

Naturalness at the 100 TeV scale

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However...

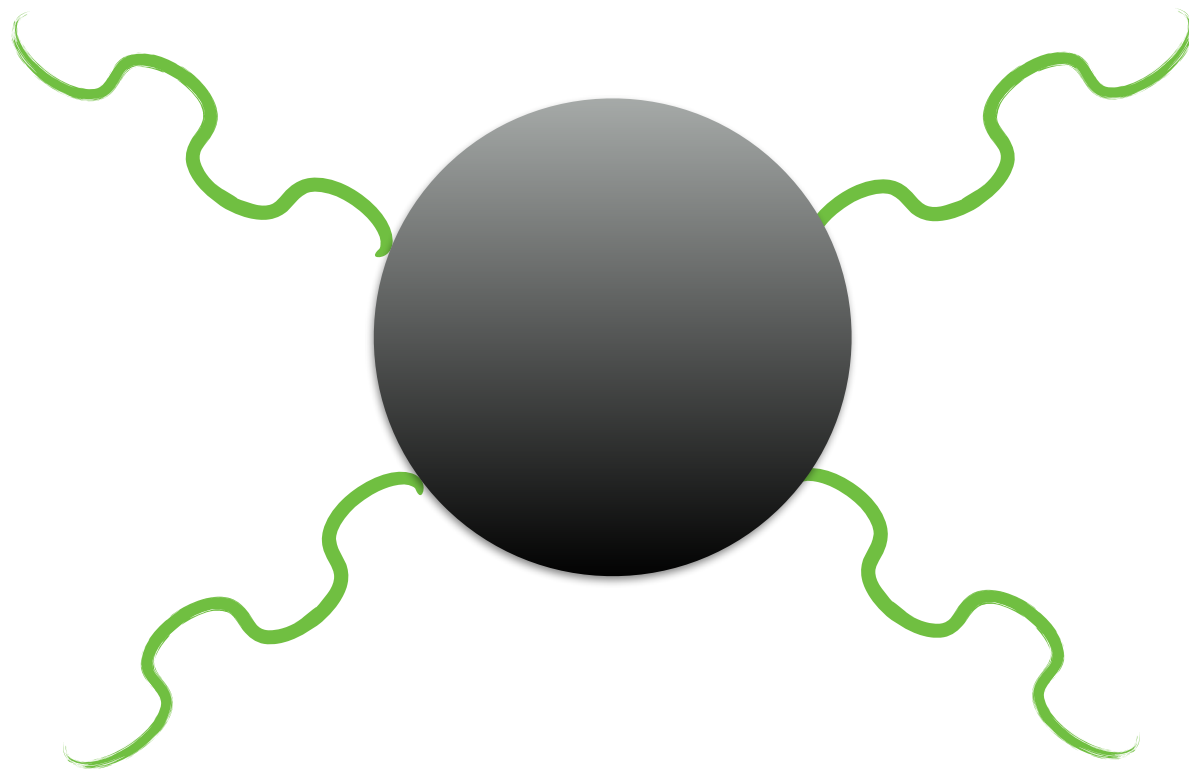
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However...

It is extremely useful to have specific motivation to shape the goals of future colliders.

Pre-Higgs Guarantee

Planning for colliders was simple following the discovery of W/Z bosons:



Consistency gave us a no-lose theorem.

Violation of unitarity in VV scattering



Standard Model breaks down parametrically near weak scale

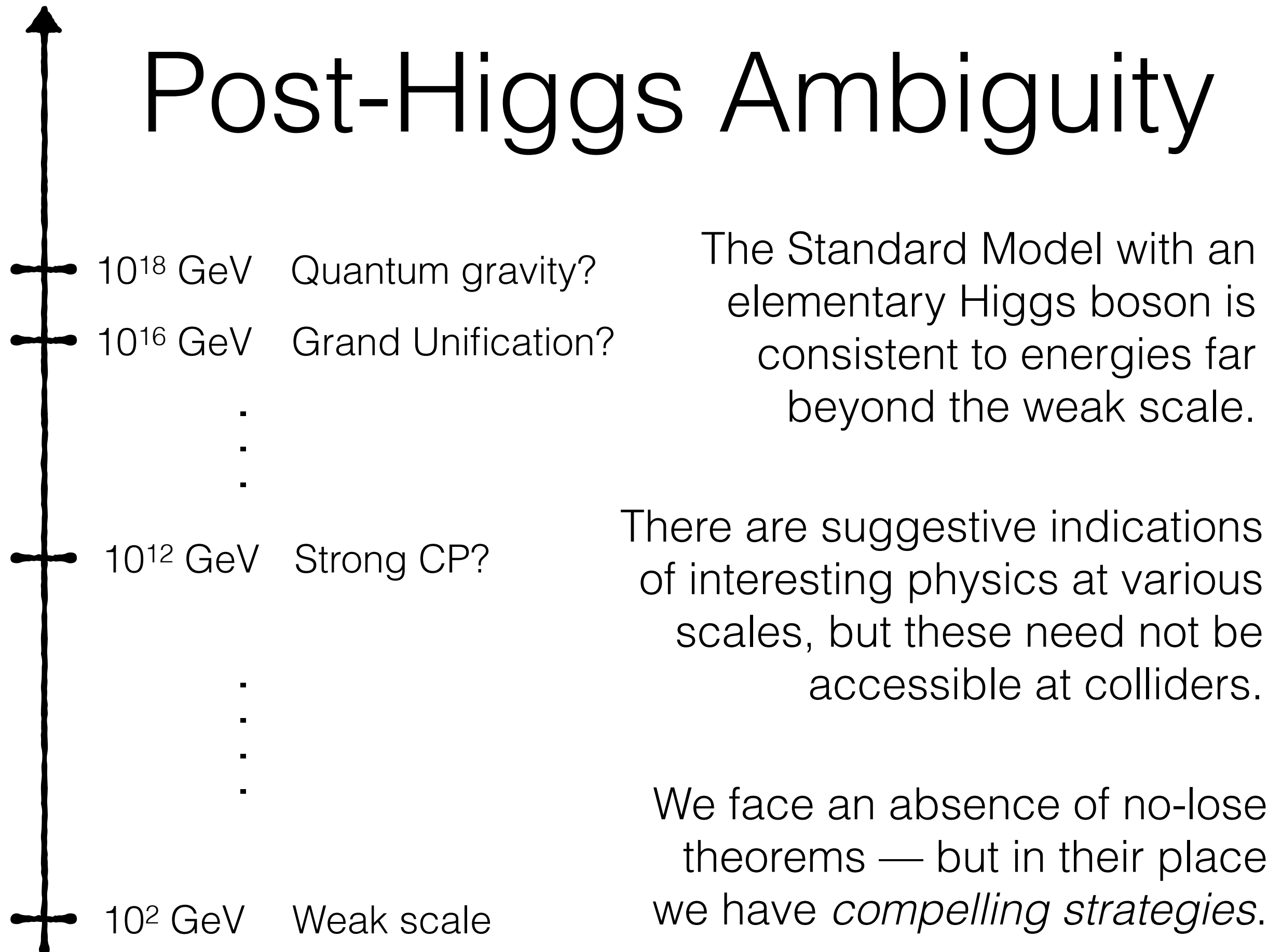


Consistency demands new physics (e.g. Higgs mechanism)



Higgs discovery @ LHC

Post-Higgs Ambiguity

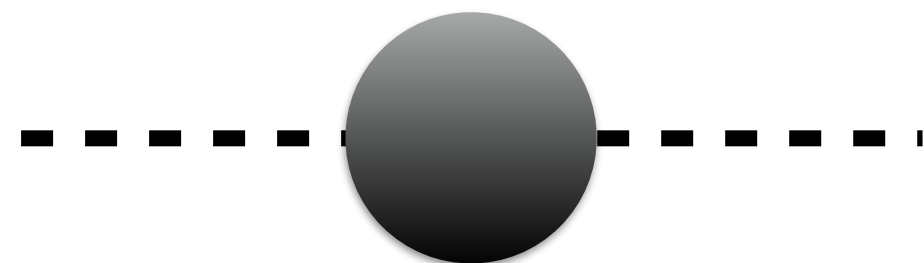


The naturalness strategy

In the SM, m_h is a parameter: not predicted, and worse, incalculable (elementary scalars are special).

In a theory where m_h is calculable, new physics beyond the SM enters at a scale Λ .

We see a *hierarchy problem*: quantum contributions to m_h are *at least* around this scale Λ .



A Feynman diagram representing a tadpole loop. It consists of a central black circle (loop) connected to a horizontal dashed line. The dashed line extends to the left and ends in a vertical line with an arrow pointing upwards, representing an external scalar field. To the right of the loop, the equation $\delta m_h \propto \Lambda$ is written.

$$\delta m_h \propto \Lambda$$

Natural if $\delta m_h \sim m_h$.

($\delta m_h \gg m_h$ unnatural or UV miracle)

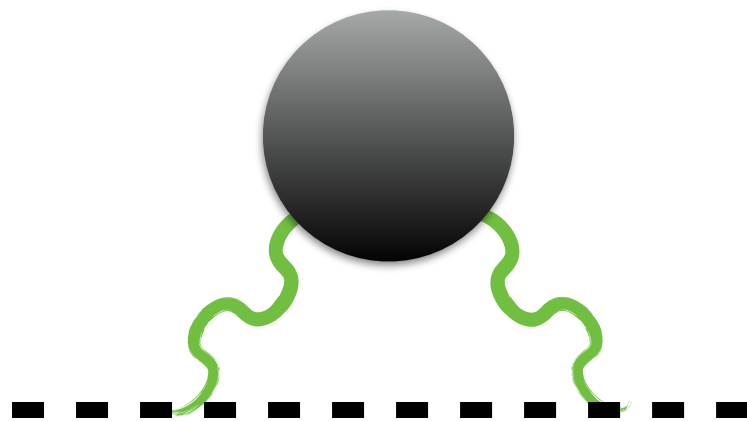


The naturalness strategy

This is a *strategy* for new physics near m_h , not a *no-lose theorem*, because the theory does not break down if it is unnatural.

But naturalness has often been a very *successful* strategy.

E.g. charged pions

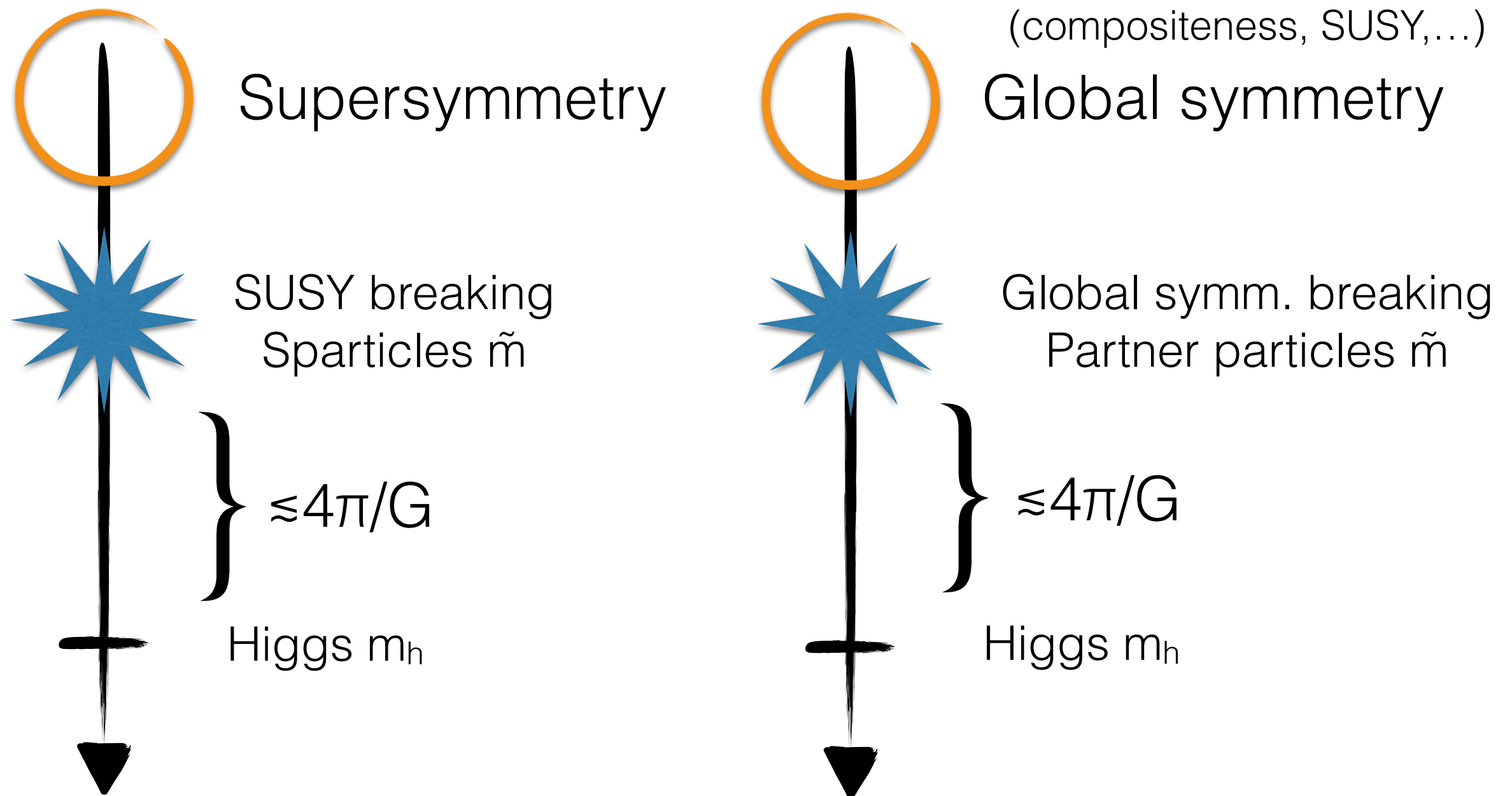


Electromagnetic contribution to the charged pion mass sensitive to the cutoff of the pion EFT.

$$\delta m^2 \sim \frac{3e^2}{16\pi^2} \Lambda^2$$

Naturalness suggests $\Lambda \sim 850$ MeV.
Rho meson (new physics!) enters at 770 MeV.

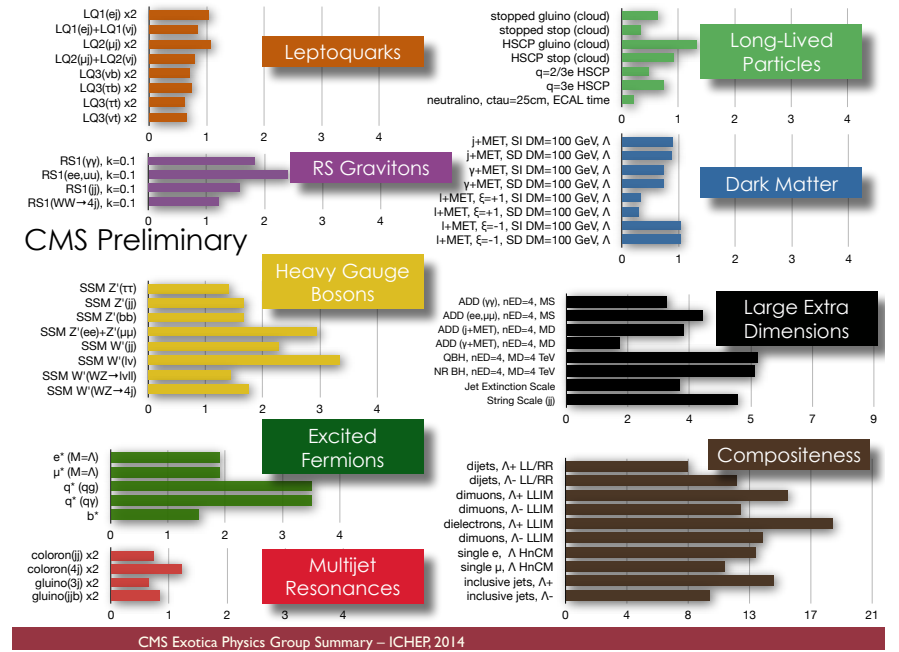
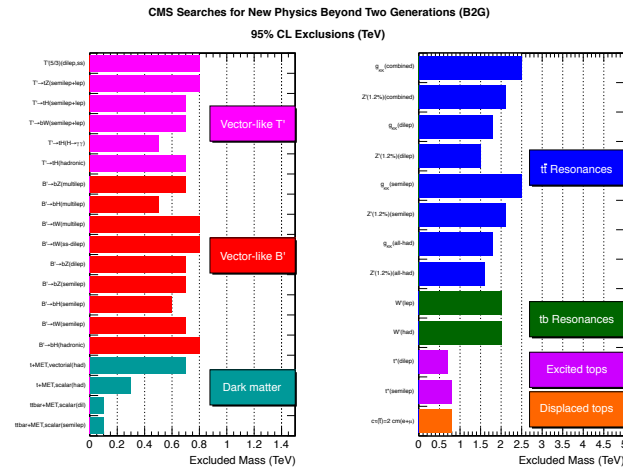
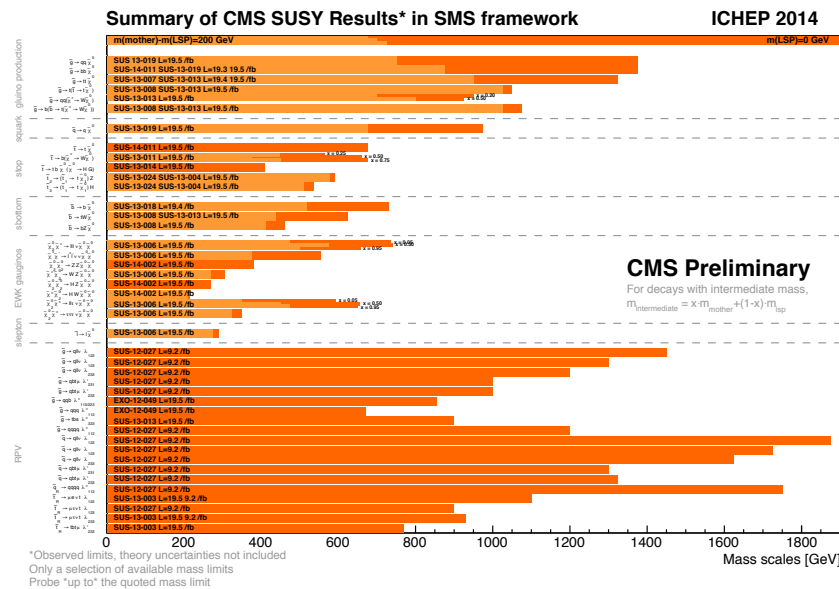
Electroweak naturalness



Continuous symmetries \rightarrow partner states w/ SM quantum #s

$$m_h^2 \sim \frac{3y_t^2}{4\pi^2} \tilde{m}^2 \log(\Lambda^2/\tilde{m}^2) \quad \text{Totally natural: } \tilde{m} \lesssim 200 \text{ GeV}$$

A physics driver @ LHC



170 of these 226 channels tied to naturalness

ATLAS SUSY Searches* - 95% CL Lower Limits

Status: Feb 2015

Model	e, μ, τ, γ	Jets	E_{miss}^T	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference				
Inclusive Searches	MSUGRA/CMSM	0	2-6 jets	Yes	20.3	\tilde{g}	$m(\tilde{g})$	1405.7875		
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{t}_1^0$	0	2-6 jets	Yes	20.3	\tilde{g}	$m(\tilde{t}_1^0)=0 \text{ GeV}, m(1^{\text{st}} \text{ gen. } \tilde{q})=m(2^{\text{nd}} \text{ gen. } \tilde{q})$	1405.7875		
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{t}_1^0$ (compressed)	1 γ	0-1 jet	Yes	20.3	\tilde{g}	$m(\tilde{g})=m(\tilde{t}_1^0)=m(\tilde{c})$	1411.1559		
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow q\tilde{t}_1^0$	0	2-6 jets	Yes	20.3	\tilde{g}	$m(\tilde{t}_1^0)=0 \text{ GeV}$	1405.7875		
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow q\tilde{t}_1^0$	1 e, μ	3-6 jets	Yes	20	\tilde{g}	$m(\tilde{t}_1^0)=300 \text{ GeV}, m(\tilde{t}^0)=0.5(m(\tilde{t}_1^0)+m(\tilde{g}))$	1501.03555		
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow q\tilde{t}_1^0$	2 e, μ	0-3 jets	-	20	\tilde{g}	$m(\tilde{t}_1^0)=0 \text{ GeV}$	1501.03555		
	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow q\tilde{t}_1^0$	1-2 $\tau + 0-1 \ell$	0-2 jets	Yes	20.3	\tilde{g}	$\tan\beta=20$	1407.0603		
	GMSB (bino NLSP)	2 γ	-	Yes	20.3	\tilde{g}	$m(\tilde{t}_1^0)=50 \text{ GeV}$	ATLAS-CONF-2014-001		
	GGM (wino NLSP)	1 $e, \mu + \gamma$	-	Yes	4.8	\tilde{g}	$m(\tilde{t}_1^0)=50 \text{ GeV}$	ATLAS-CONF-2012-144		
	GGM (higgsino-bino NLSP)	1 e, μ	1 b	Yes	4.8	\tilde{g}	$m(\tilde{t}_1^0)=220 \text{ GeV}$	1211.1167		
	GGM (higgsino NLSP)	2 e, μ (Z)	0-3 jets	Yes	5.8	\tilde{g}	$m(\text{NLSP})=200 \text{ GeV}$	ATLAS-CONF-2012-152		
	Gravitino LSP	0	mono-jet	Yes	20.3	$k^{1/2}$ scale	$m(\text{NLSP})=1.8 \times 10^{-4} \text{ eV}, m(\tilde{g})=m(\tilde{g})=1.5 \text{ TeV}$	1502.01518		
3 γ gen. & med.	$\tilde{g} \rightarrow b\tilde{t}_1^0$	0	3 b	Yes	20.1	\tilde{g}	$m(\tilde{t}_1^0)=400 \text{ GeV}$	1407.0600		
	$\tilde{g} \rightarrow t\tilde{t}_1^0$	0	7-10 jets	Yes	20.3	\tilde{g}	$m(\tilde{t}_1^0)=350 \text{ GeV}$	1308.1841		
	$\tilde{g} \rightarrow t\tilde{t}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	$m(\tilde{t}_1^0)=400 \text{ GeV}$	1407.0600		
	$\tilde{g} \rightarrow b\tilde{t}_1^0$	0-1 e, μ	3 b	Yes	20.1	\tilde{g}	$m(\tilde{t}_1^0)=300 \text{ GeV}$	1407.0600		
3 γ gen. squarks direct production	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{t}_1^0$	0	2 b	Yes	20.1	\tilde{g}	$m(\tilde{t}_1^0)=90 \text{ GeV}$	1308.2631		
	$\tilde{b}_1\tilde{b}_1, \tilde{b}_1 \rightarrow b\tilde{t}_1^0$	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}	$m(\tilde{t}_1^0)=2 \text{ MeV}$	1404.2500		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow b\tilde{t}_1^0$	1-2 e, μ	1-2 b	Yes	4.7	\tilde{t}_1	$m(\tilde{t}_1^0)=2m(\tilde{t}_1^0), m(\tilde{t}_1^0)=55 \text{ GeV}$	1209.2102, 1407.0593		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow W\tilde{t}_1^0$ or \tilde{t}_1^0	2 e, μ	0-2 jets	Yes	20.3	\tilde{t}_1	$m(\tilde{t}_1^0)=1 \text{ GeV}$	1403.4853, 1412.4742		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{t}_1^0$	0-1 e, μ	1-2 b	Yes	20	\tilde{t}_1	$m(\tilde{t}_1^0)=1 \text{ GeV}$	1407.0583, 1406.1122		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow q\tilde{t}_1^0$	0	mono-jet+tag jets	Yes	20.3	\tilde{t}_1	$m(\tilde{t}_1^0)=m(\tilde{t}_1^0)=85 \text{ GeV}$	1407.0608		
	$\tilde{t}_1\tilde{t}_1$ (natural GMSB)	2 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	$m(\tilde{t}_1^0)=150 \text{ GeV}$	1403.5222		
	$\tilde{t}_1\tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{t}_1 + Z$	3 e, μ (Z)	1 b	Yes	20.3	\tilde{t}_1	$m(\tilde{t}_1^0)=200 \text{ GeV}$	1403.5222		
	EW direct	$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow \ell\tilde{\nu}_\ell$	2 e, μ	0	Yes	20.3	\tilde{L}_R	$m(\tilde{L}_R^0)=0 \text{ GeV}$	1403.5294	
		$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow \ell\tilde{\nu}_\ell$	2 e, μ	0	Yes	20.3	\tilde{L}_R^0	$m(\tilde{L}_R^0)=0 \text{ GeV}, m(\tilde{L}_R, \tilde{\nu})=0.5(m(\tilde{L}_R^0)+m(\tilde{L}_R^0))$	1403.5294	
$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow \ell\tilde{\nu}_\ell$		2 τ	-	Yes	20.3	\tilde{L}_R	$m(\tilde{L}_R^0)=0 \text{ GeV}, m(\tilde{L}_R, \tilde{\nu})=0.5(m(\tilde{L}_R^0)+m(\tilde{L}_R^0))$	1407.0350		
$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow \ell\tilde{\nu}_\ell$		3 e, μ	0	Yes	20.3	$\tilde{L}_R^0, \tilde{L}_R^{\pm}$	$m(\tilde{L}_R^0)=m(\tilde{L}_R^{\pm})=0, m(\tilde{L}_R, \tilde{\nu})=0.5(m(\tilde{L}_R^0)+m(\tilde{L}_R^0))$	1402.7029		
$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow \ell\tilde{\nu}_\ell$		2-3 e, μ	0-2 jets	Yes	20.3	$\tilde{L}_R^0, \tilde{L}_R^{\pm}$	$m(\tilde{L}_R^0)=m(\tilde{L}_R^{\pm})=0, m(\tilde{L}_R, \tilde{\nu})=0.5(m(\tilde{L}_R^0)+m(\tilde{L}_R^0))$	1403.5294, 1402.7029		
$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow \ell\tilde{\nu}_\ell$		e, μ, γ	0-2 b	Yes	20.3	$\tilde{L}_R^0, \tilde{L}_R^{\pm}$	$m(\tilde{L}_R^0)=m(\tilde{L}_R^{\pm})=0, m(\tilde{L}_R, \tilde{\nu})=0.5(m(\tilde{L}_R^0)+m(\tilde{L}_R^0))$	1501.07110		
$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow \ell\tilde{\nu}_\ell$		4 e, μ	0	Yes	20.3	$\tilde{L}_R^0, \tilde{L}_R^{\pm}$	$m(\tilde{L}_R^0)=m(\tilde{L}_R^{\pm})=0, m(\tilde{L}_R, \tilde{\nu})=0.5(m(\tilde{L}_R^0)+m(\tilde{L}_R^0))$	1405.5086		
Long-lived particles		Direct $\tilde{L}_R\tilde{L}_R$ prod., long-lived \tilde{L}_R^0	Disapp. trk	1 jet	Yes	20.3	\tilde{L}_R^0	$m(\tilde{L}_R^0)=m(\tilde{L}_R^0)=160 \text{ MeV}, \tau(\tilde{L}_R^0)=0.2 \text{ ns}$	1310.3675	
	Stable, stopped \tilde{R} -hadron	0	1-5 jets	Yes	27.9	\tilde{L}_R^0	$m(\tilde{L}_R^0)=100 \text{ GeV}, 10 \mu\text{s} < \tau(\tilde{L}_R^0) < 1000 \text{ s}$	1310.6584		
	Stable \tilde{R} -hadron	trk	-	-	19.1	\tilde{L}_R^0	$10\text{-} \tan\beta=50$	1411.6795		
	GMSB, stable $\tilde{L}_R^0 \rightarrow \tilde{L}_R + \tau(\tilde{\nu}_\ell, \tilde{\nu}_\ell) + \tau(e, \mu)$	1-2 μ	-	-	19.1	\tilde{L}_R^0	$2 < \tau(\tilde{L}_R^0) < 3 \text{ ns}, \text{SPS8 model}$	1411.6795		
	GMSB, $\tilde{L}_R^0 \rightarrow \tilde{L}_R + \tau$	2 γ	-	Yes	20.3	\tilde{L}_R^0	$1.5 < \tau < 156 \text{ min}, \text{BR}(\mu \rightarrow \mu, \tilde{L}_R^0)=108 \text{ GeV}$	1409.5542		
	$\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{t}_1^0$ (RPV)	1 μ , displ. vtx	-	-	20.3	\tilde{L}_R^0		ATLAS-CONF-2013-092		
	RPV	LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu$	2 e, μ	-	-	4.6	$\tilde{\nu}_\tau$	$A_{11}=0.10, A_{12}=0.05$	1212.1272	
		LFV $pp \rightarrow \tilde{\nu}_\tau + X, \tilde{\nu}_\tau \rightarrow e + \mu + \tau$	1 $e, \mu + \tau$	-	-	4.6	$\tilde{\nu}_\tau$	$A_{11}=0.10, A_{123}=0.05$	1212.1272	
		Bilinear RPV CMSM	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{L}_R, \tilde{g}	$m(\tilde{g})=m(\tilde{L}_R), \tau_{\text{NLSP}} < 1 \text{ mm}$	1404.2500	
		$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow W\tilde{L}_R^0$	4 e, μ	-	Yes	20.3	\tilde{L}_R	$m(\tilde{L}_R^0)=0.2m(\tilde{L}_R^0), A_{123}=0$	1405.5086	
$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow W\tilde{L}_R^0$		3 $e, \mu + \tau$	-	Yes	20.3	\tilde{L}_R	$m(\tilde{L}_R^0)=0.2m(\tilde{L}_R^0), A_{123}=0$	1405.5086		
$\tilde{L}_R\tilde{L}_R, \tilde{L}_R \rightarrow W\tilde{L}_R^0$		0	6-7 jets	Yes	20.3	\tilde{L}_R	$\text{BR}(\mu \rightarrow \mu, \tilde{L}_R^0)=\text{BR}(\tau \rightarrow \tau, \tilde{L}_R^0)=0\%$	ATLAS-CONF-2013-091		
Other	$\tilde{g} \rightarrow t\tilde{t}_1^0, \tilde{t}_1 \rightarrow b\tilde{t}_1^0$	2 e, μ (SS)	0-3 b	Yes	20.3	\tilde{g}		1404.250		
	Scalar charm, $\tilde{c} \rightarrow c\tilde{L}_R^0$	0	2 c	Yes	20.3	\tilde{c}	$m(\tilde{c}^0)=200 \text{ GeV}$	1501.01325		
					$\sqrt{s} = 7 \text{ TeV}$ full data	$\sqrt{s} = 8 \text{ TeV}$ partial data	$\sqrt{s} = 8 \text{ TeV}$ full data	10^{-1}	1	Mass scale [TeV]

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

ATLAS Exotics Searches* - 95% CL Exclusion

Status: ICHEP 2014

	Model	ℓ, γ	Jets	E^{miss}	$\int \mathcal{L} dt [\text{fb}^{-1}]$	Mass limit	Reference	
Extra dimensions	ADD $G_{KK} + g/q$	–	1-2 j	Yes	4.7	M_0 4.37 TeV	$n = 2$ 1210.4491	
	ADD non-resonant $\ell\ell$	$2e, \mu$	–	–	20.3	M_0 5.2 TeV	$n = 3$ HLZ ATLAS-CONF-2014-030	
	ADD QBH $\rightarrow \ell q$	$1e, \mu$	1 j	–	20.3	M_0 5.2 TeV	1311.2006	
	ADD QBH	–	2 j	–	20.3	M_0 5.82 TeV	$n = 6$ to be submitted to PRD	
	ADD BH high N_{ch}	2μ (SS)	–	–	20.3	M_0 5.7 TeV	$n = 6, M_0 = 1.5$ TeV, non-rot BH 1308.4075	
	ADD BH high Σpr	$\geq 1e, \mu$	$\geq 2 j$	–	20.3	M_0 6.2 TeV	$n = 6, M_0 = 1.5$ TeV, non-rot BH 1405.4254	
	RS1 $G_{KK} \rightarrow \ell\ell$	$2e, \mu$	–	–	20.3	G_{KK} mass 2.68 TeV	$k/M_{Pl} = 0.1$ 1405.4123	
	RS1 $G_{KK} \rightarrow WW \rightarrow \ell\nu\ell\nu$	$2e, \mu$	–	Yes	4.7	G_{KK} mass 1.23 TeV	$k/M_{Pl} = 0.1$ 1208.2880	
	Bulk RS $G_{KK} \rightarrow ZZ \rightarrow \ell\ell q\bar{q}$	$2e, \mu$	2 j / 1 j	–	20.3	G_{KK} mass 730 GeV	$k/M_{Pl} = 1.0$ ATLAS-CONF-2014-039	
	Bulk RS $G_{KK} \rightarrow HH \rightarrow b\bar{b}b\bar{b}$	–	4 b	–	19.5	G_{KK} mass 590-710 GeV	$k/M_{Pl} = 1.0$ ATLAS-CONF-2014-005	
Gauge bosons	Bulk RS $G_{KK} \rightarrow \ell\ell$	$1e, \mu$	$\geq 1b, \geq 1j/2j$	Yes	14.3	G_{KK} mass 2.0 TeV	BR = 0.925 ATLAS-CONF-2013-052	
	S^1/Z_2 ED	$2e, \mu$	–	–	5.0	$M_{KK} \approx R^{-1}$ 4.71 TeV	1209.2535	
	UED	2γ	–	Yes	4.8	Compact, scale R^{-1} 1.41 TeV	ATLAS-CONF-2012-072	
	SSM $Z' \rightarrow \ell\ell$	$2e, \mu$	–	–	20.3	Z' mass 2.9 TeV	$\eta = +1$ 1405.4123	
	SSM $Z' \rightarrow \tau\tau$	2τ	–	–	19.5	Z' mass 1.9 TeV	$\eta_{LL} = -1$ ATLAS-CONF-2013-066	
	SSM $W' \rightarrow \ell\nu$	$1e, \mu$	–	Yes	20.3	W' mass 3.28 TeV	ATLAS-CONF-2014-017	
	EGM $W' \rightarrow WZ \rightarrow \ell\nu\ell'\ell'$	$3e, \mu$	–	Yes	20.3	W' mass 1.52 TeV	1406.4456	
	EGM $W' \rightarrow WZ \rightarrow q\bar{q}\ell\ell$	$2e, \mu$	2 j / 1 j	–	20.3	W' mass 1.59 TeV	ATLAS-CONF-2014-039	
	LRSM $W'_\mu \rightarrow \ell\bar{\ell}$	$1e, \mu$	2 b, 0-1 j	Yes	14.3	W' mass 1.84 TeV	ATLAS-CONF-2013-050	
	LRSM $W'_\mu \rightarrow \ell\bar{\ell}$	$0e, \mu$	$\geq 1b, 1 j$	–	20.3	W' mass 1.77 TeV	to be submitted to EPJ	
CI	CI $q\bar{q}q\bar{q}$	–	2 j	–	4.8	–	1210.1718	
	CI $q\bar{q}\ell\ell$	$2e, \mu$	–	–	20.3	A 21.6 TeV	ATLAS-CONF-2014-030	
	CI $u\bar{u}t\bar{t}$	$2e, \mu$ (SS) $\geq 1b, \geq 1j$	Yes	14.3	–	3.3 TeV	$ C = 1$ ATLAS-CONF-2013-051	
DM	EFT D5 operator (Dirac)	–	$0e, \mu$	1-2 j	Yes	10.5	M_0 731 GeV	at 90% CL for $m(\chi) < 80$ GeV
	EFT D9 operator (Dirac)	–	$0e, \mu$	1 j, $\leq 1 j$	Yes	20.3	M_0 2.4 TeV	at 90% CL for $m(\chi) < 100$ GeV
LQ	Scalar LQ 1 st gen	$2e$	$\geq 2 j$	–	1.0	LQ mass 660 GeV	$\beta = 1$ 1112.4828	
	Scalar LQ 2 nd gen	2μ	$\geq 2 j$	–	1.0	LQ mass 685 GeV	$\beta = 1$ 1203.3172	
	Scalar LQ 3 rd gen	$1e, \mu, 1\tau$	1 b, 1 j	–	4.7	LQ mass 534 GeV	$\beta = 1$ 1303.0526	
	Vector-like quark $TT \rightarrow Ht + X$	$1e, \mu$	$\geq 2b, \geq 4 j$	Yes	14.3	T mass 790 GeV	T in (T,B) doublet	
Heavy quarks	Vector-like quark $TT \rightarrow Wb + X$	$1e, \mu$	$\geq 1b, \geq 3 j$	Yes	14.3	T mass 670 GeV	isospin singlet	
	Vector-like quark $TT \rightarrow Zt + X$	$2/2-3e, \mu$	$\geq 2/2-1b$	–	20.3	T mass 735 GeV	T in (T,B) doublet	
	Vector-like quark $BB \rightarrow Zb + X$	$2/2-3e, \mu$	$\geq 2/2-1b$	–	20.3	B mass 755 GeV	B in (B,Y) doublet	
	Vector-like quark $BB \rightarrow Wt + X$	$2e, \mu$ (SS) $\geq 1b, \geq 1 j$	Yes	14.3	B mass 720 GeV	B in (T,B) doublet		
	Excited quark $q^* \rightarrow q\gamma$	1γ	1 j	–	20.3	q^* mass 3.5 TeV	only u^* and d^* , $A = m(q^*)$	
Excited fermions	Excited quark $q^* \rightarrow qg$	–	2 j	–	20.3	q^* mass 4.06 TeV	only u^* and d^* , $A = m(q^*)$	
	Excited quark $b^* \rightarrow Wt$	1 or $2e, \mu$	1 b, 2 j or 1 j	Yes	4.7	b^* mass 870 GeV	left-handed coupling	
	Excited lepton $\ell^* \rightarrow \ell\gamma$	$2e, \mu, 1\gamma$	–	–	13.0	ℓ^* mass 2.2 TeV	$A = 2.2$ TeV	
	LRSM $a_T \rightarrow W\gamma$	$1e, \mu, 1\gamma$	–	Yes	20.3	W mass 960 GeV	$m(W_0) = 2$ TeV, no mixing	
Other	LRSM Majorana ν	$2e, \mu$	2 j	–	2.1	N^0 mass 1.5 TeV	$V_{\mu 0} = 0.05, V_{\mu 1} = 0.063, V_{\mu 2} = 0$ DY production, BR($H^{\pm\pm} \rightarrow \ell\ell$) = 1	
	Type III Seesaw	$2e, \mu$	–	–	5.8	N^{\pm} mass 245 GeV	ATLAS-CONF-2013-019	
	Higgs triplet $H^{\pm\pm} \rightarrow \ell\ell$	$2e, \mu$ (SS)	–	–	4.7	$H^{\pm\pm}$ mass 409 GeV	1210.5070	
	Multi-charged particles	–	–	–	4.4	multi-charged particle mass 490 GeV	DY production, $ q = 4e$	
	Magnetic monopoles	–	–	–	2.0	monopole mass 862 GeV	DY production, $ g = 1g_D$	
							1207.6411	

$\sqrt{s} = 7$ TeV

$\sqrt{s} = 8$ TeV

10^{-1}

1

10

Mass scale [TeV]

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

Signs of naturalness

“Colorful” naturalness

10 TeV

 \tilde{w}

 w', z'

 \tilde{g}

 $\tilde{t}_L \quad \tilde{t}_R \quad \tilde{b}_L$

 $t'_L \quad t'_R \quad b'_L$

 \tilde{h}

 h

 h

Supersymmetry

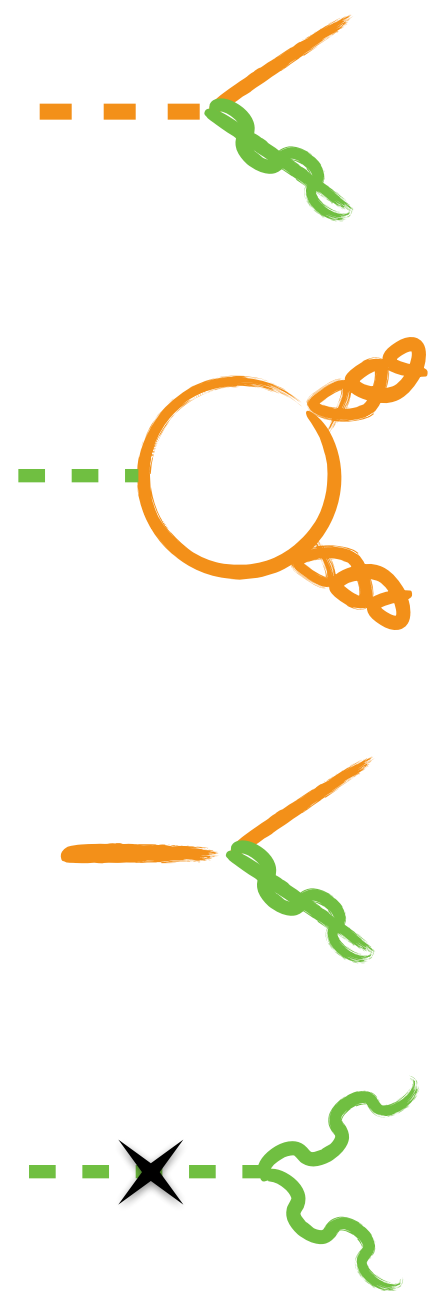
Global symmetry

Simple game for LHC: look for QCD-charged partners.



Colorful naturalness

Experimental handles

- 
- SUSY: Direct searches (and indirect searches).
 - Look for colored partner states (stops, gluinos)
 - Look for $O(\text{loop} * v/m)$ Higgs coupling deviations.
 - Global: Direct and indirect searches.
 - Look for colored partner states (vector-like t')
 - Look for $O(v/f)$ Higgs coupling deviations.

This is our current search program for naturalness. But...

“Neutral” naturalness

10 TeV

 \tilde{w}

 w', z'

 $\tilde{t}_L \quad \tilde{t}_R \quad \tilde{b}_L$

 $t'_L \quad t'_R \quad b'_L$

 \tilde{h}

 h

 h

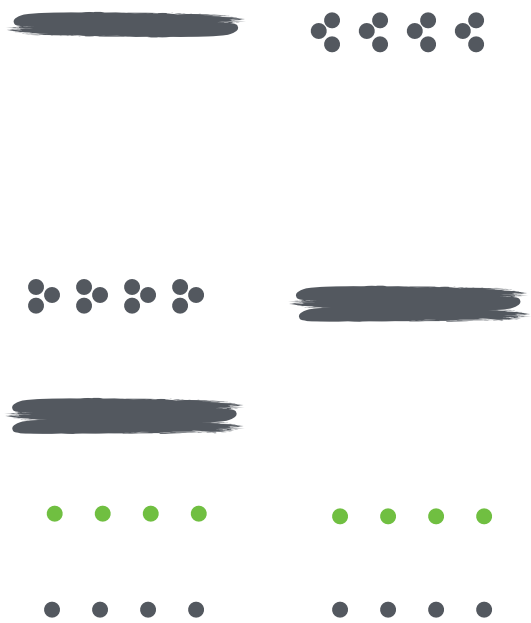
 g'

 g'

(In progress)

Twin Higgs

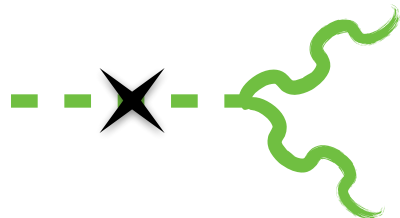
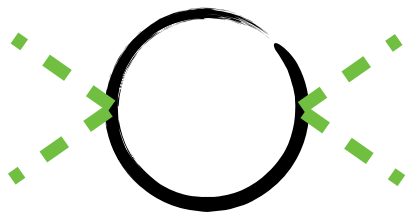
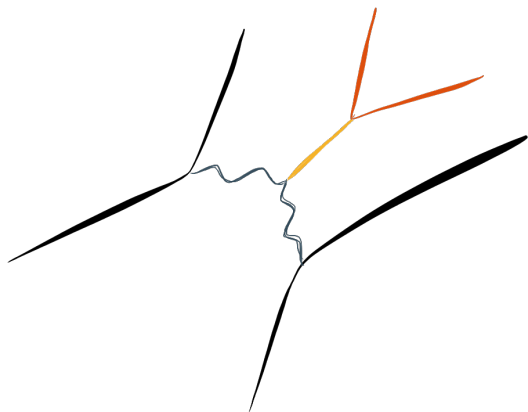
[Chacko, Goh, Harnik]



Neutral naturalness

Experimental handles

- SUSY: Direct searches (and indirect searches).
 - Look for off-shell Higgs portal.
 - Look for $O(\text{loop} \cdot v/m)$ Higgs coupling deviations.
 - *Look for the UV completion.*
- Global: Direct and indirect searches.
 - Look for $O(v/f)$ Higgs coupling deviations.
 - Look for displaced decays [\[NC, Katz, Strassler, Sundrum\]](#)
 - *Look for the UV completion.*



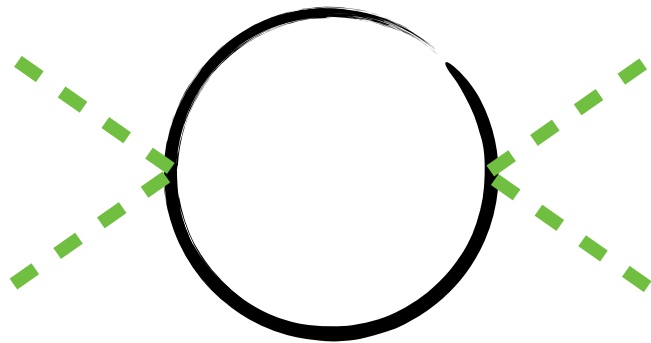


Neutral naturalness

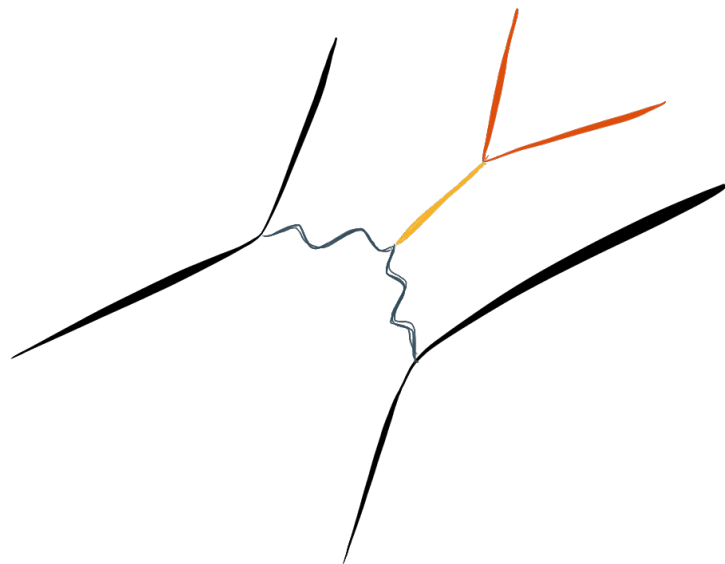


Higgs couplings: accustomed to looking for corrections to loop-level couplings ($h \rightarrow \gamma\gamma, gg$), but even loops of neutral states can be seen.

[NC, Englert, McCullough; Henning, Lu, Murayama; NC, Farina, McCullough, Perelstein]



$$\frac{c_H}{m_\phi^2} (\partial_\mu |H|^2)^2 \rightarrow \delta\sigma_{Zh} = -2c_H \frac{v^2}{m_\phi^2}$$



Direct searches: states lighter than $m_h/2$ easily constrained by Higgs width; if heavier than $m_h/2$, can still produce via an off-shell Higgs. Look for associated production + invisible.

[Curtin, Meade, Yu; NC, Lou, McCullough, Thalapillil]

Colorful naturalness

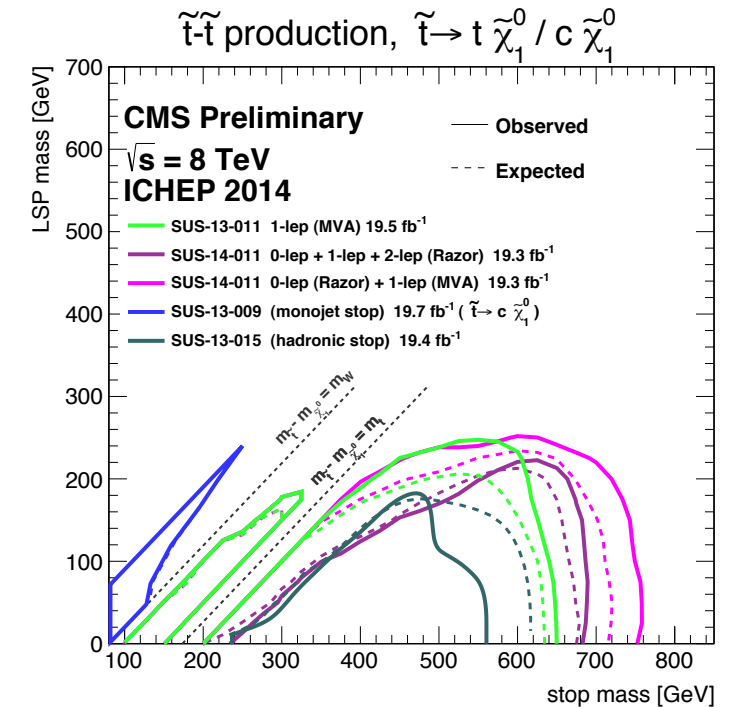
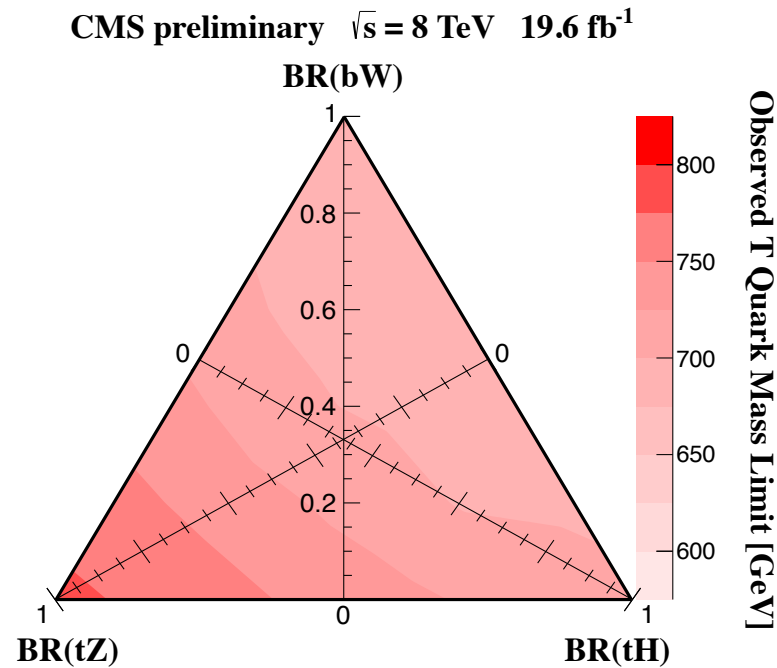
@LHC

Where we are:
“generically”

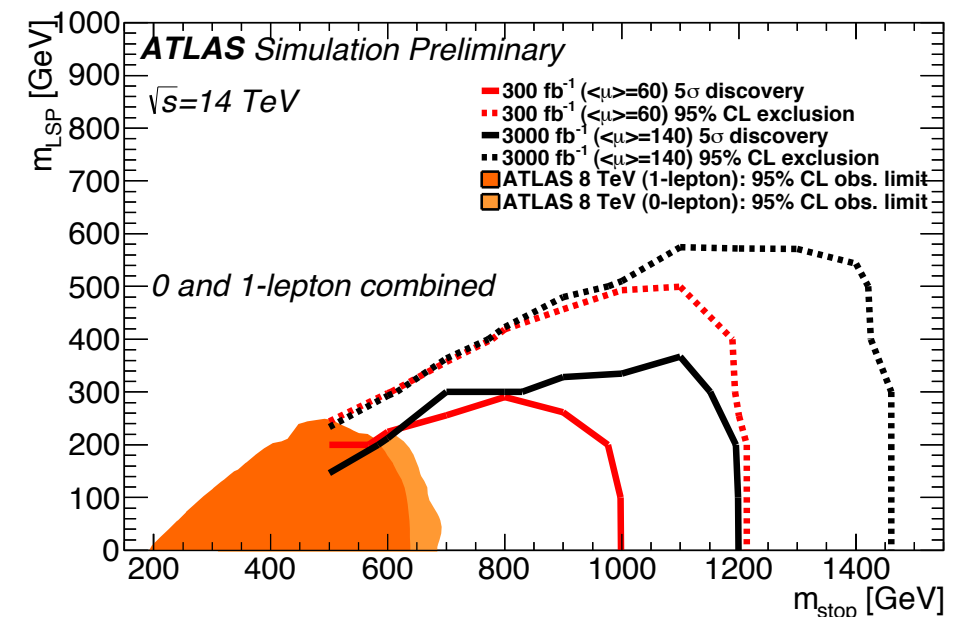
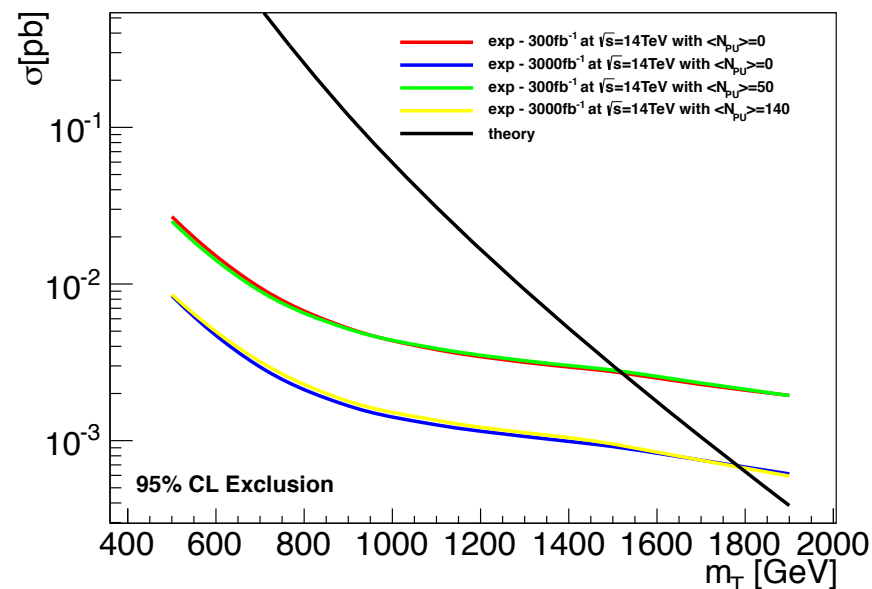
~7% tuning level

Where we'll be
@ end of LHC:
“generically”

~1% level (global)
~2% level (SUSY)



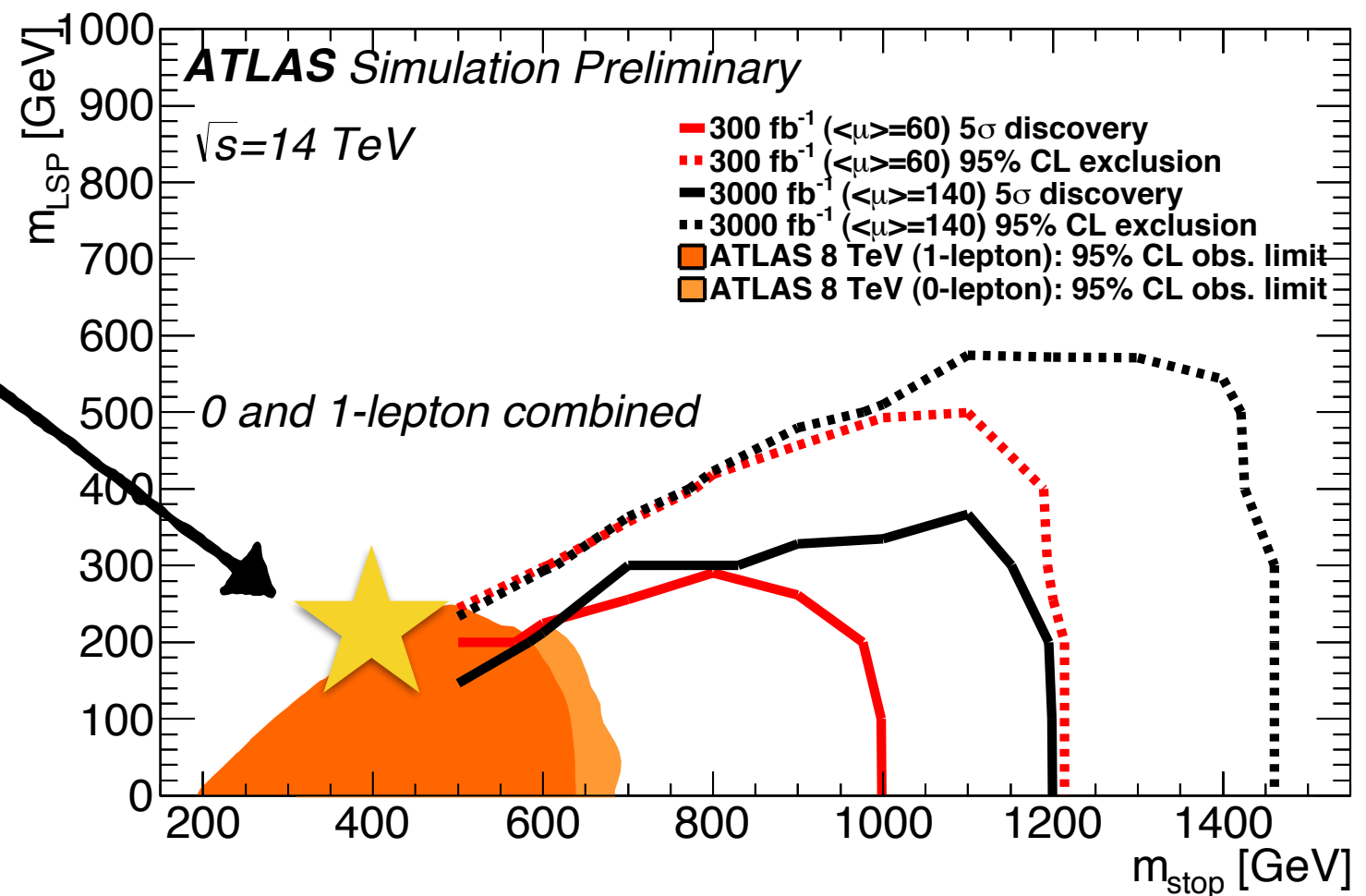
[Bhattacharya, George, Heintz, Kumar, Narain, Stupak]



And yet...

We could live right here

Completely natural, but in a kinematic region that is hard to cover @ LHC.



...or the conventional collider signals could be eroded or reduced by modest complications of the theory (RPV, stealth, etc.)

Neutral naturalness

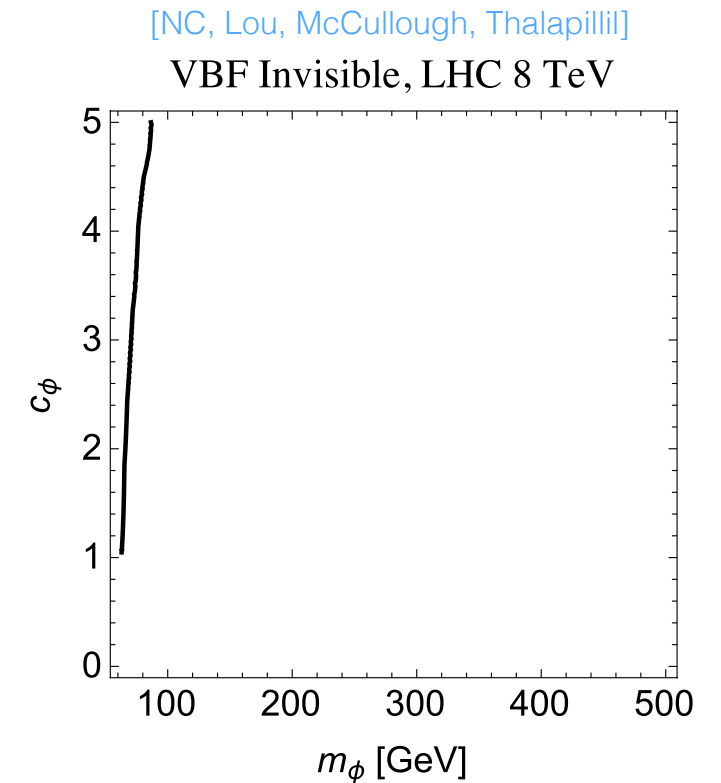
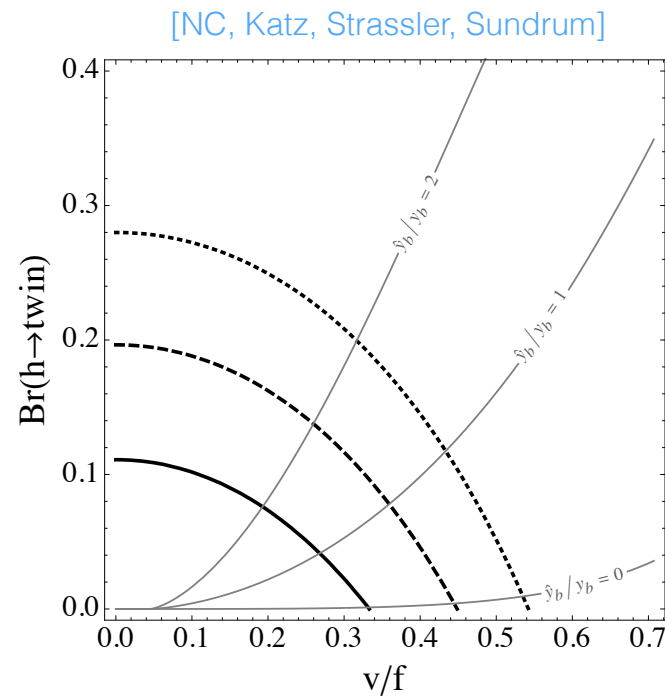
@LHC

Where we are:

***natural (at worst
30% for global)***

Where we'll be
@ end of LHC:

***natural (at worst
20% for global)***

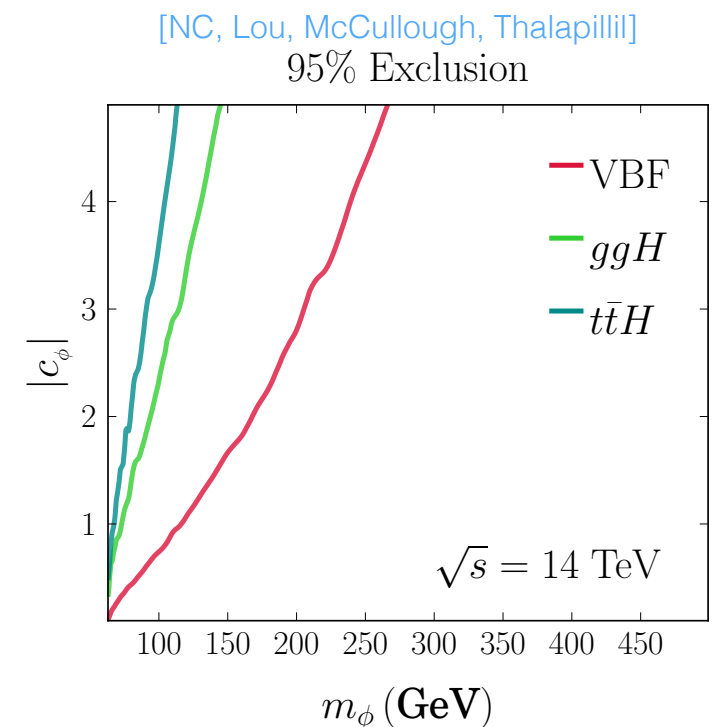


95% CL bounds

$$v/f \lesssim 0.31 \text{ (0.25)}$$

(ATLAS)

$\text{Br}(\text{inv.}) \lesssim 10\%$

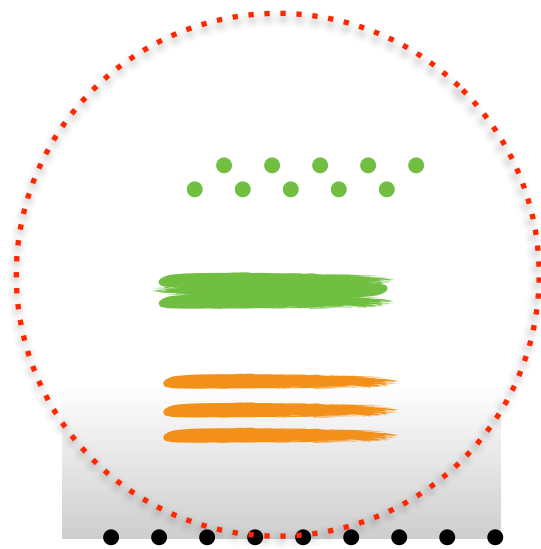


The question of electroweak naturalness
cannot be settled at the LHC.

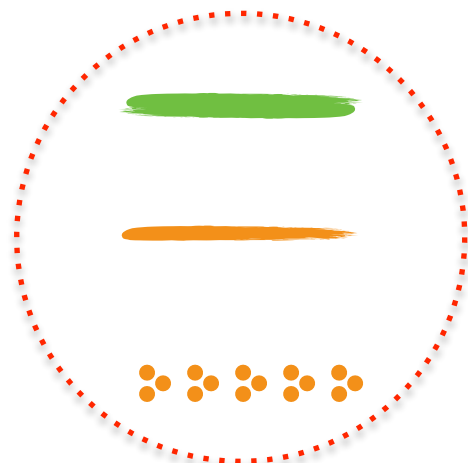
Settling the question of naturalness is a
compelling strategy for future colliders.

Naturalness at future colliders

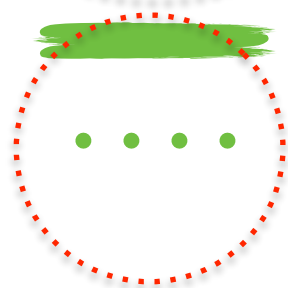
Three major opportunities



Uncover UV structure
well beyond LHC reach



Extend reach of LHC for
new particles important
for naturalness



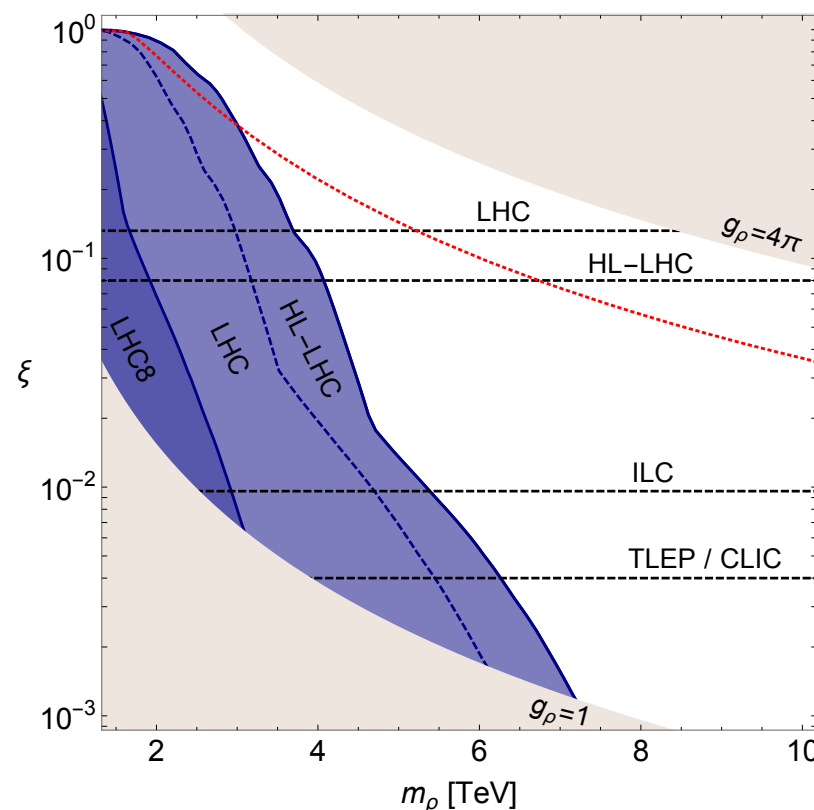
Cover holes from LHC with
precision Higgs measurements

Colorful naturalness

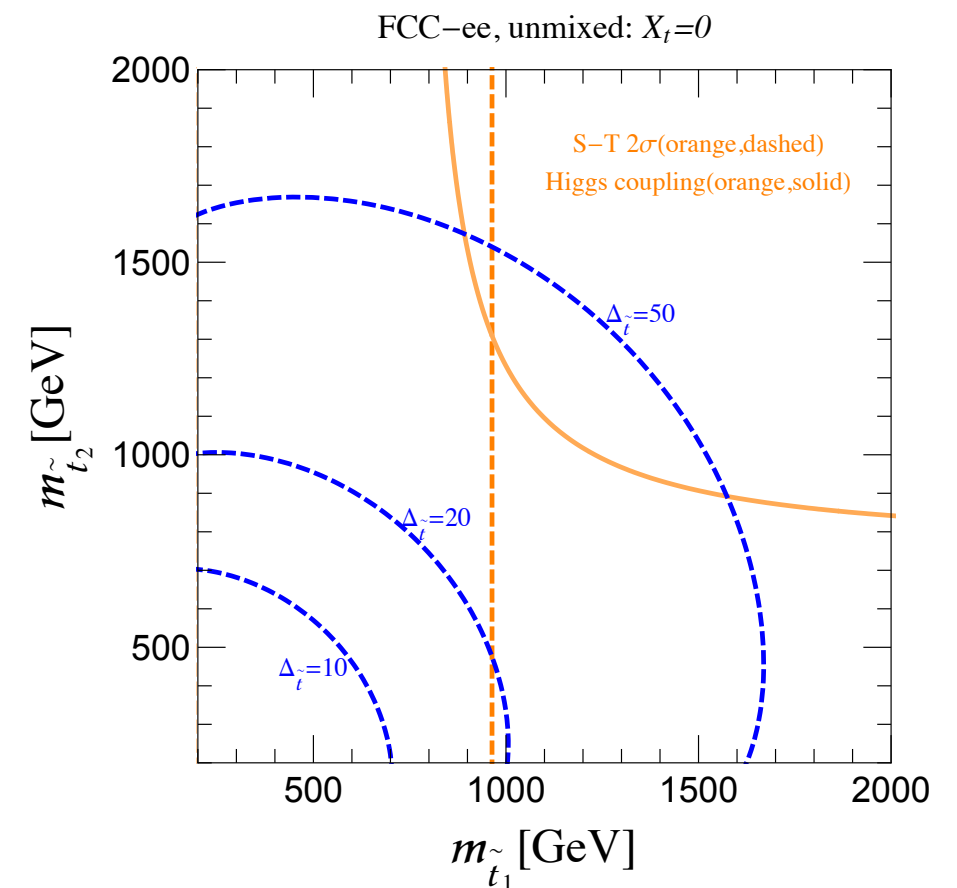
Probing at a Higgs factory:

Look for $\mathcal{O}(\text{loop} \cdot v/m)$ [SUSY] or $\mathcal{O}(v/f)$ [global] Higgs coupling deviations; precision electroweak corrections.

[Thamm, Torre, Wulzer]



[Fan, Reece, Wang]



Where we'll be @ Higgs factory:
Sensitive to kinematic holes at LHC.

~1-2% level

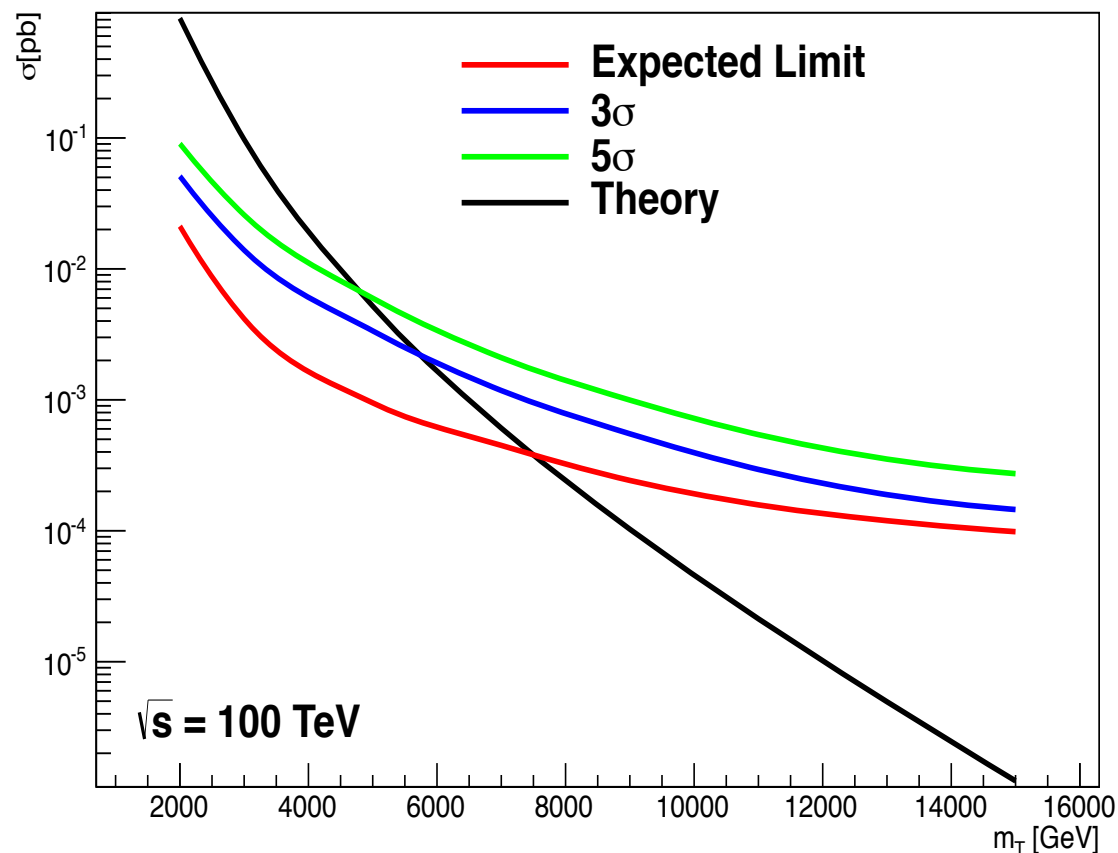
Colorful naturalness

Probing at 100 TeV:

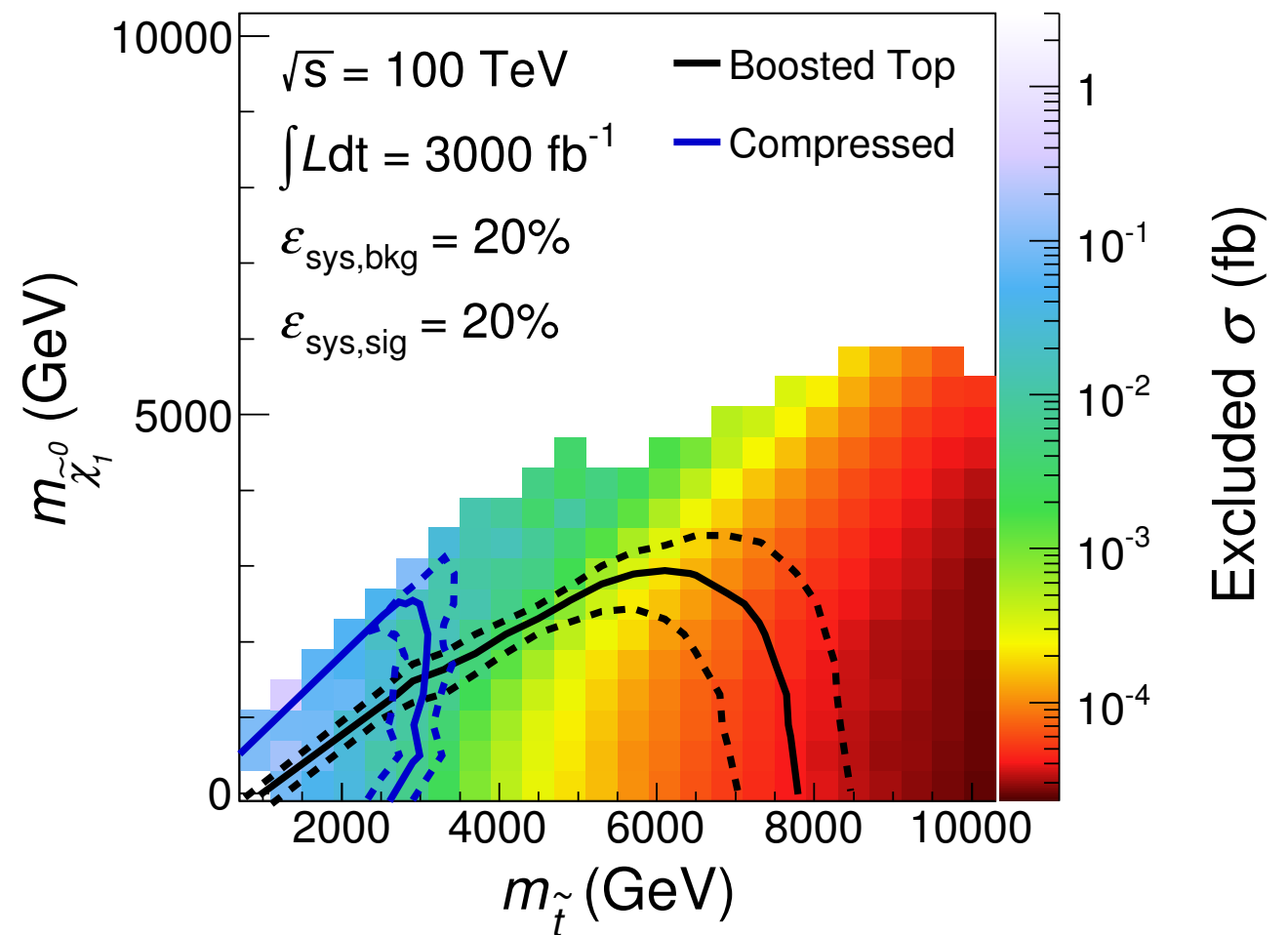
Look for the light partner states

[Cohen, D'Agnolo, Hance, Lou, Wacker]

[Ahuja, Black]



CL_s Exclusion



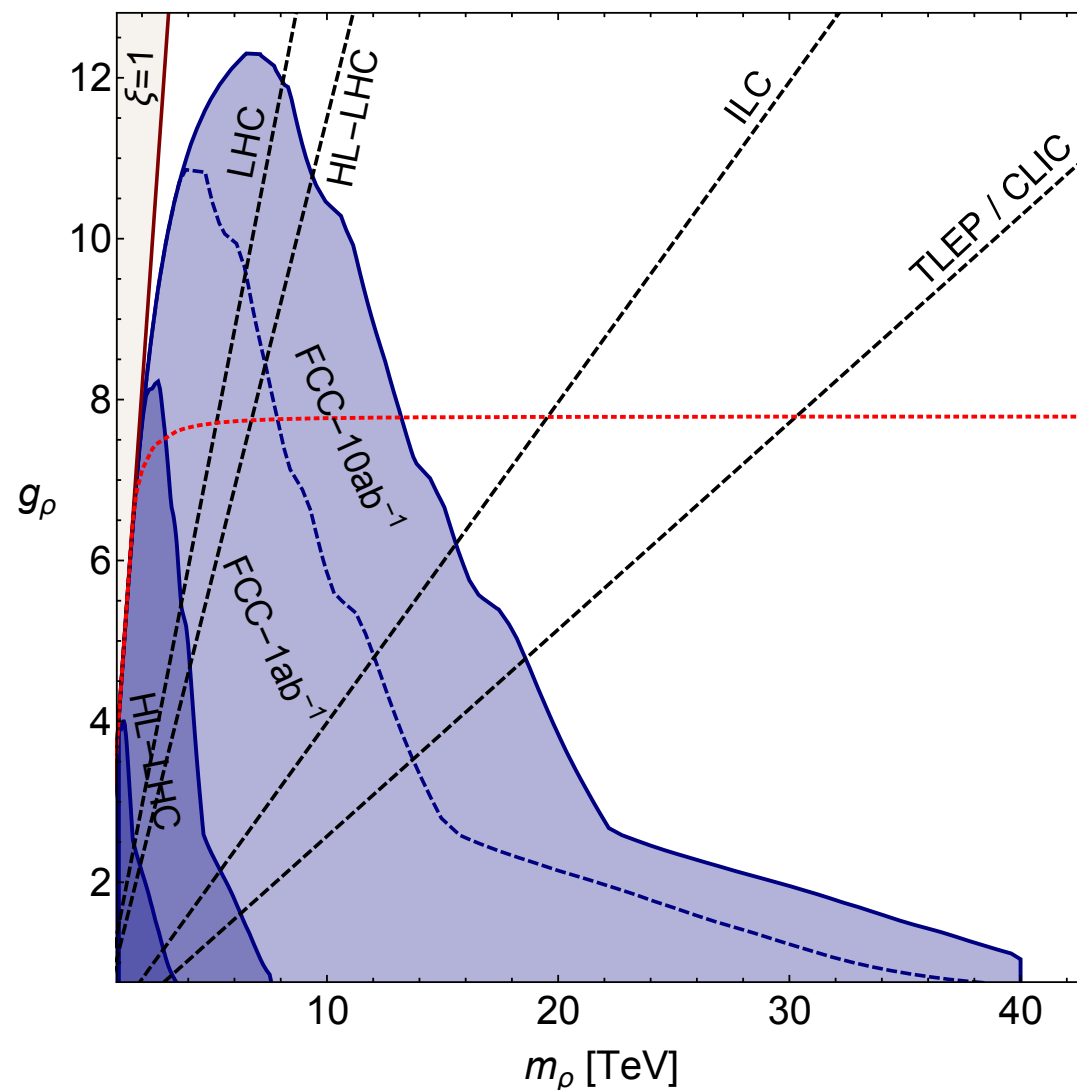
Where we'll be @ 100 TeV: “generically”

~.05% level

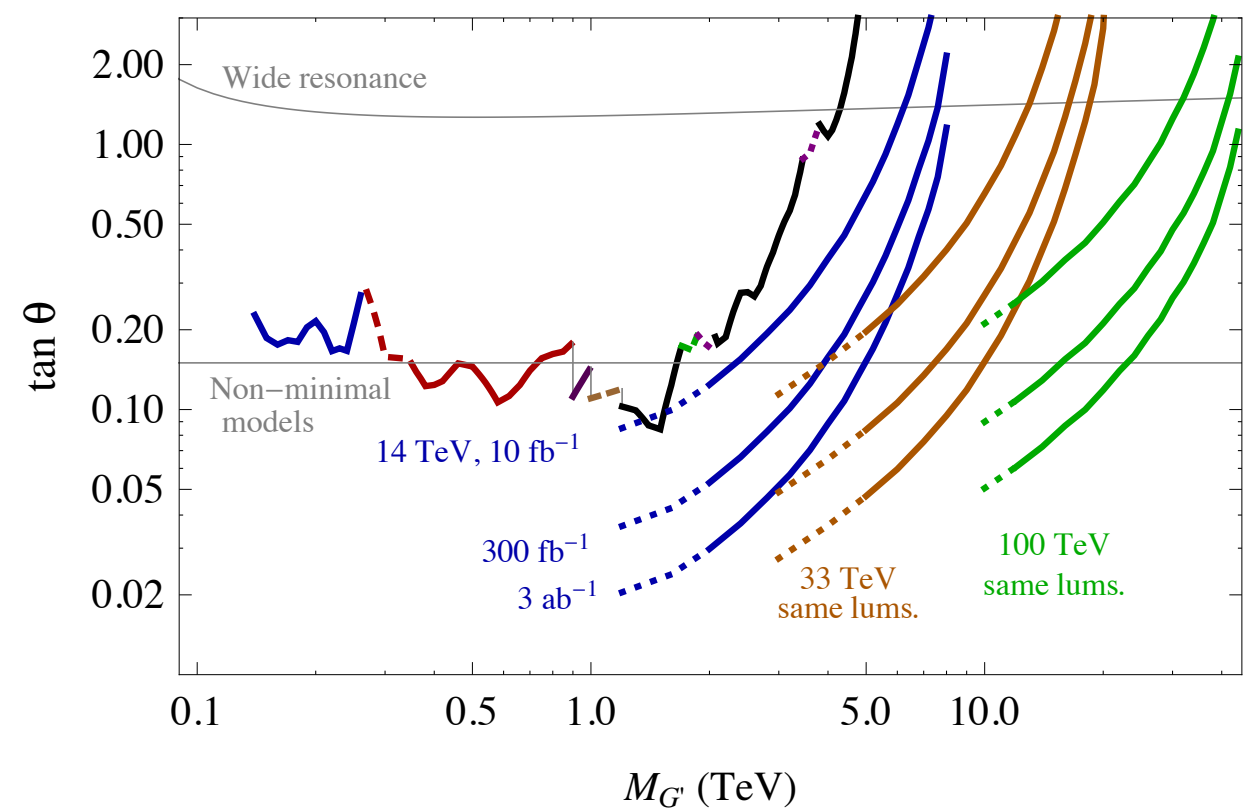
Colorful naturalness

Probing at 100 TeV:
...or for the UV physics

[Thamm, Torre, Wulzer]



[Felix Yu]



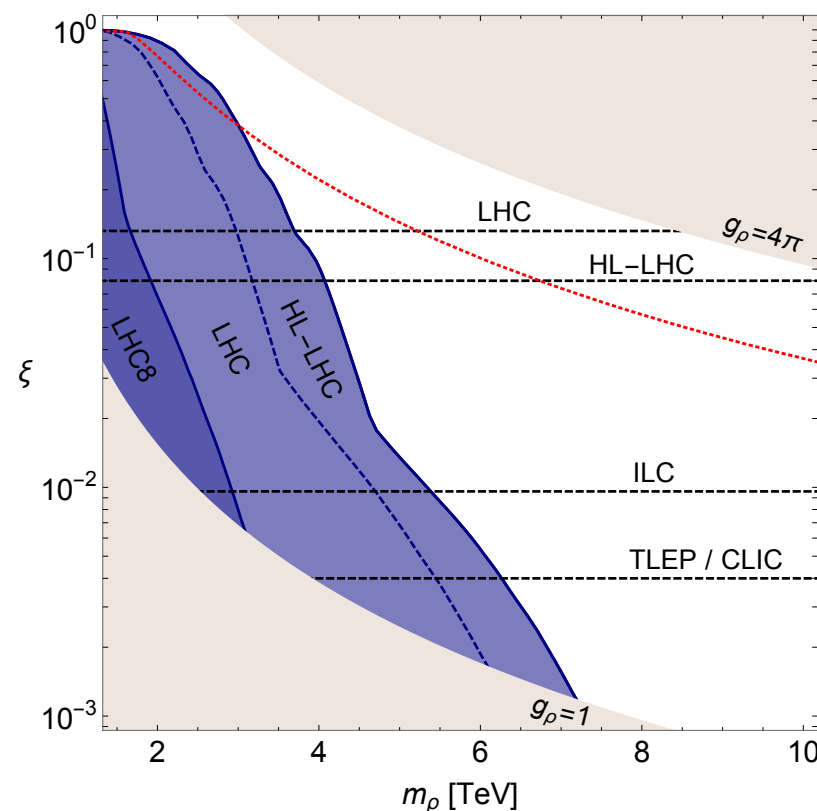
Even if light states are hard to find, can directly access heavy resonances

Neutral naturalness

Probing at a Higgs factory:

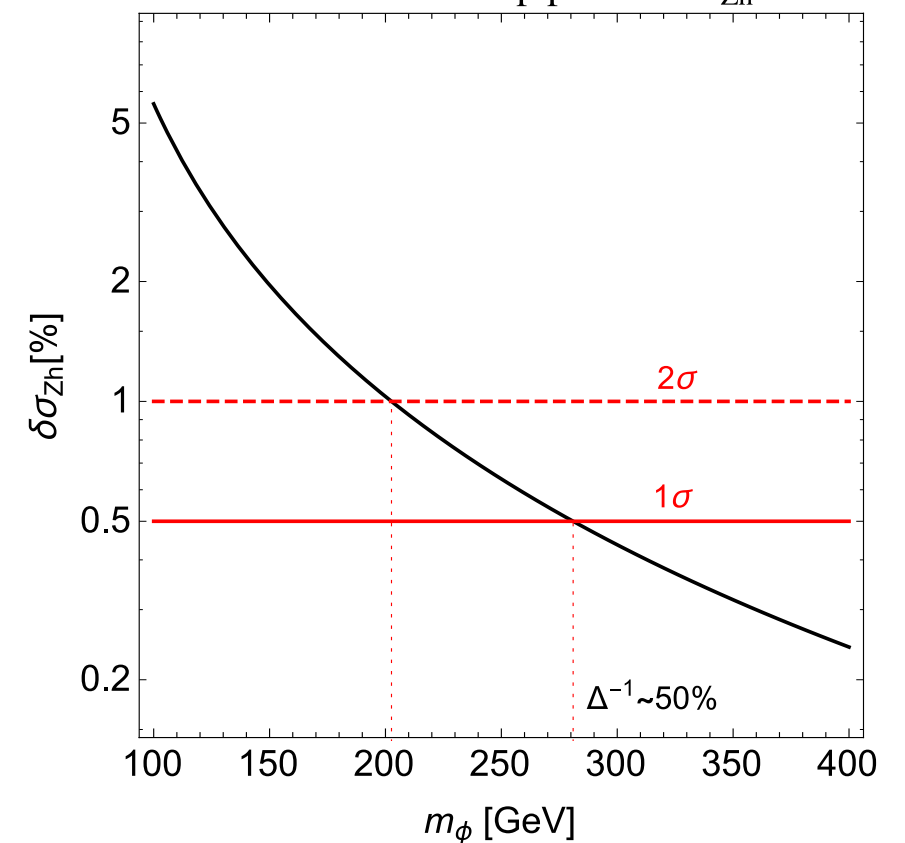
Look for $\mathcal{O}(\text{loop} \cdot v/m)$ oblique [SUSY] or $\mathcal{O}(v/f)$ [global] Higgs coupling deviations.

[Thamm, Torre, Wulzer]



[NC, Englert, McCullough]

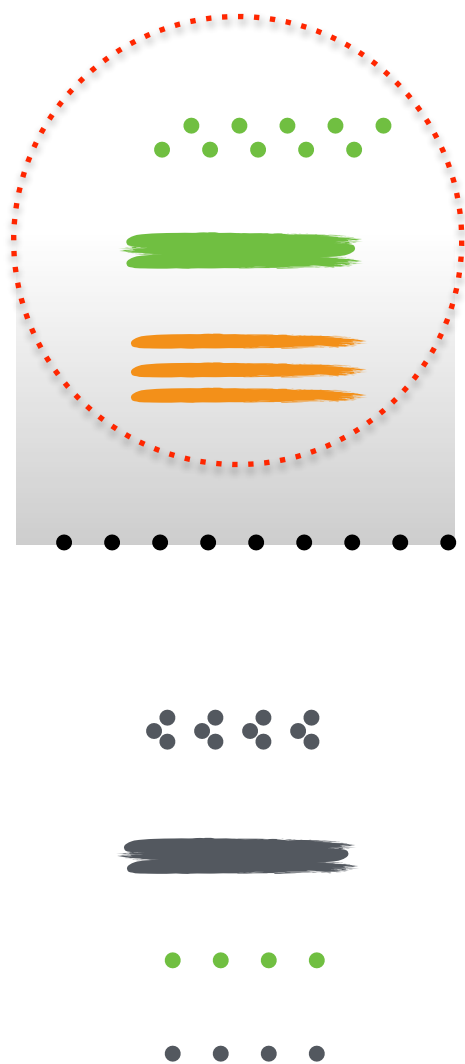
Neutral scalar top partner $\delta\sigma_{Zh}$



Where we'll be @ Higgs factory:

~1% level (global)
~50% level (SUSY)

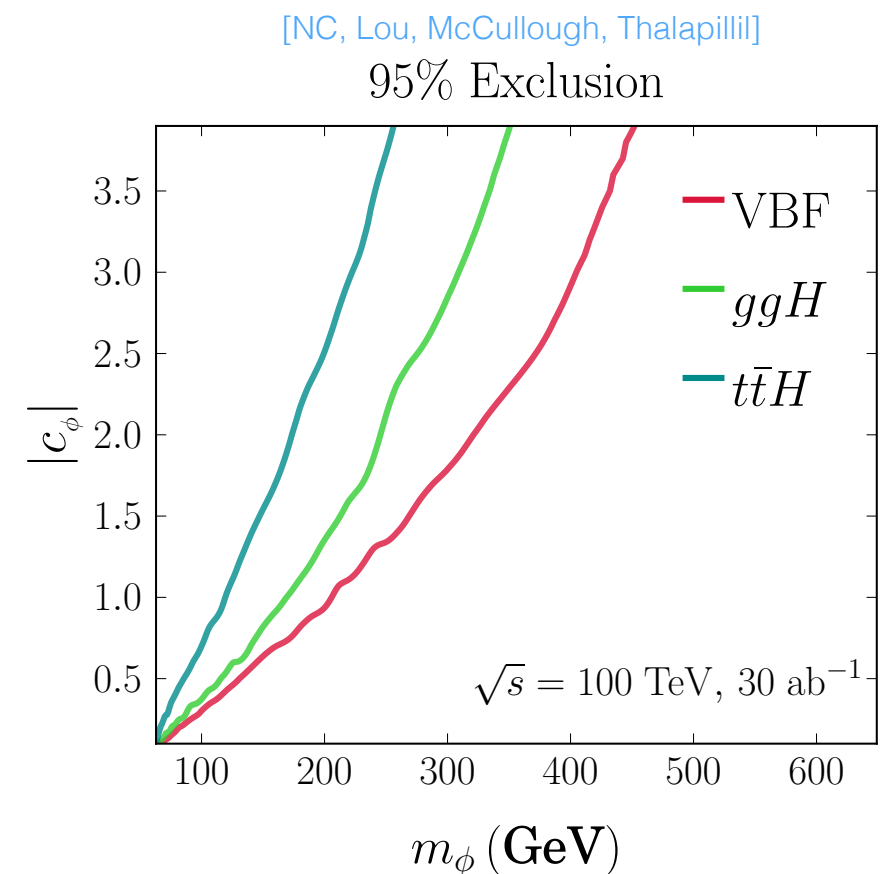
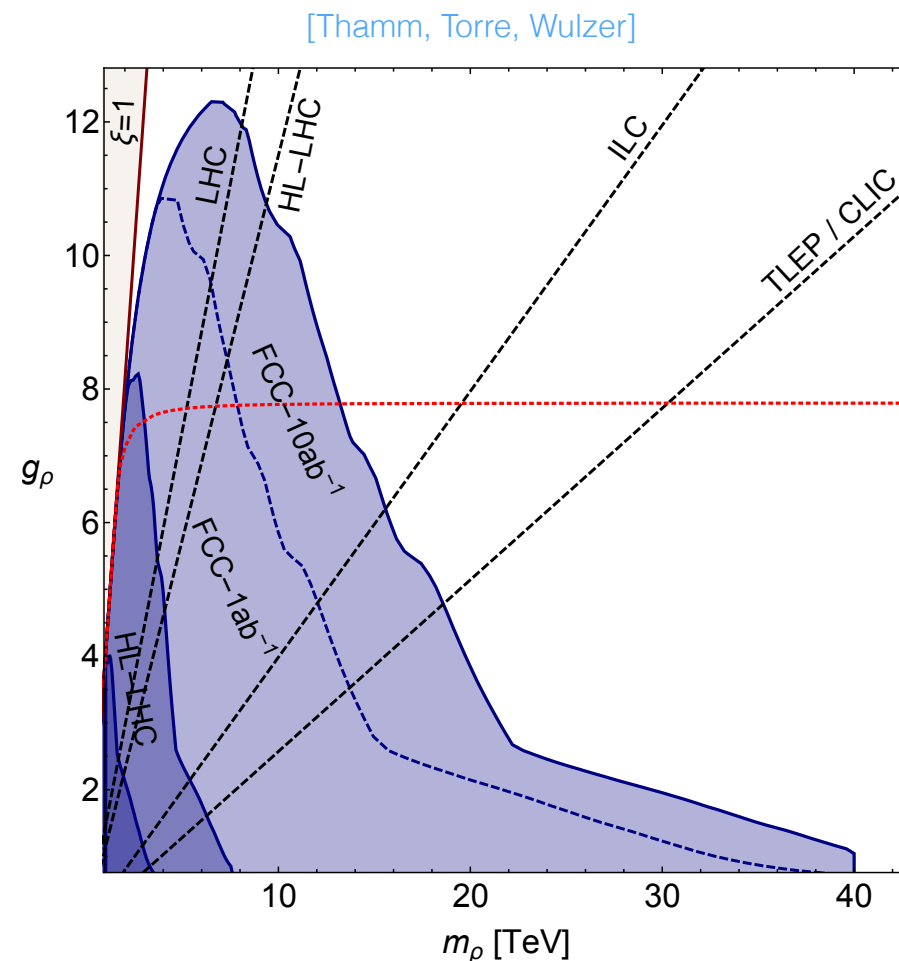
Even if the light natural states are neutral, there are heavier states with SM charges



Neutral naturalness

Probing at 100 TeV

Look for the UV completion, or probe light states via the Higgs portal.



Where we'll be @ 100 TeV:

~1% level

Conclusions

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Conclusions

- Naturalness is one of the most compelling motivations for new physics near the weak scale.
- The LHC will eventually probe conventional “colorful” theories to (at best) the $\sim 1\%$ level.
- But it will leave kinematic regions in conventional theories — and all regions of more novel theories — essentially untested, and the status of naturalness truly unresolved.
- A Higgs factory & 100 TeV collider can uniformly probe natural symmetry-based theories to the $\sim 1\%$ level with powerful complementarity.