Much Ado About Naturalness

Nathaniel Craig UC Santa Barbara



KITP EnerVac19

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The Naturalness Strategy

Param	UV sensitivity	Natural if	NP	Scale	Natural?
"m _e "	$e^2\Lambda$	Λ ≲ 5 MeV	Positron	511 keV	\checkmark
m _{π±} ² - m _{π0} ²	$\frac{3\alpha}{4\pi}\Lambda^2$	Λ ≲ 850 MeV	Rho	770 MeV	\checkmark
M _{KL} -M _{KS}	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4} \Lambda^2$	Λ ≲ 2 GeV	Charm	1.2 GeV	\checkmark
m _H ²	$-\frac{6y_t^2}{16\pi^2}\Lambda^2 + \dots$	Λ ≲ 500 GeV	?	?	?

Implementation is up to us

We've refined this strategy using some rules of thumb, *for example...*

- 1. The Standard Model coupled to gravity is a generic EFT.
- 2. The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.
- 3. Symmetries imply new particles charged under the SM.

Thus far...



AILAS EXOLICS	Searcnes" -	95%	° UL	opper Exclusion Limits	AIL	45 Preliminar
Status: July 2018				ſĹ	$dt = (3.2 - 79.8) \text{ fb}^{-1}$	$\sqrt{s} = 8, 13 \text{ Te}$
Model	ℓ,γ Jets†	Emiss	∫£ dt[fb	limit		Reference
ADD $G_{XX} + g/q$ ADD non-resonant $\gamma\gamma$ ADD OBH ADD BH high $\sum pr$ ADD BH high $\sum pr$ ADD BH nutljet RSI $G_{KX} \rightarrow \gamma\gamma$ Buik RS $G_{KX} \rightarrow \psiW/ZZ$ Buik RS $G_{KX} \rightarrow tt$ 2UED / RPP	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Yes - - - 1/2j Yes 3 j Yes	36.1 36.7 37.0 3.2 3.6 36.7 36.1 36.1 36.1 36.1	Mp 2,7 Ar 6 Ar 6 Ma 6 Max 2.3 TeV Karmets 2.8 TeV	$ \begin{array}{ll} \sigma=2 & \\ \sigma=3\text{HZ}\text{NLO} & \\ \sigma=3\text{HZ}\text{NLO} & \\ \sigma=6 & \\ \sigma=6, M_0=3\text{TeV}, \sigma\in \text{H} \\ \sigma=0, M_0=3\text{TeV}, \sigma\in \text{H} \\ \lambda/M_m=0.1 & \\ \lambda/M_m=1.0 & \\ \Gamma/m=15\% & \\ \mathrm{Ter}(1,1,2(A^{(1,1)}\rightarrow\text{tr})=1 & \\ \end{array} $	1711.03301 1707.04147 1703.09217 1606.02285 1512.02586 1707.04147 CERN-EP.2018-179 1804.10823 1803.09578
$\begin{array}{c} \operatorname{SSM} Z' \to \ell\ell \\ \operatorname{SSM} Z' \to \tau\tau \\ \operatorname{Leptisphicitic} Z' \to bb \\ \operatorname{Leptisphicitic} Z' \to tt \\ \operatorname{SSM} W' \to \tau\tau \\ \operatorname{SSM} W' \to \tau\nu \\ \operatorname{SSM} W' \to \tau\nu \\ \operatorname{SSM} W' \to tb \\ \operatorname{LRSM} W'_{\mu} \to tb \\ \operatorname{LRSM} W'_{\mu} \to tb \end{array}$	$2 e, \mu$ - 2τ - - 2b $1 e, \mu > 1b_i > 1d_i$ $1 e, \mu$ - 1τ - $el B 0 e, \mu > 2J$ multi-channel multi-channel	- - Yes Yes -	36.1 36.1 36.1 79.8 36.1 79.8 36.1 36.1 36.1	21 mass 4.5 TeV 21 mass 2.4 TeV 21 mass 2.1 TeV 21 mass 3.0 TeV 21 mass 3.0 TeV 3.0 TeV 3.0 TeV 7 mass 3.0 TeV 9 mass 3.0 TeV 1 mass 3.0 TeV 1 mass 3.1 TeV 2.4 TeV 2.4 TeV 1 mass 2.4 TeV	$\Gamma/m = 1\%$ $g_V = 3$ $g_V = 3$	1707.02424 1709.07342 1805.03290 1804.10823 ATLAS-CONF-2018-01 1801.05992 ATLAS-CONF-2018-01 1712.06518 CERN-EP-2018-142
Cl qqqq Cl £t qq Cl £t tt	– 2j 2e,μ – ≥1e,μ ≥1b,≥1	- - ! Yes	37.0 36.1 36.1	A A A 2.57 TeV	21.8 TeV η _{1k} 40.0 TeV η _k C _{tc} = 4π	1703.09217 1707.02424 CERN-EP-2018-174
Axial-vector mediator (Dirac Di Colored scalar mediator (Dirac VV _{XX} EFT (Dirac DM)	$\begin{array}{cccc} \text{M}) & 0 \ e, \mu & 1-4 \ j \\ \text{cDM}) & 0 \ e, \mu & 1-4 \ j \\ & 0 \ e, \mu & 1 \ J, \le 1 \end{array}$	Yes Yes j Yes	36.1 36.1 3.2	mmod 1.55 TeV mmod 1.67 TeV M. 700 GeV	g_q =0.25, g_{χ} =1.0, $m(\chi)$ = 1 GeV g=1.0, $m(\chi)$ = 1 GeV $m(\chi)$ < 150 GeV	1711.03301 1711.03301 1608.02372
Scalar LQ 1 st gen Scalar LQ 2 nd gen Scalar LQ 3 nd gen	$2 e \ge 2j$ $2 \mu \ge 2j$ $1 e, \mu \ge 1 b, \ge 3$	- - J Yes	3.2 3.2 20.3	LO mass 1.1 TeV LO mais 1.05 TeV LO mais 640 GeV	$\beta = 1$ $\beta = 1$ $\beta = 0$	1605.05035 1605.09035 1508.04735
$\begin{array}{c} VLQ\; TT \rightarrow Ht/Zt/Wb + X\\ VLQ\; BB \rightarrow Wt/Zb + X\\ VLQ\; BB \rightarrow Wt/Zb + X\\ VLQ\; T_{33} T_{33} T_{33} \rightarrow Wt + 2\\ VLQ\; V \rightarrow Wb + X\\ VLQ\; B \rightarrow Hb + X\\ VLQ\; QQ \rightarrow WqWq \end{array}$	$\begin{array}{ll} \mbox{multi-channel} \\ \mbox{multi-channel} \\ \mbox{X} & 2(SS)/>3 \ e, \mu \geq 1 \ b, \geq 1 \\ \ 1 & e, \mu & \geq 1 \ b, \geq 1 \\ \ 0 & e, \mu, 2 \ \gamma & \geq 1 \ b, \geq 1 \\ \ 1 & e, \mu & \geq 4 \ j \end{array}$	j Yes Lj Yes Lj Yes Yes	36.1 36.1 3.2 79.8 20.3	1 mass 1.37 TeV 13 TeV 1.34 TeV 1,94 TeV 1.34 TeV V mass 1.34 TeV 0 mass 1.21 TeV 0 mass 1.21 TeV	$\begin{array}{l} \mathrm{SU}(2) \mbox{ doublet} \\ \mathrm{SU}(2) \mbox{ doublet} \\ \mathfrak{U}(T_{2/3} \rightarrow MP) = 1, \mbox{ c}(T_{2/3}MP) = 1 \\ \mathfrak{D}(Y \rightarrow MP) = 1, \mbox{ c}(YMP) = 1/\sqrt{2} \\ \mathfrak{K}_{B} = 0.5 \end{array}$	ATLAS-CONF-2018-XX ATLAS-CONF-2018-XX CERN-EP-2018-171 ATLAS-CONF-2018-07 ATLAS-CONF-2018-XX 1509.04261
Excited quark $q^* \rightarrow qg$ Excited quark $q^* \rightarrow qg$ Excited quark $b^* \rightarrow bg$ Excited quark $b^* \rightarrow bg$ Excited lepton t^* Excited lepton v^*	- 2j 1γ 1j - 1b.1j 3 e,μ - 3 e,μ,τ -	-	37.0 36.7 36.1 20.3 20.3	6.0 TeV 6.0 TeV 4"mass 6.0 TeV 5.1 TeV 5.1 TeV * mass 2.6 TeV * mass 3.5 TeV * mass 3.5 TeV	only u^* and a^* , $\Lambda = m(q^*)$ only u^* and a^* , $\Lambda = m(q^*)$ $\Lambda = 3.0 \text{ TeV}$ $\Lambda = 1.6 \text{ TeV}$	1703.09127 1709.10440 1805.09299 1411.2921 1411.2921
Type III Seesaw LRSM Majorana v Higgs triblet ##™ → ℓℓ Higgs triblet ##™ → fr Monatap (non-res prod) Multi-harged particles Magnetic monopoles	$\begin{array}{cccccccccccccccccccccccccccccccccccc$	Yes - - Yes -	79.8 20.3 36.1 20.3 20.3 20.3 20.3 7.0	M ⁴ mosta 560 GeV M ⁴ mosta 2.0 TeV M ⁴ mosta 870 GeV M ⁴ mosta 620 GeV M ⁴ mosta 057 GeV morecelo most 057 GeV morecelo most 1.14 TeV	$\begin{split} m(W_0) &= 2 \cdot 4 \cdot \frac{1}{9} V, \text{ so mixing} \\ DY production \\ DY production, \mathcal{D}(H_1^+ \to t_7) = 1 \\ \mathbf{a}_{a,a,m} = 0 \cdot 2 \\ DY production, a = b c \\ DY production, a = 1 c_7, \text{ spin } 1/2 \end{split}$	ATLAS-CONF-2018-02 1906.05020 1710.09748 1411.2921 1410.504 1504.04188 1509.08059
	$\sqrt{s} = 8 \text{ TeV}$ $\sqrt{s} = 1$	3 TeV		10 ⁻¹ 1	¹⁰ Mass scale [TeV]	



TLAS SUSV Searches* - 95% CL Lower Limits				
	ATLAS SUSY	Searches* - 95%	CL Lower Li	mits

ATLAS Preliminary

Mo	del	e, μ, τ, γ	Jets	$E_{\mathrm{T}}^{\mathrm{miss}}$	∫£ d1[ſb	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$ $\sqrt{s} = 13 \text{ TeV}$	Reference
<i>ą̃ą̃, ą̃</i> →.	$q \tilde{\xi}_1^0$	0 mono-jet	2-6 jets 1-3 jets	Yes Yes	36.1 36.1	₹ [2x, 5x Degen.] 0.9 ₹ [1x, 8x Degen.] 0.43 0.71	1.55 m(ℓຶ່)<100 GeV m(ຊັ)-m(ℓຶ່)=5 GeV	1712.02832 1711.03901
<u>8</u> 8, 8→	$q \bar{q} \tilde{\ell}_1^0$		2-6 jets	Yes	36.1	ž ž Forbidden	2.0 m(₹1)<200 CeV 0.95-1.6 m(₹1)=900 GeV	1712.02332 1712.02332
<u>8</u> 8.8→	$q\bar{q}(\ell\ell)\tilde{k}_{1}^{0}$	3 е, µ ее, µµ	4 jets 2 jets	- Yes	36.1 36.1	ž B	1.85 m(ℓ ₁ ⁰)<800 GeV 1.2 m(ℓ ₁ ⁰)-50 GeV	1706.03731 1805.11381
<u>8</u> 8, 8→4	$qqWZ \tilde{t}_1^0$	0 3 e, µ	7-11 jets 4 jets	Yes -	36.1 36.1	ž ž 0.96	1.8 m(ξ ⁰) <400 GeV m(ĝ)-m(ζ ⁰)=200 GeV	1708.02794 1706.03731
<u>8</u> 8, 8→1	$i\tilde{\chi}_{1}^{0}$	0-1 e,μ 3 e,μ	3 <i>b</i> 4 jets	Yes	36.1 36.1	ê R	2.0 m(ℓ ²) ~200 GeV 1.25 m(ℓ) =300 GeV	1711.01901 1706.03731
<i>b</i> ₁ <i>b</i> ₁ , <i>b</i> ₁	$_{1}\rightarrow b\tilde{\chi}_{1}^{0}/t\tilde{\chi}_{1}^{\pm}$		Multiple Multiple Multiple		36.1 36.1 36.1	δ1 Forbidden 0.9 δ1 Forbidden 0.58-0.82 δ1 Forbidden 0.7	$m_1 \tilde{\xi}_1^{(l)} = 300 \text{ GeV}, \text{BR}(h \tilde{\xi}_1^{(l)}) = 1$ $m_1 \tilde{\xi}_2^{(l)} = 300 \text{ GeV}, \text{BR}(h \tilde{\xi}_1^{(l)}) = \text{BR}(h \tilde{\xi}_1^{(l)}) = 0.5$ $m_1 \tilde{\xi}_1^{(l)} = 200 \text{ GeV}, m_1 \tilde{\xi}_1^{(l)} = 300 \text{ GeV}, \text{BR}(h \tilde{\xi}_1^{(l)}) = 1$	1708.09266, 1711.03301 1708.09266 1706.03731
5 ^b 1 ^b 1, <i>ī</i> 1 ⁱ	$\tilde{t}_1, M_2 = 2 \times M_1$		Multiple Multiple		36.1 36.1	īι 0.7 ī ₁ Forbidden 0.9	m(x₁)=60 GeV m(𝑘)=200 GeV	1709.04183, 1711.11520, 1708.03247 1709.04183, 1711.11520, 1708.03247
「 前前, 前一 前前, 前一	$\rightarrow Wh \tilde{\chi}_1^0 \text{ or } \tilde{\chi}_1^0$ LSP	0-2 e, µ 0)-2 jets/1-2 Multiple Multiple	b Yes	36.1 36.1 36.1	<i>i</i> ₁ 1.0 <i>i</i> ₁ 0.4-0.9 <i>i</i> ₁ 0.6-0.8	m(ξ ²)=1 GeV m(ξ ²)=150 GeV, m(ξ ²)+m(ξ ² ₁)=5 GeV, t ₁ ≈ t ₂ , m(ξ ²)=300 GeV, m(ξ ²)+m(ξ ² ₁)=5 GeV, t ₁ ≈ t ₂ .	1506.09616, 1709.04183, 1711.11520 1709.04183, 1711.11520 1709.04183, 1711.11520
ξ <i>i</i> ₁ <i>i</i> ₁ , We <i>i</i> ₁ <i>i</i> ₁ , <i>i</i> ₁ -	əll-Tempered LSP →ck ⁰ /čč.č→ck ⁰	o	Multiple 2c	Yes	36.1 36.1	<i>ī</i> ₁ 0.48-0.84 <i>ī</i> ₁ 0.85	$m(\tilde{\xi}_{1}^{0}) = 150 \text{ GeV}, m(\tilde{\xi}_{1}^{+}) - m(\tilde{\xi}_{1}^{0}) = 5 \text{ GeV}, \tilde{t}_{1} \approx \tilde{t}_{L}$ $m(\tilde{\xi}_{1}^{0}) = 0 \text{ GeV}$	1709.04183, 1711.11520 1805.01649
			mono-jet	Yes	36.1	71 0.46 71 0.43	m[ī₁,ż)-m(ξ₁)=50 GeV m(ī₁,ż)-m(ξ₁)=5 GeV	1805.01649 1711.03301
<i>ī</i> ₂ <i>ī</i> ₂ , <i>ī</i> ₂ -	$\rightarrow \tilde{t}_1 + h$	1-2 e, µ	4 b	Yes	36.1	ī ₂ 0.32-0.88	$m(\bar{k}_1^0)=0$ GeV, $m(\bar{k}_1)-m(\bar{k}_1^0)=180$ GeV	1706.03986
$ ilde{\chi}_1^\pm ilde{\chi}_2^0$ via	a WZ	2-3 e, μ ee, μμ	≥1	Yes Yes	36.1 36.1	$\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0}$ 0.6 $\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0}$ 0.17	m(ℓ ₁ ⁰)=0 m(ℓ ₁ [±])·m(ℓ ₁ ⁰)=10 GeV	1403.5294, 1805.02293 1712.08119
$ \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0} \text{ via} $ $ \tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\pm} \mu \tilde{\chi} $	a Wh ${}^{0}_{2}, \tilde{\chi}^{+}_{1} \rightarrow \tilde{\tau} \nu(\tau \tilde{\nu}), \tilde{\chi}^{0}_{2} \rightarrow \tilde{\tau} \tau(\nu \tilde{\nu})$	<i>llilγy/lbb</i> 2 τ		Yes Yes	20.3 36.1	$\frac{\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0}}{\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0}}$ 0.26 $\frac{\tilde{\chi}_{1}^{+}/\tilde{\chi}_{2}^{0}}{\tilde{\chi}_{1}^{-}/\tilde{\chi}_{2}^{0}}$ 0.76	$m(\tilde{k}_{1}^{0})=0$ $m(\tilde{k}_{1}^{0})=0$, $m(\tau, \tilde{\nu})=0.\pm(m(\tilde{k}_{1}^{0})+m(\tilde{k}_{1}^{0}))$ $m(\tilde{k}_{1}^{-1})-m(\tilde{k}_{2}^{0})=100$ GeV, $m(\tau, \tilde{\nu})=0.5(m(\tilde{k}_{1}^{0})+m(\tilde{k}_{1}^{0}))$	1501.07110 1708.07875 1708.07875
δ l _{l,R} l _{l,R}	$t, \bar{t} \rightarrow t \tilde{X}_1^0$	2 e,μ 2 e,μ	0 ≥1	Yes Yes	36.1 36.1	₹ 0.5 ₹ 0.18	$m(\tilde{\ell}_1^0)=0$ $m(\tilde{\ell}_1^2-m(\tilde{\ell}_1^0)=5~{ m GeV}$	1803.02762 1712.08119
ĤĤ, Ĥ-	→ħĞ/ZĞ	0 4 e, µ	≥ 3b 0	Yes Yes	36.1 36.1	11 0.13-0.23 0.29-0.88 11 0.3	$BR(\tilde{x}_1^0 \rightarrow kG)=1$ $BR(\tilde{x}_1^0 \rightarrow ZG)=1$	1806.04030 1804.03602
Direct $\hat{\lambda}$	$\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	Yes	36.1	<i>x</i> ⁺ ₁ 0.46 <i>x</i> [−] ₁ 0.15	Pure Wino Pure Higgsino	1712.02118 ATL-PHYS-PUB-2017-019
Stable i Metasta GMSB, gg, X ⁰ ₁	ğ R-hadron able ğ R-hadron, ğ→qqk ⁰ λ ⁰ →γđ, long-lived λ ⁰ ×eev/eµx/µµv	SMP 2 y displ.ee/eµ/µ	- Multiple - µ -	Yes	3.2 32.8 20.3 20.3	ž z (n;2)=100 ns,0.2 ns) Z 0.44 ž	1.6 1.6 2.4 m(វ,ີ)=100 GeV 1 <π(វ,ີ) <3 m, SP\$8 model 1.3 € <π(វ,ີ) <1000 mm, m(វື,ື)=1 TeV	1606.05129 1710.04901,1604.04520 1409.5542 1504.05162
LFV pp $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{1}$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow 0$	$\rightarrow \tilde{r}_{\tau} + X, \tilde{r}_{\tau} \rightarrow e \mu / e \tau / \mu \tau$ $p_2^D \rightarrow W W / Z \ell \ell \ell \ell r r r$ $q q \tilde{\chi}_1^0, \tilde{\chi}_1^D \rightarrow q q q$	еµ,ет,µт 4 е,µ 0 4-	- 0 5 large- <i>R</i> je Multiple	- Yes ats -	3.2 36.1 36.1 36.1	$ \begin{array}{l} \bar{\mu}_{1} & \\ \bar{\lambda}_{1}^{2} / \bar{\mu}_{2}^{2} & [\lambda_{01} \neq 0, \lambda_{01} \neq 0] \\ \bar{\mu}_{1} & [m_{1} \bar{\lambda}_{1}^{2} - 200 \text{ GeV}] \\ \bar{\mu}_{1} & [m_{1} \bar{\mu}_{2} - 200 \text{ GeV}] \\ \bar{\mu}_{1} & [m_{1} \bar{\mu}_{2} - 4, 2 + 5] \end{array} $	1.9 X ² ₃₁₁ =0.11. Å _{132(133/233} =0.97 1.33 m(t ²)==100 GeV 1.3 1.9 2.0 m(t ²)=200 GeV, bro-liko	1607.08079 1804.03662 1804.03568 ATLAS-CONF-2018-003
$\tilde{g}\tilde{g}, \tilde{g} \rightarrow$ $\tilde{t}\tilde{t}, \tilde{t} \rightarrow t\tilde{X}$ $\tilde{t}_1\tilde{t}_1, \tilde{t}_1 -$ $\tilde{t}_1\tilde{t}_2, \tilde{t}_2$	$bbs / \tilde{g} \rightarrow t \tilde{k}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow t bs$ $\hat{k}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow t bs$ $\rightarrow bs$ $\rightarrow bf$	0	Multiple Multiple 2 jets + 2 h		36.1 36.1 36.7	ĝ [J ₂₀ =1, 10 2] ĝ [J ₂₀ =2α-4, 1α-2] 0.55 1.0 ĵ, [qq ks] 0.42 0.51 7.	1.8 2.1 m(k ²)-200 GeV, bino-iko 5 m(k ²)-200 GeV, bino-iko 0.4.1 45 BR/(i)/(_ib)/(_	ATLAS-CONF-2018-003 ATLAS-CONF-2018-003 1710.07171 1710.05544
		- cip	20					

Only a spectron of the available mass limits on new states of phenometria is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made. Mass scale [TeV]

†Small-radius (large-radius) jets are denoted by the letter j (J).

Rules of thumb probably still correct; continuing to test them experimentally is an excellent idea. But it is hard to say much new along these lines, so null results invite exploring other avenues.

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2. The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.

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Discrete symmetries



E.g. "Twin Higgs" [Chacko, Goh, Harnik '05, ...]

Higgs is a pNGB of an accidental SU(4), but spectrum only respects a Z₂

$$\Delta V = -\frac{6y_t^2}{16\pi^2} \Lambda^2 \left(|H_A|^2 + |H_B|^2 \right) + \dots$$

$$\Delta m_H^2 = -\frac{6y_t^2}{16\pi^2}\Lambda^2 + \frac{6y_t^2}{16\pi^2}\Lambda^2 - 6\frac{y_t^2}{16\pi^2}(m_T^2 - m_t^2)\log\frac{\Lambda^2}{m_T^2}$$

Still a plethora of new particles, not interacting via SM gauge forces but coupling to Higgs.

Why Not?

Higgs portal maintains equilibrium down to T~GeV

 $\Delta N_{eff} >> 1$

Options are

Change the cosmology Signals in CMB: N_{eff} , $\sum m_v$,

twin BAO...

- RHN decay
- Saxion decay
- Early v' decoupling

[Chacko, NC, Fox, Harnik '16; NC, Koren, Trott '16; Chacko, Curtin, Geller, Tsai '18, ...]

Change the spectrum

Copious new physics at ~few TeV Higgs signals @ LHC

- Fraternal Twin Higgs
- Holographic Twin Higgs
- Composite Twin Higgs
- Orbifold Higgs
- ...



Higgs portal observables

 $\sim tuning$

When all is said and done, scale of new charged states (c.f. usual continuous symmetry solutions) [NC, Howe '13; Contino et al. '17]

$$m_*^2 \sim m_{*,\mathrm{cts}}^2 \times \left(\frac{g_*}{g_{SM}}\right)^2$$

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Relaxion

What if the weak scale is selected by scanning?

The idea: couple Higgs to field whose minimum sets $m_H=0$ The problem: How to make $m_H=0$ a special point of potential?



But: immense energy stored in evolving field, need dissipation.

[Graham, Kaplan, Rajendran '15]

Relaxion

Simplest version: an axion coupled to QCD during inflation.



 $\Lambda^4(H)\cos(\phi/f) + F(g\phi) + (-M^2 + g\phi)|H|^2$

Viable for Higgs + non-compact axion + inflation w/

• Very low Hubble scale ($\ll \Lambda_{QCD}$) • 10 Giga-years of inflation

Why not? Various other subtleties regarding technical naturalness, trans-Planckian field excursions, CC, fine-tuning to inflationary sector; need to solve strong CP problem. *New UV considerations.*

Extensive development, e.g. [Espinosa et al. '15; Hardy '15; Gupta et al '15; Batell, Giudice, McCullough '15; Choi, Im '15; Kaplan, Rattazzi '15; Di Chiara et al. '15; Ibanez et al. '15; Hook, Marques-Tavares '16; Nelson, Prescod-Weinstein '17; ...]

See also: NNaturalness [Arkani-Hamed et al. '16]

New Signals



+5th force for $m_{\phi} < eV$ & cosmology for $eV < m_{\phi} < MeV$

[Flacke, Friquele, Fuchs, Gupta, Perez '16] 0.05 PIN NO POO 0.04 0.03 sin² θ 0.02 0.01 0.00 30 10 20 40 50 60 m_{ϕ} [GeV]

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*assuming 〈φ〉 breaks CP

[Hook, Marques-Tavares '16; Fonseca, Morgante, Servant '18]

Particle production relaxion

Alternative possibility: keep bumps across entire potential, turn on dissipation at a special point of potential.

Novel source of dissipation: particle production

$$\begin{array}{ll} \text{Consider axion-like couplings to} & \mathcal{L} \supset -\frac{\phi}{4f} F \tilde{F} \\ \text{E.O.M. for transverse} & \ddot{A}_{\pm} + \left(k^2 + m_A^2 \pm \frac{k \dot{\phi}}{f}\right) A_{\pm} = 0 \\ \text{polarizations:} & \ddot{A}_{\pm} + \left(k^2 + m_A^2 \pm \frac{k \dot{\phi}}{f}\right) A_{\pm} = 0 \\ \text{For } \dot{\phi} \approx \text{constant} & A_{\pm}(k) \propto e^{i\omega_{\pm}t} & \omega_{\pm}^2 = k^2 + m_A^2 \pm \frac{k \dot{\phi}}{f} \end{array}$$

Exponentially growing solution for $\omega_{\pm}^2 < 0 \Rightarrow |\dot{\phi}| \gtrsim 2 f m_A$ Growing mode drains energy from $\dot{\phi}$

Particle production relaxion

Apply to relaxion: use electroweak gauge fields



Important subtlety: can't couple to pairs of photons! (Not a tuning, can be made natural with symmetries, e.g., $SU(2)_L \times SU(2)_R$)

Requiring sub-Planckian field excursions & avoiding overshoot bounds cutoff

Corresponding decay constant

$$\Lambda \lesssim (M_{\rm Pl}v^5)^{1/6} \sim 50 \,\mathrm{TeV}$$
$$f \sim \frac{\dot{\phi}}{v} \sim \frac{\Lambda^2}{v} \lesssim 10^4 \,\mathrm{TeV}$$

New Signals

Even if tree-level relaxion couplings to SM states are engineered to be



[NC, Hook, Kasko '18]

 $\frac{\phi}{f} \left(g^2 W \widetilde{W} - g'^2 B \widetilde{B} \right) \quad \mbox{in the} \\ {\rm UV}...$

...radiative couplings to fermions induced at one loop, photon pairs at one & two loops [Bauer, Neubert, Thamm '17; NC, Hook, Kasko '18]



 $f_{\gamma} \sim 16\pi^2 \frac{m_W^2}{m_a^2} f_a + (16\pi^2)^2 \frac{m_f^2}{m_a^2} f_a$

Astrophysical and collider signatures abound; still viable parameter space [Fonseca, Morgante, Servant '18]

1905.04246



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(Electric) weak gravity conjecture: an abelian gauge theory must contain a state of charge *q* and mass *m* satisfying

[Arkani-Hamed, Motl, Nicolis, Vafa '07]

[Cheung, Remmen '14]: If mass of WGC particle is UV sensitive, then for fixed UV-insensitive parameters, satisfying the WGC would mandate fine-tuning. (Or: would orchestrate correlations among UV contributions)

Application to SM: charge SM fermions under weakly gauged (unbroken) U(1)_{B-L} (bounds currently q \leq 10⁻²⁴). Cancel anomalies with RHN v_R

Neutrino mass from EWSB $y_{\nu}H\bar{L}\nu_R \rightarrow m_{\nu} \sim y_{\nu}v$

If lightest neutrino is WGC particle, $m_v \sim 0.1 \text{ eV}, q \ge 10^{-29}$

 $q > \frac{m}{M_{Pl}}$

For fixed y, q, satisfying WGC places an upper bound on v

18 See also: [Ibañez, Martin-Lozano, Valenzuela '17,...]

Things that could go wrong:

- WGC could be satisfied by states outside EFT
- Satisfying WGC could compel the appearance of a new light state that enforces apparent UV correlations (e.g. relaxion)
- Apparently UV-sensitive parameters might control apparently UV-insensitive ones (e.g. emergent gauge fields)

Thing that certainly goes wrong:

• Magnetic WGC implies cutoff of U(1) at $~~\Lambda \lesssim g M_{Pl}$

First order of business: can m, Λ be raised to the weak scale?

New U(1) _x plus matter		$SU(2)_L$	$U(1)_Y$	$U(1)_X$
acquiring some mass	L		+1/2	+1
from the Higgs. E.g	L^c		-1/2	-1
	N	_	0	+1
[NC, Garcia Garcia, Koren '19]	N^c		0	—1

 $-\mathcal{L} \supset \left\{ m_L L L^c + m_N N N^c + y H^{\dagger} L N^c + \tilde{y} H L^c N \right\} + \text{h.c.}$

Best option: $m_N < m_L$, lightest mass eigenstate χ_1 is WGC particle

 $\begin{array}{ll} \mbox{Then for fixed} \\ \mbox{(technically natural)} \\ \mbox{g, m}_{\rm L}, \, \mbox{m}_{\rm N}, \, \mbox{y}, \end{array} & v^2 \lesssim \frac{2}{y^2} \left(m_{\chi_1}^2 + m_{\chi_1} (m_L - m_N) - m_L m_N \right) \\ \end{array}$

Still have a notion of sensitivity of the weak scale to parameters involved in the bound



Quantify
with e.g. $\Delta_x \equiv \left| \frac{\partial \log v^2}{\partial \log x} \right|$ Here $\Delta_m \propto \frac{m_N m_L}{y^2 v^2}$

Not surprising: WGC particle should get "most of" its mass from EWSB.

Surprisingly predictive: look for new singlet fermions coupled to the Higgs at/below the weak scale.

DM story interesting...

Second order of business: can the magnetic WGC scale be something less severe than the SM cutoff? Only confident that Λ ~ scale associated w/ structure of magnetic monopoles

E.g. t' Hooft-Polyakov monopoles $SU(2)_X \xrightarrow[\langle Adi \rangle]{} U(1)_X$

"
$$\Lambda$$
" = $m_W = g_2 f = 2gf \lesssim 2gM_{\rm Pl}$

W's would trivialize bound from vanilla electric WGC, but not e.g. unit charge version (charge \pm 2 under U(1)_X)

Alternately: WGC w/ scalar fields [Palti '17, Palti & Lüst '17]

$$m^2 \lesssim (g^2 - \mu^2) M_{\rm Pl}^2$$

Worth refining conjectures & exploring further even out of skepticism: could point to WGC conjectures ripe for counterexamples.

Direct UV/IR Mixing

Take the bull by the horns...

Study field theories with UV/IR mixing Canonical example:

QFT on non-commutative spacetime $[\hat{x}^{\mu}, \hat{x}^{\nu}] = i\theta^{\mu\nu}$ UV/IR mixing from "uncertainty principle" $\Delta \hat{x}^{\mu} \Delta \hat{x}^{\nu} \ge \frac{1}{2} |\theta^{\mu\nu}|$

Caveats: Lorentz violating; Minkowski NCQFT unitary only for space-space non-commutativity (i.e. θ⁰ⁱ=0). *Not the theory of our universe, but a useful toy model.* (See e.g. [Heckman & Verlinde '14])



NCQFT

Two common approaches:

1. QFT on commutative coordinates w/ star product:

$$f(x) \star g(x) = \exp\left(\frac{i}{2}\theta_{\mu\nu}\partial_{y}^{\mu}\partial_{z}^{\nu}\right)f(y)g(z)\Big|_{y=z=x}$$

2. Seiberg-Witten map [Seiberg, Witten '99]:

I.e.,
$$f \star g = f \cdot g + \frac{i}{2} \theta^{\mu\nu} \partial_{\mu} \cdot \partial_{\nu} g + \mathcal{O}(\theta^2)$$
 and e.g.
 $\hat{A}_{\mu}[A] = A_{\mu} + \frac{1}{4} \theta^{\rho\sigma} \{A_{\sigma}, \partial_{\rho} A_{\mu}\} + \frac{1}{4} \theta^{\rho\sigma} \{F_{\rho\mu}, A_{\sigma}\} + \mathcal{O}(\theta^2)$

Equivalent to any finite order in θ (i.e., option (2) defines a lowenergy effective action), but UV/IR mixing only apparent in (1).

, t

NCQFT: ϕ^4

Consider just
$$\phi^4$$
 in
Euclidean d=4: $\mathcal{L} = \frac{1}{2} \left(\partial_\mu \phi\right)^2 + \frac{1}{2} m^2 \phi^2 + \frac{1}{4!} g^2 \phi \star \phi \star \phi \star \phi$

Quadratic terms identical to commutative theory

Interactions associated w/ additional phases:

$$V(k_1, k_2, k_3, k_4) = e^{-\frac{i}{2}\sum_{i < j} k_{i\mu}\theta^{\mu\nu}k_{j\nu}}$$

Not invariant under arbitrary permutations of k

Planar graphs: reduces to an overall phase involving external momenta

Nonplanar graphs: additional phases from crossing lines

Feynman rules as usual modulo phases in nonplanar diagrams:

 $\sim e^{ip_{\mu}\theta^{\mu
u}k_{
u}}$

[Minwalla, Seiberg, Van Raamsdonk '99]

NCQFT: ϕ^4

Compute one-loop radiative corrections to scalar 2-pt function. Both "planar" and "non-planar" diagrams at one loop:



[Minwalla, Seiberg, Van Raamsdonk '99 Alvarez-Gaume, Vazquez-Mozo '03]

New "poles"

1-loop 1PI quadratic effective action:
$$\frac{1}{2} \left(p^2 + M^2 + \frac{g^2}{96\pi^2 (p \circ p + 1/\Lambda^2)} + \dots \right) \phi(p)\phi(-p)$$

w/ renormalized mass M: $M^2 = m^2 + \frac{g^2 \Lambda^2}{48\pi^2} - \frac{g^2 m^2}{48\pi^2} \ln \frac{\Lambda^2}{m^2}$

Action @ infinite cutoff:

$$\frac{1}{2} \left(p^2 + M^2 + \frac{g^2}{96\pi^2 p \circ p} + \dots \right) \phi(p)\phi(-p)$$

Two poles in $\Lambda \rightarrow \infty$ action:

1. Usual one (ϕ quanta) at $p^2 + m^2 = \mathcal{O}(g^2)$ 2. New one at $p \circ p = -\frac{g^2}{96\pi^2} \frac{1}{p_c^2 + m^2} + \dots$

Second pole signals existence of new light "particle" arising from high-momentum modes of φ

Wilsonian interpretation

Normally require renormalizable Wilsonian action to satisfy

- 1. Correlation functions well-defined as $\Lambda \rightarrow \infty$
- 2. Correlation functions at finite Λ differ from limiting value by O(1/ Λ) at all momenta

Badly violated
$$\frac{1}{2}\left(p^2 + M^2 + \frac{g^2}{96\pi^2(p \circ p + 1/\Lambda^2)} + \dots\right)\phi(p)\phi(-p)$$

here at small p.

Restore Wilsonian interpretation w/ new particle x:

$$\delta \mathcal{L} = \frac{1}{2} \partial \chi \circ \partial \chi + \frac{1}{2} \Lambda^2 (\partial \circ \partial \chi)^2 + i \frac{1}{\sqrt{96\pi^2}} g \chi \phi$$

Quadratic, so integrate out: $+\frac{1}{2}\frac{1}{96\pi^2}\left(\frac{g^2}{p \circ p} - \frac{g^2}{p \circ p + 1/\Lambda^2}\right)\phi(p)\phi(-p)$

What have we learned?

High-momentum modes of massive fields in a non-commutative scalar theory are "dual" to additional (peculiar) light fields

4d fields in case of quadratic divergences, 5d for linear divergences, 6d for logarithmic divergences

In a fantasy application to the hierarchy problem, apparently light scalars are the χ fields, not the φ fields

$$\delta \mathcal{L} = \frac{1}{2} \partial \chi \circ \partial \chi + \frac{1}{2} \Lambda^2 (\partial \circ \partial \chi)^2 + i \frac{1}{\sqrt{96\pi^2}} g \chi \phi$$

Just a fantasy in this setting, but worth understanding basic features & trying to extract lessons [NC, Koren, *to appear*] Other controlled QFTs with similar features?



Conclusions

- 1. The Standard Model coupled to gravity is a generic EFT.
- 2. The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.
- 3. Symmetries imply new particles charged under the SM.

Conclusions

- 1. The Standard Model coupled to gravity is a generic EFT.
- The solutions to the hierarchy problem involve symmetries, low cutoffs, or anthropics.
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Relaxing these rules of thumb is constructive and leads to new signatures associated with naturalness. Only beginning to explore the possibilities....

Conclusions

Hard not to notice patterns among the three naturalness problems...

	Hierarchy Problem	CC Problem	Strong CP
Continuous symm.	SUSY, global	SUSY	U(1) _{PQ}
Discrete symm.	Z ₂	E→-E	P/CP
Dynamical field	Relaxion	Abbott	U(1) _{PQ}
Anthropics	Atomic principle	Structure formation	?
UV/IR mixing	WGC/NCQFT/	Holography	?

Thank you!