Predicting the Higgs Mass

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CERN-TH

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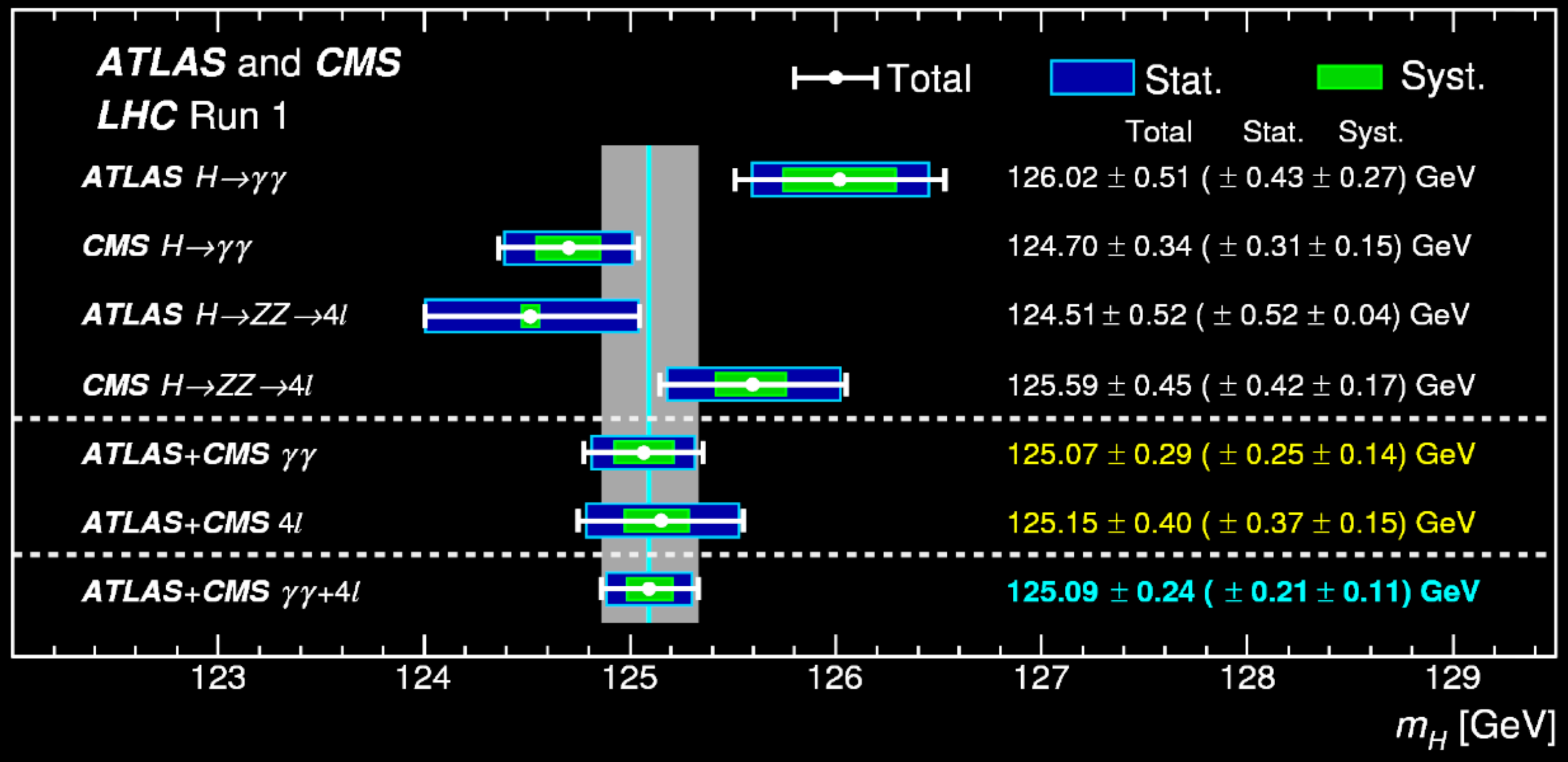
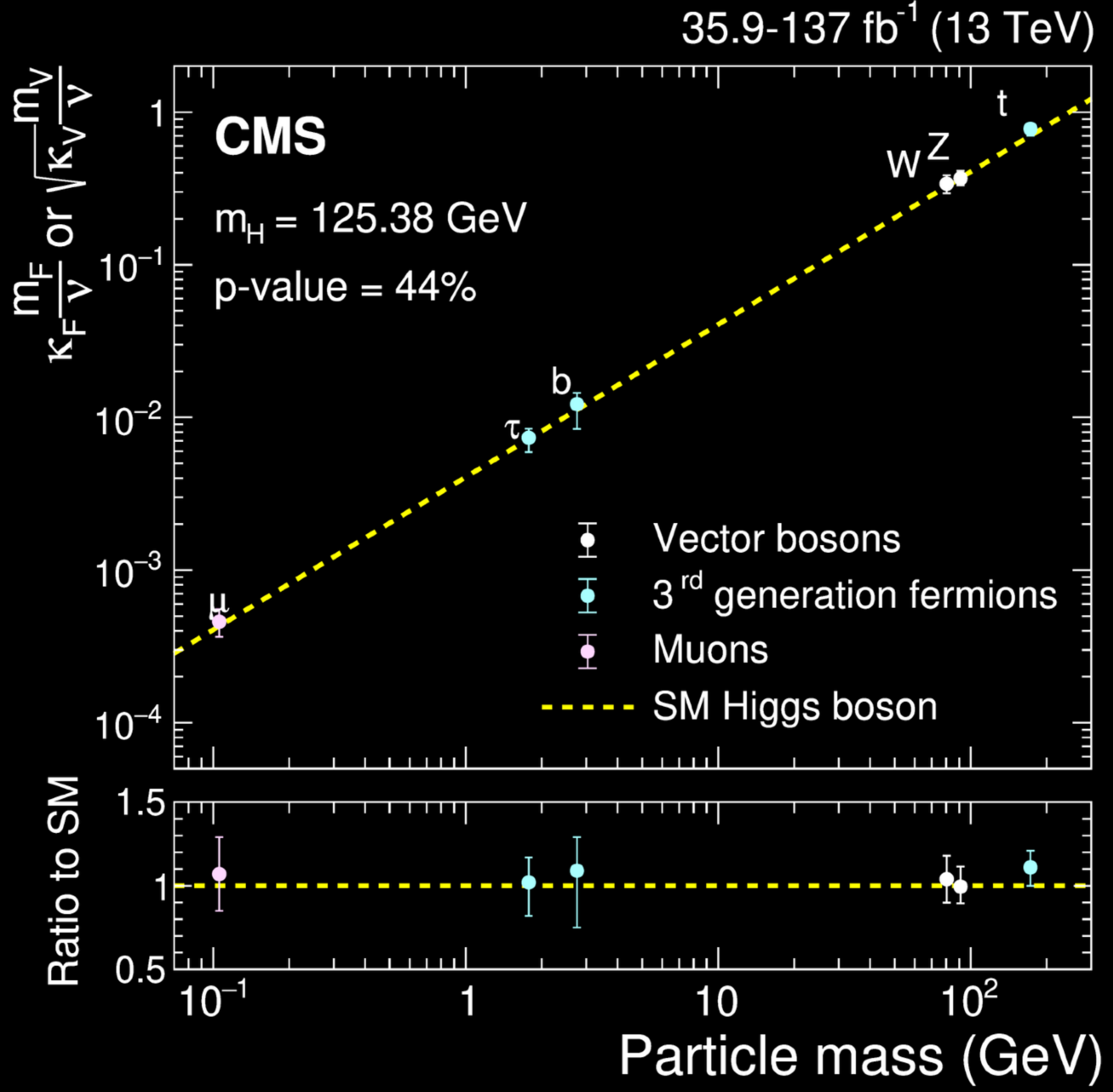
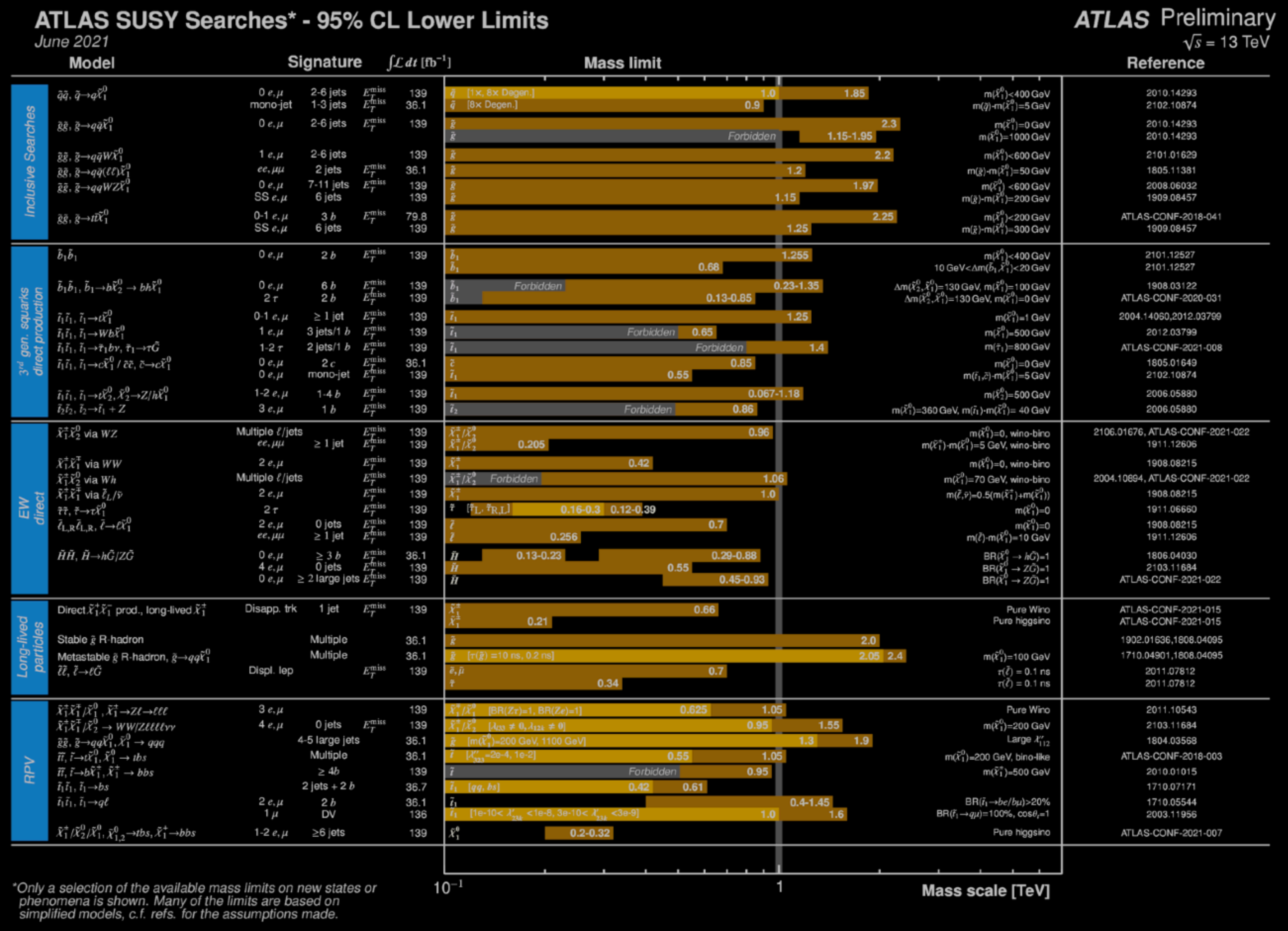
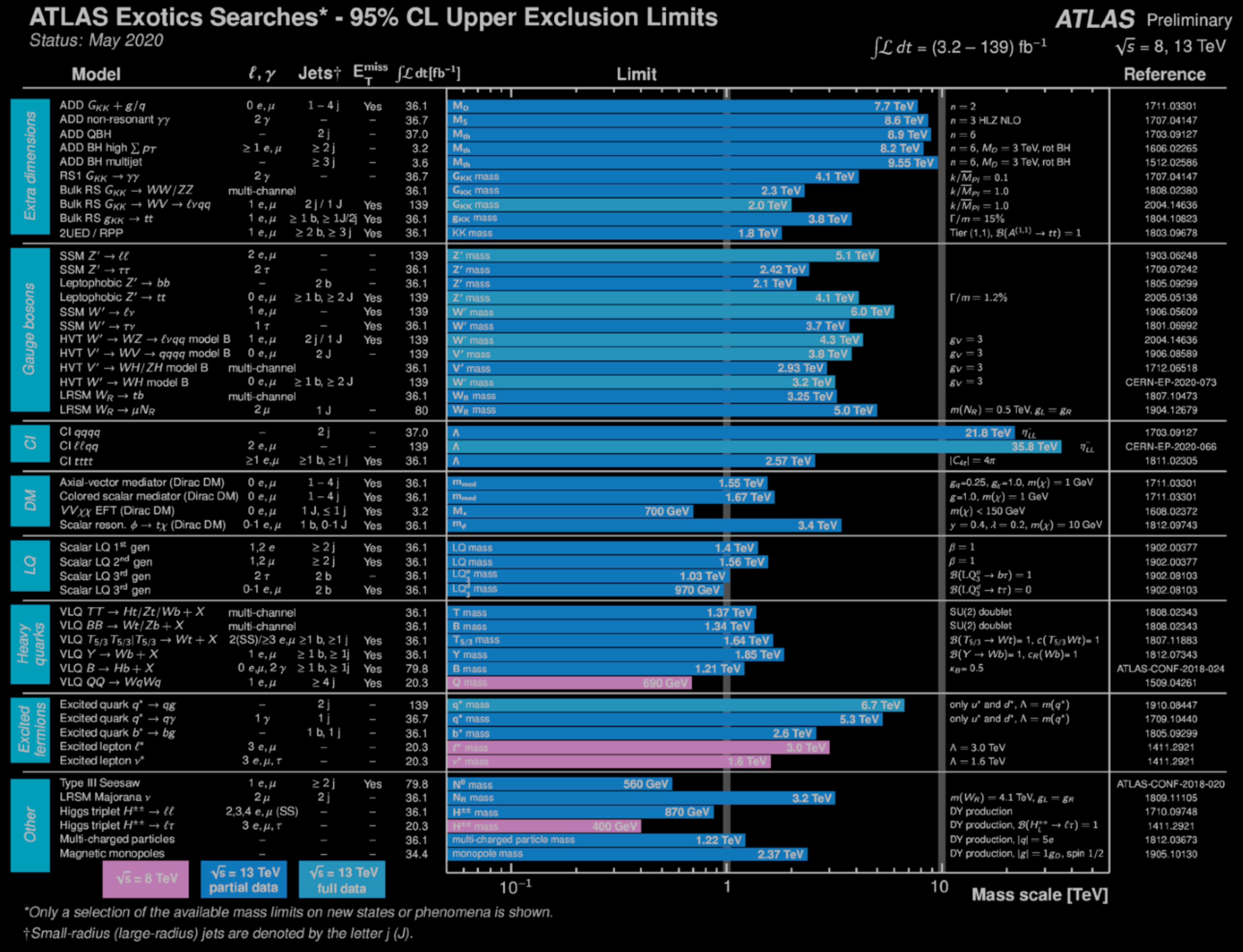

ATLAS and CMS
LHC Run 1
Total
Stat.
Syst.
Total Stat. Syst.
ATLAS H→γγ 126.02 ± 0.51 (± 0.43 ± 0.27) GeV
CMS H→γγ 124.70 ± 0.34 (± 0.31 ± 0.15) GeV
ATLAS H→ZZ→4l 124.51 ± 0.52 (± 0.52 ± 0.04) GeV
CMS H→ZZ→4l 125.59 ± 0.45 (± 0.42 ± 0.17) GeV
ATLAS+CMS γγ 125.07 ± 0.29 (± 0.25 ± 0.14) GeV
ATLAS+CMS 4l 125.15 ± 0.40 (± 0.37 ± 0.15) GeV
ATLAS+CMS γγ+4l 125.09 ± 0.24 (± 0.21 ± 0.11) GeV
123
124
125
126
127
128
129
m_H [GeV]


35.9-137 fb⁻¹ (13 TeV)
CMS
m_H = 125.38 GeV
p-value = 44%
κ_F m_F/v or √κ_V m_V/v
1
10⁻¹
10⁻²
10⁻³
10⁻⁴
t
W
Z
b
τ
μ
Vector bosons
3rd generation fermions
Muons
SM Higgs boson
Ratio to SM
1.5
1
0.5
10⁻¹
1
10
10²
Particle mass (GeV)

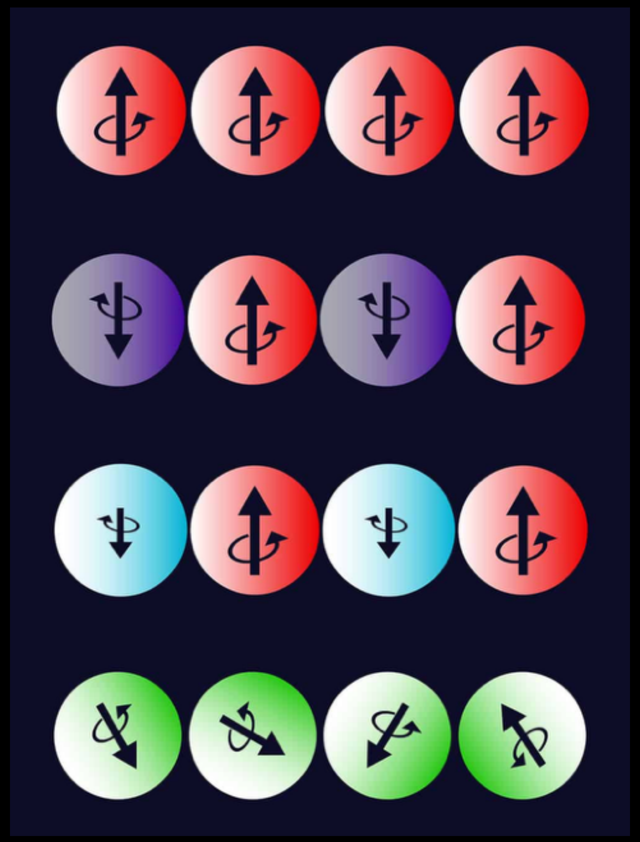
vs.


ATLAS SUSY Searches* - 95% CL Lower Limits
June 2021
ATLAS Preliminary
√s = 13 TeV
Model
Signature
∫L dt [fb⁻¹]
Mass limit
Reference
Inclusive Searches
3rd gen. squarks direct production
EW direct
Long-lived particles
RPV
*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.
10⁻¹
1
Mass scale [TeV]

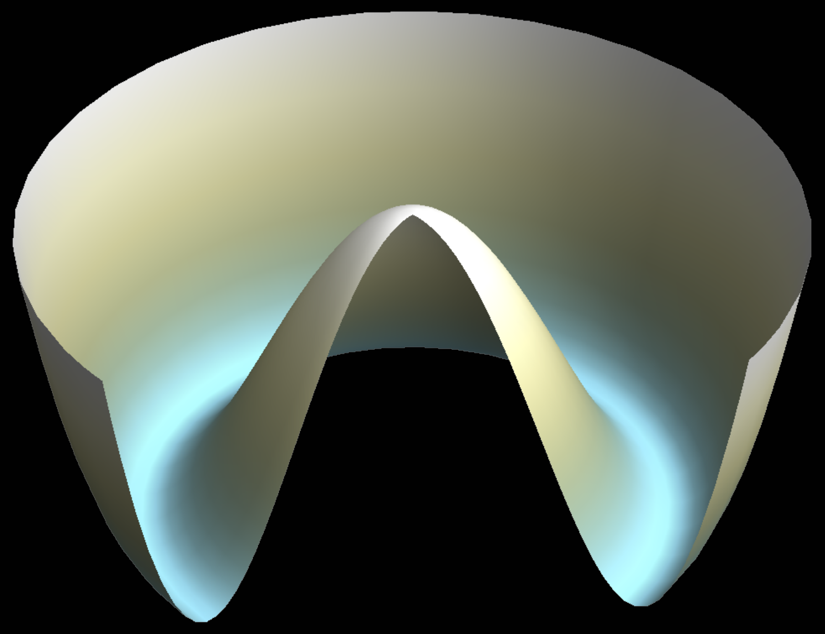

ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits
Status: May 2020
ATLAS Preliminary
∫L dt = (3.2 – 139) fb⁻¹
√s = 8, 13 TeV
Model
ℓ, γ
Jets†
E_T^miss
∫L dt[fb⁻¹]
Limit
Reference
Extra dimensions
Gauge bosons
CI
DM
LQ
Heavy quarks
Excited fermions
Other
√s = 8 TeV
√s = 13 TeV partial data
√s = 13 TeV full data
10⁻¹
1
10
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).

A Superconducting Analogy

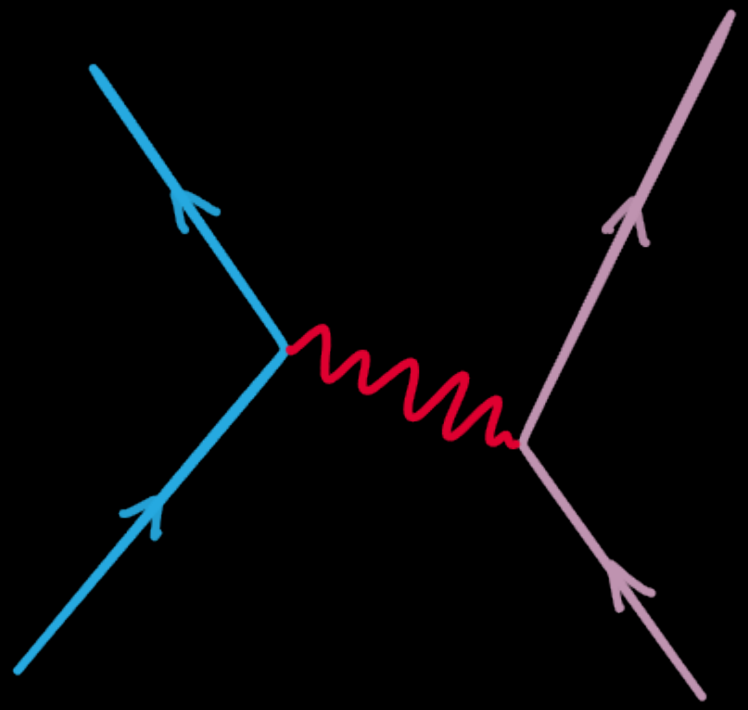
High-Tc Superconductors



Ginzburg-Landau Theory



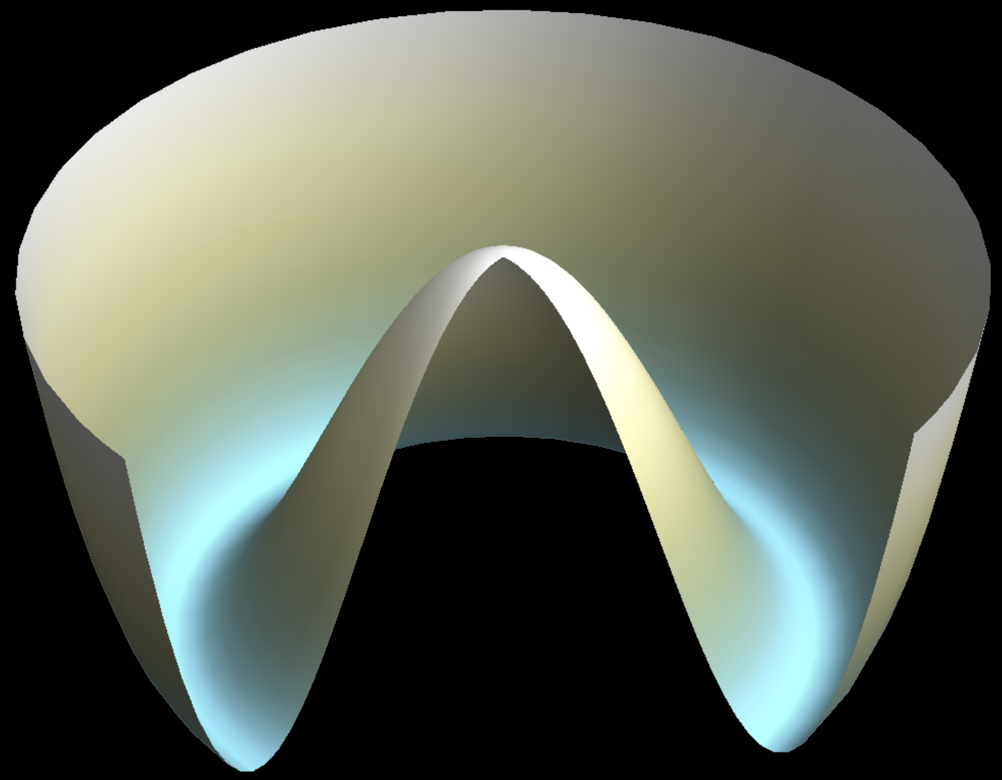
Low-Tc Superconductors (BCS)



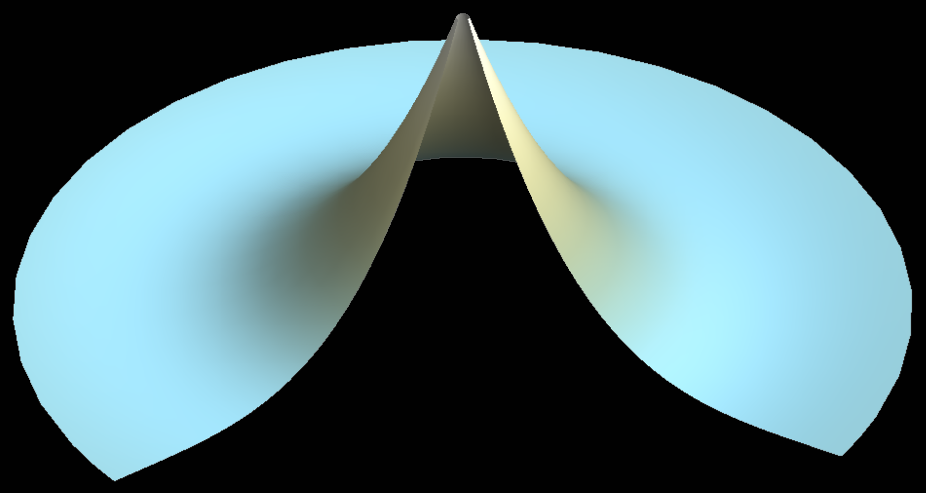
$$F = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \frac{1}{2m}|(-i\hbar\vec{\nabla} - g\vec{A})\psi|^2 + \ldots$$

> "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*

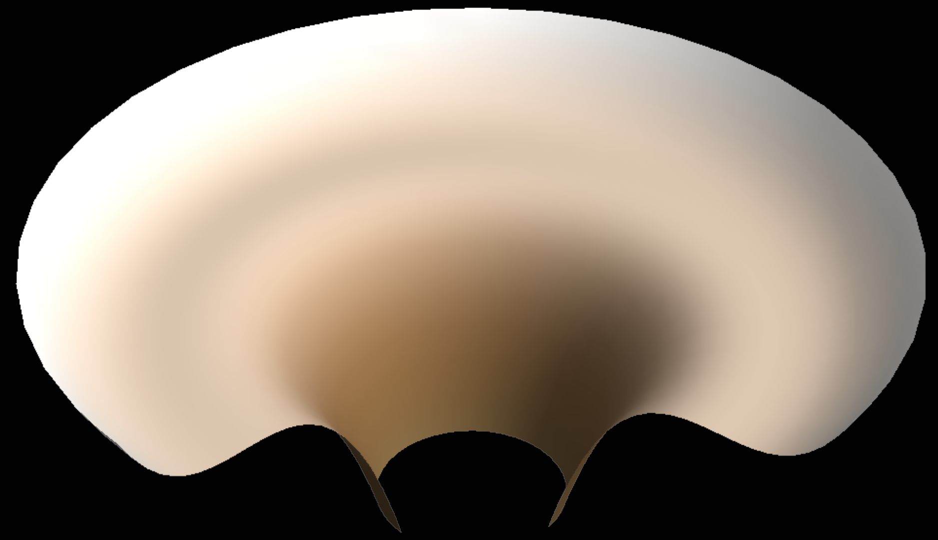
Is it even a Ginzburg-Landau model?

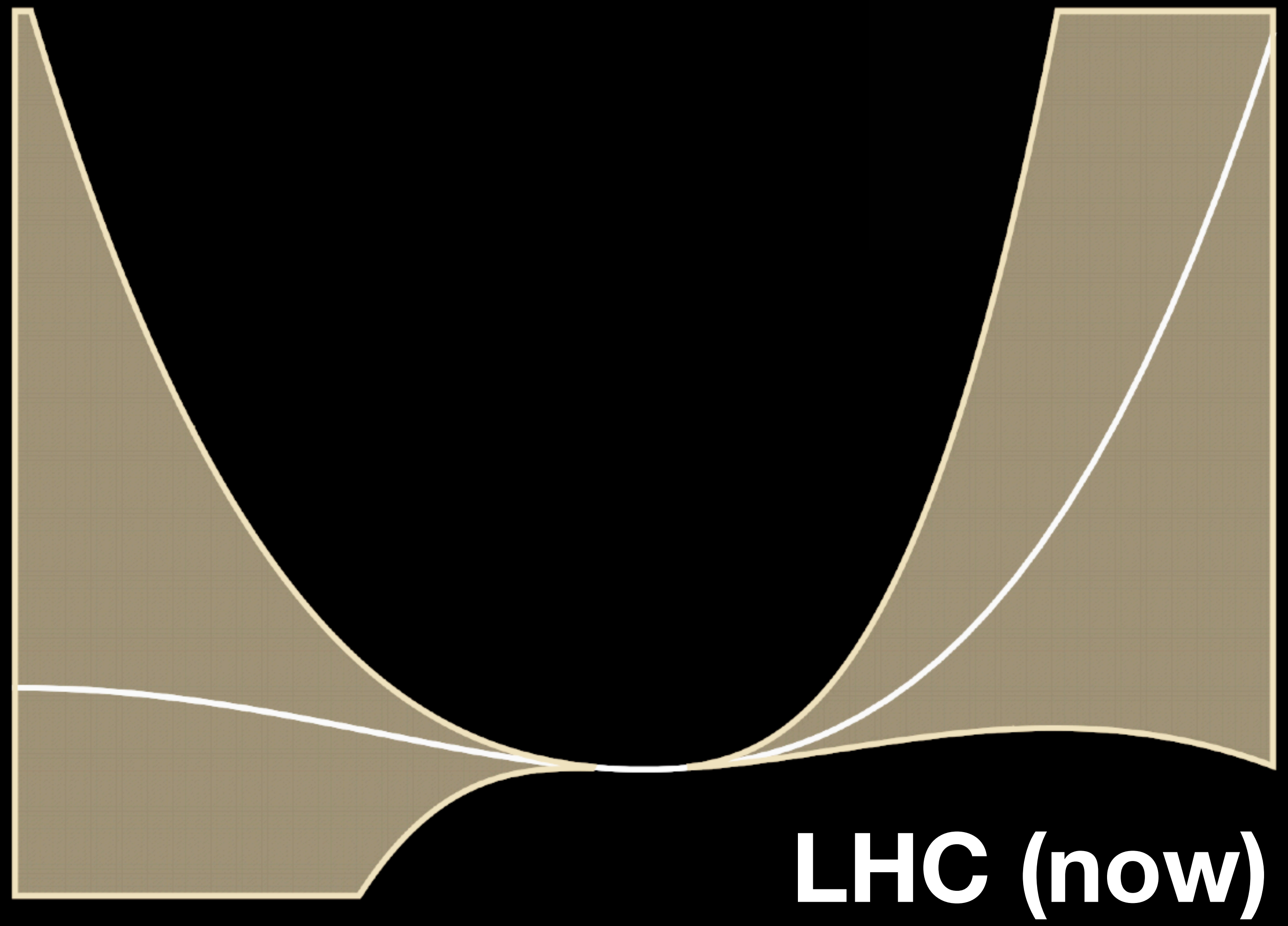


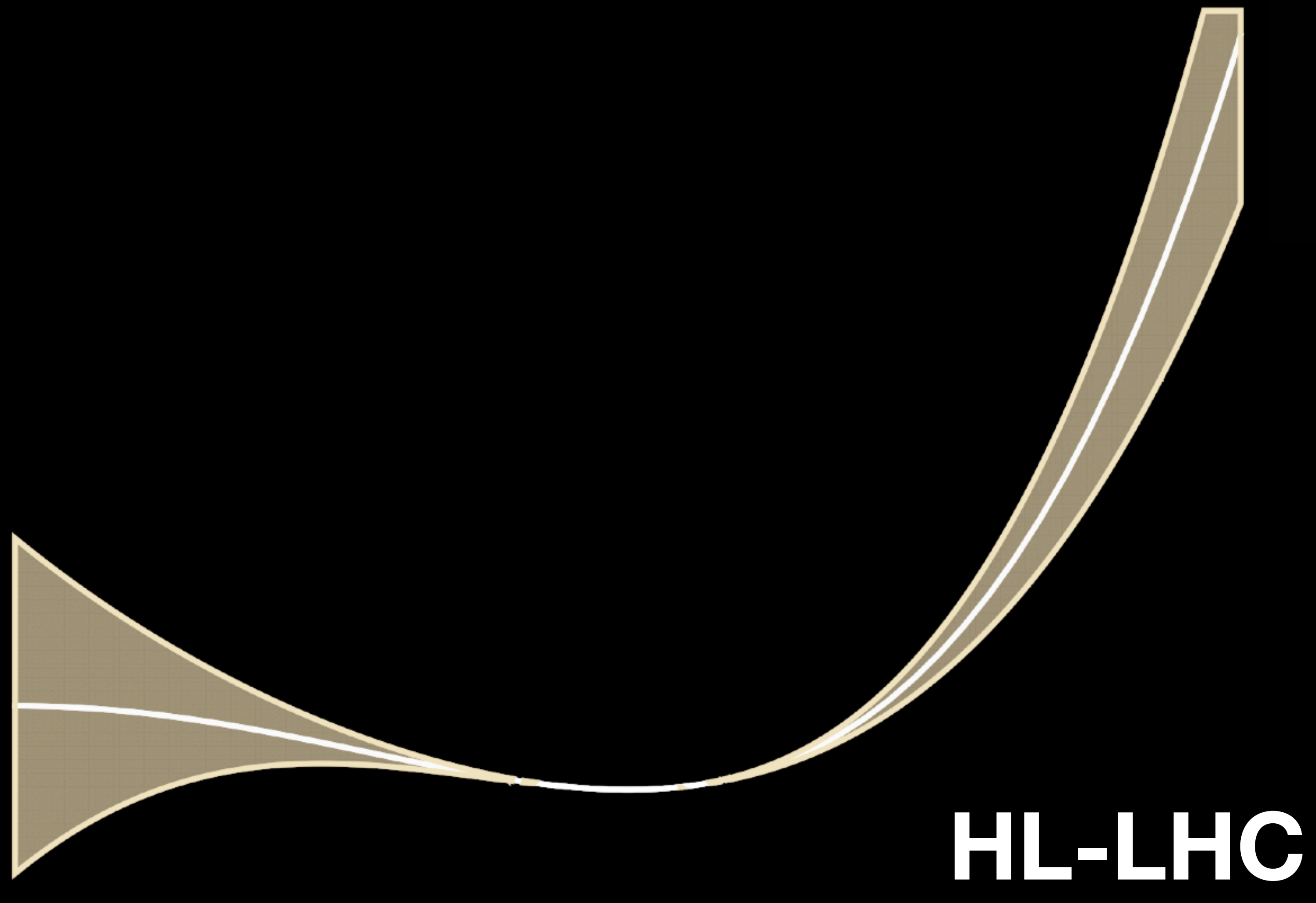
vs.



or

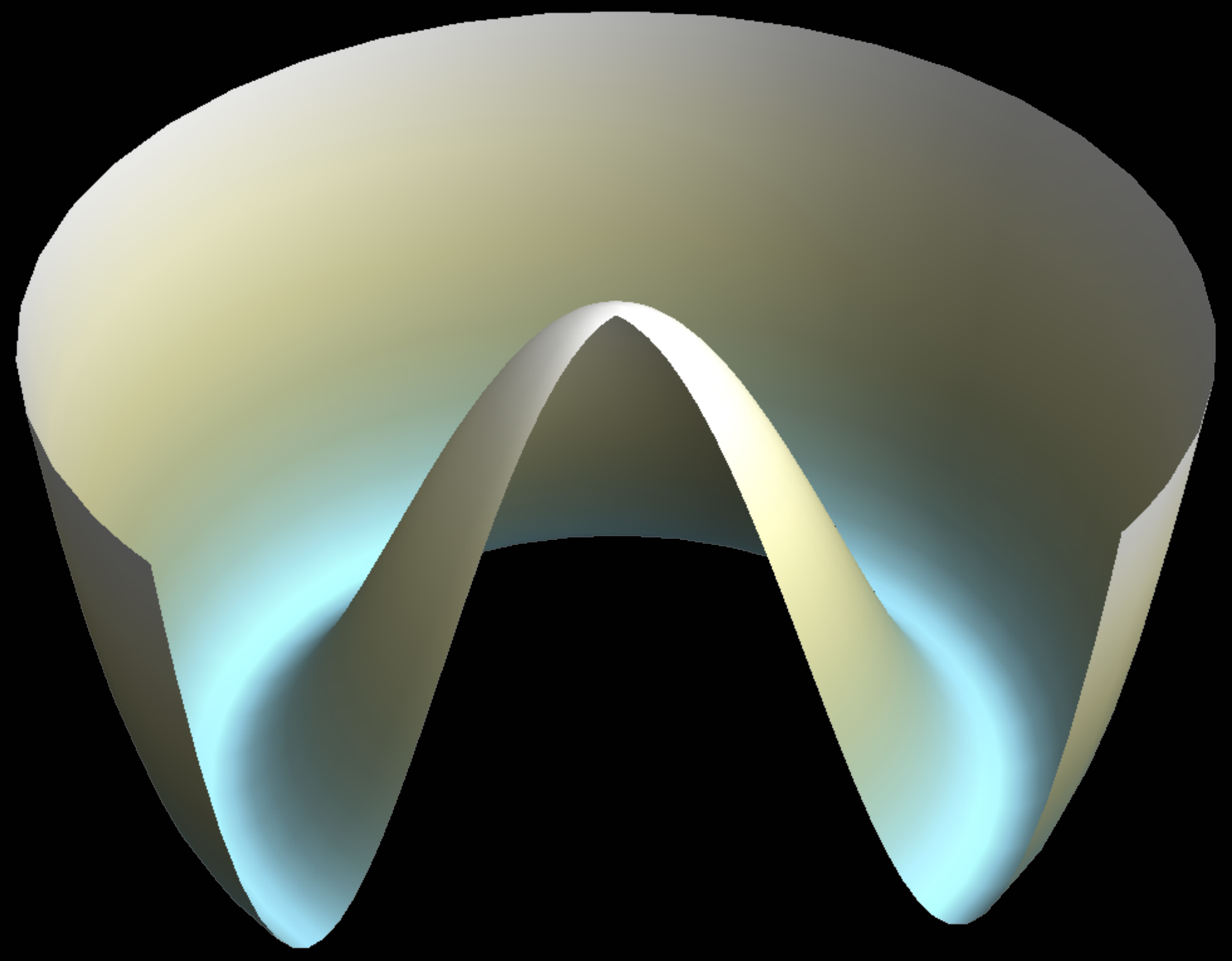




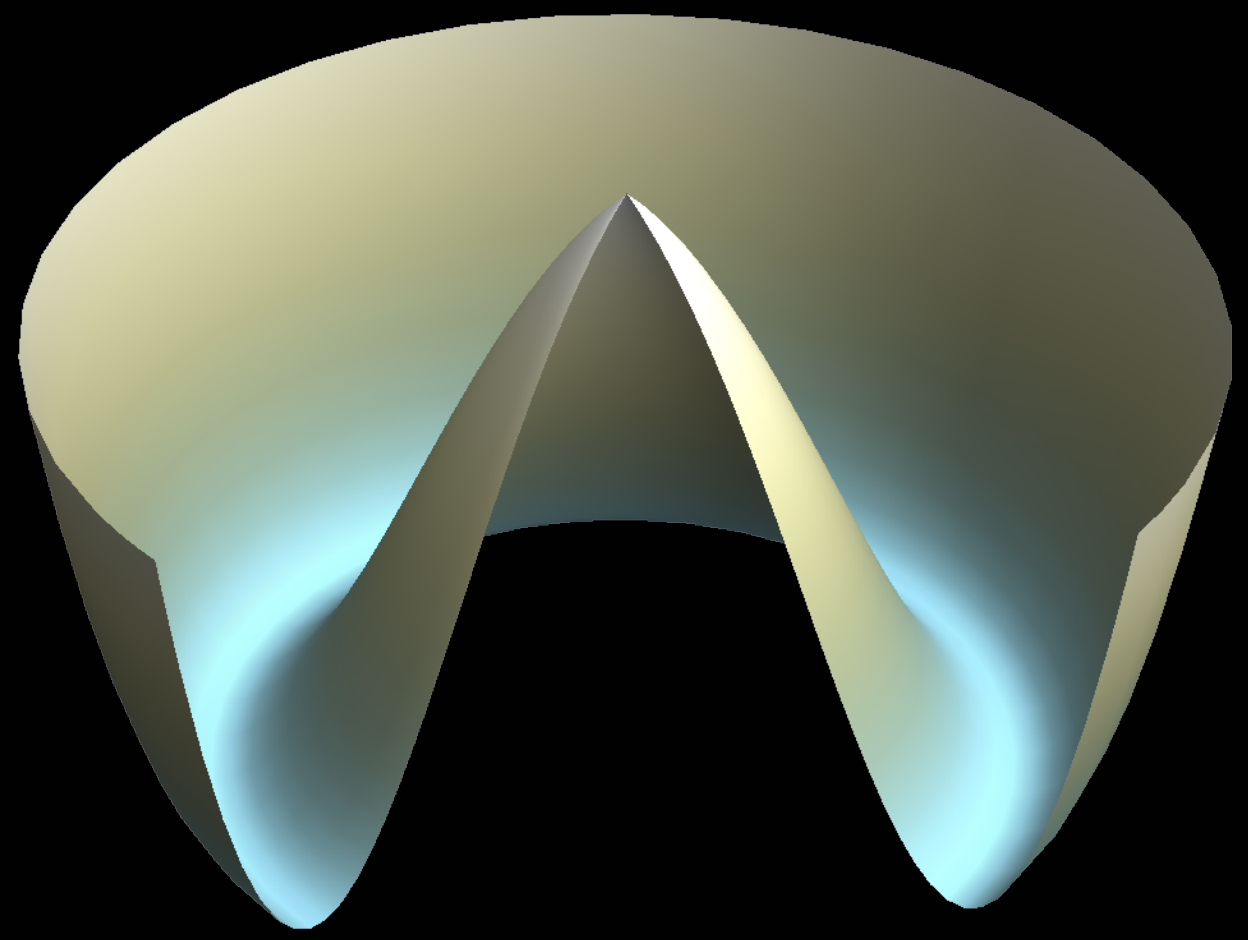


(If you like this way of presenting Higgs self-coupling precision, please feel free to use it w/ credit to R. Petrossian-Byrne.)

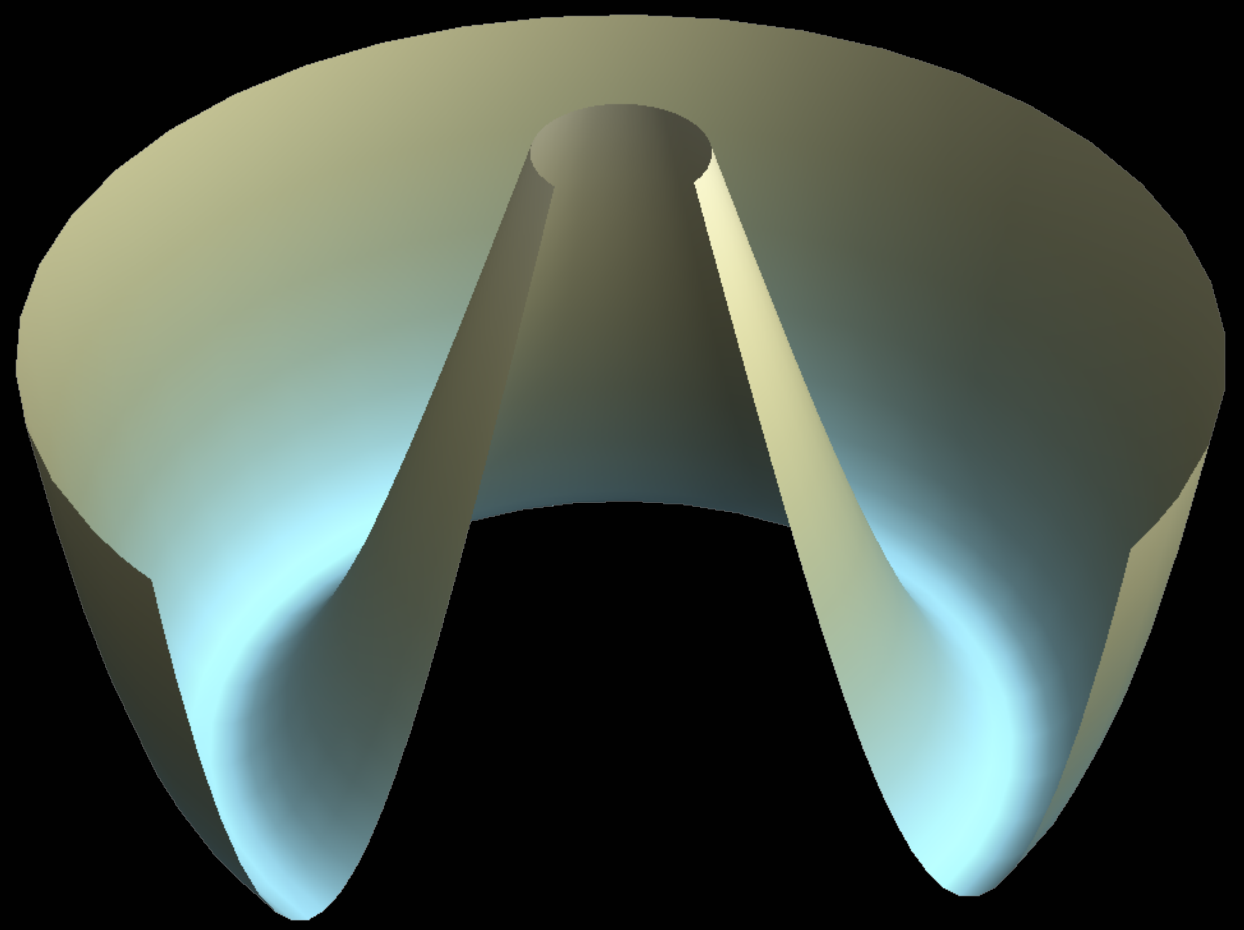
Does it even restore EW symmetry?



vs.



or

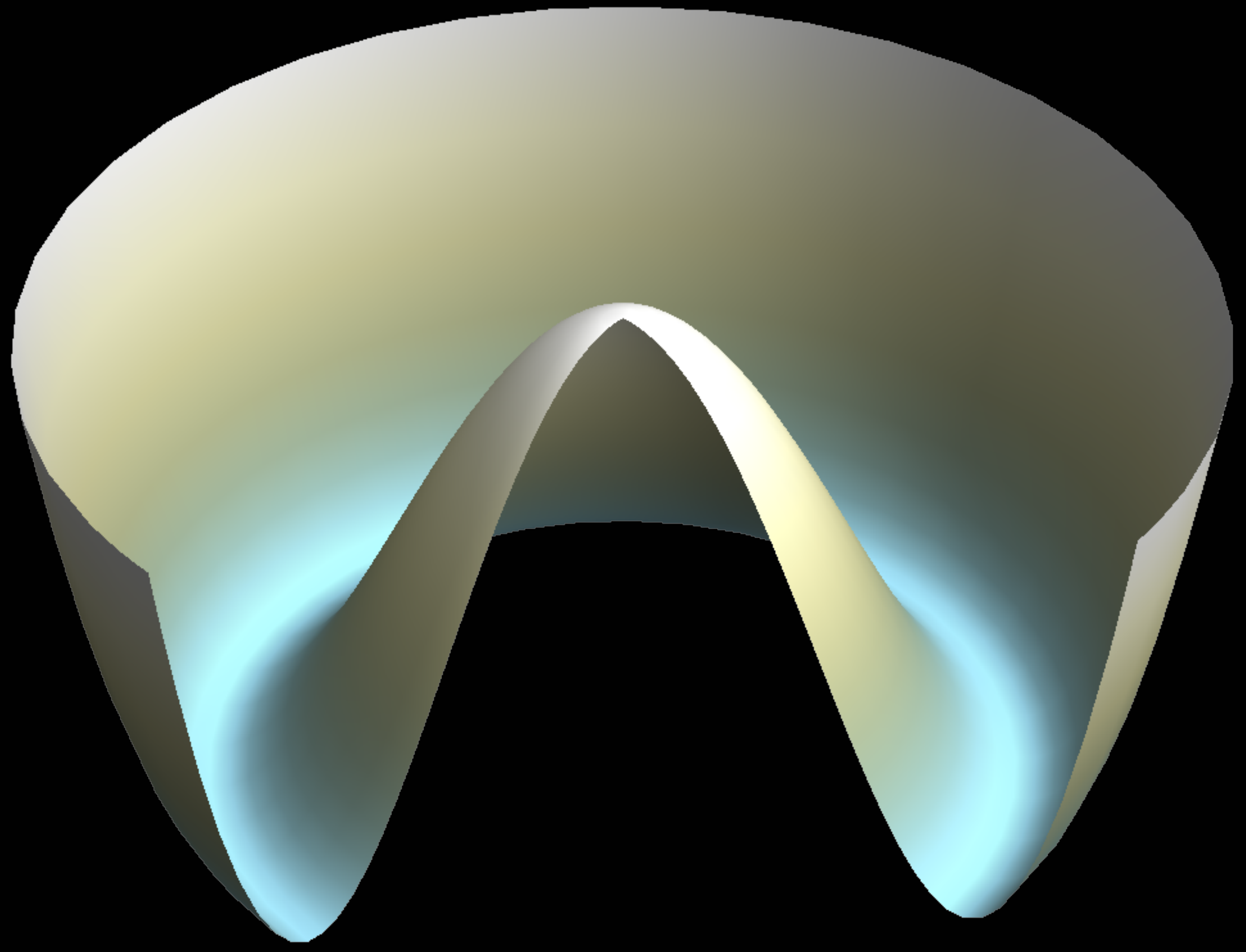


Best probed in vector boson scattering with 3+ bosons in the final state…

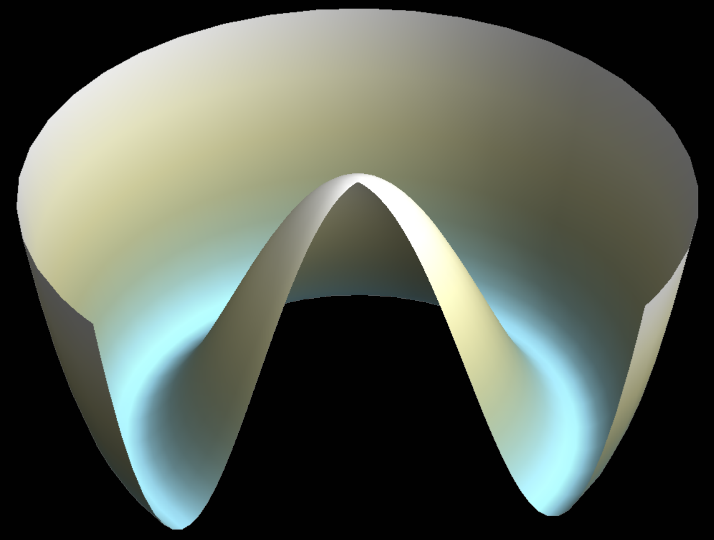
[Chang & Luty ’19, Falkowski & Rattazzi ’19, Cohen, NC, Lu, Sutherland ’21]

What is the microscopic theory?

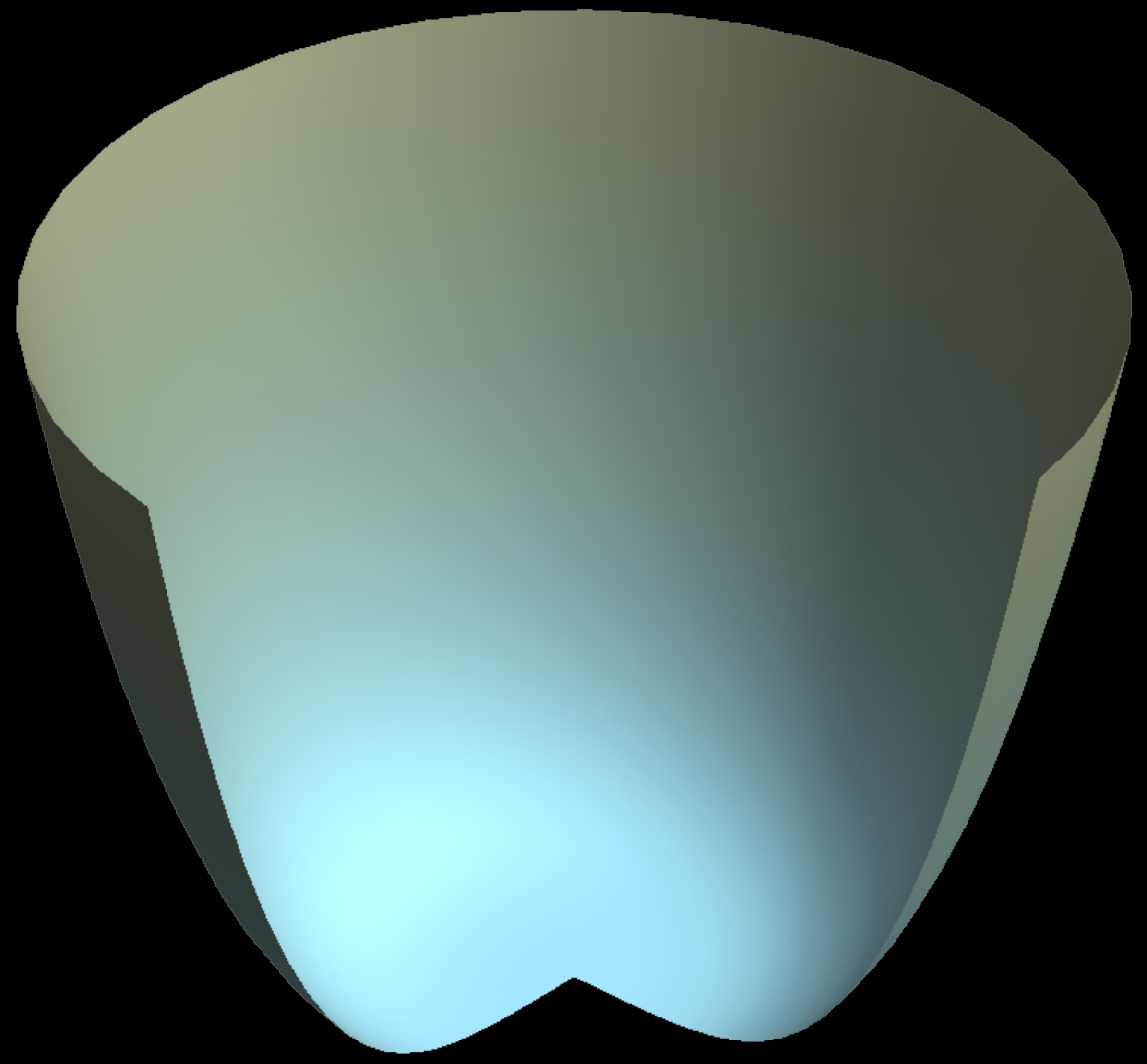
Why is electroweak symmetry broken, and what sets the scale?



vs.



or



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

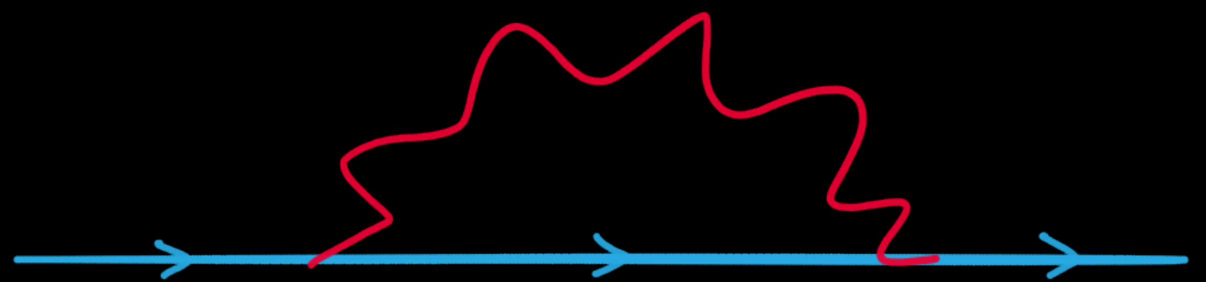
Of course, we know m_h=125 GeV, so the aim should be to use this data to predict new phenomena.

The Naturalness Strategy

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

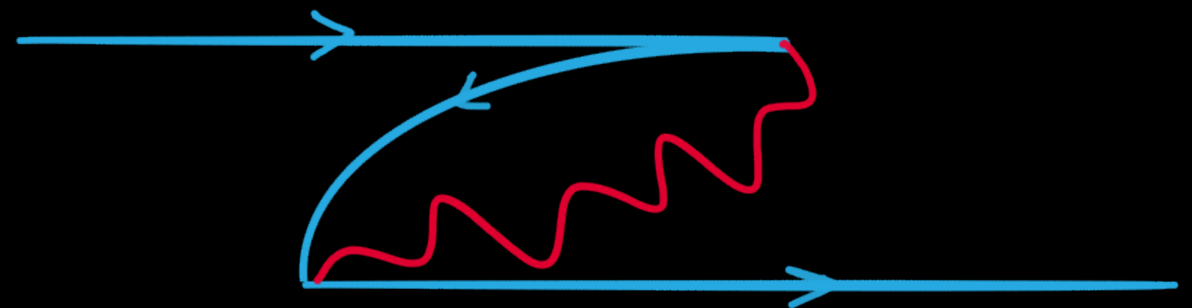
Ultimately, new states appear & UV sensitivity replaced by finite contributions.

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



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

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



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

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 MeV	Positron	511 keV	✓
$m_{\pi\pm}^2 - m_{\pi 0}^2$	$\frac{3\alpha}{4\pi}\Lambda^2$	$\Lambda \lesssim$ 850 MeV	Rho	775 MeV	✓
m_{KL}-m_{KS}	$\frac{s_c^2 f_K^2 m_{K_L^0}}{24\pi^2 v^4}\Lambda^2$	$\Lambda \lesssim$ 2 GeV	Charm	1.2 GeV	✓
m_H^2	$-\frac{6y_t^2}{16\pi^2}\Lambda^2 + \ldots$	$\Lambda \lesssim$ 500 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

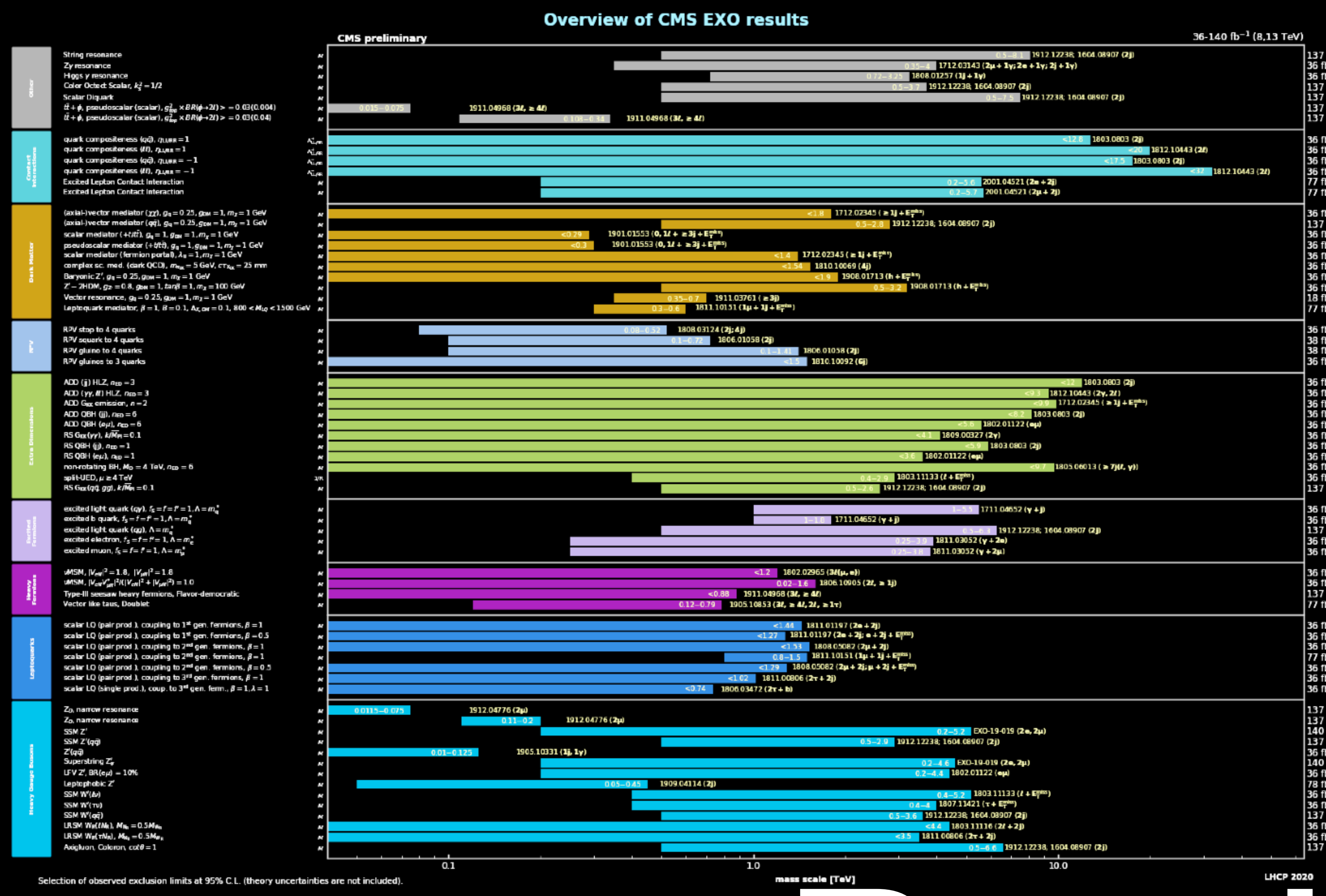
- New physics around the TeV scale…
- …coupling to the Higgs

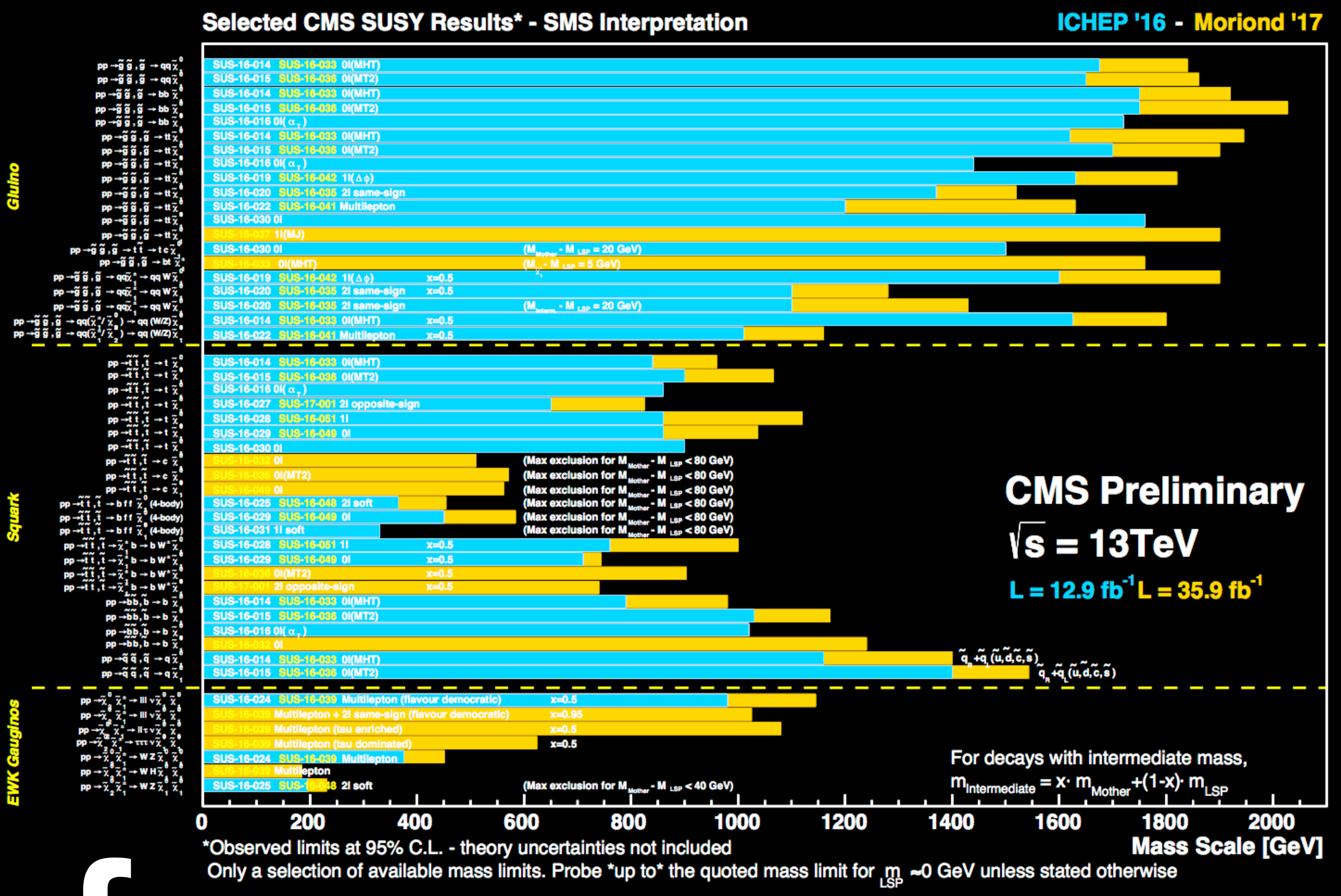
Strong motivation for beyond-the-Standard Model physics connected to Higgs! But maybe too broad to be useful guidance to experiment.

To make further progress, we come up with models.
Easiest path: work by analogy with known examples.

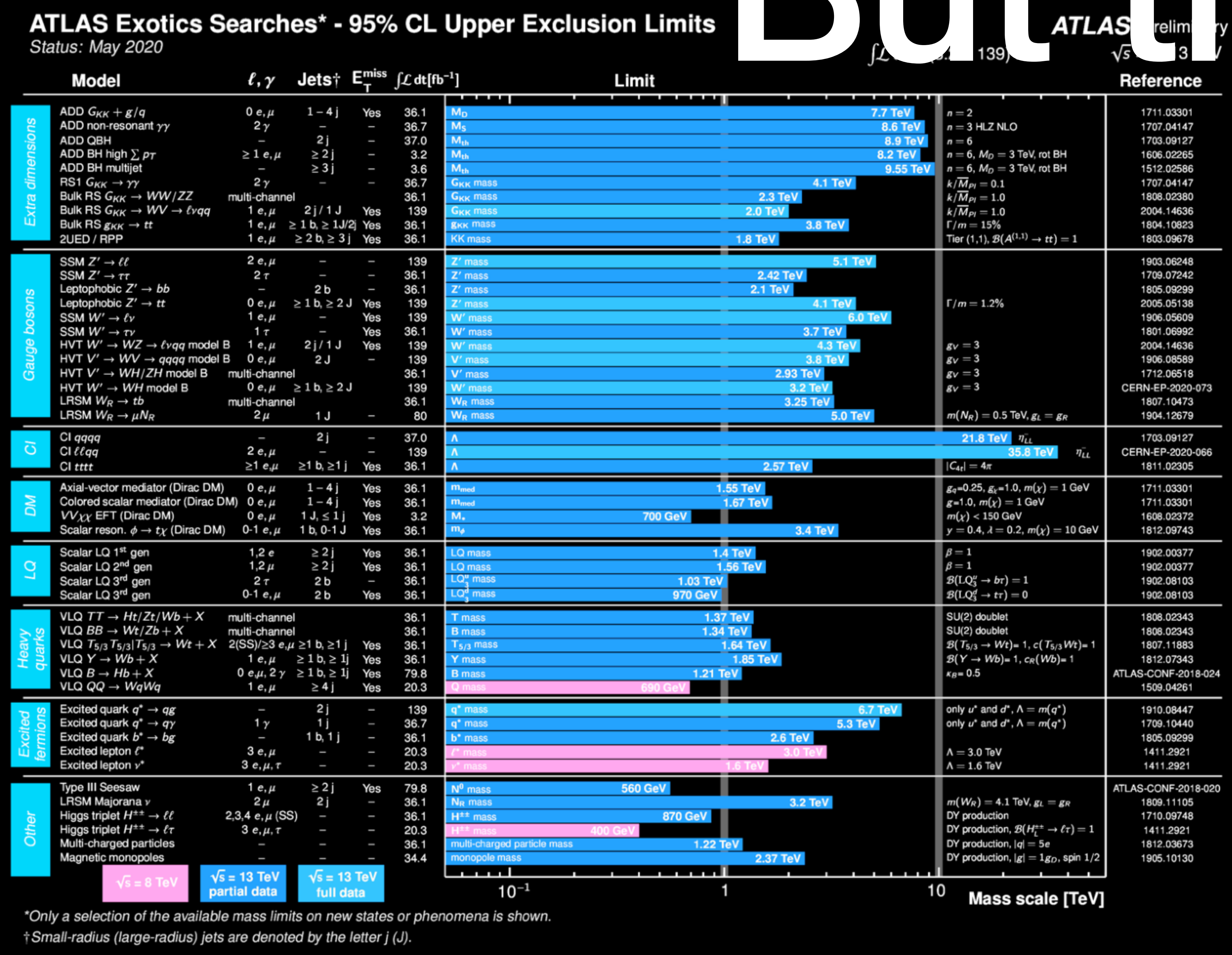
Supersymmetry: Relate Higgs to a fermion, *a la* electron.

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


Overview of CMS EXO results
CMS preliminary
36-140 fb⁻¹ (8,13 TeV)
mass scale [TeV]
LHCP 2020
Selection of observed exclusion limits at 95% C.L. (theory uncertainties are not included).


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, m_intermediate = x· m_Mother +(1-x)· m_LSP
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

But thus far…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Model
Limit
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Extra dimensions
Gauge bosons
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LQ
Heavy quarks
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Other
√s = 8 TeV
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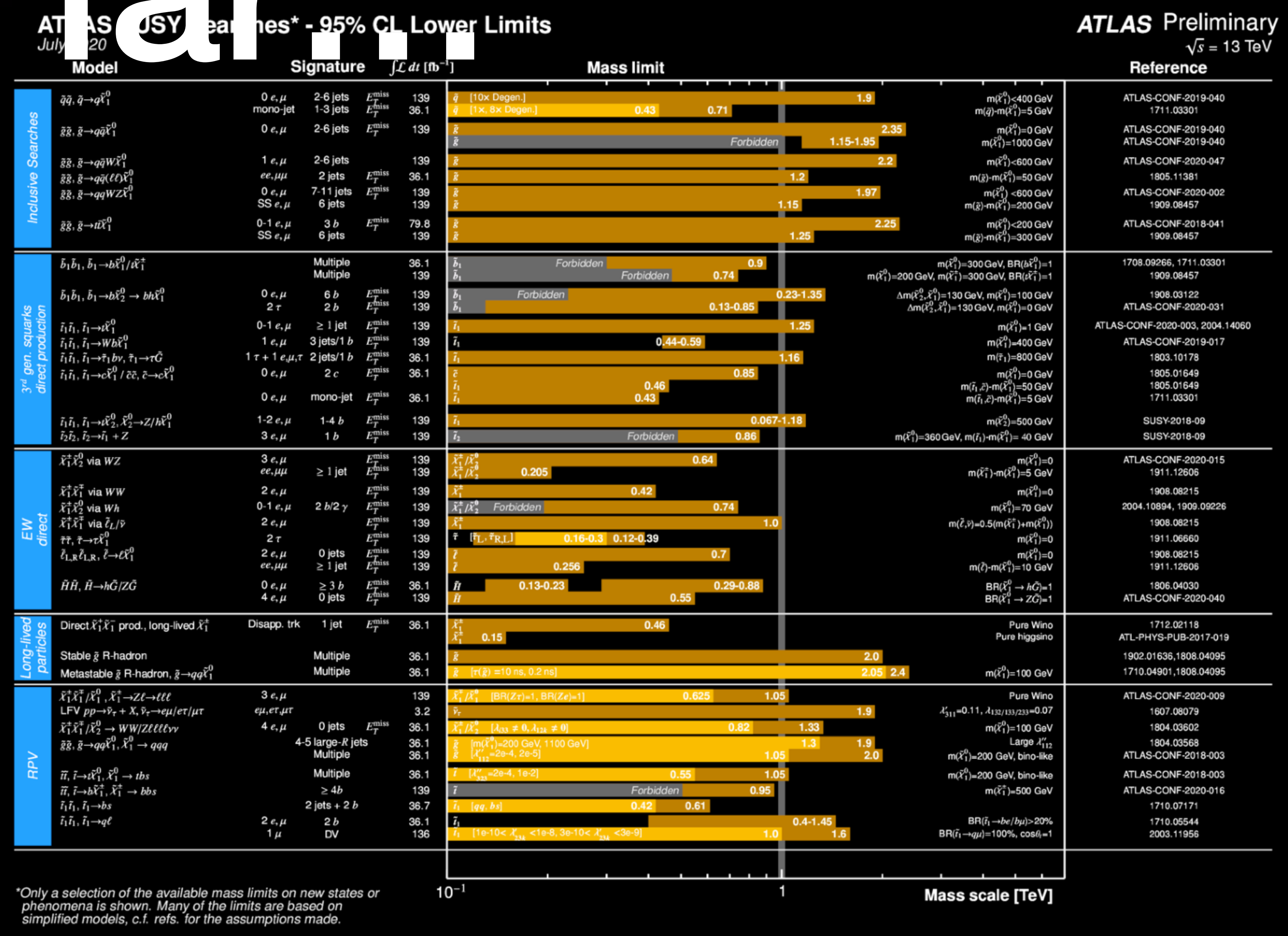
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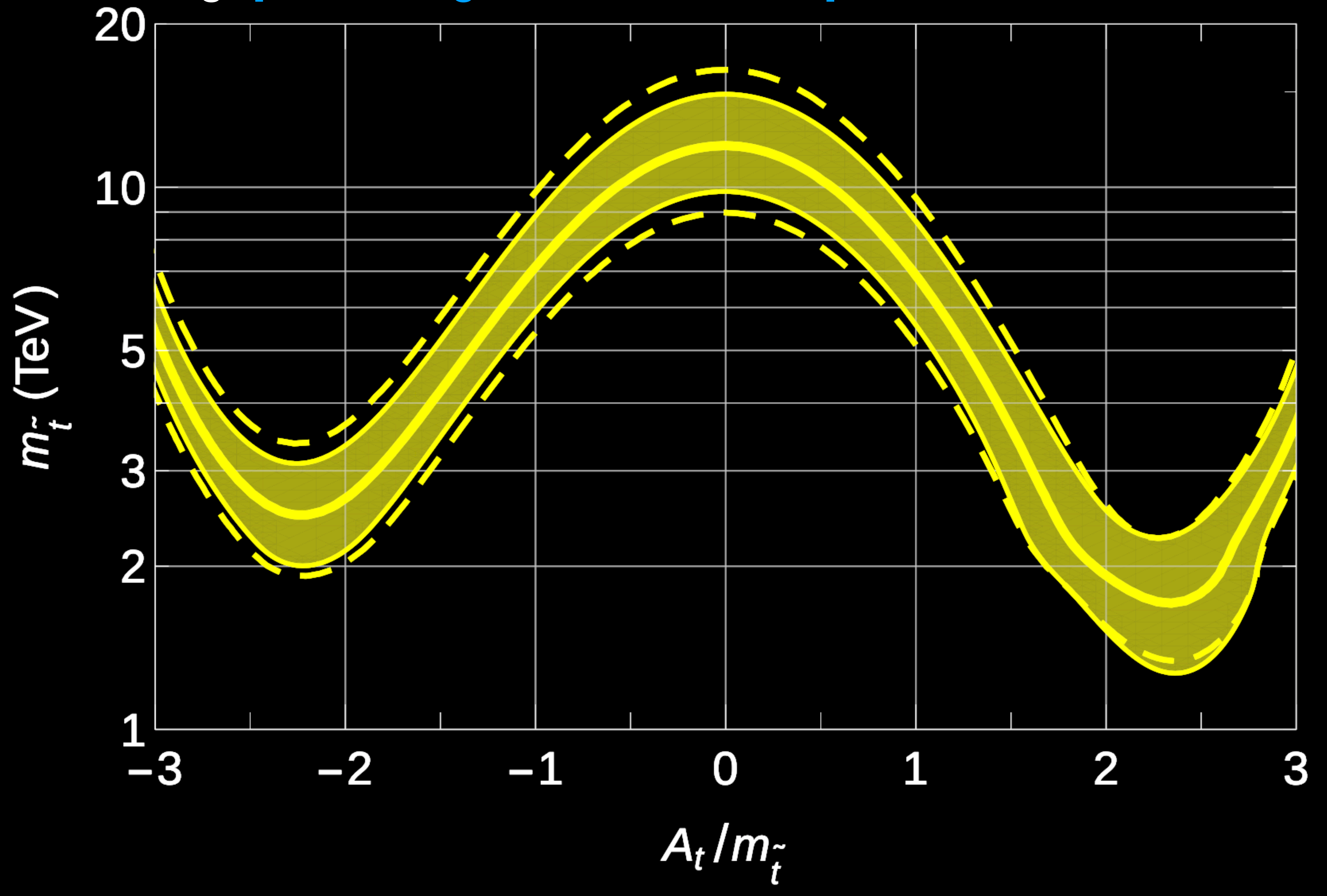
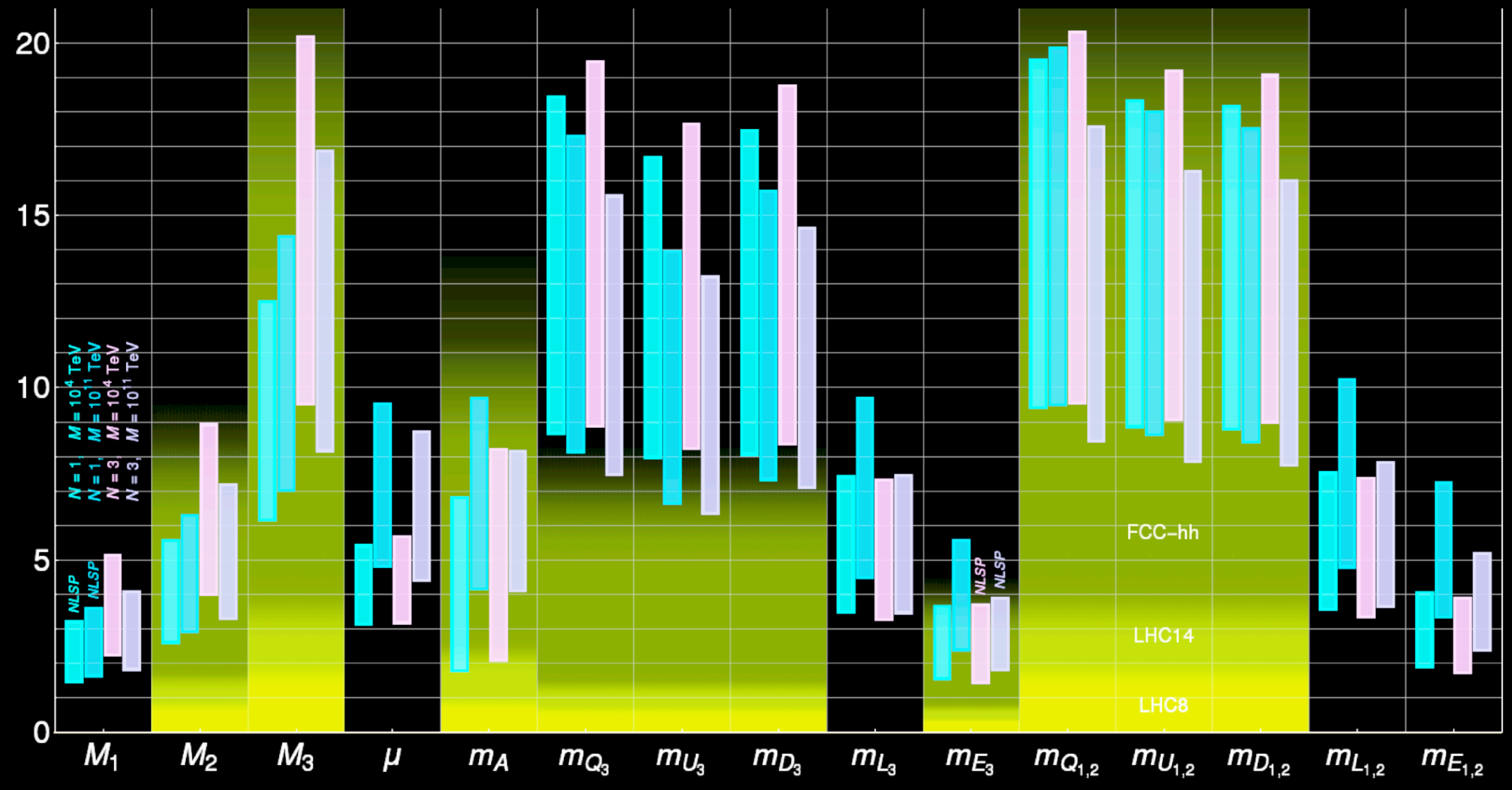
Higgs Mass vs. Naturalness

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.

E.g. [Pardo Vega & Villadoro ’15]



Minimal Gauge Mediation



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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  (SUSY, global sym, **discrete sym**, …)

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  (anthropics, **NNaturalness, crunching**, **sliding**…)

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  (SUSY, global sym, **discrete sym**, …)
- **Adjustment**: $m_H^2 \sim m_{UV}^2 + m_{IR}^2 \ll m_{UV}^2$
  (**relaxion, self-organization**, …)
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- **Unnaturalness**: $m_H^2 \sim \Sigma m_{UV}^2 \ll m_{UV}^2$
  (anthropics, **NNaturalness, crunching**, **sliding**…)
- **Un-effectiveness**: $m_H^2 \sim m_{UVIR}^2$
  (**modular invariance, quantum gravity**, …)

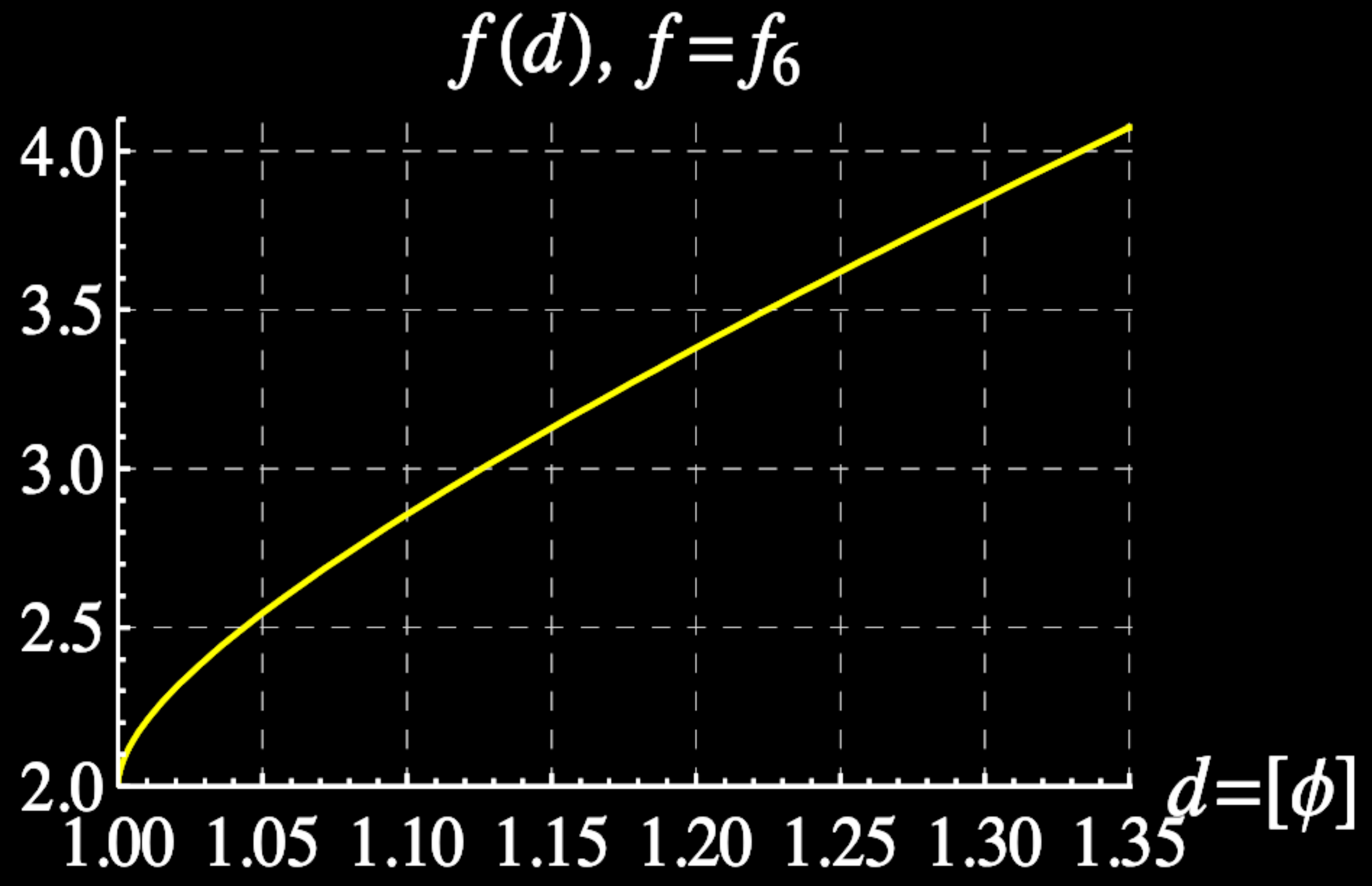
The Value of Being Wrong

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

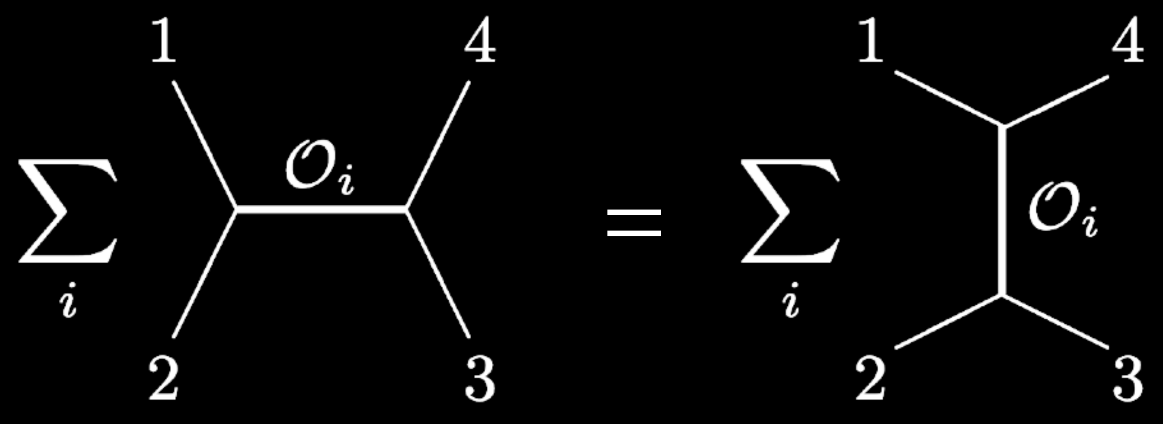
For example…

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

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



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

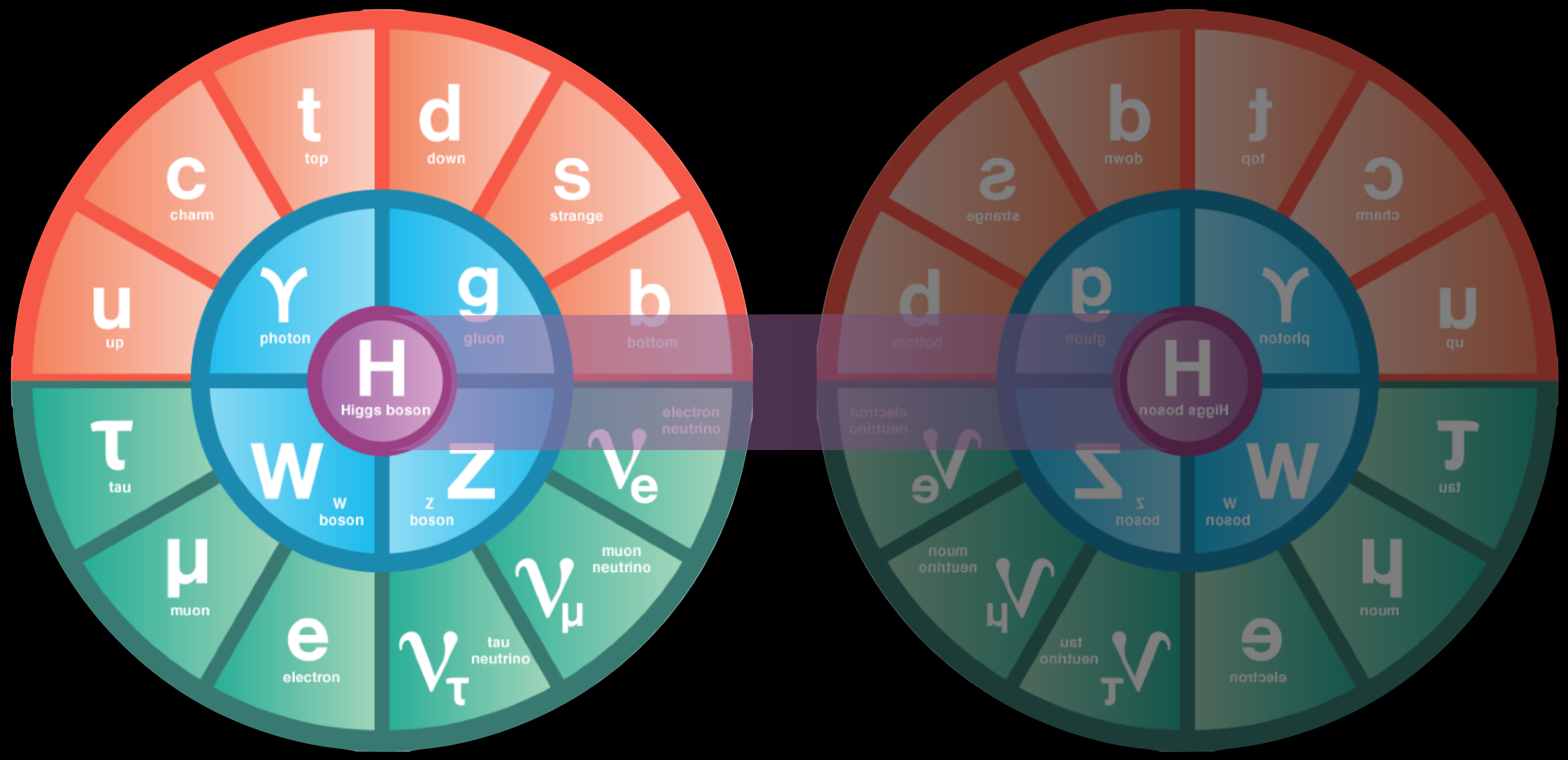


Possible Paths

Discrete symmetries

[Chacko, Goh, Harnik ’05, …]

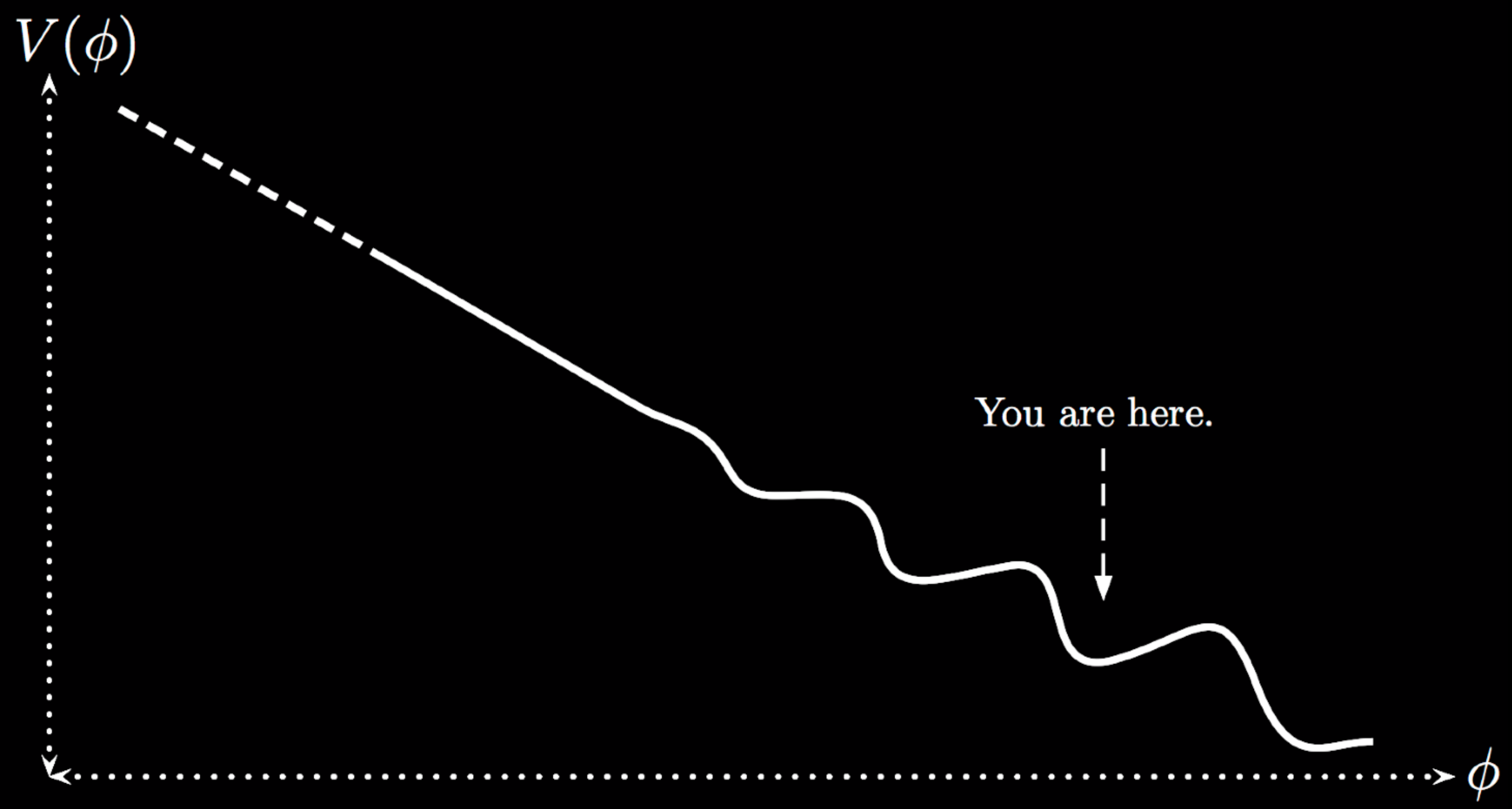
Discrete symmetries relate the Standard Model to mirror copies; new physics at the weak scale is SM-neutral



Cosmological Relaxion

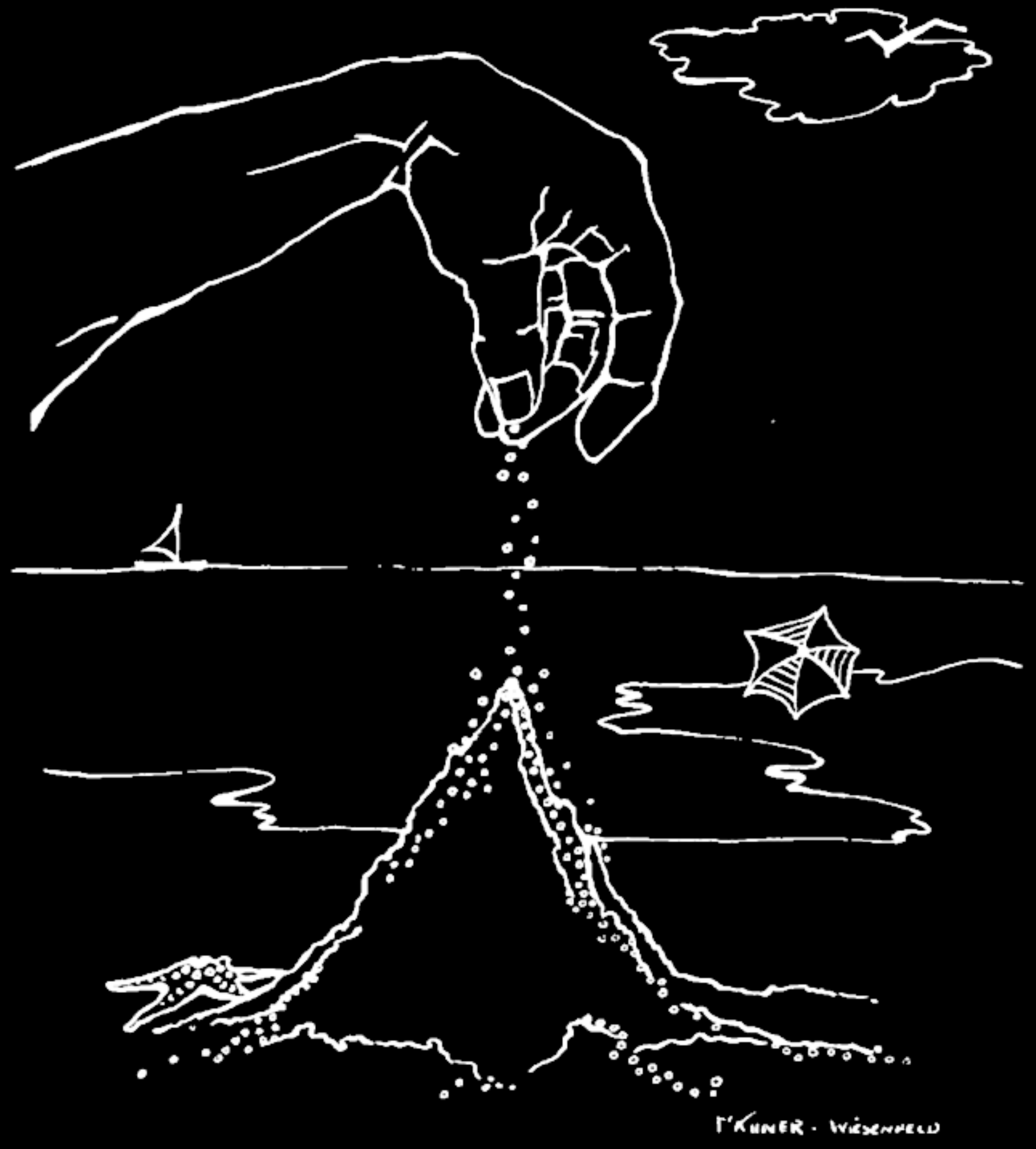
[Dvali, Vilenkin ’03; Dvali ’04; Graham, Kaplan, Rajendran ’15, …]

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

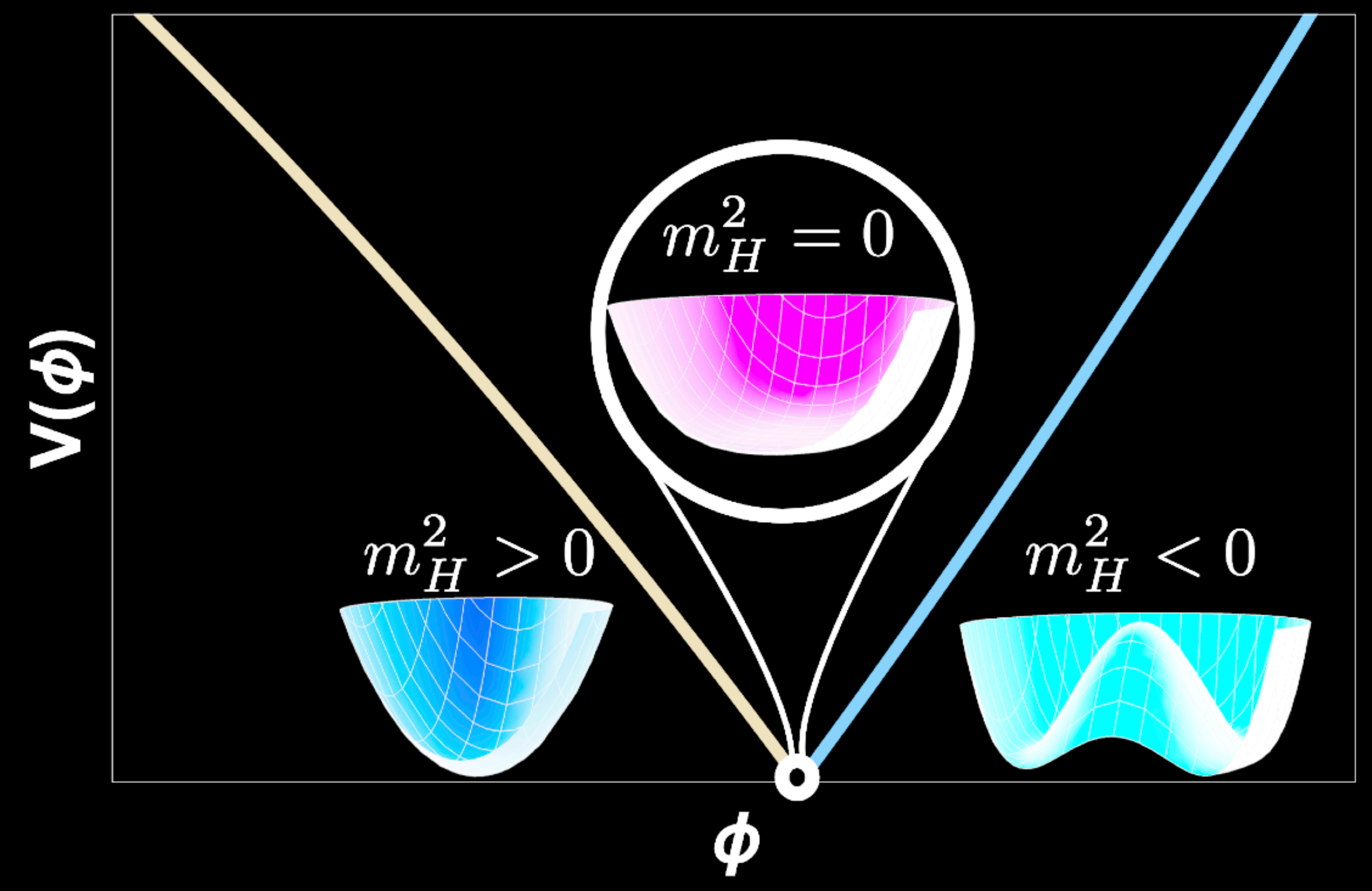


Self-Organized Criticality

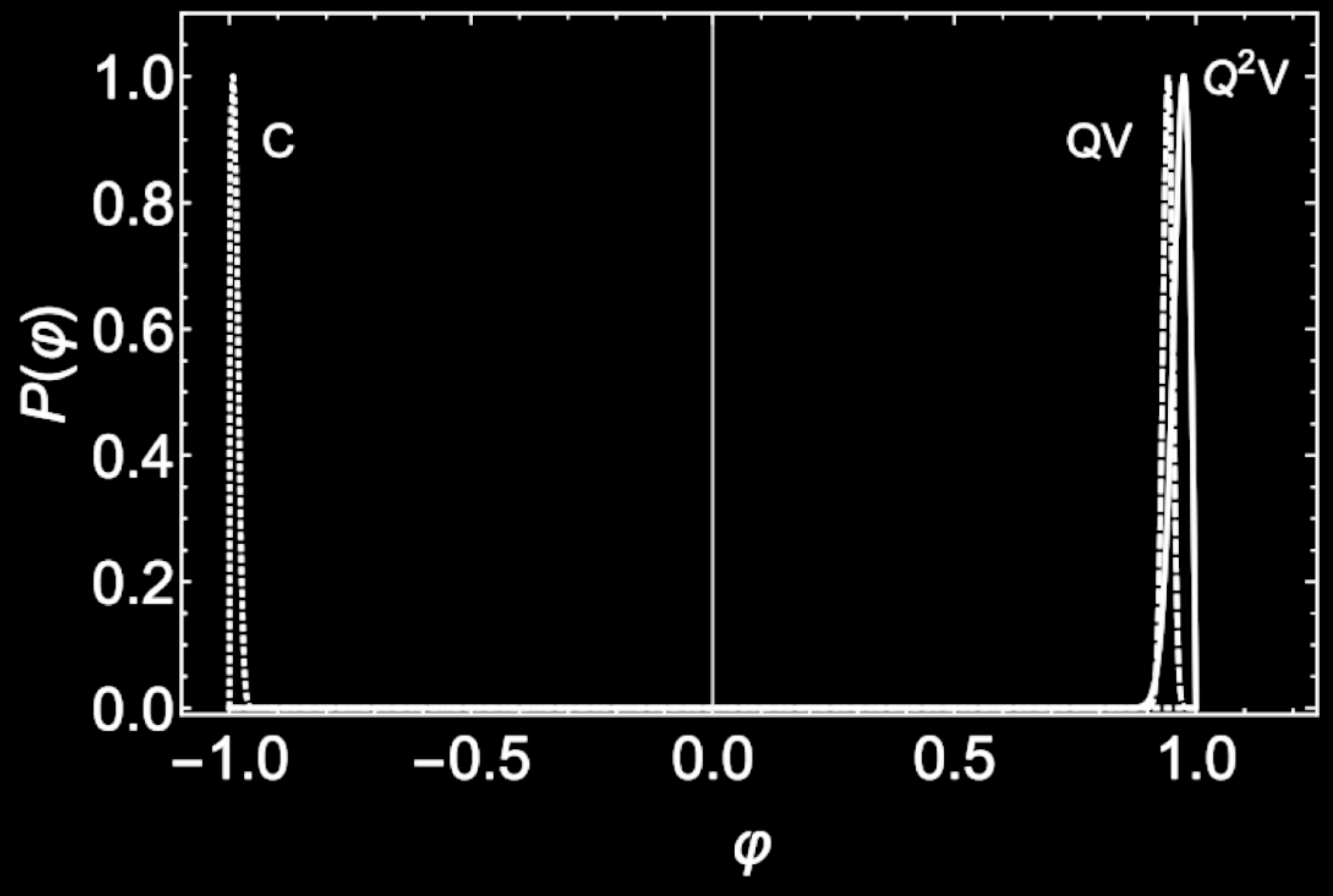
Some systems evolve into critical states on their own (sandpiles, *a la* [Bak, Tang, Wiesenfeld '84]
Lessons for the weak scale? [Giudice '08]



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



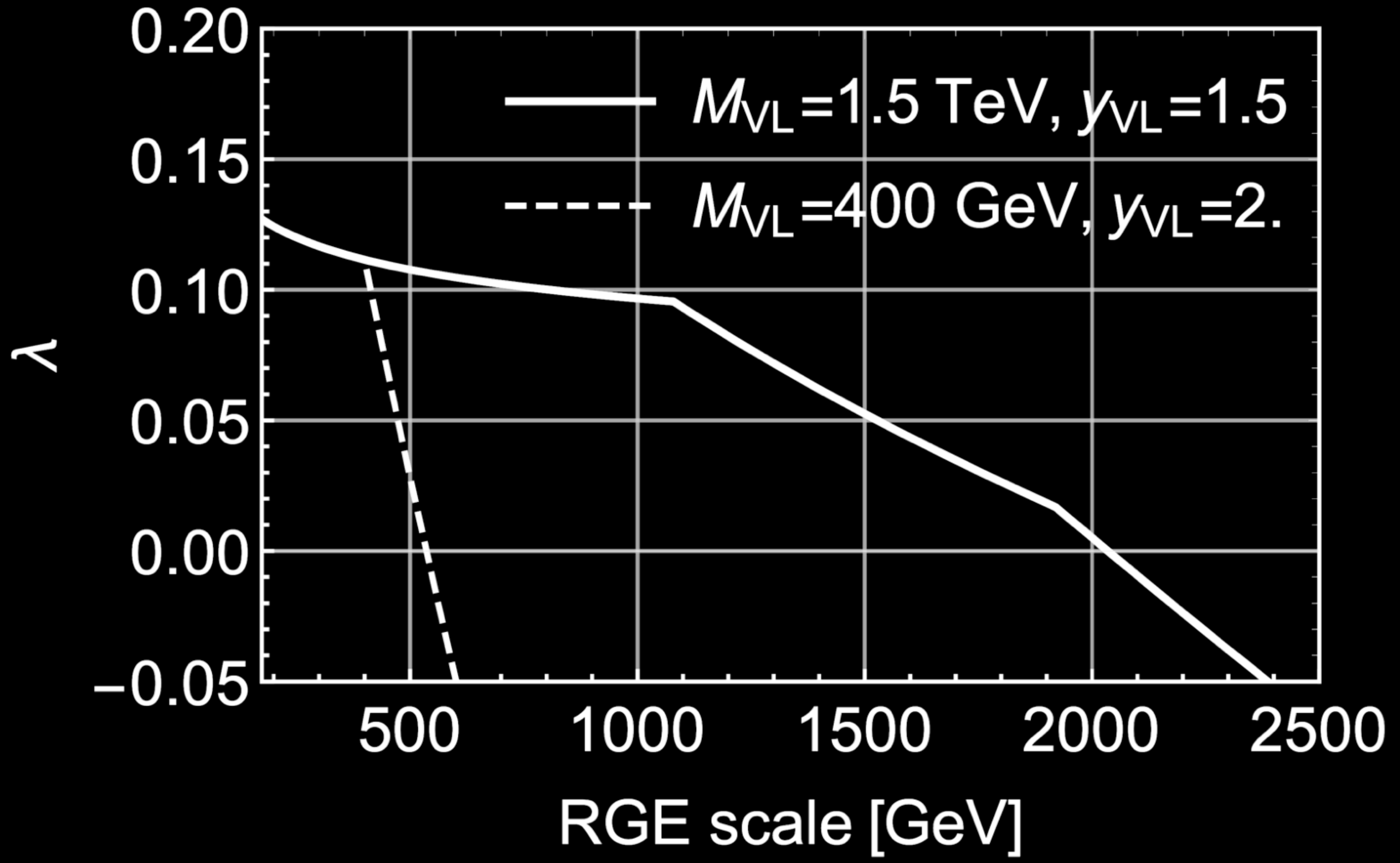
Localization of scalar fields exponentially close to critical points during eternal inflation
[Giudice, McCullough, You '21]
[Khoury et al. '19-'20]



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 $\lambda(\Lambda_I) = 0$ ⇨ $v \sim \Lambda_I$



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/

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

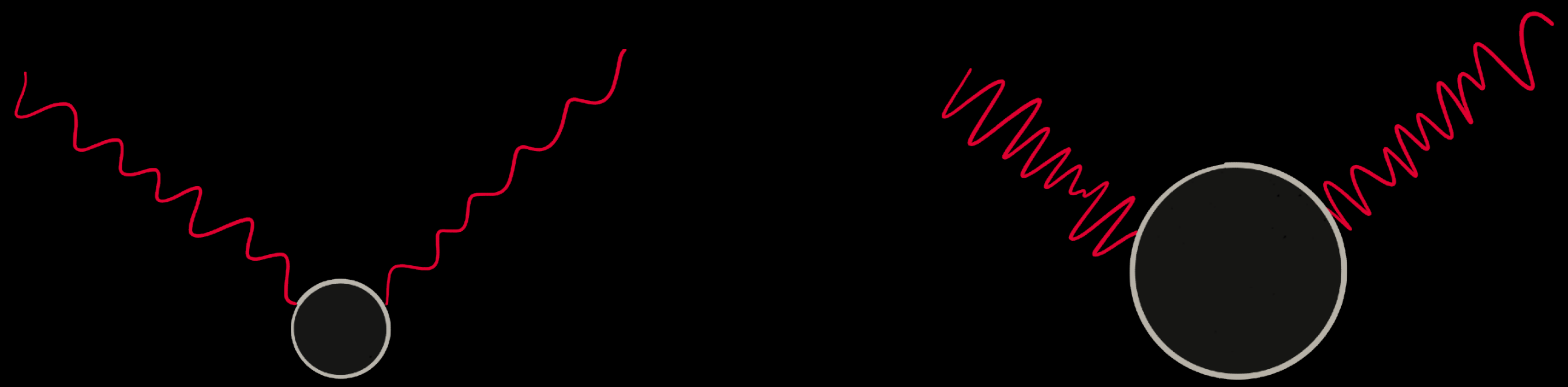
[Giudice, McCullough, You '21]

Un-effectiveness

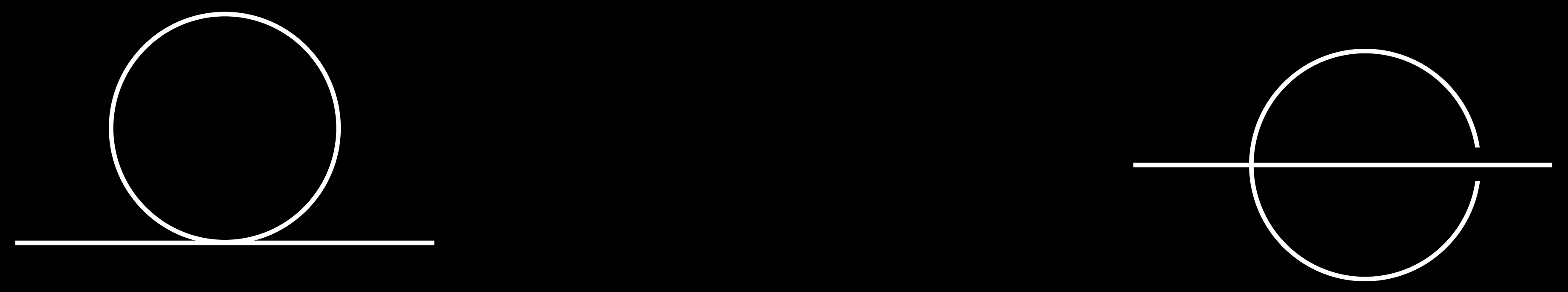
Essential feature of the hierarchy problem: the UV doesn't know about the IR
…unless it does?

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]



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

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

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

Modular Invariance

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

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

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

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

Then many *nondegenerate* spectra have vanishing supertraces

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

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

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?

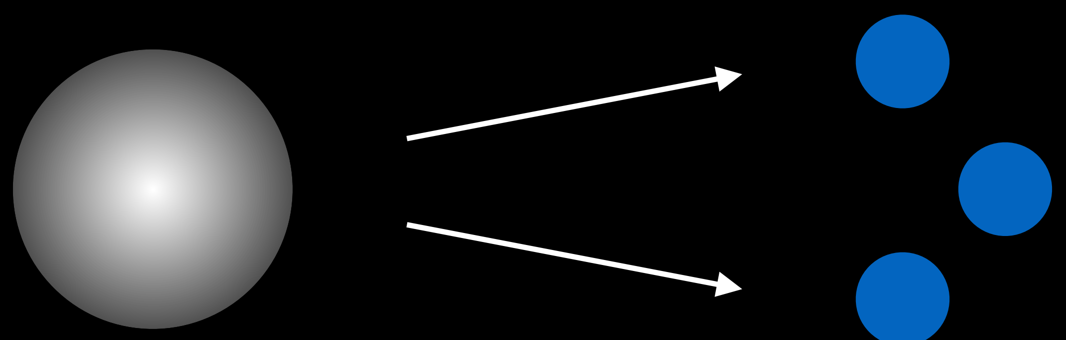
The Weak Gravity Conjecture

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

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

[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: $mQ/q < M$

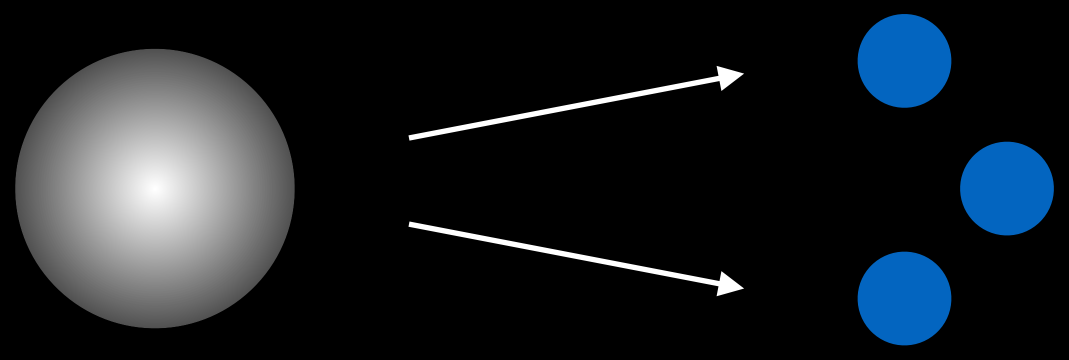
Then BH satisfies $Z = Q\,M_{Pl}/M < z = q\,M_{Pl}/m$

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

⇒ $q > m/M_{Pl}$ 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: $m \leq (gq) M_{\text{Pl}}$

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

Magnetic WGC: $\Lambda \lesssim g M_{\text{Pl}}$

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

+Scalar WGC: $m \leq \sqrt{g^2 q^2 - \mu^2} M_{\text{Pl}}$

[Palti ‘17]

dS WGC: $m^2 \gtrsim gq M_{\text{Pl}} H$

[Montero, Van Riet, Venken ‘19]

Axion WGC: $f \leq (1/S) M_{\text{Pl}}$

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

New hierarchies from field theory + gravity.

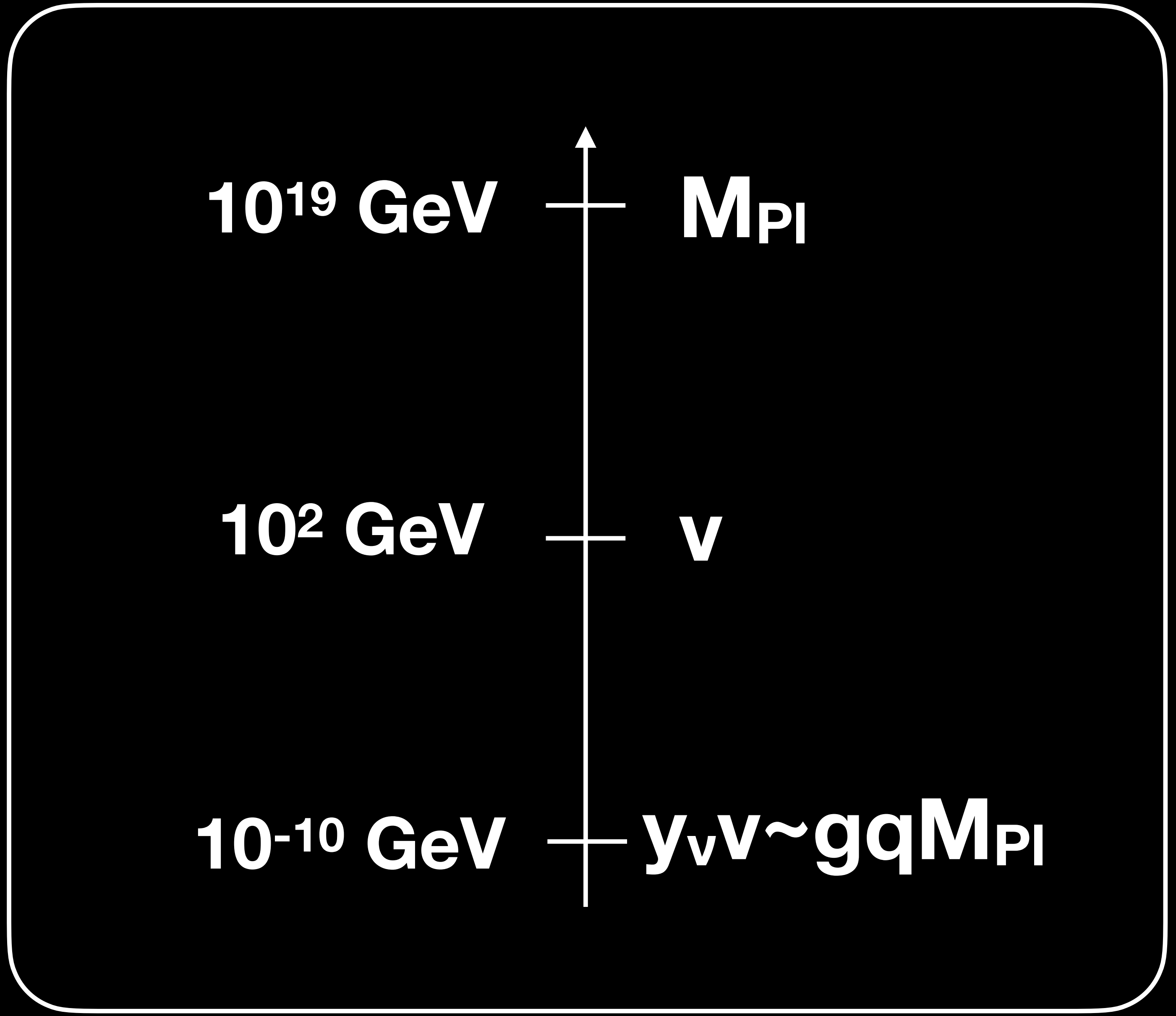
Recent review: [Harlow, Heidenreich, Reece, Rudelius ’22]

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 $0\nu\beta\beta$)



10^{19} GeV — M_{Pl}

10^{2} GeV — v

10^{-10} GeV — $y_\nu v \sim gqM_{Pl}$

Neutrino mass from Higgs

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

If lightest neutrino is WGC particle,

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

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

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

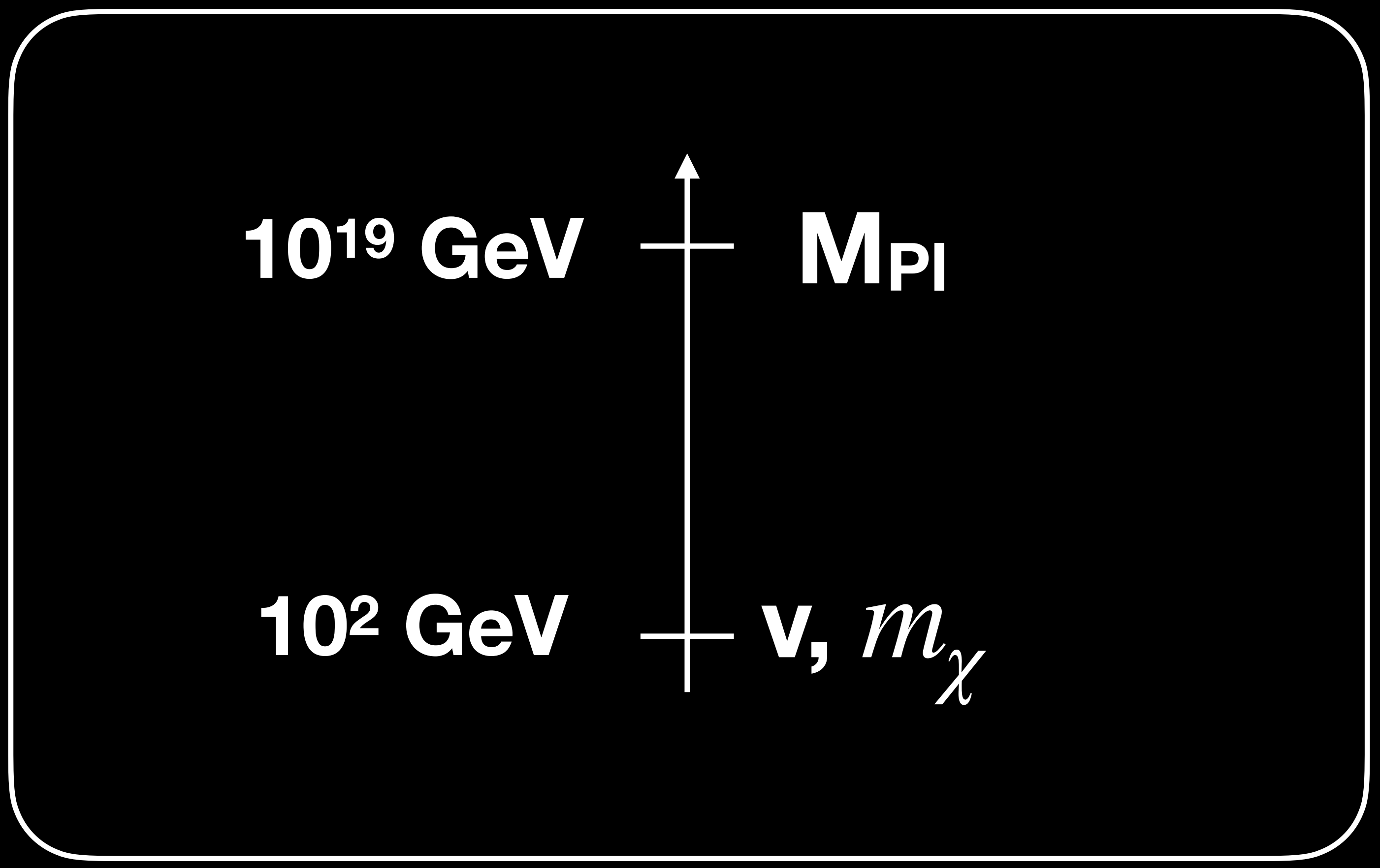
Weak Gravity, Weak Scale?

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},…

- **Unnaturalness**: $m_H^2 \sim \Sigma m_{UV}^2 \ll m_{UV}^2$
  Varied, but often promising cosmological signals (N_{eff}, …)

- **Un-effectiveness**: $m_H^2 \sim m_{UVIR}^2$
  Higgs properties, spacetime symmetries, ???

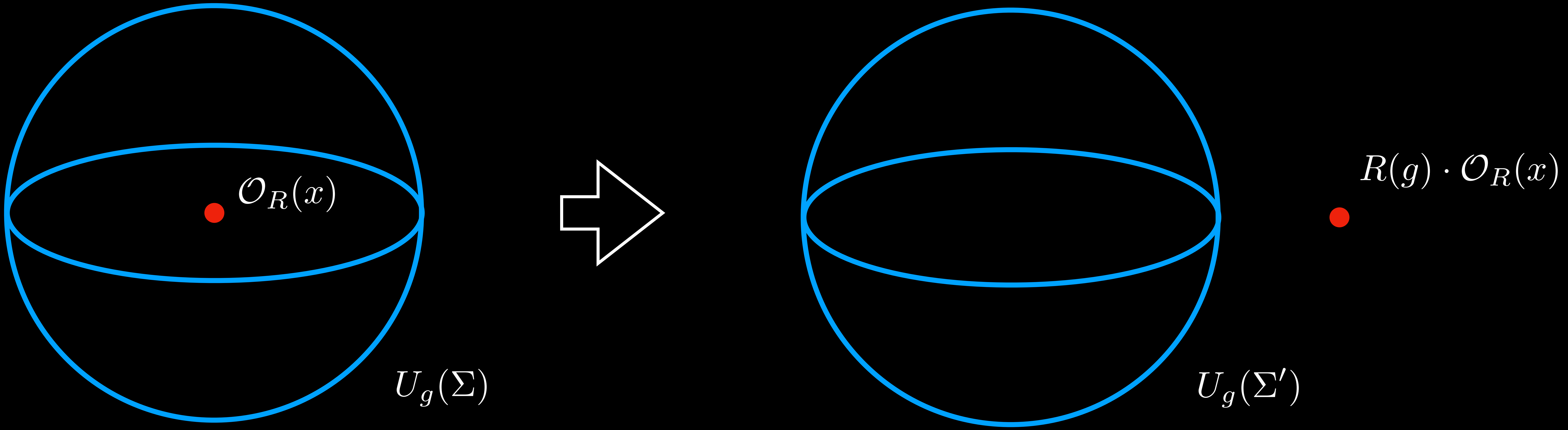
Looking forward…

New perspective on old symmetries…

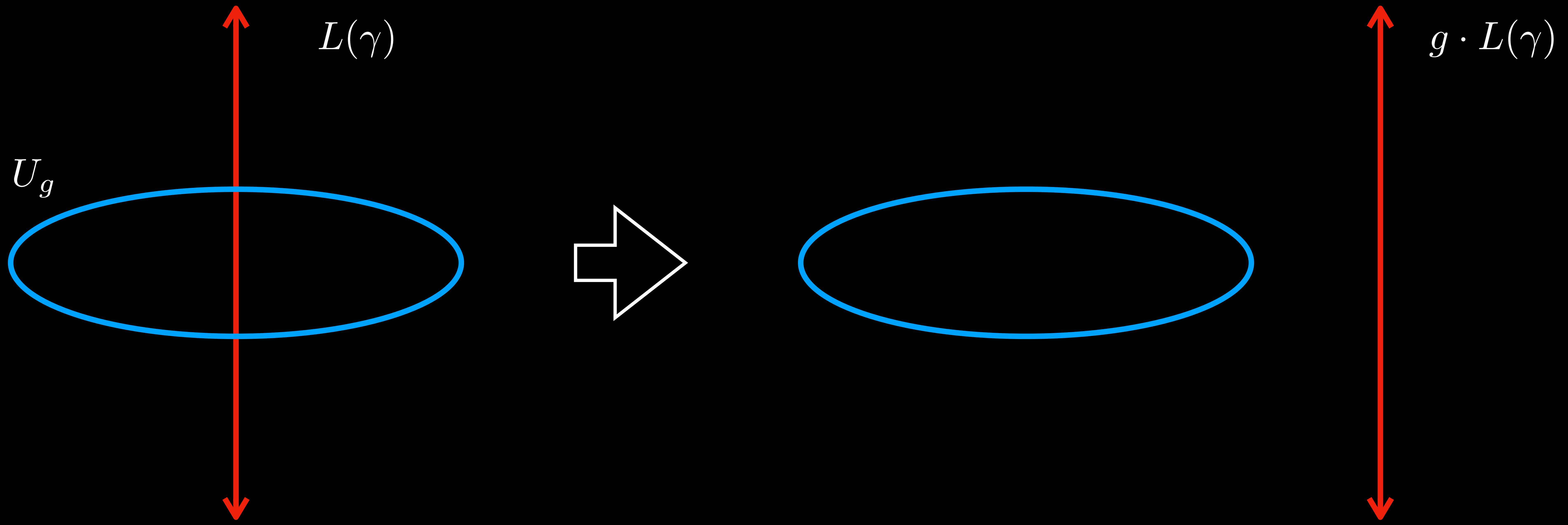
[Gaiotto, Kapustin, Sieberg, Willett ’14; Aharony, Seiberg, Tachikawa ’13; …]

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

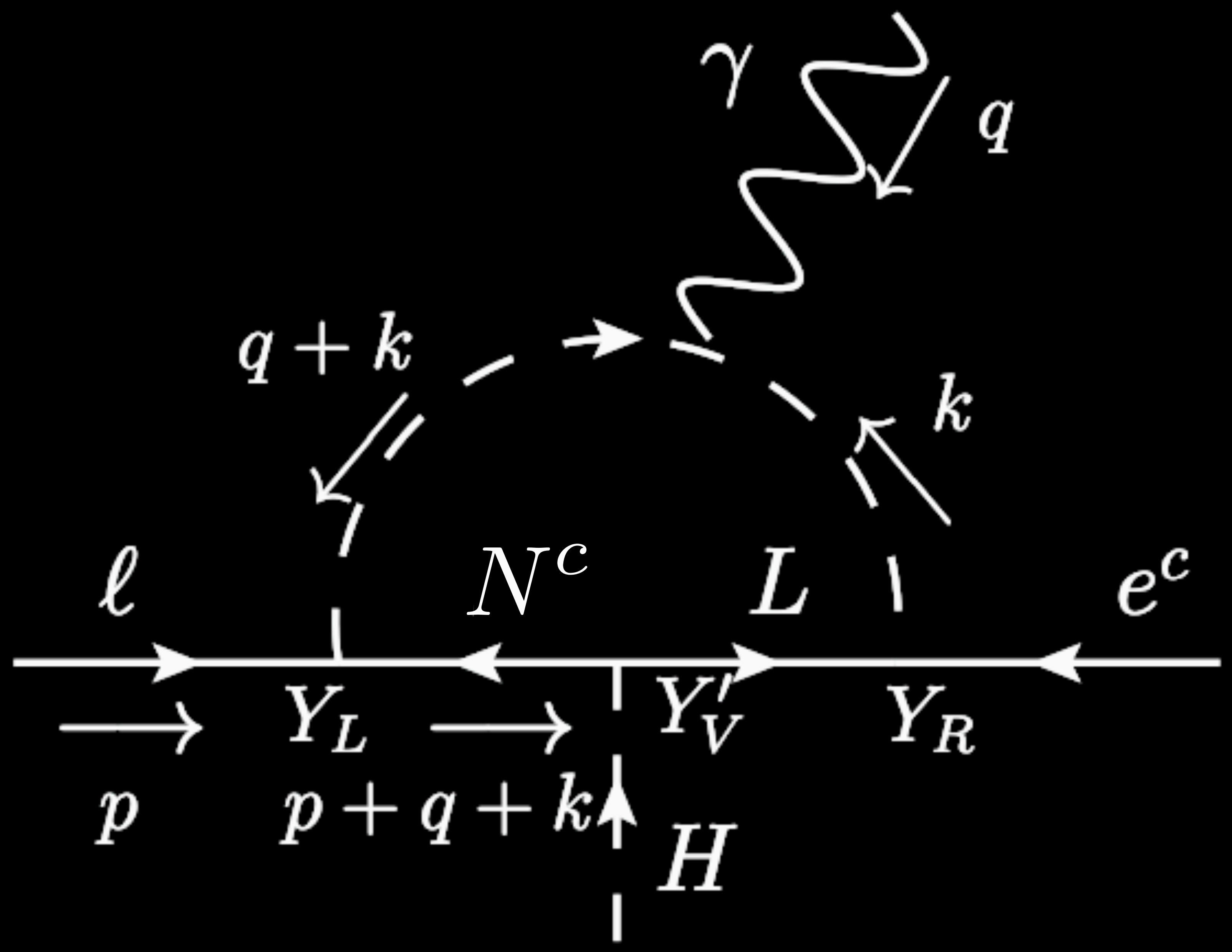
Spontaneous breaking in the Coulomb phase → massless photon is the Goldstone (vector) boson

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 $a \times b = \Sigma_c N_{ab}^c c$

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"

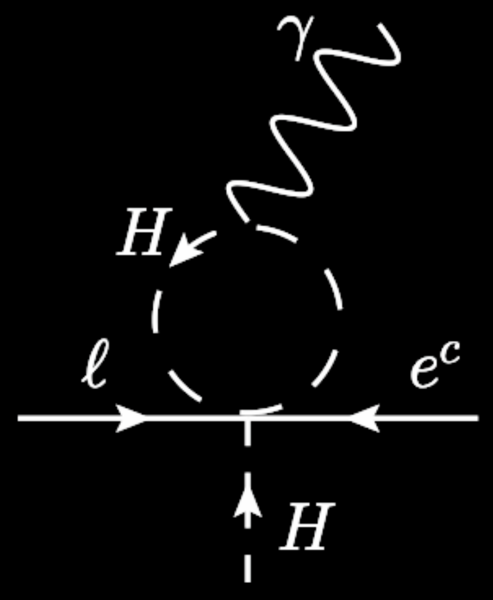
$$\int_0^\infty \frac{dk^2}{k^2} k^2 f'(k^2)$$

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

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

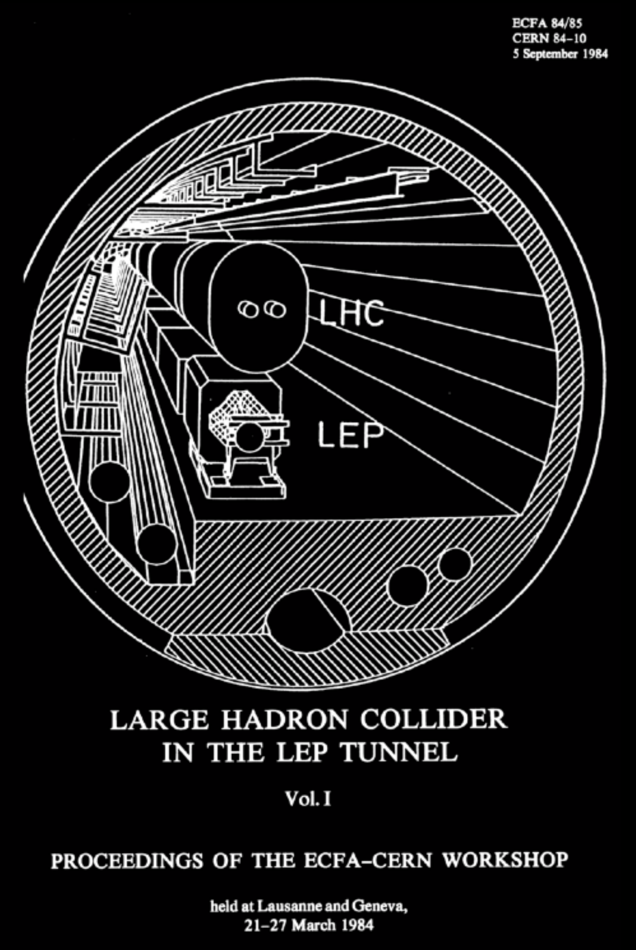
⇨

Between scales IR contribution nonzero but $\Delta a_\mu = 0$



Closing thoughts

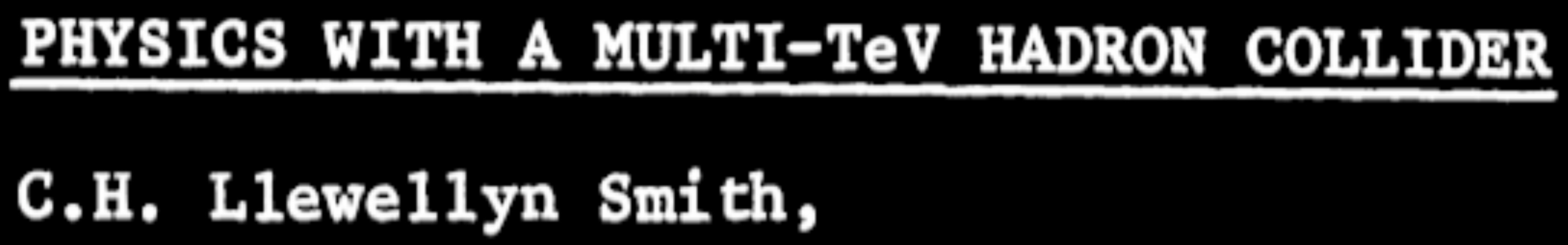
- We have a profound opportunity to “predict” the Higgs mass (i.e., to use the measured Higgs mass to infer other sharply defined phenomena).
- “Naturalness” often arises along the way, but exists in a broader context of predictive frameworks.
- While some approaches to this prediction are well-explored, 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.


ECFA 84/85
CERN 84-10
5 September 1984

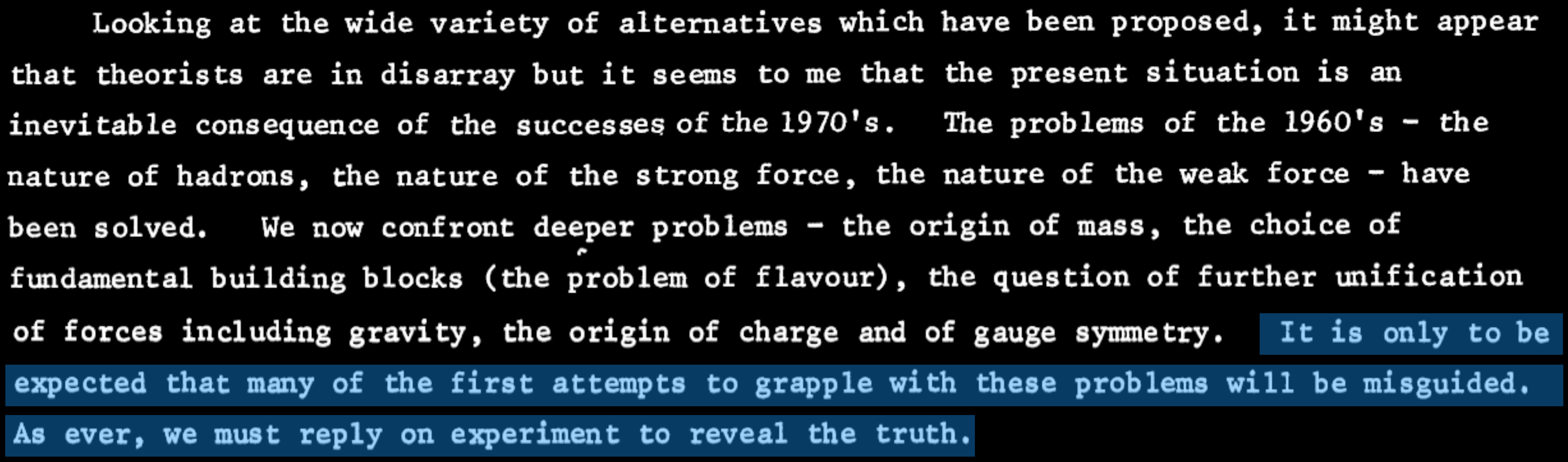
LARGE HADRON COLLIDER
IN THE LEP TUNNEL
Vol. I

PROCEEDINGS OF THE ECFA-CERN WORKSHOP

held at Lausanne and Geneva,
21-27 March 1984


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!