermion** dark matter.



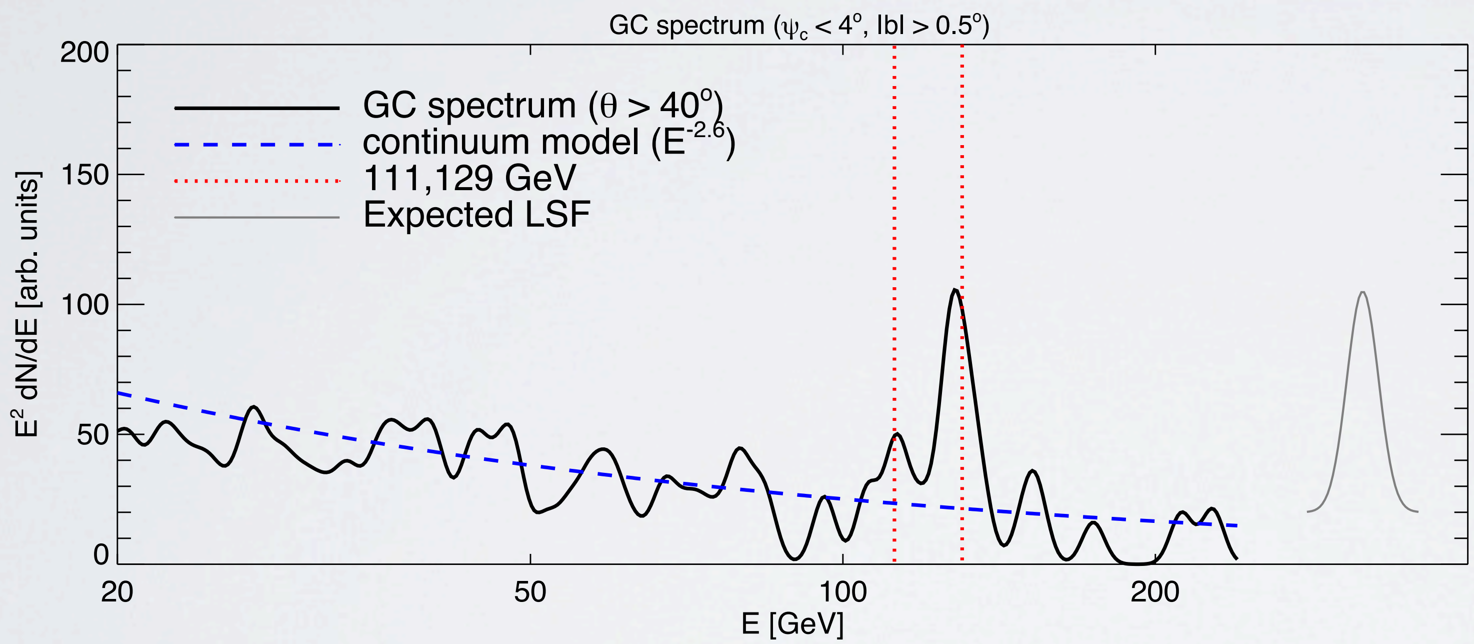
Supersymmetrically break a U(1): Goldstone boson has a "Goldstone fermion" partner. Annihilates through anomaly to gg, γγ, γZ.

Thermal relic abundance from p-wave:



THE FERMI 130 GEV LINE

You all already know about it....

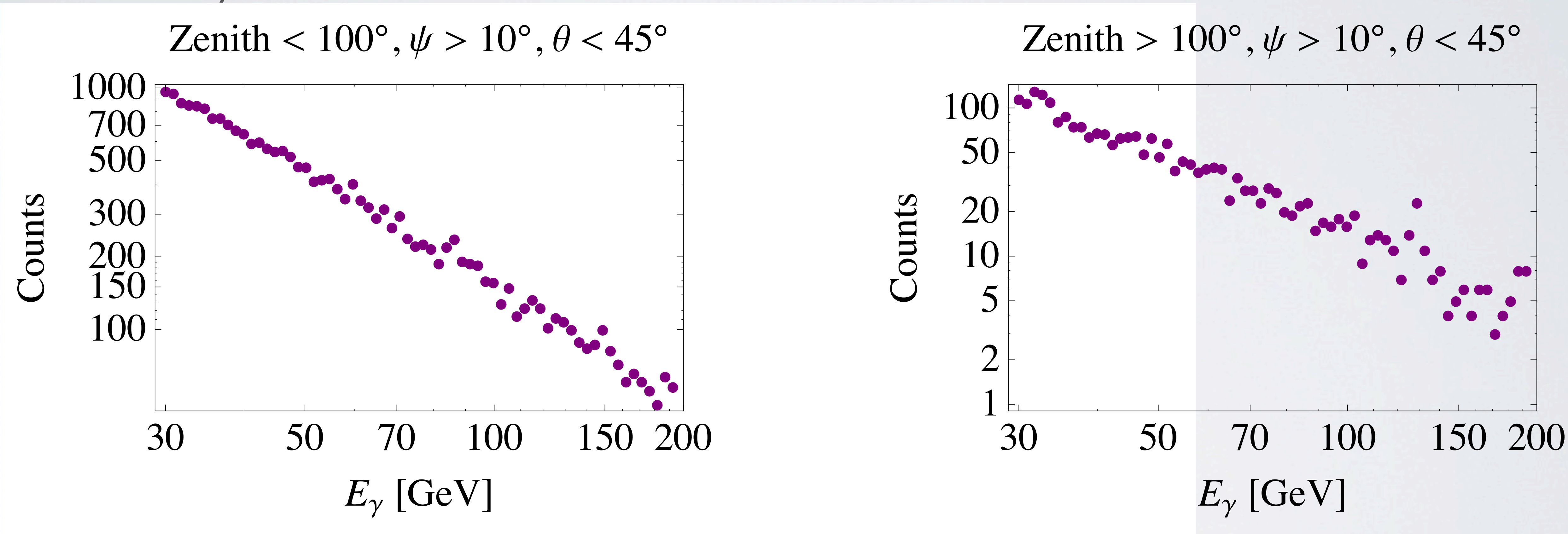


from Su/Finkbeiner, 1206.1616

Note possibility of two lines consistent with **γγ** and **γ**Z, which would be a **real** smoking gun if they're both high significance with more data....

THE FERMI 130 GEV LINE

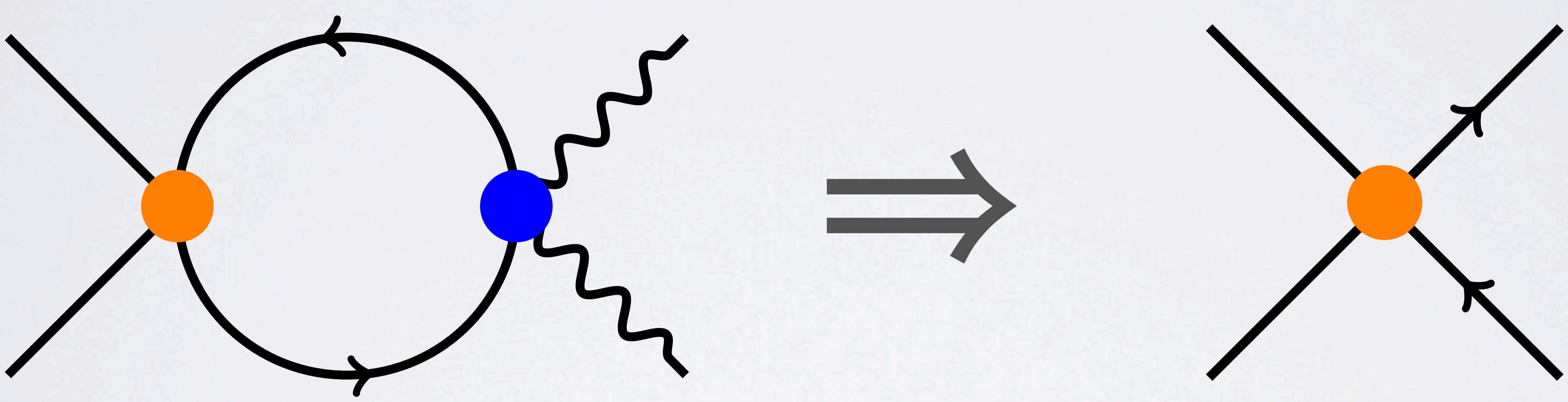
And you probably also know something odd appears when you look at the Earth:



But let's set that aside for now (hard to think of what could lead to a spurious effect only when looking in certain places....)

THE FERMI 130 GEV LINE

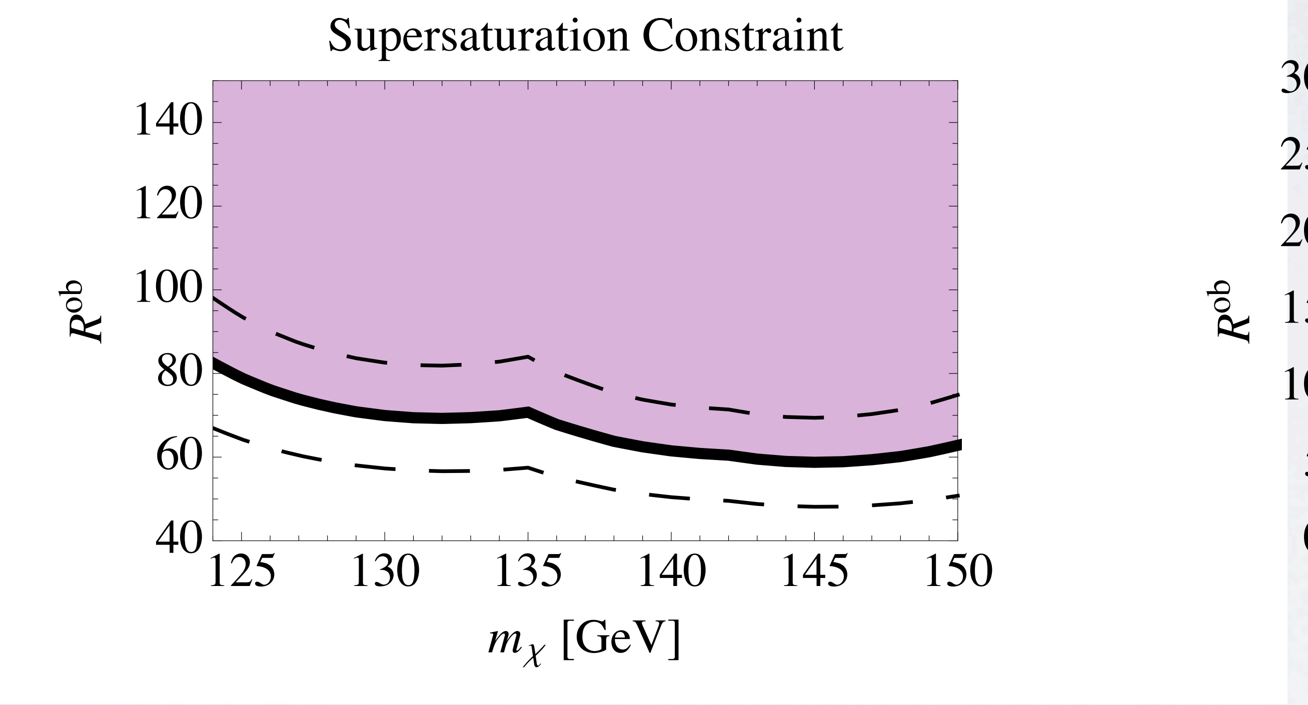
Dark matter isn't charged, so need particles running in a loop (case of strongly-bound composite of charged particles is essentially this loop with a 4π coupling)

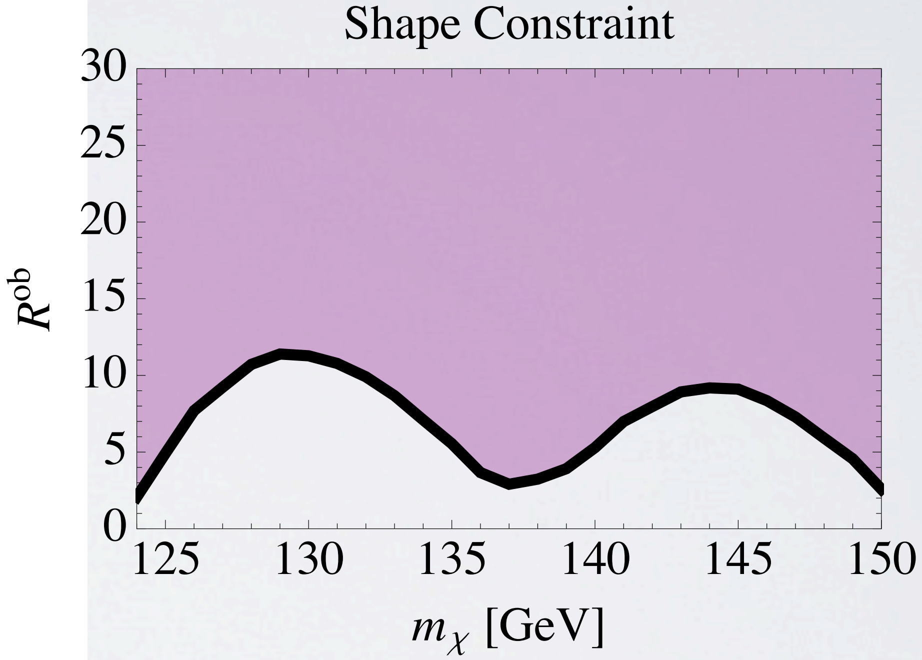


If the particle running in the loop is light enough, usually expect the tree-level process to be larger by a factor of $(\alpha/\pi)^{-2}$. In severe tension with continuum gamma ray bounds (unless only electrons and muons).

THE FERMI 130 GEV LINE

Whatever else it may be, it is **not** a signal of **MSSM** dark matter. (It may be SUSY DM, but not minimal SUSY.)

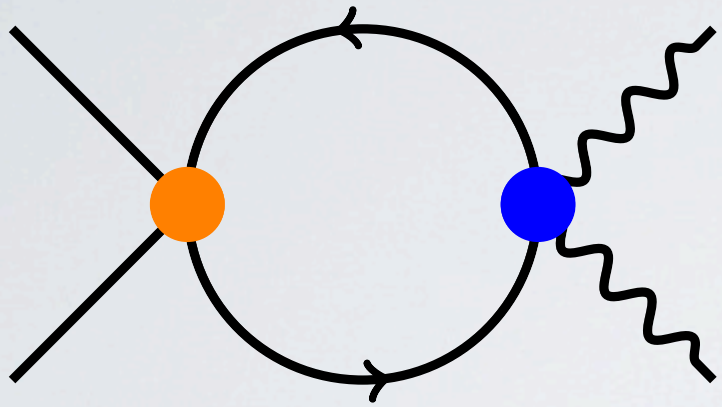




Cohen, Lisanti, Slatyer, Wacker 1207.0800: bound on tree annihilation to WW, ZZ relative to gamma-ray line. (See also Buchmuller & Garny, 1206.7056.)

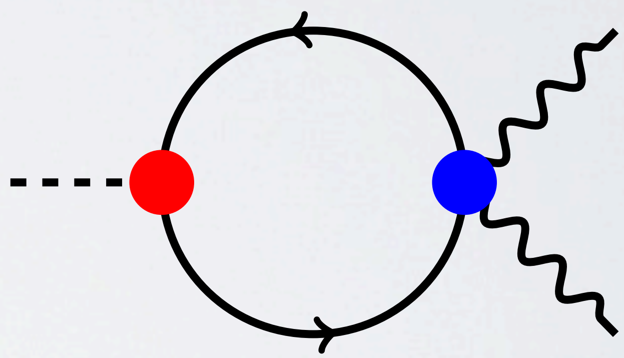
MSSM always has large tree/loop ratio.

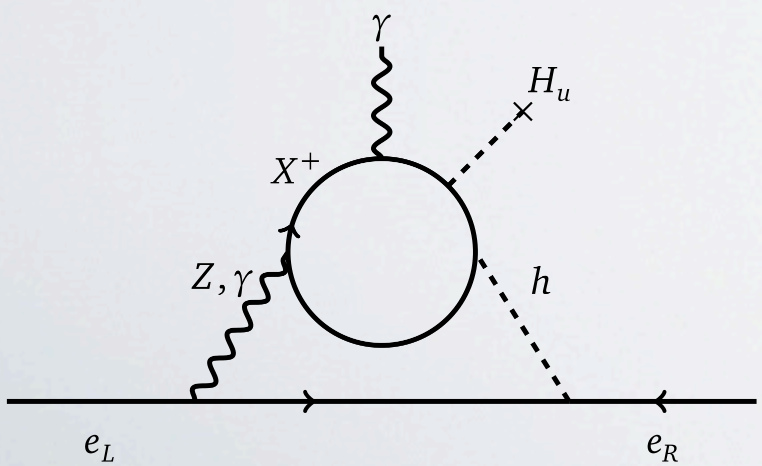
NEW CHARGED PARTICLES ON THE HORIZON?



Fermi-LAT 130 GeV line: dark matter annihilating through a loop?

Modified Higgs to diphoton rate: a loop? (Fewest problems if charged but uncolored scalars.)





Near future: improved bound (or signal) of electron EDM from ThO (DeMille / Doyle / Gabrielse ACME collaboration)

AXIONS

Axions remain **extremely** well-motivated theoretically. The moduli cosmology scenarios mentioned earlier open up higher decay constants than the oft-quoted “axion window” as viable options (e.g. Kawasaki, Moroi, Yanagida, hep-ph/9510461).

Clever recent idea: Graham & Rajendran, 1101.2691. Cold molecule interferometry to find time-varying dipole moments induced by axion DM. A very different form of dark matter direct detection!

WHAT'S NEXT?

- If SUSY is right, could well be **beyond the MSSM.**
- Precision measurements of Higgs properties will either make the nightmare scenario more likely or give us confidence that new weak-scale physics is waiting for us.
- The Fermi-LAT 130 GeV line is tantalizing: hard to explain, but esp. if the second line at 111 GeV is there, hard to ignore.
- Keep looking for hard-to-find but theoretically motivated options: nonthermal wino DM, axions....
- Still hoping for more surprises!

BACKUPS

PGB HIGGS?

- Georgi/Kaplan '84: strong dynamics can break a global symmetry, leaving Higgs as a **pseudo-Nambu-Goldstone boson**, which gets a potential from explicit symmetry breaking
- Fermion mass generation is still a mess, like in technicolor
  (Randall-Sundrum is an incantation that doesn't solve your strong dynamics problems: existence of the theory?)
- Often must tune contributions that want the wrong vacuum alignment against others (naively, mass $<<$ VEV $\sim f_\pi$)
- Personal aesthetic bias: messy theories we should ignore unless data tells us otherwise

MSSM + SINGLET

One of the most familiar ways to lift the Higgs mass is to add a singlet superfield *S* and

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

Contributes to the potential: $|F_S|^2 = \left|\frac{\partial W}{\partial S}\right|^2 \supset |\lambda H_u H_d|^2$

New quartic means **larger Higgs mass**

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New quartic m

New quartic involves H_u and H_d; maximized at small tan beta.

MSSM + SINGLET?

Tension whenever there is a fundamental singlet scalar: **tadpole** vs **domain wall**

One way out: not really a fundamental singlet; it's a ***bound state*** of stuff with charges.

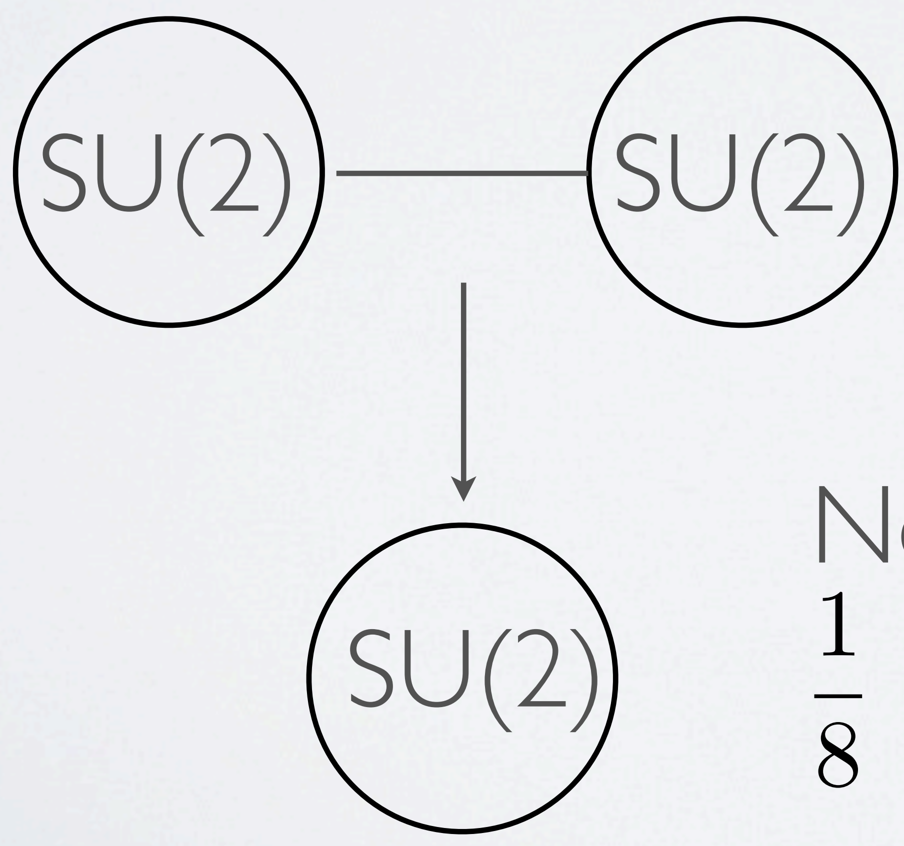
Examples: Fat Higgs (Harnik, Kribs, Larson, Murayama), composite stop & Higgs (Csáki, Randall, Terning)

Objections: coincidence of scales (tuning!), gauge coupling unification is generically spoiled.

NON-DECOUPLING D-TERMS?

Charge the Higgs under another asymptotically free gauge group (e.g. Batra, Delgado, Kaplan, Tait, hep-ph/0309149) to get new *D*-term quartics and maintain perturbativity to high scales.

e.g.



Break nonsupersymmetrically to the diagonal.

New terms of same form as

$$\frac{1}{8}\left(g^2 + g'^2\right)\left(\left|H_u^0\right|^2 - \left|H_d^0\right|^2\right)^2$$

COUPLINGS

MSSM: b-quark Yukawa is $y_b H_d b\bar{b}$

Large $\tan\beta$: y_b large, light Higgs h mostly H_u.

$$m_b = y_b v_d = y_b v \cos\beta$$

Due to h admixture of up- and down-type Higgses, find different coupling from the SM:

$$g_{hb\bar{b}}/g_{hb\bar{b}}^{SM} = -\frac{\sin\alpha}{\cos\beta} \approx 1 + \frac{2m_Z^2}{m_A^2}$$

COUPLINGS

MSSM: **mixing** with heavy state near m_A produces:

$$g_{hb\bar{b}}/g_{hb\bar{b}}^{SM} = -\frac{\sin\alpha}{\cos\beta} \approx 1 + \frac{2m_Z^2}{m_A^2}$$

NMSSM: **mix with singlet S**. Tends to lower the branching ratio of Higgs to $b\bar{b}$. (Hence: raises photon BR.)

New *D*-terms: $\delta\left(|H_u|^2 - |H_d|^2\right)^2$

Alters up/down-type Higgs mixing relative to MSSM; changes corrections (see Blum & D'Agnolo, 1202.2364.)

COUPLINGS

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

(Shifman et al.)

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:

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

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:

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

REMARKS

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

Any heavy matter with mass proportional to the Higgs VEV contributes with the same sign -- whether it's a fermion or a scalar. Also, nondecoupling.

This tends to *increase* gluon fusion (reinforcing top contribution) and *decrease* photon BR (because *W* loop has the other sign.)

Sum eigenstates: $$\sum_i \frac{\partial \log M_i(v)}{\partial v} = \frac{\partial \log \det M(v)}{\partial v}$$

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.

HIGGS COUPLINGS FOR NATURAL MODELS

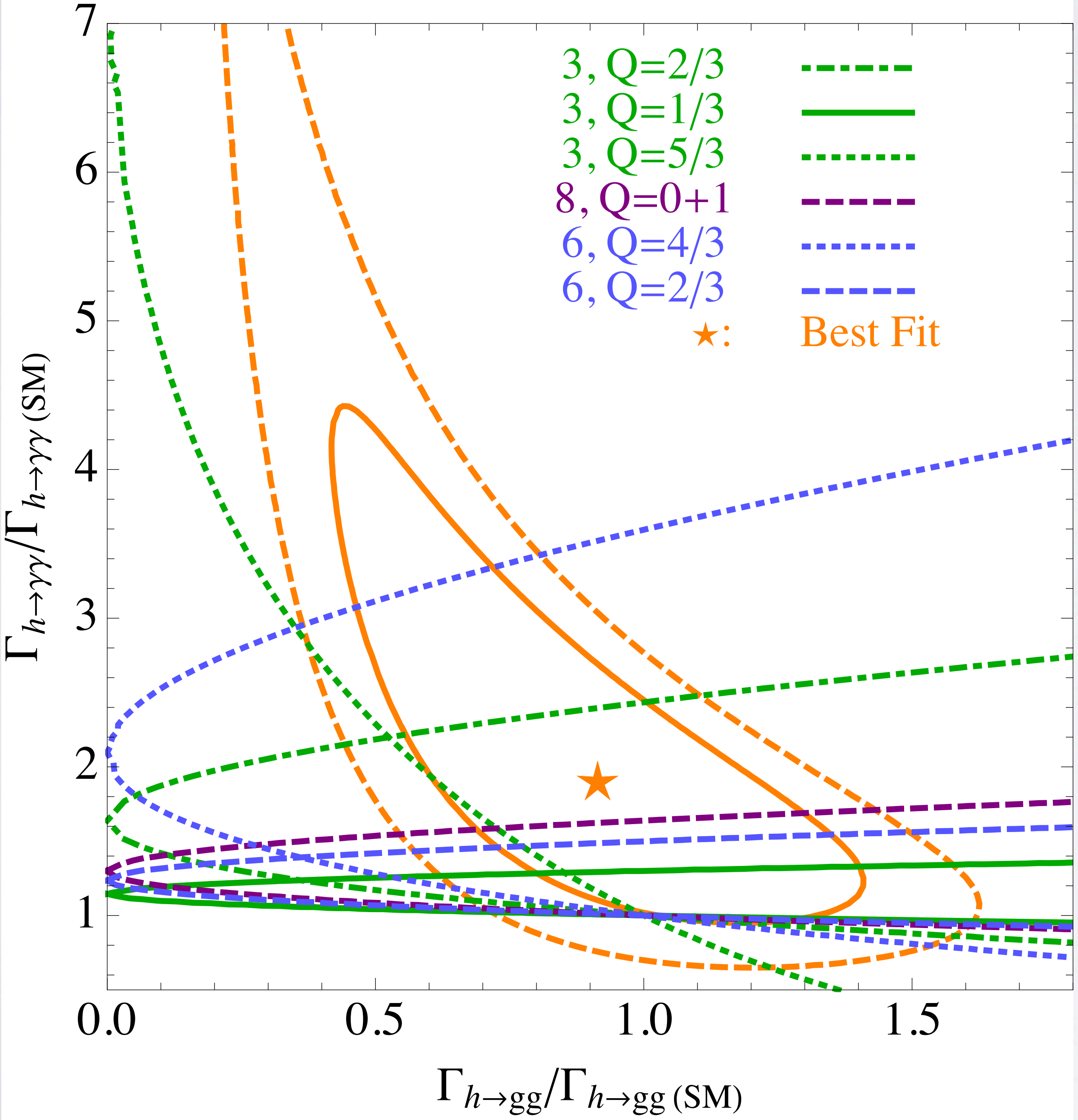
Two effects we've discussed impact the Higgs production and decay:

Mixing alters $b\bar{b}$ rate, thus changing all other smaller branching ratios.

Loops alter *gg* and **γγ** couplings.

"Typically," in natural models, can have effects ~20% or more.

HIGGS: NEW PARTICLES IN LOOPS?



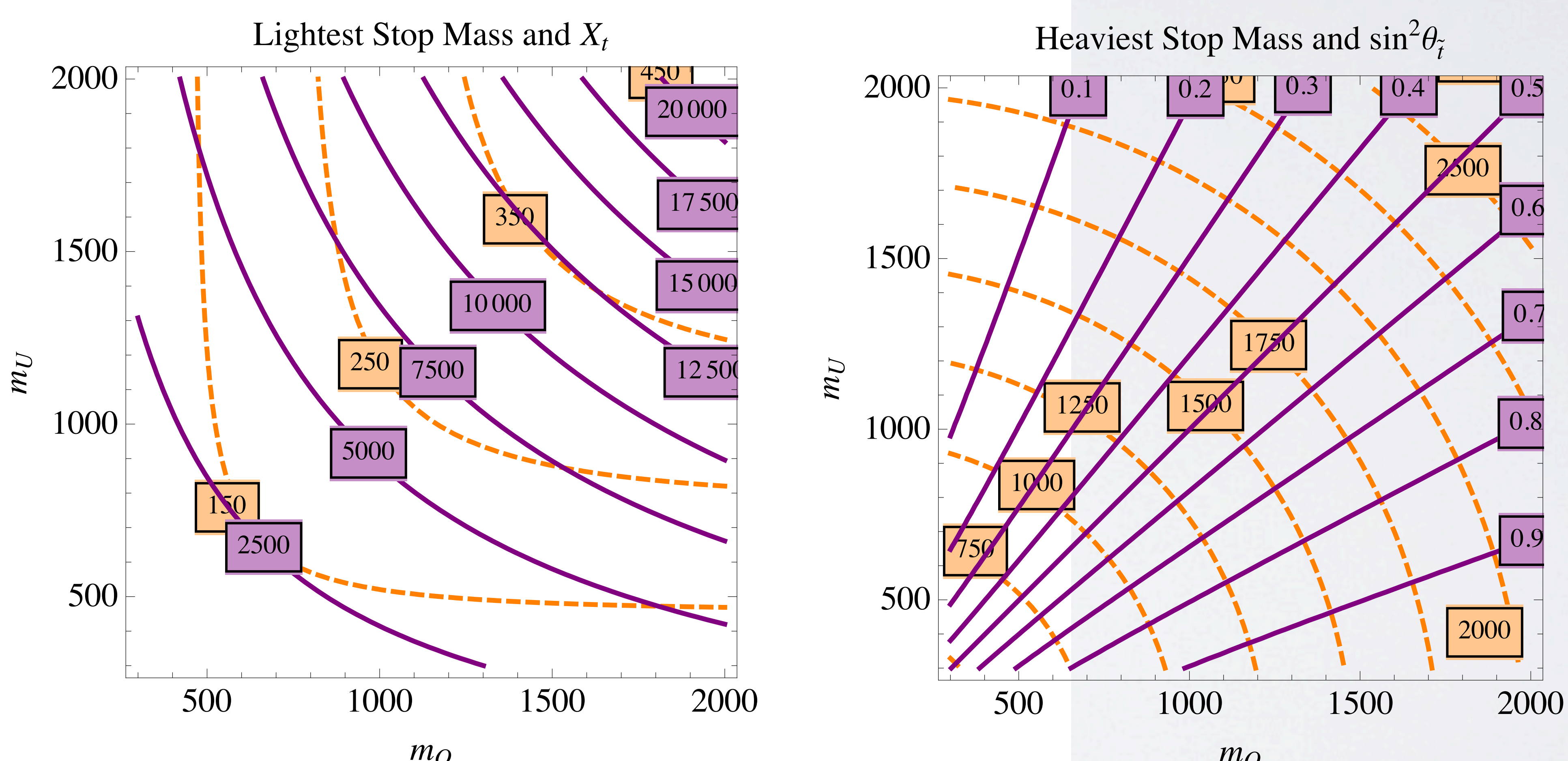
Simplified fit (only ATLAS and CMS WW, ZZ, gamma-gamma from 7+8 TeV; no VBF, taus, etc.)

Invert the sign of *hGG* amplitude?

See also Giardino et al. 1207.1347; Buckley & Hooper 1207.1445; Cohen & Schmaltz 1207.3495....

HIGGS: NEW PARTICLES IN LOOPS?

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



But scalars are bad too, if corrections are this large: huge negative threshold corrections to Higgs quartic, color/charge-breaking minima. Reece, to appear on hep-ph (next week?)