

VACUUM EVOLUTION OF THE R2HDM AND THE INDUCED GRAVITATIONAL WAVE AND COLLIDER PHENOMENOLOGY

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Collaborative Research Center TRR 257



Particle Physics Phenomenology after the Higgs Discovery



Based on:

L. Biermann, CB, R. Boto, M. M. Mühlleitner, R. Santos, J. Viana [[2608.25636](#)]

IRN Terascale Fall Meeting @ Heidelberg – 20/10/2026

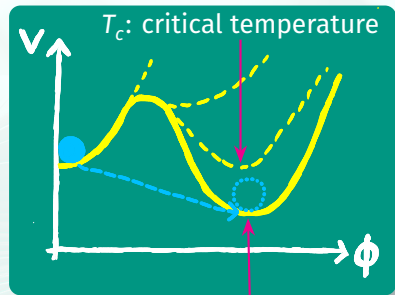
Outline

- 1 Motivation
- 2 One-loop effective potential at finite T
- 3 Parameter scan and results
- 4 Summary

Once upon a time, there was a phase transition...

- Baryogenesis: Sakharov conditions [Sakharov, '67] require **strong first-order phase transitions** (SFOPTs)
- Evolution of scalar potential V with temperature T :

Symmetric (high T) $\rightarrow$... $\rightarrow$ EW-broken ($T = 0$)



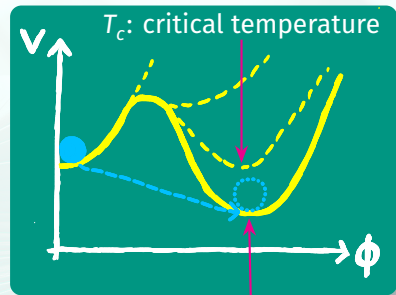
$T_n/T_p/T_{\text{compl}} < T_c$:
nucleation/percolation/
completion temperature

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- ▶ Intermediate Neutral or even “exotic” phases with **CP-violating** or **charge-breaking** vacua? [Aoki et al., '23]
 - * 1-step ($S \rightarrow$ EW) or multi-step ($S \rightarrow N \rightarrow \dots \rightarrow$ EW) phase transitions?
- ▶ Interplay between **collider constraints** and **gravitational-wave (GW) signals**?



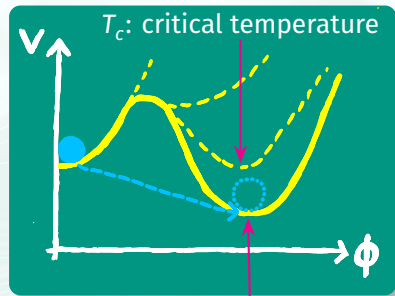
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$T_n/T_p/T_{\text{compl}} < T_c$:
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Excellent testbed for BSM physics with extended scalar sectors

For the CP-conserving 2HDM: ... [Basler et al., '16][Dorsch et al., '17][Andersen et al., '17][Bernon et al., '17][Su et al., '20]

[Aoki et al., '21][Gonçalves et al., '21][Biekötter et al., '22-'23][Bittar et al., '25][Anisha et al., '25][Lee et al., '25][Bhatnagar et al., '25] ...

Theory uncertainties, gauge dependence: ... [Ramsey-Musolf et al., '11-'25][Croon et al., '20][Athron et al., '22][Keus et al., '25][Biekötter et al., '25]...

The CP-conserving 2-Higgs-Doublet Model

Tree-level scalar potential of the real 2HDM:

$$V_{\text{tree}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 (\Phi_1^\dagger \Phi_2 + h.c.) + \frac{\lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\ + \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + h.c.]$$

with

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + \omega_1 + i\psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + \omega_{\text{CB}} + i\eta_2 \\ \zeta_2 + \omega_2 + i(\psi_2 + \omega_{\text{CP}}) \end{pmatrix}$$

and real fields $\rho_i, \eta_i, \zeta_i, \psi_i$ ($i = 1, 2$), and VEVs ω_j ($j = 1, 2, \text{CP}, \text{CB}$)

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Present-day EW-breaking vacuum at zero temperature $T = 0$ (with $v_j \equiv \omega_j|_{T=0}$):

$$v_{\text{CB}} = v_{\text{CP}} = 0 \quad \text{and} \quad v^2 = v_{\text{EW}}^2 \equiv v_1^2 + v_2^2 = (246.22 \text{ GeV})^2 \quad \text{and} \quad \tan \beta \equiv v_2/v_1$$

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and real fields $\rho_i, \eta_i, \zeta_i, \psi_i$ ($i = 1, 2$), and VEVs ω_j ($j = 1, 2, \text{CP, CB}$)

- Physical input parameters: $m_{H_1}, m_{H_2}, m_A, m_{H^\pm}, m_{12}^2, \tan \beta, \alpha, v_{\text{EW}}$, here only type I with the mixing angle α of the CP-even states
- Normal hierarchy:** $m_{H_1} = m_{H_{\text{SM}}} < m_{H_2}$; **Inverted hierarchy:** $m_{H_1} < m_{H_2} = m_{H_{\text{SM}}}$

Effective potential at finite temperatures T

Full 1-loop effective potential:

$$V_{\text{eff}}(T = 0) = V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}}$$

with

- ▶ V_{CW} : 1-loop Coleman-Weinberg potential ($\overline{\text{MS}}$)
 - ▶ V_{CT} : (finite) counterterm potential (“OS-like”)
- T -independent ($T = 0$)  [Quiros, hep-ph/9901312]

$$V_{\text{CW}} = \frac{1}{64\pi^2} \sum_{i=S,G,F} n_i m_i^4 \left[\ln \left(\frac{m_i^2}{\mu^2} \right) - c_i \right]$$

with n_i the degrees of freedom, m_i the field-dependent masses, μ the renormalisation scale, and c_i field-dependent constants (S, G, F : sum extending over all scalar/gauge boson/fermionic fields)

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Effective (= zero external momentum) **trilinear Higgs couplings at NLO** defined as:

$$\lambda_{H_i H_j H_k}^{\text{eff, NLO}} \equiv \left. \frac{\partial^3 V_{\text{eff}}(T = 0)}{\partial H_i \partial H_j \partial H_k} \right|_{\Phi = \langle \Phi \rangle} = \left. \frac{\partial^3 (V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}})}{\partial H_i \partial H_j \partial H_k} \right|_{\Phi = \langle \Phi \rangle}$$

with H_i, H_j, H_k corresponding to the mass eigenstates and $\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} (0, v_i)^T$

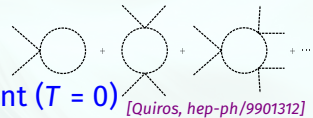
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Full 1-loop effective potential including thermal corrections:

$$V_{\text{eff}}(T) = V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}} + V_T(T)$$

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 - ▶ $V_T(T)$: 1-loop thermal corrections at **finite T** + daisy resummation
- T -independent ($T = 0$)



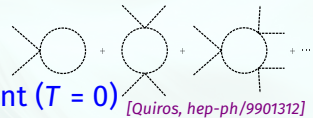
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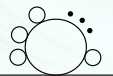
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[Quiros, hep-ph/9901312]



- ▶ Resum ‘**daisy**’ diagrams to recover perturbativity [Arnold, Espinosa, '92][Parwani, '92]
- ⇒ Mass eigenvalues obtain T -dependent **Debye corrections** $m^2 \rightarrow m^2 + \Pi(T)$
 (other methods e.g.: Partial Dressing [Bittar et al., '25], dimensional reduction/3D EFT [Farakos et al., '94-'95] [Braaten et al., '95][Ekstedt et al., '22])
- ▶ V_{CW} evaluated in Landau gauge (on gauge-indep. treatment: [Ramsey-Musolf et al., '11-'25])

Finite ‘on-shell-like’ renormalisation

V_{CW} calculated in $\overline{\text{MS}}$ scheme $\rightarrow$ introduces dependence on $\overline{\text{MS}}$ scale μ

► Add **counterterm potential** V_{CT} to **change renormalisation scheme**:

$$V_{\text{CT}} = V_{\text{CT}}(\delta m_{11}^2, \delta m_{22}^2, \delta m_{12}^2, \delta \lambda_1, \delta \lambda_2, \delta \lambda_3, \delta \lambda_4, \delta \lambda_5, \dots)$$

Finite counterterms are fixed by the ‘on-shell-like’ renormalisation conditions:

$$\partial_{\phi_i} (V_{\text{CW}} + V_{\text{CT}}) \big|_{\Phi=\langle\Phi\rangle, T=0} \stackrel{!}{=} 0, \quad \partial_{\phi_i} \partial_{\phi_j} (V_{\text{CW}} + V_{\text{CT}}) \big|_{\Phi=\langle\Phi\rangle, T=0} \stackrel{!}{=} 0,$$

with $\phi_i, \phi_j \in \{\rho_1, \eta_1, \zeta_1, \psi_1, \rho_2, \eta_2, \zeta_2, \psi_2\}$ and $\langle\Phi_i\rangle_{T=0} = \frac{1}{\sqrt{2}} (0, v_i)^T$

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- Conditions keep the **physical masses**, **mixing angles**, **VEVs** at $T = 0$ at their **tree-level values** (and independent of μ) $\Rightarrow$ convenient for parameter scans
- Residual μ dependence at $T > 0$ and beyond masses (e.g. trilinear couplings)!

Program toolchain: scans

ScannerS [Mühlleitner, Sampaio, Santos, Wittbrodt ('13-'20)] [<https://gitlab.com/jonaswittbrodt/ScannerS>]

- Generate parameter points for the R2HDM type I (random/ML/targeted scans)
- Constraints from:
 - * **theory**: bounded-from-below, perturbative unitarity, absolute stability
[Branco et al., '11] [Barroso et al., '13]
 - * **experiment**: B -physics, HiggsTools, STU -parameters
[Haller et al., '18] [Bechtle et al., '08-'26] [Peskin et al., '92]



BSMPT v3



Analysis/plots

Program toolchain: phase evolution

ScannerS



BSMPT v3 [Basler, Biermann, Mühlleitner, Müller, Santos, Viana ('18-)'24] [<https://github.com/BSMPT/BSMPT>]

- ▶ From the particle physics model to GW signal predictions
- ▶ Phase tracking from T_{high} down to $T_{\text{low}} = 0 \text{ TeV}$ with T_{high} chosen as 1 TeV
- ▶ Calculation of **bounce solution**: transition rate from false to true vacuum:

$$\Gamma(\vec{\phi}_f \rightarrow \vec{\phi}_t) \equiv A(T) e^{-S_E} \quad [\text{Coleman '77}]$$

with S_E : Euclidean action of classical path, $A(T)$: temperature-dependent prefactor

- ▶ Tests for **NLO stability** and **EW symmetry restoration (EWSR)**
- ▶ Calculation of T_i , $\xi_p = \frac{\Delta\omega}{T_p}$, PT strength α and inverse duration β/H , GW signals



Analysis/plots

T_i : T_{crit} (critical temperature)
 T_{nucl} (nucleation temperature)
 T_{perc} (percolation temperature)
 T_{compl} (completion temperature)

Program toolchain: analysis of phase transition types

ScannerS



BSMPT v3

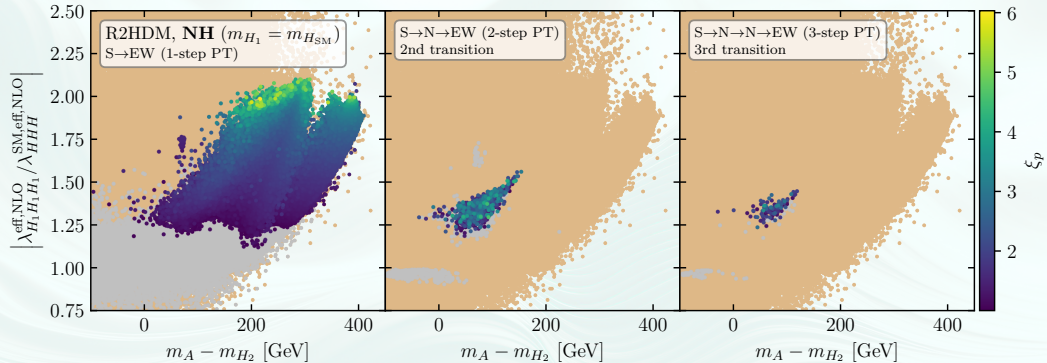


Analysis and sorting of different types of phase transitions

- ▶ Study of single- and multi-step phase transitions **that end in the correct EW phase** (i.e. that are not **trapped** in a false vacuum at $T = 0$)
- ▶ Sort points according to transition history: $S \rightarrow EW$, $S \rightarrow N \rightarrow EW$, $S \rightarrow CP \rightarrow EW$, $CB \rightarrow S \rightarrow EW$, ...
- ▶ Rescan regions in vicinity of interesting points to optimise ξ_p and GW signal strength, number of multi-step PTs

Normal hierarchy: mass gap

[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



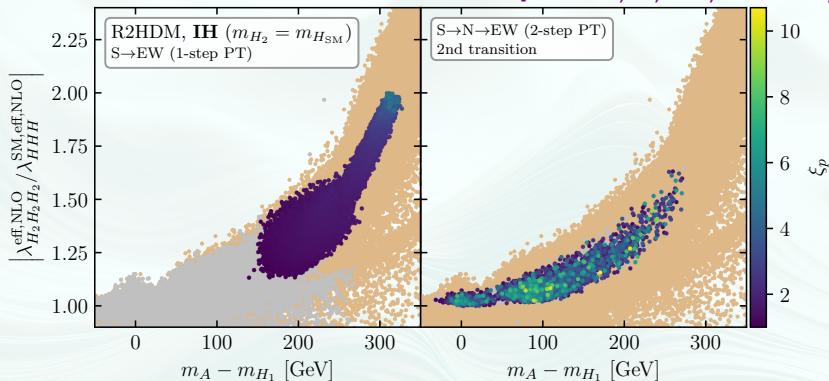
- ▶ **1-step:** stronger ξ_p for higher trilinear coupling modifier; SFOPTs possible for **very small to large mass gap**
- ▶ **Multi-step:** no visible correlation between ξ_p and trilinear coupling; generally small mass gap

light-brown points: full scan sample
grey (coloured) points: $\xi_p < 1$ ($\xi_p \geq 1$)

$$\xi_p \equiv \frac{\sqrt{\sum_{i=1,2,\text{CB,CP}} [\omega_i^{\text{true}}(T_p) - \omega_i^{\text{false}}(T_p)]^2}}{T_p}$$

Inverted hierarchy: mass gap

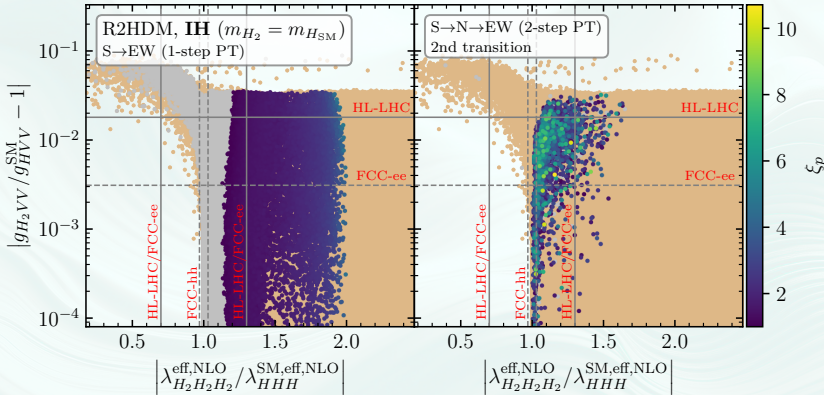
[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



- **1-step:** strong ξ_p require large mass gap; stronger correlation between mass gap and trilinear coupling modifier
- **Multi-step:** strong ξ_p possible also for zero/small mass gap and SM-like λ_{HHH} !

Inverted hierarchy: triple-Higgs vs. Higgs-gauge couplings

[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



1-step **SFOPT** points:

- Insensitive to Higgs-gauge couplings
- No strong PTs for SM-like trilinear Higgs couplings

Multi-step **SFOPT** points:

- Future colliders constrain multi-step SFOPT points to have **more and more SM-like couplings**

Potential of future colliders to **constrain different parameter regions** of **strong** 1- and 2-step phase transitions!

Intermezzo: gravitational-wave signals in a nutshell

Power spectrum of GWs:

$$h^2\Omega_{\text{GW}}(f) = h^2\Omega_{\text{coll}}(f) + h^2\Omega_{\text{sw}}(f) + h^2\Omega_{\text{turb}}(f) \quad f: \text{frequency}$$

- Sources: bubble collisions, **sound waves**, magnetohydrodynamic turbulence
- Dominant $h^2\Omega_{\text{sw}}$ fitted with **double broken power law** and **shape function S_2** :

$$h^2\Omega_{\text{sw}}^{\text{DBPL}}(f) = h^2\Omega_2^{\text{sw}} \times S_2(f, f_1^{\text{sw}}, f_2^{\text{sw}})$$

where Ω_2^{sw} and frequencies $f_1^{\text{sw}}, f_2^{\text{sw}}$ are calculated by BSMPTv3 in terms of the phase transition properties

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Can a GW signal be detected? $\Rightarrow$ **Signal-to-noise ratio (SNR)**:

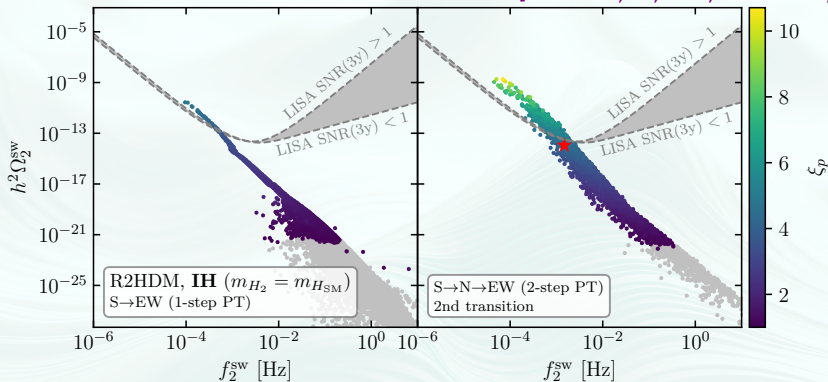
$$\text{SNR} = \sqrt{\mathcal{T} \int_{f_{\min}}^{f_{\max}} df \left[\frac{h^2\Omega_{\text{GW}}(f)}{h^2\Omega_{\text{Sens}}(f)} \right]^2}$$

with $h^2\Omega_{\text{Sens}}$: sensitivity of LISA experiment, $\mathcal{T}$: data acquisition time, $f_{\min/\max}$: sensitive frequency range

- A GW signal is considered to be **detectable** if **SNR $\gtrsim 10$**

Inverted hierarchy: gravitational-wave frequency spectra

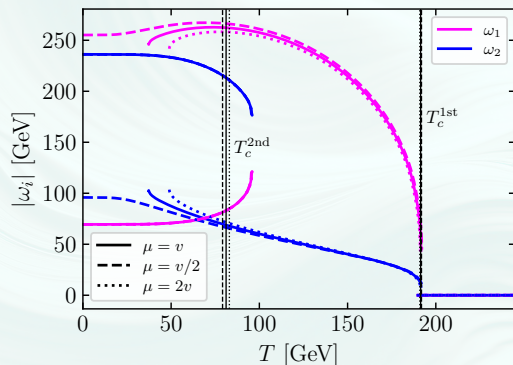
[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



- Most $\xi_p > 1$ points show a correlation between f_2^{sw} and $h^2 \Omega_2^{\text{sw}}$
- Stronger GW signals for multi-step PTs than for 1-step PTs

Choice of renormalisation scale for benchmark point

Vacuum evolution for benchmark point
BP★ (inverted hierarchy, $S \rightarrow N \rightarrow EW$):



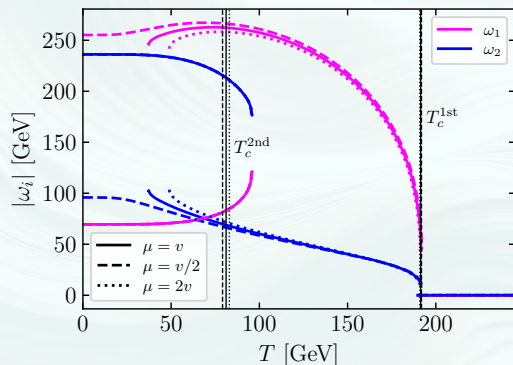
[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]

	Relative error		
	$\mu = v_{EW}$	$\mu = v_{EW}/2$	$\mu = 2v_{EW}$
$\Delta\omega(T_c)$ [GeV]	230.3	+3.1%	-3.1%
$\Delta\omega(T_n)$ [GeV]	239.6	+1.9%	-2.7%
$\Delta\omega(T_p)$ [GeV]	238.9	+1.7%	-2.6%
T_c [GeV]	81.15	-2.5%	+2.3%
T_n [GeV]	55.09	-22%	+14%
T_p [GeV]	53.20	-25%	+15%
Δ_{cp}^T	0.3444	+44%	-24%
α	0.07101	+219%	-44%
β/H	560.9	-60%	+57%
SNR(3y)	0.3299	+1630%	-86%

(for 2nd transition)

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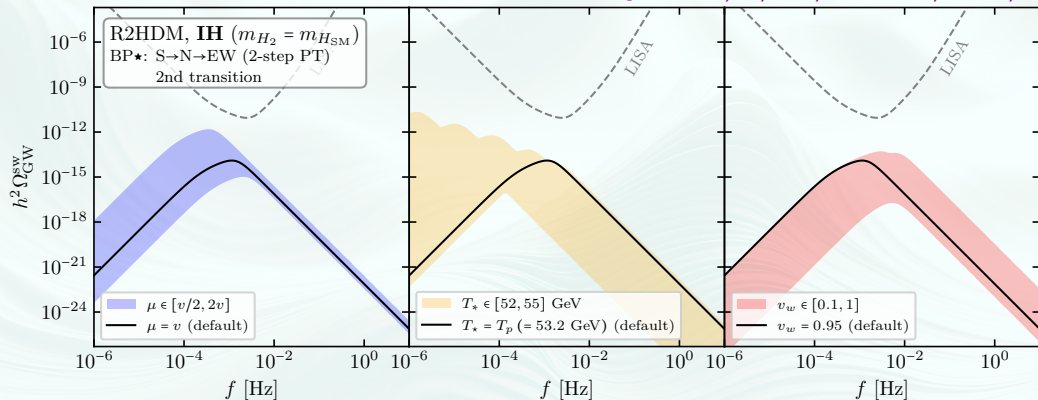
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Uncertainties on gravitational-wave spectra

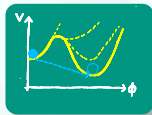
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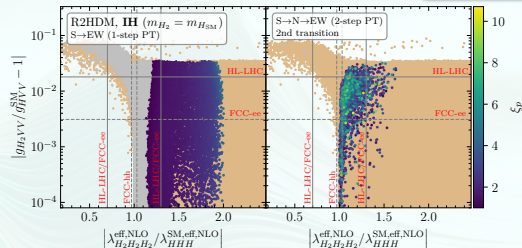
- ▶ BP*: showing only dominant sound-wave spectrum
- ▶ Variation of renormalisation scale, transition temperature, wall velocity
- ▶ Uncertainties can lead to changes of the SNR of **orders of magnitude!**

Summary and conclusions

Vacuum evolution and phase transitions of the real 2HDM



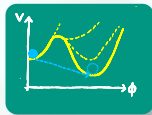
- ▶ Comprehensive parameter scan in the R2HDM type I with **BSMPTv3**
- ▶ **1-step** and **multi-step SFOPTs** with distinct parameter regions
⇒ Important interplay between **GW** and **collider phenomenology**
- ▶ **Large parametric and perturbative uncertainties** on GW predictions!



[Biermann, CB, Boto, Mühlleitner, Santos, Viana; 2608.25636]

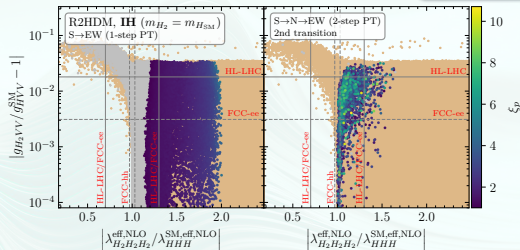
Summary and conclusions

Vacuum evolution and phase transitions of the real 2HDM



- ▶ Comprehensive parameter scan in the R2HDM type I with **BSMPTv3**
- ▶ **1-step** and **multi-step SFOPTs** with distinct parameter regions
 $\Rightarrow$ Important interplay between **GW** and **collider phenomenology**
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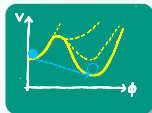
[Biermann, CB, Boto, Mühlleitner, Santos, Viana; 2608.25636]



Study of **precision improvements**, **theory uncertainties**; inclusion of **CP violation**

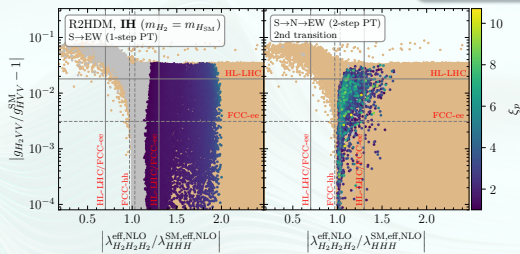
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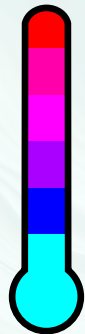
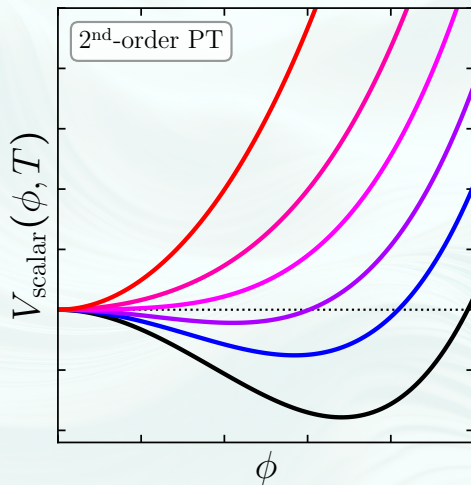
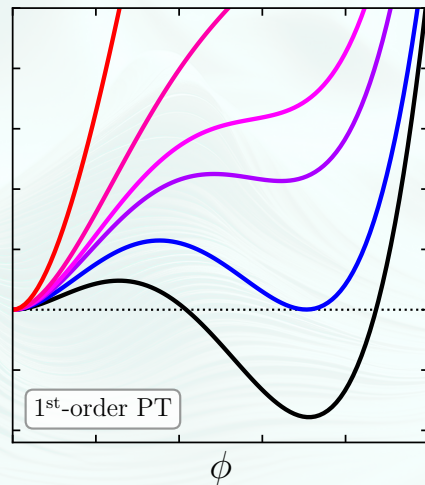


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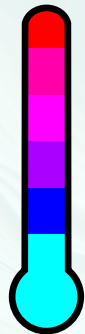
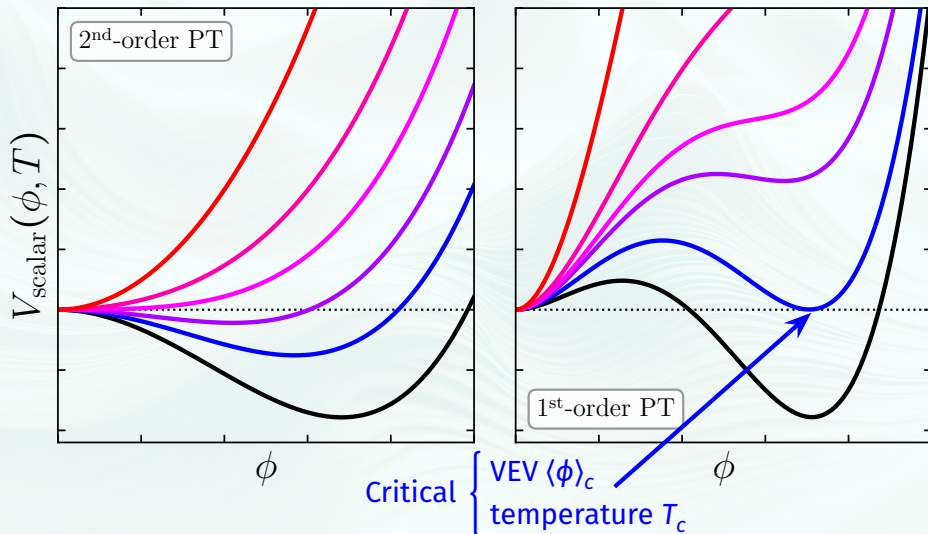
THANK YOU FOR YOUR ATTENTION! 😊

Backup

Once upon a time, there was a phase transition (PT)...



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2HDM mass eigenstates

Mass basis at $T = 0$

$$\Phi_1 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_1 + i\eta_1 \\ \zeta_1 + v_1 + i\psi_1 \end{pmatrix}, \quad \Phi_2 = \frac{1}{\sqrt{2}} \begin{pmatrix} \rho_2 + i\eta_2 \\ \zeta_2 + v_2 + i\psi_2 \end{pmatrix}$$

$\zeta_1, \zeta_2, \psi_1, \psi_2$ and $\rho_1, \rho_2, \eta_1, \eta_2$

mixing to

$H_1, H_2, A, H^\pm$ and would-be Goldstones $G^0, G^\pm$

- CP-even H_1, H_2 with $m_{H_1} < m_{H_2}$; CP-odd A with m_A ; charged $H^\pm$ with $m_{H^\pm}$

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- ▶ CP-even H_1, H_2 with $m_{H_1} < m_{H_2}$; CP-odd A with m_A ; charged $H^\pm$ with $m_{H^\pm}$
- ▶ Physical input parameters: $m_{H_1}, m_{H_2}, m_A, m_{H^\pm}, m_{12}^2, \tan \beta, \alpha, v_{EW}$
with the mixing angle α of the CP-even states
- ▶ “Normal hierarchy” (NH): $m_{H_1} = m_{H_{SM}}$; “Inverted hierarchy” (IH): $m_{H_2} = m_{H_{SM}}$

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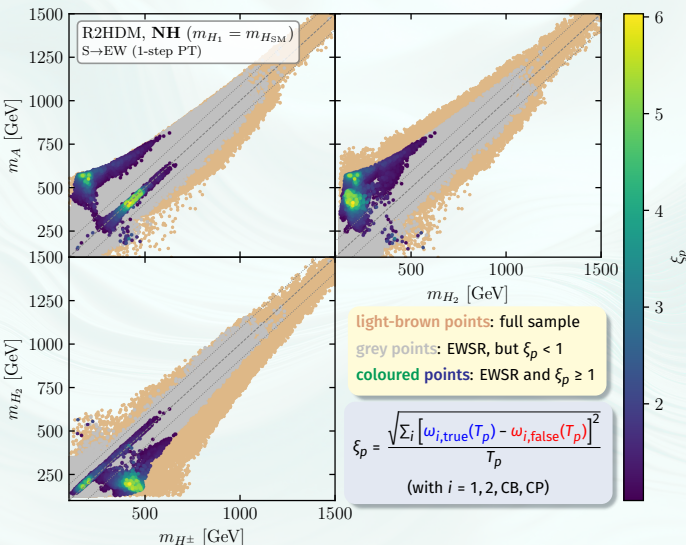
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Normal hierarchy: mass distribution



[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]

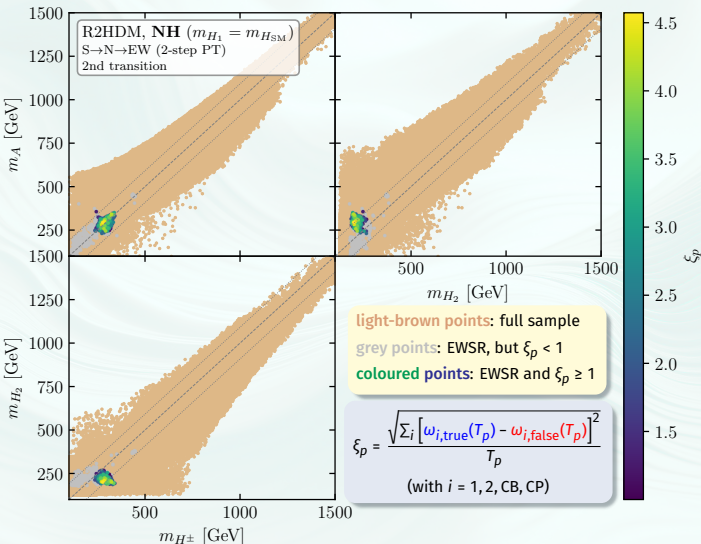
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- $m_{H^\pm} \lesssim 700$ GeV
- For strong $\xi_p > 4$: degeneracy:
 $m_{H^\pm} \approx m_A$ or $m_{H^\pm} \approx m_{H_2}$

2- and 3-step SFOPT points:

- Localized around
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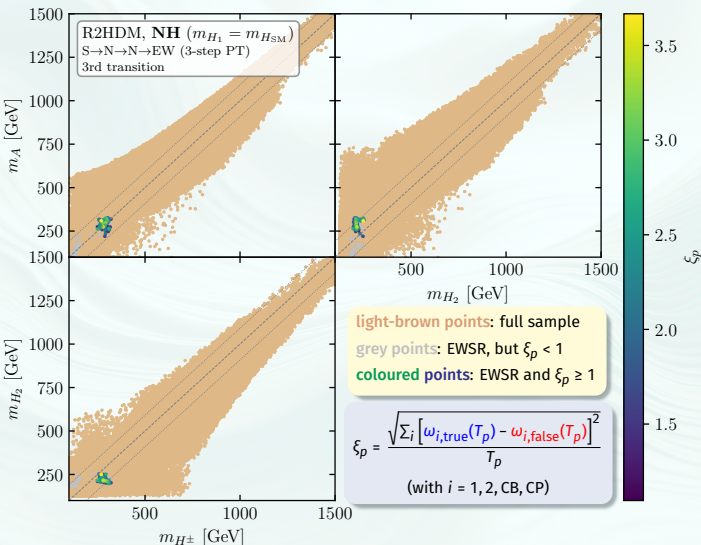
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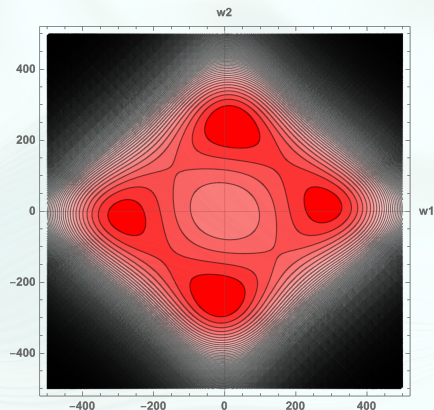
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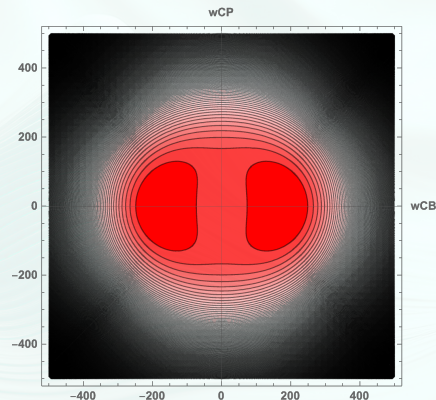
Types of vacua in the 2HDM

Type of vacuum	$\sqrt{2} \langle \Phi_1 \rangle$	$\sqrt{2} \langle \Phi_2 \rangle$
Symmetric	$\begin{pmatrix} 0 \\ 0 \end{pmatrix}$	$\begin{pmatrix} 0 \\ 0 \end{pmatrix}$
Neutral EW-breaking	$\begin{pmatrix} 0 \\ \omega_1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ \omega_2 \end{pmatrix}$
CP-breaking	$\begin{pmatrix} 0 \\ \omega_1 \end{pmatrix}$	$\begin{pmatrix} 0 \\ \omega_2 + i\omega_{\text{CP}} \end{pmatrix}$
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One-loop thermal corrections for $T \rightarrow \infty$

$$V_T \stackrel{T \rightarrow \infty}{\approx} - \sum_k n_k \begin{cases} \frac{\pi^2}{90} T^4 - \frac{1}{24} m_k^2 T^2 + \frac{1}{12\pi} \bar{m}_k^3 T & k = H^\pm, h, H, A, W_L, Z_L, \gamma_L \\ \frac{\pi^2}{90} T^4 - \frac{1}{24} m_k^2 T^2 + \frac{1}{12\pi} m_k^3 T & k = W_T, Z_T \\ \frac{7\pi^2}{720} T^4 - \frac{1}{48} m_k^2 T^2 & k = t, b, \tau \end{cases}$$

with

- ▶ n_k : number of d.o.f.s of field k
- ▶ $\bar{m}_k$ (m_k): mass eigenvalue for field k including (excluding) thermal Debye corrections from Daisy resummation

Thermal evolution

Full one-loop effective potential including thermal corrections:

$$V_{\text{eff}}(T) = V_{\text{tree}} + V_{\text{CW}} + V_{\text{CT}} + V_T(T)$$

CW: Coleman-Weinberg potential

CT: counterterm potential

T: thermal corrections

In high- T limit: T dependence in V_{eff} from

$$m_{ij}^2(T) = m_{ij}^2 + c_i T^2$$

for m_{11}^2 and m_{22}^2 and with

$$c_i = \frac{1}{12} (3\lambda_i + 2\lambda_3 + \lambda_4) + \frac{1}{16} (3g^2 + g'^2) \\ + \delta_{i2} \frac{1}{12} (y_\tau^2 + 3y_b^2 + 3y_t^2)$$

including gauge and Yukawa couplings

Electroweak symmetry (non-)restoration in the 2HDM

Is the EW symmetry always restored at $T \rightarrow \infty$? $\Rightarrow$ Check for minimum at origin

Extract leading term $\propto T^2$ for $T \rightarrow \infty$:

$$\text{Hessian } H_{ij} \equiv \left. \frac{\partial^2 V_T}{\partial \bar{\omega}_i \partial \bar{\omega}_j} \right|_{\bar{\omega}_{ij}=0} \Rightarrow \mathcal{H} \equiv \lim_{T \rightarrow \infty} \frac{H}{T^2} = \lim_{T \rightarrow \infty} \frac{1}{T^2} \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} = \begin{pmatrix} \mathcal{H}_{11} & 0 \\ 0 & \mathcal{H}_{22} \end{pmatrix}$$

with

$$\begin{aligned} \mathcal{H}_{11} &= c_1 - \frac{1}{16\pi} \left[\sqrt{2} (3g^3 + g'^3) + 4 (3\sqrt{c_1} \lambda_1 + \sqrt{c_2} (2\lambda_3 + \lambda_4)) \right] \\ \mathcal{H}_{22} &= c_2 - \frac{1}{16\pi} \left[\sqrt{2} (3g^3 + g'^3) + 4 (3\sqrt{c_2} \lambda_2 + \sqrt{c_1} (2\lambda_3 + \lambda_4)) \right] \end{aligned}$$

$\Rightarrow$ Condition for a minimum at the origin: $\mathcal{H}_{11} > 0$ and $\mathcal{H}_{22} > 0$

Finite ‘on-shell-like’ renormalisation

V_{CW} calculated in $\overline{\text{MS}}$ scheme $\rightarrow$ introduces dependence on $\overline{\text{MS}}$ scale μ

► Add **counterterm potential** V_{CT} to **change renormalisation scheme**:

$$\begin{aligned}
 V_{\text{CT}} = & \delta m_{11}^2 \Phi_1^\dagger \Phi_1 + \delta m_{22}^2 \Phi_2^\dagger \Phi_2 - \delta m_{12}^2 (\Phi_1^\dagger \Phi_2 + \text{h.c.}) + \frac{\delta \lambda_1}{2} (\Phi_1^\dagger \Phi_1)^2 + \frac{\delta \lambda_2}{2} (\Phi_2^\dagger \Phi_2)^2 \\
 & + \delta \lambda_3 (\Phi_1^\dagger \Phi_1) (\Phi_2^\dagger \Phi_2) + \delta \lambda_4 (\Phi_1^\dagger \Phi_2) (\Phi_2^\dagger \Phi_1) + \frac{\delta \lambda_5}{2} [(\Phi_1^\dagger \Phi_2)^2 + \text{h.c.}] \\
 & + \delta T_1 (\zeta_1 + \omega_1) + \delta T_2 (\zeta_2 + \omega_2) + \delta T_{\text{CP}} (\psi_2 + \omega_{\text{CP}}) + \delta T_{\text{CB}} (\rho_2 + \omega_{\text{CB}})
 \end{aligned}$$

Finite counterterms are fixed by the ‘on-shell-like’ renormalisation conditions:

- Conditions keep the **physical masses**, **mixing angles**, **VEVs** at $T = 0$ at their **tree-level values** (and independent of μ) $\Rightarrow$ convenient for parameter scans
- Residual μ dependence at $T > 0$ and beyond masses (e.g. trilinear couplings)!

Finite renormalisation constants for the 2HDM

From [Basler et al., 1803.02846]

$$\delta m_{11}^2 = \frac{1}{2} H_{\zeta_1, \zeta_1}^{\text{CW}} + H_{\psi_1, \psi_1}^{\text{CW}} - \frac{5}{2} H_{\rho_1, \rho_1}^{\text{CW}} + \frac{1}{2} \frac{v_2}{v_1} \left(H_{\zeta_1, \zeta_2}^{\text{CW}} - H_{\eta_1, \eta_2}^{\text{CW}} \right) + t v_2^2$$

$$\delta m_{22}^2 = \frac{1}{2} \left(H_{\zeta_2, \zeta_2}^{\text{CW}} - 3 H_{\eta_2, \eta_2}^{\text{CW}} \right) + \frac{1}{2} \frac{v_1}{v_2} \left(H_{\zeta_1, \zeta_2}^{\text{CW}} - H_{\eta_1, \eta_2}^{\text{CW}} \right) + \frac{v_1^2}{v_2^2} \left(H_{\psi_1, \psi_1}^{\text{CW}} - H_{\rho_1, \rho_1}^{\text{CW}} \right) + v_1^2 t$$

$$\delta m_{12}^2 = H_{\eta_1, \eta_2}^{\text{CW}} + \frac{v_1}{v_2} \left(H_{\psi_1, \psi_1}^{\text{CW}} - H_{\rho_1, \rho_1}^{\text{CW}} \right) + v_1 v_2 t$$

$$\delta \lambda_1 = \frac{1}{v_1^2} \left[2 H_{\rho_1, \rho_1}^{\text{CW}} - H_{\zeta_1, \zeta_1}^{\text{CW}} - H_{\psi_1, \psi_1}^{\text{CW}} \right] - \frac{v_2^2}{v_1^2} t$$

$$\delta \lambda_2 = \frac{1}{v_2^2} \left[H_{\eta_2, \eta_2}^{\text{CW}} - H_{\zeta_2, \zeta_2}^{\text{CW}} \right] + \frac{v_1^2}{v_2^4} \left(H_{\rho_1, \rho_1}^{\text{CW}} - H_{\psi_1, \psi_1}^{\text{CW}} \right) - \frac{v_1^2}{v_2^2} t$$

$$\delta \lambda_3 = \frac{1}{v_1 v_2} \left(H_{\eta_1, \eta_2}^{\text{CW}} - H_{\zeta_1, \zeta_2}^{\text{CW}} \right) + \frac{1}{v_2^2} \left(H_{\rho_1, \rho_1}^{\text{CW}} - H_{\psi_1, \psi_1}^{\text{CW}} \right) - t$$

$$\delta \lambda_4 = t$$

$$\delta \lambda_5 = \frac{2}{v_2^2} \left(H_{\psi_1, \psi_1}^{\text{CW}} - H_{\rho_1, \rho_1}^{\text{CW}} \right) + t$$

$$\delta T_1 = H_{\eta_1, \eta_2}^{\text{CW}} v_2 + H_{\rho_1, \rho_1}^{\text{CW}} v_1 - N_{\zeta_1}^{\text{CW}}, \quad \delta T_2 = H_{\eta_1, \eta_2}^{\text{CW}} v_1 + H_{\eta_2, \eta_2}^{\text{CW}} v_2 - N_{\zeta_2}^{\text{CW}}, \quad \delta T_{\text{CP}} = \frac{v_1^2}{v_2} H_{\zeta_1, \psi_1}^{\text{CW}} + H_{\zeta_1, \psi_2}^{\text{CW}} v_1 - N_{\psi_2}^{\text{CW}}, \quad \delta T_{\text{CB}} = -N_{\rho_2}^{\text{CW}}$$

$$N_{\phi_i}^{\text{CW}} \equiv \frac{\partial V_{\text{CW}}}{\partial \phi_i} \quad H_{\phi_i \phi_j}^{\text{CW}} \equiv \frac{\partial^2 V_{\text{CW}}}{\partial \phi_i \partial \phi_j}$$

t : free parameter, chosen such that $\delta \lambda_4 = 0$.

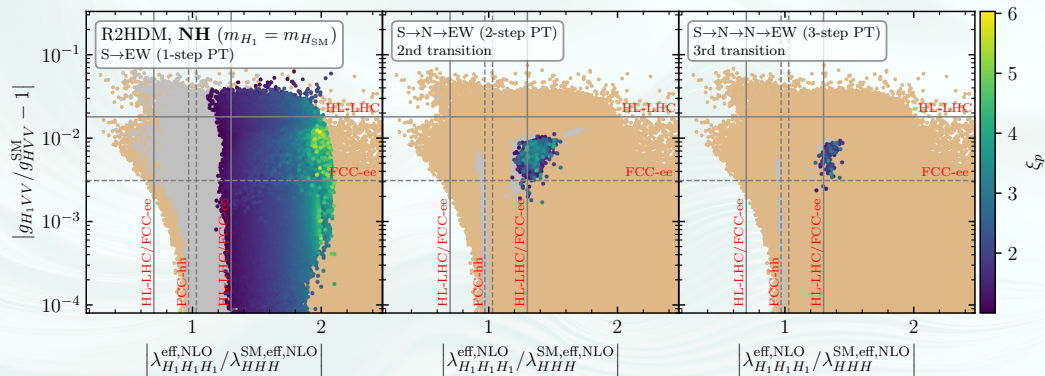
Scan ranges

	m_{H_1} [GeV]	m_{H_2} [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	$\tan \beta$	$c_{H_2 VV}$	m_{12}^2 [GeV ²]
NH	125.09	[130, 1500]	[30, 1500]	[30, 1500]	[0.8, 250]	[-0.5, 0.5]	$[10^{-3}, 10^6]$
IH	[30, 120]	125.09	[30, 1500]	[30, 1500]	[0.8, 120]	[-0.5, 0.5]	$[10^{-3}, 10^6]$

Table : Scan ranges of the R2HDM type 1 input parameters, where NH or ‘normal hierarchy’ (IH or ‘inverted hierarchy’) refers to the set-up where the lighter (heavier) of the two CP-even neutral Higgs bosons is the SM-like Higgs H_{SM} , *i.e.* $H_1(H_2) \equiv H_{\text{SM}}$.

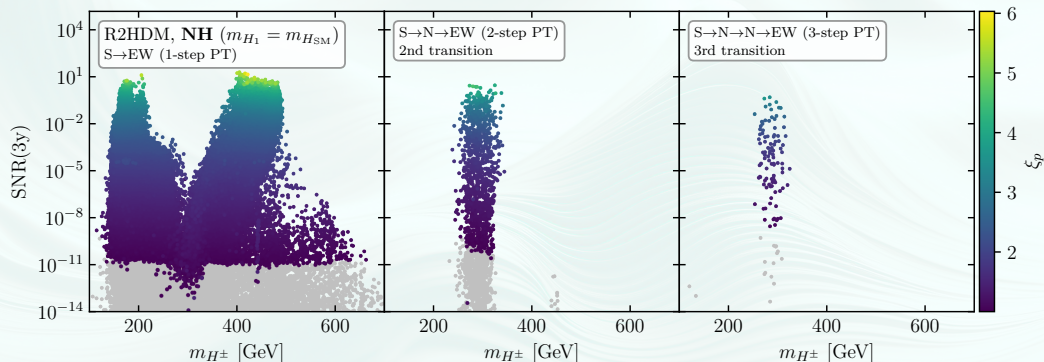
Normal hierarchy: triple-Higgs vs. Higgs-gauge couplings

[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



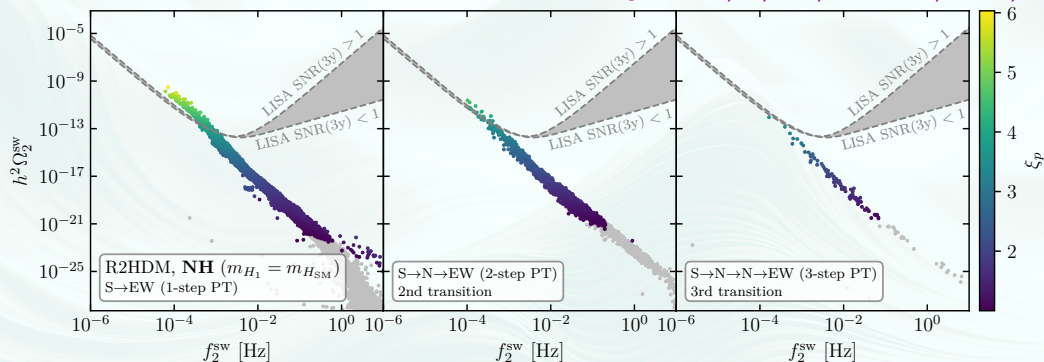
Normal hierarchy: signal-to-noise ratios for gravitational waves

[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



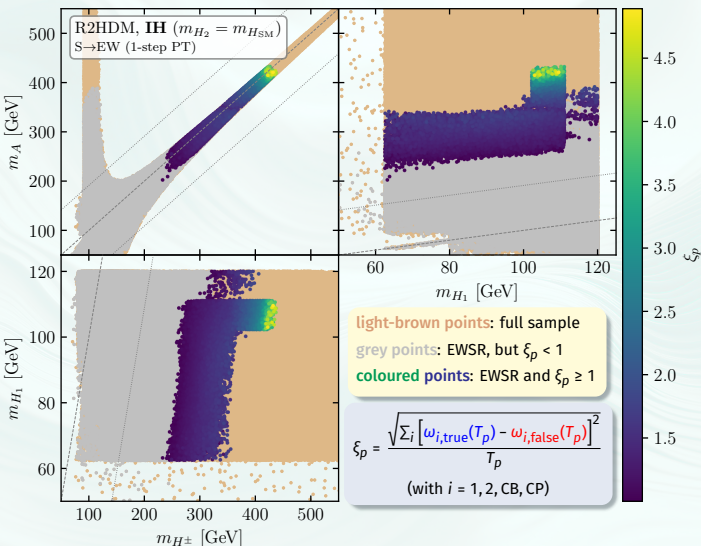
Normal hierarchy: gravitational-wave frequency spectra

[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



- Points above (below) LISA curve: $\text{SNR}(3y) > 1$ (< 1); points inside grey band: $\text{SNR}(3y)$ depends on f_1^{sw}
- Stronger GW signals for 1-step PTs than for multi-step PTs

Inverted hierarchy: mass distribution



[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]

1-step SFOPT points:

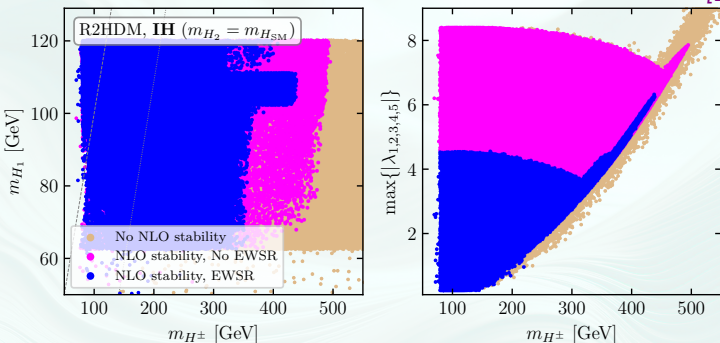
- ▶ $250 \text{ GeV} < m_{H^\pm} < 450 \text{ GeV}$
- ▶ Distinct region for large ξ_p and large $m_{H^\pm}$ due to **requirement of EW symmetry restoration**

2-step SFOPT points:

- ▶ Somewhat similar, slightly lower range of $m_{H^\pm}$ compared to 1-step points
- ▶ No distinct regions for strong ξ_p

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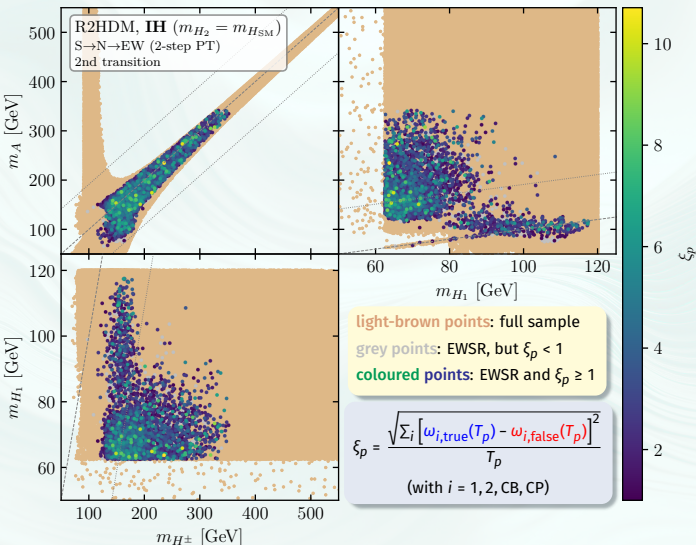
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[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]

1-step SFOPT points:

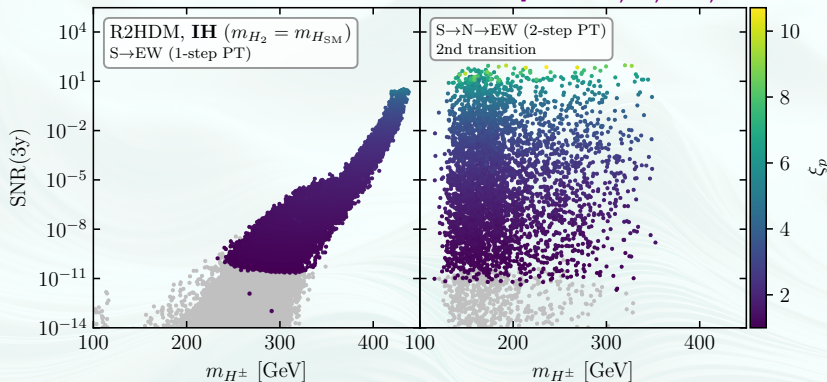
- ▶ $250 \text{ GeV} < m_{H^\pm} < 450 \text{ GeV}$
- ▶ Distinct region for large ξ_p and large $m_{H^\pm}$ due to **requirement of EW symmetry restoration**

2-step SFOPT points:

- ▶ Somewhat similar, slightly lower range of $m_{H^\pm}$ compared to 1-step points
- ▶ No distinct regions for strong ξ_p

Inverted hierarchy: signal-to-noise ratios for gravitational waves

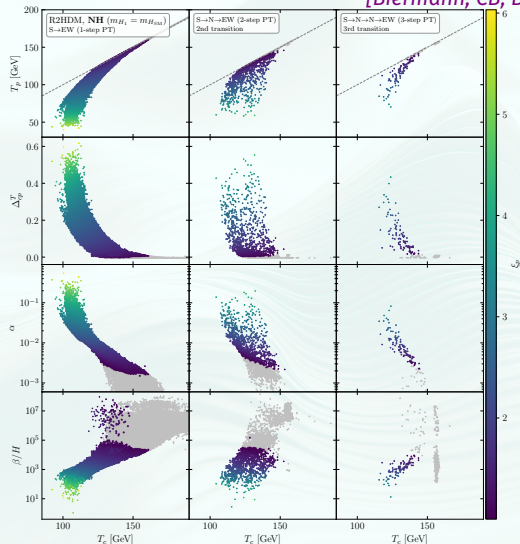
[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



- **Distinct parameter space** for largest SNR values for 1-step ($m_{H^\pm} \gtrsim 400$ GeV) and 2-step PTs ($100 \text{ GeV} < m_{H^\pm} < 350$ GeV)
- $\Rightarrow$ Simultaneous measurement of $H^\pm$ and GWs: **hints** towards transition history

Normal hierarchy: thermal parameters

[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]



Inverted hierarchy: thermal parameters

[Biermann, CB, Boto, Mühlleitner, Santos, Viana '26]

