

A Composite Light Stop

John Terning UC Davis

Csaba Csaki and Lisa Randall hep-ph/1201.1293

Outline

Motivation

Seiberg Duality

Composite Models

Composite SUSY Breaking

Light Stop

Conclusion

Discovering Hierarchies

SPS: W, Z \rightarrow gauge hierarchy

LEP: no light Higgs \rightarrow little hierarchy

Tevatron: top \rightarrow Yukawa hierarchy

LHC: no light SUSY \rightarrow squark mass hierarchy

Discovering Hierarchies

SPS: W, Z \rightarrow gauge hierarchy

LEP: no light Higgs \rightarrow little hierarchy

Tevatron: top \rightarrow Yukawa hierarchy

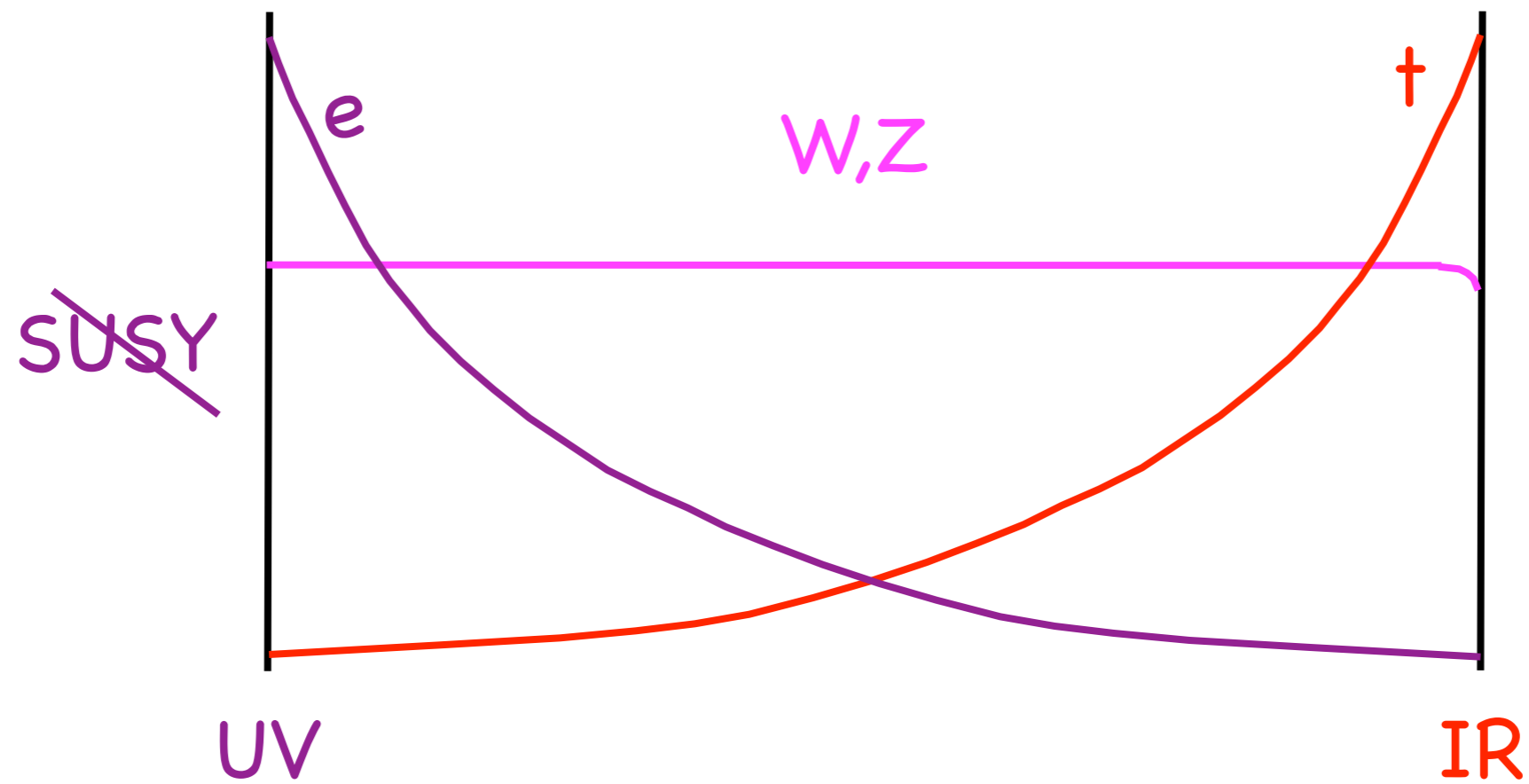
LHC: no light SUSY \rightarrow squark mass hierarchy

Minimal Composite SSM

can resolve all these

hierarchy problems

Realistic SUSY RS



SUSY QCD

	$SU(N)$	$SU(F)$	$SU(F)$	$U(1)_B$	$U(1)_R$
Q	\square	\square	$\mathbf{1}$	1	$\frac{F-N}{F}$
\bar{Q}	$\bar{\square}$	$\mathbf{1}$	$\bar{\square}$	-1	$\frac{F-N}{F}$

$$Q_i = (\phi_i, \psi_i)$$

$$\bar{Q}_i = (\bar{\phi}_i, \bar{\psi}_i)$$

Dual Theory

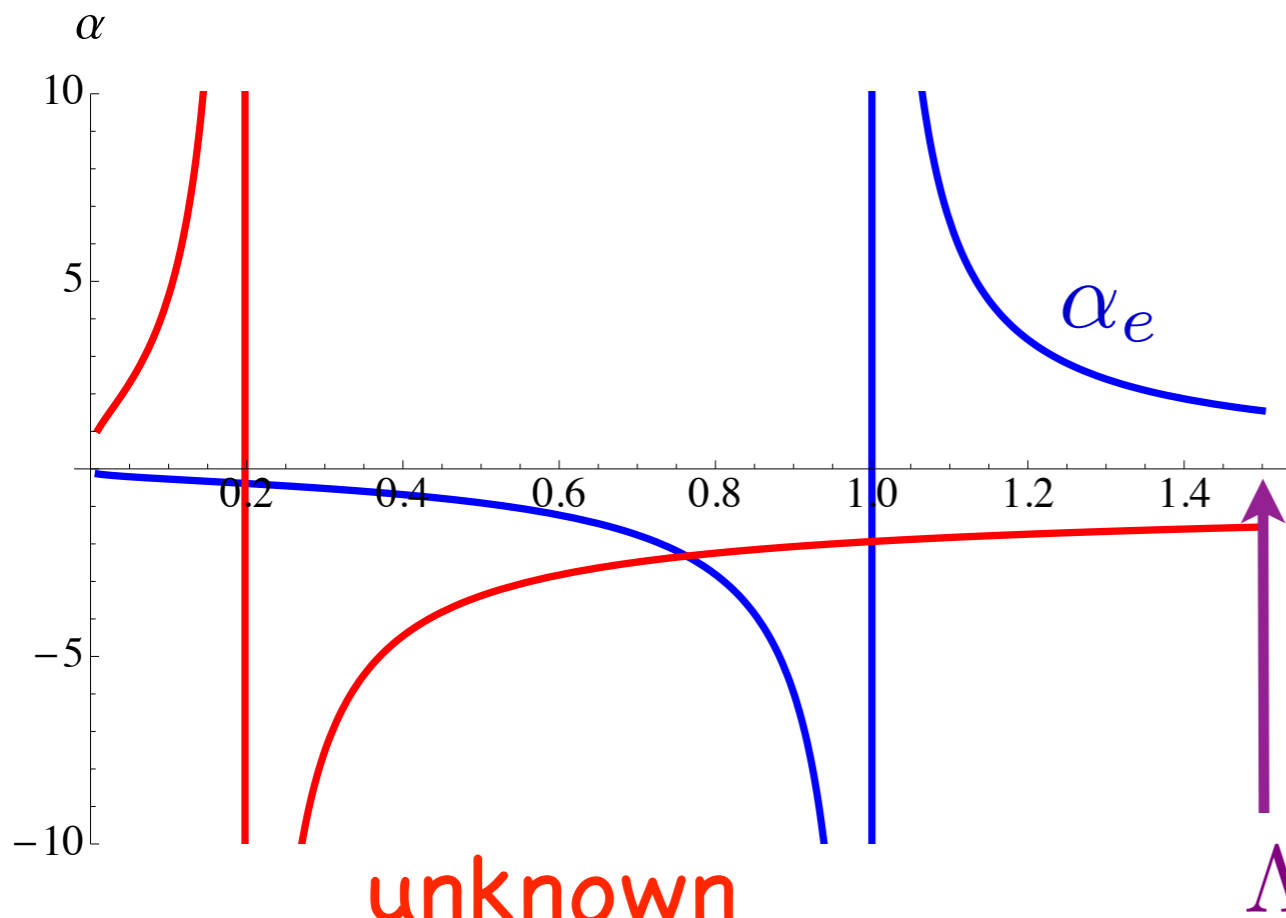
	$SU(F - N)$	$SU(F)$	$SU(F)$	$U(1)$	$U(1)_R$
q	\square	$\bar{\square}$	$\mathbf{1}$	$\frac{N}{F-N}$	$\frac{N}{F}$
\bar{q}	$\bar{\square}$	$\mathbf{1}$	\square	$-\frac{N}{F-N}$	$\frac{N}{F}$
M	$\mathbf{1}$	\square	$\bar{\square}$	0	$2\frac{F-N}{F}$

$$W = \frac{\tilde{M} q \bar{q}}{\Lambda}$$

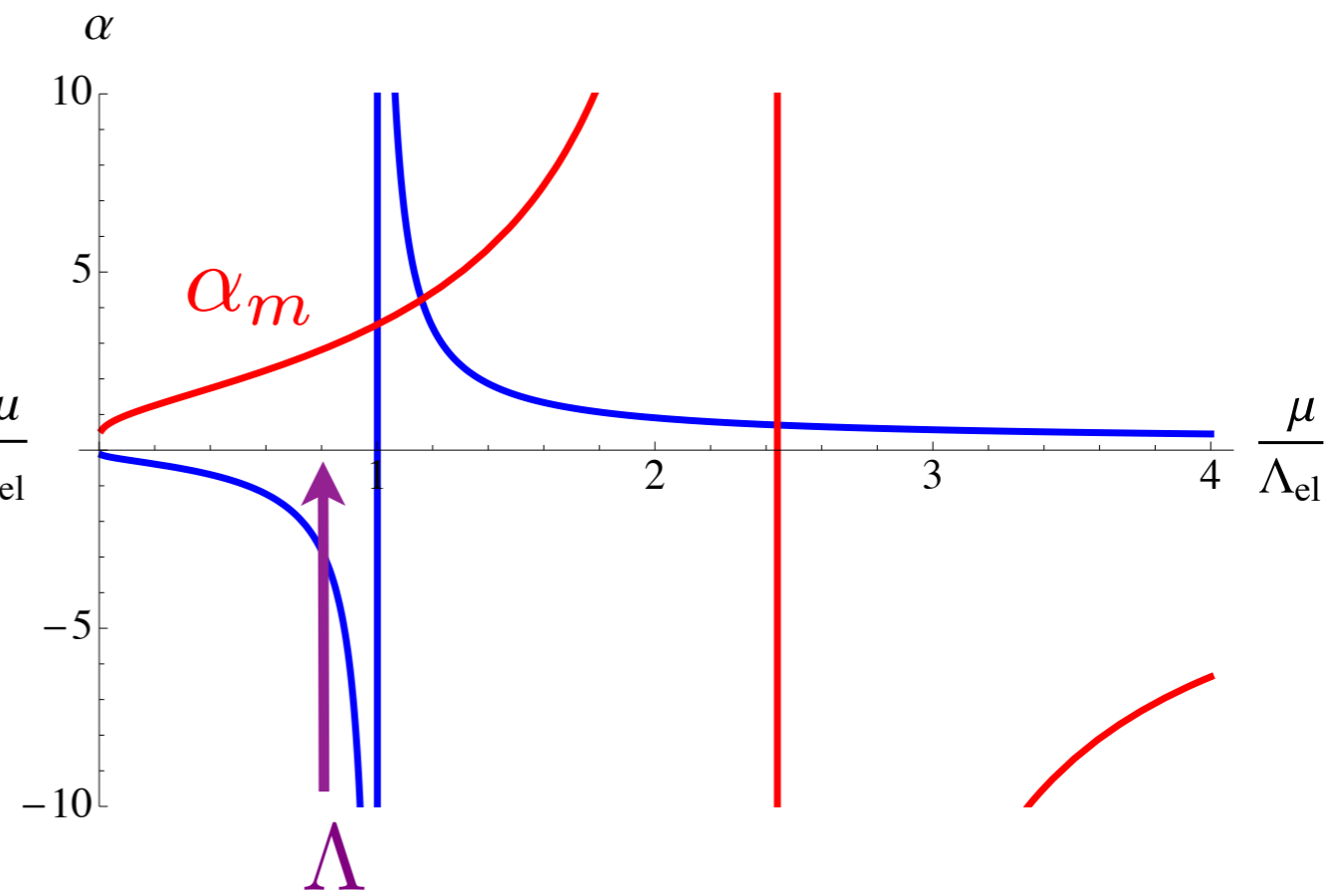
$$\Lambda_{\text{el}}^{b_{\text{el}}} \Lambda_{\text{mag}}^{b_{\text{mag}}} = (-1)^N \Lambda^{b_{\text{el}} + b_{\text{mag}}}$$

Dual Gauge Coupling

$$\frac{1}{g_{\text{el}}^2(|\Lambda|)} = \frac{b_{\text{el}}}{8\pi^2} \log\left(\frac{|\Lambda|}{\Lambda_{\text{el}}}\right) = -\frac{b_{\text{mag}}}{8\pi^2} \log\left(\frac{|\Lambda|}{\Lambda_{\text{mag}}}\right) = -\frac{1}{g_{\text{mag}}^2(|\Lambda|)}$$



unknown
strong dynamics



Yukawa Landau pole

Dual Theory

$$W = \frac{\tilde{M} q \bar{q}}{\Lambda}$$

$$\tilde{M} = M \Lambda_{\text{el}}$$

$$W = y M q \bar{q}$$

$$y = \frac{\Lambda_{\text{el}}}{\Lambda} < 4\pi$$

Magnetic Coupling

$$y = \frac{\Lambda_{\text{el}}}{\Lambda} < 4\pi$$

$$g_{\text{mag}}^2(\Lambda_{\text{el}}) > \frac{8\pi^2}{F \log(4\pi)} \approx \frac{31}{F}$$

realistic dual for SM gauge groups
need to mix with weakly coupled gauge group

Electric Theory

	$SU(6)$	$SU(8)_1$	$SU(8)_2$	$U(1)_V$	$U(1)_R$
Q	\square	$\bar{\square}$	$\mathbf{1}$	$\frac{1}{24}$	$\frac{1}{4}$
\bar{Q}	$\bar{\square}$	$\mathbf{1}$	$\bar{\square}$	$-\frac{1}{24}$	$\frac{1}{4}$

Dual Theory

	$SU(2)_L$	$SU(8)_1$	$SU(8)_2$	$U(1)_V$	$U(1)_R$
q	\square	\square	$\mathbf{1}$	$\frac{1}{8}$	$\frac{1}{4}$
\bar{q}	$\bar{\square}$	$\mathbf{1}$	\square	$-\frac{1}{8}$	$\frac{1}{4}$
M	$\mathbf{1}$	$\bar{\square}$	$\bar{\square}$	0	$\frac{3}{2}$

$$W = y M q \bar{q}$$

$$SU(8)_1 \supset SU(3) \times SU(3) \times SU(2)_{R,1}$$

$$SU(8)_2 \supset SU(3)_G \times SU(3) \times SU(2)_{R,2}$$

Dual Theory

	$SU(2)_L$	$SU(8)_1$	$SU(8)_2$	$U(1)_V$	$U(1)_R$
q	\square	\square	$\mathbf{1}$	$\frac{1}{8}$	$\frac{1}{4}$
\bar{q}	$\bar{\square}$	$\mathbf{1}$	\square	$-\frac{1}{8}$	$\frac{1}{4}$
M	$\mathbf{1}$	$\bar{\square}$	$\bar{\square}$	0	$\frac{3}{2}$

$$q = \begin{pmatrix} t_n \\ b_n \end{pmatrix}_L, \begin{pmatrix} c_n \\ s_n \end{pmatrix}_L, H_u, H'_d$$

$$\bar{q} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L, \begin{pmatrix} u_n \\ d_n \end{pmatrix}_L, H_d, H'_u$$

Csaki, Shirman, JT hep-ph/1106.3074

Dual Theory

	$SU(2)_L$	$SU(8)_1$	$SU(8)_2$	$U(1)_V$	$U(1)_R$
q	\square	\square	$\mathbf{1}$	$\frac{1}{8}$	$\frac{1}{4}$
\bar{q}	$\bar{\square}$	$\mathbf{1}$	\square	$-\frac{1}{8}$	$\frac{1}{4}$
M	$\mathbf{1}$	$\bar{\square}$	$\bar{\square}$	0	$\frac{3}{2}$

$$M = \begin{pmatrix} & & & & \bar{\nu}_e & \bar{e} \\ & V_n^{1,j} & & V_n^{2,j} & \bar{\nu}_\mu & \bar{\mu} \\ & & & & \bar{\nu}_\tau & \bar{\tau} \\ C_p^1 \epsilon_{mnp} + X_{m,n}^1 & & C_p^2 \epsilon_{mnp} + X_{m,n}^2 & & \bar{u}_n & \bar{d}_n \\ & \bar{b}_n & & \bar{s}_n & S & T^- \\ & \bar{t}_n & & \bar{c}_n & T^+ & S' \end{pmatrix}$$

Hypercharge

$$Y = Q_V + \left(T_{(1)}^{R,3} - T_{(2)}^{R,3} \right) + \frac{1}{24} \left(T_{(1)}^8 - T_{(2)}^8 \right) - \frac{1}{3} T_{(2)}^3$$

$$T_{(i)}^3 = \begin{pmatrix} \mathbf{I} & & & \\ & -\mathbf{I} & & \\ & & 0 & \\ & & & 0 \end{pmatrix}, \quad T_{(i)}^8 = \begin{pmatrix} \mathbf{I} & & & \\ & \mathbf{I} & & \\ & & -3 & \\ & & & -3 \end{pmatrix}$$

$$T_{(i)}^{R,3} = \begin{pmatrix} 0 & & & \\ & 0 & & \\ & & \frac{1}{2} & \\ & & & -\frac{1}{2} \end{pmatrix}$$

Yukawas

$$W = y M q \bar{q}$$

$$W \supset y [L_i H_u \bar{\nu}_i + L_i H'_d \bar{e}_i + Q_1 H_u \bar{u}_1 + Q_1 H'_d \bar{d}_1 + Q_j H_d \bar{d}_j + Q_j H'_u \bar{u}_j]$$

$$i = 1, 2, 3 \text{ and } j = 2, 3$$

$SU(2)_L$ coupling

either

- add spectators to get a ridiculous amount of running
- mix with a elementary $SU(2)$

$$\frac{1}{g^2} = \frac{1}{g_{\text{comp}}^2} + \frac{1}{g_{\text{elem}}^2}$$

Minimal Composite SSM

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

Minimal Composite SSM

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

$$W = y M q \bar{q}$$

Minimal Composite SSM

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

$$q = Q_3, \mathcal{H}, H_d$$

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

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

MCSSM

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

$$\langle \mathcal{H} \rangle = \mathcal{F} \gg f$$

$$m_{W'} \sim g_{\text{comp}} \mathcal{F} \qquad m_{E,X} \sim y \mathcal{F}$$

EW S B

$$V = y^2 |H_u H_d - f^2|^2 + y^2 |S|^2 (|H_u|^2 + |H_d|^2) \\ + m_S^2 |S|^2 + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 \\ + (A S H_u H_d + T S + h.c.) + \frac{g^2 + g'^2}{8} (|H_u|^2 - |H_d|^2)^2$$

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

Fine Tuning

$$\langle S \rangle = \frac{\sqrt{2} (Av^2 \sin \beta \cos \beta - 2T)}{2m_S^2 + y^2 v^2}$$

neglecting g^2 terms

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

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

Fine Tuning

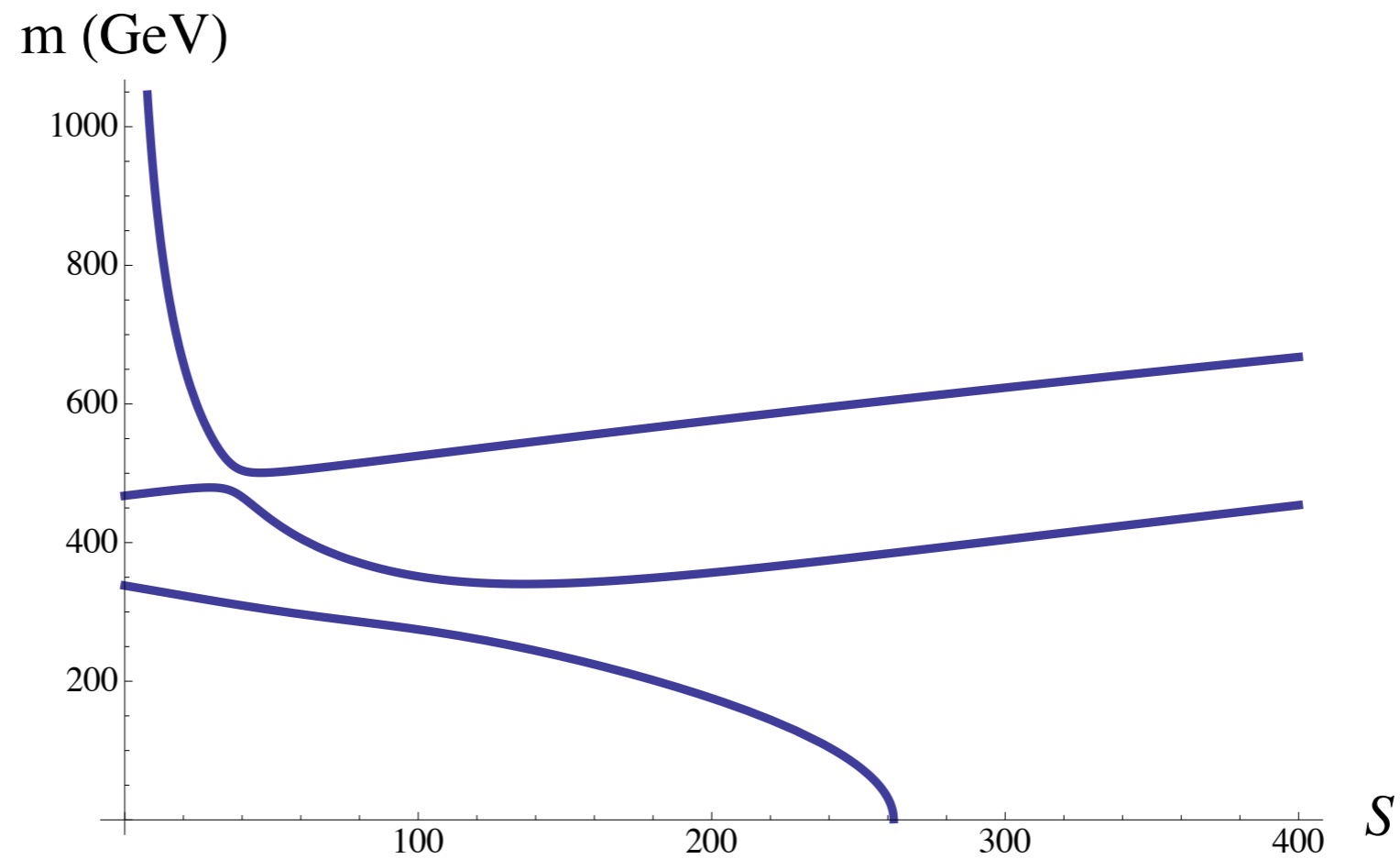
$$\frac{y^2 v^2}{m_{H_u}^2}$$

two-loop:

$$\Delta m_{H_u}^2 \sim -\frac{2y_t^2 \alpha_s^2}{\pi^3} |m_{\tilde{g}}|^2 \log^2 \frac{\Lambda}{\text{TeV}}$$

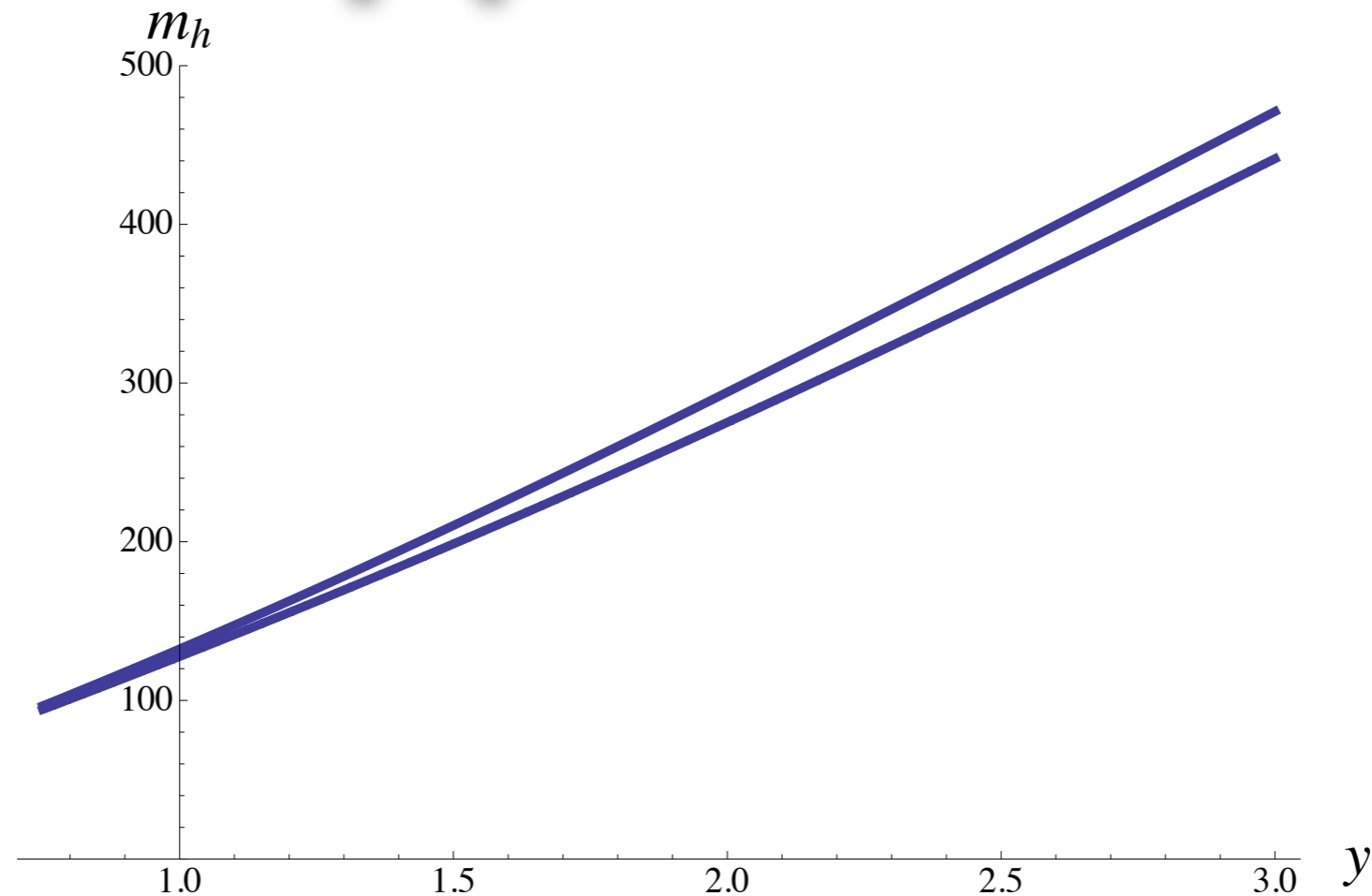
3 TeV gluino \rightarrow 10% tuning

CP Even Scalars



$\beta = 0.7$, $f = 200$ GeV, $A = -800$ GeV, $T = 0$, and $y = 2$

m_h Upper Bound



for a fixed Higgsino mass $y \langle S \rangle = 100$ GeV (upper line)
and $y \langle S \rangle = 150$ GeV (lower line)

Soft SUSY Breaking

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

$$Z = 1 - \theta^2 B - \bar{\theta}^2 B - \theta^2 \bar{\theta}^2 (m^2 - |B|^2)$$

$$S = \frac{1}{2g} - i \frac{\theta_{YM}}{32\pi^2} + \theta^2 \frac{m_\lambda}{g^2}$$

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

Arkani-Hamed, Giudice, Luty, Rattazzi [hep-ph/9803290](#)

Soft SUSY Breaking

$$\begin{aligned} Q &\rightarrow e^A Q, & \bar{Q} &\rightarrow e^A \bar{Q} \\ Z &\rightarrow e^{-A-A^\dagger}, & \Lambda_h &\rightarrow e^{2F/b A} \Lambda_h \\ \Lambda^2 &= \Lambda_h^\dagger Z^{2F/b} \Lambda_h \rightarrow \Lambda^2 \end{aligned}$$

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

Composites

$$Q\bar{Q} \leftrightarrow M, \quad Q^N \leftrightarrow q^{F-N}, \quad \bar{Q}^N \leftrightarrow \bar{q}^{F-N}$$

$$q \rightarrow e^{AN/(F-N)} q$$

$$\bar{q} \rightarrow e^{AN/(F-N)} \bar{q}$$

$$M \rightarrow e^{2A} M$$

Composite Soft SUSY Breaking

$$\mathcal{L} = \int d^4\theta \left[\frac{M^\dagger Z^2 M}{\Lambda^2} + \frac{q^\dagger Z^{N/(F-N)} e^{\tilde{V}} q}{\Lambda^{(4N-2F)/(F-N)}} + \frac{\bar{q}^\dagger Z^{N/(F-N)} e^{\tilde{V}} \bar{q}}{\Lambda^{(4N-2F)/(F-N)}} \right]$$

$$+ \int d^2\theta \left[S \tilde{W}^\alpha \tilde{W}_\alpha + \frac{y M q \bar{q}}{\Lambda_h^{b/(F-N)}} + \mu_f M \right] + h.c.$$

$$m_M^2 = 2 \frac{3N - 2F}{b} m^2, \quad m_q^2 = -\frac{3N - 2F}{b} m^2$$

Arkani-Hamed, Rattazzi [hep-th/9804068](https://arxiv.org/abs/hep-th/9804068)

Composite Soft SUSY Breaking

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

$$A = 0$$

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

$$y f^2 \equiv \mu_f \Lambda$$

cf Luty, Rattazzi [hep-th/9908085](https://arxiv.org/abs/hep-th/9908085)

Hierarchy of Soft SUSY Breaking

$$A \sim m_{\tilde{t}} \sim m_H \sim \frac{m_{UV}^2}{\Lambda} \ll m_{UV}$$
$$T \sim f^2 m_{UV} \ll m_{UV}^3$$

Light Stop












$$m_{\tilde{t}}^2 = \begin{pmatrix} m_{Q33}^2 + m_t^2 + \delta_u & v(A s_\beta - \mu_{\text{eff}} y_t c_\beta)/\sqrt{2} \\ v(A s_\beta - \mu_{\text{eff}} y_t c_\beta)/\sqrt{2} & m_{\bar{u}33}^2 + m_t^2 + \delta_{\bar{u}} \end{pmatrix}$$

$$\mu \sim A \ll m_{UV}$$

$$m_{Q33} \sim m_{\bar{u}33} \ll m_{UV}$$

large mixing, light stop

MCSSMTools /

name	age	message	history
 BMPGMSB/	October 04, 2011	# On branch master [jterning]	
 BMPSUGRA/	October 04, 2011	# On branch master [jterning]	
 EXPCON/	October 04, 2011	# On branch master [jterning]	
 SAMPLES/	November 03, 2011	updated dample files [jterning]	
 main/	November 03, 2011	simplified input [jterning]	
 micromegas_2.2/	October 13, 2011	tab warnings fixed [jterning]	
 sources/	November 03, 2011	simplified input [jterning]	
 .gitignore	October 13, 2011	tab warnings fixed [jterning]	
 Makefile	October 04, 2011	# On branch master [jterning]	
 README	November 03, 2011	improved README [jterning]	
 run	October 04, 2011	# On branch master [jterning]	

README

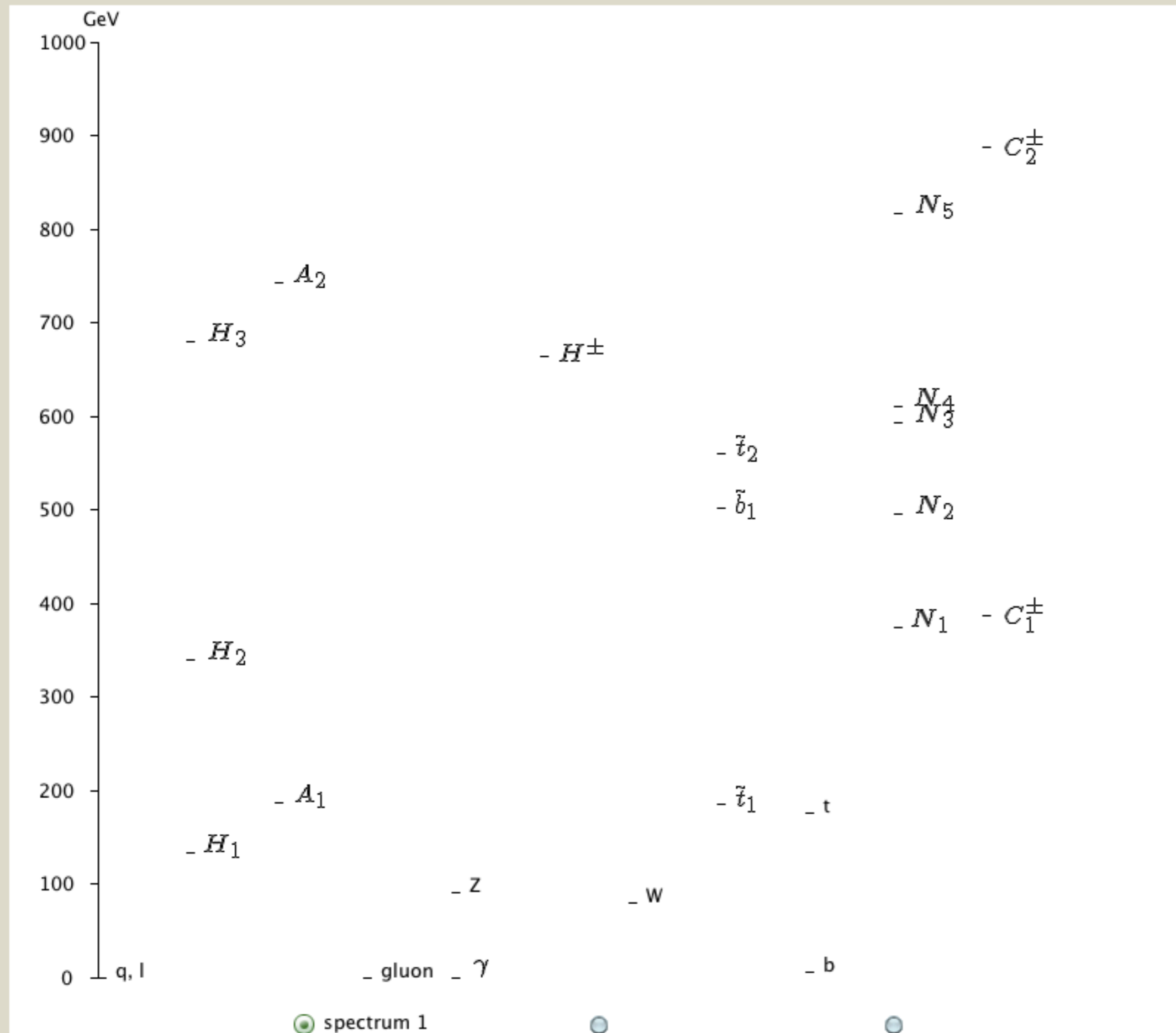
This program calculates the spectrum of the Minimal Composite Supersymmetric Standard Model. It was hacked by Csaba Csaki and John Terning, based on the code NMSSMTools by Ulrich Ellwanger, John F. Gunion, Cyril Hugonie, C.-C. Jean-Louis, Debottam Das, and Ana M. Teixeira for more information on NMSSMTools see <http://www.th.u-psud.fr/NMHDECAY/nmssmtools.html> For those familiar with NMSSMTools we have kept the same file names and structure.

HOW TO USE MCSSMTOOLS:

COMPILATION:

On Mac OS X you will need a modern fortran compiler, which can be downloaded from <http://hpc.sourceforge.net/>.

Spectrum for the Minimal Composite SSM



Conclusions

SUSY Composite Models

solve the four hierarchy problems:
gauge, Yukawa, little, and squark mass

they predict a sparse superpartner
spectrum with a very light stop