A Critical Look at the Higgs

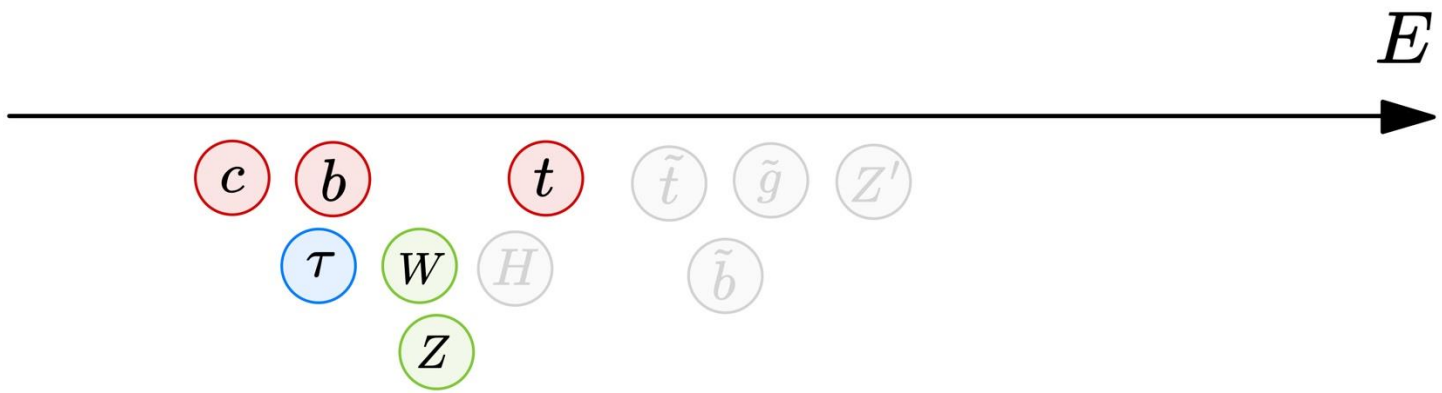
Based on 2412.03542

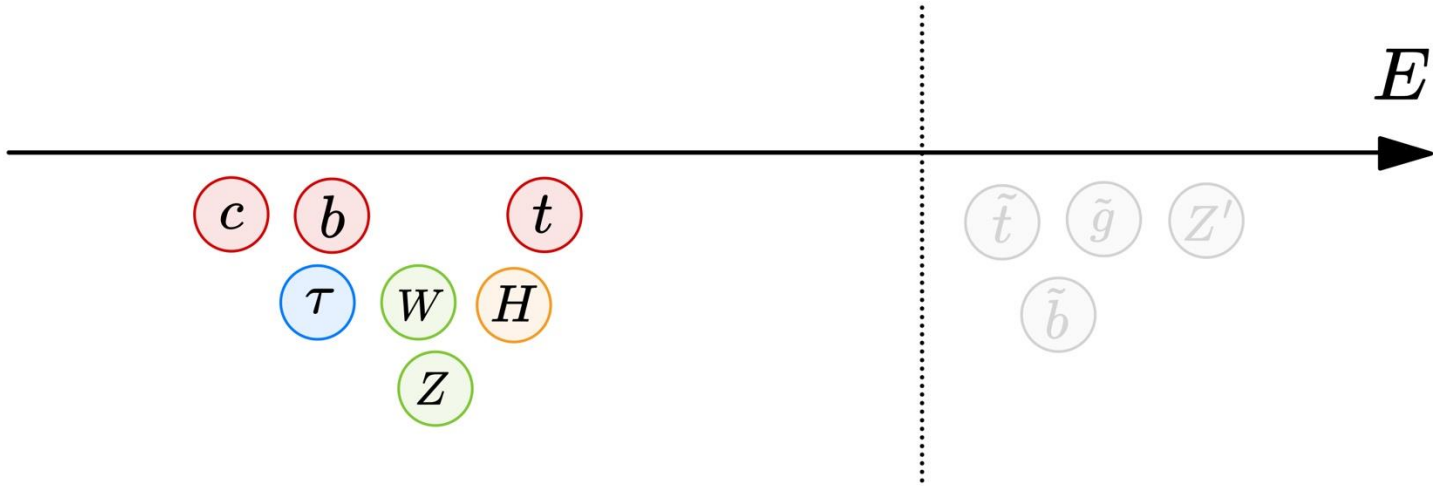
Maximilian Detering

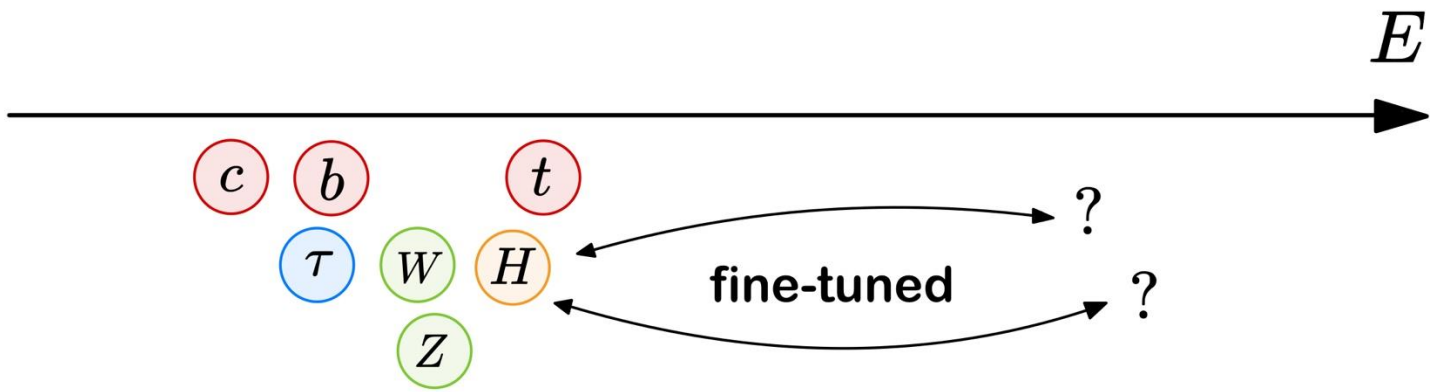
New Approaches to Naturalness

Institut de Physique des 2 Infinis de Lyon, France

21 May 2025


E
c
b
t
$\tilde{t}$
$\tilde{g}$
Z'
τ
W
H
$\tilde{b}$
Z


E
c
b
t
τ
W
H
Z
$\tilde{t}$
$\tilde{g}$
Z'
$\tilde{b}$


E
c
b
t
τ
W
H
Z
?
fine-tuned
?

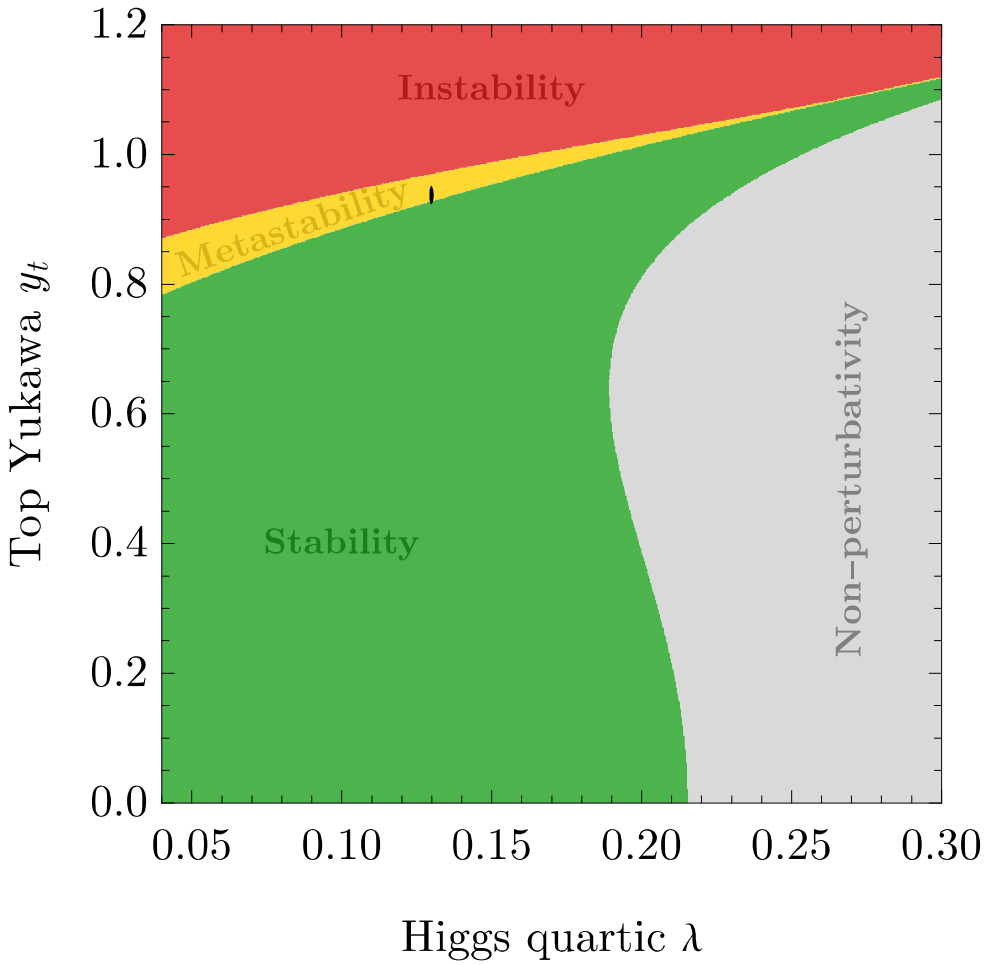
Higgs mass not a fundamental parameter but special value explained as critical point in parameter space

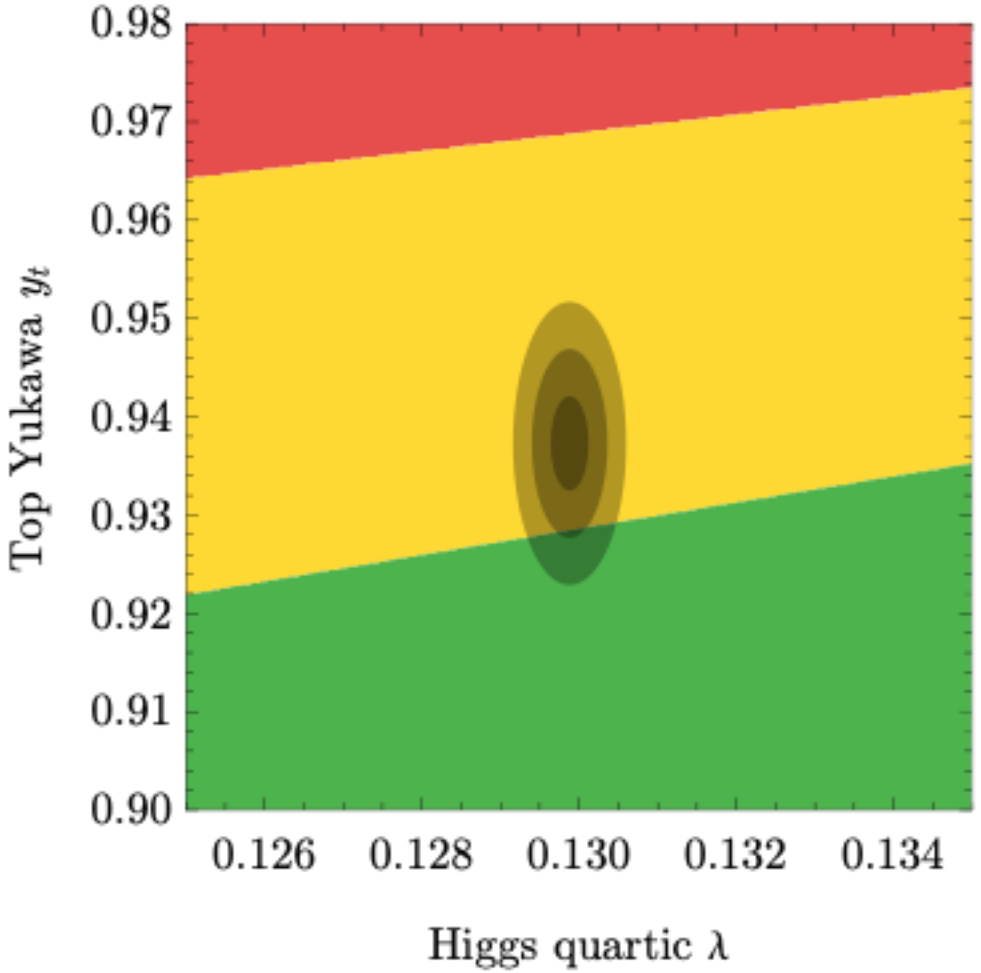
Criticality

- **Classical (thermal)** phase transitions with varying thermodynamical parameters
- **Quantum** Phase Transition through change of external parameters
- **Critical values** of the parameters mark the transition
- Unconventional in particle physics context but **common in dynamical systems**

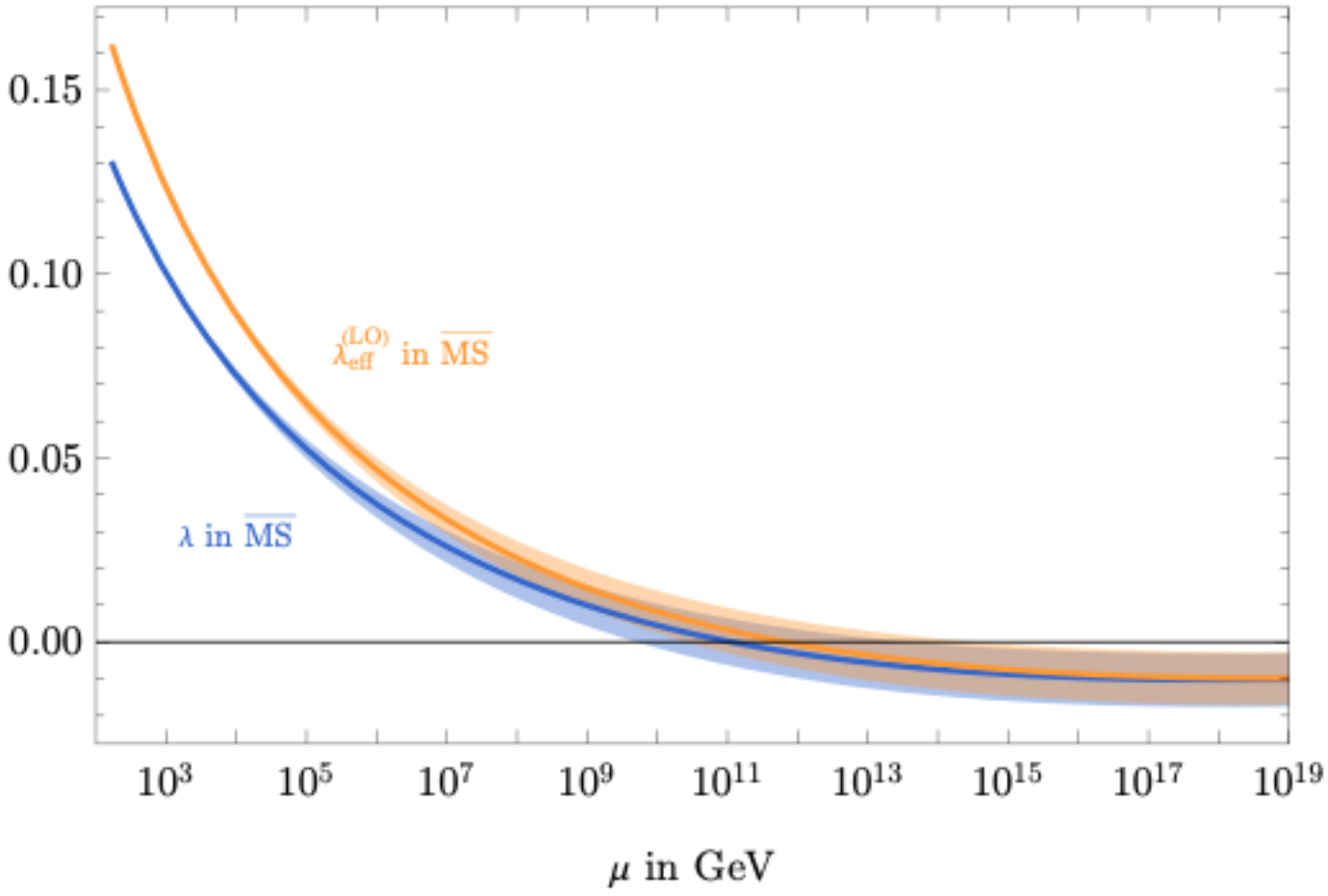
Phases of the Standard Model

see also Buttazzo et al. ‘13, Degrassi et al. ‘12



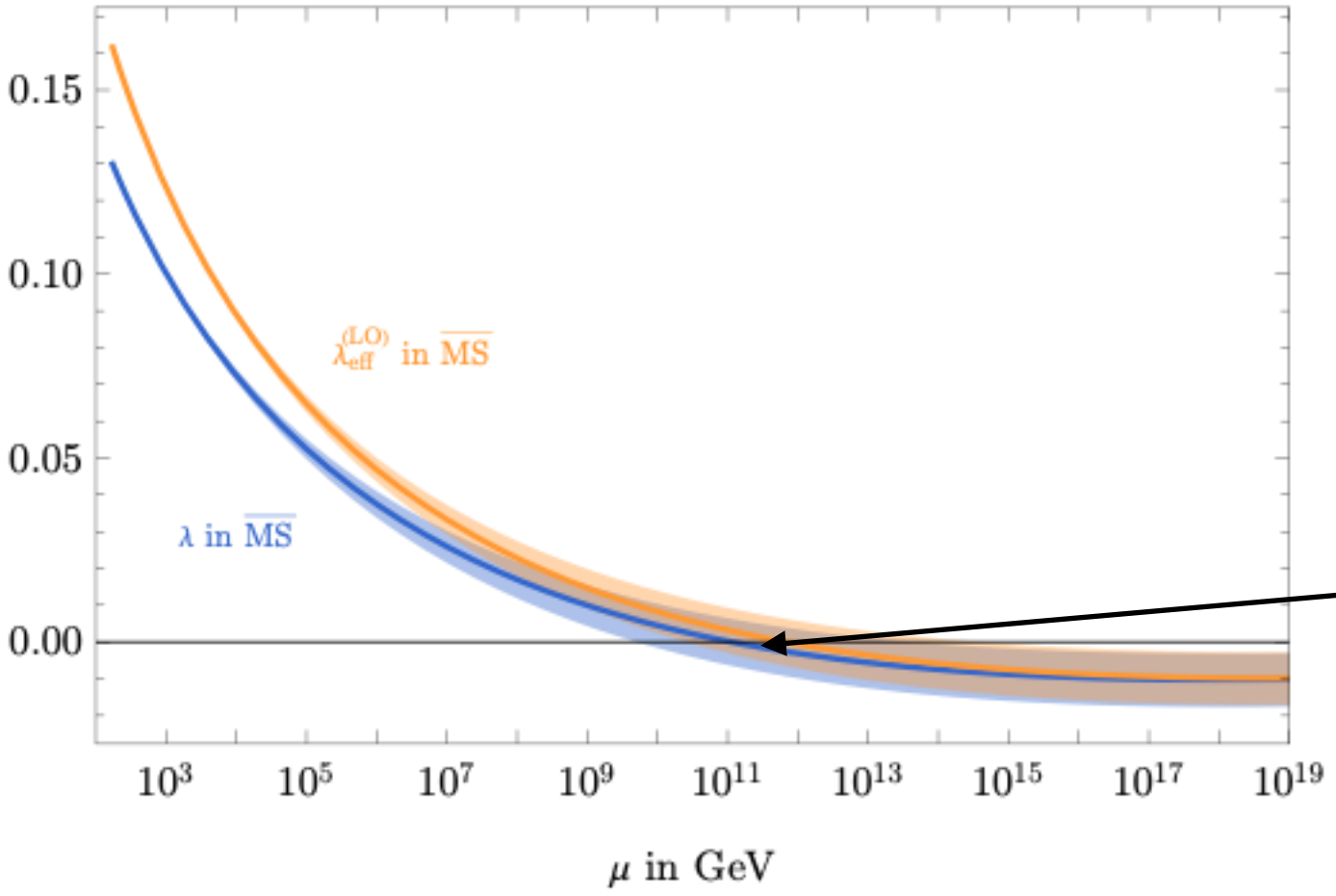


Electroweak Vacuum Metastability



$$\beta_\lambda^{(1)} \sim \lambda(\lambda + y_t^2 + \text{gauge terms}) - y_t^4 + \text{gauge terms}$$

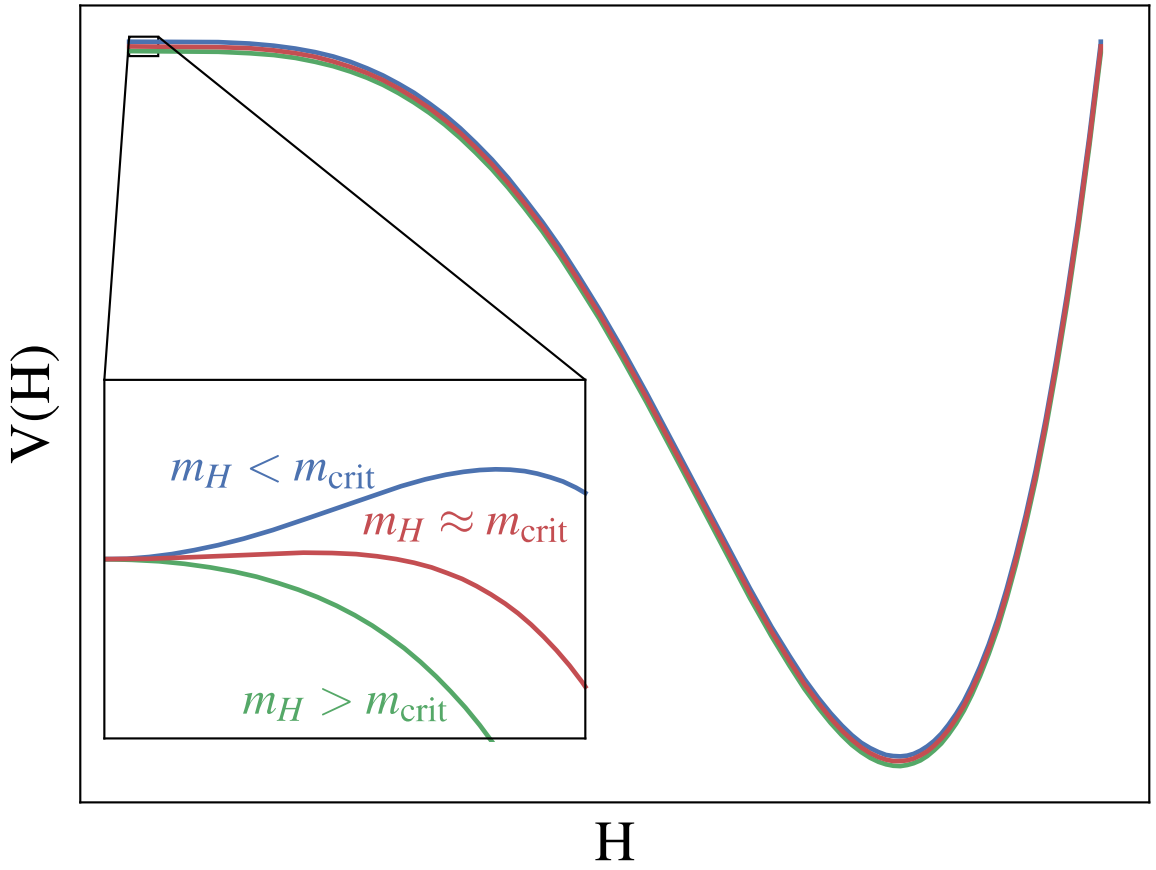
Electroweak Vacuum Metastability



$$\beta_\lambda^{(1)} \sim \lambda(\lambda + y_t^2 + \text{gauge terms}) - y_t^4 + \text{gauge terms}$$

$$\lambda(\mu_I) = 0$$

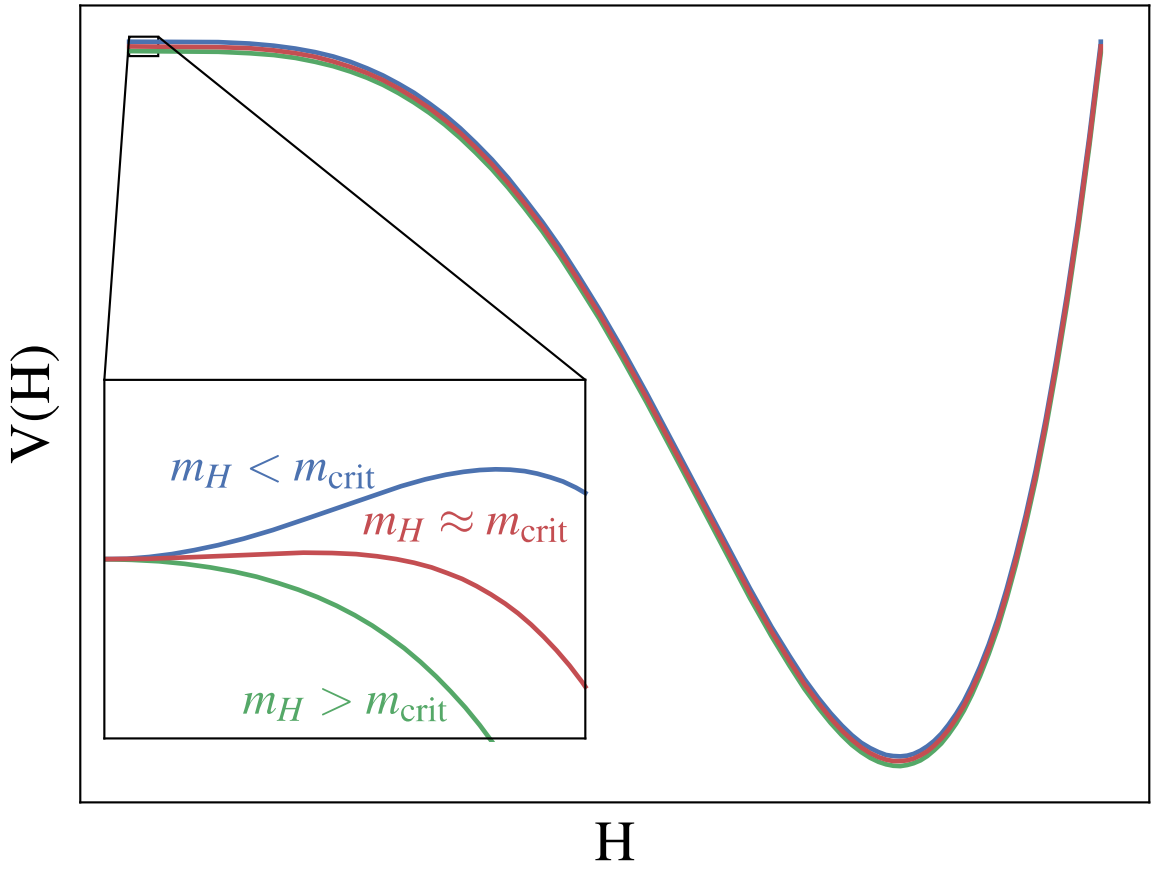
Higgs Criticality



- Instability scale implies critical value for Higgs mass parameter
- IR + UV vacuum for $m_H < m_{\text{crit}}$
- Near-critical point m $\approx m_{\text{crit}}$
- Only UV vacuum for $m_H > m_{\text{crit}}$
- Metastability bound

$$m_H^2 < m_{crit}^2 = -\frac{1}{2}\, e^{-\frac{3}{2}}\, \beta_\lambda(\mu_I)\, \mu_I^2$$

Higgs Criticality



But why should we expect to live near a critical point?

Self-organised criticality

- Criticality acts as an attractor — Bak, Tang, Wiesenfeld ‘87
- Localisation near critical point during inflation — McCullough, Giudice, You ‘21
- Background field varies and coupled to some operator $\mathcal{O}$ whose expectation value changes as ϕ passes through some critical value ϕ_c

$$V = (\phi - \phi_c)\mathcal{O}$$

- If $\langle \mathcal{O} \rangle$ changes across ϕ_c, stochastic evolution could localise ϕ near ϕ_c
- Vacuum transition dynamics in the string landscape — Khoury, Parrikar ‘19
- See also Thomas’ Talk

Vacuum Selection

- Small Higgs mass may just be the result of vacuum selection
- Given that we find ourselves in the IR vacuum, we expect an upper bound on the Higgs mass
- Does not explain *why* we are in the phase with an IR vacuum

  → selection could be realised through dynamical mechanisms mentioned
- General expectation: Higgs mass comparable to metastability bound
- But Higgs mass in the SM with substantial hierarchy to metastability bound
- Prediction: New physics leading to a saturated metastability bound

see also MD, Enguita, Gavela, Steingasser, You ‘25

Axion-Higgs Criticality

- **Motivated** BSM candidate (dark matter, pNGB of global symmetries, prevalent in string theories)
- Axion-like particles are **naturally light**
- Consider simple potential

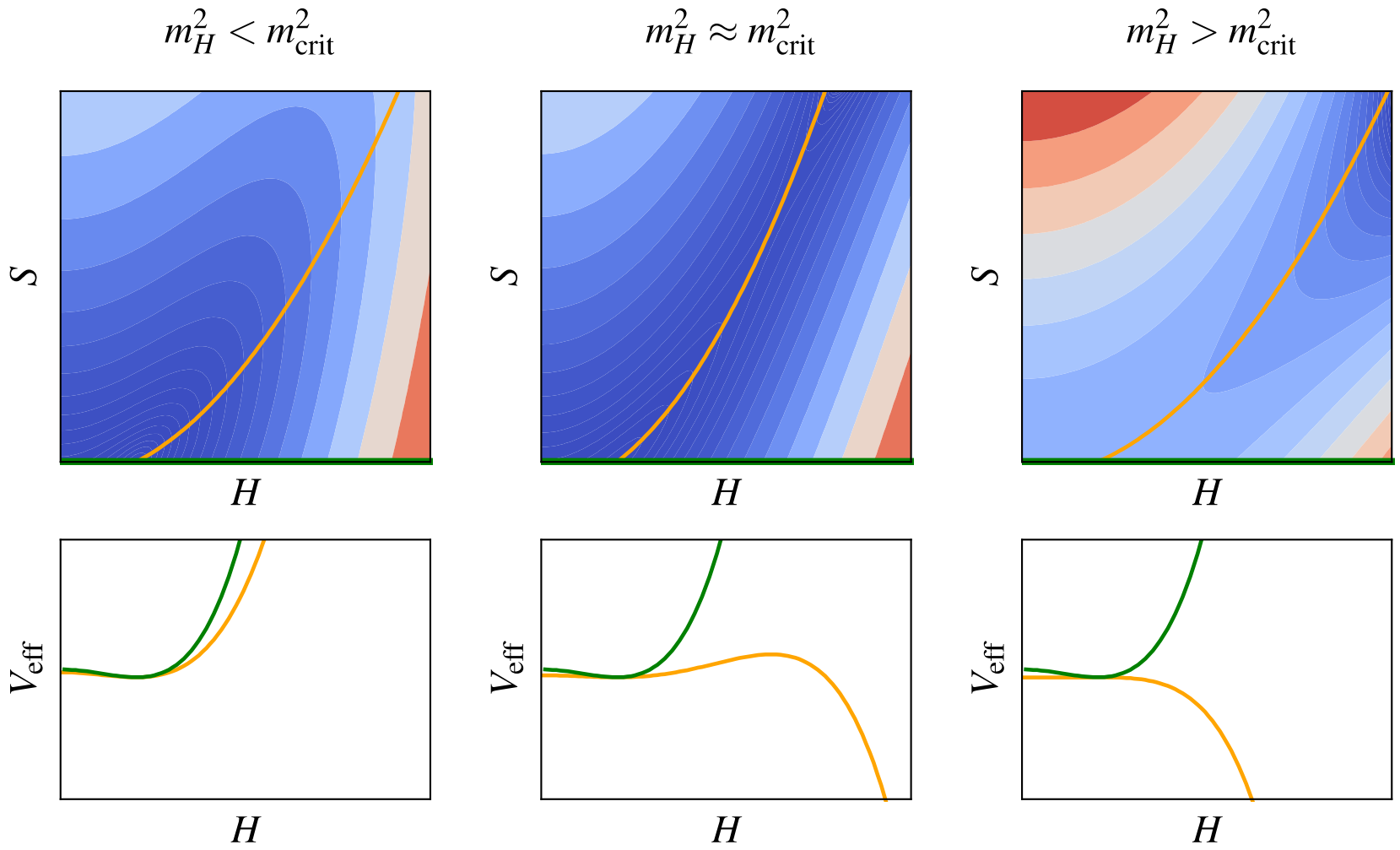
$$V_S = m_S^2 f^2 \left(1 - \cos\left(\frac{S}{f}\right)\right) - A f H^2 \cos\left(\frac{S}{f} - \delta\right)$$

- Large decay constant

$$V_S = \frac{m_S^2}{2} S^2 - A \sin\delta S H^2$$

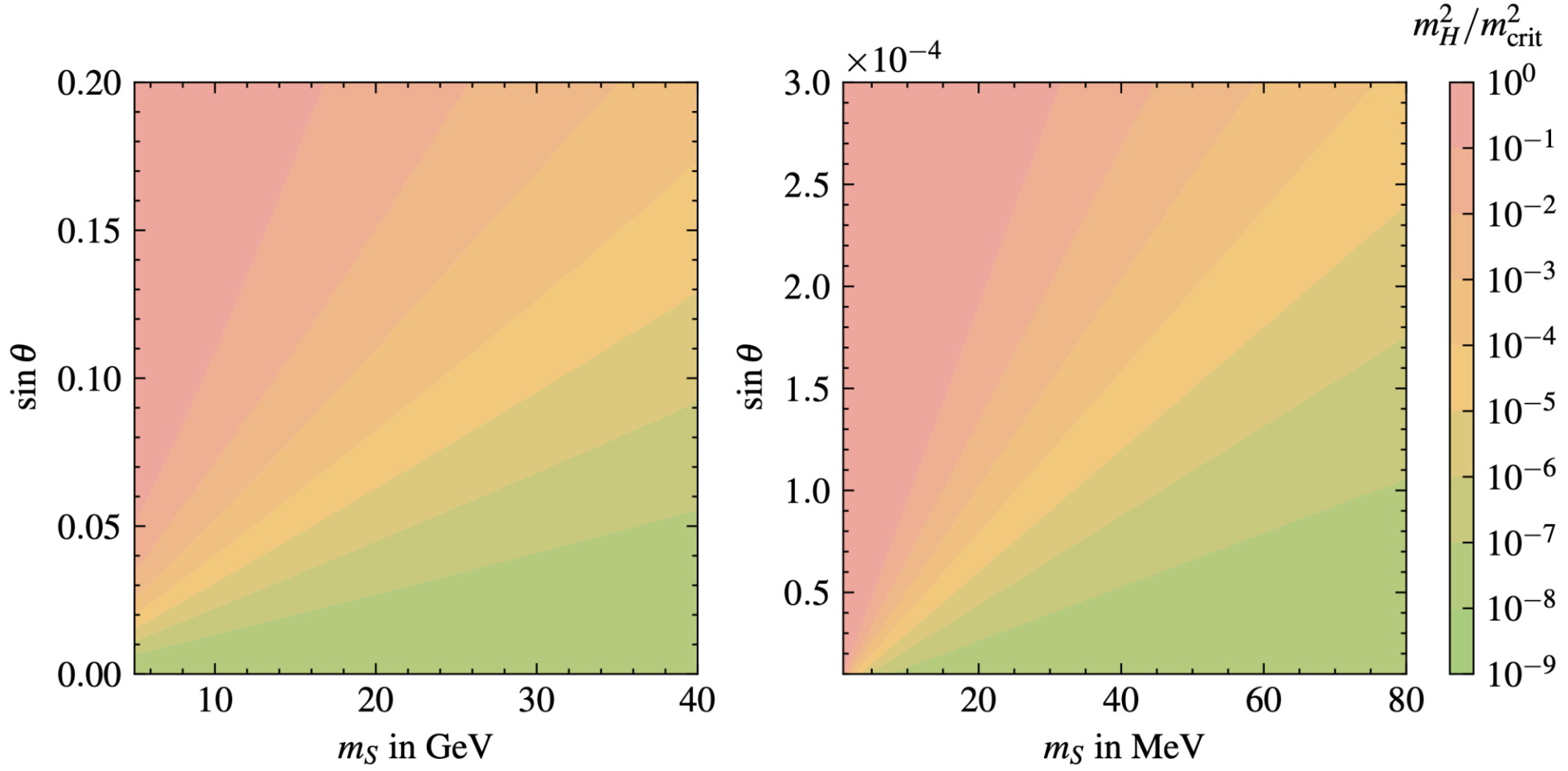
- Criticality through **mixing with Higgs** and **destabilising effect** on scalar potential

Axion-Higgs Criticality



Axion-Higgs Criticality

MD, You ‘24

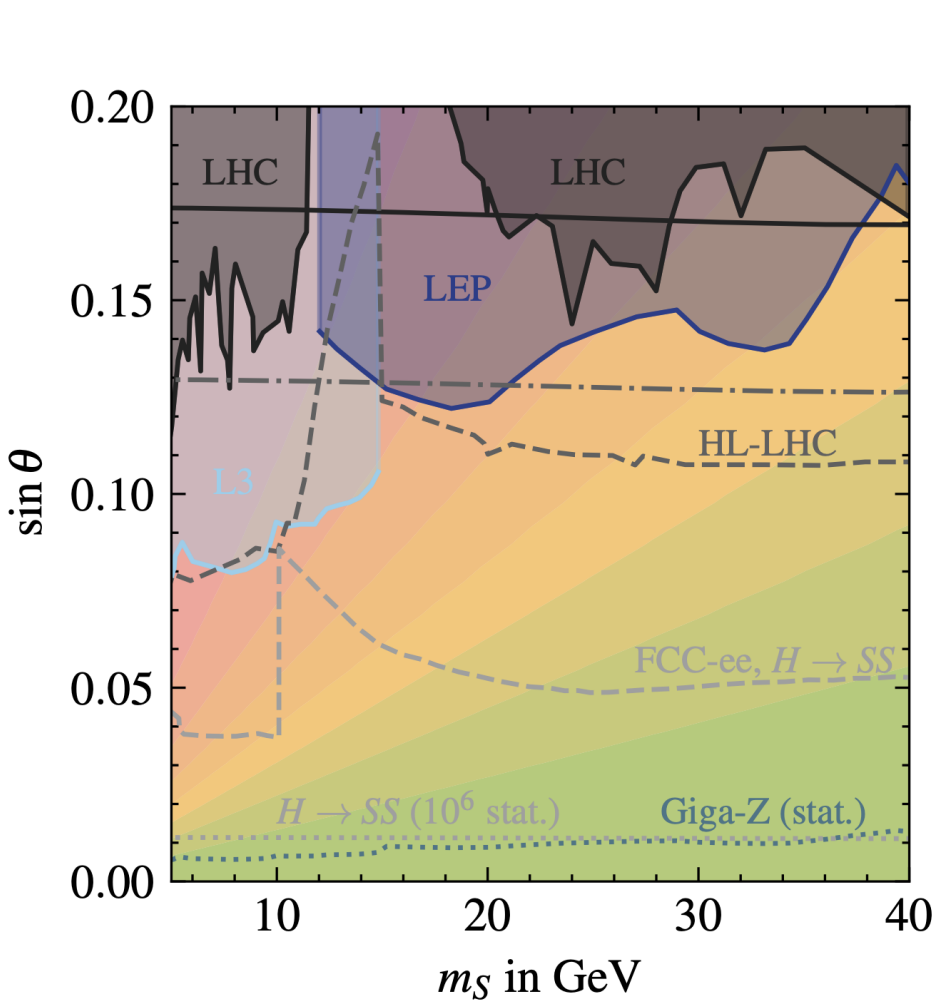


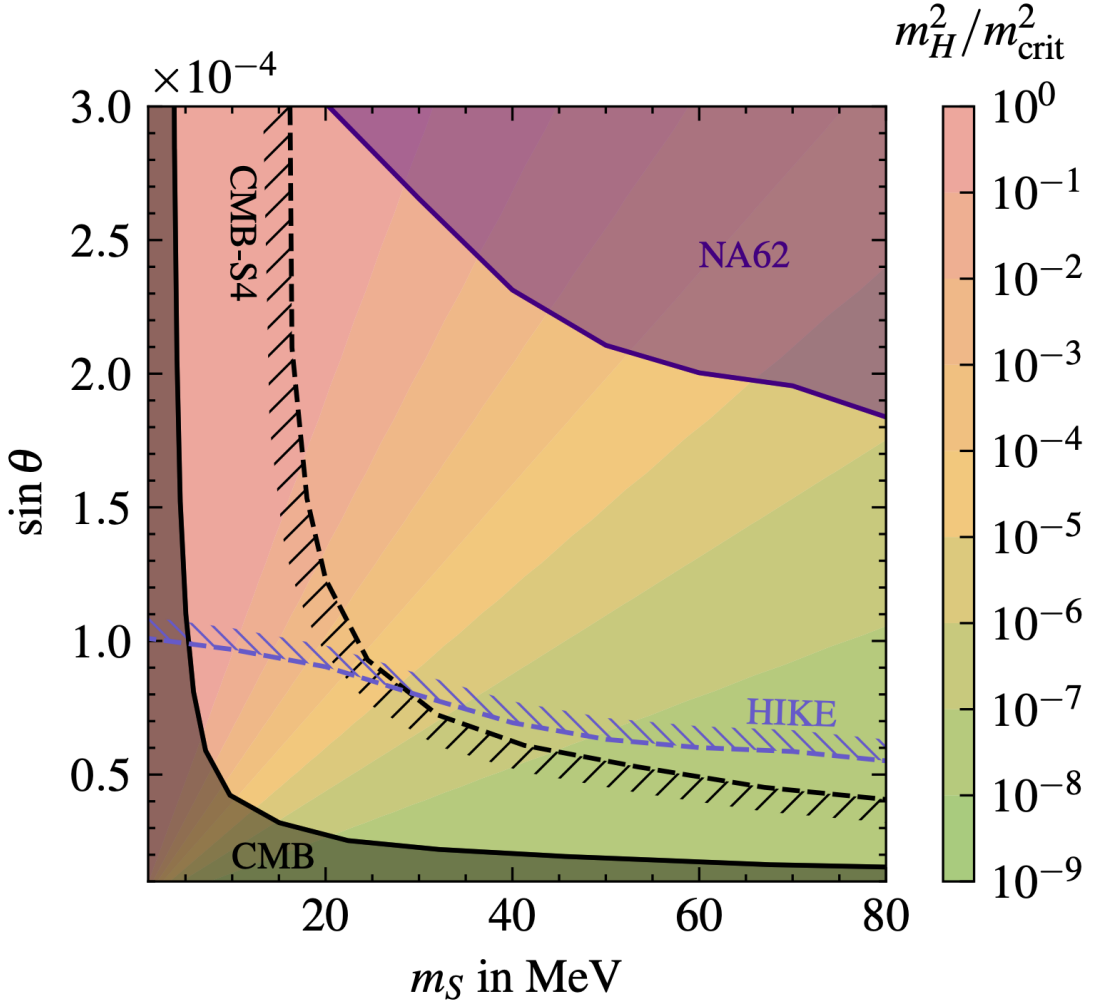
Experimental Signatures

- Scalar direct production (SZZ vertex)
- Higgs decays
- Exotic Meson decays
- Effective number of relativistic degrees of freedom

Axion-Higgs Criticality

MD, You ‘24





Concluding Remarks

- Fine-tuning as result of **near-criticality**
- If Higgs mass is explained through cosmological criticality, then new physics coupled to the Higgs is expected
- **Criticality as new paradigm** for model building beyond naturalness
- Parameter space for Axion-Higgs Criticality **comprehensively probable** by future experiments

Concluding Remarks

- Fine-tuning as result of **near-criticality**
- If Higgs mass is explained through cosmological criticality, then new physics coupled to the Higgs is expected
- **Criticality as new paradigm** for mod
  naturalness
- Parameter space for Axion-Higgs Crit
  probable by future experiments

Upcoming Work:

- Dark Matter connection to Higgs criticality
- Critical Split SUSY