Light Stops from Seiberg Duality

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General

Moriond Electroweak:

- – Higgs
- – Flavor
- – Neutrinos
- – Precision SM
- – Stability of SM
  - SUSY, RS, Compositeness,…

- Easy to forget that they are all supposed to be related
- True model should explain everything
- That's why so challenging

- My first Moriond ε'/ε large m_t–>
- Last one: warped extra d
- Today—SUSY with light stop

Theory

- Explore alternatives
  - Data (what we see and don’t see) to give us clues
  - Model-building guides searches
- Ultimately complete and correct model
- Explain
  - Higgs sector
  - Stability of Higgs sector
  - Flavor
    - Quarks
    - Leptons

For example…

- RS:
  - Designed to solve hierarchy
  - But flavor and RS essential
    - And natural
- Bonus: Studies yield general lessons
  - Composite/elementary mixing
  - Anarchy—very general Yukawa coupling
- One test: θ_{13} (w/ Perez)
  - General terms:
  - No special relations among angles
  - Generic Yukawa (anarchy)
  - EXPECT not very suppressed mixing angle
  - Important as test of flavor ideas
    - Not just CP violation
- Also have potential to explain A_{CP}

JHEP 0901:077,2009.
arXiv:0805.4652

Yet Puzzle and Worry

- RS, SUSY (and most theories explaining hierarchy) want light spectra (~few hundred GeV)
- Experiments—both direct and indirect—point to heavier spectra
- Perhaps we are totally wrong
- Perhaps we are too simplistic

Challenges

- RS-models
  - Explain flavor amazingly well with low scale
  - Few TeV KK modes work due to wavefunction suppression
  - Even so, KK modes heavy
  - Higgs lighter
- Supersymmetry
  - Gluino, squark “heavy”
    - Pushes naturalness
  - Higgs mass
    - Pushes parameters
  - Indirect constraints
    - ***How to reconcile flavor, Higgs sector

What Data is Telling Us

- We need to search more creatively
- OR
- Current models not the answer

- Whether we like it or not,
- Data points to two-scales
- Necessarily more subtle models
- RS needs a bit of tuning or additional ingredient to explain light Higgs
  - PGB models
- SUSY's best implementation might involve split spectrum

- Rest of talk: focus will be supersymmetry
  - Among other things, people seemed surprised not yet found…

Insight: More Minimal Supersymmetric Model

Cohen Kaplan Nelson

- Introduces idea of split spectrum
- Ask what is essential for SUSY to protect hierarchy

✓ Simply control radiative corrections
  - Dominant ones involve stop
  - Light: stop, Higgs, gauginos

✓ Today: naturalness and constraints perhaps point to split spectrum with stop light others heavy

- Is this reasonable?
- Maybe! Top already distinguished
- Could there be connection between its heavier mass and differences in SUSY spectrum?

Top solves the puzzle?

- Key Observation:
  - Quarks really are different
    - Top much heavier
  - Maybe partners are too?

Compositeness?

- ✓ Potential to explain large top Yukawa and large top quark mass
  - Higgs and top composite
- ✓ Also of course, beautiful explanation of electroweak symmetry breaking
  - Solves hierarchy
  - Can be compositeness Higgs
- ✓ Gives natural additional scale
  - 10-100 TeV
- But
  - Potentially other flavor issues
    - RS has taught us that partial compositeness likely the solution
    - Mix with elementary
    - Alternative: think of large anomalous dimensions

Supersymmetry AND Compositeness?

- Overkill?
- But problems of two types of theories complementary
- Ideas already existing trying to combine ideas
- Seiberg duality AUTOMATICALLY HAS BOTH
  - At least existing examples
- Idea in Seiberg duality:
  - Strongly interacting theory has dual weakly coupled GAUGE description
  - One way to understand emergence of gauge bosons is through supersymmetry protecting gauge group away from Higgs stage

Use lessons from Seiberg duality and RS

- Composite SM interesting idea
- Seiberg duality realizes this possibility
- RS does too
  - More realistic in both cases is partial compositeness
    - Mixture of composite gauge bosons and elementary
    - Allows correct weak coupling
    - Also interesting flavor possibilities
      - In RS gauge bosons in the bulk
      - Also top composite
      - Others elementary
    - Also Higgs partially composite
      - Mixture of elementary and composite
      - Satisfies both Englert conditions

Meanwhile…

- New models of supersymmetric standard model
- Minimal composite model of Csaki, Shirman, and Terning
- Based on Seiberg duality, partial compositeness
- Naturally combines compositeness and supersymmetry
  - Entire model based on both
  - Supersymmetry essential to composite gauge bosons

Ingredients

- Seiberg duality
- Csaki, Shirman, Terning Minimal SUSY Composite Model
- Feed in supersymmetry breaking
  - On elementary side with interesting consequences on dual side

- Yields two-scale spectrum naturally
- Different experimental consequences

Seiberg Duality

- No details here
- Basic idea: strongly interacting theory might have realization in terms of perturbative composite theory
- In certain supersymmetric examples, Seiberg has shown what those theories are
- New gauge groups emerge and old ones disappear
  - Naturally includes both supersymmetry and compositeness
- Of interest to us will be a theory at the border of the conformal window

MCSSM: Minimal Composite Supersymmetric Standard Model

Csaki, Shirman, Terning

Electric Theory

	$SU(4)$	$SU(6)_1$	$SU(6)_2$	$U(1)_V$	$U(1)_R$
Q	$\square$	$\overline{\square}$	$\mathbf{1}$	1	$\frac{1}{3}$
$\bar{Q}$	$\overline{\square}$	$\mathbf{1}$	$\overline{\square}$	-1	$\frac{1}{3}$

Magnetic Theory

	$SU(2)_{\rm mag}$	$SU(6)_1$	$SU(6)_2$	$U(1)_V$	$U(1)_R$
q	$\square$	$\square$	$\mathbf{1}$	2	$\frac{2}{3}$
$\bar{q}$	$\overline{\square}$	$\mathbf{1}$	$\square$	-2	$\frac{2}{3}$
M	$\mathbf{1}$	$\overline{\square}$	$\overline{\square}$	0	$\frac{2}{3}$

Superpotential

$$W = y\bar{q}Mq \ .$$

So Model

- Small flavor symmetry
  - Not much composite—not even full 3rd generation
- Composite:
- – $\text{Stop}_{\text{right}}$
- – Q^3_{left}
- – Higgs
  - Composite Higgs mixes with Φ through conjugage field Φ'
- – EW gauge bosons
  - In fact partially composite
  - 2 SU(2)xU(1)s broken to one
    - Necessary for weak enough coupling
    - Necessary for elementary quark masses
- – Lots of heavy stuff at composite scale

Now With Supersymmetry Breaking

✓ A model that automatically matches data

✓ Naturally provides hierarchies

– Usual hierarchy: light Higgs
    - But Higgs mass not constrained so no MSSM-like naturalness issue even w125 GeV Higgs
    - Naturally accommodates 125 GeV Higgs

– Little hierachy: compositeness scale but supersymmetry keeps Higgs and others light

– Hierarchy in flavor: top heavier

– Hierarchy in SUSY spectrum: stop, gauge bosons and EW partners, Higgs are light

- Keep in mind model already existed
    - Not cooked up to match data

Key Result

- SUSY breaking communicated in very interesting way AUTOMATICALLY
- And leads to several categories of compelling experimental consequences
- For this particular phase,
- Supersymmetry breaking NOT TRANSFERRED TO COMPOSITE FIELDS at leading order
- Natural hierarchy in spectrum
  - Elementary fields big soft masses
  - Composite fields suppressed soft masses
  - NICE coincidence that top should be composite
    - For experts, opposite to what happens in single sector models
    - Supersymmetry transferred MORE to composites

Partial Understanding

(IR contribution symmetry argument not presented here)

- Assume SUSY breaking in electric UV theory
- Intuition from RS : composite IR degrees of freedom are insensitive to SUSY breaking, while elementary degrees of freedom (UV localized) experience SUSY breaking
- Composites get much bigger renormalization group running

$$m_{el}^2(\mu) = m_{UV}^2 \left(\frac{\mu}{\Lambda}\right)^{\mathcal{O}(\alpha)}$$

$$m_{comp}^2(\mu) = m_{IR}^2 + m_{UV}^2 \left(\frac{\mu}{\Lambda}\right)^{\gamma}$$

Well behaved weakly coupled Seiberg dual requires positive anomalous dimension of order one ; scales soft mass to zero
Remaining IR term has no ready interpretation but can be determined using holomorphy

Resulting Potential

$$W \supset yP(\mathcal{H}\bar{\mathcal{H}} - \mathcal{F}^2) + yS(H_u H_d - f^2) + yQ_3 H_u \bar{t} + y\mathcal{H}EX$$

$$V = y^2|H_u H_d - f^2|^2 + y^2|S|^2(|H_u|^2 + |H_d|^2) + m_S^2|S|^2 + m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2$$
$$+(ASH_u H_d + TS + h.c.) + \frac{g^2 + g'^2}{8}(|H_u|^2 - |H_d|^2)^2$$

- Two SU(2)s combine
- EWSB in SUSY limit
- Expect tanβ ~1
  - Good for heavier Higgs through singlet
  - Naturally acccommodates preferred value of ŠŞŜcalar Boson

Soft Masses for Composites: Vanish when 3N=2F

- Soft masses dimensionally suppressed $\mathcal{O}\left(m_{UV}^4/\Lambda^2\right)$
  - Don't run to deep IR
- Also corrections from perturbative SM running that can dominate when Λ large
- Also: $A = \mathcal{O}(\frac{m_{UV}^2}{\Lambda})$
- Gaugino masses for our model mixing with elementary significant
  - Elementary fields, gluino have big susy breaking masses $m_{el} \sim M_3 \sim \text{few} \cdot \text{TeV}$
  - Composite fields have small masses

$$m_{comp} \sim \frac{m_{el}^2}{\Lambda} \sim M_1 \sim M_2 \sim A \sim \text{few} \cdot 100 \text{ GeV}$$

SUSY Spectrum

- Elementary matter gets SUSY breaking mass
- Composite matter receives suppressed higher-dimensional or loop contributions
  - **Natural hierarchy in the spectrum**
  - **Exactly what is needed for natural SUSY**
- Composite superpartners are lighter
  - Stop, left-handed sbottom, Higgsinos, EW gauginos (in part due to coupling)
- Elementary partners are heavier
  - Squarks, gluino, sleptons, elementary Higgses
- Also NMSSM spectrum
  - Higgs heavy enough without heavy stop
- Perhaps what data and hierarchy point to:
  - few hundred GeV light superpartners still allowed

Key Distinguishing Experimental Features

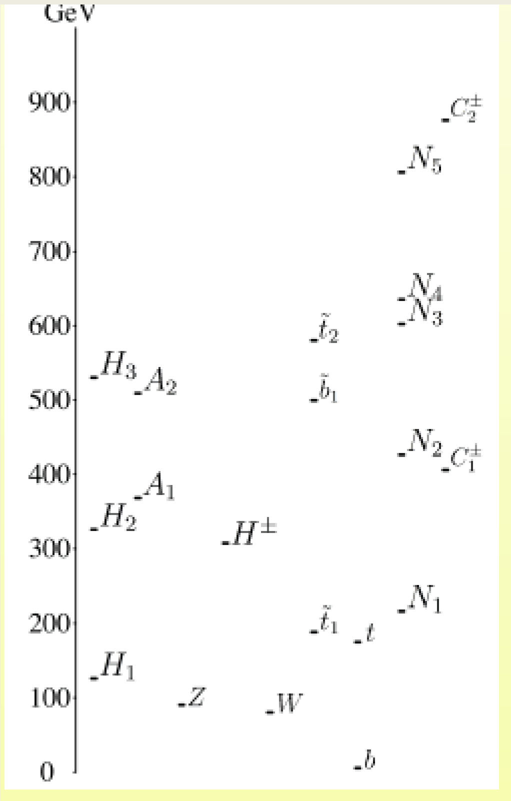
- More tops, bottoms than usual
- Reduced rates
  - Gluinos, light squarks heavy and not produced
- Possibility of stop NLSP
- Possibility of much less splitting in SUSY partners (when radiative)
- Possibility of stealth stop
  - Near degeneracy of top and stop

Several Possibilities: we consider four classes

- Stop1 nearly degenerate with top
- Light stop with few hundred GeV splitting and heavier neutralino
- Light neutralino from gauge mediation
- Light neutralino with high compositeness scale (mostly radiative contributions)

parameter	spectrum 1	spectrum 2	spectrum 3	spectrum 4
$\tan\beta$	0.85	1.3	1.0	0.97
A	300 GeV	540 GeV	350 GeV	400 GeV
T	4×10^7 GeV^3	1.4×10^7 GeV^3	3.35×10^7 GeV^3	6×10^6 GeV^3
$m_{Q_{33}}$	500 GeV	500 GeV	350 GeV	400 GeV
$m_{U_{33}}$	250 GeV	350 GeV	350 GeV	400 GeV
M_1	600 GeV	700 GeV	85 GeV	600 GeV
M_2	800 GeV	800 GeV	282 GeV	1200 GeV
m_S	400 GeV	350 GeV	350 GeV	100 GeV
M_{Sf}	0 GeV	−350 GeV	0 GeV	0 GeV
f	100 GeV	100 GeV	293 GeV	100 GeV

Spectrum I:
Stealth Stop



H_1	125 GeV	$\tilde{b}_1$	499 GeV
$\tilde{t}_1$	188 GeV	A_2	509 GeV
N_1	216 GeV	H_3	530 GeV
$H^\pm$	307 GeV	$\tilde{t}_2$	580 GeV
H_2	326 GeV	N_3	602 GeV
A_1	368 GeV	N_4	635 GeV
C_1	406 GeV	N_5	805 GeV
N_2	426 GeV	C_2	876 GeV

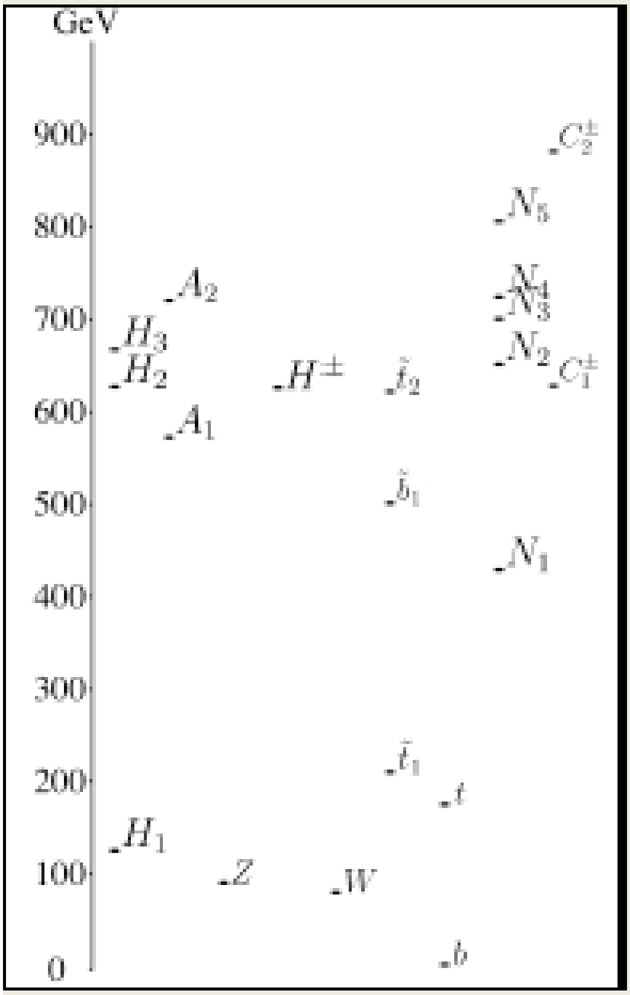
Light stop, nearly degenerate with top,
Light neutralino-not quite as light
Sbottom, other stop 500 GeVish
Aside from gauginos, all else heavy

Phenomenology of stealth stop

$\tilde{t}_1$	$\rightarrow t + LSP$	100%
C_1	$\rightarrow \tilde{t}_1 + b^{\dagger}$	84%
C_1	$\rightarrow N_1 + W^{\pm}$	16%
$\tilde{b}_1$	$\rightarrow \tilde{t}_1 + W^{-}$	97%
$\tilde{b}_1$	$\rightarrow \tilde{t}_1 + H^{-}$	3%
$\tilde{t}_2$	$\rightarrow \tilde{t}_1 + Z$	51%
$\tilde{t}_2$	$\rightarrow t + N_1$	27%
$\tilde{t}_2$	$\rightarrow b + C_1^{+}$	11%
$\tilde{t}_2$	$\rightarrow \tilde{t}_1 + H_1$	10%

- Apparent change in top cross section 10% (15 pb)
- Sbottom (heavier stop) cross section 10 fb : tt WW
  - Like sign leptons (with b tags)
- Stop: tt ZZ, tt bb W W
- Possible Chargino/Neutralino signal
  - Chargino: stop1 b, N1 W*
- Possible displaced vertex (depends on susy breaking)

Spectrum 2:
Stop NLSP but not stealthy



H_1	125 GeV	C_1	628 GeV
$\tilde{t}_1$	210 GeV	N_2	651 GeV
N_1	429 GeV	H_3	667 GeV
$\tilde{b}_1$	501 GeV	N_3	700 GeV
A_1	572 GeV	A_2	720 GeV
$\tilde{t}_2$	621 GeV	N_4	724 GeV
$H^\pm$	626 GeV	N_5	806 GeV
H_2	627 GeV	C_2	881 GeV

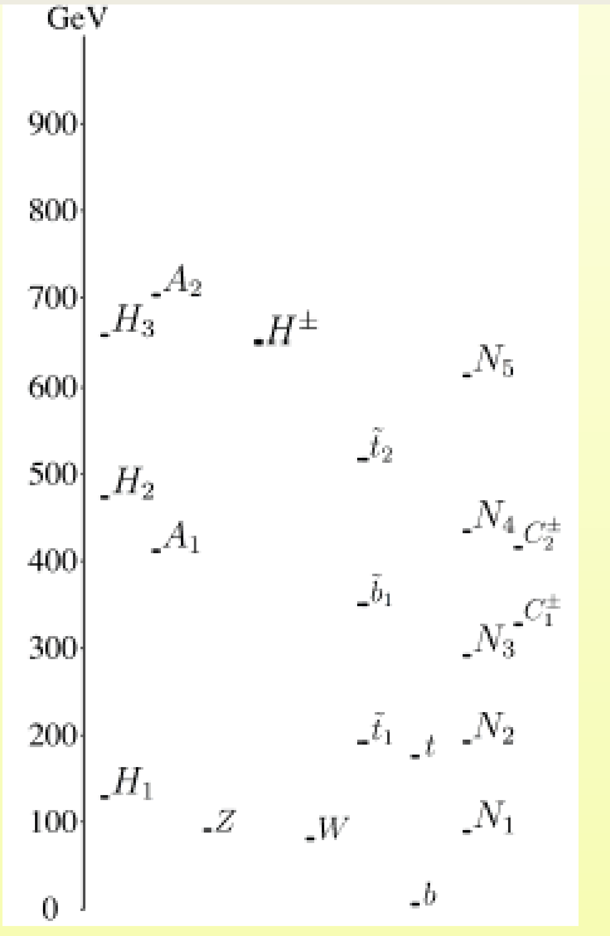
Light fields are heavier
Stop, Neutralino, stop/bottom; new N1 decay modes

Phenomenology of Heavier Stop NLSP

$\tilde{t}_1$	$\to t + LSP$	100%
N_1	$\to t + \tilde{t}^*$	50%
N_1	$\to \bar{t} + \tilde{t}$	50%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	100%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	78%
$\tilde{t}_2$	$\to \tilde{b}_1 + W^+$	14%
$\tilde{t}_2$	$\to \tilde{t}_1 + H_1$	8%

- Stop has same decay
  - Reduced cross section 8 pb (5% top)
  - Still not much missing energy
- Sbottom as before: tt WW
- Heavier stop as before: ttZZ, others (new)
- N1->tt final state (small missing energy)

Spectrum 3: Gauge mediation and neutralino LSP



N_1	88 GeV	C_2	415 GeV
H_1	128 GeV	N_4	434 GeV
$\tilde{t}_1$	191 GeV	H_2	473 GeV
N_2	192 GeV	$\tilde{t}_2$	517 GeV
N_3	291 GeV	N_5	613 GeV
C_1	327 GeV	$H^\pm$	650 GeV
$\tilde{b}_1$	350 GeV	H_3	657 GeV
A_1	412 GeV	A_2	702 GeV

Standard in some respects
Neutralino NLSP (assuming gauge mediation)
But reduced cross sections
Still light stops, others heavy

Phenomenology

$\tilde{t}_1$	$\to N_1^+ + b + W^+$	100%
$\tilde{b}_1$	$\to N_3 + b$	80%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	95%
$\tilde{b}_1$	$\to N_3 + b$	4%
$\tilde{b}_1$	$\to N_1 + b$	1%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	42%
$\tilde{t}_2$	$\to \tilde{b}_1 + W^+$	31%
$\tilde{t}_2$	$\to N_2 + t$	10%
$\tilde{t}_2$	$\to C_2^+ + b$	8%
$\tilde{t}_2$	$\to N_1 + t$	4%
$\tilde{t}_2$	$\to C_1^+ + b$	3%
$\tilde{t}_2$	$\to N_3 + t$	2%

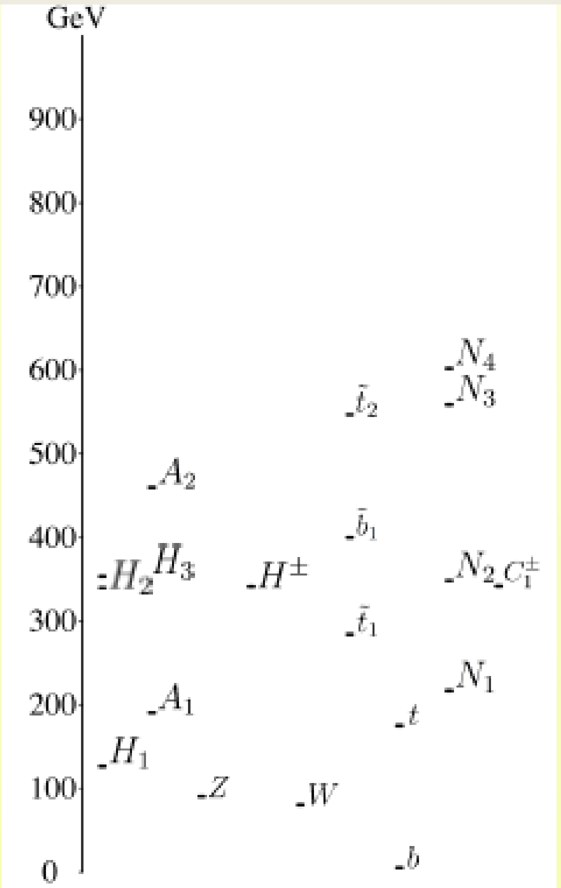
- N1->γ + gravitino (missing energy)
- Stop->t*+ N1
- Stop2->Stop+Z,sbottom +W, N+t,

C+b, jet+missing energy (t) (W)

Gauge mediation-like and reduced rates

Extra tops and Ws

Spectrum 4: Neutralino (N)LSP from High Duality Scale



H_1	126 GeV	N_2	348 GeV
A_1	190 GeV	H_3	353 GeV
N_1	217 GeV	$\tilde{b}_1$	400 GeV
$\tilde{t}_1$	284 GeV	A_2	460 GeV
H_2	339 GeV	$\tilde{t}_2$	546 GeV
$H^{\pm}$	341 GeV	N_3	559 GeV
C_1	341 GeV	N_4	602 GeV

Contributions to composite soft masses from radiative corrections,
Not from higher-dimension operators
Higgs likely to be naturally lighter since soft mass terms smaller

Phenomenology of Spectrum 4

t1->N1+b+W*

$\tilde{b}_1$	$\rightarrow \tilde{t}_1 + W^-$	100%
$\tilde{t}_2$	$\rightarrow \tilde{t}_1 + Z$	28%
$\tilde{t}_2$	$\rightarrow C_1^+ + b$	24%
$\tilde{t}_2$	$\rightarrow \tilde{b}_1 + W^+$	20%
$\tilde{t}_2$	$\rightarrow N_2 + t$	15%
$\tilde{t}_2$	$\rightarrow N_2 + t$	14%

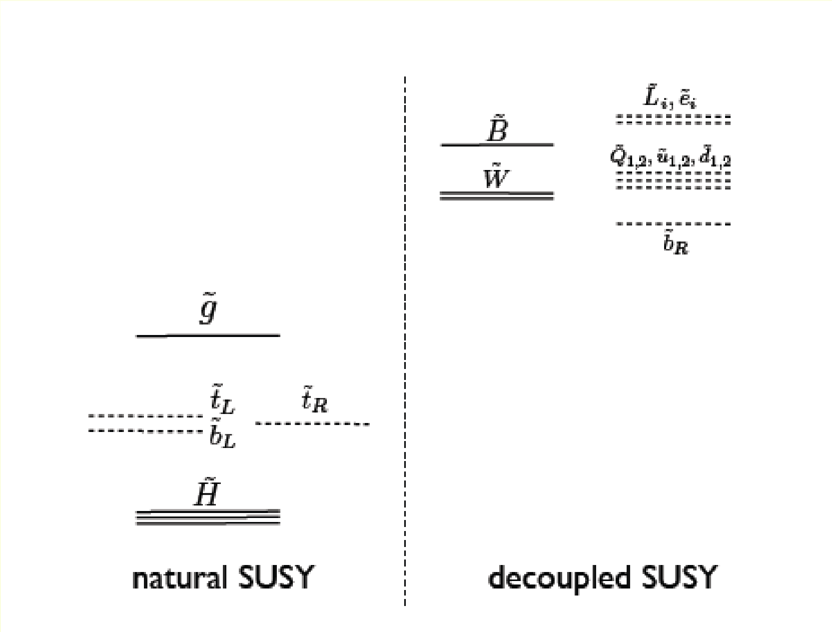
- stop->N+t* (N b W*) (4 body decay first kinematically allowed)
- Stop2->stop1+z, C+b, sbottom+W, N+t
- Sbottom->stop1+W
- Like standard SUSY in some respects at reduced rates

Conclusion

- Does supersymmetry explain hierarchy?
- Looks like more elaborate version called for involving two scales
- Searches possibly dominated by light stops, sbottoms
  – Here a rather natural model
  – Other suggestions in literature
- Important to investigate
  – Range of models
  – Range of experimental signatures
  – Note most such models have heavy gluinos so recent ATLAS mostly relevant for sbottom bound
  – But much more to come

The bounds on natural SUSY: naturalness

(Papucci, Ruderman, Weiler ’11)



Below TeV scale

Above TeV scale

Gluino and Winos not as clear-cut: gluino could be heavier, while wino definitely below TeV...

Resulting Potential

$$W \supset yP(\mathcal{H}\bar{\mathcal{H}} - \mathcal{F}^2) + yS(H_u H_d - f^2) + yQ_3 H_u \bar{t} + y\mathcal{H}EX$$

$$V = y^2|H_u H_d - f^2|^2 + y^2|S|^2(|H_u|^2 + |H_d|^2) + m_S^2|S|^2 + m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2$$
$$+(ASH_u H_d + TS + h.c.) + \frac{g^2 + g'^2}{8}(|H_u|^2 - |H_d|^2)^2$$

$$T = \mu_f \Lambda \left(-\frac{16\pi^2 m_\lambda}{bg^2} - \frac{2(2F - 3N)}{3N - F} B \right)$$

$$T \sim \mu_f \Lambda \times m_{UV}$$ ~f^2 mUV

Because mufvchosen to give EW symmetry breaking
and gaugino mass (muv) is of same size,
T has roughly EW scale in the end

Phases of Seiberg Duality

5.3. Duality

The physics of the interacting fixed point obtained for the range $\frac{3}{2}N_c < N_f < 3N_c$ has an equivalent, "magnetic," description [8]. It is based on the gauge group $SU(N_f - N_c)$, with N_f flavors of quarks q_i and $\tilde{q}^{\tilde{i}}$ and gauge invariant fields $M^i_{\tilde{j}}$ with a superpotential

$$W = \frac{1}{\mu} M^i_{\tilde{j}} q_i \tilde{q}^{\tilde{j}}. \qquad (5.5)$$

The magnetic theory has a scale $\widetilde{\Lambda}$ which is related to the scale Λ of the electric theory by

$$\Lambda^{3N_c - N_f} \widetilde{\Lambda}^{3(N_f - N_c) - N_f} = (-1)^{N_f - N_c} \mu^{N_f}, \qquad (5.6)$$

$N_c + 2 \leq N_f \leq \frac{3}{2} N_c$ non-Abelian free magnetic

$SU(N_f - N_c)$ gauge fields

We are at border; free magnetic phase but calculable using electric-magnetic duality

Embedding

$$q = Q_3, \mathcal{H}, H_d$$
$$\bar{q} = X, \bar{\mathcal{H}}, H_u$$

Third generation quark doublet, Higgses, and bifundamentals (that combine SU(2)xU(1)s)

$$M = \begin{pmatrix} V & U & \bar{t} \\ E & G+P & \phi_u \\ R & \phi_d & S \end{pmatrix}$$

V is 3 QCD antitriplets
U is a (3,2)
E is 3 doublets
G is SU(2) triplet
Φu and Φd are doublets
P and S are singlets, and R yields 3 singlets

Net Content

- Anomaly cancellation and invariance of superpotential determines hypercharge assignment

$$\pm\mathrm{diag}(\tfrac{1}{6},\tfrac{1}{6},\tfrac{1}{6},0,0,-\tfrac{1}{2}) \text{ for } q,\bar{q}$$

	Q_3	$\mathcal{H},\bar{\mathcal{H}}$	H_u	H_d	X	V	U	$\bar{t}$	E	ϕ_u	R	ϕ_d	G,P,S
Y	$\frac{1}{6}$	0	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{6}$	0	$-\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{6}$	$-\frac{1}{2}$	$\frac{2}{3}$	$\frac{1}{2}$	0

P, S only true singlets: more on that later
Need elementary gauge symmetries to be anomally free:
V', U', Pu', R', Pd' →yield masses with conjugate fields (through dim 3 ops in electric superpotential)
X, E, P, S at low energy: X a singlet P a doublet
-> W/remaining SM fermions anomaly free
Yukawa term eliminates E and X from spectrum

Superpotential

$$W \supset yP(\mathcal{H}\bar{\mathcal{H}} - \mathcal{F}^2) + yS(H_u H_d - f^2) + yQ_3 H_u \bar{t} + y\mathcal{H}EX$$

- This is still supersymmetric limit
  - Yukawas from duality
    - Note relation mu term and top mass
  - Tadpoles from assumed mass terms in electric theory
    - Note P, S only singlets so only such terms allowed
- Breaks two SU(2)s to single one
- Gives Higgs VEV
- Full answer depends on supersymmetry breaking

Supersymmetry Breaking

- When supersymmetry breaks and communicated above compositeness scale, need to derive SUSY masses from initial electric theory
- Use analytic continuation into superspace

- Note superpotential is Yukawa term and any term that matches from electric theory
- Plus these supersymmetry breaking terms

Derivation of m^2_{IR}

- Use real and chiral spurions Z and U with nonzero theta

$$
\begin{aligned}
Z &= 1-\theta^2 B-\bar{\theta}^2 B-\theta^2\bar{\theta}^2(m_{UV}^2-|B|^2)\\
U &= \frac{1}{2g^2}-i\frac{\theta_{YM}}{16\pi^2}+\theta^2\frac{m_\lambda}{g^2}\ ,
\end{aligned}
$$

$$\Lambda_h = \mu\, e^{-16\pi^2 U(\mu)/b}$$

$$b = 3N - F$$

$N = 4$ and $F = 6$.

$$\mathcal{L} = \int d^4\theta\,(Q^\dagger Z e^V Q + \bar{Q}^\dagger Z e^V \bar{Q}) + \int d^2\theta\,(U W^\alpha W_\alpha + \mu_f \bar{Q} Q) + h.c.$$

We now incorporate an anomalous U(1)
Z and U are spurions of the U(1) as well
Let us match dependence in electric and magnetic theories

More on derivation

U(1):

$$Q \to e^{A} Q \,, \qquad \bar{Q} \to e^{A} \bar{Q}$$
$$Z \to e^{-A-A^\dagger} \,, \qquad \Lambda_h \to e^{2F/b\,A} \Lambda_h$$

Define invariant that can be used to compensate dimensions:

$$\Lambda^2 = \Lambda_h^\dagger Z^{2F/b} \Lambda_h$$

Also a spurion

$$\log \frac{\Lambda}{\mu} = \frac{-8\pi^2}{bg^2} + \frac{-8\pi^2 m_\lambda}{bg^2}(\theta^2 + \bar{\theta}^2) - \frac{F}{b} m_{UV}^2 \theta^2 \bar{\theta}^2$$

$$\begin{aligned} \mathcal{L} \;=\; & \int d^4\theta \left[\frac{M^\dagger Z^2 M}{\Lambda^2} + \frac{q^\dagger Z^{N/(F-N)} e^{\tilde{V}} q}{\Lambda^{(4N-2F)/(F-N)}} + \frac{\bar{q}^\dagger Z^{N/(F-N)} e^{\tilde{V}} \bar{q}}{\Lambda^{(4N-2F)/(F-N)}} \right] \\ & + \int d^2\theta \left[U \widetilde{W}^\alpha \widetilde{W}_\alpha + \frac{y\, M q \bar{q}}{\Lambda_h^{b/(F-N)}} + \mu_f M \right] + h.c. \end{aligned}$$

Uses IR perturbativity, SUSY invariance, U(1) invariance, dimensional analysis

Higgs Potential w/SUSY Breaking

•The relevant part of the Higgs potential:

$$V = y^2|H_uH_d - f^2|^2 + y^2|S|^2(|H_u|^2 + |H_d|^2) + m_S^2|S|^2 + m_{H_u}^2|H_u|^2 + m_{H_d}^2|H_d|^2$$
$$+(ASH_uH_d + TS + h.c.) + \frac{g^2 + g'^2}{8}(|H_u|^2 - |H_d|^2)^2$$

- Usual quartic
- BUT additional NMSSM like piece
  - With big coupling
  - Related to top Yukawa
- Not MSSM potential though
  - tanβ can be about unity
    - And probably is
  - EW symmetry broken in SUSY limit
  - f determines SUSY breaking
    - Higgs mass not related to Z mass
    - But f is input parameter

Higgs Sector

Usual:
But tan beta~1

$$\langle H_u^0 \rangle = \frac{v}{\sqrt{2}} \sin\beta \,, \qquad \langle H_d^0 \rangle = \frac{v}{\sqrt{2}} \cos\beta$$

Determines mu parameter (with top Yukawa)

$$\langle S \rangle = -\frac{\sqrt{2}\,(\mathrm{A} v^2 \sin\beta\cos\beta + 2T)}{2M_S^2 + y^2 v^2}$$

But not so relevant to vacuum

$$\frac{y^2 v^2}{2} = \frac{2(y^2 f^2 - AS)}{\sin 2\beta} - 2y^2 S^2 - m_{H_u}^2 - m_{H_d}^2$$

Very little tuning

$$\frac{y^2 v^2}{2 m_{H_u}^2}$$

Gluino mass not so constrained by Higgs mass

$$\Delta m_{\tilde{t}} \sim \frac{32}{3}\frac{\alpha_s}{4\pi}|M_3|^2 \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$$

More in our model to keep stop light
(1.5 TeV still very natural)

Particle Content

- With relatively small flavor group, only one generation (and only quarks at that) participate in duality
  - Quarks and antiquarks transforming under SU(2)
  - $SU(3)_C$ is part of the global symmetry
  - There are also electric SU(2) and U(1) embedded in SU(6) to make model partially composite

Soft Masses Vanish when 3N=2F

$$m_M^2 = 2\frac{3N-2F}{b} m_{UV}^2 \ , \qquad m_q^2 = -\frac{3N-2F}{b} m_{UV}^2$$

Generally bad
Some masses tachyonic
Except special case 3N=2F
At edge of conformal window
Leading order soft masses vanish there

Also:

$$m_{\bar{\lambda}} = -\frac{3N-2F}{3N-F} m_\lambda$$

Also soft mass:

To get the soft terms that come from the superpotential couplings we must rescale the fields to get canonical Kähler terms. Since we need terms only of order θ^2 we can write

$$Z = \xi^\dagger \xi \ , \qquad \xi = 1 - \theta^2 B \tag{2.18}$$

and then rescale chiral fields only via the holomorphic quantities ξ, Λ_h. We then find the superpotential terms in the canonical basis:

$$\int d^2\theta \left(y\, Mq\bar{q} + \mu_f \Lambda_h M \xi^{\frac{2(2F-3N)}{(3N-F)}} + h.c. \right) \tag{2.19}$$

Since the cubic superpotential is independent of the supersymmetry breaking spurions, we find that the A-term vanishes in the IR limit for any F:

Soft Masses

- Strong dynamics are close to conformal
  - Guarantees masses of composite superpartners vanish at leading order
    - Assumes soft susy breaking generated above confinement scale
  - Elementary fields, gluino have big susy breaking masses

$$m_{el} \sim M_3 \sim \text{few} \cdot \text{TeV}$$

  - Composite fields have small masses

$$m_{comp} \sim \frac{m_{el}^2}{\Lambda} \sim M_1 \sim M_2 \sim A \sim \text{few} \cdot 100 \text{ GeV}$$