

New Solutions to Hierarchy Problems

Nathaniel Craig
UC Santa Barbara



DESY THEORY WORKSHOP

Particle Physics Challenges

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES



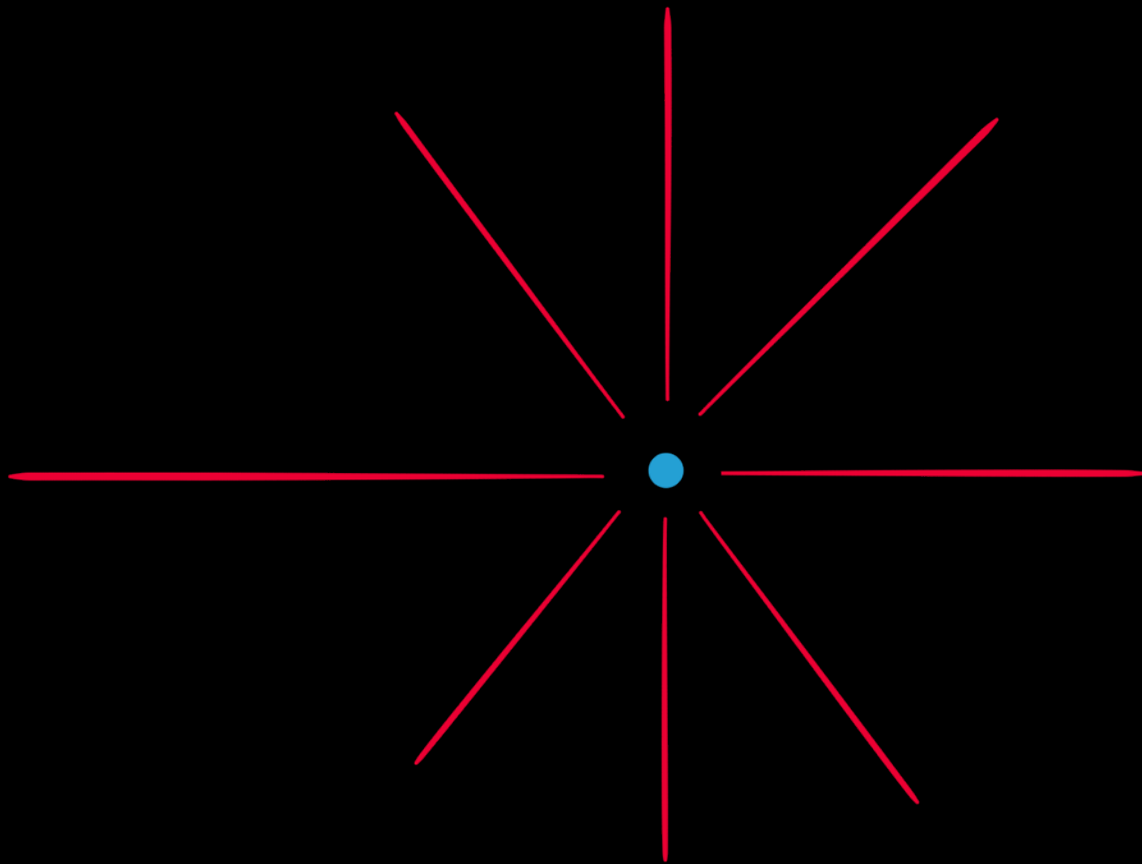
The Naturalness Strategy

An analogy

Classical E&M:
electron + E,B fields

$$\Delta E_C = \frac{1}{4\pi\epsilon_0} \frac{e^2}{r_e}$$

$$(m_e c^2)_{obs} = (m_e c^2)_{bare} + \Delta E_C$$



Experimentally $r_e \lesssim 10^{-18} \text{ cm} \Rightarrow \Delta E_C \gtrsim 100 \text{ GeV}$

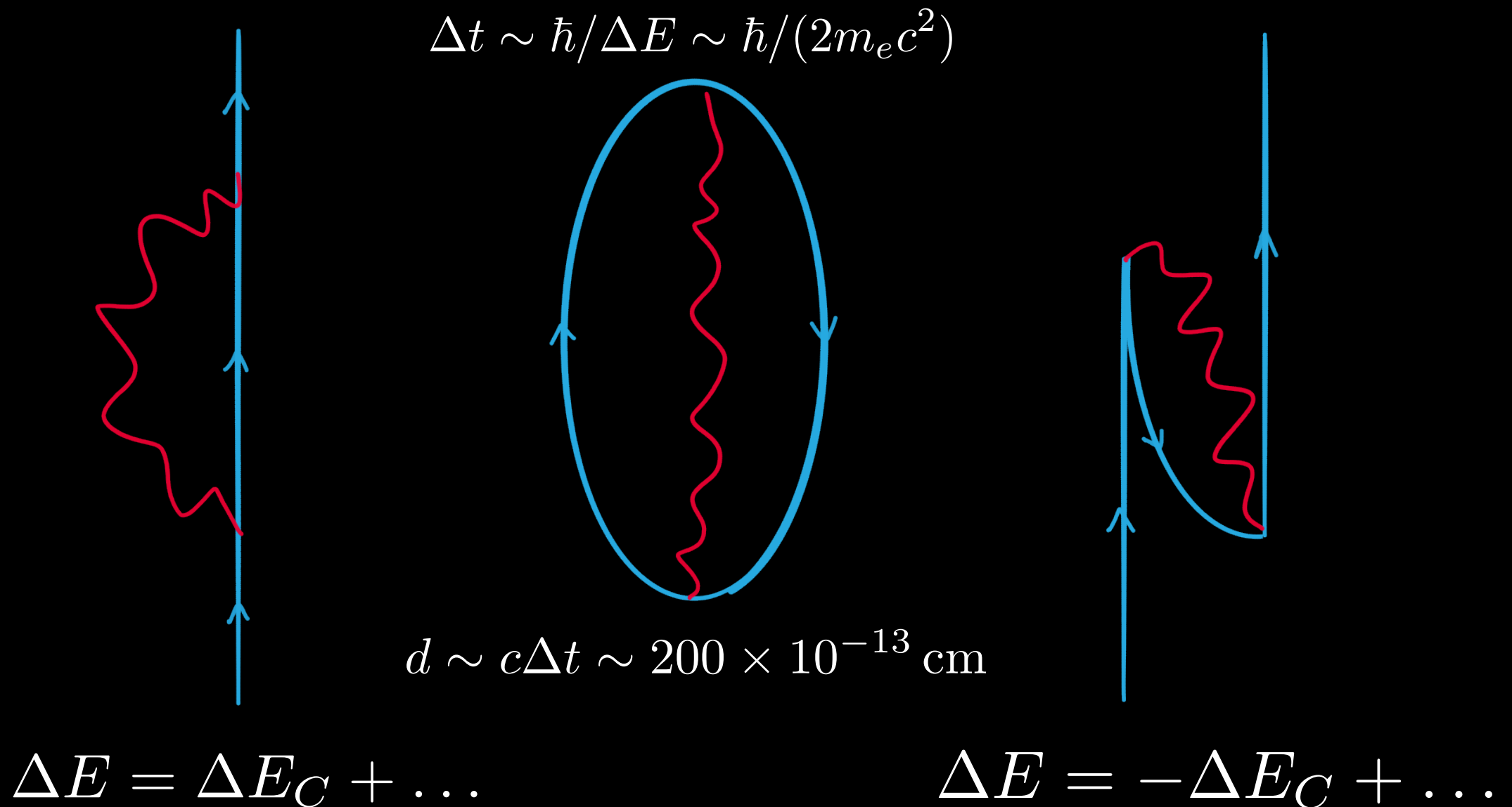
If so, $0.511 = -99999.489 + 100000.000 \text{ MeV}$

To avoid fine-tuning, i.e. for the theory to be “natural”,
need picture to change on scales below $2.8 \times 10^{-13} \text{ cm}$

The Naturalness Strategy

An analogy

Weisskopf (1939)

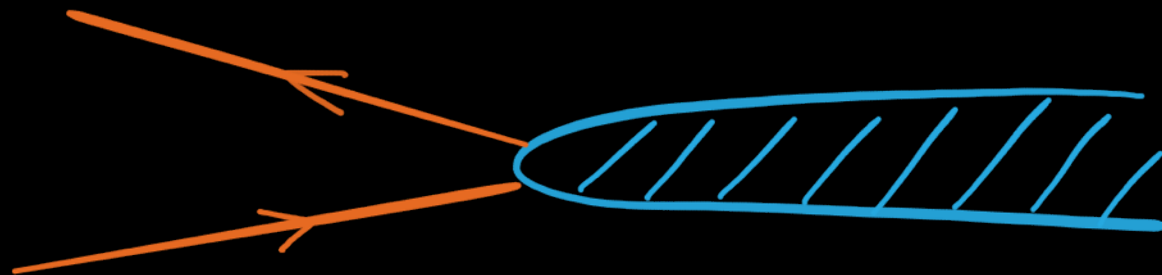


$$\Delta E = \Delta E_C - \Delta E_C + \frac{3\alpha}{4\pi} m_e c^2 \log \frac{\hbar}{m_e c r_e}$$

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The Naturalness Strategy

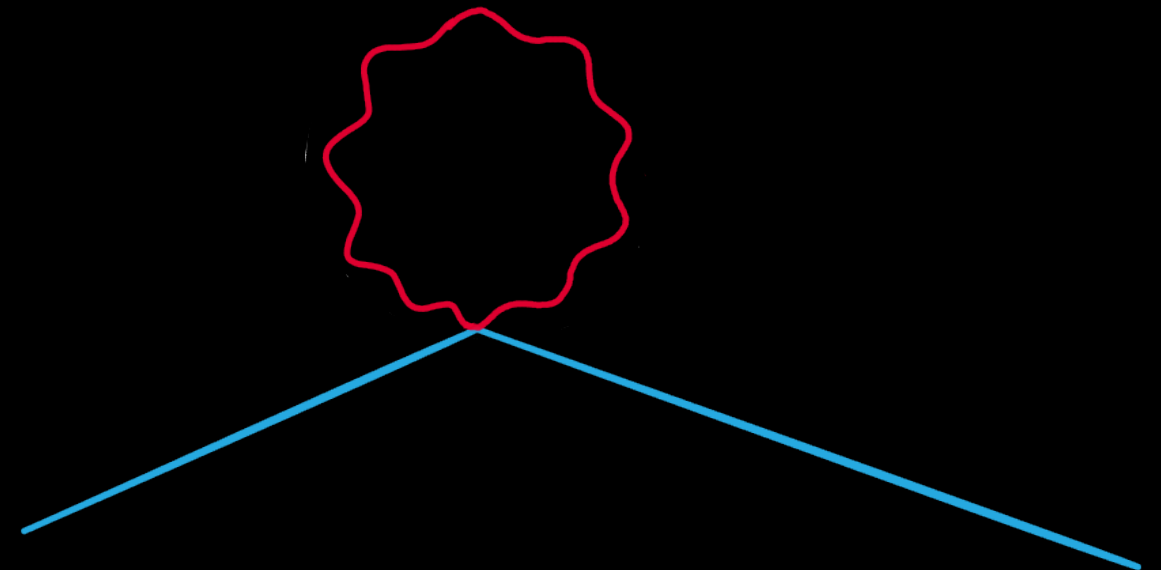
What about scalars?



Consider the pion...

Another divergence...

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = \frac{3\alpha}{4\pi} \Lambda^2$$



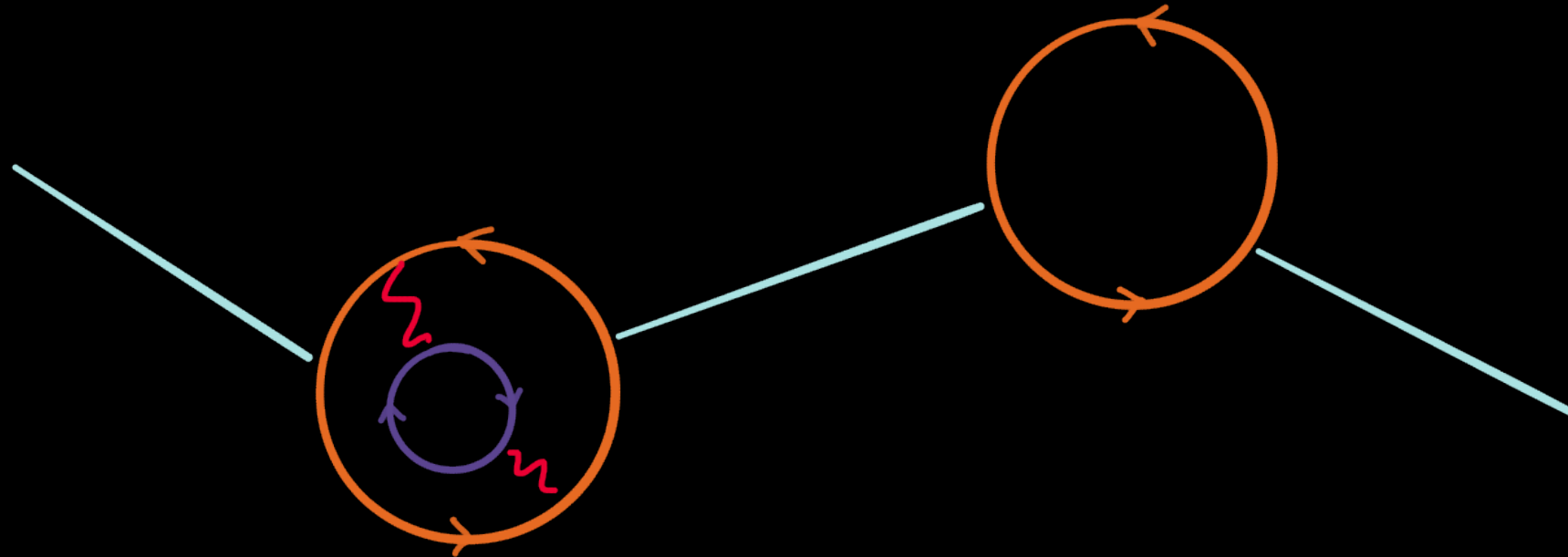
Given observed splitting, *predict* scale of new physics:

$$m_{\pi^\pm}^2 - m_{\pi^0}^2 = (35.5 \text{ MeV})^2 \Rightarrow \Lambda \lesssim 850 \text{ MeV} \quad \checkmark$$

Another (more predictive) example: K_L - K_S mass difference.

The “Hierarchy Problem”

The Higgs is an apparently elementary scalar



Assuming the Standard Model is valid down to some length scale $r_{\text{new}} \equiv \frac{\hbar c}{\Lambda}$ then we have

$$\Delta m_H^2 = \frac{\Lambda^2}{16\pi^2} \left[-6y_t^2 + \frac{9}{4}g_2^2 + \frac{3}{4}g_Y^2 + 6\lambda + \dots \right]$$

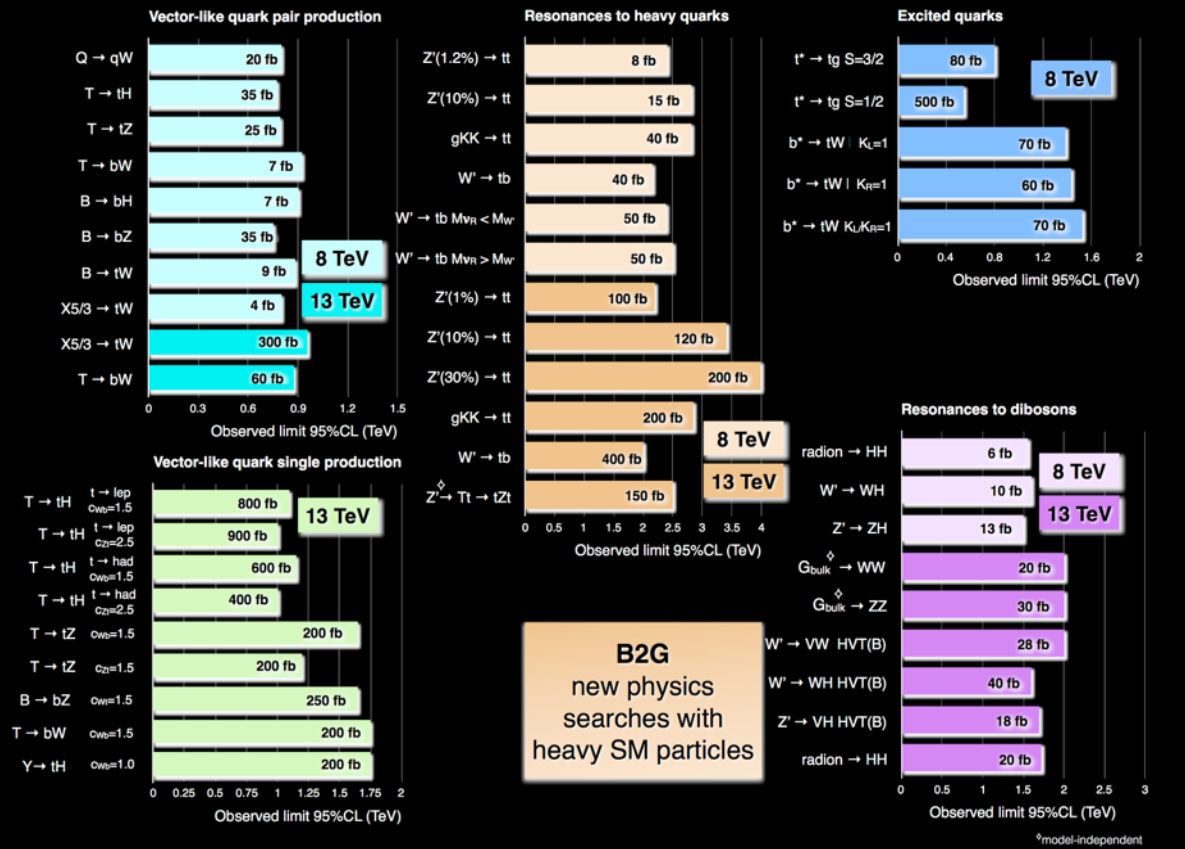
Expecting NP at Λ such that $\Delta m_H^2 \sim m_H^2$ is a *strategy*.

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.
4. Low cutoffs imply dimensional transmutation or its equivalents.

Thus far...



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018

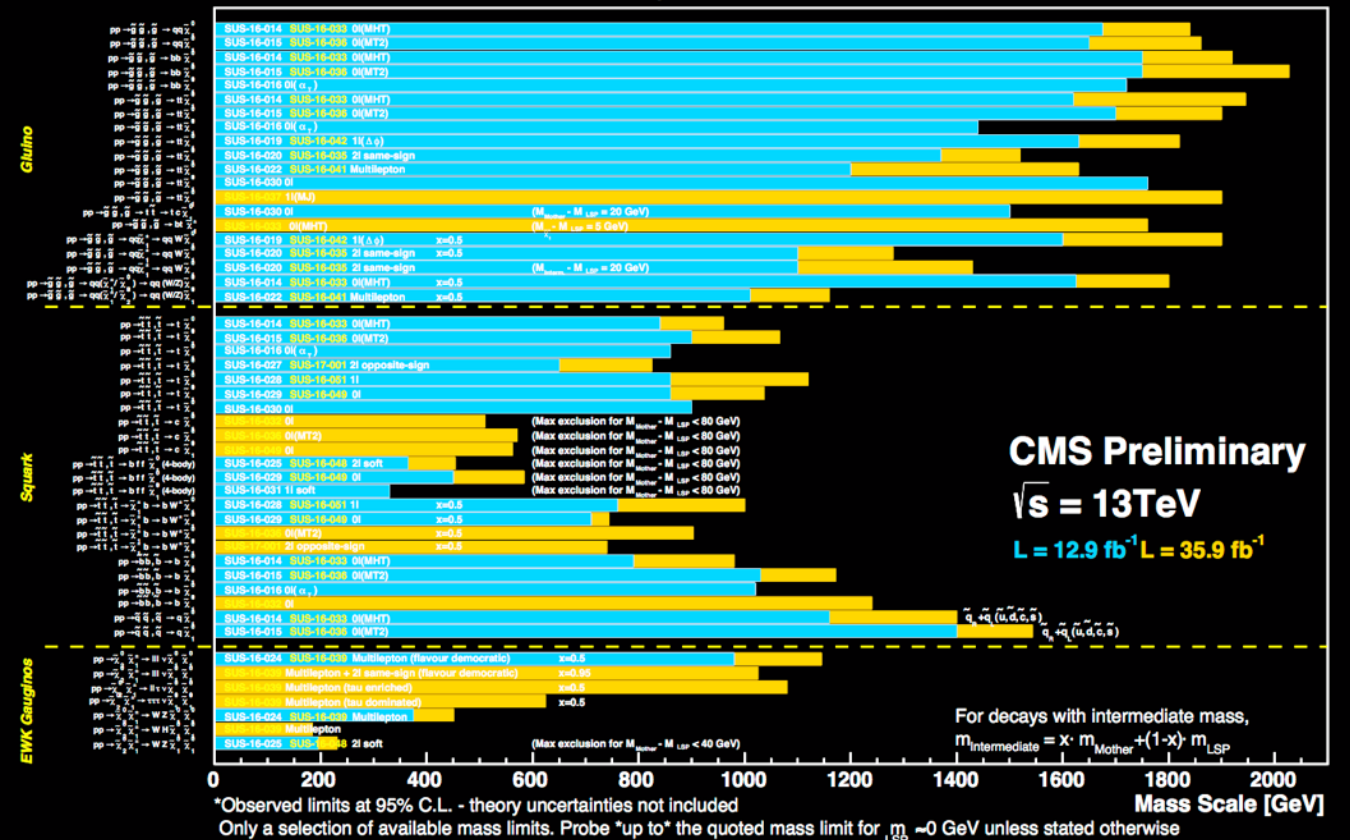
	Model	ℓ, γ	Jets†	$E_{\text{miss}}^{\text{jet}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Limit	Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	1-4	Yes	36.1	$M_{KK} \geq 7.7 \text{ TeV}$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	-	-	36.7	$M_{KK} \geq 8.6 \text{ TeV}$	1707.04147
	ADD QBH	-	2 γ	-	-	$M_{KK} \geq 8.9 \text{ TeV}$	1703.09217
	ADD BH high Σp_T	$\geq 1 e, \mu$	≥ 2	-	3.2	$M_{KK} \geq 8.2 \text{ TeV}$	1606.02205
	ADD BH multijet	-	≥ 3	-	3.6	$M_{KK} \geq 9.55 \text{ TeV}$	1512.02586
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	$M_{KK} \geq 4.1 \text{ TeV}$	1707.04147
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	$M_{KK} \geq 2.3 \text{ TeV}$	CERN-EP-2018-179
	Bulk RS $G_{KK} \rightarrow tt$	1 e, μ	$\geq 1 b, \geq 1, 2$	Yes	36.1	$M_{KK} \geq 3.8 \text{ TeV}$	1804.10823
	ZUED / RPP	1 e, μ	$\geq 2 b, \geq 3$	Yes	36.1	$M_{KK} \geq 1.8 \text{ TeV}$	1803.09678
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	36.1	$M_{Z'} \geq 4.5 \text{ TeV}$	1707.02424
	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	36.1	$M_{Z'} \geq 2.42 \text{ TeV}$	1709.07242
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2 b	-	36.1	$M_{Z'} \geq 2.1 \text{ TeV}$	1805.09299
	Leptophobic $Z' \rightarrow \tau\tau$	1 e, μ	$\geq 1 b, \geq 1, 2$	Yes	36.1	$M_{Z'} \geq 3.0 \text{ TeV}$	1804.10823
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	-	79.8	$M_{W'} \geq 5.6 \text{ TeV}$	ATLAS-CONF-2018-017
	SSM $W' \rightarrow \tau\nu$	1 τ	-	-	36.1	$M_{W'} \geq 3.7 \text{ TeV}$	1801.06992
	HVT $V' \rightarrow WW$ model B	0 e, μ	2 J	-	79.8	$M_{V'} \geq 4.15 \text{ TeV}$	ATLAS-CONF-2018-016
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	$M_{V'} \geq 2.93 \text{ TeV}$	1712.06518
	LRSM $W'_A \rightarrow tb$	multi-channel	-	-	36.1	$M_{W'_A} \geq 2.25 \text{ TeV}$	CERN-EP-2018-142
CI	CI $qqqq$	-	2 J	-	37.0	$M_{CI} \geq 21.8 \text{ TeV}$	η_{CI}
	CI $\ell\ell qq$	2 e, μ	-	-	36.1	$M_{CI} \geq 43.0 \text{ TeV}$	η_{CI}
	CI $tttt$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1$	Yes	36.1	$M_{CI} \geq 2.57 \text{ TeV}$	$ \mathcal{C}_{CI} = 4\pi$
DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4	Yes	36.1	$m_{\text{DM}} \geq 1.55 \text{ TeV}$	$g_s = 0.25, g_{\text{B}} = 1.6, m(\chi) = 1 \text{ GeV}$
	Colored scalar mediator (Dirac DM)	0 e, μ	1-4	Yes	36.1	$m_{\text{DM}} \geq 1.41 \text{ TeV}$	$g = 1.0, m(\chi) = 1 \text{ GeV}$
	VVXX EFT (Dirac DM)	0 e, μ	1 $J, \leq 1$	Yes	3.2	$M_{\text{DM}} \geq 700 \text{ GeV}$	$m(\chi) < 150 \text{ GeV}$
LQ	Scalar LQ 1 st gen	2 e	≥ 2	-	3.2	$M_{LQ} \geq 1.1 \text{ TeV}$	$\beta = 1$
	Scalar LQ 2 nd gen	2 μ	≥ 2	-	3.2	$M_{LQ} \geq 1.05 \text{ TeV}$	$\beta = 1$
	Scalar LQ 3 rd gen	1 e, μ	$\geq 1 b, \geq 2, 3$	Yes	20.3	$M_{LQ} \geq 1.58 \text{ TeV}$	$\beta = 0$
Heavy quarks	VLO $TT \rightarrow Ht/Zt/Wb + X$	multi-channel	-	-	36.1	$M_T \geq 1.37 \text{ TeV}$	SU(2) doublet
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	36.1	$M_B \geq 1.34 \text{ TeV}$	SU(2) doublet
	VLO $TT \rightarrow Wt/Zb + X$	2 (SS) $\geq 2 e, \mu$	$\geq 1 b, \geq 1$	Yes	36.1	$M_T \geq 1.84 \text{ TeV}$	$R(T_{\text{eff}}) = 1$
	VLO $Y \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1$	Yes	3.2	$M_Y \geq 1.44 \text{ TeV}$	$R(Y \rightarrow Wb) = 1, c(Y_{\text{eff}}) = 1/\sqrt{2}$
	VLO $B \rightarrow Hb + X$	0 $e, \mu, 2 \gamma$	$\geq 1 b, \geq 1$	Yes	79.8	$M_B \geq 1.21 \text{ TeV}$	$\kappa_{\text{eff}} = 0.5$
	VLO $QQ \rightarrow WqWq$	1 e, μ	$\geq 1 b, \geq 1$	Yes	20.3	$M_Q \geq 800 \text{ GeV}$	
Excited fermions	Excited quark $q^* \rightarrow qg$	-	2 J	-	37.0	$M_{q^*} \geq 8.0 \text{ TeV}$	only u^* and d^* , $\Lambda = m(q^*)$
	Excited quark $q^* \rightarrow q\gamma$	1 γ	1 J	-	36.7	$M_{q^*} \geq 5.3 \text{ TeV}$	only u^* and d^* , $\Lambda = m(q^*)$
	Excited quark $b^* \rightarrow b\gamma$	-	1 $b, 1 J$	-	36.1	$M_{b^*} \geq 2.6 \text{ TeV}$	
	Excited lepton e^*	3 e, μ	-	-	20.3	$M_{e^*} \geq 3.0 \text{ TeV}$	$\Lambda = 3.0 \text{ TeV}$
	Excited lepton τ^*	3 e, μ, τ	-	-	20.3	$M_{\tau^*} \geq 1.8 \text{ TeV}$	$\Lambda = 1.6 \text{ TeV}$
Other	Type III Seesaw	1 e, μ	≥ 2	Yes	79.8	$M_{\text{LQ}} \geq 560 \text{ GeV}$	$m(W_2) = 2.4 \text{ TeV}$, no mixing
	LRSM Majorana ν	2 e, μ	2 J	-	20.3	$M_{\text{LQ}} \geq 1.34 \text{ TeV}$	DV production
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	36.1	$M_{H^{\pm\pm}} \geq 870 \text{ GeV}$	DV production, $R(H^{\pm\pm} \rightarrow \ell\tau) = 1$
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$M_{H^{\pm\pm}} \geq 810 \text{ GeV}$	$\kappa_{\text{eff}} = 0.2$
	Monotop (non-res prod)	1 e, μ	1 b	Yes	20.3	$M_{\text{DM}} \geq 1.55 \text{ TeV}$	DY production, $ \mathcal{C} = 5\pi$
	Multi-charged particles	-	-	-	20.3	$M_{\text{DM}} \geq 1.55 \text{ TeV}$	DY production, $ \mathcal{C} = 1 \text{ GeV}$, spin 1/2
	Magnetic monopoles	-	-	-	7.0	$M_{\text{DM}} \geq 1.55 \text{ TeV}$	
		$\sqrt{s} = 13 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$				Mass scale [TeV]

*Only a selection of the available mass limits on new states or phenomena is shown.

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

Selected CMS SUSY Results* - SMS Interpretation

ICHEP '16 - Moriond '17



*Observed limits at 95% C.L. - theory uncertainties not included

Only a selection of available mass limits. Probe *up to* the quoted mass limit for $m_{\text{LSP}} \approx 0 \text{ GeV}$ unless stated otherwise

ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018

ATLAS Preliminary
 $\sqrt{s} = 7, 8, 13 \text{ TeV}$

Model	e, μ, τ, γ	Jets	$E_{\text{miss}}^{\text{jet}}$	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	$\sqrt{s} = 7, 8 \text{ TeV}$	$\sqrt{s} = 13 \text{ TeV}$	Reference	
Inclusive Searches	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0 mono-jet	2-6 jets	Yes	36.1	\tilde{g} [2x, 8x Diagon.]	$m(\tilde{g}) < 100 \text{ GeV}$	1712.02332	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	1-3 jets	Yes	36.1	\tilde{g} [1x, 6x Diagon.]	0.43 0.71	$m(\tilde{g})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$	1711.03301	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_1^0$	0	2-6 jets	Yes	36.1	\tilde{g}	Forbidden 0.95-1.6	1712.02332	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\ell\ell\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	1.85	1712.02332	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\ell\ell\tilde{\chi}_1^0$	ee, $\mu\mu$	2 jets	Yes	36.1	\tilde{g}	1.2	1805.11381	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	0	7-11 jets	Yes	36.1	\tilde{g}	1.6	1706.03731	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	0.98	1708.02794	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	0-1 e, μ	3 b	Yes	36.1	\tilde{g}	2.0	1706.03731	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0$	3 e, μ	4 jets	-	36.1	\tilde{g}	1.25	1711.01901	
3 rd gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	Multiple		36.1	\tilde{b}_1	Forbidden 0.9	$m(\tilde{b}_1)=300 \text{ GeV}, \text{BR}(\tilde{b}_1\tilde{\chi}_1^0)=1$	1708.09266	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	Multiple		36.1	\tilde{b}_1	Forbidden 0.58-0.82	$m(\tilde{b}_1)=300 \text{ GeV}, \text{BR}(\tilde{b}_1\tilde{\chi}_1^0)=0.5$	1708.09266	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	Multiple		36.1	\tilde{b}_1	Forbidden 0.7	$m(\tilde{b}_1)=300 \text{ GeV}, \text{BR}(\tilde{b}_1\tilde{\chi}_1^0)=1$	1706.03731	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	Multiple		36.1	\tilde{b}_1	Forbidden 0.9	$m(\tilde{b}_1)=60 \text{ GeV}$	1709.04183	
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\bar{b}\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	Multiple		36.1	\tilde{b}_1	Forbidden 1.0	$m(\tilde{b}_1)=200 \text{ GeV}$	1711.1520, 1708.03247	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{\chi}_1^0\tilde{\chi}_1^0$	0-2 e, μ	0-2 jets/1-2 b	Yes	36.1	\tilde{t}_1	$m(\tilde{t}_1)=1 \text{ GeV}$	1709.04183, 1711.1520, 1708.03247	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{\chi}_1^0\tilde{\chi}_1^0$	Multiple		36.1	\tilde{t}_1	0.4-0.9	$m(\tilde{t}_1)=150 \text{ GeV}, m(\tilde{t}_1^*)-m(\tilde{t}_1^*)=5 \text{ GeV}, \tilde{t}_1 = \tilde{t}_1^*$	1709.04183, 1711.1520	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{\chi}_1^0\tilde{\chi}_1^0$	Multiple		36.1	\tilde{t}_1	0.6-0.8	$m(\tilde{t}_1)=300 \text{ GeV}, m(\tilde{t}_1^*)-m(\tilde{t}_1^*)=5 \text{ GeV}, \tilde{t}_1 = \tilde{t}_1^*$	1709.04183, 1711.1520	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{\chi}_1^0\tilde{\chi}_1^0$	Multiple		36.1	\tilde{t}_1	0.48-0.84	$m(\tilde{t}_1)=150 \text{ GeV}, m(\tilde{t}_1^*)-m(\tilde{t}_1^*)=5 \text{ GeV}, \tilde{t}_1 = \tilde{t}_1^*$	1709.04183, 1711.1520	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ or $\tilde{\chi}_1^0\tilde{\chi}_1^0$	0	2c	Yes	36.1	\tilde{t}_1	0.65	$m(\tilde{t}_1)=150 \text{ GeV}, m(\tilde{t}_1^*)-m(\tilde{t}_1^*)=5 \text{ GeV}, \tilde{t}_1 = \tilde{t}_1^*$	1805.01649
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	0		Yes	36.1	\tilde{t}_1	0.46	$m(\tilde{t}_1, \tilde{t}_1^*)-m(\tilde{t}_1, \tilde{t}_1^*)=50 \text{ GeV}$	1805.01649
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{t}\tilde{\chi}_1^0/\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$	0	mono-jet	Yes	36.1	\tilde{t}_1	0.43	$m(\tilde{t}_1, \tilde{t}_1^*)-m(\tilde{t}_1, \tilde{t}_1^*)=5 \text{ GeV}$	1711.03301
$\tilde{t}_2\tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$	1-2 e, μ	4 b	Yes	36.1	\tilde{t}_2	0.32-0.88	$m(\tilde{t}_1^*)=0 \text{ GeV}, m(\tilde{t}_1)-m(\tilde{t}_1^*)=180 \text{ GeV}$	1706.03986	
EW direct	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via WZ	2-3 e, μ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_2^{\mp})=0$	1403.5294, 1806.02293	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via Wb	ee, $\mu\mu$	≥ 1	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ 0.17	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_2^{\mp})=10 \text{ GeV}$	1712.08119	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via Wb	$\ell\ell/\gamma\gamma/\ell b$	-	Yes	20.3	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ 0.26	$m(\tilde{\chi}_1^{\pm})=0$	1501.07110	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via Wb	2 τ	-	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ 0.22	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_2^{\mp})=0$	1708.07875	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via Wb	2 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ 0.5	$m(\tilde{\chi}_1^{\pm})=0$	1708.07875	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via Wb	2 e, μ	≥ 1	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ 0.18	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_2^{\mp})=5 \text{ GeV}$	1803.02762	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via Wb	0	$\geq 3b$	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ 0.13-0.23	$m(\tilde{\chi}_1^{\pm})-m(\tilde{\chi}_2^{\mp})=5 \text{ GeV}$	1712.08119	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via Wb	4 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ 0.3	$\text{BR}(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}) \rightarrow hZ\tilde{\chi}_1^0=1$	1806.04030	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ via Wb	4 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}$ 0.29-0.88	$\text{BR}(\tilde{\chi}_1^{\pm}\tilde{\chi}_2^{\mp}) \rightarrow Z\tilde{\chi}_1^0=1$	1804.03602	
Long-lived particles	Direct $\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}$ prod., long-lived $\tilde{\chi}_1^{\pm}$	Disapp. trk	1 jet	Yes	36.1	$\tilde{\chi}_1^{\pm}$ 0.15	Pure Wino	1712.02118	
	Stable \tilde{g} R-hadron	SMP	-	-	3.2	\tilde{g}	Pure Higgsino	ATL-PHYS-PUB.2017-019	
	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$	Multiple		32.8	\tilde{g} ($\tau(\tilde{g}) \approx 100 \text{ ns}, 0.2 \text{ ns}$)	1.6	$m(\tilde{g})=100 \text{ GeV}$	1606.05129	
	GMSB, $\tilde{\chi}_1^0 \rightarrow \gamma\tilde{g}$, long-lived $\tilde{\chi}_1^0$	2 γ	-	Yes	20.3	$\tilde{\chi}_1^0$	1.6	1710.04901, 1604.04520	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow ee/\mu\mu/\mu\mu\nu$	displ. ee/ $\mu\mu/\mu\mu$	-	-	20.3	\tilde{g}	1.3	1409.5542	
RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow qq\mu/\ell\tau/\mu\tau$	$qq\ell/\ell\tau/\mu\tau$	-	-	3.2	$\tilde{\nu}_\tau$	$A_{311}^{\nu}=0.11, A_{121311}^{\nu}=0.07$	1607.08079	
	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\tilde{\chi}_2^0 \rightarrow W\gamma/Z\ell\ell\ell\nu\nu$	4 e, μ	0	Yes	36.1	$\tilde{\chi}_1^{\pm}\tilde{\chi}_1^{\mp}/\tilde{\chi}_2^0\tilde{\chi}_2^0$ ($A_{311}^{\nu} \neq 0, A_{121311}^{\nu} \neq 0$)	0.62	$m(\tilde{\chi}_1^{\pm})=100 \text{ GeV}$	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{\chi}_1^0$	0	4-5 large- R jets	Yes	36.1	\tilde{g} ($m(\tilde{\chi}_1^0)=200 \text{ GeV}, 1100 \text{ GeV}$)	1.3	Large A_{311}^{ν}	1804.03602
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qq\tilde{\chi}_1^0$	Multiple		36.1	\tilde{g} ($A_{311}^{\nu}=1, 1e-2$)	1.05	$m(\tilde{g})=200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{b}s/\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\bar{b}s$	Multiple		36.1	\tilde{g} ($A_{311}^{\nu}=1, 1e-2$)	1.8	$m(\tilde{g})=200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003	
	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\bar{b}s/\tilde{g} \rightarrow t\bar{t}\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow t\bar{b}s$	Multiple		36.1	\tilde{g} ($A_{311}^{\nu}=1, 1e-2$)	0.55	$m(\tilde{g})=200 \text{ GeV}, \text{bino-like}$	ATLAS-CONF-2018-003	
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{b}s$	0	2 jets + 2 b	-	36.7	\tilde{t}_1 ($q\bar{q}, h$)	0.42	$\text{BR}(\tilde{t}_1 \rightarrow b\bar{u}/\bar{b}u) > 20\%$	1710.07171
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow t\bar{b}\ell$	2 e, μ	2 b	-	36.1	\tilde{t}_1	0.61		1710.05544

*Only a selection of the available mass limits on new states or

Mass scale [TeV]



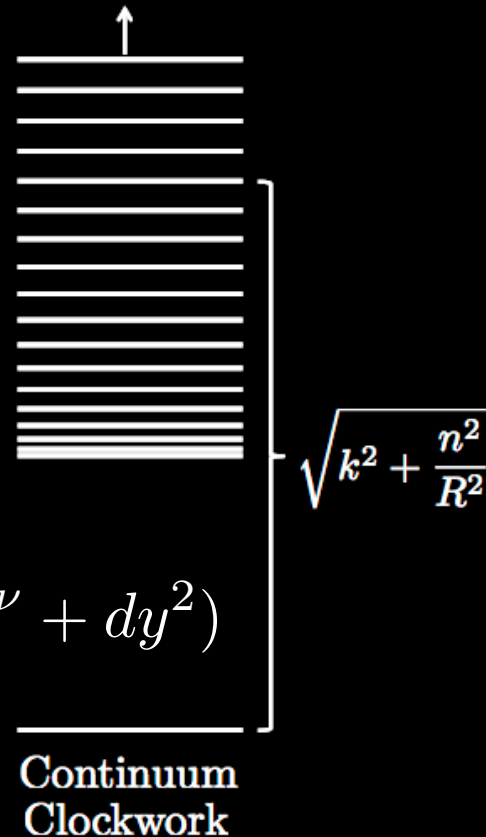
1. The Standard Model coupled to gravity is a generic EFT.
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3. Symmetries imply new particles charged under the SM.
4. Low cutoffs imply dimensional transmutation or its equivalents.

Linear Dilaton / Continuum Clockwork

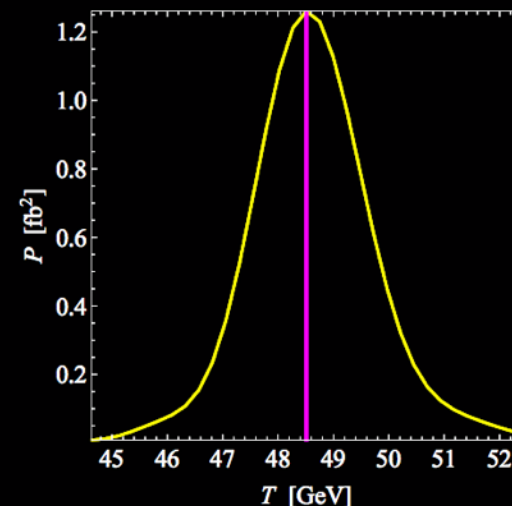
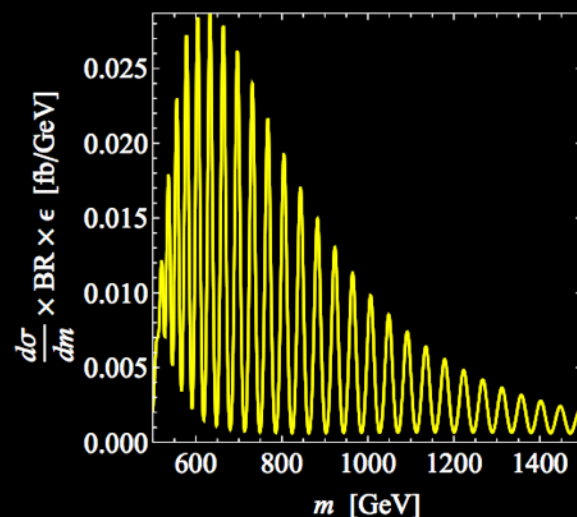
[Giudice, McCullough '16; Giudice, Kats, McCullough, Torre, Urbano '17; Antoniadis, Dimopoulos, Gideon '01; Antoniadis, Arvanitaki, Dimopoulos, Gideon '11;]

$$ds^2 = e^{\frac{4}{3}k|y|} (\eta_{\mu\nu} dx^\mu dx^\nu + dy^2)$$

$$S(y) = 2k|y|$$



[Giudice, Kats, McCullough, Torre, Urbano '17]

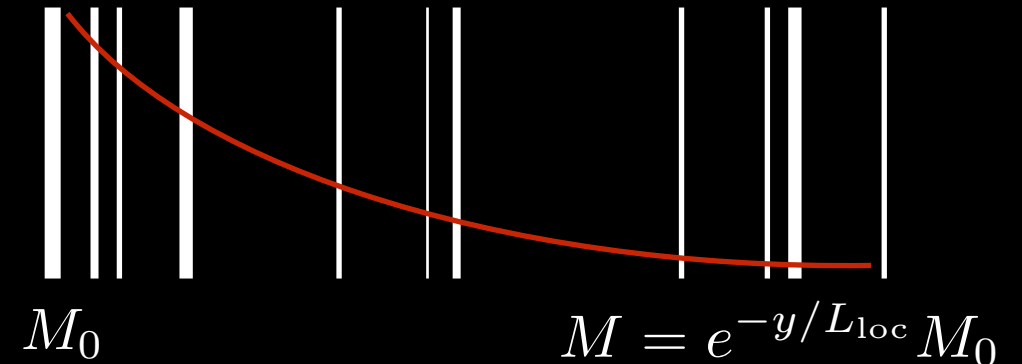


Disorder

[Rothstein '13]

Anderson localization:
exponential localization
from disorder.

Reasoning by analogy: localize
graviton zero mode w/ randomly
spaced & tensioned branes

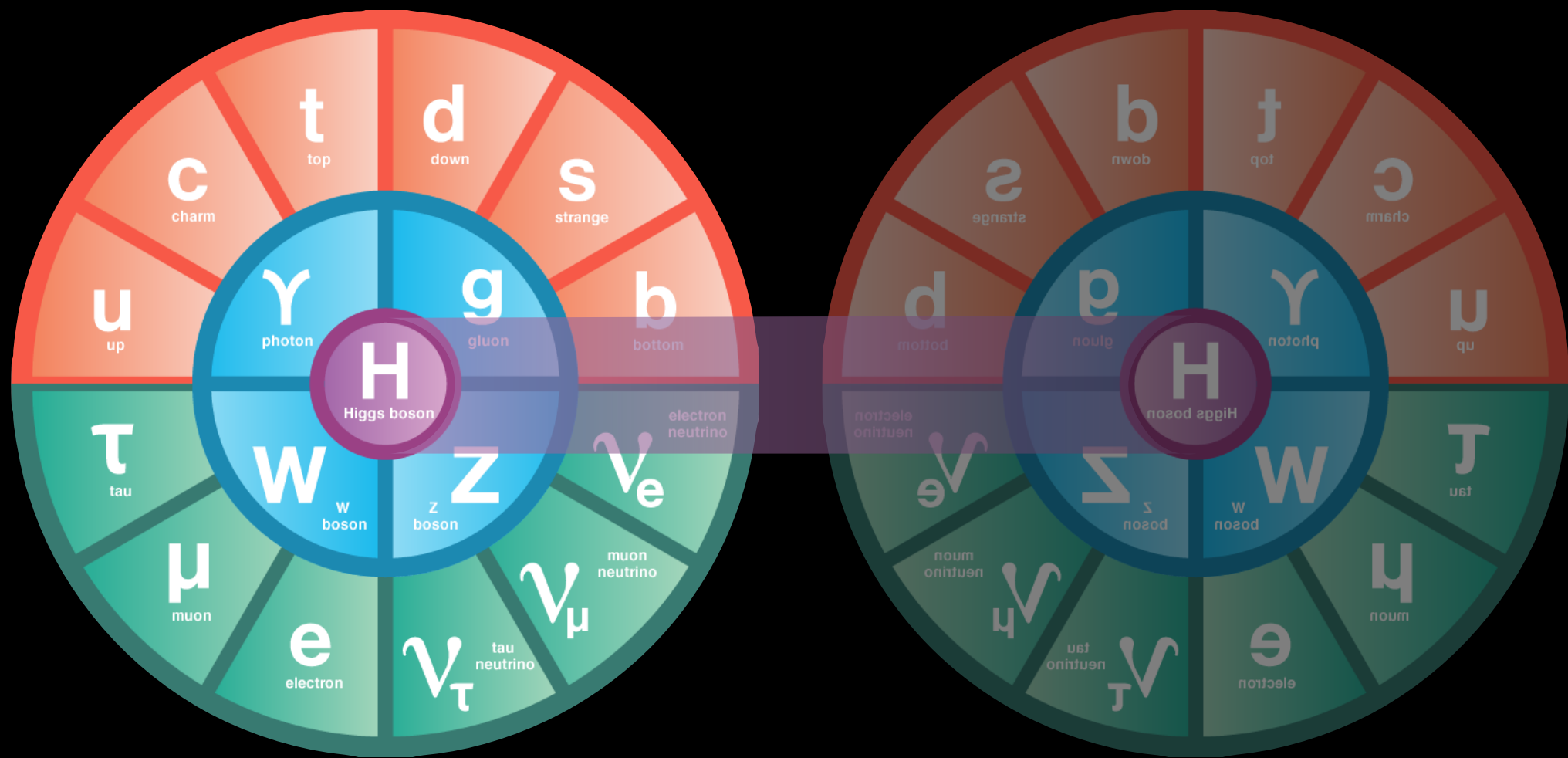


But: not obvious
that it works in detail

Related: An interesting source of exponential
hierarchies for scalars, fermions, vectors in 4
& 5 dimensions [NC, Sutherland '17]

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Discrete symmetries

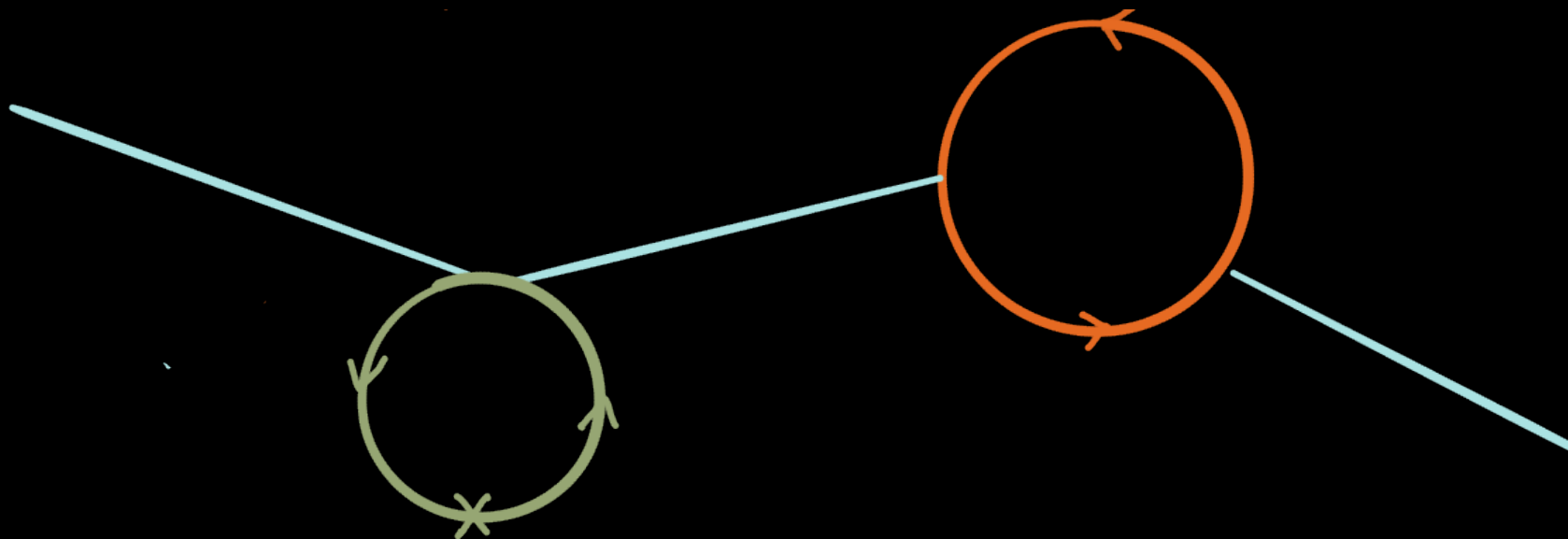


E.g. “Twin Higgs” [Chacko, Goh, Kribs '05]

Discrete symmetries

Higgs is a pNGB of an accidental SU(4), since Z_2 -symmetric mass corrections respect accidental SU(4)

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



Still a plethora of new particles, but not interacting via SM forces.

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

Why Not?

Higgs portal maintains equilibrium down to $T \sim \text{GeV}$

$$\Delta N_{\text{eff}} \gg 1$$

Options are

Change the cosmology

Signals in CMB

- RHN decay
- Saxion decay

[Chacko, NC, Fox, Harnik '16]

[NC, Koren, Trott '16]

Change the spectrum

Copious new physics at $\sim \text{few TeV}$

Signals @ LHC

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

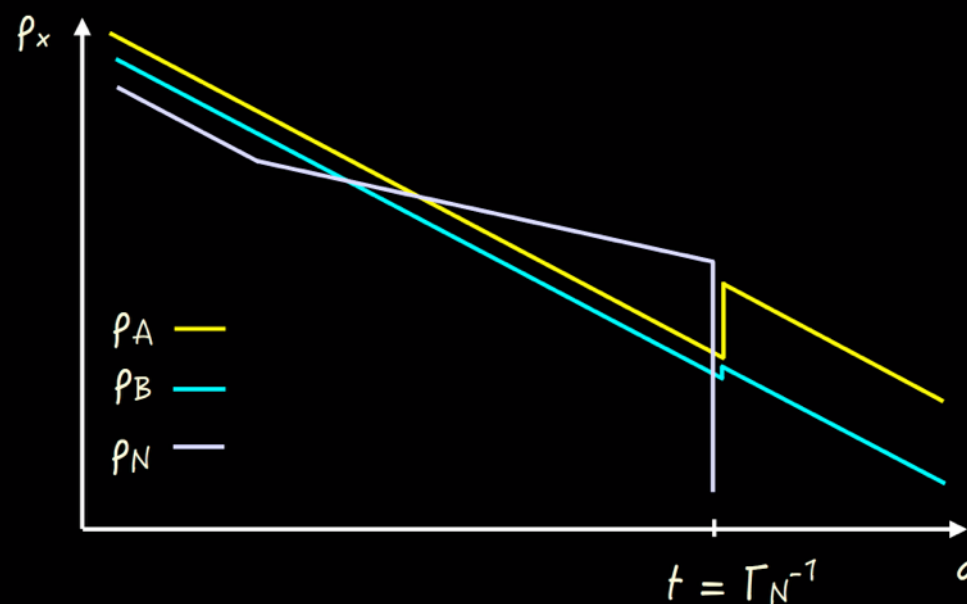
Change the Cosmology

The problem: thermal history of Z_2 -symmetric theory has too much energy density in twin ν, γ

$$\Delta N_{\text{eff}} \approx 7.4 \left. \frac{\rho_B}{\rho_A} \right|_{\text{BBN}} \approx 5.6$$

Introduce an unstable neutral particle N that

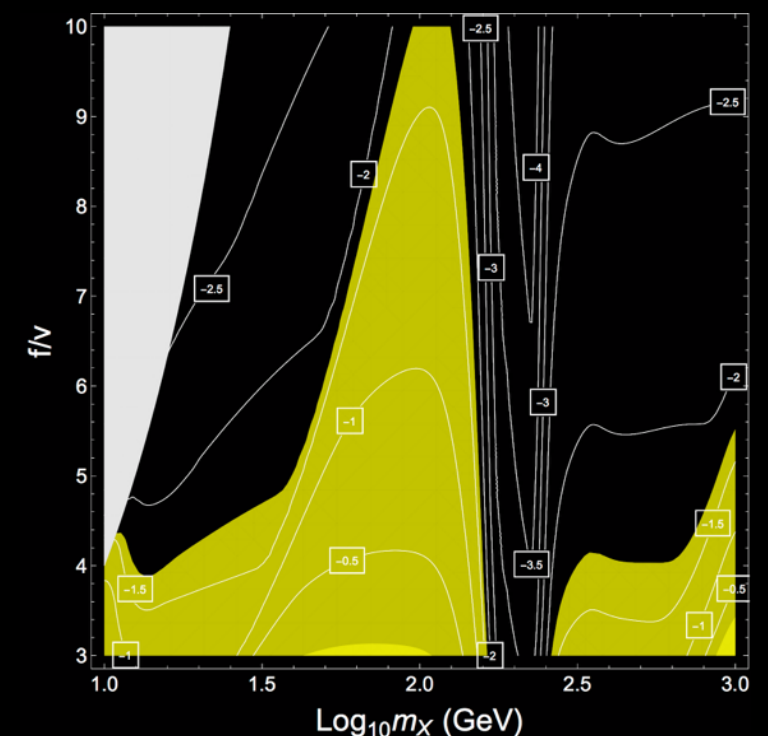
- decouples while relativistic
- decays some time thereafter
- decays primarily to A



Easy to do w/ symmetric coupling to H_A, H_B

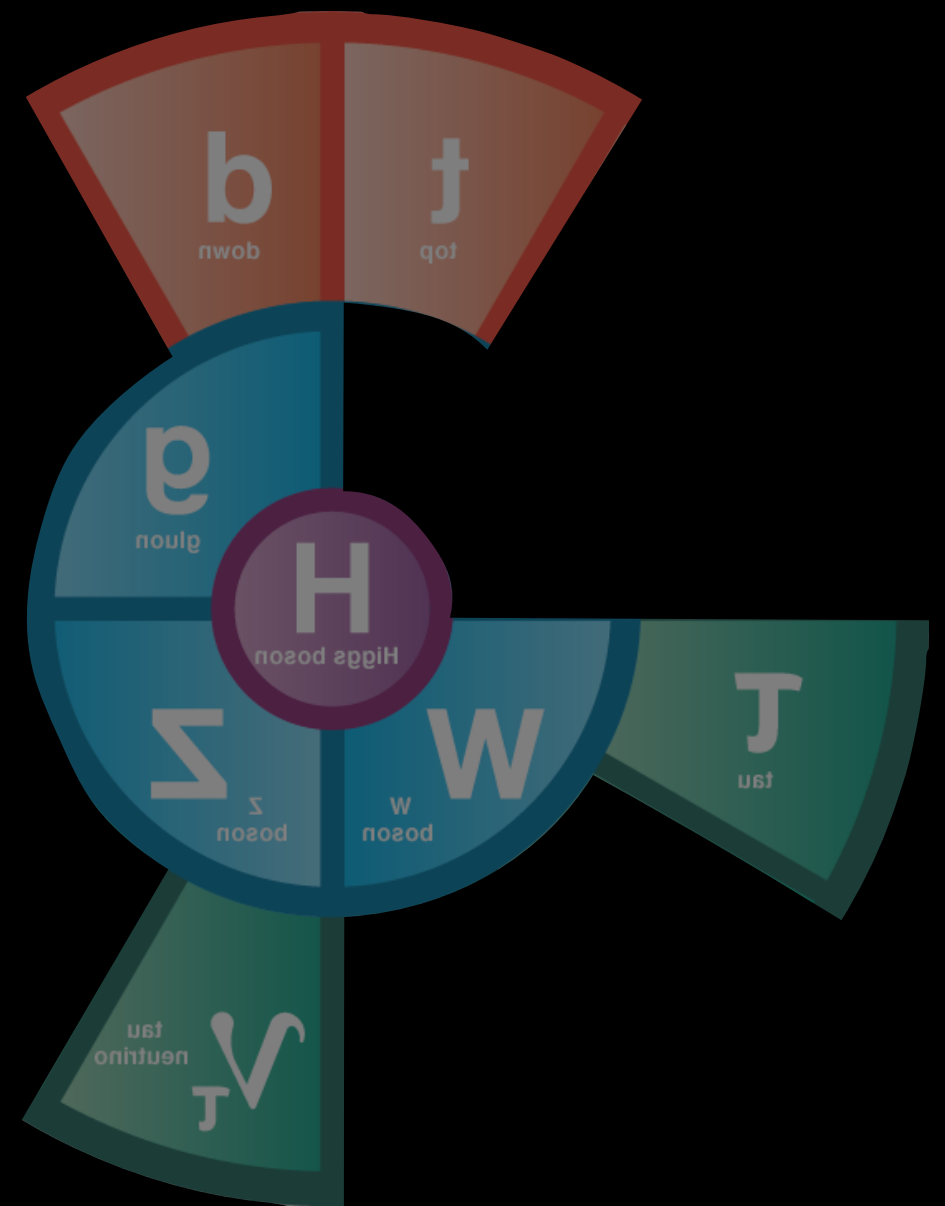
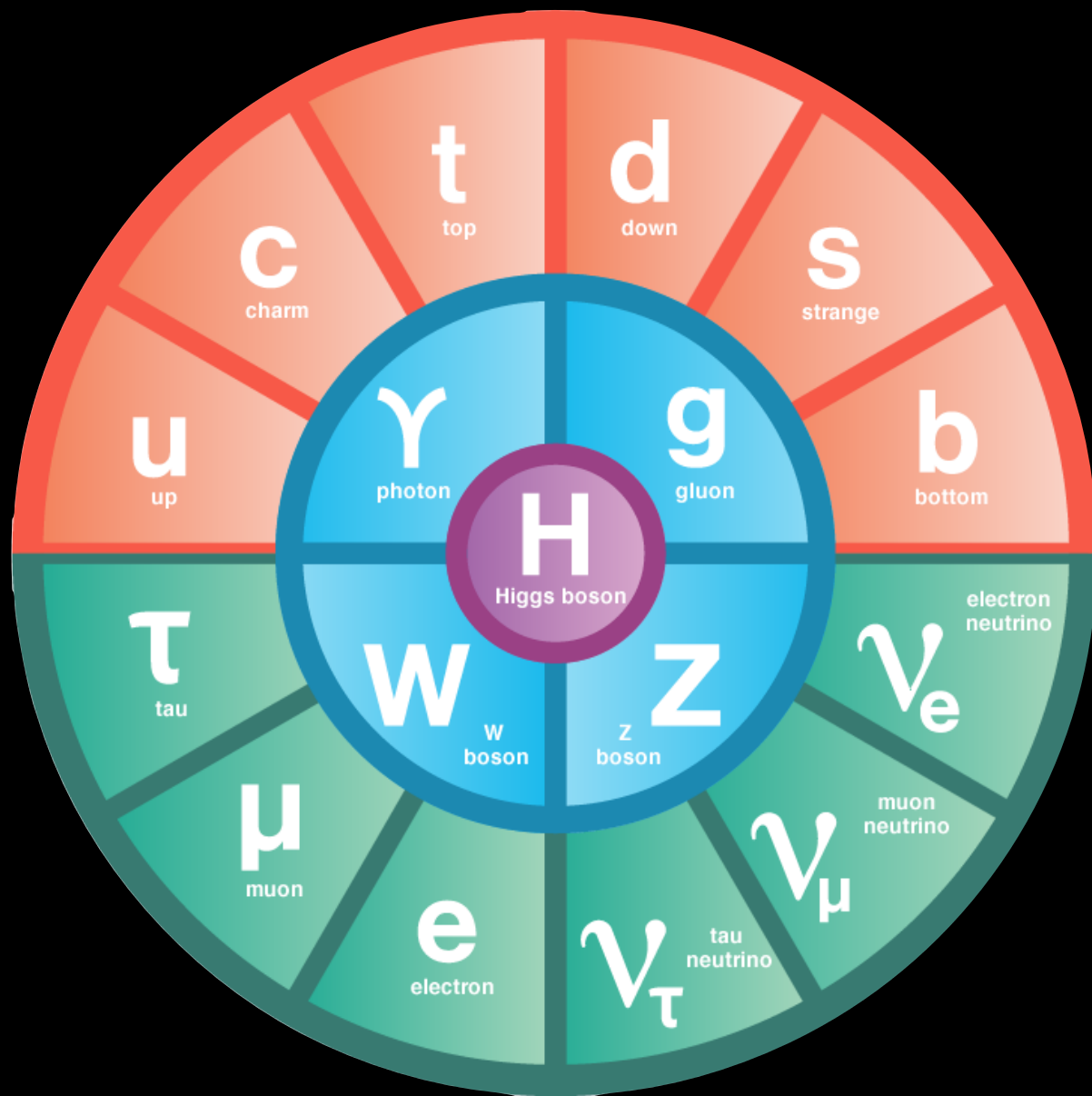
Signals now in future CMB experiments, e.g. CMB Stage-IV

[NC, Koren, Trott '16]



See also: NNaturalness [Arkani-Hamed, Cohen, D'Agnolo, Hook, Kim, Pinner '16]

Change the Spectrum

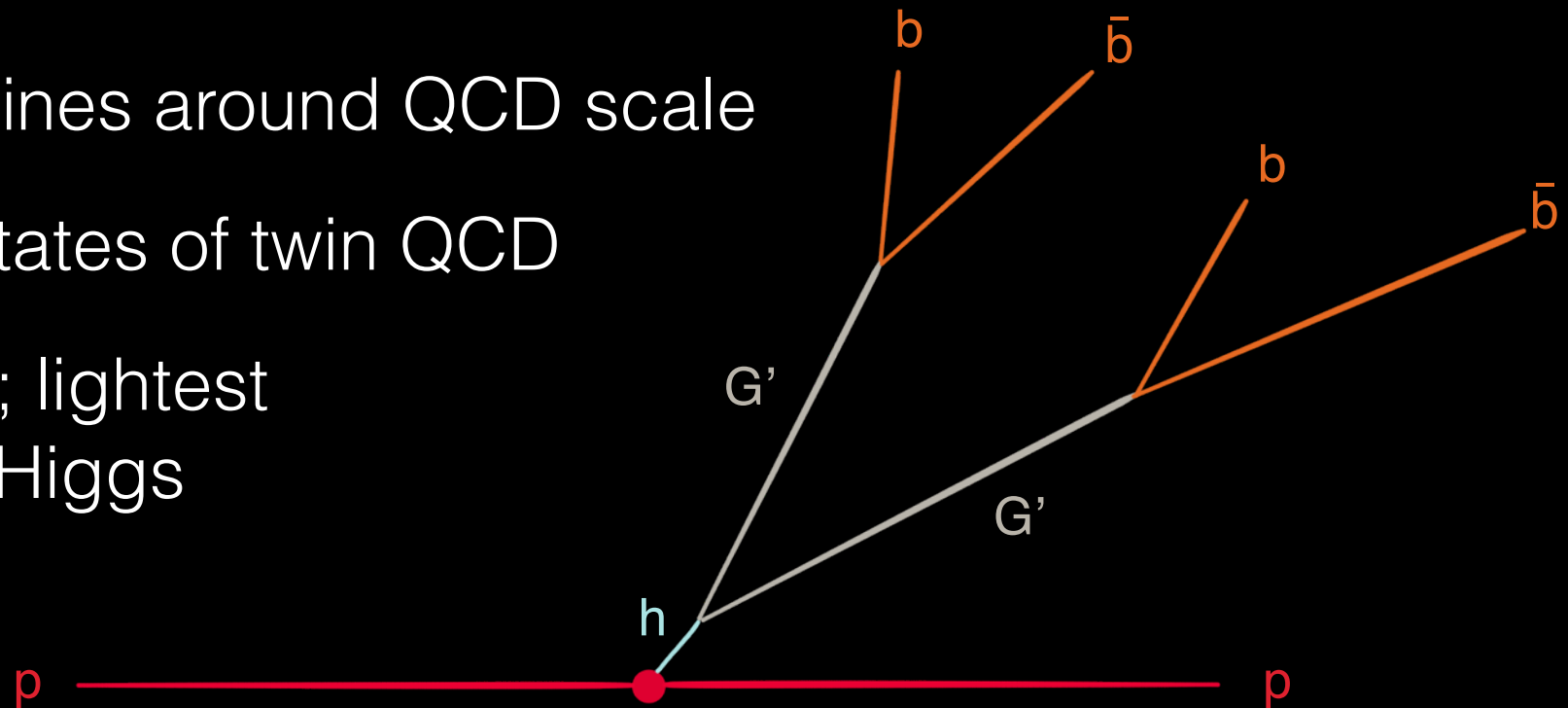


“Fraternal Twin Higgs” [NC, Katz, Strassler, Sundrum '15]

Exotic Higgs Decays

- Must have twin QCD, confines around QCD scale
- Higgs couples to bound states of twin QCD
- Glueballs most interesting; lightest have same quantum # as Higgs

$$\mathcal{L} \supset \frac{v}{f} \frac{h}{f} G'_{\mu\nu} G'^{\mu\nu}$$



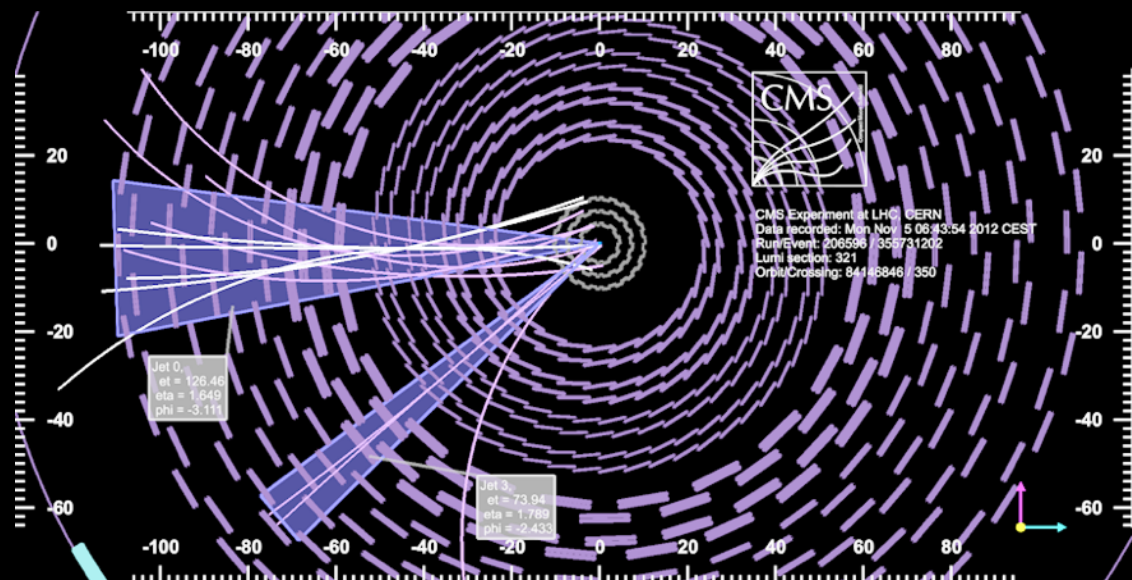
Produce in rare Higgs decays ($\text{BR} \sim 10^{-3} - 10^{-4}$)

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

Decay back to SM via Higgs

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

Long-lived, length scale \sim LHC detectors
Hidden Valley signature [Strassler, Zurek '06]



New searches & experiments

MATHUSLA

John-Paul Chou
David Curtin
Henry Lubatti

MAssive Timing Hodoscope for Ultra-Stable Neutral PArticles

Methuselah (Hebrew: מתושלח / מתושלח, Modern *Metušélāh* / *Metušálāh* Tiberian *Meṭušélāh* / *Meṭušálāh*; "Man of the dart/spear", or alternatively "his death shall bring judgment"^[1]) is the man reported to have lived the longest at the age of 969 in the Hebrew Bible.^[2]



Quanta magazine

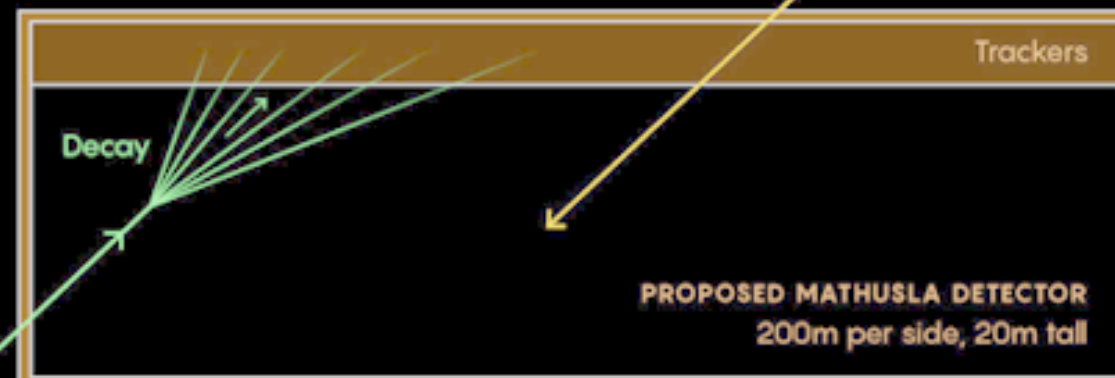
To Catch a Long-Lived Particle

Collisions at the Large Hadron Collider could be generating particles that physicists have never seen before — perhaps because they haven't been looking in the right places. So-called long-lived particles would travel dozens of meters through rock before decaying into ordinary particles. New proposed detectors such as MATHUSLA, pictured here, would be able to catch these decays.

Not to scale

③ A long-lived particle travels upward and decays into ordinary particles inside the barnlike detector. Particle trackers on the roof capture the decays.

④ Cosmic rays coming from space are traveling in the wrong direction and can be filtered out.



② Thick rock between the collision point and the detector blocks nearly all ordinary particles.

① Protons collide in the LHC tunnel 100 meters underground.

		<i>scalar</i>	<i>fermion</i>
<i>strong direct production</i> {	<i>QCD</i>	SUSY	Composite Higgs/ RS
<i>DY direct production</i> {	<i>EW</i>	folded SUSY	Quirky Little Higgs
<i>Higgs portal direct production</i> {	<i>singlet</i>	?	Twin Higgs

Mirror Glueballs
Higgs portal observables

Higgs coupling shifts
~ tuning

Hyperbolic Higgs

[Cohen, NC, Giudice, McCullough '18]

(Related: Accidental SUSY, [Cheng, Li, Salvioni, Verhaaren '18])

Instead of accidental SU(4) from Z_2 , what about “accidental SU(2,2)?”
(NB, not a symmetry of the full quadratic action)

- Take 2 copies of the MSSM, related by exchange:

$$\text{MSSM} \xleftrightarrow{Z_2} \mathcal{R}\text{MSSM}$$

- Introduce SU(2,2) symmetric tree-level potential:

$$V(H, H_{\mathcal{H}}) = \lambda (|H|^2 - |H_{\mathcal{H}}|^2)^2$$

- Lift scalars in MSSM, fermions in MSSM $_{\mathcal{H}}$ (e.g. via 5D SSSB)

$$\delta V(H, H_{\mathcal{H}}) = -c\Lambda^2 (|H|^2 - |H_{\mathcal{H}}|^2) + \dots$$

Hyperbolic Higgs

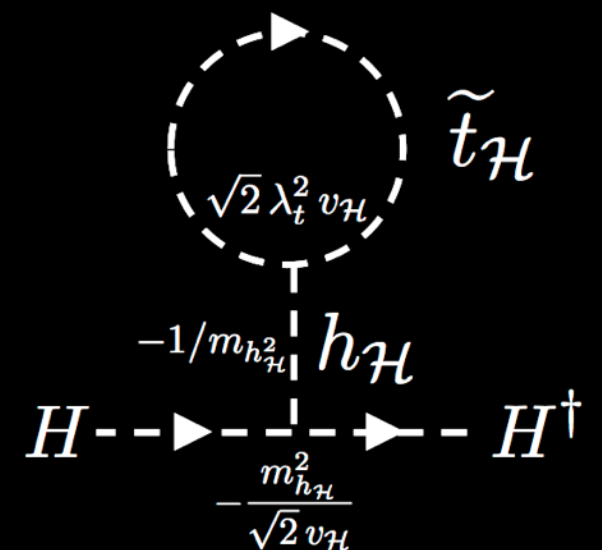
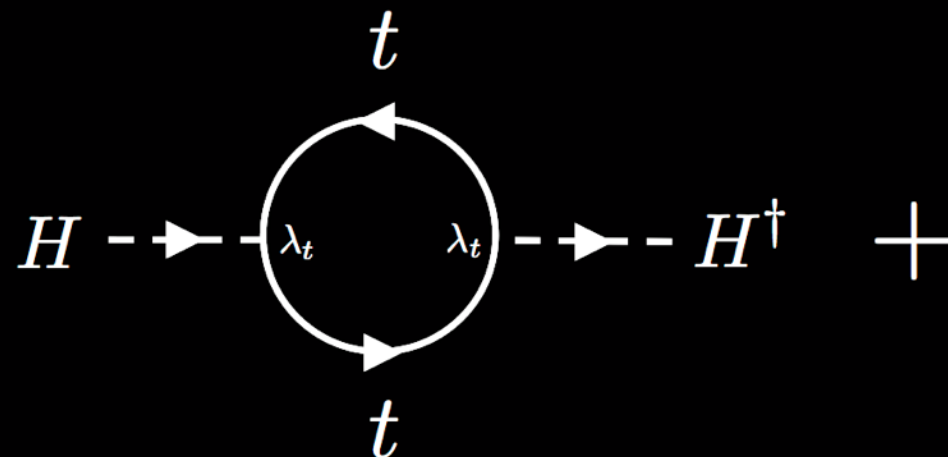
Flat direction (“goldstone” of spontaneously broken $SU(2,2)$)

$$H = H_0 \sinh \frac{H_{\text{flat}}}{f}, \quad H_{\mathcal{H}} = H_0 \cosh \frac{H_{\text{flat}}}{f}$$

Identification w/ SM-like Higgs,

$$h_{\text{SM}} = h \cos \theta + h_{\mathcal{H}} \sin \theta, \quad \tan \theta = \frac{v}{v_{\mathcal{H}}}$$

Light top partner is
SM-neutral stop of
 $\text{MSSM}_{\mathcal{H}}$



Novel dark sector phenomenology, especially if there
are hyperbolic charge- and color-breaking minima

		<i>scalar</i>	<i>fermion</i>
<i>strong direct production</i> {	<i>QCD</i>	SUSY	Composite Higgs/ RS
<i>DY direct production</i> {	<i>EW</i>	folded SUSY	Quirky Little Higgs
<i>Higgs portal direct production</i> {	<i>singlet</i>	Hyperbolic Higgs / Accidental SUSY	Twin Higgs

Mirror Glueballs

Higgs portal observables

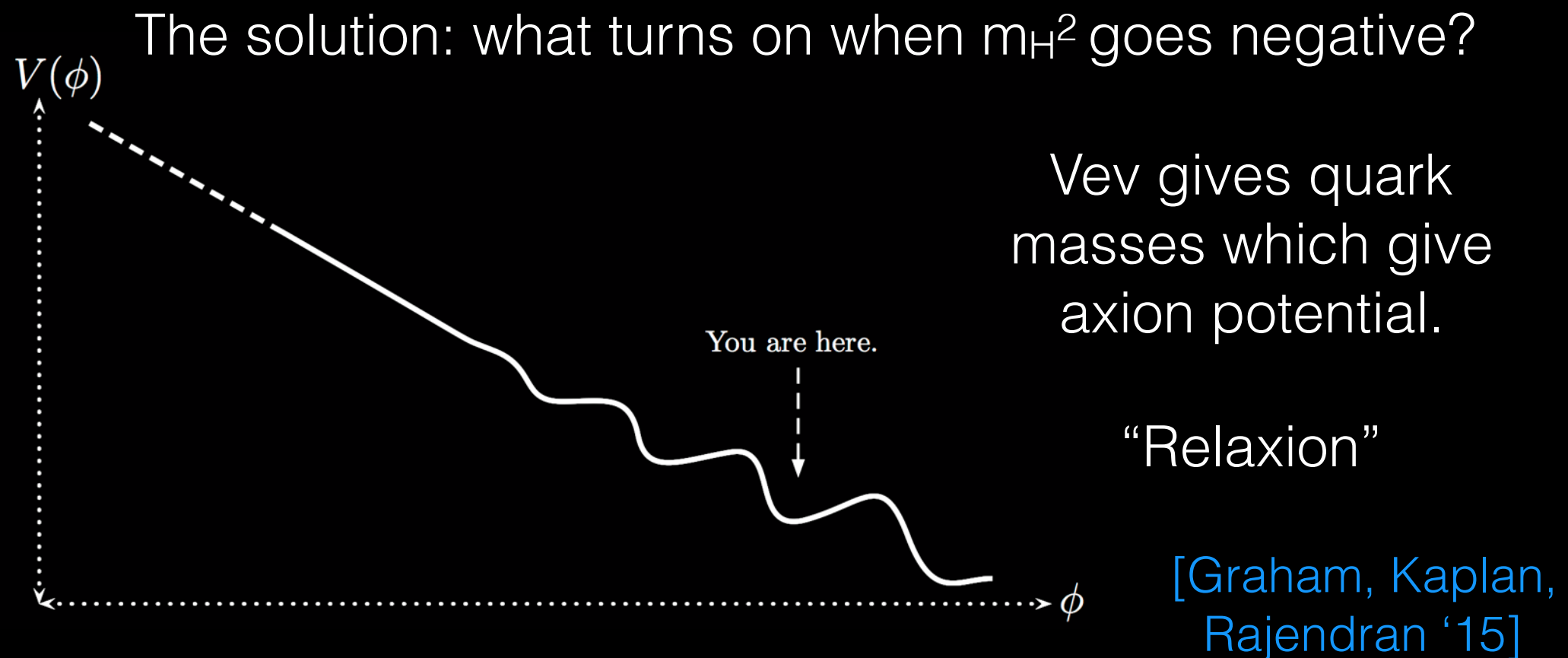
Higgs coupling shifts
~ tuning

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Relaxion

What if the weak scale is selected by scanning?

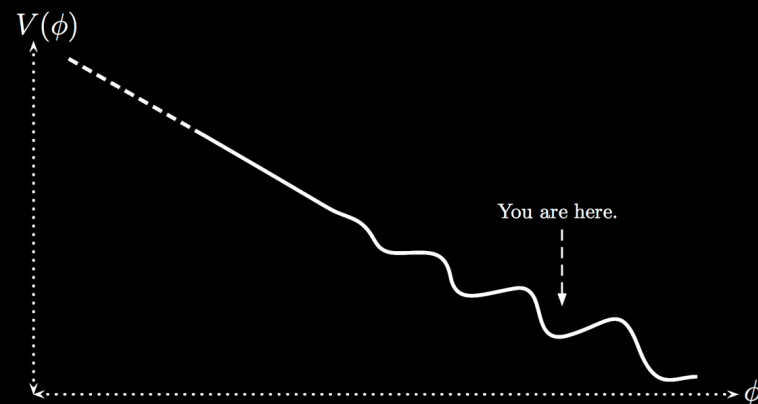
The idea: couple Higgs to field whose minimum sets $m_H=0$
The problem: How to make $m_H=0$ a special point of potential?



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

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 ($\ll \Lambda_{\text{QCD}}$)
- 10 Giga-years of inflation

Various other subtleties regarding technical naturalness, CC, avoidance of fine-tuning to inflationary sector; need to solve strong CP problem.

Forces us to grapple with new UV considerations.

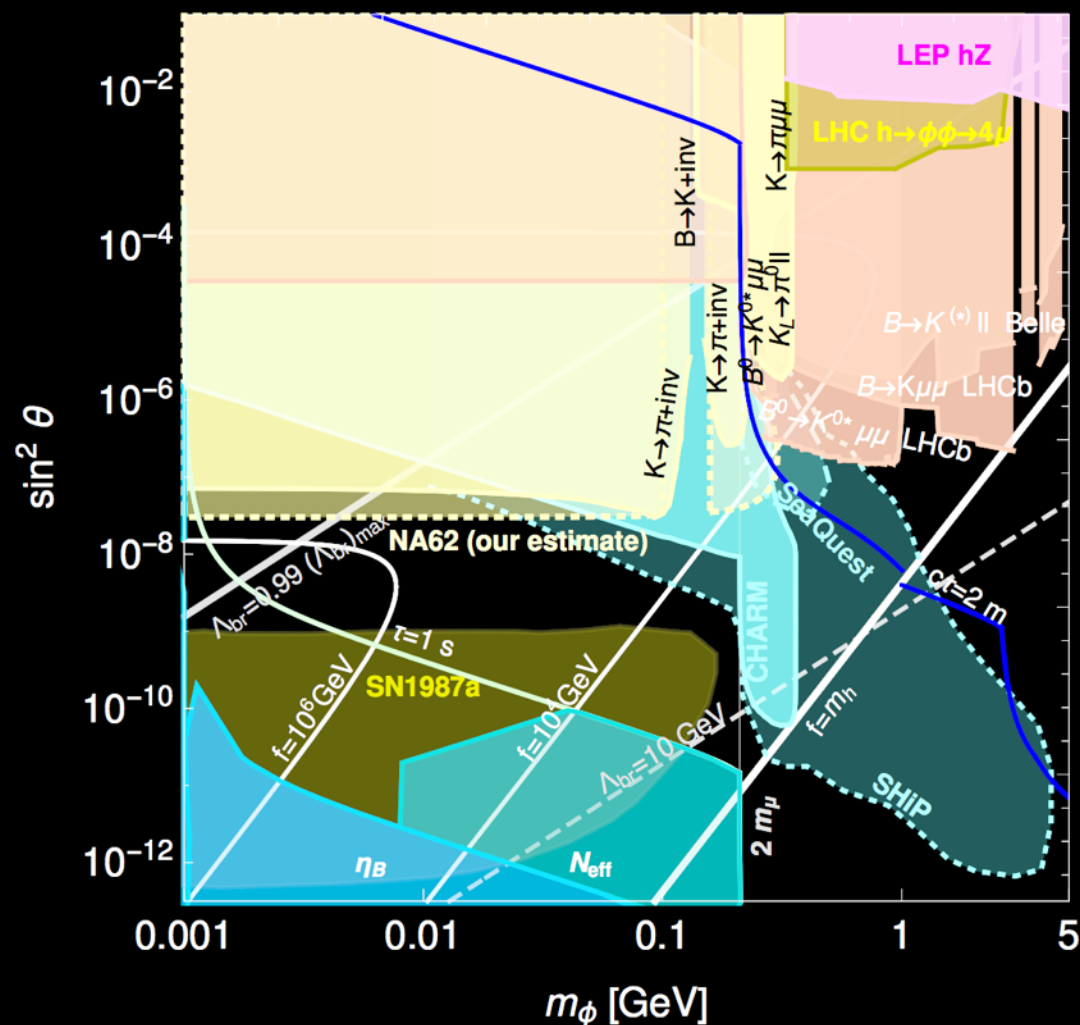
Extensive development, e.g. [Espinosa et al. '15; Hardy '15; Gupta et al '15; Batell, Giudice, McCullough '15; Choi, Im '15; Kaplan, Rattazzi '15; Di Chiara et al. '15; Ibanez et al. '15; Hook, Marques-Tavares '16; Nelson, Prescod-Weinstein '17; ...]

New Signals

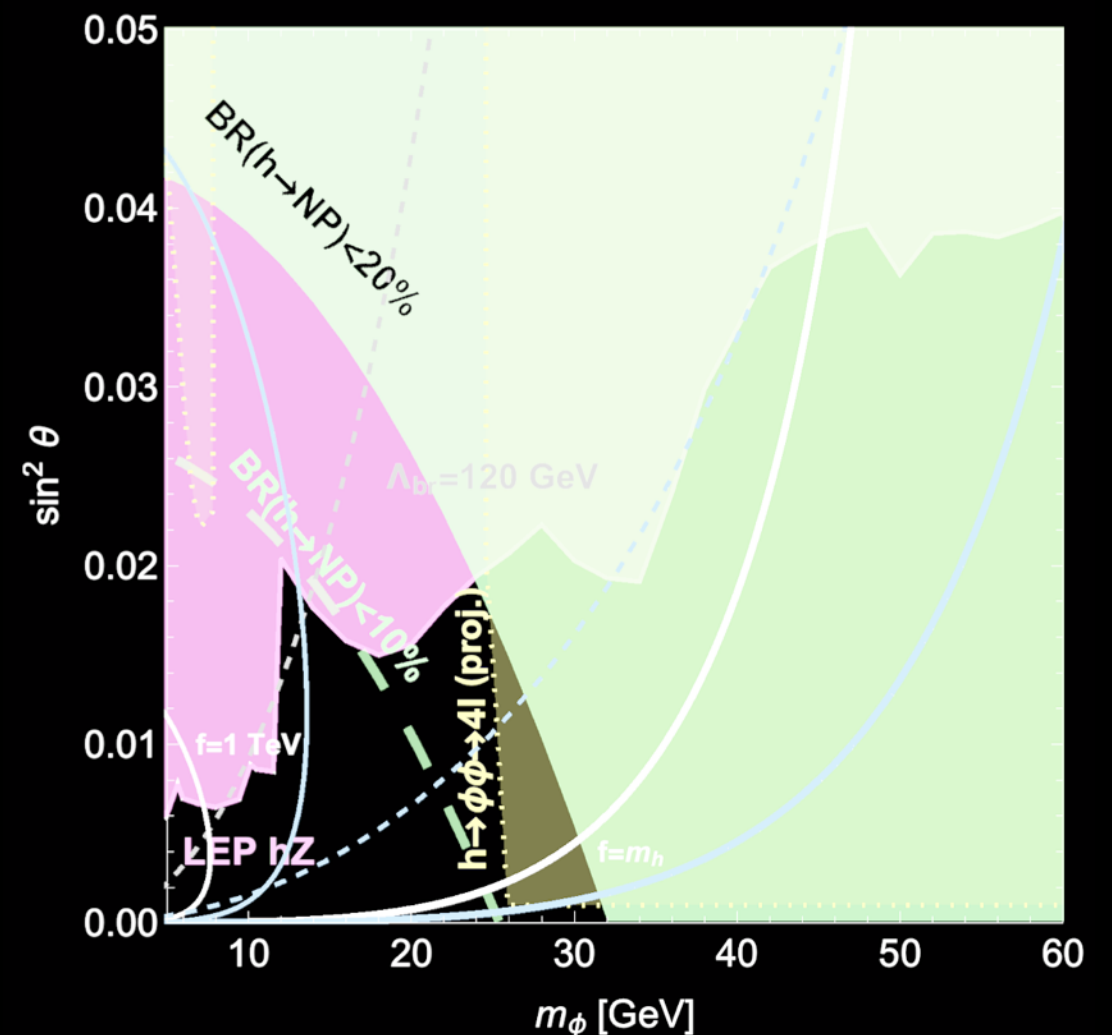
Higgs portals $g\phi|H|^2$ $\Lambda^4(H) \cos(\phi/f)$

$\Lambda^4(H) \cos(\phi/f)$ gives ϕ - H mixing* w/ $\sin \theta \approx \frac{\Lambda^4}{v f m_h^2}$

[Flacke, Friquele, Fuchs, Gupta, Perez '16]



[Flacke, Friquele, Fuchs, Gupta, Perez '16]



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

*assuming $\langle \phi \rangle$ breaks CP

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

Instead of

$$\frac{\phi}{f} G \tilde{G}$$

+ inflation



Use coupling to EWK gauge bosons:

$$\frac{\phi}{f} \left(g^2 W \tilde{W} - g'^2 B \tilde{B} \right) + \Lambda_c^4 \cos \frac{\phi}{f'}$$

Exponential production of EWK gauge bosons around $\hbar \sim v$ slows evolution

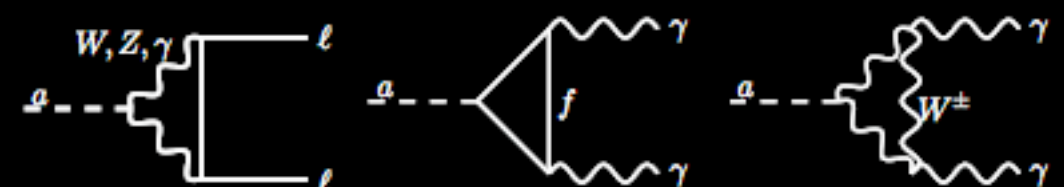
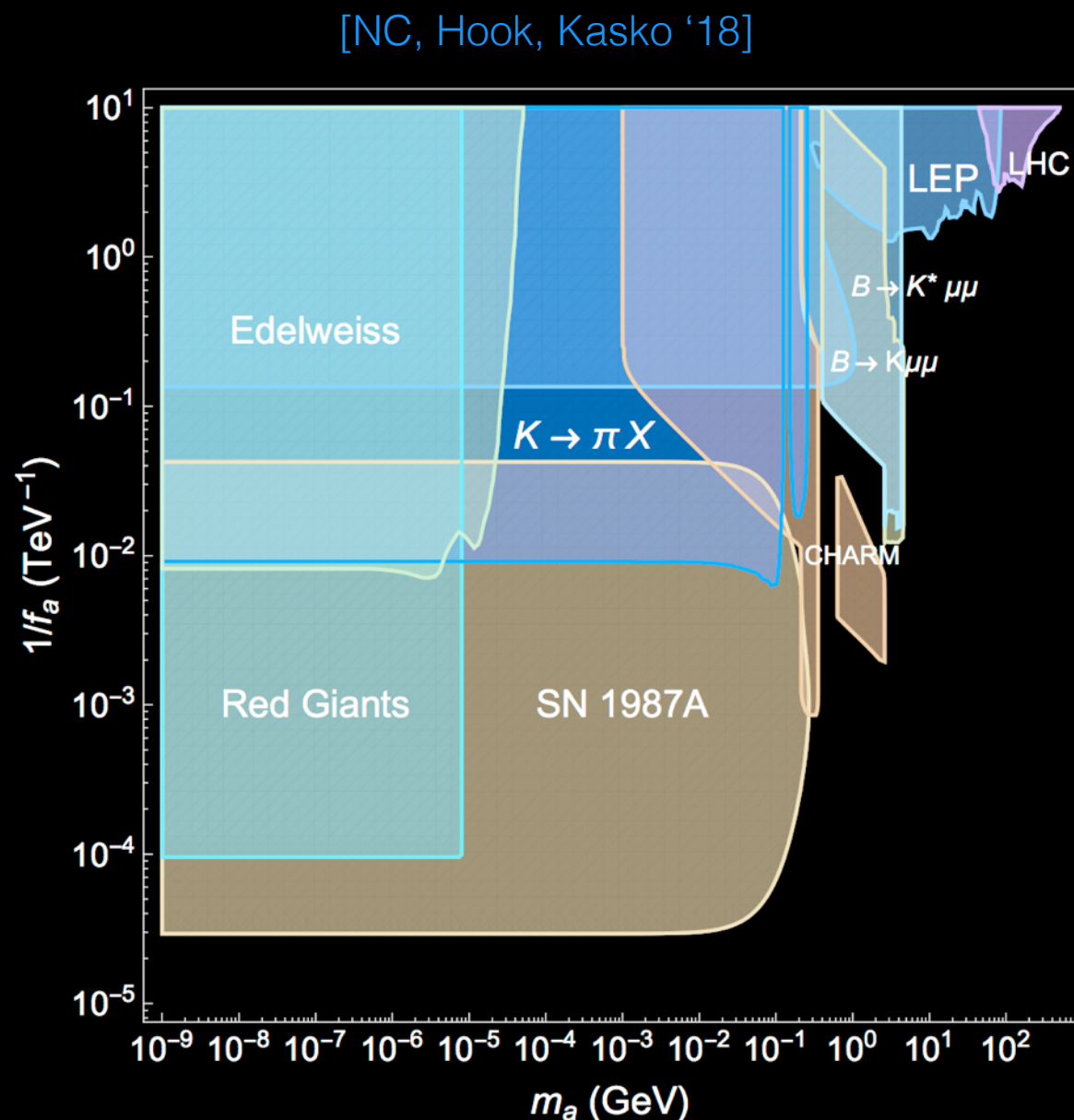
Important subtlety: can't couple to pairs of photons!
(Not a tuning, can be made natural with symmetries, e.g., $SU(2)_L \times SU(2)_R$)

New Signals

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

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

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



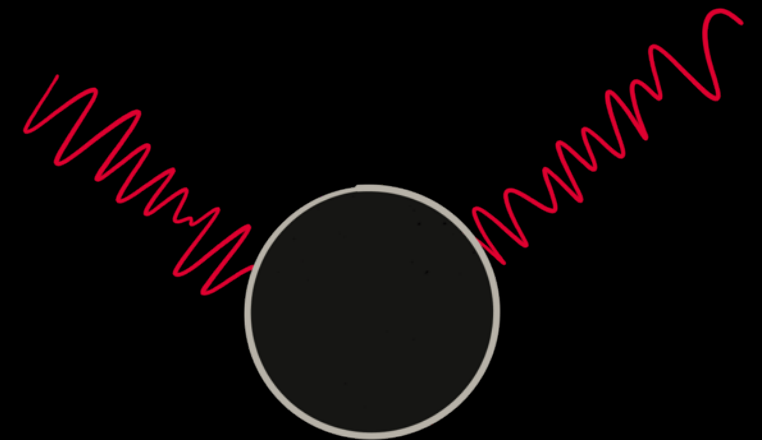
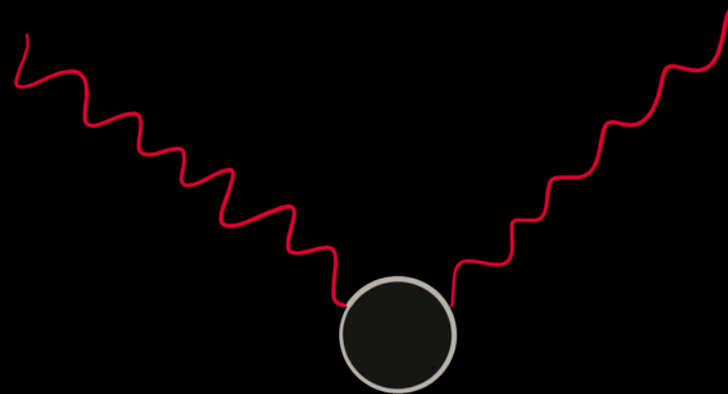
$$f_\gamma \sim 16\pi^2 \frac{m_W^2}{m_a^2} f_a + (16\pi^2)^2 \frac{m_f^2}{m_a^2} f_a$$

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

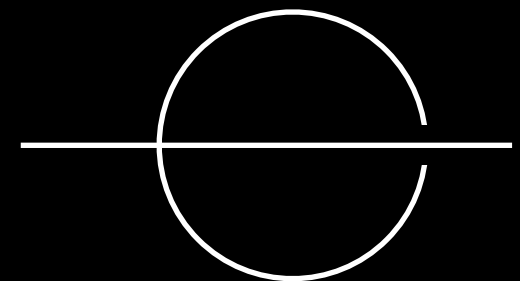
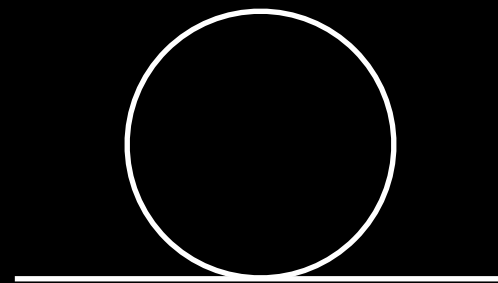
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UV/IR Mixing

Two examples of
UV/IR mixing:
Quantum gravity....



...and non-
commutative QFT.
For example
[Minwalla, Seiberg,
Van Raamsdonk '99]



$$[x^\mu, x^\nu] = i\Theta^{\mu\nu}$$

$$\sim \int \frac{d^4 k}{k^2} \sim \Lambda^2$$

$$\sim \int \frac{d^4 k}{k^2} e^{ip\Theta k} \sim \frac{1}{\Theta^2 p^2}$$

Indirect UV/IR: WGC

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

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

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

Ride the coattails [Cheung, Remmen '14]: Charge SM fermions under weakly gauged (unbroken) $U(1)_{B-L}$ (bounds currently $q \lesssim 10^{-24}$). Cancel anomalies with RHN ν_R

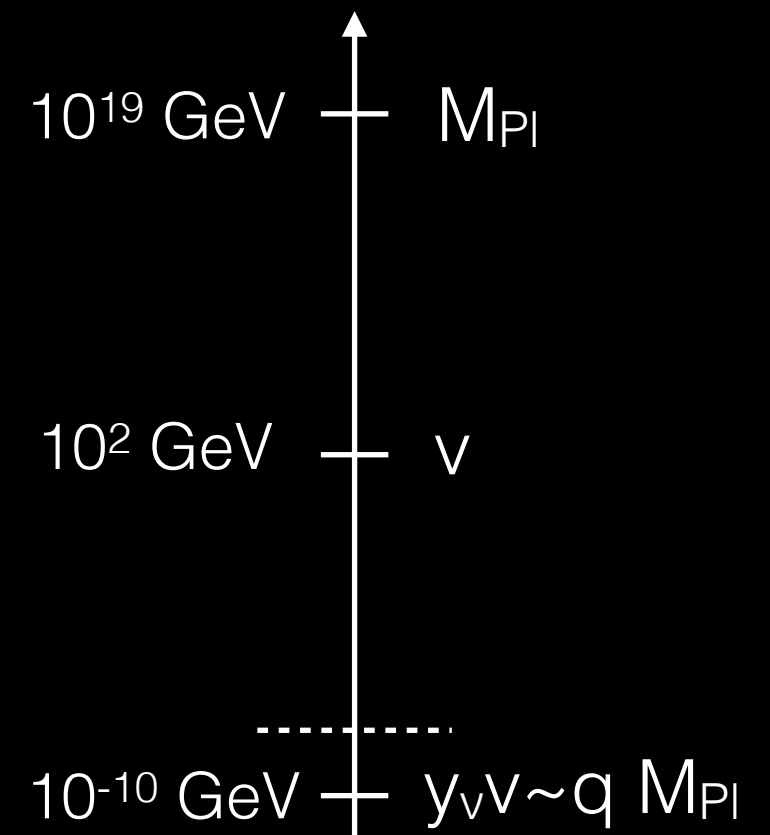
Neutrino mass is

$$y_\nu H \bar{L} \nu_R \rightarrow m_\nu \sim y_\nu v$$

$$\text{so } m_\nu \sim 0.1 \text{ eV, } q \gtrsim 10^{-29}$$

For fixed yukawa, WGC violated if v much larger

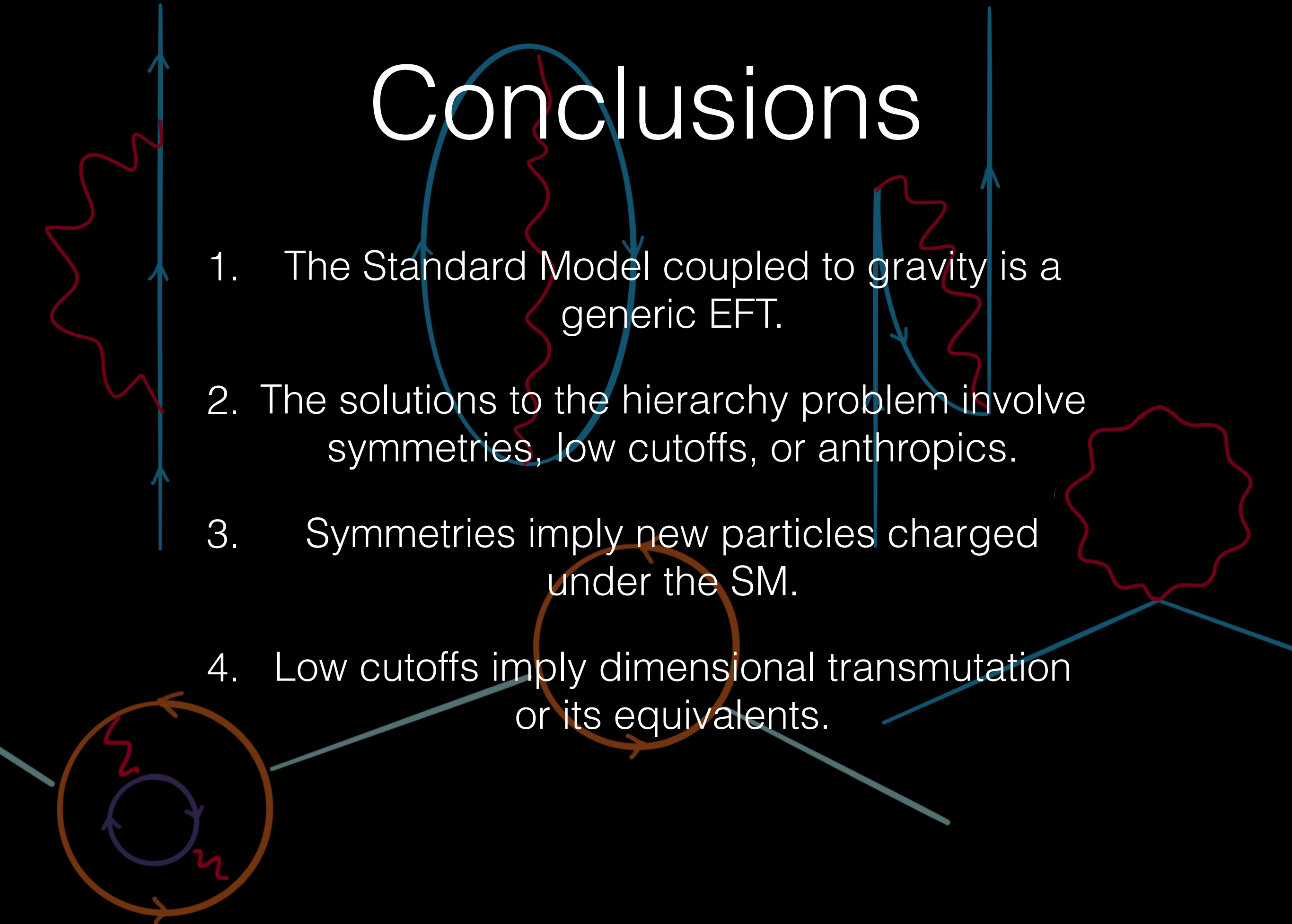
But: *magnetic* WGC implies cutoff of $U(1)$ field theory is $\Lambda \sim q M_{Pl}$



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

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.
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Conclusions

The background features several hand-drawn Feynman diagrams. On the left, a vertical blue line with an upward arrow is accompanied by a red wavy line. In the center, a blue oval with a clockwise arrow encircles the first two list items, with a red wavy line passing through it. To the right, another vertical blue line with an upward arrow is next to a red wavy line. Below the list, a blue line branches out to the right, ending in a red scalloped shape. At the bottom left, a blue circle with a clockwise arrow contains a smaller purple circle with a clockwise arrow and a red wavy line.

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.~~
4. ~~Low cutoffs imply dimensional transmutation or its equivalents.~~

New approaches & new signatures abound.

Thank you!