Natural Alternatives

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in inisor

gauge couplings unify, GUT

	Model	e,μ,τ,γ	Jets	E_{T}^{miss}	$\int \mathcal{L} dt [\mathbf{fb}]$	Mass limit	Reference
	MSUGRA/CMSSM $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q \tilde{\chi}_{1_0}^0$	0	2-6 jets 2-6 jets	Yes Yes	20.3 20.3	<i>ā</i> .ġ 1.7 TeV m(∂)=m(≿) ā 850 GeV m(ζ ²)=0 GeV, m(1 st gen. ā)=m(2 ^s	^d gen. q) 1405.7875
seuc	$\tilde{q}\tilde{q}\gamma, \tilde{q} \rightarrow q\chi_1^{\circ}$ (compressed) $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{a}\tilde{\chi}_1^{\circ}$	1γ 0	0-1 jet 2-6 jets	Yes Yes	20.3 20.3	q 250 GeV m(q̃)-m(t̃()) = m(c) ĝ 1.33 TeV m(t̃()) = 0 GeV	1411.1559 1405.7875
earc	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_{1}^{\pm} \rightarrow qqW^{\pm}\tilde{\chi}_{1}^{0}$	1 e, µ	3-6 jets	Yes	20		⁰ _i)+m(ĝ)) 1501.03555
Š	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$ CMCP ($\tilde{\ell}$ NLCP)	2 e, µ	0-3 jets	- Vaa	20	8 1.32 TeV m(λ ⁰ ₁)=0 GeV	1501.03555
sive	GGM (bino NLSP)	2 v	-2 Jets	Yes	20.3	γ 1.0 IEV all μ 20 γ 1.0 IEV m/μ ²	ATLAS-CONE-2014-00
sh	GGM (wino NLSP)	$1 e, \mu + \gamma$	-	Yes	4.8	8 619 GeV m(x ⁰)>50 GeV	ATLAS-CONF-2012-14
Ĕ	GGM (higgsino-bino NLSP)	γ	1 <i>b</i>	Yes	4.8	<i>š</i> 900 GeV m(²) ≥20 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, µ (Z)	0-3 jets	Yes	5.8	g 690 GeV m(NLSP)>200 GeV	ATLAS-CONF-2012-15
	Gravitino LSP	0	mono-jet	Yes	20.3	$F^{1/2}$ scale 865 GeV m(\tilde{G})>1.8 × 10 ⁻⁴ eV, m(\tilde{g})=m(\tilde{q}):	=1.5 TeV 1502.01518
d'	$\tilde{g} \rightarrow b \bar{b} \tilde{\chi}_{1}^{0}$	0	3 b	Yes	20.1	<u>ĝ</u> 1.25 TeV m(ℓ ₁)<400 GeV	1407.0600
ne n	$\tilde{g} \rightarrow t \bar{t} \chi_1$	0	7-10 jets	Yes	20.3	g 1.1 TeV m(X [*] ₁) <350 GeV	1308.1841
200	$g \rightarrow tt \chi_1$ $\tilde{g} \rightarrow b \tilde{t} \tilde{\chi}_1^+$	0-1 e,μ 0-1 e,μ	3 b	Yes	20.1	g 1.34 HeV m(x ₁)<400 GeV ĝ 1.3 TeV m(x ₁ ⁰)<300 GeV	1407.0600
	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0$	0	2 b	Yes	20.1	b ₁ 100-620 GeV m(ξ ⁰ ₁)<90 GeV	1308.2631
ió	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow t \tilde{\chi}_1^{\pm}$	2 e, µ (SS)	0-3 b	Yes	20.3	\tilde{b}_1 275-440 GeV $m(\tilde{\chi}_1^{\pm})=2 m(\tilde{\chi}_1^{0})$	1404.2500
n on	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow b \tilde{\chi}_1^{\pm}$	1-2 e, µ	1-2 b	Yes	4.7	\tilde{t}_1 110-167 GeV $m(\tilde{x}_1^{\pm}) = 2m(\tilde{x}_1^0), m(\tilde{x}_1^0) = 55$ GeV	1209.2102, 1407.0583
30	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0$ or $t \tilde{\chi}_1^0$	2 e, µ	0-2 jets	Yes	20.3	<i>i</i> 1 90-191 GeV 215-530 GeV m(<i>k</i> ⁰ ₁)=1 GeV	1403.4853, 1412.4742
D .	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 e,μ	1-2 b	Yes	20	<i>i</i> ₁ 210-640 GeV m(<i>x</i> ⁰)=1 GeV	1407.0583,1406.1122
ec.	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \chi_1^{\vee}$	0 m	ono-jet/c-ta	g Yes	20.3	t₁ 90-240 GeV m(t̃₁)-m(t̃₁)<85 GeV	1407.0608
di,	$\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z$	2 e, μ (Z) 3 e, μ (Z)	1 b	Yes	20.3	I_1 m(ℓ_1)>150 GeV m(ℓ_1)>150 GeV m(ℓ_1) >290-600 GeV m(ℓ_1) <200 GeV	1403.5222 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	<i>ℓ</i> 90-325 GeV m(χ ⁰ ₁)=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	$\tilde{\chi}_{1}^{\pm}$ 140-465 GeV $m(\tilde{\chi}_{1}^{0})=0$ GeV, $m(\tilde{\ell},\tilde{v})=0.5(m(\tilde{\chi}_{1}^{\pm})$	$+m(\tilde{\chi}_{1}^{0}))$ 1403.5294
J J	$\tilde{\chi}_{1}^{+}\tilde{\chi}_{1}^{-}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau}\nu(\tau\tilde{\nu})$	2 τ	-	Yes	20.3	$\tilde{\chi}_{1}^{\pm}$ 100-350 GeV m($\tilde{\chi}_{1}^{0}$)=0 GeV, m($\tilde{\tau}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_{1}^{\pm}$)	+m($\tilde{\chi}_{1}^{0}$)) 1407.0350
1 in the	$\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{2}^{0} \rightarrow \tilde{\ell}_{L} \nu \tilde{\ell}_{L} \ell(\tilde{\nu}\nu), \ell \tilde{\nu} \tilde{\ell}_{L} \ell(\tilde{\nu}\nu)$	3 e, µ	0	Yes	20.3	$\tilde{\chi}_{1}^{*}, \tilde{\chi}_{2}^{"}$ 700 GeV $m(\tilde{\chi}_{1}^{*}) = m(\tilde{\chi}_{2}^{"}), m(\tilde{\chi}_{1}^{"}) = 0, m(\tilde{\ell}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_{1}^{*}))$	$+m(\tilde{\chi}_{1}^{0}))$ 1402.7029
0	$\tilde{\chi}_1^+ \tilde{\chi}_2^0 \rightarrow W \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$	2-3 e, µ	0-2 jets	Yes	20.3	χ_1^*, χ_2^* 420 GeV $m(\chi_1^*)=m(\chi_2^0), m(\chi_1^0)=0$, sleptons	decoupled 1403.5294, 1402.7029
	$\chi_1 \chi_2 \rightarrow W \chi_1 h \chi_1, h \rightarrow b b / W W / \tau \tau / \gamma$ $\tilde{\chi}_0^0 \tilde{\chi}_0^0 \tilde{\chi}_0^0 \rightarrow \tilde{\ell}_D \ell$	γ e, μ, γ 4 e. μ	0-2 0	Yes	20.3	$\chi_1^{\prime}, \chi_2^{\prime}$ 250 GeV m(χ_1^{\prime})=m(χ_2^{\prime}), m(χ_1^{\prime})=0, sleptons $\chi_2^{\prime 0}$, 620 GeV m($\chi_2^{\prime 0}$)-m($\chi_2^{\prime 0}$)-0 m($\chi_2^{\prime 0}$)-0 (m($\chi_2^{\prime 0}$)-0 (m()(\chi_2^{\prime 0})-0 (m(\chi_2^{\prime 0}))-0 (m(\chi_2^{\prime 0}))	decoupled 1501.0/110 (\tilde{x}_{i}^{0})) 1405.5086
_	Direct $\tilde{v}^+ \tilde{v}^-$ produlong lived \tilde{v}^\pm	Disann trk	1 iot	Voc	20.0	\tilde{V}^{\pm} 270 GoV $m(\tilde{v}_{2}^{\pm}) = 0.000$	3 82 1310 3675
n s	Stable, stopped g R-hadron	0	1-5 iets	Yes	20.3	κ1 μ m(x1)-m(x1)=160 MeV, π(x1)=0 ĝ 832 GeV m(x20)=160 GeV 10 μecπ(x20)	2 115 1310.6584
cle.	Stable g R-hadron	trk	-	-	19.1	ž 1.27 TeV	1411.6795
arti	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0 \rightarrow \tilde{\tau}(\tilde{e}, \tilde{\mu}) + \tau(e, \mu)$	μ) 1-2 μ	-	-	19.1	ž ⁰ 537 GeV 10 <tanβ<50< td=""><td>1411.6795</td></tanβ<50<>	1411.6795
ğğ	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$, long-lived $\tilde{\chi}_1^0$	2γ	-	Yes	20.3	\tilde{t}_{1}^{0} 435 GeV 2< $\tau(\tilde{t}_{1}^{0})$ <3 ns, SPS8 model	1409.5542
	$\tilde{q}\tilde{q}, \tilde{\chi}_{1}^{0} \rightarrow qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	ĝ 1.0 TeV 1.5 <cr<156 br(μ)="1," m(ξ<="" mm,="" th=""></cr<156>)=108 GeV ATLAS-CONF-2013-09
	LFV $pp \rightarrow \tilde{\nu}_{\tau} + X, \tilde{\nu}_{\tau} \rightarrow e + \mu$	2 e, µ	-	-	4.6	$\bar{\nu}_r$ 1.61 TeV λ'_{311} =0.10, λ_{132} =0.05	1212.1272
	LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e(\mu) + \tau$	$1 e, \mu + \tau$	-	-	4.6	y _r 1.1 TeV λ ₃₁₁ =0.10, λ ₁₍₂₎₃₃ =0.05	1212.1272
>	Bilinear RPV GMSSM $\tilde{v}^+ \tilde{v}^- \tilde{v}^+ W \tilde{v}^0 \tilde{v}^0 V a \tilde{v}^0 \cdots \tilde{v}$	∠ e, µ (55) 4 e µ	0-3 b	Yes	20.3	g, g 1.35 lev m(q)=m(g), ct _{LSP} <1 mm γ [±] 750 GoV m ⁽²⁾ : 0 α	1404.2500
Ē	$\chi_1\chi_1, \chi_1 \rightarrow w\chi_1, \chi_1 \rightarrow eev_{\mu}, e\mu v_e$ $\tilde{\chi}^+_1 \tilde{\chi}^1 \tilde{\chi}^+_1 \rightarrow W \tilde{\chi}^0_1 \tilde{\chi}^0_1 \rightarrow \tau \tau \tilde{\chi}$	3 e. μ + τ	-	Yes	20.3		1405.5086
	$\pi_1 \pi_1, \pi_1 \rightarrow w \pi_1, \pi_1 \rightarrow \tau \tau v_e, e \tau v_\tau$ $\tilde{g} \rightarrow q q q$	0	6-7 jets	-	20.3	§ 916 GeV BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g} \rightarrow \tilde{t}_1 t, \tilde{t}_1 \rightarrow bs$	2 e, µ (SS)	0-3 b	Yes	20.3	ž 850 GeV	1404.250
	Scalar charm $\tilde{c} \rightarrow c \tilde{\chi}_{1}^{0}$	0	2.0	Yes	20.3	č 490 GeV m(ž ⁰)<200 GeV	1501.01325

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

		Model	<i>ℓ</i> ,γ	Jets	$\mathbf{E}_{\mathrm{T}}^{\mathrm{miss}}$	∫£ dt[fl	[fb ⁻¹] Mass limit	
	Extra dimensions	ADD $G_{KK} + g/q$ ADD non-resonant $\ell\ell$ ADD QBH $\rightarrow fq$ ADD QBH ADD QBH high N_{trk} ADD BH high $\sum p_T$ RSI $G_{KK} \rightarrow \ell\ell$ RSI $G_{KK} \rightarrow VWV \rightarrow \ell \nu \ell \nu$ Bulk RS $G_{KK} \rightarrow ZZ \rightarrow \ell \ell qq$ Bulk RS $G_{KK} \rightarrow t\overline{t}$ S^2/Z_2 ED VED	$\begin{array}{c} - \\ 2e, \mu \\ 1 e, \mu \\ - \\ 2\mu (SS) \\ \ge 1 e, \mu \\ 2 e, \mu \\ 2 e, \mu \\ - \\ 1 e, \mu \\ 2 e, \mu \\ - \\ 1 e, \mu \\ 2 e, \mu \\ 2 \gamma \end{array}$	1-2 j - 1 j 2 j - 2 j/1 J 4 b ≥ 1 b, ≥ 1 J/ -	Yes - - - Yes - 2j Yes - Yes	4.7 20.3 20.3 20.3 20.3 20.3 20.3 4.7 20.3 19.5 14.3 5.0 4.8	Mo 4.37 TeV Ms 5.2 T Mah 5.2 T Mah 5.2 T Mah 5.8 Z Mah 5.7 T Mah 5.7 T Mah 6 Gack mass 2.68 TeV Gack mass 1.23 TeV Gack mass 730 GeV Gack mass 590-710 GeV Back mass 2.0 TeV Makx 4.71 Te Compact. scale R ⁻¹ 1.41 TeV	ieV ieV 2 TeV 7 TeV 2 TeV 2 TeV
	I Gauge bosons	$\begin{array}{l} \text{SSM } Z' \rightarrow \ell\ell \\ \text{SSM } Z' \rightarrow \tau\tau \\ \text{SSM } W' \rightarrow \ell\nu \\ \text{EGM } W' \rightarrow WZ \rightarrow \ell\nu \ell'\ell' \\ \text{EGM } W' \rightarrow WZ \rightarrow qq\ell\ell \\ \text{LRSM } W'_R \rightarrow t\overline{b} \\ \text{LRSM } W'_R \rightarrow t\overline{b} \\ \text{Cl } qqq \\ \end{array}$	2 e,μ 2 τ 1 e,μ 3 e,μ 2 e,μ 1 e,μ 0 e,μ	$\begin{array}{c} - \\ - \\ 2 j / 1 J \\ 2 b, 0 {\text -} 1 j \\ \geq 1 b, 1 J \\ 2 j \end{array}$	- Yes Yes - Yes -	20.3 19.5 20.3 20.3 20.3 14.3 20.3 4.8	Z' mass 2.9 TeV Z' mass 1.9 TeV W' mass 3.28 TeV W' mass 1.52 TeV W' mass 1.52 TeV W' mass 1.59 TeV W' mass 1.84 TeV W' mass 1.77 TeV	7.6 TeV
DU	DM	Cl qqℓℓ Cl uutt EFT D5 operator (Dirac) EFT D9 operator (Dirac)	2 e, μ 2 e, μ (SS) 0 e, μ 0 e, μ	- ≥ 1 b, ≥ 1 j 1-2 j 1 J. < 1 j	i Yes Yes	20.3 14.3 10.5 20.3	Λ 3.3 TeV M. 731 GeV M. 2.4 TeV	
rpa	ΓØ	Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 rd gen	2 e 2 μ 1 e, μ, 1 τ	≥ 2 j ≥ 2 j 1 b, 1 j	-	1.0 1.0 4.7	L0 mass 660 GeV L0 mass 685 GeV L0 mass 534 GeV	
dar	quarks	Vector-like quark $TT \rightarrow Ht + X$ Vector-like quark $TT \rightarrow Wb + X$ Vector-like quark $TT \rightarrow Zt + X$ Vector-like quark $BB \rightarrow Zb + X$ Vector-like quark $BB \rightarrow Wt + X$	1 e, µ 1 e, µ 2/≥3 e, µ 2/≥3 e, µ 2 e, µ (SS)	$\begin{array}{l} \geq 2 \hspace{0.1cm} b, \geq 4 \\ \geq 1 \hspace{0.1cm} b, \geq 3 \\ \geq 2 / \geq 1 \hspace{0.1cm} b \\ \geq 2 / \geq 1 \hspace{0.1cm} b \\ \geq 2 / \geq 1 \hspace{0.1cm} b \\ \geq 1 \hspace{0.1cm} b, \geq 1 \end{array}$	i Yes i Yes - - i Yes	14.3 14.3 20.3 20.3 14.3	T mass 790 GeV T mass 670 GeV T mass 735 GeV B mass 755 GeV B mass 720 GeV	
Evoluted	fermions	Excited quark $q^* \rightarrow q\gamma$ Excited quark $q^* \rightarrow qg$ Excited quark $b^* \rightarrow Wt$ Excited lepton $\ell^* \rightarrow \ell\gamma$	1 γ - 1 or 2 e, μ 2 e, μ, 1 γ	1 j 2 j 1 b, 2 j or 1 –	j Yes	20.3 20.3 4.7 13.0	q* mass 3.5 TeV q* mass 3.5 TeV g* mass 4.09 TeV b* mass 870 GeV f* mass 2.2 TeV	
	Other	$\begin{split} \text{LSTC} \ a_T \to W\gamma \\ \text{LRSM Majorana }\nu \\ \text{Type III Seesaw} \\ \text{Higgs triplet } H^{\pm\pm} \to \ell\ell \\ \text{Multi-charged particles} \\ \text{Magnetic monopoles} \end{split}$	$ \begin{array}{c} 1 \ e, \mu, 1 \ \gamma \\ 2 \ e, \mu \\ 2 \ e, \mu \\ 2 \ e, \mu (SS) \\ - \\ - \\ \sqrt{s} = \end{array} $	- 2 j - - - 7 TeV	Yes 	20.3 2.1 5.8 4.7 4.4 2.0 8 TeV	ar mass 960 GeV №* mass 1.5 TeV №* mass 245 GeV H** mass 409 GeV multi-charged particle mass 490 GeV monopole mass 862 GeV 10 ⁻¹ 1	

*Only 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 uncertainty.

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The long dream

Supergravity -> String theor Susy anywhere is better susy anywhere is better. Susy anywhere is better.

gauge couplings

Energy

ins

< 1% tuning in simplest models

TeV scale supersymmetry **M**Higgs

Abundance of coloured superparters, for signatures, dark matter detected



LHC run1: We have discovered the Higgs, nothing else.

We know that a SM-like Higgs is responsible for EW symmetry breaking.

Is the EW scale natural?

The naturalness strategy is not a no-lose theorem, but has been successful in the past.







Naturalness suggests $\rightarrow \Lambda < 850 \,\mathrm{MeV}$



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'New physics': comes in at $m_{
ho}=770\,{
m MeV}$



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ho}=770\,{
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$$m_{\pi^{\pm}}^2 - m_{\pi_0}^2 \simeq \frac{3\,\alpha_{em}}{4\pi} \,\frac{m_{\rho}^2 m_{a_1}^2}{m_{a_1}^2 - m_{\rho}^2} \,\log\left(\frac{m_{a_1}^2}{m_{\rho}^2}\right) \qquad \text{Das et al '67} \\ (m_{\pi^{\pm}} - m_{\pi_0})|_{\text{TH}} \simeq 5.8\,\text{MeV} \,.$$

Bottom-up naturalness

New physics cuts off quantum corrections above TeV

insensitivity to UV scales

natural new physics

MHiggs

Supersymmetry

- Composite Higgs
- Extra-dimensions
- Technicolor (RIP)

Naturalness under attack

- LHC direct bounds
- Higgs mass
- Higgs couplings
- Flavor & CP
- EW precision tests

Strong dynamics

$$\langle \bar{\Psi}_{L}^{i} \Psi_{R}^{j} \rangle = \Lambda_{QCD}^{3} \delta_{ij} \longrightarrow \frac{SU(2)_{L} \otimes SU(2)_{R}}{SU(2)_{L+R}} \longrightarrow \mathcal{L} = f_{\pi}^{2} Tr \left[\partial_{\mu} U \partial^{\mu} U^{\dagger} \right]$$



Spontaneous breaking of G o HQCD breaks EW symmetry, $f_{\pi}^{m_W = 80\,{
m GeV}} \ll v$



No need for a Higgs scalar, completely natural.

In trouble before LHC, now dead.

Composite Higgs

Georgi, Kaplan 80's; Agashe, Contino, Pomarol '04



Higgs as an approximate pseudo Goldstone boson.

e.g.
$$SO(5)/SO(4)$$
 at scale $f \rightarrow 4$ GB

Composite Higgs



Higgs as an approximate pseudo Golstone boson.

Fermi-scale v < f from vacuum-misalignment



Higgs as an approximate pseudo Golstone boson.

Fermi-scale v < f from vacuum-misalignment

Next-to-minimal composite Higgs

Larger cosets with more scalars possible

G	H	N_G	NGBs rep. $[H] = \text{rep.}[SU(2) \times$	$\overline{SU(2)]}$
SO(5)	SO(4)	4	f 4=(f 2,f 2)	[Agashe, Contino, Pomarol,]
SO(6)	SO(5)	5	${f 5}=({f 1},{f 1})+({f 2},{f 2})$	[Gripaios, Pomarol, Riva, Serra 0902.1485]
SO(6)	$SO(4) \times SO(2)$	8	${f 4_{+2}}+{f ar 4_{-2}}=2 imes ({f 2},{f 2})$	[Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 1105.54031
SO(7)	SO(6)	6	$6 = 2 \times (1, 1) + (2, 2)$	
SO(7)	G_2	7	${f 7}=({f 1},{f 3})+({f 2},{f 2})$	[Chala 1210.6208]
SO(7)	$SO(5) \times SO(2)$	10	$10_0 = (3, 1) + (1, 3) + (2, 3)$	2)
SO(7)	$[SO(3)]^{3}$	12	(2 , 2 , 3)=3 imes(2 , 2)	
$\operatorname{Sp}(6)$	$\operatorname{Sp}(4) \times \operatorname{SU}(2)$	8	$(4, 2) = 2 \times (2, 2), (2, 2) + 2 \times$	(2 , 1) [Mrazek, Pomarol, Rattazzi, Redi, Serra, Wulzer 1105.5403]
SU(5)	$SU(4) \times U(1)$	8	$4_{-5} + \bar{4}_{+5} = 2 \times (2, 2)$	
SU(5)	SO(5)	14	14 = (3, 3) + (2, 2) + (1, 3)	1)



Higgs couplings Low energy Higgs physics from symmetries

$$\mathcal{L}_{\pi} = \frac{f^2}{4} d^i_{\mu} d^{\mu}_i = \frac{1}{2} (\partial h)^2 + \frac{g^2}{4} f^2 \sin^2 \frac{h}{f} \left(|W|^2 + \frac{1}{2c_w^2} Z^2 \right)$$
$$g_{HVV} = i \frac{g^2}{4} v \sqrt{1 - \xi} \qquad \xi \equiv \frac{v^2}{f^2} = \sin^2 \frac{\langle h \rangle}{f}$$

Fermion couplings are less sharply predicted

$$-\frac{\mathsf{h}}{\sqrt{1-\xi}} = i \frac{m_f}{v} c \qquad \qquad \text{MCHM}_5 \qquad c = \frac{1-2\xi}{\sqrt{1-\xi}}$$
$$\qquad \qquad \text{MCHM}_4 \qquad c = \sqrt{1-\xi}$$
$$\qquad \qquad \qquad \text{MCHM}_{10} \qquad \cdots$$

Higgs couplings



Indirect measurements

Collider	Energy	Luminosity	$\xi \ [1\sigma]$
LHC	$14\mathrm{TeV}$	$300 {\rm fb}^{-1}$	$6.6 - 11.4 \times 10^{-2}$
LHC	$14\mathrm{TeV}$	$3 \mathrm{ab}^{-1}$	$4 - 10 \times 10^{-2}$
ILC	$250{ m GeV}$	$250 {\rm fb}^{-1}$	$4.8 \text{-} 7.8 \times 10^{-3}$
	+ 500 GeV	$500 {\rm fb}^{-1}$	
CLIC	$350{ m GeV}$	$500 {\rm fb}^{-1}$	
	+ 1.4 TeV	$1.5\mathrm{ab}^{-1}$	2.2×10^{-3}
	+ 3.0 TeV	$2 \mathrm{ab}^{-1}$	
TLEP	$240{ m GeV}$	$10 {\rm ab}^{-1}$	2×10^{-3}
	$+ 350 \mathrm{GeV}$	$2.6 {\rm ab}^{-1}$	_ / 20

[CMS-NOTE-2012-006] [ATL-PHYS-PUB-2013-014] [Dawson et. al.1310.8361] [CLIC 1307.5288]

Flavour

Csaki, Falkowski, Weiler, '08, Neubert et.al, Buras et al

Linear mixing (partial compositeness)

$$\mathcal{L}_{\text{mix}} = \lambda_L \, q_L \mathcal{O}_L^q + \lambda_R \, t_R \mathcal{O}_R^t + \text{h.c.} + g \, A_\mu \mathcal{J}^\mu$$



Flavour

Csaki, Falkowski, Weiler, '08, Neubert et.al, Buras et al



Implications of $m_H = 125 \text{ GeV}$

Potential is fully radiatively generated Agashe et. al

$$V_{gauge}(h) = \frac{9}{2} \int \frac{d^4 p}{(2\pi)^4} \log\left(\Pi_0(p) + \frac{s_h^2}{4} \Pi_1(p)\right) \qquad s_h \equiv \sin h/f$$
$$\Pi_0(p) = \frac{p^2}{a^2} + \Pi_a(p) , \qquad \Pi_1(p) = 2\left[\Pi_{\hat{a}}(p) - \Pi_a(p)\right]$$

$$g^2$$

Implications of $m_H = 125$ GeV

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$$\Pi_0(p) = \frac{1}{g^2} + \Pi_a(p) , \qquad \Pi_1(p) = 2 \left[\Pi_{\hat{a}}(p) - \Pi_a(p) \right]$$

 $\int d^4p \,\Pi_1(p) / \Pi_0(p) < \infty$

Higgs dependent term **UV** finite

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 $\int d^4p \,\Pi_1(p) / \Pi_0(p) < \infty$

Higgs dependent term UV finite

→ 'Weinberg sum rules'

$$\lim_{p^2 \to \infty} \Pi_1(p) = 0 , \qquad \lim_{p^2 \to \infty} p^2 \Pi_1(p) = 0$$

UV finiteness requires at least two resonances

$$\Pi_1(p) = \frac{f^2 m_\rho^2 m_{a_1}^2}{(p^2 + m_\rho^2)(p^2 + m_{a_1}^2)} \qquad \text{spin}\,\mathbf{I}$$

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Similarly for SO(5) fermionic contribution Pomarol et al; Marzocca $m_h^2 \simeq \frac{N_c}{\pi^2} \left[\frac{m_t^2}{f^2} \frac{m_{Q_4}^2 m_{Q_1}^2}{m_{Q_1}^2 - m_{Q_4}^2} \log \left(\frac{m_{Q_1}^2}{m_{Q_4}^2} \right) \right]^{-\cdots} f^{-\cdots}$

> similar result in deconstruction: Matsedonskyi et al; Redi et al

5 = 4 + 1 with EM charges 5/3, 2/3, 2/3, -1/3Q4 Q1 \rightarrow solve for 170% = 125 GeV





Scan over composite Higgs parameter space



see e.g. ATLAS-CONF-2013-051

Top partners

- expect new vector-like fermions at the TeV scale
- minimal case: top-like state and heavy charge 5/3 coloured state
- non-minimal cases: top-, bottom-like states, charge -4/3, 5/3, 8/3
- either pair production, or single production in association with a b or t



G

H

 $SM \in H$



No lose for naturalness?



No lose for naturalness?



NP is related to the top by a symmetry, natural new particle mass around TeV

Symmetry commutes with color: will be produced copiously at the LHC!

No lose for naturalness?





(Evil) Twin consequences

Higgs is protected by a symmetry. All new particles below cut-off are SM singlets!

Craig, Knapen, Longhi '14, Geller, Telem, '14; Tesi et.al, '15, Barbieri, et. al '15

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What's the phenomenology?

- LHC finds Higgs and nothing else (check!)
- * Higgs is pNGB: Higgs couplings $\propto \cos(v/f)$
- * $\operatorname{Br}(h \to b_{\operatorname{twin}} b_{\operatorname{twin}}) = \operatorname{Br}(h \to \operatorname{inv.}) = \sin^2(v/f)$
- Can have displaced Higgs decays

Juknevich, Melnikov, Strassler; Craig, Katz, Strassler, Sundrum

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Juknevich, Melnikov, Strassler; Craig, Katz, Strassler, Sundrum

No meaningful constraints yet.

Naturalness potentially probed to ~20% level by end of LHC.



UV completion

• Holographic dual, 5D theory in AdS



Gauge higgs unification

• The Gauge-Higgs vev enters the fermion EOMs:

 $\Psi_q(z, v) = \Omega(z, v) \Psi_q(z)$ $\Omega(z) = e^{ig_5 \int A_5(z)}$ - The Wilson line

• Coleman-Weinberg potential for Higgs potential

$$V(h) = \frac{N}{(4\pi)^2} \int dp p^3 \log(\rho[-p^2])$$

Holographic twins

Geller, Telem; Csaki, Geller, Telem, AW



Top quark

	SO(8)	<i>SU</i> (3) _c	$U(1)_X$			SO(8)	$SU(3)_c^{\rm m}$	$U(1)_X^{\mathrm{m}}$		
Ψ_q	8	3	2/3	<i>bulk Z</i> ₂ , 7 of SU(7)	Ψ_q^m	8	3	2/3		
Ψ_t	1	3	2/3	<→	Ψ^m_t	1	3	2/3		
UV b.c. (+):	$SU(2)_L$	<i>SU</i> (3) _c	$U(1)_Y$	$UV Z_2$		$SU(2)_L$	<i>SU</i> (3) _c	$U(1)_Y$		
Q_L	2	3	1/6		Q_L^m	2	3	1/6		
t_R	1	3	2/3		t_R^m	1	3	2/3		
п Б.с. (т).	SO(7)	<i>SU</i> (3) _c	$U(1)_X$	$IR T_{a}$ 7 of SU(7)		SO(7)	$SU(3)_c^m$	$U(1)_X^{\mathrm{m}}$		
Ψ_{qL}^7, Ψ_{qL}^1	7,1	3	2/3	\longleftarrow	$\Psi_{qL}^{7m}, \Psi_{qL}^{1m}$	7,1	3	2/3		
Ψ_{tR}	1	3	2/3		Ψ^m_{tR}	1	3	2/3		

IR masses: $m_t^1 \Psi_{qL}^1 \Psi_{tR}$

IR masses: $m_t^1 \Psi_{qL}^{1m} \Psi_{tR}^m$

 $V(h) \approx -\alpha_2 \sin^2(h/f) + \frac{\alpha}{2} \sin^4(h/f) - \alpha_2 \cos^2(h/f) + \frac{\alpha}{2} \cos^4(h/f) = \alpha \sin^2(h/f) \cos^2(h/f) + c$

top + gauge

$$\begin{aligned} &\alpha_2 \sim \frac{3}{32\pi^2} y_t^2 f^2 m_{KK}^2 \\ &\alpha \sim \frac{3}{64\pi^2} y_t^4 f^4 \log \frac{2M_{KK}^2}{y_t^2 f^2} \end{aligned}$$



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Csaki, Geller, Telem, AW

Naturalness without Top-partners

- * KK tops do not enter tuning
- Tuning scales as f²/v², Higgs data
- * MKK can be as high as $4\pi f$

Need Z₂ breaking

- ***** Higgs potential $-\beta \sin^2(h/v)$
- U(1)x and mirror U(1)x mismatch

$$\beta \approx \frac{3}{128\pi^2} (g'^2 - g'^2_m) g_*^2 f^4$$

$\mathcal{L}_{\text{mix}} = \lambda \mathbf{F} \mathbf{q}_{L} \mathcal{O}_{L}^{q} + \lambda_{R} t_{R} \mathcal{O}_{R}^{t} + \text{h.c.} + \mathbf{q}_{A_{\mu}} \mathcal{J}^{\mu} \text{St}$

Csaki, Geller, Telem, AW, in prep.

RS-GIM suppresses flavor violation Rg_{ψ} q_L t_R

 q_i q_j q_l q_k

H

 $C_{K}^{4} \sim \frac{1}{M_{KK}^{2}} \frac{g_{s*}^{2}}{e^{\frac{g}{s*}}} \frac{8m_{d}m_{s}}{e^{k}e^{\frac{1}{y}}\frac{g_{\psi}}{\psi}} \frac{1 + \tilde{m}_{d}^{2}}{\tilde{m}_{d}^{2}} \qquad g_{*}^{2}f\tilde{m}_{d} > 106 \text{ TeV}$

Flavor constraint ϵ_K



$\mathcal{L}_{\text{mix}} = \lambda \mathbf{F} \mathbf{q}_{L} \mathcal{O}_{L}^{q} + \lambda_{R} t_{R} \mathcal{O}_{R}^{t} + \text{h.c.} + \mathbf{q}_{A_{\mu}} \mathcal{J}^{\mu} \text{St}$

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Csaki, Geller, Telem, AW, in prep.

RS-GIM suppresses flavor $violation_{g_{\psi}}$

 q_i q_j q_l

H

 $C_{K}^{4} \sim \frac{1}{M_{KK}^{2}} \frac{g_{s*}^{2}}{\tilde{g}_{*}^{2}} \frac{8m_{d}m_{s}}{\epsilon^{k}\epsilon_{v}^{l}} \frac{1+\tilde{m}_{d}^{2}}{\tilde{m}_{d}^{2}} \qquad \qquad g_{*}^{2}f\tilde{m}_{d} > 106 \text{ TeV}$

Flavor constraint ϵ_K



Flavour twist

Csaki, Geller, Telem, AW, in prep.

The two most stringent bounds combined

 $g_*f > 19.6 \text{ TeV}$

We can live with large coupling without paying the price of tuning (twin protection)

At the limit of perturbative control

 $g_* \approx 4\pi \to f > 1.5 \,\mathrm{TeV}$

which allows anarchic flavour with O(%) tuning.



G. Giudice

"Is neutral naturalness the beautiful reason we haven't seen anything, or the last desperate hope of theorists?"

$$\frac{N_{\text{signal-events}}(M_{\text{high}}^2, 14 \text{ TeV}, \text{Lumi})}{N_{\text{signal-events}}(M_{\text{low}}^2, 8 \text{ TeV}, 19 \text{fb}^{-1})} = 1$$

Coupling constants & other prefactors mostly cancel in the ratio.

Dependence on M and on \sqrt{s} mostly comes about through parton distribution functions (PDFs) & simple dimensions.

G. Salam, AW cern.ch/collider-reach



By the end of the year, most searches will beat 8 TeV results

[Some, e.g. excited quarks, will surpass 8 TeV with just 0.2 fb⁻¹]



Conclusions

- Run1 left the most motivated natural models in a somewhat bruised state
- Run2 will be a big jump in sensitivity
- Direct searches will take over in the exploration of compositeness
- Twin models still natural, hard to find, can explain flavour

Fin