Interplay of Collider physics and Gravitational Waves in the N2HDM

T. Biekötter[1], S. Heinemeyer[2], J. M. No[2], O. Olea[1]
G. Weiglein[1]

[1]Deutsches Elektronen-Synchrotron DESY
Hamburg, Germany

[2]Instituto de Física Teórica UAM-CSIC Madrid, Spain

2HDM working group, 28.05.20

Outline

1. Framework
   - Goals
   - N2HDM and Constraints
   - Gravitational Waves from a First Order Phase Transition
2. Our Results
   - Gravitational Waves Spectrum
   - Relations between N2HDM parameters and the type/strength of the First Order Phase Transition

Today's talk

- How do we constrain the N2HDM parameter space?

-How are Gravitational Waves produced in a First Order Phase Transition?

-Which kind of results have we already obtained?

Outline

1. Framework
   - Goals
   - N2HDM and Constraints
   - Gravitational Waves from a First Order Phase Transition
2. Our Results
   - Gravitational Waves Spectrum
   - Relations between N2HDM parameters and the type/strength of the First Order Phase Transition

Goals

- **Crossover between Higgs Phenomenology and Cosmology:**
  - Study the **Gravitational Wave** (GW) **Signal** produced in a **First Order Phase Transition** (FOPT) within the parameter space of the **N2HDM** in comparison with the expected sensitivity at **LISA**, the future GW Space Telescope.
  - Apply the **constraints from collider physics** to the N2HDM parameter space and investigate the collider phenomenology of parameter regions giving rise to a GW signal.
  - Focus on the parameter region of the N2HDM that could explain the **observed excesses in the searches for light Higgs bosons at LEP and CMS** and investigate the prospects for a GW signal.

Outline

1. Framework
   - Goals
   - N2HDM and Constraints
   - Gravitational Waves from a First Order Phase Transition
2. Our Results
   - Gravitational Waves Spectrum
   - Relations between N2HDM parameters and the type/strength of the First Order Phase Transition

N2HDM lowest order potential

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

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

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

where

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

Theoretical and Experimental Constraints on the N2HDM

- ScannerS (J. Wittbrodt, R. Coimbra, M. Sampaio, and R. Santos)

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

Theoretical and Experimental Constraints on the N2HDM

- ScannerS (J. Wittbrodt, R. Coimbra, M. Sampaio, and R. Santos)

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

Theoretical and Experimental Constraints on the N2HDM

- ScannerS (J. Wittbrodt, R. Coimbra, M. Sampaio, and R. Santos)

Theoretical
Perturbative Unitarity

*Strongly coupled theories are not handled by ScannerS

$*$Eigenvalues of $M_{2\to 2}$:

$$\left|M^i_{2\to 2}\right| \leq 8\pi$$

Theoretical and Experimental Constraints on the N2HDM

- ScannerS (J. Wittbrodt, R. Coimbra, M. Sampaio, and R. Santos)

Theoretical
Boundeness from Below

* Prerequisite to the existence of a stable vacuum

Theoretical and Experimental Constraints on the N2HDM

- ScannerS (J. Wittbrodt, R. Coimbra, M. Sampaio, and R. Santos)

Theoretical
Vacuum Stability

*****Is the EW vacuum:.
-the global minimum?
-a metastable minimum
compatible with the age of the Universe?
EVADE [W. Hollik, J. Wittbrodt, G. Weiglein, H.]

Theoretical and Experimental Constraints on the N2HDM

- ScannerS (J. Wittbrodt, R. Coimbra, M. Sampaio, and R. Santos)

Experimental
Electroweak precision constraints

* Precision measurements from EW observables sensitive to BSM effects
* S, T, U oblique parameters

Theoretical and Experimental Constraints on the N2HDM

- ScannerS (J. Wittbrodt, R. Coimbra, M. Sampaio, and R. Santos)

Experimental
Flavour Constraints

* from flavor observables
originated in
charged Higgs exchanges

Theoretical and Experimental Constraints on the N2HDM

- ScannerS (J. Wittbrodt, R. Coimbra, M. Sampaio, and R. Santos)

Experimental
Higgs Searches and Higgs measurements

* HiggsBounds and HiggsSignals

Outline

1. Framework
   - Goals
   - N2HDM and Constraints
   - Gravitational Waves from a First Order Phase Transition
2. Our Results
   - Gravitational Waves Spectrum
   - Relations between N2HDM parameters and the type/strength of the First Order Phase Transition

Thermal Scalar Potential

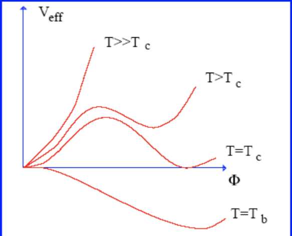
- In the context of Thermal Quantum Field Theory the effective scalar potential V_{eff} develops a temperature T dependent part.
- Pedagogical example. SM like model ϕ:
  - A and E are expressed in terms of the tree-level scalar potential parameters.
  - T_c is the critical temperature at which the symmetric vacuum ($v = 0$) becomes degenerate with the EW vacuum $v = 246\,\text{GeV}$.
  - T_b is the temperature at which the transition takes place.

Thermal effective potential:

$$V_{\text{eff}}(\phi, T) = (-m^2 + AT^2)\phi^2 - ET\phi^3 + \lambda\phi^4$$

Thermal mass:
symmetry restauration
at high temperature

Cubic term:
bosons only,
induces PT



[S.Huber]

Thermal Scalar Potential

- In the N2HDM: now the VEVs v_1, v_2 and v_S depend on the temperature.
- CosmoTransitions [C. Wainwright] tracks the dependency of the VEVs with temperature and calculates the tunneling from the symmetric vacuum to the EW one.

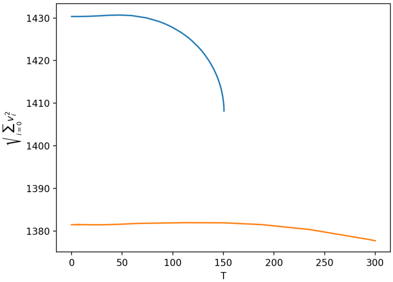


Figure: Dependence of the sum of the square root of the three VEVs squared with temperature. We can see two phases that coexist up to T~150 K.The blue one which leads to the EW minimum at T=0 and the orange one which corresponds to the symmetric minimum at high T.

Thermal Scalar Potential

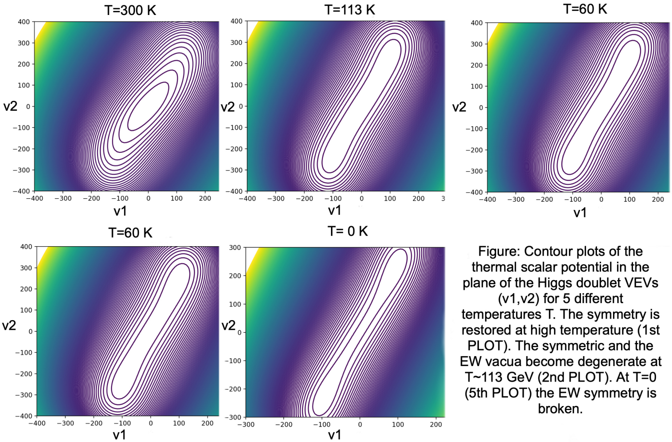


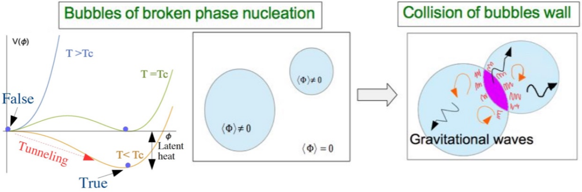
Figure: Contour plots of the thermal scalar potential in the plane of the Higgs doublet VEVs (v1,v2) for 5 different temperatures T. The symmetry is restored at high temperature (1st PLOT). The symmetric and the EW vacua become degenerate at T~113 GeV (2nd PLOT). At T=0 (5th PLOT) the EW symmetry is broken.

Figure: Same color lines denote the same value of the potential. Purple colors indicate deeper values whereas yellow colors point shallower values of the potential.s

GW production mechanism

GWs from 1stOPT

- The GWs from 1stOPT can be produced at bubble collisions in the early Universe.



Sources of GWs

1. Collision of wall
2. Plasma turbulence
3. Compression wave of plasma

- The bubble nucleation rate per unit volume per unit time:

$$\Gamma(T) \simeq T^4 e^{-\frac{S_3(T)}{T}} \qquad S_3 \equiv \int d^3r \left[\frac{1}{2}(\vec{\nabla}\varphi)^2 + V_{\text{eff}}(\varphi, T)\right]$$

- Transition temperature T_t : $\Gamma/H^4|_{T=T_t} = 1$ (S_3 : the three dimensional Euclidean action, H : the Hubble parameter)

- The GW spectrum is characterized by α and β.

  α ≃ Normalized latent heat released by PT, β ≃ 1/(The duration of PT)

Important parameters in the GW production

1. $$\alpha \Uparrow \rightarrow \smile \text{normalized released latent heat in the PT}$$

2. $$\beta \Downarrow \rightarrow \smile 1/(\text{duration of the PT})$$

Analysis Flow

1. ScannerS generates a set of random points in the N2HDM parameter space.
2. ScannerS checks wether these points pass or not the experimental and theoretical constraints mentioned above.
3. We keep the points that satisfy the constraints and we check with CosmoTransitions wether they feature a FOPT or not.
4. For the ones that produce a FOPT, we compute the GW spectrum using the output of CosmoTransitions in our own code.

Analysis Flow

1. ScannerS generates a set of random points in the N2HDM parameter space.
2. ScannerS checks wether these points pass or not the experimental and theoretical constraints mentioned above.
3. We keep the points that satisfy the constraints and we check with CosmoTransitions wether they feature a FOPT or not.
4. For the ones that produce a FOPT, we compute the GW spectrum using the output of CosmoTransitions in our own code.

Analysis Flow

1. ScannerS generates a set of random points in the N2HDM parameter space.
2. ScannerS checks wether these points pass or not the experimental and theoretical constraints mentioned above.
3. We keep the points that satisfy the constraints and we check with CosmoTransitions wether they feature a FOPT or not.
4. For the ones that produce a FOPT, we compute the GW spectrum using the output of CosmoTransitions in our own code.

Analysis Flow

1. ScannerS generates a set of random points in the N2HDM parameter space.
2. ScannerS checks wether these points pass or not the experimental and theoretical constraints mentioned above.
3. We keep the points that satisfy the constraints and we check with CosmoTransitions wether they feature a FOPT or not.
4. For the ones that produce a FOPT, we compute the GW spectrum using the output of CosmoTransitions in our own code.

Outline

1 Framework
- Goals
- N2HDM and Constraints
- Gravitational Waves from a First Order Phase Transition

2 Our Results
- Gravitational Waves Spectrum
- Relations between N2HDM parameters and the type/strength of the First Order Phase Transition

One of our predictions for the GW spectrum

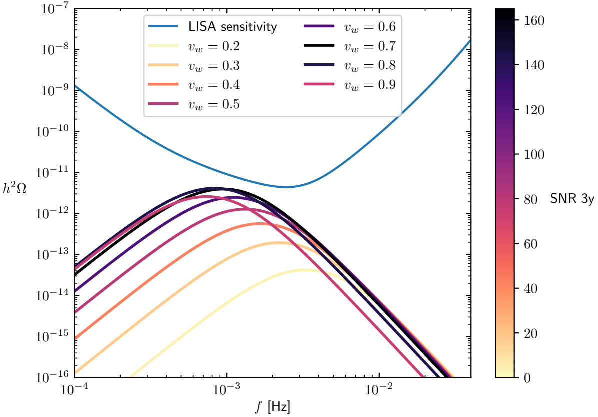


Figure: Example of a GW energy density spectrum detectable by LISA.

GW spectrum for a point that explains the 96 GeV LEP and CMS excesses

m_{H_1}	m_{H_2}	m_{H_3}	m_A	$m_{H^\pm}$	$\tan\beta$
96 GeV	125.09 GeV	410 GeV	640 GeV	650 GeV	2.46
α_1	α_2	α_3	m_{12}^2	v_S	$v = v_{EW}$
1.35	1.11	1.47	62583	1409	246.22

Yukawa type: II

Table: Parameters for a point that explains the 96 GeV LEP and CMS excesses and produces a strong GW signal.

GW spectrum for a point that explains the 96 GeV LEP and CMS excesses

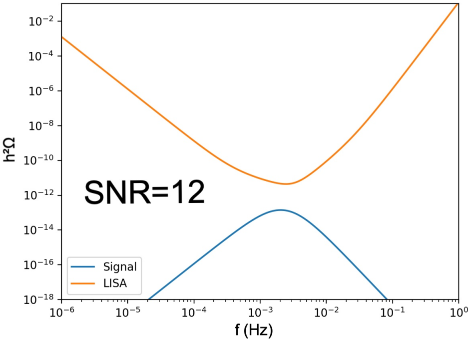
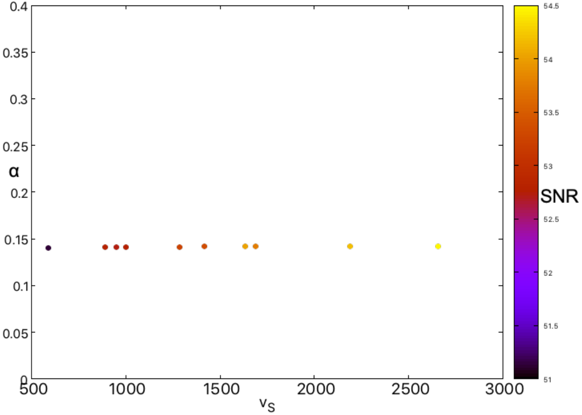


Figure: GW energy density spectrum for a FOPT for a N2HDM providing an explanation for the LEP and CMS excesses with a SNR=12 and a $v_w = 0.6$.

Outline

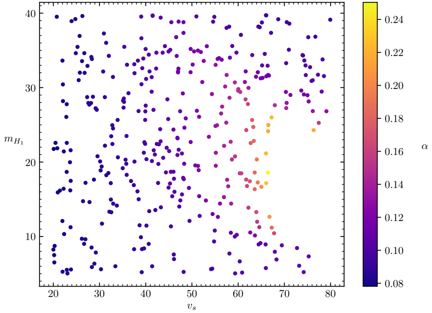
1. Framework
   - Goals
   - N2HDM and Constraints
   - Gravitational Waves from a First Order Phase Transition
2. Our Results
   - Gravitational Waves Spectrum
   - Relations between N2HDM parameters and the type/strength of the First Order Phase Transition

Relations between N2HDM parameters and the strength of the FOPT



- Scan for a point featuring a **2HDM-like** FOPT for different values of the singlet VEV at zero temperature.
- **2HDM-like transition:** the vev of the singlet do not change much **during the phase transition** $\Delta v_1, \Delta v_2 \gg \Delta v_S$ **at a finite temperature** T_t**.**

Relations between N2HDM parameters and the strength of the FOPT



- Scan for a point featuring a **singlet-driven FOPT** for different values of the singlet VEV at zero temperature and masses of the lighter CP-even scalar. The EW symmetry and the Z_2symmetry get broken in the same transition.
- **Singlet-driven transition**: the vev of the singlet significantly changes **during the phase transition.** $\Delta v_S \gg \Delta v_1, \Delta v_2$ **at a temperature** T_t.
- Way out of the "nightmare scenario": singlet detectable in GW.

Summary

- We presented some of the **results** of our ongoing project:
  - GW spectrum predictions in a N2HDM in comparison with the expected sensitivity at **LISA.**
  - Relationships between the N2HDM parameters and the strength of the FOPT.
  - Parameter regions that are compatible with an explanation to the 96 GeV LEP and CMS and are potentially accessible by GW telescopes.

THANK YOU
FOR YOUR ATTENTION
Any questions?