Constraining the real scalar singlet extension

60th Rencontres de Moriond

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

March 21, 2026

technische universität
dortmund

Real singlet extension of the SM

We 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. [L. Niemi et al, 2021].
- 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].

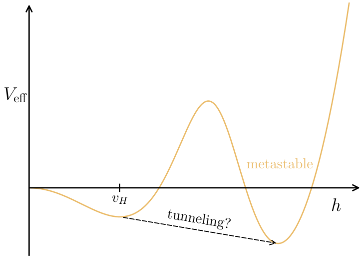
→ Both affect the Higgs self-coupling λ_{hhh}, target for the HL-LHC!

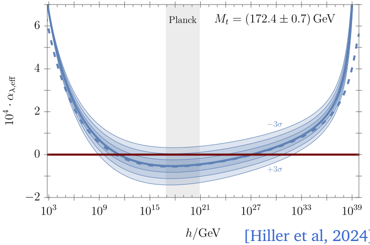
Vacuum stability

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].





[Hiller et al, 2024]

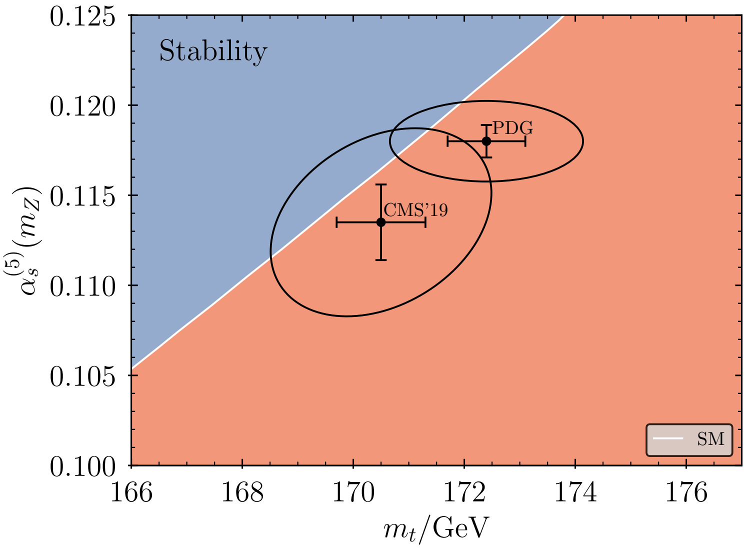
← Higgs quartic turns negative at $\approx 10^{11}$ GeV
$\Rightarrow$ **metastable vacuum.**

- Why so close to absolute stability?

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

- A singlet modifies effective potential and running of λ_H.

Vacuum stability in the SM

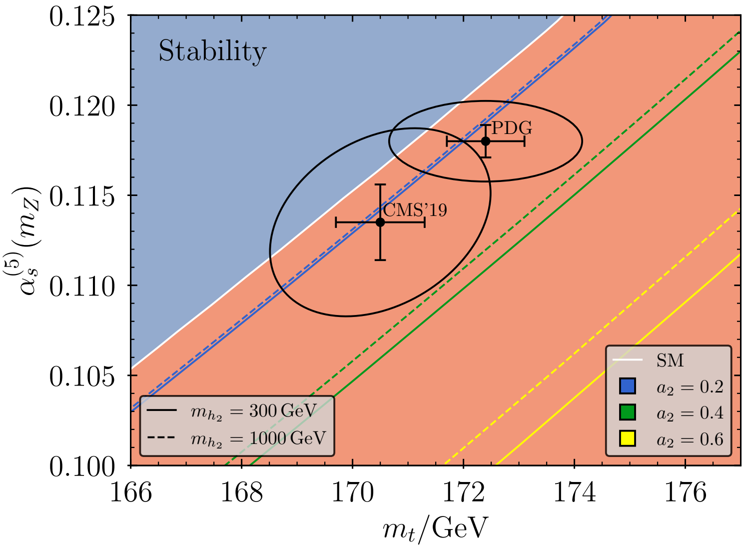


Absolute stability

Metastability/Instability

The correlation is important!

Vacuum stability in the singlet extension



Absolute stability

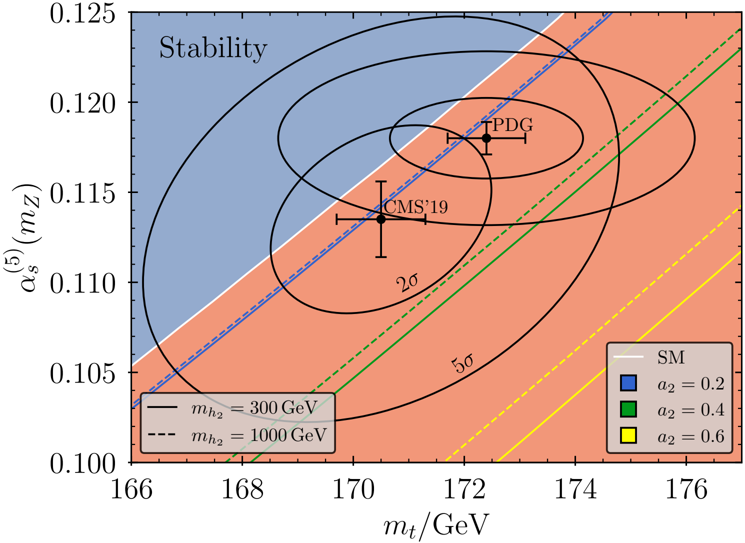
Metastability/Instability

The correlation is important!

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

  $\beta_{\lambda_H} = \beta_{\lambda_H}^{\mathrm{SM}} + \frac{1}{2(4\pi)^2}a_2^2 + \mathcal{O}(\text{2-loop}).$
- 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



Absolute stability

Metastability/Instability

The correlation is important!

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

$$\beta_{\lambda_H} = \beta_{\lambda_H}^{\text{SM}} + \frac{1}{2(4\pi)^2} a_2^2 + \mathcal{O}(\text{2-loop}).$$

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

Collider phenomenology

Simple scaling: $y_f = \cos\theta\, y_f^{\text{SM}}$, $g_{hVV} = \cos\theta\, g_{hVV}^{\text{SM}} \rightarrow \mu_{h_1} = \frac{\sigma(pp\to h_1)_{\text{measured}}}{\sigma(pp\to h)_{\text{SM}}} = cos^2(\theta)$

Run 2: $\lvert\theta\rvert < 0.3$ at 95% CL	**HL-LHC Projection:** $\lvert\theta\rvert < 0.254$ at 95% CL

[ATLAS/CMS 2504.00672]

Indirect constraints: such as self-couplings, notably $\kappa_3 = \lambda_{hhh}/\lambda_{hhh}^{\text{SM}}$.

Run 2: $-0.71 < \kappa_3 < 6.1$ at 95% CL	**HL-LHC Projection:** $\kappa_3 = 1.00^{+0.58}_{-0.52}$ at 95% CL

[PDG 2025, ATLAS/CMS Combination], [ATLAS/CMS 2504.00672]

In the alignment ($\theta \to 0$): $\delta\kappa_3$ can be an order of magnitude larger than δg_{hZZ}!

$$\delta\kappa_3 = \left(\frac{a_2}{\lambda_{h,\text{SM}}} - 3\right)\delta g_{hZZ}$$

Direct constraints: notably $h_2 \to h_1 h_1$ and $h_2 \to ZZ$ searches.

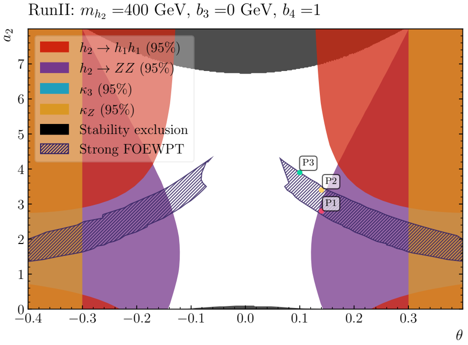
Combined results

Benchmark:

- Comparison of Run 2 and HL reach
- Theoretical + (in)direct exp. constraints

Run 2: $\lvert\theta\rvert < 0.3$	**HL:** $\lvert\theta\rvert < 0.254$	@ 95% CL
Run 2: $-0.71 < \kappa_3 < 6.1$	**HL:** $\kappa_3 = 1.00^{+0.58}_{-0.52}$	@ 95% CL

[PDG 2025], [ATLAS/CMS 2504.00672]



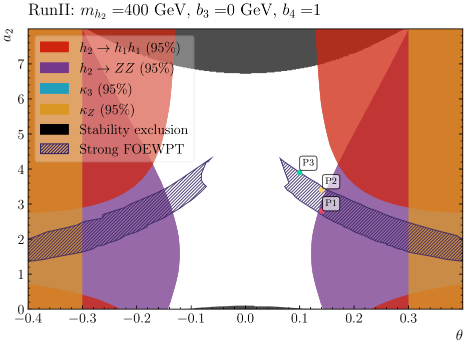
Combined results

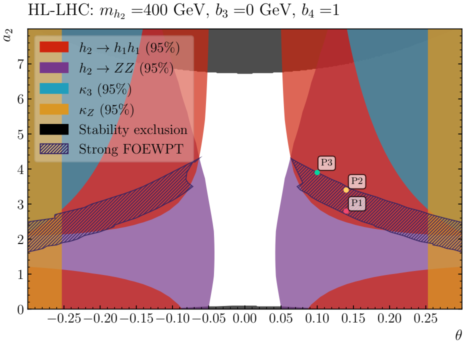
Benchmark:

- Comparison of Run 2 and HL reach
- Theoretical + (in)direct exp. constraints

Run 2: $|\theta| < 0.3$	**HL:** $|\theta| < 0.254$	@ 95% CL
Run 2: $-0.71 < \kappa_3 < 6.1$	**HL:** $\kappa_3 = 1.00^{+0.58}_{-0.52}$	@ 95% CL

[PDG 2025], [ATLAS/CMS 2504.00672]

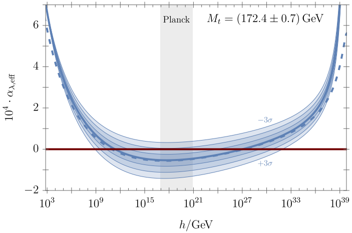


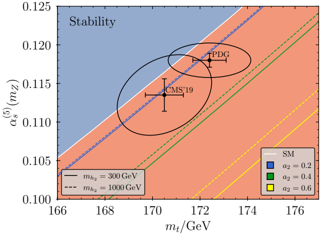


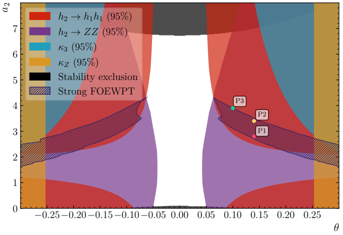
Conclusions

- An additional singlet can give rise to a SFOPT, a necessary condition for EW baryogenesis with possible GW signatures.
- The singlet can also stabilise the Higgs potential up to the Planck scale.
- Currently allowed parameter space is still large.
- The HL-LHC can probe a significant portion of the viable parameter space.

[Hiller et al, 2024]





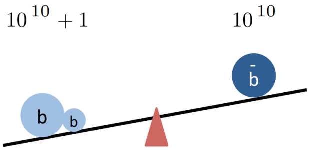


Backup

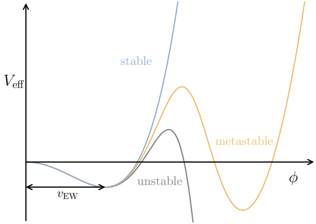
Motivation:

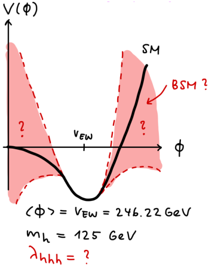
Why study (and probe) the real singlet extension of the SM?

- Missing explanation for the Baryon-Antibaryon asymmetry! [Morrissey et al, 2012].
- SM vacuum is metastable and near criticality! [Buttazzo et al, 2012].
- Existence of Higgs potential confirmed, but shape still unknown!



[K. Fuyuto, 2018]



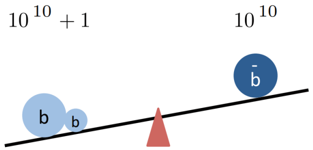


[L. Biermann, 2024]

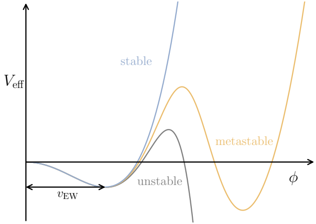
Motivation:

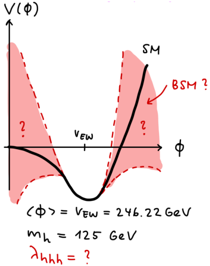
Why study (and probe) the real singlet extension of the SM?

- Missing explanation for the Baryon-Antibaryon asymmetry! [Morrissey et al, 2012].
- SM vacuum is metastable and near criticality! [Buttazzo et al, 2012].
- Existence of Higgs potential confirmed, but shape still unknown!



[K. Fuyuto, 2018]





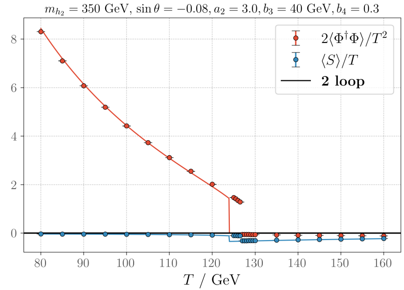
[L. Biermann, 2024]

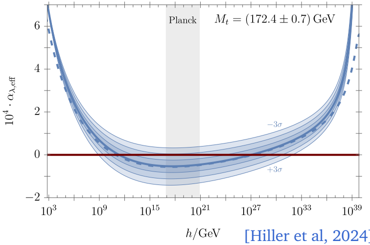
→ What can we constrain with current and future colliders?

Electroweak Phase Transition and Stability

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

- This work: dimensional reduction → **3D finite-T EFT** + 2-loop effective potential [X. Guotao et al, 2025].
- Lattice benchmarks show good agreement for strong transitions.
- Possible GW signatures.





[Hiller et al, 2024]

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

- Why so close to absolute stability?
- Stability is most sensitive to m_t and α_s. [Hiller et al, 2024].
- A singlet modifies effective potential and running of λ_H.

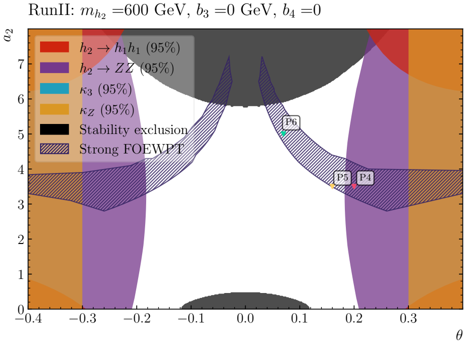
Combined results

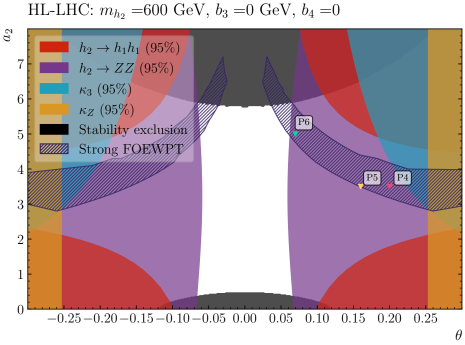
Benchmark:

- Comparison of Run 2 and HL reach
- Theoretical + (in)direct exp. constraints

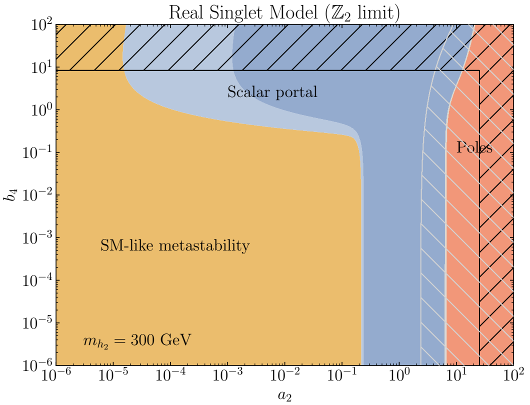
Run 2: $\lvert\theta\rvert < 0.3$	**HL:** $\lvert\theta\rvert < 0.254$	@ 95% CL
Run 2: $-0.71 < \kappa_3 < 6.1$	**HL:** $\kappa_3 = 1.00^{+0.58}_{-0.52}$	@ 95% CL

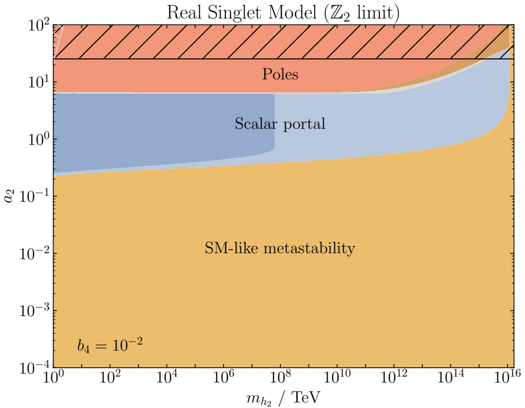
[PDG 2025], [ATLAS/CMS 2504.00672]





Example: parameter space where stability is restored





Threshold corrections to the Higgs quartic

[Hiller, Höhne, Litim, Steudtner, 2024]

Obs.	Value	$\alpha_{\lambda,\mathrm{eff}} > 0$	
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**.

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 $\Delta\alpha_e^{(5),\mathrm{had}}$
- Lepton masses $m_{e,\mu,\tau}$
- $\overline{\mathrm{MS}}$ light-quark masses: $m_b(m_b)$, $m_c(m_c)$, $m_{u,d,s}(2\,\mathrm{GeV})$

$\Rightarrow$ Newest PDG central values.

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

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