A Composite Light Stop

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Outline

- Motivation
- Seiberg Duality
- Composite Models
- Composite SUSY Breaking
- Light Stop
- Conclusion

Discovering Hierarchies

SPS: W,Z --> gauge hierarchy

LEP: no light Higgs --> little hierarchy

Tevatron: top --> Yukawa hierarchy

LHC: no light SUSY --> squark mass hierarchy

Discovering Hierarchies

SPS: W,Z --> gauge hierarchy
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Minimal Composite SSM
can resolve all these
hierarchy problems

SUSY QCD

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

$$\mathcal{Q}_i = (\phi_i, \psi_i)$$

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

Dual Theory

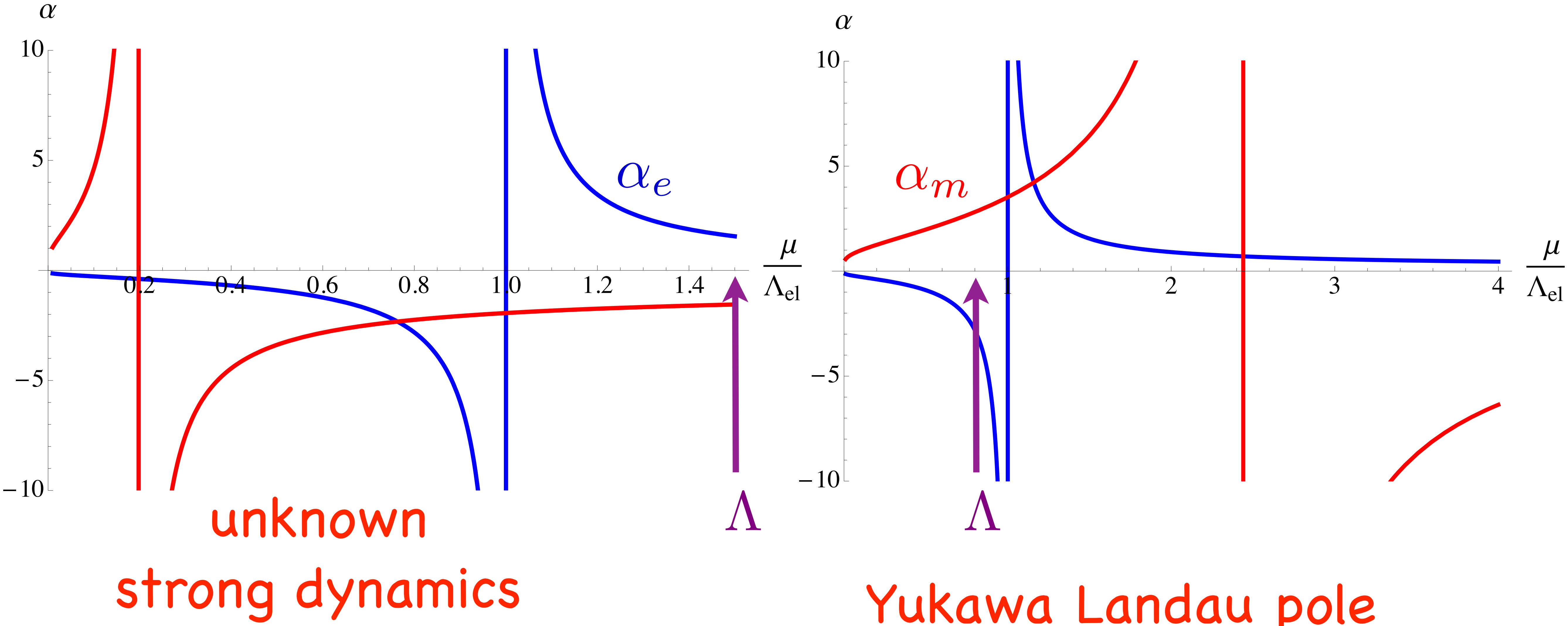
	$SU(F-N)$	$SU(F)$	$SU(F)$	$U(1)$	$U(1)_R$
q	$\square$	$\overline{\square}$	$\mathbf{1}$	$\frac{N}{F-N}$	$\frac{N}{F}$
$\bar{q}$	$\overline{\square}$	$\mathbf{1}$	$\square$	$-\frac{N}{F-N}$	$\frac{N}{F}$
M	$\mathbf{1}$	$\square$	$\overline{\square}$	0	$2\,\frac{F-N}{F}$

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

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

Dual Gauge Coupling

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



Dual Theory

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

$$\tilde{M} = M \, \Lambda_{\rm el}$$

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

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

Magnetic Coupling

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

$$g^2_{\rm mag}(\Lambda_{\rm el}) > \frac{8\pi^2}{F\log\left(4\pi\right)} \approx \frac{31}{F}$$

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

Electric Theory

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

Dual Theory

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

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

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

Hypercharge

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

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

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

Yukawas

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

$$\begin{aligned} W \quad \supset \quad & y\,[L_i H_u \bar{\nu}_i + L_i H_d' \bar{e}_i + Q_1 H_u \bar{u}_1 \\ & + Q_1 H_d' \bar{d}_1 + Q_j H_d \bar{d}_j + Q_j H_u' \bar{u}_j] \end{aligned}$$

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

$SU(2)_L$ coupling

either

- add spectators to get a ridiculous amount of running

- mix with a elementary SU(2)

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

Minimal Composite SSM

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

Minimal Composite SSM

	$SU(2)_{\rm mag}$	$SU(6)_1$	$SU(6)_2$	$U(1)_V$	$U(1)_R$
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	$\frac{2}{3}$

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

Csaki, Shirman, JT hep-ph/1106.3074

Minimal Composite SSM

	$SU(2)_{\rm mag}$	$SU(6)_1$	$SU(6)_2$	$U(1)_V$	$U(1)_R$
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	$\frac{2}{3}$

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

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

MCSSM

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

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

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

EWSB

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

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

Fine Tuning

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

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: $\dfrac{y^2 v^2}{m_{H_u}^2}$

Fine Tuning

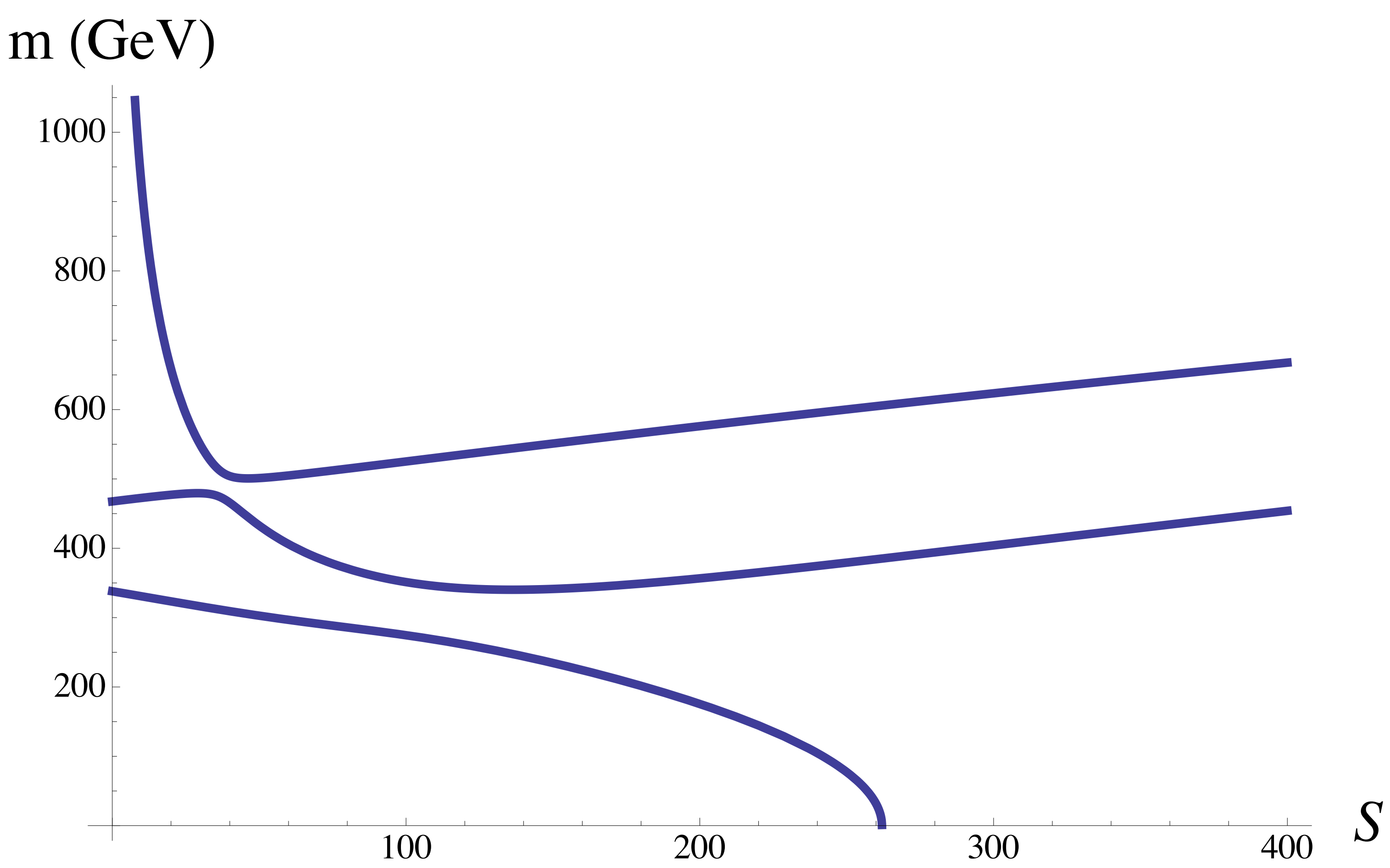
$$\frac{y^2 v^2}{m_{H_u}^2}$$

two-loop:

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

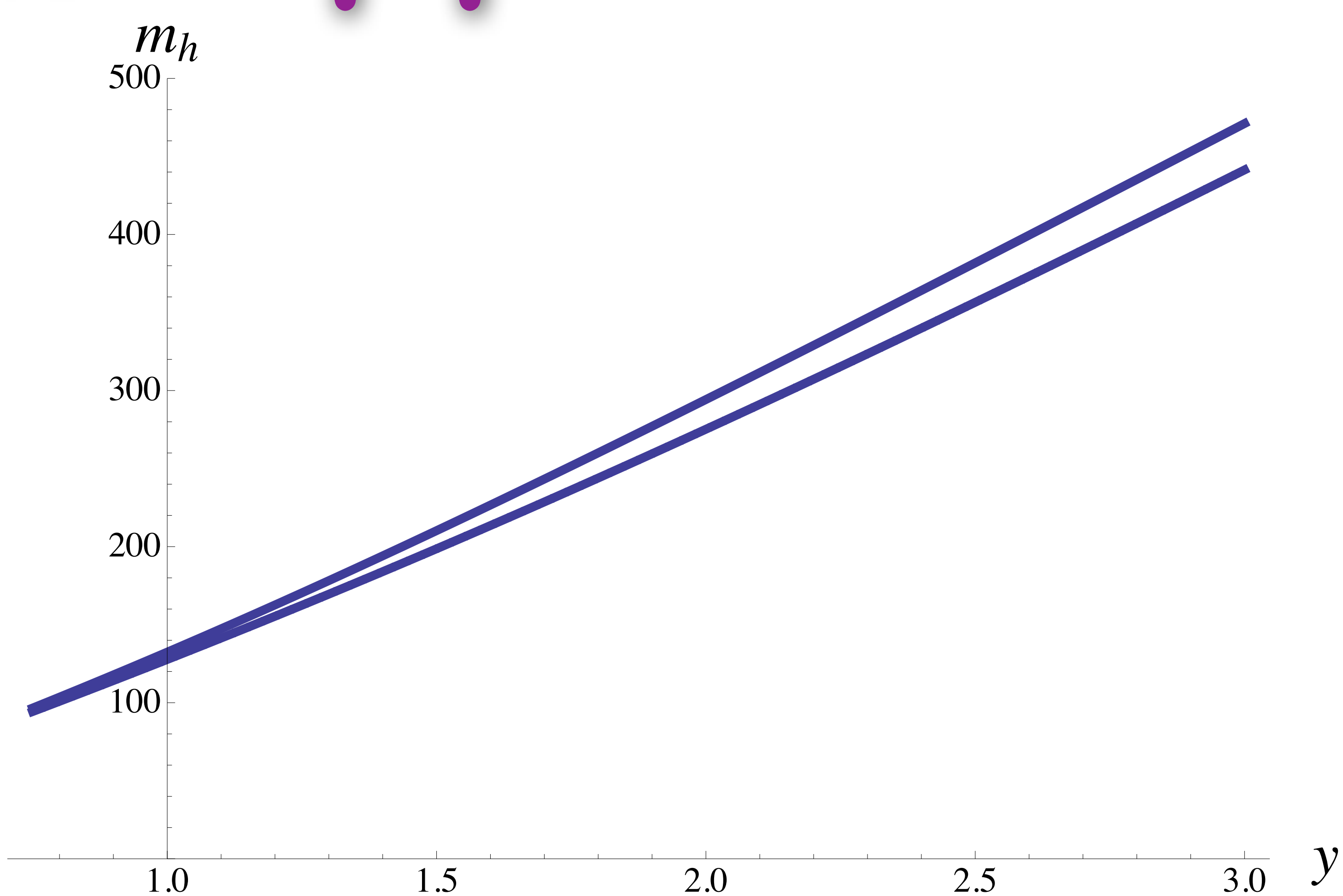
3 TeV gluino $\rightarrow$ 10% tuning

CP Even Scalars



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

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

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

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

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

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

Arkani-Hamed, Giudice, Luty, Rattazzi hep-ph/9803290

Soft SUSY Breaking

$$\mathcal{Q} \to e^{A}\mathcal{Q}\ , \qquad \bar{\mathcal{Q}} \to e^{A}\bar{\mathcal{Q}}$$

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

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

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

Composites

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

$$q \to e^{AN/(F-N)} q$$
$$\bar{q} \to e^{AN/(F-N)} \bar{q}$$
$$M \to e^{2A} M$$

Composite Soft SUSY Breaking

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

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

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

Arkani-Hamed, Rattazzi 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

Hierarchy of Soft SUSY Breaking

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

Light Stop

$$\mathbf{m}^{\mathbf{2}}_{\tilde{\mathbf{t}}} = \begin{pmatrix} m^2_{Q33} + m_t^2 + \delta_u & v(A\, s_\beta - \mu_{\rm eff}\, y_t\, c_\beta)/\sqrt{2} \\ v(A\, s_\beta - \mu_{\rm eff}\, y_t\, c_\beta)/\sqrt{2} & m^2_{\overline{u}33} + m_t^2 + \delta_{\overline{u}} \end{pmatrix}$$

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

$$m_{Q_{33}} \sim m_{\bar{u}_{33}} \ll m_{UV}$$

large mixing, light stop

MCSSMTools /

name	age	message
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]

history

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/ .
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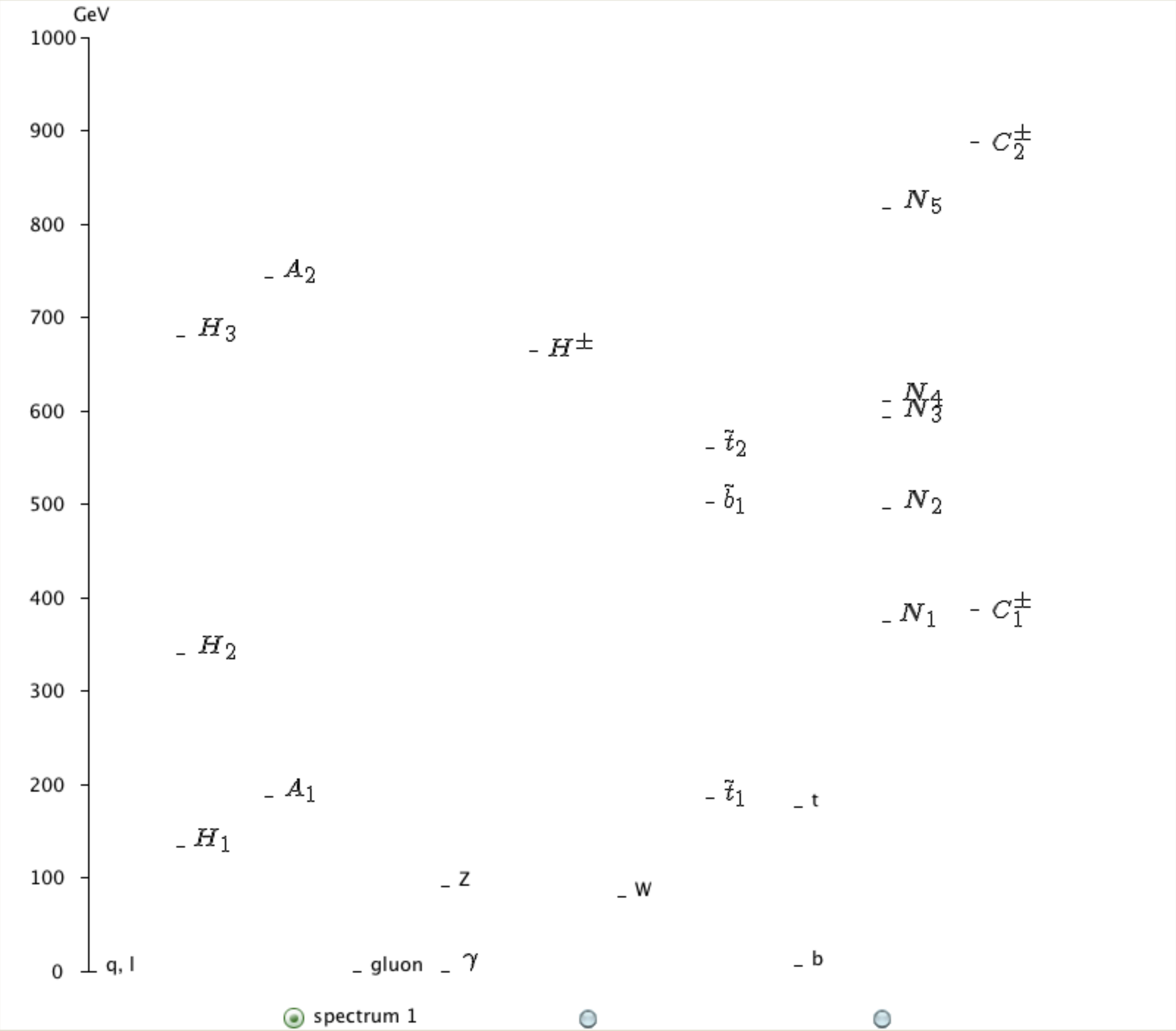
Spectrum for the Minimal Composite SSM



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