Mis ~~Dis~~placed Supersymmetry

MASS 2012
Nordita

Supersymmetry

- Naturalness (a la Wilson)
- Unification (LEP circa 1990)
- Dark Matter (LSP)

The LHC

- 2012 - announce the Higgs discovery (?)
- 2012 data - Is the electroweak scale “natural”?

Two short talks

- Displaced SUSY (a non-standard pheno)

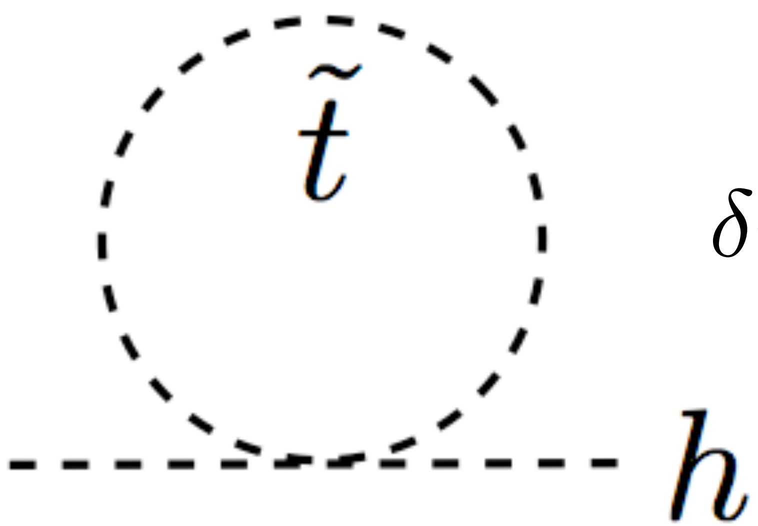
  w/ P. Graham, S. Rajendran, P. Saraswat

- Misplaced SUSY (simply unnatural)

  w/ N. Arkani-Hamed, A. Gupta, N. Weiner, T. Zorawski

Stops for Naturalness

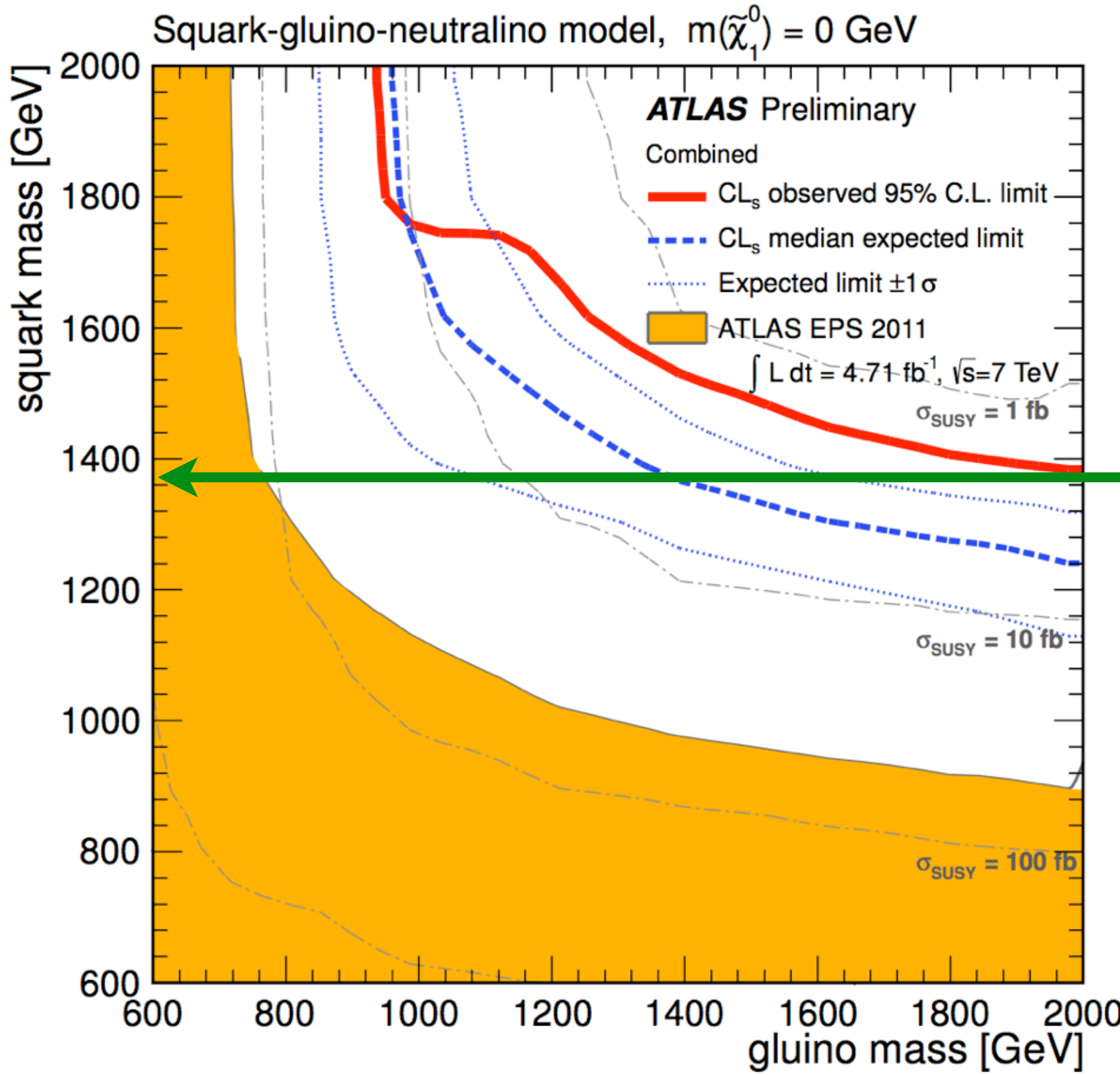
- For a weakly coupled Higgs, what cancels the top loop? Stop - but not too heavy



$$\delta m_{h_u}^2 \simeq -\frac{3y_t^2}{8\pi^2}(m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2 + A_t^2)\log\frac{M}{m_{\tilde{t}}}$$

Also for Higgs quartic - but ignore for now

State of SUSY



With maximized missing E_T

very heavy scalars (perhaps stop is split?)

Allow LSP to Decay

- Lost LSP dark matter (could be plenty of other stable particles)
- Preserve Unification! (?) and Naturalness
- R-parity violation (generally bad for proton decay: $LQD^c + LLE^c + U^cD^cD^c$)

Bilinear RPV

- Simplest GUT embedding:
- $W \supset \epsilon\mu L H_u + \epsilon\mu H_{Tu} D^c$ $\quad (\epsilon\mu \mathbf{\bar{5}5_H})$
- Doublet-triplet splitting required anyway, thus baryon number violation suppressed (p-decay).
- Bilinear terms naturally dominate if RPV is spontaneous in another sector: $\langle \mathcal{O} \rangle \neq 0$

$$\frac{\mathcal{O}}{\Lambda^{n-1}} L H_u \sim \epsilon\mu L H_u \qquad \frac{\mathcal{O}}{\Lambda^n} U^c D^c D^c \sim \epsilon \frac{\mu}{\Lambda} U^c D^c D^c$$

Bilinear RPV

$$W \supset \epsilon\mu L H_u + \mu H_u H_d$$

Rotate L and H_d:

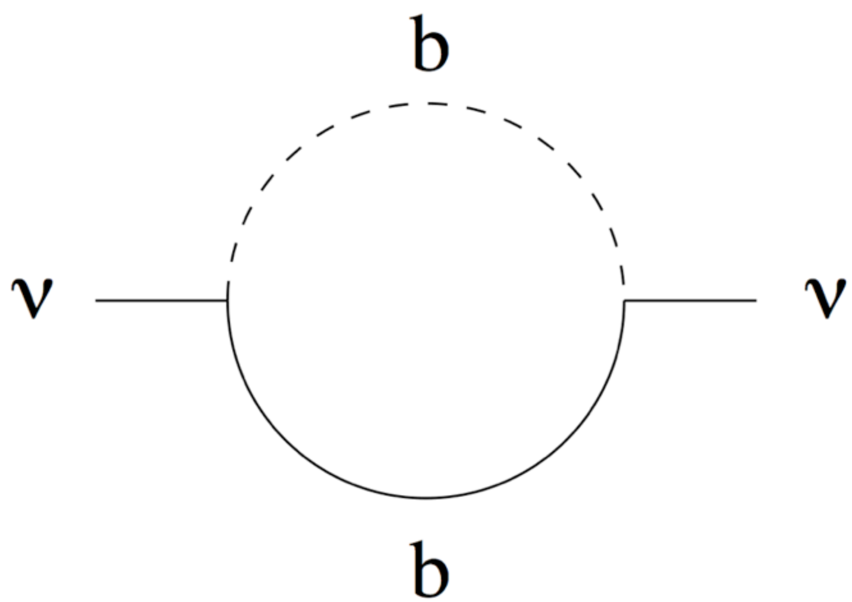
$$W \supset \epsilon y_b L Q_3 D_3^c + \epsilon y_\tau L L_3 E_3^c$$

Predictive - mostly 3rd generation

(Higgs triplet rotation gives baryon number violating coupling: $\epsilon \frac{\mu y}{M_T} U^c D^c D^c$

which is safe for GUT-scale triplet and small enough epsilon)

Bounds: nu masses



$$\Delta m_\nu \sim \frac{\epsilon^2 y_b^4}{16\pi^2} m_{weak}$$

Requires roughly: $\epsilon < 10^{-3}$

(Satisfies p-decay bounds too)

LSP decays

LSP	$\tilde{\chi}$	$\tilde{\nu}$	$\tilde{\tau}$	$\tilde{u}_L$	$\tilde{b}$
Dominant Decays	$\nu b\bar{b},\ \nu\tau l$	$b\bar{b}$	$l^{\pm}\nu$	$l^{\pm}q$	$b\nu$

- Suppressed missing energy
- Additional jets, b's
- possibly leptons

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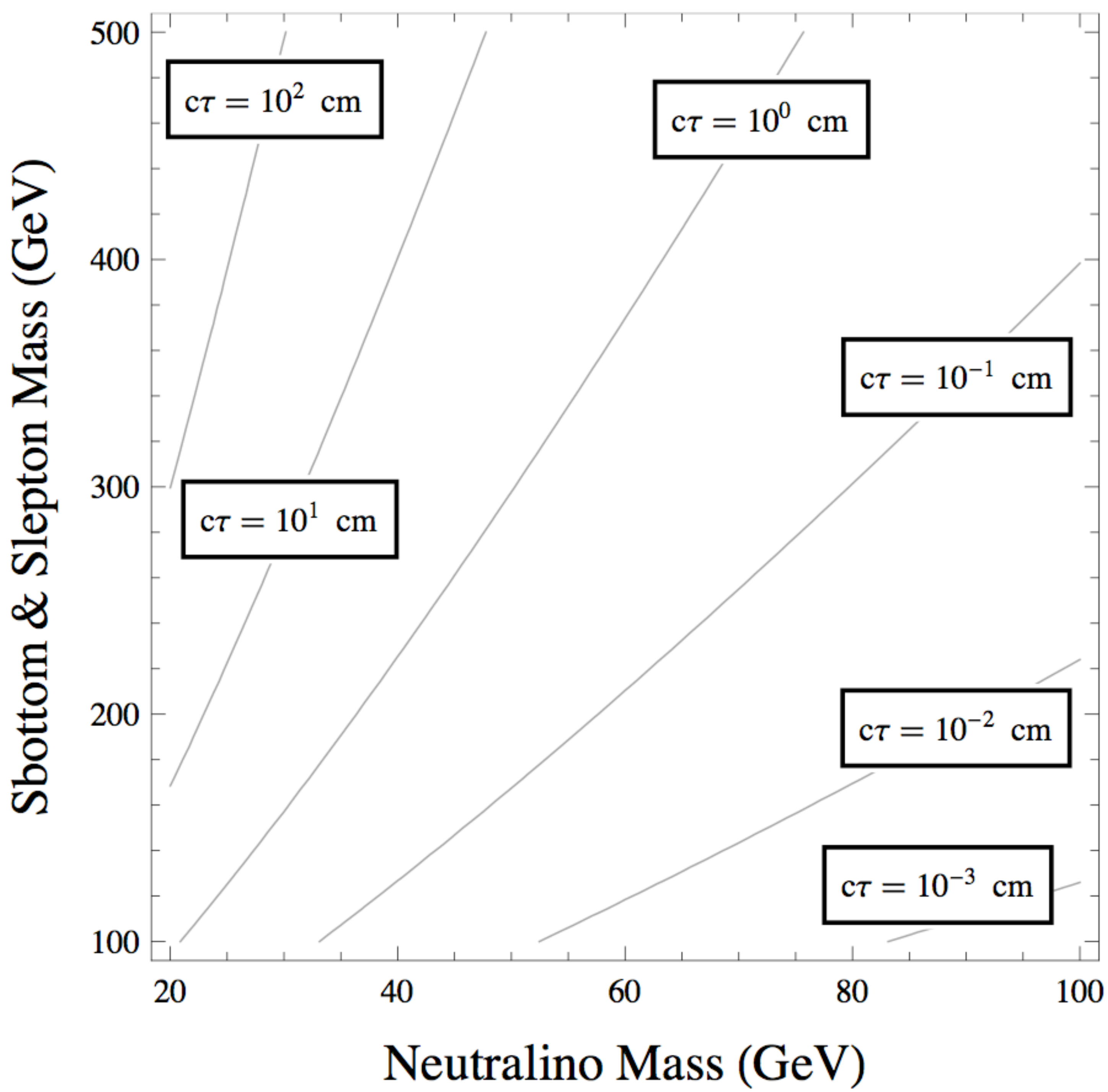
Neutralino LSP

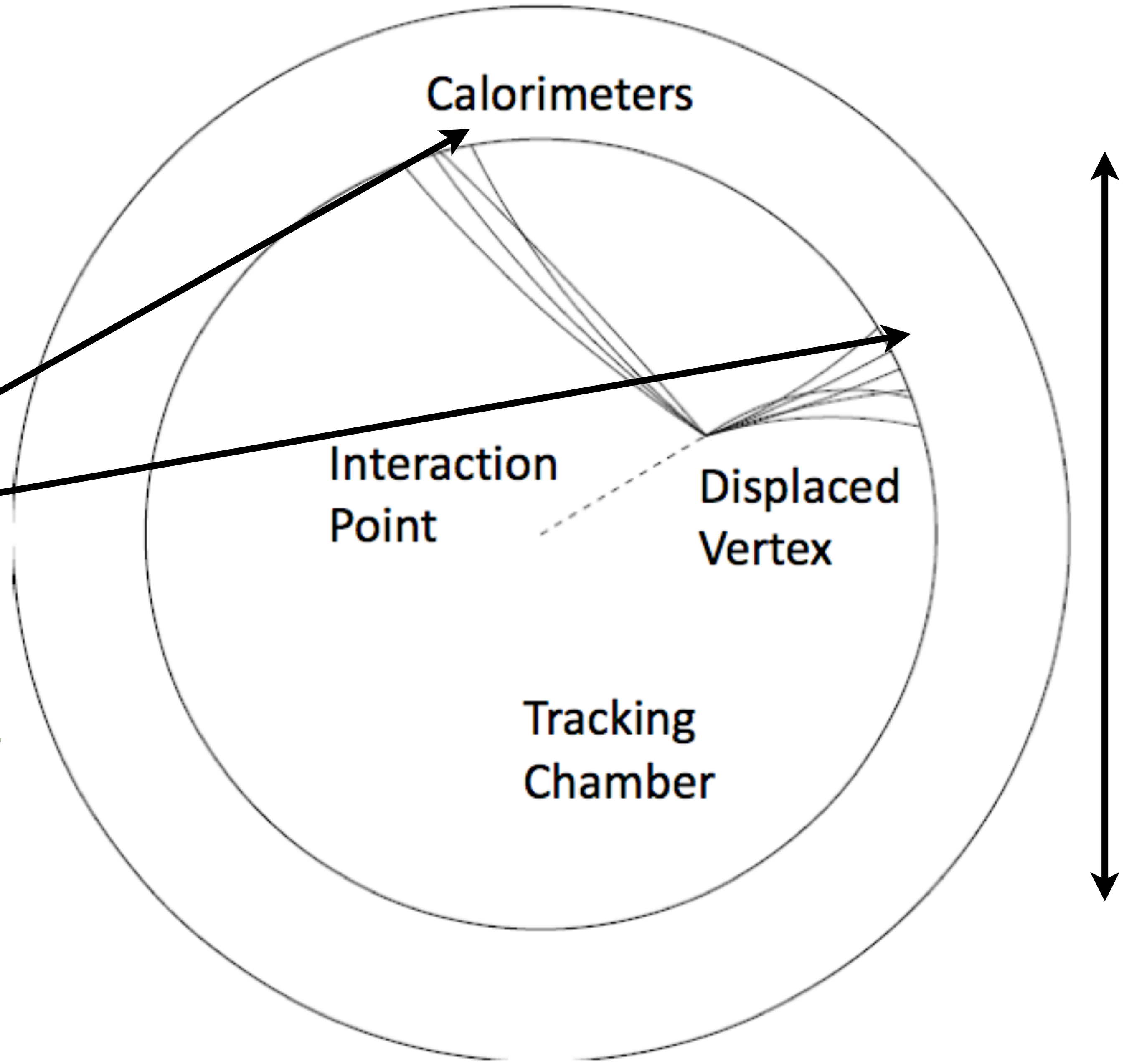


$$\epsilon = 10^{-3}$$

$$m_{\tilde{q}} = m_{\tilde{\ell}}$$

$$\tan\beta = 5$$

Displaced Vertices!



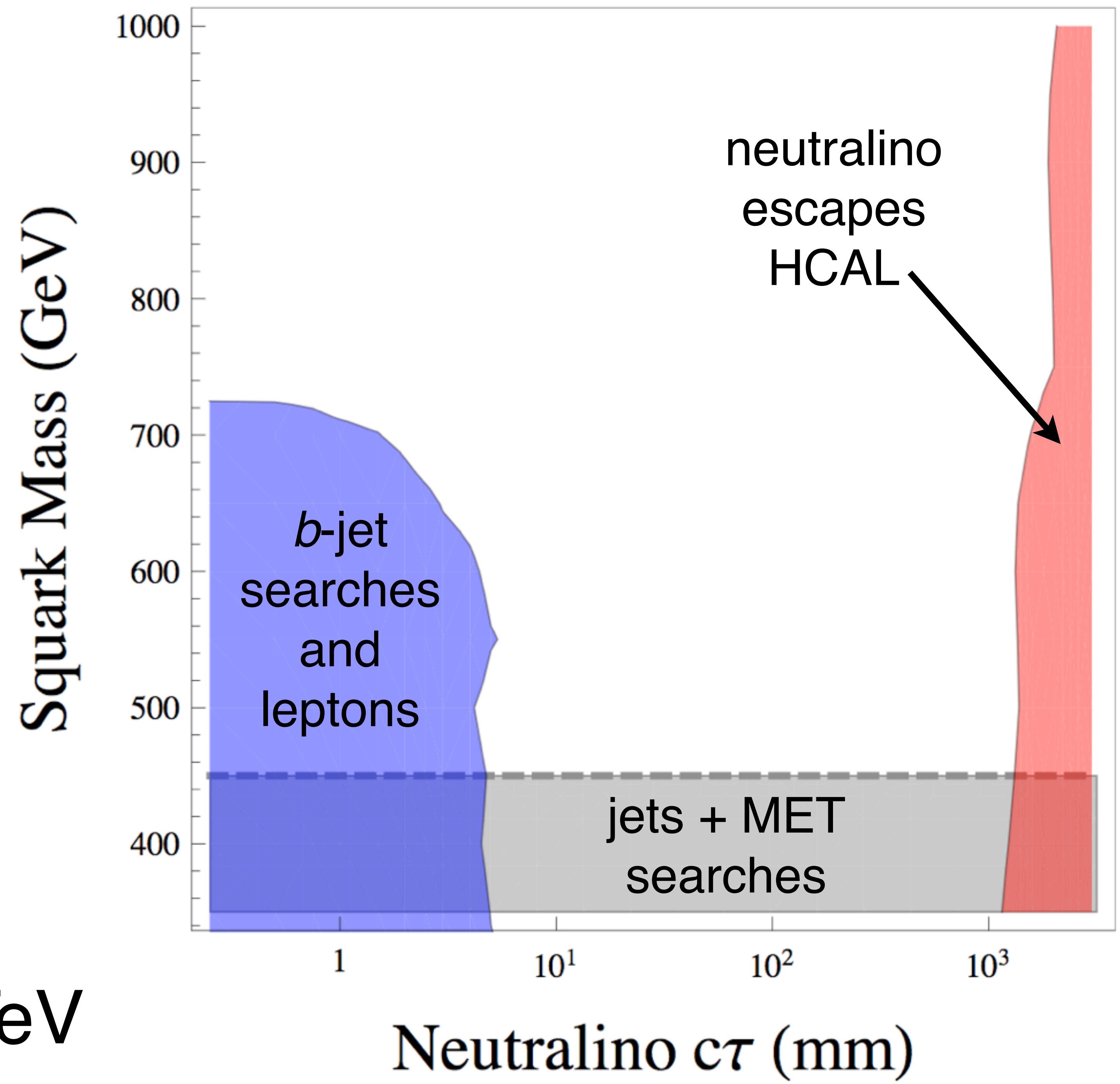
bad tracks, but HCAL deposits reduce missing E_T

Inner detector size ~ 1 meter

Displaced Vertices!

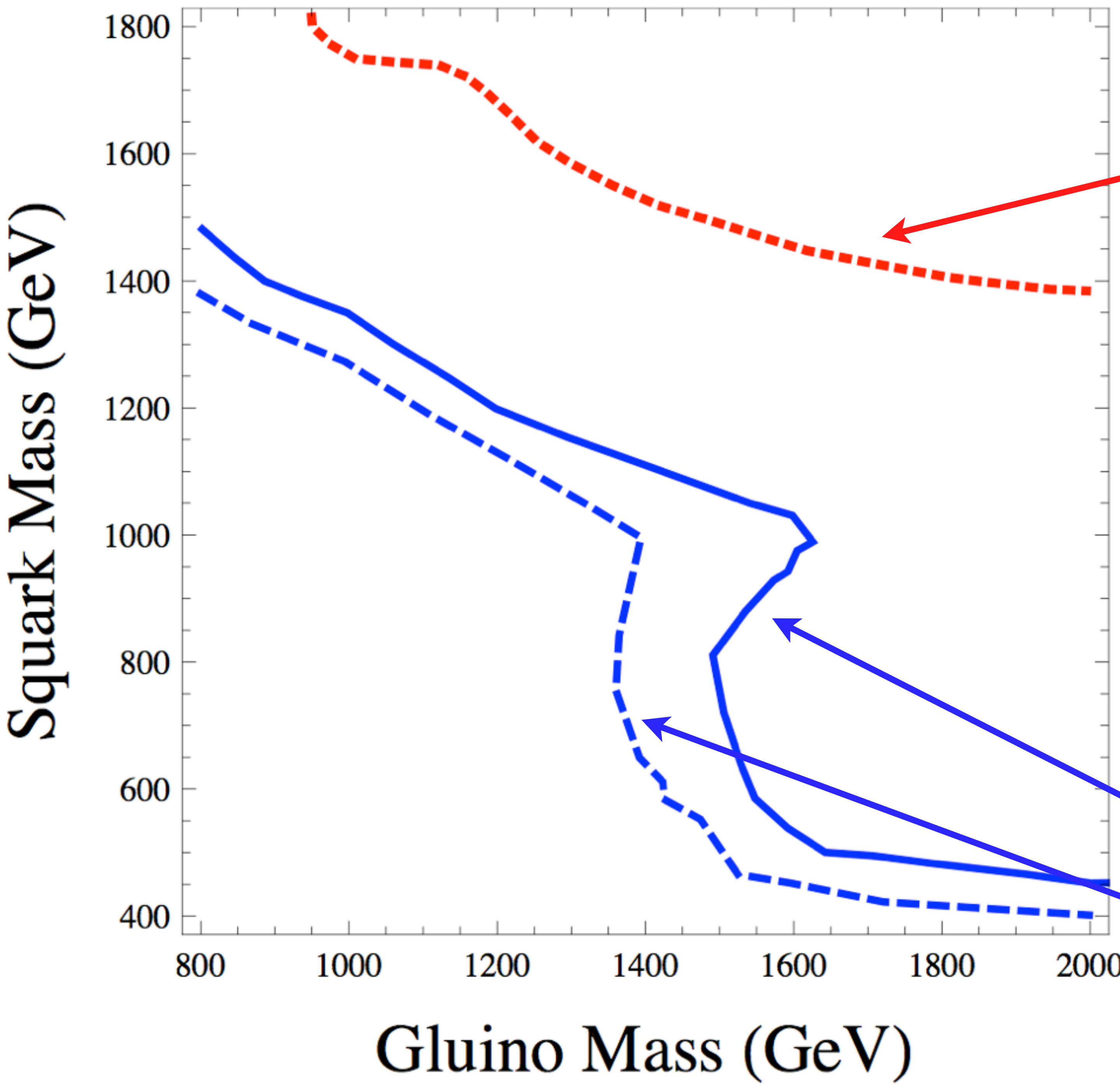
Collider Search	Issues Limiting Sensitivity to Displaced BRPV Decays
Searches in leptons and *b*-jets	Displaced tracks prevent reconstruction
Searches in jets + MET	Highly suppressed missing energy, CMS jets require good tracks
Searches for displaced vertices	Specific decay topologies not yet searched for

Neutralino LSP



Gluino: 2 TeV

Constraints on squarks and gluinos



$m_\chi = 0$,
ATLAS: stable,
3rd generation
decoupled

$m_\chi = 50$ GeV,
$\chi \to b\bar{b}\nu$
(3 gen.s)
perfect eff.
degraded 30%

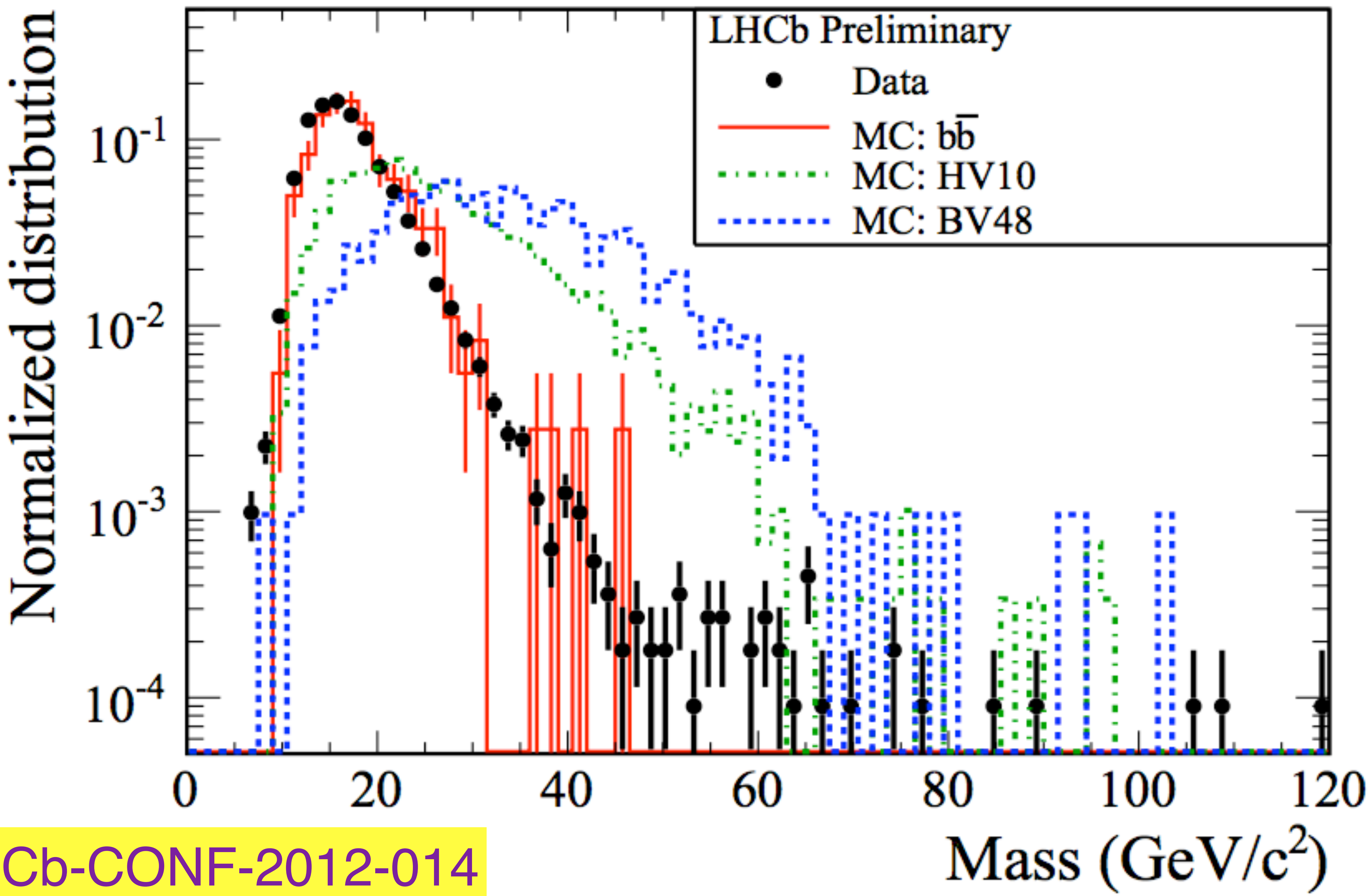
Constraints, Searches

- All squarks as low as 450 GeV
- Displaced vertex searches only significantly constrain $\chi \to \nu\mu\tau$
- Discovery: displaced vertex triggers (LHCb only?) and continued jets + MET

Displaced Conclusion

- Bilinear R-parity violation is well-motivated and consistent with low energy constraints
- RPV couplings can naturally be small, giving the LSP a macroscopic decay length
- Such decays greatly relax the constraints from existing searches on supersymmetry and squark mass in particular
- An appropriately designed search can have great discovery potential for these models.

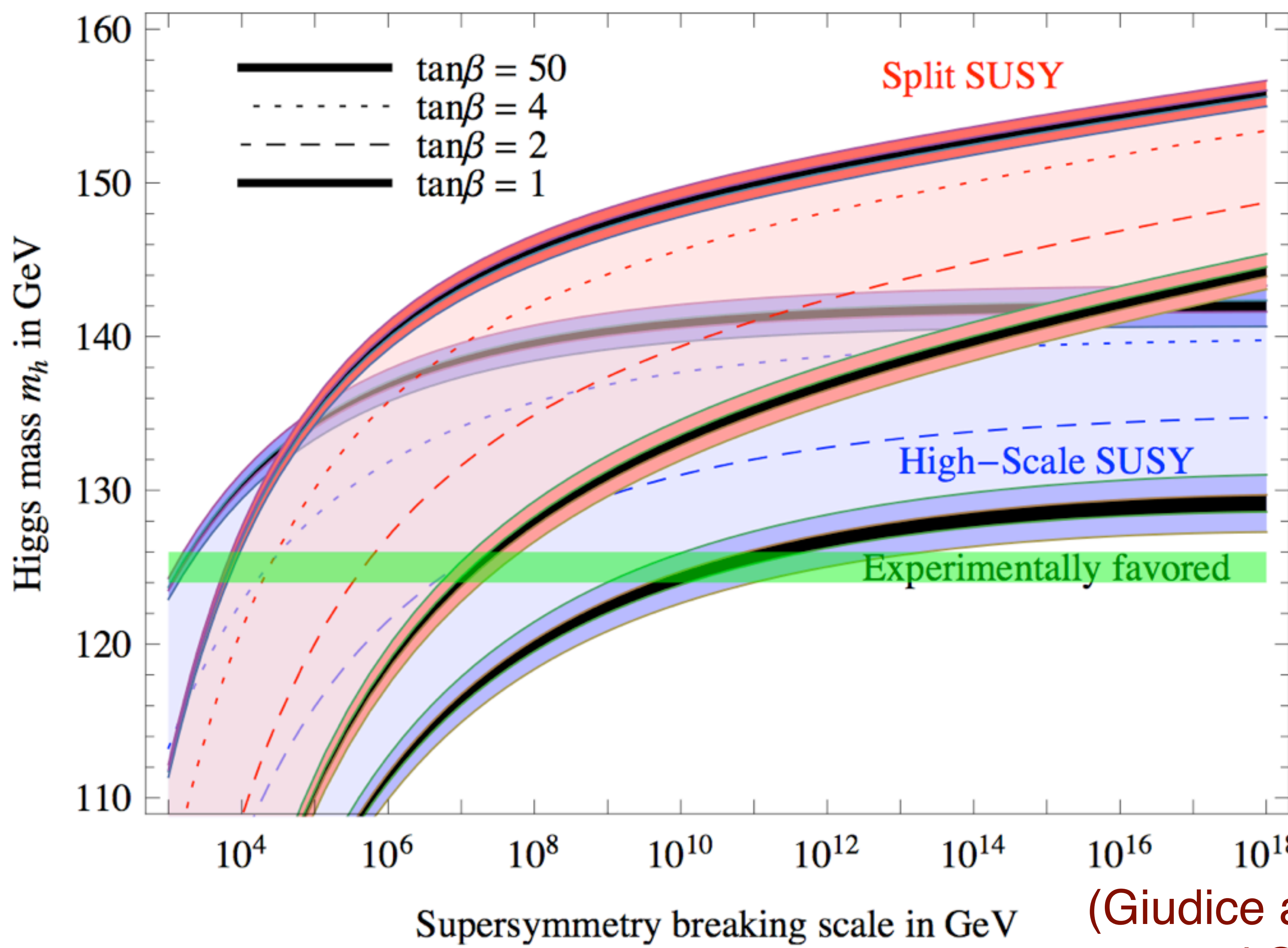
LHCb is geared up!



LHCb-CONF-2012-014

Misplaced SUSY

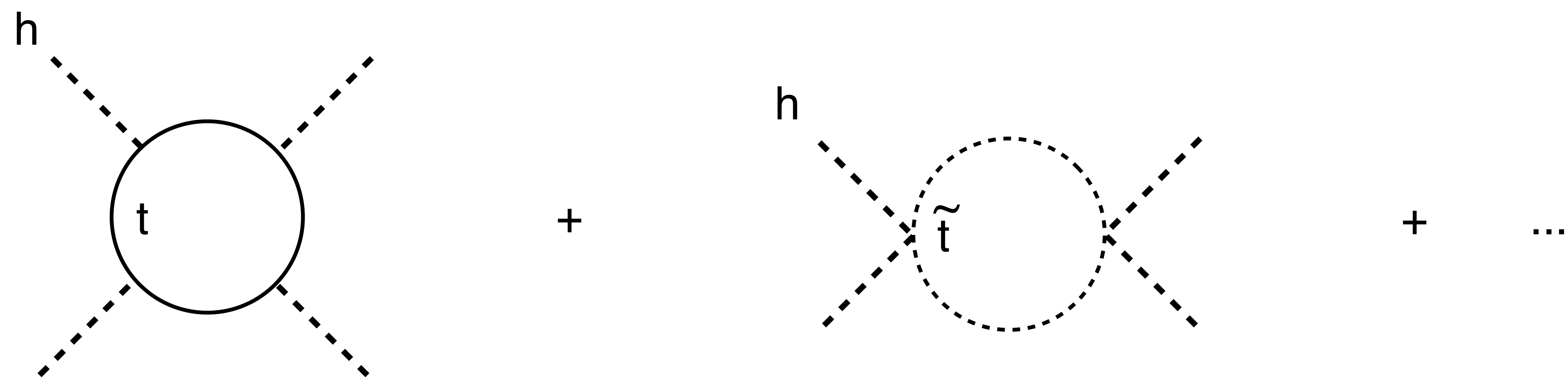
- MSSM looks challenged if you don't like tuning:



(Giudice and Strumia, 2011 and Strumia's talk!)

Higgs mass corrections

Top Yukawa coupling has a significant impact on the effective potential of the Higgs:



Depends on the stop mass logarithmically

Theory Tuning

We have been tuning for decades in ‘theory space’ simply in order to avoid tuning the quadratic term in the Higgs potential

(PeV SUSY, Split SUSY, etc...)

Sfermions vs. Gauginos

- Since the 80's, it has been clear that gauginos 'want' to be much lighter than squarks/ sleptons:

$$X \to \theta^2 F_X$$

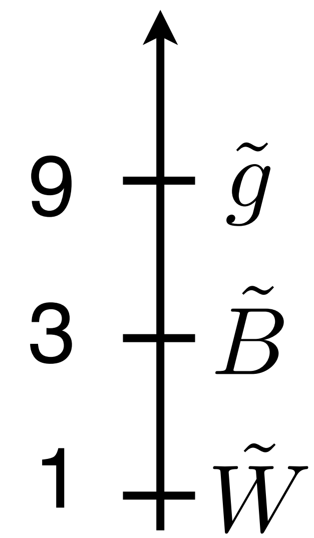
$$\int d^4\theta \frac{X^\dagger X Q^\dagger Q}{M_{pl}^2} \quad \text{and} \quad \int d^2\theta \frac{X W^\alpha W_\alpha}{M_{pl}}$$

- X can be anything for the first, must be an exact singlet for the second (hard to come by)

Anomaly Mediation

- A ubiquitous contribution to the gauginos (and A-terms) was found:

$$M_\lambda \;=\; \frac{\beta_g}{g} m_{3/2}$$

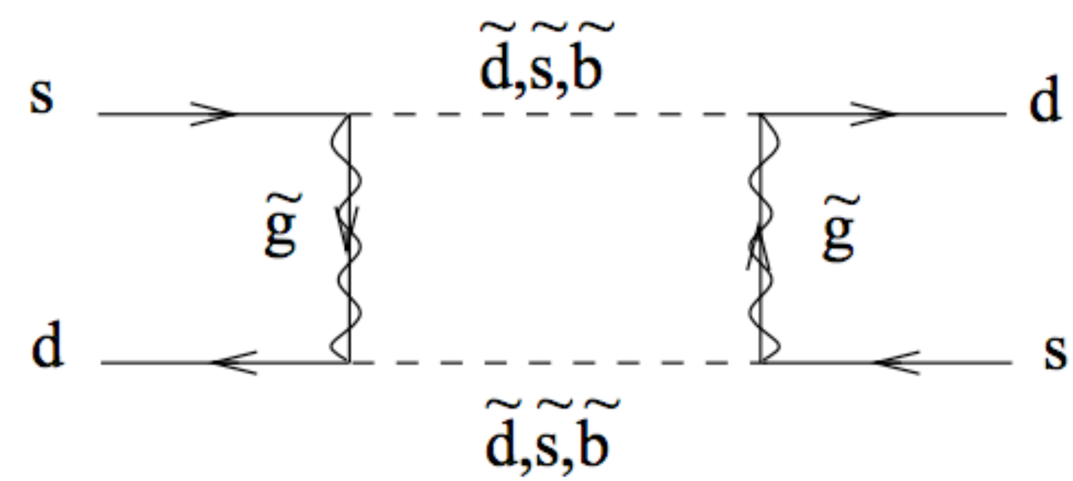


- Since $m_{3/2} \sim F/M_{pl}$, gauginos are 1-loop suppressed.

FCNC and CPV

- Contributions to K-Kbar mixing, decays, lepton flavor violation, etc, required a solution to the flavor problem (gauge mediation, gaugino mediation, ...)

or



- Scalars could be at ~ 1000 TeV

Higgsinos

- The mu-term breaks Peccei-Quinn and R symmetries - could be small
- Simplest mechanism is Giudice-Masiero

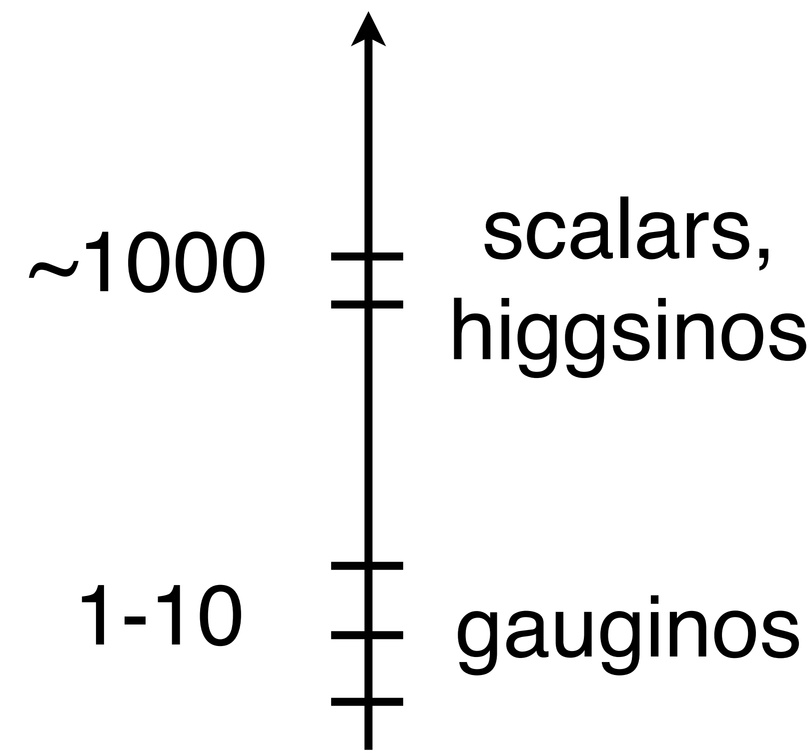
$$\int d^4\theta H_u H_d(\phi^\dagger \phi) \to \int d^4\theta H_u H_d(\phi^\dagger / \phi)$$

$$\phi = 1 + \theta^2 m_{3/2}$$

$$\mu^2 \sim B\mu \sim m_{3/2}^2$$

Simple Spectrum

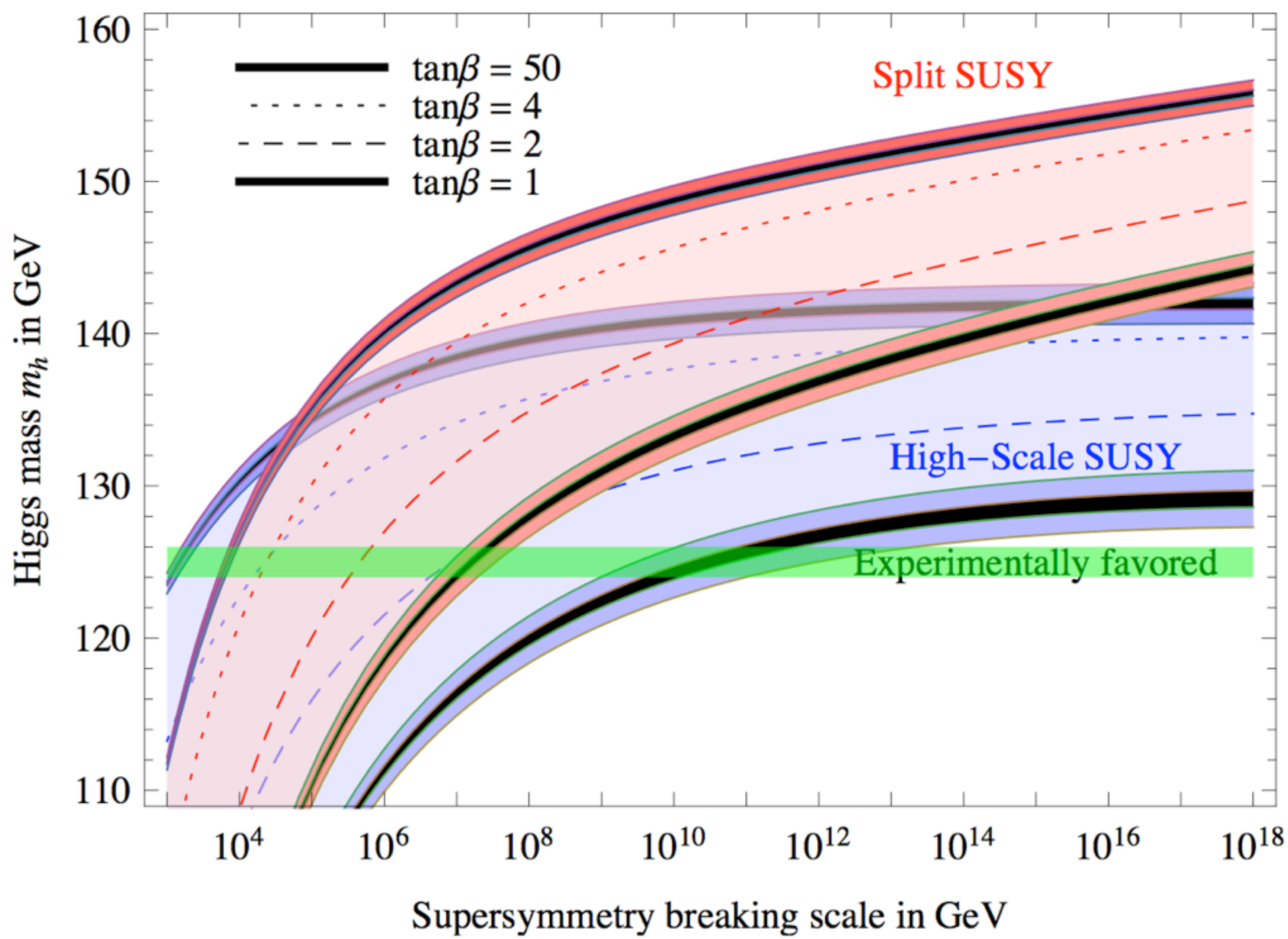
- For gravity mediation, arguable the most *natural* spectrum:



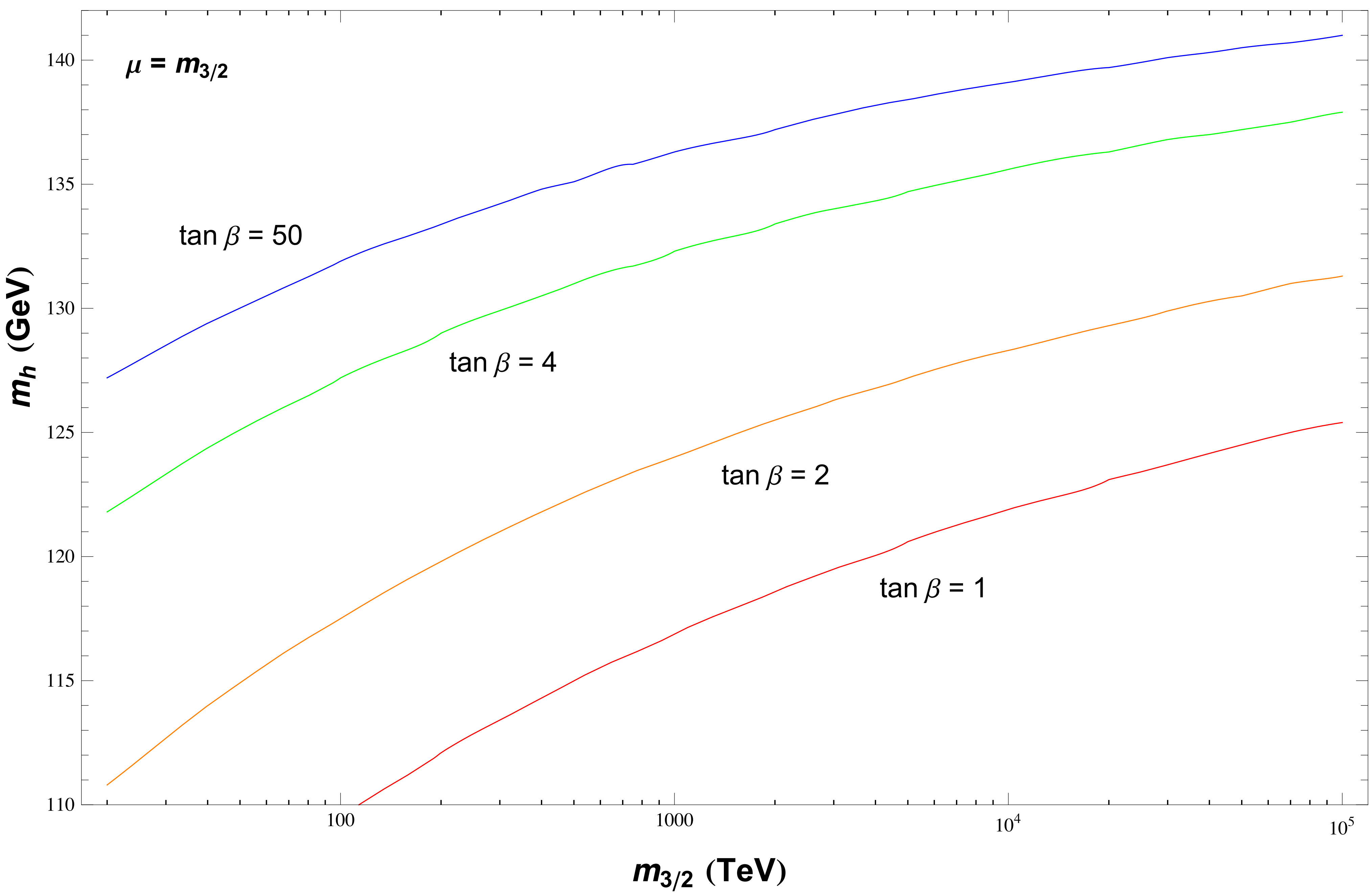
- Natural value for $\tan\beta \sim \mathcal{O}(1)$ since:

$$m_{h_u}^2 \sim m_{h_d}^2 \sim \mu^2 \sim B\mu \sim m_{3/2}^2$$

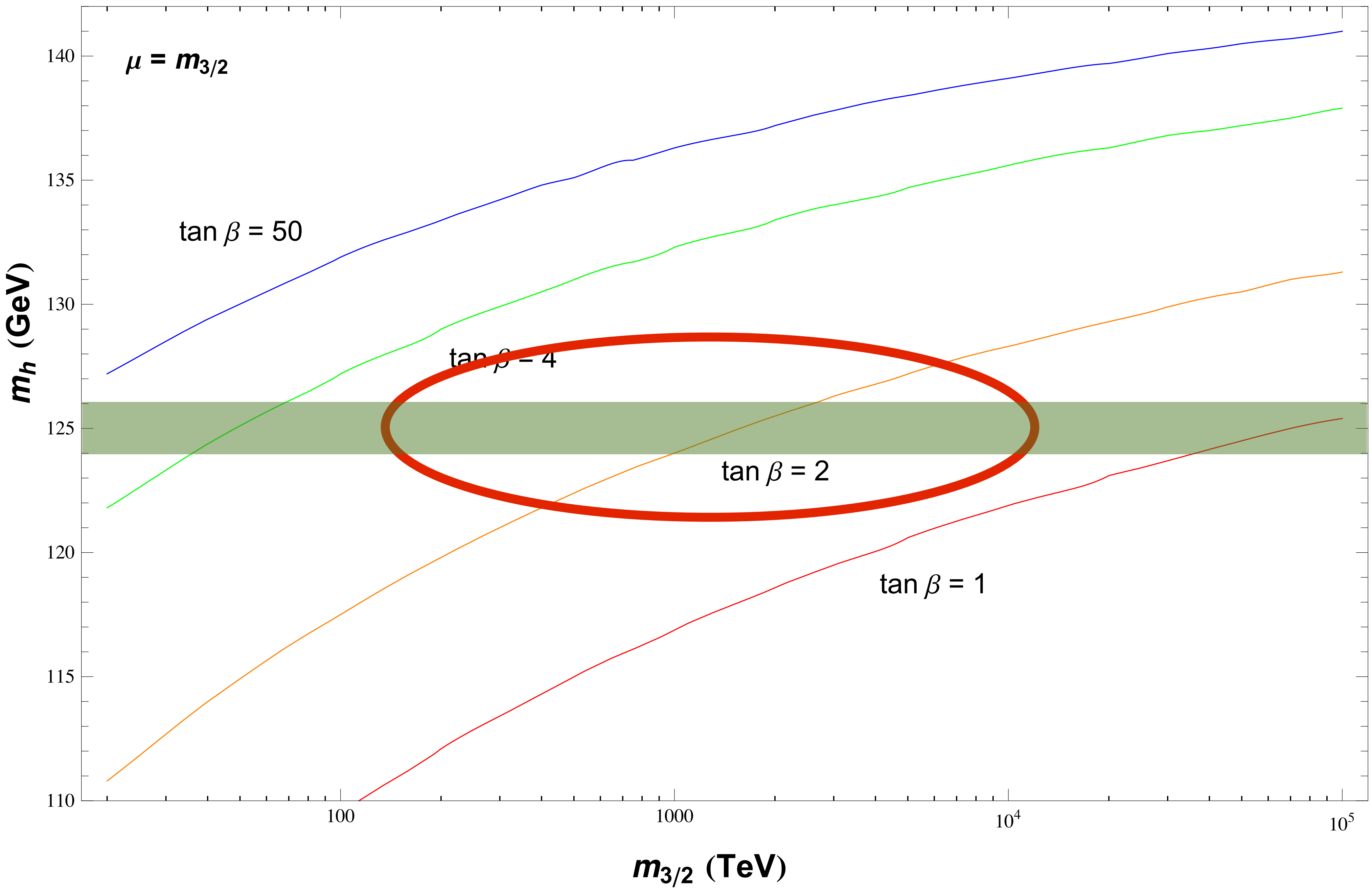
Higgs mass wants



Higgs mass wants

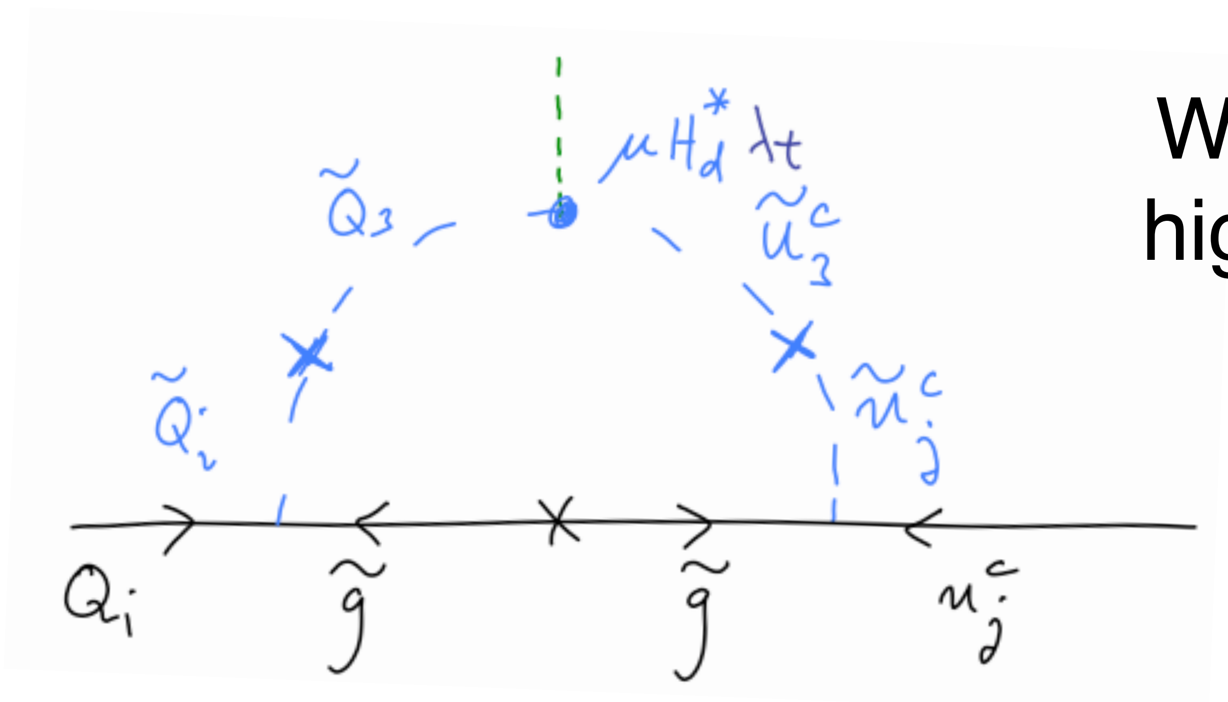


Higgs mass wants



Flavor wants a split spectrum too!

$$\delta\lambda_{up} \sim \lambda_{top}\left(\frac{\alpha_s}{\pi}\right)\left(\frac{\mu m_{\tilde{g}}}{m_s^2}\right) \sim 10^{-2} \times \left(\frac{\mu m_{\tilde{g}}}{m_s^2}\right)$$



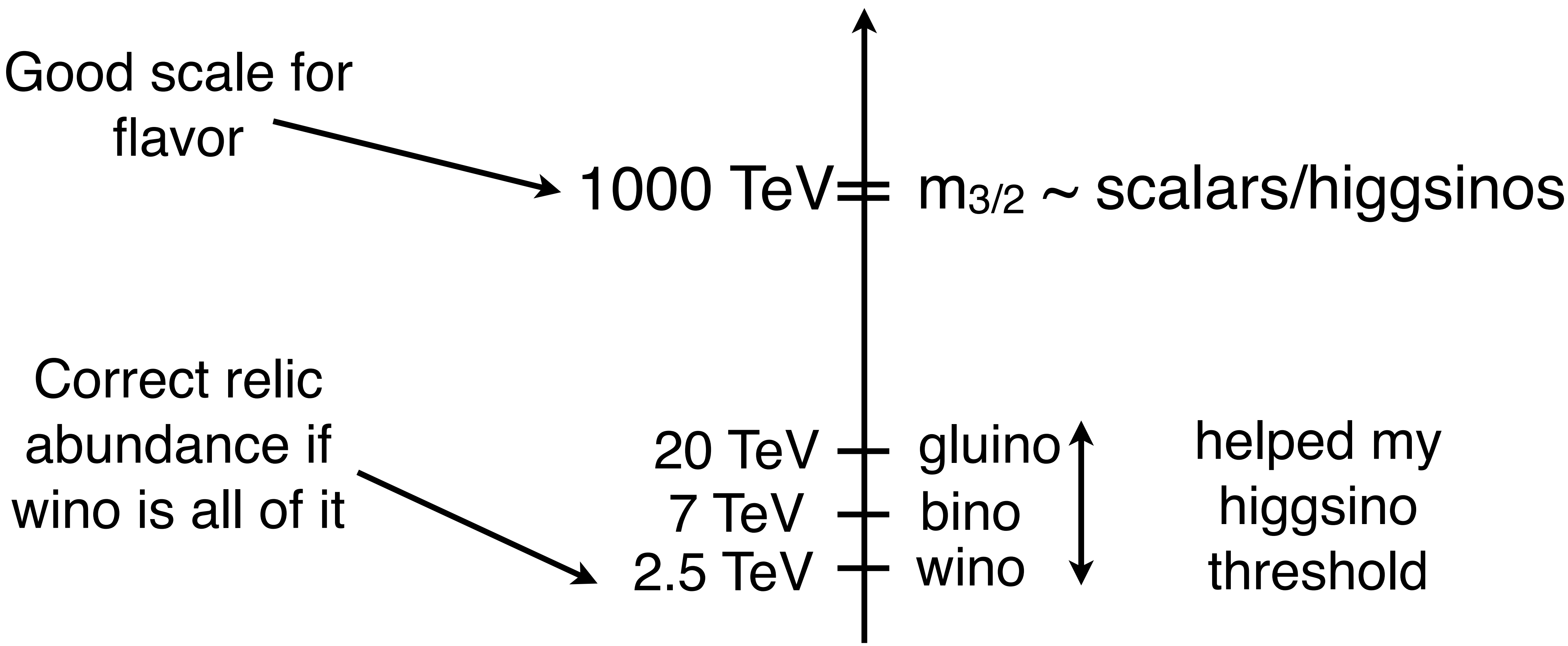
Way too big, unless gluino is light - high-scale susy has flavor problem!

Appearance of GUT-violating “SUSY slop”

Why is it tuned?

- Gauginos could have been discovered at 1 GeV!
- A ‘downward’ pressure exists from the EW scale and CC. Perhaps there are ‘upward’ pressures too?
- For another talk/project. Simply interested in phenomenology.

Minimal Spectrum



DM model dependence

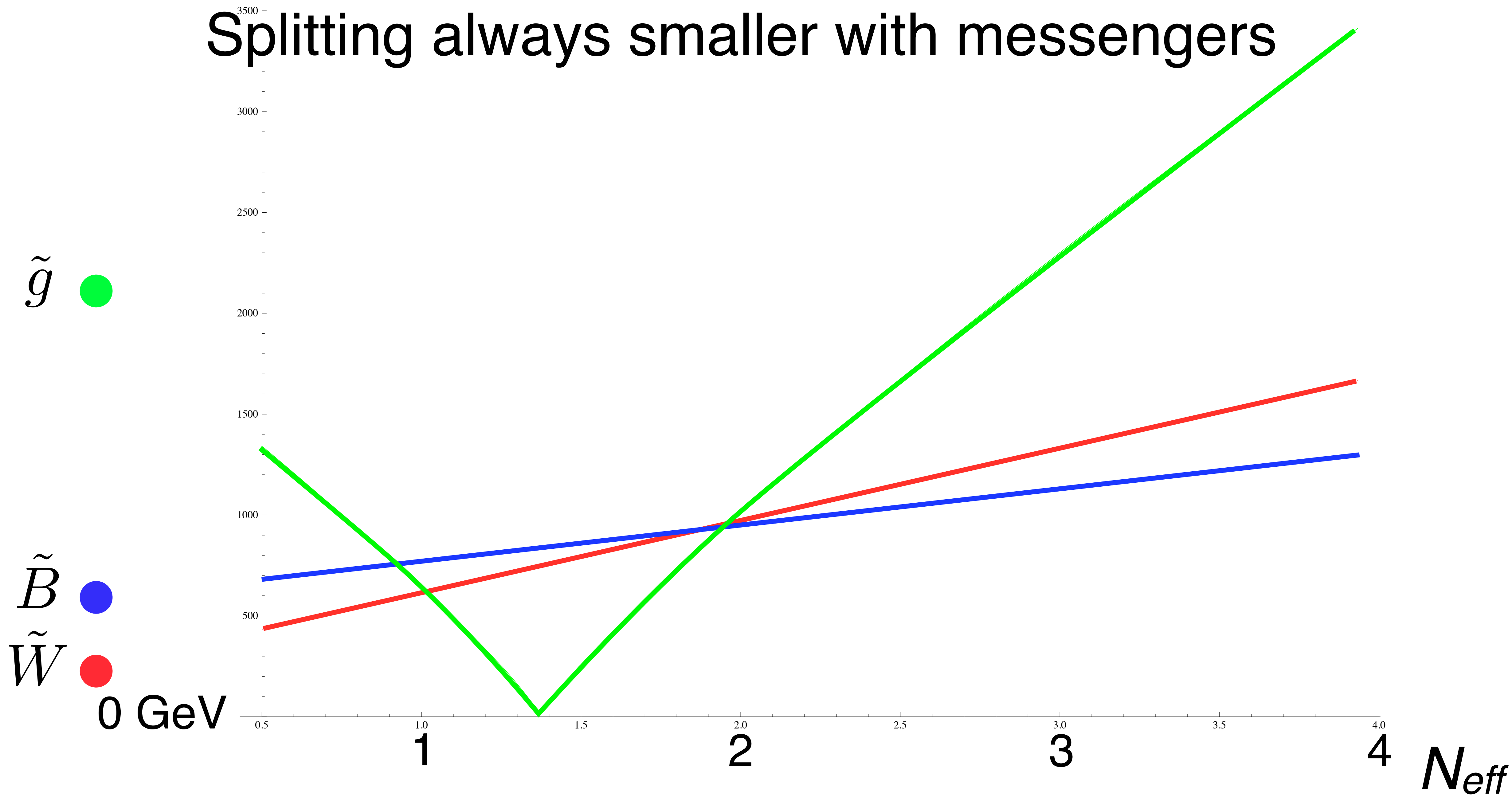
- Could be a 'well-tempered' relic - lighter okay
- Could be only part of DM (axions) - lighter required
- Could be repopulated by moduli decay (at $m_{3/2}$) - 100 GeV fine.

Additional states at $m_{3/2}$

- Vector-like states (**5** + **5** s) could appear at $m_{3/2}$ via Giudice-Masiero.
- 1-4 ‘messengers’ okay for unification, correct gaugino masses.
- may be part of flavor model at 1000 TeV.

Gaugino spectra

Splitting always smaller with messengers



Add'l mults

Higgs 125 GeV in the following:

$\alpha_s \sim .115$

$\alpha_s \sim .107$

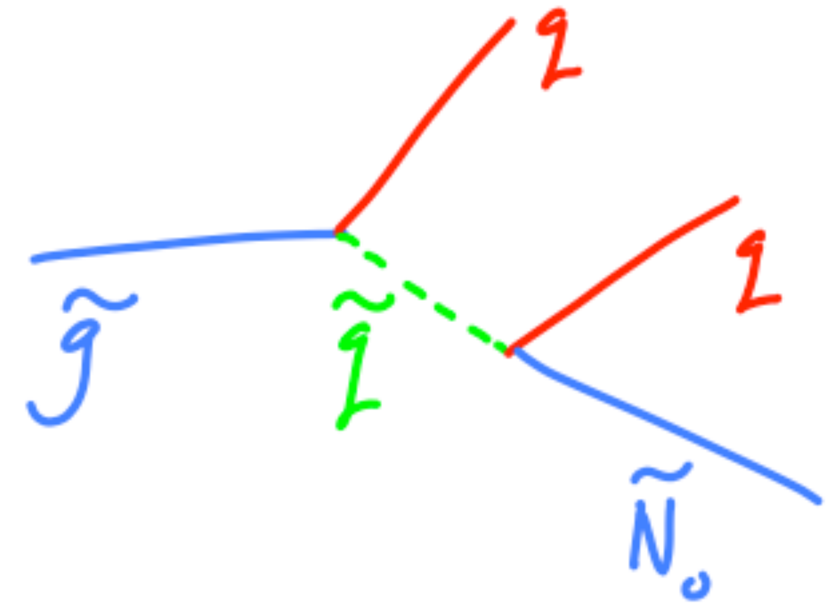
N	$\tan\beta$	m_s (TeV)	$m_{3/2}$ (TeV)	$\mu(TeV)$	M_1 (GeV)	M_2 (GeV)	M_3 (GeV)
0	4.0	80	80	80	802	377	2394
1	2.8	300	75	300	974	773	779
2	3.0	100	80	100	1307	1377	1478
3	2.7	250	50	50	945	1113	1951
4	2.7	250	50	50	1094	1409	2955
5	2.9	150	30	30	742	1025	2457

gaugino-LSP splitting small

More optimistic for LHC discovery!

Measuring fine-tuning

- Long-lived gluinos:

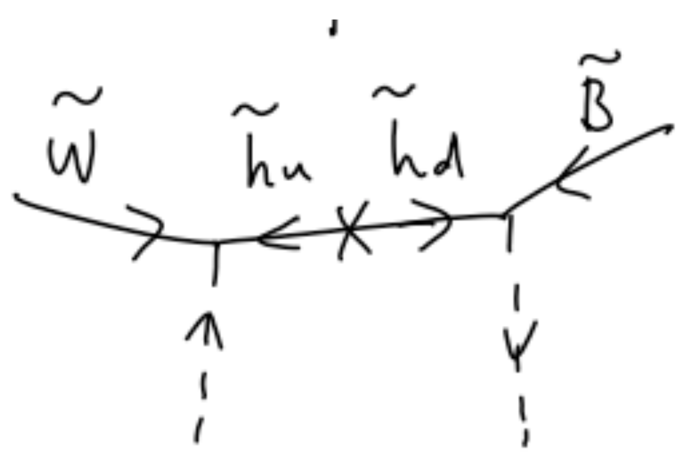


Macroscopic if $$m_{\tilde{q}} > \left(\frac{\Delta m}{1\ \mathrm{TeV}}\right)^{5/4} \times (400\ \mathrm{TeV})$$

If tops, a measure of tuning!

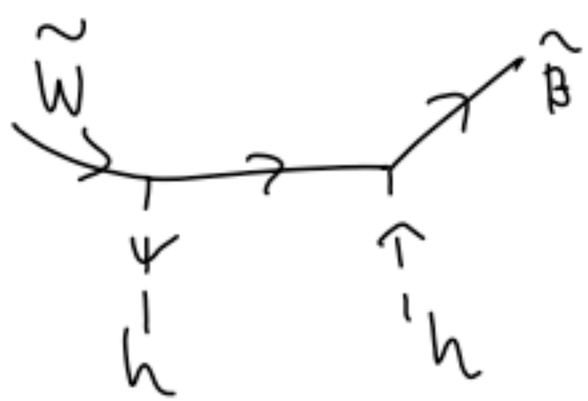
Measuring fine-tuning

- Electroweak production/decay



$$\frac{(h^\dagger \tilde{W} h)\tilde{B}}{m_{\tilde{h}}}$$

dim 5

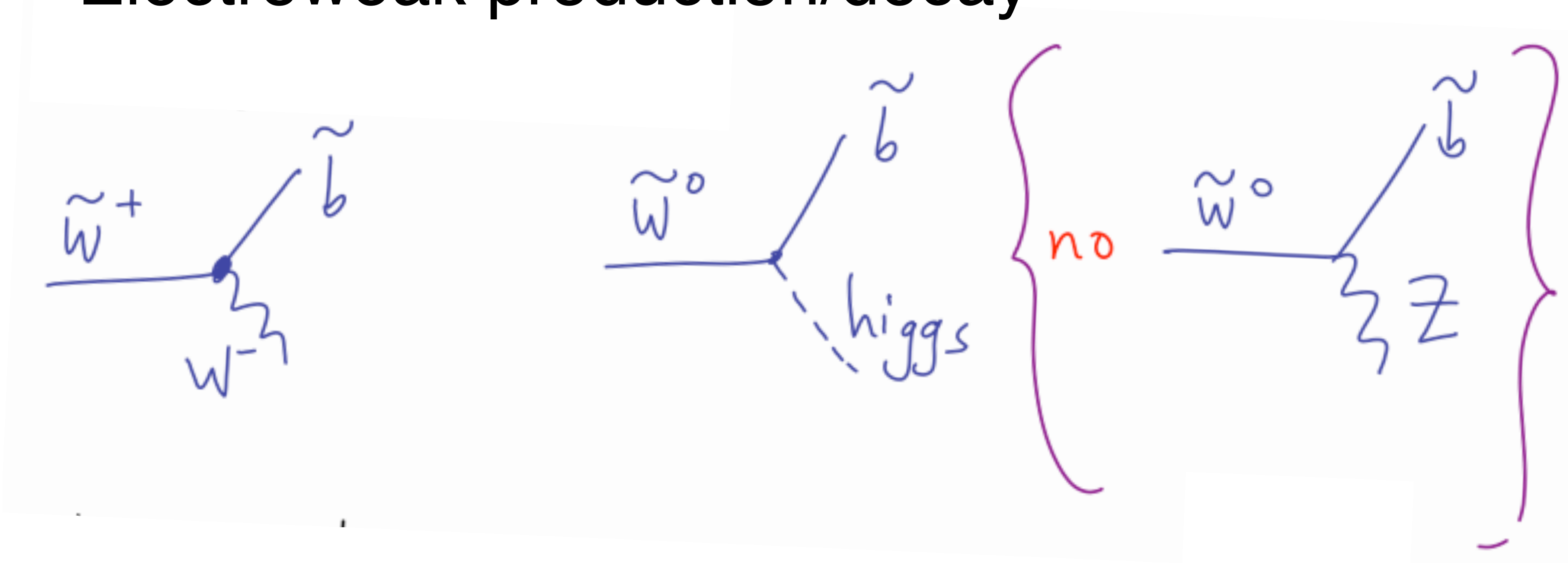


$$\frac{(h^\dagger D^\mu h)\tilde{W}\sigma_\mu \tilde{B}}{m_{\tilde{h}}^2}$$

dim 6

Measuring fine-tuning

- Electroweak production/decay

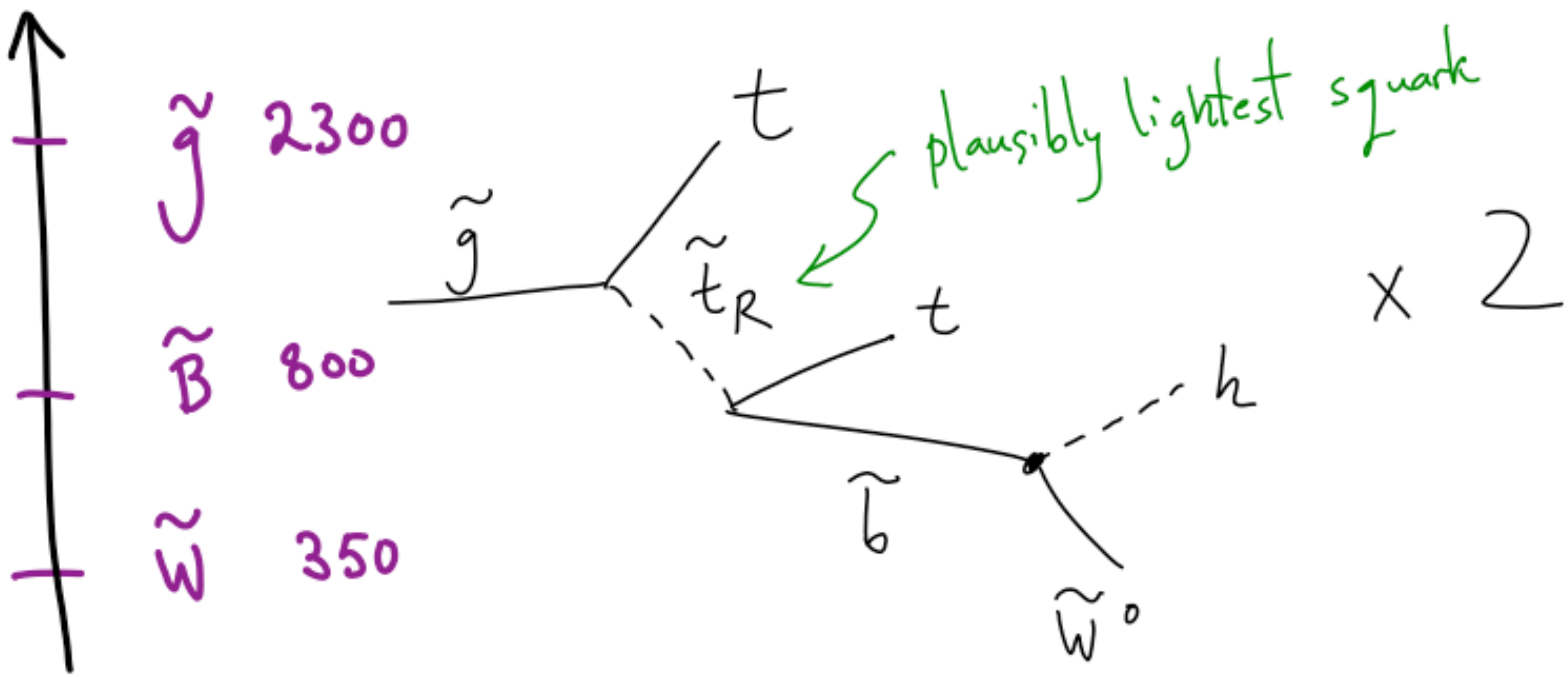


Forbidden decay to Z - BR goes like $\sim m_Z^2/m_{\tilde{h}}^2$

Could probe higgsinos to 10 TeV!

Measuring fine-tuning

Very hopeful spectra:

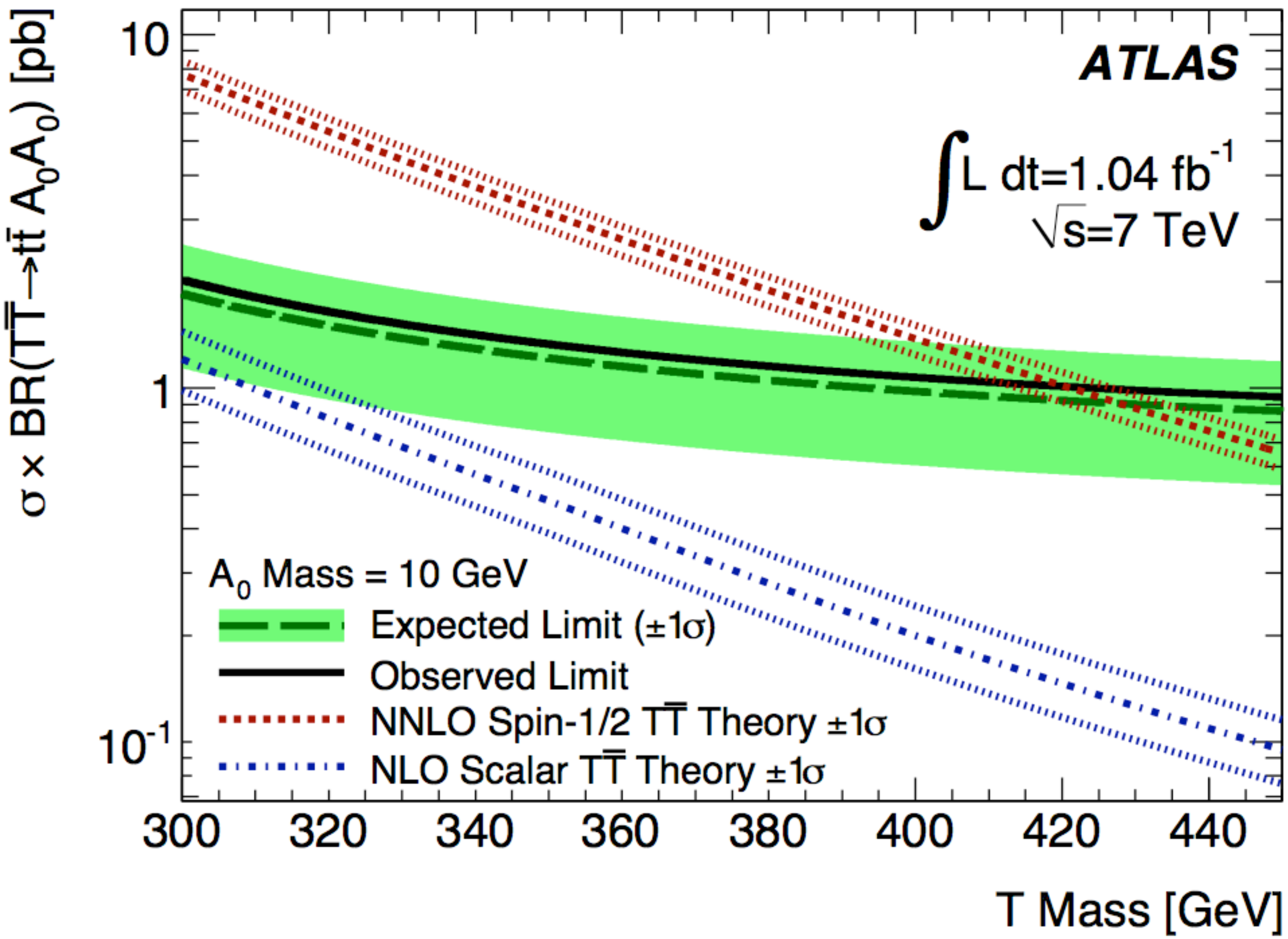


8 b's, 4 W's, missing E_T, slightly displaced tops

Killing naturalness

Rule out stops

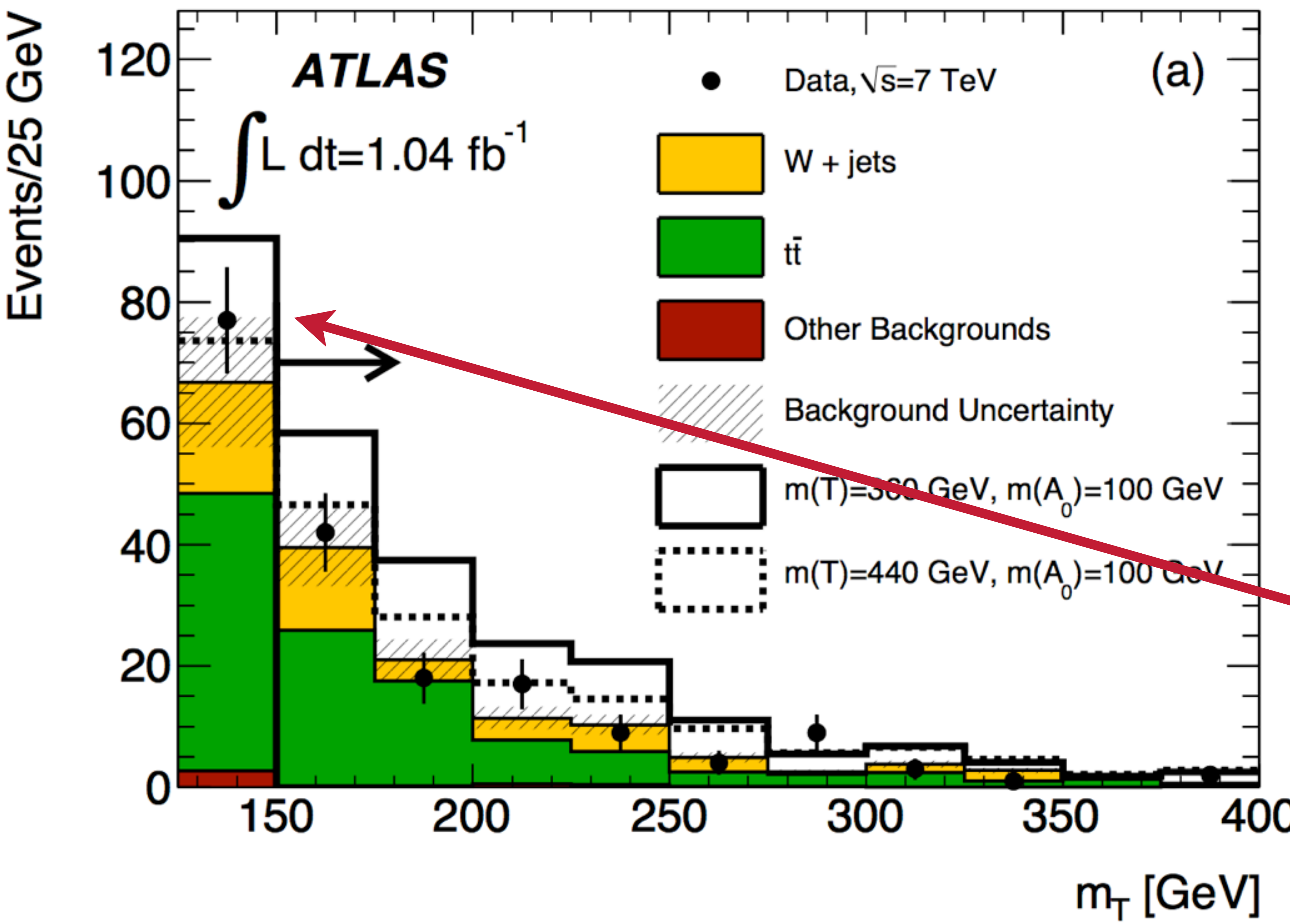
Searches: t tbar + met



Semi-leptonic tops

stop have a small cross section - about 1/6 of Dirac Fermions

Searches: t tbar + met

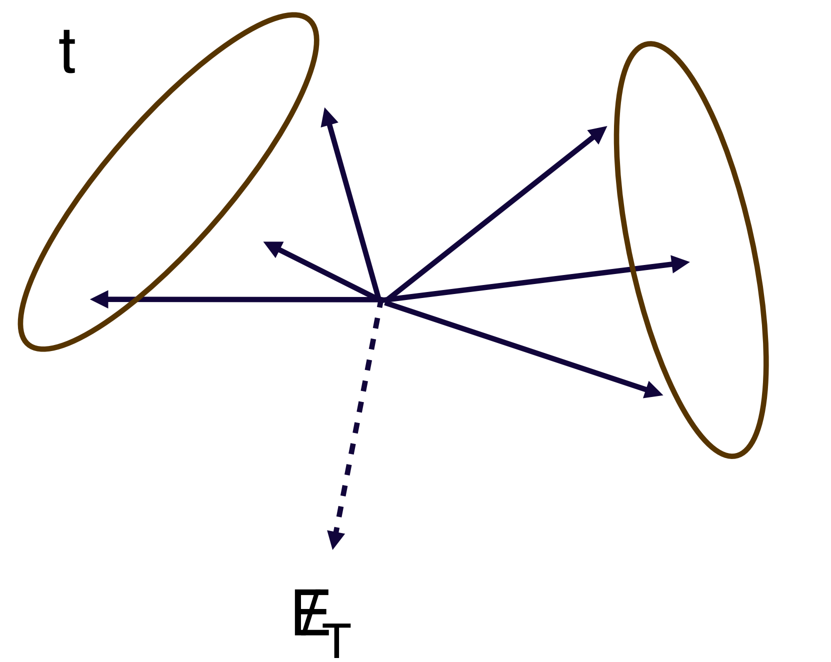


Semi-leptonic tops

Neutrino in signal and background affects efficiency of cuts

Suggest: loose ‘top tags’

- Look for fully hadronic tops: large BR and no neutrino
- “Top tag”s kill combinatoric background for a very mild cost in signal



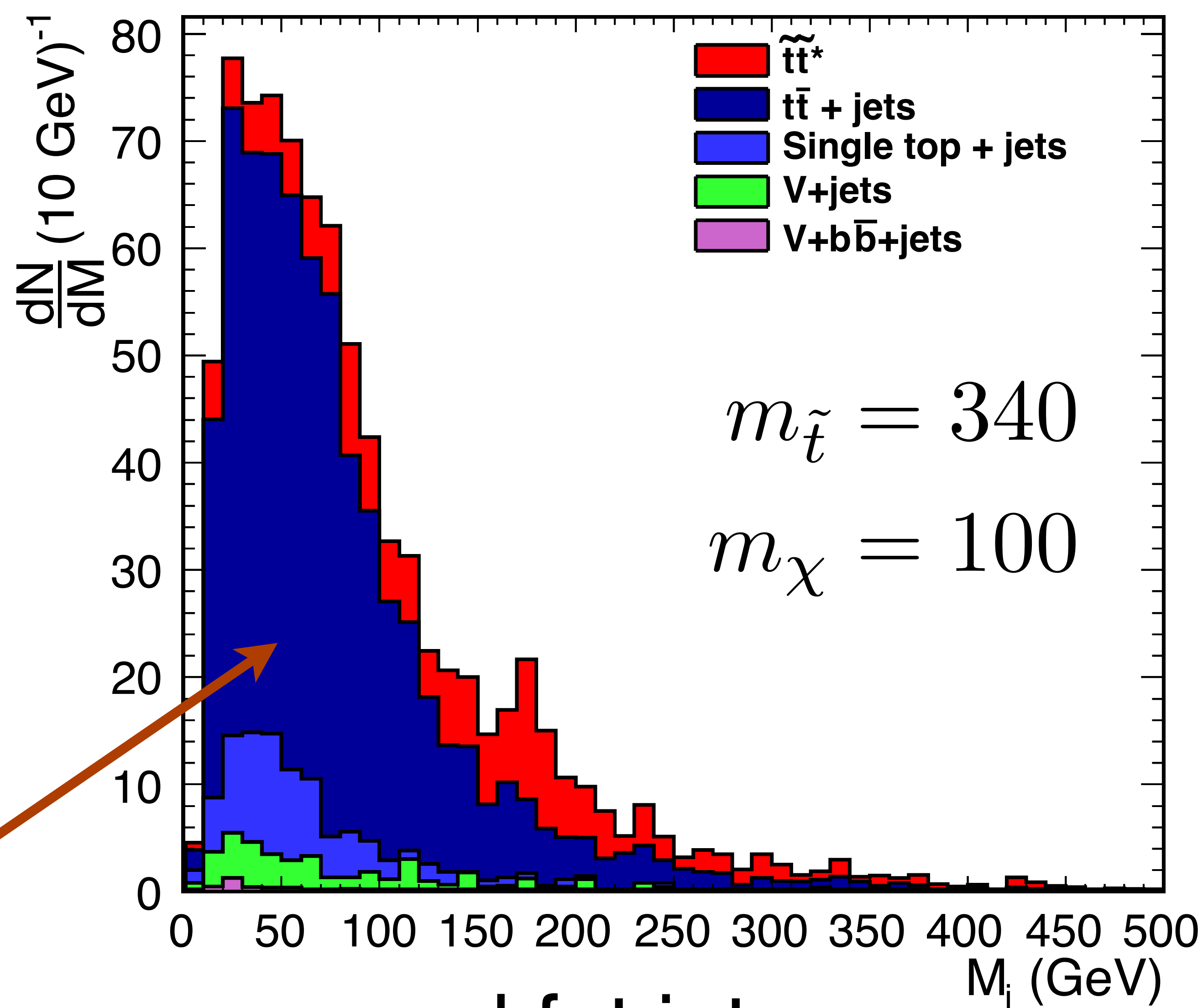
Cuts

- Veto isolated leptons, hadronic taus
- Require MET is isolated
- MET>175 GeV
- Cluster with R=1.2, require 2 fat jets, one passes HEPTopTagger, other b-tagged.

dominant background:

$$t\bar{t} + \mathrm{n}j \to (bjj)(b\tau_h\nu_\tau) + \mathrm{n}j$$

8 TeV, 20 fb^{-1}



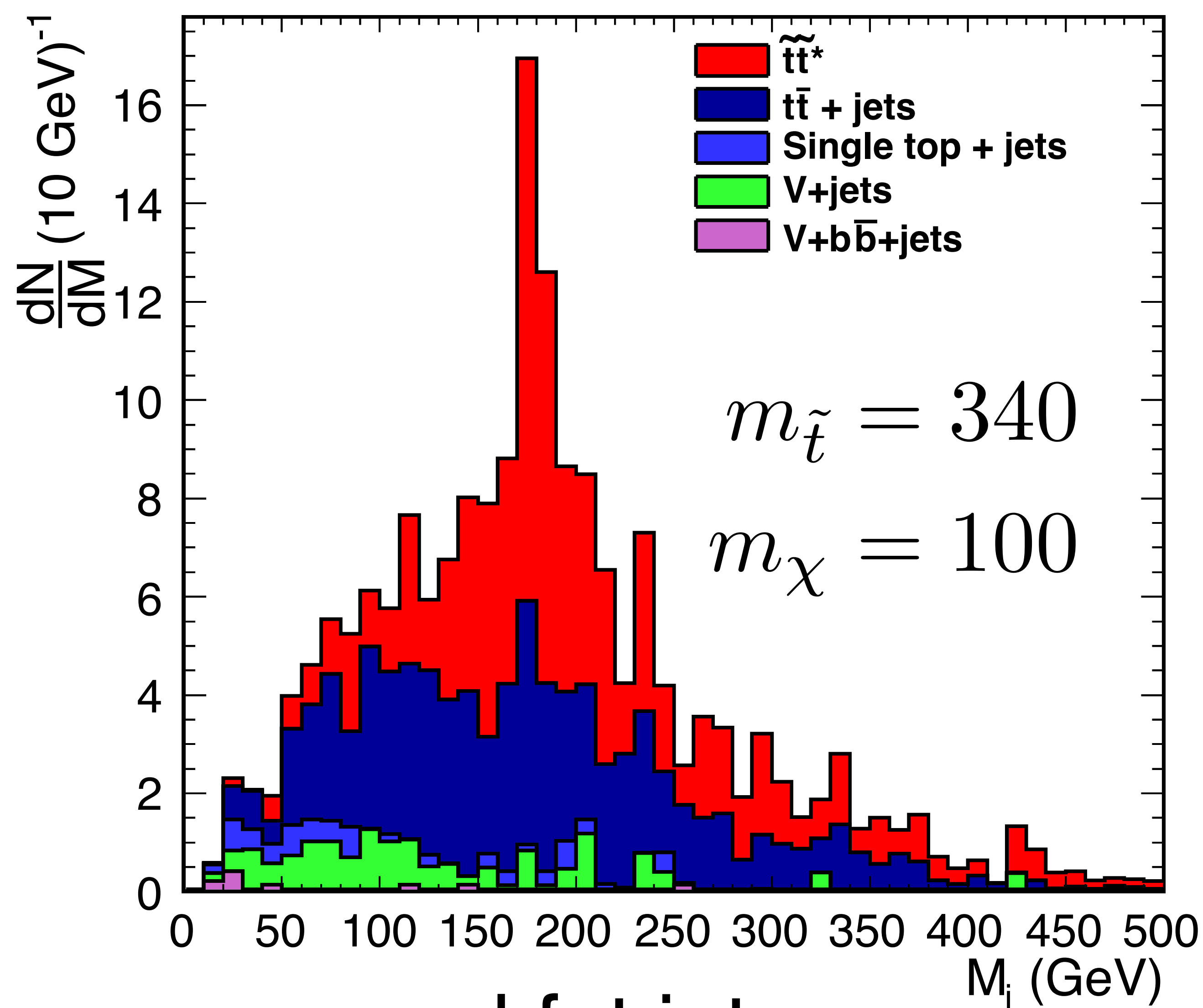
second fat jet mass

Transverse mass cuts

- m_{T2} cut on two fat jets and MET (>200 GeV)
- m_T cut on each of the two fat jets (>200 GeV)

(helps kill the tau neutrino)

8 TeV, 20 fb^{-1}



second fat jet mass

Transverse mass cuts

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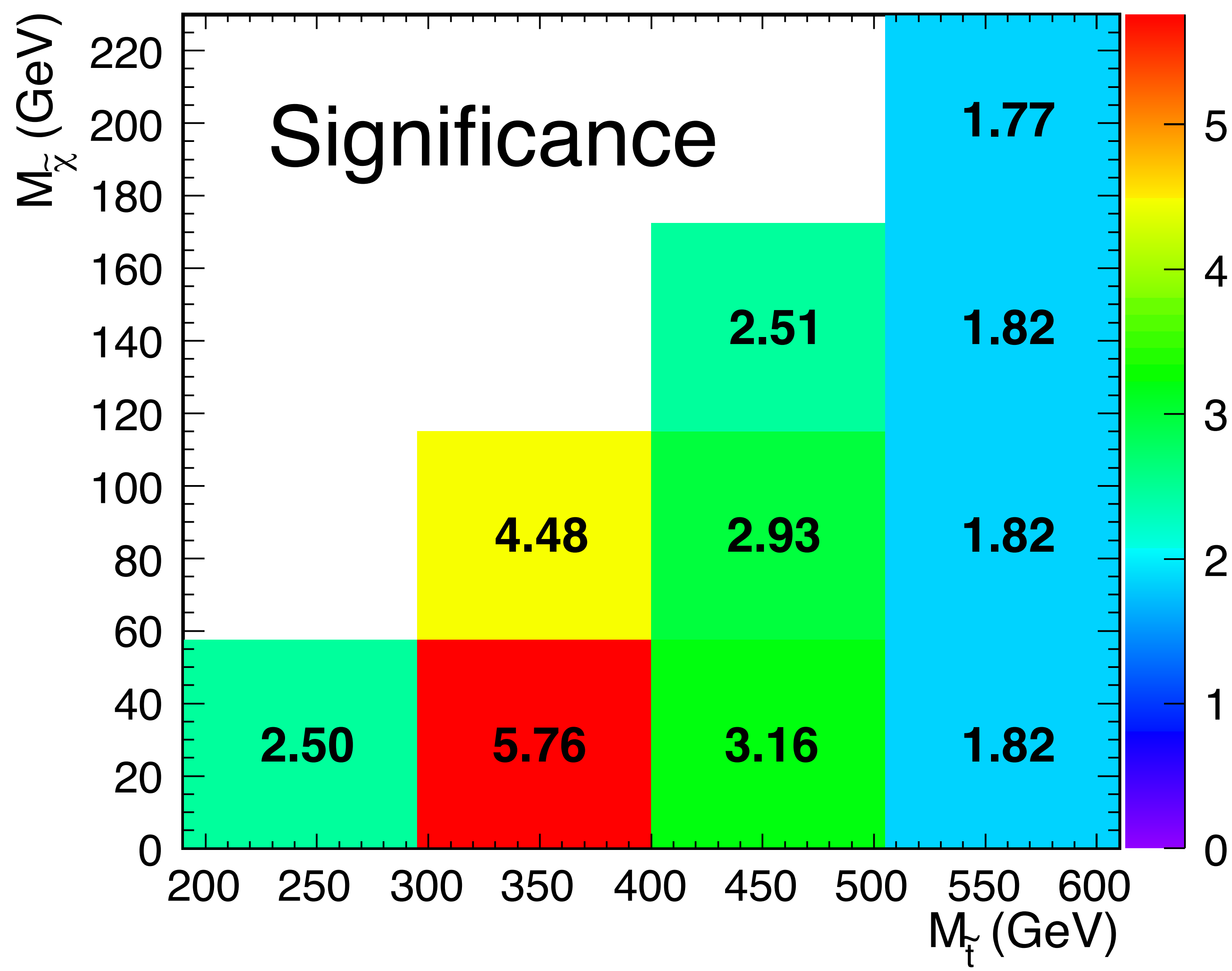
(helps kill the tau neutrino)

Can be done now!

7 TeV, 5 fb^{-1}



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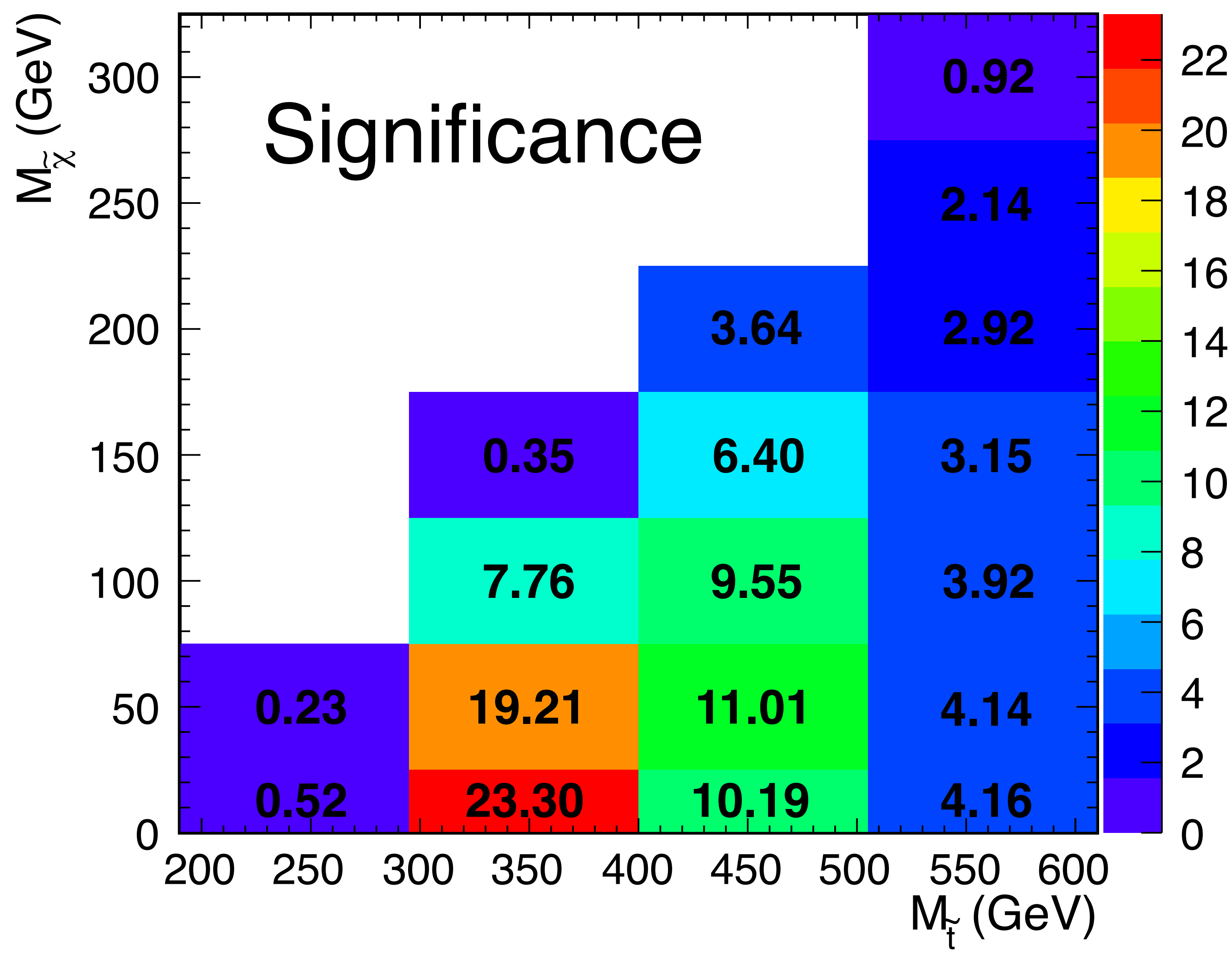

Misplaced conclusion

- Higgs at 125 GeV has us staring naturalness in the face.
- Some can be resolved this year!
- Thank you!!