**At a glance: Electroweak (EW) symmetry non-restoration (SNR) at high temperature (T) and vacua trapped in a metastable minimum at zero T are possible phenomena within the N2HDM thermal history that further constrain its parameter space**

*Several circles*, Kandinsky

# Fate of the electroweak symmetry in the early universe: Non-restoration and trapped vacua in the N2HDM

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## 1. INTRODUCTION:

The first-order EW phase transition (**FOEWPT**) has been extensively studied in the N2HDM…

but **what other finite T effects could occur within this model?**

**Trapped vacua:** Numerous studies take the existence of a critical temperature ($T_c$) as a sufficient condition for a FOEWPT. We show that this is not always the case and leads to incorrect specifications of the parameter space. **EW SNR:** It is commonly assumed that the EW symmetry gets restored at high T. This is not always the case. We define **3 coefficients to identify N2HDM points with EWSNR.**

## 2.1. MODEL:

**N2HDM = 2HDM + real scalar singlet → 3 CP-even, 1 CP-odd** Higgs boson and **2 charged** Higgs bosons. **3 real vevs.**

## 2.2. METHODS:

**1)** We apply **theoretical and experimental constraints** to the N2HDM parameter space (perturbative unitarity, flavor physics...)

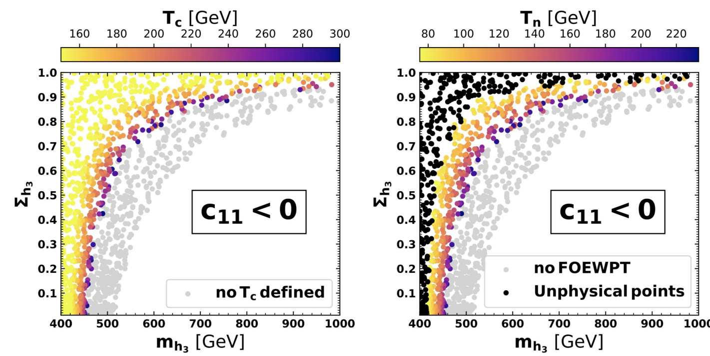
**2) Numerical analysis (studying trapped vacua).** Calculation of the **critical** and the **transition temperature ($T_n$) for N2HDM points.**

**3) Analytical analysis (studying EW SNR).** Study of the curvature of the N2HDM potential at the origin of field space in its **high-T approximation.** We defined **three coefficients $c_{ii}$** that encode the sign of the curvature of the EW preserving minima at high T:

$$H^0_{ij} = \partial^2 V/\partial\rho_i\partial\rho_j|_{(0,0,0)} \qquad c_{ii} \equiv \lim_{T\to\infty} H^0_{ii}/T^2 > 0$$

## 3. RESULTS:

**Trapped vacua:** Singlet component of one of the CP-even Higgs **vs.** its mass. **Color bar:** $T_c$ (right), $T_n$ (left). Black points **are unphysical.**




**EW SNR:** For all the points in the scan **$c_{11} < 0$** → the EW symmetry at high T can't be restored at the origin of field space and, under certain conditions, also outside.

## 4. CONCLUSIONS:

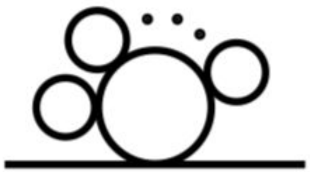
- With the coefficients **$c_{ij}$** one can easily find regions of the N2HDM parameter space **where EW SNR happens** at high T.
- The calculation of the **$T_n$ is needed** to specify the allowed parameter space.

**María Olea - DESY - ArXiv: 2103.12707**

## 1. One-loop effective potential

$$V(\rho_1,\rho_2,\rho_s,T) \equiv \underbrace{V_{\rm tree}}_{\text{tree-level potential}} + \underbrace{V_{\rm CW}}_{\text{1-loop zero-T potential}} + \underbrace{V_{\rm T}}_{\text{1-loop finite T potential}} + \underbrace{V_{\rm daisy}}_{\text{resummation of daisy diagrams}}$$

Arnold-Espinosa resummation approach



Daisy diagrams must be resummed

$$V_{\rm daisy} = -\sum_k \frac{T}{12\pi} \mathrm{Tr}\left[\left(m_k^2(\phi) + \Pi_k^2\right)^{\frac{3}{2}} - \left(m_k^2(\phi)\right)^{\frac{3}{2}}\right]$$

$$V_T(\phi_i) = \sum_j \frac{n_j T^4}{2\pi^2} J_\pm\left(\frac{m_j^2(\phi_i)}{T^2}\right)$$

$$J_\pm\left(\frac{m_j^2(\phi_i)}{T^2}\right) = \mp \int_0^\infty dx\, x^2 \log\left[1 \pm \exp\left(-\sqrt{x^2 + \frac{m_j^2(\phi_i)}{T^2}}\right)\right]$$

Gets simplified in the high T limit, which allows us to handle it analytically

## 2. EWSNR - analytical considerations. Analysis in the high T limit

$$H^0_{ij} = \partial^2 V/\partial\rho_i \partial\rho_j|_{(0,0,0)}$$

$$c_{ii} \equiv \lim_{T\to\infty} H^0_{ii}/T^2 > 0$$

Definition of the coefficients $c_{ii}$

$$c_{11} \simeq -0.025 + c_1 - \frac{1}{2\pi}\left(\frac{3}{2}\lambda_1\sqrt{c_1} + \lambda_3\sqrt{c_2} + \frac{1}{2}\lambda_4\sqrt{c_2} + \frac{1}{4}\lambda_7\sqrt{c_3}\right)$$

$$c_{22} \simeq -0.025 + c_2 - \frac{1}{2\pi}\left(\frac{3}{2}\lambda_2\sqrt{c_2} + \lambda_3\sqrt{c_1} + \frac{1}{2}\lambda_4\sqrt{c_1} + \frac{1}{4}\lambda_8\sqrt{c_3}\right)$$

$$c_{33} = c_3 - \frac{1}{2\pi}\left(\lambda_7\sqrt{c_1} + \lambda_8\sqrt{c_2} + \frac{3}{4}\lambda_6\sqrt{c_3}\right)$$

, $c_i$ are linear combinations of quartic and squared gauge couplings

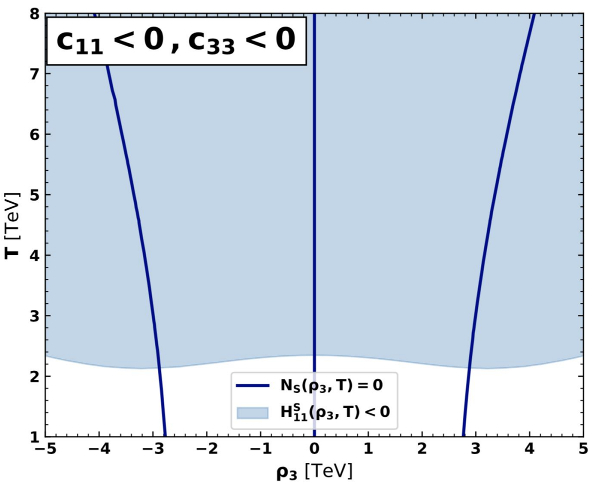
These coefficients control the simultaneous restoration of the EW and the $Z_2$ symmetry

$$H_{11}^S(\rho_3,T) = \frac{\partial^2 V}{\partial \rho_1^2}\bigg|_{(0,0,\rho_3)}$$

$$c_{11}^S = c_{11} + \mathcal{O}\left(\frac{v_S(T)^2}{T^2}\right)$$

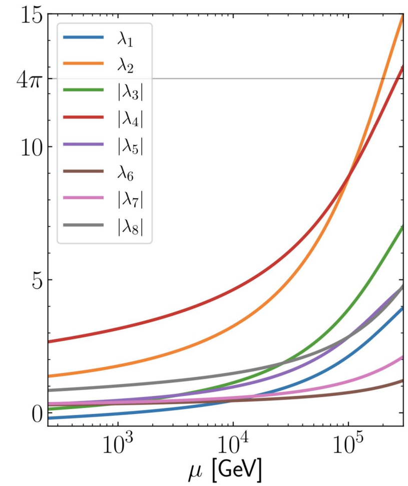
$$c_{11}^S = \lim_{T\to\infty} \frac{H_{11}^S(v_S(T),T)}{T^2}$$

Under certain conditions, $|\lambda_6|, |\lambda_7|, |\lambda_8| < 1$, the coefficients $c_{ii}$ also control the EW symmetry restoration at high T independently of the $Z_2$ symmetry restoration.




Plane T vs. $\rho_3$ (value of the singlet field of points $(0,0,\rho_3)$ where the EW symmetry is restored. **Dark blue lines $N(\rho_3,T)=0$** indicate stationary points and the **blue shaded region** shows the area where the potential is unstable in the direction of $\rho_1$.

RGE running




| | | |
|---|---|---|
| $m_{h_1}$ | $m_{h_2}$ | $m_{h_3}$ |
| 125.09 | 840 | 1355 |
| $m_A$ | $m_{H^\pm}$ | $t_\beta$ |
| 904 | 828 | 1.73 |
| $C_{h_1 t\bar{t}}$ | $C_{h_1 VV}$ | $\mathrm{sgn}(R_{13})$ |
| 0.99 | 0.96 | -1 |
| $R_{23}$ | $m_{12}^2$ | $v_S$ |
| -0.104 | $557^2$ | 2298 |

## 3. Trapped vacua

Input parameters of the scan appearing in the figures of the poster

| $m_{h_a}$ | $m_{h_b}$ | $m_{h_c}$ | $m_A$ | $m_{H^\pm}$ | $\tan\beta$ | $C^2_{h_a t\bar{t}}$ | $C^2_{h_a VV}$ | $R_{b3}$ | $m_{12}^2$ | $v_S$ |
|---|---|---|---|---|---|---|---|---|---|---|
| 125.09 | [30, 1000] | 400 | 650 | 650 | 2 | 1 | 1 | [−1, 1] | 65000 | [1, 1000] |

Computation of the transition temperature $T_n$

$$\int_{T_n}^{T_c} \frac{T^4}{H^4} \frac{A(T)}{T} e^{-S_3(T)/T}\, dT \approx 1$$

Bounce action

$$S_3 = 4\pi \int r^2 \mathrm{d}r \left[\frac{1}{2}\left(\frac{\mathrm{d}\phi_\mathrm{B}}{\mathrm{d}r}\right)^2 + V(\phi_\mathrm{B}, T)\right]$$