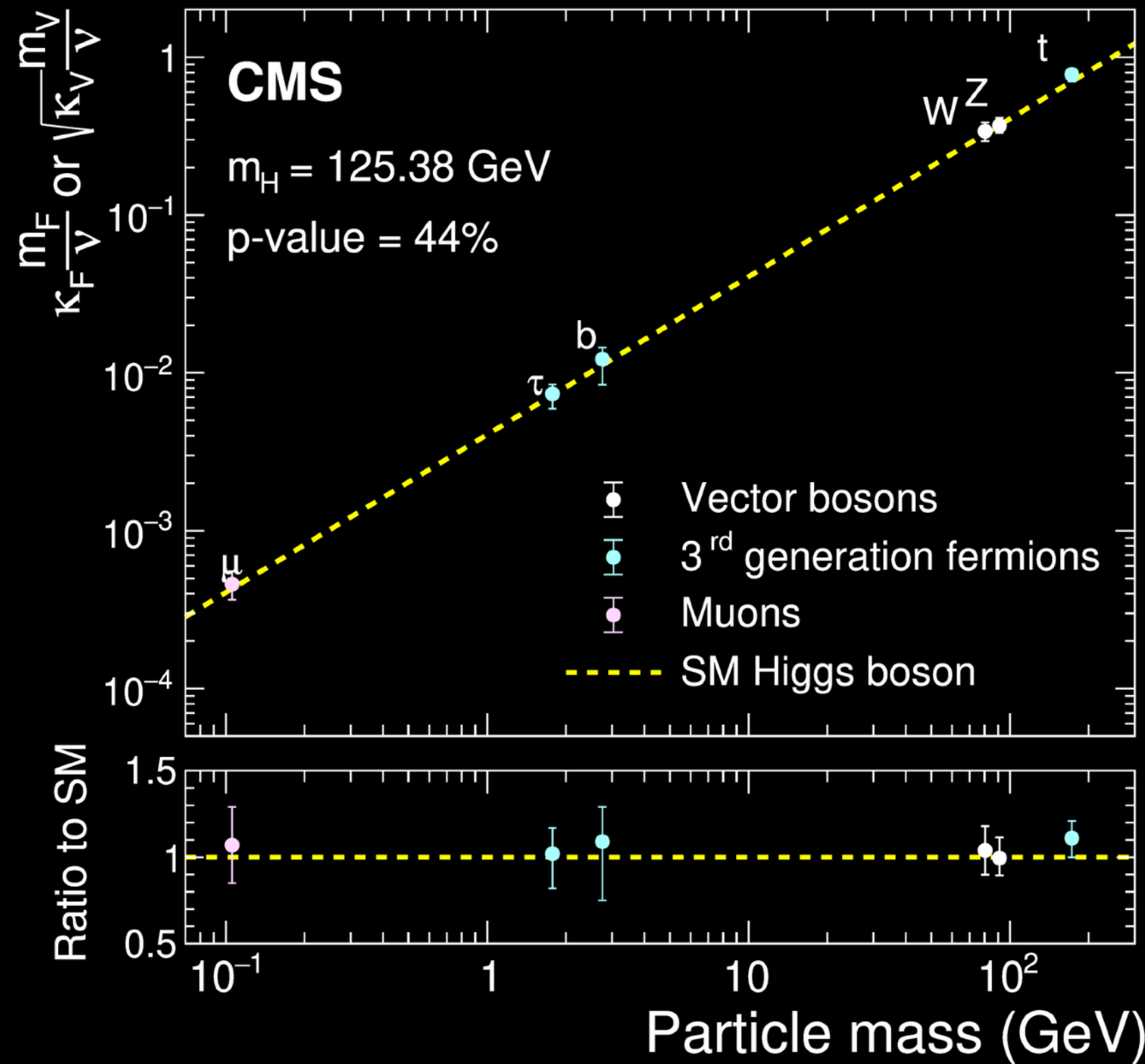
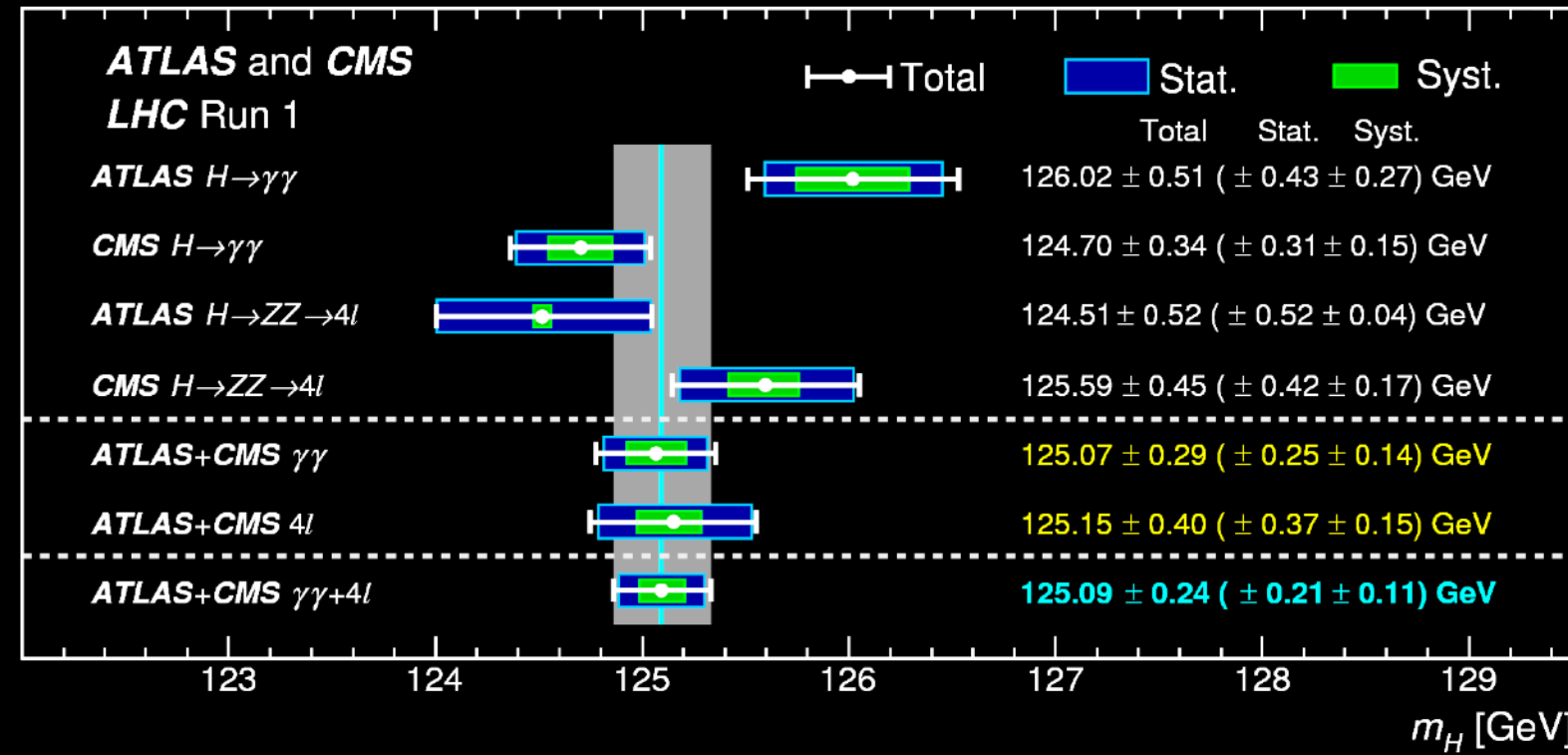


Predicting the Higgs Mass

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UCSB





ATLAS SUSY Searches* - 95% CL Lower Limits
 June 2021

Model	Signature	$\int \mathcal{L} dt$ [fb ⁻¹]	Mass limit	Reference	
Inclusive Searches	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	$m(\tilde{g}) > 400$ GeV	2010.14290
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	1-3 jets E_T^{miss}	35.1	$m(\tilde{g}) > 100$ GeV	2102.10874
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Forbidden	2010.14293
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	1 e, μ 2-6 jets E_T^{miss}	139	Forbidden	2010.14293
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	1 e, μ 2 jets E_T^{miss}	36.1	Forbidden	2101.01629
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 7-11 jets E_T^{miss}	139	Forbidden	1805.11381
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2 jets E_T^{miss}	139	Forbidden	2008.06592
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 3 jets E_T^{miss}	79.8	Forbidden	1909.08457
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2 jets E_T^{miss}	139	Forbidden	ATLAS-COBF-2018-041
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 1 jet E_T^{miss}	139	Forbidden	1909.08457
3 rd gen. squarks direct production	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	$m(\tilde{t}_1) > 400$ GeV	2101.12527
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	2101.12527
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	1908.03122
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	ATLAS-COBF-2020-021
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	2004.14002.2012.202799
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	2012.03789
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	ATLAS-COBF-2021-008
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	1805.01649
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	2102.10874
	$\tilde{t}_1, \tilde{t}_1 \rightarrow t\tilde{t}$	0 e, μ 6 jets E_T^{miss}	139	Forbidden	2008.06592
EW direct	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	$m(\tilde{\chi}_1^0) > 100$ GeV	2106.01626, ATLAS-COBF-2021-022
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	1911.12926
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	1908.08215
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	2004.14004, ATLAS-COBF-2021-022
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	1908.08215
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	1911.08680
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	1908.08215
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	1911.12926
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	1806.04930
	$\tilde{\chi}_1^0 \tilde{\chi}_1^0$ via WW	Multiple l jets E_T^{miss}	139	Forbidden	2103.11884
Long-lived particles	Stable \tilde{R} hadron	Multiple	35.1	Pure Wino	ATLAS-COBF-2021-015
	Metastable \tilde{R} hadron, $\tilde{R} \rightarrow q\tilde{q}$	Multiple	35.1	Pure Higgsino	ATLAS-COBF-2021-015
	$\tilde{R}, \tilde{R} \rightarrow q\tilde{q}$	Diapt. lep	139	$m(\tilde{R}) > 100$ GeV	1710.36011, 1808.04085
	$\tilde{R}, \tilde{R} \rightarrow q\tilde{q}$	Diapt. lep	139	$m(\tilde{R}) > 0.1$ fs	2011.27812
	$\tilde{R}, \tilde{R} \rightarrow q\tilde{q}$	Diapt. lep	139	$m(\tilde{R}) > 0.1$ fs	2011.27812
	$\tilde{R}, \tilde{R} \rightarrow q\tilde{q}$	Diapt. lep	139	Forbidden	2011.27812
	$\tilde{R}, \tilde{R} \rightarrow q\tilde{q}$	Diapt. lep	139	Forbidden	2011.27812
	$\tilde{R}, \tilde{R} \rightarrow q\tilde{q}$	Diapt. lep	139	Forbidden	2011.27812
	$\tilde{R}, \tilde{R} \rightarrow q\tilde{q}$	Diapt. lep	139	Forbidden	2011.27812
	$\tilde{R}, \tilde{R} \rightarrow q\tilde{q}$	Diapt. lep	139	Forbidden	2011.27812
RPV	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	2011.10543
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	2103.11884
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	1804.03568
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	ATLAS-COBF-2018-003
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	2010.01015
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	1710.01711
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	1710.05544
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	1807.10473
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	1804.10623
	$\tilde{g}, \tilde{q} \rightarrow q\tilde{g}$	0 e, μ 2-6 jets E_T^{miss}	139	Pure Wino	1803.09678

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
 Status: May 2020

Model	ℓ, γ	Jets [†]	E_T^{miss}	$\int \mathcal{L} dt$ [fb ⁻¹]	Limit	Reference		
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ 1-4	Yes	36.1	M_{pl}	7.7 TeV		
	ADD non-resonant $\gamma\gamma$	2 γ	-	36.7	M_{pl}	8.6 TeV		
	ADD OBH	-	2]	-	37.0	M_{pl}	8.5 TeV	
	ADD BH high Σp_T	$\geq 1 e, \mu$	$\geq 2]$	-	3.2	M_{pl}	8.2 TeV	
	ADD BH multijet	-	$\geq 3]$	-	3.6	M_{pl}	9.55 TeV	
	RS1 $G_{KK} \rightarrow \gamma\gamma$	2 γ	-	-	36.7	Grav. mass	4.1 TeV	
	Bulk RS $G_{KK} \rightarrow WW/ZZ$	multi-channel	-	-	36.1	Grav. mass	2.2 TeV	
	Bulk RS $G_{KK} \rightarrow WV \rightarrow \ell\nu q\bar{q}$	1 e, μ	2]/1 J	Yes	139	Grav. mass	2.0 TeV	
	Bulk RS $G_{KK} \rightarrow t\bar{t}$	1 e, μ	$\geq 1 b, \geq 1 J/2]$	Yes	36.1	Grav. mass	3.0 TeV	
	2UED / RPP	1 e, μ	$\geq 2 b, \geq 3 J$	Yes	36.1	KK mass	1.6 TeV	
Gauge bosons	SSM $Z' \rightarrow \ell\ell$	2 e, μ	-	-	Z' mass	5.1 TeV		
	SSM $Z' \rightarrow \tau\tau$	2 τ	-	-	Z' mass	2.42 TeV		
	Leptophobic $Z' \rightarrow b\bar{b}$	-	2 b	-	35.1	Z' mass	2.1 TeV	
	Leptophobic $Z' \rightarrow t\bar{t}$	0 e, μ	$\geq 1 b, \geq 2 J$	Yes	139	Z' mass	4.1 TeV	
	SSM $W' \rightarrow \ell\nu$	1 e, μ	-	Yes	139	W' mass	6.0 TeV	
	SSM $W' \rightarrow \tau\nu$	1 τ	-	Yes	36.1	W' mass	3.7 TeV	
	HVT $V' \rightarrow WZ \rightarrow \ell\nu q\bar{q}$ model B	1 e, μ	2]/1 J	Yes	139	V' mass	4.2 TeV	
	HVT $V' \rightarrow WV \rightarrow \ell\nu q\bar{q}$ model B	0 e, μ	2 J	-	139	V' mass	3.9 TeV	
	HVT $V' \rightarrow WH/ZH$ model B	multi-channel	-	-	36.1	V' mass	2.93 TeV	
	HVT $V' \rightarrow WH$ model B	0 e, μ	$\geq 1 b, \geq 2 J$	-	139	V' mass	3.2 TeV	
LRSM $W_R \rightarrow t\bar{b}$	multi-channel	-	-	36.1	W_R mass	3.25 TeV		
LRSM $W_R \rightarrow \mu N_e$	2 μ	1 J	-	80	W_R mass	3.2 TeV		
DM	Cl $\ell\bar{\ell} q\bar{q}$	-	-	-	A	21.8 TeV η_{Cl}		
	Cl $\ell\bar{\ell} q\bar{q}$	2 e, μ	1 J	-	139	A	8.8 TeV η_{Cl}	
	Cl $\ell\bar{\ell} q\bar{q}$	$\geq 1 e, \mu$	$\geq 1 b, \geq 1 J$	Yes	36.1	A	2.57 TeV	
	Axial-vector mediator (Dirac DM)	0 e, μ	1-4]	Yes	36.1	Mass	1.55 TeV	
	Colored scalar mediator (Dirac DM)	0 e, μ	1-4]	Yes	36.1	Mass	1.67 TeV	
	VV _{XX} EFT (Dirac DM)	0 e, μ	1 J, $\leq 1 J$	Yes	3.2	M_{pl}	700 GeV	
	Scalar reson. $\phi \rightarrow t\bar{t}$ (Dirac DM)	0 e, μ	1 b, 0-1 J	Yes	36.1	Mass	3.4 TeV	
	Scalar LO 1 st gen	1,2 e	$\geq 2 J$	Yes	36.1	LQ mass	1.4 TeV	
	Scalar LO 2 nd gen	1,2 μ	$\geq 2 J$	Yes	36.1	LQ mass	1.56 TeV	
	Scalar LO 3 rd gen	2 τ	2 b	-	36.1	LQ mass	1.03 TeV	
Scalar LO 3 rd gen	0-1 e, μ	2 b	-	36.1	LQ mass	970 GeV		
Heavy quarks	VLO $TT \rightarrow H/Z/\tau/Wb + X$	multi-channel	-	-	V mass	1.21 TeV		
	VLO $BB \rightarrow Wt/Zb + X$	multi-channel	-	-	B mass	1.34 TeV		
	VLO $T_{31} T_{32} T_{33} \rightarrow Wt + X$	2(SS) $\geq 3 e, \mu, \geq 1 b, \geq 1 J$	Yes	36.1	V mass	1.64 TeV		
	VLO $V \rightarrow Wb + X$	1 e, μ	$\geq 1 b, \geq 1 J$	Yes	36.1	V mass	1.65 TeV	
	VLO $Z \rightarrow Hb + X$	0 $e, \mu, 2 \gamma, \geq 1 b, \geq 1 J$	Yes	79.8	B mass	1.21 TeV		
	VLO $QQ \rightarrow WqWq$	1 e, μ	$\geq 4 J$	Yes	20.3	Mass	1.21 TeV	
	Excited fermions	Excited quark $q^* \rightarrow e\bar{g}$	-	2]	-	q^* mass	6.7 TeV	
		Excited quark $q^* \rightarrow e\bar{q}$	1 γ	1]	-	q^* mass	5.3 TeV	
		Excited quark $b^* \rightarrow b\bar{g}$	-	1 b, 1 J]	-	q^* mass	2.6 TeV	
		Excited lepton e^*	3 e, μ	-	-	20.3	e^* mass	6.7 TeV
Excited lepton ν^*		3 e, μ, τ	-	-	20.3	e^* mass	6.7 TeV	
Other		Type III Seesaw	1 e, μ	$\geq 2 J$	Yes	79.8	N^c mass	560 GeV
		LRSM Majorana ν	2 μ	2]	-	36.1	N^c mass	870 GeV
		Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	2,3,4 e, μ (SS)	-	-	36.1	$H^{\pm\pm}$ mass	870 GeV
		Higgs triplet $H^{\pm\pm} \rightarrow \ell\tau$	3 e, μ, τ	-	-	20.3	$H^{\pm\pm}$ mass	add GeV
		Multi-charged particles	-	-	-	36.1	multi-charged particle mass	1.22 TeV
	Magnetic monopoles	-	-	-	34.4	monopole mass	2.37 TeV	

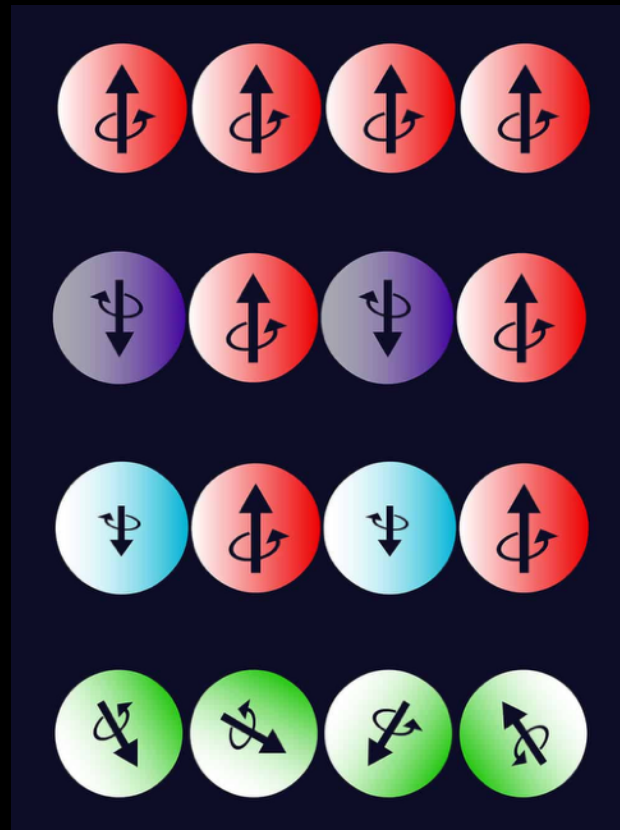
*Only a selection of the available mass limits on new states or phenomena is shown.
[†]Small-radius (large-radius) jets are denoted by the letter j (J).

ATLAS Preliminary $\sqrt{s} = 13$ TeV

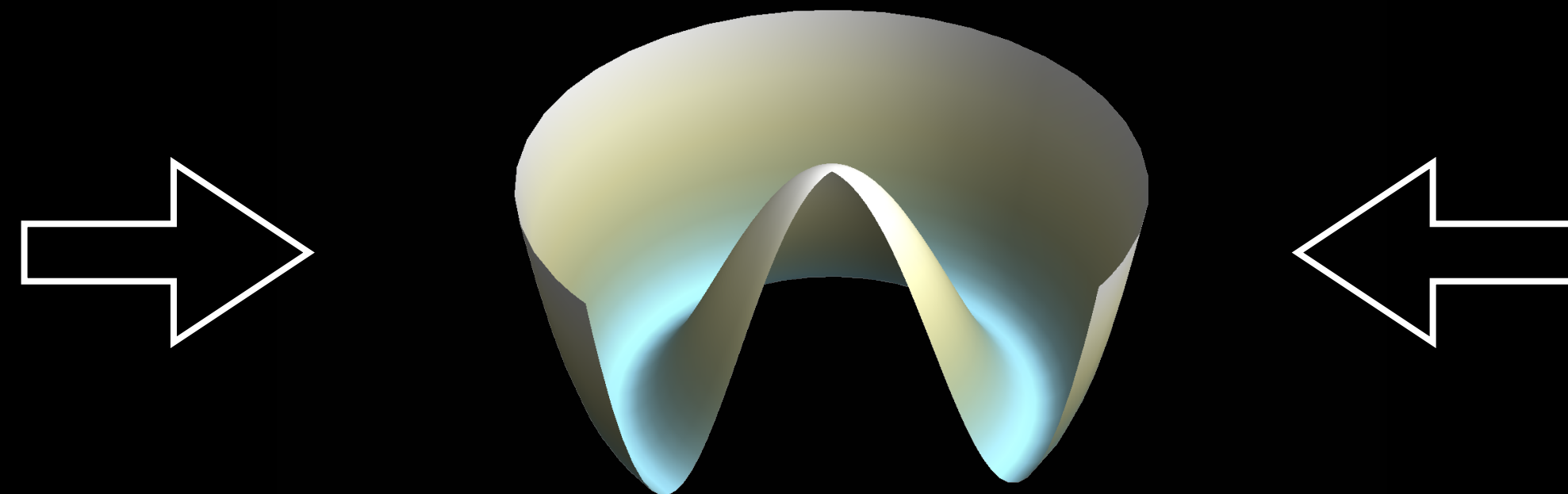
ATLAS Preliminary $\sqrt{s} = 8, 13$ TeV

A Superconducting Analogy

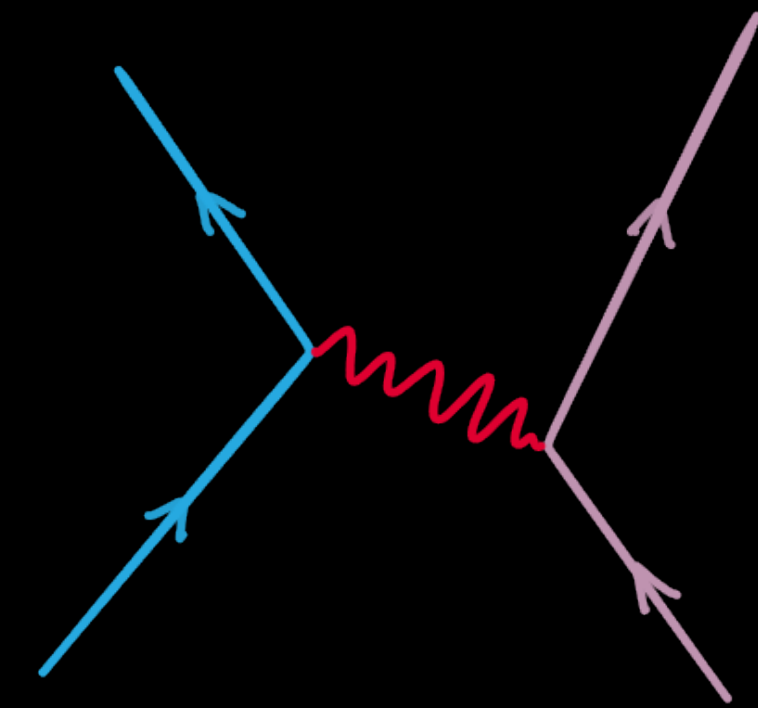
High-Tc Superconductors



Ginzburg-Landau Theory



Low-Tc Superconductors (BCS)

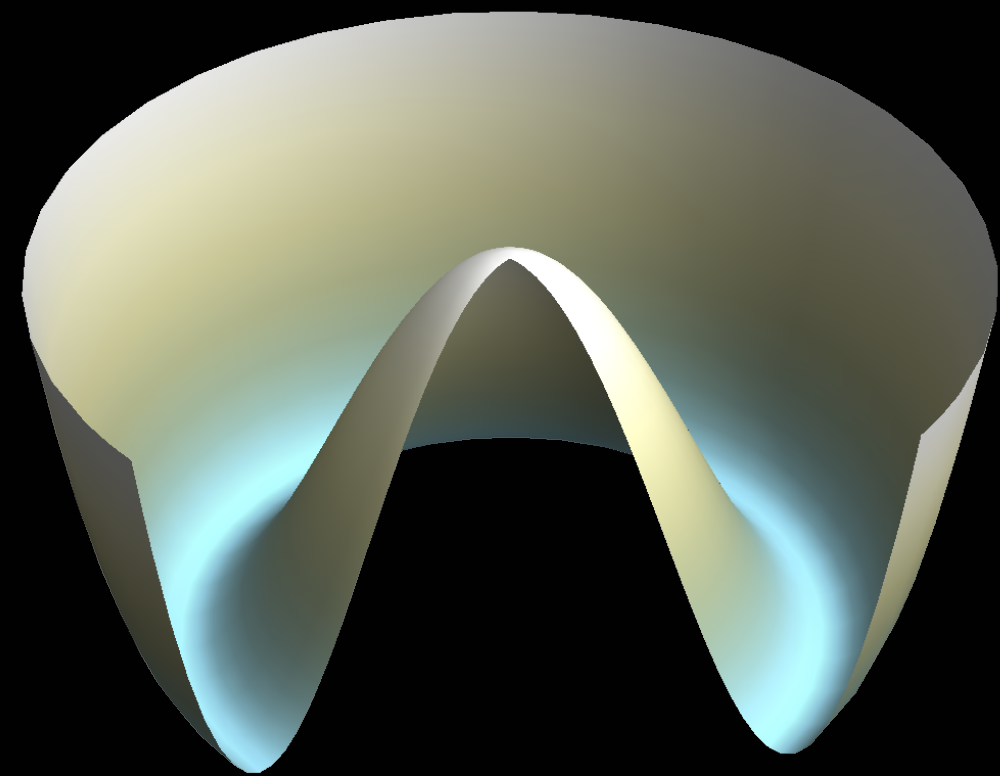


$$F = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \frac{1}{2m}|(-i\hbar\vec{\nabla} - g\vec{A})\psi|^2 + \dots$$

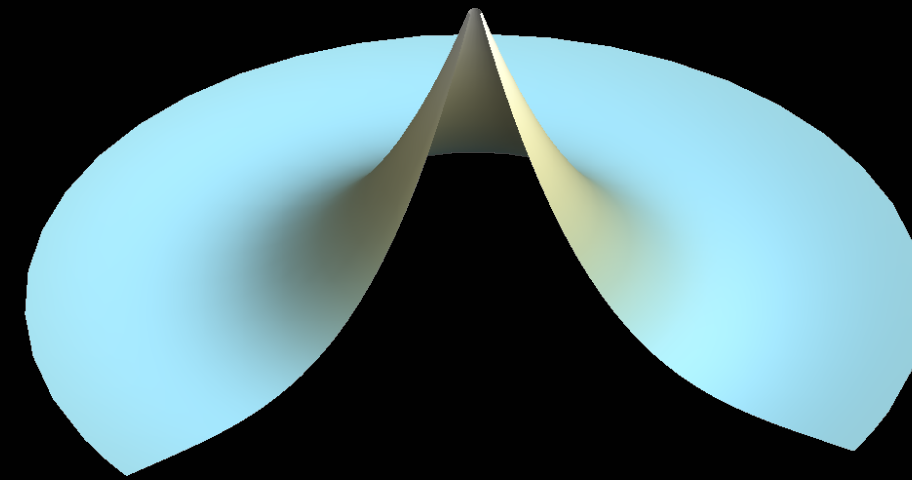
“The more ambitious goal...is to identify and understand the nature of electroweak symmetry breaking, the asymmetry that is key to the material universe. The Higgs boson is but its herald.”

–Frank Close

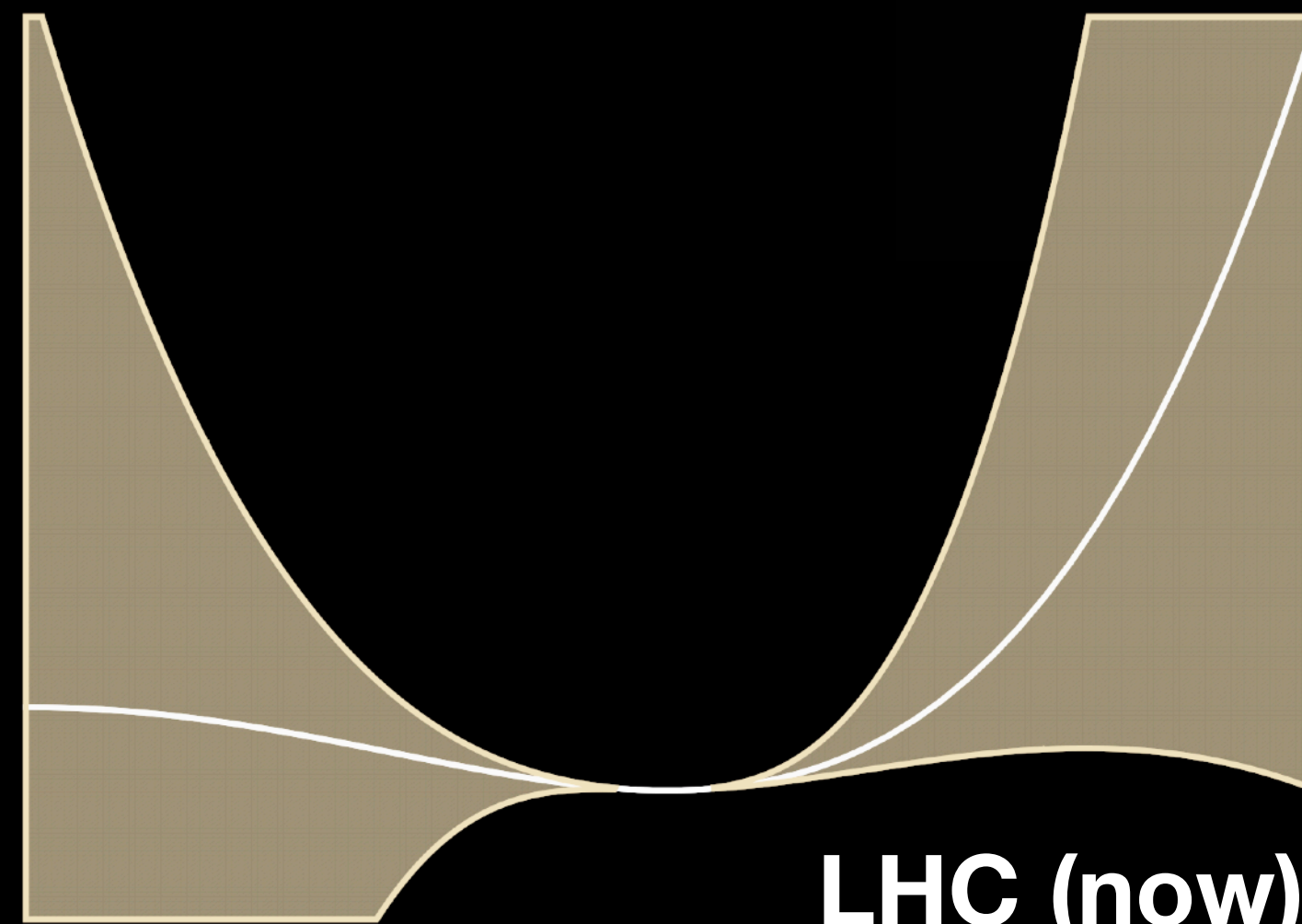
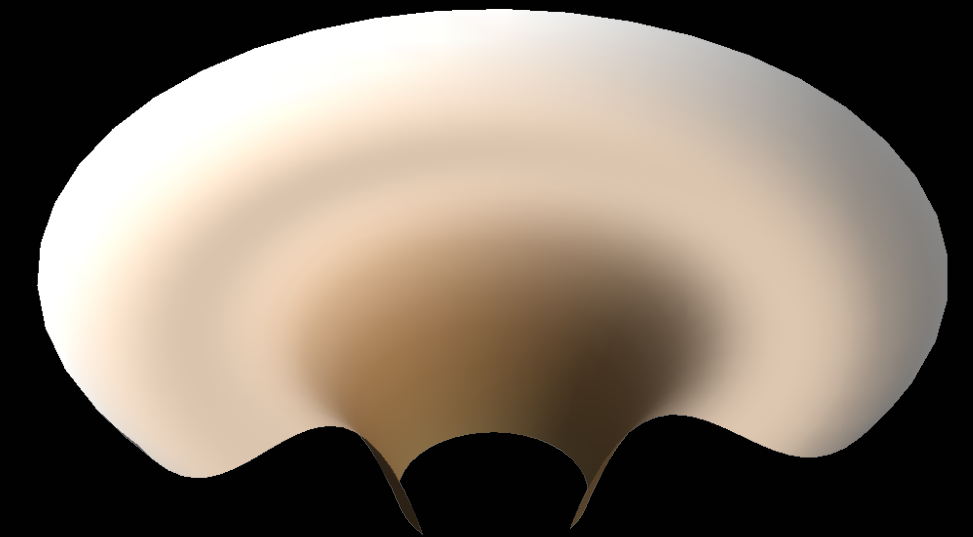
Is it even a Ginzburg-Landau model?



vs.



or

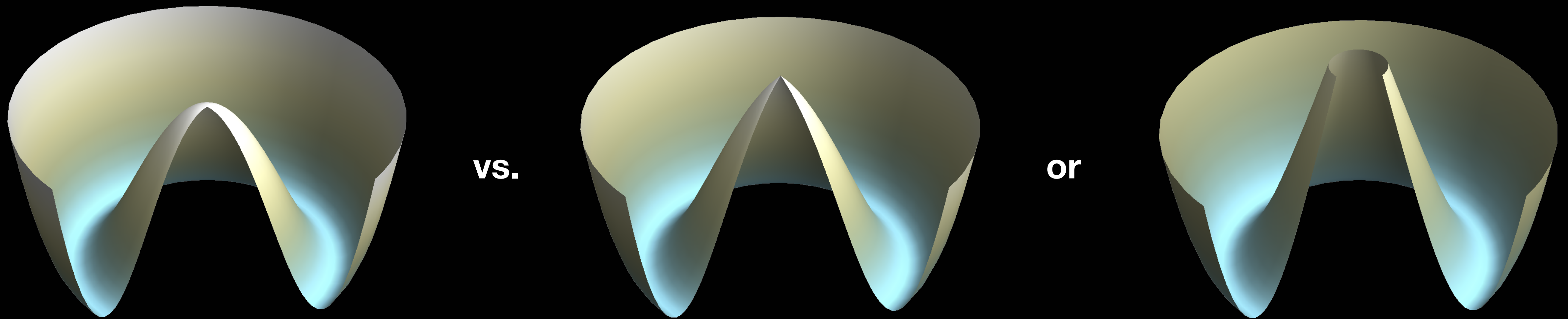


LHC (now)



HL-LHC

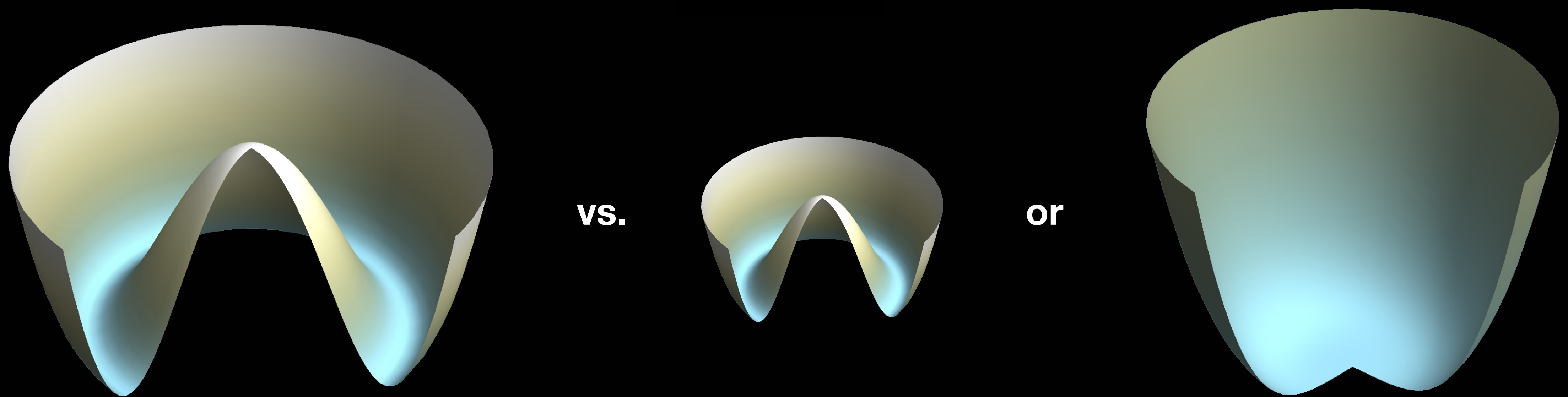
Does it even restore EW symmetry?



Best probed in vector boson scattering with 3+ bosons in the final state...
[Chang & Luty '19, Falkowski & Rattazzi '19, Cohen, NC, Lu, Sutherland '21]

What is the microscopic theory?

Why is electroweak symmetry broken, and what sets the scale?



Parameters in the Standard Model can be predicted (or correlated) in its extensions.

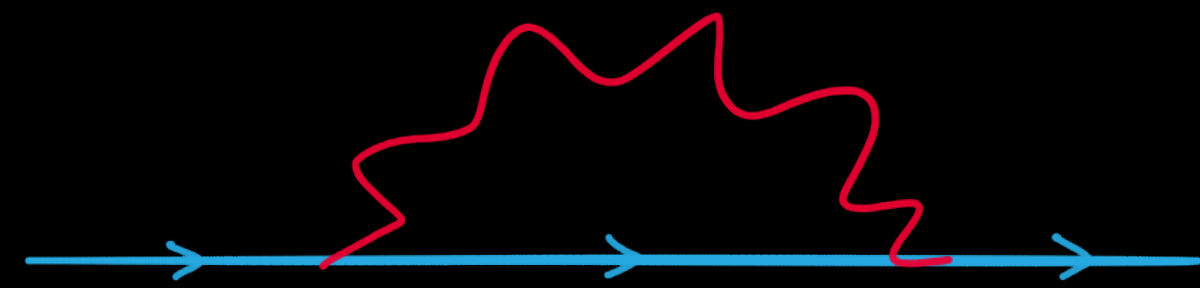
Of course, we know $m_h=125$ GeV, so the aim should be to use this data to predict new phenomena.

The Naturalness Strategy

Going up in scale through the SM, parameters in the effective theory appear UV sensitive.

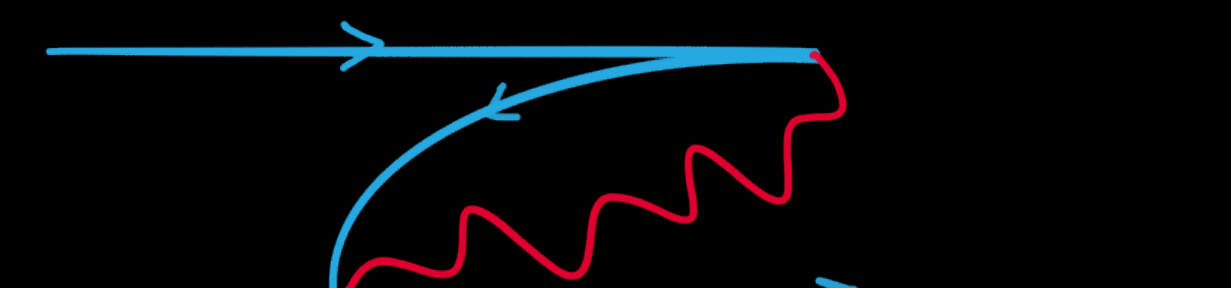
Ultimately, new states appear & UV sensitivity replaced by finite contributions.

[Weisskopf 1934-39]: Divergent self-energy of electron cured by appearance of positron.



$$\Delta E_C = \frac{e^2}{r_e} + \dots$$

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



$$\Delta E_C = -\frac{e^2}{r_e} + \dots$$

But no obvious mechanism for a charged scalar:

“This may indicate that a theory of particles obeying Bose statistics must involve new features at this critical length, or at energies corresponding to this length; whereas a theory of particles obeying the exclusion principle is probably consistent down to much smaller lengths or up to much higher energies.”

The Naturalness Strategy

Param	UV sensitivity	Natural if	NP	Scale	Natural?
m_e	$e^2 \Lambda$	$\Lambda \lesssim 5 \text{ MeV}$	Positron	511 keV	✓
$m_{\pi^\pm}^2 - m_{\pi^0}^2$	$\frac{3\alpha}{4\pi} \Lambda^2$	$\Lambda \lesssim 850 \text{ MeV}$	Rho	775 MeV	✓
$m_{K_L} - m_{K_S}$	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4} \Lambda^2$	$\Lambda \lesssim 2 \text{ GeV}$	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2} \Lambda^2 + \dots$	$\Lambda \lesssim 500 \text{ GeV}$?	?	?

Quadratic sensitivity of m_H^2 makes it a promising target for predictions.

From the “naturalness strategy” to new physics

At this level, we expect

- New physics around the TeV scale...
- ...coupling to the Higgs

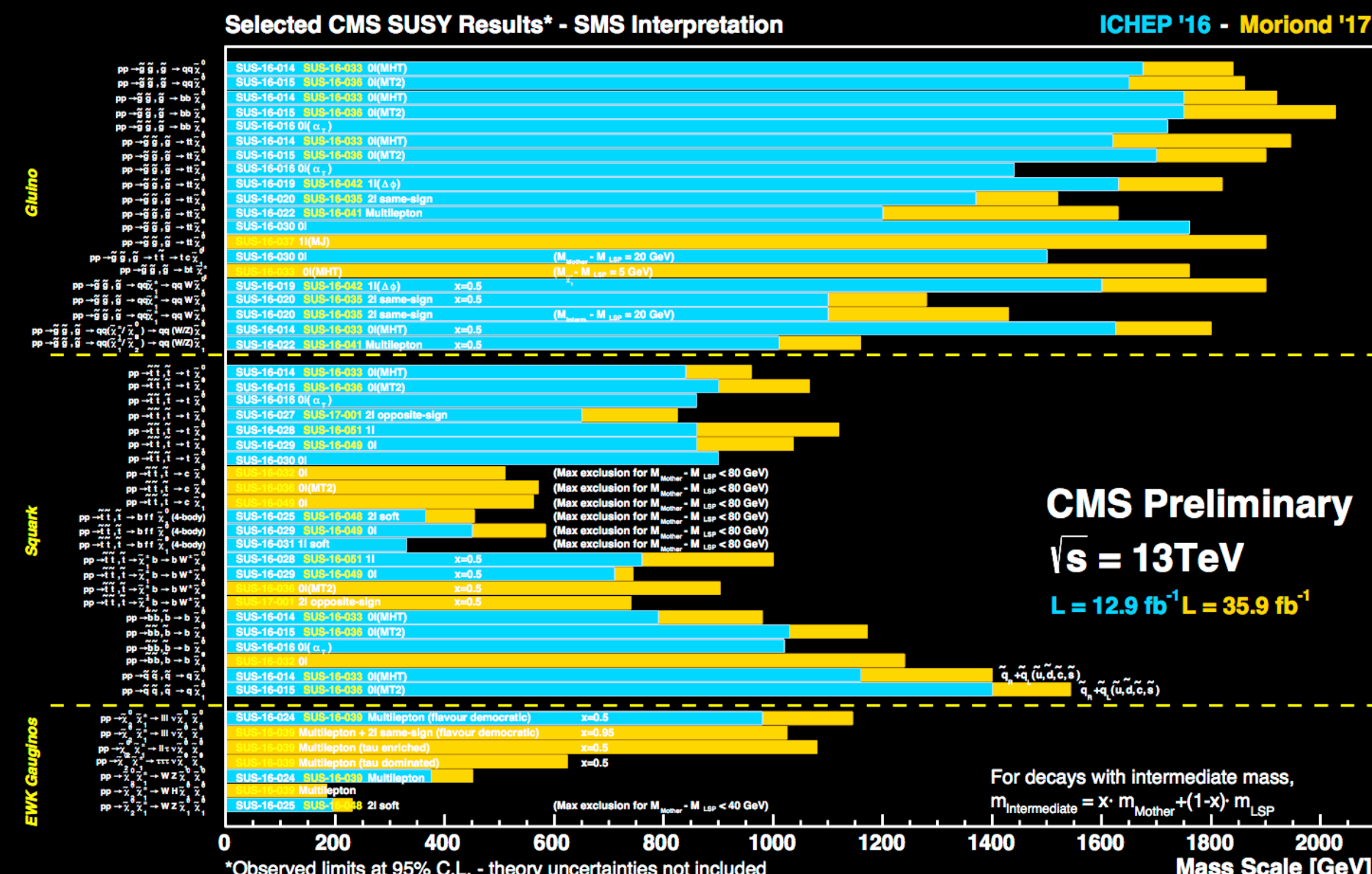
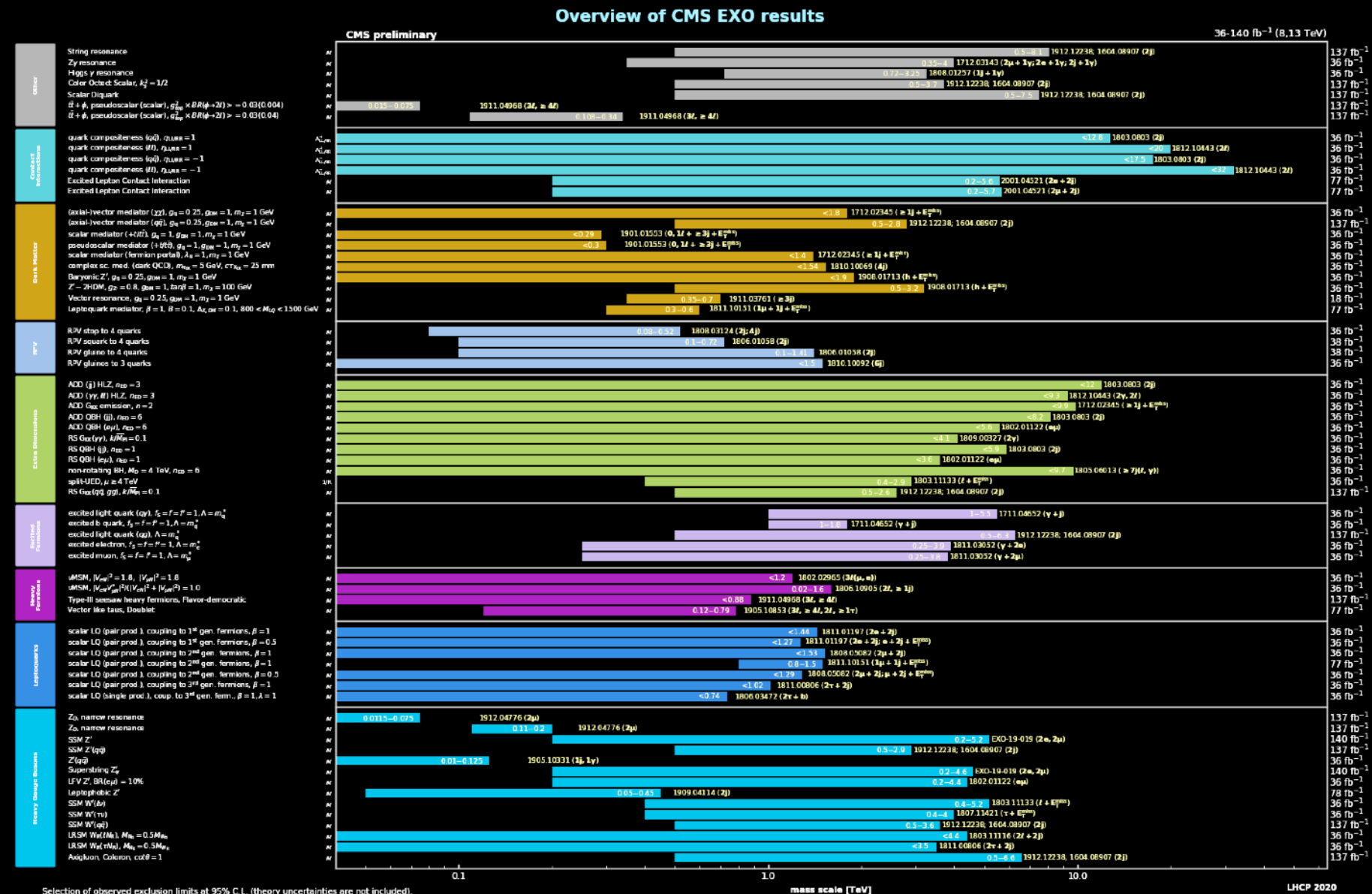
Strong motivation for beyond-the-Standard Model physics connected to Higgs! But maybe too broad to be useful guidance to experiment.

To make further progress, we come up with models.

Easiest path: work by analogy with known examples.

Supersymmetry: Relate Higgs to a fermion, *a la* electron.

Compositeness: Higgs is a composite particle, *a la* the pion.



But thus far...

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
 Status: May 2020

Model	ℓ, γ	Jets†	E _{miss}	ℒ dt [fb ⁻¹]	Limit	Reference	
Extra dimensions	ADD G _{KK} + g/q	0 e, μ	1-4 J	Yes	36.1	M _{Pl} mass 7.7 TeV	
	ADD non-resonant γγ	2 γ	-	-	36.7	M _{Pl} mass 8.6 TeV	
	ADD QBH	-	2 J	-	37.0	M _{Pl} mass 8.9 TeV	
	ADD BH high ∑ pr	≥ 1 e, μ	≥ 2 J	-	3.2	M _{Pl} mass 8.2 TeV	
	ADD BH multilepton	2 e, μ	≥ 3 J	-	2.6	M _{Pl} mass 9.55 TeV	
	RS1 G _{KK} → γγ	2 γ	-	-	36.7	G _{KK} mass 4.1 TeV	
	Bulk RS G _{KK} → WW/ZZ	multi-channel	-	-	36.1	G _{KK} mass 2.3 TeV	
	Bulk RS G _{KK} → WV → ℓνqq	1 e, μ	2 J / 1 J	Yes	199	G _{KK} mass 2.0 TeV	
	Bulk RS G _{KK} → tt	1 e, μ	≥ 1 b, ≥ 1 J/2 J	Yes	36.1	G _{KK} mass 3.8 TeV	
	ZUED / RPP	1 e, μ	≥ 2 b, ≥ 3 J	Yes	36.1	G _{KK} mass 1.8 TeV	
Gauge bosons	SSM Z' → ℓℓ	2 e, μ	-	-	199	Z' mass 5.1 TeV	
	SSM Z' → ττ	2 τ	-	-	36.1	Z' mass 2.42 TeV	
	Leptophobic Z' → bb	0 e, μ	2 b	-	36.1	Z' mass 2.1 TeV	
	Leptophobic Z' → tt	0 e, μ	≥ 1 b, ≥ 2 J	Yes	199	Z' mass 4.1 TeV	
	SSM W' → ℓν	1 e, μ	-	Yes	199	W' mass 6.8 TeV	
	SSM W' → τν	1 τ	-	Yes	36.1	W' mass 3.7 TeV	
	HVT W' → WZ → ℓνqq model B	1 e, μ	2 J / 1 J	Yes	199	W' mass 4.3 TeV	
	HVT W' → WV → qq̄qq model B	multi-channel	-	-	36.1	W' mass 3.8 TeV	
	HVT W' → WH/ZH model B	multi-channel	-	-	36.1	W' mass 2.93 TeV	
	HVT W' → WH/ZH model B	0 e, μ	≥ 1 b, ≥ 2 J	Yes	199	W' mass 3.2 TeV	
CI	CI qq̄q	2 e, μ	≥ 1 J	-	37.0	A mass 21.8 TeV	
	CI ℓℓqq	2 e, μ	-	-	199	A mass 35.8 TeV	
	CI tt̄tt̄	≥ 1 e, μ	≥ 1 b, ≥ 1 J	Yes	36.1	A mass 2.57 TeV	
	DM	Axial-vector mediator (Dirac DM)	0 e, μ	1-4 J	Yes	36.1	m _{DM} mass 1.58 TeV
		Colored scalar mediator (Dirac DM)	0 e, μ	1-4 J	Yes	36.1	m _{DM} mass 1.97 TeV
		VV _χ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 J	Yes	3.2	M _χ mass 700 GeV
		Scalar reson. φ → τχ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m _φ mass 3.4 TeV
	LO	Scalar LQ 1 st gen	1-2 e	≥ 2 J	Yes	36.1	LQ mass 1.4 TeV
		Scalar LQ 2 nd gen	1-2 e	≥ 2 J	Yes	36.1	LQ mass 1.58 TeV
		Scalar LQ 3 rd gen	2 τ	2 b	-	36.1	LQ mass 1.03 TeV
Scalar LQ 3 rd gen		0-1 e, μ	2 b	Yes	36.1	LQ mass 870 GeV	
Heavy quarks	VLQ TT → Ht/Zt/Wb + X	multi-channel	-	-	36.1	T mass 1.37 TeV	
	VLQ BB → Wt/Zb + X	multi-channel	-	-	36.1	B mass 1.34 TeV	
	VLQ T _{3/3} T _{3/3} → Wt + X	2(SS) ≥ 3 e, μ, ≥ 1 b, ≥ 1 J	Yes	36.1	T _{3/3} mass 1.64 TeV		
	VLQ V → Wb + X	1 e, μ, ≥ 1 b, ≥ 1 J	Yes	36.1	Y mass 1.85 TeV		
Excited fermions	Excited quark q* → qq	-	1 J	-	139	q* mass 6.7 TeV	
	Excited quark q* → qγ	1 γ	1 J	-	36.7	q* mass 5.3 TeV	
	Excited quark b* → bg	-	1 b, 1 J	-	20.3	b* mass 2.5 TeV	
	Excited lepton ℓ*	3 e, μ, τ	-	-	20.3	ℓ* mass 1.8 TeV	
Other	Type III Seesaw	1 e, μ	≥ 2 J	Yes	79.8	N _ν mass 560 GeV	
	LRSM Majorana ν	2 μ	2 J	-	36.1	N _ν mass 3.2 TeV	
	Higgs triplet H ^{±±} → ℓℓ	2, 3, 4 e, μ (SS)	-	-	36.1	H ^{±±} mass 870 GeV	
	Higgs triplet H ^{±±} → ℓτ	3 e, μ, τ	-	-	20.3	H ^{±±} mass 400 GeV	

ATLAS SUSY Searches* - 95% CL Lower Limits
 July 2020

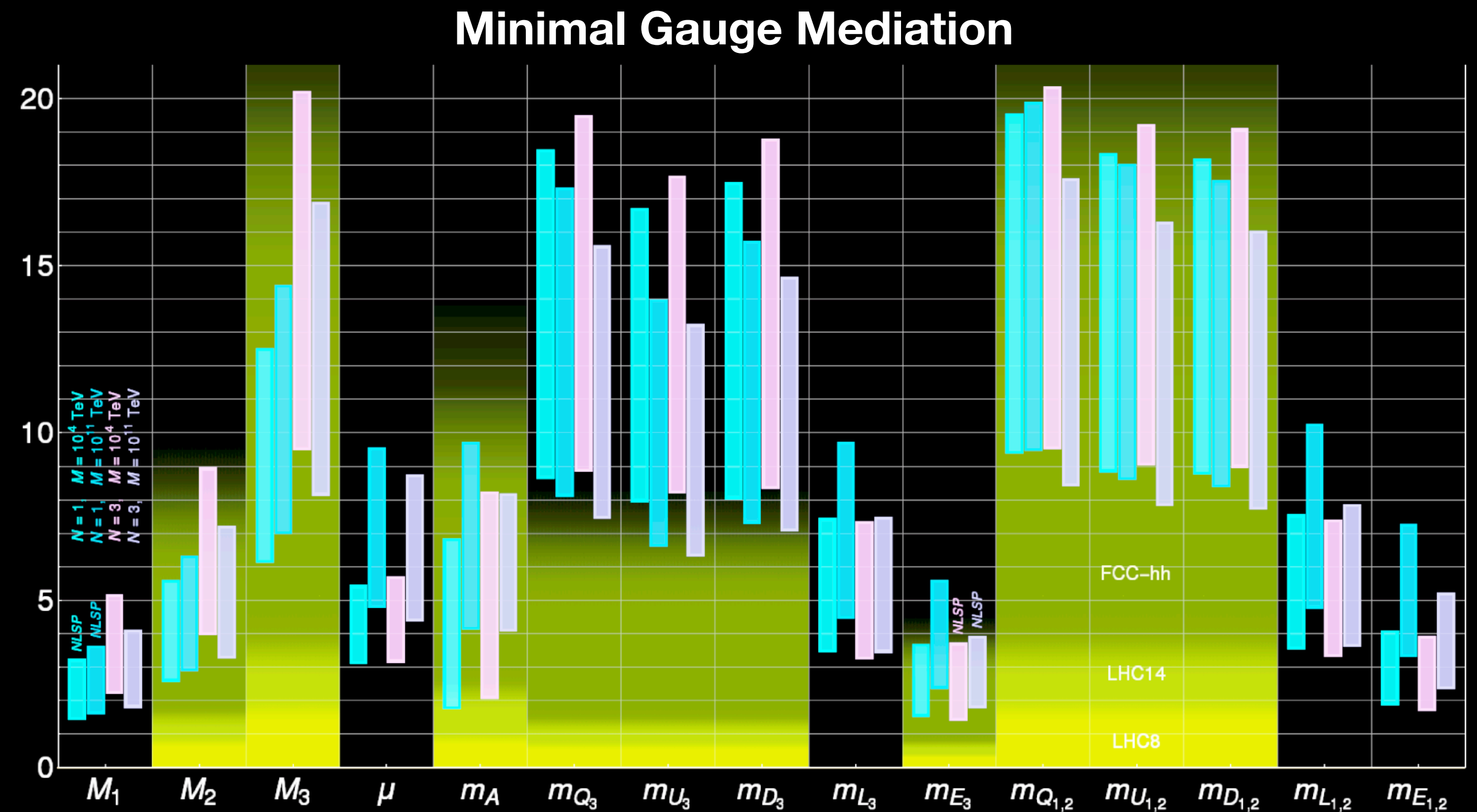
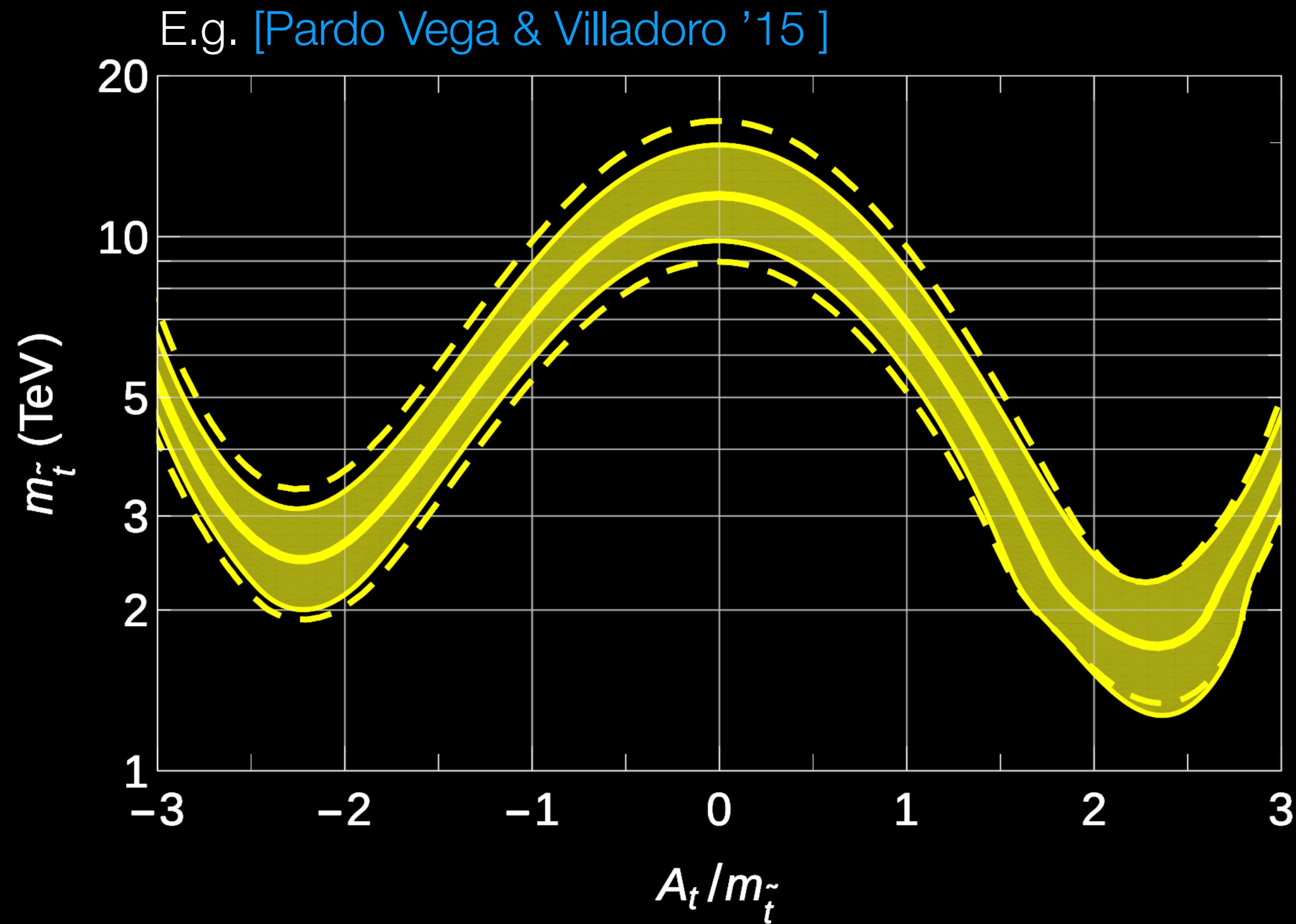
Model	Signature	ℒ dt [fb ⁻¹]	Mass limit	Reference	
Inclusive Searches	q̄q, q-qq̄	0 e, μ	2-6 jets	199	m _{χ̄₁⁰} = 420 GeV
	mono-jet	1-3 jets	ℓ ^{miss}	36.1	m _{χ̄₁⁰} = 5 GeV
	2-6 jets	ℓ ^{miss}	199	m _{χ̄₁⁰} = 0 GeV	
	3-6 jets	ℓ ^{miss}	199	m _{χ̄₁⁰} = 1000 GeV	
	1 e, μ	2-6 jets	199	m _{χ̄₁⁰} = 650 GeV	
	ee, μμ	2 jets	199	m _{χ̄₁⁰} = 50 GeV	
	0 e, μ	7-11 jets	199	m _{χ̄₁⁰} = 650 GeV	
	SS e, μ	6 jets	199	m _{χ̄₁⁰} = 200 GeV	
	0-1 e, μ	3 jets	79.8	m _{χ̄₁⁰} = 200 GeV	
	SS e, μ	6 jets	199	m _{χ̄₁⁰} = 300 GeV	
3 rd gen squarks direct production	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 300 GeV, BR(b ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 200 GeV, BR(t ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 300 GeV, BR(b ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 200 GeV, BR(t ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 300 GeV, BR(b ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 200 GeV, BR(t ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 300 GeV, BR(b ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 200 GeV, BR(t ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 300 GeV, BR(b ₁ χ̄ ₁ ⁰) = 1	
	b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 200 GeV, BR(t ₁ χ̄ ₁ ⁰) = 1	
b ₁ b ₁ , b ₁ -bb̄, t ₁ t ₁	Multiple	199	m _{χ̄₁⁰} = 300 GeV, BR(b ₁ χ̄ ₁ ⁰) = 1		
EW direct	χ̄ ₁ [±] χ̄ ₁ [±] via WZ	3 e, μ	≥ 1 jet	199	m _{χ̄₁[±]} = 1 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via WW	ee, μμ	≥ 1 jet	199	m _{χ̄₁[±]} = 5 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via Wb	2 e, μ	1 jet	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via Wτ	0-1 e, μ	2 h/2 γ	199	m _{χ̄₁[±]} = 70 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓℓ	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓτ	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓν	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓν	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓν	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓν	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV
Long-lived particles	Direct χ̄ ₁ [±] χ̄ ₁ [±] prod., long-lived χ̄ ₁ [±]	Disapp. trk	1 jet	36.1	m _{χ̄₁[±]} = 100 GeV
	Stable β R-hadron	Multiple	36.1	m _{χ̄₁[±]} = 100 GeV	
	Metastable β R-hadron, β → qq̄ℓ	Multiple	36.1	m _{χ̄₁[±]} = 100 GeV	
	χ̄ ₁ [±] χ̄ ₁ [±] via WZ	3 e, μ	≥ 1 jet	199	m _{χ̄₁[±]} = 100 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via WW	ee, μμ	≥ 1 jet	199	m _{χ̄₁[±]} = 5 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via Wb	2 e, μ	1 jet	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via Wτ	0-1 e, μ	2 h/2 γ	199	m _{χ̄₁[±]} = 70 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓℓ	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓτ	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV
	χ̄ ₁ [±] χ̄ ₁ [±] via ℓν	2 e, μ	0 jets	199	m _{χ̄₁[±]} = 0 GeV

*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 (L).

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.

Higgs Mass vs. Naturalness

Perhaps the observed Higgs mass is simply a sign that the naturalness strategy is imperfect.
E.g. in minimal SUSY frameworks the Higgs mass predicts phenomena consistent w/ data.





Possible Paths

The goal is to predict the Higgs mass. Naturalness is a promising strategy (and the one nature has repeatedly chosen), but there are also principled frameworks explaining why it might appear to fail.

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- **Un-effectiveness:** $m_H^2 \sim m_{UVIR}^2$
(**modular invariance**, **quantum gravity**, ...)

The Value of Being Wrong

All but one prediction for the Higgs mass will be wrong, but even wrong predictions profoundly broaden our horizons.

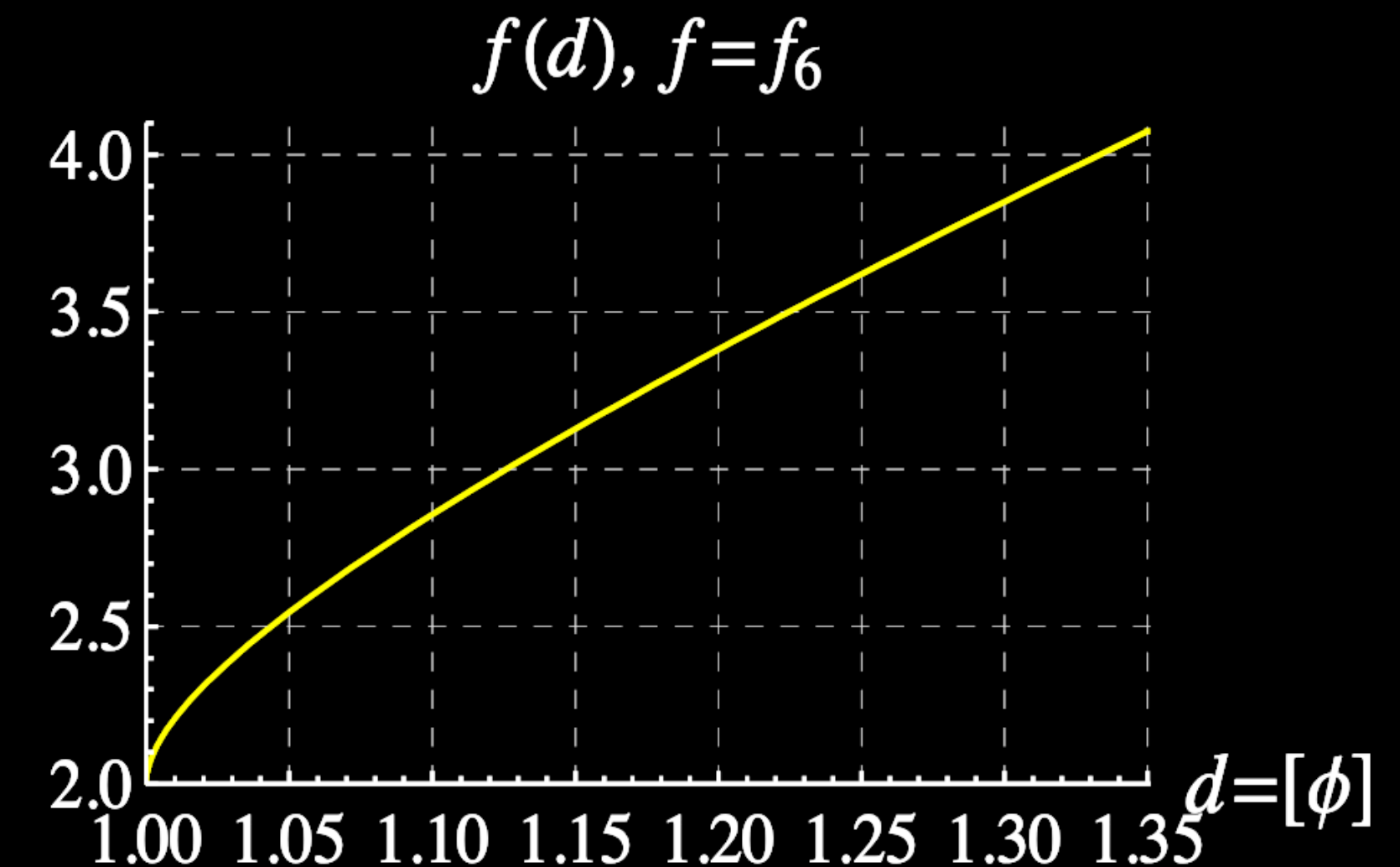
For example...

Conformal technicolor [Luty, Okui '04]: Tension between hierarchy problem ($\mathcal{O}^\dagger \mathcal{O}$) and flavor ($\mathcal{O}ff\bar{f}$) can be avoided if

$$\Delta_{\mathcal{O}} \sim 1 + \epsilon \quad \Delta_{\mathcal{O}^\dagger \mathcal{O}} \gg 2$$

[Rattazzi, Rychkov, Tonni, Vichi '08]: revive the conformal bootstrap to constrain scaling dimensions using unitarity, OPE, crossing symmetry.

$$\sum_i \begin{array}{c} 1 & & 4 \\ & \diagdown & / \\ & \mathcal{O}_i & \\ & / & \diagdown \\ 2 & & 3 \end{array} = \sum_i \begin{array}{c} 1 & & 4 \\ & / & \diagdown \\ & \mathcal{O}_i & \\ & \diagdown & / \\ 2 & & 3 \end{array}$$

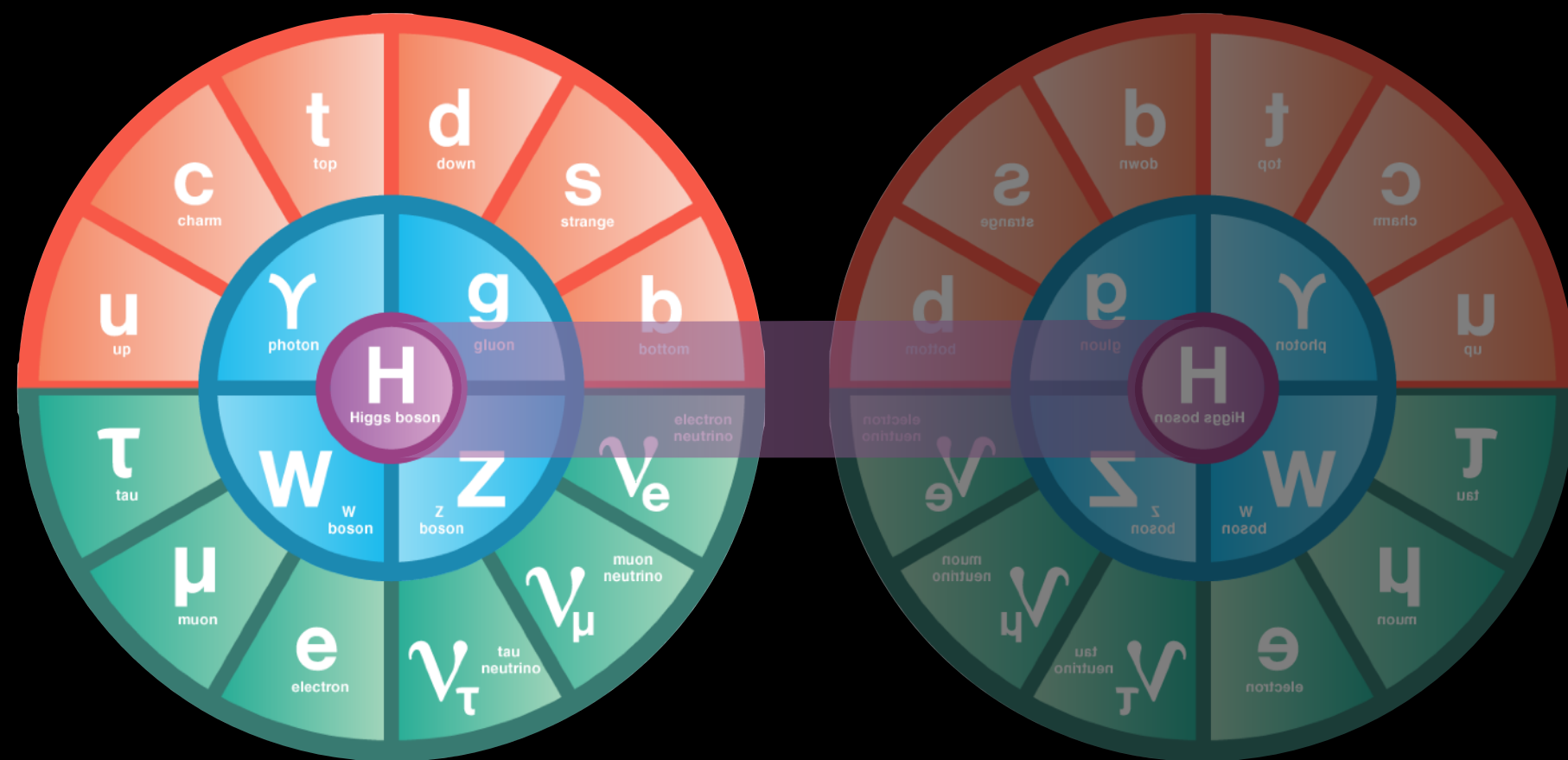


Possible Paths

Discrete symmetries

[Chacko, Goh, Harnik '05, ...]

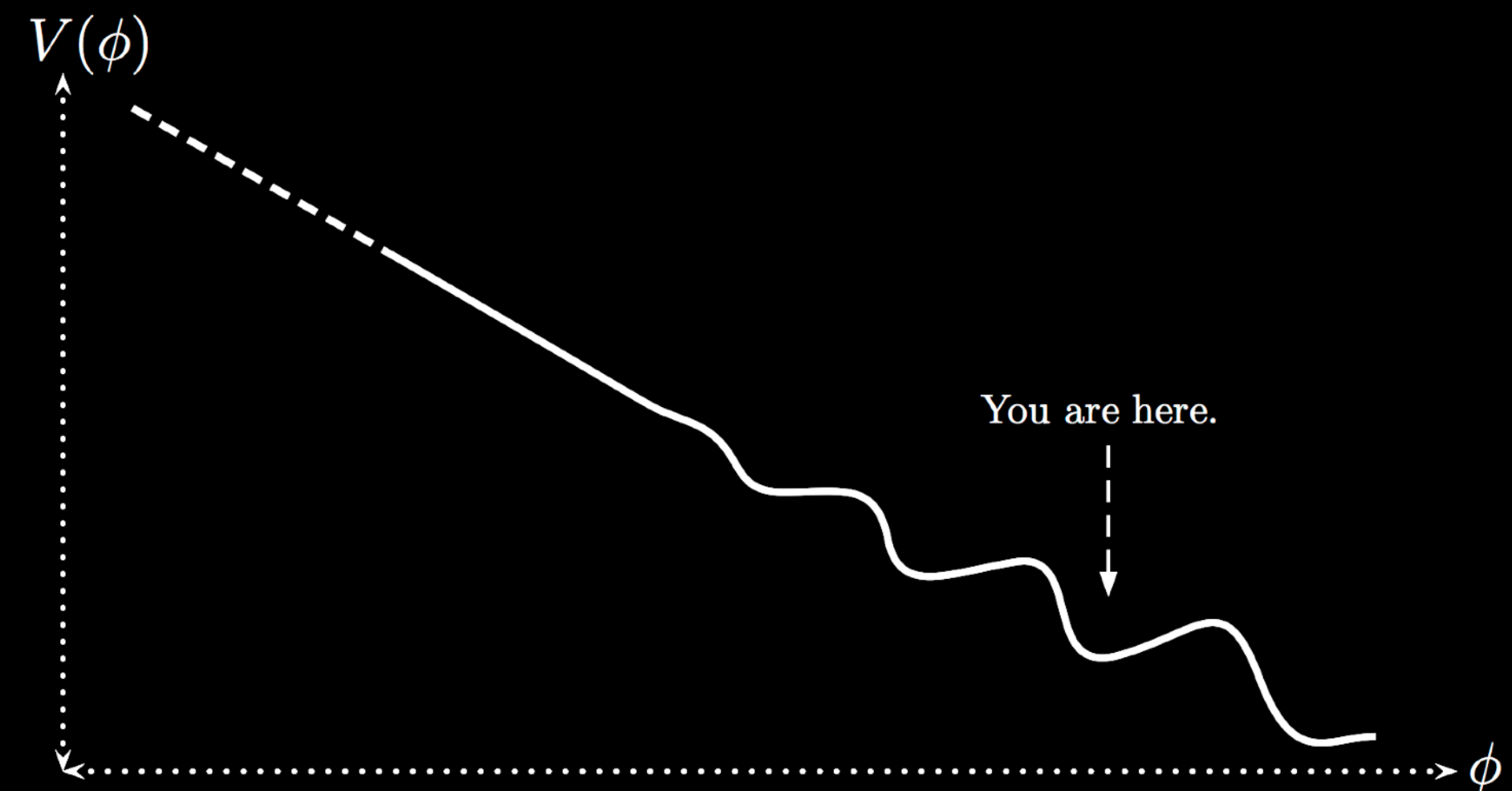
Discrete symmetries relate the Standard Model to mirror copies; new physics at the weak scale is SM-neutral



Cosmological Relaxion

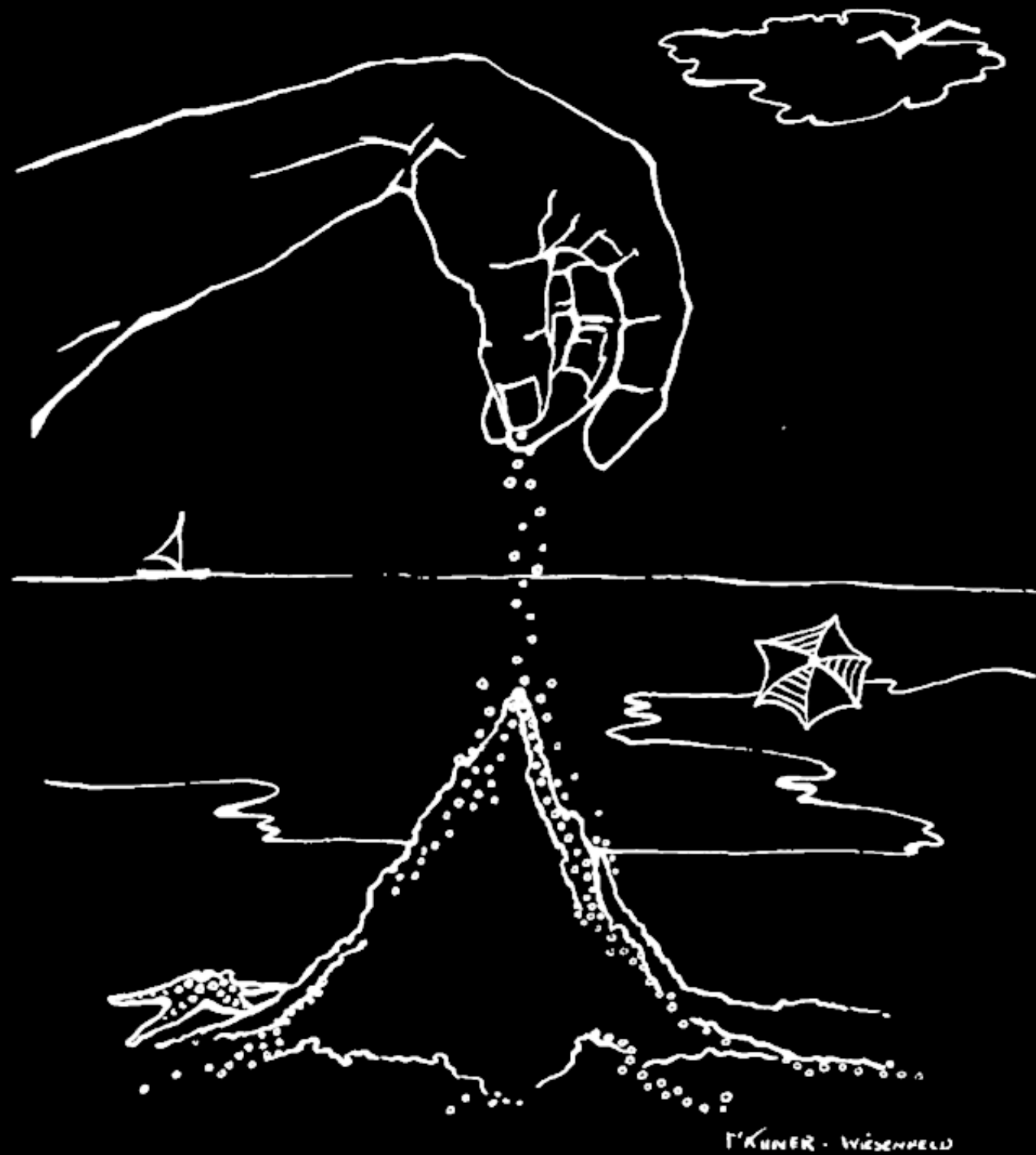
[Dvali, Vilenkin '03; Dvali '04; Graham, Kaplan, Rajendran '15, ...]

Higgs mass scans due to cosmological evolution of a light field; stops when Higgs mass passes through ~zero.

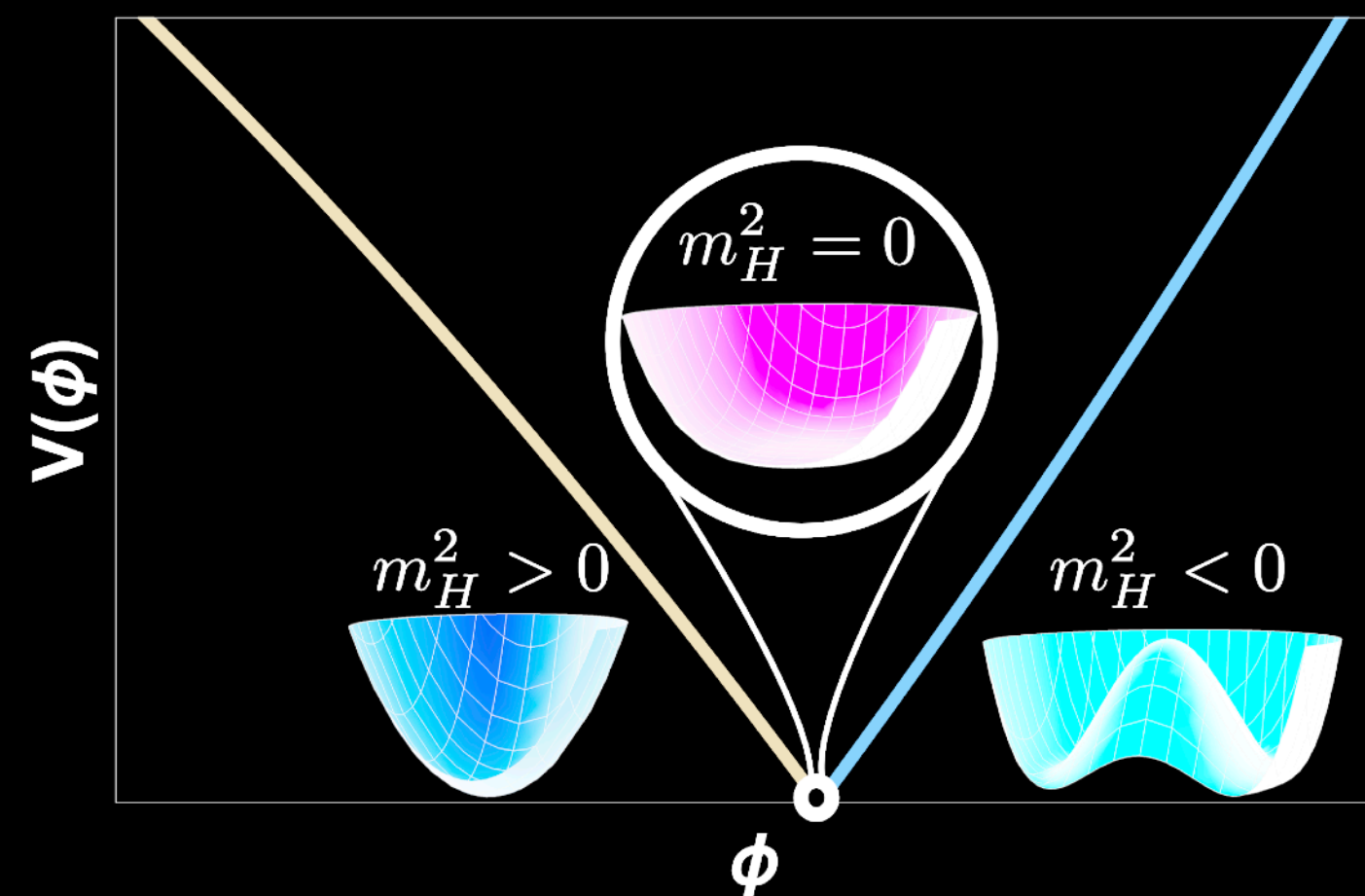


Self-Organized Criticality

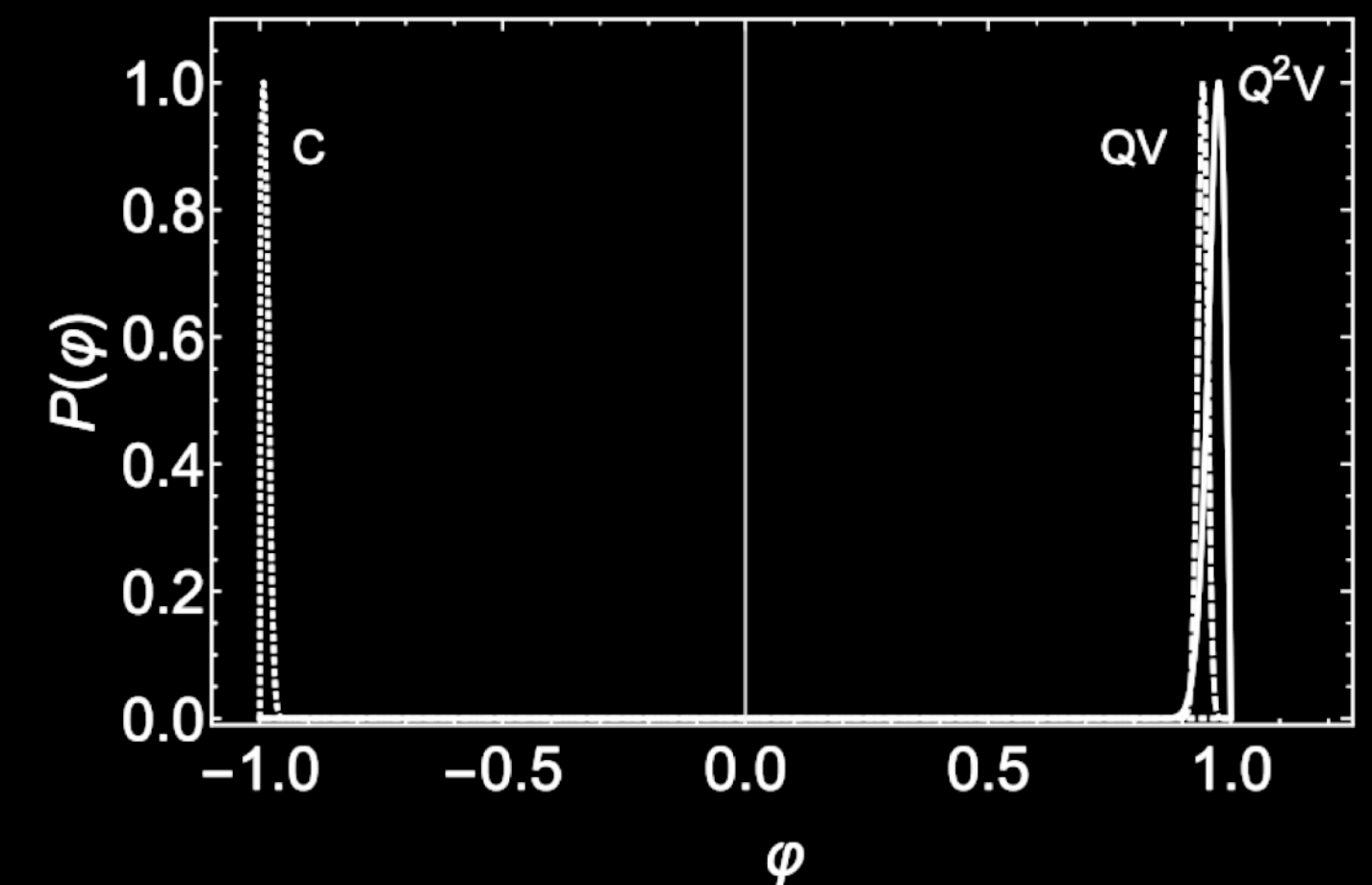
Some systems evolve into critical states on their own (sandpiles, *a la* [Bak, Tang, Wiesenfeld '84]
Lessons for the weak scale? [Giudice '08]



Vanishing Higgs mass coinciding with potential minimum for an extra-dimensional modulus field [Eroencil, Hubisz, Rigo '18]



Localization of scalar fields exponentially close to critical points during eternal inflation [Giudice, McCullough, You '21]
[Khoury et al. '19-'20]

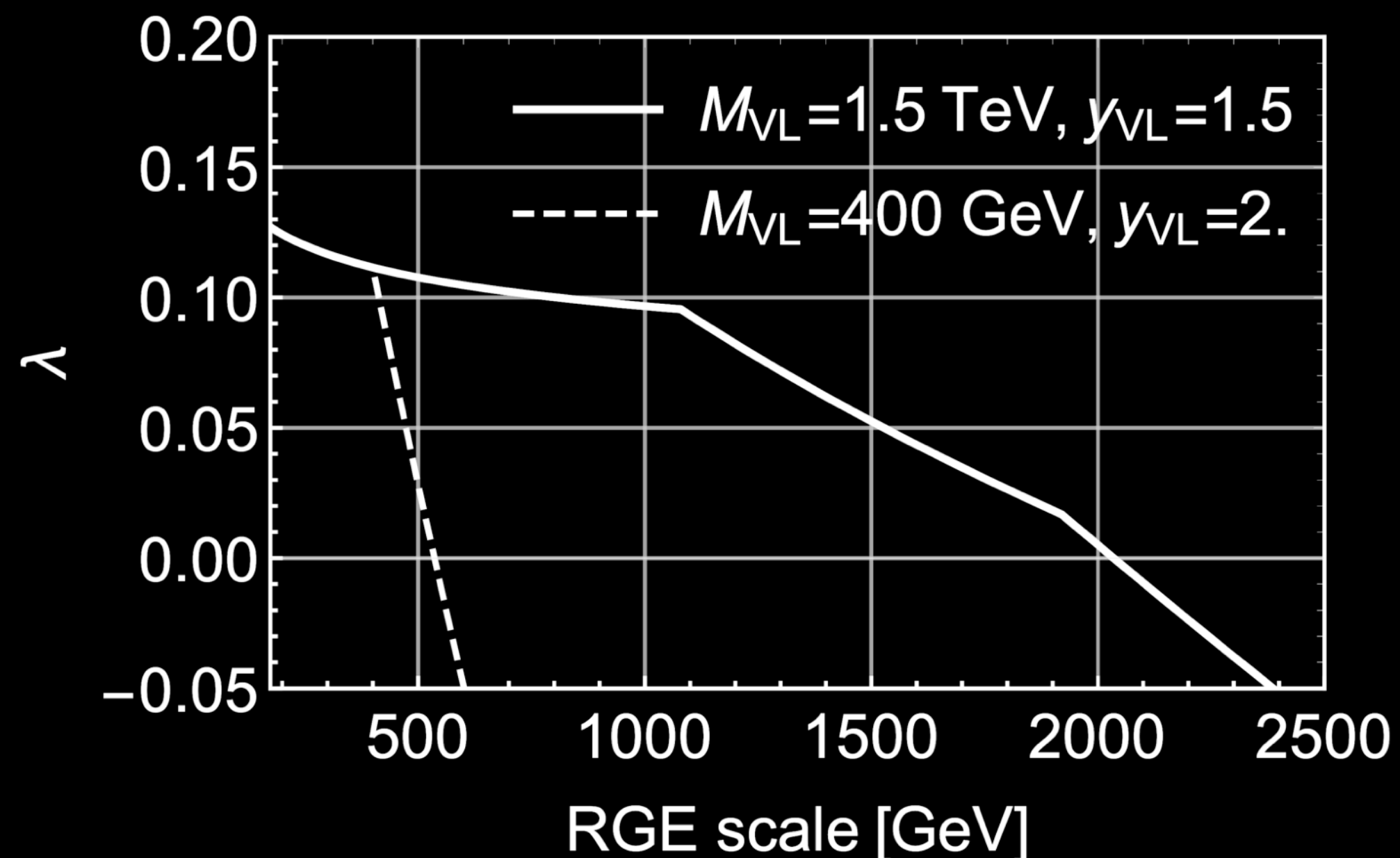


Self-Organized Localization

SOL unsuited to explaining proximity to boundary between broken & unbroken phases, but can explain proximity to a point at which two broken phase vacua cease to coexist.

E.g. in SM, second vacuum created by instability of Higgs potential associated w/ a scale $\lambda(\Lambda_I) = 0$

$$\Rightarrow v \sim \Lambda_I$$



The problem: in SM alone, $\Lambda_I \sim 10^{10} - 10^{12}$ GeV

The solution: lower Λ_I with new light states coupling strongly to the Higgs

E.g. vector-like SU(2) doublet and singlet leptons w/

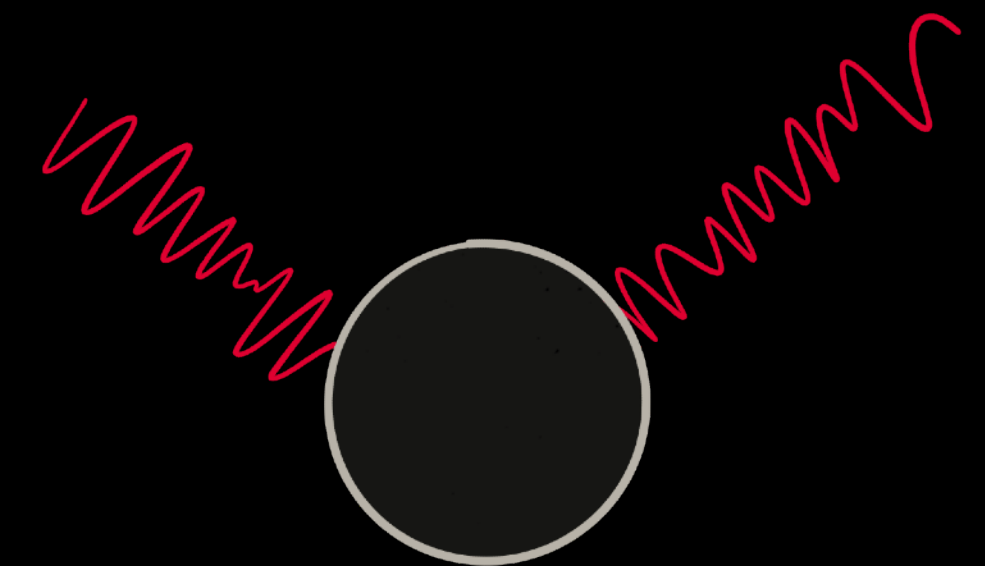
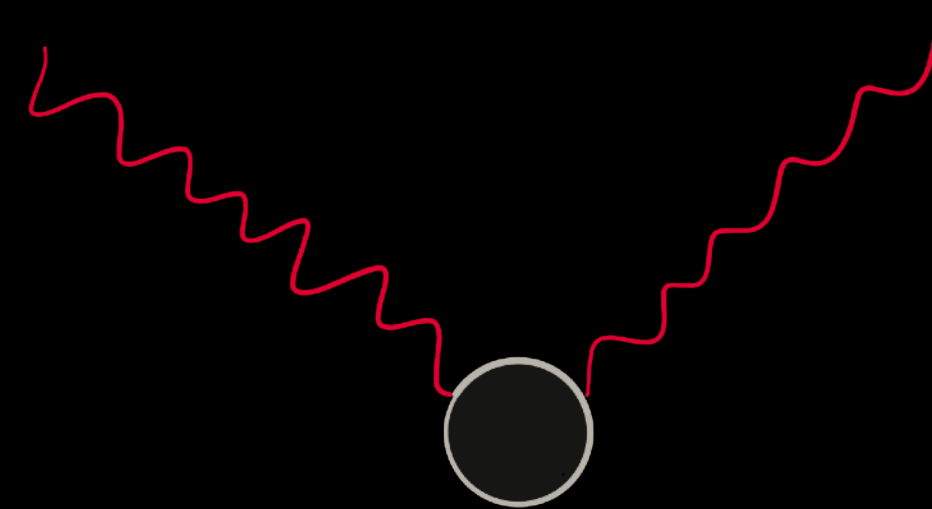
$$\mathcal{L} = -y_{VL} \bar{\psi} \chi H + \text{h.c.}$$

Un-effectiveness

Essential feature of the hierarchy problem: the UV doesn't know about the IR
 ...unless it does?

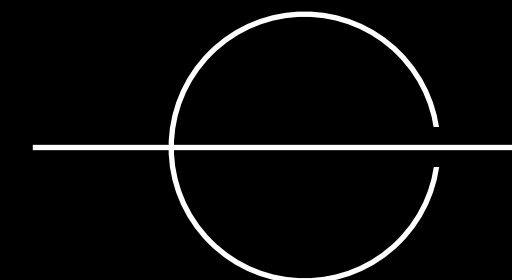
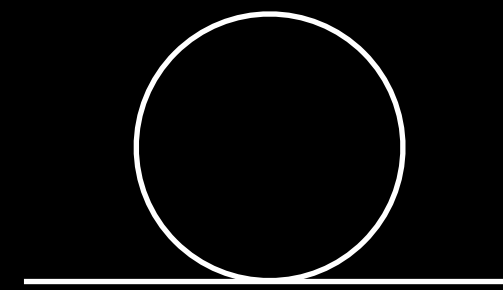
Two frameworks exhibiting UV/IR mixing:

Quantum gravity ...



...and **non-commutative QFT**.

E.g. [Minwalla, Seiberg, Van Raamsdonk '99];
 for hierarchy problem [NC, Koren '19]



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

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

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

Modular Invariance

[Dienes et al. '94-'01, Abel & Dienes '21 ...]

At heart, curing UV sensitivity is about controlling $\delta m_H^2 \sim (\text{Str} \mathcal{M}^0) \Lambda^2 + (\text{Str} \mathcal{M}^2) \log \Lambda + \dots$

For finite # of states $\text{Str} \mathcal{M}^{2\beta} \equiv \sum_{\text{states } i} (-1)^F (M_i)^{2\beta}$ Cancellations require degenerate boson/fermion pairs

For infinite # of states, suitably regularize: $\text{Str} \mathcal{M}^{2\beta} \equiv \lim_{y \rightarrow 0} \sum_{\text{states } i} (-1)^F (M_i)^{2\beta} e^{-y M_i^2}$

Then many *nondegenerate* spectra have vanishing supertraces

E.g. for masses $M_n = \sqrt{n} \mu$ and degeneracies g_n

$$g_n = \begin{cases} (-1)^n n^{2k} & \text{for any } k \in \mathbb{Z}^+ \\ (-1)^n (n^5 - n) & n \text{ even : bosons} \\ (-1)^n (n^5 + 2n^3) & n \text{ odd : fermions} \end{cases}$$

Generally satisfied when modular invariance controls the spectrum, degeneracies g_n given by the envelope of some suitable function $\Phi(n)$: string theory (SUSY or otherwise)

Nondecoupling corrections to Higgs properties?

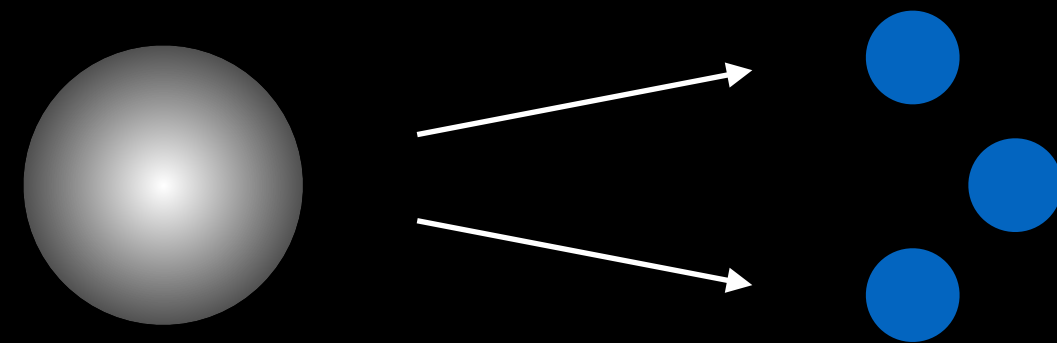
The Weak Gravity Conjecture

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

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

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

Thought experiment: consider BH of charge Q , mass M decaying to this particle



particles produced = Q/q

Energy conservation: $mQ/q < M$

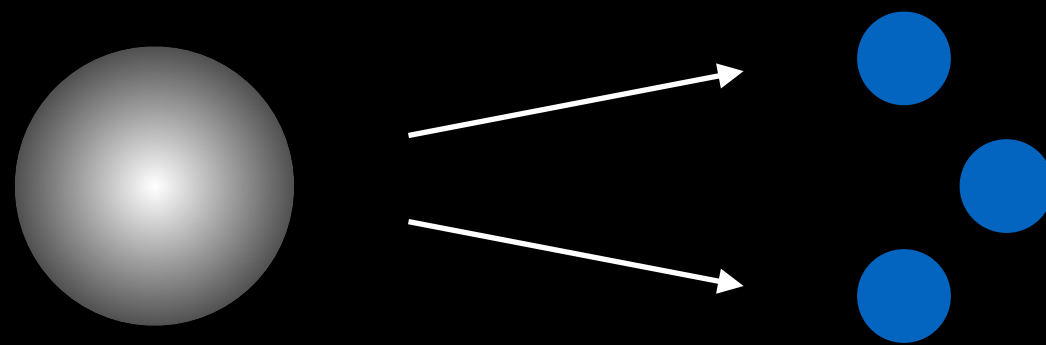
Then BH satisfies $Z = Q M_{Pl}/M < z = q M_{Pl}/m$

Extremal BH ($Z=1$) stable unless there exists a state with $z > 1$

$\Rightarrow q > m/M_{Pl}$ to avoid exactly stable black holes, remnants

Magnetic Weak Gravity Conjecture

Analogous argument for BHs carrying magnetic charge:



For monopole of size L ,
decay of extremal BH implies

$$m_{\text{mon}} \sim \frac{(2\pi/g)^2}{L} \lesssim \frac{2\pi}{g} M_{\text{Pl}}$$

$$\Rightarrow \Lambda \equiv L^{-1} \lesssim g M_{\text{Pl}}$$

*Note: cutoff need not imply appearance of quantum gravity,
only physics underlying monopole structure*

A Family of Conjectures

Electric WGC: [Arkani-Hamed, Motl, Nicolis, Vafa '07]	$m \leq (gq)M_{\text{Pl}}$
Magnetic WGC: [Arkani-Hamed, Motl, Nicolis, Vafa '07]	$\Lambda \lesssim gM_{\text{Pl}}$
+Scalar WGC: [Palti '17]	$m \leq \sqrt{g^2q^2 - \mu^2}M_{\text{Pl}}$
dS WGC: [Montero, Van Riet, Venken '19]	$m^2 \gtrsim gqM_{\text{Pl}}H$
Axion WGC: [Arkani-Hamed, Motl, Nicolis, Vafa '07]	$f \leq (1/S)M_{\text{Pl}}$

New hierarchies from field theory + gravity.

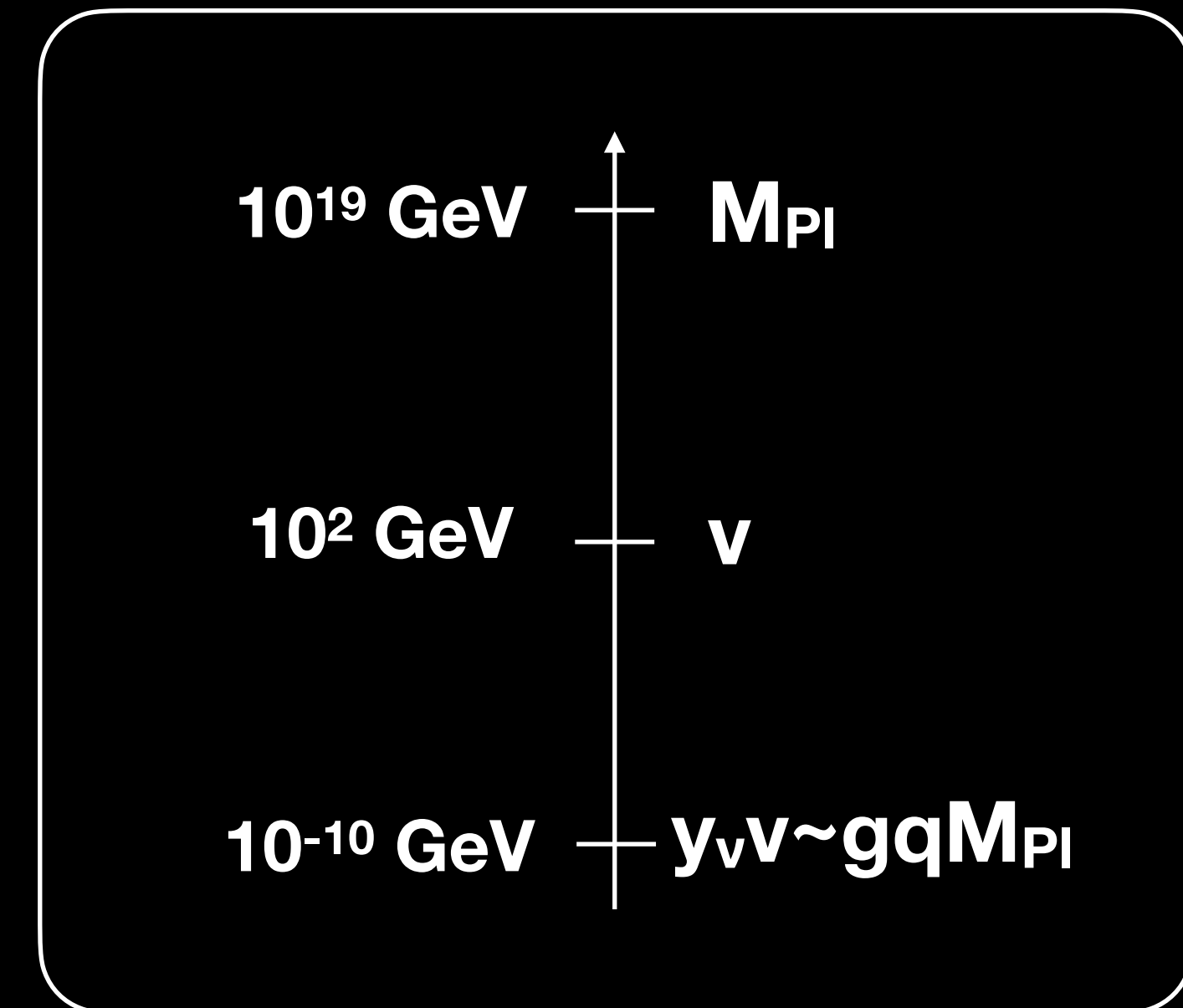
Recent review: [Harlow, Heidenreich, Reece, Rudelius '22]

Weak Gravity, Weak Scale?

[Cheung, Remmen '14]: Imagine the $U(1)_{B-L}$ symmetry of the Standard Model is an unbroken gauge symmetry (bounds from 5th force experiments require $gq \lesssim 10^{-24}$).

Anomaly free if we also add three right-handed neutrinos.

Neutrinos are Dirac particles! (no $0\nu\beta\beta$)



Neutrino mass from Higgs

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

If lightest neutrino is WGC particle,

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

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

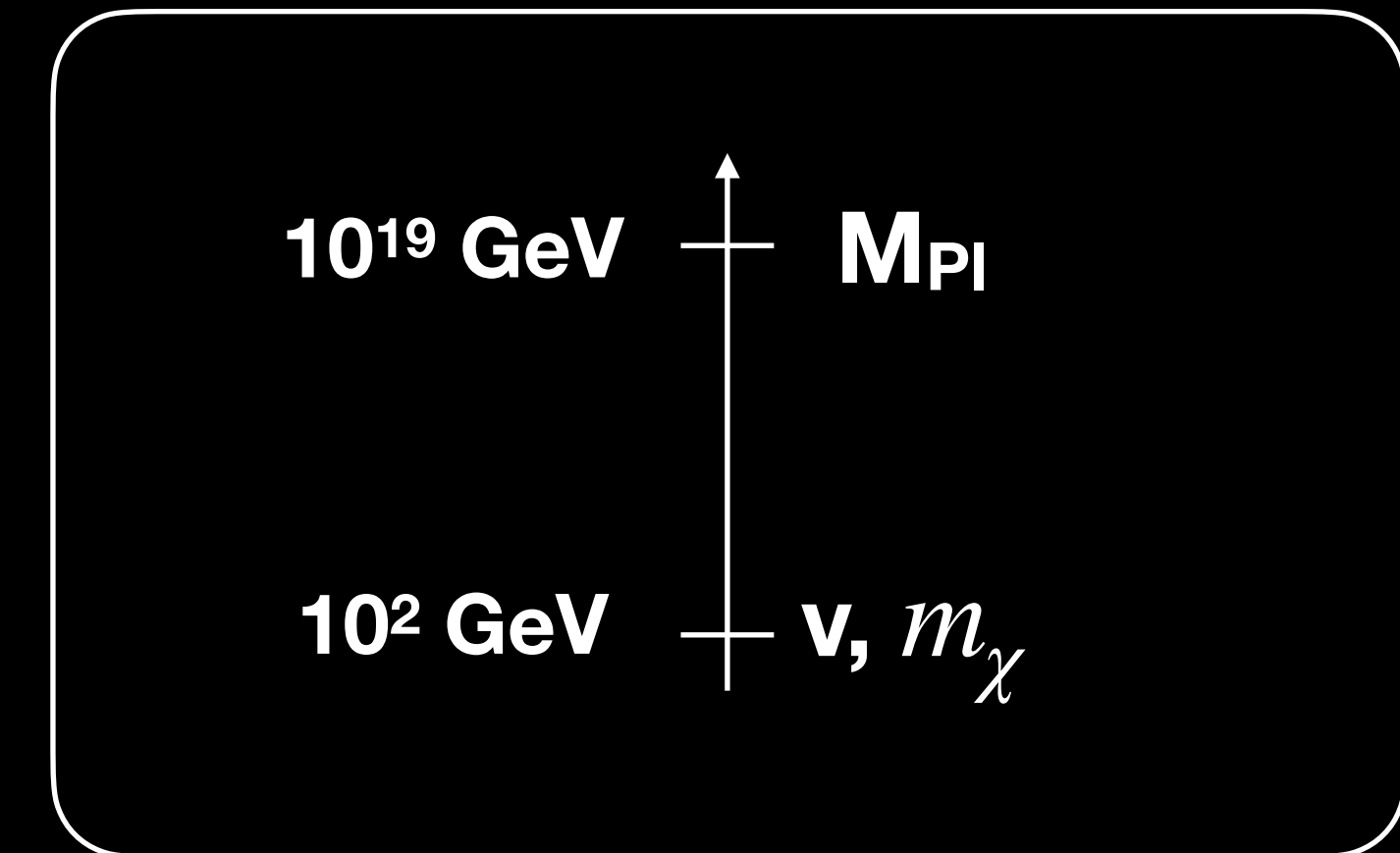
Weak Gravity, Weak Scale?

But Magnetic WGC says: cutoff near m_ν

Can m , Λ be raised to the weak scale?

Sure! [NC, Garcia Garcia, Koren '19]. Need :

1. A new U(1) gauge symmetry, not U(1)_{B-L}
2. Charged particles acquiring mass from the Higgs.



Simple option: new fermions like the lepton doublet L and right-handed neutrino N , plus conjugates L^c, N^c , and Yukawa interaction $yHLN^c$

Lightest mass eigenstate χ_1 is WGC particle. WGC bounds Higgs vev for fixed g, m_L, m_N, y . Expect new fermions around the weak scale, coupling to the Higgs boson.

Implications for Experiment

- **Naturalness:** $m_H^2 \sim m_{UV}^2$
Conventional & exotic collider signals;
Higgs properties as decisive probes.
- **Adjustment:** $m_H^2 \sim m_{UV}^2 + m_{IR}^2 \ll m_{UV}^2$
New particles coupling to the Higgs, at
or below the weak scale; N_{eff}, \dots
- **Unnaturalness:** $m_H^2 \sim \Sigma m_{UV}^2 \ll m_{UV}^2$
Varied, but often promising
cosmological signals (N_{eff}, \dots)
- **Un-effectiveness:** $m_H^2 \sim m_{UVIR}^2$
Higgs properties, spacetime
symmetries, ???

Looking forward...

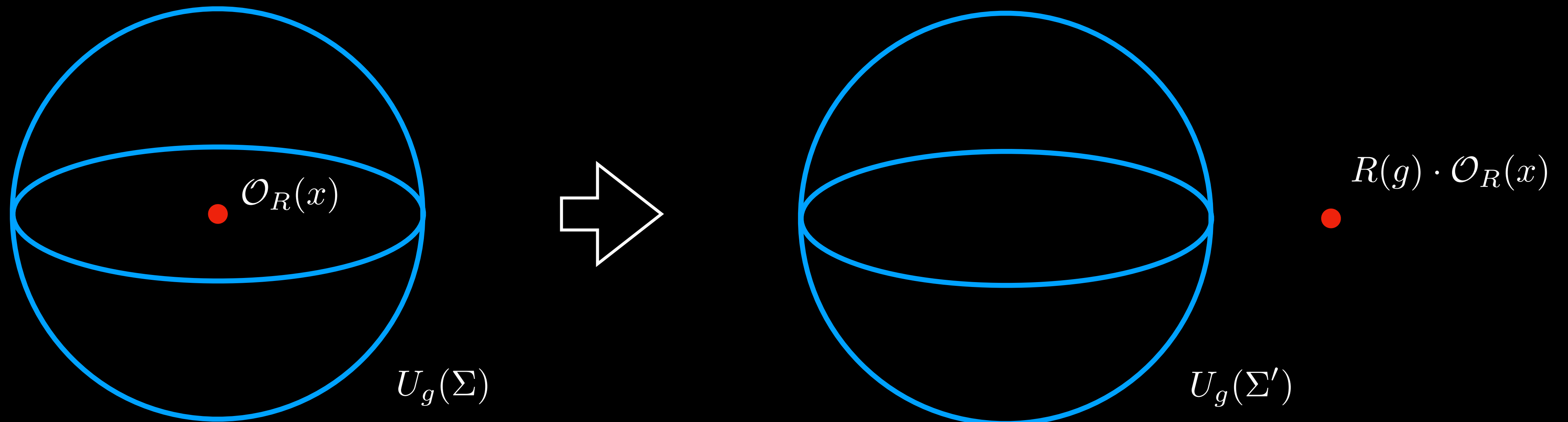


New perspective on old symmetries...

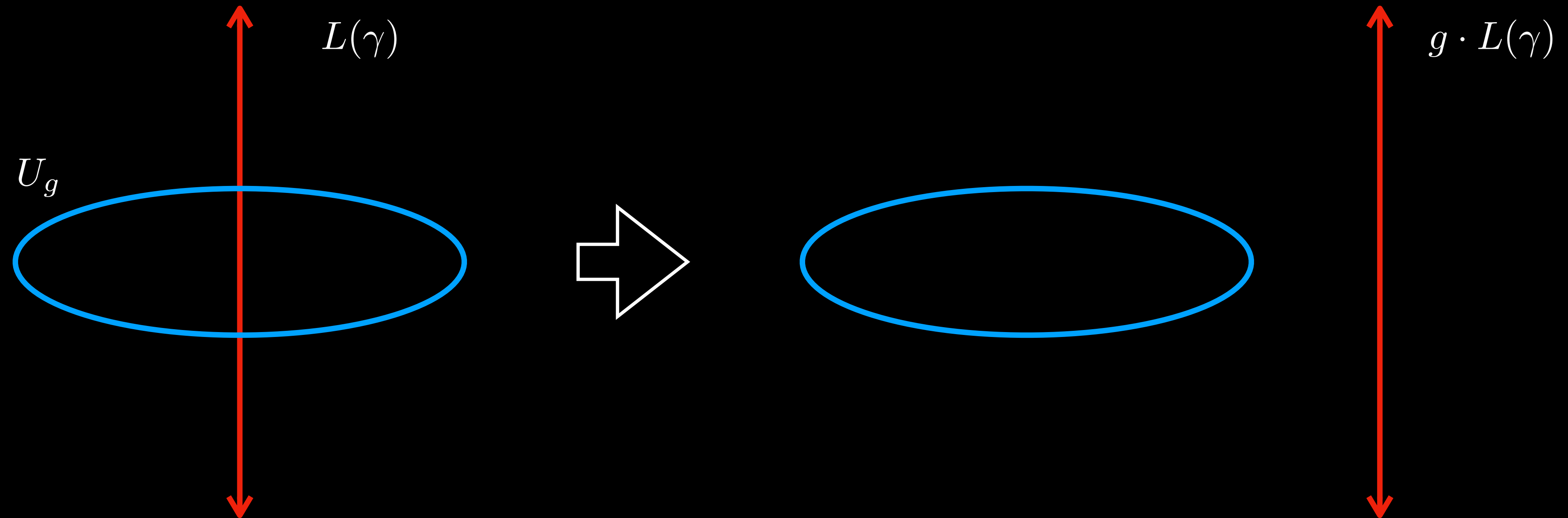
[Gaiotto, Kapustin, Sieberg, Willett '14; Aharony, Seiberg, Tachikawa '13; ...]

Symmetry defect operator $U_g(\Sigma_{d-1}) = \exp \left[i\alpha \int_{\Sigma} j^{\mu} \hat{n}_{\mu} \right]$

$$U_{g_1}(\Sigma) \cdot U_{g_2}(\Sigma) = U_{g_1 g_2}(\Sigma)$$



...leads to new symmetries



Pure U(1) gauge theory: 2 1-form symmetries

$$J^{\mu\nu}(x) \propto F^{\mu\nu}(x)$$

$$\tilde{J}^{\mu\nu}(x) \propto \tilde{F}^{\mu\nu}(x)$$

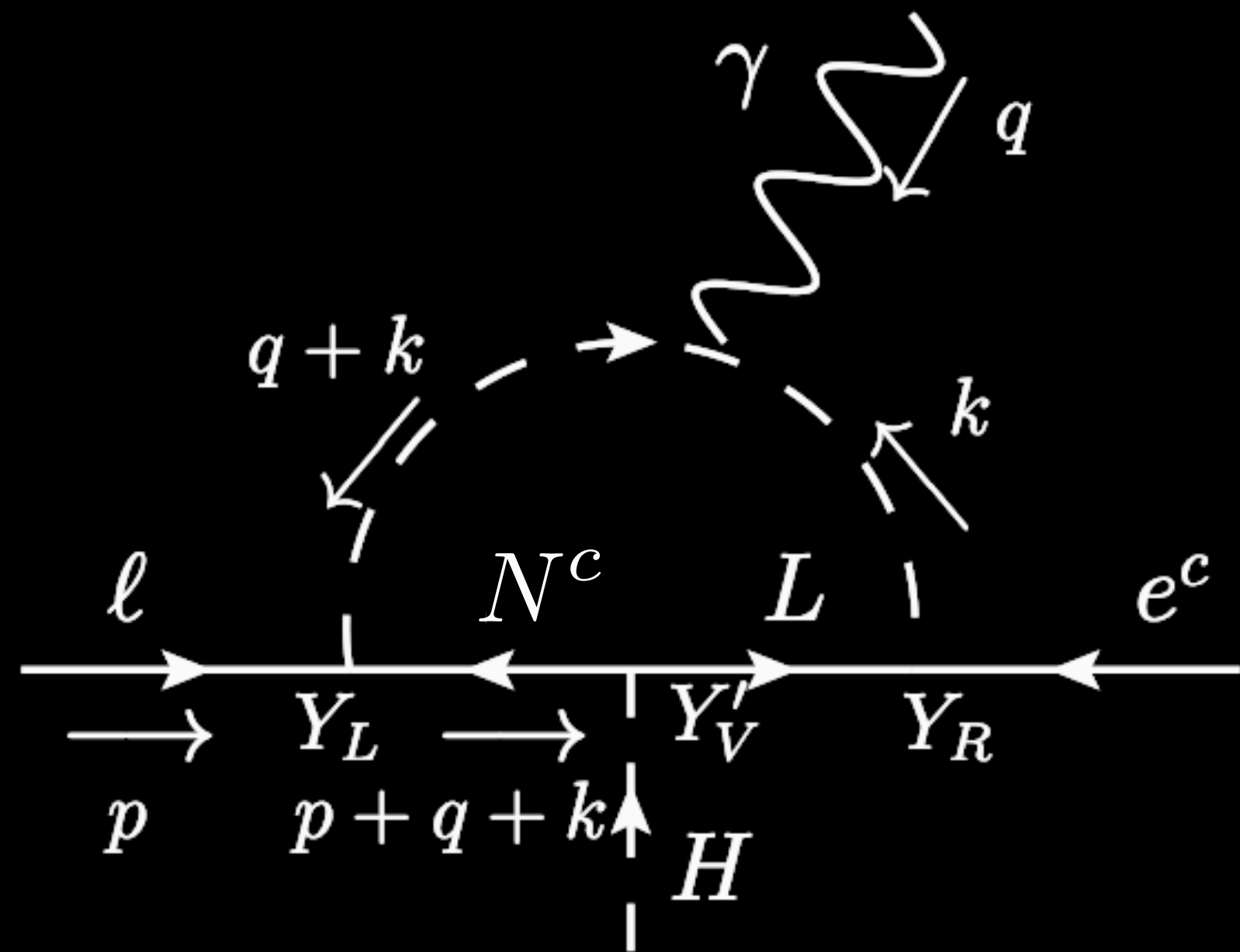
Spontaneous breaking in the Coulomb phase \rightarrow massless photon is the Goldstone (vector) boson

Properties of symmetry op.	Ordinary symmetry	Higher-form symmetry	Non-invertible symmetry
Codimension in spacetime	1	>1	≥1
Topological?	yes	yes	yes
Fusion rule	group $g_1 \times g_2 = g_3$	group $g_1 \times g_2 = g_3$	fusion ring $a \times b = \sum_c N_{ab}^c c$

See e.g. [Cordova, Dumitrescu, Intriligator, Shao '22]; pheno applications e.g. [Cordova, Hong, Koren, Ohmori '22; Cordova, Koren '22; ...]

Magic Zeroes & Hidden Symmetries

Surprises appear in the most prosaic places...



Expect: $\Delta a_\mu \sim \frac{y^3}{16\pi^2} \frac{m_\mu v}{M^2} + \mathcal{O}\left(\frac{m_\mu v^3}{M^4}\right)$

Calculate: $\Delta a_\mu \sim 0 + \frac{y^3}{16\pi^2} \frac{m_\mu v^3}{M^4} + \dots$

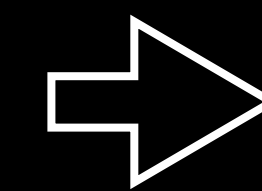
[Arkani-Hamed, Harigaya '21]

“Total derivative phenomenon”

$$\int_0^\infty \frac{dk^2}{k^2} k^2 f'(k^2)$$

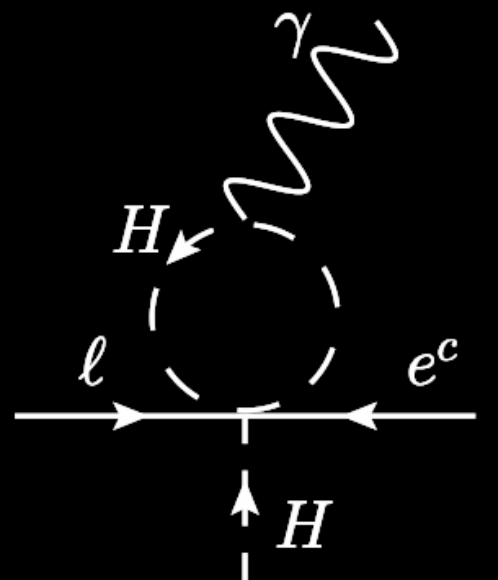
Zero can also be explained by (elaborate) symmetries [NC, Garcia Garcia, Vainshtein, Zhang '21] or on shell [Delle Rose, von Harling, Pomarol '22] but still leaves something of the form

$$\Delta a_\mu \propto A(m_1) + B(m_2) = 0$$



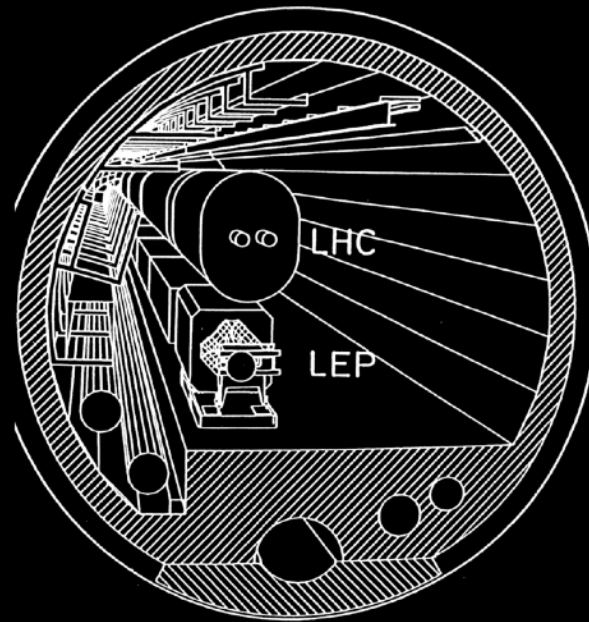
Between scales IR contribution nonzero

but $\Delta a_\mu = 0$



Closing thoughts

- We have a profound opportunity to “predict” the Higgs mass (i.e., to use the measured Higgs mass to infer other sharply defined phenomena).
- “Naturalness” often arises along the way, but exists in a broader context of predictive frameworks.
- While some approaches to this prediction are well-explored, others have only recently been discovered, and the search has only just begun.
- Even in failure, the worst we can do is deepen our understanding of QFT.
- The challenge is immense, but the greatest challenges have a tendency to catalyze the greatest progress.



LARGE HADRON COLLIDER
IN THE LEP TUNNEL

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PHYSICS WITH A MULTI-TeV HADRON COLLIDER

C.H. Llewellyn Smith,

Looking at the wide variety of alternatives which have been proposed, it might appear that theorists are in disarray but it seems to me that the present situation is an inevitable consequence of the successes of the 1970's. The problems of the 1960's - the nature of hadrons, the nature of the strong force, the nature of the weak force - have been solved. We now confront deeper problems - the origin of mass, the choice of fundamental building blocks (the problem of flavour), the question of further unification of forces including gravity, the origin of charge and of gauge symmetry. It is only to be expected that many of the first attempts to grapple with these problems will be misguided. As ever, we must reply on experiment to reveal the truth.

Thank you!

