Title: Crunchy critical natural Higgs

Speakers: Ameen Ismail

Collection/Series: Particle Physics

Subject: Particle Physics

Date: April 29, 2025 - 1:00 PM

URL: https://pirsa.org/25040129

Abstract:

I describe a new solution to the Higgs hierarchy problem based on a dynamical vacuum selection mechanism in a landscape which scans the Higgs mass. The Higgs potential only admits a stable minimum when its mass is less than a critical value, cosmologically crunching away patches with a heavier Higgs. This critical value is set by the instability scale where the Higgs quartic turns negative. I consider the phenomenology of two explicit models that address the hierarchy problem in this context.

Crunchy, critical, natural Higgs

(on the hierarchy problem, vacuum selection, and metastability)

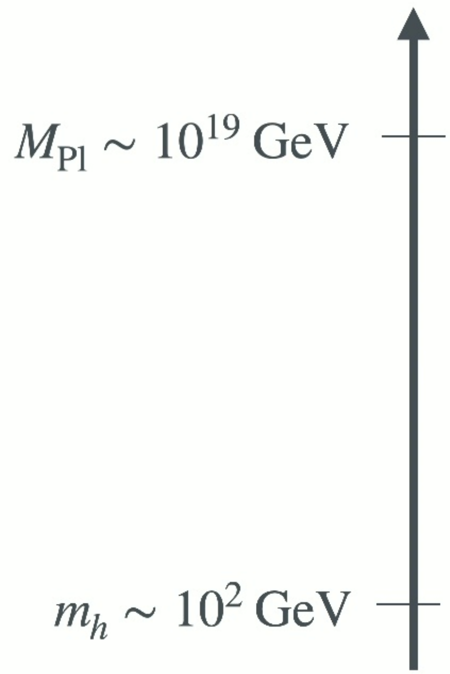
Ameen Ismail

PI Particle Seminar

2502.07876 + WIP w/ S. Benevedes and T. Steingasser
(also 2007.143976, 2210.02456)

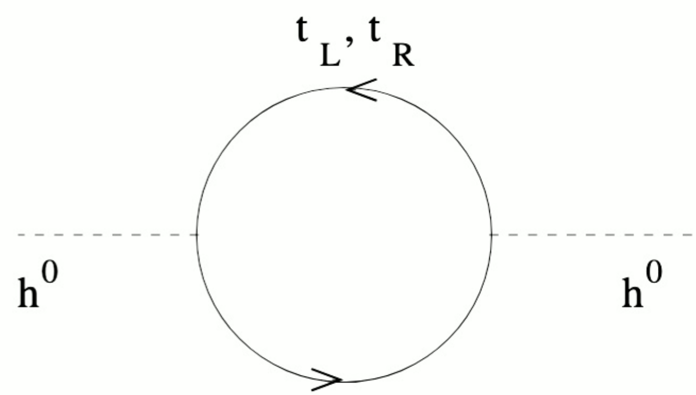
The hierarchy problem

- The Higgs mass is a relevant operator unprotected by symmetry
  - so we expect mass gets Planck-scale quantum corrections
  - implies Higgs mass is finely tuned without new physics
- Traditional solutions protect m_h^2 with a symmetry:
  - e.g. weak-scale SUSY, compositeness, RS
  - typically predict new coloured states (top partners)



Not the hierarchy problem

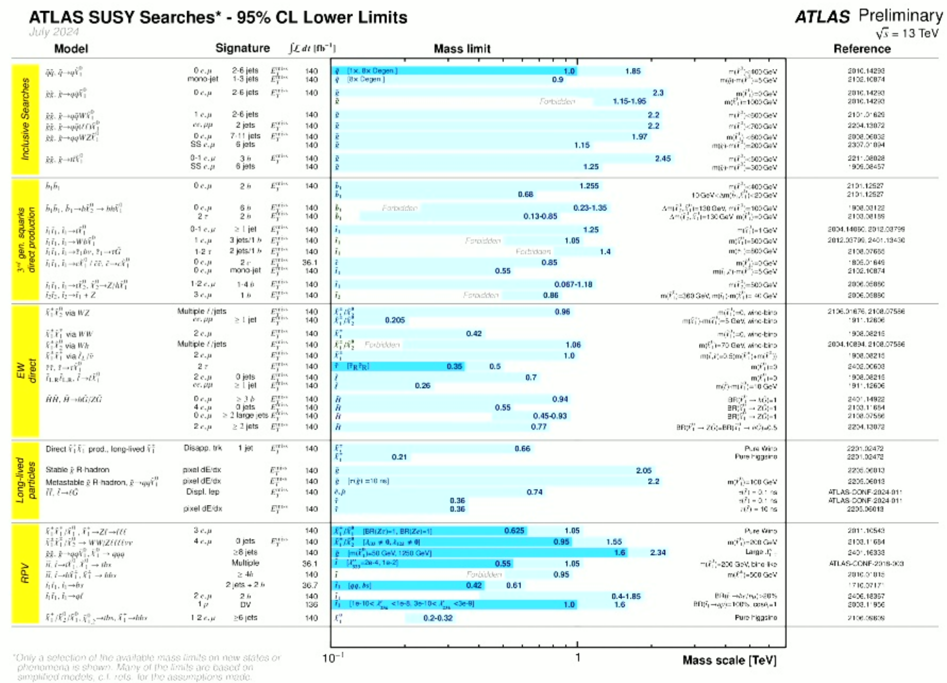
- I know how to regularize a loop diagram, I promise
- Fundamental issue is the **origin** of the weak scale, and **IR sensitivity** to UV parameters
- The loop diagram is shorthand to illustrate this sensitivity when we're too lazy to do better



$$\delta m_h^2 \sim \frac{y_t^2}{16\pi^2}\Lambda_{\rm UV}^2$$

Why bother with the Higgs hierarchy?

- Symmetry-based solutions are increasingly constrained by the LHC
- By no means am I saying they are dead!
- But it's natural to speculate of other approaches that could have different phenomenology



ATL-PHYS-PUB-2024-014

Some great ideas I won't talk about

(beyond this slide, anyway)

- Neutral naturalness / twin Higgs
- Relaxion and similar models
- NNaturalness
- I will focus on **vacuum selection**

The Twin Higgs: Natural Electroweak Breaking from Mirror Symmetry

Z. Chacko,[1] Hock-Seng Goh,[1] and Roni Harnik[2]

[1] *Department of Physics, University of Arizona, Tucson, AZ 85721*
[2] *Department of Physics, University of California, Berkeley, CA 94720*
Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Cosmological Relaxation of the Electroweak Scale

Peter W. Graham,[1] David E. Kaplan,[1,2,3,4] and Surjeet Rajendran[3]

[1] *Stanford Institute for Theoretical Physics, Department of Physics, Stanford University, Stanford, CA 94305*
[2] *Department of Physics & Astronomy, The Johns Hopkins University, Baltimore, MD 21218*
[3] *Berkeley Center for Theoretical Physics, Department of Physics, University of California, Berkeley, CA 94720*
[4] *Kavli Institute for the Physics and Mathematics of the Universe (WPI),*
Todai Institutes for Advanced Study, University of Tokyo, Kashiwa 277-8583, Japan

(Dated: June 24, 2015)

***N*naturalness**

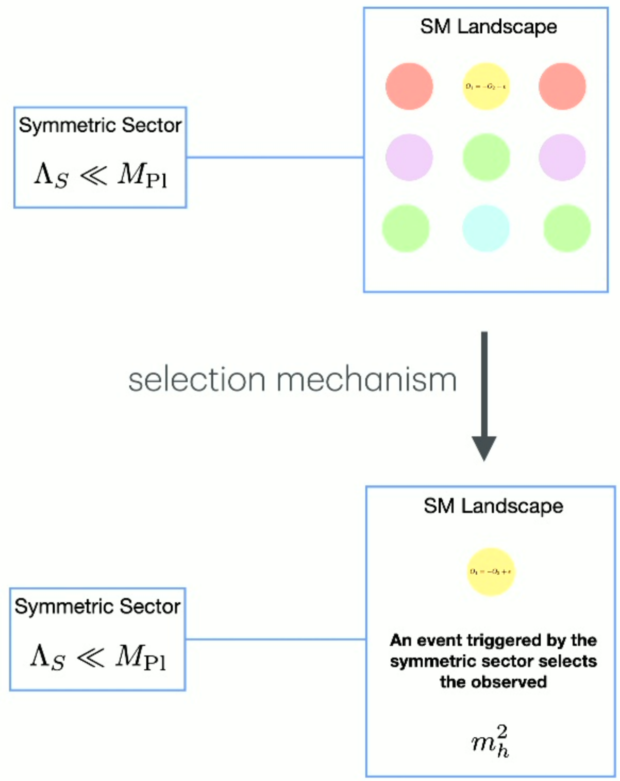
***N*ima Arkani-Hamed,[1] Timothy Cohe*N*,[2] Raffaele Tito D'Ag*N*olo,[1]
A*N*son Hook,[3] Hyu*N*g Do Kim,[4] and David Pi*N*ner[5]

[1] *School of Natural Sciences, Institute for Advanced Study, Princeton, New Jersey 08540, USA*
[2] *Institute of Theoretical Science, University of Oregon, Eugene, OR 97403, USA*
[3] *Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94305, USA*
[4] *Department of Physics and Astronomy and Center for Theoretical Physics,*
Seoul National University, Seoul 151-747, Korea
[5] *Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*

Cosmological naturalness

(vacuum selection)

- Landscape scans the Higgs mass: $m_h^2 \in (-\Lambda^2, \Lambda^2)$
- New physics removes all patches **except** those with a fine-tuned EW scale
- e.g. scalar field triggers cosmo. **crunch**
- Typical pheno: light, weakly-coupled scalar mixing with Higgs



modified from 2109.13249

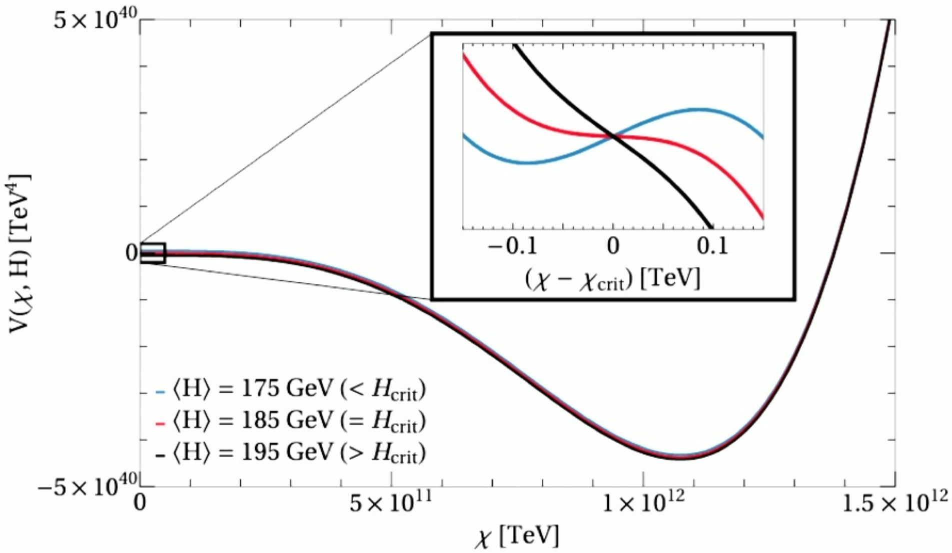
Cosmological naturalness pheno

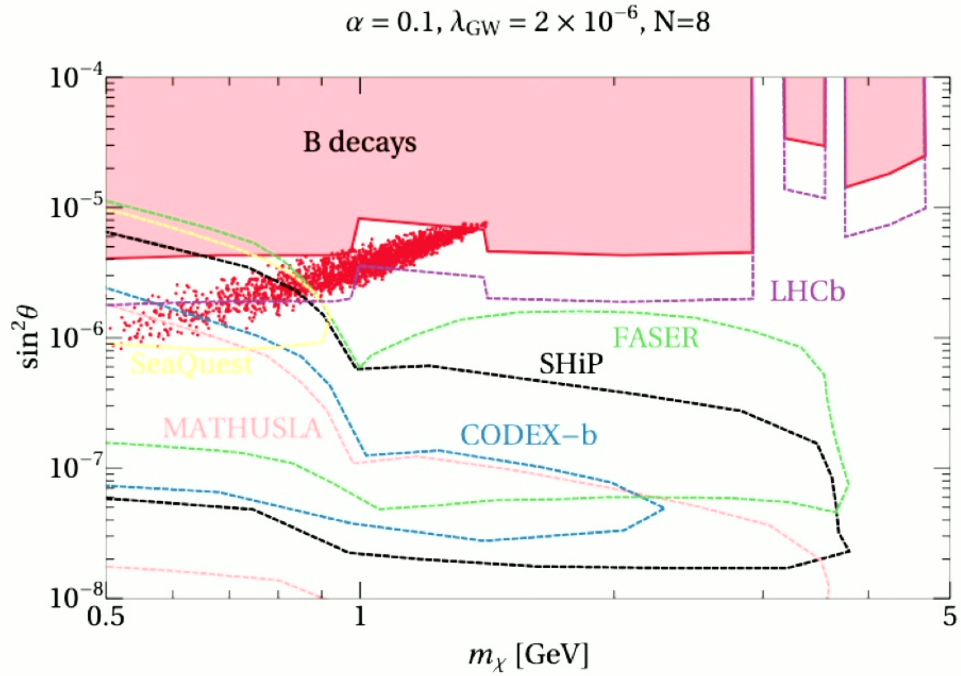
- Potential must be **sensitive** to EW-scale Higgs VEVs
- SM Higgs no good: nothing "special" about EW scale, nothing happens when m^2 crosses 0!
- So, need* a new scalar ϕ
  - Should couple to a good "trigger operator" like $G\tilde{G}$ (c.f. relaxion) (see 2012.04652)
  - Should be light compared to observed EW scale

*or we can change the Higgs potential; see the rest of this talk.

An example

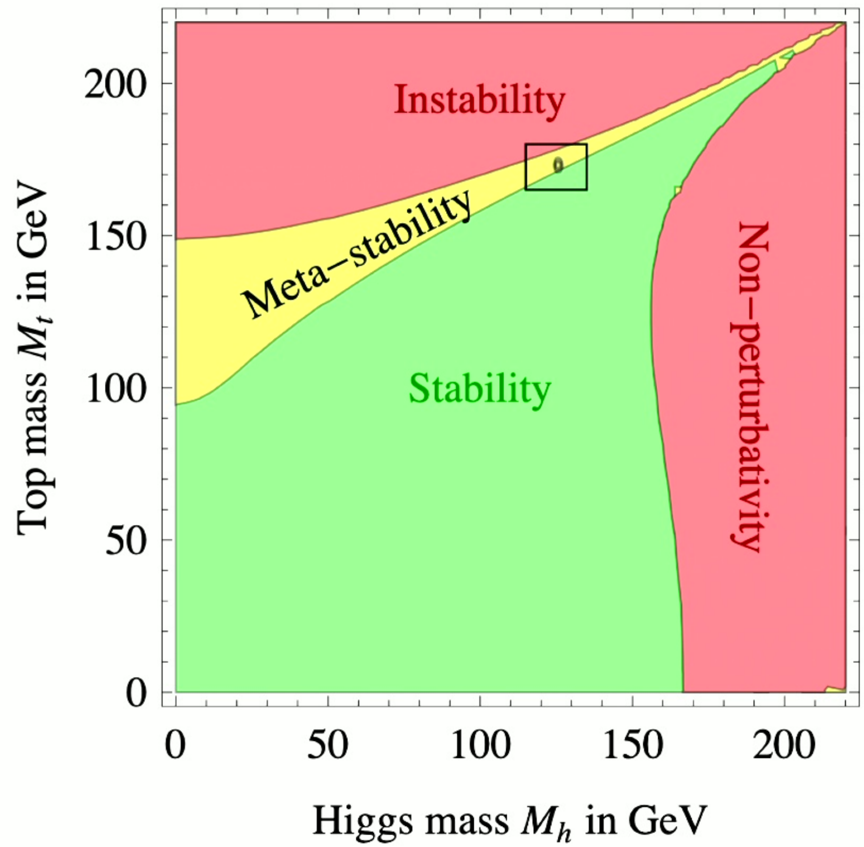
Crunching dilaton, hidden naturalness (2007.14396)





Electroweak metastability

- In the SM, EW vacuum seems to be metastable
- Quartic runs negative at **instability scale**:
  $\lambda(\mu_I) = 0, \ \mu_I \sim 10^{10}\,\mathrm{GeV}$
- Possible connections to EW hierarchy?
  - self-organized criticality (e.g. 2003.12594, 2105.08617)
  - metastability bounds (e.g. 2108.09315, 2408.10297)



1205.6497

The big picture

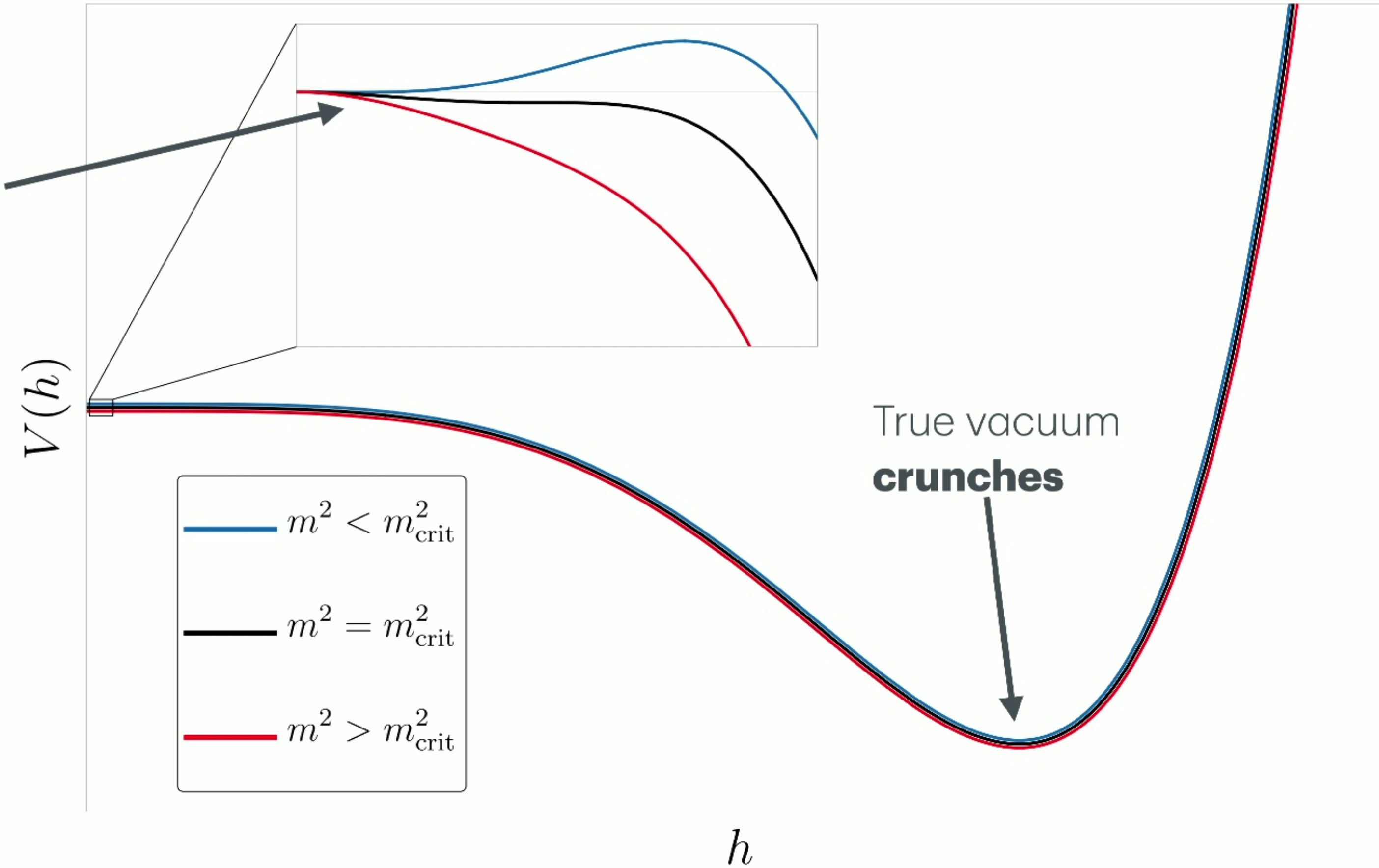
Vacuum selection via Higgs metastability

- Suppose the following:
  - There is a **landscape** that scans the Higgs mass: $V_i(h) = -m_i^2 h^2 + \lambda(h) h^4$
  - The Higgs quartic runs negative at a scale μ_I; the EW vacuum is **metastable**
  - The true vacuum, generated by UV physics, has a **large and negative** energy density
- Claim: this is sufficient to **dynamically select the EW scale** if $\mu_I \sim \mathrm{TeV}$

Potential sketch

False vacuum exists **only** when m^2 is fine-tuned:

$m^2 < m^2_{\text{crit}} \sim \mu_I^2$



The big picture

Vacuum selection via Higgs metastability

- Suppose the following:
  - There is a **landscape** that scans the Higgs mass: $V_i(h) = -m_i^2 h^2 + \lambda(h) h^4$
  - The Higgs quartic runs negative at a scale μ_I; the EW vacuum is **metastable**
  - The true vacuum, generated by UV physics, has a **large and negative** energy density
- Claim: this is sufficient to **dynamically select the EW scale** if $\mu_I \sim \mathrm{TeV}$

Three objections

- Patches that preserve EW symmetry (positive m^2)
  - These are not crunched away, so we need another way to excise such patches
  - Several ways to accomplish this; not my main focus (see Csáki, D'Agnolo, Geller, **AI** '20; D'Agnolo, Teresi '21)
- Lifetime of the false vacuum
  - Lowering μ_I destabilizes vacuum — need to ensure our patch is long-lived
  - Later, we'll use this to bound the scale of a UV completion
- CC problem: I'll assume anthropics, but dynamical mechanisms also possible (see 1912.08840)
- **More on all of these things later!**

One-loop estimate

- Potential: $V_{\text{eff}}(h) = -\frac{1}{4}m^2h^2 + \frac{1}{4}\lambda(h)h^4, \quad \lambda(h) = -b\log\frac{h}{\mu_I}$

  instability scale

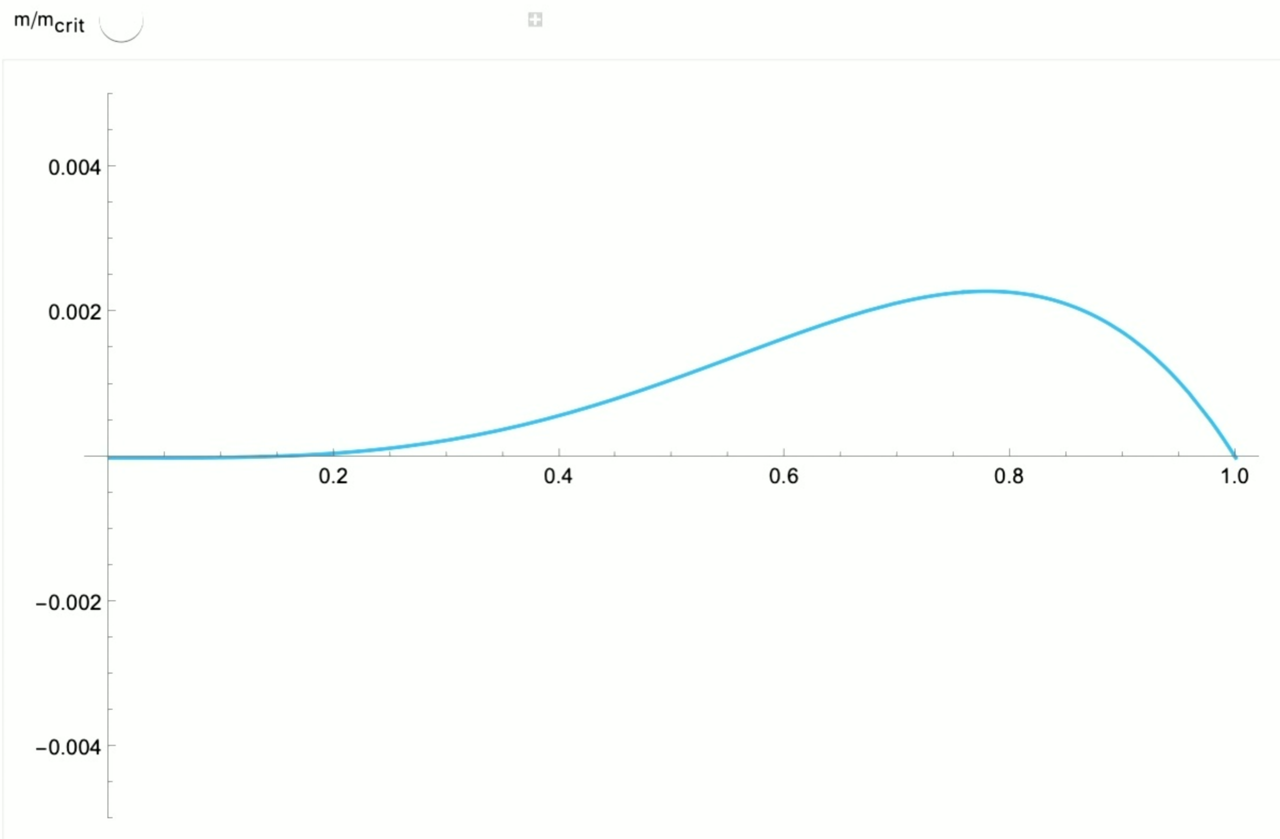
  negative β-function

- VEV satisfies $\frac{1}{2}\left|b\right| v^2\left(1 + 4\log\frac{v}{\mu_I}\right) = m^2$

- Maximized at

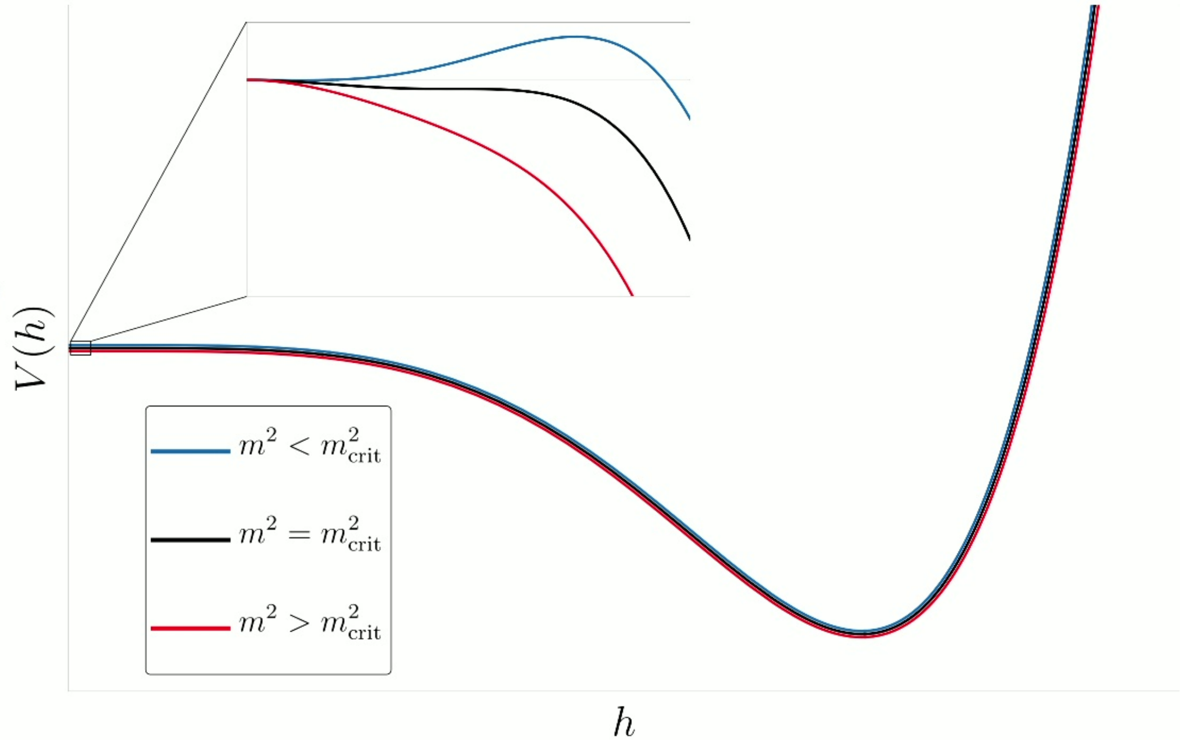
$$\boxed{v_{\text{crit}} = e^{-3/4}\mu_I,\ m_{\text{crit}}^2 = e^{-3/2}\left|b\right|\mu_I^2}$$

One-loop estimate



Vacua

False vacuum exists only when $m < m_{\text{crit}}$, typical energy density $V_{\text{eff}}(v) \sim b\mu_I^4$



Can have $\mu_I \ll \Lambda_{\text{UV}}$; instability scale generated by dim'l transmutation

True vacuum presumably generated by higher-dim operators, typical energy density $-\Lambda_{\text{UV}}^4$

Beyond one loop?

- We can be more careful, e.g. by including dim-6 term $C_6 \left|H\right|^6/\Lambda_{\rm UV}^2$:

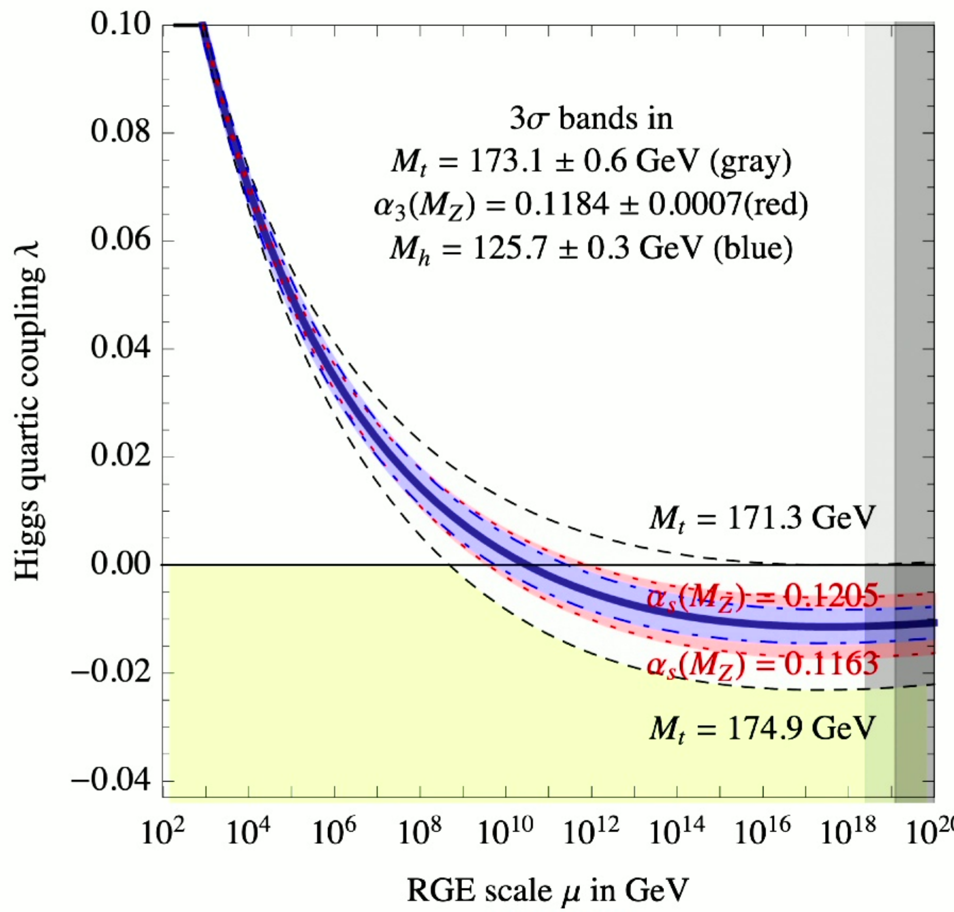
$$\frac{m^2}{|\beta_\lambda(\mu_I)|\,\mu_I^2} = 2\frac{h^2}{\mu_I^2}\left[6\frac{C_6}{|\beta_\lambda(\mu_I)|}\frac{\mu_I^2}{\Lambda^2}\frac{h^2}{\mu_I^2} - \ln\left(\frac{h}{\mu_I}e^{1/4}\right)\right]$$

(existence of false vacuum)

- **Qualitative story unchanged** as long as $\mu_I \ll \Lambda_{\rm UV}$:
  - metastable minimum when $m^2 \lesssim \mu_I^2$
  - large separation in vacuum energy b/w false and true vacua

μ_I in the SM and beyond

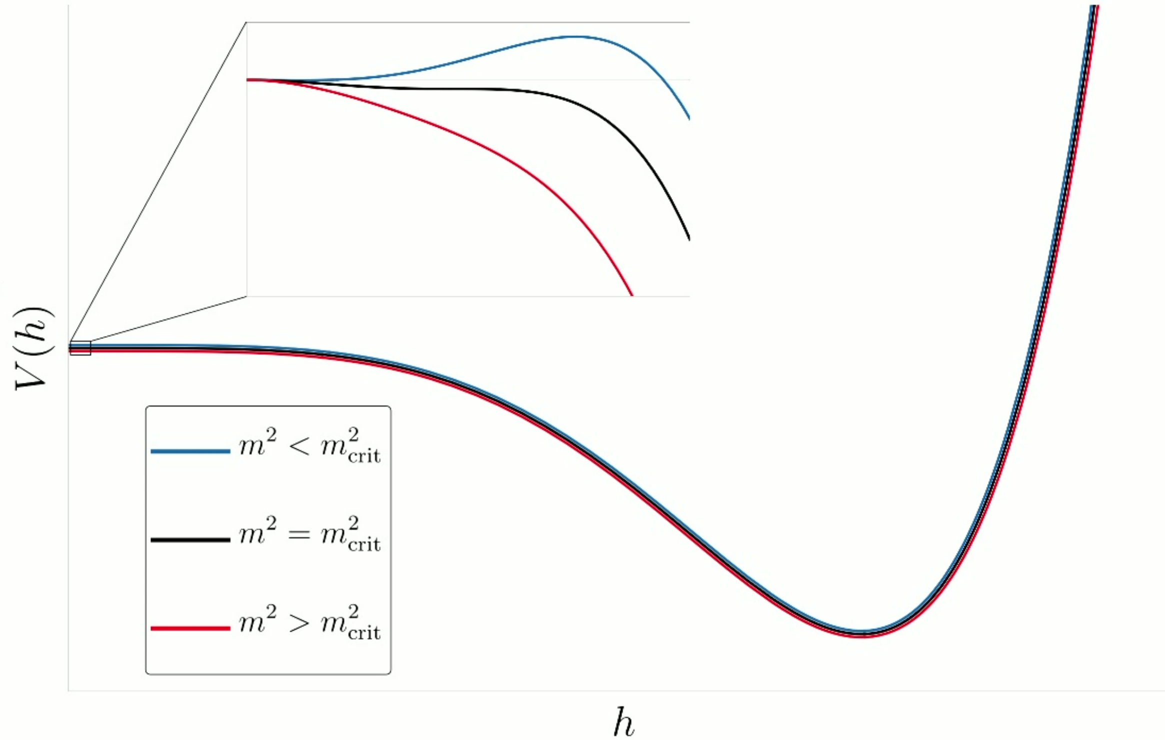
- Recall $\mu_I \sim 10^{10}$ GeV in the SM
- To address EW hierarchy, we want $\mu_I \sim$ TeV
- Our approach: add **vector-like fermions** at a TeV!



1205.6497

Vacua

False vacuum exists only when $m < m_{\text{crit}}$, typical energy density $V_{\text{eff}}(v) \sim b\mu_I^4$



Can have $\mu_I \ll \Lambda_{\text{UV}}$; instability scale generated by dim'l transmutation

True vacuum presumably generated by higher-dim operators, typical energy density $-\Lambda_{\text{UV}}^4$

TeV-scale vector-like fermions

- Distinct phenomenology from existing approaches (both symmetry-based solutions and other vacuum selection mechanisms)
- We'll focus on two simple models: **HNL** and **singlet-doublet** models
- Upshot: probe directly and indirectly at future lepton colliders

Two simple models

i) heavy neutral lepton

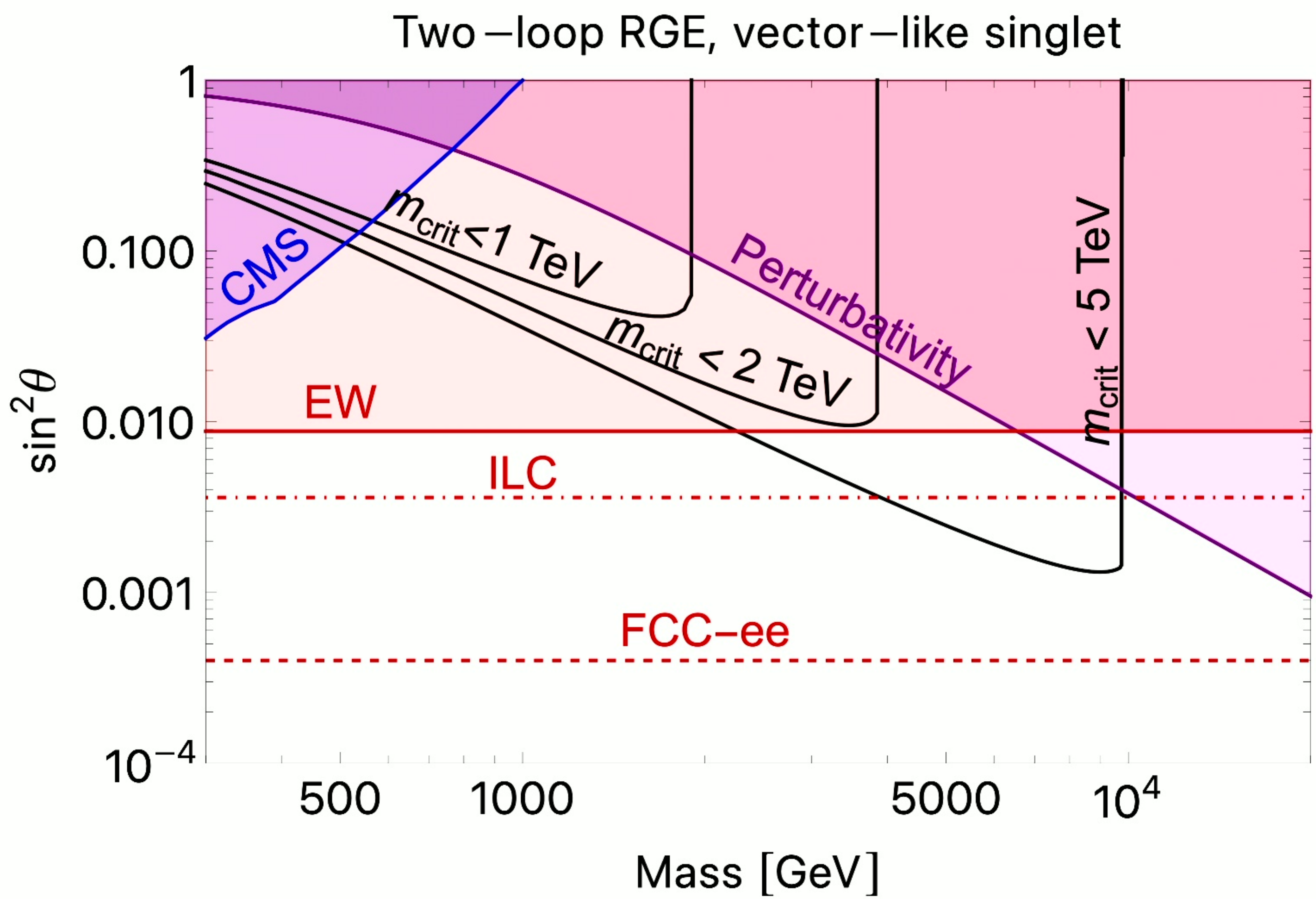
- Minimal model: vector-like pair of singlets ψ_L, ψ_R

$$-\mathscr{L}_\psi \supset M\overline{\psi_L}\psi_R + y_i\overline{L_i}\tilde{H}\psi_R + \mathrm{h.c.}$$

- Take $y_{1,2} = 0,\ y_3 = y$ — after EWSB, ψ mixes with ν_τ through an angle

$$\sin^2\theta = \frac{y^2v^2/2}{y^2v^2/2 + M^2}$$

- Drives down instability scale: $16\pi^2\Delta\beta = -2y^4 + 4\lambda y^2$



Two−loop RGE, vector−like singlet
1
0.100
0.010
0.001
10^{-4}
$\sin^2\theta$
500
1000
5000
10^4
Mass [GeV]
CMS
m_{crit}<1 TeV
m_{crit} < 2 TeV
m_{crit} < 5 TeV
Perturbativity
EW
ILC
FCC−ee

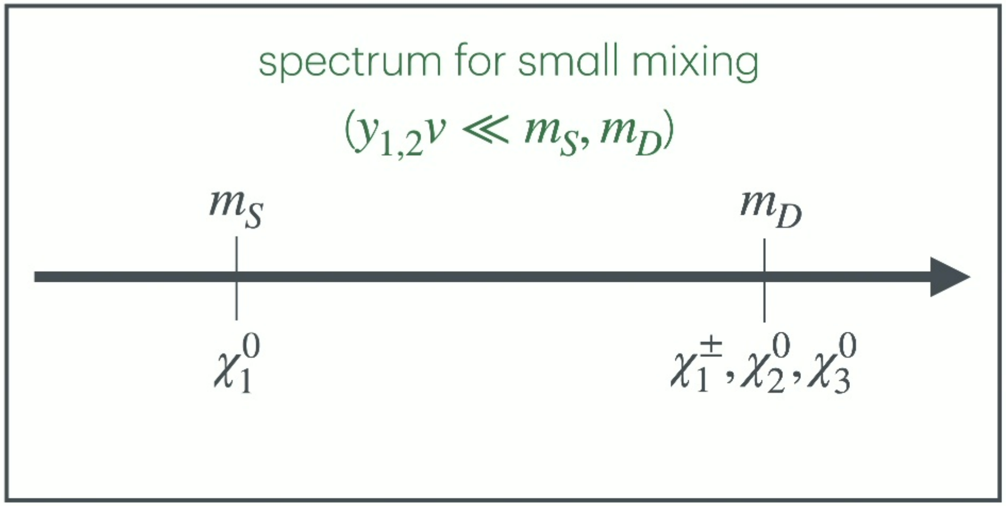
Two simple models

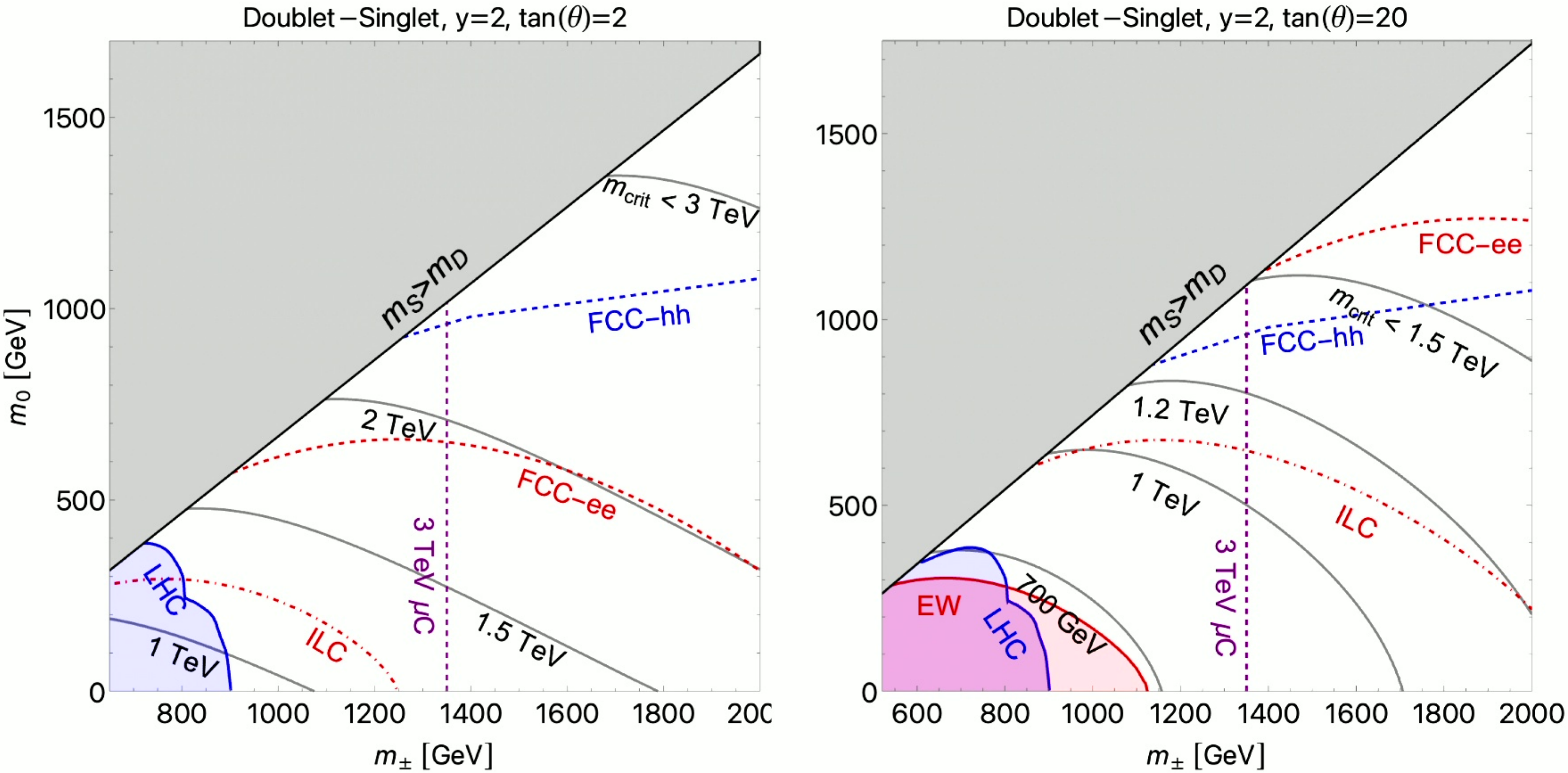
ii) singlet-doublet

- Singlet ψ_L, pair of SU(2) doublets $\chi_{L,R}$ with $Y = 1/2$

$$-\mathscr{L} \supset \frac{1}{2} m_S \overline{\psi_L} \psi_L + m_D \overline{\chi_R} \chi_L - y_1 \chi_L \tilde{H} \psi_L - y_2 \overline{\chi_R} H \psi_L$$

- Mimics Higgsino-bino system in the MSSM:
  - charged Dirac fermion with $m_\pm = m_D$
  - three neutral Majorana fermions
- Assume $m_S < m_D$ (analogy: bino-like LSP)





Doublet−Singlet, y=2, tan(θ)=2
$m_S>m_D$
m_{crit} < 3 TeV
FCC−hh
2 TeV
FCC−ee
3 TeV μC
LHC
ILC
1.5 TeV
1 TeV
1500
1000
500
0
800
1000
1200
1400
1600
1800
200
m_0 [GeV]
$m_\pm$ [GeV]
Doublet−Singlet, y=2, tan(θ)=20
$m_S>m_D$
FCC−ee
m_{crit} < 1.5 TeV
FCC−hh
1.2 TeV
1 TeV
ILC
3 TeV μC
EW
LHC
700 GeV
1500
1000
500
0
600
800
1000
1200
1400
1600
1800
2000
$m_\pm$ [GeV]

Loose end 1: vacuum lifetime

- Requiring EW vacuum lifetime to exceed age of universe:

$$\lambda \gtrsim -0.06$$

(Isidori, Ridolfi, Strumia '01)

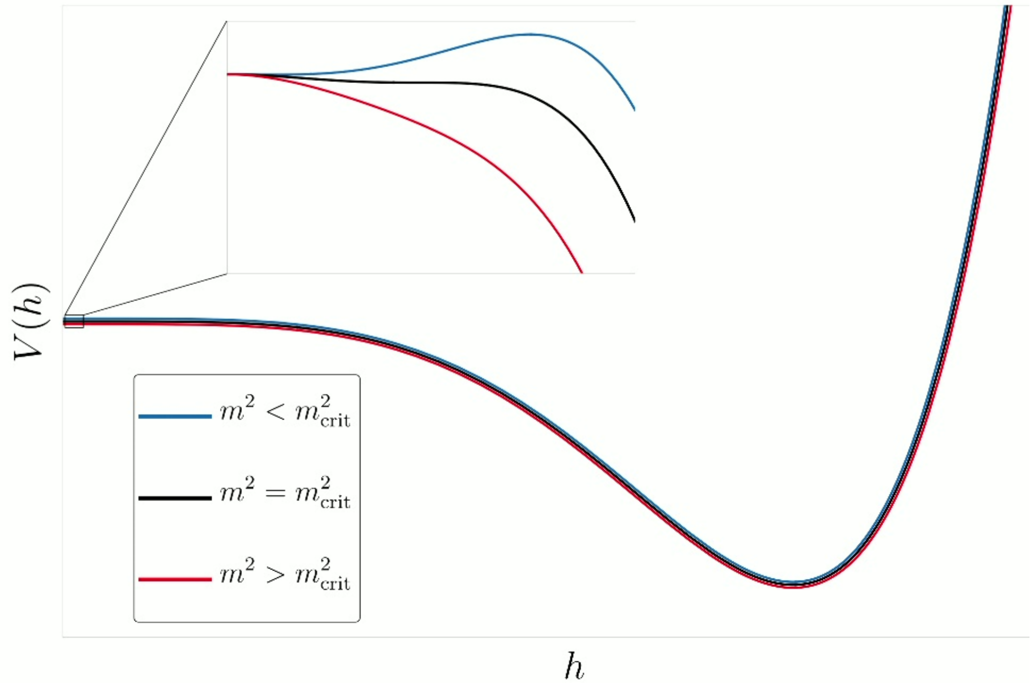
- Now we can bound the new physics scale
  - For HNL model with $M = 3\ \mathrm{TeV}, m_{\mathrm{crit}} = 5\ \mathrm{TeV}$, find $\Lambda_{\mathrm{stab}} \sim 10^3\ \mathrm{TeV}$
  - New physics could modify either the running or the tree-level potential
- Scale Λ_{stab} does **not** need to be the same as scale of true vacuum

Possible UV completions?

- Majoron model of neutrino masses (see 2503.22787)
  - Stabilizes via tree-level modification of potential (dim-6 term)
  - Without fine-tuning, $\Lambda_{\rm stab} \sim \Lambda_{\rm UV}$
- Near-conformal UV fixed point
  - Quartic approaches a constant $\lambda_{\rm UV} \gtrsim -0.06$ at high scales
  - Can naturally have $\Lambda_{\rm stab} \ll \Lambda_{\rm UV}$

Loose end 2: positive m^2

- Key point: patches where the Higgs VEV is too large crunch
- Generically expect patches with positive mass-squared, which will **always** have a metastable minimum at the origin!
- Let's see an explicit way to deal with them (likely not the only one)



One way out
(adapted from 2106.04591)

- Ultralight scalar ϕ w/ approximate shift symmetry:

$$V_\phi = -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}\lambda_\phi\phi^4 - \frac{\alpha_s}{8\pi f}\phi G\tilde{G}$$

- Some comments:
  - Expect $\lambda_\phi \sim m_\phi^2/M^2 \ll 1$, w/ shift symmetry broken at M
  - (Rel)axion-like coupling generated at UV scale f

One way out

(adapted from 2106.04591)

- Potential below the QCD scale:

$$V_\phi = -\frac{1}{2}m_\phi^2\phi^2 - \frac{1}{4}\lambda_\phi\phi^4 - \Lambda^4\cos\phi/f = \frac{1}{2}\left(-m_\phi^2 + \frac{\Lambda^4}{f^2}\right)\phi^2 - \frac{1}{4}\left(\lambda + \frac{\Lambda^4}{f^4}\right)\phi^4 + \dots$$

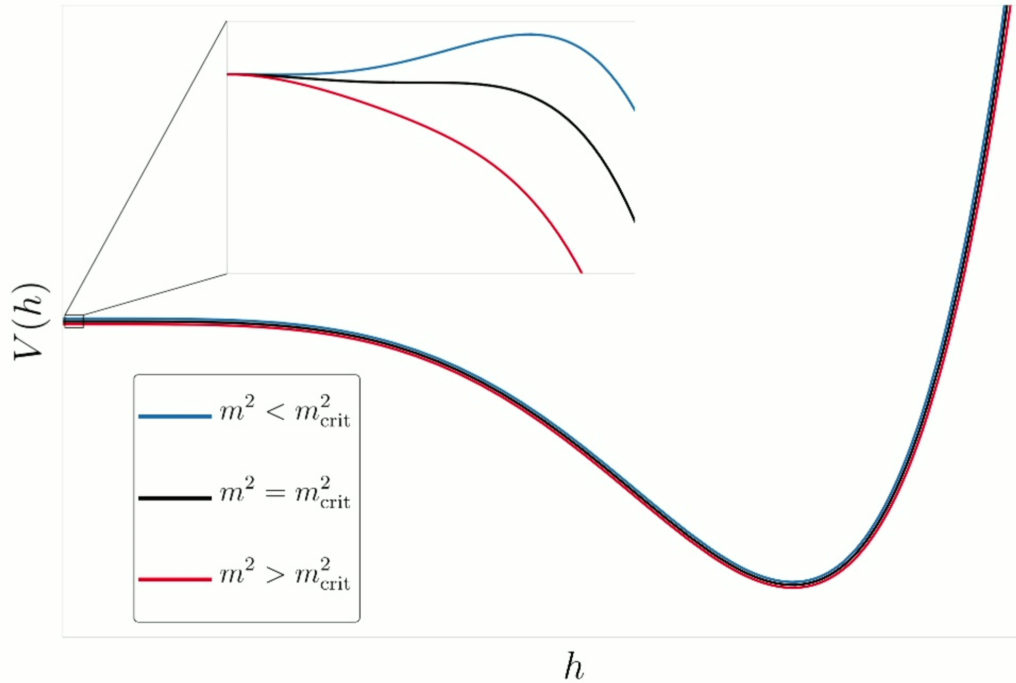
- Stable minimum for ϕ iff $\Lambda^4 \gtrsim m_\phi^2 f^2$

- But recall $\Lambda^4 \propto v$ (GOR relation), hence:

Patches with small or vanishing Higgs VEV will crunch.

Loose end 3: the CC problem

- Energy density of false vacuum: $\sim \mu_I^4$
- Energy density of true vacuum: $\sim \Lambda_{\rm UV}^4$
- Assume landscape for CC up to a cutoff scale $\Lambda_{\rm CC}$
- Need $\mu_I \lesssim \Lambda_{\rm CC} \lesssim \Lambda_{\rm UV}$, so we can solve CC problem in false vacuum but true vacuum still crunches



Summary and outlook

- This is a new take on the hierarchy problem, in which metastability helps select the EW scale
- Differences from existing ideas:
  - Symmetry-based solutions — sure, we need new particles at a TeV, but they have nothing to do with cancelling quadratic divergences
  - Other dynamical selection mechanisms — the Higgs potential itself is responsible for the vacuum selection, instead of a new scalar sector
- These differences are reflected in the pheno of our explicit models
- These models can be probed at future lepton colliders: FCC-ee, muon collider, etc.

Thank you!

Crunchy, critical, natural Higgs

- more info:
  - https://arxiv.org/abs/2502.07876
  - https://ameenismail.github.io/
  - ameenismail@uchicago.edu