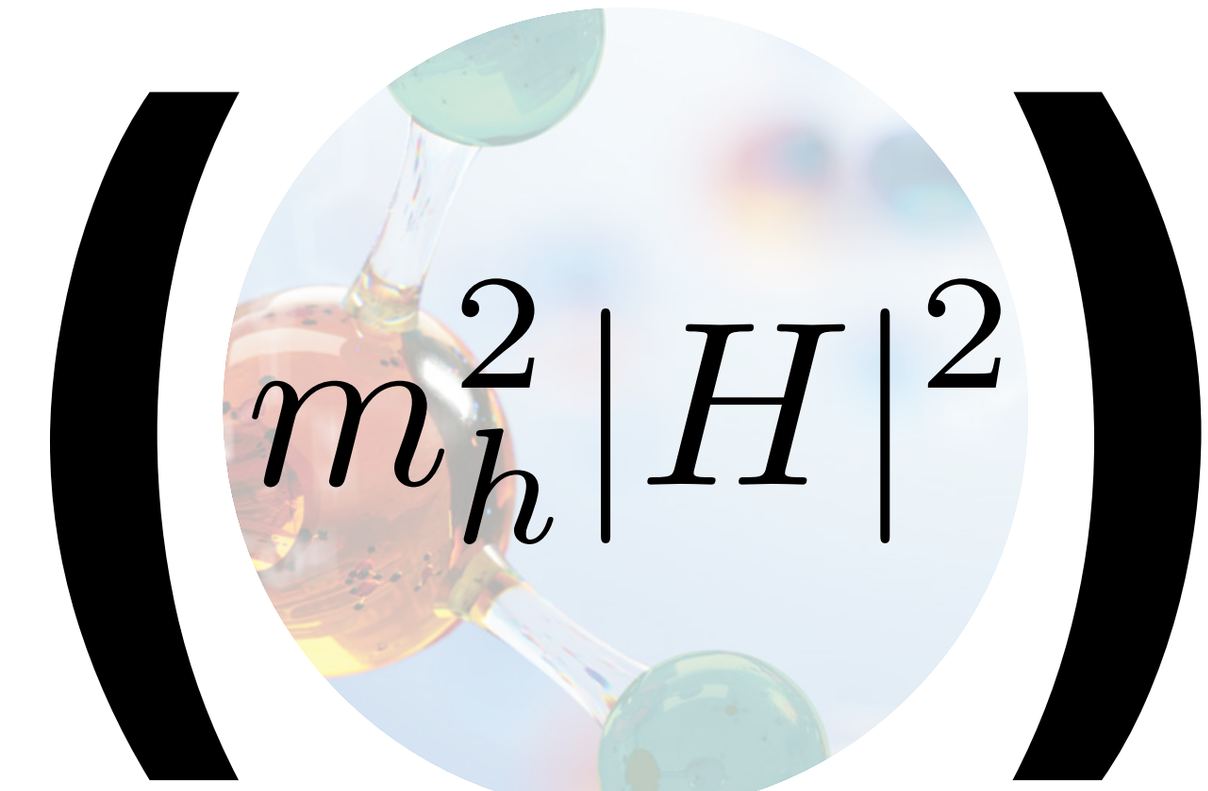
WEAK SCALE TRIGGERS AND WHERE TO FIND THEM

Raffaele Tito D'Agnolo — IPhT Saclay

Higgs Mass Squared

$$m_h^2 |H|^2$$

WEAK FORCE, STRUCTURE OF NUCLEI, COMPLEX CHEMISTRY, …



We have been looking
for answers
here for more than **40 years**

Higgs Boson

and we have
not found them

1. We tune a bit

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2. There is no mass scale beyond the SM [1305.6939]

3. The Higgs mass is an input

4. UV/IR Mixing [1909.01365]

5. Swampland on steroids

1. We tune a bit

2. There is no mass scale beyond the SM [1305.6939]

3. The Higgs mass is an input

4. UV/IR Mixing [1909.01365]

5. Swampland on steroids

6. **There is a landscape**

…

LANDSCAPES

1. One day it can be tested experimentally
2. Currently our most concrete explanation for the CC
3. It probably exists independently of the problem

$O_1 = -O_2 + \epsilon$

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LANDSCAPES

Caveats on eternal inflation, dS and AdS vacua:

[Dvali '21],[Dvali, Gomez '13-'14], [Dvali, Gomez, Zell '17], [Dvali '20]

[Ooguri, Vafa '06], [Garg, Krishnan '18], [Obied, Ooguri, Spodyneiko, Vafa '18], [Ooguri, Palti, Shiu, Vafa '18]

Is there a landscape?

1. Not that many e-folds needed to populate a landscape
2. Not every landscape is a multiverse

Change of perspective:

Can we find the origin of the weak scale early in the history of the Universe?

Historically:

Multiverse
+Anthropic selection

Recently:

New class of ideas that can be tested in the laboratory in the near future

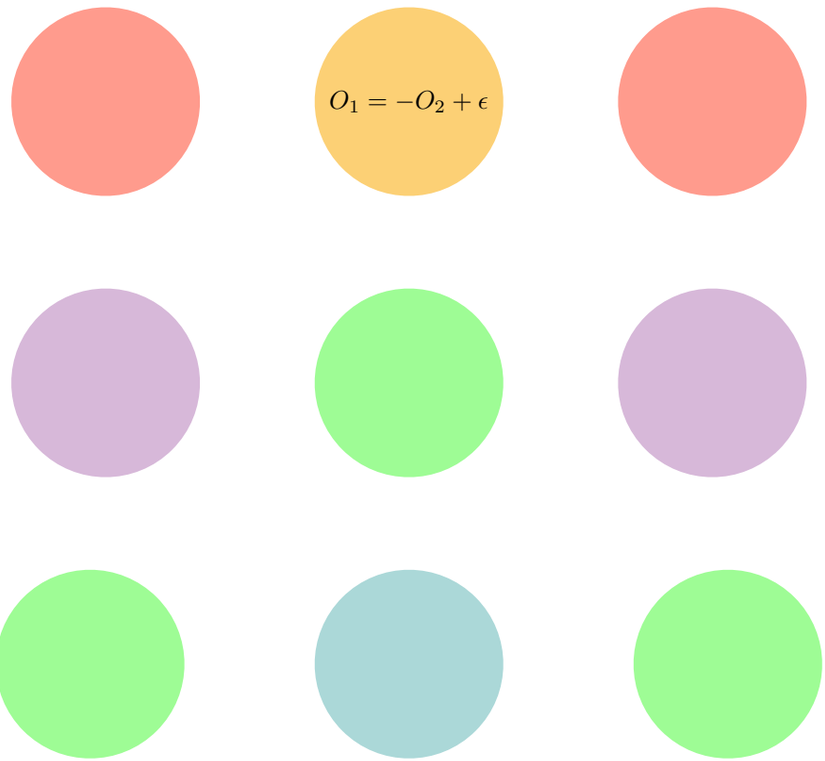
[RTD, Teresi, ’21]

2109.13249
2106.04591

Symmetric Sector

$\Lambda_S \ll M_{\rm Pl}$

SM Landscape



See tomorrow’s talk by D. Teresi

Symmetric Sector

$\Lambda_S \ll M_{\rm Pl}$

SM Landscape

$O_1 = -O_2 + \epsilon$

Sensitive to the Higgs vev

(with some exceptions)

General QFT question relevant beyond cosmological naturalness:

Does anything change (in the SM) as we vary the Higgs mass squared?

Most relevant phenomenologically:

Physics coupled to the Higgs with

$$m \lesssim v$$

One trigger = **Many solutions** to the hierarchy problem

SM TRIGGERS

[Arkani-Hamed, RTD, Kim, ’20]

Does anything change in Nature as we vary the Higgs mass squared?

$$\frac{d\log f(\langle h\rangle)}{d\log\langle h\rangle} = O(1)$$

Does anything change
as we vary the Higgs mass?

LOCAL

$$\mathrm{Tr}[G \wedge G] \equiv G\tilde{G}$$

NON-LOCAL

On-shell N-point functions of massive SM particles

Does anything change
as we vary the Higgs mass?

LOCAL

$$\mathrm{Tr}[G \wedge G] \equiv G\tilde{G}$$

NON-LOCAL

On-shell N-point functions of massive SM particles

Atomic Principle [Agrawal, Donoghue, Barr, Seckel '97]

Nnaturalness [Arkani-Hamed, Cohen, **RTD**, Hook, Kim, Pinner '16]

Selfish Higgs [Giudice, Kehagias, Riotto, '19]

$$\langle G\widetilde{G}\rangle \simeq (y_u + y_d)\langle h\rangle f_\pi^3(\langle h\rangle)\theta$$

Non-trivial!

1. $U(1)_A$ breaking that can interfere with QCD instantons

2. Sensitivity to the Higgs mass ($U(1)_A$ breaking and/or SU(3) running)

3. $\Lambda_{\rm QCD} \lesssim m_h$

[RTD, Teresi, '21]

POTENTIAL TRIGGERS

In the SM we can try other options

$$\mathrm{Tr}\left[W\widetilde{W}\right]$$

Needs extra B+L breaking

Beyond the SM

$$\frac{(Qu^c)(Qd^c)}{M^2}$$

Works only in 2HDM or for little HP

In the SM at 3 loops it's sensitive to flavor breaking by Yukawas

A BSM TRIGGER

[Arkani-Hamed, RTD, Kim, ’20]

$$H_1 H_2$$

Protected by the **Z2 symmetry**

$$H_1 H_2 \to -H_1 H_2$$

H1H2 **without Z2** first considered as ‘paleo’-trigger in: [Espinosa, Grojean,Panico, Pomarol, Pujolas ’15], [Dvali, Vilenkin ’01]. Today these models require **two coincidences of scales to be alive at the LHC**.

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

$$V_{H_1 H_2} = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + \frac{\lambda_1}{2} |H_1|^4 + \frac{\lambda_2}{2} |H_2|^4$$

$$+\lambda_3 |H_1|^2 |H_2|^2 + \lambda_4 |H_1 H_2|^2 + \left(\frac{\lambda_5}{2} (H_1 H_2)^2 + \text{h.c.} \right)$$

$$H_1 H_2 \left(B\mu + \lambda_6 |H_1|^2 + \lambda_7 |H_2|^2 \right)$$

$$B\mu = \lambda_{6,7} = 0$$

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, ’20]

$$m^2_{A,H^\pm} \sim \lambda v^2, \quad \lambda \lesssim 2$$

$$m_H^2 \sim \lambda_1 v_1^2 \leq m_h^2 = (125\ \text{GeV})^2$$

TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, '20]

For quarks and leptons we choose the

phenomenologically safest Z2 charge assignments

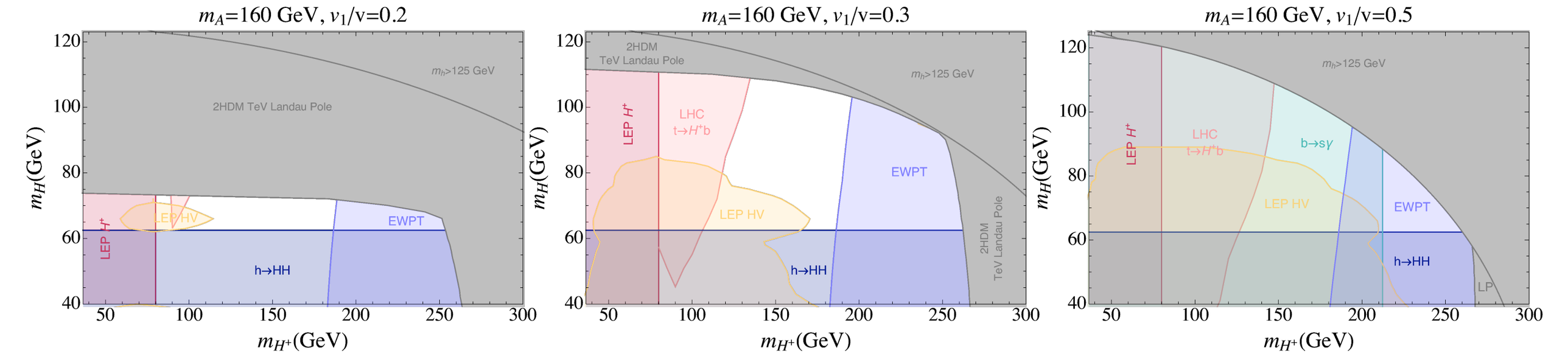
$$H_2 \to -H_2, \quad (qu^c) \to -(qu^c), \quad (qd^c) \to -(qd^c), \quad (le^c) \to -(le^c)$$

This gives

$$V_Y = Y_u q H_2 u^c + Y_d q H_2^\dagger d^c + Y_e l H_2^\dagger e^c$$

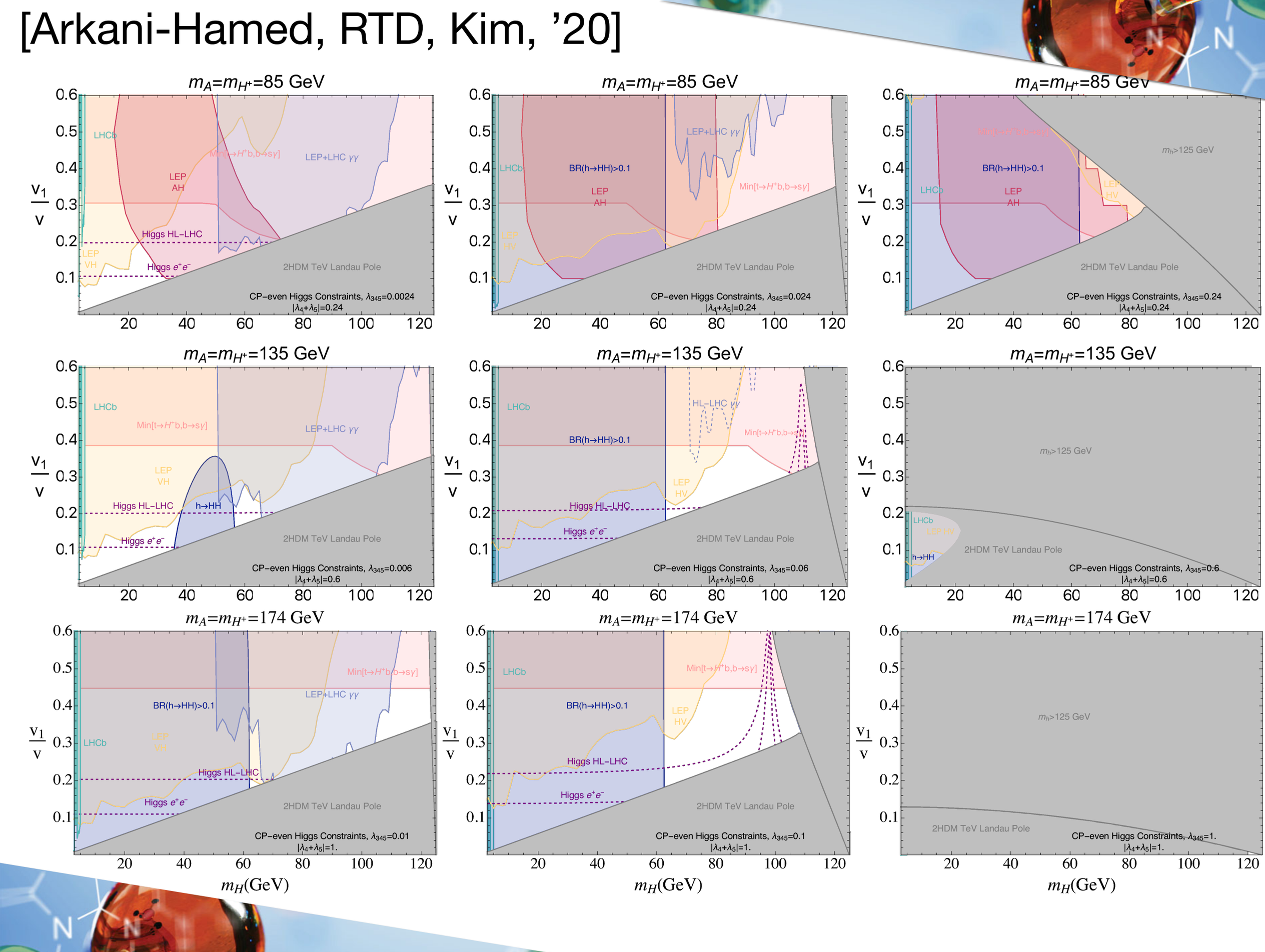
TYPE-0 2HDM

[Arkani-Hamed, RTD, Kim, ’20]



Sharp target for HL-LHC and FCC
which **can’t be decoupled**!
(See also the next slide)

[Arkani-Hamed, RTD, Kim, '20]




$G\tilde{G}$


$H_1 H_2$


$F\tilde{F}$

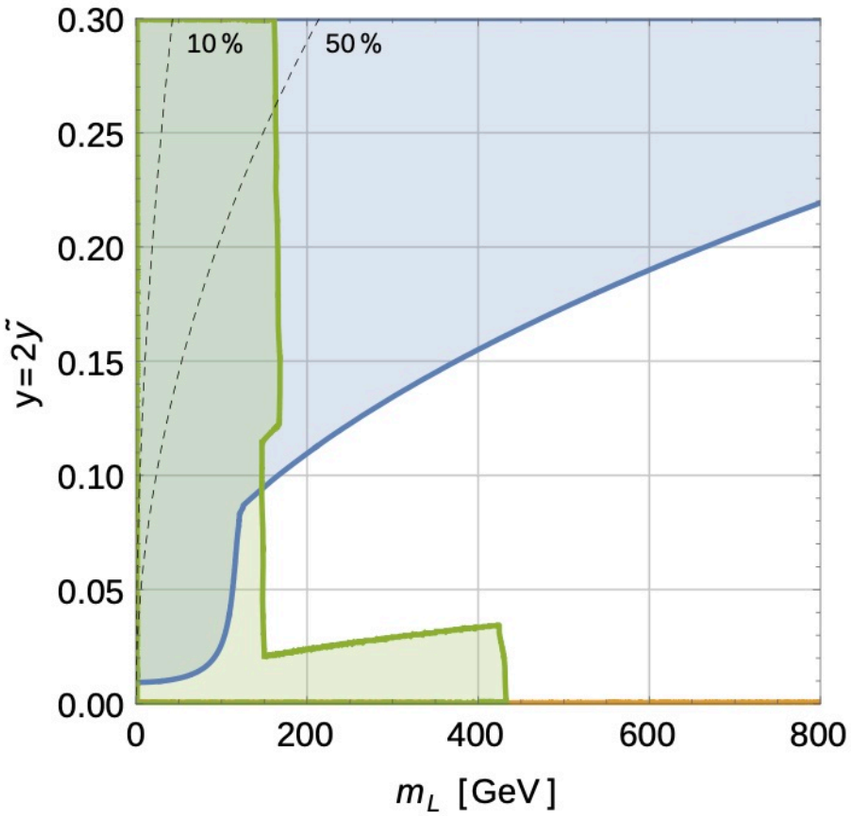
New vector-like leptons

+

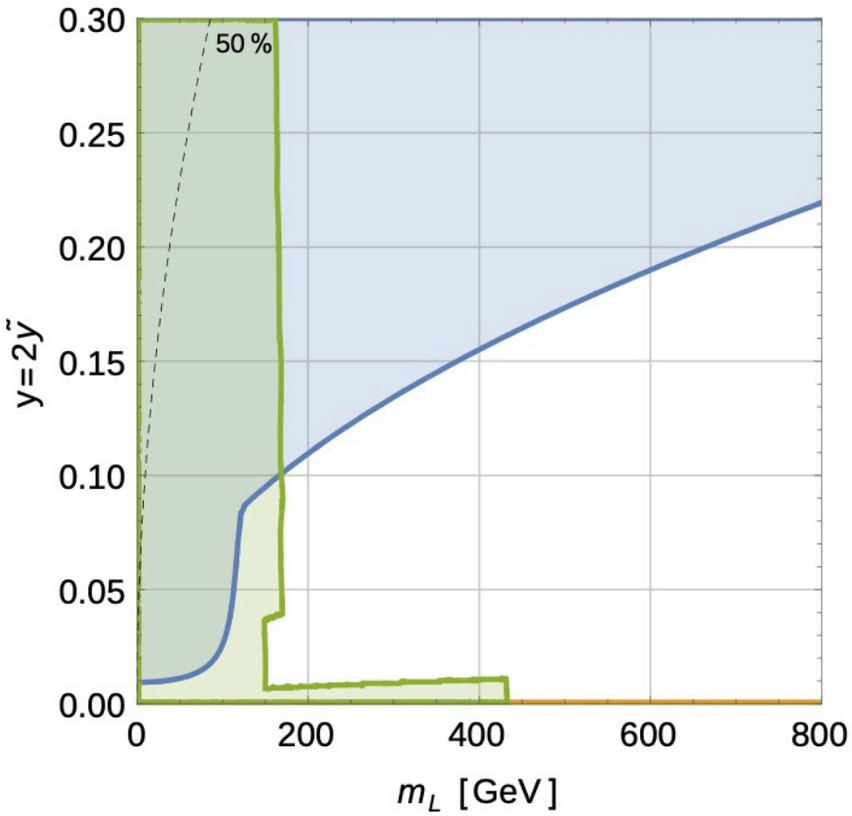
Dark confining gauge group

$$\mathcal{L} \supset -m_L L L^c - m_N N N^c - y L H N^c - y^c L^c H N + \text{h.c.} - \frac{\phi}{32\pi^2 f} F\tilde{F}$$

(c) $\Lambda = 10$ GeV



(d) $\Lambda = 25$ GeV



[Beauchesne, Bertuzzo, Grilli di Cortona ’17]


$G\tilde{G}$


$H_1 H_2$


$F\tilde{F}$

BACKUP

A SIMPLE BSM TRIGGER

$$\langle H_1 H_2 \rangle \simeq v^2 \quad \rightarrow \quad \langle H_1 \rangle \simeq \langle H_2 \rangle \simeq v^2$$

$m^2_{H_1} > 0 \quad m^2_{H_2} < 0$

$$\langle H_1 H_2 \rangle \simeq B\mu \frac{|m^2_{H_2}|}{m^2_{H_1}}$$

$$B\mu \lesssim v^2$$

$m^2_{H_1} < 0 \quad m^2_{H_2} < 0 \quad B\mu \simeq 0$

$$\langle H_1 H_2 \rangle \simeq \sqrt{|m^2_{H_1} m^2_{H_2}|}$$

$$|m^2_{H_1} - m^2_{H_2}| \lesssim v^2$$

A SIMPLE BSM TRIGGER

$$\langle H_1 H_2 \rangle \simeq v^2 \quad \rightarrow \quad \langle H_1 \rangle \simeq \langle H_2 \rangle \simeq v^2$$

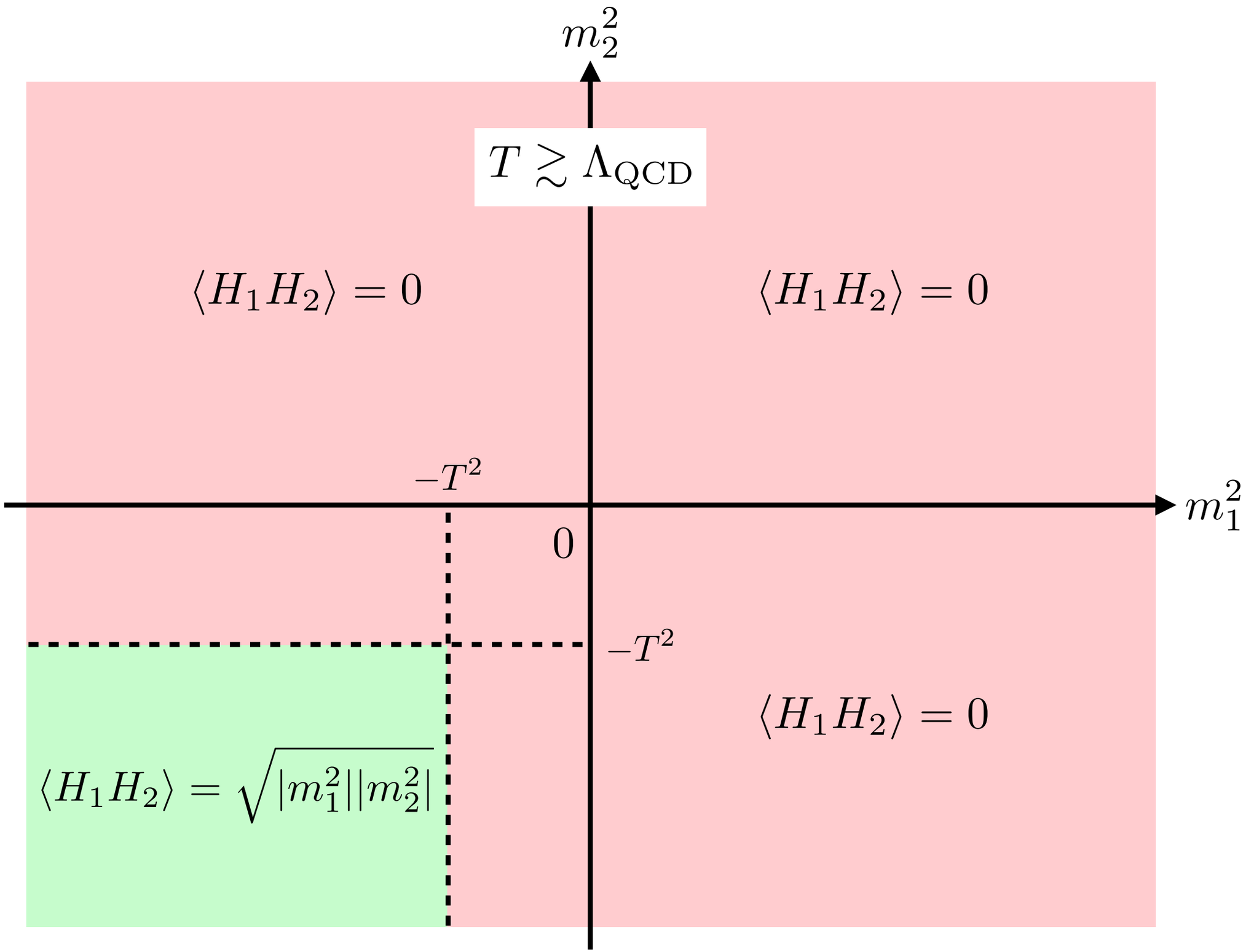
$B\mu \gtrsim v^2$

Or we are in the Z2 Case

$|m^2_{H_1} - m^2_{H_2}| \gtrsim v^2$

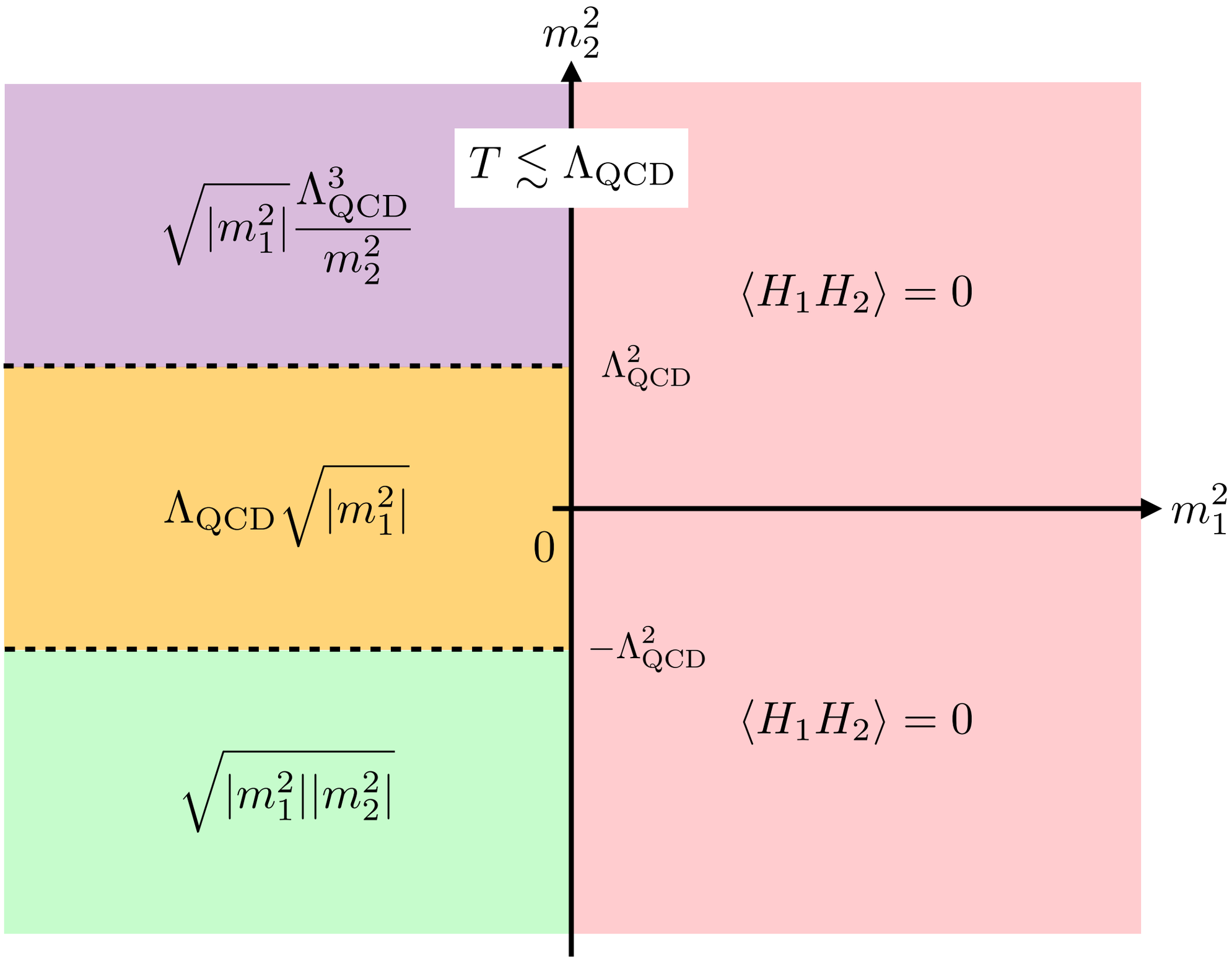
From Higgs Couplings

A SIMPLE BSM TRIGGER



N.B. in reality need tiny breaking of H1->-H1 to avoid domain walls, so “0” really means << v

A SIMPLE BSM TRIGGER



N.B. in reality need tiny breaking of H1->-H1 to avoid domain walls, so “0” really means << v

A GENERAL LESSON

Does anything change in the SM as we vary $\langle h \rangle$?

$$\frac{\alpha_s}{8\pi}(\xi\phi + \theta)\mathrm{Tr}\left[G\tilde{G}\right]$$

$$m_\pi^2 f_\pi^2 \sqrt{1 - \frac{4 m_u m_d}{(m_u + m_d)^2}\sin^2(\xi\phi + \theta)}$$

$$(y_u + y_d) v f_\pi^3 \left(\theta\xi\phi + \xi^2\phi^2 + ...\right)$$

HIERARCHY 102

Does anything change in the SM as we vary $\langle h \rangle$?

$$\xi \phi \mathrm{Tr}\left[G\widetilde{G}\right]$$

Important Pheno Message:

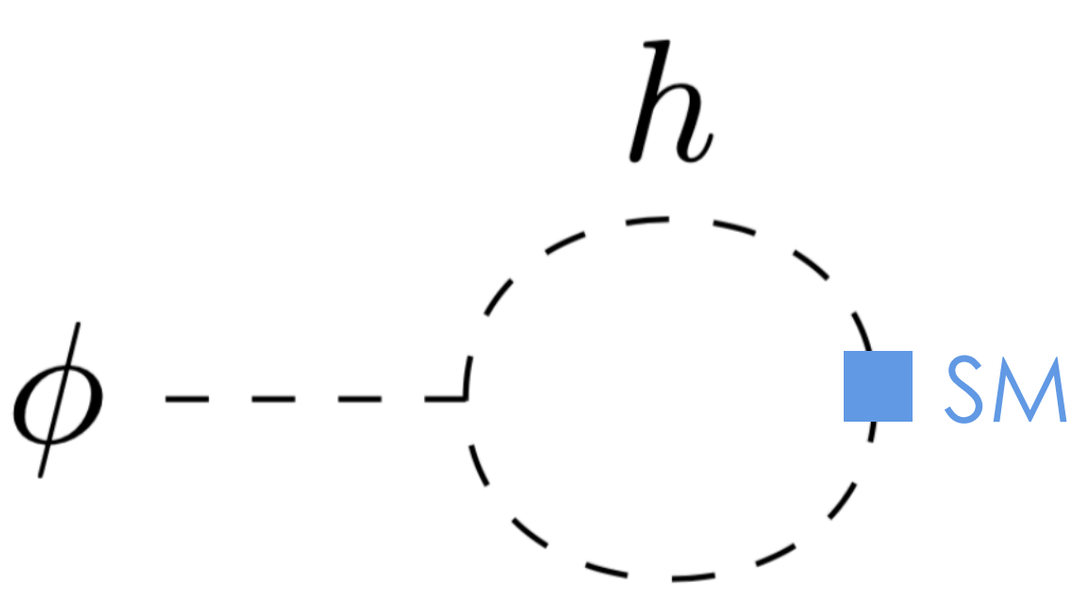
Axion-Like phenomenology can be related to the hierarchy problem

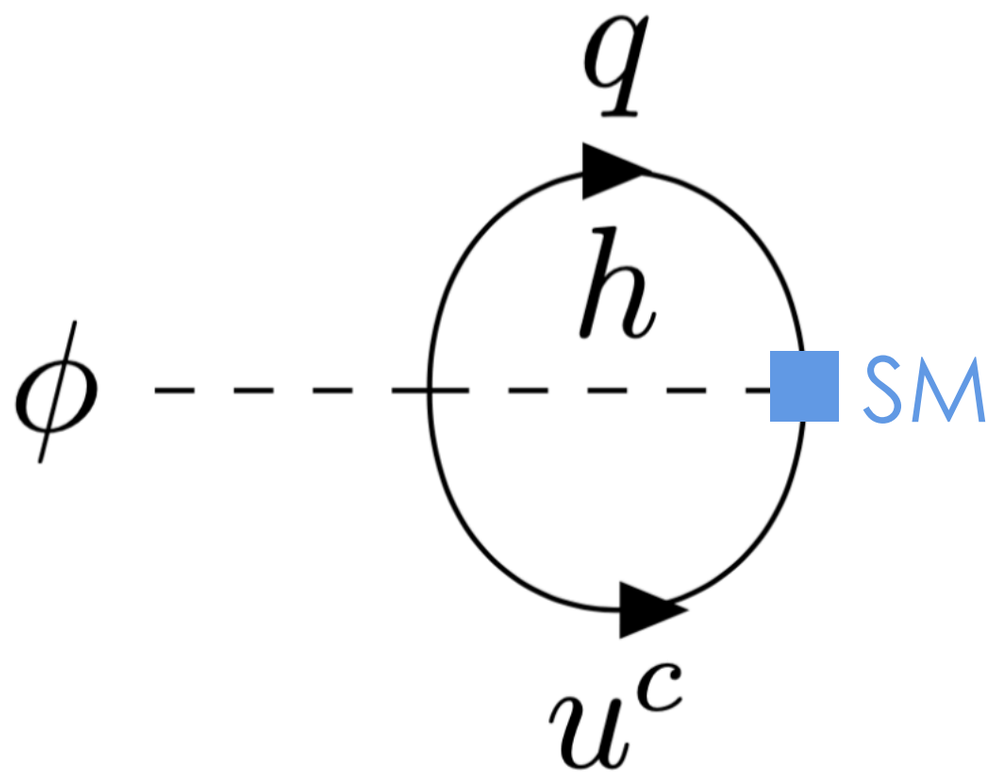
HIERARCHY 102

More precisely: add a light scalar ϕ and tiny coupling

$$\xi \phi \mathcal{O}$$

The effective tadpole for ϕ at low energy is proportional to the vev of $\mathcal{O}$





HIERARCHY 102

Does anything change in the SM as we vary $\langle h \rangle$?

$$\xi \phi \mathrm{Tr}\left[G\widetilde{G}\right]$$

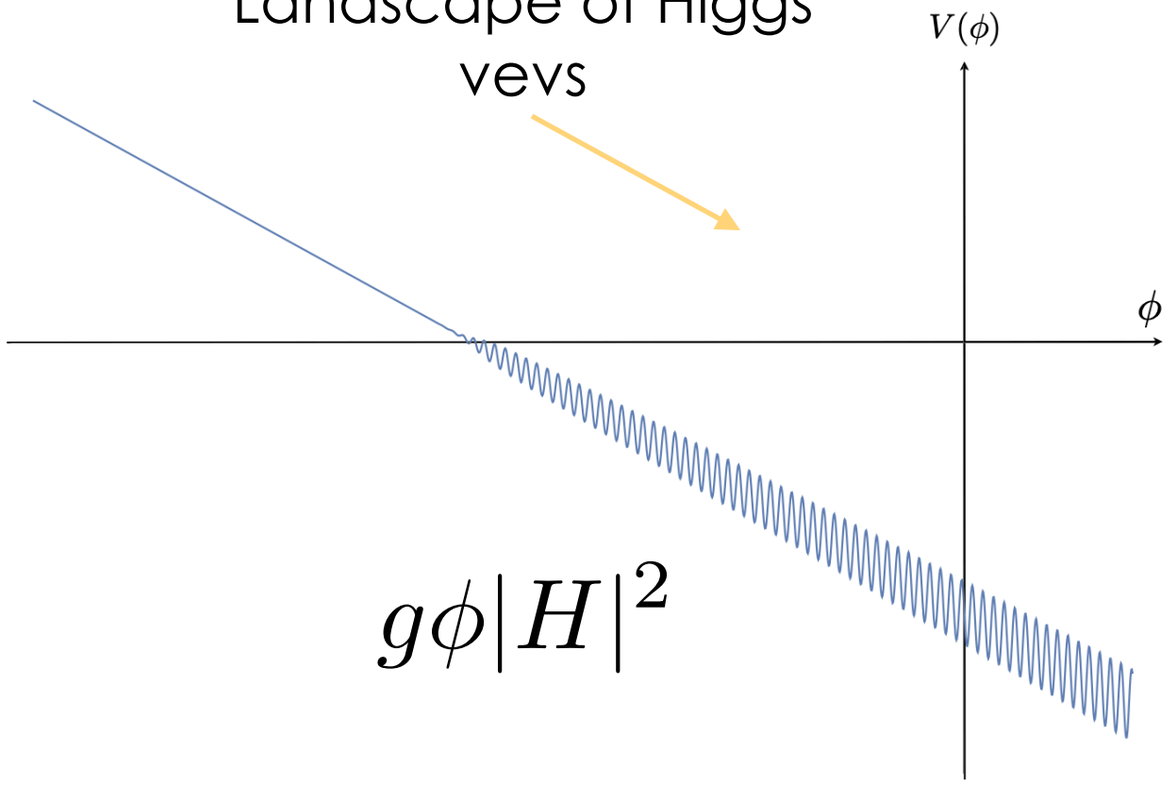
Important Pheno Message:

Axion-Like phenomenology can be related to the hierarchy problem

CAUSALLY CONNECTED LANDSCAPES

Relaxion

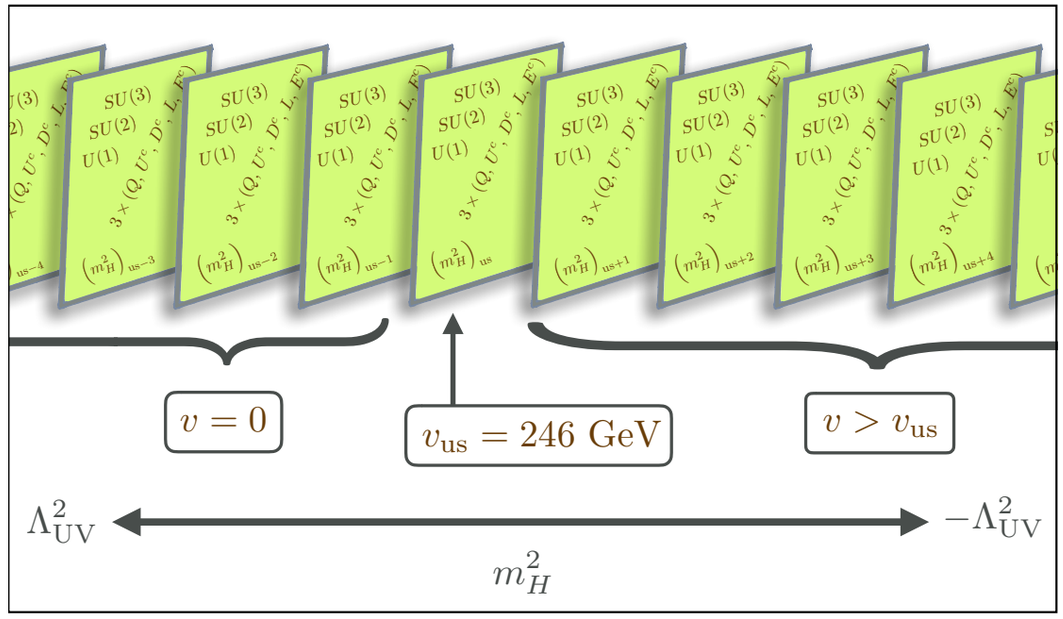
Scanning =
Landscape of Higgs vevs



[Abbott '84], [Graham, Kaplan, Rajendran '15]

Many options with fewer e-folds:
[Espinosa, Grojean, Panico, Pomarol, Pujolas, '15], …

Nnaturalness



[Arkani-Hamed, Cohen, **RTD**, Hook, Kim, Pinner '16]

EXAMPLE: ANTHROPIC

[Agrawal, Barr, Donoghue, Seckel ’97]

For complex chemistry we need a Higgs vev not too far from the QCD scale

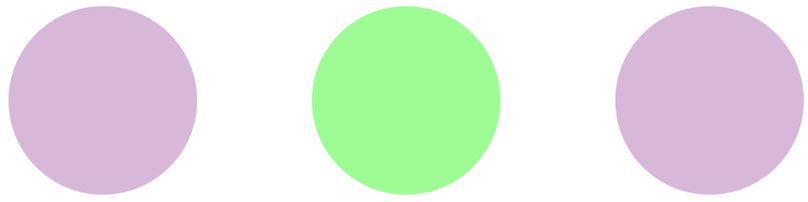
Symmetric Sector

$\Lambda_{\rm QCD} \ll M_{\rm Pl}$

QCD

$Y_q Q H q^c$

SM Landscape



“Friendly” String Landscape?

[Arakni-Hamed, Dimopoulos, Kachru, ‘05]

GENERAL STRUCTURE

[RTD, Teresi '21]

$$V = \mp m_{\pm}^2 \phi_{\pm}^2 - \lambda_{\pm} \phi_{\pm}^4 + \frac{\alpha_s}{8\pi} \left(\theta + \frac{\phi_+}{F_+} + \frac{\phi_-}{F_-} \right) G\tilde{G}$$

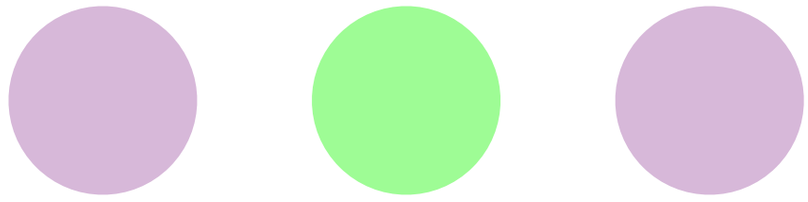
Symmetric Sector

$m_{\pm} \ll M_{\rm Pl}$

$\phi_{\pm}$

$\phi_{\pm} G\tilde{G}$

SM Landscape



"Friendly" String Landscape?

[Arakni-Hamed, Dimopoulos, Kachru, '05]

Anthropic Selection

[Agrawal, Barr, Donoghue, Seckel '97],[Arvanitaki, Dimopoulos, Gorbenko, Huang, Van Tilburg '16],

[Arkani-Hamed, RTD, Kim, '20],

[Giudice, Kehagias, Riotto, '20],

…

Statistical Selection

[Dvali, Vilenkin '03], [Dvali '04], [Geller, Hochberg, Kuflik,'18], [Giudice, McCullough, You, '21],

…

Dynamical Selection

[Graham, Rajendran, Kaplan, '15], [Arkani-Hamed, Cohen, RTD, Kim, Pinner, '16], [Csaki, RTD, Geller, Ismail, '20], [Strumia, Teresi, '20], [RTD, Teresi, '21],

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