Fate of the electroweak symmetry in the early Universe

Vacuum trapping and symmetry non restoration within the N2HDM

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Introduction

- The first-order electroweak phase transition (FOEWPT) has been extensively studied in the next-to 2HDM (N2HDM) **but which other finite-temperature effects could occur to its thermal history?**
- Two phenomena that bring new constraints to the N2HDM parameter space:
    - **Vacuum trapping**
    - **Electroweak (EW) symmetry non-restoration (SNR) at high temperature**

Introduction

- The first-order electroweak phase transition (FOEWPT) has been extensively studied in the next-to 2HDM (N2HDM) **but which other finite-temperature effects could occur to its thermal history?**
- Two phenomena that bring new constraints to the N2HDM parameter space:

Not always handled well in the literature

  - **Vacuum trapping**
  - **Electroweak (EW) symmetry non-restoration (SNR) at high temperature**

Content

Model

The tree-level N2HDM (zero-temperature)

$$V_{\text{tree}} = m_{11}^2 |\Phi_1|^2 + m_{22}^2 |\Phi_2|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + h.c.\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$

$$+\lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + h.c.\right]$$

$$+\frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\left(\Phi_1^\dagger \Phi_1\right)\Phi_S^2 + \frac{\lambda_8}{2}\left(\Phi_2^\dagger \Phi_2\right)\Phi_S^2$$

where three fields are allowed to acquire a vev

$$\Phi_1 = \begin{pmatrix} \phi_1^+ \\ \frac{1}{\sqrt{2}}\left(v_1 + \rho_1 + i\eta_1\right) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} \phi_2^+ \\ \frac{1}{\sqrt{2}}\left(v_2 + \rho_2 + i\eta_2\right) \end{pmatrix}, \quad \Phi_S = v_S + \rho_3,$$

Model

The tree-level N2HDM

- 3 CP-even, 1 CP-odd and 2 charge scalars.
- We will work in type-II.
- 12 parameters.

$$V_{\text{tree}} = m_{11}^2 \left|\Phi_1\right|^2 + m_{22}^2 \left|\Phi_2\right|^2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2 + h.c.\right) + \frac{\lambda_1}{2}\left(\Phi_1^\dagger \Phi_1\right)^2 + \frac{\lambda_2}{2}\left(\Phi_2^\dagger \Phi_2\right)^2$$

$$+\lambda_3 \left(\Phi_1^\dagger \Phi_1\right)\left(\Phi_2^\dagger \Phi_2\right) + \lambda_4 \left(\Phi_1^\dagger \Phi_2\right)\left(\Phi_2^\dagger \Phi_1\right) + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger \Phi_2\right)^2 + h.c.\right]$$

$$+\frac{1}{2} m_S^2 \Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}\left(\Phi_1^\dagger \Phi_1\right)\Phi_S^2 + \frac{\lambda_8}{2}\left(\Phi_2^\dagger \Phi_2\right)\Phi_S^2$$

where three fields are allowed to acquire a vev

$$\langle \Phi_1 \rangle \Big|_{T=0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix}, \quad \langle \Phi_2 \rangle \Big|_{T=0} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}, \quad \langle \Phi_S \rangle \big|_{T=0} = v_S$$

Model

Experimental and theoretical constraints (zero-temperature)

- **ScannerS implements some of the constraints listed below and conveniently links to other codes such as HiggsBounds, HiggsSignals and EVADE.**

Theoretical	Experimental
Perturbative Unitarity	Electroweak precision constraints
Boundeness from Below	Flavour Constraints
Vacuum Stability	Higgs Searches and Higgs measurements

EVADE

HiggsBounds and HiggsSignals

Model

The 1-loop N2HDM at finite temperature

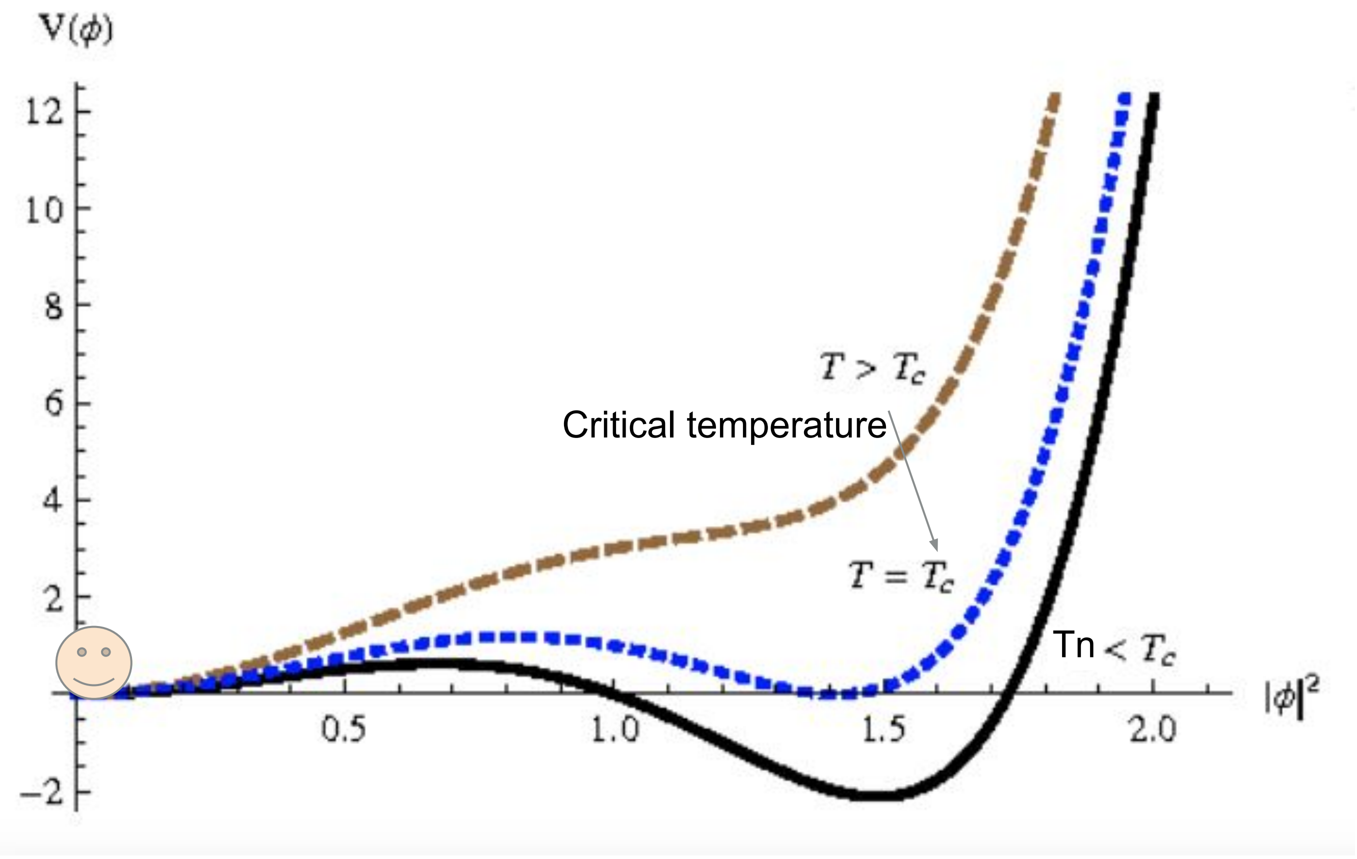
$$\mathbf{V} \equiv \underbrace{V_{\text{tree}}}_{\substack{\text{tree-level}\\\text{potential}}} + \underbrace{V_{\text{CW}}}_{\substack{\text{1-loop zero-T}\\\text{potential}}} + \underbrace{V_{\text{T}}}_{\substack{\text{1-loop finite T}\\\text{potential}}} + \underbrace{V_{\text{daisy}}}_{\substack{\text{resummation of (higher}\\\text{order) daisy diagrams}}}$$

- Breakdown of the conventional perturbative expansion.
  Daisy diagrams must be resummed.

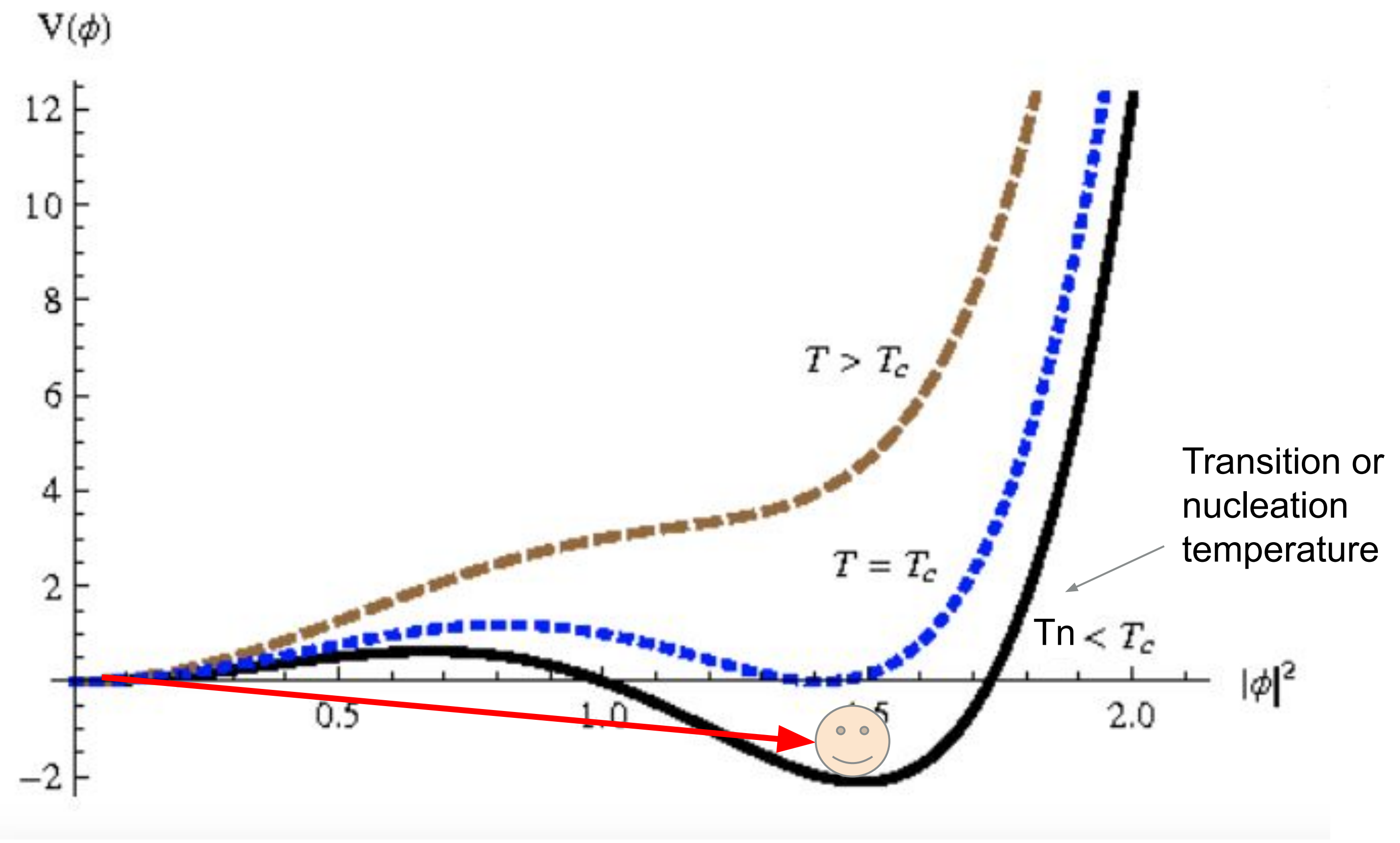
Daisy diagrams

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

FOEWPT: a reminder

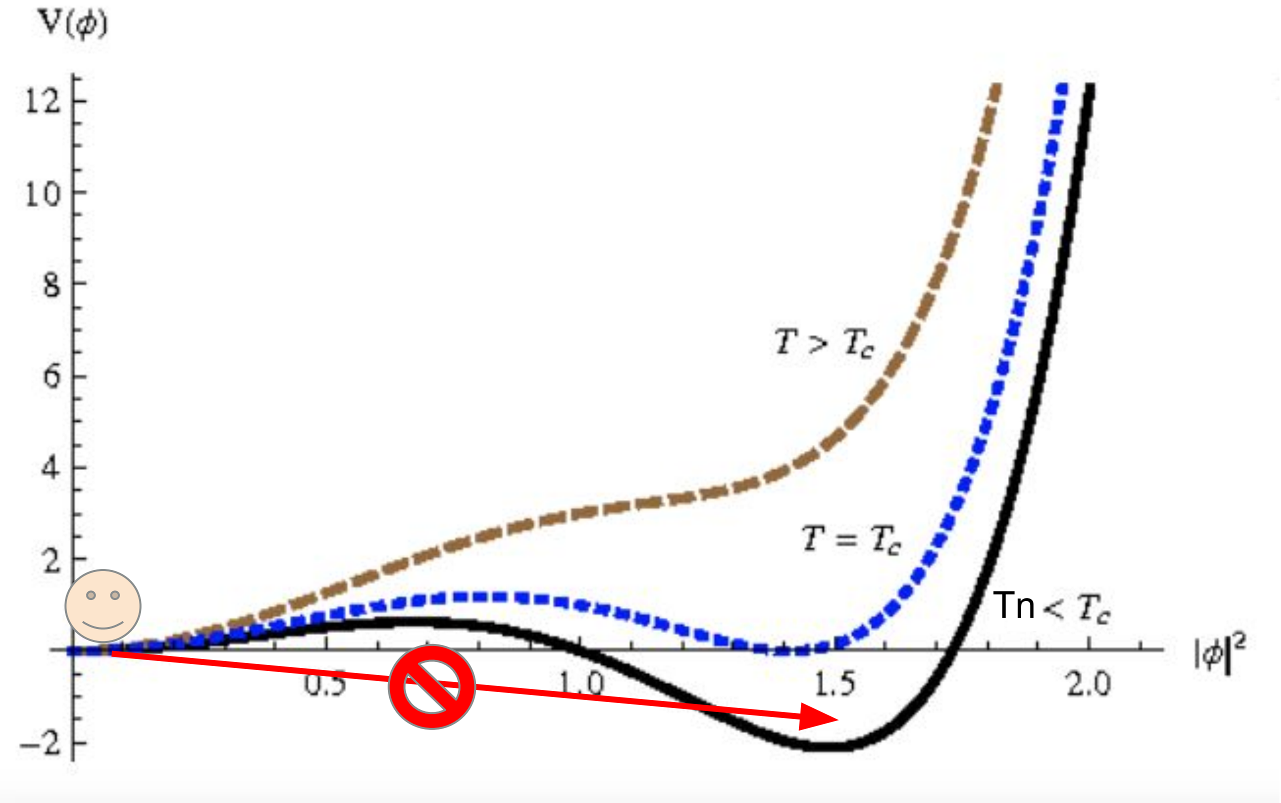


FOEWPT: a reminder



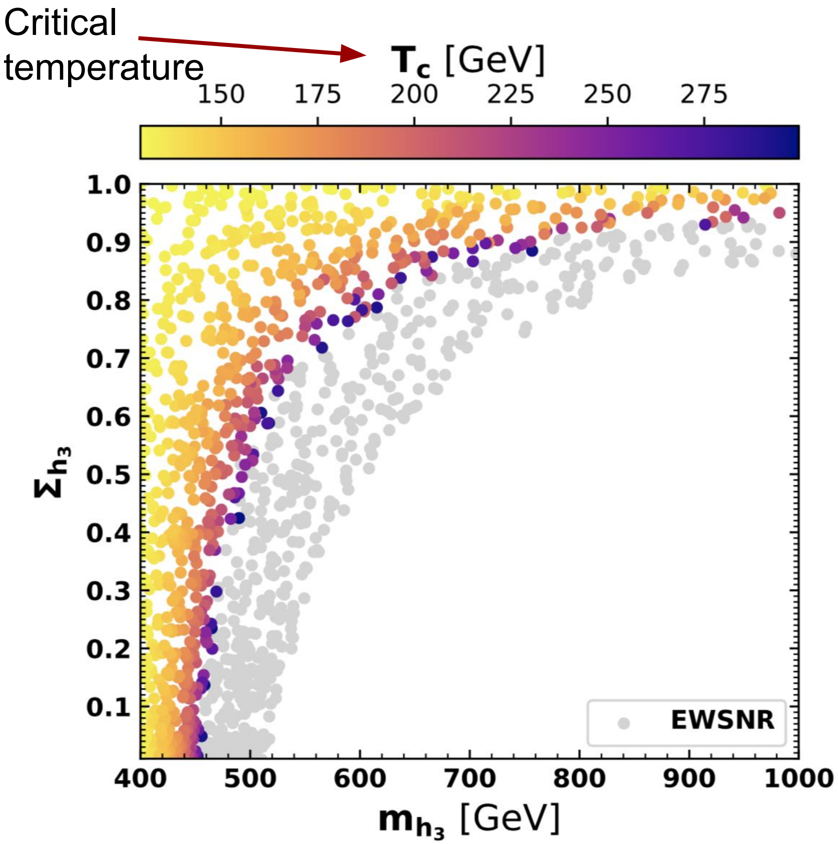
How is this picture modified by the phenomena of vacuum trapping or EW SNR?

Vacuum trapping



Vacuum trapping occurs when the energy barrier is too large or the two minima are two separated in field space that the transition probability is not big enough for the transition to take place.

Vacuum trapping

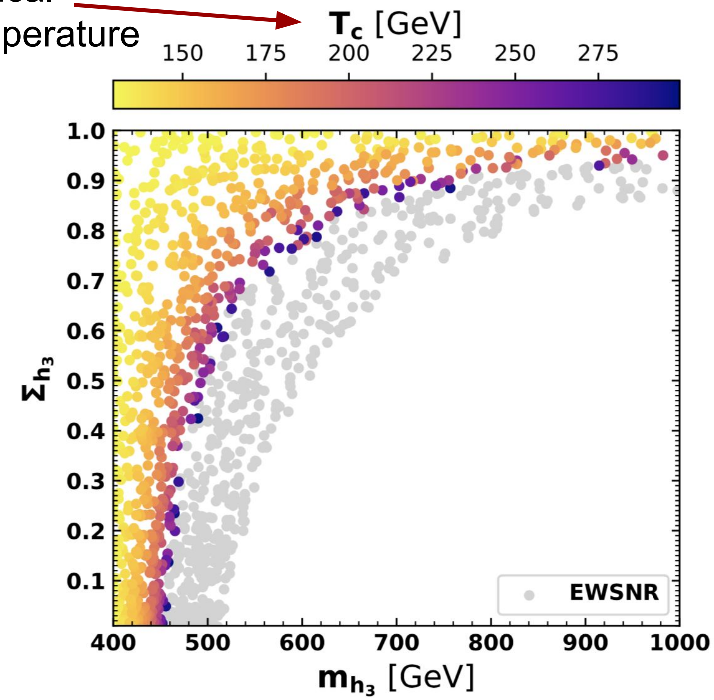


There are numerous studies that regard the existence of a critical temperature as a sufficient condition for the FOEWPT to occur.

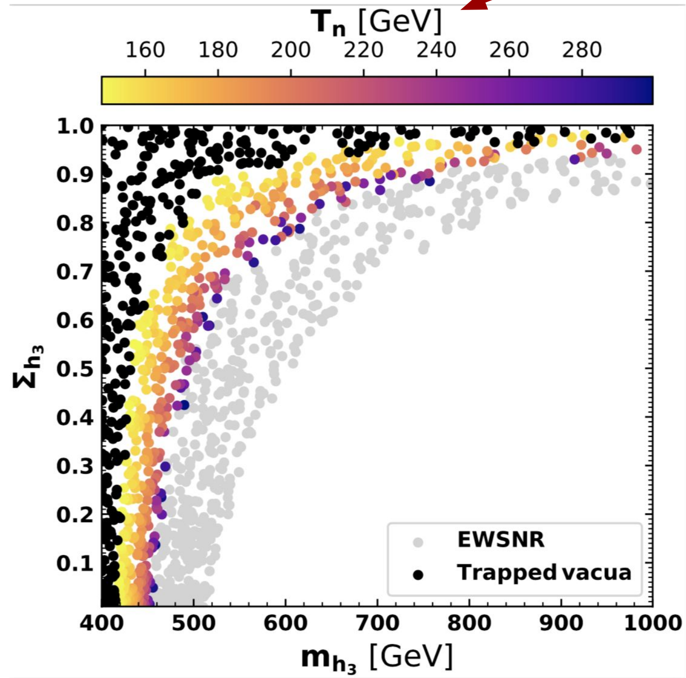
m_{h_a}	m_{h_b}	m_{h_c}	m_A	$m_{H^\pm}$	$\tan\beta$	$C^2_{h_a t\bar{t}}$	$C^2_{h_a VV}$	$\mathrm{sgn}(R_{a3})$	R_{b3}	m^2_{12}	v_S
125.09	$[30, 1000]$	400	650	650	2	1	1	$-1, 1$	$[-1, 1]$	65000	$[1, 1000]$

Vacuum trapping

Critical temperature



Nucleation temperature

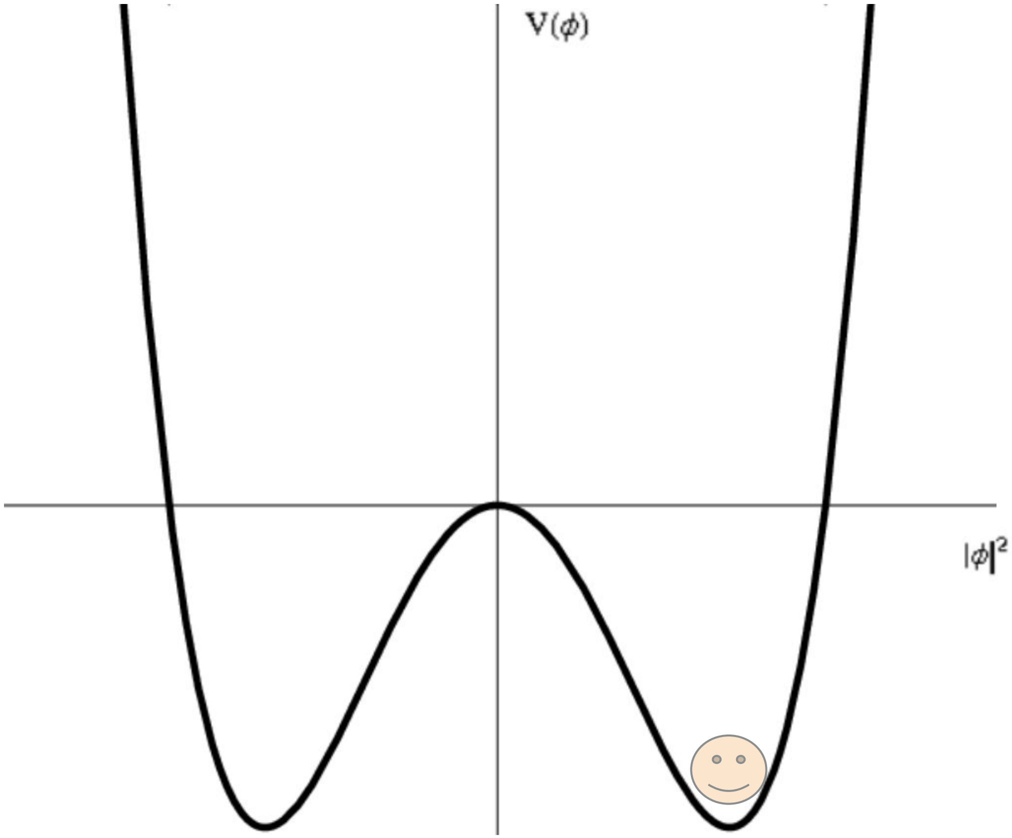


- Even though for many points a critical temperature exists, they do not feature a FOEWPT. Black points are thus **unphysical**.

m_{h_a}	m_{h_b}	m_{h_c}	m_A	$m_{H^\pm}$	$\tan\beta$	$C^2_{h_a t\bar{t}}$	$C^2_{h_a VV}$	$\mathrm{sgn}(R_{a3})$	R_{b3}	m^2_{12}	v_S
125.09	$[30, 1000]$	400	650	650	2	1	1	$-1, 1$	$[-1, 1]$	65000	$[1, 1000]$

EW SNR

At large temperature values



It is commonly **taken for granted that the EW symmetry gets restored** at high temperatures. This is **not always true** and we propose three new coefficients to **identify in which regions of the N2HDM parameter space EW SNR may appear.**

EWSNR

- The 1-loop effective potential can be approximated to a expression that can be handled **analytically** **in the high temperature limit**.

- We can compute the **curvature at the origin of field space** in this approximation. $\boxed{H^0_{ij} = \partial^2 V / \partial \rho_i \partial \rho_j |_{(0,0,0)}}$

- The conditions for the origin to be a minimum are:

$$
\begin{aligned}
H^0_{11} &> 0 \\
H^0_{11} H^0_{22} - \left(H^0_{12}\right)^2 &> 0 \\
H^0_{33} &> 0
\end{aligned}
$$

In the high temperature limit these conditions can be simply cast in

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

EWSNR

Conditions for the stability of the origin of field space at high temperature:

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

They depend only on the gauge couplings and the quartic couplings and for the **N2HDM** they are expressed as follows:

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

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

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

Linear combinations of gauge and quartic couplings

- **A negative coefficient cii** indicates that the origin of potential is unstable in the **direction of ρi** at high temperature.

EWSNR

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

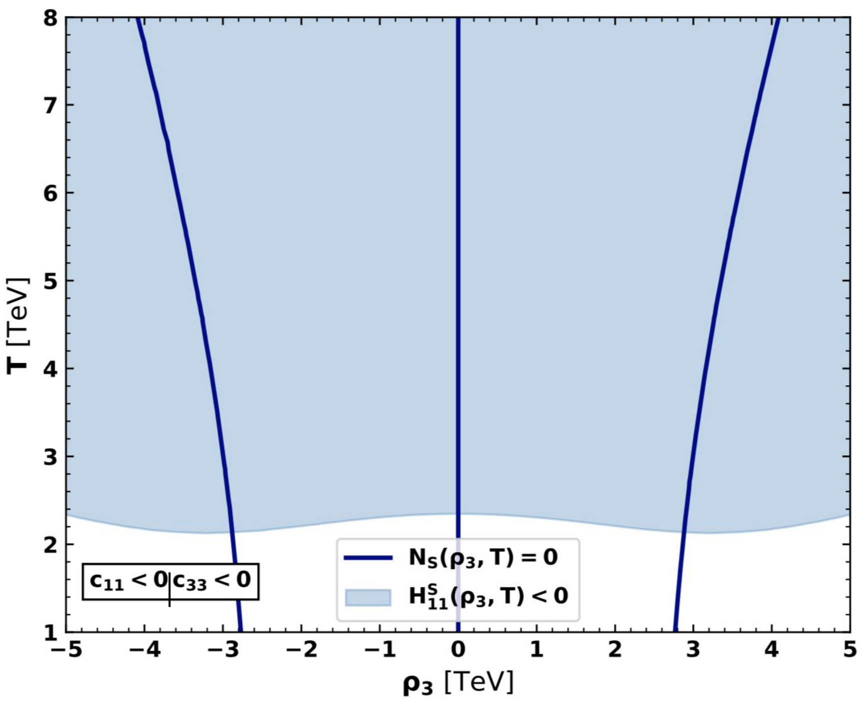
- Due to the **large positive contribution to c22** from the Yukawa coupling of the top quark, EW symmetry restoration will occur at the origin of field space when c11 >0 and c33 >0.

- In the following **c11 and c33 will be the parameters that we will use to classify** qualitatively different behaviors regarding the restoration of the electroweak symmetry.

- Even though the origin of field space is unstable in the direction of the singlet field (c33 <0), **the electroweak symmetry might still be restored in a field space point outside the origin of field space (0,0,ρ3)**. Under certain conditions, the coefficients c11 and c33 **also control the restoration behavior in this case**.

EWSNR

- **Two benchmark points scenarios that exhibit EW symmetry non-restoration in the N2HDM**

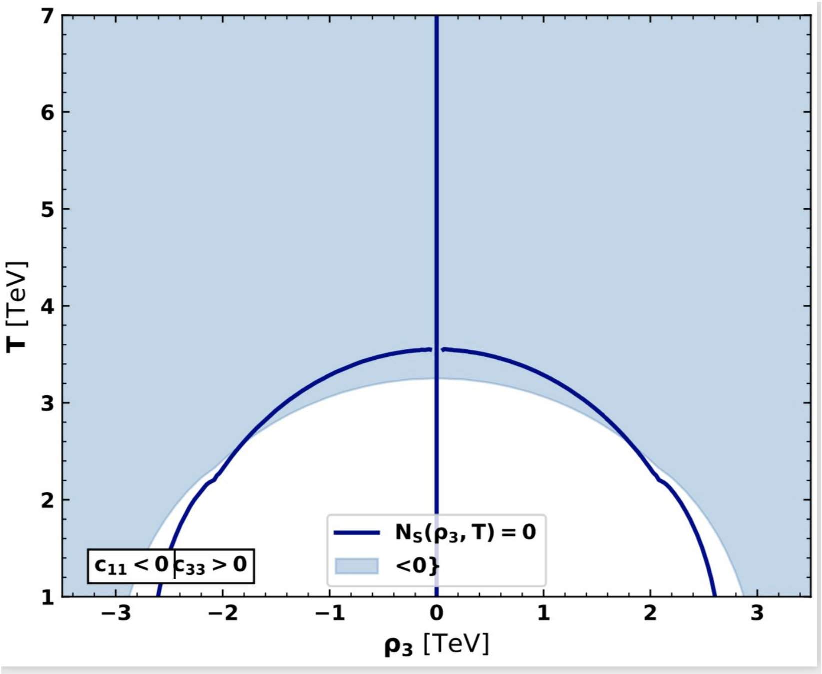


- One of them has **c11<0 and c33<0.**
- Here we show the plane T vs. ρ3. The value of ρ3 corresponds to field space points **(0,0,ρ3)** where the EW symmetry is restored. **Dark blue lines** (Ns(ρ3,T)=0) indicate **stationary points** and the **blue light shaded region** shows the region where the **potential is unstable** in the direction of one of the doublet vevs, v1.
- **c33<0** indicates that **three** stationary points are available at high temperature but due to **c11<0 none of them can be stable** in the direction of the doublet vev, v1. **Thus, the EW symmetry can't be restored.**

m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$	t_β	C_{h_1tt}	C_{h_1VV}	$\mathrm{sgn}\,(R_{13})$	R_{23}	m_{12}^2	v_S
125.09	934	1263	1008	958	1.72	0.94	0.94	-1	-0.22	604^2	2637

EWSNR

- **Two benchmark points scenarios that exhibit EW symmetry non-restoration in the N2HDM**

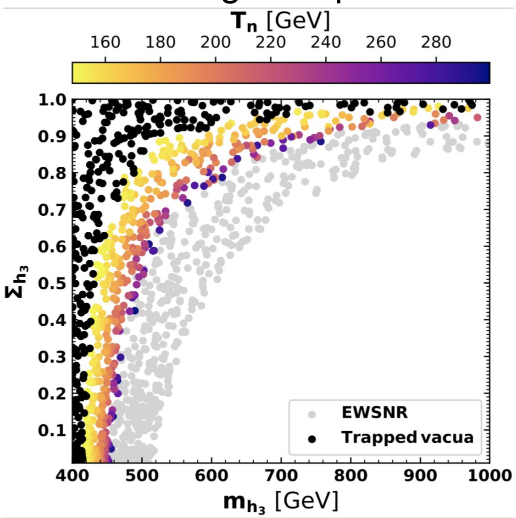


- The other one has **c11<0 and c33>0.**
- Here we show the plane T vs. ρ3. The value of ρ3 corresponds to field space points (0,0,ρ3) where the EW symmetry is restored. **Dark blue lines** (Ns(ρ3,T)=0) indicate **stationary points** and the **blue light shaded region** shows the region where the **potential is unstable** in the direction of one of the doublets vevs.
- **c33>0** indicates that **one stationary point** is available at high temperature but due to **c11<0 can not be stable** in the direction of the doublet vev, v1. **Thus, the EW symmetry can't be restored.**

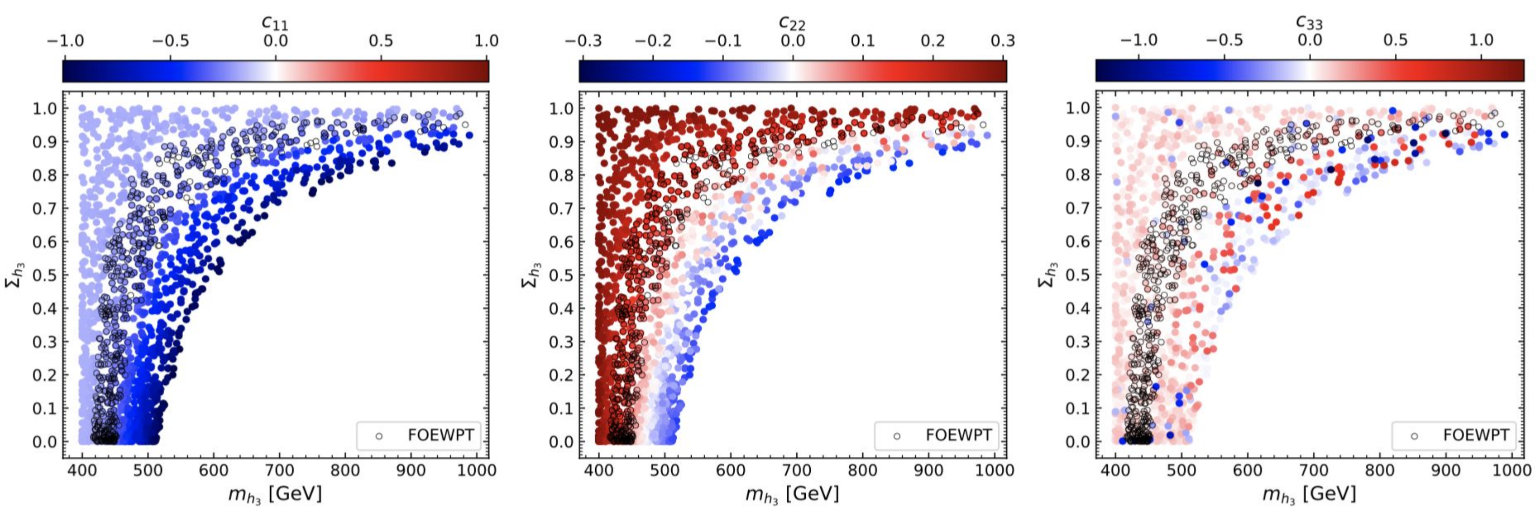
m_{h_1}	m_{h_2}	m_{h_3}	m_A	$m_{H^\pm}$	t_β	C_{h_1tt}	C_{h_1VV}	$\mathrm{sgn}\,(R_{13})$	R_{23}	m_{12}^2	v_S
125.09	835	1370	897	834	1.1	0.97	0.96	+1	0.04	559^2	2707

EWSNR & FOEWPT

- EWSNR at high temperature can be present for points that feature a FOEWPT



- For points which a transition temperature is defined feature a FOEWPT. We can compute their coefficients c11, c22 and c33 to know about the fate of the EW symmetry at high temperature.
- **For many points** the **EW symmetry will not be restored at high T due to c11 < 0**. Some of them show a FOEWPT and this two phenomena can be present in the **same thermal history**.



Conclusions

- The quick assessment of the **coefficients cii** can identify points in the N2HDM parameter space where the EW symmetry is broken at high temperature. If we are interested in a **particular thermal history** where the EW is not restored we can **easily impose this condition** to our model.

- **SNR** can be present at high temperature for points that at a lower temperature feature a **FOEWPT**.

- A finite temperature analysis and the **calculation of the transition temperature are needed** in order to correctly specify the physical parameter space of our model.

Appendix

$$
\begin{aligned}
c_{11}^S = \lim_{T\to\infty} \Bigg\{ &-0.025 + c_1 + \frac{\lambda_7}{2}\frac{v_S^2(T)}{T^2} - \frac{1}{2\pi}\Bigg(\frac{3}{2}\lambda_1\sqrt{c_1 + \frac{\lambda_7}{2}\frac{v_S^2(T)}{T^2}} \\
&+ \lambda_3\sqrt{c_2 + \frac{\lambda_8}{2}\frac{v_S^2(T)}{T^2}} + \frac{\lambda_4}{2}\sqrt{c_2 + \frac{\lambda_8}{2}\frac{v_S^2(T)}{T^2}} + \frac{\lambda_7}{4}\sqrt{c_3 + \frac{\lambda_3}{2}\lambda_6\frac{v_S^2(T)}{T^2}}\Bigg)\Bigg\} \\
= c_{11} + \mathcal{O}\left(\frac{v_S(T)^2}{T^2}\right) .
\end{aligned}
$$