STEALTHY COMPOSITE STOPS

arXiv: 1201.1293, 1211.soon

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In collaboration with C. Csáki, R. Houtz, & J. Terning

Perimeter Institute Particle Physics Seminar, 13 Nov 2012

Physics of the early LHC

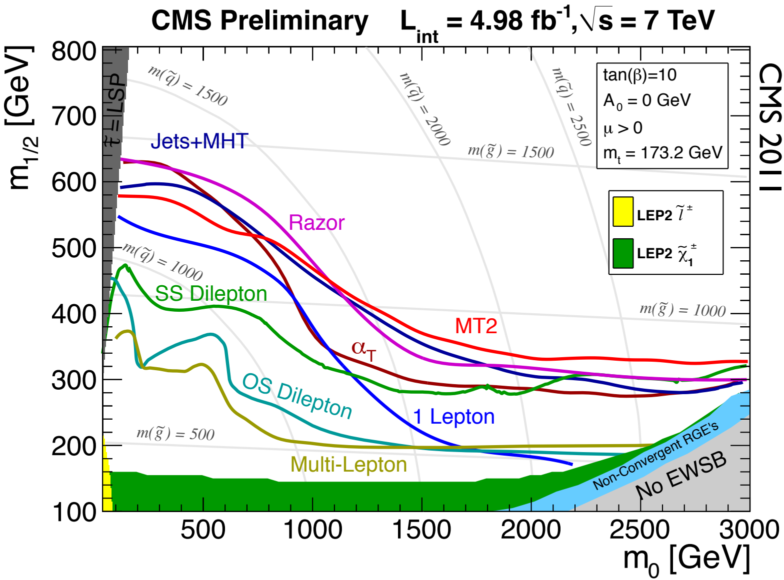
Great for the Standard Model...

... not much for new physics

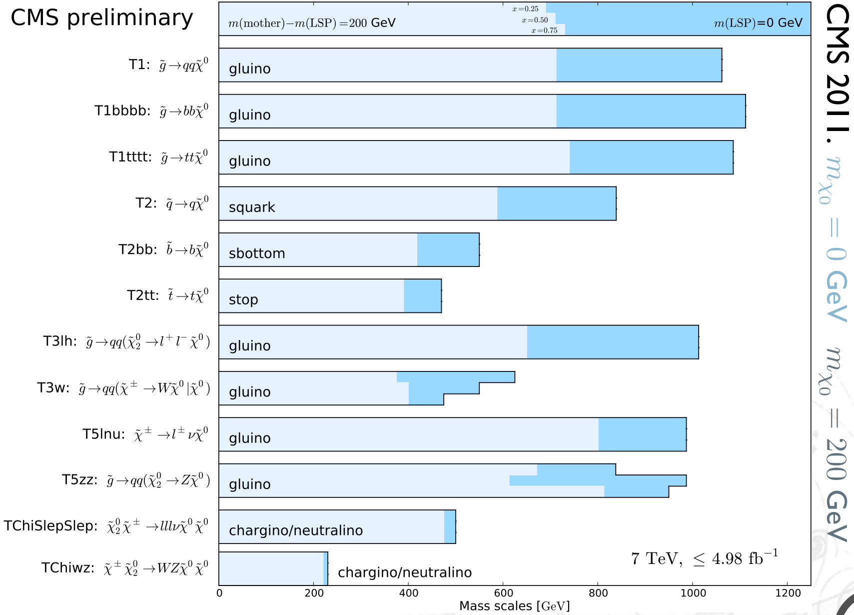
What ever happened to naturalness ?

supersymmetry ?

LHC vs. SUSY


CMS Preliminary L_{int} = 4.98 fb^{-1}, $\sqrt{s}$ = 7 TeV
CMS 2011
tan(β)=10
A_0 = 0 GeV
μ > 0
m_t = 173.2 GeV
LEP2 $\tilde{l}^{\pm}$
LEP2 $\tilde{\chi}_1^{\pm}$
$\tilde{\tau}$ = LSP
m($\tilde{q}$) = 1500
m($\tilde{q}$) = 2000
m($\tilde{q}$) = 2500
m($\tilde{q}$) = 1000
m($\tilde{g}$) = 1500
m($\tilde{g}$) = 1000
m($\tilde{g}$) = 500
Jets+MHT
Razor
SS Dilepton
MT2
α_T
OS Dilepton
1 Lepton
Multi-Lepton
Non-Convergent RGE's
No EWSB
$m_{1/2}$ [GeV]
m_0 [GeV]
800
700
600
500
400
300
200
100
500
1000
1500
2000
2500
3000

LHC vs. SUSY


CMS preliminary
$m(\text{mother})-m(\text{LSP})=200$ GeV
$x=0.25$
$x=0.50$
$x=0.75$
$m(\text{LSP})=0$ GeV
T1: $\tilde{g}\to qq\tilde{\chi}^0$
T1bbbb: $\tilde{g}\to bb\tilde{\chi}^0$
T1tttt: $\tilde{g}\to tt\tilde{\chi}^0$
T2: $\tilde{q}\to q\tilde{\chi}^0$
T2bb: $\tilde{b}\to b\tilde{\chi}^0$
T2tt: $\tilde{t}\to t\tilde{\chi}^0$
T3lh: $\tilde{g}\to qq(\tilde{\chi}^0_2\to l^+l^-\tilde{\chi}^0)$
T3w: $\tilde{g}\to qq(\tilde{\chi}^\pm\to W\tilde{\chi}^0|\tilde{\chi}^0)$
T5lnu: $\tilde{\chi}^\pm\to l^\pm\nu\tilde{\chi}^0$
T5zz: $\tilde{g}\to qq(\tilde{\chi}^0_2\to Z\tilde{\chi}^0)$
TChiSlepSlep: $\tilde{\chi}^0_2\tilde{\chi}^\pm\to lll\nu\tilde{\chi}^0\tilde{\chi}^0$
TChiwz: $\tilde{\chi}^\pm\tilde{\chi}^0_2\to WZ\tilde{\chi}^0\tilde{\chi}^0$
gluino
gluino
gluino
squark
sbottom
stop
gluino
gluino
gluino
gluino
chargino/neutralino
chargino/neutralino
7 TeV, ≤ 4.98 fb^{-1}
0
200
400
600
800
1000
1200
Mass scales [GeV]
CMS 2011. $m_{\chi_0}=0$ GeV $m_{\chi_0}=200$ GeV

LHC vs. SUSY

What it looks like:

Low-scale supersymmetry is dead. SM is tuned?

What this is really telling us:

There aren't 6 degenerate squarks or an EW-scale color octet that decay to missing energy.

If SUSY exists, then it has an interesting spectrum.

Minimally natural SUSY

The relevant question is:

Can SUSY still solve the Hierarchy problem?
(subject to LHC constraints on spectrum)

Yes. 'Natural SUSY'

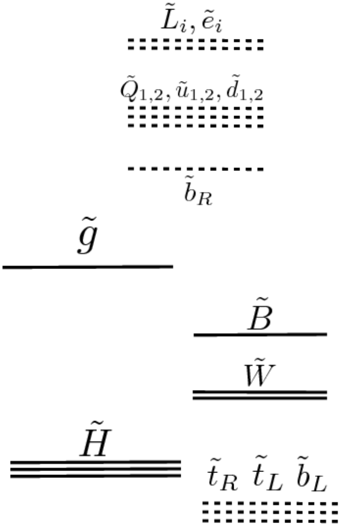
Papucci, Ruderman, Weiler (1110.6926), Brust, Katz, Lawrence, Sundrum (1110.6926), Kats, Meade, Reece, Shih (1110.6444). Dimopoulos, Giudice (hep-ph/9507282), Cohen, Kaplan, Nelson (hep-ph/9607394)

Just keep the superpartners we need for naturalness, allow others to decouple at low energies.

Minimally natural SUSY

Ingredients:

1. Light stops
2. Light Higgsinos
3. Not-too-heavy gluinos
4. Light-ish EW-inos
5. Decouple the rest



From: Papucci, Ruderman, Weiler (1110.6926)

A slight complication

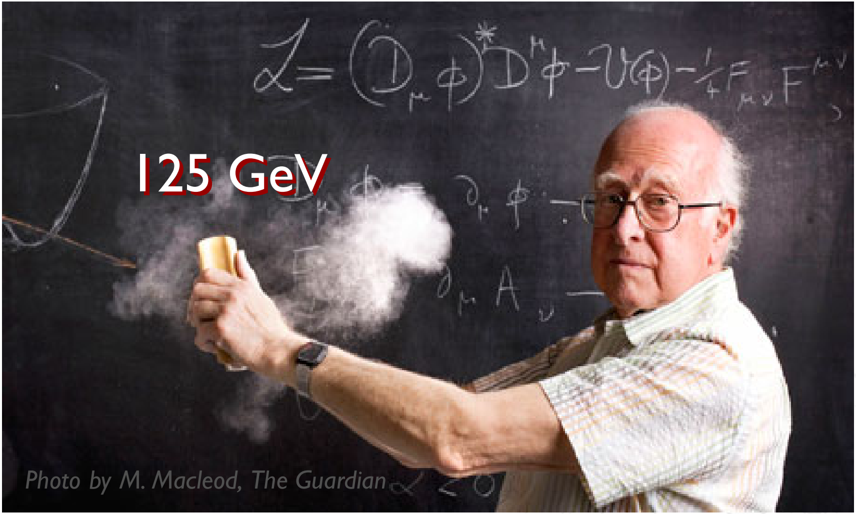


Photo by M. Macleod, The Guardian

Natural SUSY vs. $m_h = 125$ GeV

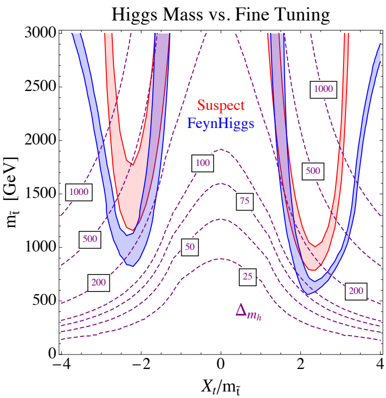
Tree level contribution from D-term quartic

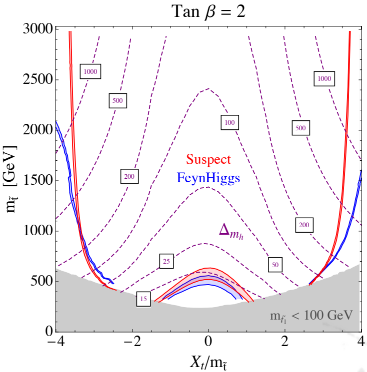
$$m^2_{h,\text{MSSM}} = m_Z^2 c_{2\beta}^2 + \frac{3m_t^4}{4\pi^2 v^2}\left[\log\left(\frac{M_S^2}{m_t^2}\right) + \textbf{mix}\right]$$

$$m^2_{h,\text{NMSSM}} = m_Z^2 c_{2\beta}^2 + \lambda^2 v^2 s_{2\beta}^2 + \textbf{loops}$$

New tree-level quartic contribution from singlet

$m_h = 125$ GeV tuning in the MSSM vs NMSSM





Hall, Pinner Ruderman (1112.2703)

Light stops: direct production

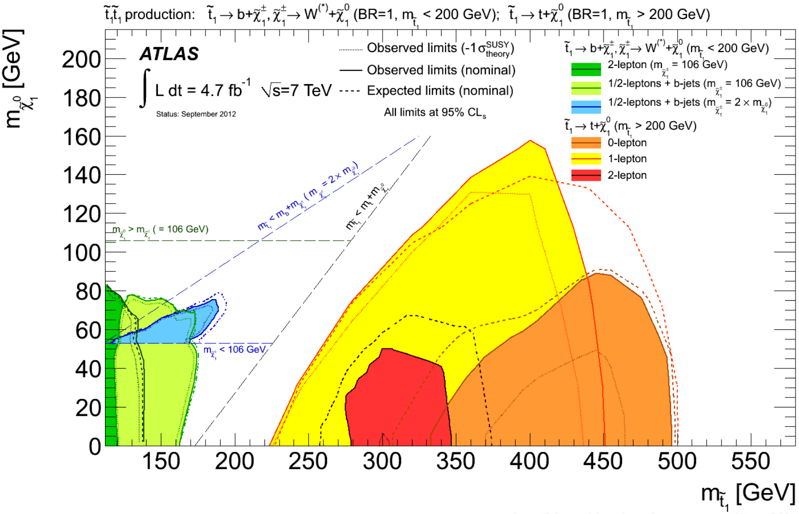
$$\tilde{t} \to bW^+\chi^0 \quad \textbf{vs.} \quad t \to bW^+$$

- **3 body**, *lightish stop*: Decay via off-shell top
  Can use $m_{\ell b}$ distributions. Chou & Peskin `hep-ph/9909536`
- **2 body**, *heavyish stop*: Decay via on-shell top
  Can make use of the MET distribution. Fermilab group `1205.5805`
- **1 body**, *stealth stop*: $m_{\chi^0} \lll m_{\tilde{t}}$, looks like $t\bar{t}$
  "Blind spot" in current analyses Katz, Meade, Reece, Shih `1110.6444`

Other: Displaced decays, stoponium, flavor violation

Light stops

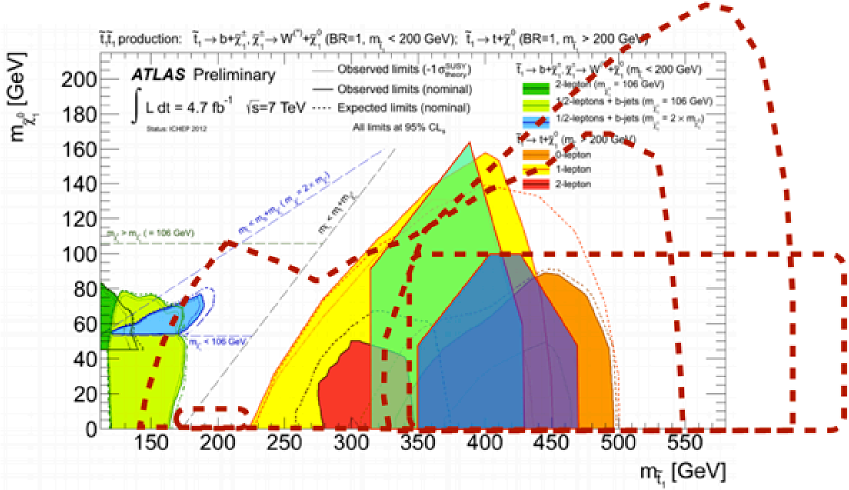
Experimental limits on direct pair production



ATLAS: `1208.4305`, `1209.2102`, `1208.1447`, `1208.2590`, `1209.4186`

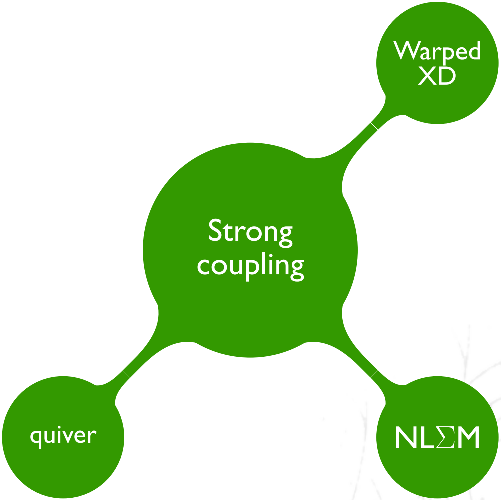
Light stops

estimated reach with 20/fb @ 8 TeV



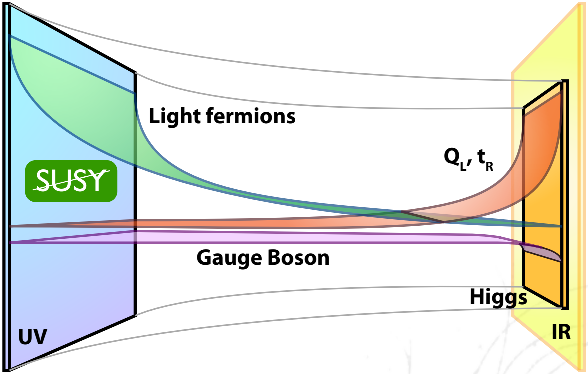
Daniele Alves, *Implications of LHC results for TeV-scale physics*, CERN 2012

UV Models: Light Stops $\leftrightarrow$ compositeness



Warped / Emergent / Accidental SUSY

Supersymmetrize the Randall-Sundrum picture:

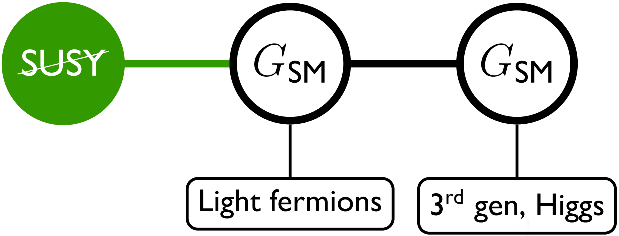


Warped fermion masses → squark spectrum

Gherghetta hep-ph/0302001; Maryland/Hopkins 0909.5430, 1110.6670

Deconstructed SUSY

Deconstruct previous picture:

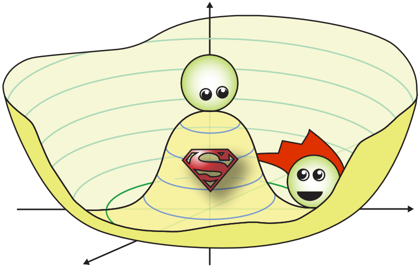


Generic feature: conventional unification difficult.

Craig, Green, Katz `1103.3708`; See also Craig, McCullough, Thaler `1203.1622`

SUSY Pseudo-Goldstone Higgs

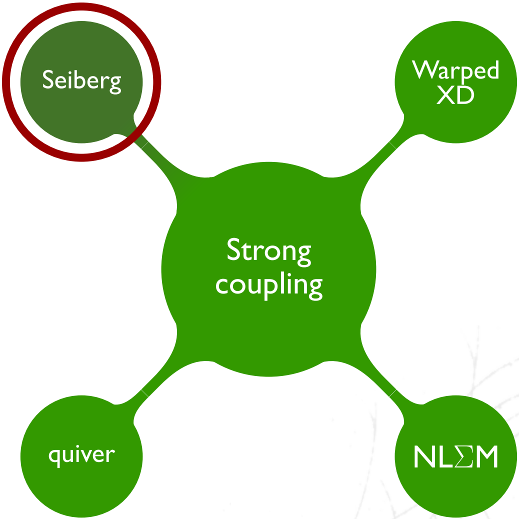
SUSY Minimal Composite Higgs



Derivative couplings of Higgs to strong sector, Yukawas from mixing with elementary states. Higgs potential different from non-SUSY case.

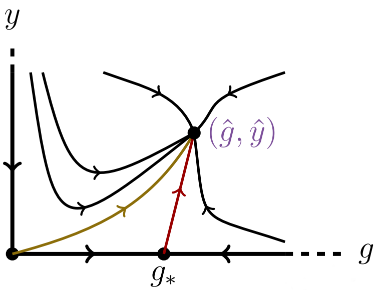
Gripaios, Redi 1004.5114

UV Models: Light Stops $\leftrightarrow$ compositeness



Seiberg Duality

Conformal window: SQCD with F flavors and N colors is dual to a magnetic theory with F flavors and $n = F - N$ colors.



Magnetic theory: dual quarks & mesons with Yukawa interaction

See, e.g., Strassler hep-th/0309149

A composite electroweak sector?

Can the W and Z be composite?
e.g. ρ meson: massive, spin-1 resonance

Abbot & Farhi ('81): model via complementarity
No explanation for electroweak couplings

Seiberg duality ('95): emergent magnetic gauge group
Komargodski ('11): magnetic gauge fields $\Leftrightarrow \rho$

Attempts: Maekawa & Takahashi ('96), Maekawa & Sato ('96), Sannino ('11)

A composite electroweak sector?

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

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

Magnetic Yukawa coupling: $\bar{q}Mq$. Flavor groups:

$$\text{SU}(8)_1 \supset \text{SU}(3) \times \text{SU}(3) \times \text{SU}(2)_{R,1}$$
$$\text{SU}(8)_2 \supset \text{SU}(3)_G \times \text{SU}(3) \times \text{SU}(2)_{R,2}$$

A composite electroweak sector?

Accommodates SM spectrum + extra pair of Higgses + junk

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

$$\bar{q} = \begin{pmatrix} \nu_{\ell,i} \\ \ell_i \end{pmatrix}_L, \begin{pmatrix} u_n \\ d_n \end{pmatrix}_L, H_d, H'_u$$

SU(3) × SU(3) × SU(2)$_{R,1}$

$$\left(\begin{array}{cc|cc} \multicolumn{2}{c|}{V_n^{ab}} & \bar{\nu}_{\ell,i} & \bar{\ell}_i \\ \hline (*C+X)^1_{mn} & (*C+X)^2_{mn} & \bar{u}_n & \bar{d}_n \\ \hline \bar{b}_n & \bar{s}_n & S & T \\ \bar{t}_n & \bar{c}_n & T^+ & S' \end{array}\right)$$

SU(3)$_G$ × SU(3) × SU(2)$_{R,2}$

A composite electroweak sector?

Features:

- $U(1)_Y \in$ anomaly-free diagonal flavor generators
- Decoupling junk by introducing elementary conjugates ($\bar{V}, \bar{C}, \bar{X}$) automatically cancels anomalies.
- B & L conserved; R-parity accidental

One big problem:

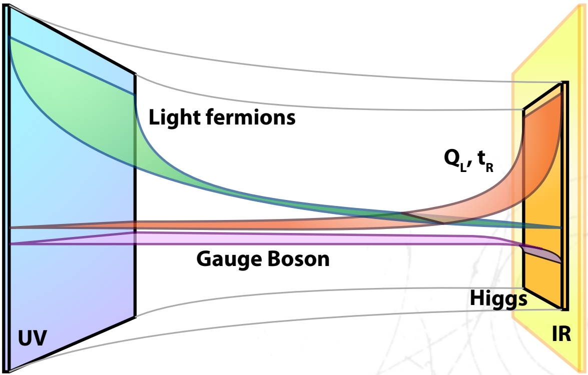
Expect magnetic coupling to be much stronger than EW couplings.

e.g. residual strong coupling between nucleons

Difficulties with a fully composite EW sector

$$y \sim \frac{\Lambda_{\text{el}}}{|\Lambda|} \lesssim 4\pi \quad \Rightarrow \quad g^{-2}_{\text{mag}}(\Lambda_{\text{el}}) = \frac{F}{8\pi^2}\frac{\Lambda_{\text{el}}}{|\Lambda|} \approx \frac{F}{31}$$

Poetically: original vs. ‘realistic’ RS1 (Suggests a solution!)



Partial Compositeness

Craig, Stolarski, Thaler 1106.2164; Csáki, Shirman, Terning 1106.3074

Work around: mix with elementary states

i.e. pull brane-localized fields into the bulk
... but need additional link fields $\mathcal{H}, \bar{\mathcal{H}}$.

$$\mathsf{SU}(2)_{\mathsf{el}} \times \mathsf{SU}(2)_{\mathsf{mag}} \xrightarrow{\mathcal{H}} \mathsf{SU}(2)_L$$

$$\frac{1}{g^2} = \frac{1}{g^2_{\mathsf{comp}}} + \frac{1}{g^2_{\mathsf{elem}}}$$

Minimize matter content:

only Higgs and 3$^{\text{rd}}$ generation composite

McSSM

Minimal Composite Supersymmetric SM

McSupersymmetry

Minimal Composite Supersymmetric SM

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

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

$$\text{SU}(6)_1 \supset \text{SU}(3)_c \times \text{SU}(2)_{\text{elem}} \times \text{U}(1)_Y \qquad q = Q_3, \mathcal{H}, H_d$$

$$\text{SU}(6)_2 \supset \text{SU}(3)_X \times \text{SU}(2)_{\text{elem}} \times \text{U}(1)_Y \qquad \bar{q} = X, \bar{\mathcal{H}}, H_u$$

Minimal Composite Supersymmetric SM

$$\text{SU}(6)_1 \supset \text{SU}(3)_c \times \text{SU}(2)_{\text{elem}} \times \text{U}(1)_Y \qquad q = Q_3, \mathcal{H}, H_d$$
$$\text{SU}(6)_2 \supset \text{SU}(3)_X \times \text{SU}(2)_{\text{elem}} \times \text{U}(1)_Y \qquad \bar{q} = X, \bar{\mathcal{H}}, H_u$$

$$W \sim \begin{pmatrix} Q_3 & \mathcal{H} & H_d \end{pmatrix} \begin{pmatrix} V & U & \bar{t} \\ E & G+P & \phi_u \\ R & \phi_d & S \end{pmatrix} \begin{pmatrix} X \\ \bar{\mathcal{H}} \\ H_u \end{pmatrix}$$

- Decouple $V, U, \phi_{u,d}, R \Rightarrow$ cancels $\text{SU}(2)_{\text{elem}}$ & $\text{SU}(3)_c$ anomalies
- X & E: $\text{SU}(2)^2_{\text{mag}} \times \text{U}(1)_Y$ anomaly $\to$ $\text{SU}(2)^2_{\text{elem}} \times \text{U}(1)_Y$
- ... cancels upon adding remaining SM elementary fermions
- Lose: accidental R-parity

Minimal Composite Supersymmetric SM

Tune electric theory with mass terms to give P, S tadpoles

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

- $yP(\mathcal{H}\bar{\mathcal{H}} - \mathcal{F}^2)$: SU$(2)_{\text{elem}} \times$ SU$(2)_{\text{mag}}$
- $yS(H_u H_d - f^2)$: 'NMSSM'
- $yQ_3 H_u \bar{t}$: Yukawa
- $y\mathcal{H}EX$: Anomaly

- elem$\times$mag$\to$ L gives heavy W', Z' 'KK gauge bosons'
- $\sim$ RS deconstruction, but no anarchic flavor
- **Tuning**: $\mathcal{F} \gg f$, $\tilde{g}$ contribution to m_h^2 ($\sim$10%),

~~SUSY~~ across a duality

Last ingredient for full theory: SUSY breaking terms

Csáki, Randall, Terning `1201.1293`

Tool: analytic continuation into superspace

Cheng & Shadmi `th/9801146`, Arkani-Hamed & Rattazzi `th/9804068`

Idea: ~~SUSY~~ $\Rightarrow$ soft terms in electric theory

- Parameterize as superspace spurions
- Promote spurions to superfields
- These exhibit a $U(1)_A$ background symmetry
- Can use this to determine LO magnetic soft terms

$\not{S}\!\!\!$SUSY across a duality

$$\mathcal{L}_{\text{elec}} = \int d^4\theta\; Q^\dagger Z Q + \bar{Q}^\dagger Z \bar{Q} + \int d^2\theta S \mathcal{W}^2 + \mu_f \bar{Q} Q$$

$$\mathcal{L}_{\text{mag}} = \int d^4\theta\; \frac{M^\dagger Z^2 M}{\Lambda^2} + \frac{q^\dagger Z^{N/(F-N)} q}{\Lambda^{(4N-2F)/(F-N)}} + (q \to \bar{q})$$

$$+ \int d^2\theta\; S \tilde{W}^2 + \frac{y M q \bar{q}}{\Lambda_h^{b/(F-N)}} + \mu_f M$$

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

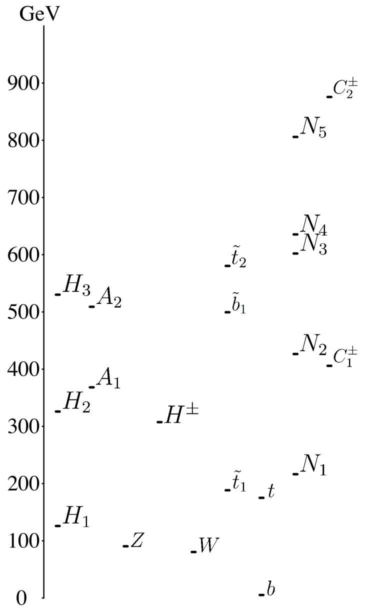
Minimal Composite Supersymmetric SM

Up to noncalculable $\mathcal{O}(m_{\text{el}}/\Lambda)$ corrections,

- Pick $m_{\text{el}} \sim \mathcal{O}(\text{TeV})$; sets M_3
- $\Lambda \sim 5\text{-}10$ TeV; sets $m_{\text{comp}} \sim \mathcal{O}(100\ \text{GeV})$
- ... sets $M_1 \sim M_2 \sim A$
- $\tan\beta \sim \mathcal{O}(1)$

End up with large mixing, light stop

Sample spectrum: stealth stop

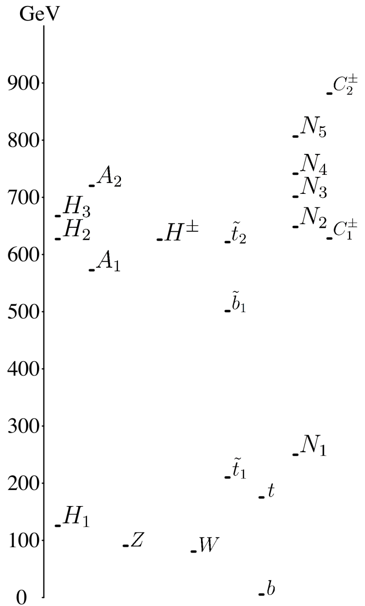


- $\tilde{t} \to t + \tilde{G}$
- $\tilde{G}$ light, low MET
- Possible displaced vertex

$$\Gamma = \frac{m_{\tilde{t}}^5}{16\pi F^2}\left(1 - \frac{m_t^2}{m_{\tilde{t}}^2}\right)^4$$

$\tilde{t}_1$	188 GeV	$\to t + \tilde{G}$
$\tilde{b}_1$	499 GeV	$\to \tilde{t}_1 + W$ (97%)
$\tilde{t}_2$	580 GeV	$\to \tilde{t}_1 + Z$ (50%)
N_1	216 GeV	
$\tilde{H}^\pm$	307 GeV	

Sample spectrum: stop NLSP, heavier neutralino

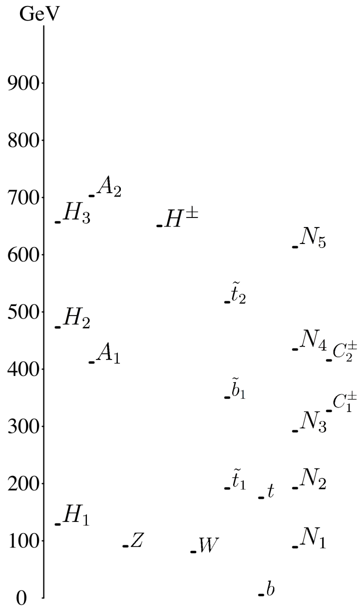


Push N_1 heavier

- Decouple more sparticles
- $N_1 \to t + \tilde{t}_1$
- $\tilde{t}_1$ still light, limited MET

$\tilde{t}_1$	210 GeV	$\to t + \tilde{G}$
$\tilde{b}_1$	501 GeV	$\to \tilde{t}_1 + W$
$\tilde{t}_2$	621 GeV	$\to \tilde{t}_1 + Z$ (78%)
N_1	429 GeV	$\to t + \tilde{t}_1^{(*)}$
$\tilde{A}_1$	572 GeV	

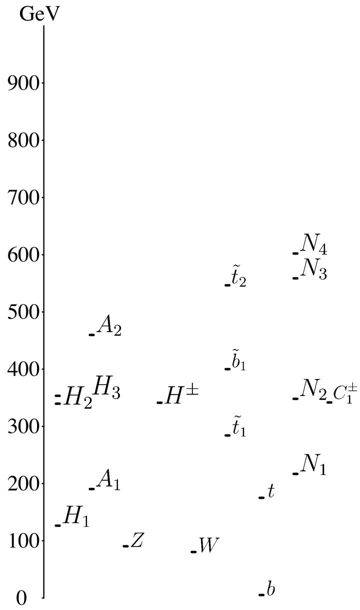
Sample spectrum: minimal gauge mediation



- $m(N_1) < m(\tilde{t}_1)$: MET
- Heavy $\tilde{g}$, $\tilde{q}_{1,2}$
- Reduced rate for CMSSM-type signal

N_1	88 GeV	$\to \gamma + \tilde{G}$
$\tilde{t}_1$	191 GeV	$\to t^* + N_1$
N_2	192 GeV	
N_3	291 GeV	
C_1	350 GeV	

Sample spectrum: high duality scale



- $m_{\tilde{q}_{1,2}}$ mainly from $\tilde{g}$ loops
- ... not power suppressed
- Other composite soft masses small
- Natural Higgs, $b \sim 50$ GeV^2
- Traditional signal at reduced rate

$\tilde{A}_1$	190 GeV	
$\tilde{N}_1$	217 GeV	
$\tilde{t}_1$	284 GeV	$\to N_1 + c$ (99%)

McPhenomenology

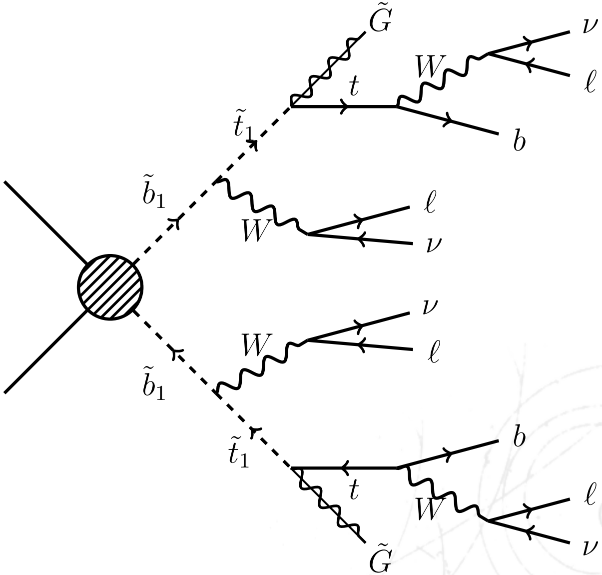
Many directions for direct $\tilde{t}$ production

e.g. Fermilab 1205.5805, Harvard 1205.5808, Hopkins/MIT 1205.5816, $\cdots$

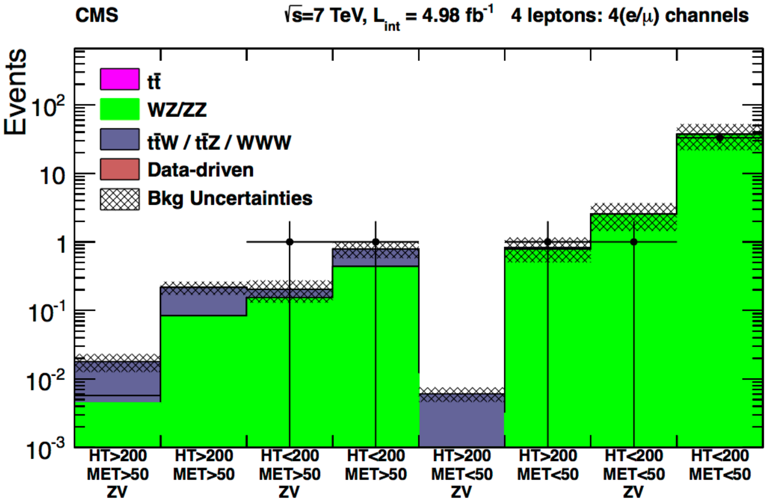
What can we do with a class of UV models?

- Identify common features of complete models
- Look for signals not necessarily present in simplified models
- Use McSSM spectra as benchmark models

McPhenomenology: multileptons



McPhenomenology: multileptons



1204.5341

McPhenomenology: multileptons

- Safe at 7/8 TeV, 20/fb
- Rescale backgrounds for 14 TeV reach using NLO σ
  Backgrounds are non-trivial, reducible contribution hard to simulate
- Pile up? Should be well approximated by 8 TeV data.
- 14 TeV with 20/fb: 8 signal + '0 background'
  in preferred high-H_T, high-MET bin

Conclusions and directions

Model building

- McSSM: class of light stops models via Seiberg duality
- To do: leftover tuning in fermion spectrum, tadpoles
- To do: R-parity, flavor, dark matter, unification

Phenomenology

- parameters $\to$ NMSSMTools $\to$ MG/Pythia/PGS
- Ongoing: 4ℓ, 3ℓ reach at 14 TeV
- To do: effect of additional states from UV theory