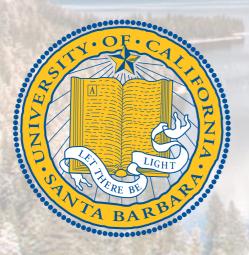
Neutral naturalness of the weak scale



Nathaniel Craig University of California, Santa Barbara

SUSY 2015

192-11.7 g

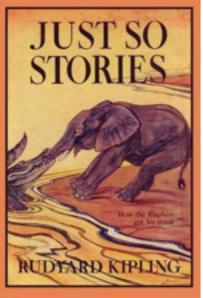
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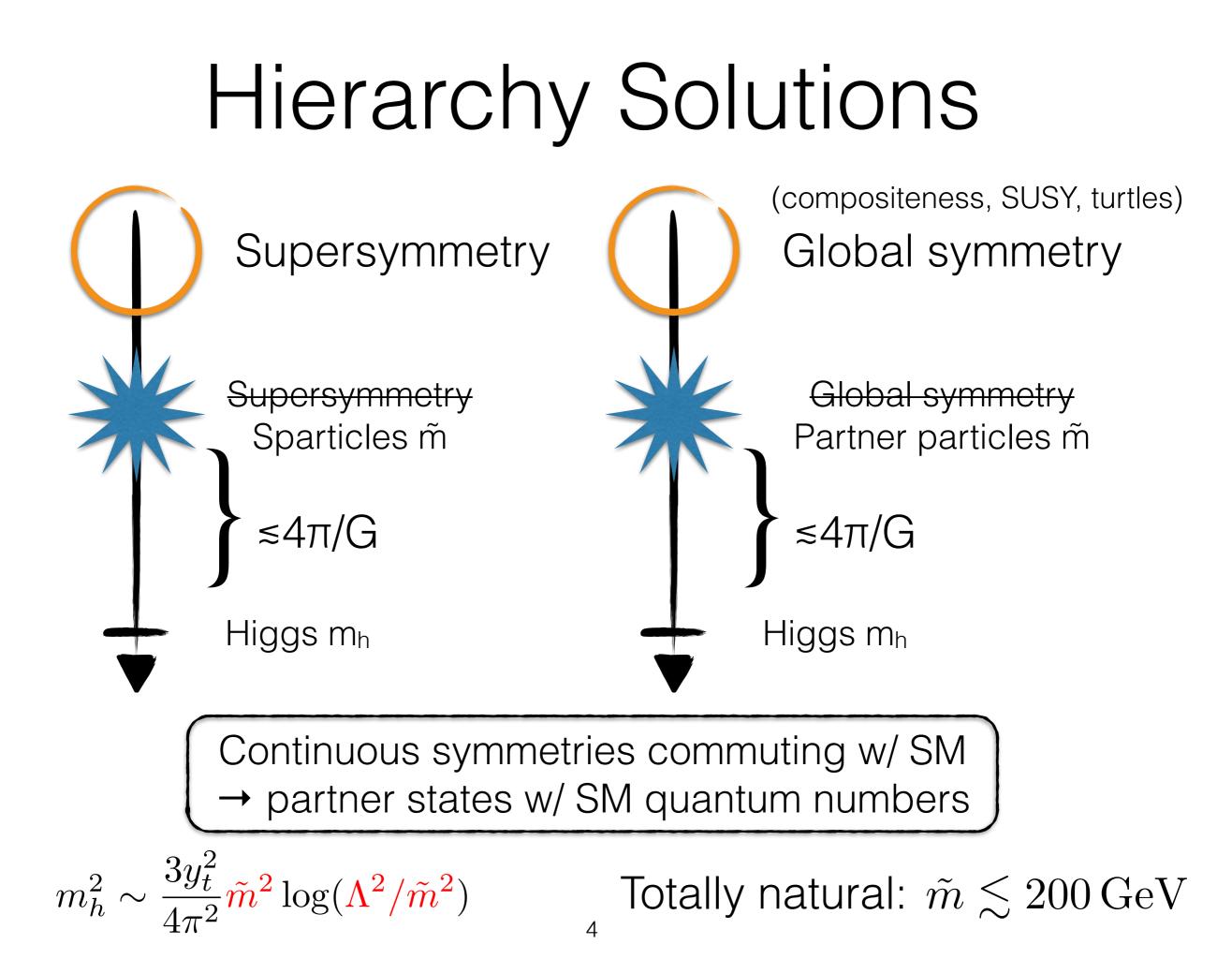
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- We expect many scales above the weak scale: flavor, dark matter, neutrino mass, gauge coupling unification, PQ symmetry breaking, ...
- At the very least, as far as we know a theory of quantum gravity should give physical thresholds around the string scale.
- An apparently elementary Higgs makes the hierarchy problem as pressing as ever.

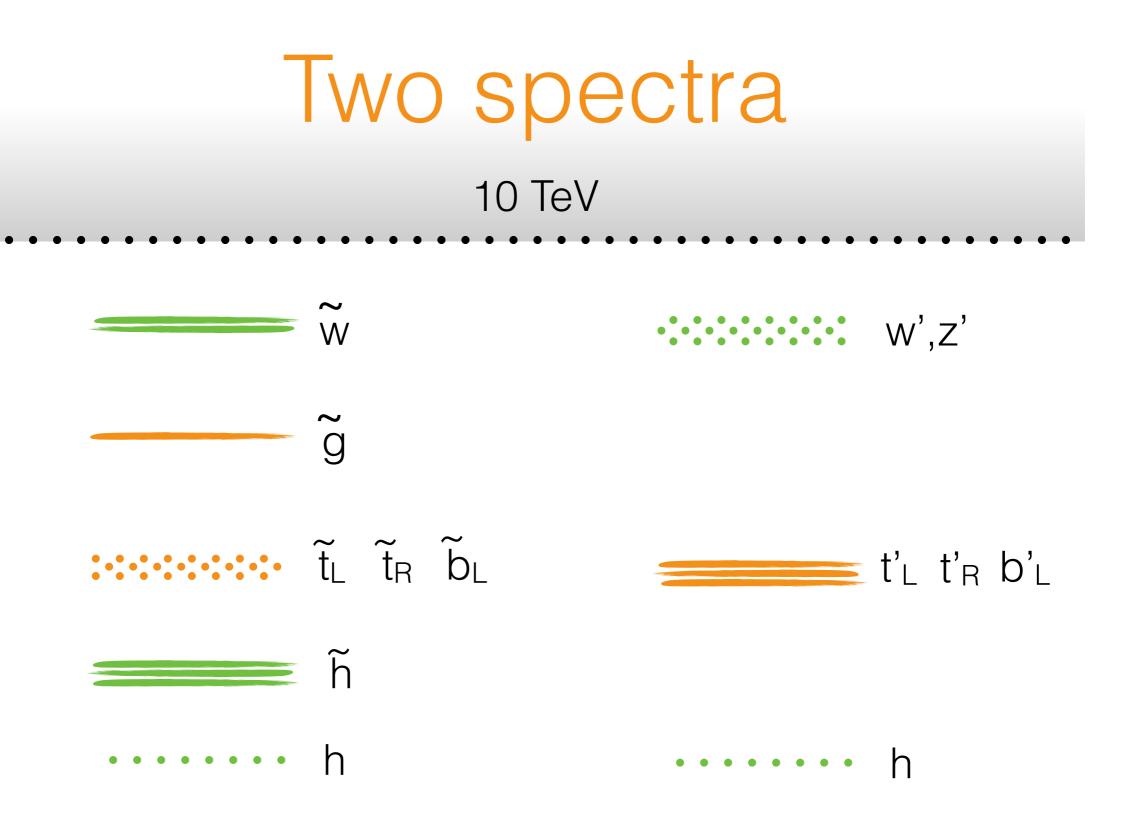


Natural vs. unnatural

Hierarchy problem is not a "just-so story"

Field Symmetry as $m \to 0$ Implication Spin-1/2 $m\Psi\bar{\Psi}$ $\Psi \to e^{i\alpha\gamma_5}\Psi$ $\delta m \propto m$ **Natural!** (chiral symmetry) Spin-1 $m^2 A_\mu A^\mu$ $A_{\mu} \to A_{\mu} + \partial_{\mu} \alpha$ $\delta m \propto m$ (gauge invariance) **Natural!** •mSpin-0 $m^2|H|^2$ $\delta m \propto \Lambda$ None **Unnatural!** З





Supersymmetry Global symmetry

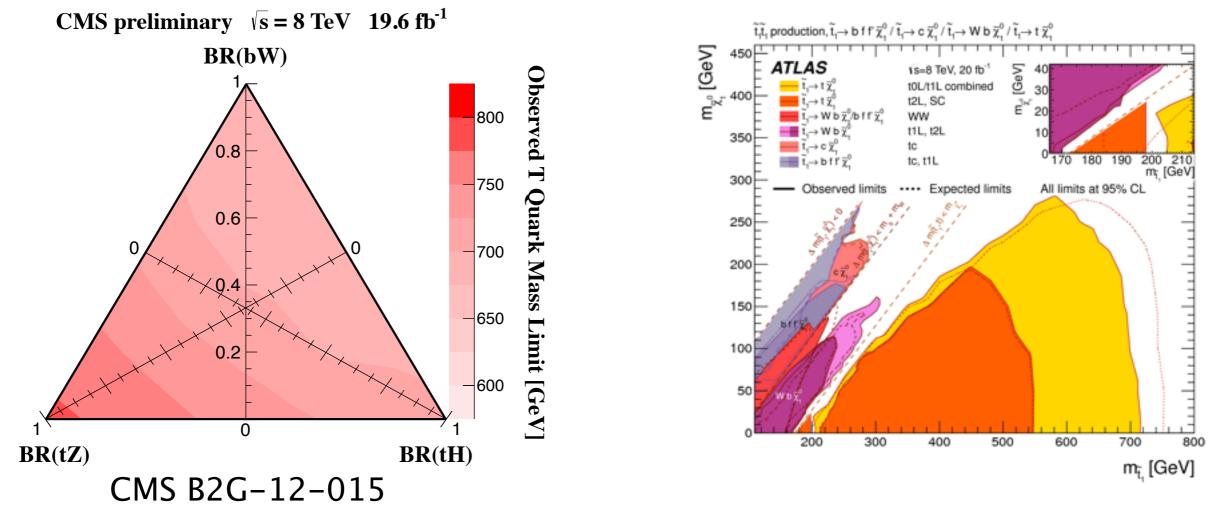
Simple game for LHC: look for colored partners.

Missing top partner problem

LHC searches driven by top partners

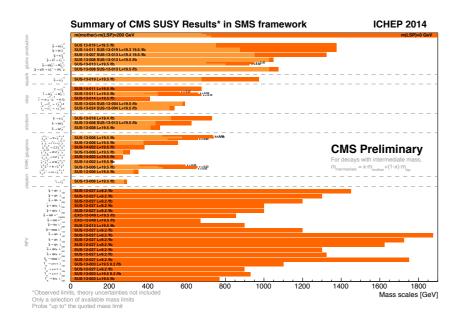
Global Symmetry

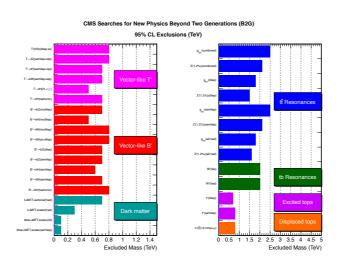
Supersymmetry

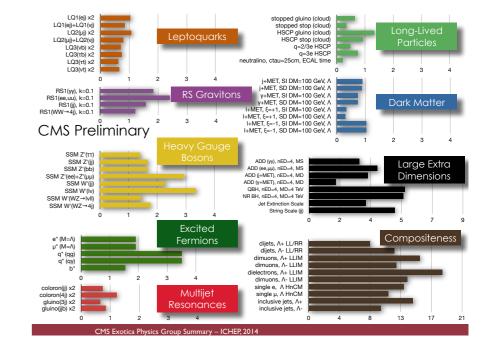


Problem 1: nothing yet (~10% tuning). Problem 2: not much new to do.

More generally...

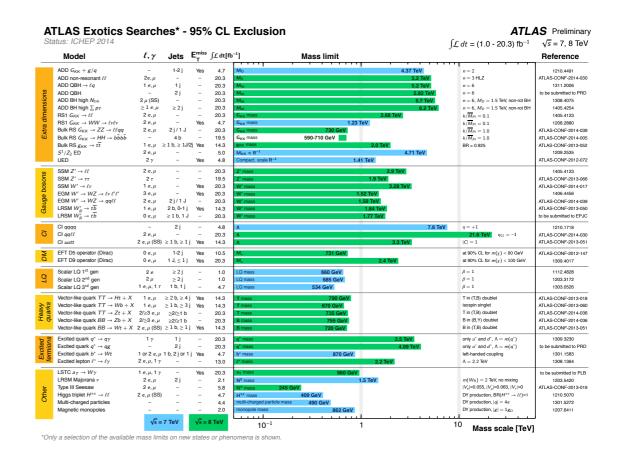






Only limits so far.

	Model	e,μ,τ,γ	Jets	$E_{\rm T}^{\rm miss}$	∫ <i>L dt</i> [fb	¹] Mass limit		Reference
	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	4. ž 1.7 TeV	m(q̃)=m(g̃)	1405.7875
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_{1}^{0}$	0	2-6 jets	Yes	20.3	<i>q̃</i> 850 GeV	$m(\tilde{\chi}_1^0)=0$ GeV, $m(1^{st} \text{ gen.} \tilde{q})=m(2^{nd} \text{ gen.} \tilde{q})$	
ß	$\tilde{q}\tilde{q}\gamma, \tilde{q}\rightarrow q\tilde{\tilde{\chi}}_{1}^{0}$ (compressed)	1γ	0-1 jet	Yes	20.3	q 250 GeV	$m(\tilde{q}) - m(\tilde{\chi}_{1}^{0}) = m(c)$	1411.1559
ocal ci leo	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$	0	2-6 jets	Yes	20.3	ž 1.33 TeV	m($\bar{\chi}_{1}^{0}$)=0 GeV	1405.7875
ġ.	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_{1}^{0}$	1 e, µ	3-6 jets	Yes	20	ž 1.2 TeV	$m(\tilde{\chi}_{1}^{0}) < 300 \text{ GeV}, m(\tilde{\chi}^{*}) = 0.5(m(\tilde{\chi}_{1}^{0}) + m(\tilde{g}))$	1501.03555
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell \ell / \ell \nu / \nu \nu)\tilde{\chi}_{1}^{0}$	2 e,µ	0-3 jets	-	20	ž 1.32 TeV	$m(\tilde{x}_1^0)=0 \text{ GeV}$	1501.03555
2	GMSB (<i>t</i> NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	ž 1.6 TeV	tanβ >20	1407.0603
5	GGM (bino NLSP)	2γ	-	Yes	20.3	ž 1.28 TeV	m(\tilde{t}_{1}^{0})>50 GeV	ATLAS-CONF-2014-00
	GGM (wino NLSP)	1 e, μ + γ γ		Yes	4.8 4.8	š 619 GeV	m({t 1 1)>50 GeV	ATLAS-CONF-2012-14 1211.1167
•	GGM (higgsino-bino NLSP) GGM (higgsino NLSP)	γ 2 e, μ (Z)	1 b 0-3 jets	Yes	4.8	ž 900 GeV	m($\tilde{\chi}_{1}^{0}$)>220 GeV m(NLSP)>200 GeV	1211.1167 ATLAS-CONF-2012-15
	Gravitino I SP	2 e, µ (Z) 0	mono-iet		5.8 20.3	ž 690 GeV F ^{1/2} scale 865 GeV	m(NLSP)>200 GeV $m(\tilde{G})>1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{g})=1.5 \text{ TeV}$	ATLAS-CONF-2012-15 1502.01518
_								
§ med.	$\bar{g} \rightarrow b\bar{b}\bar{\chi}_{1}^{0}$ $\bar{g} \rightarrow t\bar{t}\bar{\chi}_{1}^{0}$	0	3 b 7-10 iets	Yes	20.1	ž 1.25 TeV ž 1.1 TeV	$m(\tilde{\chi}_{1}^{0}) < 400 \text{ GeV}$ $m(\tilde{\chi}_{1}^{0}) < 350 \text{ GeV}$	1407.0600 1308.1841
ne.	$g \rightarrow t \tilde{\chi}_1^0$ $\tilde{g} \rightarrow t \tilde{\chi}_1^0$	0-1 e, µ	3 h	Yes	20.3	ž 1.34 TeV	$m(x_1) < 350 \text{ GeV}$ $m(\tilde{x}_1^0) < 400 \text{ GeV}$	1407 0600
100	$\tilde{g} \rightarrow b \tilde{\chi}_{1}^{+}$	0-1 e, µ	3 b	Yes	20.1	ž 1.3 TeV	m(t)<400 GeV m(t)<300 GeV	1407.0600
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$	0	2 h	Yes	20.1	δ ₁ 100-620 GeV	m($\tilde{\chi}_{1}^{0}$)<90 GeV	1308.2631
5	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow t \tilde{\chi}_1^{\pm}$	2 e. u (SS)	0-3 h	Yes	20.3	bi 275-440 GeV	$m(\tilde{x}_{1}^{0}) = 2 m(\tilde{x}_{1}^{0})$	1404.2500
Cti	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b \tilde{\chi}_1^{\pm}$	1-2 e, µ	1-2 b	Yes	4.7	7 110-167 GeV 230-460 GeV	$m(\tilde{\chi}_{1}^{0}) = 2m(\tilde{\chi}_{1}^{0}), m(\tilde{\chi}_{1}^{0})=55 \text{ GeV}$	1209.2102, 1407.0583
9	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$	2 e.µ	0-2 jets	Yes	20.3	Ĩi 90-191 GeV 215-530 GeV	$m(\tilde{\chi}_{1}^{0})=1 \text{ GeV}$	1403.4853.1412.4743
20	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 e. µ	1-2 b	Yes	20	1 210-640 GeV	$m(\tilde{x}_1^0) = 1 \text{ GeV}$	1407.0583,1406.1122
5	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$	0 m	ono-jet/c-t	tag Yes	20.3	i 90-240 GeV	m(t)-m(x) <85 GeV	1407.0608
direct production		2 e, µ (Z)	1 b	Yes	20.3	ĩ ₁ 150-580 GeV	$m(\bar{\chi}_{1}^{0}) > 150 \text{ GeV}$	1403.5222
0	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	3 e, µ (Z)	1 <i>b</i>	Yes	20.3	ĩ ₂ 290-600 GeV	m($\tilde{\chi}_{1}^{0}$)<200 GeV	1403.5222
_	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e, µ	0	Yes	20.3	7 90-325 GeV	m($\tilde{\xi}_{1}^{0}$)=0 GeV	1403.5294
	$\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, µ	0	Yes	20.3	λ ₁ [±] 140-465 GeV	$m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{+})+m(\tilde{\chi}_{1}^{0}))$	1403.5294
ಕ	$\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau}\nu(\tau\bar{\nu})$	2 τ	-	Yes	20.3	λ [±] 100-350 GeV	$m(\tilde{\chi}_{1}^{0})=0 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{n})+m(\tilde{\chi}_{1}^{0}))$	1407.0350
direct	$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{L} \nu \tilde{\ell}_{L} \ell(\tilde{\nu}\nu), \ell \tilde{\nu} \tilde{\ell}_{L} \ell(\tilde{\nu}\nu)$	3 e,µ	0	Yes	20.3		$m(\tilde{\chi}_{2}^{0}), m(\tilde{\chi}_{1}^{0})=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{+})+m(\tilde{\chi}_{1}^{0}))$	1402.7029
O	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} Z \tilde{\chi}_{1}^{0}$	2-3 e, µ	0-2 jets	Yes	20.3	x̃ [±] ₁ ,x̃ ⁰ ₂ 420 GeV	$m(\tilde{\chi}_1^a)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0$, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \rightarrow W \tilde{\chi}_{1}^{0} h \tilde{\chi}_{1}^{0}, h \rightarrow b \bar{b} / W W / \tau \tau / \tau$		0-2 b	Yes	20.3	$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0}$ 250 GeV	$m(\tilde{\chi}_1^a)=m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0)=0$, sleptons decoupled	1501.07110
	$\tilde{\chi}_2^0 \tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0 \rightarrow \tilde{\ell}_{\mathrm{R}} \ell$	4 e,µ	0	Yes	20.3	x̃ ⁰ _{2,3} 620 GeV m(x̃ ⁰ ₂)=	$n(\tilde{x}_{3}^{0}), m(\tilde{x}_{1}^{0})=0, m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{x}_{2}^{0})+m(\tilde{\chi}_{1}^{0}))$	1405.5086
	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	20.3	λ [±] 270 GeV	$m(\tilde{\chi}_{1}^{a})-m(\tilde{\chi}_{1}^{0})=160$ MeV, $\tau(\tilde{\chi}_{1}^{a})=0.2$ ns	1310.3675
θS	Stable, stopped g R-hadron Stable g R-hadron	0	1-5 jets	Yes	27.9	ž 832 GeV	$m(\tilde{\chi}_1^0)=100 \text{ GeV}, 10 \ \mu s < r(\tilde{g}) < 1000 \text{ s}$	1310.6584
tic		trk () 1-2 µ	-	-	19.1	ž 1.27 TeV	10 <tan8<50< td=""><td>1411.6795</td></tan8<50<>	1411.6795
ar	GMSB, stable $\tilde{\tau}, \tilde{\chi}_{1}^{0} \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, GMSB, \tilde{\chi}_{1}^{0} \rightarrow \gamma \tilde{G}, \text{long-lived } \tilde{\chi}_{1}^{0}$	μ) 1-2 μ 2 γ	-	Yes	19.1 20.3	x̃ ⁰ 537 GeV x̃ ⁰ 435 GeV	1u <tanp<50 2<r(<math>\tilde{U}_{1}^{0})<3 ns. SPS8 model</r(<math></tanp<50 	1411.6795 1409.5542
Long-lived particles	$\tilde{q}q, \tilde{\chi}_1^0 \rightarrow qq\mu$ (RPV)	2 γ 1 μ, displ. vtx	-	res	20.3	λ ₁ 430 GeV ã 1.0 TeV	$2 < r(\tilde{\chi}_1) < 3$ ns, SPS8 model $1.5 < cr < 156$ mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-09
-	LFV $pp \rightarrow \bar{v}_{\tau} + X, \bar{v}_{\tau} \rightarrow e + \mu$						λ ₁₁₁ =0.10, λ ₁₃₂ =0.05	
	LFV $pp \rightarrow v_{\tau} + X, v_{\tau} \rightarrow e + \mu$ LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e(\mu) + \tau$	2 e,μ 1 e,μ + τ	-		4.6 4.6	 <i>ν</i>_r 1.61 TeV <i>ν</i>_r 1.1 TeV 	$\lambda'_{311}=0.10, \lambda'_{132}=0.05$ $\lambda'_{111}=0.10, \lambda'_{1(2)33}=0.05$	1212.1272
	Bilinear RPV CMSSM	2 e, µ (SS)	0-3 b	Yes	20.3	<i>q̃. ĝ</i> 1.35 TeV	$m(\tilde{q})=m(\tilde{g}), c\tau_{LSP} < 1 \text{ mm}$	1404.2500
2	$\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow e e \tilde{v}_{\mu}, e \mu \tilde{v}_{e}$	4 e,μ		Yes	20.3	λ [±] 750 GeV	$m(\tilde{\chi}_{1}^{0}) > 0.2 \times m(\tilde{\chi}_{1}^{0}), \lambda_{121} \neq 0$	1405.5086
5	$\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow W \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow \tau \tau \tilde{\nu}_{e}, e \tau \tilde{\nu}_{\tau}$	3 e, μ + τ	-	Yes	20.3	X [±] 450 GeV	$m(\tilde{\chi}_{1}^{0})>0.2\times m(\tilde{\chi}_{1}^{+}), \lambda_{133}\neq 0$	1405.5086
	$\tilde{g} \rightarrow q\bar{q}q$	0	6-7 jets	-	20.3	ž 916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-09
	$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	2 e, µ (SS)	0-3 b	Yes	20.3	ž 850 GeV		1404.250
ner	Scalar charm, $\tilde{c} \rightarrow c \tilde{\chi}_1^0$	0	2 c	Yes	20.3	č 490 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1501.01325



ly a selection of the available mass limits on new states or phenomena is shown. All limits quoted are observed minus 1 σ theoretical signal cross section uncerta

(

But: is this all there is?

Maybe we've spent too much time under our favorite lamp-posts.



(Even if you do not find naturalness compelling, its role as a signature/search generator begs for further exploration)

Discrete symmetries

Discrete symmetry

Higgs m_h

Symmetry-based approaches to hierarchy problem employ *continuous symmetries.*

Discrete symmetry Neutral partners m Leads to partner states w/ SM quantum numbers.

Discrete symmetries can also serve to protect the Higgs.

Leads to partner states w/ non-SM quantum numbers.

"Neutral naturalness"

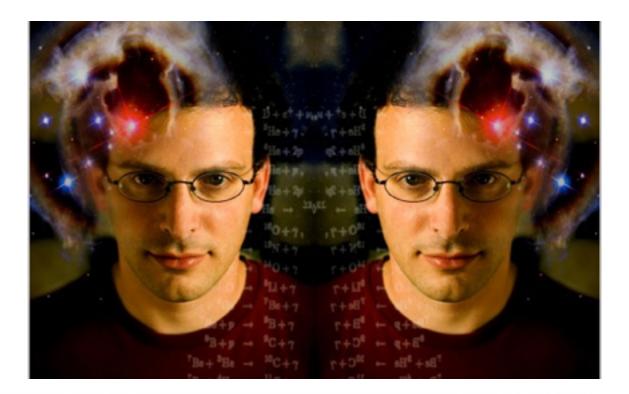
Neutral naturalness

Partner quantum #s	Global tree-level Higgs couplings	SUSY loop-level Higgs couplings
QCD x EWK	CHM, Little Higgs	MSSM
Neutral x EWK	Quirky Little Higgs	Folded SUSY
Neutral x Neutral	Twin Higgs	????

Proof of principle

The Twin Higgs

[Z. Chacko, H.-S. Goh, R. Harnik '05]



electroweak constraints are satisfied by construction. These models demonstrate that, contrary to the conventional wisdom, stabilizing the weak scale does not require new light particles charged under the Standard Model gauge groups.

Symmetry is $SM_A \times SM_B \times Z_2$

Consider a scalar H transforming as a fundamental under a global SU(4):

$$V(H) = -m^2 |H|^2 + \lambda |H|^4$$

Potential leads to spontaneous symmetry breaking,

$$|\langle H\rangle|^2 = \frac{m^2}{2\lambda} \equiv f^2$$

12

 $^{\ \ }$ $SU(4) \rightarrow SU(3)$

yields seven goldstone bosons.

UV: λ≫1 NLSM; λ≲1 LSM

The Twin Higgs Now gauge SU(2)_A x SU(2)_B c SU(4), w/ $H = \begin{pmatrix} H_A \\ H_B \end{pmatrix}$ Us Twins

Then 6 goldstones are eaten, leaving one behind.

Explicitly breaks the SU(4); expect radiative corrections.

$$V(H) \supset \frac{9}{64\pi^2} \left(g_A^2 \Lambda^2 |H_A|^2 + g_B^2 \Lambda^2 |H_B|^2 \right)$$

But these become SU(4) symmetric if $g_A=g_B$ from a Z_2 Quadratic potential has accidental SU(4) symmetry.

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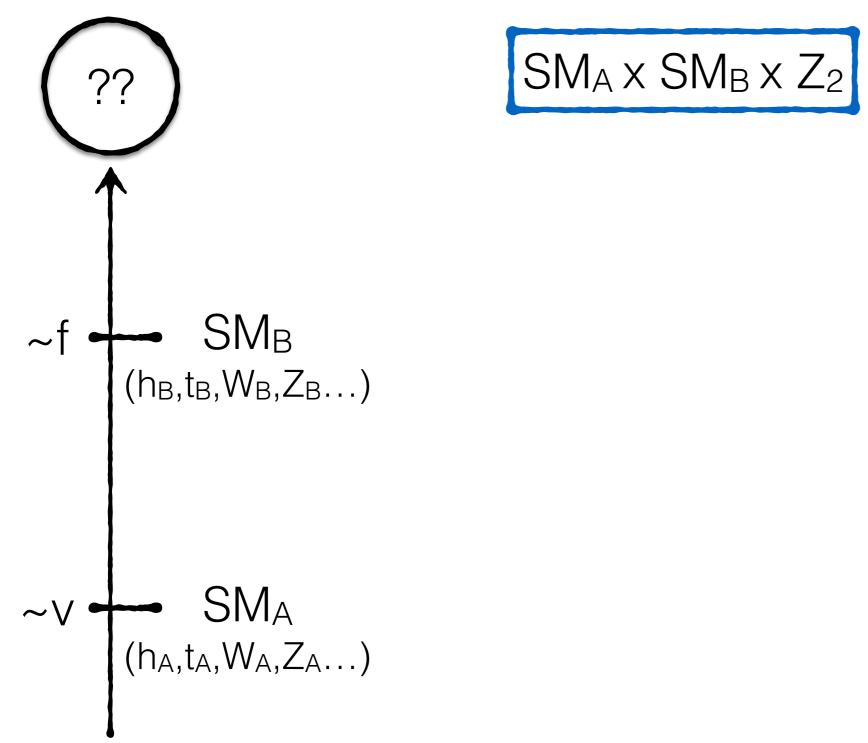
Then 6 goldstones are eaten, leaving one behind.

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$$V(H) \supset \frac{9}{64\pi^2} g^2 \Lambda^2 \left(|H_A|^2 + |H_B|^2 \right)$$

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Full theory: extend Z₂ to all SM matter and couplings.



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 $SM_A \times SM_B \times Z_2$ $V(H) \supset \frac{\Lambda^2}{16\pi^2} \left(-6y_t^2 + \frac{9}{4}g^2 + \dots \right) \left(|H_A|^2 + |H_B|^2 \right)$

 $\sim v - SM_A$ (h_A,t_A,W_A,Z_A...)

 $\sim f - SM_B$ (h_B,t_B,W_B,Z_B...)

Full theory: extend Z₂ to all SM matter and couplings.

 $SM_A\,x\,\,SM_B\,x\,\,Z_2$

 $V(H) \supset \frac{\Lambda^2}{16\pi^2} \left(-6y_t^2 + \frac{9}{4}g^2 + \dots \right) \left(|H_A|^2 + |H_B|^2 \right)$

 $|\langle H_A \rangle|^2 + |\langle H_B \rangle|^2 = f^2$

Breaks "quadratic" SU(4), higgses $EWK_A \& EWK_B$

 $\sim v - SM_A$ (h_A,t_A,W_A,Z_A...)

 $\sim f + SM_B$ (h_B,t_B,W_B,Z_B...)

Full theory: extend Z₂ to all SM matter and couplings.

 $SM_A \times SM_B \times Z_2$

→ SM_B (h_B,t_B,W_B,Z_B...)

 $\sim V - SM_A$ (h_A,t_A,W_A,Z_A...)

$$V(H) \supset \frac{\Lambda^2}{16\pi^2} \left(-6y_t^2 + \frac{9}{4}g^2 + \dots \right) \left(|H_A|^2 + |H_B|^2 \right)$$

$$\langle H_A \rangle |^2 + |\langle H_B \rangle|^2 = f^2$$

Breaks "quadratic" SU(4), higgses $EWK_A \& EWK_B$

Gives a radial mode, a goldstone mode, and eaten goldstones.

v « *f* for SM-like Higgs to be the goldstone

Full theory: extend Z₂ to all SM matter and couplings.

 $SM_A \times SM_B \times Z_2$

 $\sim f + SM_B$ (h_B,t_B,W_B,Z_B...)

 $\sim v - SM_A$ (h_A,t_A,W_A,Z_A...)

$$V(H) \supset \frac{\Lambda^2}{16\pi^2} \left(-6y_t^2 + \frac{9}{4}g^2 + \dots \right) \left(|H_A|^2 + |H_B|^2 \right)$$

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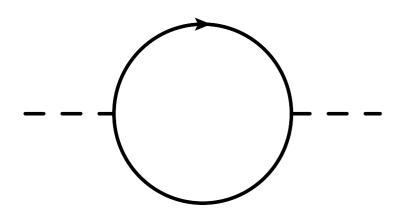
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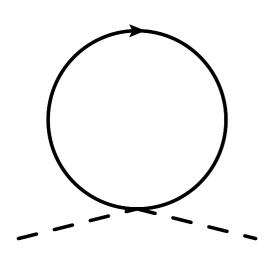
v « f for SM-like Higgs to be the goldstone

Primary coupling between SM_A and SM_B is via Higgs portal

The Twin Top



Standard Model



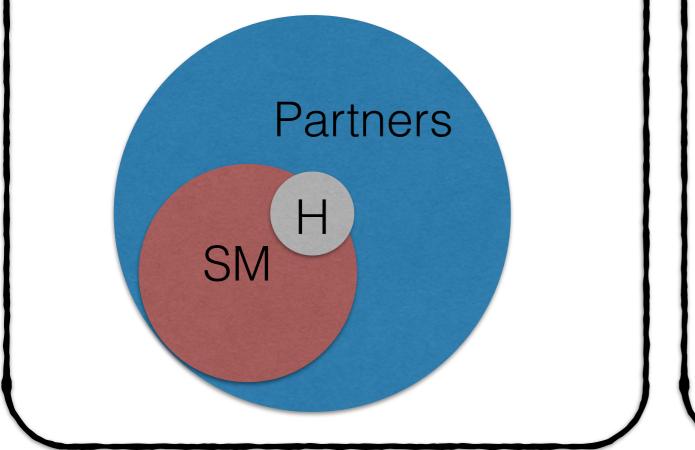
Twin top

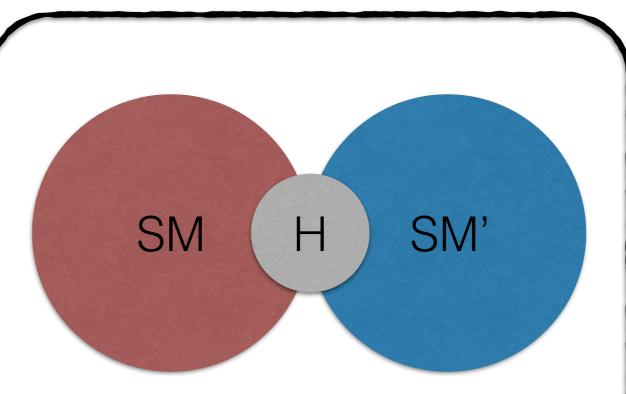
The top partner acts as we expect from global symmetry protection, but is not charged under QCD.

Symmetry protecting the Higgs takes us into a different SU(3) group. No direct limit on top partners.

The big picture

Instead of protecting Higgs w/ continuous symmetry so partners have SM charges...





Protect Higgs w/ a hidden sector mirroring the SM. Partners have no SM charges.

"Higgs is pseudo-goldstone of the accidental global symmetry of the quadratic action obeying a discrete symmetry"

UV Physics

The SUSY Twin Higgs SUSY protects the linear sigma model [Chang, Hall, Weiner '06; NC, Howe '14]

Strong

 SM_{R}

SMA

 $MSSM_A \times MSSM_B \times Z_2$

Quartic λ can be ~1; there is a perturbative radial twin Higgs mode

The Composite Twin Higgs

SMB

 SM_A

Compositeness for nonlinear sigma model

[Geller, Telem '14; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15] No perturbative radial twin Higgs mode; only fermionic partner states are light

"The twin Higgs is an example of ???"

NC, S. Knapen & P. Longhi [PRL 114, 061803 & 1411.7393/JHEP]

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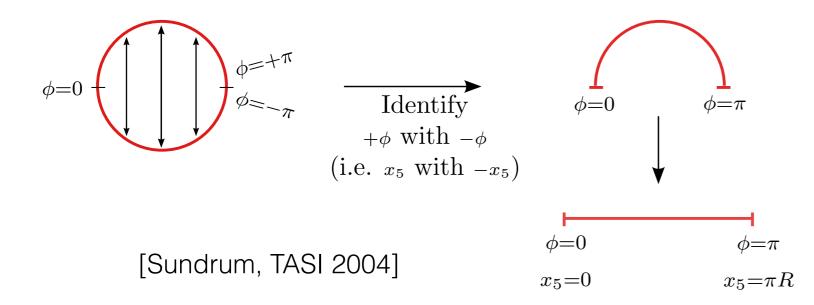
(Quotient space of manifold modded out by a discrete group) [Dixon, Harvey, Vafa, Witten, `85 & `86, Dixon, Friedan, Martinec, Shenker, `86]

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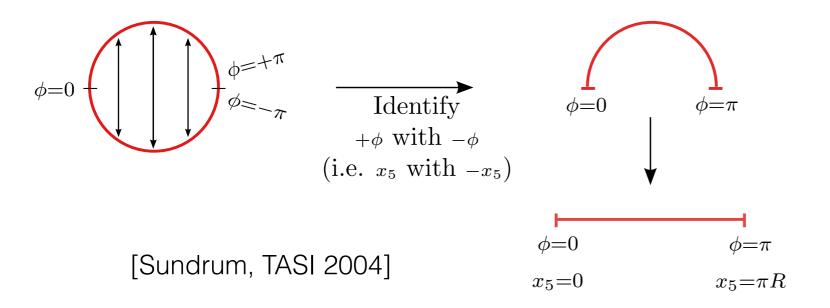
Familiar tool in string theory & field theory (realistic string compactifications, orbifold GUTs, 5D SUSY theories, etc.)

"The twin Higgs is an example of ???"

NC, S. Knapen & P. Longhi [PRL 114, 061803 & 1411.7393/JHEP]

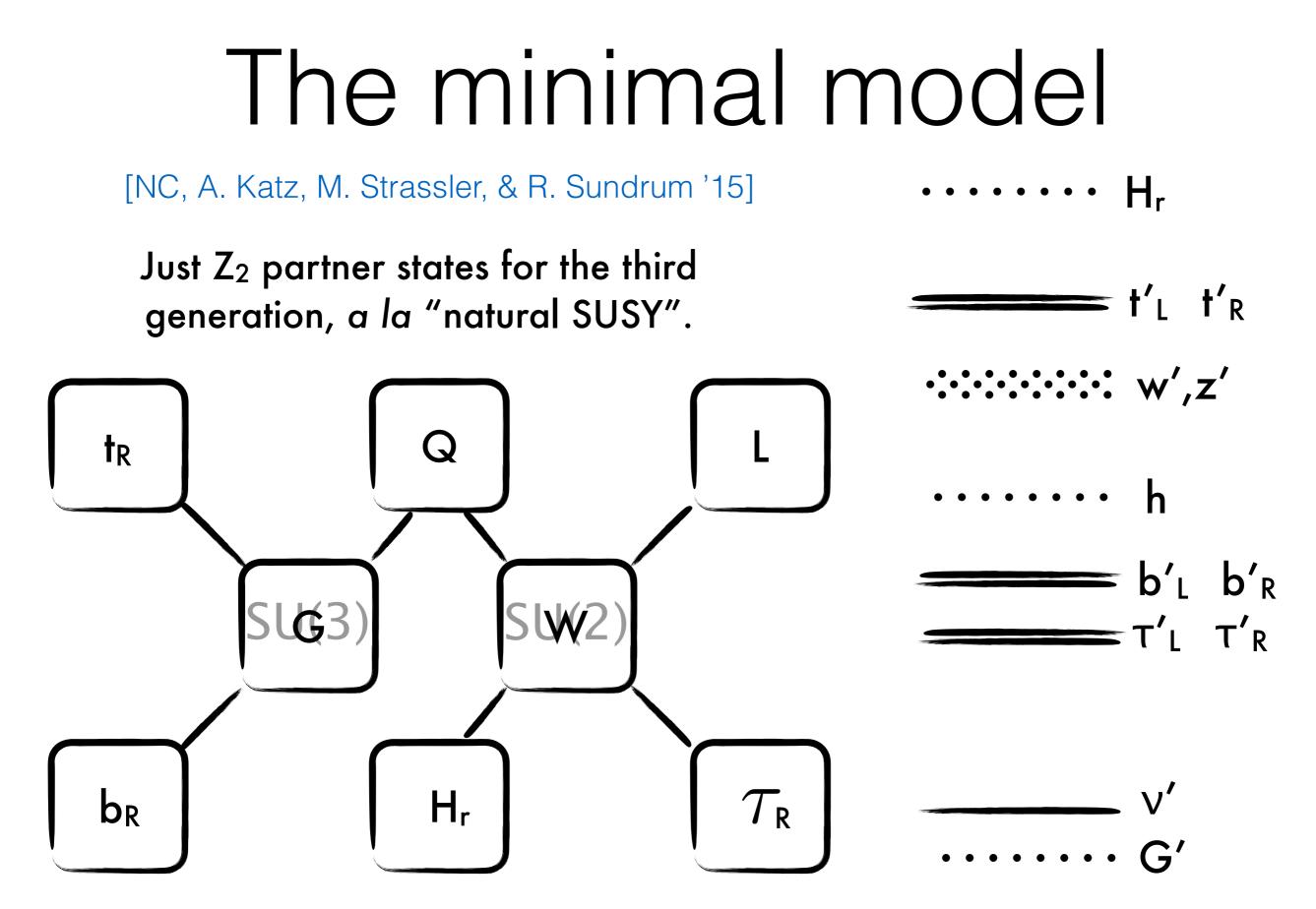
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Punchline: Many models of the twin kind, where Z₂ or larger symmetries may be exact or approximate.

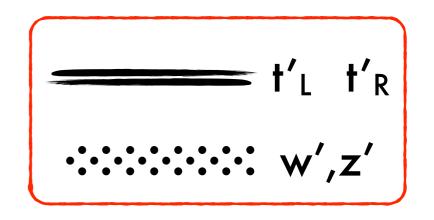


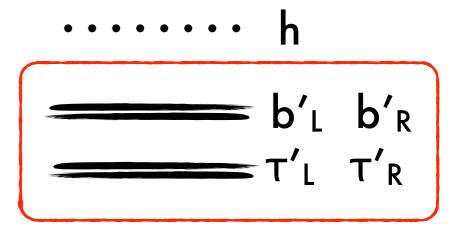
What to look for?

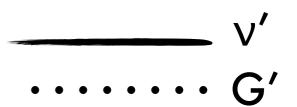
[Mixing leads to O(*v/f*)² changes in Higgs couplings; current O(20%) precision not constraining.]

- Partner states are SM neutral, couple only to the Higgs. Lighter than m_h/2: modest invisible BR (or more).
- Heavier than m_h/2: produce through an off-shell Higgs.

Hard but very interesting; directly probe naturalness ••••• H_r

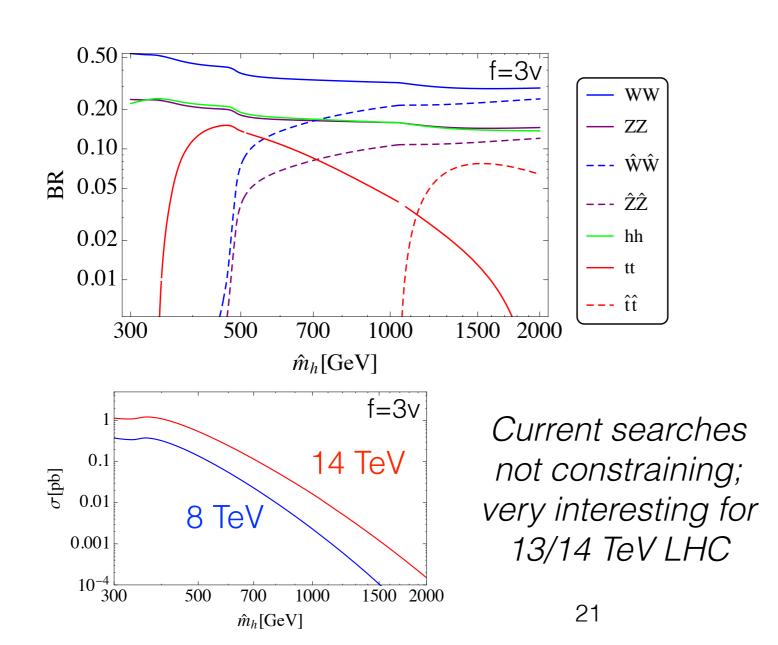


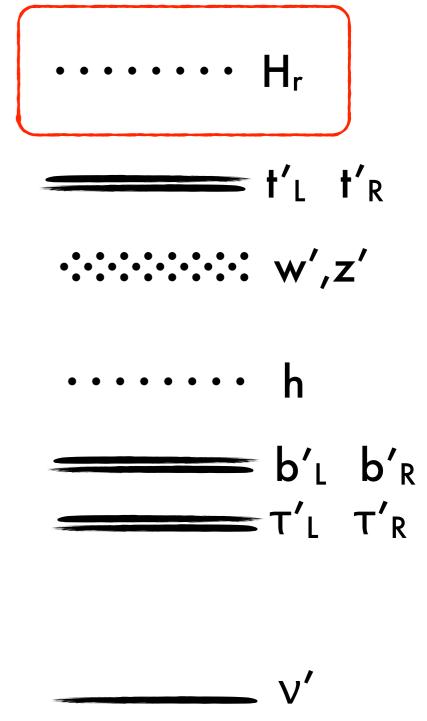




What to look for?

 Heavy radial mode may be visible in perturbative completion (e.g. SUSY). Looks like singlet mixing w/ invisible decays.



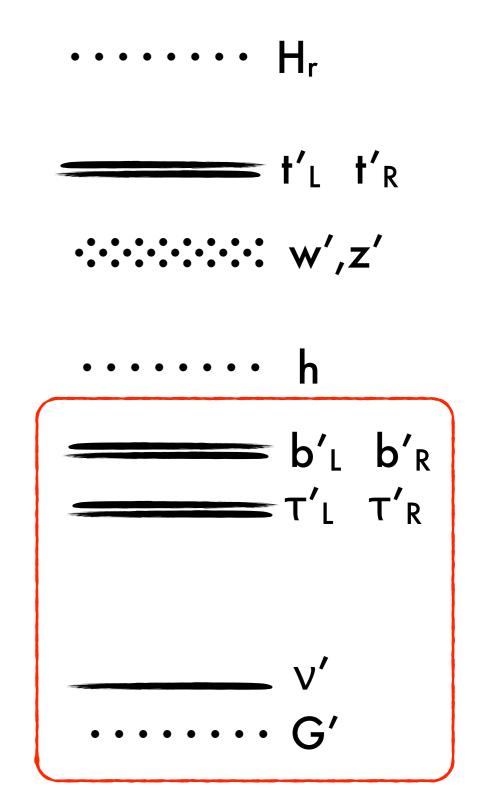


••••• G'

What to look for?

Decays into the hidden sector may come back to the Standard Model on interesting scales.

- Light fermions in the hidden sector: form light hadrons. Look for invisible decays of the Higgs.
- Light U(1) in the hidden sector: look for hidden photon phenomena.
- Light glueballs in the hidden sector...



Iwin QCD

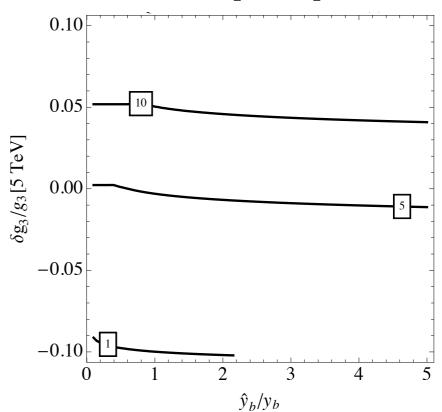
Coupling related to QCD by twin symmetry.

Must be present to keep top yukawas in twin sector(s) related to SM top yukawa.

Confinement within ~order of magnitude of QCD

If no light fermions, glueballs of twin **QCD** at bottom of the spectrum:

∧' [GeV]



$$m_{0++} \sim 7\Lambda'_{QCD}$$

Glueballs are special: mix with SM via dim-6 operator

 $\mathcal{L} \supset -\frac{\alpha'_3}{6\pi} \frac{v}{f} \frac{h}{f} G_{\mu\nu}^{'a} G_a^{'\mu\nu}$

Portal for production...

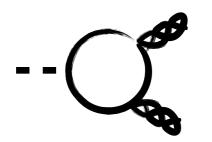
...and decay:

 $0^{++} \to h^* \to f \bar{f}$

 $gg \to h \to 0^{++} + 0^{++} + \dots$

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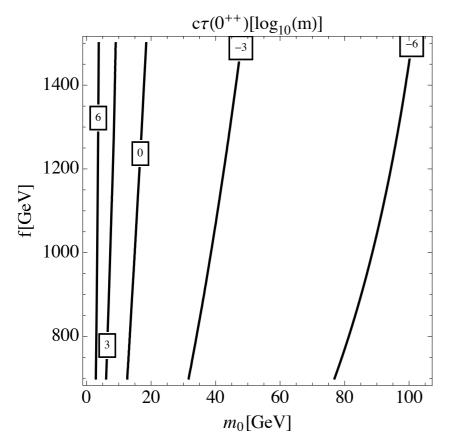
Displaced decays @ LHC



Glueballs produced through decays of Higgs into twin sector, BR ~ 0.1%-10%

Glueballs decay back to the SM through an off-shell SM higgs

$$\mathcal{L} \supset -\frac{\alpha'_3}{6\pi} \frac{v}{f} \frac{h}{f} G'^a_{\mu\nu} G'^{\mu\nu}_a \rightsquigarrow 0^{++} \to h^* \to \dots$$



Intriguing lifetime!

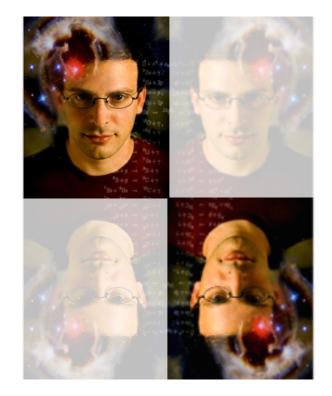
$$c\tau \approx 18 \text{ m} \times \left(\frac{10 \text{ GeV}}{m_0}\right)^7 \left(\frac{f}{500 \text{ GeV}}\right)^4$$

Strong dependence (7th power) on glueball mass → decays scan rapidly over LHC length scales.

A SUSY variation

Folded Supersymmetry

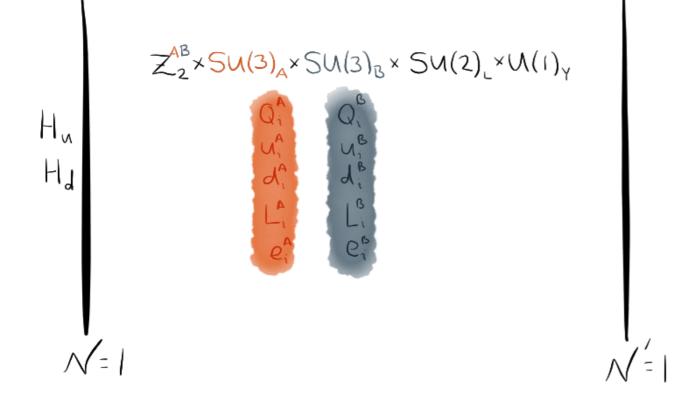
[G. Burdman, Z. Chacko, R. Harnik '06]



'folded supersymmetric' theories the one loop quadratic divergences of the Standard Model Higgs field are cancelled by opposite spin partners, but the gauge quantum numbers of these new particles are in general different from those of the conventional superpartners. This class of models is built

Symmetry is SUSY w/ [SU(3)xSU(3)fxZ2] xSU(2)xU(1)

SUSY without color

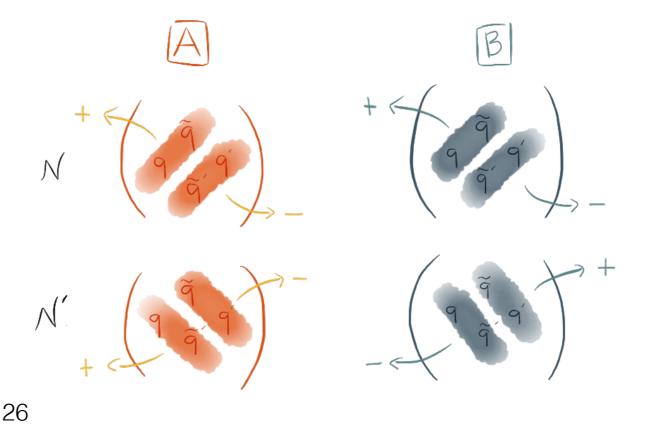


Can lead to light superpartners with different gauge quantum numbers from SM counterparts.

Folded SUSY

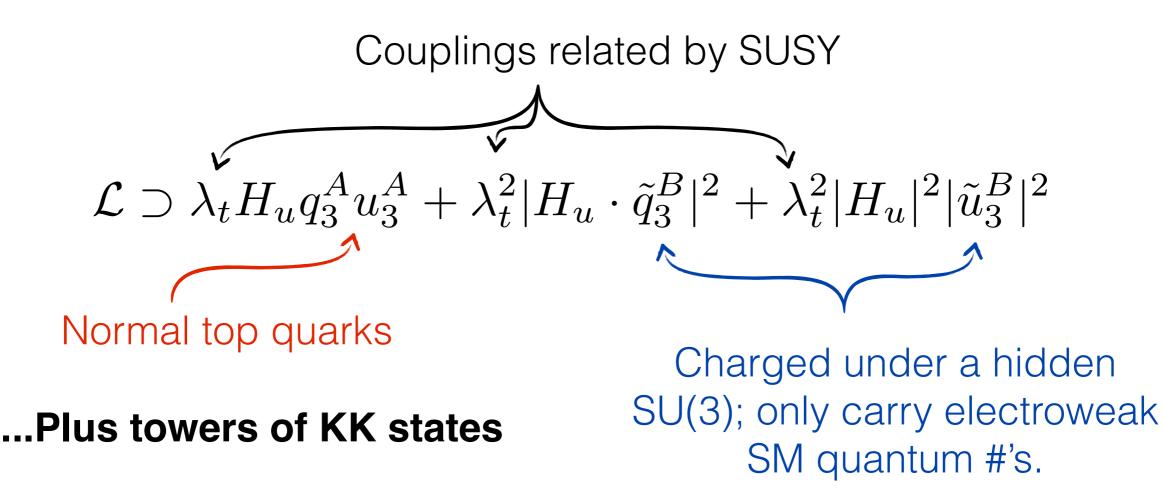
[Burdman, Chacko, Goh, Harnik '06] [Cohen, NC, Lou, Pinner '15] Want a low-energy spectrum with opposite-spin partners; start with a discrete symmetry + 5D SUSY.

Reduce symmetries & SUSY at the boundaries



Colorless Stops

Zero mode spectrum: SM fermions, folded sfermions

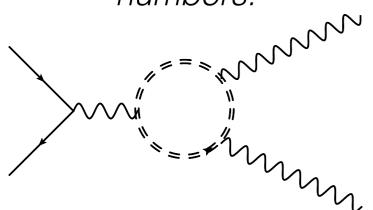


Many possible variations using the tools of 5D SUSY model-building.

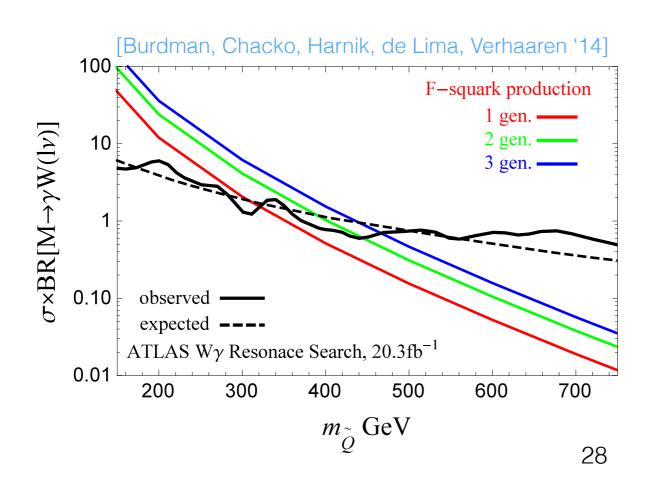
Higgs potential is finite and calculable, protected by 5D SUSY but with the lightest partner states neutral under QCD.

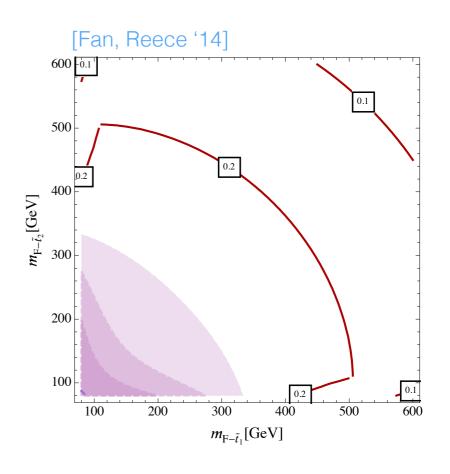
Colorless Signals

F-squarks carry electroweak quantum numbers.



- Produced via a Z, annihilate into hidden glueballs, which decay back to SM via Higgs; displaced decays @ LHC length scales.
- Produced via a *W*, annihilate back into the SM to shed their charge.
- Also leave their mark indirectly, correcting Higgs decays to photons.





Pandora's box

Much progress in recent years; much room to explore

[Chacko, Goh, Harnik '05; Barbieri, Gregoire, Hall '05; Chacko, Nomura, Papucci, Perez '05; Falkowski, Pokorski, Schmaltz '06; Chang, Hall, Weiner '06; Burdman, Chacko, Harnik '06; Foot, Volkas '06; Poland, Thaler '08; Harnik, Wizansky '08; Batra, Chacko '08; NC, Englert, McCullough '13; Chacko, Cui, Hong '13; NC, Howe '13; NC, Knapen, Longhi '14; Geller, Telem '14; Burdman, Chacko, Harnik, Lima, Verhaaren '14; NC, Lou, McCullough, Thalapillil '14; NC, Katz, Strassler, Sundrum '15; Batell,
McCullough '15; Barbieri, Greco, Rattazzi, Wulzer '15; Low, Tesi, Wang '15; NC, Katz '15; Garcia Garcia, Lasenby, March-Russell '15; Farina '15; Curtin, Verhaaren '15, Csaki, Kuflik, Lombardo, Slone '15; Kilic, Swaminathan '15; Cohen, NC, Lou, Pinner '15]



See also Friday talks by Curtin, Telem, Verhaaren, Salvioni

A plethora of new naturalness-related signatures @ LHC:

- Higgs invisible width [mirror Twin Higgs]
- Tree-level Higgs coupling deviations
 [Twin Higgs]
- Loop-level hγγ, hZZ coupling deviations [folded SUSY]

- Displaced Higgs decays [folded SUSY, fraternal Twin Higgs]
- Heavy higgs with reduced couplings, invisible width [Twin Higgs]
- Wγ, hh, displaced 4b resonances [folded SUSY]

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Thank you!