Constraining the real scalar singlet extension

VAST 26, Madrid

Moritz Bosse *in collaboration with*
Gudrun Hiller, Daniel Litim, Fabio Maltoni, Michael J. Ramsey-Musolf,
Simone Tentori and Guotao Xia

Department of High Energy Theory
TU Dortmund University

based on [2606.12533]

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technische universität dortmund

color meets flavor

Motivation

The SM Higgs potential leaves suggestive open questions:

- The electroweak vacuum is **metastable** [Buttazzo et al, 2012].
  - Not a problem for our lifetime, but… why so close to **absolute stability**?
  - Can stability be excluded?
- The (electroweak) cosmological phase transition is a **smooth crossover** [Kajantie et al, 1997].
  - This cannot explain the observed Baryon-Antibaryon asymmetry via electroweak baryogenesis.

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  - This cannot explain the observed Baryon-Antibaryon asymmetry via electroweak baryogenesis.

Could this hint at new physics beyond the Standard Model (BSM)?

BSM should hopefully ...

- Solve open problems: i.e. the Baryon-Antibaryon asymmetry
- Not create new ones: i.e. further destabilise the vacuum

Benchmark Model: Real singlet extension of the SM

Add a new gauge singlet scalar S to the SM:

$$V(H,S) = \underbrace{-\mu_H^2|H|^2 + \lambda|H|^4}_{\text{SM potential}} + \underbrace{\frac{a_1}{2}|H|^2 S + \frac{a_2}{2}|H|^2 S^2}_{\text{Portal terms}} + \underbrace{b_1 S + \frac{\mu_S^2}{2}S^2 + \frac{b_3}{3}S^3 + \frac{b_4}{4}S^4}_{\text{Singlet potential}}$$

- H and S unphysical states related to mass eigenstates $h_{1/2}$ via mixing angle θ.
- 7 independent parameters: $\{\underbrace{m_{h_1}, v_H}_{measured}, m_{h_2}, \theta, a_2, b_3, b_4\}$.
- Non-zero a_2 and b_3 can catalyze a strong first-order EW phase transition, a necessary condition for EW baryogenesis. [Profumo, Ramsey-Musolf, Shaughnessy, 2007].
- Non-zero a_2 and mixing effects can also (de)stabilize the Higgs potential up to the Planck scale. [Elias-Miro et al, 2012], [Hiller et al, 2024].

→ Both affect the Higgs self-coupling λ_{hhh}, target for the HL-LHC

Model phenomenology: Higgs couplings

Universal rescaling of Higgs couplings:

- $\kappa_f = y_f / y_{f,\mathrm{SM}} = \cos\theta$
- $\kappa_V = g_V / g_{V,\mathrm{SM}} = \cos\theta$

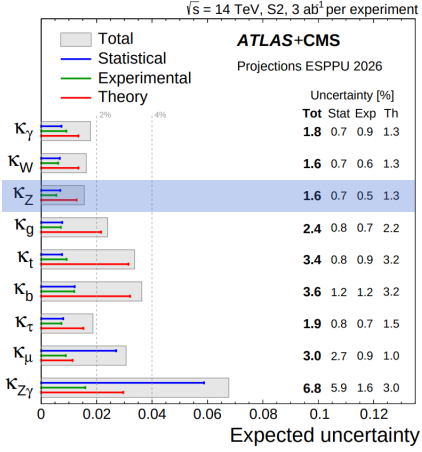
Characteristic signature for the singlet

Best probes:

- Higgs–ZZ coupling
- Total Higgs signal strength

$$\mu_{h_1} = \frac{\sigma(pp \to h_1)_{\mathrm{measured}}}{\sigma(pp \to h)_{\mathrm{SM}}} = \cos^2(\theta)$$

[ATLAS+CMS, 2504.00672]



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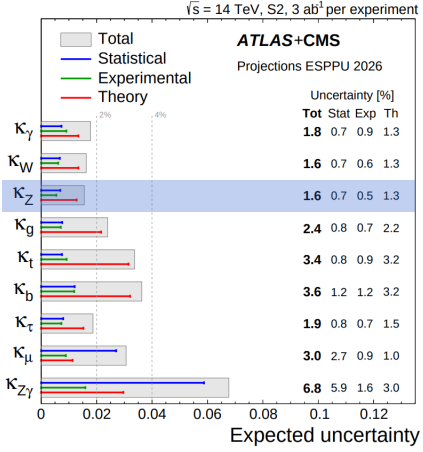
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Run 2 constraint:

$|\theta| < 0.3$ at 95% C.L.

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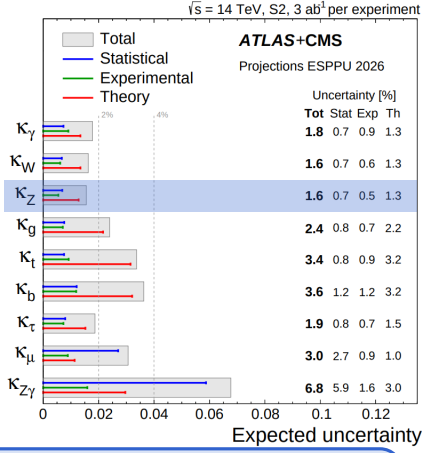
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HL-LHC projection:

$|\theta| < 0.254$ at 95% C.L.

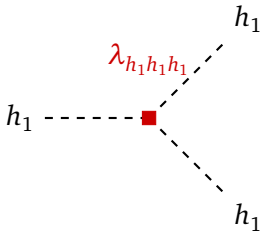
Model phenomenology: Higgs self-coupling

The trilinear can deviate significantly

$$\kappa_3 = \cos^3\theta + a_2 \frac{v_H^2}{m_{h_1}^2} \cos\theta \, \sin^2\theta - 2\sin^3\theta \, \frac{b_3}{3} \, \frac{v_H}{m_{h_1}^2}.$$

Run 2: $-0.71 < \kappa_3 < 6.1$ at 95% C.L.

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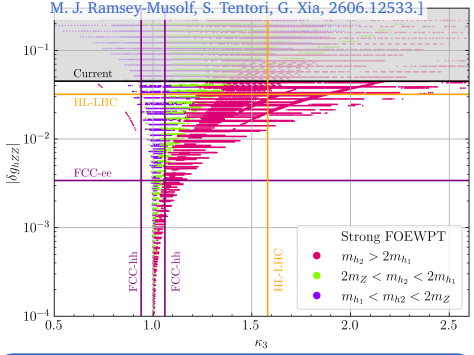
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- Di-Higgs significance @ HL-LHC $> 7\sigma$
  [ATLAS/CMS 2504.00672]
- HL-LHC will start probing SFOPTs of the model via κ_3.

[**MB**, G. Hiller, D. Litim, F. Maltoni, M. J. Ramsey-Musolf, S. Tentori, G. Xia, 2606.12533.]



HL-LHC projection:

$\kappa_3 = 1.00^{+0.58}_{-0.52}$ at 95% C.L.

Where should we look? Electroweak phase transition

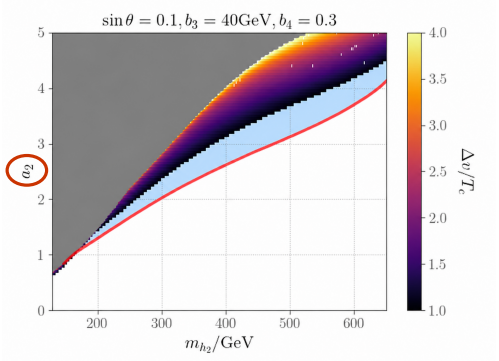
A SFOPT efficiently selects regions of parameter space

- SFOPTs are possible for sizeable regions of parameter space, with $m_{h_2} \lesssim \mathcal{O}(1\ \text{TeV})$.
- Larger scalar masses typically require larger portal couplings a_2.

$$\delta\kappa_3 = \left(\frac{a_2}{\lambda_{H,\text{SM}}} - 3\right)\delta g_{hZZ} + \mathcal{O}(\theta^3)$$

For $a_2 \sim \mathcal{O}(1)$: trilinear deviations can be $\mathcal{O}(10)$ larger than those in g_{hZZ}.

[MB, G. Hiller, D. Litim, F. Maltoni, M. J. Ramsey-Musolf, S. Tentori, G. Xia, 2606.12533.]



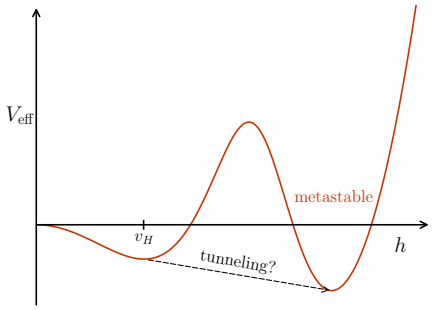
- The same sizeable portal coupling a_2 can also stabilise the Higgs potential.

Vacuum stability

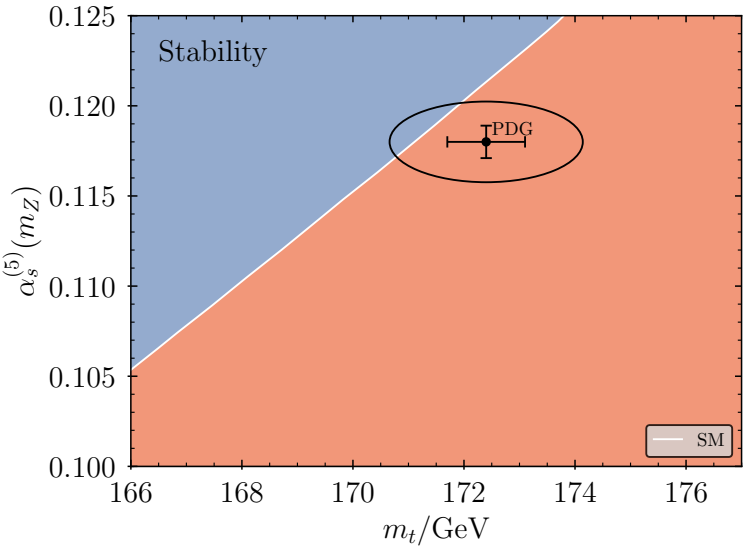
SM electroweak vacuum is metastable [Buttazzo et al., 2012]

$$V_{\text{eff,SM}} = \frac{1}{4}\,\lambda_{\text{eff,SM}}(h)\, e^{4\bar{\Gamma}(h,h_0)}\, h^4$$

- Additional deeper minimum at high scales.
- Encoded in the RG running of $\lambda_{\text{eff}}(\mu)$.
- Running is most sensitive to m_t and α_s. [Hiller et al, 2024]
- Uncertainty of m_h is negligible.



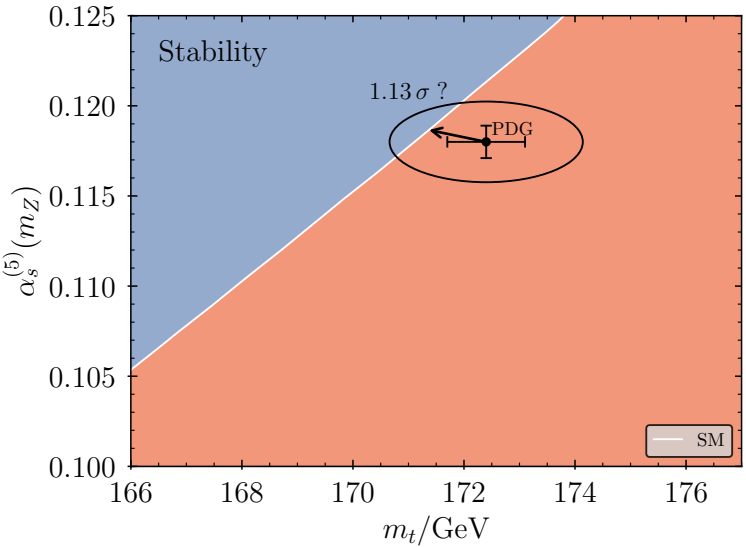
Vacuum stability in the SM



Absolute stability

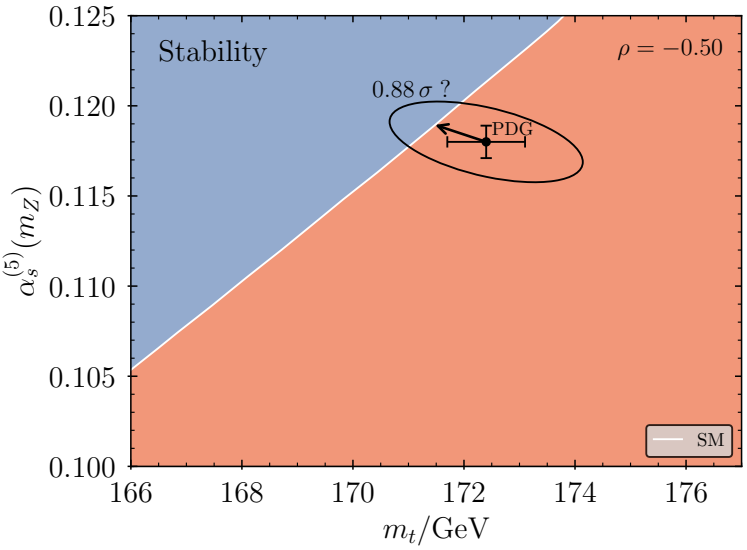
Metastability/Instability

Vacuum stability in the SM



Absolute stability
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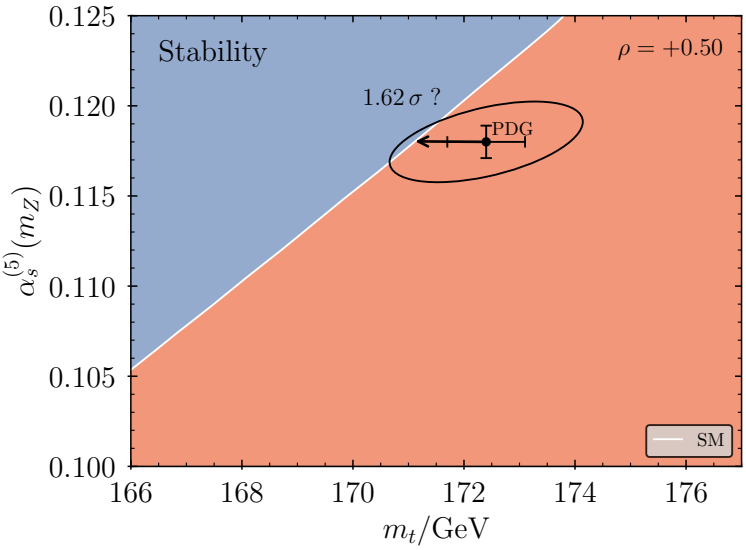
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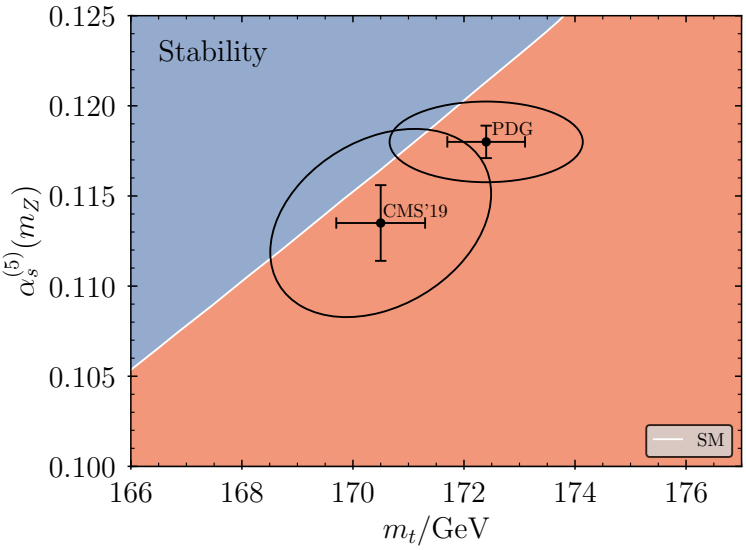


Absolute stability

Metastability/Instability

The correlation is important!

Vacuum stability in the SM

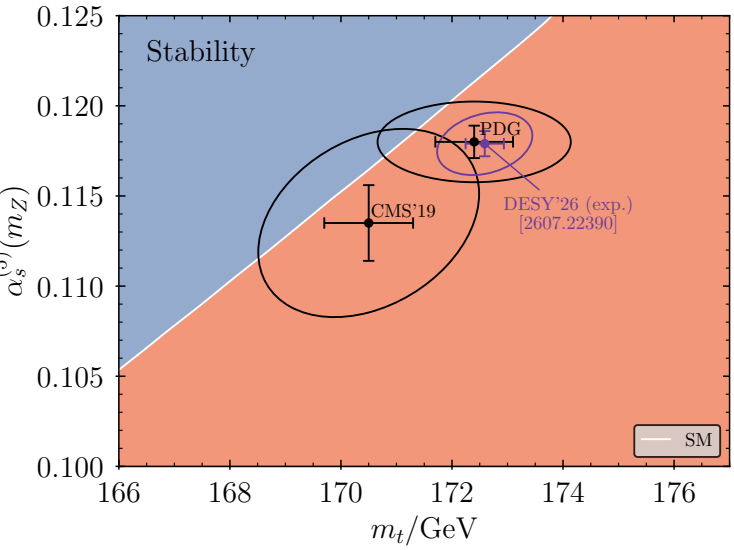


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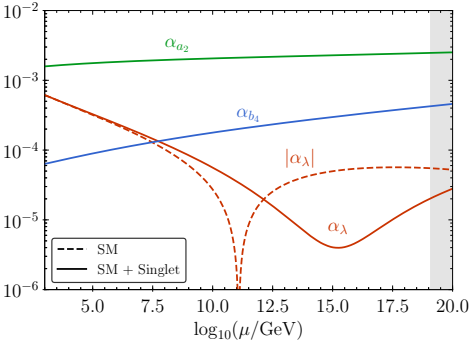
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Stabilising with a scalar portal

$$V(H,S) \supset \frac{\mu_S^2}{2}S^2 + \frac{a_2}{2}|H|^2S^2 + \frac{b_4}{4}S^4$$

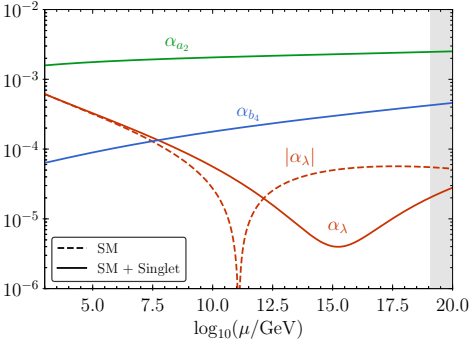
$$\Delta\beta_\lambda = \frac{1}{(4\pi)^2}\frac{a_2{}^2}{2} + \cdots$$



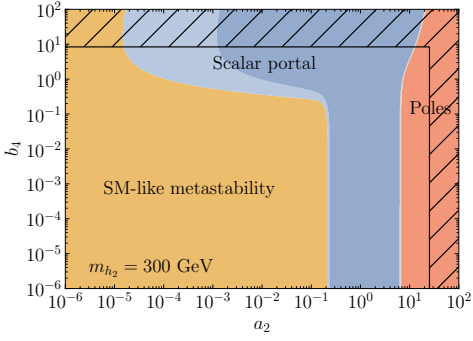
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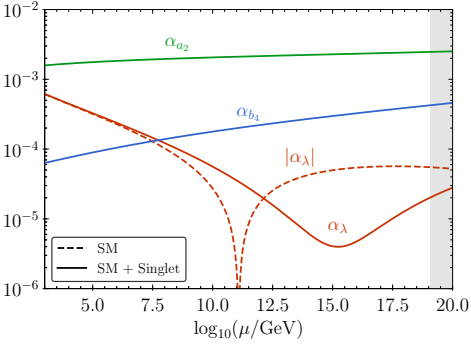
$\Longrightarrow$



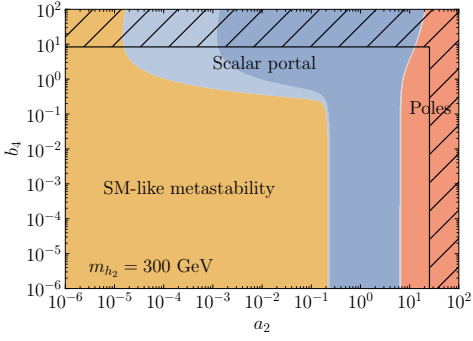
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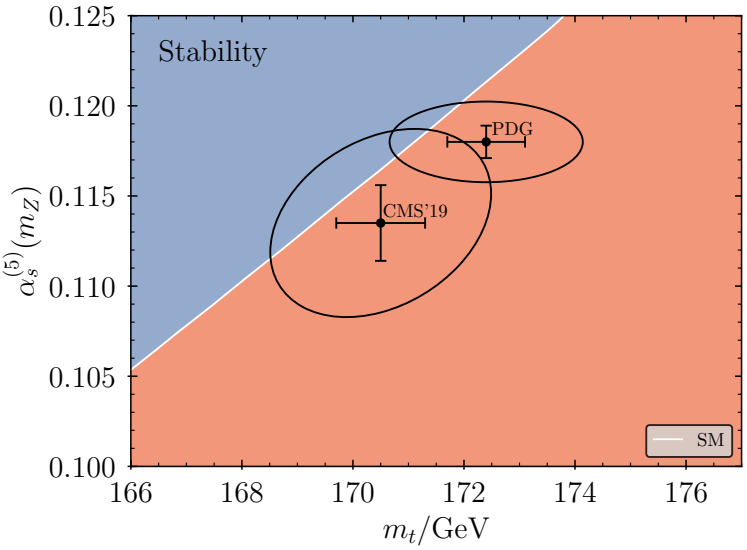


$\Longrightarrow$



- On top: mixing/threshold corrections can shift i.e. the quartic, $\lambda(\mu_0) \to \lambda(\mu_0) + \delta_\lambda(\mu_0)$.
  [Elias-Miró, Espinosa et al., 1203.0237]

Vacuum stability in the SM

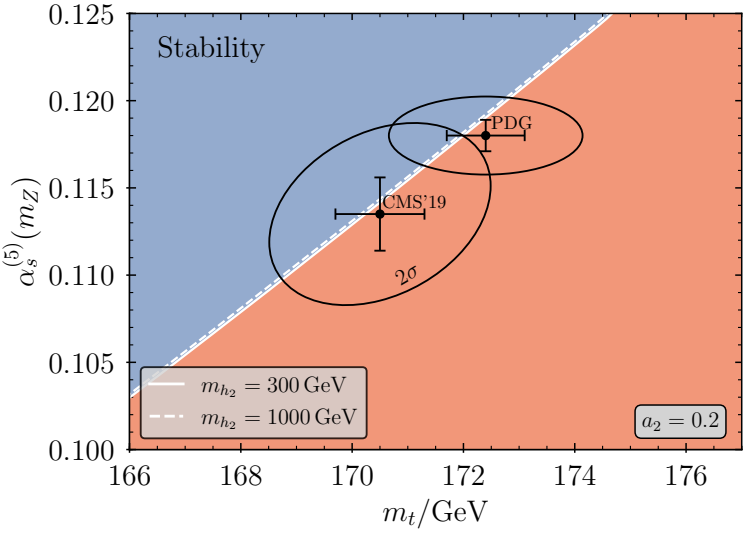


Absolute stability

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Vacuum stability in the singlet extension



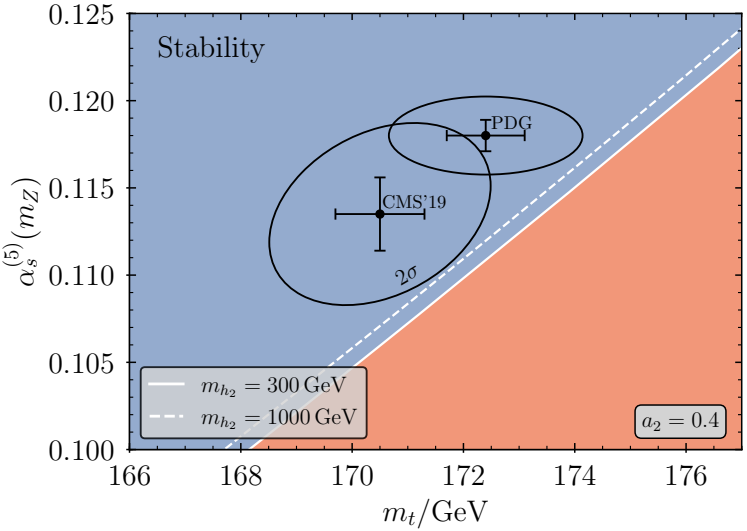
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The correlation is important!

- Higgs portal: $\propto a_2|H|^2S^2$

  $\beta_{\lambda_H} = \beta_{\lambda_H}^{\text{SM}} + \frac{1}{2(4\pi)^2} a_2^2 + \mathcal{O}(\text{2-loop})$.
- For $a_2 > 0$ stability boundary moves further right.
- Noticeable dependence on m_{h_2} (and θ, b_4).

Vacuum stability in the singlet extension



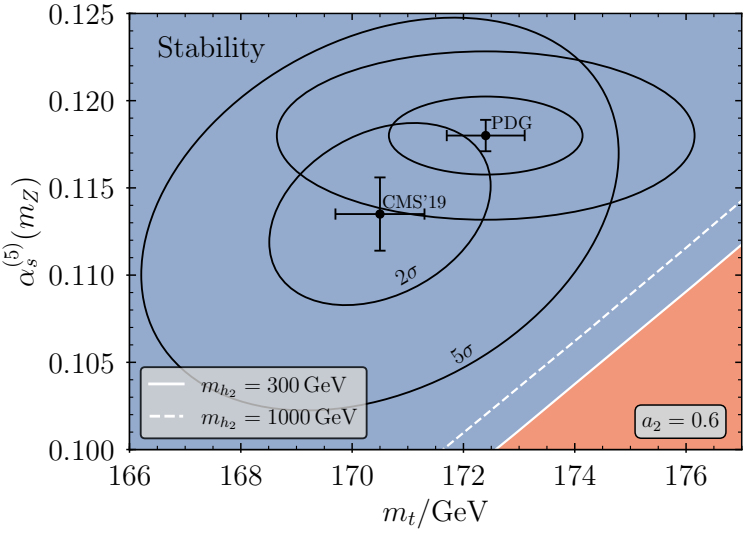
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- For $a_2 > 0$ stability boundary moves further right.
- Noticeable dependence on m_{h_2} (and θ, b_4).
- For $a_2 \simeq 0.6$ absolute stability for current central values to 5σ

Combined results: Run 2

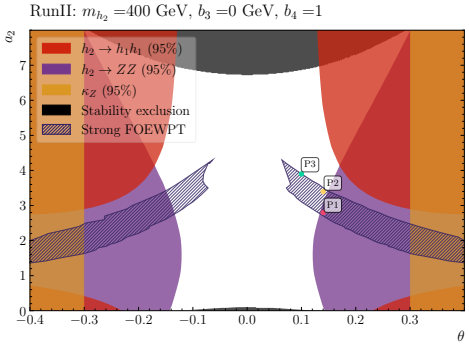
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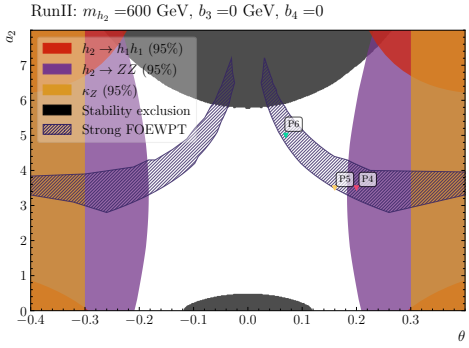
- So where are we after Run 2?

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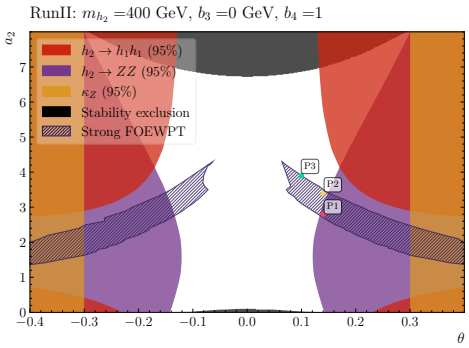


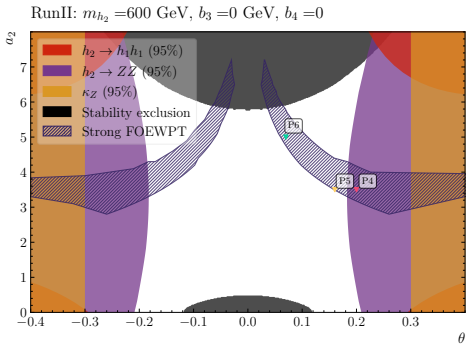
- Sizable regions with SFOPTs that are still viable by current data.
- SFOPTs not yet constrained from di-Higgs searches.

Combined results: Run 2

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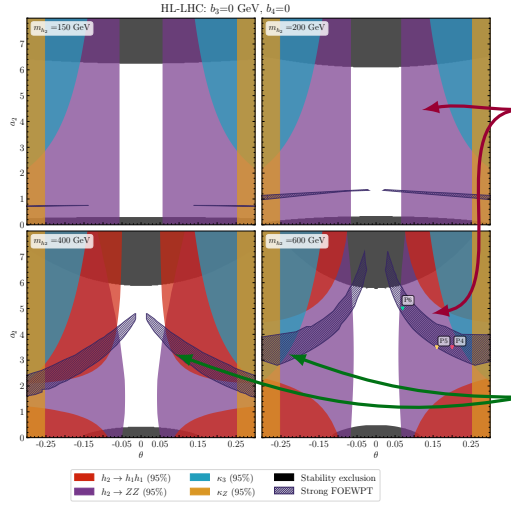




How much can the HL-LHC improve?

Combined results: HL-LHC

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$h_2 \to ZZ$
leading HL search

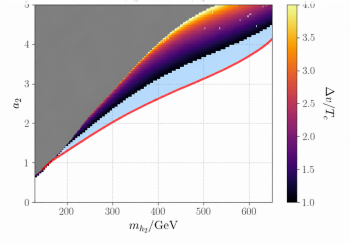
Complementary
channels probe the SFOPT-motivated region

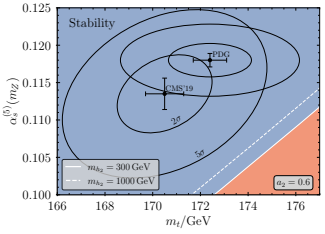
Di-Higgs
probes SFOPT regions

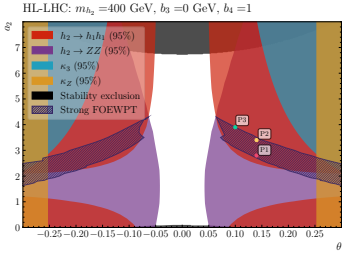
Conclusions

- A singlet can give rise to a SFOPT and stabilize the Higgs potential up to the Planck scale.
- Current data leaves a large portion of the relevant parameter space unconstrained.
- The HL-LHC is *excellent* at probing the SFOPTs of the model, but some regions (e.g. near alignment) might remain challenging.

[**MB**, G. Hiller, D. Litim, F. Maltoni, M. J. Ramsey-Musolf, S. Tentori, G. Xia, 2606.12533.]







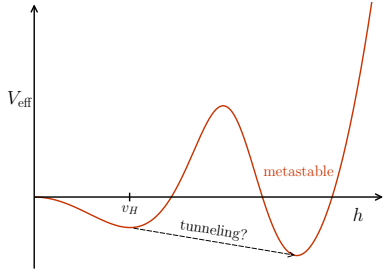
Backup

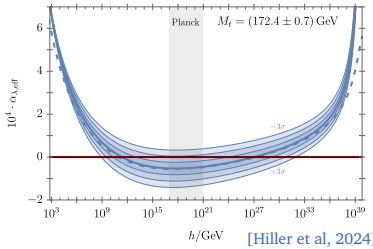
Vacuum stability

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- Additional deeper minimum at high scales.
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[Hiller et al, 2024]

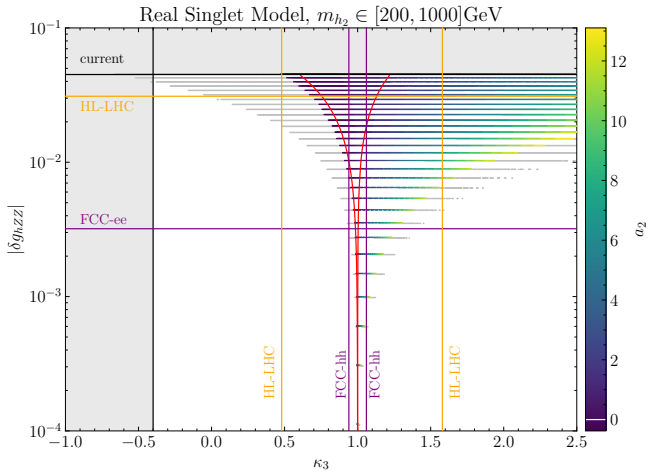
← Higgs quartic turns negative at $\approx 10^{11}$ GeV
⇒ **metastable vacuum**.

- Why so close to absolute stability?

→ **This is a target for model building**

- A singlet modifies effective potential and running of λ_H.

Stability up to the Planck scale

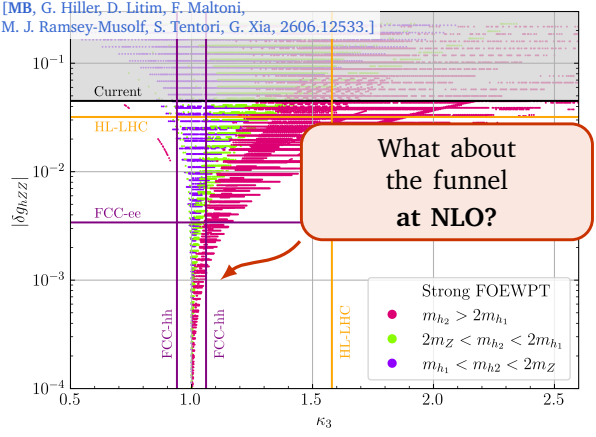


[**MB**, G. Hiller, D. Litim, F. Maltoni, M. J. Ramsey-Musolf, S. Tentori, G. Xia, 2606.12533.]

What about the seemingly inaccessible regions?

Some regions remain challenging at projected HL-LHC reach.

[**MB**, G. Hiller, D. Litim, F. Maltoni, M. J. Ramsey-Musolf, S. Tentori, G. Xia, 2606.12533.]

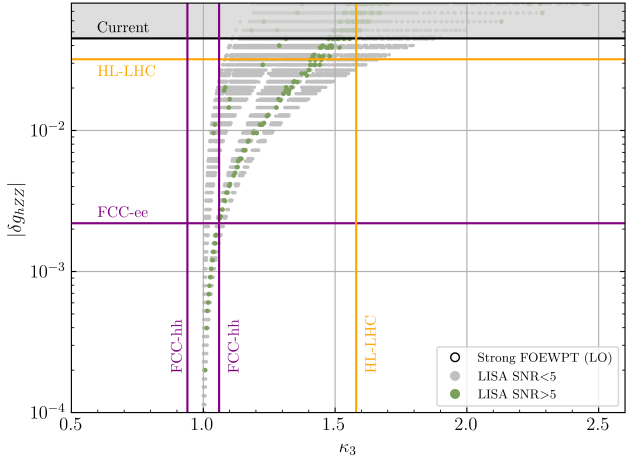


BP	$\kappa_\lambda^{(0)}$	$\kappa_\lambda^{(1)}$
1	1.0	3.0
2	1.0	4.9
3	1.1	1.4
4	1.6	3.3
5	1.3	1.3
6	1.1	1.5

Table from: [J. Braathen, S. Heinemeyer, A.P. Arnay, A. Verduras Schaedt, 2507.02569]

Gravitational Waves

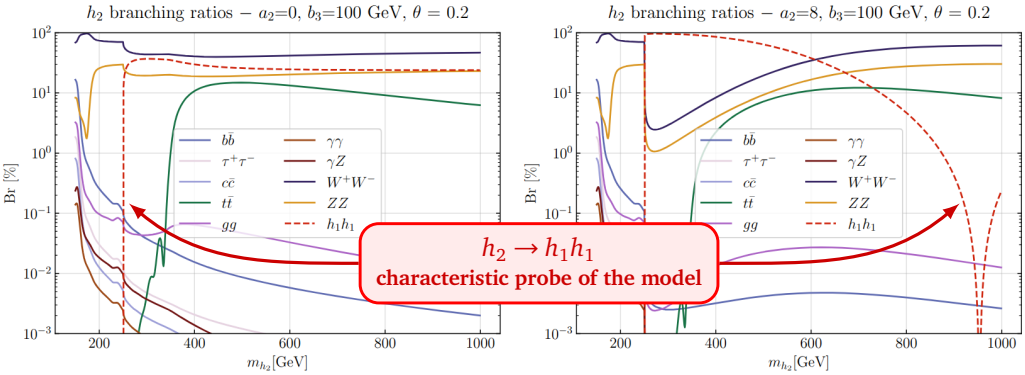
[**MB**, G. Hiller, D. Litim, F. Maltoni, M. J. Ramsey-Musolf, S. Tentori, G. Xia, 2606.12533.]



Model phenomenology: Resonant searches

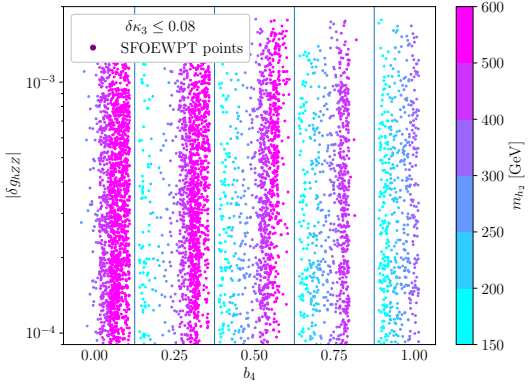
The heavy scalar can be probed through characteristic decay signatures.

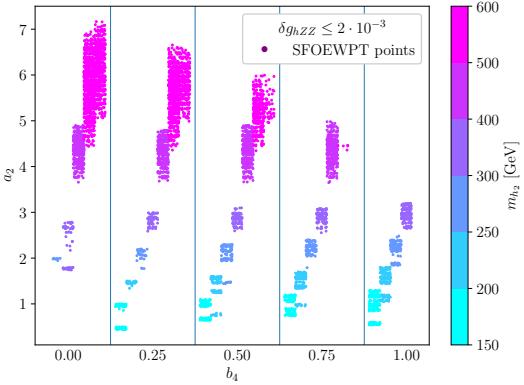
[**MB**, G. Hiller, D. Litim, F. Maltoni, M. J. Ramsey-Musolf, S. Tentori, G. Xia, 2606.12533.]



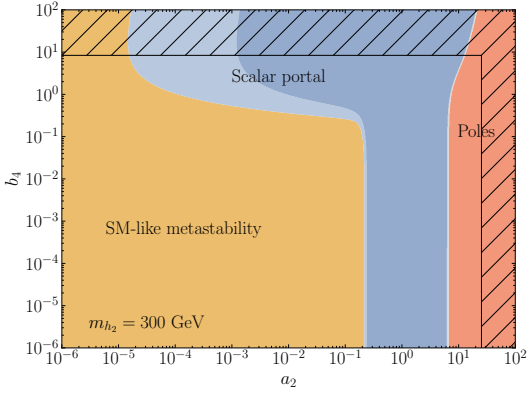
- $h_2 \to h_1h_1$ and $h_2 \to ZZ$ are particularly promising and could characterize the model if a new resonance is found.

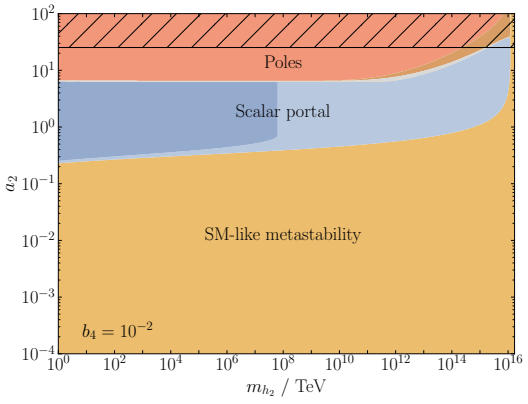
Impact of singlet self interactions





Example: parameter space where stability is restored





Threshold corrections to the Higgs quartic

[Hiller, Höhne, Litim, Steudtner, 2024]

Obs.	Value	$\alpha_{\lambda,\text{eff}} > 0$	
PDG 2024:			
m_h/GeV	125.20(11)	127.85	$+24.0\sigma$
m_t^σ/GeV	172.4(7)	171.10	$-\ 1.9\sigma$
$\alpha_s^{(5)}(m_Z)$	0.1180(9)	0.1213	$+\ 3.7\sigma$

- Stability via m_h needs 24σ deviation in Higgs mass!
- Can be interpreted as a naive deviation in λ from 0.1293 to 0.1348 at EW scale.
- This is *only* a $\sim 4.1\%$ increase in λ.

$\Rightarrow$ not relevant in the SM but **can be achieved in BSM scenarios**.

How do we compute stability in the SM?

1. Experimental Inputs

- Higgs boson mass m_h
- Top-quark pole mass m_t
- QCD coupling $\alpha_s^{(5)}(m_Z)$
- Z-boson mass m_Z
- Fermi constant G_F
- Fine-structure constant α_e & hadronic shift $\Delta\alpha_e^{(5),\text{had}}$
- Lepton masses $m_{e,\mu,\tau}$
- $\overline{\text{MS}}$ light-quark masses: $m_b(m_b)$, $m_c(m_c)$, $m_{u,d,s}(2\,\text{GeV})$

⇒ Newest PDG central values.

2. Conversion to $\overline{\text{MS}}$ scheme

- Matching: $\geq$ 2-loop electroweak + 3-loop QCD [Martin, Patel, 2018]
- Extract running couplings at reference scale: $\mu_{\text{ref}} = 200$ GeV [Alam, Martin, 2022]

3. Effective Potential Analysis

- Compute up to 3-loop (4-loop in QCD) + RG improvement [Ford, Jack, Jones, 1992] [Martin, 2013-17]
- Locate vacuum extrema/minima

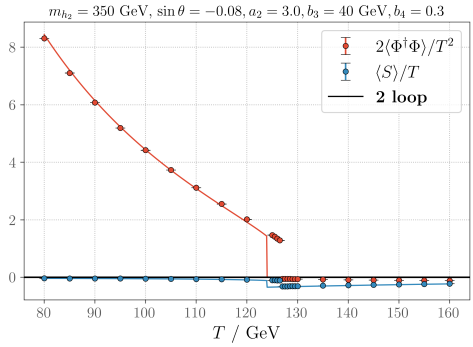
~~4. Decay Rate for Metastability~~

- Here: only absolute stability

Electroweak Phase Transition

Finite-temperature effective potential determines the EW phase transition. ⇒ crossover in the SM ↯.

- Perturbative difficulties: gauge dependence, infrared breakdown and more.
- This work: dimensional reduction → **3D finite-T EFT** + 2-loop effective potential
- lattice benchmarks show good agreement for strong transitions.



- Requiring a SFOPT places strong constraints on the parameter space.
- Greatly impacts collider phenomenology like λ_{hhh} and the hZZ-coupling.
- Furthermore, a FOPT can produce a stochastic gravitational wave background.