Domain Walls in the N2HDM: Exploring Vacuum Trapping and Scalar Potential Evolution

Master Thesis Project

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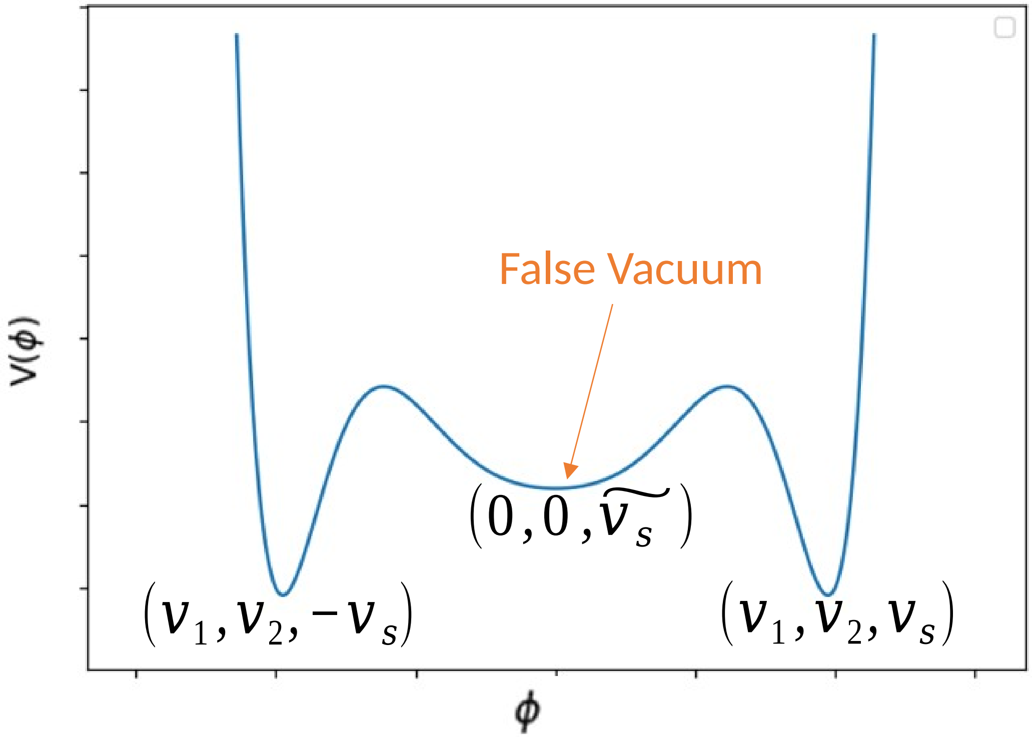
Vacuum Trapping

- Universe finds itself in a local vacuum state rather than the global one.
- Universe remains trapped in an EW symmetric phase down to T ⟶ 0.

False vacuum ⟷ Metastable vacuum state

- Prevents EWSB
- Doublet VEVs remain zero
- Unphysical parameter points



Domain Walls

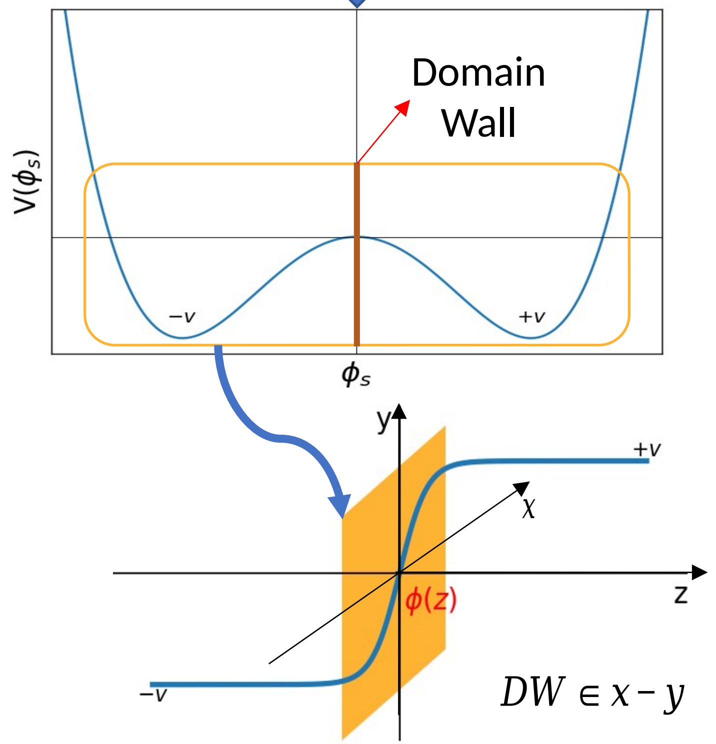
Discrete Symmetry $\xrightarrow{\text{SSB}}$ **Degenerate vacuum**

- Topological defects.
- Act as Boundaries for distinct vacuum states.
- Inside the Domain Wall

  Energy of Metastable state $>$ True EW Vacuum

- Problematic $\longrightarrow$ Dominate the energy of the universe at some point in time.
- Permitted $\longrightarrow$ For approx. discrete symmetries

  If Annihilation occurs before energy domination



Motivation

- Vacuum Trapping Provides insights into the early Universe's phase structure.
- Domain Walls may seed the nucleation process during phase transitions, affecting vacuum decay.
- Studying vacuum trapping is essential to understand the correct evolution of the universe despite vacuum trapping.

Next-to 2 Higgs Doublet Model (N2HDM)

$$\begin{aligned}\text{N2HDM} &= \text{SM}(\phi_1) + \text{Second Higgs Doublet}(\phi_2) + \text{Real Scalar Singlet}(\phi_s)\\ &= \text{2HDM}(\phi_1, \phi_2) + \text{Real Scalar Singlet}(\phi_s)\end{aligned}$$

Scalar tree-level potential

$$\begin{aligned}V &= m_{11}^2|\Phi_1|^2 + m_{22}^2|\Phi_2|^2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2\\ &+ \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{\lambda_5}{2}[(\Phi_1^\dagger\Phi_2)^2 + h.c.]\\ &\left(+\frac{1}{2}m_S^2\Phi_S^2 + \frac{\lambda_6}{8}\Phi_S^4 + \frac{\lambda_7}{2}(\Phi_1^\dagger\Phi_1)\Phi_S^2 + \frac{\lambda_8}{2}(\Phi_2^\dagger\Phi_2)\Phi_S^2\right)\end{aligned}$$

Symmetries: Z_2: $\phi_1 \to \phi_1$, $\phi_2 \to -\phi_2$ and $\phi_s \to \phi_s$, only softly broken by m_{12}^2
Z_2': $\phi_1 \to \phi_1$, $\phi_2 \to \phi_2$ and $\phi_s \to -\phi_s$, spontaneously broken by v_s

Next-to 2 Higgs Doublet Model (N2HDM)

$$V\ m_{11}^2|\phi_1|^2+\frac{\lambda_1}{2}(\phi_1^\dagger\phi_1)^2+m_{22}^2|\phi_2|^2+\frac{\lambda_2}{2}(\phi_2^\dagger\phi_2)^2+\lambda_3(\phi_1^\dagger\phi_1)(\phi_2^\dagger\phi_2)+\lambda_4(\phi_1^\dagger\phi_2)(\phi_2^\dagger\phi_1)+\frac{\lambda_5}{2}[(\phi_1^\dagger\phi_2)^2+h.c$$

$$+\frac{1}{2}m_s^2\phi_s^2+\frac{\lambda_6}{8}\phi_s^4+\frac{\lambda_7}{2}(\phi_1^\dagger\phi_1)\phi_s^2+\frac{\lambda_8}{2}(\phi_2^\dagger\phi_2)\phi_s^2$$

Symmetries: : $\phi_2 \to -\phi_2$

: $\phi_s \to -\phi_s$

Extension of Z_2 to Yukawa sector $\Rightarrow$ 4 types of the (N)2HDM

EW vacuum: ,

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

Vacuum Trapping in N2HDM

Physical Input Parameters:

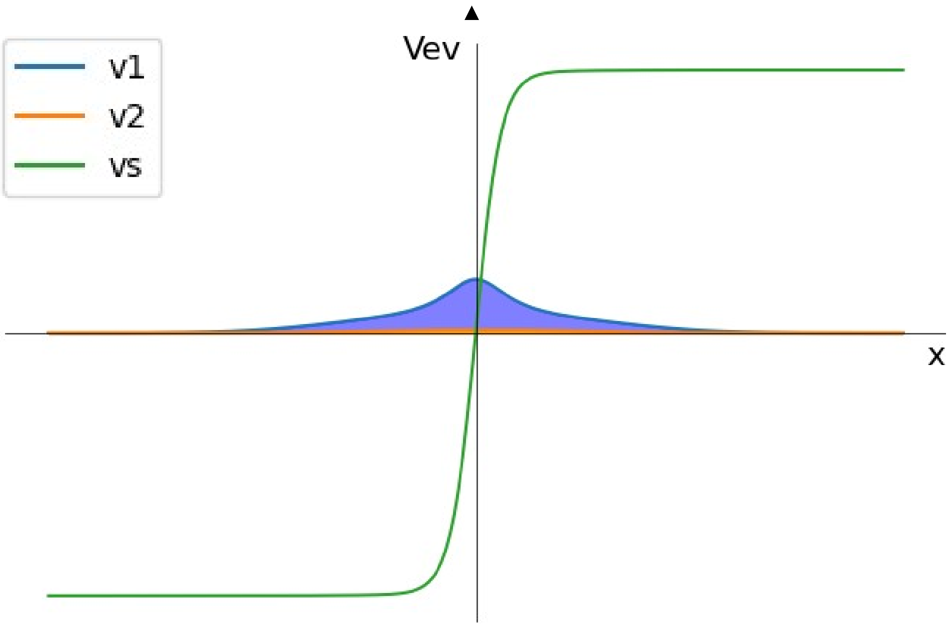
- CP-even Higgs bosons
  ,
- CP-odd Higgs bosons
- Charged Higgs bosons
- Soft breaking Z_2 term
- Singlet vev
- tan
- EW scale
- Mixing angles

125.09	400	[30, 1000]	650	2	1.10714	1.82*e-8	[-1.5, 1.5]	255^2	[1, 1000]

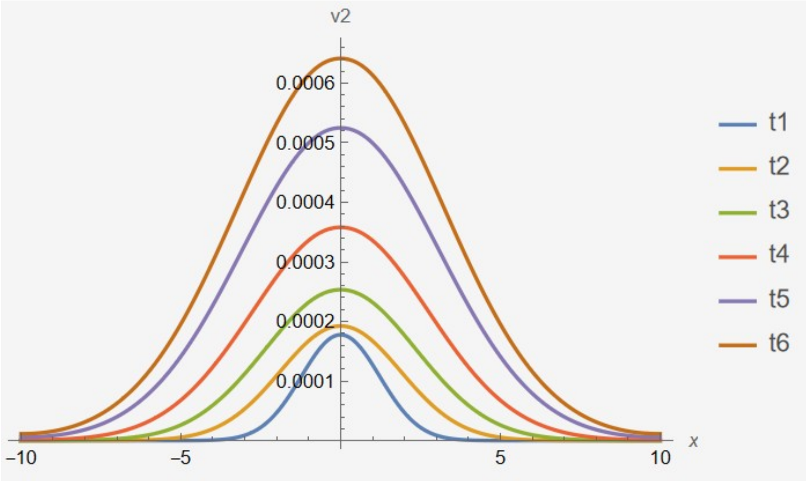
Vacuum Trapping in N2HDM

Evolution of VEVs

125.09	400	550.25	650	2	1.10714	1.82e-8	0.50065	255^2	544.63



For initialization of the fields, v_1 and v_2 were both taken as a gaussian function with a small value.



Vacuum Trapping in N2HDM

Evolution of VEVs

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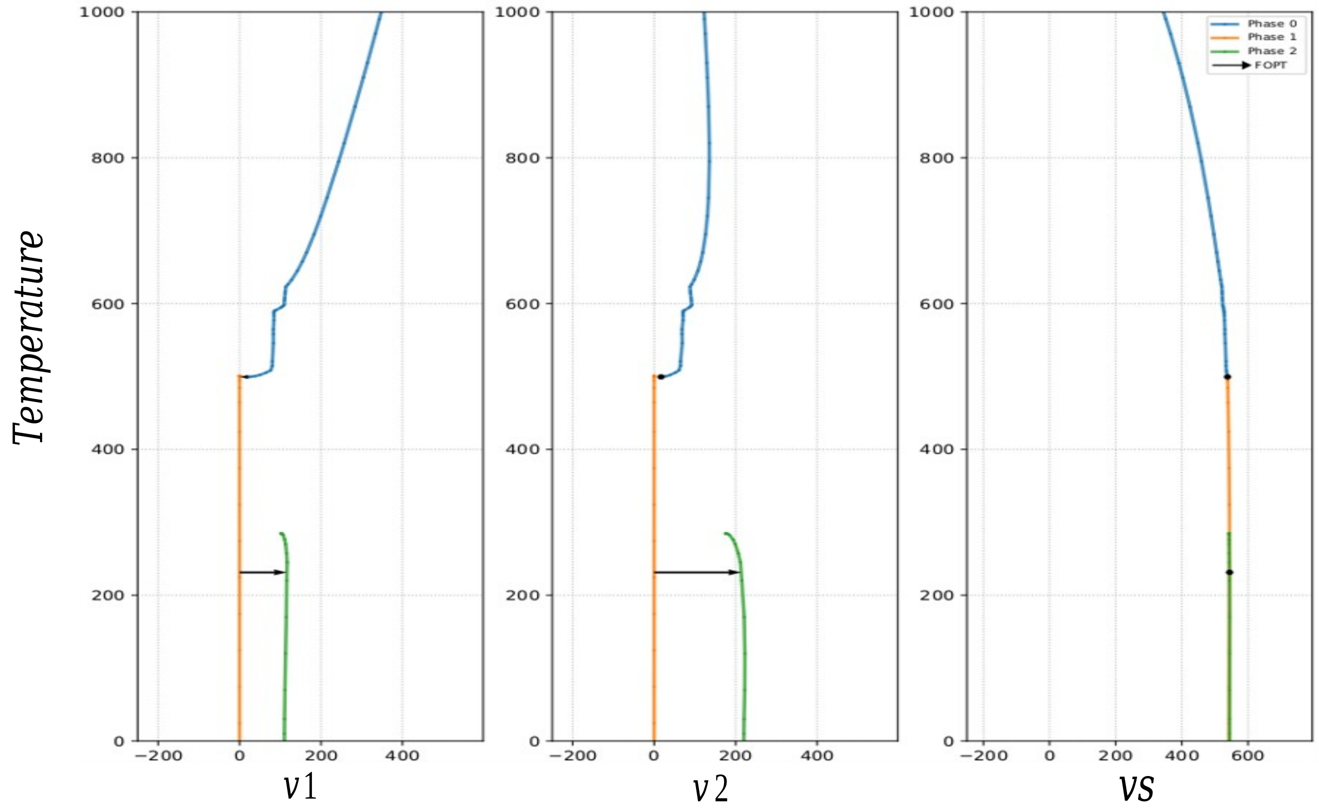


Phase Tracer: Electroweak VEVs and Singlet VEV in dependence of the temperature

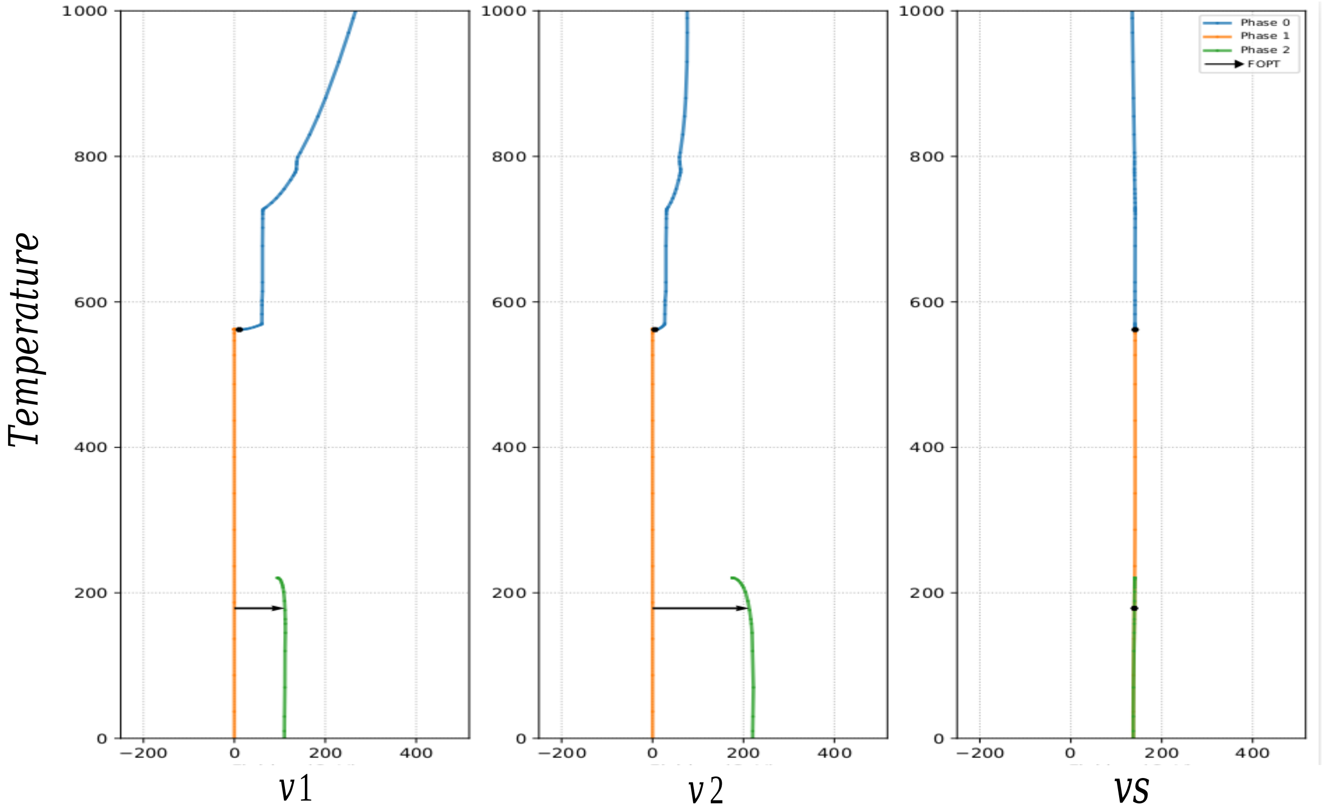
EW symmetry is broken at high temperatures and becomes unbroken at T ≈ 500 GeV.

vs decreasing for T > 500 GeV, suggesting an EW-breaking but symm. conserving vacuum configuration.

Vacuum Trapping in N2HDM

Evolution of VEVs

125.09	400	451.997	650	2	1.10715	1.82e-8	-1.18487	255^2	184.019



One of the Parameter points featuring Vacuum Trapping, obtained through ScannerS.

EW symmetry is broken at high temperatures and becomes unbroken at T ≈ 570 GeV.

Co-existence of two vacuum down to T=0.

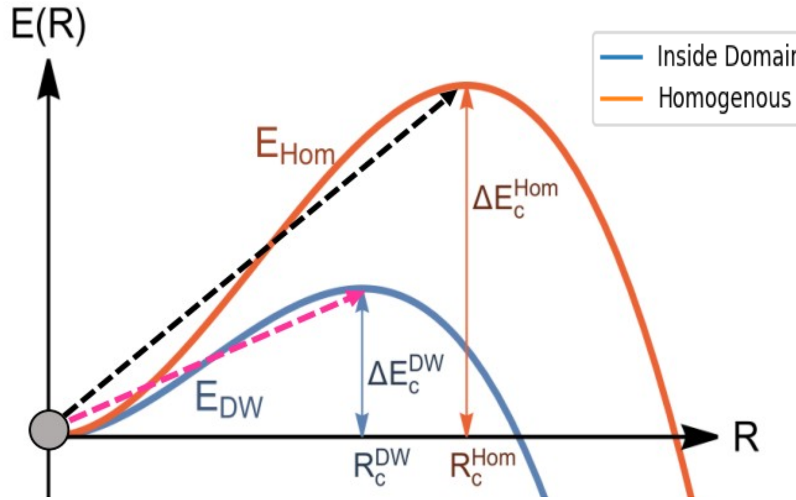
Preventing Vacuum Trapping through Domain Walls

- Bounce Action and Tunneling Rate
- Reduced Bounce Action for tunneling
- Lesser Energy barrier for Nucleation between the metastable and true vacuum states.
- Smaller Critical radius for a stable bubble to form.
- In N2HDM, the tunneling, for field moving from the meta-stable state, occurs through the Domain wall to the EW vacuum.

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

$$\Gamma(T) = A(T)\,\mathrm{e}^{-S_3(T)/T}$$

$$A(T) \approx T^4 \left(S_3/2\pi T\right)^{3/2}$$



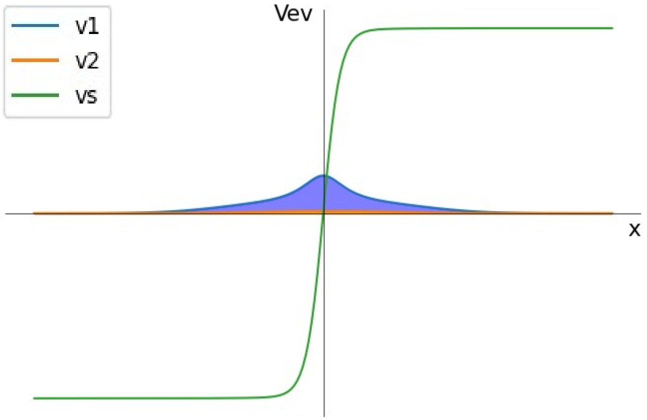
S. Blasi and A. Mariotti, *Domain Walls Seeding the Electroweak Phase Transition*

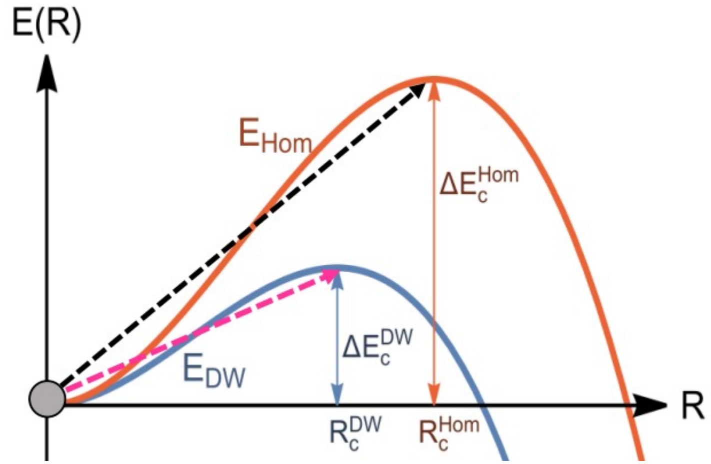
Further Research: Finite Temperature effects

- The strategy is to look for parameters featuring vacuum trapping by finding parameter points where the symmetric and broken phases coexist at temperature $T = 0$ and no nucleation occurs.
- Calculating the bounce action inside the Domain Wall which leads to the tunneling probability.
- To check which parameter points can be rescued from Vacuum Trapping through Domain Walls.

Summary and Outlook

- Vacuum Trapping in N2HDM
- Breaking of discrete symmetry related to singlet $\longrightarrow$ Domain Walls
- DWs seed the nucleation process
- Evolution of VEVs with temperature
- Finite Temperature effects
- Calculating Bounce Action and Tunneling Probability





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