The Status of Supersymmetry*

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Harvard University
at LHCP, Lund, June 16, 2016

* but ask again in six months to a year!

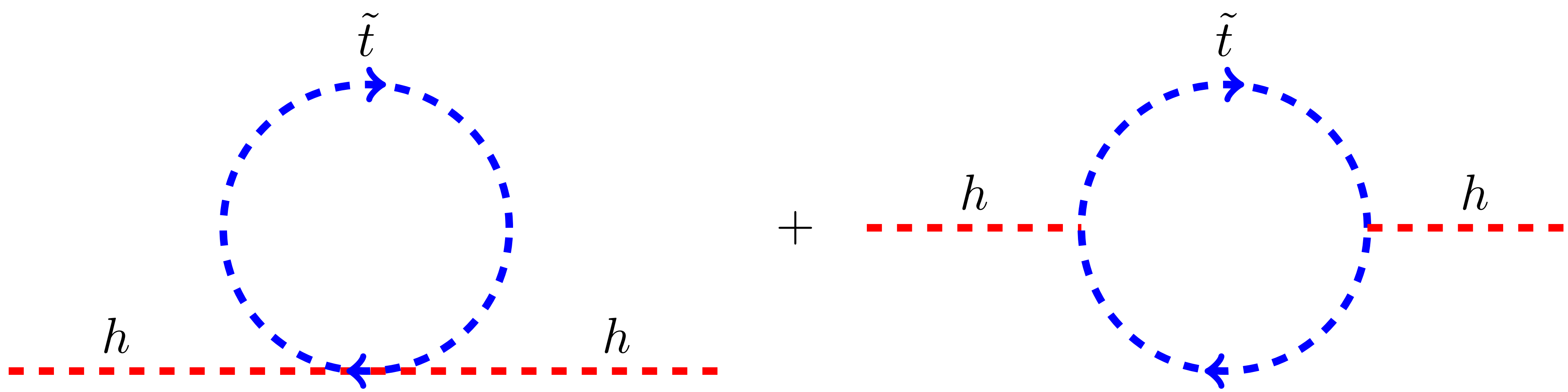
What Can SUSY Do For Us?

Current scorecard….

- Solve the “big” hierarchy problem — ?
- also the “little” hierarchy problem —fully natural EWSB — ✗ (depending on how “little”?)
- Precision gauge coupling unification — ✓
- Provide a dark matter candidate — ?

125 GeV Higgs and SUSY

In the MSSM, loops of stops generate corrections to the Higgs quartic coupling and hence (*after tuning to get the right VEV, i.e. Z boson mass*) Higgs mass:



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

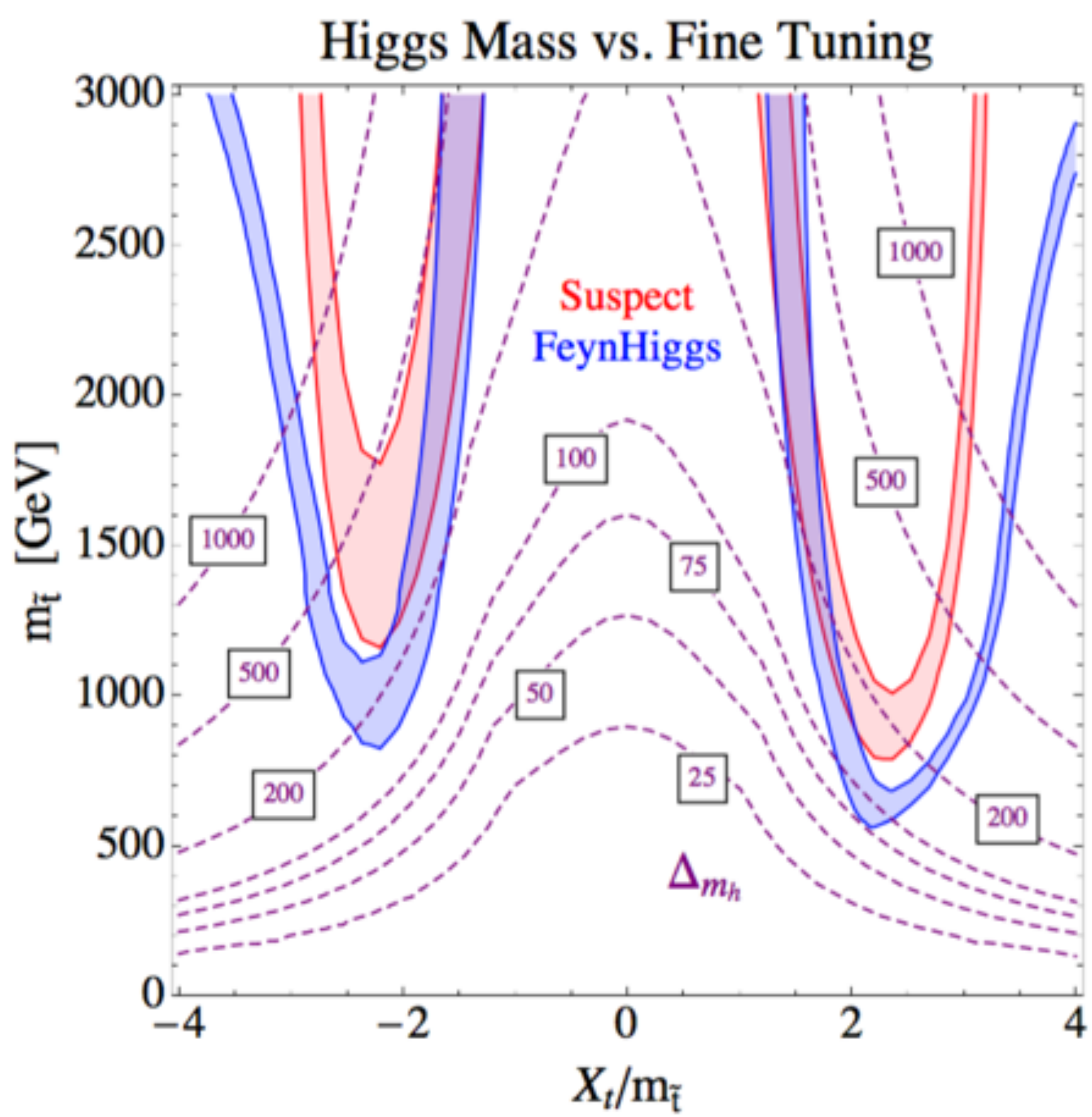
Haber, Hempfling '91

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

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

125 GeV: 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.

Two Paths to 125 GeV

Higgs at 125 GeV

Beyond MSSM,
natural

MSSM with
heavy scalars

robust experimental connection

Stop search;
Higgs sector
(rates, decays)

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

Gluino
search

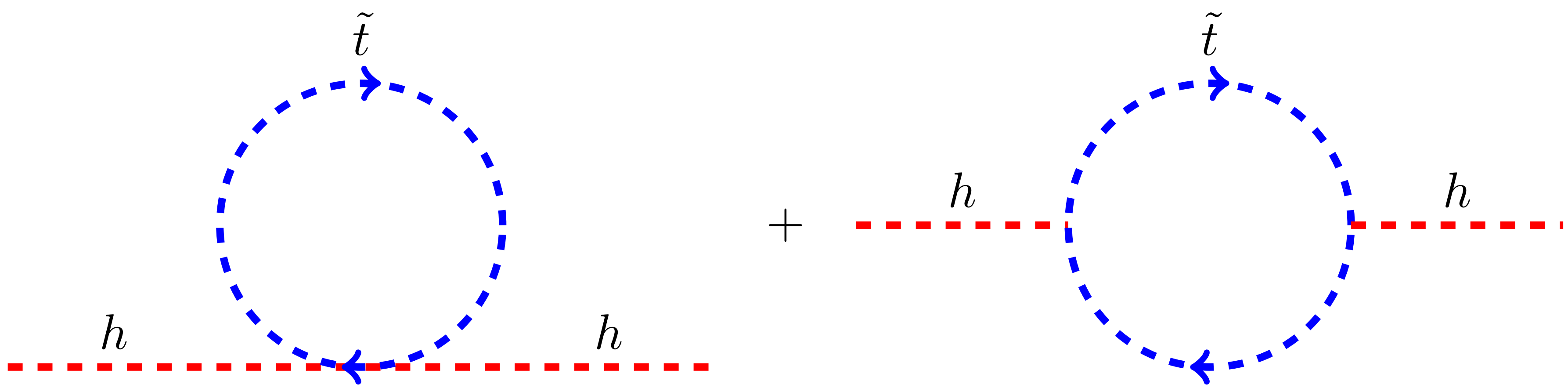
Top-down
theory

Natural SUSY

(assume beyond-MSSM physics raises Higgs to 125)

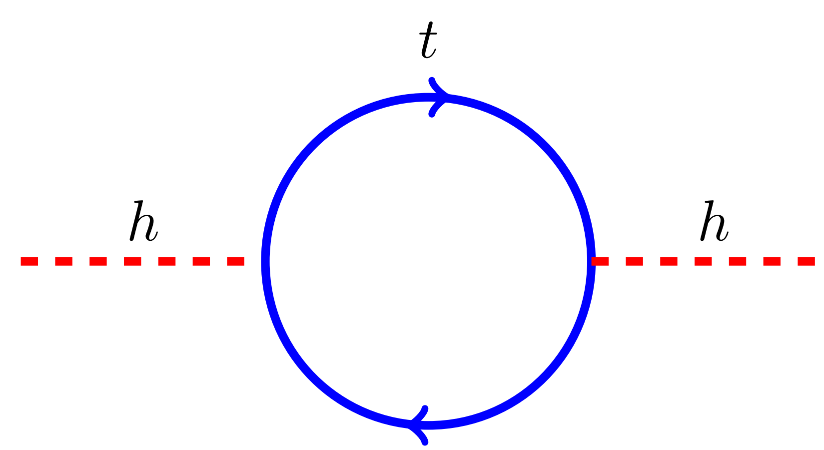
Supersymmetry and the Higgs Mass

Different-spin pieces combine to cancel large corrections.



Imperfect cancelation because SUSY is not an exact symmetry.

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

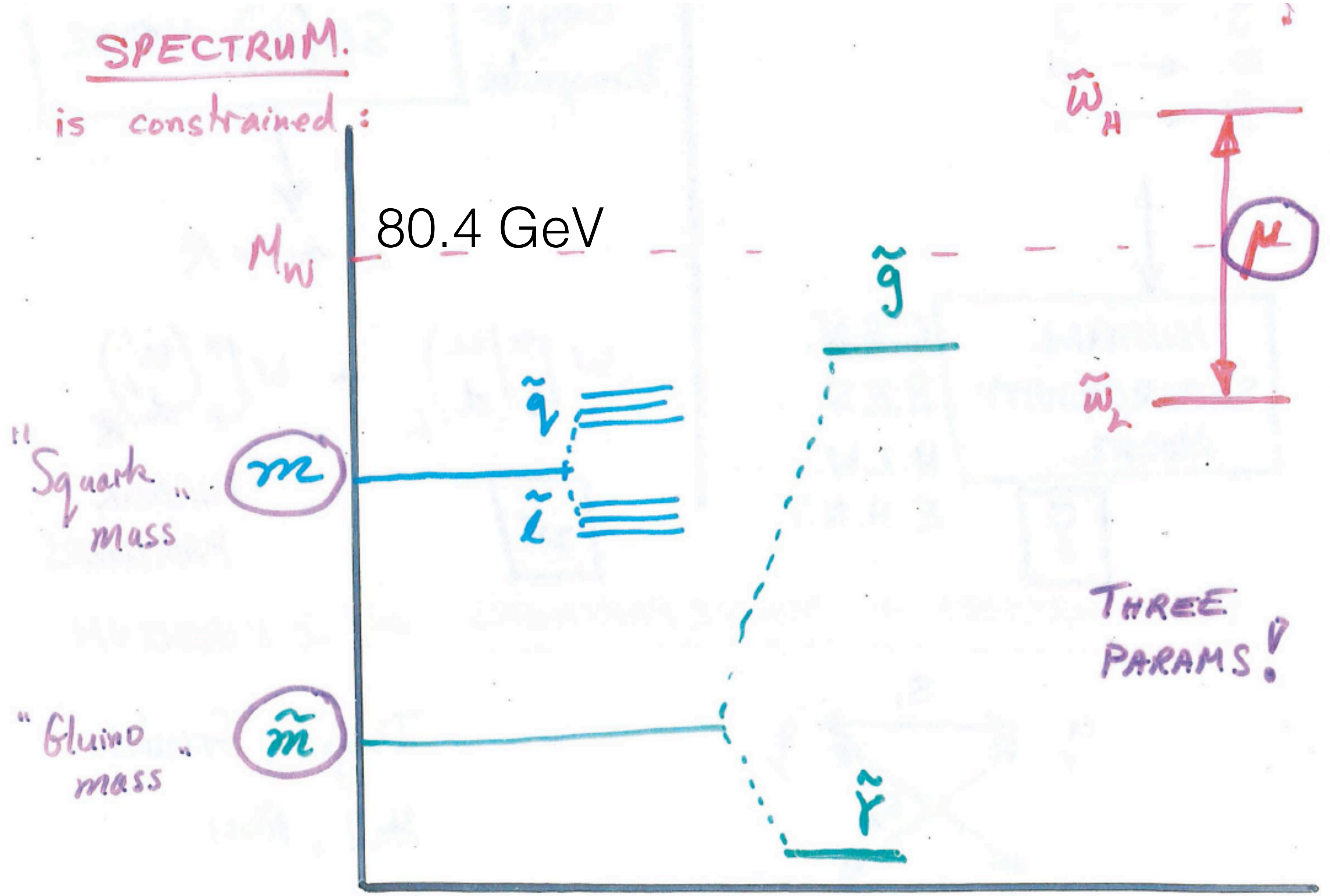


“Stop” or “scalar top”:
cancels the biggest correction.
~10% tuned if mass ~ 700 GeV.

Natural SUSY, 1984

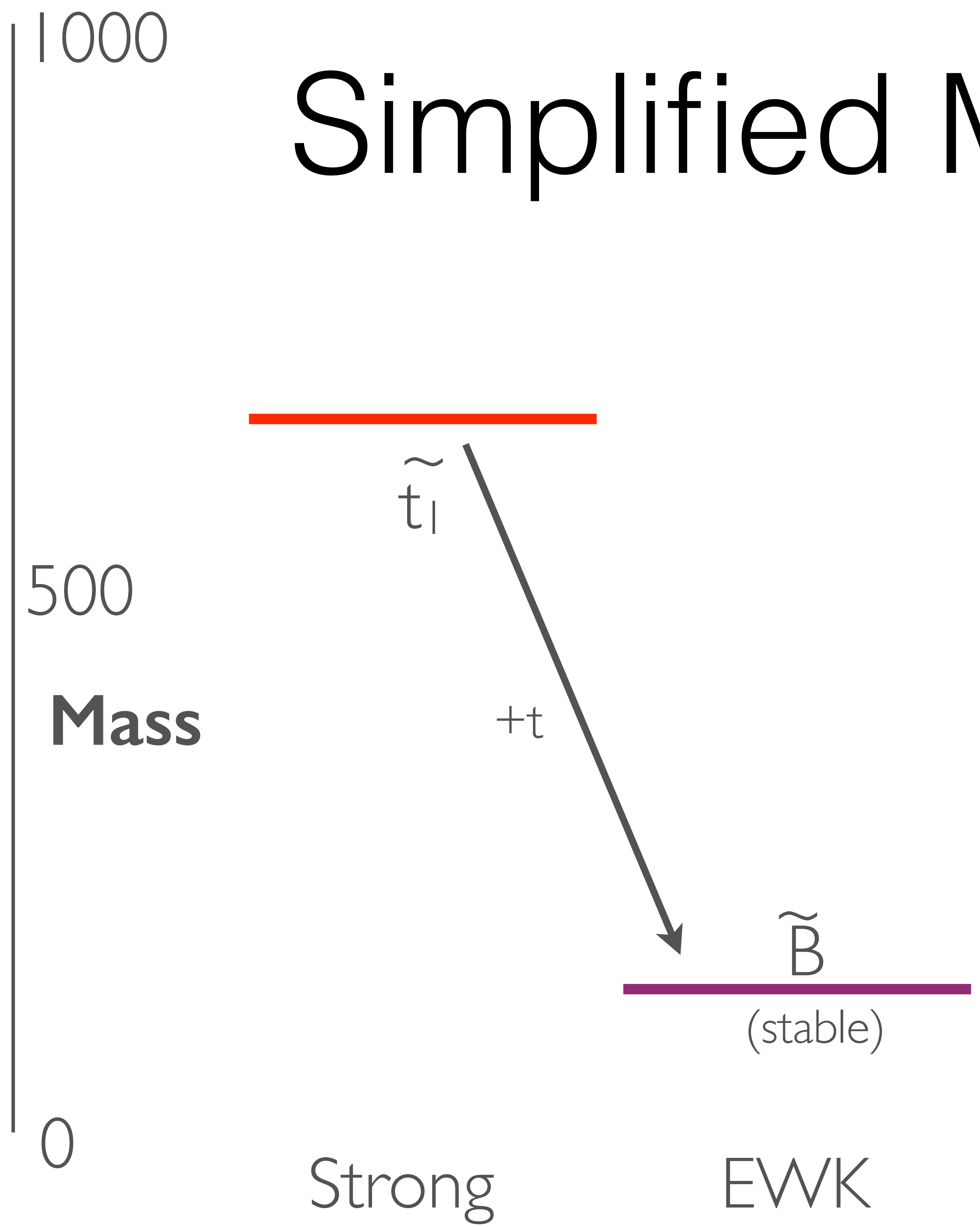
A historical relic (slide borrowed from Lawrence Hall's talk at Savasfest).

All the scalars, and the Higgs, should be at the weak scale!



We don't live in the SUSY universe as envisioned circa 1984.

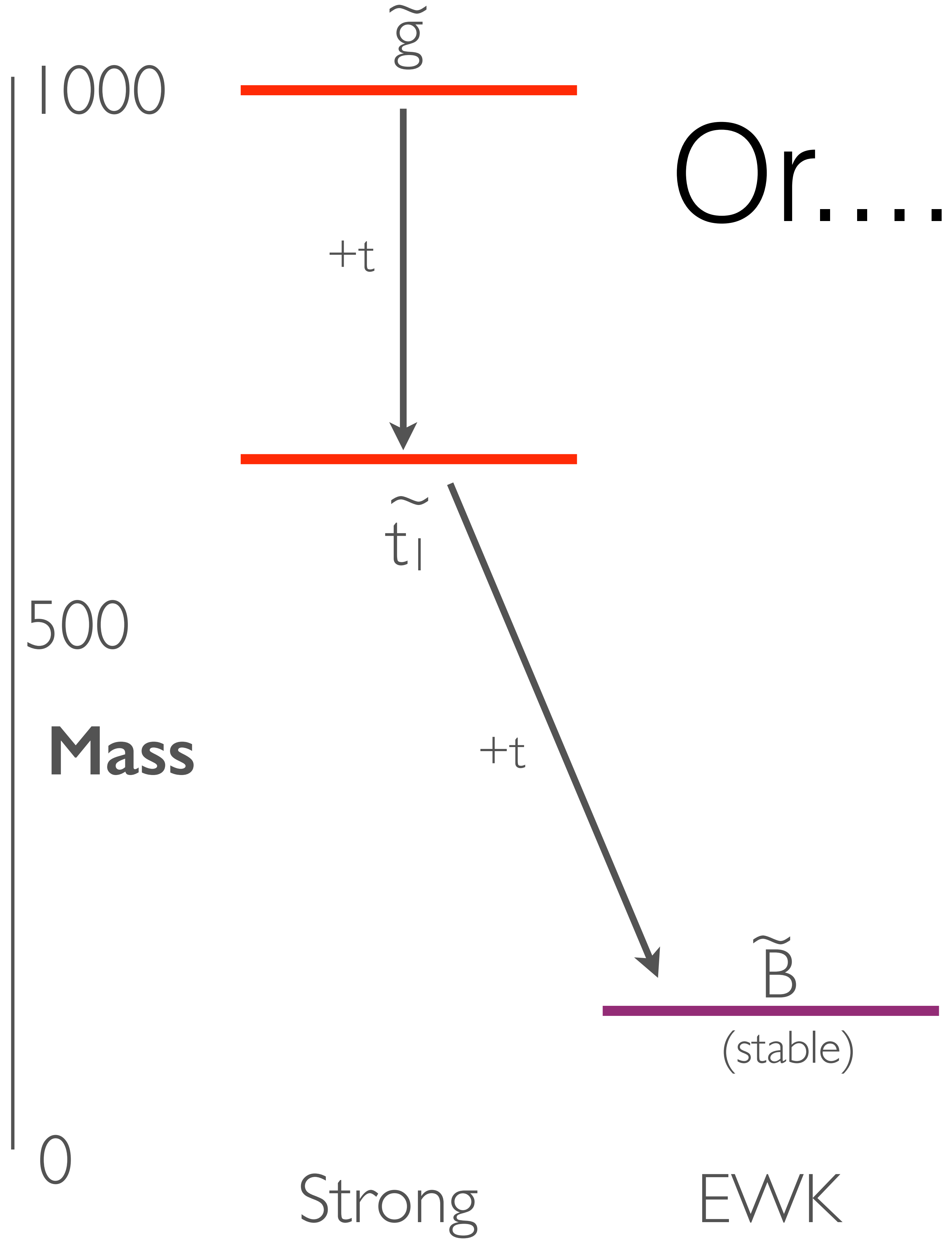
Simplified Models



Much more comprehensible than full spectrum: easy to read off fine-tuning "bottom line" (also want b +chargino)

Natural case: Meade & Reece '06; Kitano & Nomura '06; Perelstein & Spethmann '07

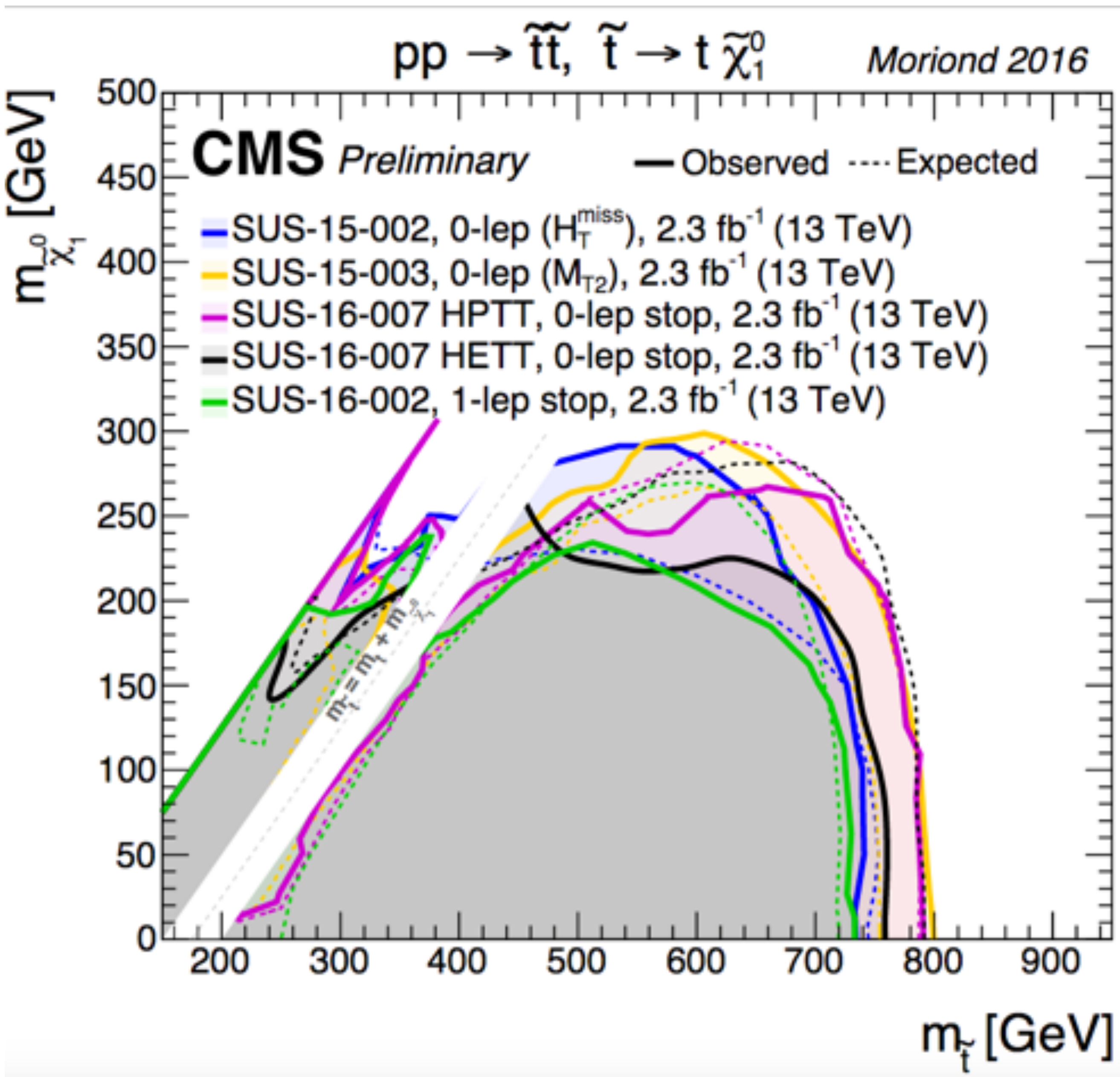
Drawing on: Dimopoulos & Giudice; Cohen, Kaplan, Nelson

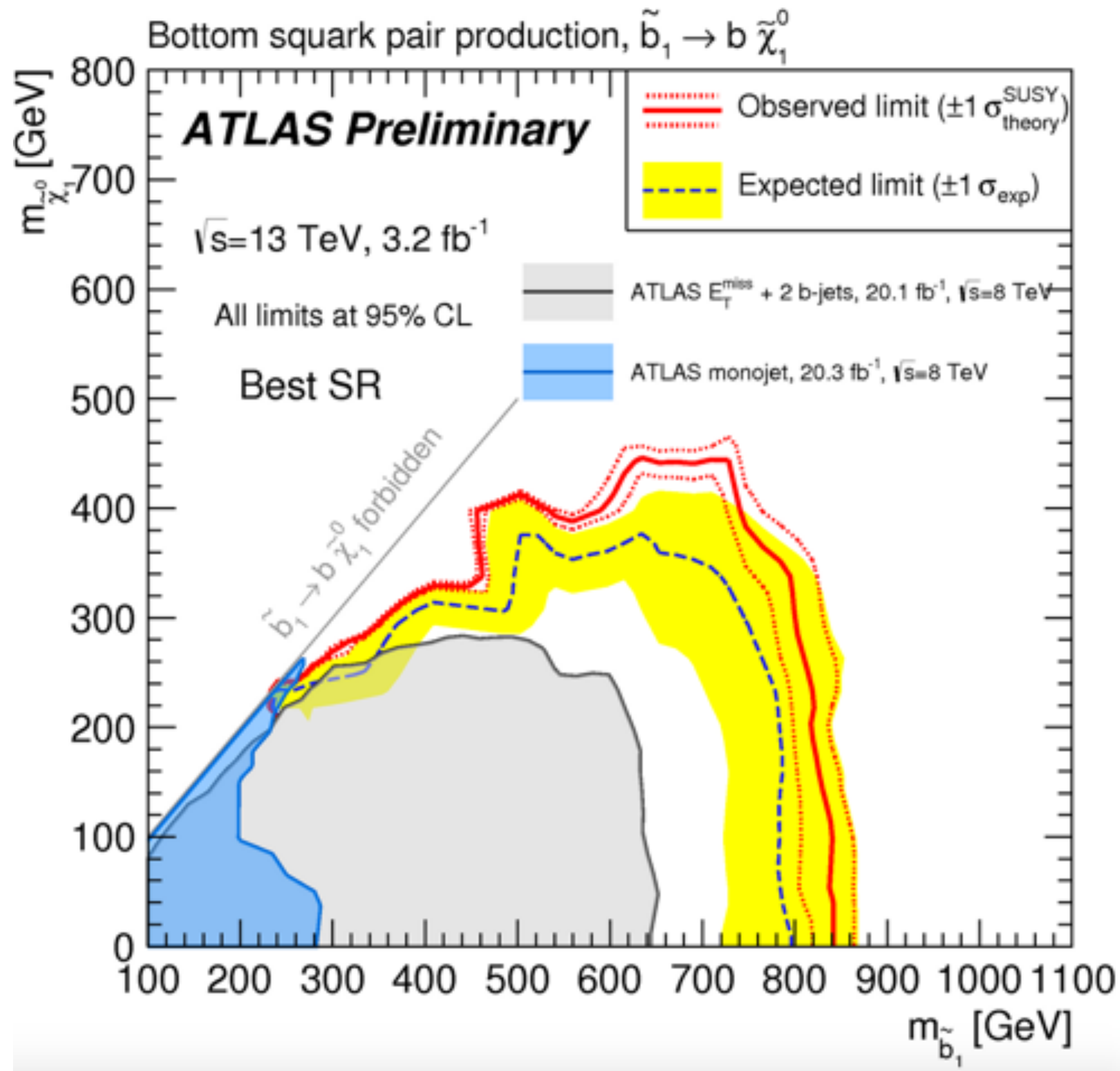


Or....

Add the **gluino**: big cross section! Most constrained.

LHC: Towards Fine-Tuning.

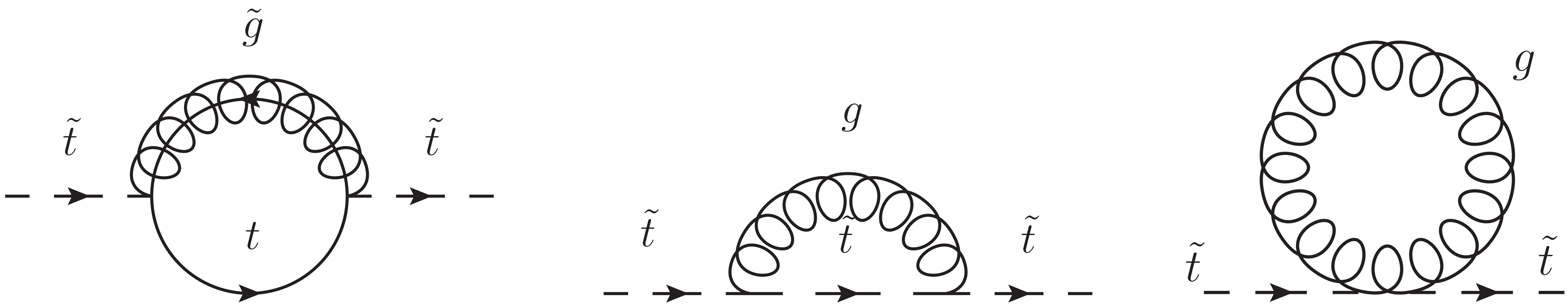




Direct searches for the stops are so far coming up empty. But lots of uncharted territory (e.g. neutralino above 300 GeV!)

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!

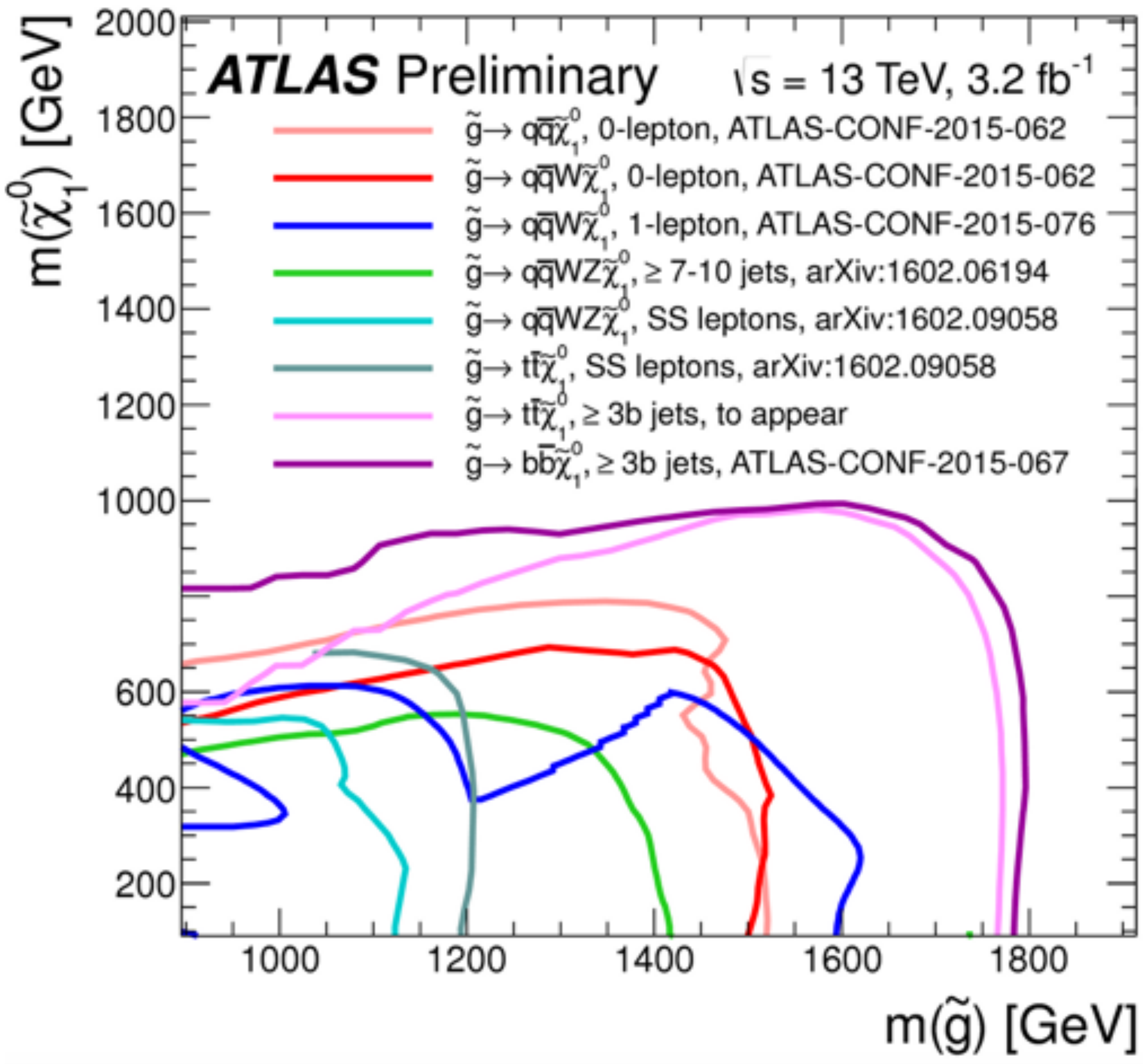


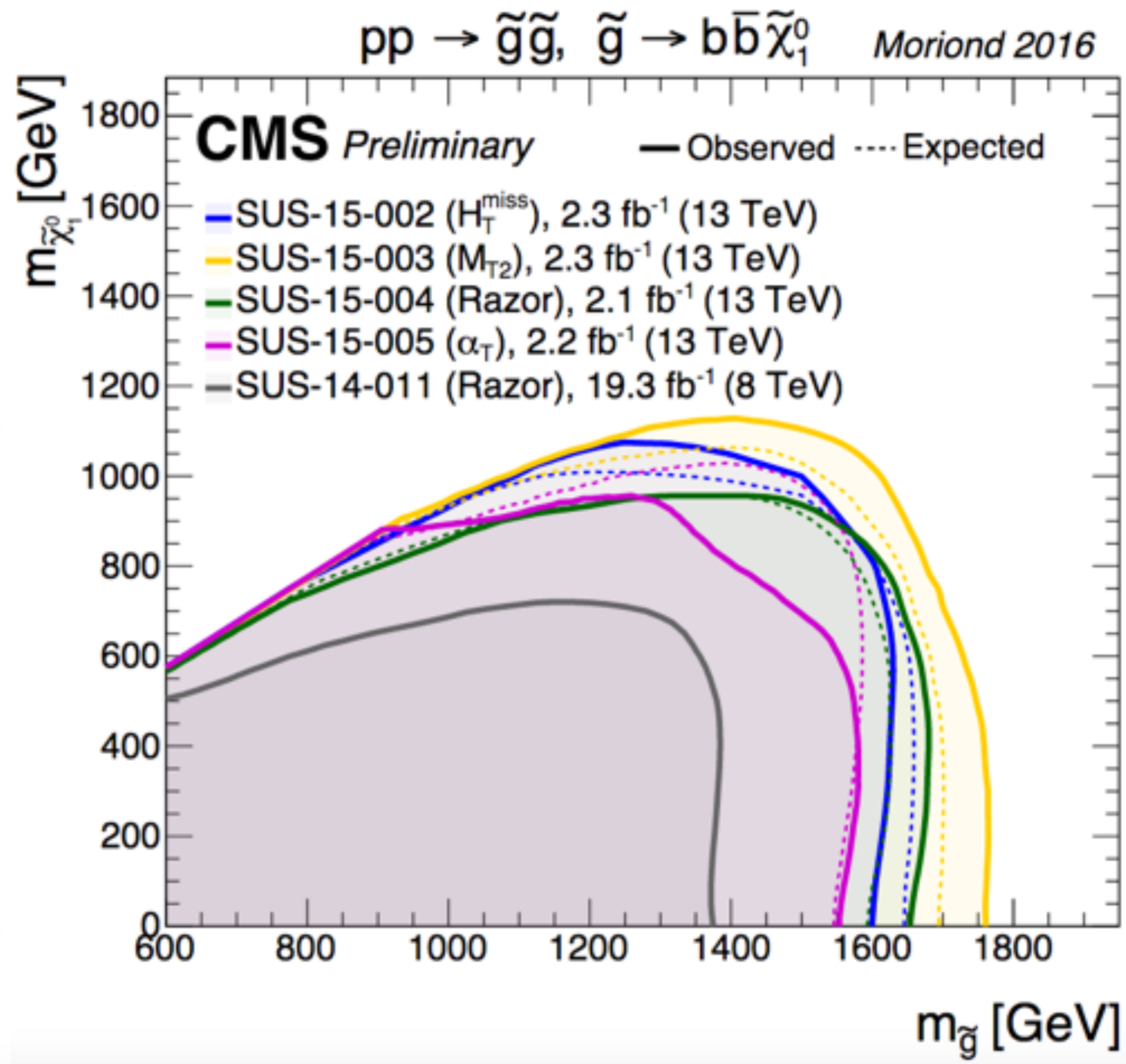
(see e.g. Brust et al. 1110.6670, Papucci et al. 1110.6926)

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

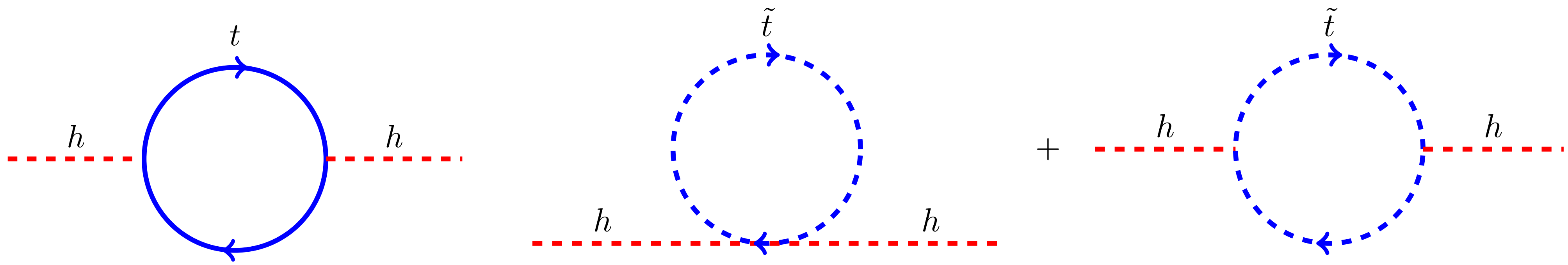
Gluino mass bounds are now above 1.5 TeV; e.g., **1.8 TeV** if gluino decays to tops.



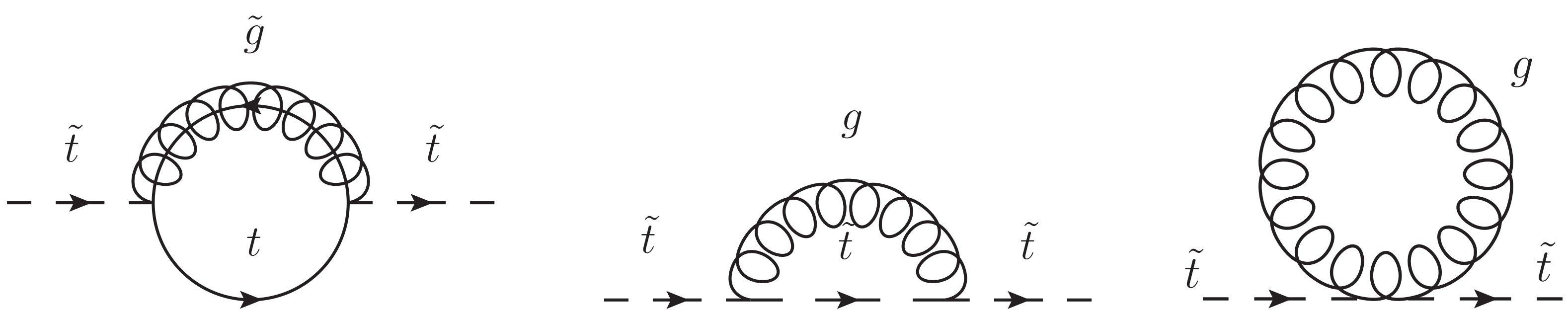


What do the searches mean?

The desired cancelations from SUSY aren't happening. Rather than corrections being **much smaller** than initial value, corrections are **canceling** to a part in ~20.



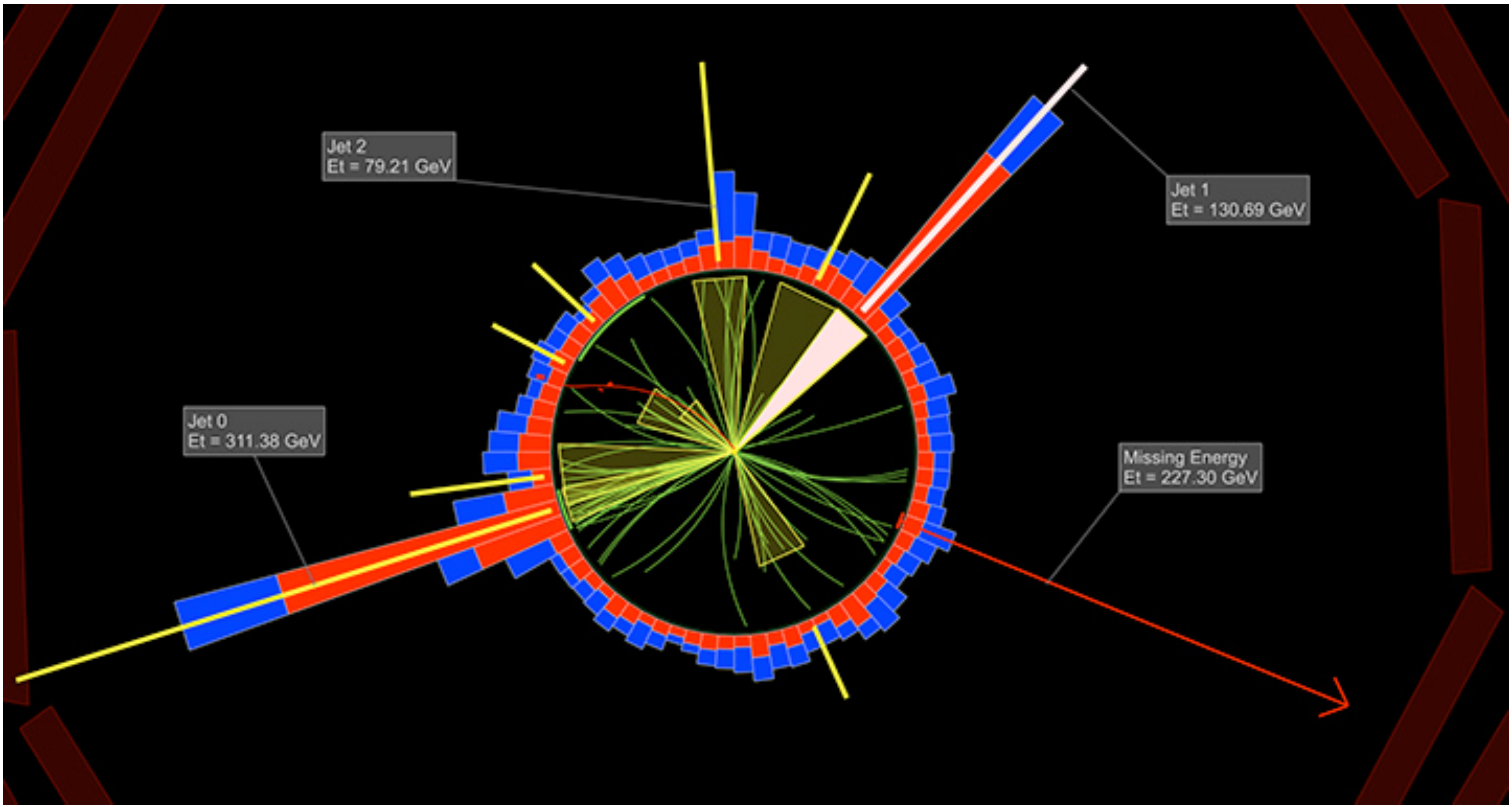
Stops above 800 GeV: ~ factor of 20 tuning.



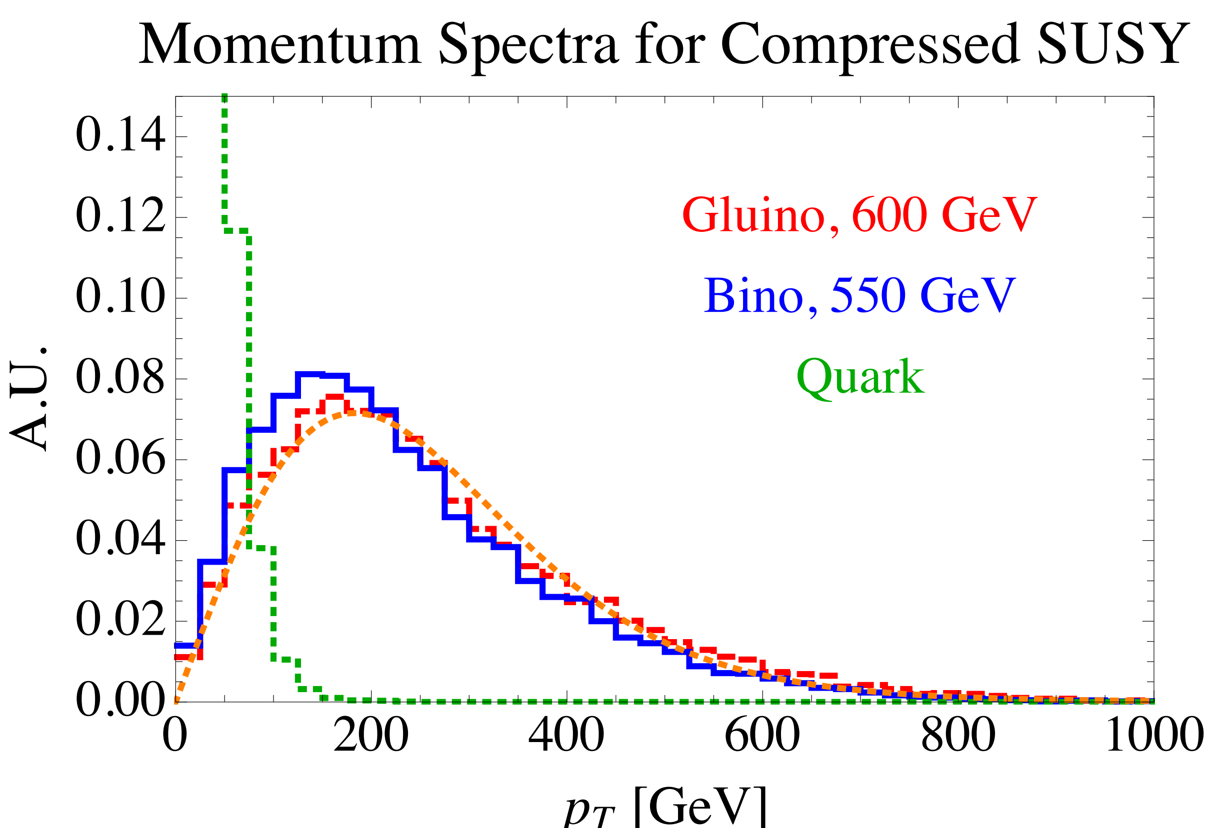
Gluinos above 1.8 TeV: ~ factor of 30 tuning. (Less if **Dirac**)

Could we have overlooked the superpartners?

Missing Transverse Momentum ("MET")

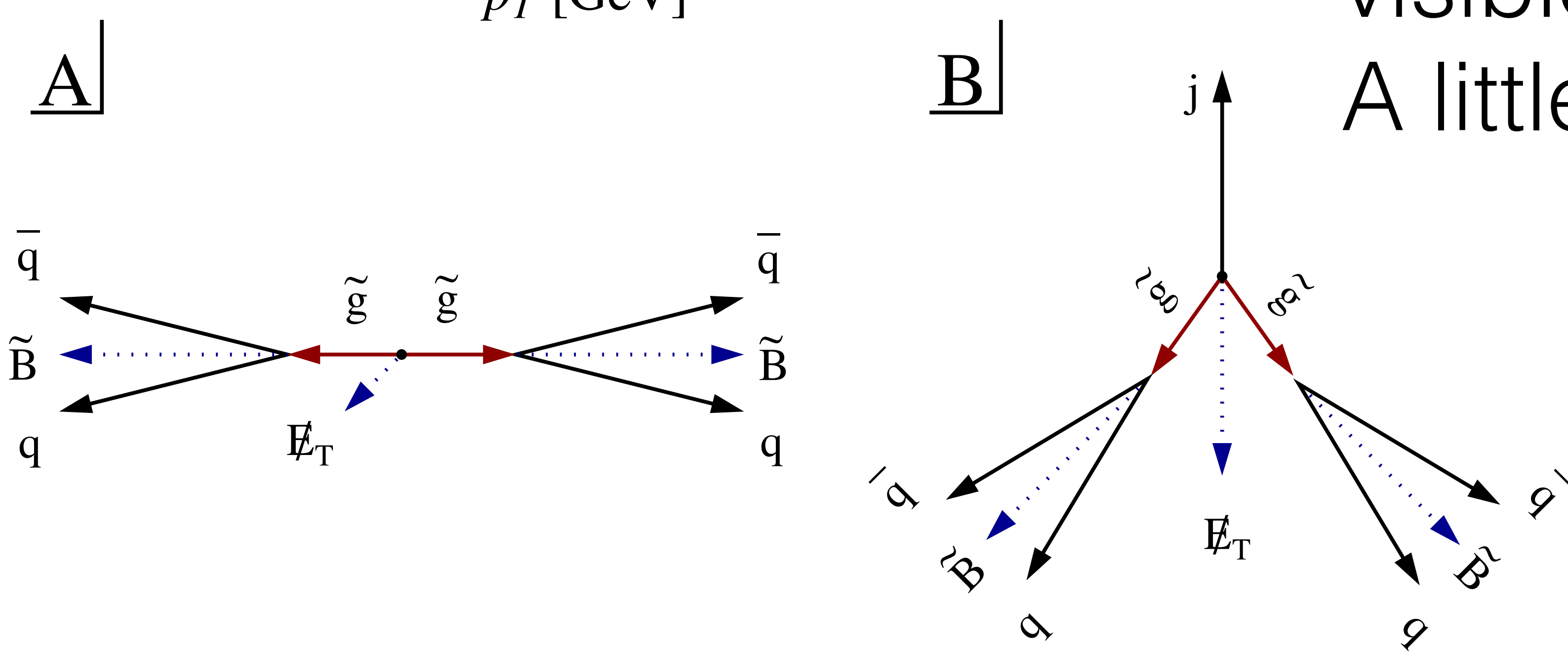


Small Phase Space



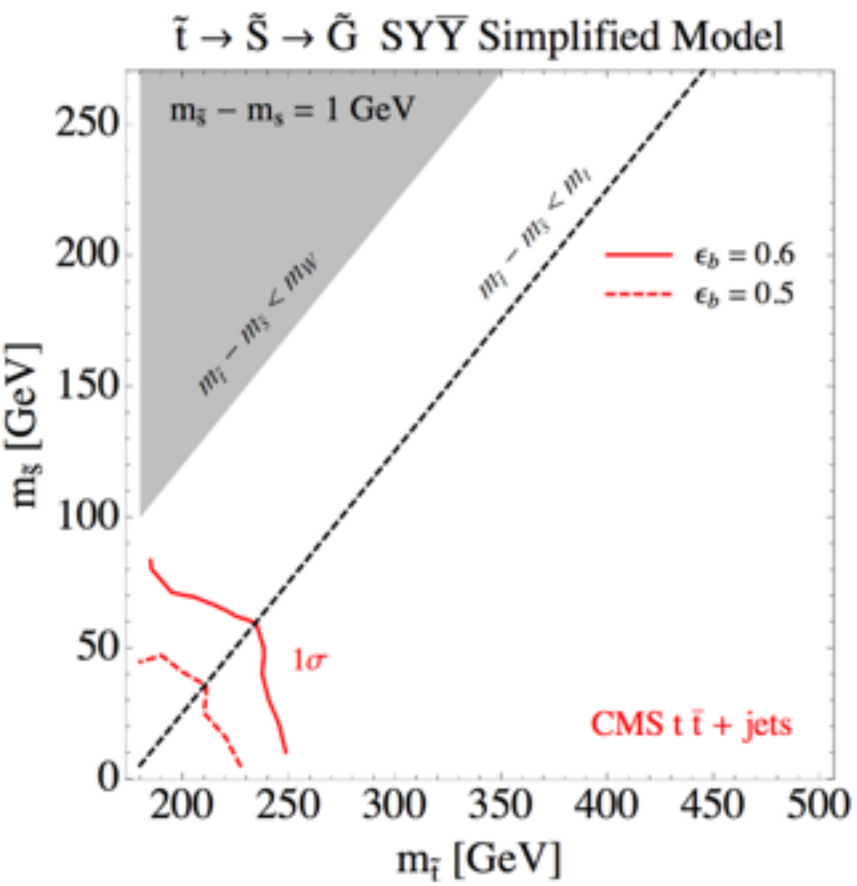
Heavy particle to one heavy and one light particle: heavy daughter inherits most of momentum in lab-frame. Light daughter is very soft.

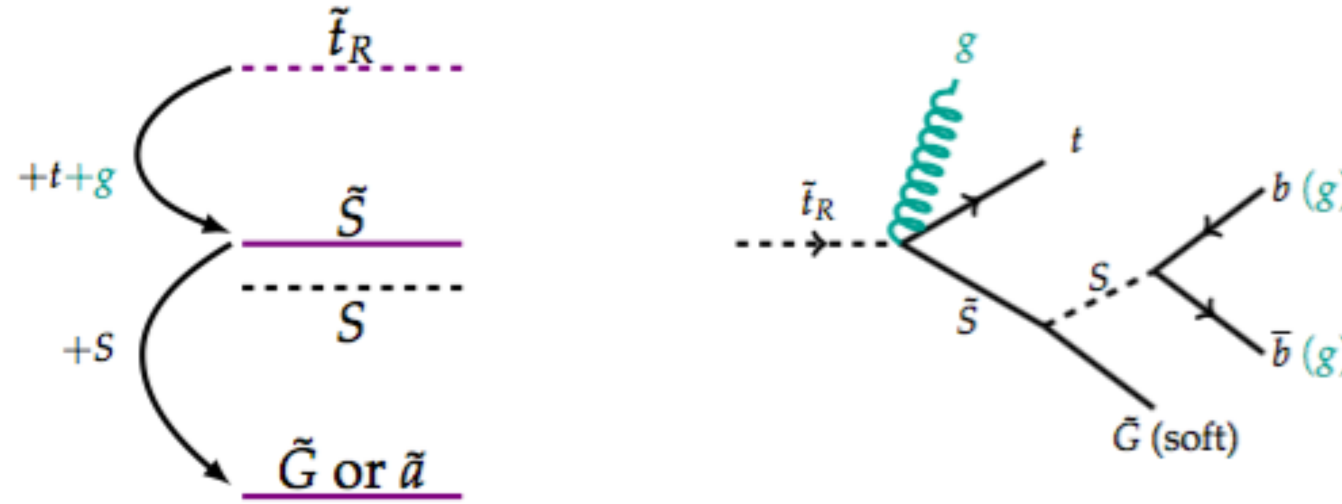
Compressed SUSY: softer visible particles.
A little artificial (tuned).



Rely on ISR recoil ("monojet"-like): Alwall, Le, Lisanti, Wacker 0803.0019

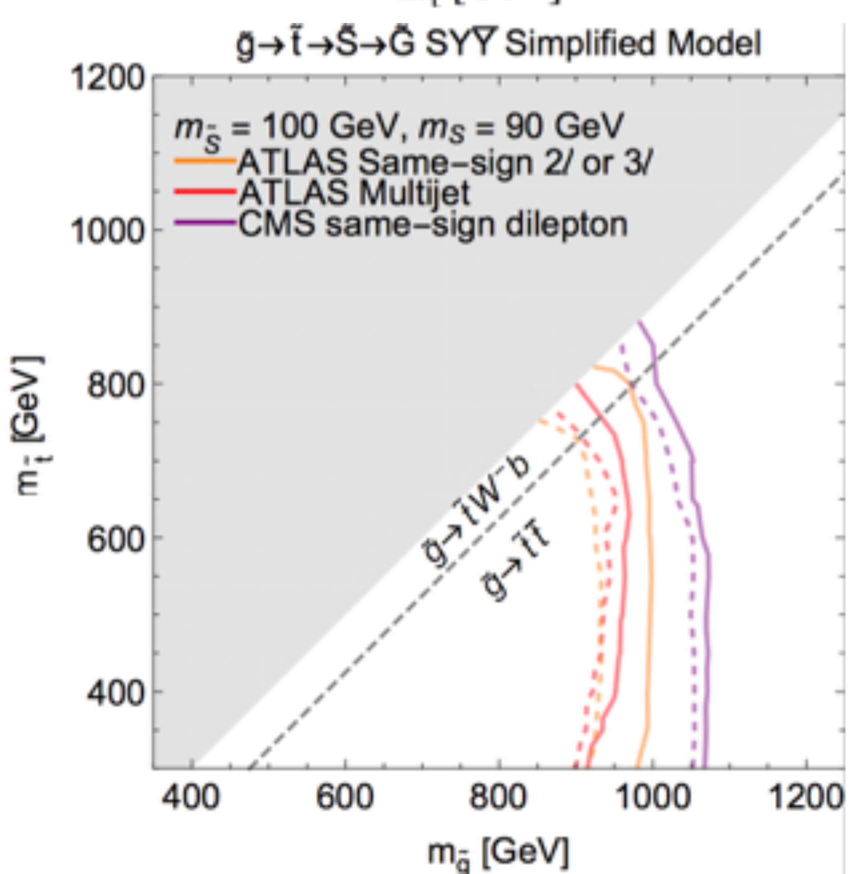
Stealth SUSY

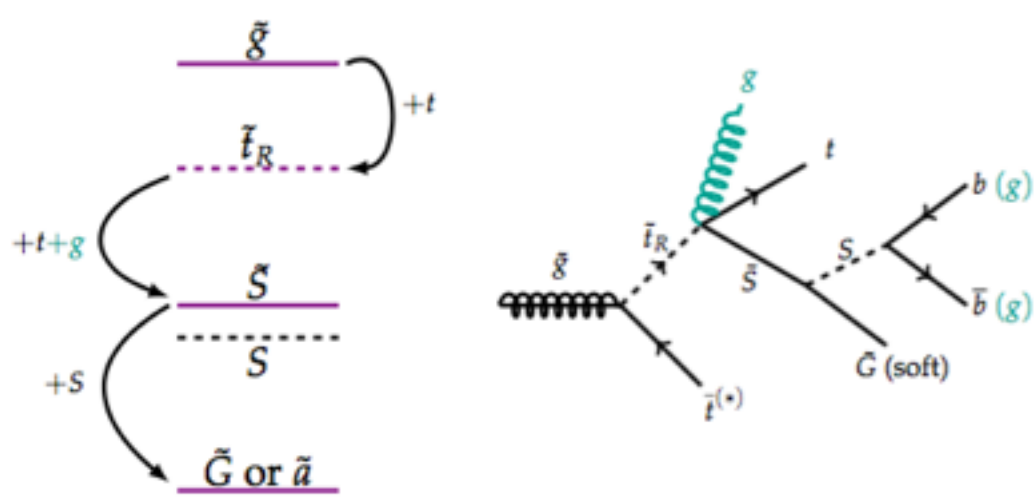




Decays through an **approximately supersymmetric hidden sector** can remove missing momentum from signal

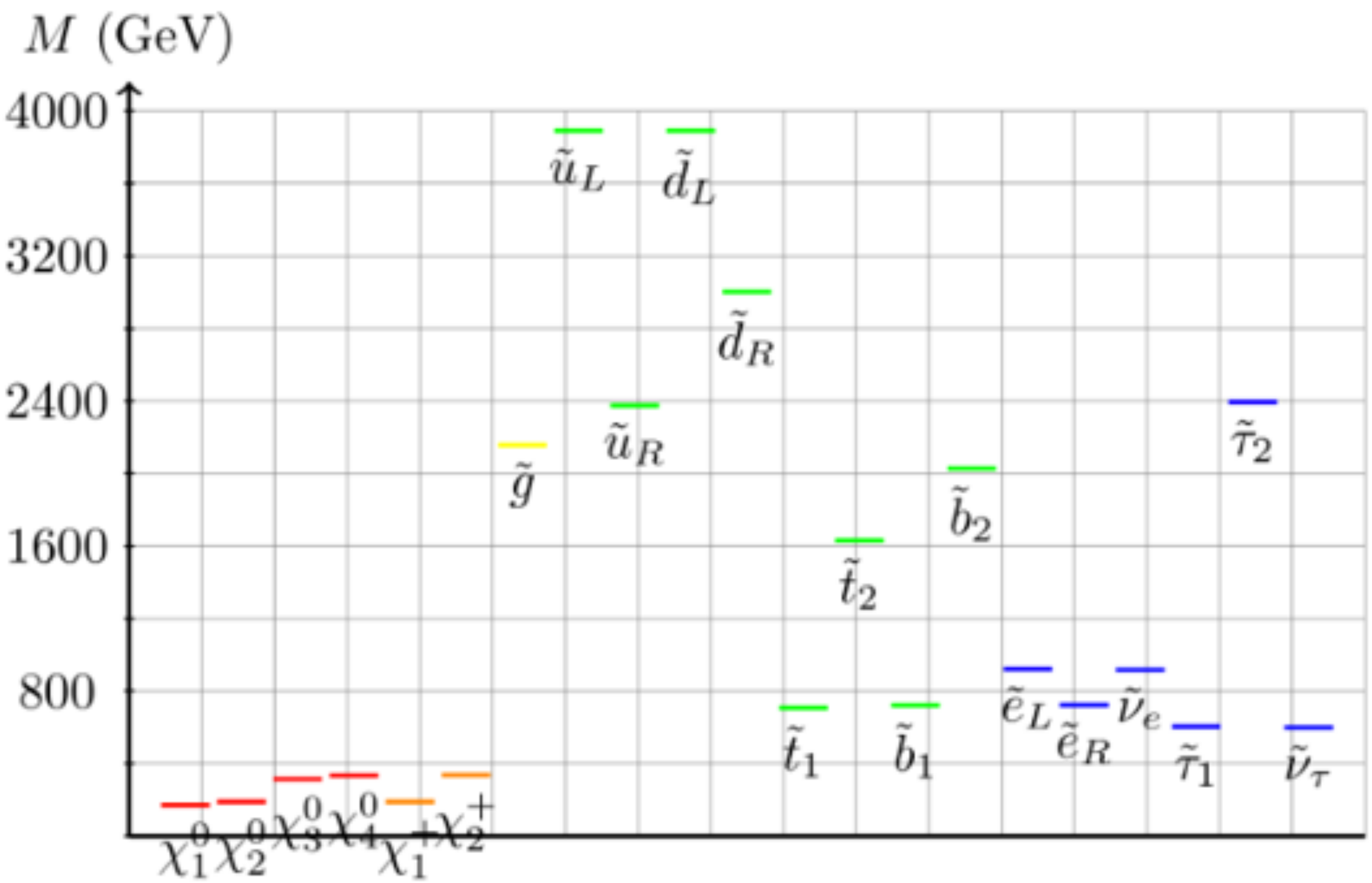
Fan, Reece, Ruderman 2011
1512.05781 Fan, Krall, Pinner, Reece, Ruderman





Gluinos still constrained (also see Evans et al. 1310.5758)

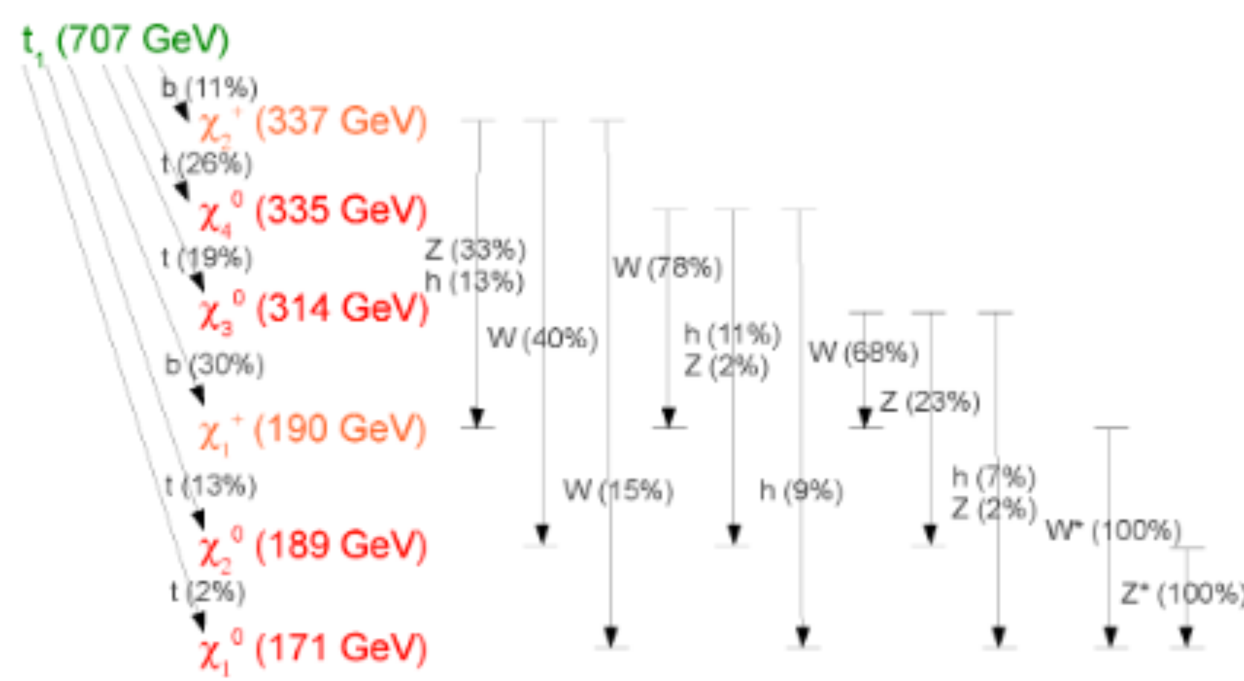
pMSSM: Many Decay Modes



Cahill-Rowley, Hewett, Ismail, Rizzo 1407.4130

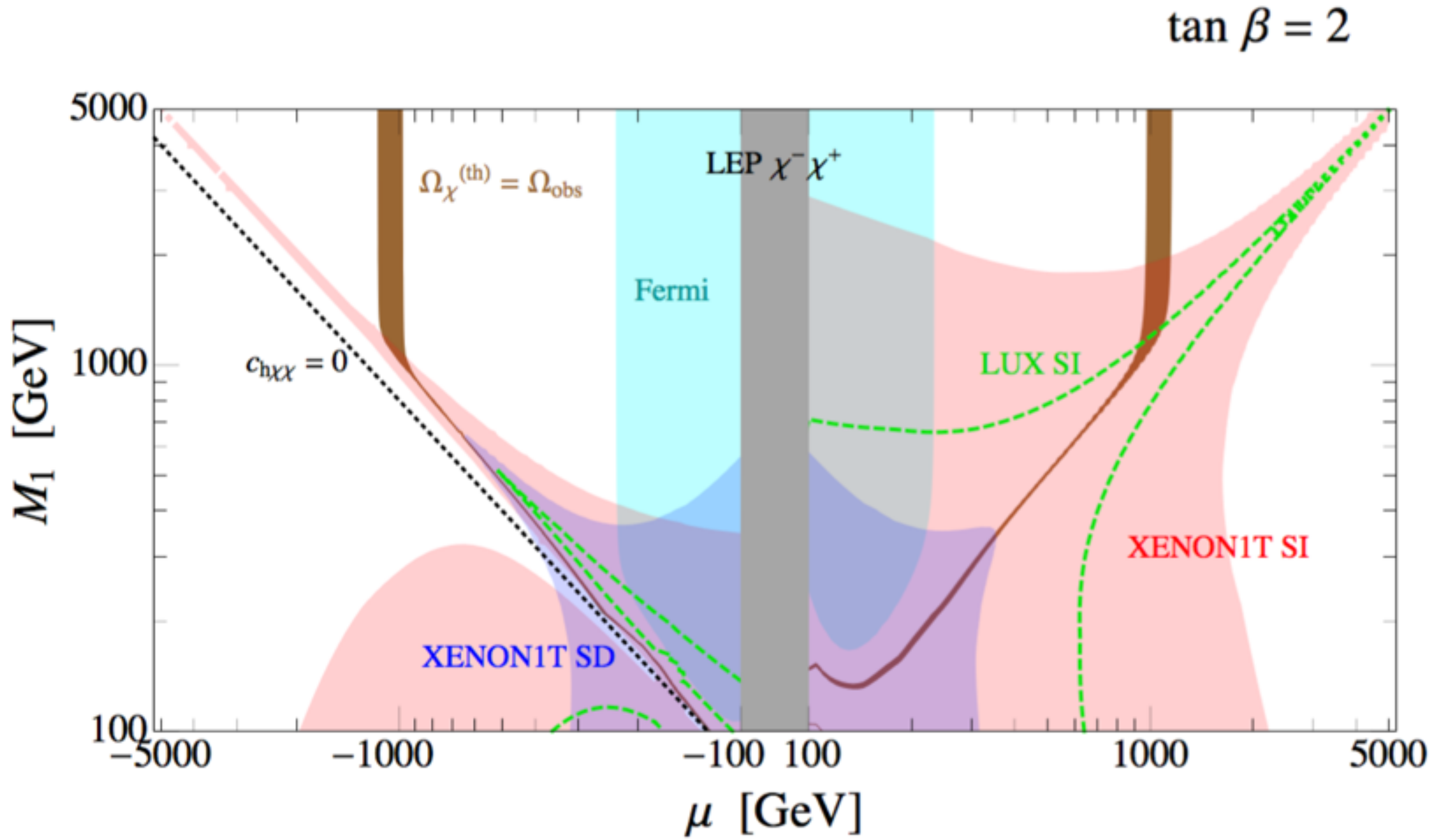
pMSSM scans (reduced parameters to satisfy flavor, CP)

If each decay mode has a small branching ratio, the bounds are weakened.



Neutralino Dark Matter

Direct Detection

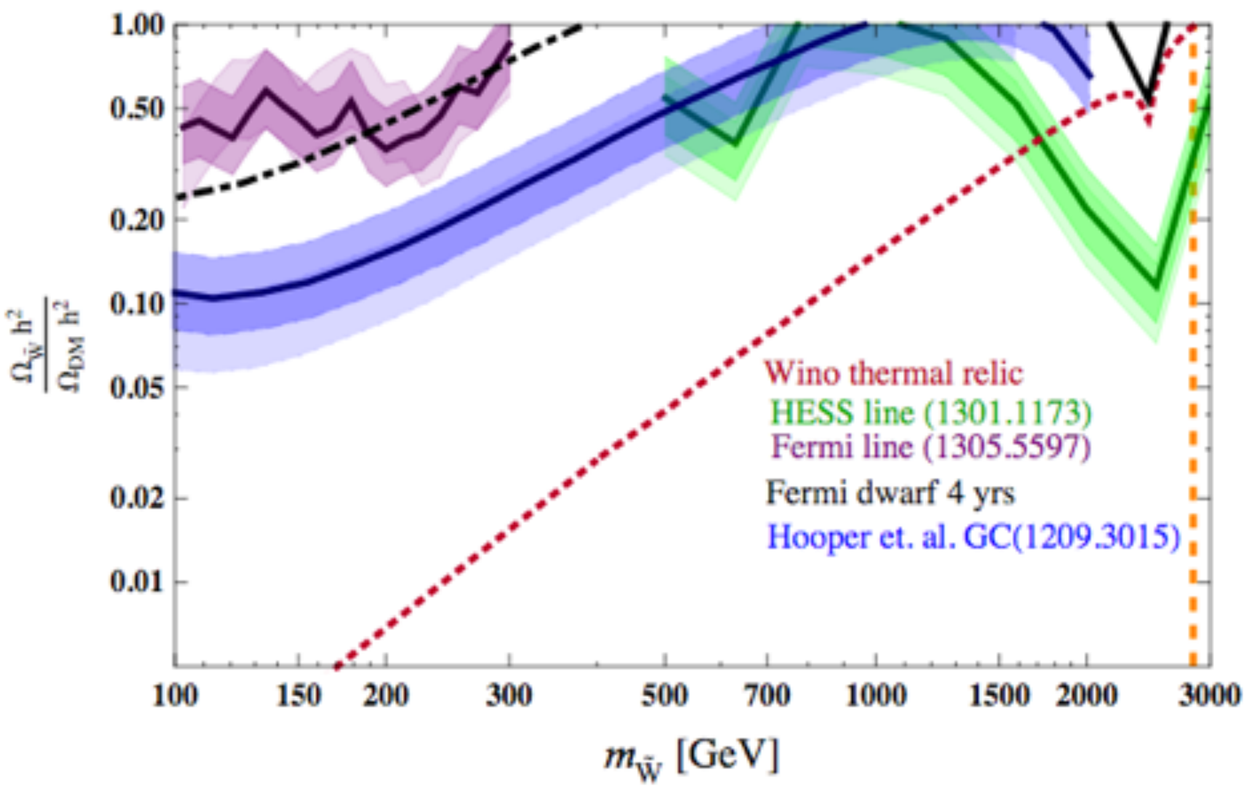


Most mixtures of gaugino and higgsino dark matter are now constrained by direct detection (esp. LUX)

Cheung, Hall, Pinner, Ruderman 1211.4873 (also Perelstein, Shakya 1107.5048, 1208.0833)

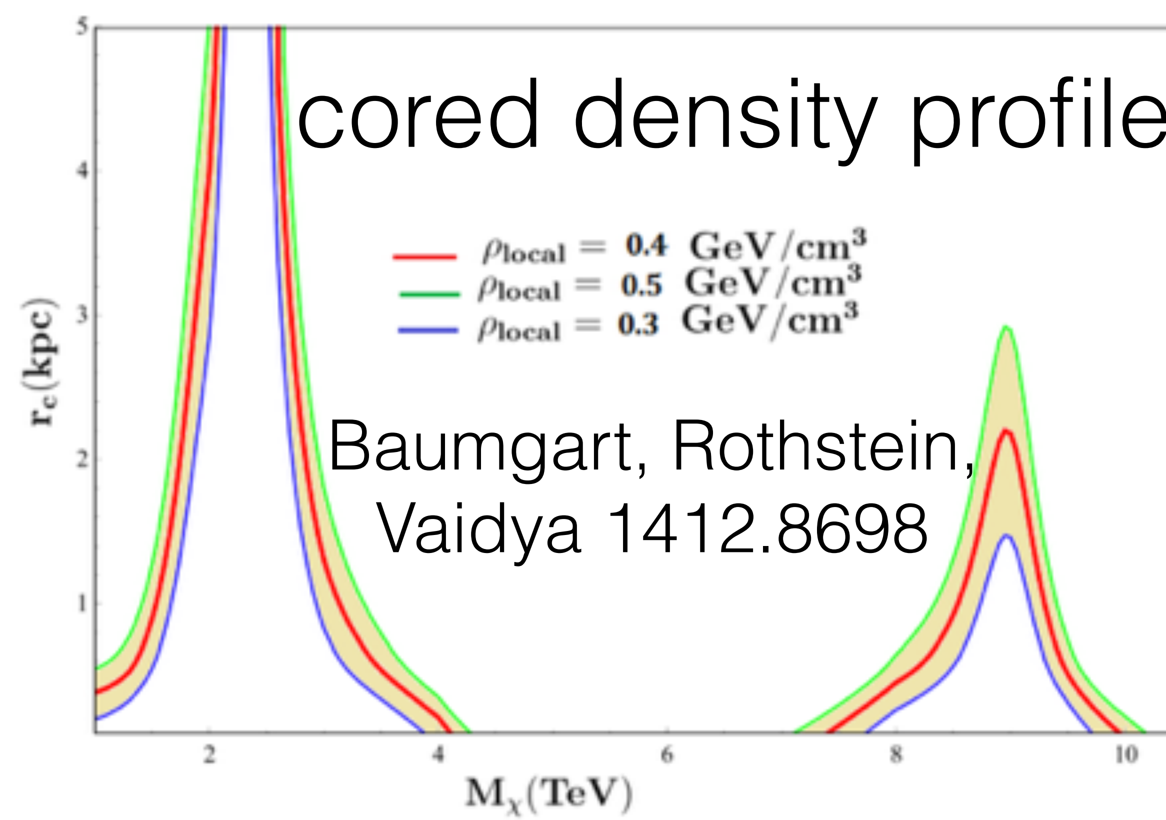
Winos are Probably not DM

Fan, MR 1307.4400; also Cohen, Lisanti, Pierce, Slatyer 1307.4082



Large annihilation cross section: ruled out by absence of **gamma ray** signals from galactic center and dwarfs.

There are astrophysical uncertainties in the GC relevant for high-mass exclusion. Low mass wino DM is robustly ruled out by dwarf galaxies.

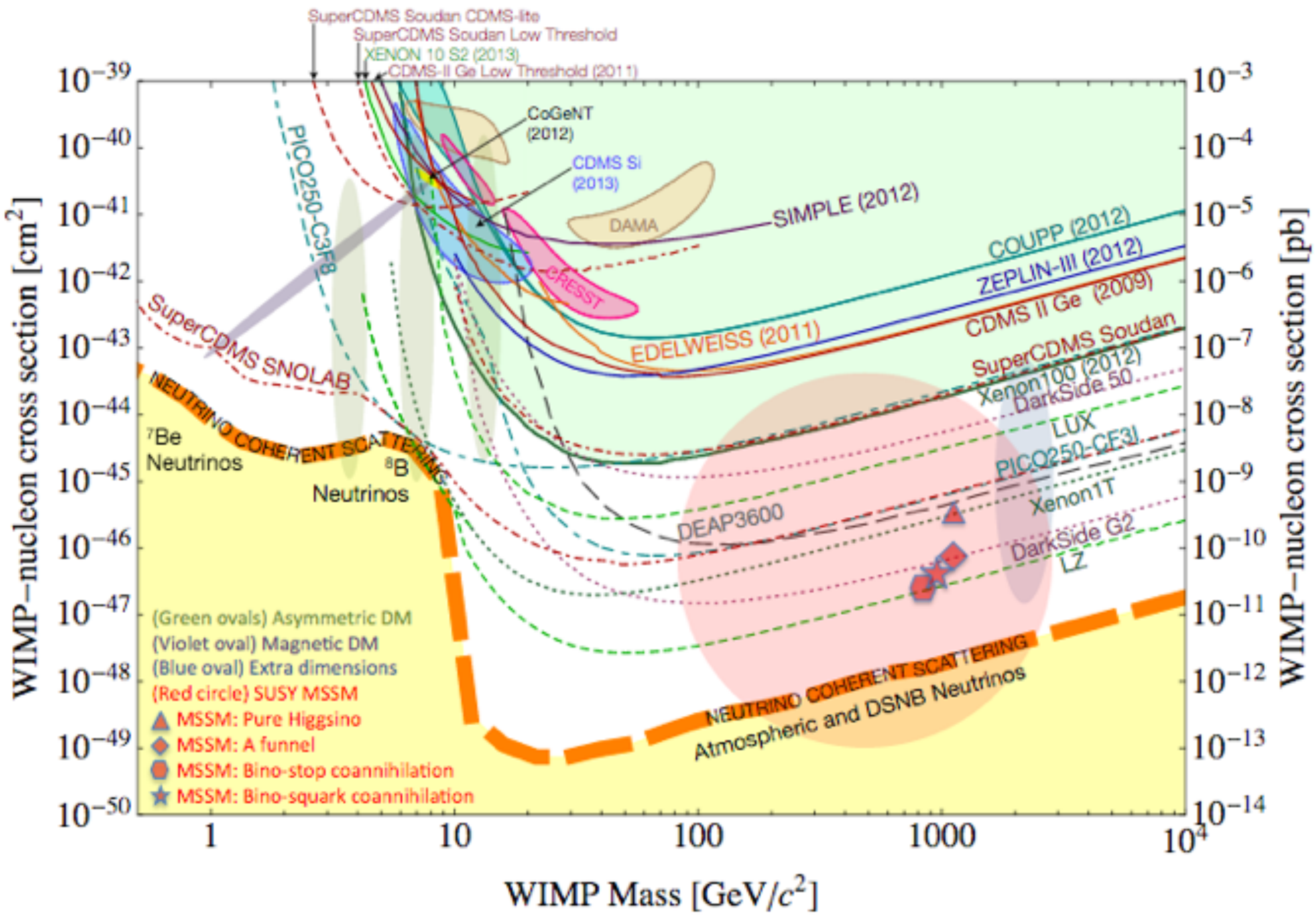


cored density profile?

Baumgart, Rothstein, Vaidya 1412.8698

Future Direct Detection

Snowmass: Cushman et al. 1310.8327



⬅ Z exchange

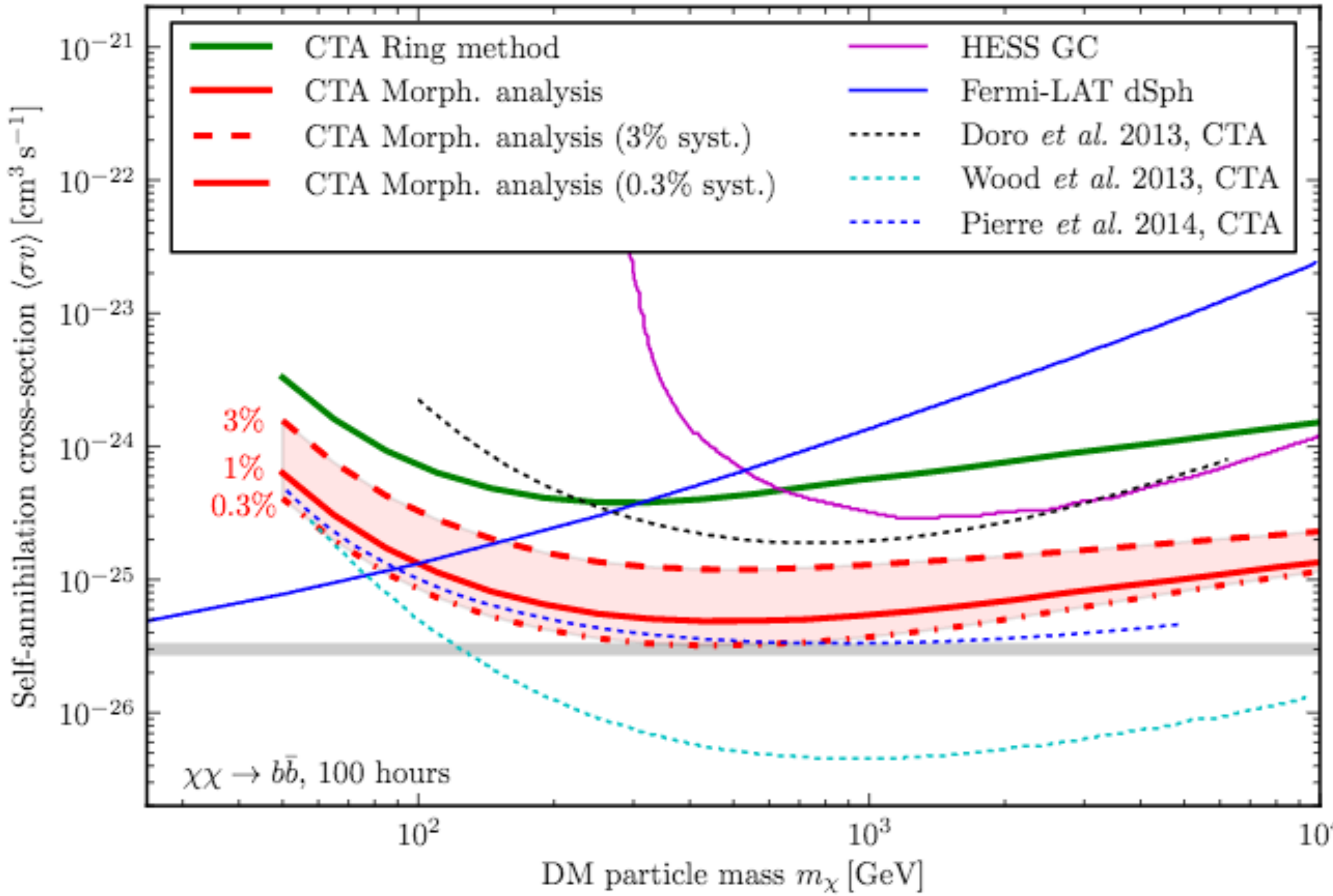
⬅ *h* exchange

⬅ *W* loop (wino)

⬅ *W* loop (higgsino)

SU(2) multiplets dominantly scattering through loops are a real challenge, beyond the next generation of experiments.

Future Indirect Detection



1408.4131
Silverwood, Weniger, Scott, Bertone

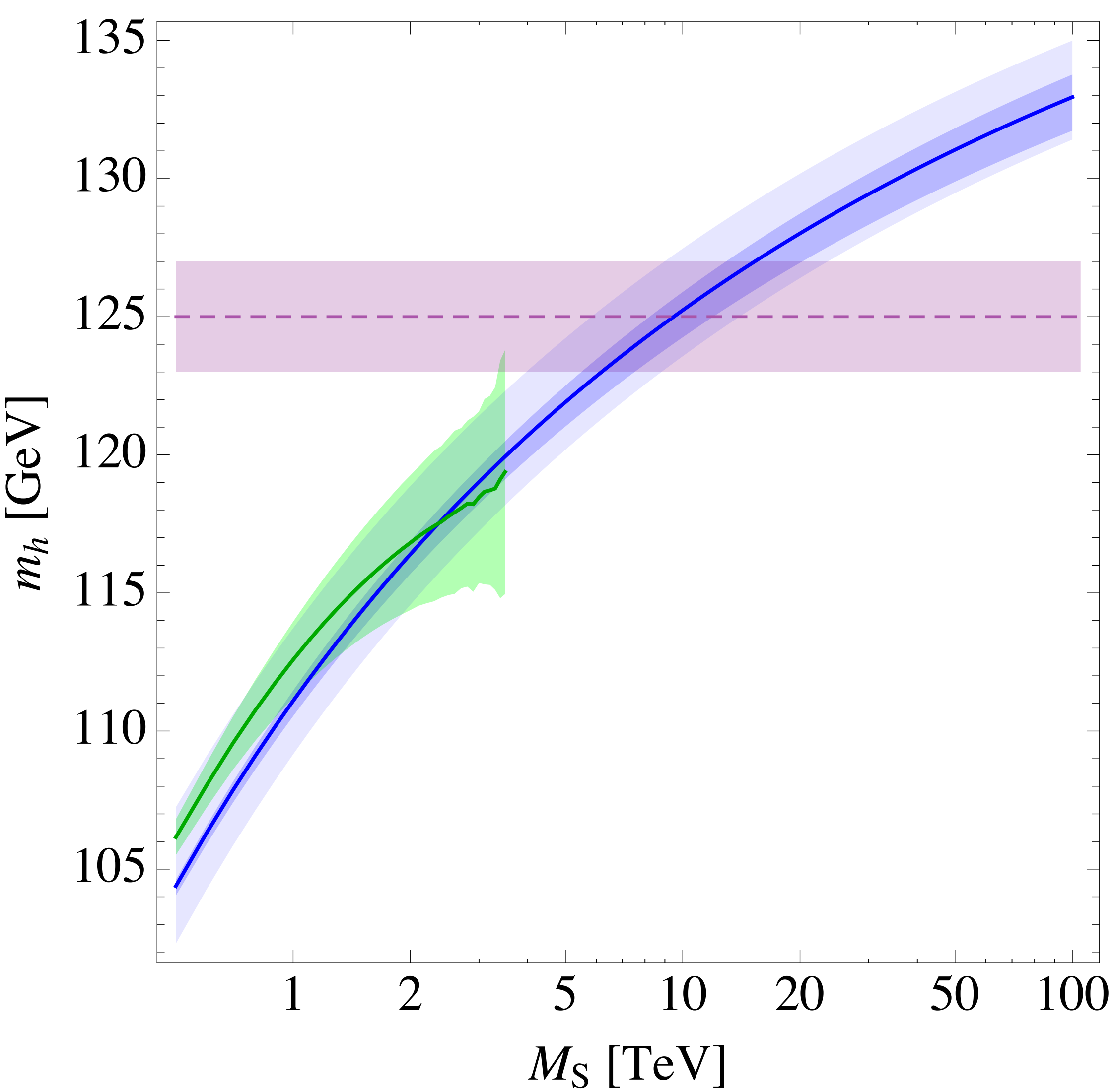
CTA (Cherenkov Telescope Array) will get *close* to ruling out thermal relic dark matter over most of the hundreds-of-GeV range, but will likely not quite reach TeV higgsinos.

(Assuming no improvements do much better than these estimates)

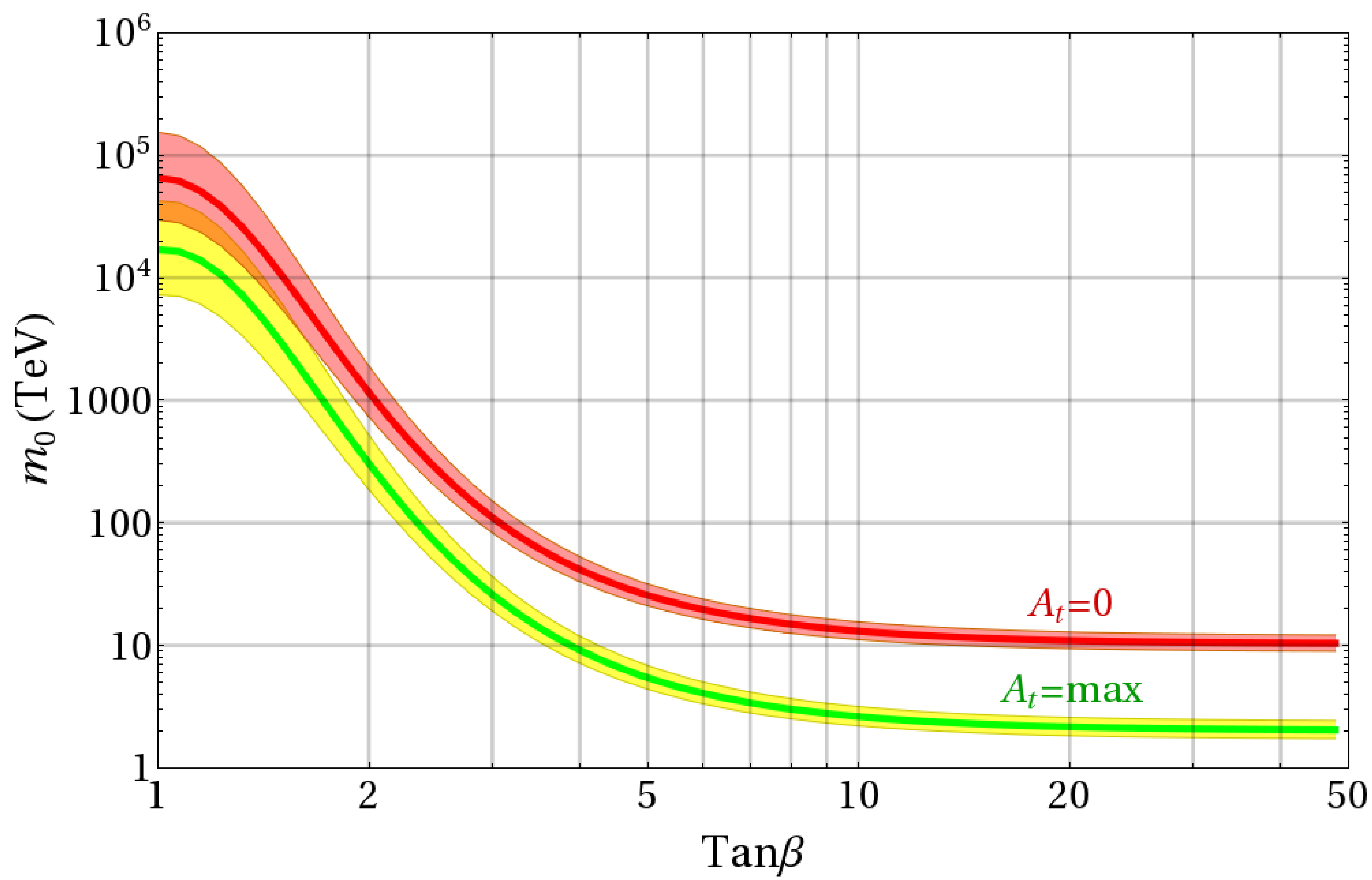
Split SUSY

Why Split?

Arkani-Hamed & Dimopoulos originally had in mind very heavy scalars. But what the Higgs points to now may be only “mildly” split SUSY, with scalars at 10s—100s TeV.

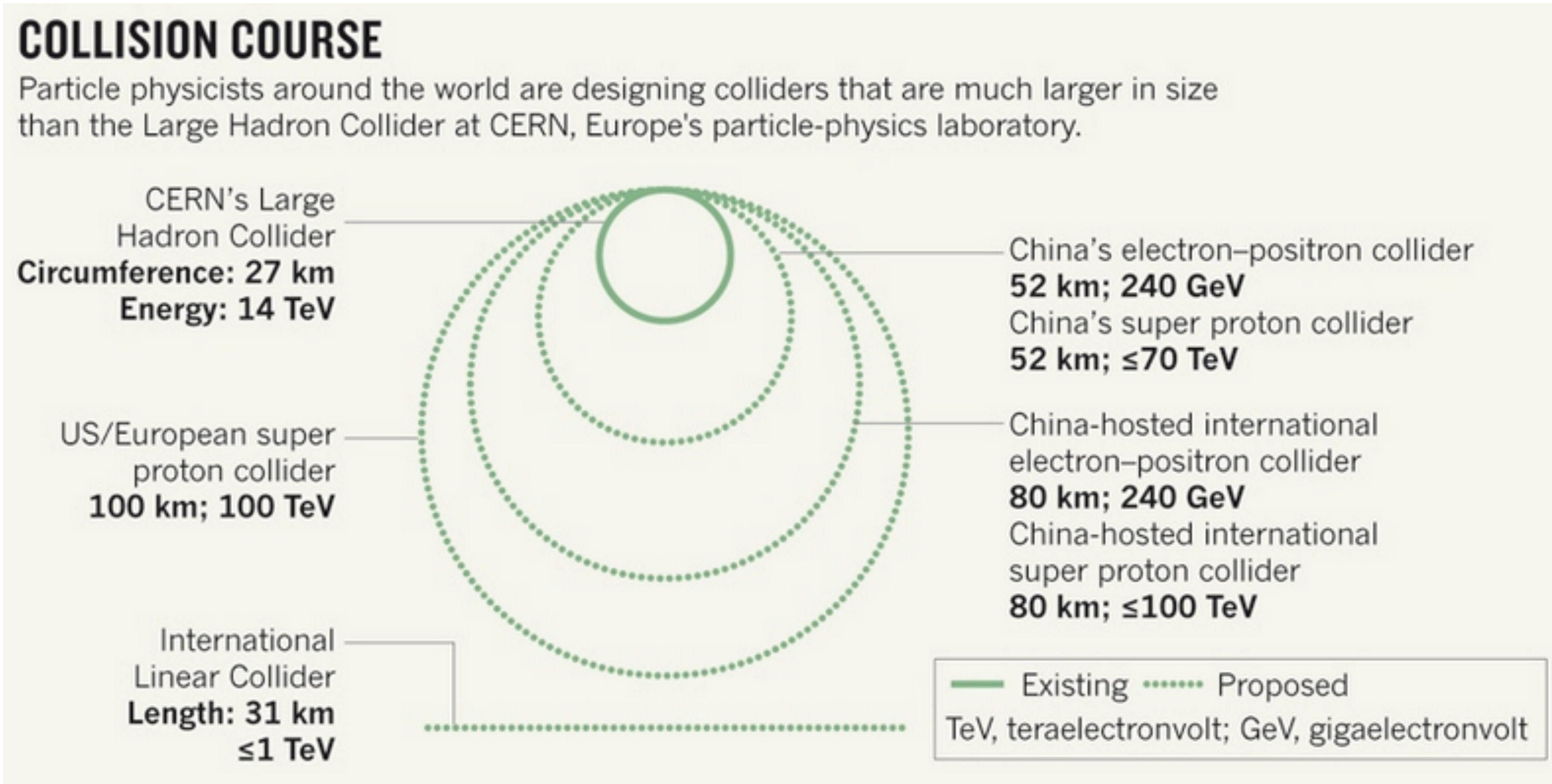


Draper, MR, Meade, Shih 1112.3068



Arvanitaki, Craig, Dimopoulos, Villadoro 1210.0555

The colliders of the future:



Nature News (E. Gibney), 2014

http://www.nature.com/news/china-plans-super-collider-1.15603

arXiv.org > hep-ph > arXiv:1606.00947

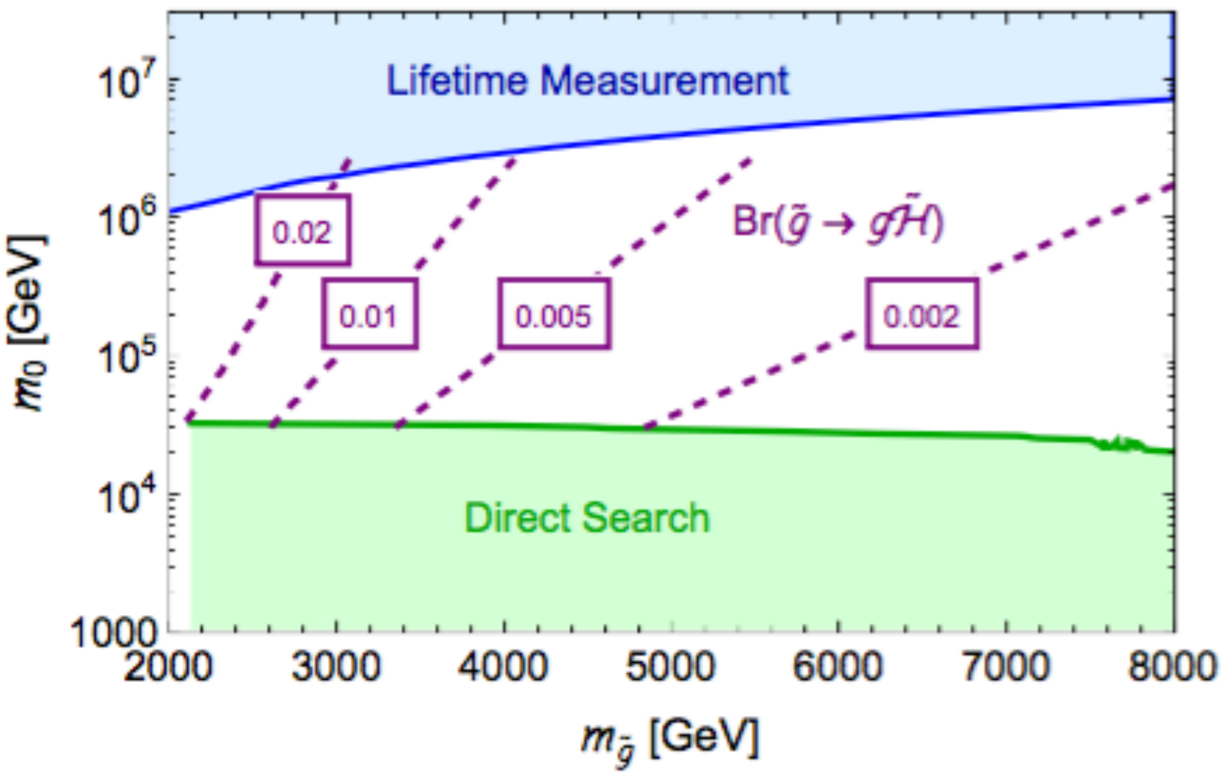
High Energy Physics – Phenomenology

Physics at a 100 TeV pp collider: beyond the Standard Model phenomena

T. Golling, M. Hance, P. Harris, M.L. Mangano, M. McCullough, F. Moortgat, P. Schwaller, R. Torre, P. Agrawal, D.S.M. Alves, S. Antusch, A. Arbey, B. Auerbach, G. Bambhaniya, M. Battaglia, M. Bauer, P.S. Bhupal Dev, A. Boveia, J. Bramante, O. Buchmueller, M. Buschmann, J. Chakrabortty, M. Chala, S. Chekanov, C.-Y. Chen, H.-C. Cheng, M. Cirelli, M. Citron, T. Cohen, N. Craig, D.

Testing MSSM 125 GeV

100 TeV collider = gluino factory! Millions of gluino pairs.



Agrawal, Fan, MR, Xue in progress

Scalar mass scale:
gluino lifetime;
log in one-loop branching ratio;
squark/gluino production
(also see Sato, Shirai, Tobioka 1207.3608)

Measuring tan beta is trickier. Several observables; which is best depends on ordering of bino, wino, and higgsino masses. For instance:

$$\frac{\Gamma(\tilde{W}^0 \to h\tilde{B}^0)}{\Gamma(\tilde{W}^0 \to Z\tilde{B}^0)} \approx \frac{4\tan^2(2\beta)\mu^2}{M_2^2}\left(\frac{1+M_1/M_2}{1-M_1/M_2}\right)^2.$$

$$\frac{\Gamma(\tilde{g} \to b\bar{b}\tilde{H}^0)}{\Gamma(\tilde{g} \to t\bar{t}\tilde{H}^0)} \propto \tan^2\beta.$$

$$\frac{\Gamma(\tilde{W}^0 \to Zh\tilde{B}^0)}{\Gamma(\tilde{W}^0 \to ZZ\tilde{B}^0)+\Gamma(\tilde{W}^0 \to hh\tilde{B}^0)} \propto \left(\frac{\sin\beta-\cos\beta}{\sin\beta+\cos\beta}\right)^2$$

Preliminary results in 1606.00947; paper this summer

Concluding Remarks

- Important to fill holes in search coverage. Stealthy, compressed, RPV, Hidden Valleys, messy spectra….
- ***Fully natural SUSY: under strain***
- **Split SUSY: simple**. ***Tuned, but could be our world.***
- "Neutral naturalness" (Twin Higgs, etc): less constrained. UV completion at ~10 TeV? *That might be SUSY's role.*
- Still room for SUSY WIMP dark matter
- Lots of **new experimental results on the horizon!**
Let's go find out what's really out there!