The Radiative Origin of the Electro-Weak and Dark Matter Scale

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PERIMETER INSTITUTE

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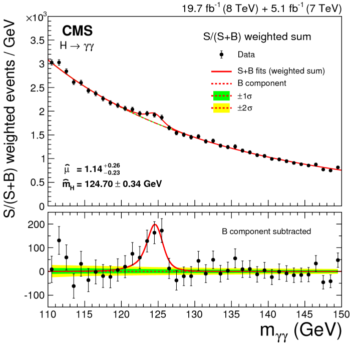
Outline

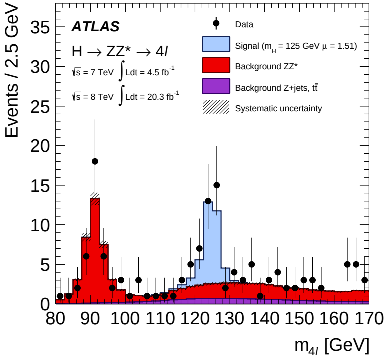
WA, Bardeen, Bauer, Carena and Lykken

"Light Dark Matter, Naturalness, and the Radiative Origin of the Electroweak Scale"

arXiv:1408.3429 [hep-ph]

The LHC Discovered the Higgs





coupling, spin and parity measurements are (so far) compatible with predictions for the elementary SM Higgs

The Hierarchy Problem

the mass of an elementary higgs is quadratically sensitive to the UV

$$(m_h^0)^2 \quad + \quad \frac{1}{16\pi^2}(\Lambda_{\text{UV}})^2 \quad \simeq \; (125~\text{GeV})^2$$

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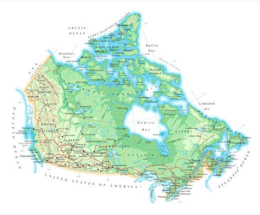

$-$

Canada
9,984,670 km^2 $\quad - \quad$ United States
9,826,675 km^2 $\quad = \quad$ 157,995 km^2

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$-$

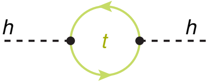
$= \quad 1~\text{Å}^2$

Canada
9,984,670 km^2 $-$ United States
9,826,675 km^2 $=$ 157,995 km^2

for $\Lambda_{\rm UV} = M_{\rm Planck}$, tuning of the Higgs mass would correspond to
the surface area of Canada and the United States
differing by approximately the size of an atom!

Finetuning and Naturalness

In the absence of a symmetry (or some form of conspiracy) enforcing cancellations, the observed electro-weak scale can only be obtained by finetuning the bare Higgs mass against the radiative corrections.



$$\simeq \quad \frac{3y_t^2}{4\pi^2}\,(\Lambda_{\rm UV})^2$$

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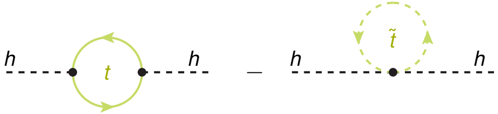
naturalness principle:

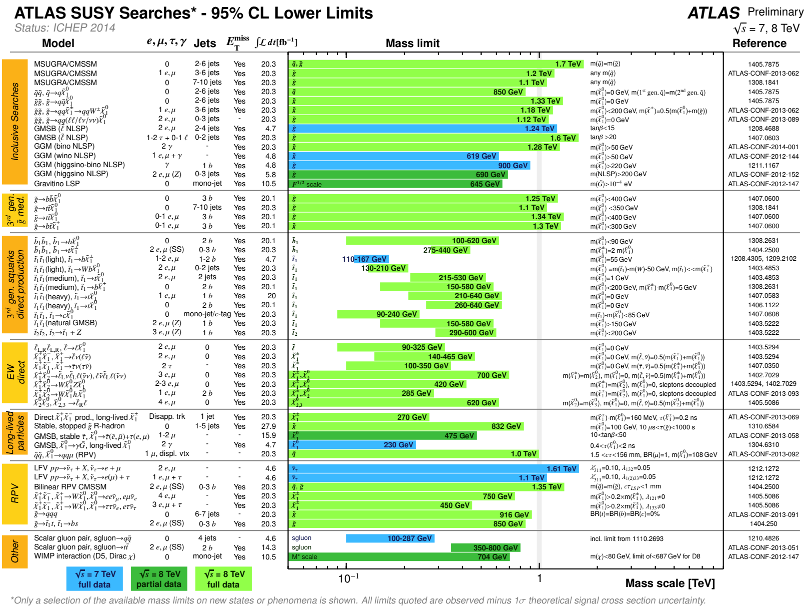
light fundamental scalars are accompanied by new physics that cancels the quadratically divergent part of the radiative corrections



$$\simeq \frac{3y_t^2}{4\pi^2}\, m_{\tilde{t}}^2 \,\log(\Lambda_{\rm UV})$$

still most popular candidate: supersymmetry

No Signs of SUSY (yet)



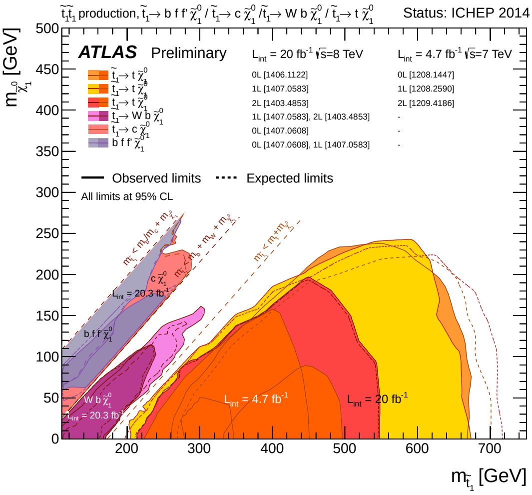
ATLAS SUSY Searches* - 95% CL Lower Limits

Status: ICHEP 2014

	Model	e, μ, τ, γ	Jets	E_T^{miss}	$\int \mathcal{L}\, dt[\mathrm{fb}^{-1}]$	Mass limit			Reference
Inclusive Searches	MSUGRA/CMSSM	0	2-6 jets	Yes	20.3	$\tilde{q}, \tilde{g}$	1.7 TeV	m($\tilde{q}$)=m($\tilde{g}$)	1405.7875
	MSUGRA/CMSSM	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.2 TeV	any m($\tilde{q}$)	ATLAS-CONF-2013-062
	MSUGRA/CMSSM	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	any m($\tilde{q}$)	1308.1841
	$\tilde{q}\tilde{q}, \tilde{q}\to q\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{q}$	850 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m(1st gen. $\tilde{q}$)=m(2nd gen. $\tilde{q}$)	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	20.3	$\tilde{g}$	1.33 TeV	m($\tilde{\chi}_1^0$)=0 GeV	1405.7875
	$\tilde{g}\tilde{g}, \tilde{g}\to qq\tilde{\chi}_1^{\pm}\to qqW^{\pm}\tilde{\chi}_1^0$	1 e, μ	3-6 jets	Yes	20.3	$\tilde{g}$	1.18 TeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}^{\pm}$)=0.5(m($\tilde{\chi}_1^0$)+m($\tilde{g}$))	ATLAS-CONF-2013-062
	$\tilde{g}\tilde{g}, \tilde{g}\to qq(\ell\ell/\ell\nu/\nu\nu)\tilde{\chi}_1^0$	2 e, μ	0-3 jets	-	20.3	$\tilde{g}$	1.12 TeV	m($\tilde{\chi}_1^0$)=0 GeV	ATLAS-CONF-2013-089
	GMSB ($\tilde{\ell}$ NLSP)	2 e, μ	2-4 jets	Yes	4.7	$\tilde{g}$	1.24 TeV	tanβ<15	1208.4688
	GMSB ($\tilde{\ell}$ NLSP)	1-2 τ + 0-1 ℓ	0-2 jets	Yes	20.3	$\tilde{g}$	1.6 TeV	tanβ >20	1407.0603
	GGM (bino NLSP)	2 γ	-	Yes	20.3	$\tilde{g}$	1.28 TeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2014-001
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	$\tilde{g}$	619 GeV	m($\tilde{\chi}_1^0$)>50 GeV	ATLAS-CONF-2012-144
	GGM (higgsino-bino NLSP)	γ	1 b	Yes	4.8	$\tilde{g}$	900 GeV	m($\tilde{\chi}_1^0$)>220 GeV	1211.1167
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	$\tilde{g}$	690 GeV	m(NLSP)>200 GeV	ATLAS-CONF-2012-152
	Gravitino LSP	0	mono-jet	Yes	10.5	$F^{1/2}$ scale	645 GeV	m($\tilde{G}$)>10^{-4} eV	ATLAS-CONF-2012-147
3^{rd} gen. $\tilde{g}$ med.	$\tilde{g}\to b\bar{b}\tilde{\chi}_1^0$	0	3 b	Yes	20.1	$\tilde{g}$	1.25 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0	7-10 jets	Yes	20.3	$\tilde{g}$	1.1 TeV	m($\tilde{\chi}_1^0$) <350 GeV	1308.1841
	$\tilde{g}\to t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.34 TeV	m($\tilde{\chi}_1^0$)<400 GeV	1407.0600
	$\tilde{g}\to b\bar{t}\tilde{\chi}_1^+$	0-1 e, μ	3 b	Yes	20.1	$\tilde{g}$	1.3 TeV	m($\tilde{\chi}_1^0$)<300 GeV	1407.0600
3^{rd} gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to b\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{b}_1$	100-620 GeV	m($\tilde{\chi}_1^0$)<90 GeV	1308.2631
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1\to t\tilde{\chi}_1^{\pm}$	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
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	1-2 e, μ	1-2 b	Yes	4.7	$\tilde{t}_1$	110-167 GeV	m($\tilde{\chi}_1^0$)=55 GeV	1208.4305, 1209.2102
	$\tilde{t}_1\tilde{t}_1$(light), $\tilde{t}_1\to Wb\tilde{\chi}_1^0$	2 e, μ	0-2 jets	Yes	20.3	$\tilde{t}_1$	130-210 GeV	m($\tilde{\chi}_1^0$) =m($\tilde{t}_1$)-m(W)-50 GeV, m($\tilde{t}_1$)<<m($\tilde{\chi}_1^{\pm}$)	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to t\tilde{\chi}_1^0$	2 e, μ	2 jets	Yes	20.3	$\tilde{t}_1$	215-530 GeV	m($\tilde{\chi}_1^0$)=1 GeV	1403.4853
	$\tilde{t}_1\tilde{t}_1$(medium), $\tilde{t}_1\to b\tilde{\chi}_1^{\pm}$	0	2 b	Yes	20.1	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)<200 GeV, m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=5 GeV	1308.2631
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	1 e, μ	1 b	Yes	20	$\tilde{t}_1$	210-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1407.0583
	$\tilde{t}_1\tilde{t}_1$(heavy), $\tilde{t}_1\to t\tilde{\chi}_1^0$	0	2 b	Yes	20.1	$\tilde{t}_1$	260-640 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1406.1122
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1\to c\tilde{\chi}_1^0$	0	mono-jet/c-tag	Yes	20.3	$\tilde{t}_1$	90-240 GeV	m($\tilde{t}_1$)-m($\tilde{\chi}_1^0$)<85 GeV	1407.0608
	$\tilde{t}_1\tilde{t}_1$(natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_1$	150-580 GeV	m($\tilde{\chi}_1^0$)>150 GeV	1403.5222
	$\tilde{t}_2\tilde{t}_2, \tilde{t}_2\to\tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	$\tilde{t}_2$	290-600 GeV	m($\tilde{\chi}_1^0$)<200 GeV	1403.5222
EW direct	$\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell}\to\ell\tilde{\chi}_1^0$	2 e, μ	0	Yes	20.3	$\tilde{\ell}$	90-325 GeV	m($\tilde{\chi}_1^0$)=0 GeV	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\ell}\nu(\ell\tilde{\nu})$	2 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}$	140-465 GeV	m($\tilde{\chi}_1^0$)=0 GeV, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1403.5294
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to\tilde{\tau}\nu(\tau\tilde{\nu})$	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
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to\tilde{\ell}_L\nu\tilde{\ell}_L\ell(\tilde{\nu}\nu), \ell\tilde{\nu}\tilde{\ell}_L\ell(\tilde{\nu}\nu)$	3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	700 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_1^{\pm}$)+m($\tilde{\chi}_1^0$))	1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 Z\tilde{\chi}_1^0$	2-3 e, μ	0	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	420 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	1403.5294, 1402.7029
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0\to W\tilde{\chi}_1^0 h\tilde{\chi}_1^0$	1 e, μ	2 b	Yes	20.3	$\tilde{\chi}_1^{\pm}, \tilde{\chi}_2^0$	285 GeV	m($\tilde{\chi}_1^{\pm}$)=m($\tilde{\chi}_2^0$), m($\tilde{\chi}_1^0$)=0, sleptons decoupled	ATLAS-CONF-2013-093
	$\tilde{\chi}_2^0\tilde{\chi}_3^0, \tilde{\chi}_{2,3}^0\to\tilde{\ell}_R\ell$	4 e, μ	0	Yes	20.3	$\tilde{\chi}_{2,3}^0$	620 GeV	m($\tilde{\chi}_2^0$)=m($\tilde{\chi}_3^0$), m($\tilde{\chi}_1^0$)=0, m($\tilde{\ell}, \tilde{\nu}$)=0.5(m($\tilde{\chi}_2^0$)+m($\tilde{\chi}_1^0$))	1405.5086
Long-lived particles	Direct $\tilde{\chi}_1^+\tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	20.3	$\tilde{\chi}_1^{\pm}$	270 GeV	m($\tilde{\chi}_1^{\pm}$)-m($\tilde{\chi}_1^0$)=160 MeV, τ($\tilde{\chi}_1^{\pm}$)=0.2 ns	ATLAS-CONF-2013-069
	Stable, stopped $\tilde{g}$ R-hadron	0	1-5 jets	Yes	27.9	$\tilde{g}$	832 GeV	m($\tilde{\chi}_1^0$)=100 GeV, 10 μs<τ($\tilde{g}$)<1000 s	1310.6584
	GMSB, stable $\tilde{\tau}, \tilde{\chi}_1^0\to\tilde{\tau}(\tilde{e}, \tilde{\mu})+\tau(e, \mu)$	1-2 μ	-	-	15.9	$\tilde{\chi}_1^0$	475 GeV	10<tanβ<50	ATLAS-CONF-2013-058
	GMSB, $\tilde{\chi}_1^0\to\gamma\tilde{G}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	4.7	$\tilde{\chi}_1^0$	230 GeV	0.4<τ($\tilde{\chi}_1^0$)<2 ns	1304.6310
	$\tilde{q}\tilde{q}, \tilde{\chi}_1^0\to qq\mu$ (RPV)	1 μ, displ. vtx	-	-	20.3	$\tilde{q}$	1.0 TeV	1.5 <$c\tau$<156 mm, BR(μ)=1, m($\tilde{\chi}_1^0$)=108 GeV	ATLAS-CONF-2013-092
RPV	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	1.61 TeV	λ'_{311}=0.10, λ_{132}=0.05	1212.1272
	LFV $pp\to\tilde{\nu}_\tau + X, \tilde{\nu}_\tau\to e(\mu) + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	1.1 TeV	λ'_{311}=0.10, $\lambda_{1(2)33}$=0.05	1212.1272
	Bilinear RPV CMSSM	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{q}, \tilde{g}$	1.35 TeV	m($\tilde{q}$)=m($\tilde{g}$), $c\tau_{LSP}$<1 mm	1404.2500
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to ee\tilde{\nu}_\mu, e\mu\tilde{\nu}_e$	4 e, μ	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	750 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{121}\neq0$	1405.5086
	$\tilde{\chi}_1^+\tilde{\chi}_1^-, \tilde{\chi}_1^+\to W\tilde{\chi}_1^0, \tilde{\chi}_1^0\to\tau\tau\tilde{\nu}_e, e\tau\tilde{\nu}_\tau$	3 $e, \mu + \tau$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}$	450 GeV	m($\tilde{\chi}_1^0$)>0.2×m($\tilde{\chi}_1^{\pm}$), $\lambda_{133}\neq0$	1405.5086
	$\tilde{g}\to qqq$	0	6-7 jets	-	20.3	$\tilde{g}$	916 GeV	BR(t)=BR(b)=BR(c)=0%	ATLAS-CONF-2013-091
	$\tilde{g}\to\tilde{t}_1 t, \tilde{t}_1\to bs$	2 e, μ (SS)	0-3 b	Yes	20.3	$\tilde{g}$	850 GeV		1404.250
Other	Scalar gluon pair, sgluon→$q\bar{q}$	0	4 jets	-	4.6	sgluon	100-287 GeV	incl. limit from 1110.2693	1210.4826
	Scalar gluon pair, sgluon→$t\bar{t}$	2 e, μ (SS)	2 b	Yes	14.3	sgluon	350-800 GeV		ATLAS-CONF-2013-051
	WIMP interaction (D5, Dirac χ)	0	mono-jet	Yes	10.5	M* scale	704 GeV	m(χ)<80 GeV, limit of<687 GeV for D8	ATLAS-CONF-2012-147

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

No Signs of SUSY (yet)



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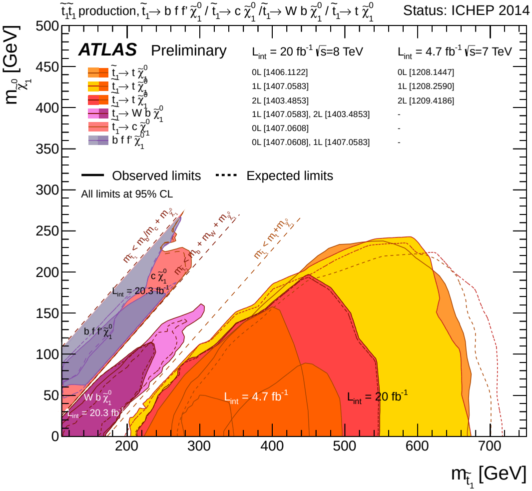

- it is possible that we just missed the superpartners at the 7/8 TeV run, and they will show up at 13 TeV

- (it happend in the past: e.g. LEP and Tevatron just missed the Higgs)

A Modified Naturalness Principle

Farina, Pappadopulo, Strumia, 1303.7244 (finite naturalness); Giudice, 1307.7879 (UV naturalness)

the higgs mass is quadratically sensitive to UV thresholds

- if there are no new particles/scales above the electro-weak scale, there is no hierarchy problem (what about gravity?)
- if new particles above the electro-weak scale are sufficiently weakly coupled to the Higgs, there is also no hierarchy problem

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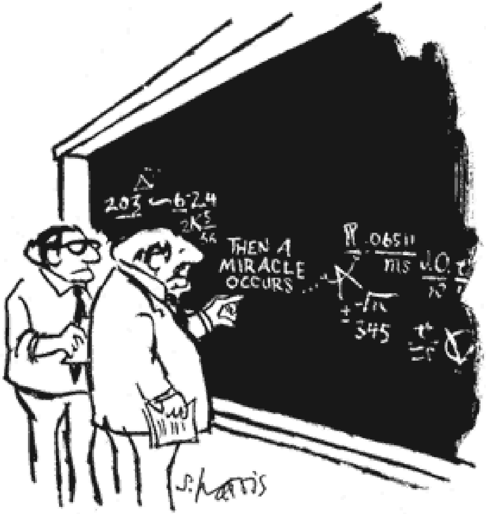
can be used as a constraint on new physics:

- right handed neutrinos from a see-saw mechanism have to be lighter than $\sim 10^7$ GeV in order to avoid fine-tuning
- minimal dark matter particles are typically bounded at the level of ~ 1 TeV in order to avoid fine-tuning

What about Gravity?



"I THINK YOU SHOULD BE MORE EXPLICIT HERE IN STEP TWO."

Three Categories of Miracles

(Giudice, 1307.7879)

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AND leads all SM couplings to fixed points (no Landau poles)

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AND leads all SM couplings to fixed points (no Landau poles)

miracle of the first degree:

gravity does do not affect the Higgs mass

AND leads all SM couplings to fixed points

AND erases any large quantum correction to the Higgs mass from physics below the Planck scale

No-Scale Models

finite naturalness is guaranteed if there are no scales in the theory (Planck scale does not count, because one assumes gravity performs a miracle of third or maybe second degree)

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- strong dynamics: use technicolor to give mass to an elementary Higgs
  (Hur, Ko 1103.2571; Heikinheimo, et al. 1304.7006; Holthausen, et al. 1310.4423)

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  (Hur, Ko 1103.2571; Heikinheimo, et al. 1304.7006; Holthausen, et al. 1310.4423)
- Coleman-Weinberg: quartic of another scalar runs negative in the IR
  (many papers in the last few years)

$$V_{\rm eff}(\Sigma) \sim \lambda \Sigma^4 + \beta_\lambda \Sigma^4 \log \Sigma ~~, \qquad \lambda < 0 ~,~~ \beta_\lambda > 0$$

electro-weak symmetry breaking generated by a negative Higgs portal

$$\lambda_{\Sigma H} \Sigma^\dagger \Sigma\, H^\dagger H \quad \to \quad \frac{\lambda_{\Sigma H} \langle \Sigma \rangle^2}{2}\, H^\dagger H$$

The Model

No Scales and a Dark Portal

a complex scalar serves as portal to a dark sector

$$\mathcal{L}_{\text{scalar}} = |D\,H|^2 + |D\,\Sigma|^2 - \frac{\lambda_H}{2}|H|^4 - \frac{\lambda_\Sigma}{2}|\Sigma|^4 - \lambda_{\Sigma H}|H|^2|\Sigma|^2$$

Possibilities for Dark Matter

- pseudoscalar component of the complex dark scalar (Gabrielli, et al. 1309.6632)
- dark gauge boson that gets mass from eating a Goldstone from the complex portal scalar (Hambye, Strumia 1306.2329)
- dark fermions that gets mass from Yukawa couplings to the complex portal scalar (WA, Bardeen, Bauer, Carena, Lykken 1408.3429)

$$\beta_{\lambda_\Sigma} \sim \frac{1}{16\pi^2}\Big(+\text{quartics} \quad +\text{gauge couplings} \quad -\text{Yukawas} \Big)$$

Dark Gauge Interactions

- introduce a dark $SU(2)_X \times U(1)_X$ gauge group

$$\mathcal{L}_{\text{gauge}} = \frac{1}{4}(W'_a)_{\mu\nu}(W'_a)^{\mu\nu} + \frac{1}{4}(B')_{\mu\nu}(B')^{\mu\nu}$$

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- the dark scalar Σ is a $SU(2)_X$ doublet with $U(1)_X$ charge $1/2$
- a dark scalar vev $\langle\Sigma\rangle = w$ breaks the dark gauge group down to a dark $U(1)$ (dark electro-magnetism)
- dark sector contains a massless dark photon, massive dark W and dark Z

$$m_{\gamma'} = 0 \ , \quad m_{W'} = \frac{w}{2} g_X \ , \quad m_{Z'} = \frac{w}{2}\sqrt{g_X^2 + {g'_X}^2}$$

- (we don't consider kinetic mixing between $U(1)_X$ and $U(1)_Y$)

The Dark Fermion Sector

- we introduce two generations of dark “leptons”

left-handed doublets $\psi_i^L = \begin{pmatrix} \chi_i^L \\ \xi_i^L \end{pmatrix}$, right-handed singlets χ_i^R , ξ_i^R

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left-handed doublets $\psi_i^L = \begin{pmatrix} \chi_i^L \\ \xi_i^L \end{pmatrix}$, right-handed singlets χ_i^R , ξ_i^R

- the two generations have opposite hypercharges to ensure cancellation of anomalies

$$\mathcal{L}_{\text{fermion}} = i\bar{\psi}_i^L \not{D} \psi_i^L + i\bar{\chi}_i^R \not{D} \chi_i^R + i\bar{\xi}_i^R \not{\partial}\, \xi_i^R$$
$$+ (Y_{\chi_1} \bar{\psi}_1^L \chi_1^R \tilde{\Sigma} + Y_{\chi_2} \bar{\psi}_2^L \chi_2^R \Sigma + Y_{\xi_1} \bar{\psi}_1^L \xi_1^R \Sigma + Y_{\xi_2} \bar{\psi}_2^L \xi_2^R \tilde{\Sigma} \ + \ \text{h.c.})$$

- fermions get masses from Yukawa interactions with the dark scalar

$$m_{\chi_i} = \frac{Y_{\chi_i}}{\sqrt{2}} w \ , \quad m_{\xi_i} = \frac{Y_{\xi_i}}{\sqrt{2}} w$$

- 2 massive, dark-charged "electrons" and 2 massive, neutral "neutrinos"

Radiative Symmetry Breaking

$$\frac{d\lambda_\Sigma}{dt} = \beta_{\lambda_\Sigma} = \frac{1}{16\pi^2}\Big(12\lambda_\Sigma^2 + 4\lambda_{\Sigma H}^2 + \frac{9}{4}g_X^4 + \frac{3}{4}(g_X')^4 + \frac{3}{2}g_X^2(g_X')^2 - 9g_X^2\lambda_\Sigma - 3(g_X')^2\lambda_\Sigma - 4\sum_i(Y_{\xi_i}^4 + Y_{\chi_i}^4) + 4\lambda_\Sigma\sum_i(Y_{\xi_i}^2 + Y_{\chi_i}^2)\Big)$$

- sizeable gauge couplings drive the dark quartic negative in the IR and a dark scalar vev is generated dynamically

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- sizeable gauge couplings drive the dark quartic negative in the IR and a dark scalar vev is generated dynamically

- dark scalar vev is transmitted to the visible sector by the portal coupling

$$\frac{\langle H\rangle^2}{\langle\Sigma\rangle^2} = \frac{v^2}{w^2} \simeq -\frac{\lambda_{\Sigma H}}{\lambda_H}$$

Scalar Spectrum

- due to the portal coupling, the dark scalar and the Higgs mix

$$\mathcal{M}^2 \simeq \frac{v^2}{2} \begin{pmatrix} 2\lambda_H & -2\sqrt{\lambda_H |\lambda_{\Sigma H}|} \\ -2\sqrt{\lambda_H |\lambda_{\Sigma H}|} & 2|\lambda_{\Sigma H}| + \lambda_H \beta_{\lambda_\Sigma} / |\lambda_{\Sigma H}| \end{pmatrix}$$

$$\begin{pmatrix} h \\ s \end{pmatrix} \to \begin{pmatrix} c_\alpha & s_\alpha \\ -s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} h \\ s \end{pmatrix} \ , \quad \sin 2\alpha = \frac{2\sqrt{\lambda_H |\lambda_{\Sigma H}|} v^2}{m_s^2 - m_h^2}$$

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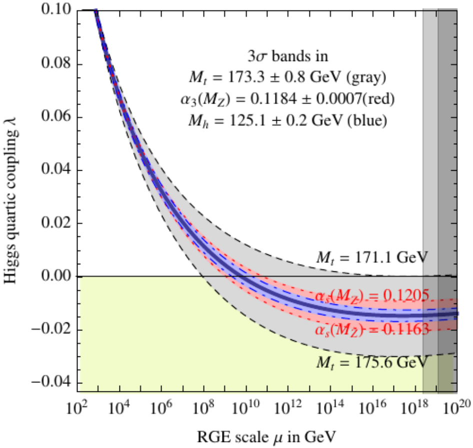
- mass of the (mostly) Higgs is corrected compared to the SM value
- mass of the (mostly) dark scalar is proportional to the beta function of the dark quartic

$$m_h^2 \simeq v^2 \left(\lambda_H - \frac{2\lambda_{\Sigma H}^2}{\beta_{\lambda_\Sigma} - 2|\lambda_{\Sigma H}|} \right) ~,~~ m_s^2 \simeq v^2 \left(\frac{\lambda_H \beta_{\lambda_\Sigma}}{2|\lambda_{\Sigma H}|} + \frac{\beta_{\lambda_\Sigma} |\lambda_{\Sigma H}|}{\beta_{\lambda_\Sigma} - 2|\lambda_{\Sigma H}|} \right)$$

Vacuum Stability

- in the SM the Higgs quartic runs negative at a scale $\sim 10^{10}$ GeV

Buttazzo, et al. 1307.3536



Vacuum Stability

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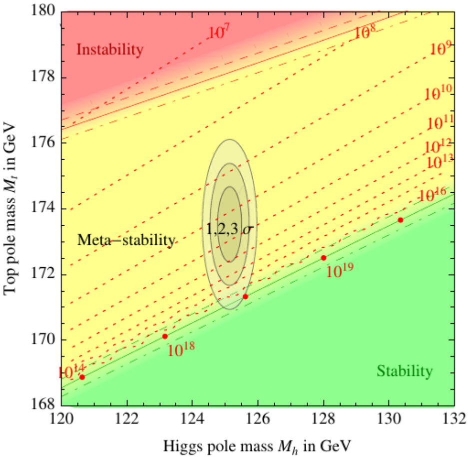


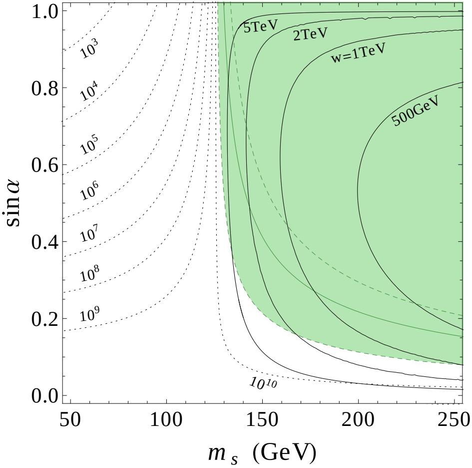
Vacuum Stability

- in the SM the Higgs quartic runs negative at a scale $\sim 10^{10}$ GeV
- electro-weak vacuum is only meta-stable
- mixing with the scalar changes the IR boundary conditions

$$\lambda_H(m_h) \simeq \lambda_H^{\rm SM}(m_h) + \frac{2\lambda_{\Sigma H}^2}{\beta_{\lambda_\Sigma} - 2|\lambda_{\Sigma H}|}$$

- scalar potential can be absolutely stable

  (see also Elias-Miro, et al. 1203.0237)



Renormalization Group Evolution

example point in parameter space

$m_h \simeq 125.5$ GeV , $m_s \simeq 168$ GeV

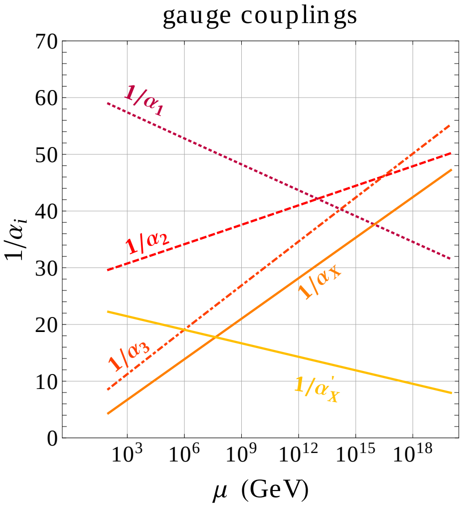
$m_{W'} \simeq 740$ GeV , $m_{Z'} \simeq 850$ GeV

$m_{\chi_1} \simeq 50$ GeV , $m_{\chi_2} \simeq 50$ GeV

$m_{\xi_1} \simeq 160$ GeV , $m_{\xi_2} \simeq 700$ GeV

- $SU(2)_X$ gauge coupling is asymptotically free

  $U(1)_X$ gauge coupling becomes large close to the Planck scale



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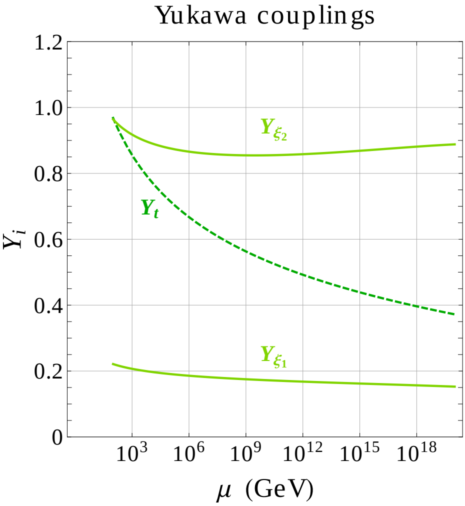

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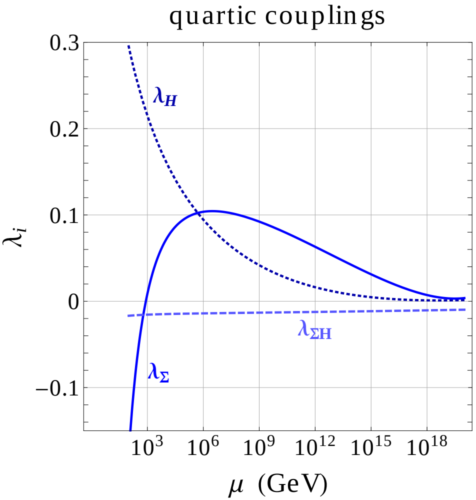
- $SU(2)_X$ gauge coupling is asymptotically free

  $U(1)_X$ gauge coupling becomes large close to the Planck scale
- Yukawa couplings show only mild scale dependence
- parameter point was chosen such that the Higgs quartic, the dark scalar quartic and their beta functions are $\sim$ 0 at the Planck scale



Higgs Phenomenology

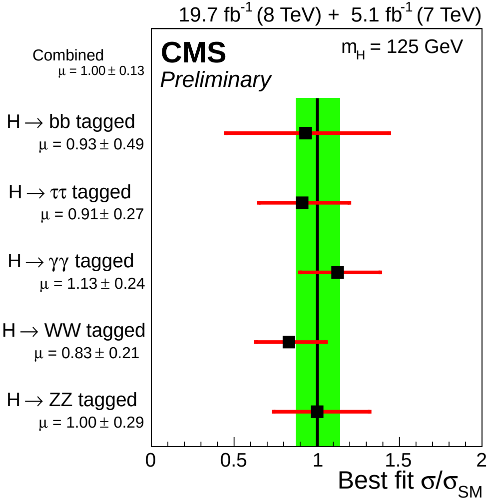
Reduced Signal Strength of the SM Higgs

- due to mixing with the dark scalar, higgs production is universally suppressed

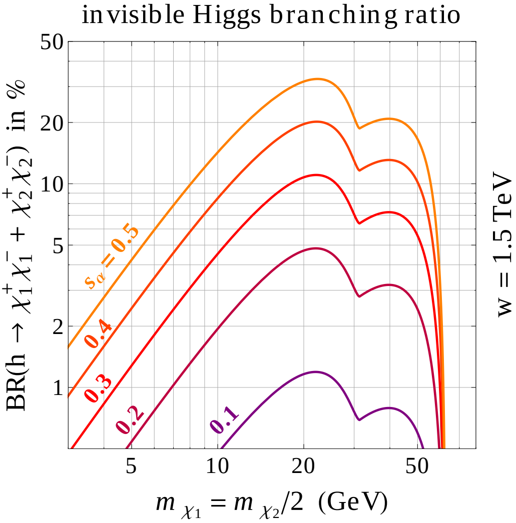
$$\sigma = c_\alpha^2 \times \sigma_{\rm SM}$$

- bound on the mixing angle

$$c_\alpha \gtrsim 0.9$$



Invisible Higgs Decays



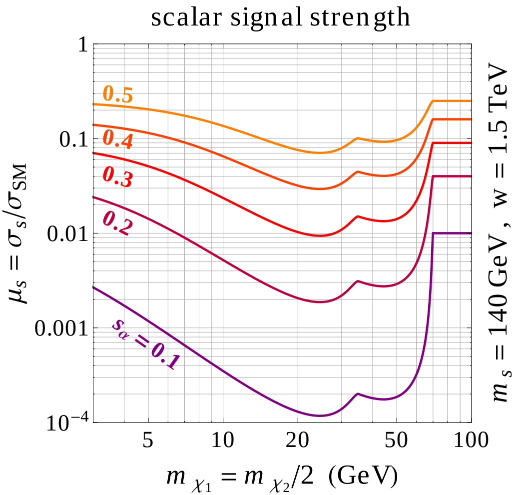
- if kinematically allowed, the Higgs can decay into dark fermions

$$\Gamma(h \to \chi\bar{\chi}) =$$

$$= \frac{Y_\chi^2}{8\pi}\, m_h\, s_\alpha^2 \left(1 - \frac{4m_\chi^2}{m_h^2}\right)^{\frac{3}{2}}$$

- for sizable mixing, the branching ratio can be O(10%)
- could be probed at a high luminosity LHC

Signals of the Dark Scalar



- looks like a second Higgs with couplings to SM reduced by s_α
- but invisible decays to dark sector can be sizable if kinematically allowed

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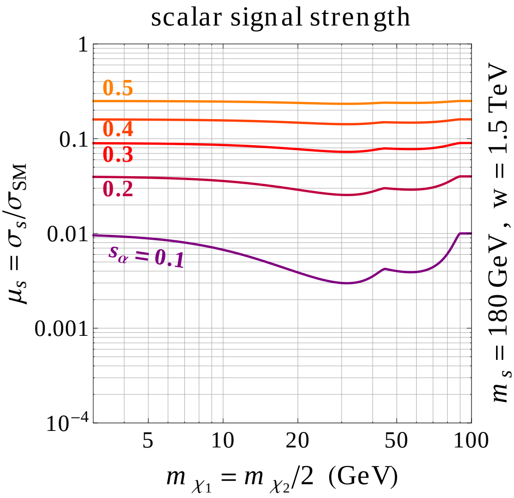

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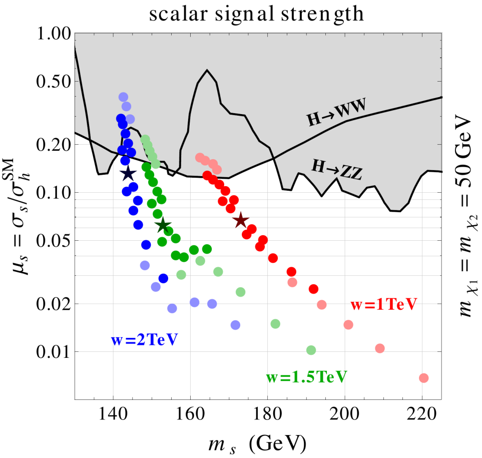
Predictions for the Dark Scalar



- dark scalar is expected below $\lesssim$ 250 GeV
- current Higgs searches already constrain parts of the parameter space
- expect signal strength of at least few % of the SM Higgs

Dark Matter Phenomenology

Dark Matter Annihilation

- four dark fermions: $\chi_1^\pm$, $\chi_2^\pm$, ξ_1^0, ξ_2^0
- three lightest are always stable
- if kinematically allowed, heaviest can decay into the other three through W exchange (e.g. $\xi_2^0 \to \xi_1^0 \chi_2^+ \chi_1^-$)

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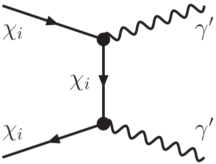

- the charged dark fermions can annihilate into dark photons
- 5%-10% charged dark matter component can be compatible with constraints

(Fan, Katz, Randall, Reece 1303.1521)

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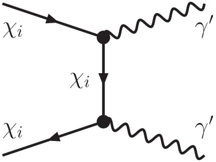
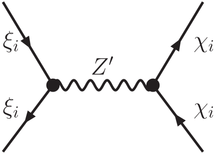
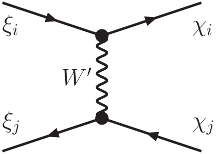
- only unsuppressed annihilation channel of the neutral dark fermions is into the charged dark fermions

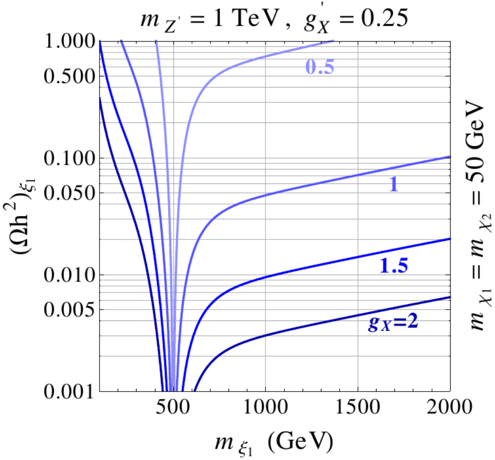
→ want $m_\xi > m_\chi$





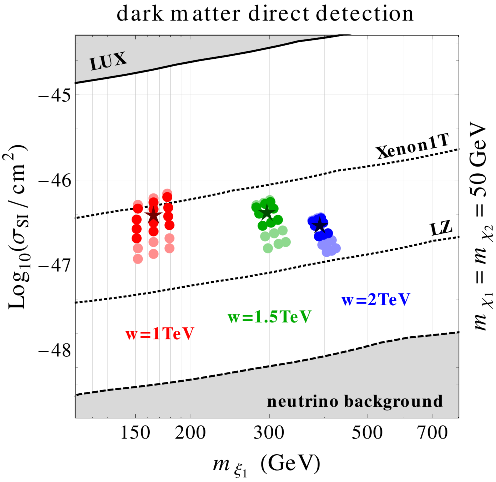


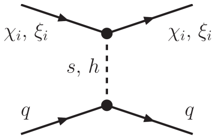
Dark Matter Relic Density



- for given gauge couplings, ξ_1^0 relic abundance depends strongly on its mass
- right relic abundance is easily obtained by adjusting $m_{\xi_1} \sim Y_{\xi_1}$

Dark Matter Direct Detection





- direct detection cross section suppressed by the Higgs mixing
- still 1-2 orders of magnitude below the current LUX constraint
- LZ should be able to cover essentially the full parameter space

Summary

- no-scale models avoid fine-tuning of the Higgs mass (if gravity has special properties)
- discussed a specific model, where the electro-weak scale and the dark matter scale are generated dynamically from the radiative breaking of a $SU(2)_X \times U(1)_X$ gauge group in a dark sector
- model makes testable predictions for

  → higgs signal strengths
  → collider signals of the dark scalar
  → dark matter direct detection
  → number of relativistic dof's in the early universe

“Of course, going from Higgs and no SUSY to modified naturalness [...] is risky.

Of course, it is much more reasonable to imagine ant***ic selection within a SUSY multiverse of branes wrapped on compactified 6 or 7 extra dimensions.”

A. Strumia

Back Up

One Loop Effective Potential

$$\begin{aligned} V_{\rm eff}(h,s) \simeq &\quad \frac{1}{8}\lambda_H(\mu_h)h^4 + \frac{1}{4}\lambda_{\Sigma H}(\mu_{sh})h^2s^2 + \frac{1}{8}\lambda_\Sigma(\mu_s)s^4 \\ + &\quad \frac{1}{16\pi^2}\Bigg\{ -3m_t^2\left[\log\left(\frac{m_t^2}{\mu_h^2}\right) - \frac{3}{2}\right] \\ &\qquad + \frac{3}{2}m_W^2\left[\log\left(\frac{m_W^2}{\mu_h^2}\right) - \frac{5}{6}\right] + \frac{3}{4}m_Z^2\left[\log\left(\frac{m_Z^2}{\mu_h^2}\right) - \frac{5}{6}\right]\Bigg\} \\ + &\quad \frac{1}{16\pi^2}\Bigg\{ -\sum_i m_{\chi_i}^2\left[\log\left(\frac{m_{\chi_i}^2}{\mu_s^2}\right) - \frac{3}{2}\right] - \sum_i m_{\xi_i}^2\left[\log\left(\frac{m_{\xi_i}^2}{\mu_s^2}\right) - \frac{3}{2}\right] \\ &\qquad + \frac{3}{2}m_{W'}^2\left[\log\left(\frac{m_{W'}^2}{\mu_h^2}\right) - \frac{5}{6}\right] + \frac{3}{4}m_{Z'}^2\left[\log\left(\frac{m_{Z'}^2}{\mu_h^2}\right) - \frac{5}{6}\right]\Bigg\}, \end{aligned}$$

where the field dependent masses are given by

$$m_t^2 = Y_t^2h^2/2\,,\ \ m_W^2 = g^2h^2/4\,,\ \ m_Z^2 = (g^2+(g')^2)h^2/4$$

$$m_{\chi_i}^2 = Y_{\chi_i}^2s^2/2\,,\ \ m_{\xi_i}^2 = Y_{\xi_i}^2s^2/2\,,\ \ m_{W'}^2 = g_X^2s^2/4\,,\ \ m_{Z'}^2 = (g_X^2+(g_X')^2)s^2/4$$

Beta Functions

$$
\begin{aligned}
\frac{d\lambda_H}{dt} = \beta_{\lambda_H} \quad &= \quad \beta^{\mathrm{SM}}_{\lambda_H} + \frac{1}{16\pi^2} 4\lambda^2_{\Sigma H} \\
\frac{d\lambda_\Sigma}{dt} = \beta_{\lambda_\Sigma} \quad &= \quad \frac{1}{16\pi^2}\Big(12\lambda^2_\Sigma + 4\lambda^2_{\Sigma H} - 9g^2_X\lambda_\Sigma - 3(g'_X)^2\lambda_\Sigma + \frac{9}{4}g^4_X + \frac{3}{4}(g'_X)^4 + \frac{3}{2}g^2_X(g'_X)^2 \\
&\qquad -4\sum_i(Y^4_{\xi_i} + Y^4_{\chi_i}) + 4\lambda_\Sigma\sum_i(Y^2_{\xi_i} + Y^2_{\chi_i})\Big) \\
\frac{d\lambda_{\Sigma H}}{dt} = \beta_{\lambda_{\Sigma H}} \quad &= \quad \frac{1}{16\pi^2}\Big[4\lambda^2_{\Sigma H} + 6(\lambda_H + \lambda_\Sigma)\lambda_{\Sigma H} - \frac{\lambda_{\Sigma H}}{2}\Big(3(g')^2 + 9g^2 + 9g^2_X + 3(g'_X)^2\Big) \\
&\qquad +\lambda_{\Sigma H}\Big(6Y^2_t + 2\sum_i(Y^2_{\xi_i} + Y^2_{\chi_i})\Big)\Big]
\end{aligned}
$$

$$
\begin{aligned}
\frac{dg_X}{dt} = \beta_{g_X} \quad &= \quad -\frac{1}{16\pi^2}\frac{39}{6}g^3_X \\
\frac{dg'_X}{dt} = \beta_{g'_X} \quad &= \quad \frac{1}{16\pi^2}\frac{13}{6}(g'_X)^3
\end{aligned}
$$

$$
\begin{aligned}
\frac{dY_{\xi_i}}{dt} = \beta_{Y_{\xi_i}} \quad &= \quad \frac{1}{16\pi^2}Y_{\xi_i}\Big(\frac{3}{2}(Y^2_{\xi_i} - Y^2_{\chi_i}) + \sum_j(Y^2_{\xi_j} + Y^2_{\chi_j}) - \frac{9}{4}g^2_X - \frac{3}{4}(g'_X)^2\Big) \\
\frac{dY_{\chi_i}}{dt} = \beta_{Y_{\chi_i}} \quad &= \quad \frac{1}{16\pi^2}Y_{\chi_i}\Big(\frac{3}{2}(Y^2_{\chi_i} - Y^2_{\xi_i}) + \sum_j(Y^2_{\xi_j} + Y^2_{\chi_j}) - \frac{9}{4}g^2_X - \frac{15}{4}(g'_X)^2\Big)
\end{aligned}
$$