



Associação do Instituto Superior Técnico para a Investigação e Desenvolvimento

Higgs vacuum stability during kination

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Based on: <u>The rise and fall of the SM Higgs: electroweak vacuum stability during kination</u>, JHEP 2024, 339 (2024) [arXiv:2402.06000]

The setup:

- Kination (w=+1) following inflation (e.g. in *Quintessential Inflation*, one extra degree of freedom φ for both inflation and dark energy)
- The Higgs is **non-minimally coupled to curvature**
- No additional BSM degrees of freedom

$$\frac{\mathcal{L}}{\sqrt{-g}} = \frac{M_{\rm P}^2}{2} R - g^{\mu\nu} (D_{\mu}H)^{\dagger} (D_{\nu}H) - \lambda \left(H^{\dagger}H - \frac{v_{\rm EW}^2}{2}\right)^2 - \xi H^{\dagger}HR + \mathcal{L}_{\rm SM} + \mathcal{L}_{\phi}$$
he outcome: SM parameters linked to post-inflationary physics
Stable Higgs field during inflation

• The Higgs is responsible for reheating the Universe after inflation via a tachyonic instability during kination

Non-minimally coupled spectator Higgs



and Broken Symmetries, Bettoni, Rubio (2022)

(Re)heating



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(Re)heating



For more details, see talk by J. Rubio:

"Hubble-induced phase transitions as a natural quintessential inflation reheating mechanism" - Thu 6/06 at 16.40 -

Beyond tree level



- $\lambda(\mu)$ runs with the energy scale and can become **negative (vacuum stability problem)**
- Important actors in the running: **loop expansion** and **top quark mass**
- Theoretical and experimental uncertainties on the top mass, with pole mass being typically smaller than reconstructed mass.

Effective potential in kination



1) Stability criterion

 $\rho_{\rm tac} < V_{\rm max}$

- Classical fluctuations can push the Higgs beyond the barrier (with catastrophic consequences)
- Non-minimal coupling amplifies fluctuations driving them close to the **instability scale**
- Parameter space (m_t, v, H_{kin})

$$\nu = \sqrt{\frac{3\xi}{2}}$$

2) Parametric formulas: $\rho_{\text{tac}}(\lambda,\xi) = 16 \mathcal{H}_{\text{kin}}^4 \exp(\beta_1 + \beta_2 \nu + \beta_3 \ln \nu)$

[*Ricci Reheating Reloaded*, GL, J.Rubio, 2307.03774]

One-loop running



• Approximate logarithmic RGI running around the instability scale

$$V_{\rm eff}^{\rm 1loop} \simeq \frac{1}{2} \xi R h^2 - \frac{3}{64\pi^2} y_{\Lambda}^4 h^4 \ln\left(\frac{h^2}{\mu_{\Lambda}^2}\right)$$

Compare to the Higgs energy density to get the stability constraint

$$\rho_{\rm tac}(\lambda,\xi) = 16 \,\mathcal{H}_{\rm kin}^4 \,\exp\left(\beta_1 + \beta_2 \,\nu + \beta_3 \ln\nu\right)$$

$$\rho_{\rm tac} < V_{\rm max}$$

- Heating temperature constraint from BBN $T_{\rm ht} > 5 \text{ MeV}$ $T_{\rm ht} = \left(\frac{30 \rho_h^{\rm ht}}{\pi^2 g_*^{\rm ht}}\right)^{1/4}$
- Test instability region with more than 1000 classical lattice simulations using *CosmoLattice*

[CosmoLattice, 2102.01031]

BBN constraints complementary in closing the parameter space

Smaller top masses imply higher instability scales

Larger separation of scales between H_{kin} and μ_{Λ} favours stability

Three-loop running



- Proceeding as before (but numerically) and testing the parameter space with thousands of lattice simulations
- **Approximation** for the 3-loop running

$$\lambda^{3\text{loop}}(\mu) = \lambda_0 + b \ln^2 \left[\frac{\mu}{q \text{ M}_{\text{P}}}\right]$$

$$\lambda_0 = 0.003297((m_h - 126.13) - 2(m_t - 171.5))$$

$$q = 0.3 \exp \left[(0.5(m_h - 126.13) - 0.03(m_t - 171.5))\right]$$

$$b = 0.00002292 - 1.12524 \times 10^{-6}((m_h - 126.13) - 1.75912(m_t - 171.5))$$

[Bezrukov, 1403.6078]

Heating temperature constraint from BBN

$$T_{\rm ht} > 5 \text{ MeV}$$
 $T_{\rm ht} = \left(\frac{30 \rho_h^{\rm ht}}{\pi^2 g_*^{\rm ht}}\right)^{1/4}$

Good **agreement** between simulations and semi-analytic results

Three-loop running (stability only)



- The semi-analytical parametric formulas can correctly identify the instability region (previous slide)
- We can use the approximated running to explore the (*m_t*, *v*) parameter space.

$$\lambda^{3\text{loop}}(\mu) = \lambda_0 + b \ln^2 \left[\frac{\mu}{q \,\mathrm{M_P}}\right]$$

$$\lambda_0 = 0.003297((m_h - 126.13) - 2(m_t - 171.5))$$

$$q = 0.3 \exp \left[(0.5(m_h - 126.13) - 0.03(m_t - 171.5)) \right]$$

$$= 0.00002292 - 1.12524 \times 10^{-6}((m_h - 126.13) - 1.75912(m_t - 171.5))$$
[Bezrukov, 1403.6078]

• We fix *H_{kin}* and compute the stability constraint keeping an **agnostic approach** about the specific value of the **top mass (ranging from 170-173 GeV)**

Combined constraints on top masses







ν

 $H_{kin}=10^{6} \text{ GeV}$

Take-home message

- Hubble-induced phase transitions are a natural occurrence for nonminimally-coupled fields in the early Universe
- Non-minimal coupling stabilises the Higgs during inflation and leads to tachyonic particle production during kination
- The Higgs can be responsible for heating, its stability can be checked against the height of the barrier in the effective potential. A connection is formed between SM parameters and physics of the early Universe

References

- The Rise and Fall of the SM Higgs: Electroweak Vacuum Stability during Kination, JHEP 2024, 339 (2024) [arXiv:2402.06000]
- *Ricci Reheating Reloaded*, JCAP 03 (2024) 033 [arXiv: 2307.03774]
- *Quintessential Inflation: A Tale of Emergent and Broken Symmetries,* D. Bettoni, J. Rubio, [arXiv:2112.11948]
- *Hubble-induced phase transitions: Walls are not forever,* D. Bettoni, J. Rubio, [arXiv:1911.03484]

Additional Slides

Quintessential inflation



and Broken Symmetries, Bettoni, Rubio (2022)

Hubble-induced phase transition on the lattice



Objective:

To characterise the nonlinear heating stage with a large number of simulations

- Classical simulations in 3+1 dimensions (with *CosmoLattice*)
- Scanning of parameter space (υ, λ) with hundreds of simulations

$$\ddot{\chi} + 3H\dot{\chi} - \frac{1}{a^2}\nabla^2\chi + \xi R\chi + \lambda\chi^3 = 0$$
$$R = -6H^2 \qquad \nu = \sqrt{\frac{3\xi}{2}}$$

Top mass measurements

ATLAS+CMS Preliminary LHC <i>top</i> WG	m _{top} summai	ry, √s = 1.96-13 TeV Nove	mber 2023
LHC comb. (Sep 2023*), 7+8 TeV LHCtop statistical uncertainty	owg [1][16]	total stat	C
total uncertainty		$m_{top} \pm total (stat \pm syst \pm recoil) [GeV$] L dt Ref.
LHC comb. (Sep 2023*), 7+8 TeV Hit		172.52 \pm 0.33 (0.14 \pm 0.30)	≤20 fb ⁻¹ [1][16]
World comb. (Mar 2014), 1.9+7 TeV	H	173.34 \pm 0.76 (0.36 \pm 0.67)	≤8.7 fb ⁻¹ , [2]
ATLAS, I+jets, 7 TeV	l	172.33 ± 1.27 (0.75 ± 1.02)	4.6 fb ⁻¹ , [3]
ATLAS, dilepton, 7 TeV	• + 1	$173.79 \pm 1.42 \; (0.54 \pm 1.31)$	4.6 fb ⁻¹ [3]
ATLAS, all jets, 7 TeV		175.1±1.8 (1.4±1.2)	4.6 fb ⁻¹ , [4]
ATLAS, dilepton, 8 TeV	-	$172.99 \pm 0.84 \; (0.41 \pm 0.74)$	20.3 fb ⁻¹ , [5]
ATLAS, all jets, 8 TeV		$173.72 \pm 1.15 \; (0.55 \pm 1.02)$	20.3 fb ⁻¹ , [6]
ATLAS, I+jets, 8 TeV		$172.08 \pm 0.91 \; (0.39 \pm 0.82)$	20.2 fb ⁻¹ , [7]
ATLAS comb. (Sep 2023*) 7+8 TeV		172.71 \pm 0.48 (0.25 \pm 0.41)	\leq 20.3 fb ⁻¹ [1]
ATLAS, leptonic inv. mass, 13 TeV	┝┼═┼┨	$174.41 {\pm}~0.81~(0.39 {\pm}~0.66 {\pm}~0.25)$	36.1 fb ⁻¹ , [8]
ATLAS, dilepton (*), 13 TeV		$172.21 {\pm}~0.80~(0.20 {\pm}~0.67 {\pm}~0.39)$	139 fb ⁻¹ [9]
CMS, I+jets, 7 TeV	1	$173.49 \pm 1.07 \; (0.43 \pm 0.98)$	4.9 fb ⁻¹ , [10]
CMS, dilepton, 7 TeV		$172.5 \pm 1.6 \; (0.4 \pm 1.5)$	4.9 fb ⁻¹ , [11]
CMS, all jets, 7 TeV		$173.49 \pm 1.39 \; (0.69 \pm 1.21)$	3.5 fb ⁻¹ , [12]
CMS, I+jets, 8 TeV		172.35 ± 0.51 (0.16 ± 0.48)	19.7 fb ⁻¹ , [13]
CMS, dilepton, 8 TeV		$172.22 \begin{array}{c} +0.91 \\ -0.95 \end{array} (0.18 \begin{array}{c} +0.89 \\ -0.93 \end{array})$	19.7 fb ⁻¹ , [14]
CMS, all jets, 8 TeV		$172.32 \pm 0.64 \; (0.25 \pm 0.59)$	19.7 fb ⁻¹ , [13]
CMS, single top, 8 TeV	+-1	$172.95 \pm 1.22 \ (0.77 \ {}^{+0.97}_{-0.93})$	19.7 fb ⁻¹ , [15]
CMS comb. (Sep 2023*), 7+8 TeV		172.52 \pm 0.42 (0.14 \pm 0.39)	≤ 19.7 fb ⁻¹ [16]
CMS, all jets, 13 TeV		$172.34 \pm 0.73 \ (0.20 \ {}^{+0.66}_{-0.72})$	35.9 fb ⁻¹ [17]
CMS, dilepton, 13 TeV		172.33 ± 0.70 (0.14 ± 0.69)	35.9 fb ⁻¹ , [18]
CMS, I+jets, 13 TeV		171.77 ± 0.37	35.9 fb ⁻¹ , [19]
CMS, single top, 13 TeV		$172.13 \begin{array}{c} +0.76 \\ -0.77 \end{array} (0.32 \begin{array}{c} +0.69 \\ -0.71 \end{array})$	35.9 fb ⁻¹ , [20]
CMS, boosted, 13 TeV	-	173.06 ± 0.84 (0.24)	138 fb ⁻¹ , [21]
* Preliminary	[1] ATLAS-CONF-2023-066 [2] arXiv:1403.4427 [3] EPJC 75 (2015) 330 [4] EPJC 75 (2015) 158 [5] PLB 761 (2016) 350 [6] JHEP 09 (2017) 118 [7] EPJC 79 (2019) 290	[8] JHEP 06 (2023) 019 [15] EPJC [9] ATLAS-CONF-2022-058 [16] CMS [10] JHEP 12 (2012) 105 [17] EPJC [11] EPJC 72 (2012) 2202 [18] EPJC [12] EPJC 74 (2014) 2758 [19] EPJC [13] PRD 93 (2016) 072004 [20] JHEF [14] PRD 93 (2016) 072004 [21] EPJC	2 77 (2017) 354 -PAS-TOP-22-001 2 79 (2019) 313 2 79 (2019) 368 2 83 (2023) 963 2 12 (2021) 161 2 83 (2023) 560
165 170	175	180	185
		100	100
m _{top} [Gev]			