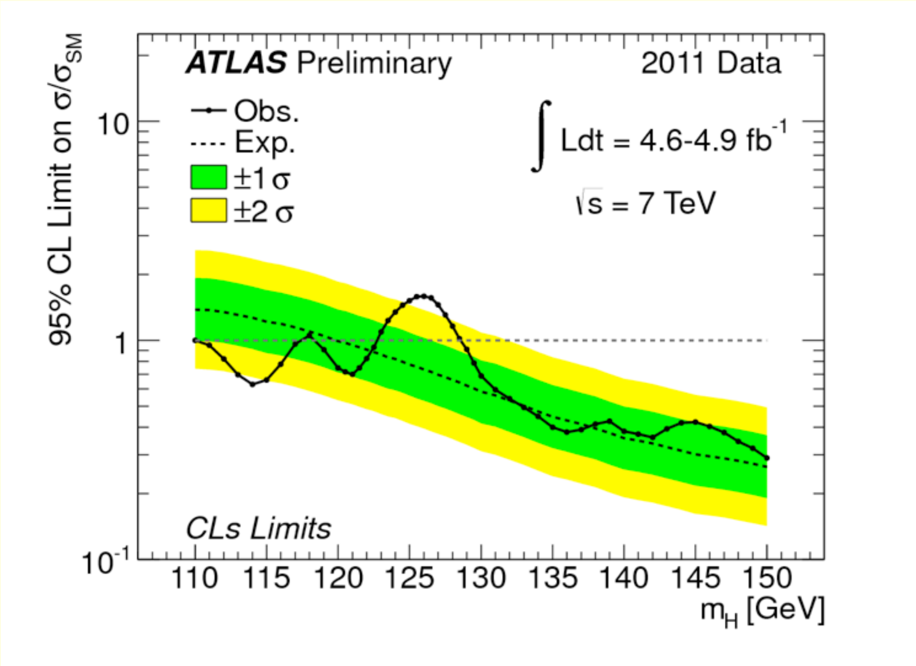
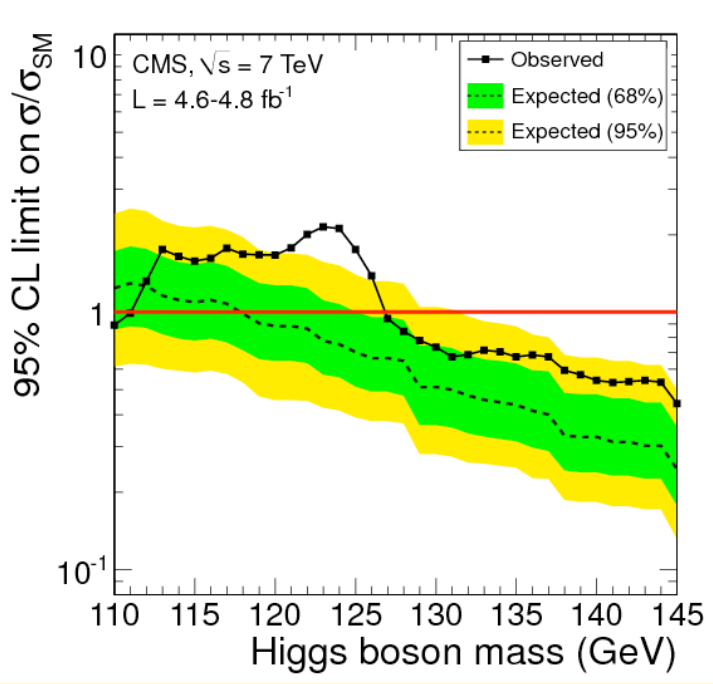
What is the alternative to the Higgs?

Csaba Csáki (Cornell)

Blois 2012

There does seem to be a Higgs-like particle at 125 GeV





I will make the assumption that this real

Higgsless

Pure MSSM Higgs sector

Alternatives to the STANDARD Higgs

Csaba Csáki (Cornell)

Blois 2012

Outline

1. Higgs in SUSY

2. Composite Higgs and $h \to \gamma\gamma$

3. Higgs or techni-dilaton?

1. Higgs and SUSY: A natural SUSY model via stop and higgs compositeness

SUSY has two problems

1. Why no MET observed?

2. How can Higgs be 125 GeV (little hierarchy)

Natural SUSY

- A possible way of accommodating SUSY with MET searches (other possibility is PRV, eg. MFV SUSY)

- First two generation squarks and gluino quite heavy

- LH stop, sbottom, RH stop light. σ_{SUSY} small.

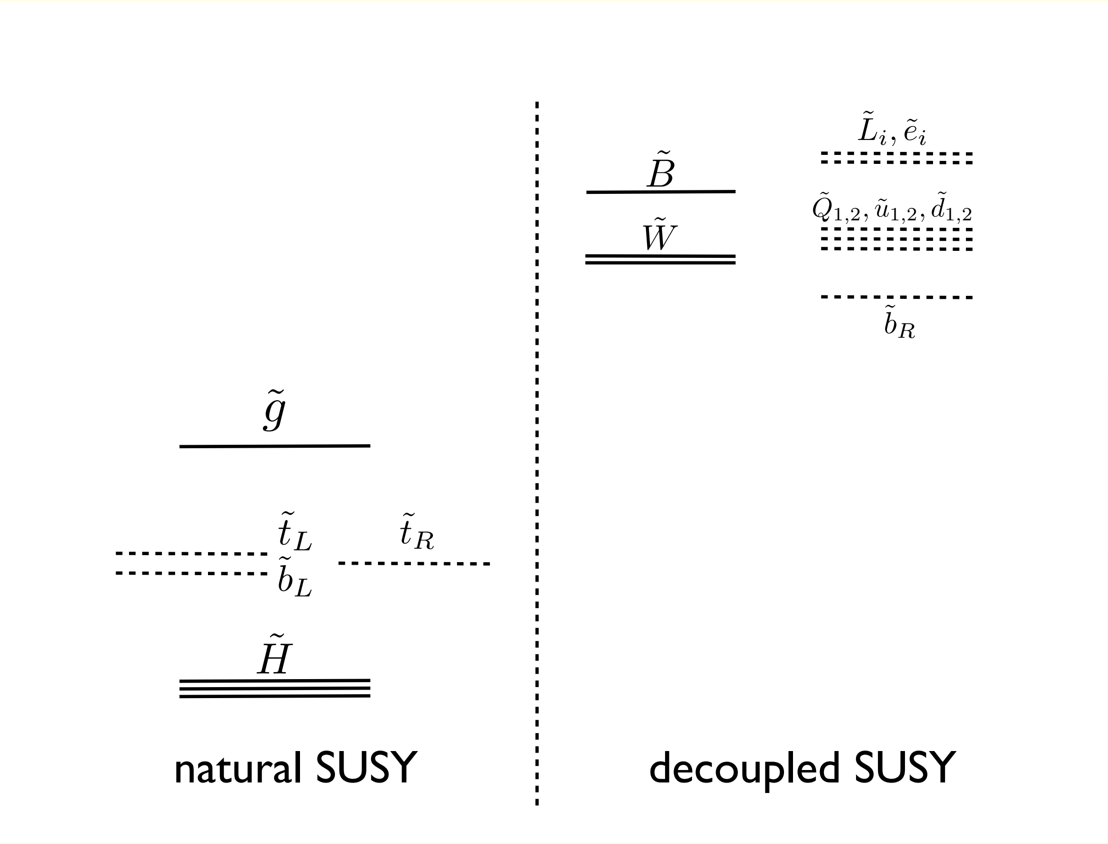
- Also solves flavor issue

- Originally suggested by Cohen, Kaplan, Nelson in '96 as ``more minimal SSM"

- Only particles needed to solve hierarchy problem are right

The bounds on natural SUSY: naturalness

(Papucci, Ruderman, Weiler '11)



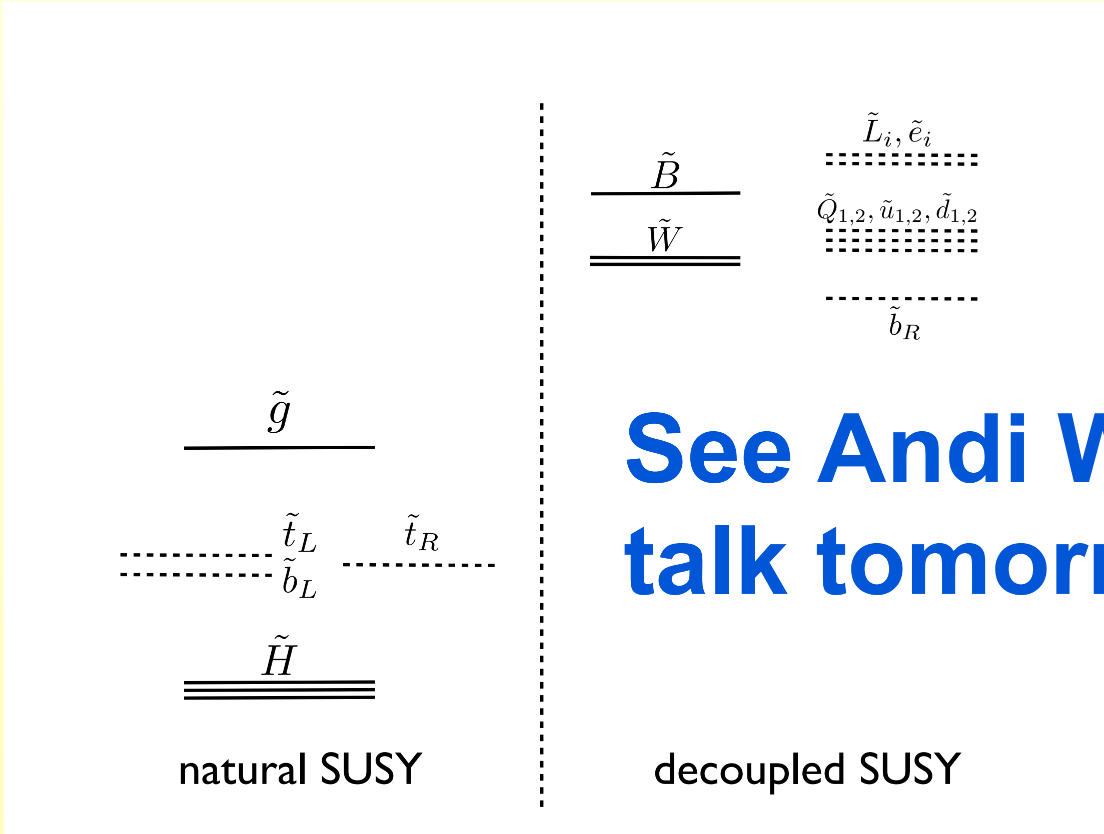
Below TeV scale

Above TeV scale

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

The bounds on natural SUSY: naturalness

(Papucci, Ruderman, Weiler ’11)



See Andi Weiler’s talk tomorrow!

Below TeV scale

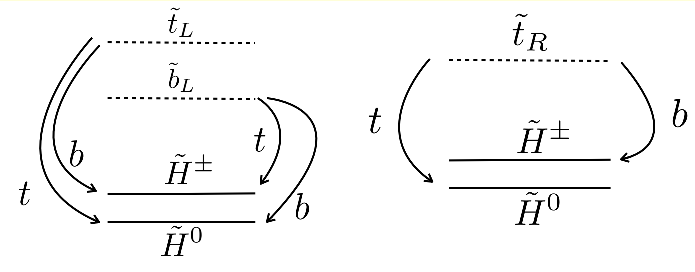
Above TeV scale

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

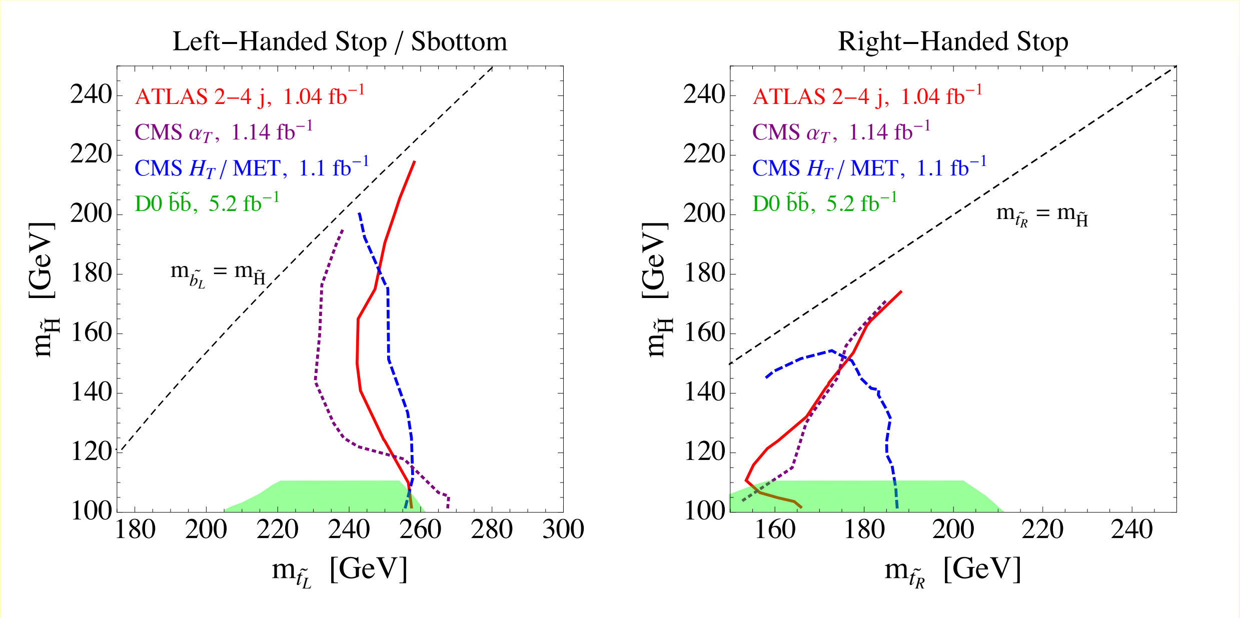
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler '11)

- Simplified model: only left handed stop/sbottom, right handed stop decaying to higgsinos:



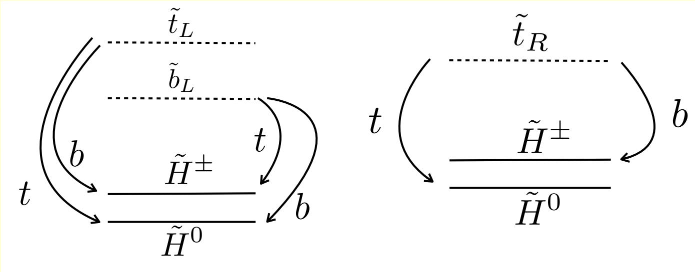
- Bounds from ~ 1 fb^{-1} data:



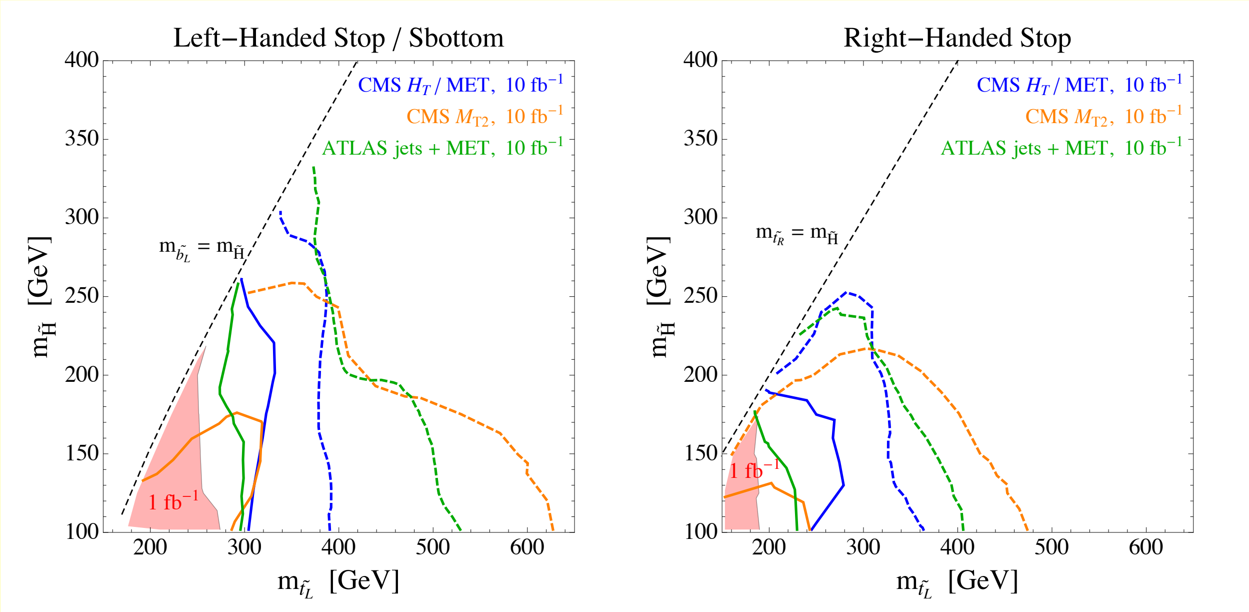
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler '11)

- Simplified model: only left handed stop/sbottom, right handed stop decaying to higgsinos:



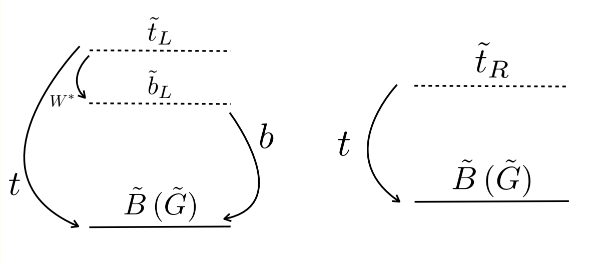
- Estimate for bounds from 10 fb^{-1} :



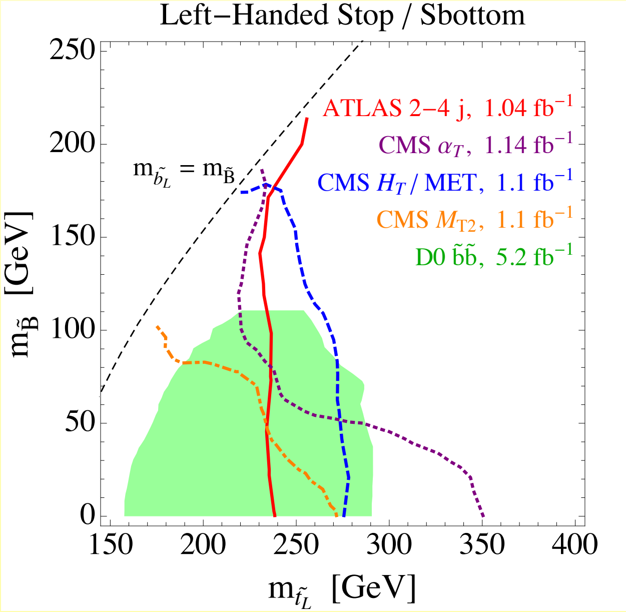
The bounds on natural SUSY: LHC

(Papucci, Ruderman, Weiler '11)

- Simplified model: only left handed stop/sbottom, right handed stop decaying to binos or gravitinos:



- Bounds from ~ 1 fb^{-1} data, no bound on RH stop.

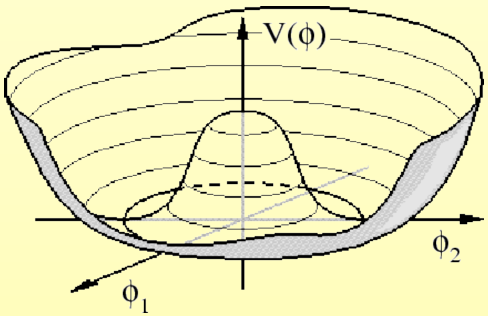


The other problem with SUSY: Little hierarchy

- Higgs mass: fixed by quartic coupling

$$V(H) = \lambda(|H|^2 - \frac{v^2}{2})^2$$

- SUSY: quartic coupling = gauge coupling (which sets W,Z mass)



- Leading result: $m_h \leq M_Z$

- But we know from LEP $m_h \geq 114\,\mathrm{GeV}$

- LHC: $m_h \sim 125\mathrm{GeV}$

- Very hard to overcome this in MSSM

- Need to assume that loop correction to quartic is large:

$$m^2_{Higgs} = M_Z^2 + \frac{3m_t^2\lambda_t^2}{4\pi^2}\log\frac{m_{\tilde{t}}}{m_t}$$

- Need large stop-top splitting

- But large loops and splittings are exactly what we are trying to avoid in SUSY

- Back to some fine tuning

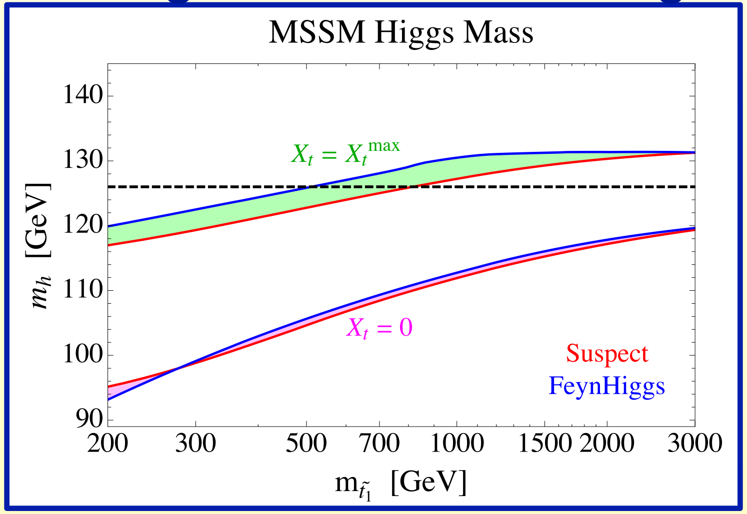
$$M_Z^2 \sim -2m^2_{H_u} \qquad \text{vs.} \qquad m^2_{H_u} = m_0^2 - \frac{3\lambda_t^2 m_{\tilde{t}}^2}{4\pi^2}\log\frac{\Lambda^2_{UV}}{m^2_{\tilde{t}}}$$

- Implies <1% tuning generically

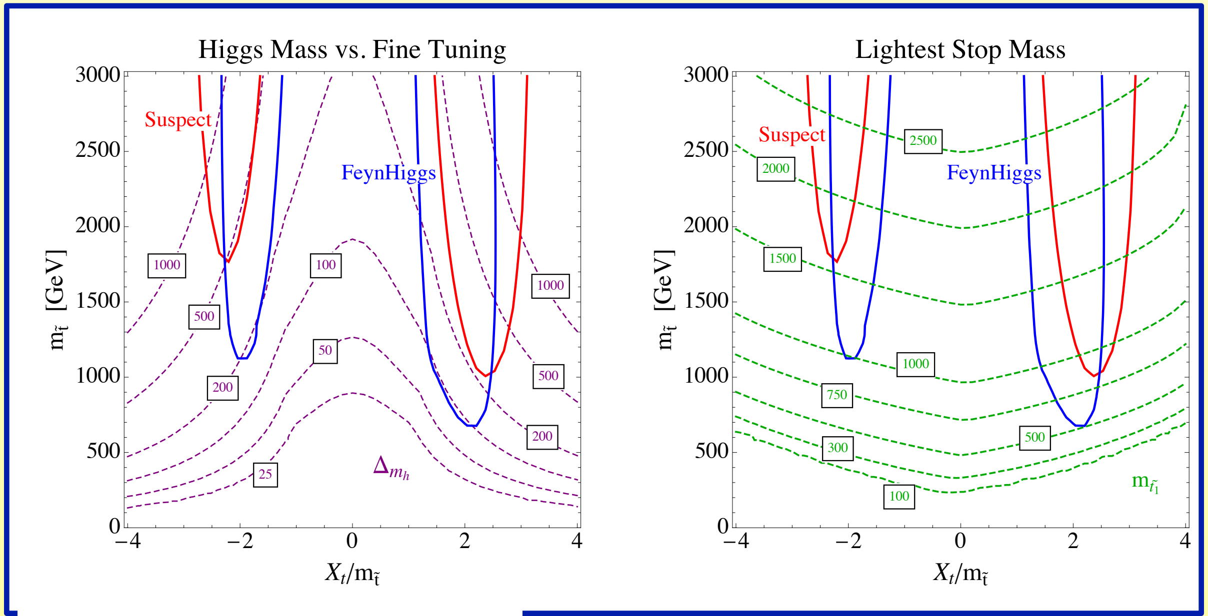
MSSM naturalness for 125 GeV Higgs

(Hall, Pinner, Ruderman, '11)

- In MSSM very hard to get 125 GeV with light stop:



- Fine tuning:



Light stops from compositeness (and a 125 GeV Higgs)

(CC, Shirman, Terning ’11
CC, Randall, Terning ’12)

- Idea: some fields composite, others not

- Additional strong confining interaction producing massless composites - can be described via “Seiberg duality”

- Have a confining gauge group (in this case SU(4)) that produces massless composite mesons, gauge fields and quarks

- Identify some of these composites with the MSSM Higgs, left handed top/stop, sbottom, right handed stop, EW gauge fields/ gauginos: the fields needed for natural SUSY

- Important ingredient: Higgs sector will NATURALLY contain a singlet and NMSSM-type superpotential: needed to lift Higgs

The Minimal Composite Supersymmetric SM (MCSSM)

(CC, Shirman, Terning '11
CC, Randall, Terning '12)

- Electric theory SU(4) with 6 flavors

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

$$W_{tree} = \mu_{\mathcal{F}}(\mathcal{Q}_4\bar{\mathcal{Q}}_4 + \mathcal{Q}_5\bar{\mathcal{Q}}_5) + \mu_f\mathcal{Q}_6\bar{\mathcal{Q}}_6$$

- Becomes strongly coupled at ~ 10 TeV, produces massless composites

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

$$W_{dyn} = y\,\bar{q}Mq\ .$$

Where is the standard model in the MCSSM?

(CC, Shirman, Terning '11
CC, Randall, Terning '12)

- Two SU(2) groups, one of them ``magnetic" composite SU(2)

- Other elementary embedded into flavor symmetry

$$SU(6)_1 \supset SU(3)_c \times SU(2)_{\rm el} \times U(1)_Y$$
$$SU(6)_2 \supset SU(3)_X \times SU(2)_{\rm el} \times U(1)_Y$$

- Composites:

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

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

- Relevant superpotential:

$$W \supset yP(\mathcal{H}\bar{\mathcal{H}} - \mathcal{F}^2) + yS(H_u H_d - f^2) + yQ_3 H_u \bar{t} + yH_u \mathcal{H}\phi_u + yH_d \bar{\mathcal{H}}\phi_d$$

A model with light stops and 125 GeV higgs

(CC, Randall, Terning '12,
CC, Shirman, Terning '11)

- The relevant part of the Higgs potential:

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

(

A model with light stops and 125 GeV higgs

(CC, Shirman, Terning '11
CC, Randall, Terning '12)

- 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 SUSY quartic

A model with light stops and 125 GeV higgs

(CC, Shirman, Terning '11
CC, Randall, Terning '12)

•The relevant part of the Higgs potential:

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

• additional NMSSM-like quartic due to confining dynamics - does not have to be small, can be > 1. tan β does NOT have to be large, in fact can be < 1

•S singlet a composite, other parameters soft breaking terms that can be estimated from strong dynamics in SUSY

•f will drive EWSB (different that MSSM, get EWSB w/o SUSY breaking). Good: higgs mass not related to Z mass, bad: why f~v?

A model with light stops and 125 GeV higgs

(CC, Shirman, Terning '11
CC, Randall, Terning '12)

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

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

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

- Fine tuning about $\frac{y^2 v^2}{2m_{H_u}^2}$ better than in MSSM, and stop can be light...

- Bound on gluino mass: don't want to lift stop too much

$\Delta m_{\tilde{t}} \sim \frac{32}{3}\frac{\alpha_s}{4\pi}|M_3|^2 \log\left(\frac{\Lambda}{\mathrm{TeV}}\right)$ will keep gluino below 1.5 TeV to have 400 GeV stop natural

The SUSY breaking hierarchy:

(CC, Randall, Terning '12)

- If strong dynamics close to conformal (depends on details of the SU(4) theory, in this case means F≥6)

- Assuming that soft breaking generated above confinement scale Λ

- Elementary fields (first two generation squarks, sleptons, gluino get mass $m_{el} \sim M_3 \sim \text{few} \cdot \text{TeV}$

- Composites get **suppressed** soft breaking masses

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

- For Λ~5-10 TeV composites in few 100 GeV range

The input parameters

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

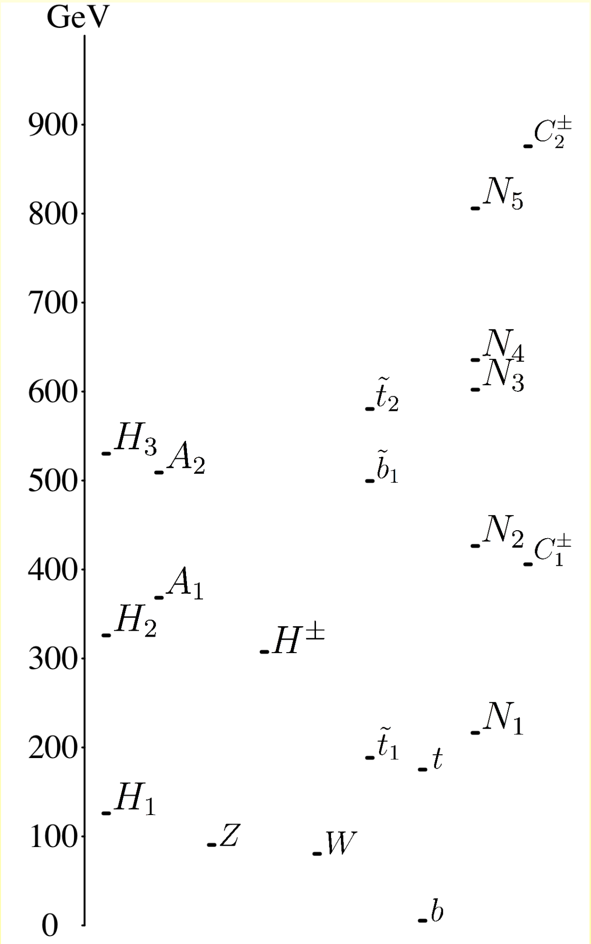
- Other parameters determined from minimizing Higgs potl

- Augmented NMSSMtools to implement different Higgs potential, calculate spectra, decay rates. Looked at four characteristic examples with very light stops (clearly can make them somewhat heavier if needed)

Four different sample spectra

(CC, Randall, Terning '12)

1. Stealth stop



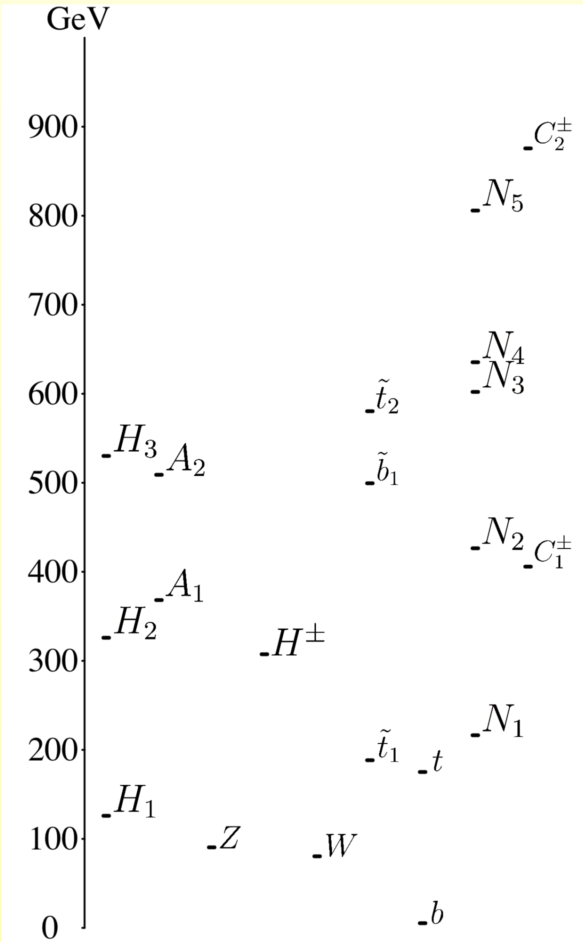
H_1	125 GeV	$\tilde{b}_1$	499 GeV
$\tilde{t}_1$	188 GeV	A_2	509 GeV
N_1	216 GeV	H_3	530 GeV
$H^\pm$	307 GeV	$\tilde{t}_2$	580 GeV
H_2	326 GeV	N_3	602 GeV
A_1	368 GeV	N_4	635 GeV
C_1	406 GeV	N_5	805 GeV
N_2	426 GeV	C_2	876 GeV

- Stop almost degenerate with top
- First neutralino close by
- Heavier stop, sbottom ~ 500 GeV
- Other fields over 1 TeV

Four different sample spectra

(CC, Randall, Terning '12)

1. Stealth stop



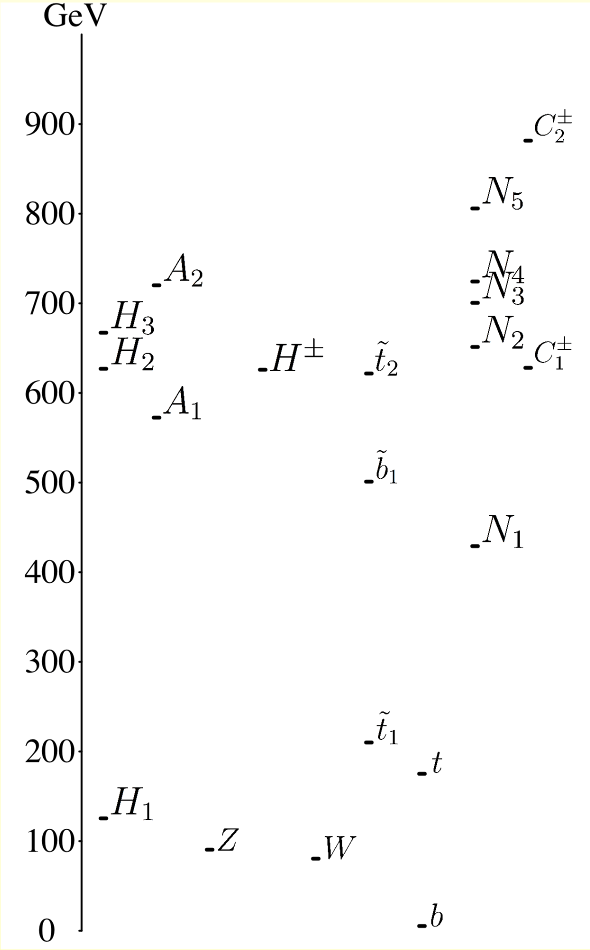
$\tilde{t}_1$	$\to t + LSP$	100%
C_1	$\to \tilde{t}_1 + b^\dagger$	84%
C_1	$\to N_1 + W^\pm$	16%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	97%
$\tilde{b}_1$	$\to \tilde{t}_1 + H^-$	3%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	51%
$\tilde{t}_2$	$\to t + N_1$	27%
$\tilde{t}_2$	$\to b + C_1^+$	11%
$\tilde{t}_2$	$\to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

- Stop decays to top + gravitino - not muc missing ET. σ~15 pb, 10% of ttbar
- Need precise σ_{top}
- Next stop, sbottom ~10 fb
- Sbottom: ttWW
- Stop2: ttZZ, ttbbW^*W^*
- Could have displaced top vertex

Four different sample spectra

(CC, Randall, Terning '12)

2. Stop NLSP with heavier N_1



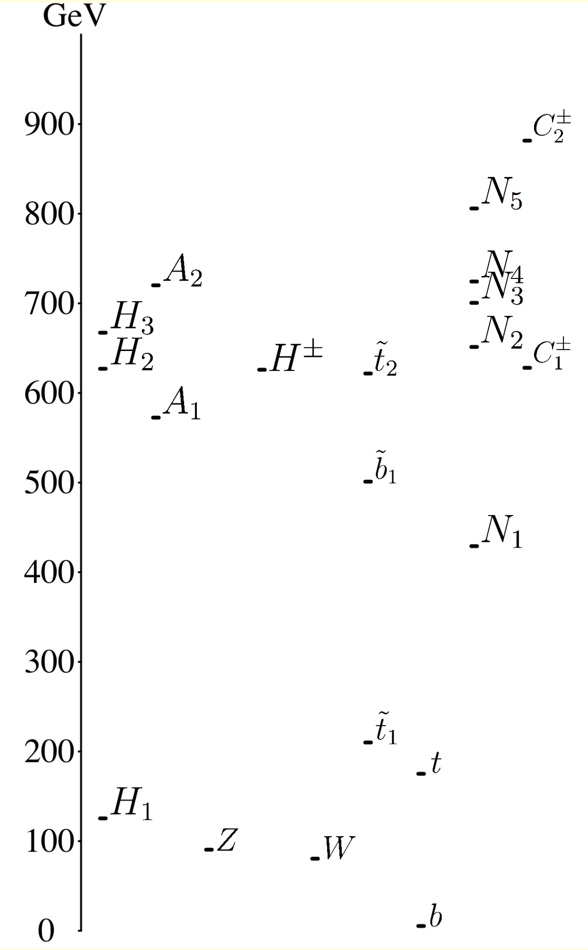
H_1	125 GeV	C_1	628 GeV
$\tilde{t}_1$	210 GeV	N_2	651 GeV
N_1	429 GeV	H_3	667 GeV
$\tilde{b}_1$	501 GeV	N_3	700 GeV
A_1	572 GeV	A_2	720 GeV
$\tilde{t}_2$	621 GeV	N_4	724 GeV
$H^\pm$	626 GeV	N_5	806 GeV
H_2	627 GeV	C_2	881 GeV

- Stop somewhat heavier, still close to t
- First neutralino heavier (should be 429 GeV)
- Heavier stop, sbottom ~ 500 GeV

Four different sample spectra

(CC, Randall, Terning ’12)

2. Stop NLSP with heavier N_1



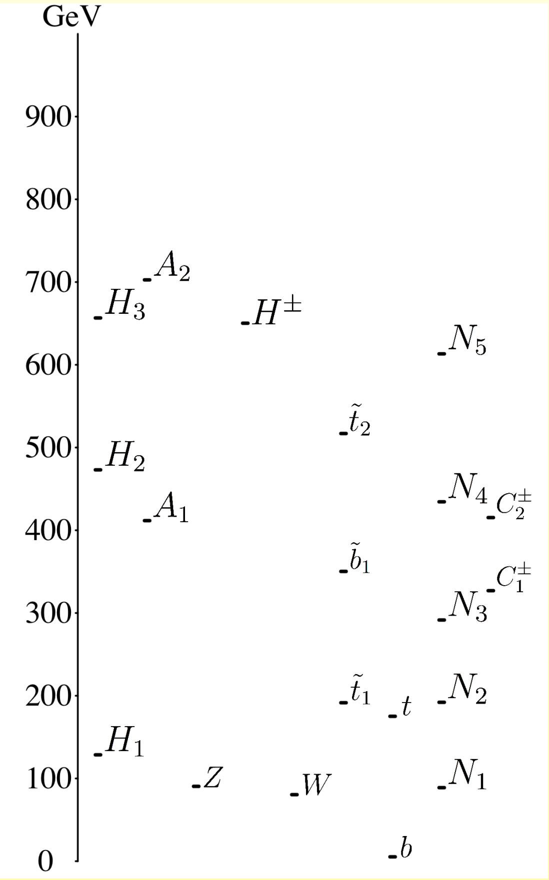
$\tilde{t}_1$	$\to t + LSP$	100%
N_1	$\to t + \tilde{t}^*$	50%
N_1	$\to \bar{t} + \tilde{t}$	50%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	100%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	78%
$\tilde{t}_2$	$\to \tilde{b}_1 + W^+$	14%
$\tilde{t}_2$	$\to \tilde{t}_1 + H_1$	8%

- •Stop decays to top + gravitino - not much missing ET. σ~8 pb, 5% of ttbar
- •Need even more precise σ_{top}
- •$N_1 \to$t+stop, tttt final states, still small missing E.
- •Sbottom: ttWW
- •Stop2: ttZZ, ttWWWW

Four different sample spectra

(CC, Randall, Terning '12)

3. Minimal gauge mediation



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

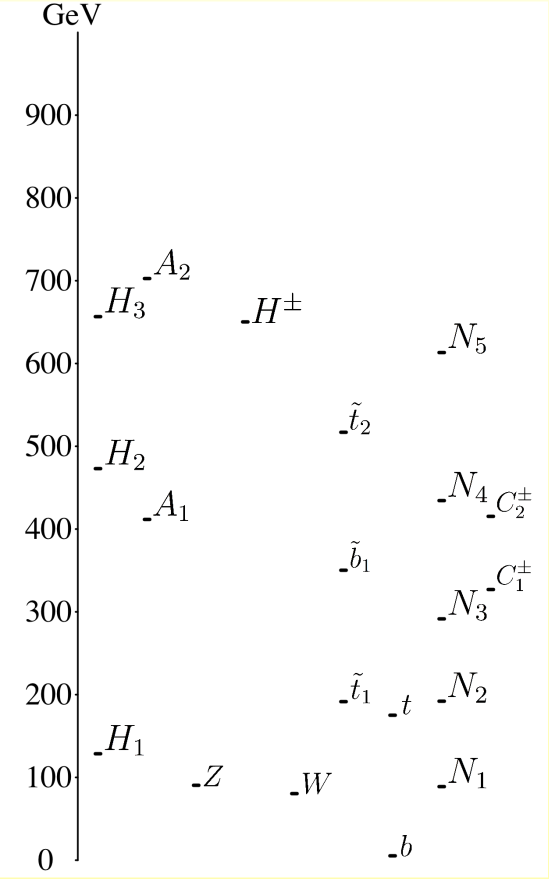
- Neutralino LSP or NLSP, missing energy, but reduced σ
- Stop still pretty light close to top

Four different sample spectra

(CC, Randall, Terning '12)

3. Minimal gauge mediation

$\tilde{t}_1$	$\to N_1^+ + b + W^+$	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%

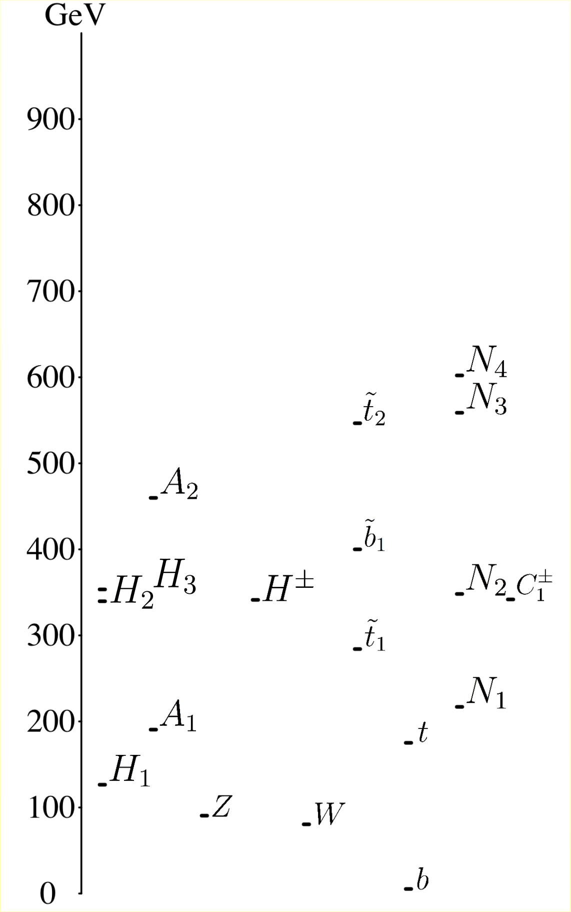


- If gauge mediation gravitino LSP
- $N_1 \to \gamma$+gravitino, missing ET
- stop$\to t^* + N_1$
- stop2$\to$stop1 Z,sbottom W,N t, C b,
- j+MET, j+t+MET, j+W/Z+MET or photons, also longer cascades

Four different sample spectra

(CC, Randall, Terning '12)

4. High duality scale



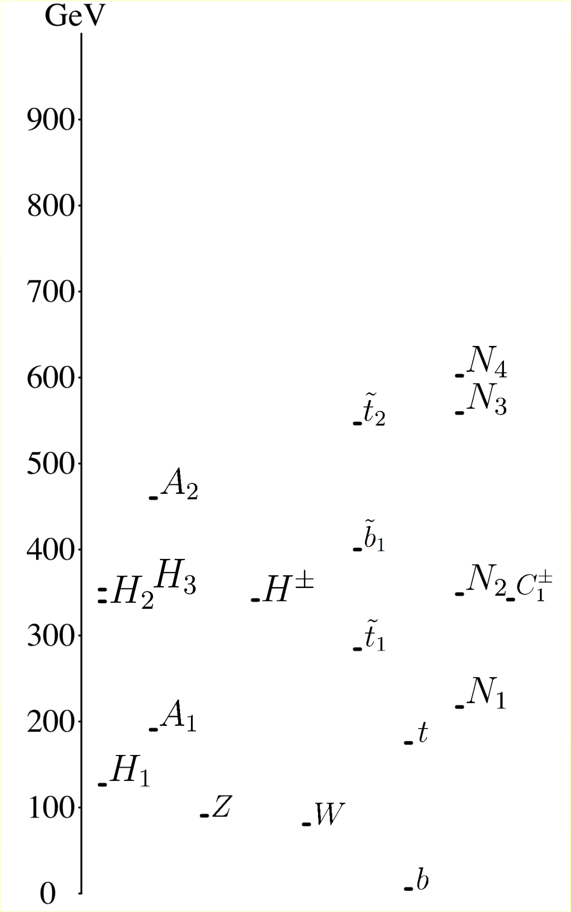
H_1	126 GeV	N_2	348 GeV
A_1	190 GeV	H_3	353 GeV
N_1	217 GeV	$\tilde{b}_1$	400 GeV
$\tilde{t}_1$	284 GeV	A_2	460 GeV
H_2	339 GeV	$\tilde{t}_2$	546 GeV
$H^\pm$	341 GeV	N_3	559 GeV
C_1	341 GeV	N_4	602 GeV

- Neutralino LSP or NLSP
- N_1 over 200 GeV, stop around 300

Four different sample spectra

(CC, Randall, Terning '12)

4. High duality scale



$\tilde{t}_1$	$\to N_1 + c$	99%
$\tilde{t}_1$	$\to N_1 + u$	1%
$\tilde{b}_1$	$\to \tilde{t}_1 + W^-$	100%
$\tilde{t}_2$	$\to \tilde{t}_1 + Z$	28%
$\tilde{t}_2$	$\to C_1^+ + b$	24%
$\tilde{t}_2$	$\to \tilde{b}_1 + W^+$	20%
$\tilde{t}_2$	$\to N_2 + t$	15%
$\tilde{t}_2$	$\to N_2 + t$	14%

- stop→N_1+c
- stop2→stop1+Z, C+b, sbottom+W,N+t
- sbottom→stop1+W
- Final states: j+MET, j+t+MET, j+W/Z +MET
- Traditional SUSY at reduced rates

Higgs branchings

SM fields	spectrum 1	spectrum 2	spectrum 3	spectrum 4
$\gamma\gamma$	1.02	1.02	0.95	0.85
gluons	0.65	0.83	0.82	0.73
WW, ZZ	0.89	0.96	0.89	0.74
$u\bar{u}$	0.72	1.0	0.89	0.72
$d\bar{d}$	1.01	0.91	0.89	0.77

Not so different from SM: plausible that LHC Higgs results can be reproduced

2. Composite Higgs and $\rho^{\pm,0}$: enhancement of $h \to \gamma\gamma$?

(Bellazzini, C.C., Hubisz, Serra, Terning '12)

Strong dynamics

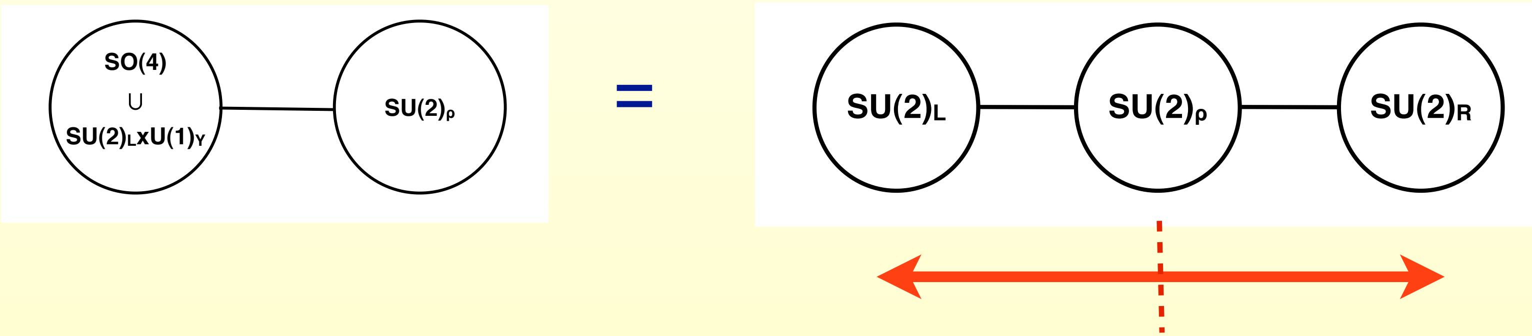
- Produces light higgs

- Additional resonances at cutoff Λ

- Higgs couplings could be different from SM values

- If higgs couplings very different from SM: unitarity may break down BEFORE cutoff scale
- Need additional light states to maintain unitarity to Λ
- Assume additional spin-1 triplet $\rho^{\pm,0}$
- Simplified model: assume custodial symmetry
- Pion Lagrangian for longi modes of W,Z from CCWZ
- Assume $\rho^{\pm,0}$ triplet of $SU(2)_C$

The moose for the simplest model:



P_{LR} parity

- Assume axial vectors integrated out
- Just use lowest states

•The Higgs Lagrangian:

$$\mathcal{L}_{\rm eff}^{(h)} = a\left(\frac{2m_W^2}{v}W_\mu^+W_\mu^- + \frac{m_Z^2}{v}Z_\mu^2\right)h + c_f\left(\frac{m_f}{v}\bar{f}f\right)h + c_\gamma\frac{\alpha}{\pi v}F_{\mu\nu}^2 h + c_g\frac{\alpha_s}{12\pi v}G_{\mu\nu}^2 h$$

• a parametrizes deviation of GB coupling - unitarity

• c_f parametrizes fermion coupling - unitarity in WW→ff channel

•The vector Lagrangian:

$$\begin{aligned}\mathcal{L}_{\rm eff}^{(\rho)} &= c_\rho\frac{m_\rho^2}{v}\left(\rho_\mu^{0\,2} + 2\rho_\mu^+\rho_\mu^-\right)h + c_{\rho Z}\left(\frac{m_Z^2}{v}Z_\mu\rho_\mu^0\right)h + c_{\rho W}\left(\frac{m_W^2}{v}W_\mu^+\rho_\mu^- + h.c.\right)h \\ &+ g_{\rho^0 WW}\left(\partial_\mu W_\nu^+ W_\mu^- - \partial_\mu W_\nu^- W_\mu^+\right)\rho_\nu^0 + g_{\rho WZ}\left[\left(\partial_\mu W_\nu^- Z_\mu - \partial_\mu Z_\nu W_\mu^-\right)\rho^{+\nu} + \text{h.c.}\right] \\ &+ \ldots + g_{\rho^0 f}\left(\bar{f}\gamma_\mu T_f^3 f\right)\rho_\mu^0 + g_{\rho^\pm f}\left(\bar{f}\gamma_\mu T^\mp f\right)\rho_\mu^\pm\end{aligned}$$

- ρVV interactions generated from ρ-V mixing~ $\frac{g}{2g_\rho}$

$$g_{\rho WW} = -g\frac{a}{2}\frac{m_W}{m_\rho} = -g\frac{g}{4g_\rho} \qquad g_{\rho WZ} = -g\frac{a}{2}\frac{m_Z}{m_\rho} = -g\frac{\sqrt{g^2+g'^2}}{4g_\rho}$$

- The parameters:

1. a: Higgs coupling suppression

2. m_ρ: the vector mass

3. c_ρ: the ρρh coupling

4. g_ρ: the ρ self-coupling

• ρVV interactions generated from ρ-V mixing~ $\frac{g}{2g_\rho}$

$$g_{\rho WW} = -g\frac{a}{2}\frac{m_W}{m_\rho} = -g\frac{g}{4g_\rho} \qquad g_{\rho WZ} = -g\frac{a}{2}\frac{m_Z}{m_\rho} = -g\frac{\sqrt{g^2+g'^2}}{4g_\rho}$$

• The parameters:

1. a: Higgs coupling suppression

2. m_ρ: the vector mass / from CCWZ $\quad a_\rho^2\frac{v^2}{2}\left(g_\rho\rho_\mu^a - E_\mu^a\right)^2$

$$m_\rho = a_\rho g_\rho v$$

3. c_ρ: the ρρh coupling

4. g_ρ: the ρ self-coupling / g_ρ expressed in terms of a_ρ and m_ρ and unitarity sum rule $\quad a^2 + 3a_\rho^2/4 = 1$ applied

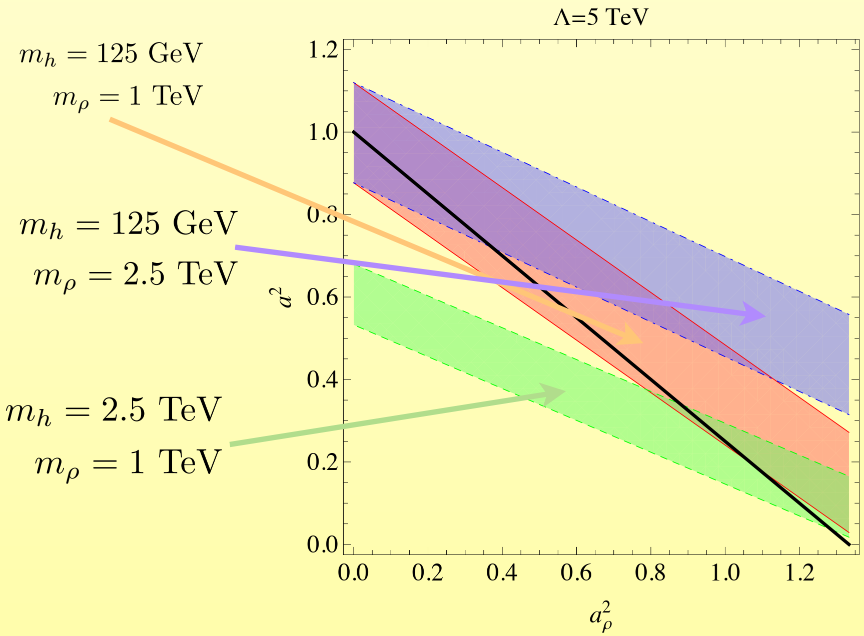
Unitarity

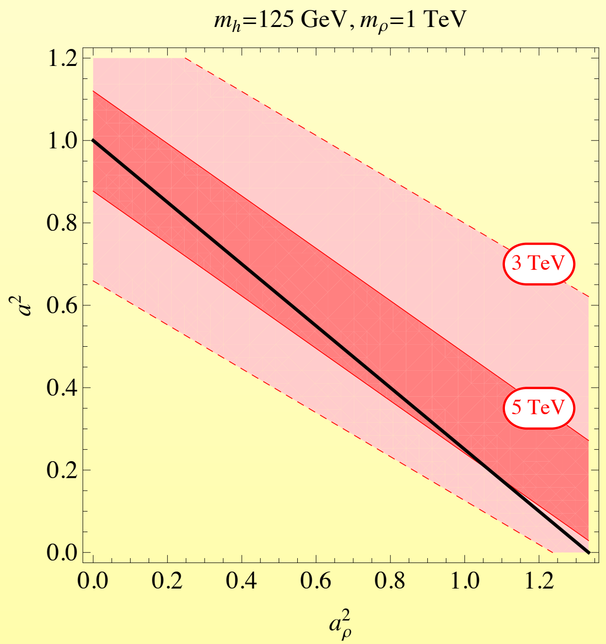
- Elastic scattering

$$A(s,t,u)^{(\pi\pi)} = \frac{s}{v^2} - \frac{a_\rho^2}{4v^2}\left[3s + m_\rho^2\left(\frac{s-u}{t-m_\rho^2} + \frac{s-t}{u-m_\rho^2}\right)\right] - \frac{a^2}{v^2}\left[\frac{s^2}{s-m_h^2}\right]$$

- Growing terms canceled if sum rule $a^2 + \frac{3}{4}a_\rho^2 = 1$

- How close do I have to be?



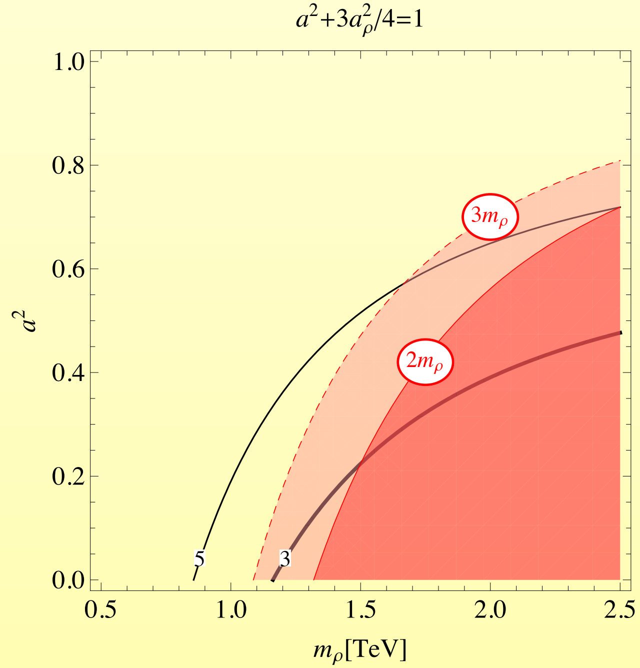


Unitarity

- Will impose sum rule and eliminate one parameter

$$a^2 + \frac{3}{4}a_\rho^2 = 1$$

- Region allowed from elastic unitarity:



- Sum rules satisfied in explicit model (eg. gauge-phobic higgs)

Unitarity

- Inelastic channels ππ→ρρ

$$A(s,t,u)^{(\rho_L\rho_L)} = \frac{s}{v^2}\left(a\,c_\rho - \frac{1}{4}\right)a_\rho^2 + \cdots$$

$$B(s,t,u)^{(\rho_L\rho_L)} = \frac{s}{4v^2}(a_\rho^2 - 1) + \frac{t}{4v^2}(a_\rho^2 - 2) + \cdots$$

- ππ→hh

$$A(s,t,u)^{(hh)} = \frac{s}{v^2}(a^2 - b) + \cdots$$

- ππ→hρ

$$A(s,t,u)^{(\rho_L h)} = i\frac{t-u}{2v^2}(a - c_\rho)a_\rho$$

- Will assume

$$b = a^2$$

$$c_\rho = a$$

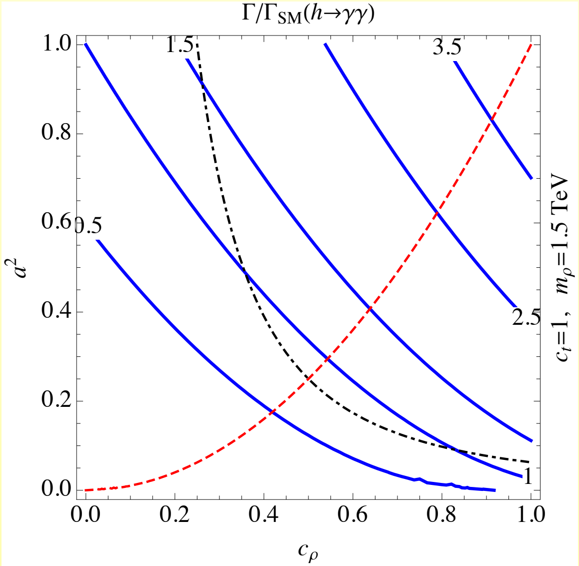
- Other channels require additional heavy states, could be close to cutoff (axial vector, heavy P odd H,...)

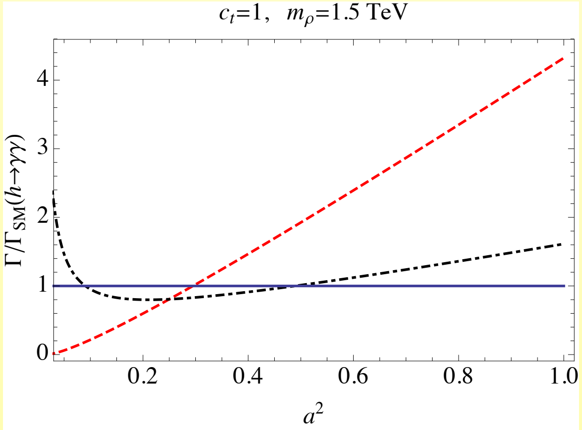
Effect of ρ on h→γγ

- Loops of ρ will contribute just like W loops

$$\Gamma/\Gamma_{\rm SM}(h \to \gamma\gamma) \simeq \left[1 + \frac{9}{8}c_\rho + \frac{9}{7}(a-1) - \frac{2}{7}(c_t - 1)\right]^2$$

- Suppression of higgs coupling can be compensated



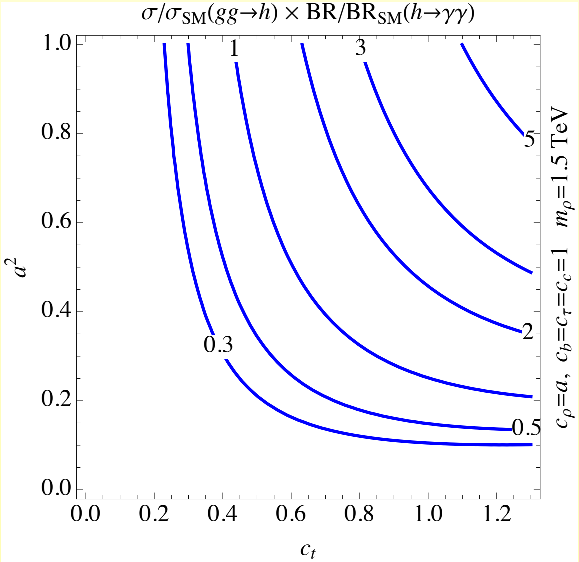


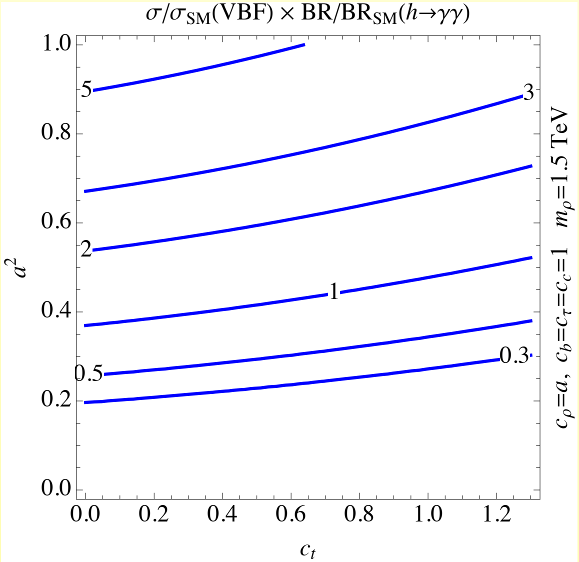
Effect of ρ on h→γγ

- The effect on σ Br:

$$\frac{\sigma}{\sigma_{\rm SM}}(gg\to h)\simeq\frac{\sigma}{\sigma_{\rm SM}}(gg\to ht\bar{t})=c_t^2 \qquad \frac{\sigma}{\sigma_{\rm SM}}(q\bar{q}\to hjj)=\frac{\sigma}{\sigma_{\rm SM}}(q\bar{q}\to hW)=a^2$$

$$\frac{\rm BR}{{\rm BR}_{\rm SM}}(h\to\gamma\gamma)\simeq\frac{\left[1+\frac{9}{8}c_\rho+\frac{9}{7}(a-1)-\frac{2}{7}(c_t-1)\right]^2}{c_b^2{\rm BR}_{\rm SM}(h\to b\bar{b})+a^2{\rm BR}_{\rm SM}(h\to VV^*)+\ldots}$$

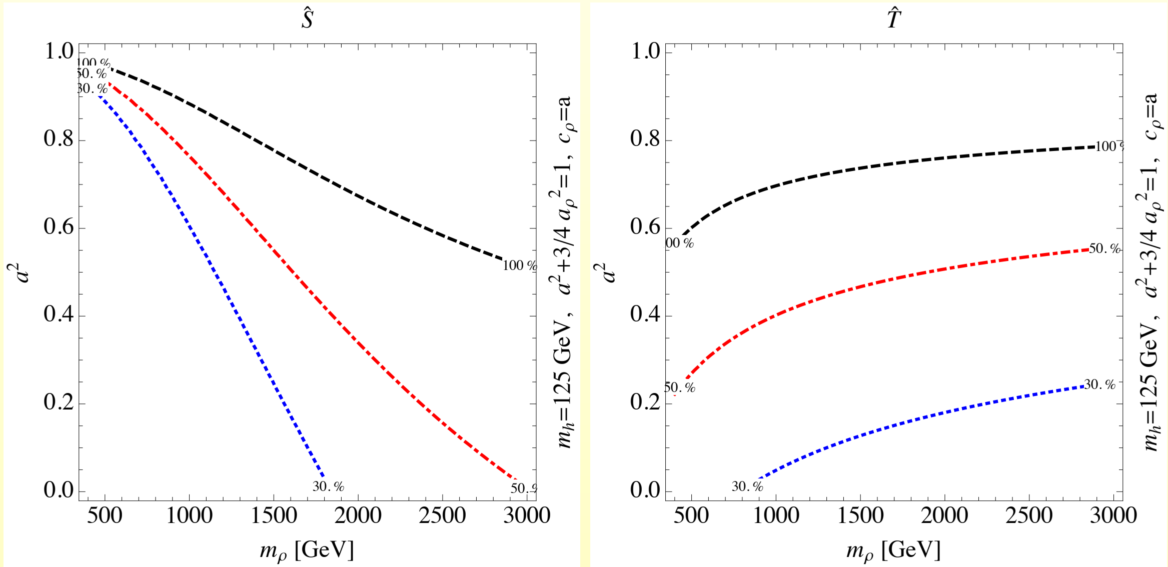




- Along unitarity sum rule (and where a not too small) mostly enhanced

Constraints on ρ: EWP

- Electroweak precision



- Tree-level UV contribution

$$\hat{S} = \frac{g_2^2}{g_2^2 + 4g_\rho^2} \simeq a_\rho^2 \frac{m_W^2}{m_\rho^2} \qquad \hat{T} = 0$$

- And loop IR contribution due to modified Higgs

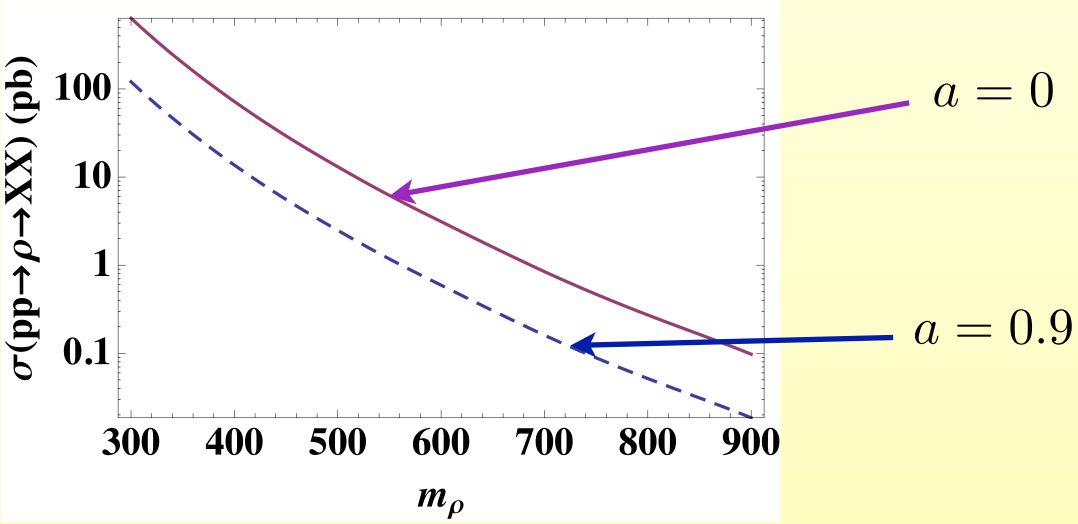
$$\delta\hat{S}_{\rm IR} = \frac{g^2}{96\pi^2}\left[(1-a^2)\log\left(\frac{\Lambda}{m_h}\right) + \log\left(\frac{m_h}{m_h(\text{ref})}\right)\right]$$

$$\delta\hat{T}_{\rm IR} = -\frac{3g'^2}{32\pi^2}\left[(1-a^2)\log\left(\frac{\Lambda}{m_h}\right) + \log\left(\frac{m_h}{m_h(\text{ref})}\right)\right]$$

Collider Constraints on ρ

- Charged ρ

- Production cross section (mainly DY):



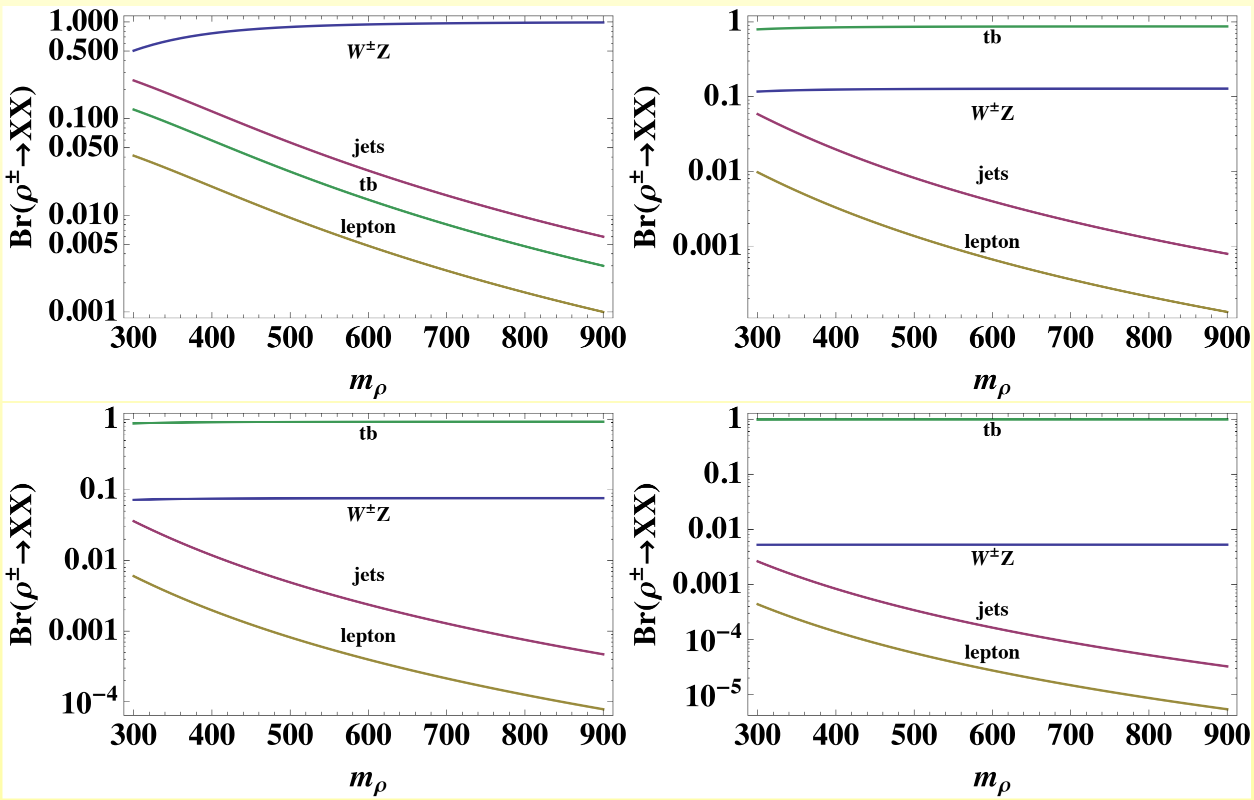
Collider Constraints on ρ

- Charged ρ

- Decay depends on coupling to fermions, diboson ρ→WZ always significant

Elem. third gen.

Comp. third gen. a=0

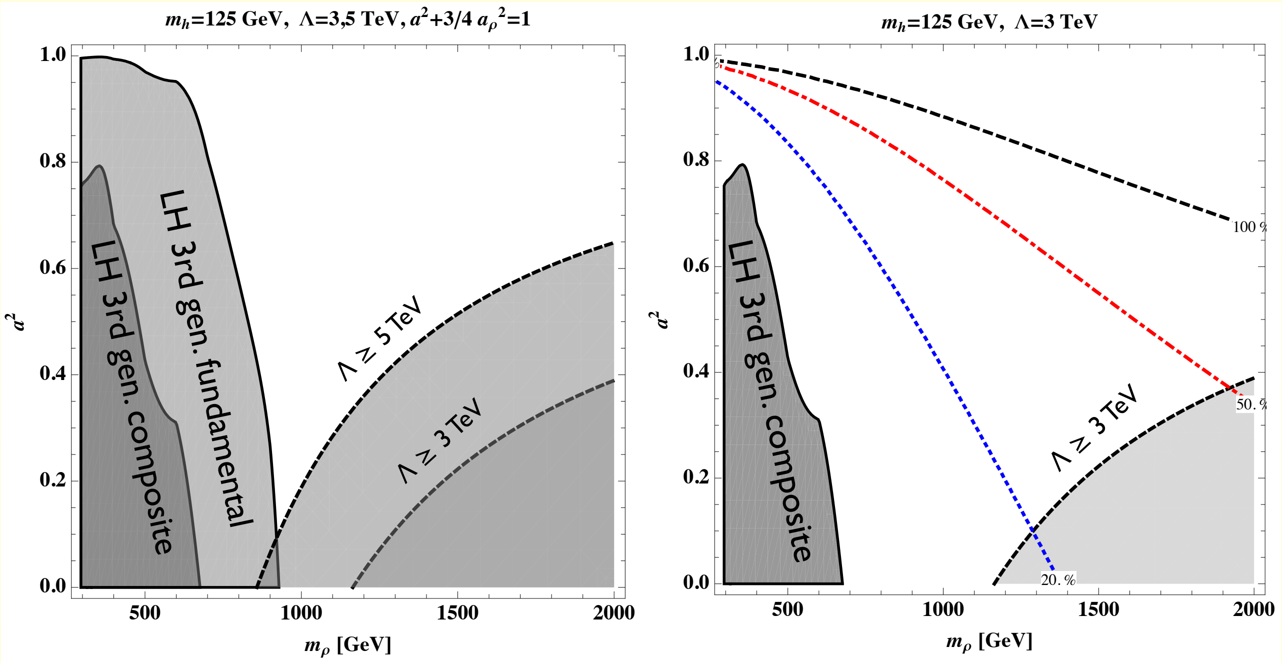


Comp. third gen. a=0.5

Comp. third gen. a=0.9

Collider Constraints on ρ

- Charged ρ→WZ→3l+ν CMS W' diboson search



- Large region allowed for 700 GeV < m_ρ<2 TeV

Collider Constraints on ρ

- Neutral ρ: WW decay should be searchable

- Higgs$\rightarrow$WW search very hard to reinterpret, highly optimized to higgs (DY production vs. VBF/gluon)

- Production $\sigma \sim 0.05$ pb too small for boosted/non-boosted ttbar resonance searches.

3. Techni-dilaton at 125 GeV?

(Bellazzini, C.C., Hubisz, Serra, Terning in progress)

An optimistic picture:

- Strong dynamics almost conformal
- Gets strong, produces condensate $\langle \mathcal{O} \rangle \sim v$
- Breaks EWS and conformality
- Produces dilaton with f~v

- Coupling to fields: $$\mathcal{L}_\chi = \frac{1}{2}\partial_\mu \bar{\chi}\partial^\mu \bar{\chi} + \frac{\bar{\chi}}{f} T^\mu{}_\mu + \cdots,$$

- If f~v about ``right" coupling to massive fields

$$\mathcal{L}_{\chi,SM} = \left(\frac{2\bar{\chi}}{f} + \frac{\bar{\chi}^2}{f^2}\right)\left[m_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu\right] + \frac{\bar{\chi}}{f}\sum_\psi m_\psi \bar{\psi}\psi,$$

(e.g. Goldberger, Grinstein, Skiba)

- Coupling to gluon, photon mostly from trace anomaly

$$(b^{IR} - b^{UV})\frac{\alpha}{8\pi}\frac{\chi}{f}G_{\mu\nu}^2$$

- b^{IR}-b^{UV} is the same form as in SM, can get arbitrarily close (or far) from SM answer by playing with the CFT matter content

- But is it reasonable to assume light dilaton?

- Argument against: if conformality broken by strong dynamics, at the breaking β and g necessarily large

- Large explicit breaking - do not expect to get a state well below Λ

(Holdom, Terning ’87; Contino, Pomarol, Rattazzi ’10; Kutasov ’11)

- Argument for: in RS can have very light radion mass if using Goldberger-Wise stabilization mechanism

(C.C. Graesser, Kribs ’00; Rattazzi, Zaffaroni ’00)

A toy example: 3-2 model

- Classic model of SUSY breaking (Affleck, Dine, Seiberg '85)

	$SU(3)$	$SU(2)$	$U(1)$	$U(1)_R$
Q	$\square$	$\square$	$1/3$	1
L	$\mathbf{1}$	$\square$	-1	-3
$\overline{U}$	$\overline{\square}$	$\mathbf{1}$	$-4/3$	-8
$\overline{D}$	$\overline{\square}$	$\mathbf{1}$	$2/3$	4

- Superpotential from tree-level + instanton:

$$W = \frac{\Lambda_3^7}{\det(\overline{Q}Q)} + \lambda\, Q\bar{D}L \ ,$$

- If λ<<1 VEVs stabilized at large values

$$\langle\phi\rangle \approx \frac{\Lambda_3}{\lambda^{1/7}}$$

$$V = |\frac{\partial W}{\partial Q}|^2 + |\frac{\partial W}{\partial \overline{U}}|^2 + |\frac{\partial W}{\partial \overline{D}}|^2 + |\frac{\partial W}{\partial L}|^2$$
$$\approx \frac{\Lambda_3^{14}}{\phi^{10}} + \lambda\frac{\Lambda_3^7}{\phi^3} + \lambda^2\phi^4 \ ,$$

A toy example: 3-2 model

- Dilaton mass: $m_{dil} \sim \lambda^{\frac{12}{7}} \Lambda_3$

- When weakly coupled: non-perturbative instanton effect breaks (approximate) conformality

- Mass of dilaton small compared to dynamical scale Λ_3

- If strongly coupled $\lambda \sim 1$ or larger - no parametric suppression (though Kähler potl. not calculable)

- SUSY and flat direction played a central role in finding a light dilaton, not expected in non-susy strong dynamics theories

The RS story for the dilaton

- Original RS: spontaneously broken conformality - exactly massless dilaton (the radion)

- Can add a small explicit breaking a la Goldberger-Wise: radion mass remains small

(C.C., Graesser, Kribs)

$$m^2_{radion} = \frac{4l^2(2k+u)u^2}{3k} e^{-2(u+k)r_0}$$

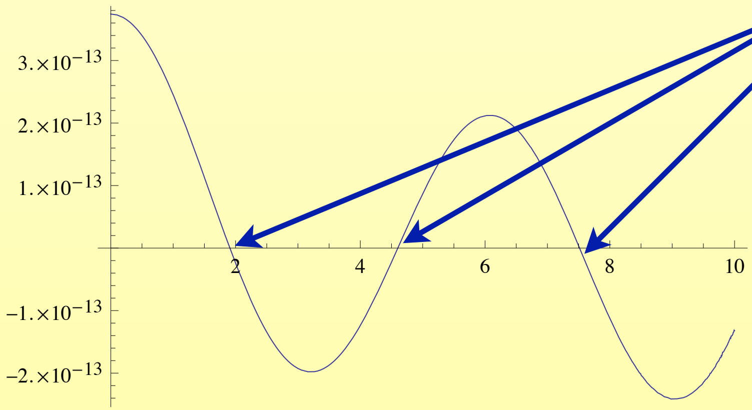
- l is a small parameter...

- BUT: we have assumed that conformality spontaneously broken - not necessarily broken by strong dynamics

The RS story for the dilaton

- An RS-type model for strong dynamics: just have a scalar field that is very flat in bulk and then suddenly blows up (over a very narrow range to limit region where $\beta \neq 0$)

- Can solve for radion mass numerically:



Zeroes mass of modes in units of KK scale

No light state

PRELIMINARY

Moral of the RS story

- While RS does have a light radion, it does not seem to be dual of a conformal breaking due to strong dynamics like in technicolor

- More realistic holographic duals of technicolor-like theories don’t seem to have a light state (as expected long time ago)

- What exactly is RS dual of? (seems more like a theory with a flat direction...)

Summary

•Hint for 125 GeV higgs(-like particle), no hint for other non-standard physics

•Implications for BSM models:

1. **SUSY**: 125 GeV problematic for MSSM, also why no MET? Possible solution: composite Higgs, 3rd gen. NMSSM. Concrete model based on Seiberg duality.

2. **Strong dynamics**: need light composite Higgs. If couplings deviate: might need other lighter resonances below cutoff. Concrete example: spin-1 triplet at 1 TeV can help unitarity, allowed by LHC.

3. **Techni-dilaton:** unlikely to be at 125 GeV.