Natural SUSY's Last Hiding Places

Matt Reece Harvard University at the Fermilab LPC, July 22, 2014

The Big Question

We want the LHC to tell us: **is electroweak symmetry breaking** *natural***?**

Early indications point to "no." But there's still some room for (more or less) natural new physics that has *hidden* so far.

How can naturalness hide, and how do we coax it out if it is hiding?

EWSB in SUSY L vv L in V were taken to be real and positive real and

Minimize potential with respect to Higgs VEVs v_u and v_d to get two equations (e.g. Martin SUSY Primer hep-ph/9709356): by convention, we have the convention of the section of t will in inze potential with respect to ringgs vers vu and vato get
two equations (e.g. Martin SUSY Primer hep-ph/9709356): minimum satisfying equation of $\frac{1}{2}$.

$$
m_{H_u}^2 + |\mu|^2 - b \cot \beta - (m_Z^2/2) \cos(2\beta) = 0,
$$

$$
m_{H_d}^2 + |\mu|^2 - b \tan \beta + (m_Z^2/2) \cos(2\beta) = 0.
$$

 Γ These alle thee-lever results in the MUSIM. A TZU OCV inggs
Means either: large loops or bevond MSSM But the main number of the same order of magnitude. These are **tree-level** results in the **MSSM**. A 125 GeV Higgs means **either: large loops or beyond MSSM**. But the main effect is to replace m_Z in these formulas with a corrected

EWSB in SUSY L N C R in C C C \Box video is not consistent with the observed Higgs mass mass mass mass mass mass \Box for the process with more general quartic terms. Adding the two EWSB equations \mathbf{A} gives 2*b* for the process with more general quartic terms. Adding the two EWSB equations $\mathcal{L}(\mathbf{r}, \mathbf{r})$

Rearranging a bit: M_1 ² M_2 ² the masses of the un-type using terms. Adding the terms that the terms in the pseudoscalar matrix. Adding the pseudoscalar matrix. Adding the other mass matrix. And the pseudoscalar matrix. On the other mass matrix. On the other matrix. On the othe Rearranging a bit: Mv^2 , Mv^2 the masses of the up-type and *^A*, (5) down-type Higgs in the Lagrangian, *b* the mass mixing: zi iyiliy
. a bit: M_{ν} ², M_{D} ² the masses of τ using the result one obtains by diagonalizing the pseudoscalar mass matrix. On the other

$$
M_U^2 + M_D^2 = \frac{2b}{\sin(2\beta)} = m_A^2, \quad \frac{1}{2}m_Z^2 = \frac{M_D^2 - M_U^2 \tan^2 \beta}{\tan^2 \beta - 1}.
$$

using the result of the result of the result of the pseudoscalar matrix. On the pseudoscalar mass matrix. On t
The other matrix of the other mass matrix. On the other matrix of the other mass matrix. On the other mass mat A **natural** theory of EwsB is one where the *DILITOT QITTOTIS* 2 within a single term. In order to have a theory that is not fine-tuned, we would like the individual terms on the A **natural** theory of EWSB is one where there are **no large** *i* either a $\overline{}$ ľ **cancellations** either **among** terms in these equations or A natural theory of EWSB is one where the **UNINGHANDIS** CRICE **ANDIS** to have the individual terms on the induction on the induction on the induction on the induction o

In order to have a theory that is not fine-tuned, we would like the individual terms on the individual terms on the individual terms on the individual terms on the individual terms on the individual terms on the individu **Constrains:**

 $\begin{array}{c} \hline \end{array}$

right-hand side to be not much larger than the terms on the left-hand side. Recalling that $|\mu|^2$ $\leq m_\tau^2$ (hinneinne) $\big)$ *µ* $\overline{}$ າea $\ddot{}$ \mathbf{l} ⇠ *< m*² *Z m*² m^2 $\frac{2}{\sqrt{2}}$ $\frac{2}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $T_{\rm F}$ inns) (stops, gluinos via the loop term) since tan *>* 1 so that the Higgs that gets a VEV has a significant component in *H*⁰ B B (heavy Higgs and H_0 +/- $\Delta 0$) T_{ref} receives the least attention, although it has been discussed at times in tim $\begin{array}{c} \hline \end{array}$ *µ* $\overline{\mathbf{a}}$ $\begin{array}{c} \hline \end{array}$ 2 \sim $\lesssim m_Z^2$ $\left|m^2_{H_u}\right|$ $\overline{\mathbf{a}}$ $\overline{}$ $|\quad$ \sim $\lesssim m_Z^2$ $m_{\tilde{E}}^2$ H_d ~ $\leq m_Z^2 \tan^2 \beta$. (heavy Higgses *H^{0,+/-}, A⁰)* (higgsinos) (higgs) $M_U^2 = \left(m_{H_u}^2\right)$ $\int_{\text{tree}} + \left(m_{H_u}^2\right)$ $\big)_{\text{loop}} + |\mu|$ 2

h h Large quantum corrections to the Higgs mass² term, if the stops are heavy or highly mixed:

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

 $\sum_{i=1}^n$ (a.g. 1110. 6926. Panucci at al.) an external line, so we do include it was a loop want to include it when we compute it when $\frac{1}{2}$ renormalization of an external line, so we don't want to include it when we compute a loop amplitude. In we expect stops to be below about *s*12*...*(*n*1) want to avoid more t want to avoid more than a factor of 10 tuning (already not really natural!) (e.g. 1110.6926 Papucci et al.) 1*^µ* (2⇤*^µ* + *k^µ* We expect stops to be below about 500 to 700 GeV, if we

stop parameter space. I will come back to this in much We're already seeing significant constraints on the natural greater detail soon.

Naturalness and Gluinos we can use this correction to estimate this correction to estimate the mass of \mathcal{L} m˜b^R ! 3TeV. (10)

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! eed the stop to be relatively light for haturalitess or a
Lit with mass corrections dominated by the diagrams in the diagrams in the diagrams in figure 4:

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.

Electroweakinos?

Superpartners of Higgs and electroweak gauge bosons are relatively unconstrained; limits mostly in scenarios that inflate the branching fraction to leptons:

Naturalness predicts light Higgsinos, but direct production of Higgsinos at the bottom of the spectrum is hard to probe.

Stop Hunting

A long-term interest of mine, starting with hep-ph/0601124 with Patrick Meade on stop/neutralino simplified models:

° scalar and the signal for the signal for the left and and and $\frac{1}{2}$ on the challenge would be using subtle > 3σ, and < 3σ. The region mt′ − m^N < 200 GeV is not investigated. mass 700 GeV, N scalar, mass 400 GeV, (σ+, σ−) = (1.31, 1.01); at right, t challenge both theoretically and experimentally and experimentally. Still, there is a large region where S/B is Figure 5: Distribution of events in the (η+, η−) plane for two points with similar cross-section and the challenge would be using subtle angular differences like those at right to check their spin. is on average more boost, so the ellipse is stretched more along the ellipse is stretched more along the n+ axis. At the time, we were sure stops would be quickly discovered

The Unnatural Truth?

Our advocacy of simplified models has been vindicated. Our confidence in naturalness, less so. **Where are the stops?**

The Higgs looks SM-like

A low-energy theorem tells us stops correct Higgs couplings to gluons or photons:

$$
\mathcal{A}_{\tilde{t}-\text{loop}}(gg \to h) \propto \frac{\partial \log \det M_{\tilde{t}}^2}{\partial v} \sim y_t m_t \frac{\tilde{m}_Q^2 + \tilde{m}_u^2 - X_t^2 \sin^2 \beta}{\tilde{m}_Q^2 \tilde{m}_u^2 - X_t^2 m_t^2 \sin^2 \beta}
$$

For light enough stops, can only avoid a big correction via a sizable mixing term X_t . Implies tuning of the coupling.

For any pair of *physical* stop masses, there's a *maximum X_t.* (On the diagonal, $X_t = 0$: symmetric matrix with off-diagonal term will *always* have two unequal eigenvalues.)

So: robust bound on light stops.

Stop constraints

Dead minimum factor of ~5 tuning, even without using direct stop searches, gluino searches, etc. "Stealth" can only help so much. Most models much worse. ruled out by Higgs coupling measurements. The three shaded purple regions, from darkest to lightest, are excluded at 3

Direct Searches

As we've already seen, direct searches probe stops up to ~700 GeV. But they *assume* particular decay modes.

Two main roles for theorists in ensuring broader coverage:

- 1. Fill gaps in existing searches through better observables.
- 2. Propose new search channels and simplified models that cover more of model space.
- I'll give examples of both.

The Unnatural Truth?

Our advocacy of simplified models has been vindicated. Our confidence in naturalness, less so. **Where are the stops?**

Small fraction of top cross section: hard to neutralinos. The rate is normalized to the number of events with two isolated leptons. ∞ continue hard to cool Small fraction of top cross section: hard to see!

Spin Correlations

This is one case where subtle angular deviations could be key to discovery:

 $\mathbb{F}_{\mathbb{F}_{q^2}}$ *,* ⇤) for *tt* ¯ production, *t* ¯˜ production, and *tt* **turned on the diagonal rate of** $\mathcal{V}(0)$ **are factorized and decay are factorized and decay are factorized and decay factorized and we respect the second and we respect the second and we respect the second and we respect** σ helicities in between σ view of the point of the point of this variable, stops are essentially are essentially defined by σ GeV stops. (See also update from $\frac{900}{400}$ Z. Han, A. Katz, arXiv:1310.0356) GeV stops. (See also update from 200 Estimate of likelihoods for 200

Stops, being scalars, look a lot like tops with no spin correlations.

7 TeV Looks SM-Like. 8 or 13 TeV: Derive Bound?

Precision Top Cross Section

Czakon, Mitov, Papucci, Ruderman, Weiler 1407.1043

 \sim \pm \sim \sim \sim \sim \sim \sim If stops look top-like, why doesn't the top cross section rule them out?

zakon & Mitov) makes eorv. New NNL systematic uncertainty on \sim progress possible. e
List é t^L ^ê C K é \mathcal{W} The bottleneck was $\big($ é theory. New NNLO+NNLL c 1 (Czakon & Mitov) makes

Precision Top Cross Section

Czakon, Mitov, Papucci, Ruderman, Weiler 1407.1043

Alternative Stop Decays

It's important to close the "stealthy stop" window for stops near 200 GeV. (See also work in progress of Czakon, Mitov, Papucci, Ruderman, Weiler.)

Another option is that stops decay in a very different way and have been missed. Lots of recent attention on RPV stops, for example Brust, Katz, Sundrum 1206.2353:

RPV is **Option #1** of many ways to *hide naturalness.* All energy goes to visible particles.

Gluino Bounds in RPV

Can get events with many hard jets: background is QCD, but QCD usually doesn't share energy among jets so evenly.

ATLAS-CONF-2013-091 the 6-quark model and (b) the 10-quark model are shown.

Gluino Bounds in RPV

Gluino Bounds in RPV: Same-Sign Dilepton $\bigcap_{n=1}^{\infty}$ $\bigcap_{n=1}^{\infty}$

- $\tilde{g} \to \tilde{t}\bar{t}$, $\tilde{t} \to \bar{b}\bar{s}$ J. Berger, M. Perelstein, M. Saelim, or P. Tanedo 1302.2146
-

Recasts CMS SSDL+b-jets, $\frac{1212.6194.~\text{B}^2}{2}$ bounds again 1212.6194. Bounds again ~800 GeV.

It's hard to hide a gluino!

Hiding Naturalness SM

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*Q**

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*Z**

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*W**

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 $\tilde{ }$

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R

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Option 2: Langthen decay chains such that missing LEPenergy is reduced. LOSP "Lightest Ordinary SuperPartner" decays. Fig. 2: Thaing cuch that micring accay chains such that mosing **OSP** "Lightest Ordinary vers, some of which decay to some pairs.

q

q "Hidden Valley" (Strassler/ Zurek): divide energy among many particles

figure from M. Strassler, $\frac{1}{2}$ may be a particle may be a particle v-particle v-particle v-particle $\frac{1}{2}$ hop prijvoor roo hep-ph/0607160

LHC

Roughly divide MET by \overline{u} #(final state particles). is a v-hadron, its decay to the Sea also be interested in the Sea also lented in the LSvP may be a by one or more long-lived R-parity-even v-hadrons, pos-See also lepton jets, etc.

Hiding Naturalness

Option 3: Adjust masses so there's little phase space for decays.

 \diagdown

Compressed SUSY:

*i*sible particles release particies. A little artificial (tuned). softer visible particles.

<u>De USB recoil</u> sulting jets are matched to partons in the matrix-element event, *d*(parton*,* jet) *< Q*PS ("monojet"-like): Alwall, Le, Lisanti, est matrix-element parton are allowed. This procedure Wacker 0803.0019 Rely on ISR recoil

 $\Lambda \cdot$ Condial Λ ET to Ω by tuning $\Omega \cdot$ otill r A: Can dial MET to 0 by tuning; B: still nonzero MET. and smooth distributions for all \mathbf{a}

cancellation of the bino's *ET*. (B) shows how initial- or final-Also see Legomple & Martin, TT00.4504. Comples The matching parameters (*Q*ME specifia. Also see LeCompte & Martin, 1105.4304: compressed spectra.

Hiding Naturalness

Option 4: Decay chains with *more* invisible particles mean *less* visible energy. Need models w/ 3-body decays.

D. Alves, J. Liu, N. Weiner 1312.4965

Like the Hidden Valley case, get an O(1) reduction in MET.

Hiding MET with MET

Increasing the amount of missing energy significantly degrades the reach of current searches.

D. Alves, J. Liu, N. Weiner 1312.4965

Models that do this are straightforward to construct.

Stealth Supersymmetry

Option 5: A *mechanism* for suppressing missing ET — *not tuning it.*

J. Fan, MR, J. Ruderman 1105.5135, 1201.4875

\blacksquare schematic of the sectors in a general stead in a general stead in a general stead model. Flavor-blind mediation Supersymmetry can hide itself!

 t_{max} is a paramatric limit, biddon cootar Ω Have a *parametric* limit: hidden sector SUSY breaking → 0 as the splitting are such that splitting are such that the typical multiplicity is low, SUSY can still be typical multiplicity in \mathcal{S}^{U} and missing $ET \rightarrow 0$.

Stealth SUSY view) searches are now underway, hoping to discover en- $Cf \cap C$ cays of superpartners. A common feature of most SUSY in figure 1. We emphasize that the scenario requires q_{χ} special tuning of masses: the approximate degeneracy between *X* and *X*˜ is enforced by a symmetry: supersym-

- missing transverse energy as a strategy to reduce Stan-• A nearly-supersymmetric *R*-parity, *R*-parity, *R*-parity, *indden sector (small δ<i>m*)
- $\overline{}$ Droograps and $\overline{}$ new items SUSY models that preserve *R*-parity, yet lack missing enlightest visible sector *R*odd particle ("LOSP") is *forced* to decay to a ible and the sector portiolo there is a lighter state that is charged under *R*-parity. • Preserves *R*-parity: stealth sector particle.
- *R*-even stealth particles docay hack to SM abouy daoit to oivi additional possibility that the thermal possibility that the second second second second second second second s decay back to SM states.

reduced. We illustrate the spectrum, and decay path,

 \tilde{q} *B*

 $q \swarrow$

Natural SUSY? $H_{\rm{H}}$ *Department of Physics, Harvard University, Cambridge, MA 02138, USA*

Stealth SUSY gives us a **new set of simplified models** to consider for how a natural stop signal could arise:
 August 18, 2013 **1 Goals**

g an _. *W*,*Z*,*h*(⇤) It's important to look for these scenarios at the LHC to make sure we're not overlooking an important signal.

H˜ ⁺ Higgsinos may also be in the decay chain for tree-level naturalness.

LOSP Decay Chains

2.4 Stop Figure 1 Not a lot of missing energy, but tops, Higgs bosons, *Z* bosons: these are not hopeless signals!

Gluino Decay Chains

Simplified model. Scripts compute branching ratios. RH stop decays: roughly half t+neutralino, half b+chargino.

Choices for 2D plots:

- singlino @ 100 GeV,
- singlet @ 90 GeV
- stop halfway between higgsinos and gluino

Easily Implement Simplified Models (Will Make Public)

SLHA Decay Table *Fecay* 1000025 1.

BLOCK QNUMBERS 5000001 # singlino singlinobar

- 1 0 # 3 times electric charge
- 2 2 $\#$ number of spin states $(2S+1)$
- 3 1 # colour rep (1: singlet, 3: triplet, 6: sextet, 8: octet)
- 4 1 # Particle/Antiparticle distinction (0=own anti)
- BLOCK QNUMBERS 5000002 # singlet singletbar
	- 1 0 # 3 times electric charge
	- 2 1 $\#$ number of spin states (2S+1)
	- 3 1 # colour rep (1: singlet, 3: triplet, 6: sextet, 8: octet)
	- 4 1 # Particle/Antiparticle distinction (0=own anti)

BLOCK MASS

DECAY 1000025 1.00000000E-04 # chi0_2 decays

- 1.00000000E+00 2 5000001 23 # BR(chi0_2 -> Z singlino)
- 0.00000000E+00 2 5000001 25 # BR(chi0 2 -> h singlino)
- # ID Width
- DECAY 1000024 1.00000000E-04 # chi+_1 decays
- 1.00000000E-00 2 5000001 24 # BR(chi+_1 -> w+ singlino)
- # ID Width
- DECAY 5000001 1.00000000E-03 # singlino decays
- # BR NDA ID1 ID2
- 1.00000000E-00 2 5000002 1000022 # BR(singlino -> singlet axino) # ID Width
- DECAY 5000002 1.00000000E-03 # singlet decays
- # BR NDA ID1 ID2
- 1.00000000E-00 2 5 -5 # BR(singlet -> b b~)

Feed to Pythia with LHE gluino or stop pairs; it does the rest

 // Generator Pythia pythia;

 pythia.readString("PartonLevel:ISR = on"); pythia.readString("PartonLevel:FSR = on"); pythia.readString("PartonLevel:MPI = on"); pythia.readString("HadronLevel:Hadronize = on");

 // SLHA file pythia.readString("SLHA:readFrom = 2"); pythia.readString("SLHA:file = " + slhafile); pythia.readString("SLHA:useDecayTable = true");

 // Initialize LHE file run pythia.readString("Beams:frameType = 4"); pythia.readString("Beams:LHEF = " + lhefile);

Stealth SUSY Bounds

Work in progress with JiJi Fan, Rebecca Krall, David Pinner, Josh Ruderman: how much of natural stealthy SUSY survives?

Determining this requires "recasting": coding up searches and making validation plots like the one at left. (ATLAS 1308.1841)

Also using Drees et al. "CheckMATE" recasting tool (1312.2591).

Not many complete results to show you so far.

The tt sample is normalised to the cross section measured in situ in the same phase space. Only *toward Stealth SLISY Ston* other *t*¯*t* events, specifically those originating from decays via *t* leptons, are considered as background. The data are reasonably well described by the simulation, both for the low transverse Toward Stealth SUSY Stop Bounds

Preliminarily, some regions of gluino parameter space are ruled out, but direct stop production in these simplified models is hard to bound with current searches. Preliminarily some regions of aluino narameter space are the state state strightly in the seem in the seem the simulation in the seeding of the simulation of the set of the state of the st verified that the result of the result of the models is hard to hound with current searches.

Toward Stealth SUSY Stop Bounds

(b) $e + \text{jets}, p_\text{T} > 25 \text{ GeV}, 5\text{th jet}$

ATI AC 1407 0001. jot⁰ multipliqity 8 n= n $P\cap\mathsf{P}\sqcup\$ the total systematic and systematic and statistical uncertainties on the combined signal and background $\sum_{n=1}^{\infty}$ The errors bar on the bar on the black points and the statistical in the statistical uncertainty we state Events/Gev 10^2 $10³$ $10⁴$ \boldsymbol{p} ata tt W+jets Multijet Single top Z+jets Diboson <u>ይታተ⊨ይተተጋ∏ (ATAS</u> \overline{s} = 7 TeV **Reserve April 2018** to antiⁿk_, R=0.4 |η| < 2.5 µ+jets Events/GeV 10^2 \mathcal{C} ี่ 401 Data tt
W<u>+j</u>ets Multijet Single top Z∓jets Diboson AT4 GD ^{||} D d<mark>t4</mark>s s = 7 TeV anti k $_{\rm t}^{\rm l}$ R=0.4 lη**| ⊱2**.5 µ+jets ATLAS 1407.0891: jet multiplicity & pt distriputions in top pair production look very SM-like. Can use to bound new physics.

Stealth Gluino Constraints

Lots of *W* bosons: leptons and MET.

Ruled out to above 1 TeV! (Solid line: estimated exclusion; dashed line: conservative estimate by a factor of 2.)

ATLAS CONF 2013-061 Search with 3 b-jets

Lessons

Stops and higgsinos can still be hiding due to relatively small cross sections.

Gluinos are very hard to hide! Bounds typically near 1 TeV even for "hidden" scenarios. **Gluino reach will improve rapidly with 13 TeV data.**

The gluino bound already puts some strain on naturalness, but it's important to fill the gaps. **Stops could already be produced and hiding in data**. Look for a wider range of decays!

Many Roads to Naturalness

- Stops: RPV, stealth, "just around the corner"?
- Higgsinos: crucial for tree-level naturalness. But very hard to see directly if LSP. (Soft leptons + ISR jets or WBF?)
- Gluinos: key for two-loop naturalness, and are easy to see (even in RPV). None so far. Should show up at 13 TeV or…?
- Heavy Higgses: matter for tree-level naturalness. Can be decoupled at large tan beta, but very large tan beta is disfavored by $b \rightarrow s\gamma$ in natural theories. Not often discussed as a SUSY naturalness signature, but important!

Suggested Strategy

"Natural SUSY" often means a particular set of theories or simplified models: light stops and higgsinos, other squarks heavy, stable LSP. Signals involve missing energy.

But many different theories can be natural.

We should aim to have a **catalogue of "natural SUSY simplified models"** capturing the **diverse possible signals**. Stealth SUSY, RPV, "Hiding MET with MET," etc.

In Run 2, attention should be given to these nonminimal models: if we're going to rule out (or find!) naturalness, important not to have too strong a theory bias.

Summary

- LHC Run 1 has put some strain on naturalness
- Important to keep looking in the hiding places: squeezed regions; R-parity violation; decays with multiple invisible particles ("hiding MET with MET"); Stealth Supersymmetry models; Hidden Valleys; long lifetimes, displaced vertices
- Would be good to see a suite of these "hidden" natural SUSY" simplified models constrained in CMS and ATLAS publications

If time allows:

Natural SUSY and b→sγ M_{max} , we would M_{max} in front of tan. For the intervals of tan. For the intervals of the for each parameter that the correct of the correction of the correction of the correction of the correct of the corre *• m*˜*^t* cannot be too large because stops are needed for one-loop naturalness (canceling the top loop diverof *Hu* and thus are enhanced by a factor of tan relative to the Standard Model amplitude [43– $\frac{1}{2}$

• Katz, M. Reece, A. Sajjad 1406. I 172 *>* 100 GeV [21–24]. The LHC will potentially strengthen this constraint, although even Λ Kotz Λ ^d Roose Λ Coijod 1406 1170 λ in train, with the loop; λ is original theory in the parts of parts o A. Katz, M. Reece, A. Sajjad 1406.1172

Stops and higgsinos, key to naturalness, give a loop *correction to b→sγ. Attitude it reactions because it reactions to the gluino mass are gluino mass in the gluino mass in the gluino mass* μ particles; hence *^µ* ⇠ Stops and higgsinos, key to naturalness, give a loop t takes a value much smaller than the set of these loop corrections, the source of t

This superintenation with the measurement of the measurement of A_{μ} μ $M_{\tilde{t}:\tilde{h}}(b \to s\gamma) \sim m_t^2 \frac{1+\mu}{4} \tan \beta$ small (LEP direct constraint) Higgsino mass μ can't be too

> ⇥ $n₆$

ں
ِ σ (naturalness)

So: coefficient not too small!

Natural SUSY and b→sγ 1.100 1.000 1.000 1.000 200
200 *At* @GeVD

Maximum tan(β) from $b \rightarrow s\gamma$ [$\mu = 100 \text{ GeV}, M_3 < 0, \Lambda = 10 \text{ TeV}$]

In natural theories, it's hard to get tan beta to be large.

Bounding tan beta with $b \rightarrow s\gamma$ $\cap \rightarrow \subset V$ \prec *At* @GeVD

Figure 1: Construction is a lower planel to got tan potate to point got In natural theories, it's hard to get tan beta to be large.

SUSY Heavy Higgs Bosons large *m*² *^A*. We will also assume that the value of ¹ is chosen to fix the Higgs mass *m*² ed. JUJT T \overline{S} *@* log *M*² \boldsymbol{J} ⇡ $\overline{1}$ $\overline{}$ 2 \mathcal{A} \mathcal{A} *m*² *^A* + *m*² *h m*² + **1** \boldsymbol{J} YS DUSUIS

 ∂ $\log v^2$ $\partial \log M_d^2$ $\overline{\mathbf{I}}$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \hline \end{array}$ \longrightarrow tan $\beta \rightarrow \infty$ \overline{n} $\frac{1}{4} + 2m_h$ $+3m_{Z}^{2}$ *m*² *h* $2m_A^2 + 2m_h^2 + 3m_Z^2$ $\frac{n}{m_h^2 \tan^2 \beta}$.

e-tuning or very Barring fine-tuning or very low-scale mediation of SUSY breaking, the bound from b→sγ leads us to expect heavy Higgs bosons (*H*⁰*, A*⁰ *, H*+/-) near the TeV scale. Could be out of LHC reach, but **a large chunk of the natural parameter space is in reach!**

 $\begin{array}{c} \hline \end{array}$ $\overline{}$

More about *R*-parity violation

RPV has received a lot of attention recently in the context of natural SUSY (hiding superpartners from the LHC).

I think we should also be thinking about RPV *in the unnatural, mini-split SUSY context*. Removes the wino DM problem. Produce **winos**, which **decay**. How do they decay?

W_{RPV} = *u^cd^cd^c* has gotten a lot of recent attention (e.g. MFV RPV). Good for hiding from LHC searches (multi-jet signals).

I want to comment on an option that received less recent attention: bilinear RPV, with 2-body wino decays at the LHC.

(for older work: see hep-ph/9612447 by Mukhopadyaya and Roy; hep-ph/0410242 by Chun and Park; also, for 3-body decays in bilinear RPV, Graham, Kaplan, Rajendran, Saraswat, 1204.6038)

Bilinear RPV

If we violate *R*-parity by violating lepton number, can add $W_{LNV} =$ 1 2 $\lambda_{ijk}L_{i}L_{j}E_{k} + \lambda'_{ijk}L_{i}Q_{j}D_{k} + \epsilon_{i}\mu L_{i}H_{u}$

the bilinear term can be rotated away, but in general still have bilinear soft terms remaining:

$$
\mathcal{L}_{LNV} \supset -\left(B_{L_i\mu}\mu\tilde{L}_iH_u + \tilde{m}_{H_d,L_i}^2\tilde{L}_iH_d^\dagger + \text{h.c.}\right)
$$

In the mini-split context would guess $B_{L_i\mu} \mu$, $\tilde{m}_{H_d,L_i}^2 \sim \epsilon m_{3/2}^2$

Once the Higgs gets a VEV, these terms become sneutrino tadpoles, so the sneutrino gets a VEV:

 $\langle \tilde{\nu} \rangle \sim \epsilon v$

Sneutrino VEVs

The sneutrino VEV has several interesting consequences. Gauginos mix with leptons:

If winos are the LSPs, this will give them new decay modes:

$$
\tilde{W}^0 \to Z\nu, W^{\pm} \ell^{\mp}
$$

$$
\tilde{W}^{\pm} \to Z\ell^{\pm}, W^{\pm} \nu
$$

This would be a worthwhile search channel at the LHC. (Probably the lepton is mostly tau? Need flavor model.)

Bilinear RPV

Also get a contribution to neutrino masses:

This implies an upper bound $\epsilon \sim 10^{-6}$.

6 This gives a *lower* bound on the lifetime of the two-body wino decays, ~ 100 microns.* So should look for

$$
\tilde{W}^0 \to Z\nu, W^{\pm}\ell^{\mp}
$$
 with displaced vertices! (Possibly
\n
$$
\tilde{W}^{\pm} \to Z\ell^{\pm}, W^{\pm}\nu
$$
 macroscopically displaced;
\n**standard lepton ID may fail**.)

* Disclaimer: I haven't plugged in all order-one factors; hope to study this more carefully soon.