Much Ado About Naturalness

Nathaniel Craig
UC Santa Barbara

KITP EnerVac19

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The Naturalness Strategy

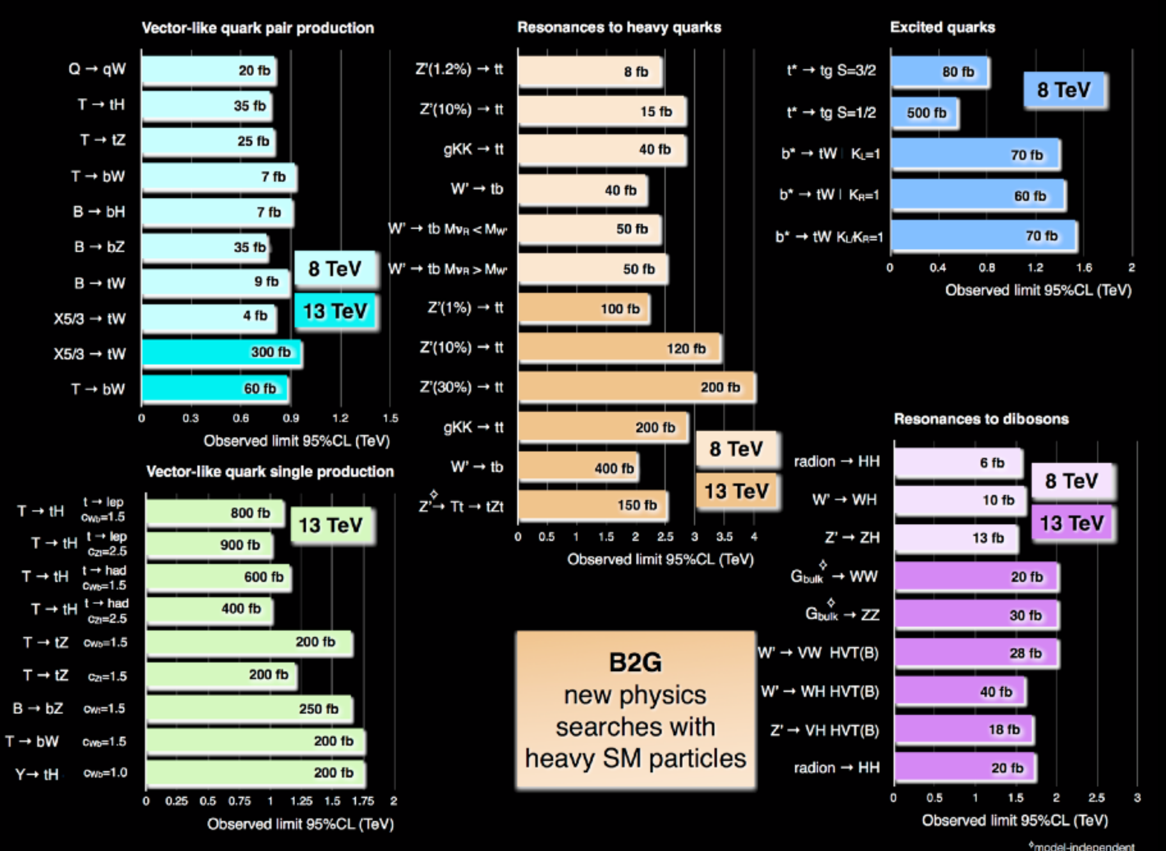
Param	UV sensitivity	Natural if	NP	Scale	Natural?
“m_e”	$e^2\Lambda$	Λ ≲ 5 MeV	Positron	511 keV	✓
$m_{\pi\pm}^2$ - $m_{\pi 0}^2$	$\frac{3\alpha}{4\pi}\Lambda^2$	Λ ≲ 850 MeV	Rho	770 MeV	✓
m_{KL}-m_{KS}	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4}\Lambda^2$	Λ ≲ 2 GeV	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2}\Lambda^2 + \dots$	Λ ≲ 500 GeV	?	?	?

Implementation is up to us

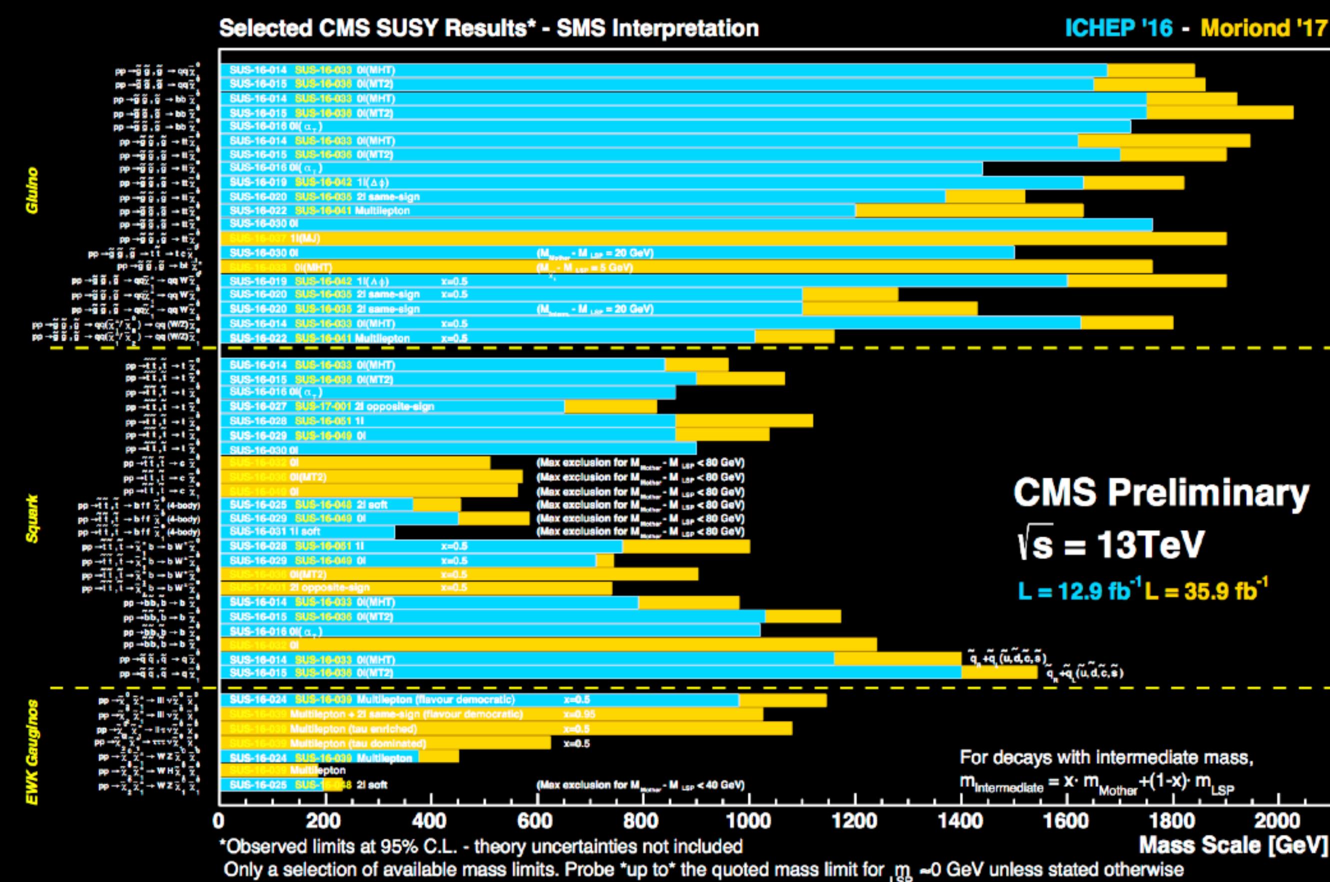
We've refined this strategy using some rules of thumb, *for example…*

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

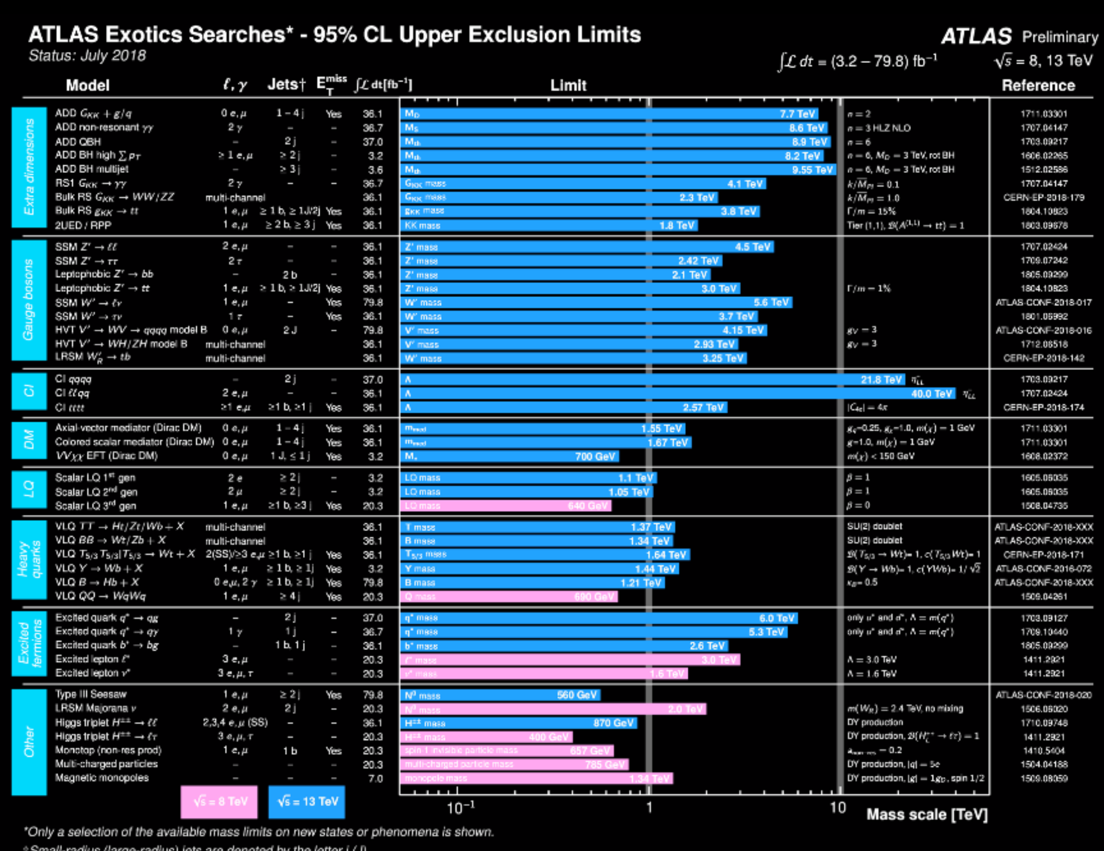
Thus far…



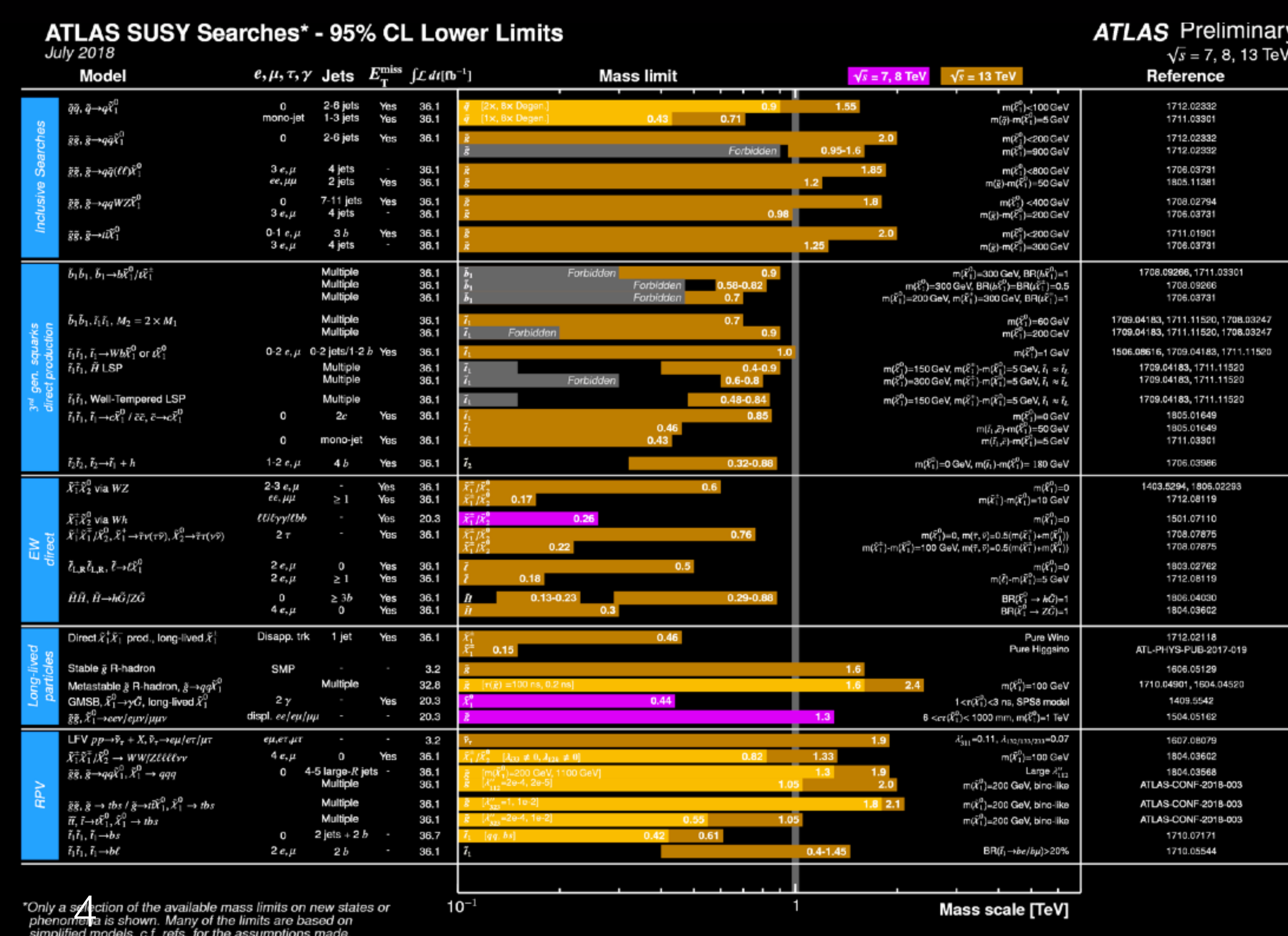
Vector-like quark pair production
Resonances to heavy quarks
Excited quarks
8 TeV
13 TeV
Observed limit 95%CL (TeV)
Vector-like quark single production
Resonances to dibosons
B2G
new physics
searches with
heavy SM particles
*model-independent



Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
Mass Scale [GeV]
*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_LSP ~0 GeV unless stated otherwise



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: July 2018
ATLAS Preliminary
√s = 8, 13 TeV
Model
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
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).



ATLAS SUSY Searches* - 95% CL Lower Limits
July 2018
ATLAS Preliminary
√s = 7, 8, 13 TeV
Model
Jets
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
Mass scale [TeV]
*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.

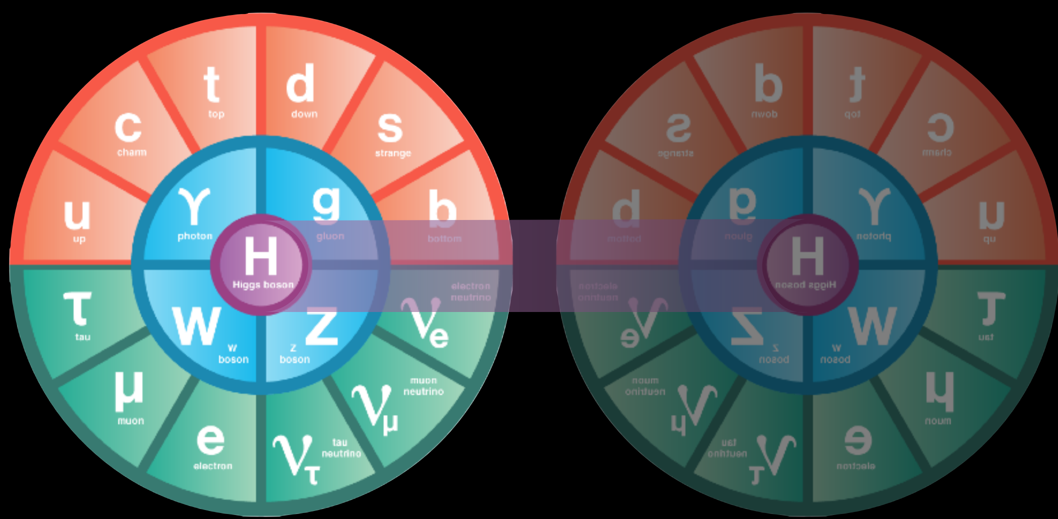
Rules of thumb probably still correct; continuing to test them experimentally is an excellent idea. But it is hard to say much new along these lines, so null results invite exploring other avenues.

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.~~

Discrete symmetries



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

Higgs is a pNGB of an accidental SU(4), but spectrum only respects a Z_2

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

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

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

Why Not?

Higgs portal maintains equilibrium down to T~GeV

$\Delta N_{eff} >> 1$

Options are

Change the cosmology

Signals in CMB: N_{eff}, $\sum m_{\nu}$, twin BAO…

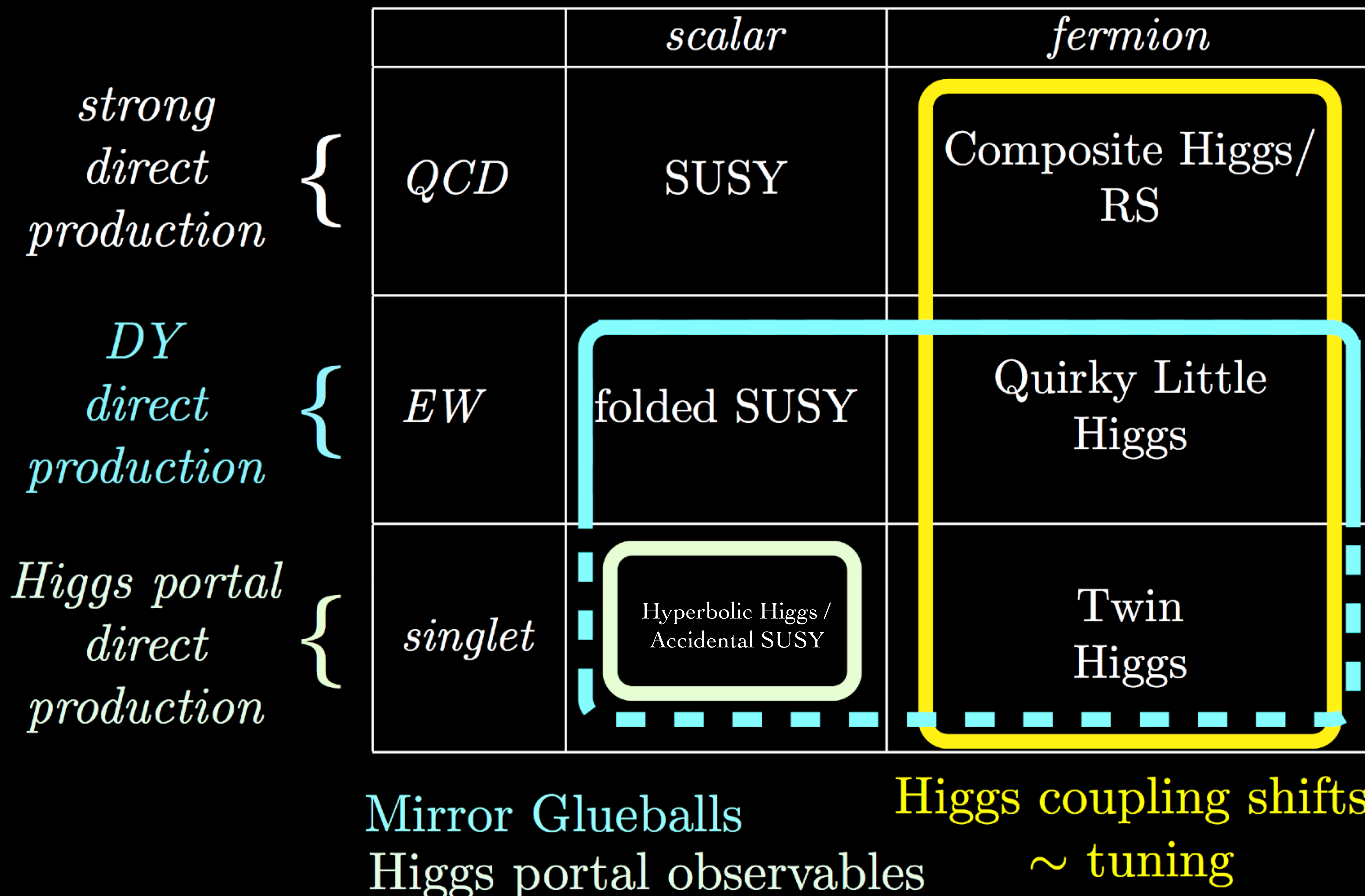
- RHN decay
- Saxion decay
- Early ν' decoupling

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

Change the spectrum

Copious new physics at ~few TeV
Higgs signals @ LHC

- Fraternal Twin Higgs
- Holographic Twin Higgs
- Composite Twin Higgs
- Orbifold Higgs
- …



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

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

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Relaxion

What if the weak scale is selected by scanning?

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

The solution: what turns on when m_H^2 goes negative?

Vev gives quark masses which contribute to axion potential.

"Relaxion"

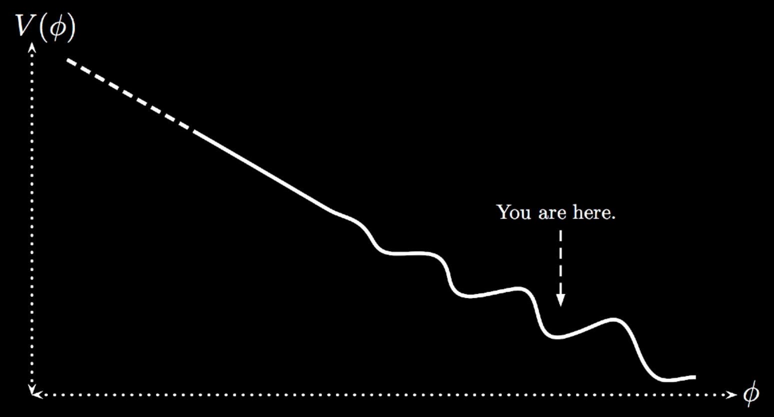
[Graham, Kaplan, Rajendran '15]

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

[Graham, Kaplan, Rajendran '15]

Relaxion

Simplest version: an axion coupled to QCD during inflation.



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

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

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

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

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

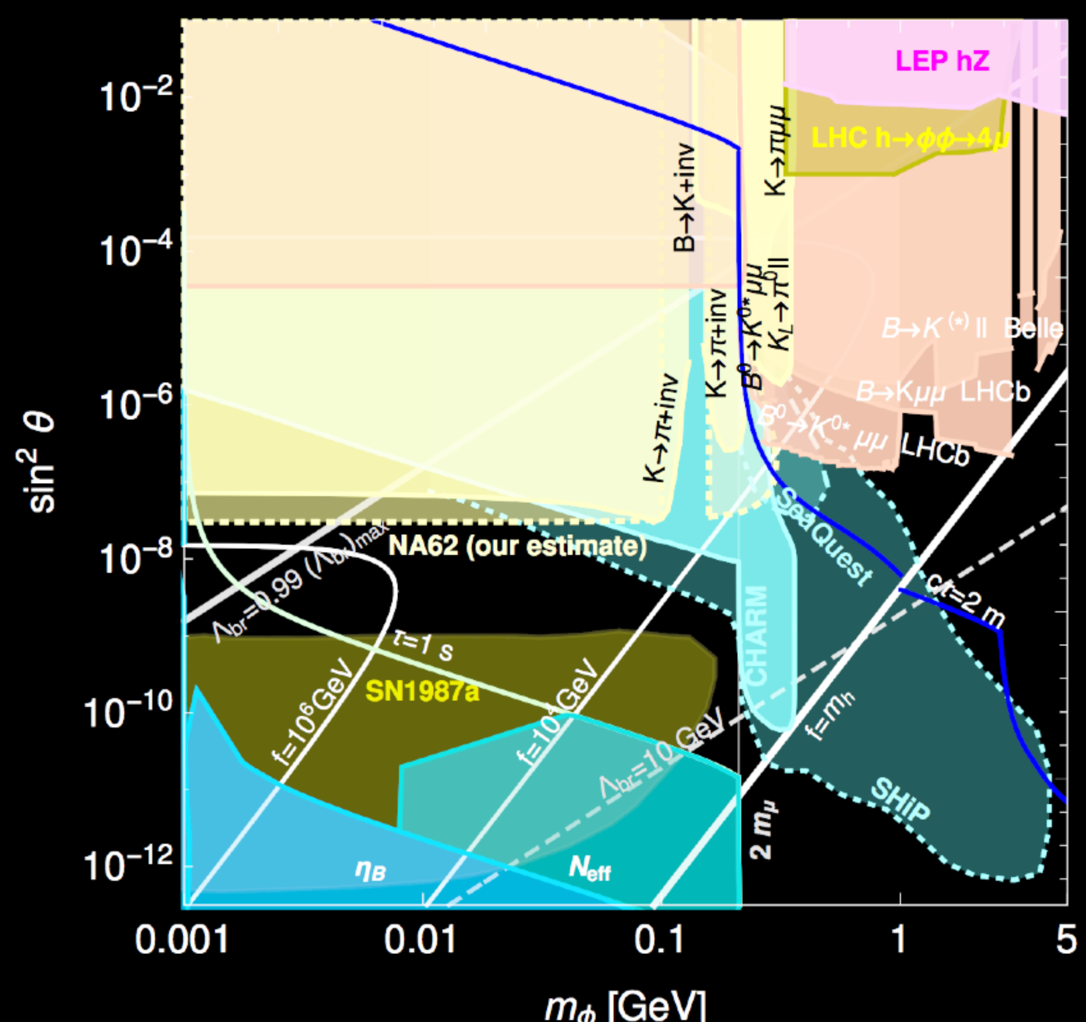
See also: NNaturalness [Arkani-Hamed et al. '16]

New Signals

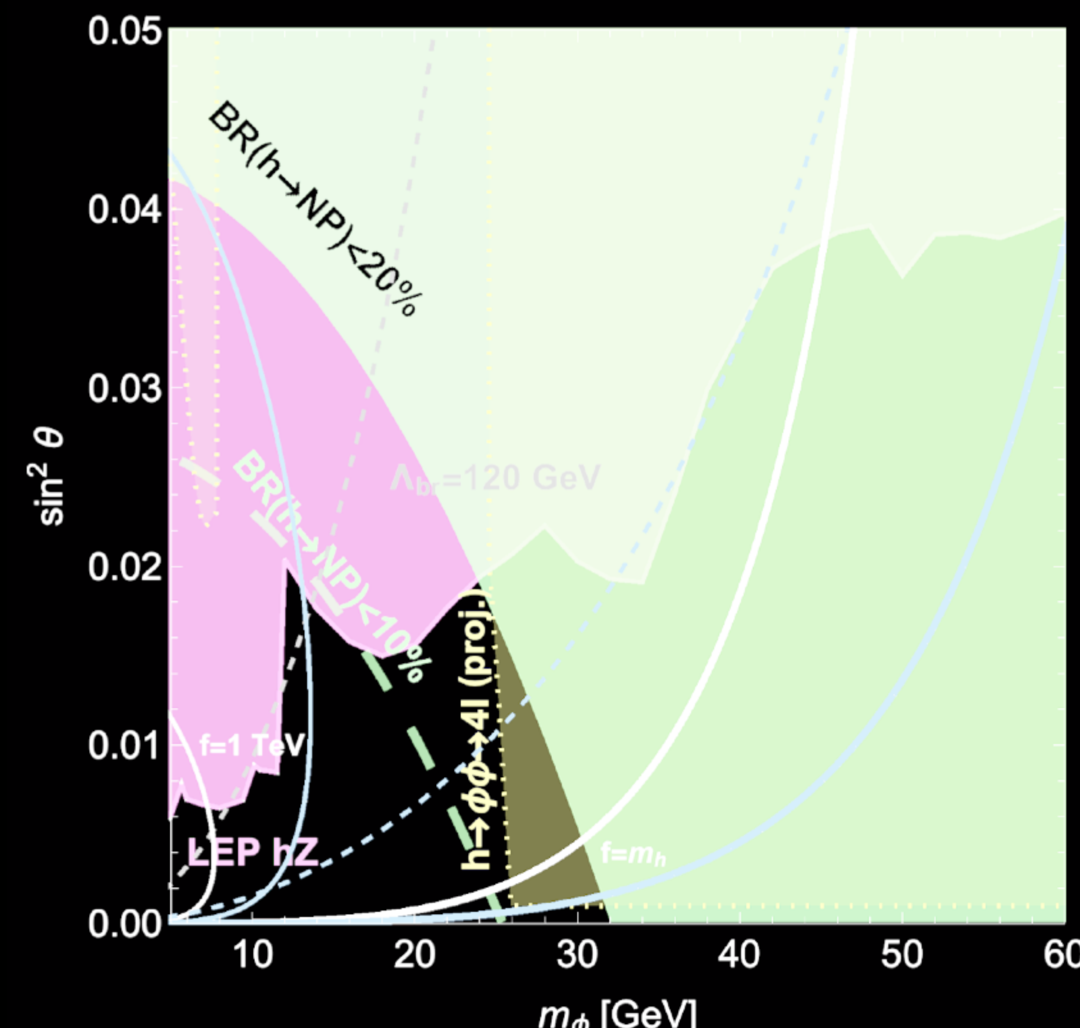
Higgs portals $g\phi|H|^2$ $\Lambda^4(H)\cos(\phi/f)$

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

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



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



+5th force for m_ϕ < eV & cosmology for eV < m_ϕ < MeV

**assuming ⟨ϕ⟩ breaks CP*

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

Particle production relaxion

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

Novel source of dissipation: particle production

Consider axion-like couplings to massive gauge field: $$\mathcal{L} \supset -\frac{\phi}{4f} F\tilde{F}$$

E.O.M. for transverse polarizations: $$\ddot{A}_\pm + \left(k^2 + m_A^2 \pm \frac{k\dot{\phi}}{f}\right) A_\pm = 0$$

For $\dot{\phi} \approx \text{constant}$ $\quad A_\pm(k) \propto e^{i\omega_\pm t}$ $\quad \omega_\pm^2 = k^2 + m_A^2 \pm \frac{k\dot{\phi}}{f}$

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

Growing mode drains energy from ϕ

Particle production relaxion

Apply to relaxion: use electroweak gauge fields

Instead of

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

+ inflation

$\Rightarrow$

Use coupling to EWK gauge bosons:

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

Exponential production of EWK gauge bosons around h~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)$_L$ x SU(2)$_R$*)

Requiring sub-Planckian field excursions & avoiding overshoot bounds cutoff

$$\Lambda \lesssim (M_{\rm Pl} v^5)^{1/6} \sim 50\,{\rm TeV}$$

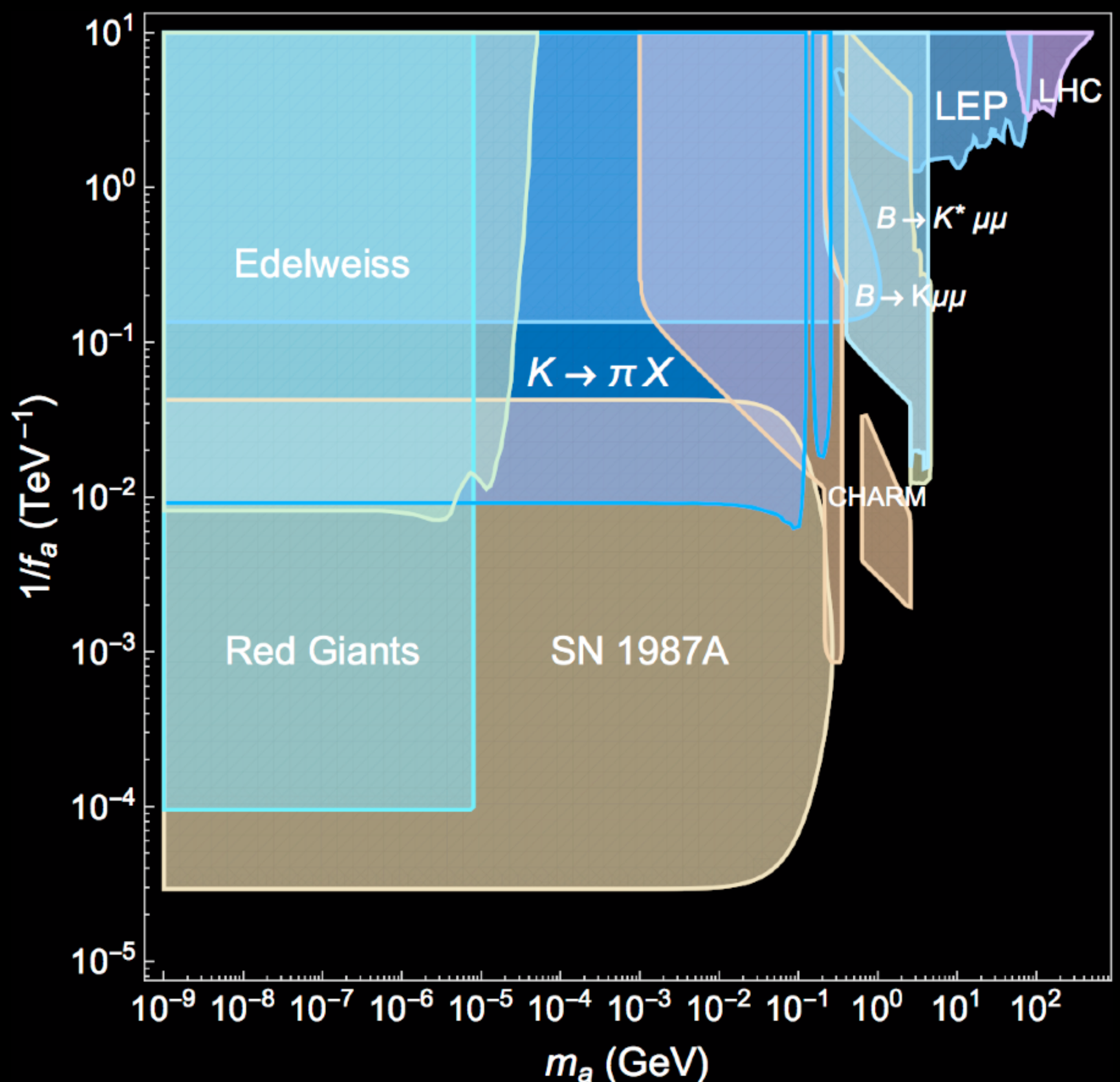
Corresponding decay constant

$$f \sim \frac{\dot{\phi}}{v} \sim \frac{\Lambda^2}{v} \lesssim 10^4\,{\rm TeV}$$

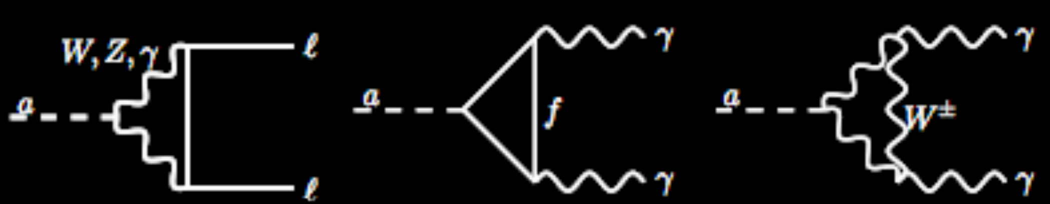
New Signals

Even if tree-level relaxion couplings to SM states are engineered to be $\frac{\phi}{f}\left(g^2 W\widetilde{W} - g'^2 B\widetilde{B}\right)$ in the UV…

[NC, Hook, Kasko '18]



…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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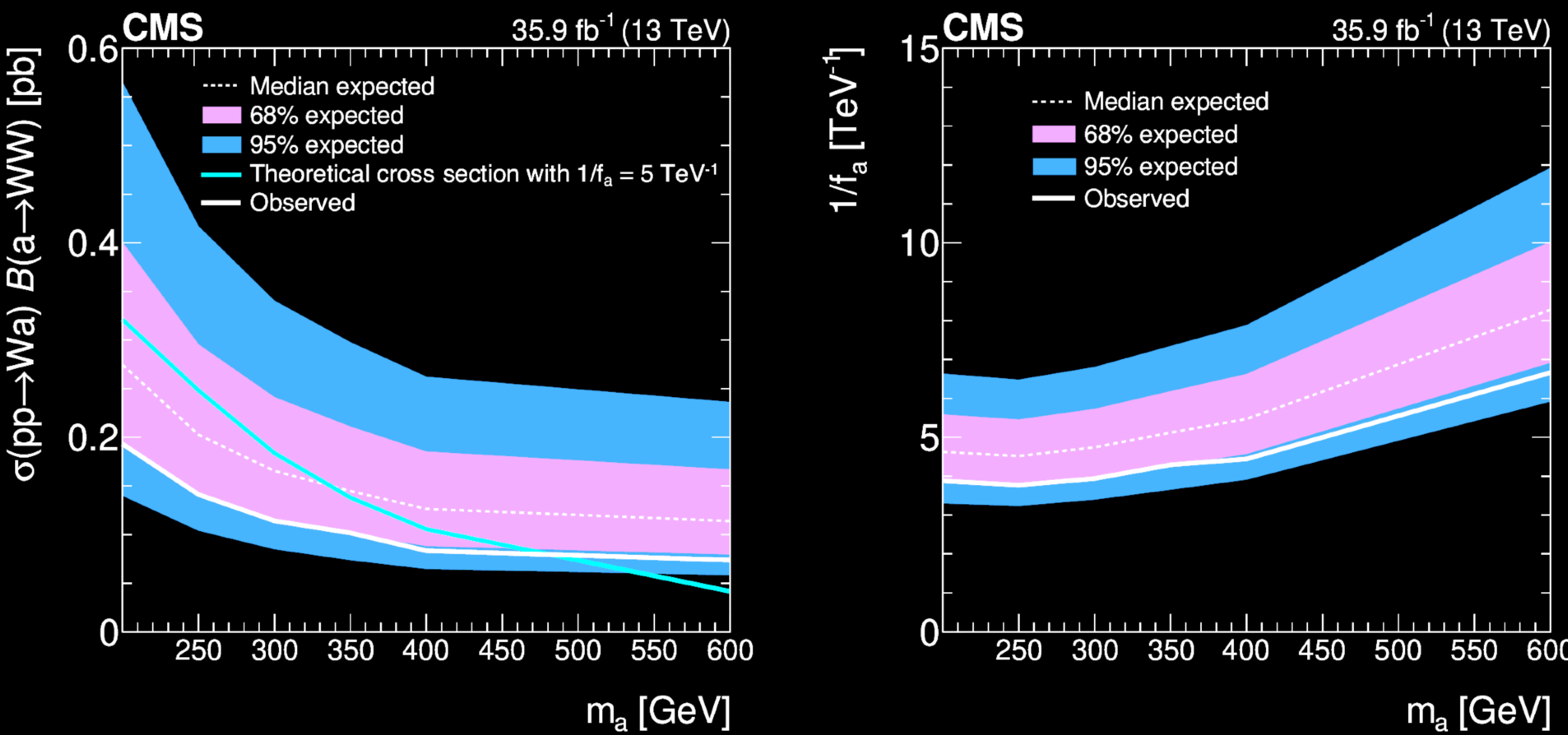

CMS
35.9 fb-1 (13 TeV)
σ(pp→Wa) B(a→WW) [pb]
0.6
0.4
0.2
0
250
300
350
400
450
500
550
600
m_a [GeV]
Median expected
68% expected
95% expected
Theoretical cross section with 1/f_a = 5 TeV-1
Observed
CMS
35.9 fb-1 (13 TeV)
1/f_a [TeV-1]
15
10
5
0
250
300
350
400
450
500
550
600
m_a [GeV]
Median expected
68% expected
95% expected
Observed

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Indirect UV/IR: WGC

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

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

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

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

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

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

If lightest neutrino is WGC particle, $m_\nu \sim 0.1$ eV, $q \gtrsim 10^{-29}$

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

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

Indirect UV/IR: WGC

Things that could go wrong:

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

Thing that certainly goes wrong:

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

Indirect UV/IR: WGC

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

New $U(1)_X$ plus matter acquiring some mass from the Higgs. E.g…

[NC, Garcia Garcia, Koren '19]

	$SU(2)_L$	$U(1)_Y$	$U(1)_X$
L	$\Box$	$+1/2$	$+1$
L^c	$\Box$	$-1/2$	-1
N	-	0	$+1$
N^c	-	0	-1

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

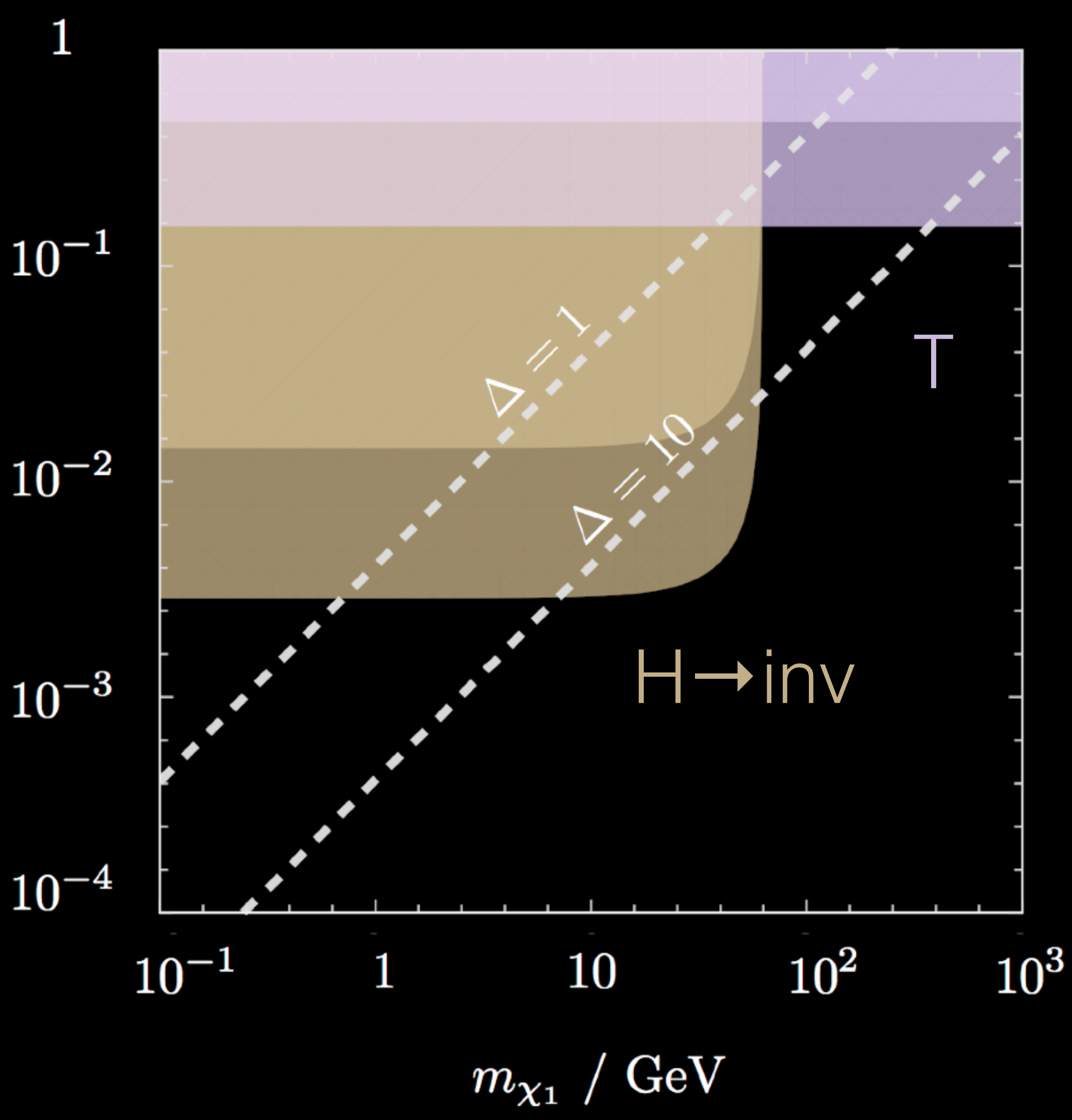
Best option: $m_N < m_L$, lightest mass eigenstate χ_1 is WGC particle

Then for fixed (technically natural) g, m_L, m_N, y,

$$v^2 \lesssim \frac{2}{y^2}\left(m_{\chi_1}^2 + m_{\chi_1}(m_L - m_N) - m_L m_N\right)$$

Indirect UV/IR: WGC

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



Quantify with e.g. $$\Delta_x \equiv \left| \frac{\partial \log v^2}{\partial \log x} \right|$$

Here $$\Delta_{\max} \sim \frac{m_N m_L}{y^2 v^2}$$

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

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

DM story interesting…

Indirect UV/IR: WGC

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

E.g. t' Hooft-Polyakov monopoles $SU(2)_X \underset{\langle \mathrm{Adj} \rangle}{\rightarrow} U(1)_X$

$$\text{“}\Lambda\text{”} = m_W = g_2 f = 2gf \lesssim 2gM_{\mathrm{Pl}}$$

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

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

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

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

Direct UV/IR Mixing

Take the bull by the horns…

Study field theories with UV/IR mixing

Canonical example:

QFT on non-commutative spacetime $[\hat{x}^\mu, \hat{x}^\nu] = i\theta^{\mu\nu}$

UV/IR mixing from “uncertainty principle” $\Delta\hat{x}^\mu \Delta\hat{x}^\nu \geq \frac{1}{2}\left|\theta^{\mu\nu}\right|$

Caveats: Lorentz violating; Minkowski NCQFT unitary only for space-space non-commutativity (i.e. $\theta^{0i}=0$).

Not the theory of our universe, but a useful toy model. (See e.g. [Heckman & Verlinde ’14])

NCQFT

Two common approaches:

1. QFT on commutative coordinates w/ star product:

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

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

I.e., $f \star g = f \cdot g + \frac{i}{2}\theta^{\mu\nu}\partial_\mu \cdot \partial_\nu g + \mathcal{O}(\theta^2)$ and e.g.

$$\hat{A}_\mu[A] = A_\mu + \frac{1}{4}\theta^{\rho\sigma}\{A_\sigma, \partial_\rho A_\mu\} + \frac{1}{4}\theta^{\rho\sigma}\{F_{\rho\mu}, A_\sigma\} + \mathcal{O}(\theta^2)$$

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

[Filk '96]

NCQFT: ϕ^4

Consider just ϕ^4 in Euclidean d=4:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 + \frac{1}{2} m^2 \phi^2 + \frac{1}{4!} g^2 \phi \star \phi \star \phi \star \phi$$

Quadratic terms identical to commutative theory

Interactions associated w/ additional phases:

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

Not invariant under arbitrary permutations of k

Planar graphs: reduces to an overall phase involving external momenta

Nonplanar graphs: additional phases from crossing lines

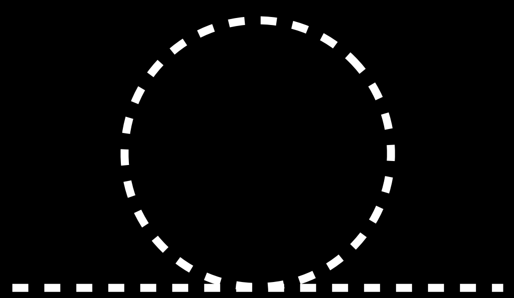
Feynman rules as usual modulo phases in nonplanar diagrams:

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

[Minwalla, Seiberg, Van Raamsdonk '99]

NCQFT: ϕ^4

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

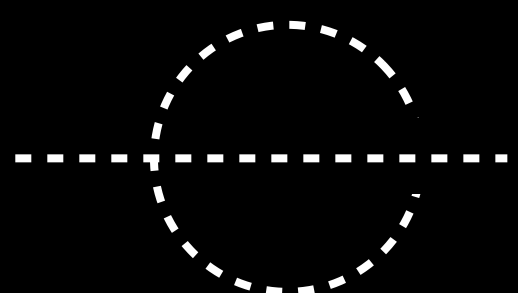


$$\sim \int \frac{d^4k}{k^2}$$

UV divergent

$$\Gamma_1^{2,p} = \frac{g^2}{48\pi^2}\left(\Lambda^2 - m^2 \log\left(\frac{\Lambda^2}{m^2}\right) + \ldots\right)$$

Akin to commutative theory



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

IR divergence!

$$\Gamma_1^{2,np} = \frac{g^2}{96\pi^2}\left(\Lambda_{\text{eff}}^2 - m^2 \log\left(\frac{\Lambda_{\text{eff}}^2}{m^2}\right) + \ldots\right)$$

Likewise, but with $\Lambda \to \Lambda_{eff}$

Appearance of a new "scale":

$$\Lambda_{\text{eff}}^2 = \frac{1}{1/\Lambda^2 + p \circ p}$$

$$\Lambda_{\text{eff}}^2 \to \begin{cases} \Lambda^2 & p \circ p \to 0 \\ \frac{1}{p \circ p} & \Lambda \to \infty \end{cases}$$

where $p \circ k = |p^\mu \theta_{\mu\nu}^2 k^\nu|$

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

New "poles"

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

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

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

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

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

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

[Minwalla, Seiberg, Van Raamsdonk '99]

Wilsonian interpretation

Normally require renormalizable Wilsonian action to satisfy

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

Badly violated here *at small p.*

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

Restore Wilsonian interpretation w/ new particle χ:

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

Quadratic, so integrate out:

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

What have we learned?

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

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

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

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

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

Conclusions

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Relaxing these rules of thumb is constructive and leads to new signatures associated with naturalness. Only beginning to explore the possibilities….

Conclusions

Hard not to notice patterns among the three naturalness problems…

	Hierarchy Problem	**CC Problem**	**Strong CP**
Continuous symm.	SUSY, global	SUSY	$U(1)_{PQ}$
Discrete symm.	Z_2	$E \to -E$	P/CP
Dynamical field	Relaxion	Abbott	$U(1)_{PQ}$
Anthropics	Atomic principle	Structure formation	?
UV/IR mixing	WGC/NCQFT/…	Holography	?

Thank you!